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The MC@NLO Event Generator*

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Abstract: This is the user's manual of MC@NLO.1.0. This package is a practical implementation, based upon the HERWIG event generator, of the recently proposed MC@NLO formalism for matching the next-to-leading order calculation of a QCD process with a parton-shower Monte Carlo simulation. The processes of standard-model vector boson pair production in hadronic collisions are available.

Keywords: QCD, Monte Carlo, NLO Computations, Resummation, Collider Physics.

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Contents

1. Generalities

In this documentation file, we briefly describe how to run the MC@NLO, implemented according to the formalism introduced in ref. [1]. The following production processes are now available (`IPROC` has the same meaning as in HERWIG [2]):

`IPROC`	Process
2850	$H_1H_2 \to \mathrm{W}^+\mathrm{W}^- + X$
2860	$H_1H_2 \to \mathrm{ZZ}+X$
2870	$H_1H_2 \to \mathrm{W}^+\mathrm{Z}+X$
2880	$H_1H_2 \to \mathrm{W}^-\mathrm{Z}+X$

Table 1: Processes implemented in MC@NLO.

1.1 Mode of operation

In the case of standard MC, a hard kinematical configuration is generated on a event-by-event basis, and it is subsequently showered and hadronized. In the case of our MC@NLO, all of the hard kinematical configurations are generated in advance, and stored in a file (which we call *event file* – see sect. 3.1); the event file is then read by HERWIG, which showers and hadronizes each hard configuration. Therefore, in the MC@NLO the reading of a hard configuration from the event file is equivalent to the generation of such a configuration in the standard MC. Apart from this difference, MC@NLO and MC behave exactly in the same way. Thus, the available user's analysis routines can be used without any modification in the case of MC@NLO. One should recall, however, that MC@NLO always generates some events with negative weights (see ref. [1]); therefore, the correct distributions are obtained by summing weights with their signs (i.e., the absolute values of the weights must *NOT* be used when filling the histograms).

With such a structure, it is natural to create two separate executables, which we improperly denote as NLO and MC. The former has the sole scope of creating the event file; the latter is just HERWIG, augmented by the capability of reading the event file.

1.2 Package files

The package consists of the following files:

- **Shell utilities**
  `MCatNLO.Script`
  `MCatNLO.inputs`
  `Makefile`

- **General purpose codes**
  `alpha.f`
  `dummies.f`
  `linux.f`
  `mcatnlo_date.f`
  `mcatnlo_int.f`
  `mcatnlo_libofpdf.f`
  `mcatnlo_mlmtopdf.f`
  `mcatnlo_pdftomlm.f`
  `mcatnlo_str.f`
  `mcatnlo_uti.f`
  `mcatnlo_uxdate.c`
  `sun.f`
  `trapfpe.c`

- **Vector boson pair production codes**
  `mcatnlo_hwanal.f`
  `mcatnlo_hwdriver.f`
  `mcatnlo_hwhvvj.f`
  `mcatnlo_vbmain.f`
  `mcatnlo_vbxsec.f`

These files can be downloaded from the Web page:

`http://www.hep.phy.cam.ac.uk/theory/webber/MCatNLO`

The vector boson pair production codes and shell utilities are only relevant to the production of W^+W^-, ZZ, and $W^\pm Z$ pairs in hadronic collisions. The general purpose codes will be used in the MC@NLO implementation of other production processes.

In addition to the files listed above, the user will need a version of the HERWIG code, which can be downloaded from the Web page:

`http://hepwww.rl.ac.uk/theory/seymour/herwig/`

As stressed in ref. [1], for the MC@NLO we don't need to modify the existing (LL) shower algorithm; thus, users can simply link (some of) the files above to their preferred HERWIG version. To be capable of handling the relevant event process codes listed in table 1, this should be public version 6.301 or higher. On most systems, users will need to delete the dummy subroutines HWHVVJ, PDFSET and STRUCTM from the standard HERWIG package, to permit linkage of the corresponding routines from the MC@NLO package.

1.3 Working environment

We have written a number of shell scripts and a `Makefile` (all listed under **Shell utilities** above) which will simplify the use of the package considerably. To use them, the computing system must support `bash` shell, and `gmake`. Should these be unavailable on the user's computing system, the compilation and running of our MC@NLO requires more detailed instructions, for which we refer the reader to app. A. This appendix will also serve as a reference for more advanced usage of the package.

