MCFM v5.2

A Monte Carlo for FeMtobarn
processes at Hadron Colliders

Users Guide

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Contents

1 Overview

MCFM is a parton-level Monte Carlo program which gives NLO predictions for a range of processes at hadron colliders. 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 W t 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].

The following recent 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. 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. 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].

2 Installation

The tar'ed, gzip'ed and uu-encoded 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 CERNLIB and LHAPDF libraries, if desired. The code has been developed and tested under Redhat Linux. Please report any compilation problems under other operating systems to the authors.

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.

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

Paramter	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	80.419 GeV	input	calculated	input	calculated
M_Z	zmass	91.188 GeV	input	input	input	calculated
m_t	mt	170.9 GeV	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.

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).

For the default scheme (`ewscheme=-1`), we use the 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 [1].

For the alternative schemes (`ewscheme=0,1,2`) the top mass is simply an additional input parameter and there are 3 other independent parameters from the remaining 5. The variable `ewscheme` then performs exactly the same role as `idef` in MadEvent [2]. `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 and LUSIFER. 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 `src/User/mdata.f`).

3.1 Parton distributions

The value of $\alpha_S(M_Z)$ is not adjustable; it is hardwired with the parton distribution. In addition, the parton distribution also specifies the number of loops that should be used in the running of α_S. The default mode of operation is to choose from a collection of modern parton distribution functions that are included with MCFM. The distributions, together with their associated $\alpha_S(M_Z)$ values, are given in Table3. For the older distributions, where the

Parameter	Fortran name	Default value
m_τ	mtau	1.777 GeV
m_τ^2	mtausq	3.1577 GeV^2
m_c^2	mcsq	2.25 GeV^2
m_b^2	mbsq	17.64 GeV^2
Γ_τ	tauwidth	2.269×10^{-12} GeV
Γ_W	wwidth	2.06 GeV
Γ_Z	zwidth	2.49 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.

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. 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).

mrs02nl	0.1197	hep-ph/0211080	mrs02nn	0.1154	hep-ph/0211080
mrs4nf3	0.1066	hep-ph/0603143	mrs4lf3	0.1186	hep-ph/0603143
mrs4nf4	0.1136	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
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
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`.

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]`

[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.

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

{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 5. $f(p_i)$ denotes a generic partonic jet.
- `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.
  - `todk` Processes 161,166,171,176,181,186 only, see sctions 7.29 and 7.30 below.

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
12	$W^+(\to \nu(p_3) + e^+(p_4)) + \gamma(p_5)$	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]	NLO
16	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + f(p_5)$	NLO
17	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + \gamma(p_5)$	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]	NLO
20	$W^+(\to \nu(p_3) + e^+(p_4)) + b(p_5) + \bar{b}(p_6)$ [massive]	LO
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]	LO
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
41	$Z^0(\to e^-(p_3) + e^+(p_4)) + f(p_5)$	NLO
42	$Z_0(\to 3 \times (\nu(p_3) + \bar{\nu}(p_4))) -$ [sum over 3 ν] $+ f(p_5)$	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
48	$Z^0(\to e^-(p_3) + e^+(p_4)) + \gamma(p_5)$	NLO
49	$Z^0(\to 3 \times (\nu(p_3) + \bar{\nu}(p_4))) -$ [sum over 3 ν] $+ \gamma(p_5)$	NLO
50	$Z^0(\to e^-(p_3) + e^+(p_4)) + b(p_5) + b(p_6)$ [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

