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Release Note – Vbfnlo 2.7.0

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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 as well as QCD-induced single and double vector boson production plus two jets in hadronic collisions at next-to-leading order (NLO) in the strong coupling constant. Furthermore, Higgs boson plus two jet production via gluon fusion at the one-loop level is included. This note briefly describes the main additional features and processes that have been added in the new release – Vbfnlo Version 2.7.0.

At NLO QCD several new processes are available. These are $W^\pm\gamma$ and HH production in VBF, the QCD-induced single and double vector boson plus two jets processes $W^\pm jj$, $W^\pm Zjj$, $W^\pm\gamma jj$, same-sign $W^\pm W^\pm jj$, and the Higgs-strahlung process $W^\pm H$ (plus jet) production. Anomalous couplings are now available for all VBF, diboson and triboson (plus jet) processes including the new VBF $W^\pm\gamma jj$ implementation, as well as in the Higgs-strahlung (plus jet) process.

Semi-leptonic decay modes are supported for the following diboson, triboson and VBF processes: VV, VVV, $VV\gamma$ production and VV production via VBF, where V denotes a massive gauge boson, i.e. $W^\pm$ or Z. Additionally, the VBF-Higgs production process with decay into WW or ZZ supports semi-leptonic decays of the gauge bosons. All these semi-leptonic processes contain the possibility to include anomalous gauge boson couplings.

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1 Introduction

Vbfnlo [1–4] is a flexible Monte Carlo (MC) program for vector boson fusion (VBF), double and triple vector boson (plus jet) as well as QCD-induced single and double vector boson plus two jets production processes at NLO QCD accuracy. The electroweak corrections to on-shell Higgs boson production via VBF have been included. 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 the (one-loop) leading-order (LO) QCD level. Vbfnlo can be run in the Minimal Supersymmetric Standard Model (MSSM), and anomalous couplings of the Higgs boson and gauge bosons have been implemented for a large fraction of the available processes. Additionally, a model for spin-2 resonances, the option to include two Higgs resonances and two Higgsless extra dimension models – the Warped Higgsless scenario and a Three-Site Higgsless Model – are included for selected processes.

Further information, and the latest version of the code, can be found on the Vbfnlo webpage

`http://www.itp.kit.edu/vbfnlo/` .

A complete process list is given in Appendix A.

2 New processes

For the latest version of Vbfnlo we have implemented several new processes at NLO QCD.

2.1 QCD-induced single and double vector boson production plus two jets

The QCD-induced production of Vjj and $VVjj$ events at $\mathcal{O}(\alpha_s^2)$ in the strong coupling constant is a new process class available in Vbfnlo 2.7.0. With the same final state particles as the corresponding VBF processes they are an irreducible background to the latter. Hence, they play an important role when studying anomalous quartic gauge couplings. They also form a relevant background in searches for physics beyond the Standard Model. In Vbfnlo 2.7.0, the production of $W^{\pm}jj$ as single boson final state and the diboson final states $W^{\pm}Zjj$ [5], $W^{\pm}\gamma jj$ [6] and same-sign $W^{\pm}W^{\pm}jj$ [7] have been included. They are available at NLO QCD accuracy including leptonic decays of the vector bosons and full off-shell and finite-width effects. Instabilities in the virtual amplitudes, which contain diagrams up to hexagon loops, can be cured by resorting to quadruple precision for problematic points, if supported by the compiler[1]. The impact of the NLO QCD corrections on the total cross section is modest for a reasonable choice of factorization and renormalization scales, but reduces the scale uncertainty significantly. In kinematic distributions a sizable phase-space dependence is observed, which leads to relevant changes in the shape of distributions. The corresponding process IDs are given in Tables 1 and 2.

[1] This has been tested with gfortran 4.7.3 and 4.8.2 as well as ifort 12.1.0.

ProcId	Process
3130	$p\overset{(-)}{p} \to W^+\, jj \to \ell^+ \nu_\ell\, jj$
3140	$p\overset{(-)}{p} \to W^-\, jj \to \ell^- \bar{\nu}_\ell\, jj$

Table 1: *Process IDs for QCD induced vector boson + 2 jet production at NLO QCD accuracy.*

ProcId	Process
3220	$p\overset{(-)}{p} \to W^+ Z\, jj \to \ell_1^+ \nu_{\ell_1} \ell_2^+ \ell_2^-\, jj$
3230	$p\overset{(-)}{p} \to W^- Z\, jj \to \ell_1^- \bar{\nu}_{\ell_1} \ell_2^+ \ell_2^-\, jj$
3250	$p\overset{(-)}{p} \to W^+ W^+\, jj \to \ell_1^+ \nu_{\ell_1} \ell_2^+ \nu_{\ell_2}\, jj$
3260	$p\overset{(-)}{p} \to W^- W^-\, jj \to \ell_1^- \bar{\nu}_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2}\, jj$
3270	$p\overset{(-)}{p} \to W^+ \gamma\, jj \to \ell^+ \nu_\ell \gamma\, jj$
3280	$p\overset{(-)}{p} \to W^- \gamma\, jj \to \ell^- \bar{\nu}_\ell \gamma\, jj$

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

2.2 $W^\pm\gamma$ production via VBF

The list of implemented VBF processes has been extended by the new $W^\pm\gamma$ final state [8,9] in Vbfnlo 2.7.0. As with other VBF processes, it allows for testing the structure of electro-weak quartic gauge couplings and appears as a background in searches for physics beyond the Standard Model. Scale uncertainties at NLO QCD are significantly reduced compared to the LO prediction and K factors are typically close to unity. The process IDs for these processes can be found in Table 3.

ProcId	Process
270	$p\overset{(-)}{p} \to W^+ \gamma\, jj \to \ell^+ \nu_\ell \gamma\, jj$
280	$p\overset{(-)}{p} \to W^- \gamma\, jj \to \ell^- \bar{\nu}_\ell \gamma\, jj$

Table 3: *Process IDs for $W^\pm\gamma$ + 2 jet production via vector boson fusion at NLO QCD accuracy.*

2.3 Double Higgs production via VBF

The production of two Higgs bosons in VBF [10, 11] contains Feynman diagrams with triple Higgs couplings and therefore allows to study the Higgs self-coupling. The NLO QCD corrections are modest, of the order of several percent for the total cross section, and theory uncertainties due to scale variation are reduced compared to LO. Decays of the Higgs bosons are not implemented so far, and the Higgs bosons are produced on-shell. The corresponding process ID is listed in Table 4.