1.4 Source and running directories

We assume that all the files of the package sit in the same directory, which we call the *source directory*. When creating the executable, our shell scripts determine the type of operating system, and create a subdirectory of the source directory, which we call the *running directory*, whose name is `Alpha`, `Sun`, or `Linux`, depending on the operating system. If the operating system is not known by our scripts, the name of the working directory is `Run`. The running directory contains all the object files and executable files, and in general all the files produced by the MC@NLO while running. It must also contain the relevant grid files (see sect. 2.1), or links to them, if the library of parton densities provided in the package is used.

2. Prior to running

Before running the code, the user needs to edit the following files:

`mcatnlo_hwanal.f`
`mcatnlo_hwdriver.f`
`mcatnlo_hwhvvj.f`
`Makefile`

We do not assume that the user will adopt the latest release of HERWIG (although we do recommend such a choice). For this reason, the files `mcatnlo_hwdriver.f` and `mcatnlo_hwhvvj.f` must be edited, in order to modify the 'INCLUDE HERWIGXX.INC' command to correspond to the version of HERWIG the user is going to adopt. `mcatnlo_hwdriver.f` contains a set of read statements, which are necessary for the MC to get the input parameters (see sect. 3 for the input procedure); these read statements must not be modified or eliminated. Also, `mcatnlo_hwdriver.f` calls the HERWIG routines which perform showering, hadronization, decays, and so forth; the user can freely modify this part, as customary in MC runs. Finally, the sample code `mcatnlo_hwanal.f` contains analysis-related routines: this file must be replaced by a file which contains the user's analysis routines.

The `Makefile` must also be edited, in order to set two variables, `HERWIGVER` and `HWUTI`. The former variable must be set equal to the object file name of the version of HERWIG currently adopted (matching the one whose common blocks are included in the files above). The variable `HWUTI` must be set equal to the list of object files that the user needs in the analysis routines. The lists of files linked by `Makefile` are reported in app. A.1. See also sect. 5.

2.1 Parton densities

Since the knowledge of the parton densities (PDFs) is necessary in order to get the physical cross section, a PDF library must be linked. The possibility exists to link the CERNLIB PDF library (PDFLIB); however, we also provide a self-contained PDF library with this package, which is faster than PDFLIB. The user may link either PDF library; all that is necessary is to set the variable `PDFLIBRARY` (in the file `MCatNLO.inputs`) equal to `THISLIB` if one wants to link to our PDF library, and equal to `PDFLIB` if one wants to link to PDFLIB. Our PDF library collects the original codes, written by the authors of the PDF fits; as such, for most of the densities it needs to read the files which contain the grids that initialize the PDFs. These files, also provided with the present package, must either be copied into the running directory, or defined in the running directory as logical links to the physical files (by using `ln -sn`).

As stressed before, consistent inputs must be given to the NLO and MC codes. However, in ref. [1] we found that the dependence upon the PDFs used by the MC is rather weak. So one may want to run the NLO and MC adopting a regular NLO-

evolved set in the former case, and the default (LO) HERWIG set in the latter (the advantage is that this option reduces the amount of running time of the MC). In order to do so, the user must set the variable `HERPDF` equal to `DEFAULT` in the file `MCatNLO.inputs`; setting `HERPDF=EXTPDF` will force the MC to use the same PDF set as the NLO code.

Regardless of the PDFs used in the MC run, users must delete the dummy PDFLIB routines PDFSET and STRUCTM from HERWIG, as explained earlier.

3. Running

It is straightforward to run the MC@NLO. First, edit

```
MCatNLO.inputs
```

and write there all the input parameters (for the complete list of the input parameters, see sect. 4). As the last line of the file `MCatNLO.inputs`, write

```
runMCatNLO
```

Finally, execute `MCatNLO.inputs` from the (bash) shell. This procedure will create the NLO and MC executables, and run them using the inputs given in `MCatNLO.inputs`, which guarantees that the parameters used in the NLO and MC runs are identical. Should the user only need to create the executables without running them, or to run the NLO or MC only, he/she should replace the call to `runMCatNLO` in the last line of `MCatNLO.inputs` by calls to

```
compileNLO
compileMC
runNLO
runMC
```

which have obvious meanings (`runXX` also creates the `XX` executable).

We stress that the input parameters are not solely related to physics (masses, CM energy, and so on); there are a few of them which control other things, such as the number of events generated. These must also be set by the user, according to his/her needs: see sect. 4.

