Repolo: REweighting POwheg events at Leading Order

– Manual for Version 1.0, based on Vfnlo-2.6.0

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Abstract

The physics potential of the LHC depends heavily on our ability to provide accurate simulations of both signal and background processes. The process of running full NLO-events plus a shower plus detector simulation plus cuts is, however, a lengthy one. In order to avoid re-running the entire sequence for anomalous HVV couplings, or for a spin-2 particle, as opposed to a Standard Model (SM) Higgs boson, it was proposed that SM Higgs events were simply reweighted for different BSM scenarios. REPOLO – REweighting POwheg events at Leading Order – uses the VBFNLO framework and reweights each SM event by a factor

$$\frac{|\mathcal{M}_{\mathrm{BSM}}|^2}{|\mathcal{M}_{\mathrm{SM}}|^2}.$$

The method does, however, have severe limitations, as a single event with a high reweighting factor (i.e. where $|\mathcal{M}_{\mathrm{SM}}|^2 \ll |\mathcal{M}_{\mathrm{BSM}}|^2$) can destroy a distribution. This means that, in practice, only SM-like distributions can be safely reweighted using REPOLO.

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Contents

1 Introduction

A full simulation of a Higgs production process at the Large Hadron Collider (Lhc) – involving simulating full NLO-events plus a shower plus detector simulation plus cuts – is very time consuming. In order to avoid re-running the entire sequence for Beyond the Standard Model (Bsm) scenarios, it has been proposed that existing Standard Model (SM) Higgs events are simply reweighted for different BSM scenarios. Repolo – REweighting POwheg events at Leading Order – reads an input Les Houches event (LHE) file and, using the Vbfnlo framework [1–3] and a `perl` script, creates a new event file where each SM event is reweighted by a factor

$$\frac{|\mathcal{M}_{\mathrm{BSM}}|^2}{|\mathcal{M}_{\mathrm{SM}}|^2}. \tag{1}$$

At present, Repolo can reweight VBF production of a "Higgs-like" boson in the following Bsm scenarios:

- MSSM (with real or complex parameters),
- anomalous HVV couplings,
- spin-2 particle (where the spin-2 particle decays into two photons).

The reweighting method does, however, have limitations in regions where

$$|\mathcal{M}_{\mathrm{SM}}|^2 \ll |\mathcal{M}_{\mathrm{BSM}}|^2.$$

In these regions a single point, with a high reweighting factor, can effectively destroy a distribution. Due to these limitations, Repolo is only semi-public – to obtain a copy of the source code, email the Vbfnlo team at

`vbfnlo@particle.uni-karlsruhe.de`

Repolo contains example input and output files in the `regress` directory for the process $pp \to Hjj \to \gamma\gamma jj$ with anomalous HVV couplings.

2 Installing Repolo

The source code of the current version of Repolo can be obtained by emailing the Vbfnlo team at

`vbfnlo@particle.uni-karlsruhe.de`

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

2.1 Prerequisites

The basic installation requires GNU `make`, a FORTRAN77[1] and a C++ compiler. Repolo offers the possibility of using the Lhapdf[2] [4] library for the parton distribution functions. Additionally, FeynHiggs[3] [5–8] can be linked to the code in order to calculate the Higgs boson sector of the MSSM, although a SLHA file can be used as an alternative. In order to calculate the Higgs propagator factors in the MSSM if FeynHiggs is not linked, the program LoopTools[4] [9, 10] is required.

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 Repolo in the location given by `[path]`. If not specified, Repolo is installed in the `root` directory.

- `--enable-spin2`
  Enable simulation of spin-2 models. Enabled by default.

- `--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-FEYNHIGGS=[path]`
  Enable the use of FeynHiggs[5] to calculate the MSSM Higgs sector parameters. Disabled by default. `[path]` specifies the location of the FeynHiggs installation.

- `--with-LOOPTOOLS=[path]`
  Enable the use of LoopTools in order to calculate the MSSM Higgs propagator factors if FeynHiggs is not linked. Disabled by default. `[path]` specifies the location of the LoopTools installation.

