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# **VBFNLO: A parton level Monte Carlo for processes with electroweak bosons – Manual for Version 2.7.0 BETA 1**

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## Abstract

VBFNLO is a flexible parton level Monte Carlo program for the simulation of vector boson fusion (VBF), 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 beta version – VERSION 2.7.0 BETA 1 – the anomalous gauge boson couplings implementation has been extended to several additional processes. Anomalous quartic couplings from dimension 8 operators have been added to all vector boson pair production processes as well as to the triple vector boson production process  $ZZZ$  and all triple vector boson production processes with a final state photon. Furthermore VBFNLO can output results not only for a specific choice of final state leptons, but also for all possible combinations of two or three lepton generations.

**Please be aware:** This beta version includes new code that has not been as extensively tested and checked as a normal release. The new additions to the code may also have affected features or processes that were present in the last stable release. Therefore any results obtained with this beta version should be treated with caution! Please inform us if you stumble on problems or bugs.

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# 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), 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 certain processes. Additionally, two Higgsless extra dimension models are included – the Warped Higgsless scenario and a Three-Site Higgsless Model – for selected processes. These models can be used to simulate the production of technicolor-type vector resonances in VBF and triple vector boson production. Diboson plus two jets production via VBF can also be run in a spin-2 model.

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

This manual supersedes the previous versions [1–3] released with VBFNLO VERSION 2.0, VERSION 2.5.0 and VERSION 2.6.0.

The beta version of VBFNLO 2.7 extends the following parts of VBFNLO VERSION 2.6:

- Anomalous triple and quartic gauge boson couplings are now included for all double vector boson production processes via VBF
- Anomalous triple and quartic gauge boson couplings are now included for  $ZZZ$  production and all triple vector boson production processes that contain a final state photon.

- The set of operators leading to with anomalous triple gauge boson couplings has been extended for the processes  $WWZ$ ,  $ZZW$  and  $WWW$ .
- VBFNLO can now output results not only for a specific choice of final state leptons, but also results summed over all possible combinations of two or three lepton generations.
- Processes 4105-7, Higgs plus two jets produced via gluon fusion, with the Higgs boson decaying into  $WW$  or  $ZZ$ , can now be run with anomalous  $HVV$  couplings in the decay and a mixed  $\mathcal{CP}$ -even –  $\mathcal{CP}$ -odd Higgs being produced.

**Please be aware:** This beta version includes new code that has not been as extensively tested and checked as a normal release. The new additions to the code may also have affected features or processes that were present in the last stable release. Therefore any results obtained with this beta version should be treated with caution! Please inform us if you stumble on problems or bugs.

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

<http://www-itp.particle.uni-karlsruhe.de/vbfno/>

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

### 2.1 Prerequisites

The basic installation requires GNU `make`, a FORTRAN77<sup>1</sup> and a C++ compiler. VBFNLO offers the possibility of using the LHAPDF<sup>2</sup> [4] library for parton distribution functions. In order to include the electroweak corrections to VBF Higgs production, the program LOOPTOOLS<sup>3</sup> [5,6] is required. Additionally, FEYNHIGGS<sup>4</sup> [7–10] 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)<sup>5</sup> is required. VBFNLO can also be linked to ROOT<sup>6</sup> and HEPMC<sup>7</sup> to produce histograms and event files in those formats.

### 2.2 Compilation and installation

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

- `--prefix=[path]`  
Install VBFNLO in the location given by `[path]`. 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 processes) is compiled<sup>8</sup>. Optionally, `[list]` gives a comma-separated list of selected processes to be compiled. Possible process names are:

<code>vbfb</code>	Vector boson fusion processes
<code>diboson</code>	Double gauge boson production
<code>triboson</code>	Triple gauge boson production
<code>dibosonjet</code>	Double gauge boson production with a hadronic jet
<code>tribosonjet</code>	Triboson production in association with a hadronic jet
<code>hjjj</code>	Higgs boson plus three jet production via vector boson fusion
<code>ggf</code>	Higgs boson plus two jet production via gluon fusion
<code>all</code>	All the above processes

---

<sup>1</sup>g77, ifort and gfortran have been tested.

<sup>2</sup><http://projects.hepforge.org/lhapdf/>

<sup>3</sup><http://www.feynarts.de/looptools/>

<sup>4</sup><http://www.feynhiggs.de/>

<sup>5</sup><http://www.gnu.org/software/gsl/>

<sup>6</sup><http://root.cern.ch/>

<sup>7</sup><http://lcgapp.cern.ch/project/simu/HepMC/>

<sup>8</sup>This is simply due to the relatively long time required to compile the hexagon routines.

- `--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-spin2`  
Enable simulation of spin-2 models. Disabled by default.
- `--with-gsl=[path]`  
Enable the use of the GNU Scientific Library. `[path]` specifies the location of the GSL installation.
- `--with-LHAPDF=[path]`  
Enable the use of LHAPDF in addition to the built-in PDF sets. Disabled by default. `[path]` specifies the location of the LHAPDF installation.
- `--with-LOOPTOOLS=[path]`  
Enable the use of LOOPTOOLS in order to calculate the electroweak corrections. If this option is not specified, the electroweak corrections cannot be included. Disabled by default. `[path]` specifies the location of the LOOPTOOLS installation.
- `--with-FEYNHIGGS=[path]`  
Enable the use of FEYNHIGGS<sup>9</sup> 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 `root` directory. Once `configure` has finished successfully, the `make` and `make install` commands will compile and install VBFNLO, respectively.

## 2.3 Source and installation directory layout

The VBFNLO source tree contains the following subdirectories:

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

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<sup>9</sup>Note that different versions of FEYNHIGGS give slightly different results as more corrections are added to the calculations. VBFNLO has been tested with FEYNHIGGS versions 2.6.x, 2.7.x, 2.8.0 and 2.8.3.



- `doc/`: The source of this manual.
- `helas/`: HELAS [11] subroutines used to calculate helicity amplitudes.
- `loops/`: One-loop tensor integrals up to six-point functions [12].
- `PDFsets/`: Built-in parton distributions (CTEQ6L1 [13] for LO and CT10 [14] for NLO calculations, as well as MRST2004qed [15] and MSTW2008 [16]).
- `phasespace/`: Specialized phase-space generators for the processes provided.
- `regress/`: Folder containing example results, together with input files, for all processes.
- `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. 4. In addition, it provides a few basic histograms. Cuts, histograms and scale choices not already provided may be added in the `utilities/cuts.F`, `utilities/histograms.F` and `utilities/scales.F` files.

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

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

## 2.4 Running the program

Both the `vbfnlo` and `ggflo` executables contained in the `bin` directory of the installation path look for input files in 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 in 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, by default, `xsection.out`) is produced, which contains only the LO and NLO cross sections, with the associated errors. Histograms and event files, in various forms, can be output as described later.

### 2.4.1 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 processes and triboson plus jet 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 are provided 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. 4.1.1.

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. 4.9) 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 MacOSX

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

## 2.6 Bug reports

Please report any problems to

`vbfnlo@particle.uni-karlsruhe.de`

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

## 2.7 License

VBFNLO is distributed under the GNU General Public License (GPL) version 2. This ensures that the source code will be available to users, grants them the freedom to use and modify the program and sets out the conditions under which it can be redistributed. However, it was developed as part of an academic research project and is the result of many years of work by the authors, which raises various issues that are not covered by the legal framework of the GPL. It is therefore distributed together with a set of guidelines<sup>10</sup>, which were originally formulated and agreed on by the MCnet collaboration for event generator software.

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<sup>10</sup>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 fermion interference contributions [17–19] are therefore disregarded. “Final state” weak bosons decay into massless leptons. Numerically small contributions from Pauli-interference effects for identical charged leptons are neglected. For final-state identified photons we employ the isolation criterion of Ref. [20]. This ensures that divergences from collinear emission of a photon from a final-state massless quark or anti-quark are avoided, while the cancellation of the infrared divergences between the virtual and the real part is kept intact.

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

$$\frac{1}{s - M_H^2 + iM_H\Gamma_H}. \quad (1)$$

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. I.e. in charged current processes such as  $WW$  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  $pp \rightarrow Hjj$  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 not be included in any processes. 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<sup>11</sup>.

#### 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  $qq' \rightarrow qq'H$  and crossing related reactions. In VBFNLO, tree level cross sections, NLO QCD corrections and 1-loop electroweak corrections (in the Standard Model and the MSSM) to the  $t$ -channel production process are provided. The subsequent decay of the Higgs boson is simulated in the narrow width approximation (NWA). For the  $H \rightarrow W^+W^-$  and the  $H \rightarrow ZZ$  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. [21–23].

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<sup>11</sup>Note that, if the file `global.inc` is changed, `make clean` must be run in the folders `utilities` and `amplitudes`, and then `make all install` must be run for the VBFNLO code.