If the shell scripts are not used to run the codes, the inputs are given to the NLO or MC codes during an interactive talk-to phase; the complete sets of inputs for our codes are reported in app. A.2.

3.1 Event file

The NLO code creates the event file. In order to do so, it goes through two steps; first it integrates the cross sections (the *integration step*), and then, using the information gathered in the integration step, produces a set of events (the *event generation step*).

The event generation step necessarily follows the integration step; however, for each integration step one can have an arbitrary number of event generation steps, i.e.,

an arbitrary number of event files. This is useful in the case in which the statistics accumulated with a given event file is not sufficient.

Suppose the user wants to create an event file; editing `MCatNLO.inputs`, the user sets `BASES=ON`, to enable the integration step, sets the parameter `NEVENTS` equal to the number of events wanted on tape, and runs the code; the information on the integration step (unreadable to the user, but needed by the code in the event generation step) is written on files whose name begin with `FPREFIX`, a string the user sets in `MCatNLO.inputs`; these files (which we denote as *data files*) have extensions `.data`. The name of the event file is `EVPREFIX.events`, where `EVPREFIX` is again a string set by the user.

Now suppose the user wants to create another event file, to increase the statistics. The user simply sets `BASES=OFF`, since the integration step is not necessary any longer (however, the data files must not be removed: the information stored there is still used by the NLO code); changes the string `EVPREFIX` (failure to do so overwrites the existing event file), while keeping `FPREFIX` at the same value as before; and changes the value of `RNDEVSEED` (the random number seed used in the event generation step; failure to do so results in an event file identical to the previous one); the number `NEVENTS` generated may or may not be equal to the one chosen in generating the former event file(s).

We point out that data and event files may be very large. If the user wants to store them in a scratch area, this can be done by setting the script variable `SCRTCH` equal to the physical address of the scratch area (see sect. 3.2).

3.2 Results

As in the case of standard HERWIG, the form of the results will be determined by the user's analysis routines. However, in addition to any files written by the user's analysis routines, the MC@NLO writes the following files:

♦ `FPREFIXNLOinput`: the input file for the NLO executable, created according to the set of input parameters defined in `MCatNLO.inputs` (where the user also sets the string `FPREFIX`). See table 2.

♦ `FPREFIXNLO.log`: the log file relevant to the NLO run.

♦ `FPREFIXxxx.data`: `xxx` can assume several different values. These are the data files created by the NLO code. They can be removed only if no further event generation step is foreseen with the currect choice of parameters.

♦ `FPREFIXMCinput`: analogous to `FPREFIXNLOinput`, but for the MC executable. See table 4.

♦ `FPREFIXMC.log`: analogous to `FPREFIXNLO.log`, but for the MC run.

♦ `EVPREFIX.events`: the event file, where `EVPREFIX` is the string set by the user in `MCatNLO.inputs`.

♦ `EVPREFIXxxx.events`: `xxx` can assume several different values. These files are temporary event files, which are used by the NLO code, and eventually removed

by the shell script. They MUST NOT be removed by the user during the run (the program will crash or give meaningless results).

By default, all the files produced by the MC@NLO are written in the running directory. However, if the variable `SCRTCH` (to be set in `MCatNLO.inputs`) is *not* blank, the data and event files will be written in the directory whose address is stored in `SCRTCH`.

4. Script variables

In the following, we list all the variables appearing in `MCatNLO.inputs`; these can be changed by the user to suit his/her needs. This must be done by editing `MCatNLO.inputs`.

`ECM` The CM energy of the colliding particles.

`FREN` The ratio between the renormalization scale, and a reference mass scale.

`FFACT` As `FREN`, for the factorization scale.

`FRENMC` As `FREN`; enters the MC-subtraction terms $\overline{\Sigma}|_{\rm MC}$ (see ref [1]).

`FFACTMC` As `FFACT`; enters the MC-subtraction terms $\overline{\Sigma}|_{\rm MC}$ (see ref [1]).

`xMASS` The mass (in GeV) of the particle `x`, with `x=W,Z,U,D,S,C,B,G`.

`IPROC` Process number that identifies the vector bosons in the final states: see table 1 for valid entries.

`PARTn` The type of the incoming particle #`n`, with `n`=1,2. HERWIG naming conventions are used (`P, PBAR, N, NBAR`).

`PDFGROUP` The name of the group fitting the parton densities used; the labeling conventions of PDFLIB are adopted.

`PDFSET` The number of the parton density set; according to PFDLIB, the pair (`PDFGROUP`, `PDFSET`) identifies the densities.

