

MCFM v8.3

A Monte Carlo for FeMtobarn
processes at Hadron Colliders

Users Guide

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1 Overview

MCFM is a parton-level Monte Carlo program that gives NLO predictions for a range of processes at hadron colliders. The program has been developed over a number of years and results have been presented in a number of published papers. The papers describing the original code and the most significant developments in the NLO implementation are:

- J. M. Campbell and R. K. Ellis,
“*An update on vector boson pair production at hadron colliders,*”
Phys. Rev. D **60**, 113006 (1999) [arXiv:hep-ph/9905386].
- J. M. Campbell, R. K. Ellis and C. Williams,
“*Vector boson pair production at the LHC,*”
JHEP **1107**, 018 (2011) [arXiv:1105.0020 [hep-ph]].
- J. M. Campbell, R. K. Ellis and W. Giele,
“*A Multi-Threaded Version of MCFM,*”
EPJ **C75**, 246 (2015) [arXiv:1503.06182 [hep-ph]].

As of v8.0 MCFM can also compute selected color-singlet processes through NNLO in QCD perturbation theory. The processes available at this precision, as well as benchmark numbers, are detailed in Section 4. When using MCFM 8.0 for NNLO calculations please refer to:

- R. Boughezal, J. M. Campbell, R. K. Ellis,
C. Focke, W. Giele, X. Liu, F. Petriello and C. Williams,
“*Color singlet production at NNLO in MCFM,*” arXiv:1605.08011.

Other relevant references, corresponding to publications associated with the implementation of specific processes at NLO and NNLO, are listed in Appendix A. Appendices F–N contain a record of changes to the code since v6.0.

2 Installation

The tar’ed and gzip’ed package may be downloaded from the MCFM home-page at <http://mcfm.fnal.gov>. After extracting, the source can be initialized by running the `./Install` command and then compiled with `make`. The makefile may be edited prior to running, to include the locations of the CERNLIB and LHAPDF libraries, if desired. The code requires and only supports the GNU compiler collection with at least version 6 and smaller than 8 including the C++11 compiler `g++` and the Fortran compiler `gfortran`.

If your GNU Fortran and GNU C++ compiler commands are different than `gfortran` and `g++` you should export the environment variables `FC` and `CXX` to match the names of the `gfortran` and `g++` compiler commands before running the `Install` script or the makefile.

Please ensure that your compiler is working and can produce executable program

files. For example when your compiler has been installed into a non-standard location you probably need to append the compiler library path to `LD_LIBRARY_PATH` (`DYLD_FALLBACK_LIBRARY_PATH` on OS X). This can be achieved, for example, as follows:

```
export LD_LIBRARY_PATH=${LD_LIBRARY_PATH}:/home/user/local/lib
```

The directory structure of the installation is as follows:

- `Doc`. The source for this document.
- `Bin`. The directory containing the executable `mcfm_omp`, and various essential files – notably the options file `input.DAT`.
- `Bin/Pdfdata`. The directory containing the PDF data-files.
- `obj`. The object files produced by the compiler.
- `src`. The Fortran source files in various subdirectories.
- `qcdloop-2.0.2`. The source files to the library QCDLoop [18, 26].
- `TensorReduction` General tensor reduction code based on the work of Passarino and Veltman [49] and Oldenborgh and Vermaseren [48].

2.1 OpenMP and MPI

MCFM uses OpenMP (Open Multi-Processing) to implement multi-threading and will automatically adjust to the number of available cpu threads. The multi-threading is implemented with respect to the integration routine Vegas, which distributes the event evaluations over the threads and combines all events at the end of every iteration.

Two environment variables are useful when using the OMP version of MCFM. The first, `OMP_STACKSIZE` may need to be set in order for the program to run correctly. On some systems, depending on the OMP implementation, the program will crash when calculating some of the more complicated processes, for example $W + 2$ jet production at NLO. Setting this variable to 16000, for instance in the Bash shell by using the command `export OMP_STACKSIZE=16000`, has been found to be sufficient for all processes. The second useful variable `OMP_NUM_THREADS` may be used to directly control the number of threads used during OMP execution (the default is the maximum number of threads available on the system).

It is also possible to run MCFM using the MPI (Message Passing Interface). To run in this mode, change the flag `USEMPI` in the makefile to `YES` and specify the MPI compiler wrappers and compilers in the makefile. By default the OpenMPI compiler wrappers `mpifort` and `mpic++` are set to use `gfortran` and `g++`.

Parameter	Name (<code>_inp</code>)	Input Value	Output Value determined by <code>ewscheme</code>			
			-1	0	1	2
G_F	<code>Gf</code>	1.16639×10^{-5}	input	calculated	input	input
$\alpha(M_Z)$	<code>aemmz</code>	1/128.89	input	input	calculated	input
$\sin^2 \theta_w$	<code>xw</code>	0.2223	calculated	input	calculated	input
M_W	<code>wmass</code>	80.385 GeV	input	calculated	input	calculated
M_Z	<code>zmass</code>	91.1876 GeV	input	input	input	calculated
m_t	<code>mt</code>	<code>input.DAT</code>	calculated	input	input	input

Table 1: Different options for the scheme used to fix the electroweak parameters of the Standard Model and the corresponding default input values. M_W and M_Z are taken from ref. [1].

3 Input parameters

MCFM allows the user to choose between a number of schemes for defining the electroweak couplings. These choices are summarized in Table 1. The scheme is selected by modifying the value of `ewscheme` in `src/User/mdata.f` prior to compilation, which also contains the values of all input parameters (see also Table 2).

The default scheme corresponds to `ewscheme=+1`. As described below, this corresponds to a scheme in which the top quark mass is an input parameter so that it is more suitable for many processes now included in the program.

The choice of (`ewscheme=-1`) enforces the use of an effective field theory approach, which is valid for scales below the top mass. In this approach there are 4 independent parameters (which we choose to be G_F , $\alpha(M_Z)$, M_W and M_Z). For further details, see Georgi [31].

For all the other schemes (`ewscheme=0, 1, 2`) the top mass is simply an additional input parameter and there are 3 other independent parameters from the remaining 5. The variable `ewscheme` then performs exactly the same role as `idef` in MadEvent [39]. `ewscheme=0` is the old MadEvent default and `ewscheme=1` is the new MadEvent default, which is also the same as that used in Alpgen [40] and LUSIFER [20]. For processes in which the top quark is directly produced it is preferable to use the schemes (`ewscheme=0, 1, 2`), since in these schemes one can adjust the top mass to its physical value (in the input file, `input.DAT`).

In the same file (`mdata.f`) one can also choose the definition that the program uses for computing transverse quantities, namely transverse momentum or transverse energy. These are defined by,

$$\begin{aligned}
 \text{transverse momentum: } & \sqrt{p_x^2 + p_y^2}, \\
 \text{transverse energy: } & \frac{E\sqrt{p_x^2 + p_y^2}}{\sqrt{p_x^2 + p_y^2 + p_z^2}}.
 \end{aligned} \tag{1}$$

The two definitions of course coincide for massless particles. The chosen definition

Parameter	Fortran name	Default value
m_τ	<code>mtau</code>	1.777 GeV
m_τ^2	<code>mtausq</code>	3.1577 GeV ²
Γ_τ	<code>tauwidth</code>	2.269×10^{-12} GeV
Γ_W	<code>wwidth</code>	2.093 GeV
Γ_Z	<code>zwidth</code>	2.4952 GeV
V_{ud}	<code>Vud</code>	0.975
V_{us}	<code>Vus</code>	0.222
V_{ub}	<code>Vub</code>	0.
V_{cd}	<code>Vcd</code>	0.222
V_{cs}	<code>Vcs</code>	0.975
V_{cb}	<code>Vcb</code>	0.

Table 2: Default values for the remaining parameters in MCFM . Γ_W and Γ_Z from ref. [1].

is used for all cuts that are applied to the process and it is the one that is used in the default set of histograms.

3.1 Parton distributions

The value of $\alpha_S(M_Z)$ is not adjustable; it is hardwired with the parton distribution. In addition, the parton distribution also specifies the number of loops that should be used in the running of α_S . The default mode of operation is to choose from a collection of modern parton distribution functions that are included with MCFM . The distributions, together with their associated $\alpha_S(M_Z)$ values, are given in Table 3. In addition to these choices, a number of historical PDF sets are also available; for details, see Appendix C. Note that, due to the memory requirements for using the NNPDF sets, in OpenMP operation it is usually necessary to increase the value of the environment variable `OMP_STACKSIZE` to avoid segmentation faults.

By editing the `makefile`, one can switch to the LHAPDF parton distribution function implementations. This requires setting the flag `PDFROUTINES` to `LHAPDF` in the `makefile`. If the library is not in one of the standard include and linker paths one must first set the variable `LHAPDFLIB` in the `makefile` to point to the directory that contains `libLHAPDF`. This version of MCFM has been explicitly tested against `LHAPDF-6.2.1`.

The parameters to choose the pdf set are then provided in `Bin/input.DAT` - the name of the group and the integer specifying the set.

If at the first execution of `mcfm` the library `libLHAPDF` cannot be found, you can add your LHAPDF library path to the environment variable `LD_LIBRARY_PATH` as follows:

```
export LD_LIBRARY_PATH=${LD_LIBRARY_PATH}:/home/user/newpath/lib
```

pdlabel	$\alpha_S(M_Z)$	order	reference
mstw8lo	0.1394	1	[41]
mstw8nl	0.1202	2	[41]
mstw8nn	0.1171	3	[41]
MMHT_lo	0.135	1	[35]
MMHT_nl	0.120	2	[35]
MMHT_nn	0.118	3	[35]
CT10.00	0.118	2	[38]
CT14.LL	0.130	1	[24]
CT14.NL	0.118	2	[24]
CT14.NN	0.118	3	[24]
CT14qed	0.118	2	[53]
NN2.3NL	0.118	2	[5]
NN2.3NN	0.118	3	[5]
NN3.OLO	0.118	1	[4]
NN3.ONL	0.118	2	[4]
NN3.ONN	0.118	3	[4]

Table 3: Modern PDF sets that are available in the code, their corresponding values of $\alpha_S(M_Z)$ and order of running, and a reference to the paper that describes their origin. Further sets, of a more historical nature, are listed in Appendix C.

4 Benchmark results at NNLO

We perform all benchmark calculations with the default set of EW parameters and for the LHC operating at $\sqrt{s} = 14$ TeV. We allow all vector bosons to be off-shell (`zerowidth` is `.false.`) and include their decays (`removebr` is `.false.`). For each Higgs boson process we consider the decay $H \rightarrow \tau^- \tau^+$. For parameters that are set in the input file we use,

$$m_H = 125 \text{ GeV}, \quad m_t = 173.3 \text{ GeV}, \quad m_b = 4.66 \text{ GeV}, \quad (2)$$

and we use the NNLO CT14 pdf set (i.e. `pdlabel` is `CT14.NN`) with $\mu_F = \mu_R = Q^2$ (i.e. we set `dynamicsscale` equal to either `m(34)` or `m(345)` or `m(3456)`, as appropriate). Our generic set of cuts is,

$$\begin{aligned} p_T(\text{lepton}) &> 20 \text{ GeV}, & |\eta(\text{lepton})| &< 2.4, \\ p_T(\text{photon 1}) &> 40 \text{ GeV}, & p_T(\text{photon 2}) &> 25 \text{ GeV}, \\ |\eta(\text{photon})| &< 2.5, & \Delta R(\text{photon 1, photon 2}) &> 0.4, \\ E_T^{\text{miss}} &> 30 \text{ GeV}, \end{aligned} \quad (3)$$

For Z production we also impose a minimum Z^* virtuality (`m34min`) of 40 GeV.

For providing benchmark runs we choose a set of integration parameters that provides approximately 1% (or smaller) Monte Carlo uncertainties for the NLO

Process	nproc	$\sigma_{\text{NLO}} \pm \delta\sigma_{\text{NLO}}^{\text{MC}}$	$\sigma_{\text{NNLO}} \pm \delta\sigma_{\text{NNLO}}^{\text{MC}} \pm \delta\sigma_{\text{NNLO}}^{\text{PC}}$
W^+	1	4.220 ± 0.002 nb	$4.19 \pm 0.02 \pm 0.043$ nb
W^-	6	3.315 ± 0.001 nb	$3.23 \pm 0.01 \pm 0.033$ nb
Z	31	885.2 ± 0.3 pb	$878 \pm 3 \pm 9$ pb
H	112	1.395 ± 0.001 pb	$1.865 \pm 0.004 \pm 0.019$ pb
$\gamma\gamma$	285	27.94 ± 0.01 pb	$43.60 \pm 0.06 \pm 0.44$ pb
W^+H	91	2.208 ± 0.002 fb	$2.268 \pm 0.007 \pm 0.023$ fb
W^-H	96	1.494 ± 0.001 fb	$1.519 \pm 0.004 \pm 0.015$ fb
ZH	110	0.7535 ± 0.0004 fb	$0.846 \pm 0.001 \pm 0.0085$ fb
$Z\gamma$	300	959 ± 8 fb	1268 ± 22 fb

Table 4: Benchmark cross-sections at NLO and NNLO, using the parameters and settings described in the text. $\delta\sigma^{MC}$ represents the uncertainty from Monte Carlo statistics, while $\delta\sigma^{PC}$ is an estimate of the uncertainty due to neglected power corrections at NNLO.

cross sections. These are `itmx1 = 4`, `itmx2 = 10` and `ncall1 = ncall2 = 400000`. For the NNLO coefficients we use `itmx1 = 4`, `itmx2 = 10` and `ncall1 = ncall2 = 800000` and set `taucut` to `1%acc`. This gives the reader an impression of the reached integration uncertainty compared to the approx. 1% error due to neglected power corrections. For the NNLO cross sections the required computing time is about one week of CPU-time, depending on the process. Corresponding input files for each process number can be found in the directory `Bin/benchmarks`.

Our benchmarks are shown in Table 4. These benchmark cross-sections may not be sufficiently accurate for all phenomenological applications but they should be able to be reproduced relatively easily, even on a desktop machine.

5 Runtime options

MCFM execution is performed in the `Bin/` directory, with syntax:

```
mcfm_omp [mydir] [myfile.DAT]
```

If no command line options are given, then `mcfm` will default to using the file `input.DAT` in the current directory for choosing options¹. The different possibilities are summarized in Table 5. In addition, if a working directory `mydir` is specified then output files will also be produced in this directory. By using these options one may, for instance, keep all input and output files for different processes in separate directories.

Each parameter in the input file is specified by a line such as

```
value [parameter]
```

¹Note that this is very different from previous versions of MCFM. All auxiliary input files from v3.2 and earlier have now been incorporated into a single file.

Command executed	Location of input file
<code>mcfm</code>	<code>input.DAT</code>
<code>mcfm myfile.DAT</code>	<code>myfile.DAT</code>
<code>mcfm mydir</code>	<code>mydir/input.DAT</code>
<code>mcfm mydir myfile.DAT</code>	<code>mydir/myfile.DAT</code>

Table 5: Summary of command line options for running `mcfm`.

and we will give a description of all the parameters below, together with valid and/or sensible inputs for `value`. Groups of parameters are separated by a blank line and a description of that section, for readability.

- `file version number`. This should match the version number that is printed when `mcfm` is executed.

{blank line}

[Flags to specify the mode in which MCFM is run]

- `nevtrequested`. The default for this parameter is `-1` and for the following three parameters it is `.false..` This corresponds to the usual mode of operation where the program produces a cross section and a selection of histograms. It is possible to generate n-tuples instead of histograms, as well as unweighted events, for some processes. Please refer to Section 7.2 for further details.
- `creatent`. *See above.*
- `dswhisto`. *See above.*
- `writerefs`. Flag to control whether or not the program writes a list of appropriate references to the output at the end of the run.
- `writetop`. Flag to control whether or not a Topdrawer histogram output file is produced. Please refer to Section 7 for further details.
- `writedat`. Flag to control whether or not the plain histogram output file is produced. Please refer to Section 7 for further details.
- `writegnu`. Flag to control whether or not a gnuplot histogram output file is produced. Please refer to Section 7 for further details.
- `writeroot`. Flag to control whether or not a ROOT script for plotting histograms is produced. Please refer to Section 7 for further details.
- `writepwg`. Flag to control whether a powheg-style analysis file is produced. This option is available only for a limited number of processes. As currently implemented it should be viewed as a development tool, not yet fully supported for the general user.
- `writetxt`. Flag to control whether or not a text file with space-separated columns is written for each histogram.

{blank line}

[General options to specify the process and execution]

- **nproc**. The process to be studied is given by choosing a process number, according to Table 9 in Appendix B. $f(p_i)$ denotes a generic partonic jet. Processes denoted as “LO” may only be calculated in the Born approximation. For photon processes, “NLO+F” signifies that the calculation may be performed both at NLO and also including the effects of photon fragmentation and experimental isolation. In contrast, “NLO” for a process involving photons means that no fragmentation contributions are included and isolation is performed according to the procedure of Frixione [29].
- **part**. This parameter has 5 possible values, described below:
 - **lo** (or **lord**). The calculation is performed at leading order only.
 - **virt**. Virtual (loop) contributions to the next-to-leading order result are calculated (+counterterms to make them finite), including also the lowest order contribution.
 - **real**. In addition to the loop diagrams calculated by **virt**, the full next-to-leading order results must include contributions from diagrams involving real gluon emission (-counterterms to make them finite). Note that only the sum of the **real** and the **virt** contributions is physical.
 - **nlo** (or **tota**). For simplicity, the **nlo** option simply runs the **virt** and **real** real pieces in series before performing a sum to obtain the full next-to-leading order result. In this case, the number of points specified by **ncall1** and **ncall2** is automatically increased when performing the **real** calculation. Sometimes it may be more efficient to do run the pieces separately by hand, (c.f. **ncall** below). For photon processes that include fragmentation, **nlo** also includes the calculation of the fragmentation (**frag**) contributions.
 - **nlocoeff**. This computes only the contribution of the NLO coefficient; it is equivalent to running **nlo** and then subtracting the result of **lo**.
 - **todk** Processes 114, 161, 166, 171, 176, 181, 186, 141, 146, 149, 233, 238, 501, 511 only, see sections 10.36 and 10.38 below.
 - **frag**. Processes 280, 285, 290, 295, 300-302, 305-307, 820-823 only, see sections 10.58, 10.61 and 10.62 below.
 - **nnlo** (and **nnlocoeff**). The computation of the NNLO prediction (or the NNLO coefficient in the expansion) is described separately below.
- **runstring**. When MCFM is run, it will write output to several files. The label **runstring** will be appended to the names of these files.
- **sqrts**. This is the centre-of-mass energy, \sqrt{s} of the colliding particles, measured in GeV.

- **ih1, ih2.** The identities of the incoming hadrons may be set with these parameters, allowing simulations for both $p\bar{p}$ (such as the Tevatron) and pp (such as the LHC). Setting **ih1** equal to $+1$ corresponds to a proton, whilst -1 corresponds to an anti-proton. Values greater than `1000d0` represent a nuclear collision, as described in Section 6.
- **hmass.** For processes involving the Higgs boson, this parameter should be set equal to the value of M_H .
- **scale.** This parameter may be used to adjust the value of the *renormalization* scale. This is the scale at which α_S is evaluated and will typically be set to a mass scale appropriate to the process (M_W, M_Z, M_t for instance). For processes involving vector bosons, setting this scale to `-1d0` chooses a scale equal to the average mass of the bosons involved.
- **facscale.** This parameter may be used to adjust the value of the *factorization* scale and will typically be set to a mass scale appropriate to the process (M_W, M_Z, M_t for instance). As above, setting it to `-1d0` will choose an appropriate value for certain processes.
- **dynamicscale** This character string is used to specify whether the renormalization, factorization and fragmentation scales are dynamic, i.e. recalculated on an event-by-event basis. If this string is set to either `.false.`, `'no'` or `'none'` then the scales are fixed for all events at the values specified by **scale**, **facscale** and **frag_scale** in the input file.

The type of dynamic scale to be used is selected by using a particular string for the variable **dynamicscale**, as indicated in Table 6. Not all scales are defined for each process, with program execution halted if an invalid selection is made in the input file. The selection chooses a reference scale, μ_0 . The actual scales used in the code are then,

$$\mu_{\text{ren}} = \text{scale} \times \mu_0, \quad \mu_{\text{fac}} = \text{facscale} \times \mu_0, \quad \mu_{\text{frag}} = \mu_{\text{ren}}.$$

Note that, for simplicity, the fragmentation scale (relevant only for processes involving photons) is set equal to the renormalization scale. In some cases it is possible for the dynamic scale to become very large. This can cause problems with the interpolation of data tables for the PDFs and fragmentation functions. As a result if a dynamic scale exceeds a maximum of 60 TeV (PDF) or 990 GeV (fragmentation) this value is set by default to the maximum.

Although not really dynamic scales, note that the strings `'MW'`, `'MZ'`, `'MH'` and `'mt'` may be used as shorthand to indicate values of μ_0 equal to M_W , M_Z , M_H and m_t .

An additional option may be used to compute the effect of scale uncertainty in a process. This is achieved by adding the string `+scalevar` to the end of the usual option for **dynamicscale**. This performs a variation of the

dynamic scale	μ_0^2	comments
m(34)	$(p_3 + p_4)^2$	
m(345)	$(p_3 + p_4 + p_5)^2$	
m(3456)	$(p_3 + p_4 + p_5 + p_6)^2$	
sqrt(M^2+pt34^2)	$M^2 + (\vec{p}_{T3} + \vec{p}_{T4})^2$	$M = \text{mass of particle 3+4}$
sqrt(M^2+pt345^2)	$M^2 + (\vec{p}_{T3} + \vec{p}_{T4} + \vec{p}_{T5})^2$	$M = \text{mass of particle 3+4+5}$
sqrt(M^2+pt5^2)	$M^2 + \vec{p}_{T5}^2$	$M = \text{mass of particle 3+4}$
sqrt(M^2+ptj1^2)	$M^2 + \vec{p}_{Tj_1}^2$	$M = \text{mass(3+4)}, j_1 = \text{leading } p_T \text{ jet}$
pt(photon)	$\vec{p}_{T\gamma}^2$	
pt(j1)	$\vec{p}_{Tj_1}^2$	
HT	$\sum_{i=1}^n p_{Ti}$	$n \text{ particles (partons, not jets)}$

Table 6: Choices of the input parameter `dynamic scale` that result in an event-by-event calculation of all relevant scales using the given reference scale-squared μ_0^2 .

scales used in Eq. (4) by a factor of two, so that it surveys the additional possibilities,

$$(2\mu_{\text{ren}}, 2\mu_{\text{fac}}), (\mu_{\text{ren}}/2, \mu_{\text{fac}}/2), \\ (2\mu_{\text{ren}}, \mu_{\text{fac}}), (\mu_{\text{ren}}/2, \mu_{\text{fac}}), (\mu_{\text{ren}}, 2\mu_{\text{fac}}), (\mu_{\text{ren}}, \mu_{\text{fac}}/2). \quad (4)$$

The histograms corresponding to these different choices are included in the output file, from which an envelope of theoretical uncertainty may be constructed by the user. If only a two-point scale variation is required, corresponding to the additional scales in the first line of Eq. (4), this may be obtained by specifying `+scalevar2`. In addition, this option requires a longer running-time than the case of no scale variation, of course.

- **zerowidth**. When set to `.true.` then all vector bosons are produced on-shell. This is appropriate for calculations of *total* cross-sections (such as when using `removebr` equal to `.true.`, below). When interested in decay products of the bosons this should be set to `.false.`
- **removebr**. When set to `.true.` the branching ratios are removed for unstable particles such as vector bosons or top quarks. See the process notes in Section 10 below for further details.
- **itmx1, itmx2**. The program will perform two runs of **VEGAS** - once for pre-conditioning and then the final run to collect the total cross-section and fill histograms. The number of sweeps for each run is given by `itmx1` (pre-conditioning) and `itmx2` (final). The default value for both is 10.
- **ncall1, ncall2**. For every sweep of **VEGAS**, the number of events generated will be `ncall1` in the pre-conditioning stage and `ncall2` in the final run. The number of events required depends upon a number of factors. The error estimate on a total cross-section will often be reasonable for a fairly

small number of events, whereas accurate histograms will require a longer run. As the number of particles in the final state increases, so should the number of calls per sweep. Typically one might make trial runs with `part` set to `lord` to determine reasonable values for `ncall11` and `ncall12`. Such values should also be appropriate for the `virt` piece of next-to-leading order and should probably be increased by a factor of ~ 5 for the `real` calculation.

- `taucut`. This sets the value of the jettiness variable T_0 that separates the resolved and unresolved regions in NNLO calculations that use zero-jettiness. Recommended values of this parameter that yield results that are affected by power corrections at the 1% and 0.2% level can be obtained by using the strings `1%acc` and `0.2%acc` respectively.
- `seed`. This is the seed for the VEGAS integration and can be altered to give different results for otherwise identical runs. Use 0 for a random seed.
- `dryrun`. The default value of this parameter is `.false..` When set to `.true.` the pre-conditioning sweeps in the VEGAS integration are skipped, with the reported results coming from a single run, (ie `itmx1` iterations of `ncall11` points each)
- `Qflag`. This only has an effect when running a $W + 2$ jets or $Z + 2$ jets process. Please see section 10.8 below.
- `Gflag`. This only has an effect when running a $W + 2$ jets or $Z + 2$ jets process. Please see section 10.8 below.
- `ewcorr`. Specifies whether or not to compute EW corrections for the process. Default is `none`. May be set to `exact` or `sudakov` for processes 31 (neutral-current DY), 157 (top-pair production) and 190 (di-jet production). For more details see section 8.

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[Heavy quark masses]

- `top mass`. The top quark pole mass (in GeV).
- `bottom mass`. The bottom quark pole mass (in GeV).
- `charm mass`. The charm quark pole mass (in GeV).

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[Pdf selection]

- `pdlabel`. The choice of parton distribution is made by inserting the appropriate 7-character code from Table 10 or 11 here. As mentioned above, this also sets the value of $\alpha_S(M_Z)$.
- `LHAPDF group`, `LHAPDF set`. These choose the parton distribution functions to be used when using the LHAPDF package – the group is specified

by a character string and the set by an integer.² For appropriate PDF sets choosing a value of -1 for the set number (`LHAPDF set`) will perform the calculation of the PDF uncertainties (see also Section 7.1, especially the caveat regarding using non-grid PDF sets).