PROCID	PROCESS	BSM
<b>100</b>	$p\bar{p}^{(-)} \rightarrow H jj$	} anomalous HVV couplings, MSSM
<b>101</b>	$p\bar{p}^{(-)} \rightarrow H jj \rightarrow \gamma\gamma jj$	
<b>102</b>	$p\bar{p}^{(-)} \rightarrow H jj \rightarrow \mu^+\mu^- jj$	
<b>103</b>	$p\bar{p}^{(-)} \rightarrow H jj \rightarrow \tau^+\tau^- jj$	
<b>104</b>	$p\bar{p}^{(-)} \rightarrow H jj \rightarrow b\bar{b} jj$	
<b>105</b>	$p\bar{p}^{(-)} \rightarrow H jj \rightarrow W^+W^- jj \rightarrow \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2} jj$	
<b>106</b>	$p\bar{p}^{(-)} \rightarrow H jj \rightarrow ZZ jj \rightarrow \ell_1^+\ell_1^-\ell_2^+\ell_2^- jj$	
<b>107</b>	$p\bar{p}^{(-)} \rightarrow H jj \rightarrow ZZ jj \rightarrow \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2} jj$	

Table 1: *Process IDs for  $p\bar{p}^{(-)} \rightarrow Hjj$  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.*

PROCID	PROCESS
<b>110</b>	$p\bar{p}^{(-)} \rightarrow H jjj$
<b>111</b>	$p\bar{p}^{(-)} \rightarrow H jjj \rightarrow \gamma\gamma jjj$
<b>112</b>	$p\bar{p}^{(-)} \rightarrow H jjj \rightarrow \mu^+\mu^- jjj$
<b>113</b>	$p\bar{p}^{(-)} \rightarrow H jjj \rightarrow \tau^+\tau^- jjj$
<b>114</b>	$p\bar{p}^{(-)} \rightarrow H jjj \rightarrow b\bar{b} jjj$
<b>115</b>	$p\bar{p}^{(-)} \rightarrow H jjj \rightarrow W^+W^- jjj \rightarrow \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2} jjj$
<b>116</b>	$p\bar{p}^{(-)} \rightarrow H jjj \rightarrow ZZ jjj \rightarrow \ell_1^+\ell_1^-\ell_2^+\ell_2^- jjj$
<b>117</b>	$p\bar{p}^{(-)} \rightarrow H jjj \rightarrow ZZ jjj \rightarrow \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2} jjj$

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

### 3.2 VBF Higgs boson production in association with three jets

Adding an extra parton to the Higgs production processes of Sec. 3.1 gives rise to  $Hjjj$  final states. The corresponding cross sections are implemented at NLO QCD accuracy (with certain approximations) in VBFNLO. A list of all available modes and corresponding process IDs is given in Table 2. Details of the calculation can be found in Ref. [24].

PROCID	PROCESS
<b>2100</b>	$p\bar{p}^{(-)} \rightarrow H\gamma jj$
<b>2101</b>	$p\bar{p}^{(-)} \rightarrow H\gamma jj \rightarrow \gamma\gamma\gamma jj$
<b>2102</b>	$p\bar{p}^{(-)} \rightarrow H\gamma jj \rightarrow \mu^+\mu^-\gamma jj$
<b>2103</b>	$p\bar{p}^{(-)} \rightarrow H\gamma jj \rightarrow \tau^+\tau^-\gamma jj$
<b>2104</b>	$p\bar{p}^{(-)} \rightarrow H\gamma jj \rightarrow b\bar{b}\gamma jj$
<b>2105</b>	$p\bar{p}^{(-)} \rightarrow H\gamma jj \rightarrow W^+W^-\gamma jj \rightarrow \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\gamma jj$
<b>2106</b>	$p\bar{p}^{(-)} \rightarrow H\gamma jj \rightarrow ZZ\gamma jj \rightarrow \ell_1^+\ell_1^-\ell_2^+\ell_2^-\gamma jj$
<b>2107</b>	$p\bar{p}^{(-)} \rightarrow H\gamma jj \rightarrow ZZ\gamma jj \rightarrow \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\gamma jj$

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

PROCID	PROCESS	BSM
<b>120</b>	$p\bar{p}^{(-)} \rightarrow Zjj \rightarrow \ell^+\ell^-jj$	$\left. \begin{array}{l} \\ \\ \\ \\ \end{array} \right\} \text{anomalous couplings}$
<b>121</b>	$p\bar{p}^{(-)} \rightarrow Zjj \rightarrow \nu_\ell\bar{\nu}_\ell jj$	
<b>130</b>	$p\bar{p}^{(-)} \rightarrow W^+jj \rightarrow \ell^+\nu_\ell jj$	
<b>140</b>	$p\bar{p}^{(-)} \rightarrow W^-jj \rightarrow \ell^-\bar{\nu}_\ell jj$	
<b>150</b>	$p\bar{p}^{(-)} \rightarrow \gamma jj$	

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. [25].

### 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 in this class. Details of the calculations can be found in Refs. [26, 27].

PROCID	PROCESS	BSM
<b>191</b>	$p\bar{p}^{(-)} \rightarrow S_2 jj \rightarrow \gamma\gamma jj$	spin-2 resonant production only

Table 5: *Process ID 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 given in Table 5. This process is only available if it has been enabled at compilation (using the `configure` flag `--enable-spin2`), and will only run if the switch `SPIN2` in `vbfno.dat` is set to `true`. The parameters of the spin-2 model are input via `spin2coupl.dat`.

### 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. This process class can also be run in the Higgsless and spin-2 models implemented in VBFNLO, with the exception of same-sign  $WW$  production. Details of the calculations can be found in Refs. [28–32].

PROCID	PROCESS	BSM
<b>200</b>	$p\bar{p}^{(-)} \rightarrow W^+W^- jj \rightarrow \ell_1^+ \nu_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2} jj$	$\left. \begin{array}{l} \text{anomalous couplings,} \\ \text{Kaluza-Klein models,} \\ \text{spin-2 models} \end{array} \right\}$
<b>210</b>	$p\bar{p}^{(-)} \rightarrow ZZ jj \rightarrow \ell_1^+ \ell_1^- \ell_2^+ \ell_2^- jj$	
<b>211</b>	$p\bar{p}^{(-)} \rightarrow ZZ jj \rightarrow \ell_1^+ \ell_1^- \nu_{\ell_2} \bar{\nu}_{\ell_2} jj$	
<b>220</b>	$p\bar{p}^{(-)} \rightarrow W^+Z jj \rightarrow \ell_1^+ \nu_{\ell_1} \ell_2^+ \ell_2^- jj$	
<b>230</b>	$p\bar{p}^{(-)} \rightarrow W^-Z jj \rightarrow \ell_1^- \bar{\nu}_{\ell_1} \ell_2^+ \ell_2^- jj$	
<b>250</b>	$p\bar{p}^{(-)} \rightarrow W^+W^+ jj \rightarrow \ell_1^+ \nu_{\ell_1} \ell_2^+ \nu_{\ell_2} jj$	$\left. \begin{array}{l} \text{anomalous couplings} \end{array} \right\}$
<b>260</b>	$p\bar{p}^{(-)} \rightarrow W^-W^- jj \rightarrow \ell_1^- \bar{\nu}_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2} jj$	

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

PROCID	PROCESS	BSM
<b>300</b>	$p\bar{p}^{(-)} \rightarrow W^+W^- \rightarrow \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}$	anomalous $HVV$ and $VVV$ couplings
<b>310</b>	$p\bar{p}^{(-)} \rightarrow W^+Z \rightarrow \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-$	} anomalous $VVV$ couplings
<b>320</b>	$p\bar{p}^{(-)} \rightarrow W^-Z \rightarrow \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-$	
<b>330</b>	$p\bar{p}^{(-)} \rightarrow ZZ \rightarrow \ell_1^-\ell_1^+\ell_2^-\ell_2^+$	anomalous $HVV$ couplings
<b>340</b>	$p\bar{p}^{(-)} \rightarrow W^+\gamma \rightarrow \ell_1^+\nu_{\ell_1}\gamma$	} anomalous $VVV$ couplings
<b>350</b>	$p\bar{p}^{(-)} \rightarrow W^-\gamma \rightarrow \ell_1^-\bar{\nu}_{\ell_1}\gamma$	
<b>360</b>	$p\bar{p}^{(-)} \rightarrow Z\gamma \rightarrow \ell_1^-\ell_1^+\gamma$	} anomalous $HVV$ couplings
<b>370</b>	$p\bar{p}^{(-)} \rightarrow \gamma\gamma$	

Table 7: *Process IDs for the diboson production processes at NLO QCD accuracy.*

### 3.7 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 7 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.

### 3.8 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 boson is replaced by an on-shell photon, giving rise to lepton production in association with photon(s) and triple photon production. In VBFNLO, the processes listed in Table 8 are implemented to NLO QCD accuracy, including full off-shell effects and spin correlations of the final state leptons and photons. For processes with three massive gauge bosons, the Higgs boson contributions are included in the Standard Model. Anomalous vector boson couplings<sup>12</sup> 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 Kaluza-Klein models. Details of the calculations can be found in Refs. [33–38].

<sup>12</sup>Some anomalous  $VVV$  ( $f_W$  and  $f_B$  or, equivalently,  $\Delta\kappa_\gamma$  and  $\Delta g_1^Z$ ) couplings also imply anomalous  $HVV$  couplings – these are automatically taken into account.

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

Table 8: *Process IDs for the triboson production processes at NLO QCD accuracy.*

PROCID	PROCESS	BSM
610	$p\bar{p} \rightarrow W^-\gamma j \rightarrow \ell^- \bar{\nu}_{\ell} \gamma j$	} anomalous couplings
620	$p\bar{p} \rightarrow W^+\gamma j \rightarrow \ell^+ \nu_{\ell} \gamma j$	
630	$p\bar{p} \rightarrow W^-Zj \rightarrow \ell_1^- \bar{\nu}_{\ell_1} \ell_2^- \ell_2^+ j$	
640	$p\bar{p} \rightarrow W^+Zj \rightarrow \ell_1^+ \nu_{\ell_1} \ell_2^- \ell_2^+ j$	

Table 9: *Process IDs for  $W\gamma j$  and  $WZj$  production at NLO QCD.*

### 3.9 Double vector boson production in association with a hadronic jet

$W\gamma$  and  $WZ$  production in association with a hard hadronic jet are available in VBFNLO at NLO QCD accuracy under the process IDs of Table 9. All off-shell and finite width effects in the fixed width scheme are included. The processes can be run with anomalous  $WWZ$  and  $WW\gamma$  couplings, input via `anomV.dat`. Details can be found in Refs. [39–42].