ProcId	Process
160	$p\overset{(-)}{p} \to HH\,jj$

Table 4: *Process ID for Higgs pair + 2 jet production via vector boson fusion at NLO QCD accuracy.*

2.4 W-Higgs associated production with up to one jet

Associated production of a Higgs boson and a $W^{\pm}$, also known as Higgsstrahlung, is one of the main Higgs production modes at the LHC. It is particularly important when the Higgs boson decays into bottom quarks, which has the largest branching ratio. There, boosted topologies allow one to enhance this process over the background and deduce information on the bottom Yukawa coupling. In Vbfnlo 2.7.0, this process is implemented at NLO QCD, both without and with an additional hard jet in the final-state [12]. The corrections to the integrated cross section show K factors of approximately 1.5 and 1.2, respectively, which is a typical size for diboson processes, and lead to reduced scale variation uncertainties. As a cross-check, also the processes without a Higgs boson in the final-state, i.e. $W^{\pm}$ and $W^{\pm}+$ jet production at NLO QCD have been calculated and are made available in this release. The implementation of all these processes includes leptonic decays and off-shell effects of the W boson. The Higgs is produced on-shell, but one can include its decays into a variety of final states. The new process IDs are given in Tables 5, 6 and 7.

3 New and extended features

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

3.1 Semi-leptonic decays

Besides the fully leptonic decays, which are implemented by default in Vbfnlo, vector bosons can also decay into a quark–anti-quark pair. For several processes Vbfnlo has been extended to also include semi-leptonic final states, i.e. final states with one vector boson decaying into a quark–anti-quark pair and the other(s) into leptons [13]. As in

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

Table 5: *Process IDs for the W production processes with up to one jet at NLO QCD accuracy.*

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

Table 6: *Process IDs for the WH production processes at NLO QCD accuracy.*

the fully leptonic decay modes, finite-width effects of the vector bosons as well as off-shell and non-resonant contributions are included. These processes have several types of applications. In experimental analyses of the VBF processes, when looking for anomalous quartic gauge couplings for example, both leptonic and semi-leptonic decay modes are

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

Table 7: *Process IDs for the WH plus jet production processes at NLO QCD accuracy.*

studied and the new implementation allows to get precise predictions for these processes. Also, the semi-leptonic decay modes of the triboson processes form the s-channel part of the corresponding VBF processes. When studying phase-space regions where the VBF approximation is not completely valid anymore, in particular for small invariant masses of the two jets of the order of the W and Z mass, these can give relevant contributions. The new implementation now allows to study their effects. Semi-leptonic decays for the vector bosons have been added for the diboson processes with two massive vector bosons ($W^\pm W^\mp$, $W^\pm Z$, ZZ), the VBF diboson processes with two massive vector bosons ($W^\pm W^\mp jj$, $W^\pm W^\pm jj$, $W^\pm Zjj$, $ZZjj$), VBF Higgs boson production with decays into $W^\pm W^\mp$ and ZZ and all triple vector boson production processes with zero or one final state photon. NLO QCD corrections to the production part are fully included. NLO QCD effects in the hadronic vector boson decay can be estimated in all cases by switching on multiplication with the corresponding overall K factor for $V \to q\bar{q}$. A complete list of process IDs, where semi-leptonic decays are implemented, is given in Tables 8 and 9. The flavour of the final-state quarks can be chosen by setting the variable `DECAY_QUARKS` in `vbfnlo.dat` to the corresponding PDG IDs.

Several issues arise with respect to the application of cuts for semi-leptonic decays. The first one concerns the definition of the two tagging jets. Choosing the two jets with

ProcId	Process
108	$\overset{(-)}{p}p \to H\,jj \to W^+W^-\,jj \to q\bar{q}\,\ell^-\bar{\nu}_\ell\,jj$
109	$\overset{(-)}{p}p \to H\,jj \to W^+W^-\,jj \to \ell^+\nu_\ell\,q\bar{q}\,jj$
1010	$\overset{(-)}{p}p \to H\,jj \to ZZ\,jj \to q\bar{q}\,\ell^+\ell^-\,jj$
201	$\overset{(-)}{p}p \to W^+W^-\,jj \to q\bar{q}\,\ell^-\bar{\nu}_\ell\,jj$
202	$\overset{(-)}{p}p \to W^+W^-\,jj \to \ell^+\nu_\ell\,q\bar{q}\,jj$
212	$\overset{(-)}{p}p \to ZZ\,jj \to q\bar{q}\,\ell^+\ell^-\,jj$
221	$\overset{(-)}{p}p \to W^+Z\,jj \to q\bar{q}\,\ell^+\ell^-\,jj$
222	$\overset{(-)}{p}p \to W^+Z\,jj \to \ell^+\nu_\ell\,q\bar{q}\,jj$
231	$\overset{(-)}{p}p \to W^-Z\,jj \to q\bar{q}\,\ell^+\ell^-\,jj$
232	$\overset{(-)}{p}p \to W^-Z\,jj \to \ell^-\bar{\nu}_\ell\,q\bar{q}\,jj$
251	$\overset{(-)}{p}p \to W^+W^+\,jj \to q\bar{q}\,\ell^+\nu_\ell\,jj$
261	$\overset{(-)}{p}p \to W^-W^-\,jj \to q\bar{q}\,\ell^-\bar{\nu}_\ell\,jj$

Table 8: *Process IDs for the VBF production processes at NLO QCD accuracy with semileptonic decays.*

the largest transverse momentum might not be the most advantageous choice, as this will occasionally select a vector boson decay product as tagging jet, which alters the distinct shape of the tagging jet distributions. Therefore, several new definitions and further options to define the tagging jets have been added. Also, the two partons which are decay products of the vector boson might be grouped into a single jet by the jet algorithm, or one of them might get combined with one of the tagging jets in VBF processes. In both cases there is no QCD singularity associated when these two partons become collinear. Hence, a flag has been implemented to select whether such configurations are allowed or not. There is, however, a problem with contributions from virtual photons, which are part of the processes with hadronically decaying Z bosons. If their invariant mass approaches zero, a QED singularity arises. This can happen either when the two partons are allowed to form a single jet, or in the real emission process, when the actual extra emission is identified as a separate jet, again allowing the two decay products to become collinear. To handle these cases, a cut on the minimal invariant mass of the vector boson can be placed. Alternatively, a cut on $m_{q\bar{q}}$ is estimated for each final-state quark flavour such that the NLO approximation for $\sigma(e^+e^- \to \text{hadrons})$ gives the same contribution as the experimental continuum data plus the contribution from the sharp resonances of the respective quark flavours [14]. This procedure approximates the correct rates from low-q^2 photons. The kinematics of the quarks in this region are not modeled correctly, but this is of minor importance as the low-q^2 region is only relevant for semileptonic decays when the decay products form a single jet. For a more detailed discussion of the various options

