Release Note – VBFNLO-2.6.0

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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 (plus jet) production in hadronic collisions at next-to-leading order (NLO) in the strong coupling constant, as well as Higgs boson plus two jet production via gluon fusion at the one-loop level. This note briefly describes the main additional features and processes that have been added in the new release – VBFNLO VERSION 2.6.0. At NLO QCD diboson production (Wγ, WZ, ZZ, Zγ and γγ), same-sign W pair production via vector boson fusion and the process Wγγj have been implemented (for which one-loop tensor integrals up to six-point functions are included). In addition, gluon induced diboson production can be studied separately at the leading order (one-loop) level. The diboson processes WW, WZ and Wγ can be run with anomalous gauge boson couplings, and anomalous couplings between a Higgs and a pair of gauge bosons is included in WW, ZZ, Zγ and γγ diboson production. The code has also been extended to include anomalous gauge boson couplings for single vector boson production via VBF, and a spin-2 model has been implemented for diboson pair production via vector boson fusion.

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1 Introduction

Vbfnlo \cite{1,2} is a flexible Monte Carlo (MC) program for vector boson fusion (VBF), double and triple vector boson (plus jet) production processes at NLO QCD accuracy. The electroweak corrections to Higgs boson production via VBF have been included. In addition, the simulation of $\mathcal{C}\mathcal{P}$-even and $\mathcal{C}\mathcal{P}$-odd Higgs boson production in gluon fusion, associated with two additional jets, is implemented at the (one-loop) LO QCD level. Vbfnlo can be run in the MSSM, 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.

Further information, and the latest version of the code, can be found on the Vbfnlo webpage http://www-itp.particle.uni-karlsruhe.de/vbfnlo/

A complete process list is given in Appendix A.

2 New processes

The latest version of Vbfnlo has several new processes implemented at NLO QCD.

2.1 Same sign $W$ pair production via VBF

Same sign $W$ pair production with two jets via vector boson fusion \cite{3} has been included in Vbfnlo 2.6.0. This process is potentially sensitive to new physics signals and, as it gives rise to same sign dilepton final states, it is also a background to new physics scenarios. To distinguish potential signatures of physics beyond the Standard Model from the effect of higher order corrections, precise theoretical predictions are essential. Although the QCD corrections to the integrated cross sections were found to be relatively small, their effect on several distributions is appreciable. When NLO QCD corrections are taken into account, the residual scale uncertainties are at the 2.5% level. The new process IDs are given in Table 1.

| ProcId | Process |
|--------|---------|
| 250    | $pp \rightarrow W^{+}W^{+}jj \rightarrow \ell_{1}^{+}\nu_{\ell_{1}}\ell_{2}^{+}\nu_{\ell_{2}} jj$ |
| 260    | $pp \rightarrow W^{-}W^{-}jj \rightarrow \ell_{1}^{-}\nu_{\ell_{1}}\ell_{2}^{-}\nu_{\ell_{2}} jj$ |

Table 1: New process IDs for diboson + 2 jet production via vector boson fusion at NLO QCD accuracy.
2.2 Diboson production and gluon-induced contributions

A good understanding of diboson processes at the LHC is essential, as not only do they allow the study of the Standard Model’s gauge structure, but they also provide a background to Higgs boson and new physics searches. Anomalous triple gauge boson couplings are included in the $WZ$ and $W\gamma$ processes\footnote{As in the rest of VBFNLO, no neutral triple gauge couplings are included.} (For contributions from anomalous $HVV$ couplings in gluon induced processes – Fig. 1 – see below.) The new processes are included at NLO QCD accuracy under the process IDs shown in Table 2.

| ProcID | Process | BSM                    |
|--------|---------|------------------------|
| 310    | $p(\bar{p}) \rightarrow W^+Z \rightarrow \ell^+_1 \nu_1 \ell^-_2 \ell^-_2$ | anomalous $VVV$ couplings |
| 320    | $p(\bar{p}) \rightarrow W^-Z \rightarrow \ell^-_1 \bar{\nu}_1 \ell^+_2 \ell^-_2$ | anomalous $HVV$ couplings |
| 330    | $p(\bar{p}) \rightarrow ZZ \rightarrow \ell^+_1 \ell^-_1 \ell^+_2 \ell^-_2$ | anomalous $VVV$ couplings |
| 340    | $p(\bar{p}) \rightarrow W^+\gamma \rightarrow \ell^+_1 \nu_1 \gamma$ | anomalous $VVV$ couplings |
| 350    | $p(\bar{p}) \rightarrow W^-\gamma \rightarrow \ell^-_1 \bar{\nu}_1 \gamma$ | anomalous $HVV$ couplings |
| 360    | $p(\bar{p}) \rightarrow Z\gamma \rightarrow \ell^+_1 \ell^-_1 \gamma$ | anomalous $HVV$ couplings |
| 370    | $p(\bar{p}) \rightarrow \gamma\gamma$ | anomalous $HVV$ couplings |

Table 2: Process IDs for the new diboson production processes at NLO QCD accuracy.