PROCID	PROCESS	BSM
<b>800</b>	$p\bar{p}^{(-)} \rightarrow W^+ \gamma \gamma j \rightarrow \ell^+ \nu_\ell \gamma \gamma j$	} anomalous couplings
<b>810</b>	$p\bar{p}^{(-)} \rightarrow W^- \gamma \gamma j \rightarrow \ell^- \bar{\nu}_\ell \gamma \gamma j$	

Table 10: *Process IDs for triboson production in association with a hadronic jet at NLO QCD.*

### 3.10 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 10. All off-shell and finite width effects in the fixed width scheme are included. Anomalous vector boson couplings are implemented, with the anomalous parameters input via `anomV.dat`. Details can be found in Ref. [43]. 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` or `--enable-processes=tribosonjet`.

### 3.11 Higgs boson production in gluon fusion with two jets

$\mathcal{CP}$ -even and  $\mathcal{CP}$ -odd Higgs boson production in gluon fusion, associated with two additional jets, is a process that first appears at the 1-loop level which, therefore, is counted as leading order in the strong coupling. This process is simulated (via the `ggflo` executable) with the full mass dependence of the top- and bottom-quark<sup>13</sup> 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 relevant process IDs are given in Table 11. Details of the calculations can be found in Refs. [44–49].

### 3.12 Gluon induced diboson production

Gluon induced diboson production can be studied separately in VBFNLO at LO with the `ggflo` executable, using the process IDs in Table 12<sup>14</sup>. 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<sup>15</sup> are included.

<sup>13</sup>The value  $m_b(M_H)$  is used.

<sup>14</sup>These are also included by default as higher order corrections to diboson production.

<sup>15</sup>Again,  $m_b(M_H)$  is used.

PROCID	PROCESS	BSM
<b>4100</b>	$p\bar{p} \rightarrow H jj$	MSSM, general 2HDM
<b>4101</b>	$p\bar{p} \rightarrow H jj \rightarrow \gamma\gamma jj$	} MSSM
<b>4102</b>	$p\bar{p} \rightarrow H jj \rightarrow \mu^+\mu^- jj$	
<b>4103</b>	$p\bar{p} \rightarrow H jj \rightarrow \tau^+\tau^- jj$	
<b>4104</b>	$p\bar{p} \rightarrow H jj \rightarrow b\bar{b} jj$	
<b>4105</b>	$p\bar{p} \rightarrow H jj \rightarrow W^+W^- jj \rightarrow \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2} jj$	} MSSM, general 2HDM, anomalous $HVV$
<b>4106</b>	$p\bar{p} \rightarrow H jj \rightarrow ZZ jj \rightarrow \ell_1^+\ell_1^-\ell_2^+\ell_2^- jj$	
<b>4107</b>	$p\bar{p} \rightarrow H jj \rightarrow ZZ jj \rightarrow \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2} jj$	

Table 11: *Process IDs for LO Higgs boson plus 2 jet production via gluon fusion. Note that these processes are accessed via the `ggflo` executable.*

PROCID	PROCESS	BSM
<b>4300</b>	$gg \rightarrow W^+W^- \rightarrow \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}$	} anomalous $HVV$ couplings
<b>4330</b>	$gg \rightarrow ZZ \rightarrow \ell_1^-\ell_1^+\ell_2^-\ell_2^+$	
<b>4360</b>	$gg \rightarrow Z\gamma \rightarrow \ell_1^-\ell_1^+\gamma$	
<b>4370</b>	$gg \rightarrow \gamma\gamma$	

Table 12: *Process IDs for the gluon induced diboson production at LO (one-loop) QCD. Note that these processes are accessed via the `ggflo` executable.*

## 4 INPUT FILES AND PARAMETERS

VBFNLO is steered through the following input files:

- `vbfnlo.dat`: General parameters for a run.
- `cuts.dat`: Values for kinematic cuts.
- `ggflo.dat`: Additional parameters for the `ggflo` program.
- `susy.dat`: Parameters describing the MSSM scenario.
- `anom_HVV.dat`: Parameters for anomalous Higgs boson couplings.
- `anomV.dat`: Parameters for anomalous gauge boson couplings.
- `kk_input.dat`: Settings for the Warped Higgsless and Three-Site Higgsless Models.

- `kk_coupl_inp.dat`: Numerical values if externally calculated Kaluza-Klein couplings and masses should be used.
- `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.

## 4.1 `vbfnlo.dat`

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

### 4.1.1 `vbfnlo.dat` – general parameters

- **PROCESS**: Process ID as described in Sec. 3. Default is 100: Higgs boson production via VBF.
- **LOPROCESS\_PLUS\_JET**: If set to `true`, the leading order process with one additional jet is generated, i.e. only the real radiation contribution is generated. This option is available for all but gluon 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 [50]:

```

11 :  $e^-$ 
12 :  $\nu_e$ 
13 :  $\mu^-$ 
14 :  $\nu_\mu$ 
15 :  $\tau^-$ 
16 :  $\nu_\tau$ 
98 : leptons are either generation 1 or generation 2
99 : any lepton

```

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.

- **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<sup>16</sup>. For an adapted grid file (see **LO\_GRID**) this parameter can be set to 1. Default is 4.

---

<sup>16</sup>For all NLO calculations the virtual contributions are calculated using the already optimized leading order grid.

- **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  $N = \text{LO\_POINTS}$ . 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<sup>17</sup>. Default is  $N = 20$ .
- **NLO\_POINTS**: Similar to **LO\_POINTS**, but for the real emission part of an NLO calculation. Default is 20.
- **LO\_GRID**: Sets the name of the grid files that are generated at the end of each iteration. Choosing **name** as the input parameter, in each iteration  $X$  a grid file **name.out.X** will be produced 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 optimised grids for all 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.

---

<sup>17</sup>The virtual contributions are calculated for  $2^N$  points only.

ID_MUF	FACTORIZATION SCALE	PROCESS CLASS
0	user defined constant scale set by MUF_USER	all
1	momentum transfer of exchanged gauge boson	vbf (except Hjjj)
2	$\min(p_T(j_i))$	vbf, tribosonjet
3	invariant mass of $VV$ system	diboson
4	invariant mass of $VVV$ system	triboson, tribosonjet
5	$\sqrt{p_T(j_1) \times p_T(j_2)}$	ggf
6	constant scale = Higgs boson mass	all
7	Minimum transverse energy of bosons	diboson, triboson

Table 13: *Factorization scale options.*

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	$\min(p_T(j_i))$	vbf, tribosonjet
3	invariant mass of $VV$ system	diboson
4	invariant mass of $VVV$ system	triboson, tribosonjet
5	$\alpha_s^4 = \alpha_s(p_T(j_1)) \times \alpha_s(p_T(j_2)) \times \alpha_s^2(m_H)$	ggf
6	constant scale = Higgs boson mass	all
7	Minimum transverse energy of bosons	diboson, triboson

Table 14: *Renormalization scale options.*

The default value is 3 (all contributions included).

- ECM: The center-of-mass energy,  $\sqrt{s}$ , of the collider, measured in GeV. Default is 8000 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 13 for a list of available options. Default is 0.
- ID\_MUR: Choice of the renormalization scale. See Table 14 for a list of available options. Default is 0.

- **MUF\_USER**: If **ID\_MUF** is set to 0, this parameter sets the user defined constant factorization scale measured in GeV. Default is 100 GeV.
- **MUR\_USER**: If **ID\_MUR** is set to 0, this parameter sets the user defined constant renormalization scale measured in GeV. Default is 100 GeV.
- **XIF**: Factor by which the factorization scale is multiplied. May be used to analyze the scale dependence of differential cross sections. Default is 1.
- **XIR**: Factor by which the renormalization scale is multiplied. May be used to analyze the scale dependence of differential cross sections. Default is 1.

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

#### 4.1.2 vbfno.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.)

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

- **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 -999 GeV, which means that the internally calculated value of the width is used. 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) or MSSM (2). Default is SM (1). Note that if **HTYPE** = 1-3 is chosen with **MODEL** = 1, the code will run in the Standard Model, but with a Higgs boson mass equal to that given by the specified MSSM parameters.
- **TOPMASS**: Top-quark mass in GeV. Default value is 172.4 GeV. If a SLHA file is being used, the SLHA value will be taken rather than the input **TOPMASS**.
- **BOTTOMMASS**: Bottom-quark pole mass in GeV, used in the calculation of the Higgs boson width and branching ratios. In the gluon fusion processes and gluon-induced contributions to diboson production,  $m_b(M_H)$  is used (which is calculated internally from the input pole mass). Default value is 4.855 GeV, which corresponds to  $m_b^{\overline{MS}}(m_b) = 4.204$  GeV. The explicit formula used is given on the VBFNLO webpage. If a SLHA file is being used, the SLHA value will be taken rather than the input **BOTTOMMASS**.

- **CHARMMASS**: Charm-quark pole mass in GeV used in the calculation of the Higgs boson width and branching ratios. Default value is 1.65 GeV, corresponding to  $m_c^{\overline{MS}}(m_c) = 1.273$  GeV. If a SLHA file is being used, the SLHA value will be taken rather than the input **CHARMMASS**.
- **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 15. The implementation of **EWScheme** was simplified for VBFNLO-2.5.0: full details of all changes and their effects, together with the explicit formulae used, are available on the VBFNLO webpage. Note that if **EWScheme** = 4 is chosen, all variables in Table 15 are taken as inputs. As the parameters are not independent, this can lead to problems if the input values are not consistent. In this scheme, all photon couplings are set according to the input variable **INVALFA** and all other couplings are set according to **FERMI\_CONST**. Note also that the choice of **EWScheme** can have a large effect on the relative size of the electroweak corrections, as the charge renormalization depends on the way in which the electromagnetic coupling in the LO cross section is parametrized. Default value is 3.
- **FERMI\_CONST**: Fermi constant, used as input for the calculation of electroweak parameters in **EWScheme** = 1-4. Default value is  $1.16637 \times 10^{-5} \text{ GeV}^{-2}$ . 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 15. If **EWScheme** = 5 is chosen, the value of  $\alpha$  should be  $\alpha(M_Z)$ , whereas if **EWScheme** = 6 is chosen, the value of  $\alpha$  should be  $\alpha(0)$ . In order to ensure backwards compatibility with previous versions of VBFNLO, as an alternative **ALFA**, the fine structure constant, can be used as an input in `vbfnlo.dat`, which is read and used only if **INVALFA** is not present. If a SLHA file is being used, the SLHA value will be taken rather than the input **INVALFA** or **ALFA**.
- **DEL\_ALFA**: Value of  $\Delta\alpha$ , where

$$\alpha(M_Z) = \frac{\alpha(0)}{1 - \Delta\alpha} \quad (2)$$

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**.