ProcId	Process
301	$p\overset{(-)}{p} \to W^+W^- \to q\bar{q}\,\ell^-\bar{\nu}_\ell$
302	$p\overset{(-)}{p} \to W^+W^- \to \ell^+\nu_\ell\,q\bar{q}$
312	$p\overset{(-)}{p} \to W^+Z \to q\bar{q}\,\ell^+\ell^-$
313	$p\overset{(-)}{p} \to W^+Z \to \ell^+\nu_\ell\,q\bar{q}$
322	$p\overset{(-)}{p} \to W^-Z \to q\bar{q}\,\ell^+\ell^-$
323	$p\overset{(-)}{p} \to W^-Z \to \ell^-\bar{\nu}_\ell\,q\bar{q}$
331	$p\overset{(-)}{p} \to ZZ \to q\bar{q}\,\ell^-\ell^+$
401	$p\overset{(-)}{p} \to W^+W^-Z \to q\bar{q}\,\ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-$
402	$p\overset{(-)}{p} \to W^+W^-Z \to \ell_1^+\nu_{\ell_1}\,q\bar{q}\,\ell_2^+\ell_2^-$
403	$p\overset{(-)}{p} \to W^+W^-Z \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,q\bar{q}$
411	$p\overset{(-)}{p} \to ZZW^+ \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\;q\bar{q}$
412	$p\overset{(-)}{p} \to ZZW^+ \to q\bar{q}\,\ell_1^+\ell_1^-\ell_2^+\nu_{\ell_2}$
421	$p\overset{(-)}{p} \to ZZW^- \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\;q\bar{q}$
422	$p\overset{(-)}{p} \to ZZW^- \to q\bar{q}\,\ell_1^+\ell_1^-\ell_2^-\bar{\nu}_{\ell_2}$
431	$p\overset{(-)}{p} \to W^+W^-W^+ \to q\bar{q}\,\ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\nu_{\ell_2}$
432	$p\overset{(-)}{p} \to W^+W^-W^+ \to \ell_1^+\nu_{\ell_1}\,q\bar{q}\,\ell_2^+\nu_{\ell_2}$
441	$p\overset{(-)}{p} \to W^-W^+W^- \to \ell_1^-\bar{\nu}_{\ell_1}\,q\bar{q}\,\ell_2^-\bar{\nu}_{\ell_2}$
442	$p\overset{(-)}{p} \to W^-W^+W^- \to q\bar{q}\,\ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}$
451	$p\overset{(-)}{p} \to ZZZ \to q\bar{q}\,\ell_1^-\ell_1^+\ell_2^-\ell_2^+$
461	$p\overset{(-)}{p} \to W^+W^-\gamma \to q\bar{q}\,\ell^-\bar{\nu}_\ell\gamma$
462	$p\overset{(-)}{p} \to W^+W^-\gamma \to \ell^+\nu_\ell\,q\bar{q}\,\gamma$
471	$p\overset{(-)}{p} \to ZZ\gamma \to \ell^-\ell^+\,q\bar{q}\,\gamma$
481	$p\overset{(-)}{p} \to W^+Z\gamma \to q\bar{q}\,\ell^-\ell^+\gamma$
482	$p\overset{(-)}{p} \to W^+Z\gamma \to \ell^+\nu_\ell\,q\bar{q}\,\gamma$
491	$p\overset{(-)}{p} \to W^-Z\gamma \to q\bar{q}\,\ell^-\ell^+\gamma$
492	$p\overset{(-)}{p} \to W^-Z\gamma \to \ell^-\bar{\nu}_\ell\,q\bar{q}\,\gamma$

Table 9: *Process IDs for the diboson and triboson production processes at NLO QCD accuracy with semileptonic decays.*

and their default values we refer the reader to the manual of Vbfnlo-2.7.0[2].

[2]http://www.itp.kit.edu/∼vbfnloweb/wiki/doku.php?id=documentation:manual

3.2 Anomalous couplings

Anomalous triple and quartic gauge boson couplings have been implemented for the remaining processes of double vector boson production via VBF, $W^\pm Zjj$, $ZZjj$, $W^\pm W^\pm jj$ and the newly added $W^\pm \gamma jj$. Also in the triboson processes, anomalous couplings are now available for all final-state configurations, namely the ZZZ process, which was the only process with three massive bosons still missing, and in all with one or more final-state photons, including the triboson+jet process $W^\pm \gamma\gamma j$. Additionally, for the triboson processes $W^\pm W^\mp W^\pm$, $W^\pm W^\mp Z$ and $W^\pm ZZ$ the set of operators leading to anomalous triple gauge boson couplings has been extended. The gluon-fusion production of a Higgs plus two jets with decays into WW or ZZ can now be used with anomalous Higgs couplings. 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`. The process IDs for the processes where anomalous couplings have been newly implemented or extended are collected in Table 10.

3.3 Two-Higgs model

For the diboson VBF processes with two massive vector bosons (200-260), which contain a Higgs propagator, a model with two CP-even Higgs bosons has been added. This can be used for example when studying heavy Higgs resonances, to account for both the discovered resonance at around 126 GeV and an additional heavy resonance. Setting the couplings appropriately, the high-energy behaviour can be adjusted so that no unitary violation occurs. This model is chosen by setting `MODEL = 3`. The mass and width of the first Higgs boson are given by `HMASS` and `HWIDTH`, while those of the second one are steered by `H2MASS` and `H2WIDTH`, respectively. The squared coupling of the Higgs to electro-weak gauge bosons can be altered by a multiplicative factor, namely `SIN2BA` for the first one and `COS2BA` for the second one. The unitarity requirement mentioned above is fulfilled by setting `SIN2BA` + `COS2BA` = 1. All variables can be found in `vbfnlo.dat`.

3.4 Spin-2 model

The list of processes available within the spin-2 model, introduced in Refs. [15, 16], has been extended. The model uses an effective Lagrangian to describe the interactions of spin-2 particles with electroweak gauge bosons. Both an isospin singlet spin-2 state and a spin-2 triplet are available. In the previous release the possibility of an additional spin-2 resonance besides Higgs and continuum diagrams has been added to the diboson VBF processes 200-230, and a spin-2 resonance decaying into a pair of photons is available with process ID 191. With VBFNLO-2.7.0, also a single spin-2 resonance decaying into $WW \to 2\ell 2\nu$, $ZZ \to 4\ell$ or $ZZ \to 2\ell 2\nu$ is added. This complements the existing full processes by allowing to study the signal process separately on its own. Note that the switch `SPIN2` in `vbfnlo.dat` needs to be set to `true` for these processes. If this switch is set to `false`, the same process but with a Higgs resonance is calculated, allowing for an easy comparison between the two possibilities. The process IDs of the new processes are listed in Table 11.