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[Jet definition and event cuts]

- `m34min`, `m34max`, `m56min`, `m56max`, `m3456min`, `m3456max`. These parameters represent a basic set of cuts that may be applied to the calculated cross-section. The only events that contribute to the cross-section will have, for example, `m34min` < `m34` < `m34max` where `m34` is the invariant mass of particles 3 and 4 that are specified by `nproc`. `m34min` > 0 is obligatory for processes which can involve a virtual photon, such as `nproc=31`.
- `inclusive`. This logical parameter chooses whether the calculated cross-section should be inclusive in the number of jets found at NLO. An *exclusive* cross-section contains the same number of jets at next-to-leading order as at leading order. An *inclusive* cross-section may instead contain an extra jet at NLO.
- `algorithm`. This specifies the jet-finding algorithm that is used, and can take the values `ktal` (for the Run II k_T -algorithm), `an kt` (for the “anti- k_T ” algorithm [10]), `cone` (for a midpoint cone algorithm), `hqrk` (for a simplified cone algorithm designed for heavy quark processes) and `none` (to specify no jet clustering at all). The latter option is only a sensible choice when the leading order cross-section is well-defined without any jet definition: e.g. the single top process, $q\bar{q}' \rightarrow t\bar{b}$, which is finite as $p_T(\bar{b}) \rightarrow 0$.
- `ptjet_min`, `letajet_max`. These specify the values of $p_{T,\min}$ and $|\eta|_{\max}$ for the jets that are found by the algorithm. A comma-separated pair may be used on either line to indicate a range of allowed values for p_T and $|\eta|$.
- `Rcut_jet`. If the final state of the chosen process contains either quarks or gluons then for each event an attempt will be made to form them into jets. For this it is necessary to define the jet separation $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ so that after jet combination, all jet pairs are separated by $\Delta R > \text{Rcut_jet}$.
- `makecuts`. If this parameter is set to `.false.` then no additional cuts are applied to the events and the remaining parameters in this section are ignored. Otherwise, events will be rejected according to a set of cuts that is specified below. Further options may be implemented by editing `src/User/gencuts.f`. A special setting of this parameter, to `LHCb`, invokes a set of cuts tailored to the LHCb experiment. This requires the specification of an additional set of parameters, as shown in the file `Bin/lhcb.DAT`. The effect of these parameters, as well as the particular LHCb cuts that

²Please see <https://lhpdf.hepforge.org/> for further details.

are applied, can be found in the file `src/Need/lhcbcode.f`.³

- `ptlepton_min`, `etalepton_max`. These specify the values of $p_{T,\min}$ and $|\eta|_{\max}$ for one of the leptons produced in the process. A comma-separated pair may be used on either line to indicate a range of allowed values for p_T and $|\eta|$.
- `etalepton_veto`. This should be specified as a pair of double precision numbers that indicate a rapidity range that should be excluded for the lepton that passes the above cuts.
- `ptmin_missing`. Specifies the minimum missing transverse momentum (coming from neutrinos).
- `ptlepton(2nd+)_min`, `etalepton(2nd+)_max`. These specify the values of $p_{T,\min}$ and $|\eta|_{\max}$ for the remaining leptons in the process. This allows for staggered cuts where, for instance, only one lepton is required to be hard and central. A comma-separated pair may be used on either line to indicate a range of allowed values for p_T and $|\eta|$.
- `etalepton(2nd+)_veto`. This should be specified as a pair of double precision numbers that indicate a rapidity range that should be excluded for the remaining leptons.
- `mtrans34cut`. For general processes, this specifies the minimum transverse mass of particles 3 and 4,

$$\text{general : } 2p_T(3)p_T(4) \left(1 - \frac{\vec{p}_T(3) \cdot \vec{p}_T(4)}{p_T(3)p_T(4)} \right) > \text{mtrans34cut} \quad (5)$$

For the $W(\rightarrow \ell\nu)\gamma$ process the role of this cut changes, to become instead a cut on the transverse cluster mass of the $(\ell\gamma, \nu)$ system,

$$W\gamma : \quad \left[\sqrt{m_{\ell\gamma}^2 + |\vec{p}_T(\ell) + \vec{p}_T(\gamma)|^2} + p_T(\nu) \right]^2 - |\vec{p}_T(\ell) + \vec{p}_T(\gamma) + \vec{p}_T(\nu)|^2 > \text{mtrans34cut}^2 \quad (6)$$

For the $Z\gamma$ process this parameter specifies a simple invariant mass cut,

$$Z\gamma : \quad m_{Z\gamma} > \text{mtrans34cut} \quad (7)$$

A final mode of operation applies to the $W\gamma$ process and is triggered by a negative value of `mtrans34cut`. This allows simple access to the cut that was employed in v6.0 of the code:

$$W\gamma, \text{ obsolete : } \quad \begin{aligned} & [p_T(\ell) + p_T(\gamma) + p_T(\nu)]^2 \\ & - |\vec{p}_T(\ell) + \vec{p}_T(\gamma) + \vec{p}_T(\nu)|^2 > |\text{mtrans34cut}| \end{aligned} \quad (8)$$

In each case the screen output indicates the cut that is applied.

³The authors are grateful to Philip Ilten (`philten@cern.ch`) for providing this code.

- `R(jet,lept)_min`. Using the definition of ΔR above, requires that all jet-lepton pairs are separated by $\Delta R > R(jet,lept)_min$.
- `R(lept,lept)_min`. When non-zero, all lepton-lepton pairs must be separated by $\Delta R > R(lept,lept)_min$.
- `Delta_eta(jet,jet)_min`. This enforces a pseudo-rapidity gap between the two hardest jets j_1 and j_2 , so that:
 $|\eta^{j_1} - \eta^{j_2}| > Delta_eta(jet,jet)_min$.
- `jets_oppem`. If this parameter is set to `.true.`, then the two hardest jets are required to lie in opposite hemispheres, $\eta^{j_1} \cdot \eta^{j_2} < 0$.
- `lepbtwnjets_scheme`. This integer parameter provides no additional cuts when it takes the value 0. When equal to 1 or 2, leptons are required to lie between the two hardest jets. With the ordering $\eta^{j^-} < \eta^{j^+}$ for the pseudo-rapidities of jets j_1 and j_2 :
`lepbtwnjets_scheme = 1` : $\eta^{j^-} < \eta^{leptons} < \eta^{j^+}$;
`lepbtwnjets_scheme = 2` : $\eta^{j^-} + Rcut_jet < \eta^{leptons} < \eta^{j^+} - Rcut_jet$.
- `ptmin_bjet`, `etamax_bjet`. If `makecuts` is `.true.` and a process involving b -quarks is being calculated, then these can be used to specify *stricter* values of p_T^{\min} and $|\eta|^{\max}$ for b -jets. A comma-separated pair may be used on either line to indicate a range of allowed values for p_T and $|\eta|$.

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[Settings for photon processes]

- `frag`. This parameter is a logical variable that determines whether the production of photons by a parton fragmentation process is included. If `frag` is set to `.true.` the code uses a standard cone isolation procedure (that includes LO fragmentation contributions in the NLO calculation). If `frag` is set to `.false.` the code implements a Frixione-style photon cut [29],

$$\sum_{i \in R_0} E_{T,i}^j < \epsilon_h E_T^\gamma \left(\frac{1 - \cos R_{i\gamma}}{1 - \cos R_0} \right)^n. \quad (9)$$

In this equation, R_0 , ϵ_h and n are defined by `cone_ang`, `epsilon_h` and `n_pow` respectively (see below). $E_{T,i}^j$ is the transverse energy of a parton, E_T^γ is the transverse energy of the photon and $R_{i\gamma}$ is the separation between the photon and the parton using the usual definition $R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$. n is an integer parameter which by default is set to 1 but can be changed by editing the file `src/User/frix.f`.

- `fragset`. A character*8 variable that is used to choose the particular photon fragmentation set. Currently implemented fragmentation functions can be called with `'BFGSet_I'`, `'BFGSet_II'` [9] or `'GdRG_LO'` [30].
- `frag_scale`. A double precision variable that will be used to choose the scale at which the photon fragmentation is evaluated.

- `ptmin_photon`. This specifies the value of p_T^{\min} for the photon with the largest transverse momentum. Note that this cut, together with all the photon cuts specified in this section of the input file, are applied even if `makecuts` is set to `.false..` A comma-separated pair may be used to indicate a range of allowed values for p_T .
- `etamax_photon`. This specifies the value of $|y|^{\max}$ for any photons produced in the process. A comma-separated pair may be used to indicate a range of allowed values for $|\eta|$.
- `ptmin_photon(2nd)` and `ptmin_photon(3rd)`. These specify the values of p_T^{\min} for the second and third photons, ordered by p_T .
- `R(photon,lept)_min`. Using the usual definition of ΔR , this requires that all photon-lepton pairs are separated by $\Delta R > \text{R(photon,lept)_min}$. This parameter must be non-zero for processes in which photon radiation from leptons is included.
- `R(photon,photon)_min`. Using the usual definition of ΔR , this requires that all photon pairs are separated by $\Delta R > \text{R(photon,photon)_min}$.
- `R(photon,jet)_min`. Using the usual definition of ΔR , this requires that all photon-jet pairs are separated by $\Delta R > \text{R(photon,jet)_min}$.
- `cone_ang`. A double precision variable that fixes the cone size (R_0) for photon isolation. This cone is used in both forms of isolation.
- `epsilon_h`. This cut controls the amount of radiation allowed in cone when `frag` is set to `.true..` If `epsilon_h < 1` then the photon is isolated using $\sum_{\in R_0} E_T(\text{had}) < \epsilon_h p_T^2$. Otherwise `epsilon_h > 1` sets $E_T(\text{had}) < E_T(\text{max})$. If the user wishes to always use a scaling or fixed isolation cut, independent of the value of `epsilon_h`, the routine `src/User/iso.f` may be edited and the value of the variable `imode` changed according to the comments. When `frag` is set to `.false.`, ϵ_h controls the amount of hadronic energy allowed inside the cone using the Frixiene isolation prescription (see above, Eq. (9)).
- `n_pow`. When using the Frixiene isolation prescription, the exponent n in Eq. (9).

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[Anomalous couplings of the W and Z]

- `enable`. Boolean flag to enable anomalous coupling contributions. False has the same effect as setting all anomalous couplings to zero, but additionally skips computation of anomalous coupling code parts.
- `Delta_g1(Z)`. See section 10.22.
- `Delta_K(Z)`. See section 10.22.
- `Delta_K(gamma)`. See sections 10.22 and 10.61.

- `Lambda(Z)`. See section 10.22.
- `Lambda(gamma)`. See sections 10.22 and 10.61.
- `h1(Z)`. See section 10.62.
- `h1(gamma)`. See section 10.62.
- `h2(Z)`. See section 10.62.
- `h2(gamma)`. See section 10.62.
- `h3(Z)`. See section 10.62.
- `h3(gamma)`. See section 10.62.
- `h4(Z)`. See section 10.62.
- `h4(gamma)`. See section 10.62.
- **Form-factor scale, in TeV**. See section 10.22.
No form-factors are applied to the anomalous couplings if this value is negative.

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[Anomalous width of the Higgs]

- `Gamma_H/Gamma_H(SM)`. For processes 123–126, 128–133 only, this variable provides a rescaling of the width of the Higgs boson. Couplings are rescaled such that the corresponding cross section close to the Higgs boson peak is unchanged. Further details of this procedure are given in [arXiv:1311.3589](#).

The final section of the input file contains settings for various technical parameters that should not normally need to be changed.

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[Technical parameters that should not normally be changed]

- `debug`. A logical variable which can be used during a debugging phase to mandate special behaviours. Passed by common block `common/debug/debug`.
- `verbose`. A logical variable which can be used during a debugging phase to write special information. Passed in common block `common/verbose/verbose`.
- `new_pspace`. A logical variable which can be used during a debugging phase to test alternative versions of the phase space. Passed in common block `common/new_pspace/new_pspace`.
- `spira`. A logical variable. If `spira` is true, we calculate the width of the Higgs boson by interpolating from a table calculated using the NLO code of M. Spira. Otherwise the LO value valid for low Higgs masses only is used.

- **noglue**. A logical variable. The default value is false. If set to true, no processes involving initial gluons are included.
- **ggonly**. A logical variable. The default value is false. If set to true, only the processes involving initial gluons in both hadrons are included.
- **gqonly**. The default value is false. If set to true, only the processes involving an initial gluon in one hadron and an initial quark or antiquark in the other hadron (or vice versa) are included.
- **omitgg**. A logical variable. The default value is false. If set to true, the gluon-gluon initial state is not included.
- **clustering**. This logical parameter determines whether clustering is performed to yield jets. Only during a debugging phase should this variable be set to false.
- **realwt**. This is a logical parameter that in general should be set to false. If set to true, mcfm samples the integral according to the unsubtracted real emission weight.
- **colourchoice**. If colourchoice=0, all colour structures are included ($W, Z + 2$ jets). If colourchoice=1, only the leading colour structure is included ($W, Z + 2$ jets).
- **rtsmin**. A minimum value of $\sqrt{s_{12}}$, which ensures that the invariant mass of the incoming partons can never be less than **rtsmin**.
- **cutoff**. A minimum value of s_{ij} , which ensures that the invariant mass squared of any pair of partons can never be less than **cutoff**.
- **aii**. A double precision variable which can be used to limit the kinematic range for the subtraction of initial-initial dipoles as suggested by Trocsanyi and Nagy [43]. The value **aii=1d0** corresponds to standard Catani-Seymour subtraction.
- **aif**. A double precision variable which can be used to limit the kinematic range for the subtraction of initial-final dipoles as suggested by Trocsanyi and Nagy [43]. The value **aif=1d0** corresponds to standard Catani-Seymour subtraction.
- **afi**. A double precision variable which can be used to limit the kinematic range for the subtraction of final-initial dipoles as suggested by Trocsanyi and Nagy [43]. The value **afi=1d0** corresponds to standard Catani-Seymour subtraction.
- **aff**. A double precision variable which can be used to limit the kinematic range for the subtraction of final-final dipoles as suggested by Trocsanyi and Nagy [43]. The value **aff=1d0** corresponds to standard Catani-Seymour subtraction.

- **bfi**. A double precision variable which can be used to limit the kinematic range for the subtraction of final-initial dipoles in the photon fragmentation case.
- **bff**. A double precision variable which can be used to limit the kinematic range for the subtraction of final-final dipoles in the photon fragmentation case.
- **mtex**. Sets the order $k = 0, 2, 4$ of the $1/m_t^k$ expansion for virtual corrections in the H +jet process 200. See section 10.39.

6 Nuclear collisions

It is possible to specify nuclear collisions by choosing values of **ih1** and/or **ih2** above 1000d0. In that case, the identity of the nucleus is specified by the atomic number and mass (Z and A respectively) as follows:

$$\mathbf{ih} = 1000Z + A. \quad (10)$$

For example, to choose an incoming lead beam one would set **ih1**=+82207d0, corresponding to $Z = 82$ and $A = 207$. When running the program, the value of **sqrts** should also be changed. This must be done by hand and is not automatically taken care of by the program. The centre-of-mass energy is decreased by a factor of $\sqrt{Z/A}$ for each nuclear beam.

The nucleon PDF's are calculated by applying the correction factors of EKS98 [27] on top of the PDF set that is selected. This construction simply corrects each parton distribution by a factor that depends on the value of (x, μ) in the event. This parametrization is limited to the region $\mu < 100$ GeV and any value above that threshold will instead default to 100 GeV.

Note that the cross-section reported by the program at the end of the run is given per nucleon per beam. Therefore the appropriate factors of A should be applied in order to obtain the total cross section.

7 Output

In addition to the direct output of the program to **stdout**, after the final sweep of **VEGAS** the program can output additional files as specified below. If a working directory was specified in the command line, then these output files will be written to that directory.

The standard output will detail the iteration-by-iteration best estimate of the total cross-section, together with the accompanying error estimate. After all sweeps have been completed, a final summary line will be printed. In the **npart = tota** case, this last line will actually be the sum of the two separate real and virtual integrations. If the **LHAPDF** package is being used and the value of **LHAPDF set** is equal to **-1**, to indicate a calculation using PDF uncertainties,

then the computed PDF uncertainty is supplied in the regular output and also echoed to the file, `pdfuncertainty.res`. The appropriate method for computing the PDF uncertainties is chosen according to the PDF set that is being used. For NNPDF sets the uncertainty is computed according to the so-called MC prescription, described in detail in Appendix B of Ref. [6]⁴. For the sets of Alekhin et al. the uncertainty is computed using the symmetric Hessian method. For all other sets – those from CTEQ and MSTW – the asymmetric Hessian uncertainties are computed using the formula given explicitly in Eqn. (43) of Ref. [14].

Other output files may be produced containing various histograms associated with the calculated process. The write-out of the different output files is controlled by logical variables at the top of the input file. The various options are:

- `writetop`: write out the histograms as a TOPDRAWER file, `outputname.top`.
- `writedat`: write out the histograms in a raw format which may be read in by a plotting package of the user's choosing, `outputname.dat`.
- `writegnu`: write out the histograms as a gnuplot file⁵, `outputname.gnu`. This can be processed by running the command `'gnuplot outputname.gnu'`, producing a postscript version of the histograms in `outputname.ps`.
- `writeroot`: write out a script, `outputname.C`, that can be executed by ROOT. Opening ROOT and running `'.x outputname.C'` produces histograms in the file `outputname.root`. The histograms can be subsequently inspected or manipulated as usual, e.g. by opening the graphical browser using `'TBrowser b;'`.

All of the output files include a summary of the options file (`input.DAT`) in the form of comments at the beginning. The structure of `outputname` is as follows:

```
procname_part_pdlablel_scale_facscale_runstring
```

where `procname` is a label assigned by the program corresponding to the calculated process; the remaining labels are as input by the user in the file `input.DAT`.

The histograms are filled via the file `src/User/nplotter.f`. For the convenience of the user a dummy routine `src/User/userplotter.f` has been provided. The user may substitute their own routine to do the plotting, by writing and compiling a routine of this name. See section 9.

For some processes a specific routine has been written to plot relevant kinematic quantities. In that case a further routine is called, e.g. `nplotter_W.only.f` for inclusive W production. In all other cases the filling of the histograms is performed by a routine in `src/User/nplotter_auto.f`. The arguments of

⁴The authors thank M. Ubiali and collaborators for providing their implementation of the MC method within the MCFM framework.

⁵For information on obtaining and using gnuplot, visit <http://www.gnuplot.info/>.

the process-specific plotting subroutines are `p,wt,wt2,switch`. `p` contains the momenta of all the particles (i.e. the four momenta of the leptons and jets). The order of the jets is not necessarily the order specified in `process.DAT`. However in the case that we have a b -quark or antiquark they are labelled by `bq` and `ba` respectively in the array `jetlabel`. `wt` (`wt2`) is the weight of the event (squared).

7.1 Histograms

Extra histograms may be added to the plotting files in a fairly straightforward manner. Each histogram is filled by making a call to the routine `bookplot` and updating the histogram counter `n` by 1. For example, the pseudorapidity of particle 3 may be plotted using the following code fragment:

```
eta3=etarap(3,p)
call bookplot(n,tag,'eta3',eta3,wt,wt2,-4d0,4d0,0.1d0,'lin')
n=n+1
```

The first two arguments of the call should not be changed. The third argument is a string which is used as the title of the plot in the output files. The fourth argument carries the variable to be plotted, which has been previously calculated. The arguments `wt` and `wt2` contain information about the phase-space weight and should not be changed. The last arguments tell the histogramming routine to use bins of size 0.1 which run from -4 to 4, and use a linear scale for the plot. A logarithmic scale may be used by changing the final argument to `'log'`.

If the `LHAPDF` package is being used and the value of `LHAPDF set` is equal to -1, to indicate a calculation using PDF uncertainties, then errors on distributions may also be accumulated. Note that, due to limitations within the `LHAPDF` distribution, calculations using error PDF sets are impractical unless the grid versions of the sets are used. The grid versions are available in `LHAPDF v.3` onwards and may be identified by the `.LHgrid` extension in the `PDFsets` directory. To use the grid version, simply pass the PDF set name, including this extension, as the value of `LHAPDF group` in the input file.

To accumulate errors in distributions, add an extra line to `nplotter.f` after the call to `bookplot` but before the counter is incremented. For example, to calculate the PDF uncertainties on the distribution of `eta3` one would simply add:

```
call ebookplot(n,tag,eta3,wt)
```

The third argument contains the variable to plot and the other entries should not be changed. The other parameters for the plot are exactly those specified on the previous line, in the call to `bookplot`. Since each PDF error distribution takes up quite a lot of memory during execution, there is a limit of 4 on the number of distributions with errors that can be calculated at one time. When calculating PDF uncertainties on distributions, the program will produce an additional file which contains the results for each PDF error set individually. In

addition, the main file will include the uncertainty limits on the distribution, obtained using the appropriate PDF uncertainty prescription as described above, on a bin-by-bin basis. Thus the resulting error limits are not simply described by a single PDF set.

7.2 Other output modes

As noted in the description of the input file, there are a number of other output modes which may be useful in certain situations. In particular, the ability to output n-tuples can be used to generate a large event record that can be subsequently analyzed according to the user's needs. Much of the code for generating these outputs can be found in `src/User/dswhbook.f`; some additional work may be required, depending on the process under study.

The simplest alternative output mode is obtained by changing the flag `dswhisto` to `.true.`. In this way, the `TOPDRAWER` output file is replaced by the file `outputname.rz` which contains the histograms in `HBOOK` format.

7.2.1 Simple n-tuple output

To obtain the simplest n-tuple output, the flag `creatent` should be set to `.true.` and the parameter `NTUPLES` in the `makefile` should be changed to either `YES` or `FROOT`. When changed to `YES`, each event that enters a histogram is also recorded as an n-tuple in the file `outputname.batchno.rz`. The `batchno` starts at zero and is incremented by one every one million events. Each event is a simple row-wise n-tuple consisting of the 4-momenta of each of the final state particles (p_x , p_y , p_z and E , in that order) followed by 5 numbers representing the event weight. The first number represents the total event weight and the others, the contribution from gluon-gluon, quark-gluon (and antiquark-gluon), quark-quark (and antiquark-antiquark) and quark-antiquark initial states. If PDF uncertainties are being calculated (using `LHAPDF`) then the total event weight corresponding to each of the additional PDF sets is also written out at this stage. Single precision is used, for economy. A simple way to analyze these n-tuples is to use the `h2root` command and then perform manipulations with the `ROOT` package. Note that these n-tuples contain no information about either the flavour or the colour of the initial or final state particles. Summation and averaging over these variables has already been performed. Furthermore, the 'events' are *weighted* - so they are not events in the traditional event generator sense.

7.2.2 n-tuples using FROOT

Output is similar when using the `FROOT` option. In this case, the program will directly fill a `ROOT` n-tuple using the `FROOT` interface of P. Nadolsky (`nadolsky@pa.msu.edu`, a version of which is included with `MCFM` (in the directory `src/User/froot.c`). The structure of the ntuples is slightly different to that above, with entries:

- `E_i`, `pxi`, `pyi`, `pzi` to specify the particle momenta, with `i` looping over all members of the final state.
- `wt_ALL`, `wt_gg`, `wt_gq`, `wt_qq`, `wt_qqb` for the total event weight and the weights in each of the parton-parton subchannels.
- `PDFjj`, where `jj` loops over all the PDF uncertainty sets (only written if appropriate).

7.2.3 Unweighted events

In order to obtain *unweighted* events, one must change the value of `nevtrequested` to an integer greater than zero, corresponding to the number of unweighted events that is required. This option is only available at lowest order at present and only for a limited number of processes. In this mode the program will first perform a run to obtain the maximum weight and then perform a simple unweighting procedure against this number. As a result this procedure is rather inefficient. Identities are assigned to the partons in the initial state according to the relative parton-parton luminosities. If the warm-up stage of the calculation is not sufficiently long, it is possible to find events with a weight greater than the maximum in the unweighting phase. In this case a warning message is written to the screen and the events are not truly unweighted without further processing by the user.

The events are written to a file with the extension `.lhe` using the LHE format. The routines that handle most of the processing can be found in `src/Need/mcfm_writelhe.f`. At present this feature is still under development.

8 Electroweak corrections

As of version 8.1, MCFM allows the calculation of weak corrections to a selection of processes: 31 (neutral-current DY), 157 (top-pair production) and 190 (di-jet production). This is controlled by the flag `ewcorr` in the input file. A complete description of the calculations is provided in Ref. [16].

By setting `ewcorr` to `sudakov`, the program performs a calculation of the leading weak corrections to these processes using a Sudakov approximation that is appropriate at high energies. The calculation of the weak corrections using the exact form of the one-loop amplitudes is obtained by using the flag `exact`. A comparison between the two approaches, together with discussions of the validity of the Sudakov approximation, may be found in Ref. [16].

For the case of top-pair and di-jet production, the weak one-loop corrections contain infrared divergences that must be cancelled against corresponding real radiation contributions (in much the same manner as a regular NLO QCD calculation). For this reason the screen output will contain two sets of iterations corresponding to the virtual and real contributions.

For all processes, performing the calculation of weak corrections enables a special mode of phase-space integration that is designed to better-sample events produced at high-energies. For this reason the VEGAS output that appears on the screen does not correspond to a physical cross-section – and a corresponding warning message to this effect will be displayed. In many cases the quantity of most interest is the relative correction to the leading order result (δ_{wk}) given by,

$$\delta_{\text{wk}} = \frac{d\sigma_{\text{wk}}^{NLO} - d\sigma^{LO}}{d\sigma^{LO}} . \quad (11)$$

It is straightforward to compute this quantity for a distribution by editing the appropriate `nplotter` routine. This is achieved by filling a histogram with the weight corresponding to the LO result, another with the weight for the NLO weak result and then an additional placeholder histogram that contains the special string `'+RELEW+'`. Examples of the syntax and correct calling sequence can be seen in the code.

9 Other user options

There are a number of other user options which are included in the file `src/User/usercode_f77.f`

- logical function `userincludedipole(nd, ppart, mcfm_result)`

Variables passed are

- `nd`: index of the dipole
- `ppart`: momenta of incoming and outgoing particles
- `mcfm_result`: the decision that was taken by `mcfm` about whether to keep this event

The program works in such a way that the cuts are applied after the phase space point has been generated but before the matrix element has been calculated. This true for the real, virtual loop and real pieces including the contributions from the subtraction dipoles. This operation is performed by the `MCFM` logical function `mcfmincludedipole`. However the (currently dummy) logical function `userincludedipole` is also always called. This allows the user to veto events that might otherwise pass the `MCFM` cuts. It can be used, e.g. to force `MCFM` to generate only events that are above some large HT threshold, which comes in useful when trying to get precision on the tails of some distributions.

- subroutine `userplotter(pjet, wt,wt2, nd)` This subroutine is called to allow the user to bin their own histograms.

Variables passed to this routine:

- `p`: 4-momenta of incoming partons($i=1,2$), outgoing leptons and jets in the format `p(i,4)` with the particles numbered according to the input file and components labelled by `(px,py,pz,E)`.

- wt: weight of this event
- wt2: weight² of this event
- nd: an integer specifying the dipole number of this contribution (if applicable), otherwise equal to zero.
- subroutine `userwriteinfo(unitno,comment_string,xsec,xsec_err,itno)`
This (currently dummy) subroutine gets called after MCFM has written its comments to one of the output files. It allows the user to write their own comments to that same file.

Variables passed to this routine:

- unitno: the unit number to which output is being sent
- comment_string: a comment character that precedes each line of output
- xsec, xsec_err: the cross section and its error (in case you care!)
- itno: the iteration number (0 at the end of the last iteration)

A similar set of routines written in fortran90 by Gavin Salam are in the file `usercode.f90`. Various C routines that may be of use are included in `cxxusercode.cc`.

10 Notes on specific processes

The processes described in the file `process.DAT` include appropriate boson decays when the parameter `removebr` is set to `.false..` In many cases a more simple calculation can be performed by setting this parameter to `.true.`, in which case these decays are not performed. Technically the full calculation including the decays is still performed but cuts are not performed on the decay products and the branching ratio is divided out, thus yielding the cross section before decay. In the notes below we indicate the simpler processes thus obtained. When running in this mode, the parameter `zerowidth` should be set to `.true.` for consistency. However in certain circumstances, for the sake of comparison, it may be useful to run with it set to `.false..`

10.1 *W*-boson production, processes 1,6

These processes represent the production of a *W* boson which subsequently decays leptonically. The calculation may be performed at NLO.

When `removebr` is true, the *W* boson does not decay.

10.2 $W + \text{jet}$ production, processes 11,16

These processes represent the production of a W boson which subsequently decays leptonically, in association with a single jet. The calculation may be performed at NLO.

When `removebr` is true, the W boson does not decay.

10.3 $W + b$ production, processes 12,17

These processes represent the production of a W boson which subsequently decays leptonically, in association with a single bottom quark, exploiting the weak transitions $c \rightarrow b$ and $u \rightarrow b$. This is produced at leading order by an initial state which contains a charm quark (or the CKM suppressed u quark) and a gluon. The effect of the bottom quark mass is included throughout the calculation. For this case the CKM matrix elements V_{cb} and V_{ub} , (if they are equal to zero in the input data file, `mdata.f`) are set equal to 0.041 and 0.00347 respectively. Otherwise the non-zero values specified in `mdata.f` are used. The calculation of this process may be performed at NLO.