EWScheme	Parameter	Default Value	Input/Calculated
1	FERMI_CONST INVALFA SIN2W WMASS ZMASS	$1.16637 \times 10^{-5} \text{ GeV}^{-2}$ 128.944341122 0.230990 79.9654 GeV 91.1876 GeV	INPUT INPUT CALCULATED CALCULATED INPUT
2	FERMI_CONST INVALFA SIN2W WMASS ZMASS	$1.16637 \times 10^{-5} \text{ GeV}^{-2}$ 132.340643024 0.222646 80.3980 GeV 91.1876 GeV	INPUT CALCULATED INPUT CALCULATED INPUT
3	FERMI_CONST INVALFA SIN2W WMASS ZMASS	$1.16637 \times 10^{-5} \text{ GeV}^{-2}$ 132.340705199 0.222646 80.3980 GeV 91.1876 GeV	INPUT CALCULATED CALCULATED INPUT INPUT
4	FERMI_CONST INVALFA SIN2W WMASS ZMASS	$1.16637 \times 10^{-5} \text{ GeV}^{-2}$ 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 15: *Electroweak input parameter schemes.*



- **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
  - diboson + jet production processes
  - triple vector boson production processes
  - triboson + jet production processes
  - $Hjj \rightarrow VVjj$  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 same sign  $WW$  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  $WW$  production. Default is set to **false**. Note that this needs to be enabled at compilation, using the **configure** option **--enable-spin2**. Spin two 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.

#### 4.1.3 `vbfnlo.dat` – parameters for event output

VBFNLO generates parton level events according to the most recent Les Houches Accord (LHA) format [51] and in the HEPMC format [52] for processes at leading order.

- `LHA_SWITCH`: Switch on or off output of LHA event files. Default is set to `false`. Note that LHA event file output is not yet available for diboson plus jet 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 `false`.
- `PRENEVUNW`: The number of events used in the last iteration in order to calculate/estimate the premaximal weight that is needed in the first step of the unweighting procedure. Default is 1000. After all events are unweighted, the maximal weight is again calculated and a reweighting procedure is applied.
- `TAUMASS`: Option to include the mass of  $\tau$  leptons in the event files. This option is only available for the `vbf` processes. Default is set to `false`.

#### 4.1.4 `vbfnlo.dat` – PDF parameters

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

- `PDF_SWITCH`: Flag to choose which PDFs are used. The options are
  - 0 : built-in PDFs CTEQ6L1 [13] for LO and CT10 [14] for NLO calculations
  - 1 : an interface to LHAPDF is provided
  - 2 : built-in PDFs MRST2004qed [15] 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 [16] 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, see `PDFsets.index` or Ref. [4]. Default is “`cteq6l1.LHpdf`” (CTEQ6L1).

- **NLO\_PDFNAME**: Name of the NLO PDF set, see `PDFsets.index` or Ref. [4]. Default is “CT10.LHgrid” (CT10).
- **LO\_PDFMEMBER**: Member PDF of the LO PDF set. Default is 0.
- **NLO\_PDFMEMBER**: Member PDF of the NLO PDF set. Default is 0.

For compatibility with earlier versions of VBFNLO, the following two variables are also supported for setting the PDF sets when using LHAPDF. If both are present, **LO\_PDFNAME** and **NLO\_PDFNAME** take precedence over **LO\_PDFSET** and **NLO\_PDFSET**, respectively.

- **LO\_PDFSET**: LHAGLUE number for the LO PDF set, see `PDFsets.index` or Ref. [4].
- **NLO\_PDFSET**: LHAGLUE number for the NLO PDF set, see `PDFsets.index` or Ref. [4].

#### 4.1.5 vbfno.dat – parameters for output and histograms

VBFNLO provides output for histograms in the following formats: TOPDRAWER<sup>18</sup>, ROOT and GNUPLOT<sup>19</sup>, 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/rootuserhisto.cpp`, which are filled with the weighted events from Monte Carlo integration. This option needs to be enabled when building VBFNLO using the option `--with-root`.
- **TOP**: Enable output of histograms in TOPDRAWER format. Default is set to `false`.
- **GNU**: Enable output of histograms in GNUPLOT format. Default is set to `true`.
- **DATA**: Enable output of raw data in a directory hierarchy. Default is set to `true`.
- **REPLACE**: Switch to overwrite existing histogram output files. Default is set to `true`.
- **ROOTFILE**: Name of the ROOT output file. Default is `histograms`.
- **TOPFILE**: Name of the TOPDRAWER output file. Default is `histograms`.
- **GNUFILE**: Name of the GNUPLOT output file. Default is `histograms`.
- **DATAFILE**: Name of the data output directory. Default is `histograms`.

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<sup>18</sup><http://www.pa.msu.edu/reference/topdrawer-docs/>

<sup>19</sup><http://www.gnuplot.info/>

## 4.2 cuts.dat – parameters for kinematic cuts

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

Jet-specific cuts:

- **RJJ\_MIN**: Minimum separation of two identified jets,  $\Delta R_{jj} = \sqrt{\Delta y_{jj}^2 + \Delta \phi_{jj}^2}$ , used by the generalised  $k_\perp$  jet finding algorithm [53] that combines all partons. Default is 0.8.
- **Y\_P\_MAX**: Maximum allowed pseudorapidity for observation of final state partons (detector edge). Default is 5.0.
- **PGENKTJET**: Exponent of the generalised  $k_\perp$  algorithm. This yields the  $k_\perp$  algorithm when setting the variable to 1, the Cambridge/Aachen algorithm [54] for 0 and the anti- $k_\perp$  algorithm [55] when setting it to  $-1$ . Default value of the floating-point number is 1.0.
- **PT\_JET\_MIN**: List of minimum transverse momenta for identified jets in descending order. The later values can be omitted if they are the same as previous values. Default is 20 GeV.
- **Y\_JET\_MAX**: Maximum allowed rapidity for identified jets. Default is 4.5.

Lepton specific cuts:

- **Y\_L\_MAX**: Maximum pseudorapidity for charged leptons. Default is 2.5.
- **PT\_L\_MIN**: Minimum transverse momentum for charged leptons. Default is 10 GeV.
- **MLL\_MIN**: Minimum invariant mass for any combination of oppositely charged leptons. Default is 15 GeV.
- **MLL\_MAX**: Maximum invariant mass for any combination of oppositely charged leptons. Default is  $10^{20}$  GeV.
- **RLL\_MIN**: Minimum separation of charged lepton pairs,  $\Delta R_{\ell\ell}$ . Default is 0.4.
- **RLL\_MAX**: Maximum separation of charged lepton pairs,  $\Delta R_{\ell\ell}$ . Default is 50.

Photon specific cuts:

- **Y\_G\_MAX**: Maximum pseudorapidity for photons. Default is 1.5.
- **PT\_G\_MIN**: Minimum transverse momentum for photons. Default is 20 GeV.
- **RGG\_MIN**: Minimum separation of photon pairs,  $\Delta R_{\gamma\gamma}$ . Default is 0.6.
- **RGG\_MAX**: Maximum separation of photon pairs,  $\Delta R_{\gamma\gamma}$ . Default is 50.
- **PHISOLCUT**: Photon isolation cut  $\delta_0$  as defined in Ref. [20]. Default is 0.7.

- **EFISOLCUT**: Efficiency  $\epsilon$  of photon isolation cut. Default is 1. The photon isolation cut is then described by:

$$\sum_i E_{T_i} \theta(\delta - R_{i\gamma}) \leq \epsilon p_{T_\gamma} \frac{1 - \cos \delta}{1 - \cos \delta_0} \text{ for all } \delta < \delta_0 \quad (3)$$

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

Additional cuts:

- **RJL\_MIN**: Minimum separation of an identified jet and a charged lepton,  $\Delta R_{j\ell}$ . Default is 0.6.
- **RJG\_MIN**: Minimum separation of an identified jet and a photon,  $\Delta R_{j\gamma}$ . Default is 0.6.
- **RLG\_MIN**: Minimum separation of a charged lepton and a photon,  $\Delta R_{\ell\gamma}$ . Default is 0.6.
- **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  $10^{20}$  GeV.

Jet veto:

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

VBF specific cuts<sup>20</sup>:

- **ETAJJ\_MIN**: Minimum required pseudorapidity gap,  $\Delta\eta_{jj}$ , between two tagging jets (the two leading jets in a  $p_T$  ordering). Default is 0.
- **YSIGN**: If set to **true**, the two tagging jets are required to be found in opposite detector hemispheres. Default is **false**.
- **LRAPIDGAP**: If set to **true** all charged leptons are required to lie between the two tagging jets in rapidity. Default is **false**.

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<sup>20</sup>These apply only to **vbf** and **ggf** processes.

- **DELY\_JL**: Minimum rapidity distance of the charged leptons from the tagging jets, if **LRAPIDGAP** is set to **true**. Default is 0.
- **GRAPIDGAP**: If set to **true** all photons are required to lie between the two tagging jets in rapidity. Default is **false**.
- **DELY\_JG**: Minimum rapidity distance of photons from tagging jets, if **GRAPIDGAP** is set to **true**. Default is 0.
- **MDIJ\_MIN**: Minimum dijet invariant mass of two tagging jets. Default is 600 GeV.
- **MDIJ\_MAX**: Maximum dijet invariant mass of two tagging jets. Default is  $10^{20}$  GeV.