In addition to the NLO QCD corrections, the gluon-induced fermionic loop processes can be included in those processes with neutral final states (including $WW$ production, which was already implemented in VBFNLO, with process ID 300). Both continuum production via box diagrams as well as production via an s-channel Higgs boson resonance (shown in Fig. 1) are available, with full interference effects.

Figure 1: Gluon-induced contributions to diboson production.

The \texttt{vbfnlo.dat} flag \texttt{FERMIONLOOP} controls these contributions:

- 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.
Although these contributions are formally of higher order, their effect can still be significant. Anomalous couplings between a Higgs boson and a pair of gauge bosons can be included in those processes with neutral final states. The gluon-induced loop diagrams can be studied separately in the new release of VBFNLO using the process IDs of Table 3 and the executable ggflo.

| ProcId | Process | BSM                          |
|--------|---------|------------------------------|
| 4300   | $gg \rightarrow W^+W^- \rightarrow \ell_1^+\nu_1\ell_2^-\bar{\nu}_2$ |                            |
| 4330   | $gg \rightarrow ZZ \rightarrow \ell_1^+\ell_1^-\ell_2^+\ell_2^-$ | anomalous HVV couplings    |
| 4360   | $gg \rightarrow Z\gamma \rightarrow \ell_1^+\ell_1^-\gamma$ |                            |
| 4370   | $gg \rightarrow \gamma\gamma$ |                            |

Table 3: Process IDs for gluon induced diboson production at LO (one-loop) QCD.

2.3 Triple vector boson production in association with a hadronic jet

Finally, the triboson plus jet processes given in Table 4 have also been included at NLO QCD level\(^2\)\(^4\). As a process involving multiple electroweak bosons and jets, this is an important channel in which to compare experimental data with the predictions of the Standard Model. The NLO QCD corrections to the total cross section are sizeable, and have a non-trivial phasespace dependence.

| ProcId | Process                                 |
|--------|-----------------------------------------|
| 800    | $p\bar{p}\rightarrow W^+\gamma\gamma j \rightarrow \ell^+\nu\gamma\gamma j$ |
| 810    | $p\bar{p}\rightarrow W^-\gamma\gamma j \rightarrow \ell^-\bar{\nu}\gamma\gamma j$ |

Table 4: Process IDs for triboson production in association with a hadronic jet at NLO QCD.

3 New features

In addition to the new processes described above, several existing procedures have been extended and new features added.

\(^2\)These processes are disabled by default and must be enabled at compilation using the configure option --enable-processes=all or --enable-processes=tribosonjet.
3.1 Tensor reduction routines

The tensor reduction routines for up to 4 external legs have been extended for general kinematics. Three and four point tensor integrals are extended to deal with Rank 3 and Rank 4 integrals, respectively. Furthermore, one-loop tensor reduction routines for up to 6 external legs have been included for the massless case. The tensor integrals are implemented following Ref. [5] and can be found in the directory `loops/TenRed`.

3.2 Anomalous couplings

Anomalous gauge boson couplings have been implemented for single vector boson production via VBF, which have been seen to have an effect on some distributions [6], such as the azimuthal angle separation of the tagging jets. The existing diboson process $pp \rightarrow WW$ has been modified to include anomalous $VVV$ couplings, as well as anomalous $HVV$ couplings in the gluon-induced contributions. The relevant process IDs are given in Table 5. To run VBFNLO with anomalous couplings, the switch ANOM_CPL in the input file `vbfnlo.dat` must be switched to true. The anomalous coupling parameters are then input via `anomV.dat` or (for $HVV$ couplings) `anom_HVV.dat`.

| ProcId | Process | BSM |
|--------|---------|-----|
| 120    | $p \bar{p} \rightarrow Z jj \rightarrow \ell^+ \ell^- jj$ | anomalous couplings |
| 121    | $p \bar{p} \rightarrow Z jj \rightarrow \nu \bar{\nu} \ell jj$ | |
| 130    | $p \bar{p} \rightarrow W^+ jj \rightarrow \ell^+ \nu \ell jj$ |
| 140    | $p \bar{p} \rightarrow W^- jj \rightarrow \ell^- \bar{\nu} \ell jj$ |
| 150    | $p \bar{p} \rightarrow \gamma jj$ | |
| 300    | $p \bar{p} \rightarrow W^+ W^- \rightarrow \ell_1^+ \nu_1 \ell_2^- \bar{\nu}_2$ | anomalous $VVV$ and $HVV$ couplings |

Table 5: Process IDs for existing processes which have been extended to include anomalous couplings.

