MCFM v6.1

A Monte Carlo for FeMtobarn
processes at Hadron Colliders

Users Guide

Authors:

John M. Campbell (johnmc@fnal.gov)
R. Keith Ellis (ellis@fnal.gov)
Ciaran Williams (ciaran@fnal.gov)

Updated: October 17th, 2011

Contents

1 Overview

MCFM is a parton-level Monte Carlo program which 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 relevant references are listed in Appendix A and a record of changes to the code since v6.0 is given in Appendix C.

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 `Install` script may be edited prior to running, to include the locations of the CERN-LIB and LHAPDF libraries, if desired. The code has been developed and tested under Redhat Linux and Mac OSX, using the compiler `gfortran`. Please report any compilation problems under other operating systems to the authors. Note that, as of version 6.0, the code requires a Fortran90 compiler.

The directory structure of the installation is as follows:

- `Doc`. The source for this document.

- `Bin`. The directory containing the executable `mcfm`, 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`. The source files to version 1.9 of the Fortran library QCDLoop [1]. The location of these libraries is set in the `makefile` (by `QLDIR` and `FFDIR`) and may be changed to reflect existing installations if desired.

The files which it is most likely that the user will need to modify are located in `src/User`. It is convenient, if one wants to modify one of these files, (or any other file in the subdirectories of the `src` directory), to copy it first to the directory where the user has installed `mcfm`. The makefile will use this file in preference to the identically named file in the sub-directories of `src`.

3 Input parameters

`MCFM` now 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).

Starting from version 5.2 of the code, the default scheme has been changed from `ewscheme=-1` (as in previous versions) 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 [2].

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

Parameter	Name (_inp)	Input Value	Output Value determined by ewscheme			
			-1	0	1	2
G_F	Gf	1.16639×10^{-5}	input	calculated	input	input
$\alpha(M_Z)$	aemmz	1/128.89	input	input	calculated	input
$\sin^2\theta_w$	xw	0.2312	calculated	input	calculated	input
M_W	wmass	80.398 GeV	input	calculated	input	calculated
M_Z	zmass	91.1876 GeV	input	input	input	calculated
m_t	mt	input.DAT	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. [20].

same role as idef in MadEvent [3]. 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 [4] and LUSIFER [5] 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,

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

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

Parameter	Fortran name	Default value
m_τ	mtau	1.777 GeV
m_τ^2	mtausq	3.1577 GeV^2
Γ_τ	tauwidth	2.269×10^{-12} GeV
Γ_W	wwidth	2.141 GeV
Γ_Z	zwidth	2.4952 GeV
V_{ud}	Vud	0.975
V_{us}	Vus	0.222
V_{ub}	Vub	0.
V_{cd}	Vcd	0.222
V_{cs}	Vcs	0.975
V_{cb}	Vcb	0.

Table 2: Default values for the remaining parameters in MCFM. Γ_W and Γ_Z from ref. [20].

are included with MCFM. The distributions, together with their associated $\alpha_S(M_Z)$ values, are given in Table 3. For the older distributions, where the coupling was specified by Λ this requires some calculation and/or guesswork.

By editing the Makefile, it is straightforward to switch to either the PDFLIB or the LHAPDF parton distribution function implementations.

To use PDFLIB, one must first set the variable CERNLIB in the makefile to point to the directory that contains libpdflib804.a and then modify PDFROUTINES to take the value PDFLIB. The parameters to choose the pdf set are then specified in Bin/input.DAT.

To use LHAPDF, one must first set the variable LHAPDFLIB in the makefile to point to the directory that contains libLHAPDF.a and then modify PDFROUTINES to take the value LHAPDF. Note that, in newer versions of LHAPDF, it may be easier to link against the static LHAPDF libraries by passing a "-static" flag to the compiler via the FFLAGS variable in the makefile, rather than using the (default) shared libraries. Particularly when compiling against both LHAPDF and CERNLIB, it may be useful to link only LHAPDF in a static manner. This can be achieved using g77, for instance, by replacing "-lLHAPDF" with "-Wl,-Bstatic -lLHAPDF -Wl,-Bdynamic" in the makefile. This version of MCFM has been explicitly tested against LHAPDF-5.5.0.

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. `MCFM` expects to find the sets in a sub-directory of `Bin` called `PDFsets`, as in the `LHAPDF` distribution. It is easiest to simply create a symbolic link appropriately.

One may always return to the built-in distributions by resetting `PDFROUTINES` to take the value `NATIVE` in the makefile, (and recompiling).

4 Runtime options

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

`mcfm [`*mydir*`] [`*myfile*`.DAT]`

The executable `mcfm` is automatically moved to `Bin` by the makefile. If no command line options are given, then `mcfm` will default to using the file `input.DAT` in the current directory for choosing options[1]. The different possibilities are summarized in Table 4. 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`]

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]`

- `evtgen`. The default for this, and the following three parameters, is `.false.` and this corresponds to the usual mode of operation. It

[1]Note 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.

is possible to generate n-tuples instead of histograms, as well as unweighted events, for some processes. Please refer to Section 6.2 for further details.

- `creatent`. *See above.*
- `skipnt`. *See above.*
- `dswhisto`. *See above.*
- `writetop`. Flag to control whether or not a Topdrawer histogram output file is produced. Please refer to Section 6 for further details.
- `writedat`. Flag to control whether or not the plain histogram output file is produced. Please refer to Section 6 for further details.
- `writegnu`. Flag to control whether or not a gnuplot histogram output file is produced. Please refer to Section 6 for further details.
- `writeroot`. Flag to control whether or not a ROOT script for plotting histograms is produced. Please refer to Section 6 for further details.

{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 7 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 [28].
- `part`. This parameter has 5 possible values, described below:
  - `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.
- `tota`. For simplicity, the `tota` 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. In practice, it may be more efficient to do run the pieces separately by hand, (c.f. `ncall` below. For photon processes that include fragmentation, `tota` also includes the calculation of the fragmentation (`frag`) contributions.
- `todk` Processes 161,166,171,176,181,186 only, see sections 7.31 and 7.32 below.
- `frag`. Processes 280, 285, 290, 295 and 300 only, see sections 7.44, 7.45 and 7.46 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 5.

- `hmass`. For processes involving the Higgs boson, this parameter should be set equal to the putative 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 5. 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,

  $$\mu_{\rm ren} = \texttt{scale} \times \mu_0 \ , \qquad \mu_{\rm fac} = \texttt{facscale} \times \mu_0 \ , \qquad \mu_{\rm frag} = \mu_{\rm ren} \ . \quad (2)$$

  Note that, for simplicity, the fragmentation scale (relevant only for processes involving photons) is set equal to the renormalization scale.

- `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 7 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 `ncall1` and `ncall2`. 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.

- `ij`. This is the seed for the `VEGAS` integration and can be altered to give different results for otherwise identical runs.

- `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 `ncall1` points each)

- `Qflag`. This only has an effect when running a $W + 2$ jets or $Z + 2$ jets process. Please see section 7.7 below.

- `Gflag`. This only has an effect when running a $W + 2$ jets or $Z + 2$ jets process. Please see section 7.7 below.

{blank line}
`[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).

{blank line}
`[Pdf selection]`

- `pdlabel`. The choice of parton distribution is made by inserting the appropriate 7-character code from Table 3 here. As mentioned above, this also sets the value of $\alpha_S(M_Z)$.

- `NGROUP, NSET`. These integers choose the parton distribution functions to be used when using the PDFLIB package.

- `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. Please see `http://durpdg.dur.ac.uk/lhapdf/` for further details. 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 6.1, especially the caveat regarding using non-grid PDF sets).