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

In VBFNLO the double real-emission corrections to  $gg \rightarrow \phi$ , which lead to  $\phi + 2$  jet events at order  $\alpha_s^4$ , are included [49]. Here,  $\phi$  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<sup>21</sup>. Interference effects between loops with bottom- and top-quarks, as well as between  $\mathcal{CP}$ -even and  $\mathcal{CP}$ -odd couplings of the heavy quarks, are fully taken into account. An option to use the large top mass approximation, which works well for intermediate Higgs boson masses (provided that the transverse momenta of the final state partons are smaller than the top-quark mass), is also implemented.

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

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

- **Q\_LOOP**: Input that sets how the Higgs boson coupling is determined.
  - **Q\_LOOP** = 0: Effective theory in the large top-quark mass limit ( $m_t \rightarrow \infty$ ).
  - **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**.

---

<sup>21</sup>The bottom quark mass is taken as  $m_b(M_H)$ .

- **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.

using the Lagrangian

$$\mathcal{L}_{\text{Yukawa}} = \bar{q} (C_{\text{even}} y_q + i C_{\text{odd}} \gamma_5 \tilde{y}_q) q \Phi. \quad (4)$$

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

$$\begin{aligned} y_b &= \tilde{y}_b = \frac{1}{v} m_b \tan \beta \\ y_t &= \tilde{y}_t = \frac{1}{v} m_t \cot \beta \end{aligned} \quad (5)$$

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 **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

$$h_i = Z_{ih} h_{\text{MSSM}} + Z_{iH} H_{\text{MSSM}} + Z_{iA} A_{\text{MSSM}} \quad (6)$$

where  $i = \text{HTYPE}$ .

#### 4.4 susy.dat – parameters in the MSSM

The file **susy.dat** is used to specify the supersymmetric parameters when working in the MSSM. This file is used either if **MODEL** = 2 in **vbfnlo.dat**, or if **HTYPE** = 1-3 in **vbfnlo.dat**. As described earlier, if **MODEL** = 2 the code will run in the MSSM, which means that the Higgs boson masses, widths and couplings will all be set to the MSSM values. If **MODEL** = 1 but **HTYPE** = 1-3, the code will run in the Standard Model, and only the Higgs boson mass will be affected. Consequently, this file affects processes 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<sup>22</sup>.
- **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 [56]
  - 2: No-mixing scenario [56]
  - 3: Gluophobic scenario [56]
  - 4: Small  $\alpha_{\text{eff}}$  scenario [56]
  - 5: CPX scenario [57]
  - 10: SPS1a<sup>23</sup> [58]
  - 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 [23].

- **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.

---

<sup>22</sup>Note that a SLHA file can also be used as the input for FEYNHIGGS by setting both **FEYNH\_SWITCH** and **SLHA\_SWITCH** to **true**.

<sup>23</sup>The SPS points are defined with low-energy parameters, as given at <http://www.ipp.p.dur.ac.uk/~georg/sps/>.



– 1: Corrected Higgs masses used in loops.

- **LOOPSQR\_SWITCH**: Flag determining whether the electroweak corrections from the (s)fermion sector will be squared – i.e. if set to **true** the amplitude is given by:

$$|\mathcal{M}_{\text{Born}}|^2 + 2\Re[\mathcal{M}_{\text{Born}}^* \mathcal{M}_{\text{loop}}] + |\mathcal{M}_{(\text{s})\text{fermion loop}}|^2 \quad (7)$$

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

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.
- **MASSH**: 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<sup>24</sup>. 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**.

## 4.5 Parameters for anomalous couplings

VBFNLO supports anomalous  $HVV$  couplings, where  $V = W, Z, \gamma$ , in both the production and the decay of a Higgs boson in VBF-type reactions, i.e. for process IDs 100-107. Anomalous  $HVV$  couplings are also included in gluon induced diboson production (processes 4300, 4330, 4360, 4370, and processes 300, 330, 360 and 370), as well as in gluon fusion processes  $Hjj \rightarrow VVjj$  (IDs 4105-7). The anomalous  $HVV$  couplings can be specified in the **anom\_HVV.dat** input file.

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<sup>24</sup>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.

Anomalous triple and quartic gauge boson couplings are available for single and double vector boson production via VBF (process IDs 120-150, 200-260) [59,61], all triple vector boson production processes (process IDs 400-530, 800, 810) [60,61], diboson production  $WW$ ,  $W^\pm\gamma$  and  $W^\pm Z$  (process IDs 300-320, 340-350) and for diboson plus jet processes  $W^\pm\gamma j$  and  $W^\pm Z j$  [39,40] (IDs 610-640). The respective parameters are set in the input file `anomV.dat`<sup>25</sup>. 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 Higgs bosons (and during the Higgs width calculations).

#### 4.5.1 `anom_HVV.dat` – anomalous $HVV$ couplings

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

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

$$\begin{aligned}\mathcal{L} = & \frac{g_{5e}^{HZZ}}{2\Lambda_5} H Z_{\mu\nu} Z^{\mu\nu} + \frac{g_{5o}^{HZZ}}{2\Lambda_5} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \frac{g_{5e}^{HWW}}{\Lambda_5} H W_{\mu\nu}^+ W_-^{\mu\nu} + \frac{g_{5o}^{HWW}}{\Lambda_5} H \tilde{W}_{\mu\nu}^+ W_-^{\mu\nu} + \\ & \frac{g_{5e}^{HZ\gamma}}{\Lambda_5} H Z_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{HZ\gamma}}{\Lambda_5} H \tilde{Z}_{\mu\nu} A^{\mu\nu} + \frac{g_{5e}^{H\gamma\gamma}}{2\Lambda_5} H A_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{H\gamma\gamma}}{2\Lambda_5} H \tilde{A}_{\mu\nu} A^{\mu\nu}\end{aligned}\quad (8)$$

where the subscript  $e$  or  $o$  refers to the  $\mathcal{CP}$ -even or  $\mathcal{CP}$ -odd nature of the individual operators [62],  $V^{\mu\nu}$  is the field strength tensor of the gauge boson  $V$  and  $\tilde{V}^{\mu\nu}$  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. [63,64]:

$$\mathcal{L}_{\text{eff}} = \frac{f_W}{\Lambda_6^2} \mathcal{O}_W + \frac{f_B}{\Lambda_6^2} \mathcal{O}_B + \frac{f_{WW}}{\Lambda_6^2} \mathcal{O}_{WW} + \frac{f_{BB}}{\Lambda_6^2} \mathcal{O}_{BB} + \text{CP-odd part} \quad (9)$$

The explicit form of the operators is<sup>26</sup>

$$\begin{aligned}\mathcal{O}_W &= (D_\mu \phi^\dagger) \widehat{W}^{\mu\nu} (D_\nu \phi) \\ \mathcal{O}_B &= (D_\mu \phi^\dagger) \widehat{B}^{\mu\nu} (D_\nu \phi) \\ \mathcal{O}_{WW} &= \phi^\dagger \widehat{W}_{\mu\nu} \widehat{W}^{\mu\nu} \phi \\ \mathcal{O}_{BB} &= \phi^\dagger \widehat{B}_{\mu\nu} \widehat{B}^{\mu\nu} \phi \\ \mathcal{O}_{WWW} &= \text{Tr} \left[ \widehat{W}_{\mu\nu} \widehat{W}^{\nu\rho} \widehat{W}_\rho{}^\mu \right],\end{aligned}\quad (10)$$

with

$$\begin{aligned}\widehat{W}_{\mu\nu} &= ig T^a W_{\mu\nu}^a \\ \widehat{B}_{\mu\nu} &= ig' Y B_{\mu\nu},\end{aligned}\quad (11)$$

<sup>25</sup>In previous versions of VBFNLO, anomalous gauge boson couplings for  $WW$  production via VBF were input via the file `anom_WW.dat`. This is no longer supported.

<sup>26</sup>Note that  $\mathcal{O}_{WWW}$  is used only in the anomalous gauge boson couplings.

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 (denoted with a tilde) are needed.

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

1. A parameterization in terms of couplings in the effective Lagrangian approach given by Eq. 8.

- **PARAMETR1**: Parameter that switches on the effective Lagrangian parameterization of Eq. (8). The default value is **true**.
- **LAMBDA5**: Mass scale  $\Lambda_5$  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:
  - **G5E\_HWW** = -0.182
  - **G5E\_HZZ** = -0.044
  - **G5E\_HGG** = 0
  - **G5E\_HGZ** = -0.178

These default values are those used in the anomalous gauge boson couplings, which are approximately the central values in the three-parameter fit given in Ref. [70].