ProcId	Process
210	$p\overset{(-)}{p} \to ZZ\,jj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\,jj$
211	$p\overset{(-)}{p} \to ZZ\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\,jj$
220	$p\overset{(-)}{p} \to W^+Z\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-\,jj$
230	$p\overset{(-)}{p} \to W^-Z\,jj \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-\,jj$
250	$p\overset{(-)}{p} \to W^+W^+\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^+\nu_{\ell_2}\,jj$
260	$p\overset{(-)}{p} \to W^-W^-\,jj \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,jj$
270	$p\overset{(-)}{p} \to W^+\gamma\,jj \to \ell^+\nu_\ell\gamma\,jj$
280	$p\overset{(-)}{p} \to W^-\gamma\,jj \to \ell^-\bar{\nu}_\ell\gamma\,jj$
400	$p\overset{(-)}{p} \to W^+W^-Z \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\ell_3^+\ell_3^-$
410	$p\overset{(-)}{p} \to ZZW^+ \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\ell_3^+\nu_{\ell_3}$
420	$p\overset{(-)}{p} \to ZZW^- \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\ell_3^-\bar{\nu}_{\ell_3}$
430	$p\overset{(-)}{p} \to W^+W^-W^+ \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\ell_3^+\nu_{\ell_3}$
440	$p\overset{(-)}{p} \to W^-W^+W^- \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\nu_{\ell_2}\ell_3^-\bar{\nu}_{\ell_3}$
450	$p\overset{(-)}{p} \to ZZZ \to \ell_1^-\ell_1^+\ell_2^-\ell_2^+\ell_3^-\ell_3^+$
460	$p\overset{(-)}{p} \to W^-W^+\gamma \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\nu_{\ell_2}\gamma$
470	$p\overset{(-)}{p} \to ZZ\gamma \to \ell_1^-\ell_1^+\ell_2^-\ell_2^+\gamma$
480	$p\overset{(-)}{p} \to W^+Z\gamma \to \ell_1^+\nu_{\ell_1}\ell_2^-\ell_2^+\gamma$
490	$p\overset{(-)}{p} \to W^-Z\gamma \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^-\ell_2^+\gamma$
500	$p\overset{(-)}{p} \to W^+\gamma\gamma \to \ell^+\nu_\ell\gamma\gamma$
510	$p\overset{(-)}{p} \to W^-\gamma\gamma \to \ell^-\bar{\nu}_\ell\gamma\gamma$
520	$p\overset{(-)}{p} \to Z\gamma\gamma \to \ell^-\ell^+\gamma\gamma$
521	$p\overset{(-)}{p} \to Z\gamma\gamma \to \nu_\ell\bar{\nu}_\ell\gamma\gamma$
530	$p\overset{(-)}{p} \to \gamma\gamma\gamma$
4105	$p\overset{(-)}{p} \to H\,jj \to W^+W^-\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,jj$
4106	$p\overset{(-)}{p} \to H\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\,jj$
4107	$p\overset{(-)}{p} \to H\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\,jj$

Table 10: *Process IDs for existing processes which have been extended to include anomalous couplings.*

3.5 Final state summed over generations

Besides decays into a single generation, results can now also be calculated summed over different generations. This applies to both the final-state leptons and, for the semileptonic

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

Table 11: *Process IDs for a spin-2 particle S_2+2 jet production via vector boson fusion at NLO QCD accuracy.*

decay modes, also the final-state quarks appearing as decay product of vector bosons. The cross section will then be summed over all possibilities, and Les Houches event files will contain events with all included generations and correct relative weights. This new option is controlled in `vbfnlo.dat` by setting the final-state lepton and quark switches `LEPTONS` and `DECAY_QUARKS`, respectively. Setting the former variable to `99` includes leptons of all three generations, while `98` uses only those of the first and second generation. The latter variable can be set to `93` to allow only first and second generation decay products, or `94` to include (massless) bottom quarks as well.

3.6 Event output

Some options have been added to make generating Les Houches event files easier. It is now possible to specify a desired number of unweighted events by setting `DESIRED_EVENT_COUNT` in `vbfnlo.dat` to the corresponding value. If this number is not yet reached after having completed the requested number of integration iterations, event generation will continue until this is completed. For some processes or parameter settings it might be difficult to get the desired number of unweighted events, because single events with large weights spoil the unweighting efficiency. For this case `PARTIAL_UNWEIGHTING = true` will give the desired number of events with unit weight and additionally a few events with weight > 1 which occured during the event generation.

4 Other changes

Since the previous release, Version 2.6.0, some changes have been made that alter previous results (events, cross sections and distributions).

4.1 Running scales in NLO calculations

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

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

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

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

A bug in the calculation of the virtual contributions for WWZ production has been fixed while comparing with the results of Ref. [17]. The new results are roughly one per cent smaller, and agree between both codes for squared amplitudes at the level of the machine precision and for integrated cross sections at the per mill level.

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

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

4.5 Event output

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

- The color information in the event output for W^-W^-jj in VBF has been fixed.
- The momenta assignment in the event output for $W^-W^+W^-$ has been corrected.

4.6 Previous changes – version 2.6.3

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

4.6.1 Event output

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

- Fixed bugs in output of particle IDs for processes 191 and 43xx: In previous versions some particles had the particle ID 0.
- Parton and beam particle IDs have been fixed for process 260.
- The tau mass can now be included in the event output of all processes. Furthermore, several bugs have been fixed in the existing implementation of tau mass inclusion.
- Several bugs have been fixed in the helicity output.

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

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

4.6.3 Electroweak corrections in the VBF Hjj processes

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

4.7 Previous changes – version 2.6.2

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

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

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

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

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

4.7.3 ZZZ production

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

4.7.4 Form factor in γjj production with anomalous couplings

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

4.8 Previous changes – version 2.6.1

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

4.8.1 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.

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

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

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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	semi-leptonic decay	VBF process	anom. gauge couplings	anom. Higgs couplings	Two-Higgs model	Kaluza-Klein model	Spin-2 model	MSSM
100	$p\overset{(-)}{p} \to H\,jj$	–	✓	–	✓	–	–	–	✓
101	$p\overset{(-)}{p} \to H\,jj \to \gamma\gamma\,jj$	–	✓	–	✓	–	–	–	✓
102	$p\overset{(-)}{p} \to H\,jj \to \mu^+\mu^-\,jj$	–	✓	–	✓	–	–	–	✓
103	$p\overset{(-)}{p} \to H\,jj \to \tau^+\tau^-\,jj$	–	✓	–	✓	–	–	–	✓
104	$p\overset{(-)}{p} \to H\,jj \to b\bar{b}\,jj$	–	✓	–	✓	–	–	–	✓
105	$p\overset{(-)}{p} \to H\,jj \to W^+W^-\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,jj$	–	✓	–	✓	–	–	–	✓
106	$p\overset{(-)}{p} \to H\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\,jj$	–	✓	–	✓	–	–	–	✓
107	$p\overset{(-)}{p} \to H\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\,jj$	–	✓	–	✓	–	–	–	✓
108	$p\overset{(-)}{p} \to H\,jj \to W^+W^-\,jj \to q\bar{q}\,\ell^-\bar{\nu}_\ell\,jj$	✓	✓	–	✓	–	–	–	✓
109	$p\overset{(-)}{p} \to H\,jj \to W^+W^-\,jj \to \ell^+\nu_\ell\,q\bar{q}\,jj$	✓	✓	–	✓	–	–	–	✓
1010	$p\overset{(-)}{p} \to H\,jj \to ZZ\,jj \to q\bar{q}\,\ell^+\ell^-\,jj$	✓	✓	–	✓	–	–	–	✓
110	$p\overset{(-)}{p} \to H\,jjj$	–	✓	–	–	–	–	–	–
111	$p\overset{(-)}{p} \to H\,jjj \to \gamma\gamma\,jjj$	–	✓	–	–	–	–	–	–
112	$p\overset{(-)}{p} \to H\,jjj \to \mu^+\mu^-\,jjj$	–	✓	–	–	–	–	–	–
113	$p\overset{(-)}{p} \to H\,jjj \to \tau^+\tau^-\,jjj$	–	✓	–	–	–	–	–	–
114	$p\overset{(-)}{p} \to H\,jjj \to b\bar{b}\,jjj$	–	✓	–	–	–	–	–	–
115	$p\overset{(-)}{p} \to H\,jjj \to W^+W^-\,jjj \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,jjj$	–	✓	–	–	–	–	–	–
116	$p\overset{(-)}{p} \to H\,jjj \to ZZ\,jjj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\,jjj$	–	✓	–	–	–	–	–	–
117	$p\overset{(-)}{p} \to H\,jjj \to ZZ\,jjj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\,jjj$	–	✓	–	–	–	–	–	–
120	$p\overset{(-)}{p} \to Z\,jj \to \ell^+\ell^-\,jj$	–	✓	✓	–	–	–	–	–
121	$p\overset{(-)}{p} \to Z\,jj \to \nu_\ell\bar{\nu}_\ell\,jj$	–	✓	✓	–	–	–	–	–
130	$p\overset{(-)}{p} \to W^+\,jj \to \ell^+\nu_\ell\,jj$	–	✓	✓	–	–	–	–	–
140	$p\overset{(-)}{p} \to W^-\,jj \to \ell^-\bar{\nu}_\ell\,jj$	–	✓	✓	–	–	–	–	–
150	$p\overset{(-)}{p} \to \gamma\,jj$	–	✓	✓	–	–	–	–	–