nproc	$f(p_1) + f(p_2) \to \ldots$	Order
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]	NLO
71	$W^+(\to \nu(p_3) + \mu^+(p_4)) + Z^0(\to e^-(p_5) + e^+(p_6))$	NLO
72	$W^+(\to \nu(p_3) + \mu^+(p_4)) + Z^0(\to \nu_e(p_5) + \bar{\nu}_e(p_6))$	NLO
73	$W^+(\to \nu(p_3) + \mu^+(p_4)) + Z^0(\to b(p_5) + \bar{b}(p_6))$	NLO
76	$W^-(\to \mu^-(p_3) + \bar{\nu}(p_4)) + Z^0(\to e^-(p_5) + e^+(p_6))$	NLO
77	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + Z^0(\to \nu(p_5) + \bar{\nu}(p_6))$	NLO
78	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + Z^0(\to b(p_5) + \bar{b}(p_6))$	NLO
81	$Z^0(\to \mu^-(p_3) + \mu^+(p_4)) + Z^0(\to e^-(p_5) + e^+(p_6))$	NLO
82	$Z^0(\to 3 \times (\nu(p_3) + \bar{\nu}(p_4))) + Z^0(\to e^-(p_5) + e^+(p_6))$	NLO
83	$Z^0(\to e^-(p_5) + e^+(p_6)) + Z^0(\to b(p_3) + \bar{b}(p_4))$	NLO
84	$Z^0(\to 3 \times (\nu(p_3) + \bar{\nu}(p_4))) + Z^0(\to b(p_5) + \bar{b}(p_6))$	NLO
86	$Z^0(\to e^-(p_5) + e^+(p_6)) + Z^0(\to \mu^-(p_3) + \mu^+(p_4))$ [no γ^*]	NLO
87	$Z^0(\to e^-(p_5) + e^+(p_6)) + Z^0(\to 3 \times (\nu(p_3) + \bar{\nu}(p_4)))$ [no γ^*]	NLO
88	$Z^0(\to e^-(p_5) + e^+(p_6)) + Z^0(\to b(p_3) + \bar{b}(p_4))$ [no γ^*]	NLO
89	$Z^0(\to 3 \times (\nu(p_3) + \bar{\nu}(p_4))) + Z^0(\to b(p_5) + \bar{b}(p_6))$ [no γ^*]	NLO
91	$W^+(\to \nu(p_3) + e^+(p_4)) + H(\to b(p_5) + \bar{b}(p_6))$	NLO
96	$W^-(\to e^-(p_3) + \bar{\nu}(p_4)) + H(\to b(p_5) + \bar{b}(p_6))$	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
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
141	$H(\to b(p_3) + \bar{b}(p_4)) + b(p_5)(+g(p_6))$	NLO
142	$H(\to b(p_3) + \bar{b}(p_4)) + \bar{b}(p_5)(+b(p_6))$	NLO
143	$H(\to b(p_3) + \bar{b}(p_4)) + b(p_5) + \bar{b}(p_6)$ [both observed]	NLO

nproc	$f(p_1) + f(p_2) \to \ldots$	Order
151	$t(\to \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\to b(p_6)) + e^-(p_7) + \bar{\nu}(p_8))$	LO
152	$t(\to \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\to \bar{b}(p_6)) + q(p_7) + \bar{q}(p_8))$	LO
156	$t(\to \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{t}(\to \bar{\nu}(p_7) + e^-(p_8) + \bar{b}(p_6)) + g(p_9)$	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
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
171	$t(\to \nu(p_3) + e^+(p_4) + b(p_5)) + \bar{b}(p_6))$ [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
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
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	$H(\to W^+(\to \nu(p_3) + e^+(p_4)) + W^-(\to e^-(p_5) + \bar{\nu}(p_6))) + f(p_7)$	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
216	$H(\to b(p_3) + \bar{b}(p_4)) + f(p_5) + f(p_6) + f(p_7)$ [WBF+jet]	NLO
217	$H(\to \tau^-(p_3) + \tau^+(p_4)) + f(p_5) + f(p_6) + f(p_7)$ [WBF+jet]	NLO
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