- **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. [65]. The parameters are  $d$ ,  $d_B$ ,  $\Delta g_1^Z$  and  $\Delta \kappa_\gamma$ , which are related to the coefficients  $f_i/\Lambda^2$  of the effective Lagrangian of Eq. 9 in the following manner [66]:

$$\begin{aligned}
 d &= -\frac{m_W^2}{\Lambda^2} f_{WW}, & \tilde{d} &= -\frac{m_W^2}{\Lambda^2} f_{\widetilde{WW}}, \\
 d_B &= -\frac{m_W^2}{\Lambda^2} \frac{\sin^2 \theta_w}{\cos^2 \theta_w} f_{BB}, & \tilde{d}_B &= -\frac{m_W^2}{\Lambda^2} \frac{\sin^2 \theta_w}{\cos^2 \theta_w} f_{\widetilde{BB}}, \\
 \Delta \kappa_\gamma &= \kappa_\gamma - 1 = \frac{m_W^2}{2\Lambda^2} (f_B + f_W), & \tilde{\kappa}_\gamma &= \frac{m_W^2}{2\Lambda^2} f_{\widetilde{B}}, \\
 \Delta g_1^Z &= g_1^Z - 1 = \frac{m_Z^2}{\Lambda^2} \frac{f_W}{2}.
 \end{aligned} \tag{12}$$

- **PARAMETR2**: Parameter that switches on the above mentioned parameterization of Eqs. 12. 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 equivalent to those for **PARAMETR1** and are given by:
  - **D\_EVEN** = 0
  - **DB\_EVEN** = 0
  - **DG1Z\_EVEN** = -0.06

– DKGAM\_EVEN = 0.077

- D\_ODD, DB\_ODD, KGAM\_ODD: Parameters that are the  $\mathcal{CP}$ -odd couplings in this parameterization with default values equal to 0.
  - HVV1: Parameter that determines which anomalous  $HVV$  couplings are used for the run. For HVV1 = 0, only the  $HZ\gamma$  coupling, for HVV1 = 1, only the  $H\gamma\gamma$  coupling, for HVV1 = 2, only the  $HZZ$  coupling and for HVV1 = 3, only the  $HWW$  coupling is used. If HVV1 is set to 4, all possible anomalous couplings are used. This is also the default value.
3. The parameterization of the anomalous couplings in terms of coefficients  $f_i/\Lambda^2$  of the effective Lagrangian in Eq. 9.
- PARAMETR3: Parameter that switches on the parameterization stated above. The default value is `false`.
  - FWW\_EVEN, FBB\_EVEN, FW\_EVEN, FB\_EVEN: Parameters that represent the coefficients of the  $\mathcal{CP}$ -even operators – i.e.  $f_i/\Lambda^2$  – with default values equivalent to those for PARAMETR1, which are given by
    - FWW\_EVEN = 0 GeV<sup>-2</sup>
    - FBB\_EVEN = 0 GeV<sup>-2</sup>
    - FW\_EVEN =  $-1.44 \times 10^{-5}$  GeV<sup>-2</sup>
    - FB\_EVEN =  $3.82 \times 10^{-5}$  GeV<sup>-2</sup>
  - FWW\_ODD, FBB\_ODD, FB\_ODD: Parameters that are the coefficients of the  $\mathcal{CP}$ -odd operators – i.e.  $f_i/\Lambda^2$  – with default values 0 GeV<sup>-2</sup>.
  - HVV2: Parameter that allows the user to choose which anomalous  $HVV$  couplings are used. For HVV2 = 0, only the  $HZ\gamma$  coupling, for HVV2 = 1, only the  $H\gamma\gamma$  coupling, for HVV2 = 2, only the  $HZZ$  coupling and for HVV2 = 3, only the  $HWW$  coupling is used. If set to 4 all possible anomalous couplings are used. The default value is 4.

Moreover, for all parameterizations, two different form factors can be chosen as described in Refs. [62,66]. They model effective, momentum dependent  $HVV$  vertices, motivated by new physics entering with a large scale  $\Lambda$  at the loop level.

$$F_1 = \frac{\Lambda^2}{q_1^2 - \Lambda^2} \frac{\Lambda^2}{q_2^2 - \Lambda^2}, \quad (13)$$

$$F_2 = -2\Lambda^2 C_0(q_1^2, q_2^2, (q_1 + q_2)^2, \Lambda^2). \quad (14)$$

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. [67].

- FORMFACTOR: Flag that switches on the above form factor. The default value is set to `false`.
- MASS\_SCALE: Characteristic mass scale,  $\Lambda$ , 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. (13) and (14). If FFAC = 1, the form factor  $F_1$  is used for the parameterization. FFAC = 2 selects  $F_2$ , which is also the default value.

Finally, the following 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. If anomalous couplings are switched on (**ANOM\_CPL** = `.true.`), these contributions are included in the production as well as the decay.

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

The anomalous triple and quartic gauge boson couplings can be set in the file `anomV.dat`. They are parameterized using an effective Lagrangian, as described in Refs. [64, 68, 69]

$$\mathcal{L}_{\text{eff}} = \frac{f_i}{\Lambda^n} \mathcal{O}_i^{n+4}, \quad (15)$$

where  $n + 4$  signifies the dimension of the operator  $\mathcal{O}_i$ . VBFNLO defines the anomalous gauge couplings in terms of the coefficients  $f_i/\Lambda^n$  of the dimension-6 and dimension-8 operators. The full list of implemented operators can be found in Appendix A.

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

$$\mathcal{L}_{WW\gamma} = -ie \left[ W_{\mu\nu}^\dagger W^\mu A^\nu - W_\mu^\dagger A_\nu W^{\mu\nu} + \kappa_\gamma W_\mu^\dagger W_\nu F^{\mu\nu} + \frac{\lambda_\gamma}{m_W^2} W_{\sigma\mu}^\dagger W_\nu^\mu F^{\nu\sigma} \right] \quad (16)$$

for the anomalous  $WW\gamma$  vertex, and

$$\mathcal{L}_{WWZ} = -ie \cot \theta_w \left[ g_1^Z (W_{\mu\nu}^\dagger W^\mu Z^\nu - W_\mu^\dagger Z_\nu W^{\mu\nu}) + \kappa_Z W_\mu^\dagger W_\nu Z^{\mu\nu} + \frac{\lambda_Z}{m_W^2} W_{\sigma\mu}^\dagger W_\nu^\mu Z^{\nu\sigma} \right] \quad (17)$$

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

$$(\Delta g_1^Z, \Delta \kappa_Z, \Delta \kappa_\gamma) = (g_1^Z, \kappa_Z, \kappa_\gamma) - 1. \quad (18)$$

These quantities are related to the coefficients of the dimension-6 operators  $\mathcal{O}_W$ ,  $\mathcal{O}_B$  and  $\mathcal{O}_{WW}$  as shown in Eqs. 12.

In order to include anomalous vector boson couplings, the parameter **ANOM\_CPL** must be switched to `true` in `vbfno.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:

- FWW: Coefficient of the operator  $\mathcal{O}_{WWW}$ , i.e.  $f_{WWW}/\Lambda^2$ . Default is set to  $9.19 \times 10^{-6} \text{ GeV}^{-2}$ .
- FW: Coefficient of the operator  $\mathcal{O}_W$ , i.e.  $f_W/\Lambda^2$ . Default is set to  $-1.44 \times 10^{-5} \text{ GeV}^{-2}$ .
- FB: Coefficient of the operator  $\mathcal{O}_B$ , i.e.  $f_B/\Lambda^2$ . Default is set to  $3.83 \times 10^{-5} \text{ GeV}^{-2}$ .

TRIANOM = 2 uses the alternative parameterization of Eqs. 16 and 17 as input:

- LAMBDA0: The quantity  $\lambda_\gamma (= \lambda_Z)$ . Default is set to 0.038.
- ZDELTAKAPPA0: The quantity  $\Delta\kappa_Z$ . Default is set to -0.082.
- ZDELTA0: The quantity  $\Delta g_1^Z$ . Default is set to -0.060.
- ADELTAKAPPA0: The quantity  $\Delta\kappa_\gamma$ . Default is set to 0.077.
- Note that, as can be seen from Eqs. 12, the quantities  $\Delta\kappa_Z$ ,  $\Delta\kappa_\gamma$  and  $\Delta g_1^Z$  are not independent, but obey the relation

$$\Delta\kappa_Z = \Delta g_1^Z - \frac{\sin^2 \theta_W}{\cos^2 \theta_W} \Delta\kappa_\gamma. \quad (19)$$

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

Default is TRIANOM = 1, and the default values are approximately the central values in the three-parameter fit given in Ref. [70]. 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.  $f_i/\Lambda^2$ . 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  $\text{GeV}^{-2}$ .
- FWWt, FWt, FBt, FBWt, FDWt, FWWt, FBBt: The coefficients of the  $\mathcal{CP}$ -odd dimension-6 operators, i.e.  $f_i/\Lambda^2$ . 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  $\text{GeV}^{-2}$ .
- FS0, FS1, FM0 - FM7, FT0 - FT2, FT5 - FT9: Parameters that give the values of the coefficients of the dimension-8 operators, i.e.  $f_i/\Lambda^4$ . The default values for these parameters are 0  $\text{GeV}^{-4}$ . Note that these are only relevant for triboson production and  $VVjj$  production via VBF.

In addition, a form factor can be applied:

$$F = \left(1 + \frac{s}{\Lambda^2}\right)^{-p}, \quad (20)$$

where  $\Lambda$  is the scale of new physics.  $s$  is a universal scale (the invariant mass of the produced bosons) for each phase-space point.

- FORMFAC: Switch determining whether the above form factor  $F$  is included. Default is set to **true**.

- **FFMASSSCALE**: Mass scale  $\Lambda$ . Default is set to 2000 GeV.
- **FFEXP**: The exponent  $p$ . Default is set to 2.

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

- **FORMFAC\_IND**: Switch determining whether individual or universal form factors are used. Default is set to **false** – universal form factors are used.

If **TRIANOM** = 1 then

- **MASS\_SCALE\_FWWW**: Mass scale  $\Lambda$  for coefficient  $f_{WWW}$ . Default is 2000 GeV.
- **FFEXP\_FWWW**: Exponent  $p$  for coefficient  $f_{WWW}$ . Default is 2.
- **MASS\_SCALE\_FW**: Mass scale  $\Lambda$  for coefficient  $f_W$ . Default is 2000 GeV.
- **FFEXP\_FW**: Exponent  $p$  for coefficient  $f_W$ . Default is 2.
- **MASS\_SCALE\_FB**: Mass scale  $\Lambda$  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  $\Lambda$  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  $\Lambda$  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  $\Lambda$  for parameter  $\lambda$ . Default is 2000 GeV.
- **FFEXP\_LAMBDA**: Exponent  $p$  for parameter  $\lambda$ . Default is 2.
- **MASS\_SCALE\_G**: Mass scale  $\Lambda$  for parameter  $\Delta g_1^Z$ . Default is 2000 GeV.
- **FFEXP\_G**: Exponent  $p$  for parameter  $\Delta g_1^Z$ . Default is 2.
- As with the anomalous parameters themselves, the formfactors in the parameterization of **TRIANOM** = 2 are not independent (see Eq. 19). 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.