ProcId	Process	semi-leptonic decay	VBF process	anom. gauge couplings	anom. Higgs couplings	Two-Higgs model	Kaluza-Klein model	Spin-2 model	MSSM
191	$p\overset{(-)}{p} \to S_2\, jj \to \gamma\gamma\, jj$	–	✓	–	–	–	–	✓	–
195	$p\overset{(-)}{p} \to S_2\, jj \to W^+W^-\, jj \to \ell_1^+ \nu_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2}\, jj$	–	✓	–	–	–	–	✓	–
196	$p\overset{(-)}{p} \to S_2\, jj \to ZZ\, jj \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-\, jj$	–	✓	–	–	–	–	✓	–
197	$p\overset{(-)}{p} \to S_2\, jj \to ZZ\, jj \to \ell_1^+ \ell_1^- \nu_{\ell_2} \bar{\nu}_{\ell_2}\, jj$	–	✓	–	–	–	–	✓	–
160	$p\overset{(-)}{p} \to HH\, jj$	–	✓	–	–	–	–	–	–
2100	$p\overset{(-)}{p} \to H\gamma\, jj$	–	✓	–	–	–	–	–	–
2101	$p\overset{(-)}{p} \to H\gamma\, jj \to \gamma\gamma\gamma\, jj$	–	✓	–	–	–	–	–	–
2102	$p\overset{(-)}{p} \to H\gamma\, jj \to \mu^+\mu^-\gamma\, jj$	–	✓	–	–	–	–	–	–
2103	$p\overset{(-)}{p} \to H\gamma\, jj \to \tau^+\tau^-\gamma\, jj$	–	✓	–	–	–	–	–	–
2104	$p\overset{(-)}{p} \to H\gamma\, jj \to b\bar{b}\gamma\, jj$	–	✓	–	–	–	–	–	–
2105	$p\overset{(-)}{p} \to H\gamma\, jj \to W^+W^-\gamma\, jj \to \ell_1^+ \nu_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2}\gamma\, jj$	–	✓	–	–	–	–	–	–
2106	$p\overset{(-)}{p} \to H\gamma\, jj \to ZZ\gamma\, jj \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-\gamma\, jj$	–	✓	–	–	–	–	–	–
2107	$p\overset{(-)}{p} \to H\gamma\, jj \to ZZ\gamma\, jj \to \ell_1^+ \ell_1^- \nu_{\ell_2} \bar{\nu}_{\ell_2}\gamma\, jj$	–	✓	–	–	–	–	–	–
200	$p\overset{(-)}{p} \to W^+W^-\, jj \to \ell_1^+ \nu_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2}\, jj$	–	✓	✓	–	✓	✓	✓	–
201	$p\overset{(-)}{p} \to W^+W^-\, jj \to q\bar{q}\, \ell^- \bar{\nu}_\ell\, jj$	✓	✓	✓	–	✓	–	–	–
202	$p\overset{(-)}{p} \to W^+W^-\, jj \to \ell^+ \nu_\ell\, q\bar{q}\, jj$	✓	✓	✓	–	✓	–	–	–
210	$p\overset{(-)}{p} \to ZZ\, jj \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-\, jj$	–	✓	✓	–	✓	✓	✓	–
211	$p\overset{(-)}{p} \to ZZ\, jj \to \ell_1^+ \ell_1^- \nu_{\ell_2} \bar{\nu}_{\ell_2}\, jj$	–	✓	✓	–	✓	✓	✓	–
212	$p\overset{(-)}{p} \to ZZ\, jj \to q\bar{q}\, \ell^+ \ell^-\, jj$	✓	✓	✓	–	✓	–	–	–
220	$p\overset{(-)}{p} \to W^+Z\, jj \to \ell_1^+ \nu_{\ell_1} \ell_2^+ \ell_2^-\, jj$	–	✓	✓	–	✓	✓	✓	–
221	$p\overset{(-)}{p} \to W^+Z\, jj \to q\bar{q}\, \ell^+ \ell^-\, jj$	✓	✓	✓	–	✓	–	–	–
222	$p\overset{(-)}{p} \to W^+Z\, jj \to \ell^+ \nu_\ell\, q\bar{q}\, jj$	✓	✓	✓	–	✓	–	–	–
230	$p\overset{(-)}{p} \to W^-Z\, jj \to \ell_1^- \bar{\nu}_{\ell_1} \ell_2^+ \ell_2^-\, jj$	–	✓	✓	–	✓	✓	✓	–
231	$p\overset{(-)}{p} \to W^-Z\, jj \to q\bar{q}\, \ell^+ \ell^-\, jj$	✓	✓	✓	–	✓	–	–	–
232	$p\overset{(-)}{p} \to W^-Z\, jj \to \ell^- \bar{\nu}_\ell\, q\bar{q}\, jj$	✓	✓	✓	–	✓	–	–	–
250	$p\overset{(-)}{p} \to W^+W^+\, jj \to \ell_1^+ \nu_{\ell_1} \ell_2^+ \nu_{\ell_2}\, jj$	–	✓	✓	–	✓	–	–	–
251	$p\overset{(-)}{p} \to W^+W^+\, jj \to q\bar{q}\, \ell^+ \nu_\ell\, jj$	✓	✓	✓	–	✓	–	–	–
260	$p\overset{(-)}{p} \to W^-W^-\, jj \to \ell_1^- \bar{\nu}_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2}\, jj$	–	✓	✓	–	✓	–	–	–
261	$p\overset{(-)}{p} \to W^-W^-\, jj \to q\bar{q}\, \ell^- \bar{\nu}_\ell\, jj$	✓	✓	✓	–	✓	–	–	–
270	$p\overset{(-)}{p} \to W^+\gamma\, jj \to \ell^+ \nu_\ell \gamma\, jj$	–	✓	✓	–	–	–	–	–
280	$p\overset{(-)}{p} \to W^-\gamma\, jj \to \ell^- \bar{\nu}_\ell \gamma\, jj$	–	✓	✓	–	–	–	–	–