3.3 Spin-2 model

A spin-2 model has been implemented, using an effective Lagrangian 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, as described in Ref. [7]. This spin-2 model is implemented for diboson plus two jets production via vector boson fusion ($pp \rightarrow W^+W^-jj$, $pp \rightarrow ZZjj$ and $pp \rightarrow WZjj$, process IDs 200 - 230). For these processes a spin-2 resonance is included in addition to the Standard Model diagrams (i.e. both Higgs boson and spin-2 diagrams are calculated).

The file `spin2coupl.dat` is used to set the parameters for the spin-2 models. It is read if the switch SPIN2 in `vbfnlo.dat` is set to true, and will only run if the spin-2 models were enabled at compilation using the configure option --enable-spin2.
For the singlet spin-2 field, $T^{\mu\nu}$, the effective Lagrangian is

$$\mathcal{L}_{\text{singlet}} = \frac{1}{\Lambda} T^{\mu\nu} \left( f_1 B^{\alpha\mu} B^\alpha_{\alpha} + f_2 W^{\alpha\nu\alpha} W^\nu_{\alpha} + f_3 \tilde{B}^{\alpha\mu} B^\alpha_{\alpha} + f_4 \tilde{W}^{\alpha\nu\mu} W^\nu_{\alpha} + 2 f_5 (D^\mu \Phi)^\dagger (D^\nu \Phi) \right),$$

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

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

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:

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

Here $p_{sp2}^2$ is the invariant mass of a virtual s-channel spin-2 particle and $q_{1,2}^2$ are the invariant masses of the electroweak bosons. The energy scale $\Lambda_{ff}$ 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 (into SM gauge bosons) of the spin-2 particles.

- 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 into SM gauge bosons for spin-2 singlet particle. Default value is 1.
- BRRATTRIPPM: Branching ratio into SM gauge bosons for charged spin-2 triplet particles. Default value is 1.
- BRRATTRIPN: Branching ratio into SM gauge bosons for neutral spin-2 triplet particle. Default value is 1.
A new process $pp \rightarrow \gamma\gamma jj$ (Table 6) has been added which includes only the resonant spin-2 diagrams – this can be compared to the existing process of Higgs boson production via VBF, where the Higgs decays into photons (process ID 101). The default values given above are intended for processes 200-230. Corresponding values for light spin-2 resonances in process 191 can be found in Ref. [7].

| ProcId | Process | BSM                  |
|--------|---------|----------------------|
| 191    | $p \bar{p} \rightarrow S_2 jj \rightarrow \gamma\gamma jj$ | spin-2 resonant production only |

Table 6: Process ID for production of a spin-2 particle $S_2$ with 2 jets via vector boson fusion at NLO QCD accuracy.

### 3.4 Histograms

The error calculation for the real emission output can now be controlled via the input file `histograms.dat`. `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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3 Note that in Ref. [7] this process is referred to as process 240.

4 Error calculation is not implemented for the other (ROOT or TopDrawer) histogram formats.
3.5 SUSY options for electroweak corrections

When running Vbfnlo in the MSSM, it is now possible to set the mass of the Higgs bosons in the electroweak loops to either their tree-level value or their corrected value, using the flag MH_LOOPS in susy.dat.

In some areas of the MSSM parameter space, the electroweak loop corrections can be the dominant contribution to the cross section. In this case, the squared electroweak corrections from the (s)fermion corrections are important and can be included in Vbfnlo using the susy.dat flag LOOPSQR_SWITCH. If set to true the amplitude is given by

\[ |M_{\text{Born}}|^2 + 2 \Re[ M_{\text{Born}}^* M_{\text{loop}}] + |M_{(s)\text{fermion loop}}|^2. \] (4)

Note that the loop squared component is only added if \(|M_{(s)\text{fermion loop}}|\) is greater than 10% of \(|M_{\text{Born}}|\).

4 Other changes

Since the previous release, VERSION 2.5.0, some changes have been made that alter previous results (events, cross sections and distributions).