{blank line}
`[Jet definition and event cuts]`

- `m34min`, `m34max`, `m56min`, `m56max`. 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), `ankt` (for the "anti-k_T" algorithm [6]), `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, $q\bar{q}' \to t\bar{b}$, which is finite as $p_T(\bar{b}) \to 0$.

- `ptjet_min, |etajet|_min, |etajet|_max`. These specify the values of $p_{T,\mathrm{min}}$, $|\eta|_{\mathrm{min}}$ and $|\eta|_{\mathrm{max}}$ for the jets that are found by the algorithm.

- `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 $\Delta R >$ `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`.

- `ptlepton_min, |etalepton|_max`. These specify the values of $p_{T,\min}$ and $|\eta|_{\max}$ for the hardest lepton produced in the process.

- `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.

- `mtrans34cut`. For general processes, this specifies the minimum transverse mass of particles 3 and 4,

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

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

$$W\gamma: \quad \left[\sqrt{m^2_{\ell\gamma} + |\vec{p_T}(\ell) + \vec{p_T}(\gamma)|^2} + p_T(\nu)\right]^2 - |\vec{p_T}(\ell) + \vec{p_T}(\gamma) + \vec{p_T}(\nu)|^2 > \texttt{mtrans34cut}^2 \tag{4}$$

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

$$Z\gamma: \quad m_{Z\gamma} > \texttt{mtrans34cut} \tag{5}$$

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:

$$\begin{aligned} W\gamma, \text{obsolete}: \quad & [p_T(\ell) + p_T(\gamma) + p_T(\nu)]^2 \\ - \quad & |\vec{p_T}(\ell) + \vec{p_T}(\gamma) + \vec{p_T}(\nu)|^2 > |\texttt{mtrans34cut}| \end{aligned} \quad (6)$$

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

- `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_opphem`. 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` : $\eta^{j-} < \eta^{\text{leptons}} < \eta^{j+}$;
  `lepbtwnjets_scheme = 2` : $\eta^{j-}+$`Rcut_jet` $< \eta^{\text{leptons}} < \eta^{j+}-$`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 $|\eta|^{\text{max}}$ for b-jets.

{blank line}
`[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 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 [28],

$$\sum_{i \in R_0} E^j_{T,i} < \epsilon_h E^\gamma_T \Big(\frac{1-\cos R_{i\gamma}}{1-\cos R_0} \Big)^n \ . \tag{7}$$

In this equation, R_0 and ϵ_h are defined by `cone_ang` and `epsilon_h` respectively (see below). $E^j_{T,i}$ is the transverse energy of a parton, E^γ_T 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`', '`BFGSetII`' [7] or '`GdRG__LO`' [8].

- `frag_scale`. A double precision variable that will be used to choose the scale at which the photon fragmentation is evaluated.

- `ptminphoton, etamaxphoton`. These specify the values of $p_T^{\rm min}$ and $|y|^{\rm max}$ for any photons produced in the process. Note that these cuts on the photons, as well as all the other cuts specified in this section of the input file, are applied even if `makecuts` is set to `.false.`.

- `R(photon,lept)_min`. Using the usual definition of ΔR, this requires that all photon-lepton pairs are separated by $\Delta R >$ `R(photon,lept)_min`. This parameter must be non-zero for processes in which photon radiation from leptons is included.

- `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 $\sum_{\in R_0} E_T(\mathrm{had}) < \epsilon_h\, p_T^\gamma$. Otherwise `epsilon_h` > 1 sets $E_T(max)$ in $\sum_{\in R_0} E_T(\mathrm{had}) < E_T(max)$. 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 Frixione isolation prescription (see above, Eq. (7)).

{blank line}
`[Anomalous couplings of the W and Z]`

- `Delta_g1(Z)`. *See section 7.20.*
- `Delta_K(Z)`. *See section 7.20.*
- `Delta_K(gamma)`. *See sections 7.20 and 7.45.*
- `Lambda(Z)`. *See section 7.20.*
- `Lambda(gamma)`. *See sections 7.20 and 7.45.*
- `h1(Z)`. *See section 7.46.*
- `h1(gamma)`. *See section 7.46.*
- `h2(Z)`. *See section 7.46.*
- `h2(gamma)`. *See section 7.46.*
- `h3(Z)`. *See section 7.46.*
- `h3(gamma)`. *See section 7.46.*
- `h4(Z)`. *See section 7.46.*
- `h4(gamma)`. *See section 7.46.*
- `Form-factor scale, in TeV`. *See section 7.20.*

{blank line}
`[How to resume/save a run]`

- `readin`. If `.true.`, the program will read in a previously saved `VEGAS` grid from the file specified by `ingridfile.grid`. Note that this, and the following 3 options, have no effect if `part` is set to `tota` (in this case, grids are automatically saved and loaded as part of the calculation).

- `writeout`. If `.true.`, the program will write out the `VEGAS` grid at the end of the run, to the file specified by `outgridfile.grid`.
- `ingridfile`. *See above.*
- `outgridfile`. *See above.*

The final section of the input file contains settings for various technical parameters that should not normally need to be changed. Prior to version 5.5, these were set in `technical.DAT`. For backwards compatibility they may still be specified in that file too, although they will be over-ridden by any settings here.

{blank line}

`[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`.
- `virtonly`. A logical variable. The default value for this variable is false. If virtonly is set to true, during the running of the real part, the effect of real radiation is neglected, and only the effect of the integrated dipoles is retained.
- `realonly`. A logical variable. The default value for this variable is false. If realonly is set to true, during the running of the real part, the effect of integrated dipoles is neglected, and only the effect of the real radiation is retained.
- `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.

- `vanillafiles`. A logical variable. The default value is false. If set to true, the output files have the generic names `mcfm-output.top` and `mcfm-output.dat`. In addition the path to the parton distribution files is truncated so that they are expected to be found in the same directory as the executable `mcfm`.

- `nmin` A technical parameter used in alternative phase space generating routines.

- `nmax` A technical parameter used in alternative phase space generating routines.

- `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 structure 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 [9]. 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 [9]. The value `afi=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 [9]. 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 [9]. 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. In this version it is not yet operative.

- `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. In this version it is not yet operative.

5 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:

$$\texttt{ih} = 1000Z + A. \tag{8}$$

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 [10] 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.

6 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 two estimates of the PDF uncertainty are also supplied in the regular output and also echoed to the file, `pdferrors.res`. The first estimate corresponds to the `HEPDATA` method, using the explicit formula given in Eqn. (43) of Ref. [11]. The second is the so-called MC prescription, described in detail in Appendix B of Ref. [12] [2].

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`.

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

- `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` file[3], `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_pdlabel_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 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_generic.f`. The arguments of the plotting subroutines (both process-specific and generic) 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).