ProcId	Process	semi-leptonic decay	VBF process	anom. gauge couplings	anom. Higgs couplings	Two-Higgs model	Kaluza-Klein model	Spin-2 model	MSSM
3130	$p\overset{(-)}{p} \to W^+\,jj \to \ell^+\nu_\ell\,jj$	–	–	–	–	–	–	–	–
3140	$p\overset{(-)}{p} \to W^-\,jj \to \ell^-\bar{\nu}_\ell\,jj$	–	–	–	–	–	–	–	–
3220	$p\overset{(-)}{p} \to W^+Z\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-\,jj$	–	–	–	–	–	–	–	–
3230	$p\overset{(-)}{p} \to W^-Z\,jj \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-\,jj$	–	–	–	–	–	–	–	–
3250	$p\overset{(-)}{p} \to W^+W^+\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^+\nu_{\ell_2}\,jj$	–	–	–	–	–	–	–	–
3260	$p\overset{(-)}{p} \to W^-W^-\,jj \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,jj$	–	–	–	–	–	–	–	–
3270	$p\overset{(-)}{p} \to W^+\gamma\,jj \to \ell^+\nu_\ell\gamma\,jj$	–	–	–	–	–	–	–	–
3280	$p\overset{(-)}{p} \to W^-\gamma\,jj \to \ell^-\bar{\nu}_\ell\gamma\,jj$	–	–	–	–	–	–	–	–
1330	$p\overset{(-)}{p} \to W^+ \to \ell^+\nu_\ell$	–	–	–	–	–	–	–	–
1340	$p\overset{(-)}{p} \to W^- \to \ell^-\bar{\nu}_\ell$	–	–	–	–	–	–	–	–
1630	$p\overset{(-)}{p} \to W^+\,j \to \ell^+\nu_\ell\,j$	–	–	–	–	–	–	–	–
1640	$p\overset{(-)}{p} \to W^-\,j \to \ell^-\bar{\nu}_\ell\,j$	–	–	–	–	–	–	–	–
300	$p\overset{(-)}{p} \to W^+W^- \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}$	–	–	✓	✓	–	–	–	–
301	$p\overset{(-)}{p} \to W^+W^- \to q\bar{q}\,\ell^-\bar{\nu}_\ell$	✓	–	✓	✓	–	–	–	–
302	$p\overset{(-)}{p} \to W^+W^- \to \ell^+\nu_\ell\,q\bar{q}$	✓	–	✓	✓	–	–	–	–
310	$p\overset{(-)}{p} \to W^+Z \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-$	–	–	✓	–	–	–	–	–
312	$p\overset{(-)}{p} \to W^+Z \to q\bar{q}\,\ell^+\ell^-$	✓	–	✓	–	–	–	–	–
313	$p\overset{(-)}{p} \to W^+Z \to \ell^+\nu_\ell\,q\bar{q}$	✓	–	✓	–	–	–	–	–
320	$p\overset{(-)}{p} \to W^-Z \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-$	–	–	✓	–	–	–	–	–
322	$p\overset{(-)}{p} \to W^-Z \to q\bar{q}\,\ell^+\ell^-$	✓	–	✓	–	–	–	–	–
323	$p\overset{(-)}{p} \to W^-Z \to \ell^-\bar{\nu}_\ell\,q\bar{q}$	✓	–	✓	–	–	–	–	–
330	$p\overset{(-)}{p} \to ZZ \to \ell_1^-\ell_1^+\ell_2^-\ell_2^+$	–	–	–	✓	–	–	–	–
331	$p\overset{(-)}{p} \to ZZ \to q\bar{q}\,\ell^-\ell^+$	✓	–	–	✓	–	–	–	–
340	$p\overset{(-)}{p} \to W^+\gamma \to \ell_1^+\nu_{\ell_1}\gamma$	–	–	✓	–	–	–	–	–
350	$p\overset{(-)}{p} \to W^-\gamma \to \ell_1^-\bar{\nu}_{\ell_1}\gamma$	–	–	✓	–	–	–	–	–
360	$p\overset{(-)}{p} \to Z\gamma \to \ell_1^-\ell_1^+\gamma$	–	–	–	✓	–	–	–	–
370	$p\overset{(-)}{p} \to \gamma\gamma$	–	–	–	✓	–	–	–	–