4.1 Allowed virtuality of resonance

In the phasespace 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.

4.2 Matrix element \(H \rightarrow ZZ \rightarrow 4\ell\)

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

4.3 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 $HHV$ couplings two types of formfactors can be applied which model effective, momentum dependent $HHV$ vertices, motivated by new physics entering with a large scale $\Lambda$ at loop level. Corrections to the $HHV$ formfactor $F_2$, where
\[
F_2 = -2\Lambda^2 C_0(q_1, q_2, (q_1 + q_2)^2, \Lambda^2).
\]
(where 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. [8]) have been made. The implementation of the parametrization described by PARAMETR3 – where the input determining the anomalous couplings is in terms of the dimension-6 operators ($O_W, O_B, O_{WW}$ and $O_{BB}$, see [9,10]) – has also been corrected.

If anomalous triple (and quartic) gauge boson couplings are being studied, a formfactor, given by
\[
F = \left(1 + \frac{s}{\Lambda^2}\right)^{-p},
\]
can be applied in order to preserve unitarity, where $\Lambda$ is again the scale of new physics. The momentum dependence of an applied formfactor (i.e. $s$) is now universal for each phasespace point, with the invariant mass of the bosons as the scale. This ensures the proper cancellations for anomalous contributions and affects both the cross sections and the distributions significantly.

The values of the formfactor scale $\Lambda$ and suppression $p$ can be set to different values for each input describing the triboson couplings. In the parameterization TRIANOM = 2 of the L3 Collaboration [11], 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 $HHV$ couplings (the anomalous $HHV$ 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).

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

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

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Appendix A: Process List

The following is a complete list of all processes available in VBFNLO, including any Beyond the Standard Model (BSM) effects that are implemented. Firstly, the processes that are accessed via the `vbfnlo` executable are given.