[1] `g77`, `ifort` and `gfortran` have been tested.
[2] `http://projects.hepforge.org/lhapdf/`
[3] `http://www.feynhiggs.de/`
[4] `http://www.feynarts.de/looptools/`
[5] Note that different versions of FeynHiggs give slightly different results as more corrections are added to the calculations. Repolo has been tested with FeynHiggs versions 2.6.x, 2.7.x, 2.8.0 and 2.8.3.

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 Repolo. If no `path` is specified, Repolo 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 Repolo, respectively.

2.3 Source and installation directory layout

The Repolo source tree contains the following subdirectories:

- `amplitudes/`: Routines to calculate matrix elements for the processes provided.
- `doc/`: The source of this manual.
- `helas/`: Helas [11] subroutines used to calculate helicity amplitudes.
- `PDFsets/`: Built-in parton distributions (CTEQ6L1 [12] for LO and CT10 [13] for NLO calculations, as well as MRST2004qed [14] and MSTW2008 [15]).
- `regress/`: Folder containing example results, together with input files.
- `src/` and `lib/`: Source code of the main programs and input files.
- `utilities/`: Routines for administrative tasks, scale choices and interfaces.

The source does not need to be modified to change the simulation parameters.

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 subdirectories:

- `bin/`: `repolo` executable.
- `include/VBFNLO/`: Repolo header files.
- `lib/VBFNLO/`: Repolo modules as dynamically loadable libraries.
- `share/VBFNLO/`: Input files, `perl` script and internal PDF tables.

2.4 Running the program

The `repolo` executable, contained in the `bin` directory of the installation path, looks for input files in the current working directory. An alternative path to input files may be specified explicitly by passing the `--input=[path]` argument to the programs, with `path` denoting the full path where input files are located. I.e. in order to run Repolo from the installation (`prefix`) directory, the command is

```
./bin/repolo --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.

REPOLO outputs a running 'log' to the terminal, containing information about the settings used. In addition, two output files are produced – `rew_sm.dat` and `rew_bsm.dat` – containing the matrix elements in the SM and the chosen BSM scenario for each event in the input LHE file. The script `reweighting.perl` (provided in `share/VBFNLO`) uses the information in `rew_sm.dat` and `rew_bsm.dat` and creates a new LHE file, using the command