When `removebr` is true, the W boson does not decay.

10.4 $W + c$ production, processes 13,18

These processes represent the production of a W boson which subsequently decays leptonically, in association with a charm quark. This is produced at leading order by an initial state which contains a strange quark (or Cabibbo suppressed d quark) and a gluon. The effect of the charm quark mass is included throughout the calculation. As of version 5.2, the calculation of this process may be performed at NLO.

When `removebr` is true, the W boson does not decay.

10.5 $W + c$ production ($m_c = 0$), processes 14,19

These processes are identical to 13 and 18 except for the fact that the charm quark mass is neglected. The calculation can currently be performed at LO only.

10.6 $W + b\bar{b}$ production, processes 20,25

These processes represent the production of a W boson which subsequently decays leptonically, in association with a $b\bar{b}$ pair. The effect of the bottom quark mass is included throughout the calculation. Beginning with MCFM version 6.0 this calculation may be performed at NLO, thanks to the incorporation of the virtual corrections from ref. [2]. When `removebr` is true, the W boson does not decay.

To select final states in which one of the b -quarks may be unobserved the user can employ processes 401–408 instead (see section 10.71). These processes use the same matrix elements but make specific requirements on the kinematics of the b -quarks and QCD radiation.

10.7 $W + b\bar{b}$ production ($m_b = 0$), processes 21,26

These processes are identical to 20 and 25 except for the fact that the bottom quark mass is neglected. This allows the calculation to be performed up to NLO, with currently calculated virtual matrix elements. These processes run considerably faster than the corresponding processes with the mass for the b quark, (20,25). In circumstances where both b quarks are at large transverse momentum, the inclusion of the mass for the b -quark is not mandatory and a good estimate of the cross section may be obtained by using these processes.

When `removebr` is true, the W boson does not decay.

10.8 $W + 2$ jets production, processes 22,27

*[For more details on this calculation, please refer to
hep-ph/0202176 and hep-ph/0308195]*

This process represents the production of a W boson and 2 jets, where the W boson decays leptonically. The calculation may be performed up to NLO, as detailed below. Virtual amplitudes are taken from ref. [7].

For these processes (and also for $Z + 2$ jet production, `nproc=44,46`) the next-to-leading order matrix elements are particularly complex and so they have been divided into two groups. The division is according to the lowest order diagrams from which they originate:

1. Diagrams involving two external quark lines and two external gluons, the “`Gflag`” contribution. The real diagrams in this case thus involve three external gluons.
2. Diagrams where all four external lines are quarks, the “`Qflag`” contribution. The real diagrams in this case involve only one gluon.

By specifying `Gflag` and `Qflag` in `input.DAT` one may select one of these options at a time. The full result may be obtained by straightforward addition of the two individual pieces, with no meaning attached to either piece separately. Both of these may be set to `.true.` simultaneously, however this may result in lengthy run-times for sufficient convergence of the integral.

When `removebr` is true, the W boson does not decay.

10.9 $W + 3$ jets production, processes 23,28

This process represents the production of a W boson and 3 jets, where the W boson decays leptonically. The calculation may be performed at LO only.

When `removebr` is true, the W boson does not decay.

10.10 $W+bb$ + jet production ($m_b = 0$), processes 24,29

These processes represent the production of a W boson which subsequently decays leptonically, in association with a $b\bar{b}$ pair and an additional jet. The effect of the bottom quark mass is neglected throughout and the calculation may be performed at LO only.

When `removebr` is true, the W boson does not decay.

10.11 Z -boson production, processes 31–33

These processes represent the production of a Z boson which subsequently decays either into electrons (`nproc=31`), neutrinos (`nproc=32`) or bottom quarks (`nproc=33`). Where appropriate, the effect of a virtual photon is also included. As noted above, in these latter cases `m34min > 0` is obligatory. The calculation may be performed at NLO, although the NLO calculation of process 33 does not include radiation from the bottom quarks (i.e. radiation occurs in the initial state only).

When `removebr` is true in process 31, the Z boson does not decay.

10.12 Z -boson production decaying to jets, processes 34–35

Radiation from the final state quarks is not included in this process.

10.13 $t\bar{t}$ production mediated by Z/γ^* -boson exchange, process 36

These processes represent the production of a virtual Z boson or photon which subsequently decays into $t\bar{t}$. The leptonic decays of the top quarks are included. Switching `zerowidth` from `.true.` to `.false.` only affects the W bosons from the top quark decay. Note that `m34min > 0` is obligatory due to the inclusion of the virtual photon diagrams. The calculation may be only be performed at LO.

10.14 Lepton pair production through photonic initial states, process 310

This process represents the production of a lepton pair through an electroweak process involving two photons in the initial state, $\gamma\gamma \rightarrow e^-e^+$.

10.15 $Z + \text{jet}$ production, processes 41–43

These processes represent the production of a Z boson and a single jet, where the Z subsequently decays either into electrons (`nproc=41`), neutrinos (`nproc=42`) or bottom quarks (`nproc=43`). Where appropriate, the effect of a virtual photon is also included. The calculation may be performed at NLO, although the NLO calculation of process 43 does not include radiation from the bottom quarks.

When `removebr` is true in process 41, the Z boson does not decay.

10.16 $Z + 2 \text{ jets}$ production, processes 44, 46

*[For more details on this calculation, please refer to
hep-ph/0202176 and hep-ph/0308195]*

These processes represents the production of a Z boson and 2 jets, including also the effect of a virtual photon (`nproc=44` only). The Z/γ^* decays to an e^+e^- pair (`nproc=44`) or into three species of neutrino (`nproc=46`). The calculation may be performed up to NLO – please see the earlier Section 10.8 for more details, especially the discussion regarding `Qflag` and `Gflag`. As of version 6.0, both of these may be set to `.true.` simultaneously but this may result in lengthy run-times for sufficient convergence of the integral. Virtual amplitudes are taken from ref. [7].

When `removebr` is true, the Z boson does not decay.

10.17 $Z + 3 \text{ jets}$ production, processes 45, 47

These processes represent the production of a Z boson and 3 jets, including also the effect of a virtual photon (`nproc=45` only). The Z/γ^* decays to an e^+e^- pair (`nproc=45`) or into three species of neutrino (`nproc=47`). The calculation may be performed at LO only.

When `removebr` is true, the Z boson does not decay.

10.18 $Z + b\bar{b}$ production, process 50

These processes represent the production of a Z boson (or virtual photon) which subsequently decays leptonically, in association with a $b\bar{b}$ pair. The effect of the bottom quark mass is included throughout the calculation. The calculation may be performed at LO only.

When `removebr` is true, the Z boson does not decay.

10.19 $Z + b\bar{b}$ production ($m_b = 0$), processes 51–53

Process 51 is identical to 50 except for the fact that the bottom quark mass is neglected. This allows the calculation to be performed up to NLO. The other

processes account for the decays into neutrinos (`nproc=52`) and bottom quarks (`nproc=53`). Note that the NLO calculation of process 53 does not currently include radiation from the bottom quarks produced in the decay.

When `removebr` is true in process 51, the Z boson does not decay.

10.20 $Z + b\bar{b} + \text{jet}$ production ($m_b = 0$), process 54

This process represents the production of a Z boson (and virtual photon) which subsequently decays leptonically, in association with a $b\bar{b}$ pair and an additional jet. The effect of the bottom quark mass is neglected throughout and the calculation may be performed at LO only.

When `removebr` is true, the Z boson does not decay.

10.21 $Z + c\bar{c}$ production ($m_c = 0$), process 56

Process 56 is the equivalent of 51, with the bottom quarks replaced by charm. Although the charm mass is neglected, the calculation contains diagrams with two gluons in the initial state and a Z coupling to the heavy quark line – hence the dependence upon the quark flavour.

When `removebr` is true in process 56, the Z boson does not decay.

10.22 Di-boson production, processes 61–89

[For more details on these calculations, please refer to hep-ph/9905386 and arXiv:1105.0020 [hep-ph]]

These processes represent the production of a diboson pair $V_1 V_2$, where V_1 and V_2 may be either a W or Z/γ^* . All the processes in this section may be calculated at NLO, with the exception of `nproc=66,69`. There are various possibilities for the subsequent decay of the bosons, as specified in the sections below. Amplitudes are taken from ref. [21]. Where appropriate, these processes include glue-gluon initiated box diagrams which first contribute at order α_s^2 but are included here in the NLO calculation. We also include singly resonant diagrams at NLO for all processes in the case `zerowidth = .false..`

For processes 62, 63, 64, 65, 74 and 75 the default behaviour is that the hadronic decay products of the bosons are clustered into jets using the supplied jet algorithm parameters, but no cut is applied on the number of jets. This behaviour can be altered by changing the value of the variable `notag` in the file `src/User/setnotag.f`.

10.22.1 WW production, processes 61-64, 69

For WW production, both W 's can decay leptonically (`nproc=61`) or one may decay hadronically (`nproc=62` for W^- and `nproc=64` for W^+). Corresponding to processes 62,64, processes 63,65 implement radiation in decay from the

hadronically decaying W 's. Process 69 implements the matrix elements for the leptonic decay of both W 's but where no polarization information is retained. It is included for the sake of comparison with other calculations. Processes 62 and 64 may be run at NLO with the option `todk`, including radiation in the decay of the hadronically decaying W . Processes 63 and 65 give the effect of radiation in the decay alone by making the choices `virt`, `real` or `tota`.

Note that, in processes 62 and 64, the NLO corrections include radiation from the hadronic decays of the W .

The NLO calculations include contributions from the process $gg \rightarrow WW$ that proceeds through quark loops. The calculation of loops containing the third quark generation includes the effect of the top quark mass (but $m_b = 0$), while the first two generations are considered massless. For numerical stability, a small cut on the transverse momentum of the W bosons is applied: $p_T(W) > 0.05$ GeV for loops containing massless (first or second generation) quarks, $p_T(W) > 2$ GeV for (t, b) loops. This typically removes less than 0.1% of the total cross section. The values of these cutoffs can be changed by editing `src/WW/gg-WW.f` and recompiling.

When `removebr` is true in processes 61 and 69, the W bosons do not decay.

10.22.2 WW +jet production, process 66

This process is only implemented for the leptonic decay modes of both W bosons and is currently limited to LO accuracy only. When `removebr` is true, the W bosons do not decay.

10.22.3 WZ production, processes 71–80

For WZ production, the W is chosen to decay leptonically. The Z (or virtual photon, when appropriate) may decay into electrons (`nproc=71,76`), neutrinos (`nproc=72,77`), a pair of bottom quarks (`nproc=73,78`), three generations of down-type quarks (`nproc=74,79`) or two generations of up-type quarks (`nproc=75,80`). In process 78 the mass of the b -quark is neglected. These processes will be observed in the final state as W -boson + two or three jets. In processes 72 and 77, a sum is performed over all three species of neutrinos.

When `removebr` is true in processes 71 and 76, neither the W or the Z boson decays.

10.22.4 ZZ production, processes 81–84, 86–90

For ZZ production, there are two sets of processes corresponding to the inclusion of a virtual photon when appropriate (`nproc=81–84`) and the case where it is neglected (`nproc=86–89`). Thus `nproc=86–89` are really for diagnostic purposes only.

The Z 's can either both decay leptonically (`nproc=81,86`), one can decay leptonically while the other decays into neutrinos (`nproc=82,87`) or bottom quarks (`nproc=83,88`), or one decays into neutrinos and the other into a bottom quark pair (`nproc=84,89`). In process 83 the mass of the b -quark is neglected. Note that, in processes 83–84 and 88–89, the NLO corrections do not include radiation from the bottom quarks that are produced by the Z decay.

The NLO calculations include contributions from the process $gg \rightarrow ZZ$ that proceeds through quark loops. The calculation of loops containing the third quark generation includes the effect of both the top and the bottom quark mass ($m_t, m_b \neq 0$), while the first two generations are considered massless. For numerical stability, a small cut on the transverse momentum of the Z bosons is applied: $p_T(Z) > 0.1$ GeV. This typically removes less than 0.1% of the total cross section. The values of these cutoffs can be changed by editing `src/ZZ/getggZZamps.f` and recompiling.

When `removebr` is true in processes 81 and 86, neither of the Z bosons decays.

In process 90 the two Z bosons decay to identical charged leptons, and interference effects between the decay products of the two Z bosons are included. This process may be calculated at LO only.

10.22.5 ZZ +jet production, process 85

This process is only implemented for the case when one Z boson decays to electrons and the other to neutrinos (i.e. the companion of `nproc=82`). It may only be calculated at LO. When `removebr` is true, the Z bosons do not decay.

10.22.6 Anomalous couplings

As of version 3.0, it is possible to specify anomalous trilinear couplings for the W^+W^-Z and $W^+W^-\gamma$ vertices that are relevant for WW and WZ production. To run in this mode, one must set `zerowidth` equal to `.true.` and modify the appropriate lines for the couplings in `input.DAT` (see below). Note that, at present, the effect of anomalous couplings is not included in the gluon-gluon initiated contributions to the WW process.

The anomalous couplings appear in the Lagrangian, $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{anom}$ as follows (where \mathcal{L}_{SM} represents the usual Standard Model Lagrangian and \mathcal{L}_{anom} is taken from Ref. [22]):

$$\begin{aligned} \mathcal{L}_{anom} = & ig_{WWZ} \left[\Delta g_1^Z (W_{\mu\nu}^* W^\mu Z^\nu - W_{\mu\nu} W^{*\mu} Z^\nu) + \Delta \kappa^Z W_\mu^* W_\nu Z^{\mu\nu} \right. \\ & \left. + \frac{\lambda^Z}{M_W^2} W_{\rho\mu}^* W_\nu^\mu Z^{\nu\rho} \right] + ig_{WW\gamma} \left[\Delta \kappa^\gamma W_\mu^* W_\nu \gamma^{\mu\nu} + \frac{\lambda^\gamma}{M_W^2} W_{\rho\mu}^* W_\nu^\mu \gamma^{\nu\rho} \right], \end{aligned}$$

where $X_{\mu\nu} \equiv \partial_\mu X_\nu - \partial_\nu X_\mu$ and the overall coupling factors are $g_{WW\gamma} = -e$, $g_{WWZ} = -e \cot \theta_w$. This is the most general Lagrangian that conserves C and P separately and electromagnetic gauge invariance requires that there is no equivalent of the Δg_1^Z term for the photon coupling.

In order to avoid a violation of unitarity, these couplings are often included only after suppression by dipole form factors,

$$\Delta g_1^Z \rightarrow \frac{\Delta g_1^Z}{(1 + \hat{s}/\Lambda^2)^2}, \quad \Delta \kappa^{Z/\gamma} \rightarrow \frac{\Delta \kappa_1^{Z/\gamma}}{(1 + \hat{s}/\Lambda^2)^2}, \quad \lambda^{Z/\gamma} \rightarrow \frac{\Delta \lambda^{Z/\gamma}}{(1 + \hat{s}/\Lambda^2)^2},$$

where \hat{s} is the vector boson pair invariant mass and Λ is an additional parameter giving the scale of new physics, which should be in the TeV range. These form factors should be produced by the new physics associated with the anomalous couplings and this choice is somewhat arbitrary. The use of the form factors can be disabled as described below.

The file `input.DAT` contains the values of the 6 parameters which specify the anomalous couplings:

```

0.0d0      [Delta_g1(Z)]
0.0d0      [Delta_K(Z)]
0.0d0      [Delta_K(gamma)]
0.0d0      [Lambda(Z)]
0.0d0      [Lambda(gamma)]
2.0d0      [Form-factor scale, in TeV]

```

with the lines representing Δg_1^Z , $\Delta \kappa^Z$, $\Delta \kappa^\gamma$, λ^Z , λ^γ and Λ [TeV] respectively. By setting the first 5 parameters to zero, as above, one recovers the Standard Model result. If the input file contains a negative value for the form-factor scale then the suppression factors described above are not applied.

10.23 WH production, processes 91-94, 96-99

These processes represent the production of a W boson which subsequently decays leptonically, in association with a Standard Model Higgs boson that decays into a bottom quark pair (`nproc=91, 96`), a pair of W bosons (`nproc=92, 97`), a pair of Z bosons (`nproc=93, 98`), or a pair of photons (`nproc=94, 99`). Note that in the cases of Higgs decay to $W, (Z)$ pairs, below the $W, (Z)$ pair threshold one of the $W, (Z)$ bosons is virtual and therefore one must set `zerowidth=false..` The calculation may be performed at NLO. Note that the bottom quarks are considered massless and radiation from the bottom quarks in the decay is not included.

When `removebr` is true, neither the W boson nor the Higgs decays.

10.24 ZH production, processes 101–109

These processes represent the production of a Z boson (or virtual photon) in association with a Standard Model Higgs boson that decays into a bottom quark pair (`nproc=101-103`), or decays into a pair of photons (`nproc=104-105`) or a pair of W bosons (`nproc=106-108`), or a pair of Z bosons (`nproc=109`). The Z subsequently decays into either an e^+e^- pair (`nproc=101, 106, 109`), neutrinos (`nproc=102, 107`) or a bottom quark pair (`nproc=103, 108`). The calculation may be performed at NLO, although radiation from the bottom quarks in the decay of the Higgs (or the Z , for processes 103, 108) is not included.

When `removebr` is true in processes 101, 106, 109, neither the Z boson nor the Higgs decays.

10.25 Higgs production, processes 111–121

These processes represent the production of a Standard Model Higgs boson that decays either into a bottom quark pair (`nproc=111`), a pair of tau's (`nproc=112`), a W^+W^- pair that further decays leptonically (`nproc=113`) a W^+W^- pair where the W^- decays hadronically (`nproc=114,115`) or a ZZ pair (`nproc=116-118`). In addition, the loop-level decays of the Higgs into a pair of photons (`nproc=119`) and the $Z\gamma$ decay are included (`nproc=120,121`).

For the case of W^+W^- process `nproc=115` gives the contribution of radiation from the hadronically decaying W^- . Process 114 may be run at NLO with the option `todk`, including radiation in the decay of the hadronically decaying W^- .⁶ For the case of a ZZ decay, the subsequent decays can either be into a pair of muons and a pair of electrons (`nproc=116`), a pair of muons and neutrinos (`nproc=117`) or a pair of muons and a pair of bottom quarks (`nproc=118`).

At LO the relevant diagram is the coupling of two gluons to the Higgs via a top quark loop. This calculation is performed in the limit of infinite top quark mass, so that the top quark loop is replaced by an effective operator. This corresponds to the effective Lagrangian,

$$\mathcal{L} = \frac{1}{12\pi v} G_{\mu\nu}^a G_a^{\mu\nu} H, \quad (12)$$

where v is the Higgs vacuum expectation value and $G_{\mu\nu}^a$ the gluon field strength tensor. The calculation may be performed at NLO, although radiation from the bottom quarks in the decay of processes 111 and 118 is not yet included.

At the end of the output the program will also display the cross section rescaled by the constant factor,

$$\frac{\sigma_{\text{LO}}(gg \rightarrow H, \text{finite } m_t)}{\sigma_{\text{LO}}(gg \rightarrow H, m_t \rightarrow \infty)}. \quad (13)$$

⁶We have not included the case of a hadronically decaying W^+ ; it can be obtained from processes `nproc=114,115` by performing the substitutions $\nu \rightarrow e^-$ and $e^+ \rightarrow \bar{\nu}$.

For the LO calculation this gives the exact result when retaining a finite value for m_t , but this is only an approximation at NLO. The output histograms are not rescaled in this way.

When `removebr` is true in processes 111,112,113,118, the Higgs boson does not decay.

Process 119 implements the decay of the Higgs boson into two photons via loops of top quarks and W -bosons. The decay is implemented using the formula Eq.(11.12) from ref. [25]. When `removebr` is true in process 119 the Higgs boson does not decay.

Processes 120 and 121 implement the decay of the Higgs boson into an lepton-antilepton pair and a photon. As usual the production of a charged lepton-antilepton pair is mediated by a Z/γ^* (process 120) and the production of three types of neutrinos $\sum \nu\bar{\nu}$ by a Z -boson (process 121). These processes are implemented using a generalization of the formula of [23]. (Generalization to take into account off-shell Z -boson and adjustment of the sign of C_2 in their Eq.(4)).

10.26 $H \rightarrow W^+W^-$ production, processes 123-126

These processes represent the production of a Higgs boson that decays to W^+W^- , with subsequent decay into leptons. For process 123, the exact form of the triangle loop coupling a Higgs boson to two gluons is included, with both top and bottom quarks circulating in the loop. This is to be contrasted with process 113 in which only the top quark contribution is included in the effective coupling approach.

Process 124 includes only the effect of the interference of the Higgs and $gg \rightarrow W^+W^-$ amplitudes, as described in ref. [13]. The calculation is available at LO only. LO corresponds to $O(\alpha_s^2)$ in this case. The calculation of loops containing the third quark generation includes the effect of the top quark mass (but $m_b = 0$), while the first two generations are considered massless. For numerical stability, a small cut on the transverse momentum of the W bosons is applied: $p_T(W) > 0.05$ GeV for loops containing massless (first or second generation) quarks, $p_T(W) > 2$ GeV for (t, b) loops. This typically removes less than 0.1% of the cross section. The values of these cutoffs can be changed by editing `src/HWW/gg.WW.int.f` and recompiling.

Process 125 includes all gg -initiated diagrams that have a Higgs boson in the s -channel, namely the square of the s -channel Higgs boson production and the interference with the diagrams that do not contain a Higgs boson, (i.e. $gg \rightarrow W^+W^- \rightarrow \nu_e e^+ e^- \bar{\nu}_e$).

The result for the square of the box diagrams alone, i.e. the process $gg \rightarrow W^+W^- \rightarrow \nu_e e^+ e^- \bar{\nu}_e$, may be obtained by running process `nproc=61` with `part=virt` and `ggonly=.true.`

Process 126 calculates the full result for this process from gg -initiated diagrams. This includes diagrams that have a Higgs boson in the s -channel, the continuum W^+W^- diagrams described above and their interference.

10.27 $H \rightarrow ZZ \rightarrow e^-e^+\mu^-\mu^+$ production, processes 128-133

These processes represent the production of a Higgs boson that decays to ZZ , with subsequent decay into charged leptons. For process 128, the exact form of the triangle loop coupling a Higgs boson to two gluons is included, with both top and bottom quarks circulating in the loop. This is to be contrasted with process 116 in which only the top quark contribution is included in the effective coupling approach.

Process 129 includes only the effect of the interference of the Higgs and $gg \rightarrow ZZ$ amplitudes. The calculation is available at LO only. LO corresponds to $O(\alpha_s^2)$ in this case. The calculation of loops containing the third quark generation includes the effect of both the top quark mass and the bottom quark, while the first two generations are considered massless. For numerical stability, a small cut on the transverse momentum of the Z bosons is applied: $p_T(Z) > 0.05$ GeV. This typically removes less than 0.1% of the cross section. The values of these cutoffs can be changed by editing `src/ZZ/getggZZamps.f` and recompiling.

Process 130 includes all gg -initiated diagrams that have a Higgs boson in the s -channel, namely the square of the s -channel Higgs boson production and the interference with the diagrams that do not contain a Higgs boson, (i.e. $gg \rightarrow Z/\gamma^* + Z/\gamma^* \rightarrow e^-e^+\mu^-\mu^+$).

Process 131 calculates the full result for this process from gg -initiated diagrams. This includes diagrams that have a Higgs boson in the s -channel, the continuum $Z/\gamma^* + Z/\gamma^*$ diagrams described above and their interference.

Process 132 gives the result for the square of the box diagrams alone, i.e. the process $gg \rightarrow Z/\gamma^* + Z/\gamma^* \rightarrow e^-e^+\mu^-\mu^+$.

Process 133 calculates the interference for the qg initiated process.

For those processes that include contributions from the Higgs boson, the form of the Higgs propagator may be changed by editing the file `src/Need/sethparams.f`. If the logical variable `CPscheme` is changed from the default value `.false.` to `.true.` then the Higgs propagator is computed using the “bar-scheme” that is implemented in the HTO code of G. Passarino [34, 50]. The value of the Higgs boson width has been computed with v1.1 of the HTO code, for Higgs masses in the interval $50 < m_H < 1500$ GeV. These values are tabulated, in 0.5 GeV increments, in the file `Bin/hto_output.dat`. The widths for other masses in this range are obtained by linear interpolation.

10.27.1 Specifying other final states

As described above, these processes refer to a final state $e^-e^+\mu^-\mu^+$. It is however possible to specify a final state that corresponds to a different set of Z boson decays. This is achieved by altering the value of `NPROC` in the input file by appending a period, followed by two 2-character strings that identify each of the decays. Possible values for the strings, and the corresponding decays, are shown in the table below.

string	Z decay
e1,EL	(e^-, e^+)
mu,MU,m1,ML	(μ^-, μ^+)
t1,TL	(τ^-, τ^+)
nu,NU,n1,NL	$(\nu, \bar{\nu}) \times 3$
bq,BQ	(b, \bar{b})

Note that, for the case of neutrino decays, the sum over three flavours of neutrino is performed. The labelling of the particles in the output is best understood by example. Setting `nproc=132.ELNU` corresponds to the process $gg \rightarrow Z/\gamma^* + Z/\gamma^* \rightarrow e^-(p_3)e^+(p_4)\nu(p_5)\bar{\nu}(p_6)$. Note that the default process corresponds to the string `ELMU` so that, for instance `nproc=132.ELMU` is entirely equivalent to `nproc=132`. The effect of changing the lepton flavour is only seen in the output of LHE events, where the correct mass is then used when producing the event record.

10.28 $e^-e^+\nu_e\bar{\nu}_e$ production, processes 1281, 1311, 1321

These processes compute cross sections relevant for the final state $e^-e^+\nu_e\bar{\nu}_e$, i.e. with charged leptons and neutrinos from the same (electron) doublet. As a result they receive contributions from diagrams with resonant ZZ propagators and resonant WW propagators. Process 1281 only includes amplitudes containing a Higgs boson c.f. processes 123 and 128. Process 1321 only includes continuum (box-diagram) amplitudes c.f. processes 127 and 132. Process 1311 includes both amplitudes and the effects of the interference between them c.f. processes 126 and 131. The effect of the interference between the WW and ZZ diagrams can be assessed by, for instance, comparing process 1281 with the sum of processes 123 and one-third of 128.ELNU, where the weighting is to divide out the natural sum over three neutrino flavours in process 128.ELNU.

Event generation is not available for these processes at present.

10.29 $e^-e^+\nu\bar{\nu}$ production, processes 1282, 1312, 1322

These processes compute cross sections relevant for the final state $e^-e^+\nu\bar{\nu}$, i.e. an electron pair and a sum over all three flavours of neutrino. For muon and tau neutrinos, only ZZ diagrams contribute. For electron neutrinos there are contributions from diagrams with resonant ZZ propagators and resonant WW propagators. Process 1282 only includes amplitudes containing a Higgs boson

c.f. processes 123 and 128. Process 1322 only includes continuum (box-diagram) amplitudes c.f. processes 127 and 132. Process 1312 includes both amplitudes and the effects of the interference between them c.f. processes 126 and 131. The effect of the interference between the WW and ZZ diagrams can be assessed by, for instance, comparing process 1282 with the sum of processes 123 and 128.ELNU.

Event generation is not available for these processes at present.

10.30 $H + b$ production, processes 136–138

[For more details on this calculation, please refer to *hep-ph/0204093*]

These processes represent the production of a Standard Model Higgs boson that decays into a pair of bottom quarks, in association with a further bottom quark. The initial state at lowest order is a bottom quark and a gluon. The calculation may be performed at NLO, although radiation from the bottom quarks in the Higgs decay is not included.

For this process, the matrix elements are divided up into a number of different sub-processes, so the user must sum over these after performing more runs than usual. At lowest order one can proceed as normal, using `nproc=136`. For a NLO calculation, the sequence of runs is as follows:

- Run `nproc=136` with `part=virt` and `part=real` (or, both at the same time using `part=tota`);
- Run `nproc=137` with `part=real`.