nproc	$f(p_1)+f(p_2)\to\ldots$	Order
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]	NLO
264	$Z^0(\to e^-(p_3)+e^+(p_4))+\bar{c}(p_5)+c(p_6)$ [1 c-tag]	NLO
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]	LO
272	$H(\tau^-(p_3)+\tau^+(p_4))+f(p_5)+f(p_6)$ [in heavy top limit]	LO
273	$H(b(p_3)+\bar{b}(p_4))+f(p_5)+f(p_6)+f(p_7)$ [in heavy top limit]	LO
274	$H(\tau^-(p_3)+\tau^+(p_4))+f(p_5)+f(p_6)+f(p_7)$ [in heavy top limit]	LO
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	$f(p_1)+b(p_2)\to W^+(\to\nu(p_3)+e^+(p_4))+c(p_5)+f(p_6)$	LO
326	$f(p_1)+b(p_2)\to W^-(\to e^-(p_3)+\bar{\nu}(p_4))+c(p_5)+f(p_6)$	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	$Z^0(\to e^-(p_3)+e^+(p_4))+b(p_5)+f(p_6)[+f(p_7)]$	NLO
342	$Z^0(\to e^-(p_3)+e^+(p_4))+b(p_5)+f(p_6)[+b\ (p_7)]$	(REAL)
346	$Z^0(\to e^-(p_3)+e^+(p_4))+b(p_5)+f(p_6)+f(p_7)$	LO
347	$Z^0(\to e^-(p_3)+e^+(p_4))+b(p_5)+f(p_6)+b\ (p_7)$	LO
351	$Z^0(\to e^-(p_3)+e^+(p_4))+c(p_5)+f(p_6)[+f(p_7)]$	NLO
352	$Z^0(\to e^-(p_3)+e^+(p_4))+c(p_5)+f(p_6)[+c\ (p_7)]$	(REAL)
356	$Z^0(\to e^-(p_3)+e^+(p_4))+c(p_5)+f(p_6)+f(p_7)$	LO
357	$Z^0(\to e^-(p_3)+e^+(p_4))+c(p_5)+f(p_6)+c\ (p_7)$	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]	–

Table 5: Processes indicated by choice of the variable nproc.

- `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` When set to `.true.` the renormalization and factorization scales are recalculated for each event. In this case, the values of `scale` and `facscale` take on a special meaning that determines the method used to calculate the scale:

  - `1d0` : $\mu^2 = M_V^2 + p_T(V)^2$ – only appropriate for processes involving a vector boson V
  - `2d0` : $\mu^2 =< p_T^{jet} >^2$ – only appropriate for processes involving jets
  - `3d0` : $\mu^2 = \hat{s}$, the partonic centre of mass energy
  - `4d0` : $\mu^2 = H_T^2$, where H_T is the scalar sum of the p_T's of all the particles in each event

Note that care must be used when selecting this option, since not all choices are appropriate for each process.

- `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 7.8 below.

- `Gflag`. This only has an effect when running a $W + 2$ jets or $Z + 2$ jets process. Please see section 7.8 below.

{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).

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`[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) and `cone` (for a midpoint cone algorithm).

- `ptmin_jet, etamin_jet, etamax_jet`. These specify the values of $p_T^{\rm min}$, $|\eta|^{\rm min}$ and $|\eta|^{\rm max}$ 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`.

- `ptmin_lepton, etamax_lepton`. These specify the values of $p_T^{\rm min}$ and $|y|^{\rm max}$ for the hardest lepton produced in the process.

- `ptmin_missing`. Specifies the minimum missing transverse momentum (coming from neutrinos).

- `ptmin_lepton(2nd+), etamax_lepton(2nd+)`. These specify the values of $p_T^{\rm min}$ and $|y|^{\rm max}$ 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.

- `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` : η^{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 $|\eta|^{\max}$ for b-jets.

- `ptminphoton, etamaxphoton`. These specify the values of $p_T^{\min}$ and $|y|^{\max}$ for any photons produced.