`LAMBDAFIVE` The value of $\Lambda_{\rm QCD}$, for five flavours and in the $\overline{\rm MS}$ scheme.

`SCHEMEOFPDF` The subtraction scheme in which the parton densities are defined.

`FPREFIX` Our integration routine creates files with names beginning with the string `FPREFIX`. Most of these files are not directly accessed by the user; for more details, see sect. 3.1.

`EVPREFIX` The name of the event file begins with this string; for more details, see sect. 3.1.

`NEVENTS` The number of events stored in the event file, eventually processed by HERWIG.

`WGTTYPE` Valid entries are 0 and 1. When set to 0, the weights are ± 1. When set to 1, the weights are $\pm w$, with w a constant such that the sum of the weights gives the total NLO rate.

`RNDEVSEED` This is the seed for the random number generation is the event generation step; must be changed in order to obtain statistically-equivalent but different event files.

`BASES` Controls the integration step; valid entries are `ON` and `OFF`. At least one run with `BASES=ON` must be performed.

`PDFLIBRARY` Valid entries are `PDFLIB` and `THISLIB`. In the former case, the local version of PDFLIB is used to compute the parton densities, whereas in the latter case the densities are obtained from our self-contained faster package.

`HERPDF` If set to `DEFAULT`, HERWIG uses its internal PDF set (controlled by `NSTRU`), regardless of the densities adopted at the NLO level. If set to `EXTPDF`, HERWIG uses the same PDFs as the NLO code.

`HWPATH` The physical address of the directory where the user's preferred version of HERWIG is stored.

`SCRTCH` The physical address of the directory where the user wants to store the data and event files. If left blank, these files are stored in the running directory.

5. `Makefile` variables

Before running the package, the user must edit the `Makefile`, in order to set the following variables. Further changes of the `Makefile` are necessary only if one wants to change the HERWIG version linked, or other files must be added for new features in the analysis routines.

`HWUTI` This variable must be set equal to a list of object files, needed by the analysis routines of the user (for example, `HWUTI=obj1.o obj2.o obj3.o` is a valid assignment)

`HERWIGVER` This variable must to be set equal to the name of the object file corresponding to the version of HERWIG linked to the package (for example, `HERWIGVER=herwig64.o` is a valid assignment)

A. Running the package without the shell scripts

In this appendix, we describe the actions that the user needs to take in order to run the package without using the shell scripts, and the `Makefile`.

A.1 Creating the executables

An MC@NLO run requires the creation of two executables, for the NLO and MC codes respectively. The files to link depend on whether one uses PDFLIB, or the PDF library provided with this package; we list them below:

- **NLO without PDFLIB:** `mcatnlo_vbmain.o mcatnlo_vbxsec.o mcatnlo_date.o mcatnlo_int.o mcatnlo_uxdate.o mcatnlo_uti.o mcatnlo_str.o mcatnlo_pdftomlm.o mcatnlo_libofpdf.o dummies.o SYSFILE`
- **NLO with PDFLIB:** `mcatnlo_vbmain.o mcatnlo_vbxsec.o mcatnlo_date.o mcatnlo_int.o mcatnlo_uxdate.o mcatnlo_uti.o mcatnlo_str.o mcatnlo_mlmtopdf.o dummies.o SYSFILE CERNLIB`
- **MC without PDFLIB:** `mcatnlo_hwanal.o mcatnlo_hwdriver.o mcatnlo_hwhvvj.o mcatnlo_str.o mcatnlo_pdftomlm.o mcatnlo_libofpdf.o dummies.o HWUTI HERWIGVER`
- **MC with PDFLIB:** `mcatnlo_hwanal.o mcatnlo_hwdriver.o mcatnlo_hwhvvj.o mcatnlo_str.o mcatnlo_mlmtopdf.o dummies.o HWUTI HERWIGVER CERNLIB`

Here, `SYSFILE` must be set either equal to `alpha.o`, or to `linux.o`, or to `sun.o`, according to the architecture of the machine on which the run is performed. For any other architecture, the user should provide a file corresponding to `alpha.f` etc., which he/she will easily obtain by modifying `alpha.f`. The variables `HWUTI` and `HERWIGVER` have been described in sect. 5. Finally, the variable `CERNLIB` must be set in order to link the local version of CERN PDFLIB. To create the object files eventually linked, static compilation is always recommended (for example, `g77 -Wall -fno-automatic` on Linux).