The sum of these yields the cross-section with one identified b -quark in the final state. To calculate the contribution with two b -quarks in the final state, one should use `nproc=138` with `part=real`.

When `removebr` is true, the Higgs boson does not decay.

10.31 $t\bar{t}$ production with 2 semi-leptonic decays, processes 141–145

These processes describe $t\bar{t}$ production including semi-leptonic decays for both the top and the anti-top. In version 6.2 we have updated this to use the one-loop amplitudes of ref. [3]. The code for the virtual amplitudes now runs about three times faster than earlier versions where the virtual amplitudes of ref. [37] were used. Switching `zerowidth` from `.true.` to `.false.` only affects the W bosons from the top quark decay, because our method of including spin correlations requires the top quark to be on shell.

Process 141 includes all corrections, i.e. both radiative corrections to the decay and to the production. This process is therefore the basic process for the description of top production where both quarks decay semi-leptonically. When `removebr` is true in process 141, the top quarks do not decay. When one wishes

to calculate observables related to the decay of the top quark, `removebr` should be false in process 141. The LO calculation proceeds as normal. At NLO, there are two options:

- `part=virt, real` or `tota` : final state radiation is included in the production stage only
- `part = todk` : radiation is included in the decay of the top quark also and the final result corresponds to the sum of real and virtual diagrams. Note that these runs automatically perform an extra integration, so will take a little longer.

Process 142 includes only the corrections in the semileptonic decay of the top quark. Thus it is of primary interest for theoretical studies rather than for physics applications. Because of the method that we have used to include the radiation in the decay, the inclusion of the corrections in the decay does not change the total cross section. This feature is explained in section 6 of ref. [12].

In the case of process 145, there are no spin correlations in the decay of the top quarks. The calculation is performed by multiplying the spin summed top production cross section, by the decay matrix element for the decay of the t and the \bar{t} . These processes may be used as a diagnostic test for the importance of the spin correlation.

10.32 $t\bar{t}$ production with decay and a gluon, process 143

This process describes lowest order $t\bar{t} + g$ production including two leptonic decays $t \rightarrow b\nu$. When `removebr` is true, the top quarks do not decay. This LO process only includes radiation only includes radiation in production.

10.33 $t\bar{t}$ production with one hadronic decay, processes 146–151

These processes describe the hadronic production of a pair of top quarks, with one quark decaying hadronically and one quark decaying semileptonically. For processes 146--148, the top quark decays semileptonically whereas the anti-top quark decays hadronically. For processes 149--151, the top quark decays hadronically whereas the anti-top quark decays semi-leptonically. The base processes for physics are process 146 and 149 which include radiative corrections in both production and decay. Switching `zerowidth` from `.true.` to `.false.` only affects the W bosons from the top quark decay, because our method of including spin correlations requires the top quark to be on shell. When one wishes to calculate observables related to the decay of the top quark, `removebr` should be false in processes 146 and 149. The LO calculation proceeds as normal. At NLO, there are two options:

- `part=virt, real` or `tota` : final state radiation is included in the production stage only

- `part = todk` : radiation is included in the decay of the top quark also and the final result corresponds to the sum of real and virtual diagrams. Note that these runs automatically perform an extra integration, so will take a little longer.

Processes 147 and 150 include only the radiative corrections in the decay of the top quark without including the radiative corrections in the hadronic decay of the W -boson. Because of the method that we have used to include the radiation in the decays, the inclusion of the corrections in this stage of the decay does not change the total cross section. Process 148 (151) includes only the radiative corrections in the hadronic decay of the W -boson coming from the anti-top (top). The inclusion of the corrections in this stage of the decay increases the partial width by the normal α_s/π factor.

10.34 $Q\bar{Q}$ production, processes 157–159

These processes calculate the production of heavy quarks (157 for top, 158 for bottom and 159 for charm) up to NLO using the matrix elements of ref. [44]. No decays are included.

10.35 $t\bar{t}$ + jet production, process 160

This process calculates the production of top quarks and a single jet at LO, without any decay of the top quarks.

10.36 Single top production, processes 161–177

[For more details on this calculation, please refer to [hep-ph/0408158](https://arxiv.org/abs/hep-ph/0408158)]

These processes represent single top production and may be calculated up to NLO as described below.

Single top production is divided as usual into s -channel (processes 171–177) and t -channel (161–167) diagrams. Each channel includes separately the production of a top and anti-top quark, which is necessary when calculating rates at the LHC. Below we illustrate the different use of these processes by considering t -channel top production (161, 162), although the procedure is the same for anti-top production (166, 167) and the corresponding s -channel processes (171, 172) and (176, 177).

To calculate cross-sections that do not include any decay of the (anti-)top quark, one should use process 161 (or, correspondingly, 166, 171 and 176) with `removebr` true. The procedure is exactly the same as for any other process. Switching `zerowidth` from `.true.` to `.false.` only affects the W boson from the top quark decay.

For processes 161, 162, 163, 166, 167 and 168 the default behaviour when `removebr` is true is that partons are clustered into jets using the supplied

jet algorithm parameters, but no cut is applied on the number of jets. This behaviour can be altered by changing the value of the variable `notag` in the file `src/User/setnotag.f`.

When one wishes to calculate observables related to the decay of the top quark, `removebr` should be false. The LO calculation proceeds as normal. At NLO, there are two options:

- `part=virt, real` or `tota` : final state radiation is included in the production stage only
- `part = todk` : radiation is included in the decay of the top quark also and the final result corresponds to the sum of real and virtual diagrams. This process can only be performed at NLO with `zerowidth = .true`. This should be set automatically. Note that these runs automatically perform an extra integration, so will take a little longer.

The contribution from radiation in the decay may be calculated separately using process 162. This process number can be used with `part=virt,real` only. To ensure consistency, it is far simpler to use 161 and this is the recommended approach.

A further option is provided for the t -channel single top process (when no top quark decay is considered), relating to NLO real radiation diagrams that contain a bottom quark. In the processes above the bottom quark is taken to be massless. To include the effect of $m_b > 0$, one can run process 163 (168) in place of 161 (166) and additionally include process 231 (236) at leading order. The non-zero bottom quark mass has little effect on the total cross section, but enables a (LO) study of the bottom quark kinematics. Higher order corrections to the bottom quark kinematics can only be studied by running process 231 (236) at NLO.

10.37 Off-shell single top production in SM and SMEFT, processes 164,169

[For more details on this calculation, please refer to ref. [46]]

The processes 164 and 169 represent off-shell single-top-quark and anti-top-quark production in the complex-mass scheme, respectively. Both the SM and contributions from the SMEFT can be calculated.

Dynamical double deep inelastic scattering scales can be consistently used at NLO by setting `dynamicsscale` to 'DDIS' and `scale=facscale` to 1d0. In this way the momentum transfer along the W -boson Q^2 is used as the scale for the light-quark-line corrections $\mu^2 = Q^2$, and $\mu^2 = Q^2 + m_t^2$ for the heavy-quark-line corrections. These scales are also consistently used for the non-resonant contributions, with QCD corrections on the ud -quark line, and separate QCD corrections on the bottom-quark line.

The new block ‘Single top SMEFT, nproc=164,169’ in the input file governs the inclusion of SMEFT operators and corresponding orders. The scale of new physics Λ can be separately set, and has a default value of 1000 GeV. The flag `enable 1/lambda4` enables the $1/\Lambda^4$ contributions, where operators $Q_{\varphi ud}^{33}$, Q_{dW}^{33} , Q_{dG}^{33} and Q_{4R} can contribute for the first time. For the non-Hermitian operators we allow complex Wilson coefficients. We also have a flag to disable the pure SM contribution, leaving only contributions from SMEFT operators either interfered with the SM amplitudes or as squared contributions at $1/\Lambda^4$. This can be used to directly and quickly extract kinematical distributions and the magnitudes of pure SMEFT contributions.

To allow for easier comparisons with previous anomalous couplings results, and possibly estimate further higher order effects, we allow for an anomalous couplings mode at LO by enabling the corresponding flag. The relations between our operators and the anomalous couplings are

For comparisons with on-shell results one needs to add up the contributions from processes 161 at NLO and from the virt and real contributions from 162, see above.

$$\begin{aligned}\delta V_L &= C_{\varphi q}^{(3,33)} \frac{m_t^2}{\Lambda^2}, \text{ where } V_L = 1 + \delta V_L, \\ V_R &= C_{\varphi ud}^{33} * \frac{m_t^2}{\Lambda^2}, \\ g_L &= -4 \frac{m_W m_t}{\Lambda^2} \cdot C_{dW}^{33}, \\ g_R &= -4 \frac{m_W m_t}{\Lambda^2} \cdot C_{uW}^{33} * ,\end{aligned}$$

where m_W is the W -boson mass, and $m_W = \frac{1}{2}g_W v$ has been used to derive this equivalence. Note that the minus sign for g_L and g_R is different from the literature. See also the publication for more information.

The analysis/plotting routine is contained in the file ‘`src/User/nplotter_ktopanom.f`’, where all observables presented in this study are implemented, and the W -boson/neutrino reconstruction is implemented and can be switched on or off.

10.38 Wt production, processes 180–187

[For more details on this calculation, please refer to *hep-ph/0506289*]

These processes represent the production of a W boson that decays leptonically in association with a top quark. The lowest order diagram involves a gluon and a bottom quark from the PDF, with the b -quark radiating a W boson and becoming a top quark. The calculation can be performed up to NLO.

Processes 180 and 185 produce a top quark that does not decay, whilst in processes 181 and 186 the top quark decays leptonically. Consistency with the

simpler processes (180,185) can be demonstrated by running process 181,186 with `removebr` set to true.

At next-to-leading order, the calculation includes contributions from diagrams with two gluons in the initial state, $gg \rightarrow Wtb$. The p_T of the additional b quark is vetoed according to the value of the parameter `ptmin_bjet` which is specified in the input file. The contribution from these diagrams when the p_T of the b quark is above `ptmin_bjet` is zero. The values of this parameter and the factorization scale (`facscale`) set in the input file should be chosen carefully. Appropriate values for both (in the range 30-100 GeV) are discussed in the associated paper.

When one wishes to calculate observables related to the decay of the top quark, `removebr` should be false. The LO calculation proceeds as normal. At NLO, there are two options:

- `part=virt, real` or `tota` : final state radiation is included in the production stage only
- `part = todk` : radiation is included in the decay of the top quark also and the final result corresponds to the sum of real and virtual diagrams. This process can only be performed at NLO with `zerowidth = .true`. This should be set automatically. Note that these runs automatically perform an extra integration, so will take a little longer.

The contribution from radiation in the decay may be calculated separately using processes 182,187. These process numbers can be used with `part=virt,real` only. To ensure consistency, it is far simpler to use 181,186 and this is the recommended approach.

10.39 $H + \text{jet}$ production with finite top-mass effects, process 200

This process represents the production of a Higgs boson in association with a single jet based on ref. [47]. Decay modes are currently unsupported/untested. The top-quark mass is taken into account exactly for the born and real-emission parts, as well as for the singular part of the virtual corrections.

The finite part of the two-loop virtual corrections can be computed in different ways.

- In a low energy asymptotic expansion in $1/m_t^k$ up to order $k = 2, 4$ by setting `mtex` to 2 or 4 in the input file. This is recommended for transverse momenta up to $\simeq 225$ GeV.
- In a high energy expansion by setting `mtex=100` in the input file. This is recommended for transverse momenta beyond 450 GeV.
- In a rescaling approach where the finite part of the two-loop virtual amplitude in the effective field theory ($m_t = \infty$) is rescaled pointwise by

the ratio of the one-loop amplitude computed with full m_t dependence to the one-loop amplitude for $m_t = \infty$. This mode is the default mode and enabled with `mtex=0` in the input file. This is the recommended approach for the intermediate energy region and for estimating top-mass uncertainties in the transition regions between these approaches.

10.40 Di-jet production, processes 190–191

Process 190 represents di-jet production through strong interactions. It may be calculated to LO only.

Process 191 is an ancillary process that is used in the calculation of weak one-loop corrections to di-jet production. When computed at LO it gives the contribution of weak ($\mathcal{O}(\alpha^2)$) and mixed weak-strong ($\mathcal{O}(\alpha\alpha_s)$) mediated processes to di-jet production. Please refer to Ref. [16] for details.

10.41 H + jet production, processes 201–210

These processes represent the production of a Higgs boson in association with a single jet, with the subsequent decay of the Higgs to either a pair of bottom quarks (processes 201, 203, 206) or to a pair of tau's (202, 204, 207), or to a pair of W 's which decay leptonically (208), or to a pair of Z 's which decay leptonically (209), or to a pair of photons (210).

The Higgs boson couples to a pair of gluons via a loop of heavy fermions which, in the Standard Model, is accounted for almost entirely by including the effect of the top quark alone. For processes 201, 202, 206, 207, the matrix elements include the full dependence on the top quark mass. The calculation can only be performed at LO. However, the Higgs boson can either be the Standard Model one (processes 201, 202) or a pseudoscalar (206, 207). Note that the pseudoscalar case corresponds, in the heavy top limit, to the effective Lagrangian,

$$\mathcal{L} = \frac{1}{8\pi v} G_{\mu\nu}^a \tilde{G}_a^{\mu\nu} A, \quad (14)$$

where $\tilde{G}_a^{\mu\nu} = i\epsilon^{\mu\nu\alpha\beta} G_{\alpha\beta}^a$. The interaction differs from the scalar case in Eq. 12 by a factor of $3/2$ and hence the rate is increased by a factor of $(3/2)^2$.

For processes 203, 204, 208, 209, 210, the calculation is performed in the limit of infinite top quark mass, so that NLO results can be obtained. The virtual matrix elements have been implemented from refs [51] and [52]. Phenomenological results have previously been given in refs. [28],[51] and [32]. Note that the effect of radiation from the bottom quarks in process 203 is not included.

When `removebr` is true in processes 201, 203, 206, 208, 209 and 210, the Higgs boson does not decay.

10.42 Higgs production via WBF, processes 211–217

[For more details on this calculation, please refer to hep-ph/0403194]

These processes provide predictions for the production of a Higgs boson in association with two jets via weak-boson fusion (WBF). The Higgs boson subsequently decays to either a pair of bottom quarks (processes 211, 216), to a pair of tau's (212, 217), to a pair of W bosons (213), to a pair of Z bosons (214), or to a pair of photons (215).

Calculations can be performed up to NLO for processes 211–215. In addition to this, processes 216 and 217 provide the lowest order calculation of the WBF reaction which radiates an additional jet.

When `removebr` is true, the Higgs boson does not decay.

10.43 $\tau^+\tau^-$ production, process 221

This process provides predictions for the production of a tau lepton pair mediated by γ^*/Z , with subsequent leptonic decays. The calculation is available at LO only. The relevant matrix elements are adapted from the ones in ref. [36].

When `removebr` is true, the tau leptons do not decay.

10.44 $e^-e^+\nu_\mu\bar{\nu}_\mu$ -pair production via WBF, processes 222

The *weak* processes occur in $O(\alpha^6)$, whereas the *strong* processes occur in $O(\alpha^4\alpha_S^2)$. These processes can currently only be calculated at lowest order.

$$\begin{aligned} 222 \quad & f(p_1) + f(p_2) \rightarrow Z(e^-(p_3), e^+(p_4))Z(\nu_\mu(p_5), \bar{\nu}_\mu(p_6)) + f(p_7) + f(p_8)[WBF] \\ 2201 \quad & f(p_1) + f(p_2) \rightarrow Z(e^-(p_3), e^+(p_4))Z(\mu^-(p_5), \mu^+(p_6)) + f(p_7) + f(p_8)[strong] \\ 2221 \quad & f(p_1) + f(p_2) \rightarrow Z(e^-(p_3), e^+(p_4))Z(\nu_\mu(p_5), \bar{\nu}_\mu(p_6)) + f(p_7) + f(p_8)[strong] \end{aligned}$$

10.45 $\nu_e e^+ \mu^- \mu^+$ -pair production via WBF, processes 223,2231

The *weak* processes occur in $O(\alpha^6)$, whereas the *strong* processes occur in $O(\alpha^4\alpha_S^2)$. These processes can currently only be calculated at lowest order.

$$\begin{aligned} 223 \quad & f(p_1) + f(p_2) \rightarrow W^+(\nu_e(p_3), e^+(p_4))Z(\mu^-(p_5), \mu^+(p_6)) + f(p_7) + f(p_8)[weak] \\ 2231 \quad & f(p_1) + f(p_2) \rightarrow W^+(\nu_e(p_3), e^+(p_4))Z(\mu^-(p_5), \mu^+(p_6)) + f(p_7) + f(p_8)[strong] \end{aligned}$$

10.46 $e^- \bar{\nu}_e \nu_\mu \mu^+$ -pair production via WBF, processes 224,2241

The *weak* processes occur in $O(\alpha^6)$, whereas the *strong* processes occur in $O(\alpha^4\alpha_S^2)$. These processes can currently only be calculated at lowest order.

$$\begin{aligned} 224 \quad & f(p_1) + f(p_2) \rightarrow W^-(e^-(p_3), \bar{\nu}_e(p_6))W^+(\nu_\mu(p_5), \mu^+(p_4)) + f(p_7) + f(p_8)[WBF] \\ 2241 \quad & f(p_1) + f(p_2) \rightarrow W^-(e^-(p_3), \bar{\nu}_e(p_6))W^+(\nu_\mu(p_5), \mu^+(p_4)) + f(p_7) + f(p_8)[strong] \end{aligned}$$

10.47 $e^- \bar{\nu}_e \mu^- \mu^+$ -pair production via WBF, processes 225,2251

The *weak* processes occur in $O(\alpha^6)$, whereas the *strong* processes occur in $O(\alpha^4 \alpha_S^2)$. These processes can currently only be calculated at lowest order.

$$\begin{aligned} 225 \quad & f(p_1) + f(p_2) \rightarrow W^-(e^-(p_3), \bar{\nu}_e(p_4))Z(\mu^-(p_5), \mu^+(p_6))) + f(p_7) + f(p_8)[\textit{weak}] \\ 2251 \quad & f(p_1) + f(p_2) \rightarrow W^-(e^-(p_3), \bar{\nu}_e(p_4))Z(\mu^-(p_5), \mu^+(p_6))) + f(p_7) + f(p_8)[\textit{strong}] \end{aligned}$$

10.48 $e^- e^+ \bar{\nu}_e \nu_e$ -pair production via WBF, processes 226

The *weak* processes occur in $O(\alpha^6)$, whereas the *strong* processes occur in $O(\alpha^4 \alpha_S^2)$. This process can currently only be calculated at lowest order.

$$226 \quad f(p_1) + f(p_2) \rightarrow e^-(p_3) + e^+(p_4) + \nu_e(p_5) + \bar{\nu}_e(p_6) + f(p_7) + f(p_8)[\textit{WBF}]$$

10.49 $\nu_e e^+ \nu_\mu \mu^+$ -pair production via WBF, processes 228,2281

This is pure electroweak process, occurring in $O(\alpha^6)$. These processes can currently only be calculated at lowest order.

$$\begin{aligned} 228 \quad & f(p_1) + f(p_2) \rightarrow W^+(\nu_e(p_3), e^+(p_4))W^+(\nu_\mu(p_5), \mu^+(p_6)) + f(p_7) + f(p_8)[\textit{WBF}] \\ 2281 \quad & f(p_1) + f(p_2) \rightarrow W^+(\nu_e(p_3), e^+(p_4))W^+(\nu_\mu(p_5), \mu^+(p_6)) + f(p_7) + f(p_8)[\textit{strong}] \end{aligned}$$

10.50 $e^- \bar{\nu}_e \mu^- \bar{\nu}_\mu$ -pair production via WBF, processes 229,2291

This is pure electroweak process, occurring in $O(\alpha^6)$. These processes can currently only be calculated at lowest order.

$$\begin{aligned} 229 \quad & f(p_1) + f(p_2) \rightarrow W^-(e^-(p_3), \bar{\nu}_e(p_4))W^+(\mu^-(p_5), \bar{\nu}_\mu(p_6)) + f(p_7) + f(p_8)[\textit{WBF}] \\ 2291 \quad & f(p_1) + f(p_2) \rightarrow W^-(e^-(p_3), \bar{\nu}_e(p_4))W^+(\mu^-(p_5), \bar{\nu}_\mu(p_6)) + f(p_7) + f(p_8)[\textit{strong}] \end{aligned}$$

10.51 t -channel single top with an explicit b -quark, processes 231–240

[For more details on this calculation, please refer to *arXiv:0903.0005 [hep-ph]*]

These represent calculations of the t -channel single top (231) and anti-top (231) processes in a scheme with four flavours of quark in the proton, so that b -quarks are not present in the proton. The b -quark is instead explicitly included in the final state.

Processes 232 and 236 represent t -channel single top production in association with a further jet and may be calculated at LO only.

Processes 233 and 238 are the complete four-flavour scheme t -channel single top production processes. These are therefore the processes that should be used for most physics applications. When one wishes to calculate observables related to the decay of the top quark, `removebr` should be false in processes 233 and 236. The LO calculation proceeds as normal. At NLO, there are two options:

- `part=virt`, `real` or `tota` : final state radiation is included in the production stage only
- `part = todk` : radiation is included in the decay of the top quark also and the final result corresponds to the sum of real and virtual diagrams. Note that these runs automatically perform an extra integration, so will take a little longer.

Processes 234 and 239 give the extra contribution due to radiation in top decay. These processes are mainly of theoretical interest.

Processes 235 and 240 are the leading order single top processes with an extra radiated parton. These processes do not include jets produced in the decay process.

10.52 W^+W^+ +jets production, processes 251,252

These processes represent the production of two W^+ bosons in association with two (process 251) or three (process 252) jets. The lowest order at which two positively charged W bosons can be produced is with two jets. This process is only implemented for leptonic decays of the W particles. The calculation is available at LO only. The calculation and code are from ref. [42]. `removebr` is not implemented and has no effect.

10.53 $Z + Q$ production, processes 261–267

[For more details on this calculation, please refer to *hep-ph/0312024*]

These processes represent the production of a Z boson that decays into a pair of electrons, in association with a heavy quark, Q .

For processes 261, 262, 266 and 267 the initial state at lowest order is the heavy quark and a gluon and the calculation may be performed at NLO. As for $H + b$ production, the matrix elements are divided into two sub-processes at NLO. Thus the user must sum over these after performing more runs than usual. At lowest order one can proceed as normal, using `nproc=261` (for $Z + b$) or `nproc=262` (for $Z + c$). For a NLO calculation, the sequence of runs is as follows:

- Run `nproc=261` (or 262) with `part=virt` and `part=real` (or, both at the same time using `part=tota`);
- Run `nproc=266` (or 267) with `part=real`.

The sum of these yields the cross-section with one identified heavy quark in the final state when `inclusive` is set to `.false.`. To calculate the rate for at least one heavy quark, `inclusive` should be `.true.`

For processes 263 and 264, the calculation uses the matrix elements for the production of a Z and a heavy quark pair and demands that one of the heavy quarks is not observed. It may either lie outside the range of p_T and η required

for a jet, or both quarks may be contained in the same jet. Due to the extra complexity (the calculation must retain the full dependence on the heavy quark mass), this can only be computed at LO.

When `removebr` is true, the Z boson does not decay.

10.54 $H + 2$ jet production, processes 270–274

These processes represent the production of a Standard Model Higgs boson in association with two jets. The Higgs boson subsequently decays to either a pair of photons (`nproc=270`), a bottom quark pair (`nproc=271`), a pair of tau's (`nproc=272`), a pair of leptonically decaying W 's (`nproc=273`) or a pair of leptonically decaying Z 's (`nproc=274`).

The matrix elements are included in the infinite top mass limit using the effective Lagrangian approach.

When `removebr` is true, the Higgs boson does not decay.

10.55 $H + 3$ jet production, processes 275–278

These processes represent the production of a Standard Model Higgs boson in association with three jets. The Higgs boson subsequently decays to either a bottom quark pair (`nproc=275`), or a pair of tau's (`nproc=276`) or a pair of W 's that decay leptonically into a single generation of leptons (`nproc=278`) or a pair of Z 's that decay leptonically into a single generation of leptons (`nproc=279`). The matrix elements are included in the infinite top mass limit using an effective Lagrangian approach. These calculations can be performed at LO only.

When `removebr` is true, the Higgs boson does not decay.

10.56 Direct γ production, processes 280–282

These processes represent the production a real photon. Since this process includes a real photon, the cross section diverges when the photon is very soft or in the direction of the beam. Thus in order to produce sensible results, the input file must supply values for both `ptmin_photon` and `etamax_photon`. This will ensure that the cross section is well-defined.

The calculation of process 282 is only available at leading order.

10.57 Direct $\gamma +$ heavy flavour production, processes 283–284

These processes represent the production a real photon with a b quark or a charm quark. Since this process includes a real photon, the cross section diverges when the photon is very soft or in the direction of the beam. Thus in order to produce sensible results, the input file must supply values for both `ptmin_photon` and `etamax_photon`. This will ensure that the cross section is well-defined.

The calculation of process 283–284 is only available at leading order.

10.58 $\gamma\gamma$ production, processes 285-286

Process 285 represents the production of a pair of real photons. Since this process includes two real photons, the cross section diverges when one of the photons is very soft or in the direction of the beam. Thus in order to produce sensible results, the input file must supply values for both `ptmin_photon` and `etamax_photon`. This will ensure that the cross section is well-defined.

The calculation of process 285 may be performed at NLO using either the Frixione algorithm [29] or standard cone isolation. This process also includes the one-loop gluon-gluon contribution as given in ref. [8]. The production of a photon via parton fragmentation is included at NLO and can be run separately by using the `frag` option in `part`. This option includes the contributions from the integrated photon dipole subtraction terms and the LO QCD matrix element multiplied by the fragmentation function.

The phase space cuts for the final state photons are defined in `input.DAT`, for multiple photon processes such as 285 - 287 the p_T 's of the individual photons (hardest, second hardest and third hardest or softer) can be controlled independently. The remaining cuts on $R_{\gamma j}$, η_γ etc. are applied universally to all photons. Users wishing to alter this feature should edit the file `photon.cuts.f` in the directory `src/User`.

Process 286, corresponding to $\gamma\gamma$ +jet production, can be computed at leading order only.

10.59 $\gamma\gamma\gamma$ production, process 287

Process 287 represents the production of three real photons. The cross section diverges when one of the photons is very soft or in the direction of the beam. Thus in order to produce sensible results, the input file must supply values for both `ptmin_photon` and `etamax_photon`. This will ensure that the cross section is well-defined.

The calculation of process 285 may be performed at NLO using either the Frixione algorithm [29] or standard cone isolation. The production of a photon via parton fragmentation is included at NLO and can be run separately by using the `frag` option in `part`. This option includes the contributions from the integrated photon dipole subtraction terms and the LO QCD matrix element multiplied by the fragmentation function. The phase space cuts for the final state photons are defined in `input.DAT`, for multiple photon processes such as 285 - 287 the p_T 's of the individual photons (hardest, next-to hardest and softest) can be controlled independently. The remaining cut on $R_{\gamma j}$, η_γ etc. are applied universally to all photons. Users wishing to alter this feature should edit the file `photon.cuts.f` in the directory `src/User`.

10.60 $\gamma\gamma\gamma$ production, process 289

Process 289 represents the production of four real photons. The cross section diverges when one of the photons is very soft or in the direction of the beam. Thus in order to produce sensible results, the input file must supply values for both `ptmin_photon` and `etamax_photon`. This will ensure that the cross section is well-defined.