- `conephoton, coneptcut`. These constitute a photon isolation cut which ensures that the amount of hadronic transverse momentum in a cone around each photon is less than a specified fraction of the photon's p_T.

$$\sum_{R<R_0} p_T^{\text{hadronic}} < f \times p_T^{photon},$$

  where R_0 and f are specified by `cone_photon` and `cone_ptcut` respectively.

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`[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 section 7.20.*

- `Lambda(Z)`. *See section 7.20.*

- `Lambda(gamma)`. *See section 7.20.*

- `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.*

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:

$$\texttt{ih} = 1000Z + A. \tag{1}$$

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 decreasd by a factor of $\sqrt{Z/A}$ for each nuclear beam.

The nucleon PDF's are calculated by applying the correction factors of EKS98 [8] 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 will output two additional files. 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.

The two other output files are `outputname.dat` and `outputname.top`, which contain data for various histograms associated with the calculated process. The first of these is in a raw format which may be read in by a plotting package of the user's choosing. The other file contains the histograms as a `TOPDRAWER` file, as well as 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_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 setup in the file `src/User/nplotter.f`. The arguments of this subroutine are `p,wt,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` is the weight of the event.

6.1 Histograms

Extra histograms may be added to the file `src/User/nplotter.f` in a fairly straightforward manner. Each histogram is filled by making a call to the routine `bookplot` and updating the histogram counter `n` by 1. For example:

```
call bookplot(n,tag,'    eta3',eta3,wt,-5d0,5d0,0.5d0,'lin')
n=n+1
```

The first two arguments of the call should not be changed. The third argument is a string describing the plot which will be used for the title in `TOPDRAWER`. The fourth argument carries the variable to be plotted, which has been previously calculated. The argument `wt` contains the phase-space

weight and should not be changed. The last arguments tell the histogramming routine to use bins of size `0.5` which run from `-5` to `5`, 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 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 users 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.

To obtain the simplest n-tuple output, the flag `creatent` should be set to `.true.` . In this case, 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 millions 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. 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 are not events in the traditional event generator sense.

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 described 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. 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 $W\gamma$ production, processes 12,17

These processes represent the production of a W boson which subsequently decays leptonically, in association with a real photon. The calculation may be performed at NLO. Note however that the contribution in which a jet fragments into a photon is not included, so these processes are currently of limited utility.

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

7.4 $W + c$ production, processes 13,18

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

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

7.5 $W + c$ production ($m_c = 0$), processes 14,19

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

7.6 $W + b\bar{b}$ production, processes 20,25

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

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

7.7 $W + b\bar{b}$ production ($m_b = 0$), processes 21,26

These processes are identical to `20` and `25` except for the fact that the bottom quark mass is neglected. This allows the calculation to be performed up to NLO, with currently calculated virtual matrix elements.

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

7.8 $W + 2$ jets production, processes 22,27

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

This process represents the production of a W boson and 2 jets, where the W boson decays leptonically. The calculation may be performed up to NLO, as detailed below.

For these processes (and also for $Z + 2$ jet production, `nproc=44`) 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. In the lowest order calculation, both of these may be set to `.true.` simultaneously - however this is the only case where this is possible.

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

7.9 $W + 3$ jets production, processes 23,28

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

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

7.10 $W + b\bar{b}+$ 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.

7.11 Z-boson production, processes 31–33

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

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

7.12 $Z+$ 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.

7.13 $Z + 2$ jets production, process 44

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

This process represents the production of a Z boson and 2 jets, including also the effect of a virtual photon. The Z/γ^* decays to an e^+e^- pair. The calculation may be performed up to NLO - please see the earlier Section 7.8 for more details, especially the discussion `Qflag` and `Gflag`.

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

7.14 $Z + 3$ jets production, process 45

This process represents the production of a Z boson and 3 jets, including also the effect of a virtual photon. The Z/γ^* decays to an e^+e^- pair. The calculation may be performed at LO only.

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

7.15 $Z\gamma$ production, processes 48,49

These processes 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=48`) or neutrinos (`nproc=49`). The calculation may be performed at NLO. However since the contribution of a jet fragmenting into a photon is not included, these processes are currently of limited utility.