6.1 Histograms

Extra histograms may be added to the plotting files, e.g. `nplotter_generic.f` in a fairly straightforward manner. Each histogram is filled by making a call

[3]For information on obtaining and using `gnuplot`, visit http://www.gnuplot.info/.

to the routine `bookplot` and updating the histogram counter `n` by 1. For example:

```
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, which is obtained by choosing the extremal values of the

weights in all PDF sets, on a bin-by-bin basis. Thus the resulting error limits are not simply described by a single PDF set.

6.2 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.

6.2.1 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.

6.2.2 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).

6.2.3 Unweighted events

Note that this option is both extremely limited and inefficient.

In order to obtain *unweighted* events, one must change the flag `evtgen` to `.true.` . This option is only available at lowest order at present. 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. In this mode the program will also assign identities to the particles in the initial state, according to the relative parton-parton luminosities. The routines that handle most of the processing can be found in `src/User/eventhandler.f`. Much of this code was tailored to diboson production in Run II of the Tevatron, so further work by the user is almost certainly required.

7 Notes on specific processes

Note that, as of version 4.0, the version of each process described in the file`process.DAT` includes all appropriate boson decays. This is the calculation that is performed when the parameter `removebr` is set to `.false.` , as indicated above.

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.` also, for consistency. However in certain circumstances, for the sake of comparison, it may be useful to run with it set to `.false.` .

7.1 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.

7.2 $W+$ 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.

7.3 $W + c$ 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.

7.4 $W + c$ 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.

7.5 $W + b\bar{b}$ 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. [13]. 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 7.51). These processes use the same matrix elements but make specific requirements on the kinematics of the b-quarks and QCD radiation.

7.6 $W + b\bar{b}$ 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.

7.7 $W + 2$ 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. [14].

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.

7.8 $W + 3$ 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.

7.9 $W + b\bar{b}+$ 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.

7.10 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.

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

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

7.12 $t\bar{t}$ production mediated by $Z/\gamma^{\star}$-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.

7.13 $Z+$ 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.

7.14 $Z + 2$ 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 7.7 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. [14].

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

7.15 $Z + 3$ 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.

7.16 $Z + b\bar{b}$ 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.

7.17 $Z + b\bar{b}$ 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.

7.18 $Z + b\bar{b}+$ 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.

7.19 $Z + c\bar{c}$ 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.

7.20 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_1V_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=64,66`. There are various possibilities for the subsequent decay of the bosons, as specified in the sections below. Amplitudes are taken from ref. [15]. Where appropriate, these processes include glue-glue 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.`.

7.20.1 WW production, processes 61-64

For WW production, both W's can decay leptonically (`nproc=61`) or one may decay hadronically (`nproc=62` for W^- and `nproc=63` for W^+). Process `64` 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. Note that, in processes `62` and `63`, the NLO corrections do not include radiation from the hadronic decays of the W.

The NLO calculations include contributions from the process $gg \to WW$ 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 `64`, the W bosons do not decay.

7.20.2 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.

7.20.3 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.

7.20.4 ZZ production, processes 81–84, 86–89

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.

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

7.20.5 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.

7.20.6 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. [16]):

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

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 included in `MCFM` only after suppression by dipole form factors,

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

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 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.

7.21 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.

7.22 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.

7.23 Higgs production, processes 111–117

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`) or a ZZ pair. For the case of a ZZ decay, the subsequent decays can either be into a pair of muons and a pair of electrons (`nproc=114`), a pair of electrons and neutrinos (`nproc=115`) or a pair of muons and a pair of bottom quarks (`nproc=116`).

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. The calculation may be performed at NLO, although radiation from the bottom quarks in the decay of processes `111` and `116` is not included.

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

$$\frac{\sigma_{\rm LO}(gg \to H, \text{finite } m_t)}{\sigma_{\rm LO}(gg \to H, m_t \to \infty)} \,. \tag{9}$$

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`–`114`, the Higgs boson does not decay.