### 4.5.3 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,  $\Delta g_1^Z$  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.  $WWZ$  tribo-son 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<sup>27</sup>. 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.

## 4.6 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 [71, 72] at LO and NLO QCD level (see, for example, Ref. [73] 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 [74]. 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 [74] (`true`) or the Warped Higgsless Model [71] (`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.

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<sup>27</sup> `TRIANOM=1` in `anomV.dat` corresponds to `PARAMETR3=true` in `anom_HVV.dat`, and `TRIANOM=2` corresponds to `PARAMETR2=true`.



- **KKMAXZ**: The maximum number of Kaluza-Klein  $Z_k$  states to be included on top of the Standard Model  $Z$  boson, which corresponds to  $Z_{k=0}$ . All states  $k \geq 3$  are phenomenologically irrelevant. Default is 1.
- **KKMAXG**: The maximum number of Kaluza-Klein  $Z'_k$  bosons that are excitations of the Standard Model photon  $Z'_{k=0}$ . States  $k \geq 2$  are phenomenologically irrelevant. Default is 1.
- **WPMAS**:  $W_{k=1}$  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. [75], 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 [76] 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\_Wx-Wy-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\_Wx-Wy-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\_Wx-Wy-Wz-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\_Wx-Wy-Zz-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\_Wx-Wy-Gz-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\_Wx-Wy-Gz-ZX**: List of couplings between Kaluza-Klein states:  $W_x^\pm - W_y^\pm - Z'_z - Z_0$  to  $W_x^\pm - W_y^\pm - Z'_z - Z_{\text{KMAXZ}}$ .

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

#### 4.7 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 `vbfno.dat` is set to **true**, and will only run if the spin-2 models were enabled at compilation using the `configure` option `--enable-spin2`.

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 Ref. [32]. For the singlet spin-2 field,  $T^{\mu\nu}$ , the effective Lagrangian is

$$\mathcal{L}_{\text{singlet}} = \frac{1}{\Lambda} T_{\mu\nu} \left( f_1 B^{\alpha\nu} B_\alpha^\mu + f_2 W_i^{\alpha\nu} W_\alpha^{i,\mu} + f_3 \tilde{B}^{\alpha\nu} B_\alpha^\mu + f_4 \tilde{W}_i^{\alpha\nu} W_\alpha^{i,\mu} + 2f_5 (D^\mu \Phi)^\dagger (D^\nu \Phi) \right), \quad (21)$$

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

$$\mathcal{L}_{\text{triplet}} = \frac{1}{\Lambda} T_{\mu\nu j} \left( f_6 (D^\mu \Phi)^\dagger \sigma^j (D^\nu \Phi) + f_7 W_\alpha^{j,\mu} B^{\alpha\nu} \right), \quad (22)$$

where  $W$  and  $B$  are the usual electroweak field strength tensors,  $\tilde{W}$  and  $\tilde{B}$  the dual field strength tensors,  $\Phi$  is the Higgs field and  $D^\mu$  is the covariant derivative.  $f_i$  are variable coupling parameters and  $\Lambda$  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:

$$f(q_1^2, q_2^2, p_{\text{sp2}}^2) = \left( \frac{\Lambda_{ff}^2}{|q_1^2| + \Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|q_2^2| + \Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|p_{\text{sp2}}^2| + \Lambda_{ff}^2} \right)^{n_{ff}}. \quad (23)$$

Here  $p_{\text{sp2}}^2$  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  $\Lambda_{ff}$  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**: Coupling parameters for the spin-2 singlet field. Default values are **F1=F2=F5=1**, **F3=F4=0**.
- **F6, F7**: Coupling parameters for the spin-2 triplet field. Default values are set to 1.
- **LAMBDA**: Energy scale of the couplings in GeV. Default value is 1500 GeV.
- **LAMBDAFF**: Energy scale of the formfactor in GeV. Default value is 3000 GeV.
- **NFF**: Exponent of the formfactor. Default value is 4.

Note that a graviton corresponds to **F1=F2=F5=1** and **F3=F4=F6=F7=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. Default value is 1000 GeV.
- **MSP2TRIPPM**: Mass of charged spin-2 triplet particles in GeV. Default value is 1000 GeV.
- **MSP2TRIPN**: Mass of neutral spin-2 triplet particle in GeV. Default value is 1000 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.

These default values are intended for the processes 200-230. Respective values for light spin-2 resonances in process 191 can be found in Ref. [32]<sup>28</sup>.

## 4.8 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.4.1.5.

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<sup>29</sup>.

VBFNLO can calculate the Monte Carlo error for each bin and output this to 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\_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 0.2.

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<sup>28</sup>Note that in Ref. [32], process 191 ( $pp \rightarrow \text{spin-2 } jj \rightarrow \gamma\gamma jj$ ) is referred to as process 240.

<sup>29</sup>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 pseudorapidity of tagging jets. Default range is -5 to 5.
- HIST\_ID5: Range for pseudorapidity of tagging jet with higher  $p_T$ . Default range is -5 to 5.
- HIST\_ID6: Range for pseudorapidity of tagging jet with lower  $p_T$ . Default range is -5 to 5.
- HIST\_ID7: Range for  $p_T^{\max}$  of leptons. Default range is 0 to 500 GeV.
- HIST\_ID8: Range for  $p_T^{\min}$  of leptons. Default range is 0 to 500 GeV.
- HIST\_ID9: Range for  $\eta_{\max}$  of leptons. Default range is 0 to 5.
- HIST\_ID10: Range for  $\eta_{\min}$  of leptons. Default range is 0 to 5.
- HIST\_ID11: Range for azimuthal angle (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  $d^2S/(d\eta_{jj}dm_{jj})$ . Default ranges are 0 to 6 for the  $\eta$  ( $x$ ) axis and 0 to 800 GeV for the  $m_{jj}$  ( $y$ ) axis.

## 4.9 random.dat — parameters for seeds

To run with different seeds, simply set the variable `SEED` in the file `random.dat` to a different integer value.

## 5 CHANGES

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

### 5.1 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.

### 5.2 Symmetry factor $ZZ \rightarrow \ell^+ \ell^- \ell^+ \ell^-$

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

### 5.3 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.

#### 5.3.1 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.

- $pp \rightarrow Hjj \rightarrow ZZjj \rightarrow \ell^+ \ell^- \nu \bar{\nu} jj$  via vector boson fusion (process ID 107) and gluon fusion (process ID 4107)
- $pp \rightarrow Hjjj \rightarrow ZZjjj \rightarrow \ell^+ \ell^- \nu \bar{\nu} jjj$  (process ID 117)
- $pp \rightarrow H\gamma jj \rightarrow ZZ\gamma jj \rightarrow \ell^+ \ell^- \nu \bar{\nu} \gamma jj$  (process ID 2107)
- $pp \rightarrow ZZjj \rightarrow \ell^+ \ell^- \nu \bar{\nu} jj$  (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.

#### 5.3.2 Matrix element $H \rightarrow ZZ \rightarrow 4\ell$

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

### 5.3.3 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  $\Lambda$  at loop level. Corrections to the  $HVV$  formfactor  $F_2$  (see Eq. 14) 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

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

can be applied in order to preserve unitarity, where  $\Lambda$  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  $\Lambda$  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.  $\Delta g_1^Z$ ,  $\Delta\kappa_\gamma$  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).

### 5.3.4 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.

## 5.4 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, <http://www-itp.particle.uni-karlsruhe.de/vbfnlo/>.

### 5.4.1 EWScheme

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

### 5.4.2 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.

## 6 CHECKS

Extensive checks for the LO and the real emission amplitudes, as well as for the total LO cross sections, have been performed for all processes implemented in VBFNLO. Born amplitudes and real emission diagrams have been compared with the fully automatically generated results provided by MADGRAPH [77]. 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<sup>30</sup> [78, 79], SHERPA<sup>31</sup> [80] and/or HELAC-PHEGAS<sup>32</sup> [81–83], a completely automatic parton level event generator based on Dyson-Schwinger recursive equations.

LHA event files for the LO processes have been tested with HERWIG++<sup>33</sup> [84], 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<sup>34</sup>. In Ref. [85], 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. [86, 87], and the VV2H program<sup>35</sup>. For the dominant  $t$ - and  $u$ -channel contributions which are implemented in VBFNLO, good agreement has been found. For the triboson processes a comparison for the production of on-shell gauge bosons without leptonic decays has been performed with the results presented in Ref. [88]. Additionally, the tree-level results for  $W^\pm\gamma\gamma$  have been compared to the results with an on-shell  $W$  boson of Ref. [89]. Again, in both cases good agreement has been found. Triple photon production has been tested against FEYNARTS, FORMCALC and HADCALC [5, 6, 90]. Results for the  $\mathcal{CP}$ -odd and  $\mathcal{CP}$ -even Higgs boson production via gluon fusion have been tested against FEYNARTS and FORMCALC [91, 92].

All fermion loops have been checked against results obtained with FEYNARTS, FORMCALC and LOOPTOOLS. Diboson processes have been checked against MCFM<sup>36</sup> [93–95] and the gluon-gluon loops have also been checked against GG2VV<sup>37</sup> [96, 97].