The calculation of process 289 may be performed at NLO using either the Frixione algorithm [29] or standard cone isolation. The production of a photon via parton fragmentation is included at NLO and can be run separately by using the `frag` option in `part`. This option includes the contributions from the integrated photon dipole subtraction terms and the LO QCD matrix element multiplied by the fragmentation function. The phase space cuts for the final state photons are defined in `input.DAT`, for multiple photon processes such as 285 - 289 the p_T 's of the individual photons (hardest, next-to-hardest and softest) can be controlled independently. The remaining cut on $R_{\gamma j}$, η_γ etc. are applied universally to all photons. Users wishing to alter this feature should edit the file `photon_cuts.f` in the directory `src/User`.

Note that for this process the second softest and softest photons are forced to have equal minimum p_T , defined by the `[ptmin_photon(3rd)]` variable in the input file.

10.61 $W\gamma$ production, processes 290-297

These processes represent the production of a W boson which subsequently decays leptonically, in association with a real photon. Since this process includes a real photon, the cross section diverges when the photon is very soft or in the direction of the beam. Thus in order to produce sensible results, the input file must supply values for both `ptmin_photon` and `etamax_photon`. Moreover, when the parameters `zerowidth` and `removebr` are set to `.false`, the decay $W \rightarrow \ell\nu$ will include photon radiation from the lepton, so that a non-zero `R(photon,lept)_min` should also be supplied. This will ensure that the cross section is well-defined. Virtual amplitudes are taken from ref. [21].

The calculation of processes 290 and 295 may be performed at NLO using the Frixione algorithm [29] or standard isolation.

For processes 290 and 295 the role of `mtrans34cut` changes to become a cut on the transverse mass on the M_{345} system, i.e. the photon is included with the leptons in the cut.

10.61.1 Anomalous $WW\gamma$ couplings

Processes 290-297 may also be computed including the effect of anomalous $WW\gamma$ couplings, making use of the amplitudes calculated in Ref. [19]. Including only dimension 6 operators or less and demanding gauge, C and CP invariance

gives the general form of the anomalous vertex [19],

$$\Gamma_{WW\gamma}^{\alpha\beta\mu}(q, \bar{q}, p) = \bar{q}^\alpha g^{\beta\mu} \left(2 + \Delta\kappa^\gamma + \lambda^\gamma \frac{q^2}{M_W^2} \right) - q^\beta g^{\alpha\mu} \left(2 + \Delta\kappa^\gamma + \lambda^\gamma \frac{\bar{q}^2}{M_W^2} \right) + (\bar{q}^\mu - q^\mu) \left[-g^{\alpha\beta} \left(1 + \frac{1}{2} p^2 \frac{\lambda^\gamma}{M_W^2} \right) + \frac{\lambda^\gamma}{M_W^2} p^\alpha p^\beta \right] \quad (15)$$

where the overall coupling has been chosen to be $-|e|$. The parameters that specify the anomalous couplings, $\Delta\kappa^\gamma$ and λ^γ , are specified in the input file as already discussed in Section 10.22. If the input file contains a negative value for the form-factor scale Λ then no suppression factors are applied to the anomalous couplings. Otherwise, the couplings are included in MCFM only after suppression by dipole form factors,

$$\Delta\kappa^\gamma \rightarrow \frac{\Delta\kappa_1^\gamma}{(1 + \hat{s}/\Lambda^2)^2}, \quad \lambda^\gamma \rightarrow \frac{\Delta\lambda^\gamma}{(1 + \hat{s}/\Lambda^2)^2},$$

where \hat{s} is the $W\gamma$ pair invariant mass.

The Standard Model cross section is obtained by setting $\Delta\kappa^\gamma = \lambda^\gamma = 0$.

10.62 $Z\gamma$, production, processes 300, 305

Processes 300 and 305 represent the production of a Z boson (or virtual photon for process 300) in association with a real photon based on ref. [15]. The Z/γ^* subsequently decays into either an e^+e^- pair (`nproc=300`) or neutrinos (`nproc=305`). Since these processes include a real photon, the cross section diverges when the photon is very soft or in the direction of the beam. Thus in order to produce sensible results, the input file must supply values for both `ptmin_photon` and `etamax_photon`. Moreover, when the parameters `zerowidth` and `removebr` are set to `.false.` the decay $Z \rightarrow e^-e^+$ (`nproc=300`) will include photon radiation from both leptons, so that a non-zero `R(photon,lept)_min` should also be supplied. This will ensure that the cross section is well-defined. The calculation of processes 300 may be performed at NNLO using the Frixione algorithm [29] or standard isolation.

For the process 300 the role of `mtrans34cut` changes to become a cut on the invariant mass on the M_{345} system, i.e. the photon is included with the leptons in the cut.

10.62.1 Anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings

Processes 300-305 may also be computed including the effect of anomalous couplings between Z bosons and photons. Note that, at present, the effect of anomalous couplings is not included in the gluon-gluon initiated contributions.

The anomalous $Z\gamma Z$ vertex (not present at all in the Standard Model), considering operators up to dimension 8, is given by [19],

$$\Gamma_{Z\gamma Z}^{\alpha\beta\mu}(q_1, q_2, p) = \frac{i(p^2 - q_1^2)}{M_Z^2} \left(h_1^Z (q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}) \right. \\ \left. + \frac{h_2^Z}{M_Z^2} p^\alpha (p \cdot q_2 g^{\mu\beta} - q_2^\mu p^\beta) - h_3^Z \varepsilon^{\mu\alpha\beta\nu} q_{2\nu} - \frac{h_4^Z}{M_Z^2} \varepsilon^{\mu\beta\nu\sigma} p^\alpha p_\nu q_{2\sigma} \right) \quad (16)$$

where the overall coupling has been chosen to be $|e|$ (and $\epsilon^{0123} = +1$). The non-standard $Z_\alpha(q_1)\gamma_\beta(q_2)\gamma_\mu(p)$ momentum-space vertex can be obtained from this equation by setting $q_1^2 \rightarrow 0$ and replacing $h_i^Z \rightarrow h_i^\gamma$. The parameters that specify the anomalous couplings, h_i^Z and h_i^γ (for $i = 1 \dots 4$), are specified in the input file as, e.g. `h1(Z)` and `h1(gamma)`. If the input file contains a negative value for the form-factor scale Λ then no suppression factors are applied to these anomalous couplings. Otherwise, the couplings are included in MCFM only after suppression by dipole form factors,

$$h_{1,3}^{Z/\gamma} \rightarrow \frac{h_{1,3}^{Z/\gamma}}{(1 + \hat{s}/\Lambda^2)^3}, \quad h_{2,4}^{Z/\gamma} \rightarrow \frac{h_{2,4}^{Z/\gamma}}{(1 + \hat{s}/\Lambda^2)^4},$$

where \hat{s} is the $Z\gamma$ pair invariant mass. Note that these form factors are slightly different from those discussed in Sections 10.22 and 10.61. The form factors can be modified in `src/Need/set_anomcoup.f`.

The Standard Model cross section is obtained by setting $h_i^Z = h_i^\gamma = 0$ for $i = 1 \dots 4$.

10.63 $Z\gamma\gamma$ production processes, 301, 306

Processes 301 and 306 represent the production of a Z boson (or virtual photon for process 301) in association with two photons. The Z/γ^* subsequently decays into either an e^+e^- pair (`nproc=301`) or neutrinos (`nproc=306`). Since these processes include real photons, the cross section diverges when either of the photons is very soft or in the direction of the beam. Thus in order to produce sensible results, the input file must supply values for both `ptmin_photon` and `etamax_photon`. Moreover, when the parameters `zerowidth` and `removebr` are set to `.false.` the decay $Z \rightarrow e^-e^+$ (`nproc=301`) will include photon radiation from both leptons, so that a non-zero `R(photon,lept)_min` should also be supplied. This will ensure that the cross section is well-defined. Anomalous couplings are not currently implemented for these processes.

10.64 $Z\gamma j$, production, processes 302, 307

Processes 302 and 307 represent the production of a Z boson (or virtual photon) in association with a real photon and at least one jet. The Z/γ^* subsequently decays into either an e^+e^- pair (`nproc=302`) or neutrinos (`nproc=307`). Since

these processes include a real photon and a jet, the cross section diverges when the photon or jet is very soft or in the direction of the beam. Thus in order to produce sensible results, the input file must supply values for both `ptmin_photon` and `etamax_photon`, and `ptjet_min` and `etajet_max`. Moreover, when the parameters `zerowidth` and `removebr` are set to `.false`. the decay $Z \rightarrow e^-e^+$ (`nproc=302`) will include photon radiation from both leptons, so that a non-zero `R(photon,lept)_min` should also be supplied. This will ensure that the cross section is well-defined. The calculation of processes 302 and 307 may be performed at NLO using the Frixione algorithm [29] or standard isolation. Anomalous couplings are not currently implemented for these processes.

10.65 $Z\gamma j$ and $Z\gamma jj$, 303, 304, 308 and 309

These processes are available at LO only. The Z/γ^* subsequently decays into either an e^+e^- pair (`nproc=303,304`) or neutrinos (`nproc=308,309`). Since these processes include a real photon and a jet, the cross section diverges when a photon or a jet is very soft or in the direction of the beam. Thus in order to produce sensible results, the input file must supply values for both `ptmin_photon` and `etamax_photon`, and `ptjet_min` and `etajet_max`. Moreover, when the parameters `zerowidth` and `removebr` are set to `.false`. the decay $Z \rightarrow e^-e^+$ (`nproc=303, 304`) will include photon radiation from both leptons, so that a non-zero `R(photon,lept)_min` should also be supplied. This will ensure that the cross section is well-defined. Anomalous couplings are not currently implemented for these processes.

10.66 $W + Q + \text{jet}$ production processes 311–326

These processes represent the production of a W boson that decays leptonically, in association with a heavy quark, Q and an additional light jet. In processes 311 and 316 Q is a bottom quark, whilst processes 321 and 326 involve a charm quark. In these processes the quark Q occurs as parton PDF in the initial state. The initial state in these processes consists of a light quark and a heavy quark, with the light quark radiating the W boson. These calculations may be performed at LO only.

When `removebr` is true, the W boson does not decay.

10.67 $W + c + \text{jet}$ production, processes 331, 336

These processes represent the production of a W boson that decays leptonically, in association with a charm quark and an additional light jet.

In contrast to processes 321 and 326 described above, the initial state in this case consists of two light quarks, one of which is a strange quark which radiates the W boson. The calculation may be performed at LO only.

When `removebr` is true, the W boson does not decay.

10.68 $Z + Q$ +jet production, processes 341–357

[For more details on this calculation, please refer to *hep-ph/0510362*]

These processes represent the production of a Z boson that decays into a pair of electrons, in association with a heavy quark, Q and an untagged jet.

For processes 341 and 351 the initial state at lowest order is the heavy quark and a gluon and the calculation may be performed at NLO. Thus in these processes the quark Q occurs as parton PDF in the initial state. As for $H + b$ and $Z + Q$ production, the matrix elements are divided into two sub-processes at NLO. Thus the user must sum over these after performing more runs than usual. At lowest order one can proceed as normal, using `nproc=341` (for Zbj) or `nproc=351` (for Zcj). For a NLO calculation, the sequence of runs is as follows:

- Run `nproc=341` (or 351) with `part=virt` and `part=real` (or, both at the same time using `part=tota`);
- Run `nproc=342` (or 352) with `part=real`.

The sum of these yields the cross-section with one identified heavy quark and one untagged jet in the final state when `inclusive` is set to `.false.`. To calculate the rate for at least one heavy quark and one jet (the remaining jet may be a heavy quark, or untagged), `inclusive` should be `.true.`.

Processes 346, 347 and 356, 357 are the lowest order processes that enter the above calculation in the real contribution. They can be computed only at LO.

When `removebr` is true, the Z boson does not decay.

10.69 $c\bar{s} \rightarrow W^+$, processes 361–363

These processes represent the production of a W^+ from a charm and anti-strange quark at LO. The W^+ boson decays into a neutrino and a positron.

The NLO corrections to this LO process include a contribution of the form, $g\bar{s} \rightarrow W^+\bar{c}$. For process 361 this contribution is calculated in the approximation $m_c = 0$ at NLO. In order to perform the NLO calculation for a non-zero value of m_c , one must instead sum the results of processes 362 and 363 for `part=tota`.

10.70 $W\gamma\gamma$ production, processes 370-371

These processes represent the production of a W boson which subsequently decays leptonically, in association with two real photons. Since this process includes real photons, the cross section diverges when the photon is very soft or in the direction of the beam. Thus in order to produce sensible results, the input file must supply values for both `ptmin_photon` and `etamax_photon`. Moreover, when the parameters `zerowidth` and `removebr` are set to `.false.` the decay

Process (W^+/W^-)	<code>inclusive=.false.</code>	<code>inclusive=.true.</code>
401/406	(b) or (\bar{b})	$+$ (b, \bar{b}) or (b, j) or (\bar{b}, j)
402/407	(B)	$+$ (B, j)
403/408	(b, \bar{b})	(no extra configurations)

Table 7: The different final states allowed in the calculation of processes 401–408. A jet containing both b and \bar{b} quarks is denoted by B and a light (quark or gluon) jet by j . The inclusive (right-hand) column also allows the final states in the exclusive (middle) column.

$W \rightarrow \ell\nu$ will include photon radiation from the lepton, so that a non-zero `R(photon,lept)_min` should also be supplied. This will ensure that the cross section is well-defined.

These processes may be computed at leading order only.

10.71 $W+Q$ production in the 4FNS, processes 401–408

These processes represent the production of a W boson and one or more jets, at least one of which is a b -quark, calculated in the 4-flavour number scheme (4FNS). This implies that contributions that explicitly contain a b -quark in the initial state are not included. These processes all use the same matrix elements as processes 20 and 25 (see section 10.6), but make different cuts on the final state. The final state is specified by the process number and the value of the flag `inclusive`, as shown in Table 7. An additional flag is hard-coded into the file `src/User/filterWbbmas.f` to control the inclusion of the 3-jet configuration, (b, \bar{b}, j) when `inclusive` is set to `.true.`. By default this is included, `veto3jets = .false.`. If this flag is set to `.true.` then the (b, \bar{b}, j) contribution is not included in processes 401, 402, 406, 407.

As usual, jets may be unobserved as a result of them falling outside the p_T and rapidity ranges specified in the input file. In addition, the number of jets may be different from the number of partons in the matrix element calculation as a result of merging in the jet algorithm.

10.72 $W+Q$ production in the 5FNS, processes 411, 416

These processes represent production of a W boson in association with a b -jet, computed in the 5-flavour number scheme, i.e. a b -quark is present in the initial state. The lowest order processes are the same as in processes 311, 316. The results at NLO are not physical cross sections since part of the corrections are not included in order to avoid double-counting with the 4FNS process (processes 401 and 406). To obtain combined 4FNS+5FNS predictions, the user should select process 421 (W^+) or 426 (W^-).

10.73 $W+Q$ production in the combined 4FNS/5FNS, processes 421, 426

These processes represent the production of a W boson and one or more jets, at least one of which is a b -quark, calculated by combining the 4- and 5-flavour results of processes 401, 411 (for 421) and 406, 416 (for 426). The selection of the final state is the same as for processes 401 and 406, as described in Section 10.71. The procedure for combining the two calculations is described in refs. [11, 17].

10.74 $W + b\bar{b} + \text{jet}$ production, processes 431,436

These processes represent the production of a W boson which subsequently decays leptonically, in association with a $b\bar{b}$ pair and an additional jet. The effect of the bottom quark mass is included (c.f. the massless approximation used in processes 24, 29) and the calculation may be performed at LO only.

When `removebr` is true, the W boson does not decay.

10.75 $W + t\bar{t}$ processes 500–516

These processes represent the production of a W^\pm boson which subsequently decays leptonically, in association with a $t\bar{t}$ pair. In all except processes 500 and 510 the decays of the top and anti-top quark are included. Processes 501, 502 and 511, 512 refer to the semileptonic decay of the top and antitop quarks, with the latter process in each pair giving the radiation in the decay of the top and antitop. Process 503 (513) refers to the semileptonic decay of the top (antitop) and the hadronic decay of the antitop (top). Processes 506(516) gives the semileptonic decay of the antitop(top) and the hadronic decay of the top(antitop). Processes 506(516) do not give same sign lepton events, so they may be of less phenomenological importance. For this reason we have not yet included radiation in the decay for these processes.

For processes 503, 506, 513 and 516 the default behaviour is that the hadronic decay products are clustered into jets using the supplied jet algorithm parameters, but no cut is applied on the number of jets. This behaviour can be altered by changing the value of the variable `notag` in the file `src/User/setnotag.f`.

The top quarks are always produced on-shell, which is a necessity for a gauge invariant result from this limited set of diagrams, but all spin correlations are included. Switching `zerowidth` from `.true.` to `.false.` only affects the W bosons (both the directly produced one and from the top quark decay). Processes 501 and 511 may be run at NLO with the option `todk`, including radiation in the decay of the top quark, see section 10.31.

10.76 $Zt\bar{t}$ production, processes 529–533

These processes represent the production of a Z boson in association with a pair of top quarks. For process 529, neither the top quarks nor the Z -boson decays. In processes 530–533, the top quarks are always produced on-shell, which is a necessity for a gauge invariant result from this limited set of diagrams. Switching `zerowidth` from `.true.` to `.false.` only affects the Z and the W bosons from the top quark decay. In process 530 the Z boson decays into an electron pair, whilst in 531 the decay is into a massless bottom quark pair. In process 532–533 the Z boson decays into an electron pair, whilst on or other of the top quark or top anti-quark decays hadronically. The calculations can be performed at LO only.

For processes 532 and 533 the default behaviour is that the hadronic decay products are clustered into jets using the supplied jet algorithm parameters, but no cut is applied on the number of jets. This behaviour can be altered by changing the value of the variable `notag` in the file `src/User/setnotag.f`.

When `removebr` is true in process 530, the top quarks and the Z boson do not decay.

10.77 Ht and $H\bar{t}$ production, processes 540–557

[For more details on this calculation, please refer to *arXiv:1302.3856*]

These processes describe the production of a single top quark (540, 544, 550, 554) or antiquark (541, 547, 551, 557) by W exchange in the t -channel, in association with a Higgs boson. These processes can be performed at NLO. For processes 540, 541, 550, 551, the top quark does not decay, but the Higgs boson decays to $b\bar{b}$, (540, 541), or to $\gamma\gamma$, (550, 551). Processes 544, 547 and 554, 557 include the decay of the top quark and antiquark in the approximation in which the top quark is taken to be on shell allowing a clean separation between production and decay.

It is possible to study the effects of anomalous couplings of the Higgs boson to the top quark and W bosons. These are parametrized by $c_{t\bar{t}H} = g_{t\bar{t}H}/g_{t\bar{t}H}^{SM}$ and $c_{WWH} = g_{WWH}/g_{WWH}^{SM}$ respectively, so that $c_{t\bar{t}H} = c_{WWH} = 1$ in the SM. Different couplings may be chosen by modifying the variables `cttH` and `cWWH` in `src/Need/reader_input.f` and recompiling.

10.78 Zt and $Z\bar{t}$ production, processes 560–569

[For more details on this calculation, please refer to *arXiv:1302.3856*]

These processes describe the production of a single top quark (or antiquark) by W exchange in the t -channel, in association with a Z boson. Processes 560, 561, 564, 567 can be performed at NLO. Processes 560–563 are for stable top quarks, whereas processes 564–569 include the decay of the top quark and antiquark in

the approximation in which the top quark is taken to be on shell allowing a clean separation between production and decay.

For processes 564 and 567 the default behaviour is that the hadronic decay products are clustered into jets using the supplied jet algorithm parameters, but no cut is applied on the number of jets. This behaviour can be altered by changing the value of the variable `notag` in the file `src/User/setnotag.f`.

10.79 HH production, processes 601–602

These processes represent the production of a pair of Higgs bosons. The production proceeds through gluon-fusion one-loop diagrams involving loops of top quarks. The formulae implemented in the code are taken from ref. [33], where the two Higgs bosons are treated as being on-shell. To enforce this condition, the code sets `zerowidth` to `true`, overriding the value set in the input file. The calculation can be performed at LO only, (i.e. one-loop order only). Two decays of the Higgs bosons are currently foreseen, although other decays can easily be implemented. In process 601, one Higgs boson decays to a pair of b -quarks, and the other decays to a pair of τ 's. In process 602, one Higgs boson decays to a pair of b -quarks, and the other decays to a pair of photons.

10.80 $Ht\bar{t}$ production, processes 640–660

These processes represent the production of a Higgs boson in association with a pair of top quarks. The calculation can be performed at LO only.

For process 640, neither the top quarks nor the Higgs boson decays. In processes 641–647, the top quarks are always produced on-shell, which is a necessity for a gauge invariant result from this limited set of diagrams. Switching `zerowidth` from `.true.` to `.false.` only affects the Higgs and the W bosons from the top quark decay. In process 641 both the top quarks decay leptonically and the Higgs boson decays into a pair of bottom quarks. Consistency with the simpler process (640) can be demonstrated by running process 641 with `removebr` set to `true`. In process 644 the top quark decays leptonically and the anti-top quark decays hadronically and the Higgs boson decays into a pair of bottom quarks. In process 647 the anti-top quark decays leptonically and the top quark decays hadronically and the Higgs boson decays into a pair of bottom quarks.

Processes 651–657 correspond to processes 641–647 but with the Higgs decaying to two photons. Processes 661–667 correspond to processes 641–647 but with the Higgs decaying to two W -bosons which subsequently decay leptonically.

10.81 Dark Matter Processes Mono-jet and Mono-photon 800-848

[For more details on this calculation, please refer to *arXiv:1211.6390*]

This section provides an overview of the Dark Matter (DM) processes available in MCFM . Since these processes are quite different in the range of possible input parameters (reflecting the range of potential BSM operators) the majority of the new features are controlled by the file `dm_parameters.DAT` located in the `Bin` directory. We begin this section by describing the inputs in this file. Note that these processes are still controlled, as usual by `input.DAT` which is responsible for selecting the process, order in perturbation theory, PDFs and phase space cuts etc. The new file controls only the new BSM parameters in the code.

- `[dm mass]` This parameter sets the mass of the dark matter particle m_χ .
- `[Lambda]` Controls the mass scale associated with the suppression of the higher dimensional operator in the effective theory approach. Note that each operator has a well defined scaling with respect to Lambda, so cross sections and distributions obtained with one particular value can be readily extended to determine those with different Λ .
- `[effective theory]` Is a logical variable which controls whether or not the effective field theory is used in the calculation of the DM process. If this value is set to `.false.` then one must specify the mass of the light mediator and its width (see below for more details).
- `[Yukawa Scalar couplings]` Is a logical variable which determines if the scalar and pseudo scalar operators scale with the factor m_q/Λ (`.true.`) or 1 (`.false.`).
- `[Left handed DM couplings]` and `[Right handed DM couplings]` These variables determine the coupling of the various flavours of quarks to the DM operators. The default value is 1. Note that the code uses the fact that vector operators scale as $(L + R)$ and axial operators scale as $(L - R)$ in constructing cross sections. Therefore you should be careful if modifying these parameters. For the axial and pseudo scalar operators the code will set the right-handed couplings to be the negative of the left handed input couplings (if this is not already the case from the setup) and inform the user it has done so. The most likely reason to want to change these values is to inspect individual flavour operators separately, i.e. to investigate an operator which only couples to up quarks one would set all couplings to 0d0 apart from `[up type]` which would be left as 1d0.
- `[mediator mass]` If `[effective theory]` is set to `.false.` this variable controls the mass of the mediating particle.
- `[mediator width]` If `[effective theory]` is set to `.false.` this variable controls the width of the mediating particle
- `[g_x]` If `[effective theory]` is set to `.false.` this variable controls the coupling of the mediating particle to the DM.
- `[g_q]` If `[effective theory]` is set to `.false.` this variable controls the coupling of the mediating particle to the quarks.

We now discuss some details of the specific DM process.

- Processes 800 and 820 produce the mono-jet or mono-photon signature through the following vector operator,

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}, \quad (17)$$

These processes are available at NLO and include the usual treatment of photons. See for instance the $V\gamma$ processes (~ 300) in this manual for more details on photon setup in `MCFM`. As discussed above the code will calculate left and right-handed helicity amplitudes and build the vector operators from $(L + R)$. Therefore you should ensure that the Left and right-handed couplings are equal in `dm_parameters.DAT`. Processes 840 and 845 represent the production of DM plus two jets or DM plus one jet and one photon and are available at LO.

- Processes 801 and 821 produce the mono-jet or mono-photon signature through the following axial-vector operator,

$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5q)}{\Lambda^2}, \quad (18)$$

These processes are available at NLO and include the usual treatment of photons. See for instance the $V\gamma$ processes (~ 300) in this manual for more details on photon setup in `MCFM`. As discussed above the code will calculate left and right-handed helicity amplitudes and build the axial vector operators from $(L - R)$. By default the code will enforce the right handed couplings to equal to the negative of the left handed couplings, if this is not already the case in `dm_parameters.DAT`. Therefore the user does not have to change this file when switching between vector and axial vector operators. Processes 841 and 846 represent the production of DM plus two jets or DM plus one jet and one photon and are available at LO.

- Processes 802 and 822 produce the mono-jet or mono-photon signature through the following scalar operator,

$$\mathcal{O}_S = \frac{\Delta(\bar{\chi}\chi)(\bar{q}q)}{\Lambda^2}, \quad (19)$$

These processes are available at NLO and include the usual treatment of photons. See for instance the $V\gamma$ processes (~ 300) in this manual for more details on photon setup in `MCFM`. As discussed above the code will calculate left and right-handed helicity amplitudes and build the vector operators from $(L + R)$. Therefore you should ensure that the Left and right-handed couplings are equal in `dm_parameters.DAT`. For these processes Δ is fixed from the value of `[Yukawa Scalar Couplings]` if this is `.true.` then $\Delta = m_q/\Lambda$ else $\Delta = 1$.

Processes 842 and 847 represent the production of DM plus two jets or DM plus one jet and one photon and are available at LO.

- Processes 803 and 823 produce the mono-jet or mono-photon signature through the following pseudo-scalar operator,

$$\mathcal{O}_{PS} = \frac{m_q(\bar{\chi}\gamma_5\chi)(\bar{q}\gamma_5q)}{\Lambda^3}. \quad (20)$$

These processes are available at NLO and include the usual treatment of photons. See for instance the $V\gamma$ processes (~ 300) in this manual for more details on photon setup in MCFM. As discussed above the code will calculate left and right-handed helicity amplitudes and build the pseudo scalar operators from $(L - R)$. By default the code will enforce the right handed couplings to equal to the negative of the left handed couplings, if this is not already the case in `dm_parameters.DAT`. Therefore the user does not have to change this file when switching between scalar and pseudo scalar operators. Processes 841 and 846 represent the production of DM plus two jets or DM plus one jet and one photon and are available at LO. For these processes Δ is fixed from the value of `[Yukawa Scalar Couplings]` if this is `.true.` then $\Delta = m_q/\Lambda$ else $\Delta = 1$.

Processes 843 and 848 represent the production of DM plus two jets or DM plus one jet and one photon and are available at LO.

- Process 804 produces the mono-jet signature through the following gluon induced operator,

$$\mathcal{O}_g = \alpha_s \frac{(\chi\bar{\chi})(G_a^{\mu\nu}G_{a,\mu\nu})}{\Lambda^3}, \quad (21)$$

This process is available at NLO. Process 844 represents the production of DM plus two jets and is available at LO. Since this operator is higher dimensional, extensions to a theory in which there is a light mediator requires the definition of two new scales (one for the EFT in the loop defining the operator). In this version we therefore do not consider in a theory with a light mediator.

- Process 805 is a separate case of the scalar operator for top quarks

$$\mathcal{O}_S^{m_t} = \frac{m_t(\bar{\chi}\chi)(\bar{q}q)}{\Lambda^3}, \quad (22)$$

This process is available at LO and proceeds through a gluon loop.

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The routine XLUDecomp is taken from looptools and is adapted from Michael Rauch.