Process `117` 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. [17]. When `removebr` is true in process `117` the Higgs boson does not decay.

7.24 $H \to W^+W^+$+ production, processes 121,122

These processes represent the production of a Higgs boson that decays to W^+W^-, with subsequent decay into leptons. For process `121`, 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.

For process 122 the cross section also includes the effect of the interference of the Higgs and $gg \to W^+W^-$ amplitudes, as described in ref. [18]. 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.

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

7.25 W^+W^++jets production, processes 131,132

These processes represent the production of two W^+ bosons in association with two (process 131) or three (process 132) 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. [19]. `removebr` is not implemented and has no effect.

7.26 $H + b$ production, processes 141–143

[*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=141`. For a NLO calculation, the sequence of runs is as follows:

- Run `nproc=141` with `part=virt` and `part=real` (or, both at the same time using `part=tota`);

- Run `nproc=142` 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=143` with `part=real`.

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

7.27 $t\bar{t}$ production with decay, processes 151–153

These processes describe $t\bar{t}$ production including two leptonic decays $t \to bl\nu$ (process `151`) and one leptonic and one hadronic decay (`152`). The computation may be performed at NLO, using the virtual amplitudes presented in ref. [21].

Switching `zerowidth` from `.true.` to `.false.` only affects the W bosons from the top quark decay. When `removebr` is true in process `151`, the top quarks do not decay.

In the case of process 153, 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.

7.28 $t\bar{t}$ production with decay and a gluon, process 156

This process describes lowest order $t\bar{t} + g$ production including two leptonic decays $t \to bl\nu$. The input flag `zerowidth` must be set to true for this case.

When `removebr` is true, the top quarks do not decay.

7.29 $Q\overline{Q}$ 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. [22]. No decays are included.

7.30 $t\bar{t}$+ 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.

7.31 Single top production, processes 161–177

[*For more details on this calculation, please refer to 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.

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.

7.32 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, $gg \to Wtb$. 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.

7.33 $Ht\bar{t}$ production, processes 190 and 191

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 `190`, neither the top quarks nor the Higgs boson decays. In process `191`, 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 `191` both the top quarks decay leptonically and the Higgs boson decays into a pair of bottom quarks. Consistency with the simpler process (`190`) can be demonstrated by running process `191` with `removebr` set to true.

7.34 $Zt\bar{t}$ production, processes 196 and 197

These processes represent the production of a Z boson in association with a pair of top quarks which both decay leptonically. 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 `196` the Z boson decays into an electron pair, whilst in `197` the decay is into a massless bottom quark pair. The calculations can be performed at LO only.

When `removebr` is true in process `196`, the top quarks and the Z boson do not decay.

7.35 $W^{\pm}t\bar{t}$ production, processes 198 and 199

These processes represent the production of a W boson in association with a pair of top quarks which both decay semi-leptonically. 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 W bosons (both the directly produced one and from the top quark decay).

When `removebr` is true in processes `198` and `199`, the W boson does not decay.

7.36 $H+$ 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`).

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 [23] and [24]. Phenomenological results have previously been given in refs. [25],[23] and [26]. 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.

7.37 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.

7.38 $\tau^+\tau^-$ 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. [27].

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

7.39 t-channel single top with an explicit b-quark, processes 231–237

[*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.

7.40 $Z + Q$ 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.

7.41 $H + 2$ jet production, processes 271–274

These processes represent the production of a Standard Model Higgs boson in association with two jets. The Higgs boson subsequently decays to either a 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.

7.42 $H + 3$ jet production, processes 275, 276

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`).

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.

7.43 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.

7.44 $\gamma\gamma$ production, processes 285-286

These processes represent the production 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 [28] or standard cone isolation. This process also includes the one-loop gluon-gluon contribution as given in ref. [29]. 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.

Process `285` can be run using different cuts for each photon. Setting the first 9 characters of the runstring to `Stag_phot` will apply the following default cuts:

$p_T^{\gamma_1} > 40$ GeV, $p_T^{\gamma_2} >$ `ptmin_photon` GeV, $|\eta^{\gamma_i}| <$ `etamax_photon`

These values can be changed by editing the file photon_cuts.f in src/User.

7.45 $W\gamma$ 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 $W \to \ell\nu$ 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. [15].

The calculation of processes `290` and `295` may be performed at NLO using the Frixione algorithm [28] 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.