```
./reweighting.perl input_events.lhe reweighted_events.lhe
```

where `input_events.lhe` is the original event file, and `reweighted_events.lhe` is the new, reweighted, event file.

2.5 MacOSX

Unfortunately, owing to the library set-up, at the moment REPOLO 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 REPOLO, as well as the versions of compilers and external libraries used.

2.7 License

REPOLO 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[6], which were originally formulated and agreed on by the MCnet collaboration for event generator software.

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

3 Processes

In the following sections, we describe the production processes and decay modes implemented in Repolo, 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 Repolo s-channel exchange contributions and kinematically suppressed fermion interference contributions [16–18] are therefore disregarded. "Final state" weak bosons decay into massless leptons. Numerically small contributions from Pauli-interference effects for identical charged leptons are neglected.

3.1 VBF Higgs boson production in association with two jets

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

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

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

3.2 VBF production of a spin-2 particle

Repolo can simulate the production of a spin-2 particle via VBF, which then decays into two photons, with the process ID give in Table 2. 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 `vbfnlo.dat` is set to `true`. Details of the calculation can be found in Ref. [23].

ProcId	Process	Bsm
191	$p\overset{(-)}{p} \to \text{spin-2}\, jj \to \gamma\gamma\, jj$	spin-2 resonant production only

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

4 Input files and parameters

Repolo is steered through the following input files:

- `repolo.dat`: General parameters for a Repolo run.
- `susy.dat`: Parameters describing the MSSM scenario.
- `anom_HVV.dat`: Parameters for anomalous Higgs boson couplings.
- `spin2coupl.dat`: Settings for the spin-two models.

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

4.1 `repolo.dat`

`repolo.dat` is the main input file for Repolo. The following inputs are required:

- `PROCESS`: Process ID as described in Sec. 3. Default is 100: Higgs boson production via VBF.
- `LEPTONS`: Choice of the final state leptons (decay products of W and Z bosons) according to the MC particle numbering scheme [24]:

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

  If the selected configuration is not available, the appropriate first-generation leptons are used as default values.
- `INPUT_FILE`: Name of input Les Houches Event file. Default is `pwgevents.lhe`.
- `ID_MUF`: Choice of the factorization scale. See Table 3 for a list of available options. Default is 0.
- `ID_MUR`: Choice of the renormalization scale. See Table 3 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`.

ID_MUF and ID_MUR	Factorization and Renormalization Scale
0	user defined constant scale set by MUF_USER
1	momentum transfer of exchanged gauge boson
2	$\min(p_{\mathrm{T}}(j_i))$
6	constant scale = Higgs boson mass

Table 3: *Factorization and renormalization scale options.*

4.1.1 repolo.dat – BSM choice

Repolo can reweight Standard Model events to three different types of BSM scenario: the MSSM, anomalous HVV couplings and a spin two model. The particular BSM scenario is chosen using the following inputs.

- MODEL: This flag determines whether we are working in the SM (1) or MSSM (2). Default is SM (1).
- ANOM_CPL: If set to true, anomalous Higgs boson couplings are used. Anomalous coupling parameters are set via the file anom_HVV.dat. Default is set to true.
- SPIN2: Option for the spin-2 models. This is available for the process $pp \to S_2jj \to \gamma\gamma jj$ (process ID 191). Default is set to false. Spin-2 parameters are set via the file spin2coupl.dat.

4.1.2 repolo.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 Repolo 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.

- `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. 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 `TAUMASS`.

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

- `FERMI_CONST`: Fermi constant, used as input for the calculation of electroweak parameters in `EWSCHEME` = 1-4. Default value is 1.16637×10^{-5} GeV^{-2}. If a SLHA file is being used, the SLHA value will be taken rather than the input `FERMI_CONST`.