A MCFM references

As general references for NLO computations with MCFM, please use:

- J. M. Campbell and R. K. Ellis,
“*An update on vector boson pair production at hadron colliders,*”
Phys. Rev. D **60**, 113006 (1999) [arXiv:hep-ph/9905386].
- J. M. Campbell, R. K. Ellis and C. Williams,
“*Vector boson pair production at the LHC,*”
JHEP **1107**, 018 (2011) [arXiv:1105.0020 [hep-ph]].
- J. M. Campbell, R. K. Ellis and W. Giele,
“*A Multi-Threaded Version of MCFM,*”
EPJ **C75**, 246 (2015) [arXiv:1503.06182 [hep-ph]].

When using MCFM 8.0, or later versions, for NNLO calculations of color-singlet processes please refer to:

- R. Boughezal, J. M. Campbell, R. K. Ellis,
C. Focke, W. Giele, X. Liu, F. Petriello and C. Williams,
“*Color singlet production at NNLO in MCFM,*” arXiv:1605.08011.

For calculations of electroweak corrections please refer to:

- J. M. Campbell, D. Wackerroth and J. Zhou,
“*A Study of Weak Corrections to Drell-Yan, Top-quark pair and Di-jet Production at High Energies with MCFM,*” arXiv:1608.03356.

Additional references to the program may be used depending on the process under study. The relevant papers are:

- J. M. Campbell and R. K. Ellis,
“*Radiative corrections to $Z b$ anti- b production,*”
Phys. Rev. D **62**, 114012 (2000) [arXiv:hep-ph/0006304].
- J. Campbell and R. K. Ellis,
“*Next-to-leading order corrections to $W + 2jet$ and $Z + 2jet$ production at hadron colliders,*”
Phys. Rev. D **65**, 113007 (2002) [arXiv:hep-ph/0202176].
- J. Campbell, R. K. Ellis, F. Maltoni and S. Willenbrock,
“*Higgs boson production in association with a single bottom quark,*”
Phys. Rev. D **67**, 095002 (2003) [arXiv:hep-ph/0204093].
- J. Campbell, R. K. Ellis and D. L. Rainwater,
“*Next-to-leading order QCD predictions for $W + 2jet$ and $Z + 2jet$ production*”

- at the CERN LHC,”
 Phys. Rev. D **68**, 094021 (2003) [arXiv:hep-ph/0308195].
- J. Campbell, R. K. Ellis, F. Maltoni and S. Willenbrock,
 “Associated production of a Z boson and a single heavy-quark jet,”
 Phys. Rev. D **69**, 074021 (2004) [arXiv:hep-ph/0312024].
 - E. L. Berger and J. Campbell,
 “Higgs boson production in weak boson fusion at next-to-leading order,”
 Phys. Rev. D **70**, 073011 (2004) [arXiv:hep-ph/0403194].
 - J. Campbell, R. K. Ellis and F. Tramontano,
 “Single top production and decay at next-to-leading order,”
 Phys. Rev. D **70**, 094012 (2004) [arXiv:hep-ph/0408158].
 - J. Campbell and F. Tramontano,
 “Next-to-leading order corrections to Wt production and decay,”
 Nucl. Phys. B **726**, 109 (2005) [arXiv:hep-ph/0506289].
 - J. Campbell, R.K. Ellis, F. Maltoni and S. Willenbrock,
 “Production of a Z boson and two jets with one heavy quark tag,”
 Phys. Rev. D **73**, 054007 (2006) [arXiv:hep-ph/0510362].
 - J. M. Campbell, R. Frederix, F. Maltoni and F. Tramontano,
 “t-channel single top production at hadron colliders,”
 Phys. Rev. Lett. **102** (2009) 182003, [arXiv:0903.0005 [hep-ph]].
 - J. M. Campbell, R. K. Ellis and G. Zanderighi,
 “Next-to-leading order Higgs + 2 jet production via gluon fusion,”
 JHEP **0610**, 028 (2006) [arXiv:hep-ph/0608194].
 - J. Campbell, R.K. Ellis, F. Maltoni and S. Willenbrock,
 “Production of a W boson and two jets with one b-quark tag,”
 Phys. Rev. D **75**, 054015 (2007) [arXiv:hep-ph/0611348].
 - J. M. Campbell, R. K. Ellis, F. Febres Cordero, F. Maltoni, L. Reina,
 D. Wackerroth and S. Willenbrock,
 “Associated Production of a W Boson and One b Jet,”
 Phys. Rev. D **79**, 034023 (2009) [arXiv:0809.3003 [hep-ph]].
 - J. M. Campbell, R. K. Ellis and C. Williams,
 “Hadronic production of a Higgs boson and two jets at next-to-leading order,”
 Phys. Rev. D **81** 074023 (2010), [arXiv:1001.4495 [hep-ph]].
 - S. Badger, J. M. Campbell and R. K. Ellis,
 “QCD corrections to the hadronic production of a heavy quark pair and a
 W-boson including decay correlations,”
 JHEP **1103**, 027 (2011) [arXiv:1011.6647 [hep-ph]].
 - F. Caola, J. M. Campbell, F. Febres Cordero, L. Reina and D. Wackerroth,
 “NLO QCD predictions for W + 1 jet and W + 2 jet production with at least

one b jet at the 7 TeV LHC,
arXiv:1107.3714 [hep-ph].

- J. M. Campbell, R. K. Ellis and C. Williams,
“*Gluon-gluon contributions to $W^+ W^-$ production and Higgs interference effects,*”
JHEP **1110**, 005 (2011), arXiv:1107.5569 [hep-ph].
- J. M. Campbell and R. K. Ellis,
“*Top-quark processes at NLO in production and decay,*”
arXiv:1204.1513 [hep-ph], FERMILAB-PUB-12-078-T.
- J. M. Campbell and R. K. Ellis,
“ *$t\bar{t}W^\pm$ production and decay at NLO,*”
JHEP **1207**, 052 (2012), [arXiv:1204.5678 [hep-ph]].
- J. M. Campbell, H. B. Hartanto and C. Williams
“*Next-to-leading order predictions for $Z\gamma$ +jet and $Z\gamma\gamma$ final states at the LHC*” JHEP **1211**, 162 (2012), [arXiv:1208.0566 [hep-ph]].
- P. J. Fox and C. Williams
“*Next-to-leading order predictions for Dark Matter Production at Hadron Colliders*” [arXiv:1211.6390 [hep-ph]].
- J. M. Campbell, R. K. Ellis and R. Röntsch, “*Single top production in association with a Z boson at the LHC,*” arXiv:1302.3856 [hep-ph].
- J. M. Campbell, R. K. Ellis and C. Williams, “*Associated Production of a Higgs Boson at NNLO*”, arXiv:1601.00658 [hep-ph].
- J. M. Campbell, R. K. Ellis, Ye Li and C. Williams, “*Predictions for Diphoton Production at the LHC through NNLO in QCD*”, arXiv:1603.02663 [hep-ph].
- Tobias Neumann and Ciaran Williams. “The Higgs boson at high p_T ”. *Phys. Rev. D* 95.1 (2017), p. 014004. DOI: 10.1103/PhysRevD.95.014004. arXiv: 1609.00367 [hep-ph]
- John M. Campbell, Tobias Neumann, and Ciaran Williams. “ $Z\gamma$ production at NNLO including anomalous couplings”. *Submitted to: JHEP* (2017). arXiv: 1708.02925 [hep-ph]
- Tobias Neumann. “NLO Higgs+jet production at large transverse momenta including top quark mass effects”. *J. Phys. Comm.* 2.9 (2018), p. 095017. DOI: 10.1088/2399-6528/aadfbf. arXiv: 1802.02981 [hep-ph]
- Tobias Neumann and Zack Edward Sullivan. “Off-Shell Single-Top-Quark Production in the Standard Model Effective Field Theory”. *JHEP* 06 (2019), p. 022. DOI: 10.1007/JHEP06(2019)022. arXiv: 1903.11023 [hep-ph]

The following publications have also made use of calculations implemented in MCFM, but the corresponding code has not yet been made public. Versions of the code that contain these calculations will be released in the future.

- J. Campbell, F. Maltoni and F. Tramontano,
“*QCD corrections to J/ψ and Υ production at hadron colliders,*”
Phys. Rev. Lett. **98**, 252002 (2007) [arXiv:hep-ph/0703113].
- R. K. Ellis, K. Melnikov and G. Zanderighi,
“*Generalized unitarity at work: first NLO QCD results for hadronic $W+3$ jet production,*” arXiv:0901.4101 [hep-ph].

B Processes included in MCFM

nproc	$f(p_1) + f(p_2) \rightarrow \dots$	Order
1	$W^+(\rightarrow \nu(p_3) + e^+(p_4))$	NNLO
6	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4))$	NNLO
11	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + f(p_5)$	NLO
12	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + \bar{b}(p_5)$	NLO
13	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + \bar{c}(p_5)$	NLO
14	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + \bar{c}(p_5)[\text{massless}]$	LO
16	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + f(p_5)$	NLO
17	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + b(p_5)$	NLO
18	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + c(p_5)$	NLO
19	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + c(p_5)[\text{massless}]$	LO
20	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + b(p_5) + b(p_6)[\text{massive}]$	NLO
21	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + b(p_5) + \bar{b}(p_6)$	NLO
22	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + f(p_5) + f(p_6)$	NLO
23	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + f(p_5) + f(p_6) + f(p_7)$	LO
24	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + b(p_5) + \bar{b}(p_6) + f(p_7)$	LO
25	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + b(p_5) + \bar{b}(p_6)[\text{massive}]$	NLO
26	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + b(p_5) + \bar{b}(p_6)$	NLO
27	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + f(p_5) + f(p_6)$	NLO
28	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + f(p_5) + f(p_6) + f(p_7)$	LO
29	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + b(p_5) + \bar{b}(p_6) + f(p_7)$	LO
31	$Z(\rightarrow e^-(p_3) + e^+(p_4))$	NNLO
310	$Z(\rightarrow e^-(p_3) + e^+(p_4))$ [photon induced]	LO
32	$Z(\rightarrow 3 \times (\nu(p_3) + \bar{\nu}(p_4)))$	NNLO
33	$Z(\rightarrow b(p_3) + \bar{b}(p_4))$	NLO
34	$Z(\rightarrow 3 \times (d(p_5) + \bar{d}(p_6)))$	NLO
35	$Z(\rightarrow 2 \times (u(p_5) + \bar{u}(p_6)))$	NLO
36	$Z \rightarrow t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow \bar{b}(p_6) + e^-(p_7) + \bar{\nu}(p_8))$	LO
41	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + f(p_5)$	NLO
42	$Z_0(\rightarrow 3 \times (\nu(p_3) + \bar{\nu}(p_4))) + f(p_5)$	NLO
43	$Z(\rightarrow b(p_3) + \bar{b}(p_4)) + f(p_5)$	NLO
44	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + f(p_5) + f(p_6)$	NLO
45	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + f(p_5) + f(p_6) + f(p_7)$	LO
46	$Z(\rightarrow 3 \times (\nu(p_3) + \bar{\nu}(p_4))) + f(p_5) + f(p_6)$	NLO
47	$Z(\rightarrow 3 \times (\nu(p_3) + \bar{\nu}(p_4))) + f(p_5) + f(p_6) + f(p_7)$	LO
50	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + \bar{b}(p_5) + b(p_6)[\text{massive}]$	LO
51	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + \bar{b}(p_6)$	NLO
52	$Z_0(\rightarrow 3 \times (\nu(p_3) + \bar{\nu}(p_4))) + b(p_5) + \bar{b}(p_6)$	NLO
53	$Z(\rightarrow b(p_3) + \bar{b}(p_4)) + b(p_5) + \bar{b}(p_6)$	NLO
54	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + \bar{b}(p_6) + f(p_7)$	LO

56	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + c(p_5) + \bar{c}(p_6)$	NLO
61	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + W^-(\rightarrow e^-(p_5) + \bar{\nu}(p_6))$	NLO
62	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + W^-(\rightarrow q(p_5) + \bar{q}(p_6))$	NLO
63	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + W^-(\rightarrow q(p_5) + \bar{q}(p_6))[\text{rad.in.dk}]$	NLO
64	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4))W^+(\rightarrow q(p_5) + \bar{q}(p_6))$	NLO
65	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4))W^+(\rightarrow q(p_5) + \bar{q}(p_6))[\text{rad.in.dk}]$	NLO
66	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + W^-(\rightarrow e^-(p_5) + \bar{\nu}(p_6)) + f(p_7)$	LO
69	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + W^-(\rightarrow e^-(p_5) + \bar{\nu}(p_6))[\text{no pol}]$	LO
71	$W^+(\rightarrow \nu(p_3) + \mu^+(p_4)) + Z(\rightarrow e^-(p_5) + e^+(p_6))$	NLO
72	$W^+(\rightarrow \nu(p_3) + \mu^+(p_4)) + Z(\rightarrow 3 \times (\nu_e(p_5) + \bar{\nu}_e(p_6)))$	NLO
73	$W^+(\rightarrow \nu(p_3) + \mu^+(p_4)) + Z(\rightarrow b(p_5) + \bar{b}(p_6))$	NLO
74	$W^+(\rightarrow \nu(p_3) + \mu^+(p_4)) + Z(\rightarrow 3 \times (d(p_5) + \bar{d}(p_6)))$	NLO
75	$W^+(\rightarrow \nu(p_3) + \mu^+(p_4)) + Z(\rightarrow 2 \times (u(p_5) + \bar{u}(p_6)))$	NLO
76	$W^-(\rightarrow \mu^-(p_3) + \bar{\nu}(p_4)) + Z(\rightarrow e^-(p_5) + e^+(p_6))$	NLO
77	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + Z(\rightarrow 3 \times (\nu_e(p_5) + \bar{\nu}_e(p_6)))$	NLO
78	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + Z(\rightarrow b(p_5) + \bar{b}(p_6))$	NLO
79	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + Z(\rightarrow 3 \times (d(p_5) + \bar{d}(p_6)))$	NLO
80	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + Z(\rightarrow 2 \times (u(p_5) + \bar{u}(p_6)))$	NLO
81	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + Z(\rightarrow \mu^-(p_5) + \mu^+(p_6))$	NLO
82	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + Z(\rightarrow 3 \times (\nu(p_5) + \bar{\nu}(p_6)))$	NLO
83	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + Z(\rightarrow b(p_5) + \bar{b}(p_6))$	NLO
84	$Z(\rightarrow b(p_3) + \bar{b}(p_4)) + Z(\rightarrow 3 \times (\nu(p_5) + \bar{\nu}(p_6)))$	NLO
85	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + Z(\rightarrow 3 \times (\nu(p_5) + \bar{\nu}(p_6))) + f(p_7)$	LO
86	$Z(\rightarrow \mu^-(p_3) + \mu^+(p_4)) + Z(\rightarrow e^-(p_5) + e^+(p_6))[\text{no gamma}^*]$	NLO
87	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + Z(\rightarrow 3 \times (\nu(p_5) + \bar{\nu}(p_6)))[\text{no gamma}^*]$	NLO
88	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + Z(\rightarrow b(p_5) + \bar{b}(p_6))[\text{no gamma}^*]$	NLO
89	$Z(\rightarrow b(p_3) + \bar{b}(p_4)) + Z(\rightarrow 3 \times (\nu(p_5) + \bar{\nu}(p_6)))[\text{no gamma}^*]$	NLO
90	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + Z(\rightarrow e^-(p_5) + e^+(p_6))$	NLO
91	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + H(\rightarrow b(p_5) + \bar{b}(p_6))$	NNLO
92	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + H(\rightarrow W^+(\nu(p_5), e^+(p_6))W^-(e^-(p_7), \bar{\nu}(p_8)))$	NNLO
93	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + H(\rightarrow Z(e^-(p_5), e^+(p_6)) + Z(\mu^-(p_7), \mu^+(p_8)))$	NNLO
94	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + H(\rightarrow \gamma(p_5) + \gamma(p_6))$	NNLO
96	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + H(\rightarrow b(p_5) + \bar{b}(p_6))$	NNLO
97	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + H(\rightarrow W^+(\nu(p_5), e^+(p_6))W^-(e^-(p_7), \bar{\nu}(p_8)))$	NNLO
98	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + H(\rightarrow Z(e^-(p_5), e^+(p_6)) + Z(\mu^-(p_7), \mu^+(p_8)))$	NNLO
99	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + H(\rightarrow \gamma(p_5) + \gamma(p_6))$	NNLO

101	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + H(\rightarrow b(p_5) + \bar{b}(p_6))$	NNLO
102	$Z(\rightarrow 3 \times (\nu(p_3) + \bar{\nu}(p_4))) + H(\rightarrow b(p_5) + \bar{b}(p_6))$	NLO
103	$Z(\rightarrow b(p_3) + \bar{b}(p_4)) + H(\rightarrow b(p_5) + \bar{b}(p_6))$	NLO
104	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + H(\rightarrow \gamma(p_5) + \gamma(p_6))$	NNLO
105	$Z(\rightarrow 3 \times (\nu(p_3) + \bar{\nu}(p_4))) + H(\rightarrow \gamma(p_5) + \gamma(p_6))$	NLO
106	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + H(\rightarrow W^+(\nu(p_5), e^+(p_6))W^-(e^-(p_7), \bar{\nu}(p_8)))$	NNLO
107	$Z(\rightarrow 3 \times (\nu(p_3) + \bar{\nu}(p_4))) + H(\rightarrow W^+(\nu(p_5), e^+(p_6))W^-(e^-(p_7), \bar{\nu}(p_8)))$	NLO
108	$Z(\rightarrow b(p_3) + \bar{b}(p_4)) + H(\rightarrow W^+(\nu(p_5), e^+(p_6))W^-(e^-(p_7), \bar{\nu}(p_8)))$	NLO
109	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + H(\rightarrow Z(e^-(p_5), e^+(p_6)) + Z(\rightarrow \mu^-(p_7), \mu^+(p_8)))$	NLO
110	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + H(\rightarrow \tau^-(p_5)\tau^+(p_6))$	NNLO
111	$H(\rightarrow b(p_3) + \bar{b}(p_4))$	NNLO
112	$H(\rightarrow \tau^-(p_3) + \tau^+(p_4))$	NNLO
113	$H(\rightarrow W^+(\nu(p_3) + e^+(p_4)) + W^-(e^-(p_5) + \bar{\nu}(p_6)))$	NLO
114	$H(\rightarrow W^+(\nu(p_3) + e^+(p_4)) + W^-(q(p_5) + \bar{q}(p_6)))$	NLO
115	$H(\rightarrow W^+(\nu(p_3) + e^+(p_4)) + W^-(q(p_5) + \bar{q}(p_6)))[rad.in.dk]$	NLO
116	$H(\rightarrow Z(\rightarrow e^-(p_3) + e^+(p_4)) + Z(\rightarrow \mu^-(p_5) + \mu^+(p_6)))$	NLO
117	$H(\rightarrow Z(\rightarrow 3 \times (\nu(p_3) + \bar{\nu}(p_4))) + Z(\rightarrow \mu^-(p_5) + \mu^+(p_6)))$	NLO
118	$H(\rightarrow Z(\rightarrow \mu^-(p_3) + \mu^+(p_4)) + Z(\rightarrow b(p_5) + \bar{b}(p_6)))$	NLO
119	$H(\rightarrow \gamma(p_3) + \gamma(p_4))$	NNLO
120	$H(\rightarrow Z(\rightarrow \mu^-(p_3) + \mu^+(p_4)) + \gamma(p_5))$	NLO
121	$H(\rightarrow Z(\rightarrow 3 \times (\nu(p_3) + \bar{\nu}(p_4))) + \gamma(p_5))$	NLO
123	$H(\rightarrow W^+(\nu(p_3) + e^+(p_4)) + W^-(e^-(p_5) + \bar{\nu}(p_6)))$ [t, b loops, exact]	LO
124	$H(\rightarrow W^+(\nu(p_3) + e^+(p_4)) + W^-(e^-(p_5) + \bar{\nu}(p_6)))$ [only H, gg→WW int]	LO
125	$H(\rightarrow W^+(\nu(p_3) + e^+(p_4)) + W^-(e^-(p_5) + \bar{\nu}(p_6)))$ [$ H ^2$ and H,gg→WW int]	LO
126	$W^+(\nu(p_3) + e^+(p_4)) + W^-(e^-(p_5) + \bar{\nu}(p_6))$ [gg only, (H + gg→WW) squared]	LO
128	$H(\rightarrow Z(\rightarrow e^-(p_3) + e^+(p_4)) + Z(\rightarrow \mu^-(p_5) + \mu^+(p_6)))$ [t, b loops, exact]	LO
129	$H(\rightarrow Z(\rightarrow e^-(p_3) + e^+(p_4)) + Z(\rightarrow \mu^-(p_5) + \mu^+(p_6)))$ [only H, gg→ZZ int]	LO
130	$H(\rightarrow Z(\rightarrow e^-(p_3) + e^+(p_4)) + Z(\rightarrow \mu^-(p_5) + \mu^+(p_6)))$ [$ H ^2$ and H,gg→ZZ int]	LO
131	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + Z(\rightarrow \mu^-(p_5) + \mu^+(p_6))$ [gg only, $ H + gg \rightarrow ZZ ^2$]	LO
132	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + Z(\rightarrow \mu^-(p_5) + \mu^+(p_6))$ [(gg→ZZ) squared]	LO
1281	$H(\rightarrow e^-(p_3) + e^+(p_4)\nu_e(p_5) + \bar{\nu}_e(p_6))$ [top, bottom loops, exact]	LO
1311	$e^-(p_3) + e^+(p_4) + \nu_e(p_5) + \bar{\nu}_e(p_6)$ [gg only, (H + gg→ZZ) squared]	LO
1321	$e^-(p_3) + e^+(p_4) + \nu_e(p_5) + \bar{\nu}_e(p_6)$ [(gg→ZZ) squared]	LO
1282	$H(\rightarrow e^-(p_3) + e^+(p_4) + \nu(p_5) + \bar{\nu}(p_6))$ [top, bottom loops, exact]	LO
1312	$e^-(p_3) + e^+(p_4) + \nu(p_5) + \bar{\nu}(p_6)$ [gg only, (H + gg→ZZ) squared]	LO
1322	$e^-(p_3) + e^+(p_4) + \nu(p_5) + \bar{\nu}(p_6)$ [(gg→ZZ) squared]	LO
133	$H(\rightarrow Z(\rightarrow e^-(p_3) + e^+(p_4)) + Z(\rightarrow \mu^-(p_5) + \mu^+(p_6) + f(p_7))$ [intf,no p_7 cut]	LO

136	$H(\rightarrow b(p_3) + \bar{b}(p_4)) + b(p_5)(+g(p_6))$	NLO
137	$H(\rightarrow b(p_3) + \bar{b}(p_4)) + \bar{b}(p_5)(+b(p_6))$	(REAL)
138	$H(\rightarrow b(p_3) + \bar{b}(p_4)) + b(p_5) + \bar{b}(p_6)$ [both observed]	(REAL)
141	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8))$	NLO
142	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8))$ [rad.in.dk]	NLO
143	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8)) + f(p_9)$	LO
144	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8))$ (uncorr)	NLO
145	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8))$ [rad.in.dk],uncorr	NLO
146	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + q(p_7) + \bar{q}(p_8))$	NLO
147	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + q(p_7) + \bar{q}(p_8))$ [rad.in.top.dk]	NLO
148	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + q(p_7) + \bar{q}(p_8))$ [rad.in.W.dk]	NLO
149	$t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8))$	NLO
150	$t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8))$ [rad.in.top.dk]	NLO
151	$t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8))$ [rad.in.W.dk]	NLO
157	$t\bar{t}$ [for total Xsect]	NLO
158	$b\bar{b}$ [for total Xsect]	NLO
159	$c\bar{c}$ [for total Xsect]	NLO
160	$t\bar{t} + g$ [for total Xsect]	LO
161	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + q(p_6)$ [t-channel]	NLO
162	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + q(p_6)$ [decay]	NLO
163	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + q(p_6)$ [t-channel] $mb > 0$	NLO
164	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + q(p_6)$ [full off-shell t-channel] $mb = 0$	NLO
166	$\bar{t}(\rightarrow e^-(p_3) + \bar{\nu}(p_4) + \bar{b}(p_5)) + q(p_6)$ [t-channel]	NLO
167	$\bar{t}(\rightarrow e^-(p_3) + \bar{\nu}(p_4) + \bar{b}(p_5)) + q(p_6)$ [rad.in.dk]	NLO
168	$\bar{t}(\rightarrow e^-(p_3) + \bar{\nu}(p_4) + \bar{b}(p_5)) + q(p_6)$ [t-channel] $mb > 0$	NLO
169	$\bar{t}(\rightarrow e^-(p_3) + \bar{\nu}(p_4) + \bar{b}(p_5)) + q(p_6)$ [full off-shell t-channel] $mb = 0$	NLO
171	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{b}(p_6)$ [s-channel]	NLO
172	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{b}(p_6)$ [decay]	NLO
176	$\bar{t}(\rightarrow e^-(p_3) + \bar{\nu}(p_4) + \bar{b}(p_5)) + b(p_6)$ [s-channel]	NLO
177	$\bar{t}(\rightarrow e^-(p_3) + \bar{\nu}(p_4) + \bar{b}(p_5)) + b(p_6)$ [rad.in.dk]	NLO
180	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + t(p_5)$	NLO
181	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + t(\nu(p_5) + e^+(p_6) + b(p_7))$	NLO
182	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + t(\nu(p_5) + e^+(p_6) + b(p_7))$ [rad.in.dk]	NLO
183	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + t(\nu(p_5) + e^+(p_6) + b(p_7)) + b(p_8)$	LO
184	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + t(p_5) + b(p_6)$ [massive b]	LO
185	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + \bar{t}(p_5)$	NLO
186	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + \bar{t}(e^-(p_5) + \bar{\nu}(p_6) + \bar{b}(p_7))$	NLO
187	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + \bar{t}(e^-(p_5) + \bar{\nu}(p_6) + \bar{b}(p_7))$ [rad.in.dk]	NLO