ProcId	Process	semi-leptonic decay	VBF process	anom. gauge couplings	anom. Higgs couplings	Two-Higgs model	Kaluza-Klein model	Spin-2 model	MSSM
1300	$p\overset{(-)}{p} \to W^+H \to \ell^+\nu_\ell H$	–	–	✓	–	–	–	–	–
1301	$p\overset{(-)}{p} \to W^+H \to \ell^+\nu_\ell \gamma\gamma$	–	–	✓	–	–	–	–	–
1302	$p\overset{(-)}{p} \to W^+H \to \ell^+\nu_\ell \mu^+\mu^-$	–	–	✓	–	–	–	–	–
1303	$p\overset{(-)}{p} \to W^+H \to \ell^+\nu_\ell \tau^+\tau^-$	–	–	✓	–	–	–	–	–
1304	$p\overset{(-)}{p} \to W^+H \to \ell^+\nu_\ell b\bar{b}$	–	–	✓	–	–	–	–	–
1305	$p\overset{(-)}{p} \to W^+H \to W^+W^+W^- \to \ell_1^+\nu_{\ell_1}\ell_2^+\nu_{\ell_2}\ell_3^-\bar{\nu}_{\ell_3}$	–	–	✓	–	–	–	–	–
1306	$p\overset{(-)}{p} \to W^+H \to W^+ZZ \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-\ell_3^+\ell_3^-$	–	–	✓	–	–	–	–	–
1307	$p\overset{(-)}{p} \to W^+H \to W^+ZZ \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-\nu_{\ell_3}\bar{\nu}_{\ell_3}$	–	–	✓	–	–	–	–	–
1310	$p\overset{(-)}{p} \to W^-H \to \ell^-\bar{\nu}_\ell H$	–	–	✓	–	–	–	–	–
1311	$p\overset{(-)}{p} \to W^-H \to \ell^-\bar{\nu}_\ell \gamma\gamma$	–	–	✓	–	–	–	–	–
1312	$p\overset{(-)}{p} \to W^-H \to \ell^-\bar{\nu}_\ell \mu^+\mu^-$	–	–	✓	–	–	–	–	–
1313	$p\overset{(-)}{p} \to W^-H \to \ell^-\bar{\nu}_\ell \tau^+\tau^-$	–	–	✓	–	–	–	–	–
1314	$p\overset{(-)}{p} \to W^-H \to \ell^-\bar{\nu}_\ell b\bar{b}$	–	–	✓	–	–	–	–	–
1315	$p\overset{(-)}{p} \to W^-H \to W^-W^+W^- \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\nu_{\ell_2}\ell_3^-\bar{\nu}_{\ell_3}$	–	–	✓	–	–	–	–	–
1316	$p\overset{(-)}{p} \to W^-H \to W^-ZZ \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-\ell_3^+\ell_3^-$	–	–	✓	–	–	–	–	–
1317	$p\overset{(-)}{p} \to W^-H \to W^-ZZ \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\ell_2^-\nu_{\ell_3}\bar{\nu}_{\ell_3}$	–	–	✓	–	–	–	–	–
610	$p\overset{(-)}{p} \to W^-\gamma j \to \ell^-\bar{\nu}_\ell \gamma j$	–	–	✓	–	–	–	–	–
620	$p\overset{(-)}{p} \to W^+\gamma j \to \ell^+\nu_\ell \gamma j$	–	–	✓	–	–	–	–	–
630	$p\overset{(-)}{p} \to W^-Zj \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^-\ell_2^+ j$	–	–	✓	–	–	–	–	–
640	$p\overset{(-)}{p} \to W^+Zj \to \ell_1^+\nu_{\ell_1}\ell_2^-\ell_2^+ j$	–	–	✓	–	–	–	–	–
1600	$p\overset{(-)}{p} \to W^+H\,j \to \ell^+\nu_\ell H\,j$	–	–	✓	–	–	–	–	–
1601	$p\overset{(-)}{p} \to W^+H\,j \to \ell^+\nu_\ell \gamma\gamma\,j$	–	–	✓	–	–	–	–	–
1602	$p\overset{(-)}{p} \to W^+H\,j \to \ell^+\nu_\ell \mu^+\mu^-\,j$	–	–	✓	–	–	–	–	–
1603	$p\overset{(-)}{p} \to W^+H\,j \to \ell^+\nu_\ell \tau^+\tau^-\,j$	–	–	✓	–	–	–	–	–
1604	$p\overset{(-)}{p} \to W^+H\,j \to \ell^+\nu_\ell b\bar{b}\,j$	–	–	✓	–	–	–	–	–
1605	$p\overset{(-)}{p} \to W^+H\,j \to W^+W^+W^-\,j \to \ell_1^+\nu_{\ell_1}\ell_2^+\nu_{\ell_2}\ell_3^-\bar{\nu}_{\ell_3}\,j$	–	–	✓	–	–	–	–	–
1606	$p\overset{(-)}{p} \to W^+H\,j \to W^+ZZ\,j \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-\ell_3^+\ell_3^-\,j$	–	–	✓	–	–	–	–	–
1607	$p\overset{(-)}{p} \to W^+H\,j \to W^+ZZ\,j \to \ell_1^+\nu_{\ell_1}\ell_2^+\ell_2^-\nu_{\ell_3}\bar{\nu}_{\ell_3}\,j$	–	–	✓	–	–	–	–	–

ProcId	Process	semi-leptonic decay	VBF process	anom. gauge couplings	anom. Higgs couplings	Two-Higgs model	Kaluza-Klein model	Spin-2 model	MSSM
1610	$p\overset{(-)}{p} \to W^- H\, j \to \ell^- \bar\nu_\ell H\, j$	–	–	✓	–	–	–	–	–
1611	$p\overset{(-)}{p} \to W^- H\, j \to \ell^- \bar\nu_\ell \gamma\gamma\, j$	–	–	✓	–	–	–	–	–
1612	$p\overset{(-)}{p} \to W^- H\, j \to \ell^- \bar\nu_\ell \mu^+\mu^-\, j$	–	–	✓	–	–	–	–	–
1613	$p\overset{(-)}{p} \to W^- H\, j \to \ell^- \bar\nu_\ell \tau^+\tau^-\, j$	–	–	✓	–	–	–	–	–
1614	$p\overset{(-)}{p} \to W^- H\, j \to \ell^- \bar\nu_\ell b\bar b\, j$	–	–	✓	–	–	–	–	–
1615	$p\overset{(-)}{p} \to W^- H\, j \to W^- W^+ W^-\, j \to \ell_1^- \bar\nu_{\ell_1} \ell_2^+ \nu_{\ell_2} \ell_3^- \bar\nu_{\ell_3}\, j$	–	–	✓	–	–	–	–	–
1616	$p\overset{(-)}{p} \to W^- H\, j \to W^- ZZ\, j \to \ell_1^- \bar\nu_{\ell_1} \ell_2^+ \ell_2^- \ell_3^+ \ell_3^-\, j$	–	–	✓	–	–	–	–	–
1617	$p\overset{(-)}{p} \to W^- H\, j \to W^- ZZ\, j \to \ell_1^- \bar\nu_{\ell_1} \ell_2^+ \ell_2^- \nu_{\ell_3} \bar\nu_{\ell_3}\, j$	–	–	✓	–	–	–	–	–
400	$p\overset{(-)}{p} \to W^+W^-Z \to \ell_1^+ \nu_{\ell_1} \ell_2^- \bar\nu_{\ell_2} \ell_3^+ \ell_3^-$	–	–	✓	–	–	✓	–	–
401	$p\overset{(-)}{p} \to W^+W^-Z \to q\bar q\, \ell_1^- \bar\nu_{\ell_1} \ell_2^+ \ell_2^-$	✓	–	✓	–	–	–	–	–
402	$p\overset{(-)}{p} \to W^+W^-Z \to \ell_1^+ \nu_{\ell_1}\, q\bar q\, \ell_2^+ \ell_2^-$	✓	–	✓	–	–	–	–	–
403	$p\overset{(-)}{p} \to W^+W^-Z \to \ell_1^+ \nu_{\ell_1} \ell_2^- \bar\nu_{\ell_2}\, q\bar q$	✓	–	✓	–	–	–	–	–
410	$p\overset{(-)}{p} \to ZZW^+ \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^- \ell_3^+ \nu_{\ell_3}$	–	–	✓	–	–	✓	–	–
411	$p\overset{(-)}{p} \to ZZW^+ \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-\, q\bar q$	✓	–	✓	–	–	–	–	–
412	$p\overset{(-)}{p} \to ZZW^+ \to q\bar q\, \ell_1^+ \ell_1^- \ell_2^+ \nu_{\ell_2}$	✓	–	✓	–	–	–	–	–
420	$p\overset{(-)}{p} \to ZZW^- \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^- \ell_3^- \bar\nu_{\ell_3}$	–	–	✓	–	–	✓	–	–
421	$p\overset{(-)}{p} \to ZZW^- \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-\, q\bar q$	✓	–	✓	–	–	–	–	–
422	$p\overset{(-)}{p} \to ZZW^- \to q\bar q\, \ell_1^+ \ell_1^- \ell_2^- \bar\nu_{\ell_2}$	✓	–	✓	–	–	–	–	–
430	$p\overset{(-)}{p} \to W^+W^-W^+ \to \ell_1^+ \nu_{\ell_1} \ell_2^- \bar\nu_{\ell_2} \ell_3^+ \nu_{\ell_3}$	–	–	✓	–	–	✓	–	–
431	$p\overset{(-)}{p} \to W^+W^-W^+ \to q\bar q\, \ell_1^- \bar\nu_{\ell_1} \ell_2^+ \nu_{\ell_2}$	✓	–	✓	–	–	–	–	–
432	$p\overset{(-)}{p} \to W^+W^-W^+ \to \ell_1^+ \nu_{\ell_1}\, q\bar q\, \ell_2^+ \nu_{\ell_2}$	✓	–	✓	–	–	–	–	–
440	$p\overset{(-)}{p} \to W^-W^+W^- \to \ell_1^- \bar\nu_{\ell_1} \ell_2^+ \nu_{\ell_2} \ell_3^- \bar\nu_{\ell_3}$	–	–	✓	–	–	✓	–	–
441	$p\overset{(-)}{p} \to W^-W^+W^- \to \ell_1^- \bar\nu_{\ell_1}\, q\bar q\, \ell_2^- \bar\nu_{\ell_2}$	✓	–	✓	–	–	–	–	–
442	$p\overset{(-)}{p} \to W^-W^+W^- \to q\bar q\, \ell_1^+ \nu_{\ell_1} \ell_2^- \bar\nu_{\ell_2}$	✓	–	✓	–	–	–	–	–
450	$p\overset{(-)}{p} \to ZZZ \to \ell_1^- \ell_1^+ \ell_2^- \ell_2^+ \ell_3^- \ell_3^+$	–	–	✓	–	–	–	–	–
451	$p\overset{(-)}{p} \to ZZZ \to q\bar q\, \ell_1^- \ell_1^+ \ell_2^- \ell_2^+$	✓	–	✓	–	–	–	–	–