7.45.1 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. [30]. Including only dimension 6 operators or less and demanding gauge, C and CP invariance gives the general form of the anomalous vertex [30],

$$\begin{aligned}\Gamma^{\alpha\beta\mu}_{WW\gamma}(q,\bar{q},p) &= \bar{q}^{\alpha}g^{\beta\mu}\Big(2+\Delta\kappa^{\gamma}+\lambda^{\gamma}\frac{q^2}{M_W^2}\Big)-q^{\beta}g^{\alpha\mu}\Big(2+\Delta\kappa^{\gamma}+\lambda^{\gamma}\frac{\bar{q}^2}{M_W^2}\Big)\\ &\quad+(\bar{q}^{\mu}-q^{\mu})\Big[-g^{\alpha\beta}\Big(1+\frac{1}{2}p^2\frac{\lambda^{\gamma}}{M_W^2}\Big)+\frac{\lambda^{\gamma}}{M_W^2}p^{\alpha}p^{\beta}\Big], \quad (10)\end{aligned}$$

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 7.20. In particular, these couplings are included in MCFM only after suppression by dipole form factors,

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

In these formulae, $\hat{s}$ is the $W\gamma$ pair invariant mass and Λ is an additional parameter giving the scale of new physics that should also be provided in the input file.

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

7.46 $Z\gamma$ production, processes 300-305

Processes 300 and 305 represent the production of a Z boson (or virtual photon) in association with a real photon. 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 $Z\to e^-e^+$ (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. Virtual amplitudes are taken from ref. [15]. The calculation of processes `300` may be performed at NLO using the Frixione algorithm [28] or standard isolation. Process `302` represents the production of a Z boson (or virtual photon) in association with a real photon and an additional jet. This process may be calculated at leading order only. When `removebr` is true in process `300` or `302` the Z boson does not decay.

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.

7.46.1 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, making use of the amplitudes calculated in Ref. [30]. 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 [30],

$$\Gamma^{\alpha\beta\mu}_{Z\gamma Z}(q_1,q_2,p) = \frac{i(p^2-q_1^2)}{M_Z^2}\Bigg(h_1^Z(q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}) + \frac{h_2^Z}{M_Z^2}p^\alpha\Big(p\cdot q_2\; g^{\mu\beta} - q_2^\mu p^\beta\Big) - h_3^Z\varepsilon^{\mu\alpha\beta\nu}q_{2\,\nu} - \frac{h_4^Z}{M_Z^2}\varepsilon^{\mu\beta\nu\sigma}p^\alpha p_\nu q_{2\,\sigma}\Bigg) \quad (11)$$

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 $q_1^2 \to 0$ and replacing $h_i^Z \to h_i^\gamma$. The parameters that specify the anomalous couplings, h_i^Z and h_i^γ (for $i = 1\ldots4$), are specified in the input file as, e.g. `h1(Z)` and `h1(gamma)`. Moreover, these couplings are included in `MCFM` only after suppression by dipole form factors,

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

In these formulae, $\hat{s}$ is the $Z\gamma$ pair invariant mass and Λ is an additional parameter giving the scale of new physics that should also be provided in

the input file. Note that these form factors are slightly different from those discussed in Sections 7.20 and 7.45.

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

7.47 $W + Q+$ 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.

7.48 $W + c+$ 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.

7.49 $Z + Q+$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.

7.50 $c\overline{s} \to W^+$, 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, $g\overline{s} \to W^+\overline{c}$. 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`.

7.51 $W+Q$ 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 7.5), 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 6. An additional flag is hard-coded into the file `src/User/filterWbbmas.f` to control the inclusion of the 3-jet configuration, $(b, \overline{b}, j)$. By default this is omitted, `veto3jets =`

`.true.`. If this flag is set to `.false.` and `inclusive` set to `.true.` then the $(b, \bar{b}, j)$ contribution is 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.

7.52 $W+Q$ 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^-).

7.53 $W + Q$ 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 7.51. The procedure for combining the two calculations is described in refs. [31, 32].

7.54 $W + b\bar{b}+$ 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.

Acknowledgments

We are happy to acknowledge Fabrizio Caola, Fabio Maltoni, Francesco Tramontano and Giulia Zanderighi for their contributions to the code.

A MCFM references

The preferred reference to the program depends upon the process under study. The relevant papers 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 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. Wackeroth 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]].

- J. M. Campbell, R. K. Ellis and C. Williams,
  "Vector boson pair production at the LHC,"
  FERMILAB-PUB-11-182-T, [arXiv:1105.0020 [hep-ph]].

- F. Caola, J. M. Campbell, F. Febres Cordero, L. Reina and D. Wackeroth,
  "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,"
  arXiv:1107.5569 [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].

mstw8lo	0.1394	0901.0002 [hep-ph]	mstw8nl	0.1202	0901.0002 [hep-ph]
mstw8nn	0.1171	0901.0002 [hep-ph]	mrs02nl	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	mrs01lo	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
cteq66m	0.118	0802.0007 [hep-ph]	cteq61m	0.118	hep-ph/0303013
cteq6_m	0.118	hep-ph/0201195	cteq6_d	0.118	hep-ph/0201195
cteq6_l	0.118	hep-ph/0201195	cteq6l1	0.130	hep-ph/0201195
cteq5hq	0.118	hep-ph/9903282	cteq5f3	0.106	hep-ph/9903282
cteq5f4	0.112	hep-ph/9903282	cteq5_m	0.118	hep-ph/9903282
cteq5_d	0.118	hep-ph/9903282	cteq5_l	0.127	hep-ph/9903282
cteq5l1	0.127	hep-ph/9903282	cteq5hj	0.118	hep-ph/9903282
cteq5m1	0.118	hep-ph/9903282	ctq5hq1	0.118	hep-ph/9903282
cteq4a5	0.122	hep-ph/9606399	cteq4hj	0.116	hep-ph/9606399
cteq4lq	0.114	hep-ph/9606399	cteq4_m	0.116	hep-ph/9606399
cteq4_d	0.116	hep-ph/9606399	cteq4_l	0.132	hep-ph/9606399
cteq4a1	0.110	hep-ph/9606399	cteq4a2	0.113	hep-ph/9606399
cteq4a3	0.116	hep-ph/9606399	cteq4a4	0.119	hep-ph/9606399
cteq3_m	0.112	MSU-HEP/41024	cteq3_l	0.112	MSU-HEP/41024
cteq3_d	0.112	MSU-HEP/41024			

Table 3: Available pdf sets, their corresponding values of $\alpha_S(M_Z)$ and a reference to the paper or preprint that describes their origin.