190	$f(p_3) + f(p_4)$	LO
191	$f(p_3) + f(p_4)$ [mixed QCD/EW]	NLO
200	$H + f(p_5)$, see section 10.39	NLO
201	$H(\rightarrow b(p_3) + \bar{b}(p_4)) + f(p_5)$ [full mt dep.]	LO
202	$H(\rightarrow \tau^-(p_3) + \tau^+(p_4)) + f(p_5)$ [full mt dep.]	LO
203	$H(\rightarrow b(p_3) + \bar{b}(p_4)) + f(p_5)$	NNLO
204	$H(\rightarrow \tau^-(p_3) + \tau^+(p_4)) + f(p_5)$	NNLO
205	$H(\rightarrow Z(\mu^-(p_3) + \mu^+(p_4)) + \gamma(p_5)) + f(p_5)$	NLO
206	$A(\rightarrow b(p_3) + \bar{b}(p_4)) + f(p_5)$ [full mt dep.]	LO
207	$A(\rightarrow \tau^-(p_3) + \tau^+(p_4)) + f(p_5)$ [full mt dep.]	LO
208	$H(\rightarrow W^+(\nu(p_3), e^+(p_4))W^-(e^-(p_5), \bar{\nu}(p_6))) + f(p_7)$	NLO
209	$H(\rightarrow Z(\rightarrow e^-(p_3), e^+(p_4))Z(\rightarrow \mu^-(p_5), \mu^+(p_6))) + f(p_7)$	NLO
210	$H(\rightarrow \gamma(p_3) + \gamma(p_4)) + f(p_5)$	NNLO
211	$H(\rightarrow b(p_3) + \bar{b}(p_4)) + f(p_5) + f(p_6)$ [WBF]	NLO
212	$H(\rightarrow \tau^-(p_3) + \tau^+(p_4)) + f(p_5) + f(p_6)$ [WBF]	NLO
213	$H(\rightarrow W^+(\nu(p_3), e^+(p_4))W^-(e^-(p_5), \bar{\nu}(p_6))) + f(p_7) + f(p_8)$ [WBF]	NLO
214	$H(\rightarrow Z(\rightarrow e^-(p_3), e^+(p_4)) + Z(\rightarrow \mu^-(p_5), \mu^+(p_6))) + f(p_7) + f(p_8)$ [WBF]	NLO
215	$H(\rightarrow \gamma(p_3) + \gamma(p_4)) + f(p_5) + f(p_6)$ [WBF]	NLO
216	$H(\rightarrow b(p_3) + \bar{b}(p_4)) + f(p_5) + f(p_6) + f(p_7)$ [WBF+jet]	LO
217	$H(\rightarrow \tau^-(p_3) + \tau^+(p_4)) + f(p_5) + f(p_6) + f(p_7)$ [WBF+jet]	LO
221	$\tau^-(\rightarrow e^-(p_3) + \bar{\nu}_e(p_4) + \nu_\tau(p_5)) + \tau^+(\rightarrow \bar{\nu}_\tau(p_6) + \nu_e(p_7) + e^+(p_8))$	LO
220	$Z(\rightarrow e^-(p_3), e^+(p_4))Z(\rightarrow \mu^-(p_5), \mu^+(p_6))) + f(p_7) + f(p_8)$ [weak]'	LO
2201	$Z(\rightarrow e^-(p_3), e^+(p_4))Z(\rightarrow \mu^-(p_5), \mu^+(p_6))) + f(p_7) + f(p_8)$ [strong]'	LO
222	$Z(\rightarrow e^-(p_3), e^+(p_4))Z(\rightarrow \nu_\mu(p_5), \bar{\nu}_\mu(p_6))) + f(p_7) + f(p_8)$ [weak]'	LO
2221	$Z(\rightarrow e^-(p_3), e^+(p_4))Z(\rightarrow \nu_\mu(p_5), \bar{\nu}_\mu(p_6))) + f(p_7) + f(p_8)$ [strong]'	LO
224	$W^-(e^-(p_3), \bar{\nu}_e(p_6))W^+(\nu_\mu(p_5), \mu^+(p_4)) + f(p_7) + f(p_8)$ [weak]'	LO
2241	$W^-(e^-(p_3), \bar{\nu}_e(p_6))W^+(\nu_\mu(p_5), \mu^+(p_4)) + f(p_7) + f(p_8)$ [strong]'	LO
226	$e^-(p_3) + e^+(p_4) + \nu_e(p_5) + \bar{\nu}_e(p_6) + f(p_7) + f(p_8)$ [weak]'	LO
228	$W^+(\nu_e(p_3), e^+(p_4))W^+(\nu_\mu(p_5), \mu^+(p_6)) + f(p_7) + f(p_8)$ [weak]'	LO
2281	$W^+(\nu_e(p_3), e^+(p_4))W^+(\nu_\mu(p_5), \mu^+(p_6)) + f(p_7) + f(p_8)$ [strong]'	LO
229	$W^-(e^-(p_3), \bar{\nu}_e(p_4))W^-(\mu^-(p_5), \bar{\nu}_\mu(p_6)) + f(p_7) + f(p_8)$ [weak]'	LO
2291	$W^-(e^-(p_3), \bar{\nu}_e(p_4))W^-(\mu^-(p_5), \bar{\nu}_\mu(p_6)) + f(p_7) + f(p_8)$ [strong]'	LO
223	$W^+(\nu_e(p_3), e^+(p_4))Z(\rightarrow \mu^-(p_5), \mu^+(p_6))) + f(p_7) + f(p_8)$ [weak]'	LO
2231	$W^+(\nu_e(p_3), e^+(p_4))Z(\rightarrow \mu^-(p_5), \mu^+(p_6))) + f(p_7) + f(p_8)$ [strong]'	LO
225	$W^-(e^-(p_3), \bar{\nu}_e(p_4))Z(\rightarrow \mu^-(p_5), \mu^+(p_6))) + f(p_7) + f(p_8)$ [weak]'	LO
2251	$W^-(e^-(p_3), \bar{\nu}_e(p_4))Z(\rightarrow \mu^-(p_5), \mu^+(p_6))) + f(p_7) + f(p_8)$ [strong]'	LO

231	$t(p_3) + b(p_4) + q(p_5)$ [t-channel]	NLO
232	$t(p_3) + \bar{b}(p_4) + q(p_5) + q(p_6)$ [t-channel]	LO
233	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{b}(p_6) + q(p_7)$ [t-channel]	NLO
234	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{b}(p_6) + q(p_7)$ [t-channel, rad.in.dk]	NLO
235	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{b}(p_6) + q(p_7) + f(p_8)$ [t-channel]	LO
236	$\bar{t}(p_3) + b(p_4) + q(p_5)$ [t-channel]	NLO
237	$\bar{t}(p_3) + b(p_4) + q(p_5) + q(p_6)$ [t-channel]	LO
238	$\bar{t}(\rightarrow e^-(p_3) + \bar{\nu}(p_4) + \bar{b}(p_5)) + b(p_6) + q(p_7)$ [t-channel]	NLO
239	$\bar{t}(\rightarrow e^-(p_3) + \bar{\nu}(p_4) + \bar{b}(p_5)) + b(p_6) + q(p_7)$ [t-channel, rad.in.dk]	NLO
240	$\bar{t}(\rightarrow e^-(p_3) + \bar{\nu}(p_4) + \bar{b}(p_5)) + b(p_6) + q(p_7) + f(p_8)$ [t-channel]	LO
251	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + W^+(\rightarrow \nu(p_5) + e^+(p_6)) + f(p_7) + f(p_8)$	LO
252	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + W^+(\rightarrow \nu(p_5) + e^+(p_6)) + f(p_7) + f(p_8) + f(p_9)$	LO
253	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + Z(\rightarrow e^-(p_5) + e^+(p_6)) + f(p_7) + f(p_8)$	LO
254	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + Z(\rightarrow e^-(p_5) + e^+(p_6)) + f(p_7) + f(p_8)$	LO
255	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + Z(\rightarrow e^-(p_5) + e^+(p_6)) + b(p_7) + f(p_8)$	LO
256	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + Z(\rightarrow e^-(p_5) + e^+(p_6)) + b(p_7) + f(p_8)$	LO
259	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + Z(\rightarrow e^-(p_5) + e^+(p_6)) + b(p_7) + b(p_8)$	LO
260	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + Z(\rightarrow e^-(p_5) + e^+(p_6)) + b(p_7) + b(p_8)$	LO
261	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5)$	NLO
262	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + c(p_5)$	NLO
263	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + \bar{b}(p_5) + b(p_6)$ [1 b-tag]	LO
264	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + \bar{c}(p_5) + c(p_6)$ [1 c-tag]	LO
266	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5)(+\bar{b}(p_6))$	NLO
267	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + c(p_5)(+\bar{c}(p_6))$	NLO

270	$H(\gamma(p_3) + \gamma(p_4)) + f(p_5) + f(p_6)$ [in heavy top limit]	NLO
271	$H(b(p_3) + \bar{b}(p_4)) + f(p_5) + f(p_6)$ [in heavy top limit]	NLO
272	$H(\tau^-(p_3) + \tau^+(p_4)) + f(p_5) + f(p_6)$ [in heavy top limit]	NLO
273	$H(\rightarrow W^+(\nu(p_3), e^+(p_4))W^-(e^-(p_5), \bar{\nu}(p_6))) + f(p_7) + f(p_8)$	NLO
274	$H(\rightarrow Z(e^-(p_3), e^+(p_4))Z(\mu^-(p_5), \mu^+(p_6))) + f(p_7) + f(p_8)$	NLO
275	$H(b(p_3) + \bar{b}(p_4)) + f(p_5) + f(p_6) + f(p_7)$ [in heavy top limit]	LO
276	$H(\tau^-(p_3) + \tau^+(p_4)) + f(p_5) + f(p_6) + f(p_7)$ [in heavy top limit]	LO
278	$H(\rightarrow W^+(\nu(p_3), e^+(p_4))W^-(e^-(p_5), \bar{\nu}(p_6))) + f(p_7) + f(p_8) + f(p_9)$	LO
279	$H(\rightarrow Z(e^-(p_3), e^+(p_4))Z(\mu^-(p_5), \mu^+(p_6))) + f(p_7) + f(p_8) + f(p_9)$	LO
280	$\gamma(p_3) + f(p_4)$	NLO+F
282	$f(p_1) + f(p_2) \rightarrow \gamma(p_3) + f(p_4) + f(p_5)$	LO
283	$f(p_1) + f(p_2) \rightarrow \gamma(p_3) + b(p_4)$	LO
284	$f(p_1) + f(p_2) \rightarrow \gamma(p_3) + c(p_4)$	LO
285	$f(p_1) + f(p_2) \rightarrow \gamma(p_3) + \gamma(p_4)$	NLO+F, NNLO
286	$f(p_1) + f(p_2) \rightarrow \gamma(p_3) + \gamma(p_4) + f(p_5)$	LO
287	$f(p_1) + f(p_2) \rightarrow \gamma(p_3) + \gamma(p_4) + \gamma(p_5)$	NLO+F
289	$f(p_1) + f(p_2) \rightarrow \gamma(p_3) + \gamma(p_4) + \gamma(p_5) + \gamma(p_6)$	NLO+F
290	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + \gamma(p_5)$	NLO+F
292	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + \gamma(p_5) + f(p_6)$	LO
295	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + \gamma(p_5)$	NLO+F
297	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + \gamma(p_5) + f(p_6)$	LO
300	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + \gamma(p_5)$	NNLO
301	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + \gamma(p_5) + \gamma(p_6)$	NLO + F
302	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + \gamma(p_5) + f(p_6)$	NLO
303	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + \gamma(p_5) + \gamma(p_6) + f(p_7)$	LO
304	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + \gamma(p_5) + f(p_6) + f(p_7)$	LO
305	$Z(\rightarrow 3(\nu(p_3) + \bar{\nu}(p_4))) + \gamma(p_5)$	NNLO
306	$Z(\rightarrow 3(\nu(p_3) + \bar{\nu}(p_4))) + \gamma(p_5) + \gamma(p_6)$	NLO + F
307	$Z(\rightarrow 3(\nu(p_3) + \bar{\nu}(p_4))) + \gamma(p_5) + f(p_6)$	NLO
308	$Z(\rightarrow 3(\nu(p_3) + \bar{\nu}(p_4))) + \gamma(p_5) + \gamma(p_6) + f(p_7)$	LO
309	$Z(\rightarrow 3(\nu(p_3) + \bar{\nu}(p_4))) + \gamma(p_5) + f(p_6) + f(p_7)$	LO
311	$f(p_1) + b(p_2) \rightarrow W^+(\rightarrow \nu(p_3) + e^+(p_4)) + b(p_5) + f(p_6)$	LO
316	$f(p_1) + b(p_2) \rightarrow W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + b(p_5) + f(p_6)$	LO
321	$f(p_1) + c(p_2) \rightarrow W^+(\rightarrow \nu(p_3) + e^+(p_4)) + c(p_5) + f(p_6)$	LO
326	$f(p_1) + c(p_2) \rightarrow W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + c(p_5) + f(p_6)$	LO
331	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + c(p_5) + f(p_6)$ [c-s interaction]	LO
336	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + c(p_5) + f(p_6)$ [c-s interaction]	LO
341	$f(p_1) + b(p_2) \rightarrow Z(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6)$ [+f(p ₇)]	NLO
342	$f(p_1) + b(p_2) \rightarrow Z(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6)$ [+b(p ₇)]	(REAL)
346	$f(p_1) + b(p_2) \rightarrow Z(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6) + f(p_7)$	LO
347	$f(p_1) + b(p_2) \rightarrow Z(\rightarrow e^-(p_3) + e^+(p_4)) + b(p_5) + f(p_6) + \bar{b}(p_7)$	LO

351	$f(p_1) + c(p_2) \rightarrow Z(\rightarrow e^-(p_3) + e^+(p_4)) + c(p_5) + f(p_6) [+f(p_7)]$	NLO
352	$f(p_1) + c(p_2) \rightarrow Z(\rightarrow e^-(p_3) + e^+(p_4)) + c(p_5) + f(p_6) [+ \bar{c}(p_7)]$	(REAL)
356	$f(p_1) + c(p_2) \rightarrow Z(\rightarrow e^-(p_3) + e^+(p_4)) + c(p_5) + f(p_6) + f(p_7)$	LO
357	$f(p_1) + c(p_2) \rightarrow Z(\rightarrow e^-(p_3) + e^+(p_4)) + c(p_5) + f(p_6) + \bar{c}(p_7)$	LO
361	$c(p_1) + \bar{s}(p_2) \rightarrow W^+(\rightarrow \nu(p_3) + e^+(p_4)) [\text{mc}=0 \text{ in NLO}]$	NLO
362	$c(p_1) + \bar{s}(p_2) \rightarrow W^+(\rightarrow \nu(p_3) + e^+(p_4)) [\text{massless corrections only}]$	NLO
363	$c(p_1) + \bar{s}(p_2) \rightarrow W^+(\rightarrow \nu(p_3) + e^+(p_4)) [\text{massive charm in real}]$	NLO
370	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + \gamma(p_5) + \gamma(p_6)$	LO
371	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + \gamma(p_5) + \gamma(p_6)$	LO
401	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + b(p_5) [1,2 \text{ or } 3 \text{ jets, 4FNS}]$	NLO
402	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + (b + \bar{b})(p_5) [1 \text{ or } 2 \text{ jets, 4FNS}]$	NLO
403	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + b(p_5) + \bar{b}(p_6) [2 \text{ or } 3 \text{ jets, 4FNS}]$	NLO
406	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + b(p_5) [1,2 \text{ or } 3 \text{ jets, 4FNS}]$	NLO
407	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + (b + \bar{b})(p_5) [1 \text{ or } 2 \text{ jets, 4FNS}]$	NLO
408	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + b(p_5) + \bar{b}(p_6) [2 \text{ or } 3 \text{ jets, 4FNS}]$	NLO
411	$f(p_1) + b(p_2) \rightarrow W^+(\rightarrow \nu(p_3) + e^+(p_4)) + b(p_5) + f(p_6) [5\text{FNS}]$	NLO
416	$f(p_1) + b(p_2) \rightarrow W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + b(p_5) + f(p_6) [5\text{FNS}]$	NLO
421	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + b(p_5) [1,2 \text{ or } 3 \text{ jets, 4FNS+5FNS}]$	NLO
426	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + b(p_5) [1,2 \text{ or } 3 \text{ jets, 4FNS+5FNS}]$	NLO
431	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + b(p_5) + b(p_6) + f(p_7) [\text{massive}]$	LO
436	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + b(p_5) + \bar{b}(p_6) + f(p_7) [\text{massive}]$	LO
500	$W^+(\rightarrow \nu(p_3) + e^+(p_4)) + t(p_5) + \bar{t}(p_6) [\text{massive}]$	NLO
501	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8)) + W^+(\nu(p_9), \mu^+(p_{10}))$	NLO
502	(same as process 501 but with radiation in decay)	NLO
503	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + q(p_7) + q(p_8)) + W^+(\nu(p_9), \mu^+(p_{10}))$	NLO
506	$t(\rightarrow q(p_3) + q(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8)) + W^+(\nu(p_9), \mu^+(p_{10}))$	NLO
510	$W^-(\rightarrow e^-(p_3) + \bar{\nu}(p_4)) + t(p_5) + \bar{t}(p_6) [\text{massive}]$	NLO
511	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8)) + W^-(\mu^-(p_9), \bar{\nu}(p_{10}))$	NLO
512	(same as process 511 but with radiation in decay)	NLO
513	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + q(p_7) + q(p_8)) + W^-(\mu^-(p_9), \bar{\nu}(p_{10}))$	NLO
516	$t(\rightarrow q(p_3) + q(p_4) + b(p_5)) + \bar{t}(\rightarrow b(p_6) + e^-(p_7) + \bar{\nu}(p_8)) + W^-(\mu^-(p_9), \bar{\nu}(p_{10}))$	NLO
529	$Z(\rightarrow e^-(p_3) + e^+(p_4)) + t(p_5) + \bar{t}(p_6)$	LO
530	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_6)) + Z(e^-(p_9), e^+(p_{10}))$	LO
531	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_6)) + Z(b(p_9), b(p_{10}))$	LO
532	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow q(p_7) + \bar{q}(p_8) + b(p_6)) + Z(e^-(p_9), e^+(p_{10}))$	LO
533	$t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow e^-(p_7) + \bar{\nu}(p_8) + b(p_6)) + Z(e^-(p_9), e^+(p_{10}))$	LO

540	$H(b(p_3) + b(p_4)) + t(p_5) + q(p_6)$	NLO
541	$H(b(p_3) + \bar{b}(p_4)) + \bar{t}(p_5) + q(p_6)$	NLO
544	$H(b(p_3) + \bar{b}(p_4)) + t(\nu(p_5) + e^+(p_6) + b(p_7)) + q(p_9)$	NLO
547	$H(b(p_3) + \bar{b}(p_4)) + \bar{t}(e^-(p_5) + \bar{\nu}(p_6) + b(p_7)) + q(p_9)$	NLO
550	$H(\gamma(p_3) + \gamma(p_4)) + t(p_5) + q(p_6)$	NLO
551	$H(\gamma(p_3) + \gamma(p_4)) + \bar{t}(p_5) + q(p_6)$	NLO
554	$H(\gamma(p_3) + \gamma(p_4)) + t(\nu(p_5) + e^+(p_6) + b(p_7)) + q(p_9)$	NLO
557	$H(\gamma(p_3) + \gamma(p_4)) + \bar{t}(e^-(p_5) + \bar{\nu}(p_6) + b(p_7)) + q(p_9)$	NLO
560	$Z(e^-(p_3) + e^+(p_4)) + t(p_5) + q(p_6)$	NLO
561	$Z(e^-(p_3) + e^+(p_4)) + \bar{t}(p_5) + q(p_6)$	NLO
562	$Z(e^-(p_3) + e^+(p_4)) + t(p_5) + q(p_6) + f(p_7)$	LO
563	$Z(e^-(p_3) + e^+(p_4)) + \bar{t}(p_5) + q(p_6) + f(p_7)$	LO
564	$Z(e^-(p_3) + e^+(p_4)) + t(\rightarrow \nu(p_5) + e^+(p_6) + b(p_7)) + q(p_8)$	NLO
566	$Z(e^-(p_3) + e^+(p_4)) + t(\rightarrow \nu(p_5) + e^+(p_6) + b(p_7)) + q(p_8) + f(p_9)$	LO
567	$Z(e^-(p_3) + e^+(p_4)) + \bar{t}(\rightarrow e^-(p_5) + \bar{\nu}(p_6) + \bar{b}(p_7)) + q(p_8)$	NLO
569	$Z(e^-(p_3) + e^+(p_4)) + \bar{t}(\rightarrow e^-(p_5) + \bar{\nu}(p_6) + \bar{b}(p_7)) + q(p_8) + f(p_9)$	LO
601	$H(b(p_3) + b(p_4)) + H(\tau^-(p_5) + \tau^+(p_6))$	LO
602	$H(b(p_3) + \bar{b}(p_4)) + H(\gamma(p_5) + \gamma(p_6))$	LO
640	$t(p_3) + \bar{t}(p_4) + H(p_5)$	LO
641	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow \bar{\nu}(p_7) + e^-(p_8) + \bar{b}(p_6)) + H(b(p_9) + \bar{b}(p_{10}))$	LO
644	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow \bar{q}(p_7) + q(p_8) + \bar{b}(p_6)) + H(b(p_9) + \bar{b}(p_{10}))$	LO
647	$t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow \bar{\nu}(p_7) + e^-(p_8) + \bar{b}(p_6)) + H(b(p_9) + \bar{b}(p_{10}))$	LO
651	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow \bar{\nu}(p_7) + e^-(p_8) + \bar{b}(p_6)) + H(\gamma(p_9) + \gamma(p_{10}))$	LO
654	$t(\rightarrow \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\rightarrow \bar{q}(p_7) + q(p_8) + \bar{b}(p_6)) + H(\gamma(p_9) + \gamma(p_{10}))$	LO
657	$t(\rightarrow q(p_3) + \bar{q}(p_4) + b(p_5)) + \bar{t}(\rightarrow \bar{\nu}(p_7) + e^-(p_8) + \bar{b}(p_6)) + H(\gamma(p_9) + \gamma(p_{10}))$	LO
661	$t(\rightarrow \nu(p_3)e^+(p_4)b(p_5)) + \bar{t}(\rightarrow \bar{\nu}(p_7)e^-(p_8)\bar{b}(p_6)) + H(W^+(p_9, p_{10})W^-(p_{11}, p_{12}))$	LO
664	$t(\rightarrow \nu(p_3)e^+(p_4)b(p_5)) + \bar{t}(\rightarrow \bar{q}(p_7)q(p_8)\bar{b}(p_6)) + H(W^+(p_9, p_{10})W^-(p_{11}, p_{12}))$	LO
667	$t(\rightarrow q(p_3)\bar{q}(p_4)b(p_5)) + \bar{t}(\rightarrow (\bar{\nu}(p_7)e^-(p_8)\bar{b}(p_6)) + H(W^+(p_9, p_{10})W^-(p_{11}, p_{12}))$	LO

Table 8: Processes indicated by choice of the variable `nproc`.

800	$V \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5)$ [Vector Mediator]	NLO
801	$A \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5)$ [Axial Vector Mediator]	NLO
802	$S \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5)$ [Scalar Mediator]	NLO
803	$PS \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5)$ [Pseudo Scalar Mediator]	NLO
804	$GG \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5)$ [Gluonic DM operator]	NLO
805	$S - -(\chi(p_3) + \bar{\chi}(p_4)) + f(p_5)$ [Scalar Mediator, mt loops]	NLO
820	$V \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5)$ [Vector Mediator]	NLO + F
821	$A \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5)$ [Axial Vector Mediator]	NLO + F
822	$S \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5)$ [Scalar Mediator]	NLO + F
823	$PS \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5)$ [Pseudo Scalar Mediator]	NLO + F
840	$V \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5) + f(p_6)$ [Vector Mediator]	LO
841	$A \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5) + f(p_6)$ [Axial Vector Mediator]	LO
842	$S \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5) + f(p_6)$ [Scalar Mediator]	LO
843	$PS \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5) + f(p_6)$ [Pseudo Scalar Mediator]	LO
844	$GG \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + f(p_5) + f(p_6)$ [Gluonic DM operator]	LO
845	$V \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5) + f(p_6)$ [Vector Mediator]	LO
846	$A \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5) + f(p_6)$ [Axial Vector Mediator]	LO
847	$S \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5) + f(p_6)$ [Scalar Mediator]	LO
848	$PS \rightarrow (\chi(p_3) + \bar{\chi}(p_4)) + \gamma(p_5) + f(p_6)$ [Pseudo Scalar Mediator]	LO
902	Check of Volume of 2 particle phase space	
903	Check of Volume of 3 particle phase space	
904	Check of Volume of 4 particle phase space	
905	Check of Volume of 5 particle phase space	
906	Check of Volume of 6 particle phase space	
908	Check of Volume of 8 particle phase space	
909	Check of Volume of 4 particle massive phase space	
910	Check of Volume of 3 particle (2 massive) phase space	
911	Check of Volume of 5 particle W+t (with decay) massive phase space	
912	Check of Volume of 5 particle W+t (no decay) massive phase space	
913	Check of Volume of 5 particle W+t+g (in decay) massive phase space	
914	Check of Volume of 5 particle W+t+g (in production) massive phase space	

Table 9: Processes indicated by choice of the variable `nproc`.

C Historical PDF sets

The availability of a number of historical PDF sets is retained in the code. These should typically not be used in modern analyses, but they may be helpful for comparison with older codes or in specialized cases.

These distributions, together with their associated $\alpha_S(M_Z)$ values, are given in Tables 10 and 11. For the older distributions, where the coupling was specified by Λ this requires some calculation and/or guesswork.

mrstqed	0.1205	hep-ph/0411040	mrs02n1	0.1197	hep-ph/0211080
mrs02nn	0.1154	hep-ph/0211080	mrs4nf3	0.1083	hep-ph/0603143
mrs4lf3	0.1186	hep-ph/0603143	mrs4nf4	0.1153	hep-ph/0603143
mrs4lf4	0.1251	hep-ph/0603143	mrs0119	0.119	hep-ph/0110215
mrs0117	0.117	hep-ph/0110215	mrs0121	0.121	hep-ph/0110215
mrs01_j	0.121	hep-ph/0110215	mrs011o	0.130	hep-ph/0201127
mrs99_1	0.1175	hep-ph/9907231	mrs99_2	0.1175	hep-ph/9907231
mrs99_3	0.1175	hep-ph/9907231	mrs99_4	0.1125	hep-ph/9907231
mrs99_5	0.1225	hep-ph/9907231	mrs99_6	0.1178	hep-ph/9907231
mrs99_7	0.1171	hep-ph/9907231	mrs99_8	0.1175	hep-ph/9907231
mrs99_9	0.1175	hep-ph/9907231	mrs9910	0.1175	hep-ph/9907231
mrs9911	0.1175	hep-ph/9907231	mrs9912	0.1175	hep-ph/9907231
mrs98z1	0.1175	hep-ph/9803445	mrs98z2	0.1175	hep-ph/9803445
mrs98z3	0.1175	hep-ph/9803445	mrs98z4	0.1125	hep-ph/9803445
mtungb1	0.109	hep-ph/9803445	mrs98z5	0.1225	hep-ph/9803445
mrs96r1	0.113	PLB387 (1996) 419	mrs96r2	0.120	PLB387 (1996) 419
mrs96r3	0.113	PLB387 (1996) 419	mrs96r4	0.120	PLB387 (1996) 419
mrs95ap	0.1127	PLB354 (1995) 155	mrs95_g	0.1148	PLB354 (1995) 155
hmrs90e	0.09838	Durham DTP-90-04	hmrs90b	0.10796	Durham DTP-90-04

Table 10: Historical MRS-type pdf sets, their corresponding values of $\alpha_S(M_Z)$ and a reference to the paper or preprint that describes their origin.

cteq61m	0.118	hep-ph/0303013	cteq66m	0.118	0802.0007 [hep-ph]
cteq6_d	0.118	hep-ph/0201195	cteq6_m	0.118	hep-ph/0201195
cteq611	0.130	hep-ph/0201195	cteq6_l	0.118	hep-ph/0201195
cteq5f3	0.106	hep-ph/9903282	cteq5hq	0.118	hep-ph/9903282
cteq5_m	0.118	hep-ph/9903282	cteq5f4	0.112	hep-ph/9903282
cteq5_l	0.127	hep-ph/9903282	cteq5_d	0.118	hep-ph/9903282
cteq5hj	0.118	hep-ph/9903282	cteq511	0.127	hep-ph/9903282
ctq5hq1	0.118	hep-ph/9903282	cteq5m1	0.118	hep-ph/9903282
cteq4hj	0.116	hep-ph/9606399	cteq4a5	0.122	hep-ph/9606399
cteq4_m	0.116	hep-ph/9606399	cteq41q	0.114	hep-ph/9606399
cteq4_l	0.132	hep-ph/9606399	cteq4_d	0.116	hep-ph/9606399
cteq4a2	0.113	hep-ph/9606399	cteq4a1	0.110	hep-ph/9606399
cteq4a4	0.119	hep-ph/9606399	cteq4a3	0.116	hep-ph/9606399
cteq3_l	0.112	MSU-HEP/41024	cteq3_m	0.112	MSU-HEP/41024
			cteq3_d	0.112	MSU-HEP/41024

Table 11: Historical CTEQ-type pdf sets, their corresponding values of $\alpha_S(M_Z)$ and a reference to the paper or preprint that describes their origin.