| ProcID | Process                                      | BSM                                |
|--------|----------------------------------------------|------------------------------------|
| 100    | $p p \rightarrow Hjj$                       |                                    |
| 101    | $p p \rightarrow Hjj \rightarrow \gamma\gamma jj$ |                                    |
| 102    | $p p \rightarrow Hjj \rightarrow \mu^+\mu^- jj$ |                                    |
| 103    | $p p \rightarrow Hjj \rightarrow \tau^+\tau^- jj$ |                                    |
| 104    | $p p \rightarrow Hjj \rightarrow b\bar{b} jj$ |                                    |
| 105    | $p p \rightarrow Hjj \rightarrow W^+W^- jj \rightarrow \ell_1^+\nu_{\ell_1}\ell_2^\pm\nu_{\ell_2} jj$ | anomalous HVV couplings, MSSM     |
| 106    | $p p \rightarrow Hjj \rightarrow ZZ jj \rightarrow \ell_1^+\ell_1^-\ell_2^+\ell_2^- jj$ |                                    |
| 107    | $p p \rightarrow Hjj \rightarrow ZZ jj \rightarrow \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2} jj$ |                                    |
| 110    | $p p \rightarrow Hjjj$                      |                                    |
| 111    | $p p \rightarrow Hjjj \rightarrow \gamma\gamma jjj$ |                                    |
| 112    | $p p \rightarrow Hjjj \rightarrow \mu^+\mu^- jjj$ |                                    |
| 113    | $p p \rightarrow Hjjj \rightarrow \tau^+\tau^- jjj$ |                                    |
| 114    | $p p \rightarrow Hjjj \rightarrow b\bar{b} jjj$ |                                    |
| 115    | $p p \rightarrow Hjjj \rightarrow W^+W^- jjj \rightarrow \ell_1^+\nu_{\ell_1}\ell_2^\pm\nu_{\ell_2} jjj$ |                                    |
| 116    | $p p \rightarrow Hjjj \rightarrow ZZ jjj \rightarrow \ell_1^+\ell_1^-\ell_2^+\ell_2^- jjj$ |                                    |
| 117    | $p p \rightarrow Hjjj \rightarrow ZZ jjj \rightarrow \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2} jjj$ |                                    |
| 2100   | $p p \rightarrow H\gamma jj$                |                                    |
| 2101   | $p p \rightarrow H\gamma jj \rightarrow \gamma\gamma jj$ |                                    |
| 2102   | $p p \rightarrow H\gamma jj \rightarrow \mu^+\mu^- jj$ |                                    |
| 2103   | $p p \rightarrow H\gamma jj \rightarrow \tau^+\tau^-\gamma jj$ |                                    |
| 2104   | $p p \rightarrow H\gamma jj \rightarrow b\bar{b}\gamma jj$ |                                    |
| 2105   | $p p \rightarrow H\gamma jj \rightarrow W^+W^-\gamma jj \rightarrow \ell_1^+\nu_{\ell_1}\ell_2^\pm\nu_{\ell_2}\gamma jj$ |                                    |
| 2106   | $p p \rightarrow H\gamma jj \rightarrow ZZ\gamma jj \rightarrow \ell_1^+\ell_1^-\ell_2^\pm\gamma jj$ |                                    |
| 2107   | $p p \rightarrow H\gamma jj \rightarrow ZZ\gamma jj \rightarrow \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\gamma jj$ | |
| ProcId | Process | BSM |
|--------|---------|-----|
| 120    | $p p \rightarrow Zjj \rightarrow ℓ^+ ℓ^- jj$ | anomalous couplings |
| 121    | $p p \rightarrow Zjj \rightarrow ν_ℓ \bar{ν}_ℓ jj$ | |
| 130    | $p p \rightarrow W^+ jj \rightarrow ℓ^+ ν_ℓ jj$ | |
| 140    | $p p \rightarrow W^- jj \rightarrow ℓ^- \bar{ν}_ℓ jj$ | |
| 150    | $p p \rightarrow γ jj$ | |
| 191    | $p p \rightarrow S_2 jj \rightarrow γγ jj$ | only spin-2 resonant production |
| 200    | $p p \rightarrow W^+ W^- j j \rightarrow ℓ^+_1 ν_ℓ_1 ℓ^-_2 ν_ℓ_2 jj$ | anomalous couplings, Kaluza-Klein & spin-2 models |
| 210    | $p p \rightarrow ZZ j j \rightarrow ℓ^+_1 ℓ^-_1 ℓ^+_2 ℓ^-_2 jj$ | |
| 211    | $p p \rightarrow ZZ j j \rightarrow ℓ^+_1 ℓ^-_1 ν_ℓ_2 ν_ℓ_2 jj$ | |
| 220    | $p p \rightarrow W^+ Z jj \rightarrow ℓ^+_1 ν_ℓ_1 ℓ^-_2 ℓ^-_2 jj$ | |
| 230    | $p p \rightarrow W^- Z jj \rightarrow ℓ^-_1 ν_ℓ_1 ℓ^+_2 ℓ^-_2 jj$ | |
| 250    | $p p \rightarrow W^+ W^- jj \rightarrow ℓ^+_1 ν_ℓ_1 ℓ^+_2 ν_ℓ_2 jj$ | |
| 260    | $p p \rightarrow W^- W^- jj \rightarrow ℓ^-_1 ν_ℓ_1 ℓ^+_2 ν_ℓ_2 jj$ | |
| 300    | $p p \rightarrow W^+ W^- \rightarrow ℓ^+_1 ν_ℓ_1 ℓ^-_2 ν_ℓ_2$ | anomalous VVV and HVV couplings |
| 310    | $p p \rightarrow W^+ Z \rightarrow ℓ^+_1 ν_ℓ_1 ℓ^+_2 ℓ^-_2$ | anomalous VVV couplings |
| 320    | $p p \rightarrow W^- Z \rightarrow ℓ^-_1 ν_ℓ_1 ℓ^+_2 ℓ^-_2$ | anomalous VVV couplings |
| 330    | $p p \rightarrow ZZ \rightarrow ℓ^+_1 ℓ^-_1 ℓ^+_2 ℓ^-_2$ | anomalous HVV couplings |
| 340    | $p p \rightarrow W^+ γ \rightarrow ℓ^+_1 ν_ℓ_1 γ$ | anomalous VVV couplings |
| 350    | $p p \rightarrow W^- γ \rightarrow ℓ^-_1 ν_ℓ_1 γ$ | anomalous VVV couplings |
| 360    | $p p \rightarrow Zγ \rightarrow ℓ^+_1 ℓ^-_1 γ$ | anomalous HVV couplings |
| 370    | $p p \rightarrow γγ$ | |