- `INVALFA`: One over the fine structure constant, used as input for `EWSCHEME` = 1, 4, 5 and 6. Within the other schemes this parameter is calculated. The default value depends on the choice of `EWSCHEME`, as given in Table 4. If `EWSCHEME = 5` is chosen, the value of α should be $\alpha(M_Z)$, whereas if `EWSCHEME = 6` is chosen, the value of α should be $\alpha(0)$. In order to ensure backwards compatibility with previous versions of VBFNLO, as an alternative `ALFA`, the fine structure constant, can be used as an input in `repolo.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`.

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

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

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

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

Table 4: *Electroweak input parameter schemes.*

4.2 `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 if `MODEL = 2` in `repolo.dat` in `repolo.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.

- `FEYNH_SWITCH`: Determines whether FeynHiggs is used to calculate the MSSM Higgs boson sector. Default is `false`. It is recommended that FeynHiggs is used.
- `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[7].
- `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 [25]
  - `2`: No-mixing scenario [25]
  - `3`: Gluophobic scenario [25]
  - `4`: Small α_{eff} scenario [25]
  - `5`: CPX scenario [26]
  - `10`: SPS1a[8] [27]
  - `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.

  Default is `1`. These options are discussed in more detail on the VBFNLO webpage, as well as in [21].
- `DELMB_SWITCH`: Switch determining whether or not to correct the bottom-quark Yukawa coupling. Default is `false`.

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

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

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

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

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

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

Note that it is standard to use as input the mass of the $\mathcal{CP}$-odd Higgs boson, M_A, when working in the MSSM with real parameters and the mass of the charged Higgs boson, $M_{H^\pm}$, when working in the MSSM with complex parameters[9]. 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`.

4.3 Parameters for anomalous couplings

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

4.3.1 `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 `repolo.dat` is set to `true`. Among the anomalous coupling input parameters, the user can choose between three different parameterizations.

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

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

[9] 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.

where the subscript e or o refers to the $\mathcal{CP}$-even or $\mathcal{CP}$-odd nature of the individual operators [28].

An alternative approach is to write the effective Lagrangian in terms of the operators $\mathcal{O}_{WW}$, $\mathcal{O}_{BB}$, $\mathcal{O}_W$ and $\mathcal{O}_B$ and their corresponding $\mathcal{CP}$-odd operators according to Refs. [29, 30]:

$$\mathcal{L}_{\text{eff}} = \frac{f_W}{\Lambda_6^2}\mathcal{O}_W + \frac{f_B}{\Lambda_6^2}\mathcal{O}_B + \frac{f_{WW}}{\Lambda_6^2}\mathcal{O}_{WW} + \frac{f_{BB}}{\Lambda_6^2}\mathcal{O}_{BB} + \text{ CP-odd part} \tag{3}$$

The explicit form of the operators is

$$\begin{aligned} \mathcal{O}_W &= (D_\mu\phi^\dagger)\widehat{W}^{\mu\nu}(D_\nu\phi) \\ \mathcal{O}_B &= (D_\mu\phi^\dagger)\widehat{B}^{\mu\nu}(D_\nu\phi) \\ \mathcal{O}_{WW} &= \phi^\dagger\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\phi \\ \mathcal{O}_{BB} &= \phi^\dagger\widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\phi, \end{aligned} \tag{4}$$

with

$$\begin{aligned} \widehat{W}_{\mu\nu} &= igT^aW^a_{\mu\nu} \\ \widehat{B}_{\mu\nu} &= ig'YB_{\mu\nu}, \end{aligned} \tag{5}$$

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

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

1. A parameterization in terms of couplings in the effective Lagrangian approach given by Eq. 2.

   - `PARAMETR1`: Parameter that switches on the effective Lagrangian parameterization of Eq. 2. The default value is `true`.
   - `LAMBDA5`: Mass scale Λ_5 in units of GeV with 480 GeV chosen as default.
   - `G5E_HWW, G5E_HZZ, G5E_HGG, G5E_HGZ`: Parameters that determine the couplings g_{5e}^{HVV} of the $\mathcal{CP}$-even dimension five operators. Their default values are:
     - 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. [31].