D Version 8.3 changelog

- New processes 164,169 for off-shell SM and SMEFT single-top-quark and anti-quark production, respectively. With this a new input.DAT block 'Single top SMEFT' is introduced which sets the SMEFT parameters, see description for process 164.
- Improve QCDLoop 2 interface performance with OpenMP. We no longer initialize the library with each call and keep a global cache per thread.
- New dynamic scale 'fixed', which keeps the settings for the fixed scales but runs all dynamicscale code. This is mostly useful for debugging.
- Toggle for rapidity/pseudorapidity in definition of R and jet cuts, in mdata.f.
- 'writetxt' option in input.DAT, which writes each histogram as a plain text file with space-separated columns.
- Add COPYING.txt GPL license file.
- Fixed jets_oppem, which likely had no effect, depending on compiler.

E Version 8.2 changelog

- Implemented H+jet high energy amplitudes [45]. See description for process 200.

F Version 8.1 changelog

- Implemented one-loop electroweak corrections for Z , $t\bar{t}$ and di-jet production.
- Implemented $Z\gamma$ process at NNLO including anomalous couplings [15].
- Implemented $Z\gamma$ decay for $H + jet$ production.
- Implemented $H+2jet$ process with a finite top-quark mass and $H+jet$ with finite top-quark mass effects [47]. This adds a new parameter [mtex] to the the input file, which specifies to which order in $1/m_t^k$ ($k=0,2,4$) the finite part of the virtual corrections are computed.
- Support for random seeds by setting the seed value (previously [ij]) to 0.
- Support for boosted (as opposed to hadronic) definition of jettiness, which is also now as default.
- Support for p_T and rapidity ranges for most cuts in the input file.
- Added native implementation of two PDF sets containing photons (mrstqed, CT14qed).

- Modified format of input file slightly to allow for p_T and rapidity ranges for most cuts.
- **EXPERIMENTAL:** Integration routine that adaptively selects the cross section contribution with the largest integration uncertainty. It also adapts integration calls in the warmup phase and then continuously increases them to not run into grid bias problems. This integration can be enabled by setting `newIntegration` to `.true.` in `Need/mcfmmain.f.` After each iteration a snapshot is saved for resumption. When `readin` is set to `.true.` in the `gridinfo_logic` common block, the integration will be resumed from any stage. Currently this integration mode does not stop the integration, but the user can at any point abort manually when the desired precision has been reached. It has only been thoroughly tested with $Z\gamma$ and H +jet. Other processes might need tweaks or specific initializations.
- Fixed FROOT implementation.
- Upgraded QCDLoop to QCDLoop 2.
- Using new random number generator (Mersenne Twister) from `libstdc++` (C++11).
- Fixed bug concerning integration uncertainty of histogram bins.
- Fixed bug in implementation of H +jet processes with finite top-quark mass effects (201, 202, 206, 207) when using `zerowidth = F.`
- Removed flags `virtonly,realonly,vanillafiles,creategrid` in `input.DAT,` as well as broken parameters for resuming integrations.
- Removed support for PDFLIB.
- Removed `noomp` version. If just a single thread is wanted, please set `OMP_NUM_THREADS` to 1.

G Version 8.0 changelog

- Introduced NNLO capability for color-singlet processes.
- Overall improvement in speed.
- Added native support for additional pdf sets, NNPDF, CT14, MMHT.
- Fixed small asymmetry in calculation of $W + 1$ jet process at NLO.
- Fixed per-mille level bug in NLO calculations of $W, Z, H + 2$ jet processes.
- Replace QCDLoop by QCDLoop 2.

H Version 7.0 changelog

- Implementation of OpenMP (Open Multi-processing)
- Inclusion of four-photon process at NLO, `nproc=289`.
- Inclusion of vector boson fusion/vector boson scattering processes at LO, `nproc=220,2201,222,2221,224,2241,226,228,2281,229,2291,223,2231,225,2251`.
- After Higgs discovery, added s-channel Higgs diagrams to the $gg \rightarrow VV$ process, in VV production processes, `nproc=61,62,64,81-84,86-90`

I Version 6.7 changelog

- Fixed errors reported in histograms
- Changed implementation of PDF uncertainty output for cross sections and histograms; code now differentiates between appropriate calculations for CTEQ and MSTW, NNPDF, Alekhin et al
- Added possibility of (unweighted) LHE output for select LO processes
- Added a check to VEGAS to enable graceful exit if integral is zero
- Included changes to allow production of grids for use with APPLGRID
- Moved $H + b$ processes from `nproc=131,132,133` to `nproc=136,137,138`
- Added effect of massive loops in $gg \rightarrow ZZ$ box process and interference with Higgs diagrams, `nproc=128,129,130,131,132,133`
- Changed implementation of $gg \rightarrow WW$ interference-related processes `nproc=126,127` to the same style as $gg \rightarrow ZZ$, `nproc=123,124,125,126`
- Added 1-loop HH processes, `nproc=601,602`
- Added triphoton process at NLO, `nproc=287`
- Added $W\gamma\gamma$ process at LO, `nproc=370,371`
- New, faster implementation of H+5 parton amplitudes
- Added two new cuts to the input file, `ptmin_photon(3rd)` and `R(photon,jet)_min`
- Added a flag to the input file to control creation of APPLGRID output, `creategrid`
- Changed previous `evtgen` logical flag in input file to an integer, `nevtrequested`
- Added a line in the input file to allow for an anomalous Higgs width for `nproc=128,129,130,131,133`

J Versions 6.6 and 6.5 changelog

- Moved the ttH processes to the 640's
- Added tH and $\bar{t}H$ processes.
- Added tZ and $\bar{t}Z$ processes.
- Added $\gamma + b$ and $\gamma + c$ process at leading order.
- Added $WZ + 2$ parton processes.
- Shuffled 144 and 145.
- Added new Dark Matter mono-jet and mono-photon processes (with process numbers in the 800's)

K Version 6.4 changelog

K.1 Code changes

- Corrected bug in implementation of $H\bar{q}qg$ virtual amplitudes.
- Enabled effect of `removebr` for process 307.
- Fixed the implementation of a dynamic scale for single top + b processes.
- Added a new scale choice for top production ($m(345)^2 + p_T(345)^2$).
- Improved numerical stability in calculation of virtual contribution to process 201 and in calculation of real corrections to processes 180–187.

L Version 6.3 changelog

- Implementation of new processes:
 - Added processes 63,65 giving the radiation in the hadronic decay of the W^+W^- process.
 - Added processes 114 and 115 giving the $gg \rightarrow H \rightarrow WW$ process with radiation in the hadronic decay of the W .
 - Added processes 501–516 giving the production and decay of $t\bar{t}W^\pm$ including radiation in the semi-leptonic decay of the top and the anti-top.
 - Added processes 120 and 121 giving the $H \rightarrow Z/\gamma^*(\rightarrow \bar{l}l) + \gamma$ in the gluon fusion production process
 - Added processes in the range 300–309 describing production of $Z + \gamma + \gamma$ and $Z + \gamma + \text{jet}$ at NLO.

- Process numbers from version 6.2 were moved to make space (e.g. old 64 → 69 and old 63 → 64, old 192 – 198 → 500 – 531.).

L.1 Code changes

- Lengthened the number of characters allowed for the input parameter LHAPDF `group`, that is read from the input file.
- Removed the tacit assumption of unitarity in processes, 13 and 18, subprocess $gg \rightarrow \bar{q}$, allowing arbitrary values of V_{cs} and V_{cd} .
- Corrected closed fermion loop virtual corrections to the $gg \rightarrow Z + 2$ -jet subprocess which were assigned to the wrong helicities in error. This bug was of minor numerical importance.
- Fixed number of jets expected in `nplotter_generic.f` for ZH and WH processes with `removebr=T`.
- Added additional parameters to the input files, especially for powheg style output and photon cuts, as specified in section 3.
- changed `mbook` so that zero bins still appear in the Topdrawer output, (for consistency, especially for combining runs).
- Removed a correction used to debug hadronic W decays, that was erroneously left in the code. The hadronic branching ratio of the W now changes at NLO as it should.
- Corrected bug that led to the W^-t process (187) being calculated incorrectly.
- Removed a bug that caused the real part Higgs+1 jet process (203) to crash (in version 6.2 only).
- Coupling of Higgs boson to top and bottom quarks expressed in terms of the running mass.
- Corrected normalization of pseudoscalar Higgs cross section (processes 206 and 207) and set active quark in the loop to be the top rather than the bottom.

M Version 6.2 changelog

A number of changes to the code and input files have been implemented between v6.1 and v6.2. These are listed below.

M.1 Input file changes

- Implementation of new processes:

- Added process 233-235 and 238-240 that give results in the four-flavour scheme with top decay.
- Added process 270 (Higgs + 2 jets, with Higgs decaying to $\gamma\gamma$).
- Added LO processes 278 and 279 (Higgs + 3 jets with Higgs decaying to WW or ZZ).
- Adding process 90 for identical fermions in ZZ decay.
- Added processes 12 and 17, Wb production from charm quarks

M.2 Code changes

- Included new plotting routines for s-channel single top, 4F t-channel single top and top pair production,
 - `nplotter_ttbbar.f`, `nplotter_4ftwdk.f`, `nplotter_ttbar.f`
- Corrected all nplotter files to ensure ntuple output.
- Added CT10 parton distributions.
- Upgraded treatment of $t\bar{t}$ one-loop matrix elements for processes 141-150 to use results of ref. [3] rather than ref. [37] with consequent improvement in speed.
- Updated check on whether non-zero m_{56} cut is applied to exclude $Z \rightarrow$ neutrino processes (for which is is not needed).
- Removed overcounting of neutrinos for non-resonant diagrams in the ZZ process.
- Removed effect of m_{34} for dirgam process 280. Therefore for this process m_{34} cut is not operative.
- Corrected ZZ processes 80-90 where the Z 's decayed differently to different final states. There was a bug in the gluon-gluon contribution since
 - `gg_ZZ.f`
 did not handle the different couplings for $Z(3+4)$ and $Z(5+6)$ correctly.
- Removed dependence on path in
 - `ffinit_mine.f`
 and modified Install script to create symbolic links.
- Updated handling of anomalous couplings to allow for no form-factors if $\text{tevscale} < 0$, see section 10.22.6.
- Moved processes (151-156 to 141-151), (131, 132 to 251, 252) and (141-143 to 131-133).
- Improved implementation of p_T cut in

`gg_WW.f`, `gg_ZZ.f`

- Added improvements to `mbook.f` for Root histogram errors
- Corrected `masscuts.f` to avoid problems with m_{56} cut.

N Version 6.1 changelog

A number of changes to the code and input files have been implemented between v6.0 and v6.1. These are listed below.

N.1 Input file changes

- Implementation of new processes:
 - Higgs decay modes for various production channels (93, 94, 98, 99, 104, 105, 109, 210, 214, 215).
 - Calculation of $gg \rightarrow H \rightarrow WW$ including exact top and bottom loops (121) and interference with S.M. box diagrams (122).
 - Production of top pairs in association with a W (198, 199).
 - Direct photon production including fragmentation (280).
 - Reorganization of Wb calculations in 4FNS (401-408), 5FNS (411, 416) and when combined (421, 426).
- Addition of flags `writetop`, `writedat`, `writegnu` and `writeroot` to input file, to control writing of output into Topdrawer, plain ascii, gnuplot and root script files.
- New flag to trigger exclusion of gluon-gluon initiated sub-processes (`omitgg`).
- New lines in input file to specify anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings.
- Changed implementation of transverse mass cut (`m34transcut`) to be process-specific (see manual).
- Added fragmentation functions of Gehrmann-de Ridder and Glover (see description of `fragset` in manual).
- Added ability to over-ride switching from a scaling to a fixed isolation cut according to value of `epsilon_h` (see manual).
- Changed the role of `dynamicsscale` from a boolean flag to a string variable specifying the type of dynamic scale to be applied. See manual for description of new scale choices available.

N.2 Code changes

- Re-enabled n-tuple output for processes with specific `nplotter` routines.

- Corrected phase-space generation for diphoton and direct photon production when cut on $p_T(\text{photon})$ is less than cut on $p_T(\text{jet})$.
- Corrected implementation of errors in histogram output.
- Added code to allow histogram output in `gnuplot` and `root` format.
- Corrected virtual amplitudes for WZ production with $Z \rightarrow$ neutrinos (72, 77).
- Corrected implementation of processes 52, 53, 54.
- Implemented anomalous couplings for $W\gamma$ and $Z\gamma$ processes.
- Corrected calculation of $W + 2$ jet and $Z + 2$ jet processes with `Gflag = Qflag = .true.` and a dynamic scale.
- Added non-perturbative contributions to fragmentation functions.
- Fixed implementation of finite m_t correction factor that is applied to $gg \rightarrow H$ cross-sections. Differences with v6.0 for $m_H > 2m_t$ only.
- Added ability to calculate direct photon production including fragmentation contributions.
- Corrected definition of array containing particle momenta in $H + 1$ jet virtual routines (v6.0 results for these processes may be compiler-dependent).
- Corrected implementation of invariant mass cuts for cases when invariant masses do not correspond to electroweak bosons.
- Allowed off-shell W bosons in top decays for processes 36, 151, 152 and 153.

References

- [1] Claude Amsler et al. “Review of Particle Physics”. *Phys. Lett.* B667 (2008), pp. 1–1340. DOI: 10.1016/j.physletb.2008.07.018.
- [2] Simon Badger, John M. Campbell, and R. K. Ellis. “QCD corrections to the hadronic production of a heavy quark pair and a W-boson including decay correlations”. *JHEP* 03 (2011), p. 027. DOI: 10.1007/JHEP03(2011)027. arXiv: 1011.6647 [hep-ph].
- [3] Simon Badger, Ralf Sattler, and Valery Yundin. “One-Loop Helicity Amplitudes for $t\bar{t}$ Production at Hadron Colliders”. *Phys. Rev.* D83 (2011), p. 074020. DOI: 10.1103/PhysRevD.83.074020. arXiv: 1101.5947 [hep-ph].
- [4] Richard D. Ball et al. “Parton distributions for the LHC Run II”. *JHEP* 04 (2015), p. 040. DOI: 10.1007/JHEP04(2015)040. arXiv: 1410.8849 [hep-ph].

- [5] Richard D. Ball et al. “Parton distributions with LHC data”. *Nucl. Phys.* B867 (2013), pp. 244–289. DOI: 10.1016/j.nuclphysb.2012.10.003. arXiv: 1207.1303 [hep-ph].
- [6] Richard D. Ball et al. “A Determination of parton distributions with faithful uncertainty estimation”. *Nucl. Phys.* B809 (2009). [Erratum: Nucl. Phys.B816,293(2009)], pp. 1–63. DOI: 10.1016/j.nuclphysb.2008.09.037, 10.1016/j.nuclphysb.2009.02.027. arXiv: 0808.1231 [hep-ph].
- [7] Zvi Bern, Lance J. Dixon, and David A. Kosower. “One loop amplitudes for $e^+ e^-$ to four partons”. *Nucl. Phys.* B513 (1998), pp. 3–86. DOI: 10.1016/S0550-3213(97)00703-7. arXiv: hep-ph/9708239 [hep-ph].
- [8] Zvi Bern, Lance J. Dixon, and Carl Schmidt. “Isolating a light Higgs boson from the diphoton background at the CERN LHC”. *Phys. Rev.* D66 (2002), p. 074018. DOI: 10.1103/PhysRevD.66.074018. arXiv: hep-ph/0206194 [hep-ph].
- [9] L. Bourhis, M. Fontannaz, and J. P. Guillet. “Quarks and gluon fragmentation functions into photons”. *Eur. Phys. J.* C2 (1998), pp. 529–537. DOI: 10.1007/s100520050158. arXiv: hep-ph/9704447 [hep-ph].
- [10] Matteo Cacciari, Gavin P. Salam, and Gregory Soyez. “The Anti- k_t jet clustering algorithm”. *JHEP* 04 (2008), p. 063. DOI: 10.1088/1126-6708/2008/04/063. arXiv: 0802.1189 [hep-ph].
- [11] J. M. Campbell et al. “NLO QCD predictions for $W + 1$ jet and $W + 2$ jet production with at least one b jet at the 7 TeV LHC”. *Phys. Rev.* D86 (2012), p. 034021. DOI: 10.1103/PhysRevD.86.034021. arXiv: 1107.3714 [hep-ph].
- [12] John M. Campbell and R. Keith Ellis. “Top-Quark Processes at NLO in Production and Decay”. *J. Phys.* G42.1 (2015), p. 015005. DOI: 10.1088/0954-3899/42/1/015005. arXiv: 1204.1513 [hep-ph].
- [13] John M. Campbell, R. Keith Ellis, and Ciaran Williams. “Gluon-Gluon Contributions to $W^+ W^-$ Production and Higgs Interference Effects”. *JHEP* 10 (2011), p. 005. DOI: 10.1007/JHEP10(2011)005. arXiv: 1107.5569 [hep-ph].
- [14] John M. Campbell, J. W. Huston, and W. J. Stirling. “Hard Interactions of Quarks and Gluons: A Primer for LHC Physics”. *Rept. Prog. Phys.* 70 (2007), p. 89. DOI: 10.1088/0034-4885/70/1/R02. arXiv: hep-ph/0611148 [hep-ph].
- [15] John M. Campbell, Tobias Neumann, and Ciaran Williams. “ $Z\gamma$ production at NNLO including anomalous couplings”. *Submitted to: JHEP* (2017). arXiv: 1708.02925 [hep-ph].
- [16] John M. Campbell, Doreen Wackerroth, and Jia Zhou. “Study of weak corrections to Drell-Yan, top-quark pair, and dijet production at high energies with MCFM”. *Phys. Rev.* D94.9 (2016), p. 093009. DOI: 10.1103/PhysRevD.94.093009. arXiv: 1608.03356 [hep-ph].
- [17] John M. Campbell et al. “Associated Production of a W Boson and One b Jet”. *Phys. Rev.* D79 (2009), p. 034023. DOI: 10.1103/PhysRevD.79.034023. arXiv: 0809.3003 [hep-ph].

- [18] Stefano Carrazza, R. Keith Ellis, and Giulia Zanderighi. “QCDLoop: a comprehensive framework for one-loop scalar integrals”. *Comput. Phys. Commun.* 209 (2016), pp. 134–143. DOI: 10.1016/j.cpc.2016.07.033. arXiv: 1605.03181 [hep-ph].
- [19] D. De Florian and A. Signer. “W gamma and Z gamma production at hadron colliders”. *Eur. Phys. J. C* 16 (2000), pp. 105–114. DOI: 10.1007/s100520050007. arXiv: hep-ph/0002138 [hep-ph].
- [20] Stefan Dittmaier and Markus Roth. URL: <http://wwwth.mppmu.mpg.de/members/roth/Lusifer/lusifer.html>.
- [21] Lance J. Dixon, Z. Kunszt, and A. Signer. “Helicity amplitudes for $O(\alpha_s)$ production of W^+W^- , $W^\pm Z$, ZZ , $W^\pm\gamma$, or $Z\gamma$ pairs at hadron colliders”. *Nucl. Phys.* B531 (1998), pp. 3–23. DOI: 10.1016/S0550-3213(98)00421-0. arXiv: hep-ph/9803250 [hep-ph].
- [22] Lance J. Dixon, Z. Kunszt, and A. Signer. “Vector boson pair production in hadronic collisions at order α_s : Lepton correlations and anomalous couplings”. *Phys. Rev.* D60 (1999), p. 114037. DOI: 10.1103/PhysRevD.60.114037. arXiv: hep-ph/9907305 [hep-ph].
- [23] A. Djouadi et al. “The Higgs photon - Z boson coupling revisited”. *Eur. Phys. J. C* 1 (1998), pp. 163–175. DOI: 10.1007/BF01245806. arXiv: hep-ph/9701342 [hep-ph].
- [24] Sayipjamal Dulat et al. “New parton distribution functions from a global analysis of quantum chromodynamics”. *Phys. Rev.* D93.3 (2016), p. 033006. DOI: 10.1103/PhysRevD.93.033006. arXiv: 1506.07443 [hep-ph].
- [25] R. Keith Ellis, W. James Stirling, and B. R. Webber. “QCD and collider physics”. *Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol.* 8 (1996), pp. 1–435.
- [26] R. Keith Ellis and Giulia Zanderighi. “Scalar one-loop integrals for QCD”. *JHEP* 02 (2008), p. 002. DOI: 10.1088/1126-6708/2008/02/002. arXiv: 0712.1851 [hep-ph].
- [27] K. J. Eskola, V. J. Kolhinen, and C. A. Salgado. “The Scale dependent nuclear effects in parton distributions for practical applications”. *Eur. Phys. J. C* 9 (1999), pp. 61–68. DOI: 10.1007/s100520050513, 10.1007/s100529900005. arXiv: hep-ph/9807297 [hep-ph].
- [28] D. de Florian, M. Grazzini, and Z. Kunszt. “Higgs production with large transverse momentum in hadronic collisions at next-to-leading order”. *Phys. Rev. Lett.* 82 (1999), pp. 5209–5212. DOI: 10.1103/PhysRevLett.82.5209. arXiv: hep-ph/9902483 [hep-ph].
- [29] Stefano Frixione. “Isolated photons in perturbative QCD”. *Phys. Lett.* B429 (1998), pp. 369–374. DOI: 10.1016/S0370-2693(98)00454-7. arXiv: hep-ph/9801442 [hep-ph].
- [30] A. Gehrmann-De Ridder and E. W. Nigel Glover. “Final state photon production at LEP”. *Eur. Phys. J. C* 7 (1999), pp. 29–48. DOI: 10.1007/s100520050382, 10.1007/s100529800958. arXiv: hep-ph/9806316 [hep-ph].

- [31] Howard Georgi. “Effective field theory and electroweak radiative corrections”. *Nucl. Phys.* B363 (1991), pp. 301–325. DOI: 10.1016/0550-3213(91)80022-E.
- [32] Christopher J. Glosser and Carl R. Schmidt. “Next-to-leading corrections to the Higgs boson transverse momentum spectrum in gluon fusion”. *JHEP* 12 (2002), p. 016. DOI: 10.1088/1126-6708/2002/12/016. arXiv: hep-ph/0209248 [hep-ph].
- [33] E. W. Nigel Glover and J. J. van der Bij. “Higgs boson pair production via gluon fusion”. *Nucl. Phys.* B309 (1988), pp. 282–294. DOI: 10.1016/0550-3213(88)90083-1.
- [34] Stefano Goria, Giampiero Passarino, and Dario Rosco. “The Higgs Boson Lineshape”. *Nucl. Phys.* B864 (2012), pp. 530–579. DOI: 10.1016/j.nuclphysb.2012.07.006. arXiv: 1112.5517 [hep-ph].
- [35] L. A. Harland-Lang et al. “Parton distributions in the LHC era: MMHT 2014 PDFs”. *Eur. Phys. J. C* 75.5 (2015), p. 204. DOI: 10.1140/epjc/s10052-015-3397-6. arXiv: 1412.3989 [hep-ph].
- [36] R. Kleiss and W. James Stirling. “Top quark production at hadron colliders: Some useful formulae”. *Z. Phys.* C40 (1988), pp. 419–423. DOI: 10.1007/BF01548856.
- [37] J. G. Korner and Z. Merebashvili. “One loop corrections to four point functions with two external massive fermions and two external massless partons”. *Phys. Rev.* D66 (2002), p. 054023. DOI: 10.1103/PhysRevD.66.054023. arXiv: hep-ph/0207054 [hep-ph].
- [38] Hung-Liang Lai et al. “New parton distributions for collider physics”. *Phys. Rev.* D82 (2010), p. 074024. DOI: 10.1103/PhysRevD.82.074024. arXiv: 1007.2241 [hep-ph].
- [39] Fabio Maltoni and Tim Stelzer. “MadEvent: Automatic event generation with MadGraph”. *JHEP* 02 (2003), p. 027. DOI: 10.1088/1126-6708/2003/02/027. arXiv: hep-ph/0208156 [hep-ph].
- [40] Michelangelo L. Mangano et al. URL: <http://mlm.home.cern.ch/mlm/alpgen/>.
- [41] A. D. Martin et al. “Parton distributions for the LHC”. *Eur. Phys. J.* C63 (2009), pp. 189–285. DOI: 10.1140/epjc/s10052-009-1072-5. arXiv: 0901.0002 [hep-ph].
- [42] Tom Melia et al. “Next-to-leading order QCD predictions for W^+W^+jj production at the LHC”. *JHEP* 12 (2010), p. 053. DOI: 10.1007/JHEP12(2010)053. arXiv: 1007.5313 [hep-ph].
- [43] Zoltan Nagy. “Next-to-leading order calculation of three jet observables in hadron hadron collision”. *Phys. Rev.* D68 (2003), p. 094002. DOI: 10.1103/PhysRevD.68.094002. arXiv: hep-ph/0307268 [hep-ph].
- [44] P. Nason, S. Dawson, and R. Keith Ellis. “The Total Cross-Section for the Production of Heavy Quarks in Hadronic Collisions”. *Nucl. Phys.* B303 (1988), pp. 607–633. DOI: 10.1016/0550-3213(88)90422-1.
- [45] Tobias Neumann. “NLO Higgs+jet production at large transverse momenta including top quark mass effects”. *J. Phys. Comm.* 2.9 (2018), p. 095017. DOI: 10.1088/2399-6528/aadfbf. arXiv: 1802.02981 [hep-ph].

- [46] Tobias Neumann and Zack Edward Sullivan. “Off-Shell Single-Top-Quark Production in the Standard Model Effective Field Theory”. *JHEP* 06 (2019), p. 022. DOI: 10.1007/JHEP06(2019)022. arXiv: 1903.11023 [hep-ph].
- [47] Tobias Neumann and Ciaran Williams. “The Higgs boson at high p_T ”. *Phys. Rev. D* 95.1 (2017), p. 014004. DOI: 10.1103/PhysRevD.95.014004. arXiv: 1609.00367 [hep-ph].
- [48] G.J. van Oldenborgh and J.A.M. Vermaseren. “New Algorithms for One Loop Integrals”. *Z.Phys.* C46 (1990), pp. 425–438. DOI: 10.1007/BF01621031.
- [49] G. Passarino and M.J.G. Veltman. “One Loop Corrections for e+ e- Annihilation Into mu+ mu- in the Weinberg Model”. *Nucl.Phys.* B160 (1979), p. 151. DOI: 10.1016/0550-3213(79)90234-7.
- [50] Giampiero Passarino, Christian Sturm, and Sandro Uccirati. “Higgs Pseudo-Observables, Second Riemann Sheet and All That”. *Nucl. Phys.* B834 (2010), pp. 77–115. DOI: 10.1016/j.nuclphysb.2010.03.013. arXiv: 1001.3360 [hep-ph].
- [51] V. Ravindran, J. Smith, and W. L. Van Neerven. “Next-to-leading order QCD corrections to differential distributions of Higgs boson production in hadron hadron collisions”. *Nucl. Phys.* B634 (2002), pp. 247–290. DOI: 10.1016/S0550-3213(02)00333-4. arXiv: hep-ph/0201114 [hep-ph].
- [52] Carl R. Schmidt. “ $H \rightarrow ggg(gqq)$ at two loops in the large- M_t limit”. *Phys. Lett.* B413 (1997), pp. 391–395. DOI: 10.1016/S0370-2693(97)01102-7. arXiv: hep-ph/9707448 [hep-ph].
- [53] Carl Schmidt et al. “CT14QED parton distribution functions from isolated photon production in deep inelastic scattering”. *Phys. Rev. D* 93.11 (2016), p. 114015. DOI: 10.1103/PhysRevD.93.114015. arXiv: 1509.02905 [hep-ph].