A.2 The input files

In this appendix, we describe the inputs to be given to the NLO and MC executables. When the shell scripts are used to run the MC@NLO, two files are created, `FPREFIXNLOinput` and `FPREFIXMCinput`, which are read by the NLO and MC executable respectively. We start by considering the inputs for the NLO executable, presented in table 2. The variables whose name is in uppercase characters have been described in sect. 4. The other variables are assigned by the shell script. Their default values are given in table 3. Users who run the package without the script should use the values given in table 3. The variable `zi` controls, to a certain extent, the number of negative-weight events generated by the MC@NLO (see ref. [1]). Therefore, the user may want to tune this parameter in order to reduce as much as possible the number of negative-weight events. We stress that the MC code will not change this number; thus, the tuning can (and must) be done only by running the

'FPREFIX'	! prefix for BASES files
'EVPREFIX'	! prefix for event files
ECM FFACT FREN FFACTMC FRENMC	! energy, scalefactors
IPROC	! 2850/60/70/80=WW/ZZ/ZW+/ZW-
WMASS ZMASS	! M_W, M_Z
UMASS DMASS SMASS CMASS BMASS GMASS	! quark and gluon masses
'PART1' 'PART2'	! hadron types
'PDFGROUP' PDFSET	! PDF group and id number
LAMBDAFIVE	! Lambda_5, <0 for default
'SCHEMEOFPDF'	! scheme
NEVENTS	! number of events
WGTTYPE	! 0 => wgt=+1/-1, 1 otherwise
RNDEVSEED	! seed for rnd numbers
zi	! zi
$\texttt{nitn}_1$ $\texttt{nitn}_2$	! itmx1,itmx2

Table 2: Sample input file for the NLO code. FPREFIX and EVPREFIX must be understood with SCRTCH in front (see sect. 4).

Variable	Default value
zi	0.1
$\texttt{nitn}_i$	10/0 (BASES=ON/OFF)

Table 3: Default values for script-generated variables in FPREFIXNLOinput.

NLO code. The variables $\texttt{nitn}_i$ control the integration step (see sect. 3.1), which can be skipped by setting $\texttt{nitn}_i = 0$. If one needs to perform the integration step, we suggest setting these variables as indicated in table 3.

We now turn to the inputs for the MC executable, presented in table 4. The variables whose names are in uppercase characters have been described in sect. 4. The other variables are assigned by the shell script. Their default values are given in table 5. The user can freely change the values of esctype and pdftype; on the other hand, the value of beammom must always be equal to half of the hadronic CM energy.

'EVPREFIX.events'	! event file
NEVENTS	! number of events
esctype	! 0->EMSCA=sqrt(s)-2*pT, 1->EMSCA=sqrt(s)
pdftype	! 0->Herwig PDFs, 1 otherwise
'PART1' 'PART2'	! hadron types
beammom beammom	! beam momenta
IPROC	! 2850/60/70/80=WW/ZZ/ZW+/ZW-
'PDFGROUP'	! PDF group (1)
PDFSET	! PDF id number (1)
'PDFGROUP'	! PDF group (2)
PDFSET	! PDF id number (2)
LAMBDAFIVE	! Lambda_5, <0 for default
WMASS WMASS ZMASS	! M_W+, M_W-, M_Z
UMASS DMASS SMASS CMASS BMASS GMASS	! quark and gluon masses

Table 4: Sample input file for the MC code, resulting from setting HERPDF=DEFAULT, which implies pdftype=1. Setting HERPDF=EXTPDF results in an analogous file, with pdftype=0, and without the lines concerning PDFGROUP and PDFSET. EVPREFIX must be understood with SCRTCH in front (see sect. 4).

Variable	Default value
esctype	0
pdftype	0/1 (HERPDF=DEFAULT/EXTPDF)
beammom	EMC/2

Table 5: Default values for script-generated variables in MCinput.

References

[1] S. Frixione and B. R. Webber, JHEP **0206** (2002) 029 [hep-ph/0204244].

[2] G. Marchesini, B. R. Webber, G. Abbiendi, I. G. Knowles, M. H. Seymour and L. Stanco, Comput. Phys. Commun. **67** (1992) 465; G. Corcella, I.G. Knowles, G. Marchesini, S. Moretti, K. Odagiri, P. Richardson, M.H. Seymour and B.R. Webber, JHEP **0101** (2001) 010 [hep-ph/0011363]; hep-ph/0107071.