   - `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. [32]. The parameters are d, d_B, Δg_1^Z and $\Delta\kappa_\gamma$, which are related to the coefficients f_i/Λ^2 of the effective Lagrangian of Eq. 3 in the following manner [33]:

$$
\begin{aligned}
d &= -\frac{m_W^2}{\Lambda^2}\, f_{WW}\,, & \tilde{d} &= -\frac{m_W^2}{\Lambda^2}\, f_{\tilde{W}W}\,,\\
d_B &= -\frac{m_W^2}{\Lambda^2}\,\frac{\sin^2\theta_w}{\cos^2\theta_w}\, f_{BB}\,, & \tilde{d}_B &= -\frac{m_W^2}{\Lambda^2}\,\frac{\sin^2\theta_w}{\cos^2\theta_w}\, f_{\tilde{B}B}\,,\\
\Delta\kappa_\gamma &= \kappa_\gamma - 1 = \frac{m_W^2}{2\Lambda^2}\,(f_B + f_W)\,, & \tilde{\kappa}_\gamma &= \frac{m_W^2}{2\Lambda^2}\, f_{\tilde{B}}\,,\\
\Delta g_1^Z &= g_1^Z - 1 = \frac{m_Z^2}{\Lambda^2}\,\frac{f_W}{2}\,.
\end{aligned}
\tag{6}
$$

   - `PARAMETR2`: Parameter that switches on the above mentioned parameterization of Eqs. 6. 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:
     - 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/Λ^2 of the effective Lagrangian in Eq. 3.

   - `PARAMETR3`: Parameter that switches on the parameterization stated above. The default value is `false`.
   - `FWW_EVEN, FBB_EVEN, FW_EVEN, FB_EVEN`: Parameters that represent the coefficients of the $\mathcal{CP}$-even operators – i.e. f_i/Λ^2 – with default values equal to
     - FWW_EVEN = 0 GeV^{-2}
     - FBB_EVEN = 0 GeV^{-2}
     - FW_EVEN = -1.44 $\times$ 10^{-5} GeV^{-2}
     - FB_EVEN = 3.82 $\times$ 10^{-5} GeV^{-2}
   - `FWW_ODD, FBB_ODD, FB_ODD`: Parameters that are the coefficients of the $\mathcal{CP}$-odd operators – i.e. f_i/Λ^2 – with default values 0 GeV^{-2}.
   - `HVV2`: Parameter that allows the user to choose which anomalous HVV couplings are used. For `HVV2` = 0, only the $HZ\gamma$ coupling, for `HVV2` = 1, only the $H\gamma\gamma$ coupling, for `HVV2` = 2, only the HZZ coupling and for `HVV2` = 3, only the HWW coupling is used. If set to 4 all possible anomalous couplings are used. The default value is 4.

Moreover, for all parameterizations, two different form factors can be chosen as described in Refs. [28, 33]. They model effective, momentum dependent HVV vertices, motivated by new physics entering with a large scale Λ at the loop level.

$$F_1 = \frac{\Lambda^2}{q_1^2 - \Lambda^2} \frac{\Lambda^2}{q_2^2 - \Lambda^2}, \tag{7}$$

$$F_2 = -2\,\Lambda^2\, C_0\big(q_1^2, q_2^2, (q_1+q_2)^2, \Lambda^2\big). \tag{8}$$

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. [34].

- `FORMFACTOR`: Flag that switches on the above form factor. The default value is set to `false`.
- `MASS_SCALE`: Characteristic mass scale, Λ, of new physics in units of GeV. The default value is 200 GeV.
- `FFAC`: Parameter that is used to select one particular form factor out of Eqs. (7) and (8). 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.

Alternatively, 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.

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

REPOLO 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. [23]. For the singlet spin-2 field, $T^{\mu\nu}$, the effective Lagrangian is

$$\mathcal{L}_{\text{singlet}} = \frac{1}{\Lambda} T_{\mu\nu} \left(f_1 B^{\alpha\nu} B^{\mu}_{\alpha} + f_2 W_i^{\alpha\nu} W_{\alpha}^{i,\mu} + f_3 \widetilde{B}^{\alpha\nu} B^{\mu}_{\alpha} + f_4 \widetilde{W}_i^{\alpha\nu} W_{\alpha}^{i,\mu} + 2 f_5 (D^{\mu}\Phi)^{\dagger} (D^{\nu}\Phi) \right), \tag{9}$$

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

$$\mathcal{L}_{\text{triplet}} = \frac{1}{\Lambda} T_{\mu\nu j} \left(f_6 (D^\mu \Phi)^\dagger \sigma^j (D^\nu \Phi) + f_7 W_\alpha^{j,\mu} B^{\alpha\nu} \right), \tag{10}$$

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

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

$$f(q_1^2, q_2^2, p_{\text{sp2}}^2) = \left(\frac{\Lambda_{ff}^2}{|q_1^2| + \Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|q_2^2| + \Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|p_{\text{sp2}}^2| + \Lambda_{ff}^2} \right)^{n_{ff}}. \tag{11}$$

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

The input parameters used by REPOLO 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 `20000` GeV.
- `LAMBDAFF`: Energy scale of the formfactor in GeV. Default value is `4000` GeV.
- `NFF`: Exponent of the formfactor. Default value is `3`.

REPOLO 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 `120` GeV.
- `MSP2TRIPPM`: Mass of charged spin-2 triplet particles in GeV. Default value is `120` GeV.
- `MSP2TRIPN`: Mass of neutral spin-2 triplet particle in GeV. Default value is `120` 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`.

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