anomalous couplings

Kaluza-Klein models, spin-2 models
| ProcId | Process | BSM |
|--------|---------|-----|
| 400 | $p^+ \to W^+ W^- Z \to \ell_1^+ \nu_1 \ell_2^- \bar{\nu}_3 \ell_3^- \bar{\nu}_3$ | anomalous couplings, Kaluza-Klein models |
| 410 | $p^+ \to ZZW^+ \to \ell_1^+ \ell_2^- \ell_3^- \nu_{\ell_3}$ | |
| 420 | $p^+ \to ZZW^- \to \ell_1^- \ell_2^+ \ell_3^- \ell_3^- \nu_{\ell_3}$ | |
| 430 | $p^+ \to W^+ W^- W^- \to \ell_1^+ \nu_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2} \ell_3^- \nu_{\ell_3}$ | |
| 440 | $p^+ \to W^- W^+ W^- \to \ell_1^- \bar{\nu}_{\ell_1} \ell_2^+ \nu_{\ell_2} \ell_3^- \bar{\nu}_{\ell_3}$ | |
| 450 | $p^+ \to ZZZ \to \ell_1^- \ell_2^+ \ell_2^+ \ell_3^- \ell_3^- \nu_{\ell_3}$ | |
| 460 | $p^+ \to W^- W^+ \gamma \to \ell_1^- \ell_2^+ \ell_2^+ \nu_{\ell_2} \gamma$ | |
| 470 | $p^+ \to ZZ \gamma \to \ell_1^- \ell_2^- \ell_2^- \ell_2^- \gamma$ | |
| 480 | $p^+ \to W^+ Z \gamma \to \ell_1^+ \nu_{\ell_1} \ell_2^- \ell_2^- \gamma$ | |
| 490 | $p^+ \to W^- Z \gamma \to \ell_1^- \bar{\nu}_{\ell_1} \ell_2^- \ell_2^- \gamma$ | |
| 500 | $p^+ \to W^+ \gamma \gamma \to \ell_2^- \nu_{\ell_2} \gamma \gamma$ | |
| 510 | $p^+ \to W^- \gamma \gamma \to \ell_2^- \bar{\nu}_{\ell_2} \gamma \gamma$ | |
| 520 | $p^+ \to Z \gamma \gamma \to \ell_2^- \ell_2^- \gamma \gamma$ | |
| 530 | $p^+ \to \gamma \gamma \gamma$ | |
| 610 | $p^\gamma \to W^- j \to \ell_2^- \bar{\nu}_{\ell_2} j$ | anomalous couplings |
| 620 | $p^\gamma \to W^+ j \to \ell_2^+ \nu_{\ell_2} j$ | |
| 630 | $p^\gamma \to W^- Z j \to \ell_2^- \bar{\nu}_{\ell_2} \ell_2^+ j$ | |
| 640 | $p^\gamma \to W^+ Z j \to \ell_2^+ \nu_{\ell_2} \ell_2^+ j$ | |
| 800 | $p^\gamma \to W^+ \gamma j \to \ell_2^+ \nu_{\ell_2} \gamma j$ | |
| 810 | $p^\gamma \to W^- \gamma j \to \ell_2^- \bar{\nu}_{\ell_2} \gamma j$ | |
The processes accessed via the executable `ggflo` are given below.

| ProcId | Process | Bsm |
|--------|---------|-----|
| 4100   | $pp \rightarrow Hjj$ | MSSM, general 2HDM |
| 4101   | $pp \rightarrow Hjj \rightarrow \gamma\gamma jj$ | |
| 4102   | $pp \rightarrow Hjj \rightarrow \mu^+\mu^- jj$ | |
| 4103   | $pp \rightarrow Hjj \rightarrow \tau^+\tau^- jj$ | |
| 4104   | $pp \rightarrow Hjj \rightarrow b\bar{b} jj$ | |
| 4105   | $pp \rightarrow Hjj \rightarrow W^+W^- jj \rightarrow \ell_1^+\nu_1\ell_2^-\bar{\nu}_2 jj$ | |
| 4106   | $pp \rightarrow Hjj \rightarrow ZZ jj \rightarrow \ell_1^+\ell_1^-\ell_2^+\ell_2^- jj$ | |
| 4107   | $pp \rightarrow Hjj \rightarrow ZZ jj \rightarrow \ell_1^+\nu_1\ell_2^-\bar{\nu}_2 jj$ | |
| 4300   | $gg \rightarrow W^+W^- \rightarrow \ell_1^+\nu_1\ell_2^-\bar{\nu}_2$ | |
| 4330   | $gg \rightarrow ZZ \rightarrow \ell_1^+\ell_1^-\ell_2^+\ell_2^-$ | |
| 4360   | $gg \rightarrow Z\gamma \rightarrow \ell_1^+\ell_1^-\gamma$ | |
| 4370   | $gg \rightarrow \gamma\gamma$ | anomalous $HVV$ couplings |