When `removebr` is true in process `48`, 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 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 this calculation, please refer to hep-ph/9905386*]

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`. There are various possibilities for the subsequent decay of the bosons, as specified in the sections below.

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.

When removebr is true in processes 61 and 64, the W bosons do not decay.

7.20.2 WZ production, processes 71–73, 76–78

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) or a pair of bottom quarks (nproc=73,78). Note that, in processes 73 and 78, the NLO corrections do not include radiation from the bottom quarks that are produced by the Z decay.

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

7.20.3 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). 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.

7.20.4 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).

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):

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

where $X_{\mu\nu} \equiv \partial_\mu X_\nu - \partial_\nu X_\mu$ and the overall coupling factors are $g_{WWZ} = -e$, $g_{WW\gamma} = -e\cot\theta_w$. 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 91,96

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. The calculation may be performed at NLO, although 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 101–103

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. The Z/γ^* subsequently decays into either an e^+e^- pair (`nproc=101`), neutrinos (`nproc=102`) or a further bottom quark pair (`nproc=103`). The calculation may be performed at NLO, although radiation from the bottom quarks in the decay of the Higgs (or the Z, for process `103`) is not included.

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

7.23 Higgs production, processes 111–116

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`).

The calculation is performed in the limit of infinite top quark mass, so that at LO the relevant diagram is the coupling of two gluons to the Higgs via a top quark loop. The calculation may be performed at NLO, although radiation from the bottom quarks in the decay of processes `111` and `116` is not included.

When `removebr` is true in processes `111`–`114`, the Higgs boson does not decay.

7.24 $H + b$ 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.

7.25 $t\bar{t}$ production with decay, processes 151 and 152

These processes describe lowest order $t\bar{t}$ production including two leptonic decays $t \to bl\nu$ (process `151`) and one leptonic and one hadronic decay (`152`). We use the matrix elements of ref. [9].

When `removebr` is true in process `151`, the top quarks do not decay.

7.26 $t\bar{t}$ production with decay and a gluon, process 156

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

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

7.27 $Q\overline{Q}$ 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. [7]. No decays are included.

7.28 $t\bar{t}$+ 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.

7.29 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.

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.

7.30 Wt production, processes 180–186

[*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 `ptbjetmin` which is specified in the input file. The contribution from these diagrams when the p_T of the b quark is above `ptbjetmin` 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.

7.31 $Ht\bar{t}$ 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`, 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.

7.32 $Zt\bar{t}$ 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. In process `196` the Z boson decays into an electron pair, whilst in `197` the decay is into a bottom quark pair. The calculations can be performed at LO only.

When `removebr` is true in process `196`, the Z boson does not decay.

7.33 $H+$ jet production, processes 201–208

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 lepronically (`208`).

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` and `204`, 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 [4] and [5]. Phenomenological results have previously been given in refs. [3],[4] and [6]. 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` and `208`, the Higgs boson does not decay.

7.34 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`) or to a pair of tau's (`212,217`).

Calculations can be performed up to NLO for processes `211` and `212`. 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.

7.35 $\tau^+\tau^-$ production, process 221

This process provides predictions for the production of a tau lepton pair, with subsequent leptonic decays. The calculation is available at LO only. The relevant matrix elements are adapted from the ones in ref. [9].

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

7.36 $Z + Q$ 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.

7.37 $H + 2$ jet production, processes 271, 272

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`), or a pair of tau's (`nproc=272`).

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.

7.38 $H + 3$ jet production, processes 273, 274

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=273`), or a pair of tau's (`nproc=274`).

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.

7.39 $W+Q+$ jet production (Q pdf), 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.

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.

7.40 $W + c+$ 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.

7.41 $Z + Q+$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. As for $H + b$ and $Z + Q$ production, the matrix elements are divided into two subprocesses 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.

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