Command executed	Location of input file
`mcfm`	`input.DAT`
`mcfm myfile.DAT`	`myfile.DAT`
`mcfm mydir`	`mydir/input.DAT`
`mcfm mydir myfile.DAT`	`mydir/myfile.DAT`

Table 4: Summary of command line options for running `mcfm`.

`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)`	$M^2+(\vec{p_{T_3}}+\vec{p_{T_4}})^2$	M = mass of particle 3+4
`sqrt(M^2+pt5^2)`	$M^2+\vec{p_{T_5}}^2$	M = mass of particle 3+4
`pt(photon)`	$\vec{p_{T_\gamma}}^2$	
`HT`	$\sum_{i=1}^{n} p_{Ti}$	n final state particles (partons, not jets)

Table 5: Choices of the input parameter `dynamicscale` that result in an event-by-event calculation of all relevant scales using the given reference scale-squared μ_0^2.

Process (W^+/W^-)	`inclusive=.false.`	`inclusive=.true.`
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 6: 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.

B Processes included in MCFM

nproc	$f(p_1) + f(p_2) \to \ldots$	Order
1	$W^+(\to \nu(p_3) + e^+(p_4))$	NLO
6	$W^-(\to e^-(p_3) + \bar{\nu}(p_4))$	NLO
11	$W^+(\to \nu(p_3) + e^+(p_4)) + f(p_5)$	NLO
13	$W^+(\to \nu(p_3) + e^+(p_4)) + \bar{c}(p_5)$	NLO
14	$W^+(\to \nu(p_3) + e^+(p_4)) + \bar{c}(p_5)$[massless]	LO
16	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + f(p_5)$	NLO
18	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + c(p_5)$	NLO
19	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + c(p_5)$[massless]	LO
20	$W^+(\to \nu(p_3) + e^+(p_4)) + b(p_5) + \bar{b}(p_6)$[massive]	NLO
21	$W^+(\to \nu(p_3) + e^+(p_4)) + b(p_5) + \bar{b}(p_6)$	NLO
22	$W^+(\to \nu(p_3) + e^+(p_4)) + f(p_5) + f(p_6)$	NLO
23	$W^+(\to \nu(p_3) + e^+(p_4)) + f(p_5) + f(p_6) + f(p_7)$	LO
24	$W^+(\to \nu(p_3) + e^+(p_4)) + b(p_5) + \bar{b}(p_6) + f(p_7)$	LO
25	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + b(p_5) + \bar{b}(p_6)$[massive]	NLO
26	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + b(p_5) + \bar{b}(p_6)$	NLO
27	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + f(p_5) + f(p_6)$	NLO
28	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + f(p_5) + f(p_6) + f(p_7)$	LO
29	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + b(p_5) + \bar{b}(p_6) + f(p_7)$	LO
31	$Z^0(\to e^-(p_3) + e^+(p_4))$	NLO
32	$Z^0(\to 3 \times (\nu(p_3) + \bar{\nu}(p_4)))$	NLO
33	$Z^0(\to b(p_3) + \bar{b}(p_4))$	NLO
34	$Z^0(\to 3 \times (d(p_5) + \bar{d}(p_6)))$	NLO
35	$Z^0(\to 2 \times (u(p_5) + \bar{u}(p_6)))$	NLO
36	$Z \to t(\to \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\to \bar{b}(p_6) + e^-(p_7) + \bar{\nu}(p_8))$	LO
41	$Z^0(\to e^-(p_3) + e^+(p_4)) + f(p_5)$	NLO
42	$Z_0(\to 3 \times (\nu(p_3) + \bar{\nu}(p_4))) + f(p_5)$	NLO
43	$Z^0(\to b(p_3) + \bar{b}(p_4)) + f(p_5)$	NLO
44	$Z^0(\to e^-(p_3) + e^+(p_4)) + f(p_5) + f(p_6)$	NLO
45	$Z^0(\to e^-(p_3) + e^+(p_4)) + f(p_5) + f(p_6) + f(p_7)$	LO
46	$Z^0(\to 3 \times (\nu(p_3) + \bar{\nu}(p_4)) + f(p_5) + f(p_6)$	NLO
47	$Z^0(\to 3 \times (\nu(p_3) + \bar{\nu}(p_4)) + f(p_5) + f(p_6) + f(p_7)$	LO
50	$Z^0(\to e^-(p_3) + e^+(p_4)) + \bar{b}(p_5) + b(p_6)$[massive]	LO
51	$Z^0(\to e^-(p_3) + e^+(p_4)) + b(p_5) + \bar{b}(p_6)$	NLO
52	$Z_0(\to 3 \times (\nu(p_3) + \bar{\nu}(p_4))) + b(p_5) + \bar{b}(p_6)$	NLO
53	$Z^0(\to b(p_3) + \bar{b}(p_4)) + b(p_5) + \bar{b}(p_6)$	NLO
54	$Z^0(\to e^-(p_3) + e^+(p_4)) + b(p_5) + \bar{b}(p_6) + f(p_7)$	LO

56	$Z^0(\to e^-(p_3)+e^+(p_4))+c(p_5)+\bar{c}(p_6)$	NLO
61	$W^+(\to \nu(p_3)+e^+(p_4))+W^-(\to e^-(p_5)+\bar{\nu}(p_6))$	NLO
62	$W^+(\to \nu(p_3)+e^+(p_4))+W^-(\to q(p_5)+\bar{q}(p_6))$	NLO
63	$W^+(\to q(p_3)+\bar{q}(p_4))+W^-(\to e^-(p_5)+\bar{\nu}(p_6))$	NLO
64	$W^+(\to \nu(p_3)+e^+(p_4))+W^-(\to e^-(p_5)+\bar{\nu}(p_6))$[no pol]	LO
66	$W^+(\to \nu(p_3)+e^+(p_4))+W^-(\to e^-(p_5)+\bar{\nu}(p_6))+f(p_7)$	LO
71	$W^+(\to \nu(p_3)+\mu^+(p_4))+Z^0(\to e^-(p_5)+e^+(p_6))$	NLO
72	$W^+(\to \nu(p_3)+\mu^+(p_4))+Z^0(\to 3\times(\nu_e(p_5)+\bar{\nu}_e(p_6)))$	NLO
73	$W^+(\to \nu(p_3)+\mu^+(p_4))+Z^0(\to b(p_5)+\bar{b}(p_6))$	NLO
74	$W^+(\to \nu(p_3)+\mu^+(p_4))+Z^0(\to 3\times(d(p_5)+\bar{d}(p_6)))$	NLO
75	$W^+(\to \nu(p_3)+\mu^+(p_4))+Z^0(\to 2\times(u(p_5)+\bar{u}(p_6)))$	NLO
76	$W^-(\to \mu^-(p_3)+\bar{\nu}(p_4))+Z^0(\to e^-(p_5)+e^+(p_6))$	NLO
77	$W^-(\to e^-(p_3)+\bar{\nu}(p_4))+Z^0(\to 3\times(\nu(p_5)+\bar{\nu}(p_6)))$	NLO
78	$W^-(\to e^-(p_3)+\bar{\nu}(p_4))+Z^0(\to b(p_5)+\bar{b}(p_6))$	NLO
79	$W^-(\to e^-(p_3)+\bar{\nu}(p_4))+Z^0(\to 3\times(d(p_5)+\bar{d}(p_6)))$	NLO
80	$W^-(\to e^-(p_3)+\bar{\nu}(p_4))+Z^0(\to 2\times(u(p_5)+\bar{u}(p_6)))$	NLO
81	$Z^0(\to \mu^-(p_3)+\mu^+(p_4))+Z^0(\to e^-(p_5)+e^+(p_6))$	NLO
82	$Z^0(\to e^-(p_3)+e^+(p_4))+Z^0(\to 3\times(\nu(p_5)+\bar{\nu}(p_6)))$	NLO
83	$Z^0(\to e^-(p_3)+e^+(p_4))+Z^0(\to b(p_5)+\bar{b}(p_6))$	NLO
84	$Z^0(\to b(p_3)+\bar{b}(p_4))+Z^0(\to 3\times(\nu(p_5)+\bar{\nu}(p_6)))$	NLO
85	$Z^0(\to e^-(p_3)+e^+(p_4))+Z^0(\to 3\times(\nu(p_5)+\bar{\nu}(p_6)))+f(p_7)$	LO
86	$Z^0(\to \mu^-(p_3)+\mu^+(p_4))+Z^0(\to e^-(p_5)+e^+(p_6))$[no gamma*]	NLO
87	$Z^0(\to e^-(p_3)+e^+(p_4))+Z^0(\to 3\times(\nu(p_5)+\bar{\nu}(p_6)))$[no gamma*]	NLO
88	$Z^0(\to e^-(p_3)+e^+(p_4))+Z^0(\to b(p_5)+\bar{b}(p_6))$[no gamma*]	NLO
89	$Z^0(\to b(p_3)+\bar{b}(p_4))+Z^0(\to 3\times(\nu(p_5)+\bar{\nu}(p_6)))$[no gamma*]	NLO
91	$W^+(\to \nu(p_3)+e^+(p_4))+H(\to b(p_5)+\bar{b}(p_6))$	NLO
92	$W^+(\to \nu(p_3)+e^+(p_4))+H(\to W^+(\nu(p_5),e^+(p_6))W^-(e^-(p_7),\bar{\nu}(p_8)))$	NLO
93	$W^+(\to \nu(p_3)+e^+(p_4))+H(\to Z(e^-(p_5),e^+(p_6))+Z(\mu^-(p_7),\mu(p_8)))$	NLO
94	$W^+(\to \nu(p_3)+e^+(p_4))+H(\to \gamma(p_5)+\gamma(p_6)$	NLO
96	$W^-(\to e^-(p_3)+\bar{\nu}(p_4))+H(\to b(p_5)+\bar{b}(p_6))$	NLO
97	$W^-(\to e^-(p_3)+\bar{\nu}(p_4))+H(\to W^+(\nu(p_5),e^+(p_6))W^-(e^-(p_7),\bar{\nu}(p_8)))$	NLO
98	$W^-(\to e^-(p_3)+\bar{\nu}(p_4))+H(\to Z(e^-(p_5),e^+(p_6))+Z(\mu^-(p_7),\mu^+(p_8)))$	NLO
99	$W^-(\to e^-(p_3)+\bar{\nu}(p_4))+H(\to \gamma(p_5)+\gamma(p_6))$	NLO

101	$Z^0(\to e^-(p_3)+e^+(p_4))+H(\to b(p_5)+\bar{b}(p_6))$	NLO
102	$Z^0(\to 3\times(\nu(p_3)+\bar{\nu}(p_4)))+H(\to b(p_5)+\bar{b}(p_6))$	NLO
103	$Z^0(\to b(p_3)+\bar{b}(p_4))+H(\to b(p_5)+\bar{b}(p_6))$	NLO
104	$Z^0(\to e^-(p_3)+e^+(p_4))+H(\to \gamma(p_5)+\gamma(p_6))$	NLO
105	$Z^0(\to\to 3\times(\nu(p_3)+\bar{\nu}(p_4)))+H(\to \gamma(p_5)+\gamma(p_6))$	NLO
106	$Z^0(\to e^-(p_3)+e^+(p_4))+H(\to W^+(\nu(p_5),e^+(p_6))W^-(e^-(p_7),\bar{\nu}(p_8)))$	NLO