ProcId	Process	semi-leptonic decay	VBF process	anom. gauge couplings	anom. Higgs couplings	Two-Higgs model	Kaluza-Klein model	Spin-2 model	MSSM
460	$p\overset{(-)}{p} \to W^-W^+\gamma \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^+\nu_{\ell_2}\gamma$	–	–	✓	–	–	–	–	–
461	$p\overset{(-)}{p} \to W^+W^-\gamma \to q\bar{q}\,\ell^-\bar{\nu}_\ell\gamma$	✓	–	✓	–	–	–	–	–
462	$p\overset{(-)}{p} \to W^+W^-\gamma \to \ell^+\nu_\ell\,q\bar{q}\,\gamma$	✓	–	✓	–	–	–	–	–
470	$p\overset{(-)}{p} \to ZZ\gamma \to \ell_1^-\ell_1^+\ell_2^-\ell_2^+\gamma$	–	–	✓	–	–	–	–	–
471	$p\overset{(-)}{p} \to ZZ\gamma \to \ell^-\ell^+\,q\bar{q}\,\gamma$	✓	–	✓	–	–	–	–	–
480	$p\overset{(-)}{p} \to W^+Z\gamma \to \ell_1^+\nu_{\ell_1}\ell_2^-\ell_2^+\gamma$	–	–	✓	–	–	–	–	–
481	$p\overset{(-)}{p} \to W^+Z\gamma \to q\bar{q}\,\ell^-\ell^+\gamma$	✓	–	✓	–	–	–	–	–
482	$p\overset{(-)}{p} \to W^+Z\gamma \to \ell^+\nu_\ell\,q\bar{q}\,\gamma$	✓	–	✓	–	–	–	–	–
490	$p\overset{(-)}{p} \to W^-Z\gamma \to \ell_1^-\bar{\nu}_{\ell_1}\ell_2^-\ell_2^+\gamma$	–	–	✓	–	–	–	–	–
491	$p\overset{(-)}{p} \to W^-Z\gamma \to q\bar{q}\,\ell^-\ell^+\gamma$	✓	–	✓	–	–	–	–	–
492	$p\overset{(-)}{p} \to W^-Z\gamma \to \ell^-\bar{\nu}_\ell\,q\bar{q}\,\gamma$	✓	–	✓	–	–	–	–	–
500	$p\overset{(-)}{p} \to W^+\gamma\gamma \to \ell^+\nu_\ell\gamma\gamma$	–	–	✓	–	–	–	–	–
510	$p\overset{(-)}{p} \to W^-\gamma\gamma \to \ell^-\bar{\nu}_\ell\gamma\gamma$	–	–	✓	–	–	–	–	–
520	$p\overset{(-)}{p} \to Z\gamma\gamma \to \ell^-\ell^+\gamma\gamma$	–	–	✓	–	–	–	–	–
521	$p\overset{(-)}{p} \to Z\gamma\gamma \to \nu_\ell\bar{\nu}_\ell\gamma\gamma$	–	–	✓	–	–	–	–	–
530	$p\overset{(-)}{p} \to \gamma\gamma\gamma$	–	–	✓	–	–	–	–	–
800	$p\overset{(-)}{p} \to W^+\gamma\gamma j \to \ell^+\nu_\ell\gamma\gamma j$	–	–	✓	–	–	–	–	–
810	$p\overset{(-)}{p} \to W^-\gamma\gamma j \to \ell^-\bar{\nu}_\ell\gamma\gamma j$	–	–	✓	–	–	–	–	–

The gluon-fusion processes accessed via the executable `ggflo` are given below.

ProcId	Process	gluon-fusion process	semi-leptonic decay	anom. Higgs couplings	general 2HDM	MSSM
4100	$\overset{(-)}{p}p \to H\,jj$	✓	–	–	✓	✓
4101	$p\overset{(-)}{p} \to H\,jj \to \gamma\gamma\,jj$	✓	–	–	–	✓
4102	$p\overset{(-)}{p} \to H\,jj \to \mu^+\mu^-\,jj$	✓	–	–	–	✓
4103	$p\overset{(-)}{p} \to H\,jj \to \tau^+\tau^-\,jj$	✓	–	–	–	✓
4104	$p\overset{(-)}{p} \to H\,jj \to b\bar{b}\,jj$	✓	–	–	–	✓
4105	$p\overset{(-)}{p} \to H\,jj \to W^+W^-\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,jj$	✓	–	✓	✓	✓
4106	$p\overset{(-)}{p} \to H\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\,jj$	✓	–	✓	✓	✓
4107	$p\overset{(-)}{p} \to H\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\,jj$	✓	–	✓	✓	✓
4300	$p\overset{(-)}{p} \to W^+W^- \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}$	✓	–	✓	–	–
4301	$p\overset{(-)}{p} \to W^+W^- \to q\bar{q}\,\ell^-\bar{\nu}_\ell$	✓	✓	✓	–	–
4302	$p\overset{(-)}{p} \to W^+W^- \to \ell^+\nu_\ell\,q\bar{q}$	✓	✓	✓	–	–
4330	$p\overset{(-)}{p} \to ZZ \to \ell_1^-\ell_1^+\ell_2^-\ell_2^+$	✓	–	✓	–	–
4331	$p\overset{(-)}{p} \to ZZ \to q\bar{q}\,\ell^-\ell^+$	✓	✓	✓	–	–
4360	$p\overset{(-)}{p} \to Z\gamma \to \ell_1^-\ell_1^+\gamma$	✓	–	✓	–	–
4370	$p\overset{(-)}{p} \to \gamma\gamma$	✓	–	✓	–	–