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<sup>30</sup><http://madgraph.hep.uiuc.edu/>

<sup>31</sup><http://www.sherpa-mc.de/>

<sup>32</sup><http://helac-phegas.web.cern.ch/helac-phegas/>

<sup>33</sup><http://projects.hepforge.org/herwig/>

<sup>34</sup><http://omnibus.uni-freiburg.de/~sd565/programs/hawk/hawk.html>

<sup>35</sup><http://people.web.psi.ch/spira/vv2h/>

<sup>36</sup><http://mcfm.fnal.gov/>

<sup>37</sup><http://gg2VV.hepforge.org/>



## 7 OUTLOOK

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

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## A LIST OF OPERATORS FOR ANOMALOUS GAUGE BOSON COUPLINGS

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. [63,64] and the dimension-8 operators are taken from [69].<sup>38</sup> More details on the implementation of these operators can be found in Refs. [59–61].

With the building blocks

$$\begin{aligned}\widehat{W}_{\mu\nu} &= igT^a W_{\mu\nu}^a \\ \widehat{B}_{\mu\nu} &= ig'Y B_{\mu\nu} \\ D_\mu &= \partial_\mu + igT^a W_\mu^a + ig'Y B_\mu,\end{aligned}\tag{25}$$

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.

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

$$\begin{aligned}\mathcal{O}_W &= (D_\mu\Phi)^\dagger \widehat{W}^{\mu\nu} (D_\nu\Phi) \\ \mathcal{O}_B &= (D_\mu\Phi)^\dagger \widehat{B}^{\mu\nu} (D_\nu\Phi) \\ \mathcal{O}_{WWW} &= Tr \left[ \widehat{W}_{\mu\nu} \widehat{W}^{\nu\rho} \widehat{W}_\rho{}^\mu \right] \\ \mathcal{O}_{WW} &= \Phi^\dagger \widehat{W}_{\mu\nu} \widehat{W}^{\mu\nu} \Phi \\ \mathcal{O}_{BB} &= \Phi^\dagger \widehat{B}_{\mu\nu} \widehat{B}^{\mu\nu} \Phi.\end{aligned}\tag{26}$$

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

$$\begin{aligned}\mathcal{O}_{\widetilde{W}} &= (D_\mu\Phi)^\dagger \widehat{\widetilde{W}}^{\mu\nu} (D_\nu\Phi) \\ \mathcal{O}_{\widetilde{B}} &= (D_\mu\Phi)^\dagger \widehat{\widetilde{B}}^{\mu\nu} (D_\nu\Phi) \\ \mathcal{O}_{\widetilde{WWW}} &= Tr \left[ \widehat{\widetilde{W}}_{\mu\nu} \widehat{W}^{\nu\rho} \widehat{W}_\rho{}^\mu \right] \\ \mathcal{O}_{\widetilde{WW}} &= \Phi^\dagger \widehat{\widetilde{W}}_{\mu\nu} \widehat{W}^{\mu\nu} \Phi \\ \mathcal{O}_{\widetilde{BB}} &= \Phi^\dagger \widehat{\widetilde{B}}_{\mu\nu} \widehat{B}^{\mu\nu} \Phi \\ \mathcal{O}_{D\widetilde{W}} &= Tr \left( [D_\mu, \widehat{\widetilde{W}}_{\nu\rho}] [D^\mu, \widehat{\widetilde{W}}^{\nu\rho}] \right) \\ \mathcal{O}_{B\widetilde{W}} &= \Phi^\dagger \widehat{B}_{\mu\nu} \widehat{\widetilde{W}}^{\mu\nu} \Phi.\end{aligned}\tag{27}$$

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

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<sup>38</sup>We obtain slightly different expressions for the dimension-8 operators compared to [69], as they omit the gauge couplings in the field strength tensor expressions ( $\widehat{W}_{\mu\nu} = iT^a W_{\mu\nu}^a$  and  $\widehat{B}_{\mu\nu} = iY B_{\mu\nu}$ ).

constrained by electroweak precision tests. Furthermore, only 5 of these 7 operators are linearly independent. For example  $\mathcal{O}_{\widetilde{W}}$  and  $\mathcal{O}_{B\widetilde{W}}$  can be written as

$$\begin{aligned}\mathcal{O}_{\widetilde{W}} &= -2\mathcal{O}_{\widetilde{B}} - \mathcal{O}_{\widetilde{B}B} \\ \mathcal{O}_{B\widetilde{W}} &= \mathcal{O}_{\widetilde{B}} - \frac{1}{2}\mathcal{O}_{\widetilde{W}W} + \frac{1}{2}\mathcal{O}_{\widetilde{B}B}.\end{aligned}\tag{28}$$

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

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

$$\begin{aligned}\mathcal{L}_{S,0} &= [(D_\mu\Phi)^\dagger D_\nu\Phi] \times [(D^\mu\Phi)^\dagger D^\nu\Phi] \\ \mathcal{L}_{S,1} &= [(D_\mu\Phi)^\dagger D^\mu\Phi] \times [(D_\nu\Phi)^\dagger D^\nu\Phi]\end{aligned}\tag{29}$$

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

$$\begin{aligned}\mathcal{L}_{M,0} &= \text{Tr} [\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}] \times [(D_\beta\Phi)^\dagger D^\beta\Phi] \\ \mathcal{L}_{M,1} &= \text{Tr} [\hat{W}_{\mu\nu} \hat{W}^{\nu\beta}] \times [(D_\beta\Phi)^\dagger D^\mu\Phi] \\ \mathcal{L}_{M,2} &= [\hat{B}_{\mu\nu} \hat{B}^{\mu\nu}] \times [(D_\beta\Phi)^\dagger D^\beta\Phi] \\ \mathcal{L}_{M,3} &= [\hat{B}_{\mu\nu} \hat{B}^{\nu\beta}] \times [(D_\beta\Phi)^\dagger D^\mu\Phi] \\ \mathcal{L}_{M,4} &= [(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi] \times \hat{B}^{\beta\nu} \\ \mathcal{L}_{M,5} &= [(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi] \times \hat{B}^{\beta\mu} \\ \mathcal{L}_{M,6} &= [(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\nu} D^\mu\Phi] \\ \mathcal{L}_{M,7} &= [(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\mu} D^\nu\Phi]\end{aligned}\tag{30}$$

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

$$\begin{aligned}\mathcal{L}_{T,0} &= \text{Tr} [\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}] \times \text{Tr} [\hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta}] \\ \mathcal{L}_{T,1} &= \text{Tr} [\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta}] \times \text{Tr} [\hat{W}_{\mu\beta} \hat{W}^{\alpha\nu}] \\ \mathcal{L}_{T,2} &= \text{Tr} [\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta}] \times \text{Tr} [\hat{W}_{\beta\nu} \hat{W}^{\nu\alpha}] \\ \mathcal{L}_{T,5} &= \text{Tr} [\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}] \times \hat{B}_{\alpha\beta} \hat{B}^{\alpha\beta} \\ \mathcal{L}_{T,6} &= \text{Tr} [\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta}] \times \hat{B}_{\mu\beta} \hat{B}^{\alpha\nu} \\ \mathcal{L}_{T,7} &= \text{Tr} [\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta}] \times \hat{B}_{\beta\nu} \hat{B}^{\nu\alpha} \\ \mathcal{L}_{T,8} &= \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \hat{B}_{\alpha\beta} \hat{B}^{\alpha\beta} \\ \mathcal{L}_{T,9} &= \hat{B}_{\alpha\mu} \hat{B}^{\mu\beta} \hat{B}_{\beta\nu} \hat{B}^{\nu\alpha}\end{aligned}\tag{31}$$

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

$$\begin{aligned}
\mathcal{L}_{eff} = & \mathcal{L}_{SM} \\
& + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_{WWW}}{\Lambda^2} \mathcal{O}_{WWW} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} \\
& + \frac{f_{Wt}}{\Lambda^2} \mathcal{O}_{\widetilde{W}} + \frac{f_{Bt}}{\Lambda^2} \mathcal{O}_{\widetilde{B}} + \frac{f_{WWWt}}{\Lambda^2} \mathcal{O}_{\widetilde{W}WW} + \frac{f_{WWt}}{\Lambda^2} \mathcal{O}_{\widetilde{W}W} + \frac{f_{BBt}}{\Lambda^2} \mathcal{O}_{\widetilde{B}B} \\
& + \frac{f_{DWt}}{\Lambda^2} \mathcal{O}_{D\widetilde{W}} + \frac{f_{BWt}}{\Lambda^2} \mathcal{O}_{B\widetilde{W}} \\
& + \frac{f_{S0}}{\Lambda^4} \mathcal{L}_{S,0} + \frac{f_{S1}}{\Lambda^4} \mathcal{L}_{S,1} \\
& + \frac{f_{M0}}{\Lambda^4} \mathcal{L}_{M,0} + \frac{f_{M1}}{\Lambda^4} \mathcal{L}_{M,1} + \frac{f_{M2}}{\Lambda^4} \mathcal{L}_{M,2} + \frac{f_{M3}}{\Lambda^4} \mathcal{L}_{M,3} \\
& + \frac{f_{M4}}{\Lambda^4} \mathcal{L}_{M,4} + \frac{f_{M5}}{\Lambda^4} \mathcal{L}_{M,5} + \frac{f_{M6}}{\Lambda^4} \mathcal{L}_{M,6} + \frac{f_{M7}}{\Lambda^4} \mathcal{L}_{M,7} \\
& + \frac{f_{T0}}{\Lambda^4} \mathcal{L}_{T,0} + \frac{f_{T1}}{\Lambda^4} \mathcal{L}_{T,1} + \frac{f_{T2}}{\Lambda^4} \mathcal{L}_{T,2} + \frac{f_{T5}}{\Lambda^4} \mathcal{L}_{T,5} + \frac{f_{T6}}{\Lambda^4} \mathcal{L}_{T,6} + \frac{f_{T7}}{\Lambda^4} \mathcal{L}_{T,7}. \quad (32)
\end{aligned}$$

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