107	$Z^0(\to 3\times(\nu(p_3)+\bar{\nu}(p_4)))+H(\to W^+(\nu(p_5),e^+(p_6))W^-(e^-(p_7),\bar{\nu}(p_8)))$	NLO
108	$Z^0(\to b(p_3)+\bar{b}(p_4))+H(\to W^+(\nu(p_5),e^+(p_6))W^-(e^-(p_7),\bar{\nu}(p_8)))$	NLO
109	$Z^0(\to e^-(p_3)+e^+(p_4))+H(\to Z(e^-(p_5),e^+(p_6))+Z(\mu^-(p_7),\mu^+(p_8)))$	NLO
111	$H(\to b(p_3)+\bar{b}(p_4))$	NLO
112	$H(\to \tau^-(p_3)+\tau^+(p_4))$	NLO
113	$H(\to W^+(\nu(p_3)+e^+(p_4))+W^-(e^-(p_5)+\bar{\nu}(p_6)))$	NLO
114	$H(\to Z^0(\mu^-(p_3)+\mu^+(p_4))+Z^0(e^-(p_5)+e^+(p_6))$	NLO
115	$H(\to Z^0(3\times(\nu(p_3)+\bar{\nu}(p_4)))+Z^0(e^-(p_5)+e^+(p_6))$	NLO
116	$H(\to Z^0(\mu^-(p_3)+\mu^+(p_4))+Z^0(b(p_5)+\bar{b}(p_6))$	NLO
117	$H(\to \gamma(p_3)+\gamma(p_4))$	NLO
121	$H(\to W^+(\nu(p_3)+e^+(p_4))+W^-(e^-(p_5)+\bar{\nu}(p_6)))$[top, bottom loops, exact]	LO
122	$H(\to W^+(\nu(p_3)+e^+(p_4))+W^-(e^-(p_5)+\bar{\nu}(p_6)))$[+ interf. with $gg\to WW$]	LO
131	$W^+(\to \nu(p_3)+e^+(p_4))+W^+(\to \nu(p_5)+e^+(p_6))+f(p_7)+f(p_8)$	LO
132	$W^+(\to \nu(p_3)+e^+(p_4))+W^+(\to \nu(p_5)+e^+(p_6))+f(p_7)+f(p_8)+f(p_9)$	LO
141	$H(\to b(p_3)+b(p_4))+b(p_5)(+g(p_6))$	NLO
142	$H(\to b(p_3)+\bar{b}(p_4))+\bar{b}(p_5)(+b(p_6))$	(REAL)
143	$H(\to b(p_3)+\bar{b}(p_4))+b(p_5)+\bar{b}(p_6)$[both observed]	(REAL)
151	$t(\to \nu(p_3)+e^+(p_4)+b(p_5))+\bar{t}(\to \bar{b}(p_6)+e^-(p_7)+\bar{\nu}(p_8))$	NLO
152	$t(\to \nu(p_3)+e^+(p_4)+b(p_5))+\bar{t}(\to \bar{b}(p_6)+q(p_7)+\bar{q}(p_8))$	NLO
153	$t(\to \nu(p_3)+e^+(p_4)+b(p_5))+\bar{t}(\to \bar{b}(p_6)+e^-(p_7)+\bar{\nu}(p_8))(uncorr)$	NLO

156	$t(\to \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\to \bar{b}(p_6) + e^-(p_7) + \bar{\nu}(p_8)) + f(p_9)$	LO
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	$t(\to \nu(p_3) + e^+(p_4) + b(p_5)) + q(p_6)$[t-channel]	NLO
162	$t(\to \nu(p_3) + e^+(p_4) + b(p_5)) + q(p_6)$[decay]	NLO
163	$t(\to \nu(p_3) + e^+(p_4) + b(p_5)) + q(p_6)$[t-channel]$mb > 0$	NLO
166	$\bar{t}(\to e^-(p_3) + \bar{\nu}(p_4) + \bar{b}(p_5)) + q(p_6)$[t-channel]	NLO
167	$\bar{t}(\to e^-(p_3) + \bar{\nu}(p_4) + \bar{b}(p_5)) + q(p_6)$[decay]	NLO
168	$\bar{t}(\to e^-(p_3) + \bar{\nu}(p_4) + \bar{b}(p_5)) + q(p_6)$[t-channel]$mb > 0$	NLO
171	$t(\to \nu(p_3) + e^+(p_4) + b(p_5)) + b(p_6))$[s-channel]	NLO
172	$t(\to \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{b}(p_6))$[decay]	NLO
176	$\bar{t}(\to e^-(p_3) + \bar{\nu}(p_4) + \bar{b}(p_5)) + b(p_6))$[s-channel]	NLO
177	$\bar{t}(\to e^-(p_3) + \bar{\nu}(p_4) + \bar{b}(p_5)) + b(p_6))$[decay]	NLO
180	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + t(p_5)$	NLO
181	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + t(\nu(p_5) + e^+(p_6) + b(p_7))$	NLO
182	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + t(\nu(p_5) + e^+(p_6) + b(p_7))$[decay]	NLO
183	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + t(\nu(p_5) + e^+(p_6) + b(p_7)) + b(p_8)$	LO
184	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + t(p_5) + b(p_6)$[massive b]	LO
185	$W^+(\to \nu(p_3) + e^+(p_4)) + \bar{t}(p_5)$	NLO
186	$W^+(\to \nu(p_3) + e^+(p_4)) + \bar{t}(e^-(p_5) + \bar{\nu}(p_6) + \bar{b}(p_7)$	NLO
187	$W^+(\to \nu(p_3) + e^+(p_4)) + \bar{t}(e^-(p_5) + \bar{\nu}(p_6) + \bar{b}(p_7)$[decay]	NLO
190	$t(p_3) + \bar{t}(p_4) + H(p_5)$	LO
191	$t(\to \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\to \bar{\nu}(p_7) + e^-(p_8) + \bar{b}(p_6)) + H(p_9 + p_{10})$	LO
196	$t(\to \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\to \bar{\nu}(p_7) + e^-(p_8) + \bar{b}(p_6)) + Z(e^-(p_9), e^+(p_{10}))$	LO
197	$t(\to \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\to \bar{\nu}(p_7) + e^-(p_8) + \bar{b}(p_6)) + Z(b(p_9), \bar{b}(p_{10}))$	LO
198	$t(\to \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\to \bar{\nu}(p_7) + e^-(p_8) + \bar{b}(p_6)) + W^+(\nu(p_9), \mu^+(p_{10}))$	LO
199	$t(\to \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\to \bar{\nu}(p_7) + e^-(p_8) + \bar{b}(p_6)) + W^-(\mu^-(p_9), \bar{\nu}(p_{10}))$	LO

201	$H(\to b(p_3)+\bar{b}(p_4))+f(p_5)$[full mt dep.]	LO
202	$H(\to \tau^-(p_3)+\tau^+(p_4))+f(p_5)$[full mt dep.]	LO
203	$H(\to b(p_3)+\bar{b}(p_4))+f(p_5)$	NLO
204	$H(\to \tau^-(p_3)+\tau^+(p_4))+f(p_5)$	NLO
206	$A(\to b(p_3)+\bar{b}(p_4))+f(p_5)$[full mt dep.]	LO
207	$A(\to \tau^-(p_3)+\tau^+(p_4))+f(p_5)$[full mt dep.]	LO
208	$H(\to W^+(\nu(p_3),e^+(p_4))W^-(e^-(p_5),\bar{\nu}(p_6)))+f(p_7)$	NLO
209	$H(\to Z^+(e^-(p_3),e^+(p_4))Z(\mu^-(p_5),\mu^+(p_6)))+f(p_7)$	NLO
210	$H(\to \gamma(p_3)+\gamma(p_4))+f(p_5)$	NLO
211	$H(\to b(p_3)+\bar{b}(p_4))+f(p_5)+f(p_6)$[WBF]	NLO
212	$H(\to \tau^-(p_3)+\tau^+(p_4))+f(p_5)+f(p_6)$[WBF]	NLO
213	$H(\to W^+(\nu(p_3),e^+(p_4))W^-(e^-(p_5),\bar{\nu}(p_6)))+f(p_7)+f(p_8)$[WBF]	NLO
214	$H(\to Z(e^-(p_3),e^+(p_4))+Z(\mu^-(p_5),\mu^+(p_6)))+f(p_7)+f(p_8)$[WBF]	NLO
215	$H(\to \gamma(p_3)+\gamma(p_4))+f(p_5)+f(p_6)$[WBF]	NLO
216	$H(\to b(p_3)+\bar{b}(p_4))+f(p_5)+f(p_6)+f(p_7)$[WBF+jet]	LO
217	$H(\to \tau^-(p_3)+\tau^+(p_4))+f(p_5)+f(p_6)+f(p_7)$[WBF+jet]	LO
221	$\tau^-(\to e^-(p_3)+\bar{\nu}_e(p_4)+\nu_\tau(p_5))+\tau^+(\to \bar{\nu}_\tau(p_6)+\nu_e(p_7)+e^+(p_8))$	LO
231	$t(p_3)+\bar{b}(p_4)+q(p_5)$[t-channel]	NLO
232	$t(p_3)+\bar{b}(p_4)+q(p_5)+q(p_6)$[t-channel]	LO
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
261	$Z^0(\to e^-(p_3)+e^+(p_4))+b(p_5)$	NLO
262	$Z^0(\to e^-(p_3)+e^+(p_4))+c(p_5)$	NLO
263	$Z^0(\to e^-(p_3)+e^+(p_4))+\bar{b}(p_5)+b(p_6)$[1 b-tag]	LO
264	$Z^0(\to e^-(p_3)+e^+(p_4))+\bar{c}(p_5)+c(p_6)$[1 c-tag]	LO
266	$Z^0(\to e^-(p_3)+e^+(p_4))+b(p_5)(+\bar{b}(p_6))$	NLO
267	$Z^0(\to e^-(p_3)+e^+(p_4))+c(p_5)(+\bar{c}(p_6))$	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	$H(\to W^+(\nu(p_3),e^+(p_4))W^-(e^-(p_5),\bar{\nu}(p_6)))+f(p_7)+f(p_8)$	NLO
274	$H(\to Z^+(e^-(p_3),e^+(p_4))Z(\mu^-(p_5),\mu^+(p_6)))+f(p_7)+f(p_8)$	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
280	$\gamma(p_3)+f(p_4)$	NLO+F
282	$f(p_1)+f(p_2)\to\gamma(p_3)+f(p_4)+f(p_5)$	LO
285	$f(p_1)+f(p_2)\to\gamma(p_3)+\gamma(p_4)$	NLO+F
286	$f(p_1)+f(p_2)\to\gamma(p_3)+\gamma(p_4)+f(p_5)$	LO
290	$W^+(\to\nu(p_3)+e^+(p_4))+\gamma(p_5)$	NLO+F
292	$W^+(\to\nu(p_3)+e^+(p_4))+\gamma(p_5)+f(p_6)$	LO
295	$W^-(\to e^-(p_3)+\bar{\nu}(p_4))+\gamma(p_5)$	NLO+F
297	$W^-(\to e^-(p_3)+\bar{\nu}(p_4))+\gamma(p_5)+f(p_6)$	LO
300	$Z^0(\to e^-(p_3)+e^+(p_4))+\gamma(p_5)$	NLO+F
302	$Z^0(\to e^-(p_3)+e^+(p_4))+\gamma(p_5)+f(p_6)$	LO
305	$Z^0(\to 3\times(\nu(p_3)+\bar{\nu}(p_4)))+\gamma(p_5)$	NLO+F
311	$f(p_1)+b(p_2)\to W^+(\to\nu(p_3)+e^+(p_4))+b(p_5)+f(p_6)$	LO
316	$f(p_1)+b(p_2)\to W^-(\to e^-(p_3)+\bar{\nu}(p_4))+b(p_5)+f(p_6)$	LO
321	$f(p_1)+c(p_2)\to W^+(\to\nu(p_3)+e^+(p_4))+c(p_5)+f(p_6)$	LO
326	$f(p_1)+c(p_2)\to W^-(\to e^-(p_3)+\bar{\nu}(p_4))+c(p_5)+f(p_6)$	LO
331	$W^+(\to\nu(p_3)+e^+(p_4))+c(p_5)+f(p_6)$[c-s interaction]	LO
336	$W^-(\to e^-(p_3)+\bar{\nu}(p_4))+c(p_5)+f(p_6)$[c-s interaction]	LO
341	$f(p_1)+b(p_2)\to Z^0(\to e^-(p_3)+e^+(p_4))+b(p_5)+f(p_6)[+f(p_7)]$	NLO
342	$f(p_1)+b(p_2)\to Z^0(\to e^-(p_3)+e^+(p_4))+b(p_5)+f(p_6)[+\bar{b}(p_7)]$	(REAL)
346	$f(p_1)+b(p_2)\to Z^0(\to e^-(p_3)+e^+(p_4))+b(p_5)+f(p_6)+f(p_7)$	LO
347	$f(p_1)+b(p_2)\to Z^0(\to e^-(p_3)+e^+(p_4))+b(p_5)+f(p_6)+\bar{b}(p_7)$	LO

351	$f(p_1) + c(p_2) \to Z^0(\to e^-(p_3) + e^+(p_4)) + c(p_5) + f(p_6)[+f(p_7)]$	NLO
352	$f(p_1) + c(p_2) \to Z^0(\to e^-(p_3) + e^+(p_4)) + c(p_5) + f(p_6)[+\bar{c}(p_7)]$	(REAL)
356	$f(p_1) + c(p_2) \to Z^0(\to e^-(p_3) + e^+(p_4)) + c(p_5) + f(p_6) + f(p_7)$	LO
357	$f(p_1) + c(p_2) \to Z^0(\to e^-(p_3) + e^+(p_4)) + c(p_5) + f(p_6) + \bar{c}(p_7)$	LO
361	$c(p_1) + \bar{s}(p_2) \to W^+(\to \nu(p_3) + e^+(p_4))$[mc=0 in NLO]	NLO
362	$c(p_1) + \bar{s}(p_2) \to W^+(\to \nu(p_3) + e^+(p_4))$[massless corrections only]	NLO
363	$c(p_1) + \bar{s}(p_2) \to W^+(\to \nu(p_3) + e^+(p_4))$[massive charm in real]	NLO
401	$W^+(\to \nu(p_3) + e^+(p_4)) + b(p_5)$ [1,2 or 3 jets, 4FNS]	NLO
402	$W^+(\to \nu(p_3) + e^+(p_4)) + (b + \bar{b})(p_5)$ [1 or 2 jets, 4FNS]	NLO
403	$W^+(\to \nu(p_3) + e^+(p_4)) + b(p_5) + \bar{b}(p_6)$ [2 or 3 jets, 4FNS]	NLO
406	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + b(p_5)$ [1,2 or 3 jets, 4FNS]	NLO
407	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + (b + \bar{b})(p_5)$ [1 or 2 jets, 4FNS]	NLO
408	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + b(p_5) + \bar{b}(p_6)$ [2 or 3 jets, 4FNS]	NLO
411	$f(p_1) + b(p_2) \to W^+(\to \nu(p_3) + e^+(p_4)) + b(p_5) + f(p_6)$ [5FNS]	NLO
416	$f(p_1) + b(p_2) \to W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + b(p_5) + f(p_6)$ [5FNS]	NLO
421	$W^+(\to \nu(p_3) + e^+(p_4)) + b(p_5)$ [1,2 or 3 jets, 4FNS+5FNS]	NLO
426	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + b(p_5)$ [1,2 or 3 jets, 4FNS+5FNS]	NLO
431	$W^+(\to \nu(p_3) + e^+(p_4)) + b(p_5) + \bar{b}(p_6) + f(p_7)$ [massive]	LO
436	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + b(p_5) + \bar{b}(p_6) + f(p_7)$ [massive]	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 7: Processes indicated by choice of the variable `nproc`.

C 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.

C.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 $gg \to H \to WW$ 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 `dynamicscale` 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.

C.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(photon) is less than cut on p_T(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 $Z \to$ 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 $gg \to H$ 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] R. K. Ellis and G. Zanderighi, JHEP **0802**, 002 (2008) [arXiv:0712.1851 [hep-ph]].

[2] H. Georgi, Nucl. Phys. B **363**, 301 (1991).

[3] F. Maltoni and T. Stelzer, JHEP **0302**, 027 (2003) [arXiv:hep-ph/0208156].

[4] Michelangelo L. Mangano, Mauro Moretti, Fulvio Piccinini, Roberto Pittau and Antonello Polosa, *http://mlm.home.cern.ch/mlm/alpgen/*

[5] Stefan Dittmaier and Markus Roth, *http://wwwth.mppmu.mpg.de/members/roth/Lusifer/lusifer.html*

[6] M. Cacciari, G. P. Salam and G. Soyez, JHEP **0804**, 063 (2008) [arXiv:0802.1189 [hep-ph]].

[7] L. Bourhis, M. Fontannaz and J. P. Guillet, Eur. Phys. J. C **2**, 529 (1998) [arXiv:hep-ph/9704447].

[8] A. Gehrmann-De Ridder, E. W. N. Glover, Eur. Phys. J. **C7**, 29-48 (1999). [hep-ph/9806316].

[9] Z. Nagy, Phys. Rev. D **68**, 094002 (2003) [arXiv:hep-ph/0307268].

[10] K. J. Eskola, V. J. Kolhinen and C. A. Salgado, Eur. Phys. J. C **9**, 61 (1999) [arXiv:hep-ph/9807297].

[11] J. M. Campbell, J. W. Huston and W. J. Stirling, Rept. Prog. Phys. **70**, 89 (2007) [arXiv:hep-ph/0611148].

[12] R. D. Ball *et al.* [NNPDF Collaboration], Nucl. Phys. B **809**, 1 (2009) [arXiv:0808.1231 [hep-ph]].

[13] S. Badger, J. M. Campbell and R. K. Ellis, arXiv:1011.6647 [hep-ph].

[14] Z. Bern, L. J. Dixon and D. A. Kosower, Nucl. Phys. B **513**, 3 (1998) [arXiv:hep-ph/9708239].

[15] L. J. Dixon, Z. Kunszt and A. Signer, Nucl. Phys. B **531**, 3 (1998) [arXiv:hep-ph/9803250].

[16] L. J. Dixon, Z. Kunszt, A. Signer, Phys. Rev. **D60**, 114037 (1999). [hep-ph/9907305].

[17] R. K. Ellis, W. J. Stirling and B. R. Webber, Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol. **8**, 1 (1996).

[18] J. M. Campbell, R. K. Ellis and C. Williams, arXiv:1107.5569 [hep-ph].

[19] T. Melia, K. Melnikov, R. Rontsch and G. Zanderighi, JHEP **1012**, 053 (2010) [arXiv:1007.5313 [hep-ph]].

[20] C. Amsler *et al.* [Particle Data Group], Phys. Lett. B **667**, 1 (2008) and 2009 partial update for the 2010 edition.

[21] J. G. Korner and Z. Merebashvili, Phys. Rev. D **66**, 054023 (2002) [arXiv:hep-ph/0207054].

[22] P. Nason, S. Dawson and R. K. Ellis, Nucl. Phys. B **303**, 607 (1988).

[23] V. Ravindran, J. Smith and W. L. Van Neerven, Nucl. Phys. B **634**, 247 (2002) [arXiv:hep-ph/0201114].

[24] C. R. Schmidt, Phys. Lett. B **413**, 391 (1997) [arXiv:hep-ph/9707448].

[25] D. de Florian, M. Grazzini and Z. Kunszt, Phys. Rev. Lett. **82**, 5209 (1999) [arXiv:hep-ph/9902483].

[26] C. J. Glosser and C. R. Schmidt, JHEP **0212**, 016 (2002) [arXiv:hep-ph/0209248].

[27] R. Kleiss and W. J. Stirling, Z. Phys. C **40**, 419 (1988).

[28] S. Frixione, Phys. Lett. B **429**, 369 (1998) [arXiv:hep-ph/9801442].

[29] Z. Bern, L. J. Dixon and C. Schmidt, Phys. Rev. D **66**, 074018 (2002) [arXiv:hep-ph/0206194].

[30] D. De Florian and A. Signer, Eur. Phys. J. C **16**, 105 (2000) [arXiv:hep-ph/0002138].

[31] J. M. Campbell, R. K. Ellis, F. Febres Cordero, F. Maltoni, L. Reina, D. Wackeroth and S. Willenbrock, Phys. Rev. D **79**, 034023 (2009) [arXiv:0809.3003 [hep-ph]].

[32] F. Caola, J. M. Campbell, F. Febres Cordero, L. Reina and D. Wackeroth, arXiv:1107.3714 [hep-ph].