

# RunMC - an object-oriented analysis framework for Monte Carlo simulation of high-energy particle collisions

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## Abstract

RunMC is an object-oriented framework aimed to generate and to analyse high-energy collisions of elementary particles using Monte Carlo simulations. This package, being based on C++ adopted by CERN as the main programming language for the LHC experiments, provides a common interface to different Monte Carlo models using modern physics libraries. Physics calculations (projects) can easily be loaded and saved as external modules. This simplifies the development of complicated calculations for high-energy physics in large collaborations. This desktop program is open-source licensed and is available on the LINUX and Windows/Cygwin platforms.

*Key words:* event generators, QCD, high-energy physics, data analysis, C/C++  
*PACS:* 12.38.-t, 02.70.Uu

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## 1 Tabular Summary

Title of program	RunMC version 3.3
Catalogue identifier:	
Distribution format:	tar.gz
Computer:	x86, SGI, Sun Microsystems
Operating system:	Linux, Windows/Cygwin
Memory required:	32 Mbytes
No. of bits in a word:	32
No. of processors used:	1
Parallelized?:	No
No of lines in distributed program:	~ 600000
No of bytes in distributed program:	49 Mbytes
Typical running time:	0.004-0.01 sec. per event
Programming language used:	C/C++, Fortran, Java, bash
Program requirements:	g77, g++, make, X11, Java JRE1.4 and higher
Nature of the physical problem:	Simulation of high-energy collisions of elementary particles
Method of solution:	Monte Carlo method
External libraries:	CLHEP, ROOT, CERNLIB with PDFLIB
References:	<a href="http://www.desy.de/~chekanov/runmc/">http://www.desy.de/~chekanov/runmc/</a> <a href="http://www.hep.anl.gov/chakanau/runmc/">http://www.hep.anl.gov/chakanau/runmc/</a>

## 2 Introduction

General-purpose Monte Carlo (MC) models for high-energy collisions of elementary particles are important tools used by theorists and experimentalists in their research. At present, the MC models written in FORTRAN are widely used in many high-energy physics laboratories worldwide (CERN, HERA, Fermilab etc.). These models are known to be fast, robust and well tested.

However, the main choice for future high-energy experiments is an object-oriented programming language, either C++ (the LHC experiments at CERN)

or Java (the NLC project). Recently, a few steps towards converting the FORTRAN MC models to the C++ programming language were already undertaken [1,2]. Such rewriting can take some time, since complicated physics codes written in the old-fashioned FORTRAN 77 language cannot be easily converted to the modern object-oriented programming language. Furthermore, the MC models written in C++ require a thoughtful verification to insure that their predictions are consistent with the original FORTRAN-based MC programs, as well as with the physics results obtained in the past. Such verifications will go over certain time, and a tool which allows to perform such comparisons is urgently needed.

Clearly, a program which allows running of both FORTRAN-coded and C++ MC models using a common C++ programming environment should be valuable. This is important not only for comparisons and verifications of these MC models. Such a C++ framework can also extend the lifetime of FORTRAN-based models especially for the LHC, NLC and TEVATRON communities, and can provide compatibility of most popular MC models with the new software to be used in the future. In this approach, the MC output should be converted to C++ classes for further analysis or graphical representation (histograms).

The RunMC package provides this possibility. In addition, the graphical user interface (GUI) of this package was designed to be as user friendly as possible. It helps to initialise the MC models and the user calculations, as well as to monitor the event generation. It also provides a significant flexibility to fill histograms and, at the same time, different MC models can be generated without changing the user code and histogram settings. In future, Monte Carlo models based on C++ can also be included. Thus, RunMC will provide a unified approach to generate and analyse very different MC models independent of their native codes.

The RunMC program fully complies with the change in the programming paradigm of data analysis. Instead of the FORTRAN-based analysis tools, such as PAW [3] and HBOOK [4], it uses the modern CERN C++ analysis packages, CLHEP [5,6] and ROOT [7,8]. Therefore, the program meets the requirements of future high-energy experiments.

In this respect, the RunMC program is similar to the JetWeb server [9], which also provides the ability to compare the existing MC models and to confirm the physics assumptions they contain. However, in contrast to JetWeb, the RunMC program was designed as a standalone desktop application. Therefore, the user has full access to his calculations and to the program itself.

The RunMC package is not only a common C++ front-end of Monte Carlo models designed to work with a modern graphical analysis environment. Within this approach, the concept of project modules was introduced. A project file,

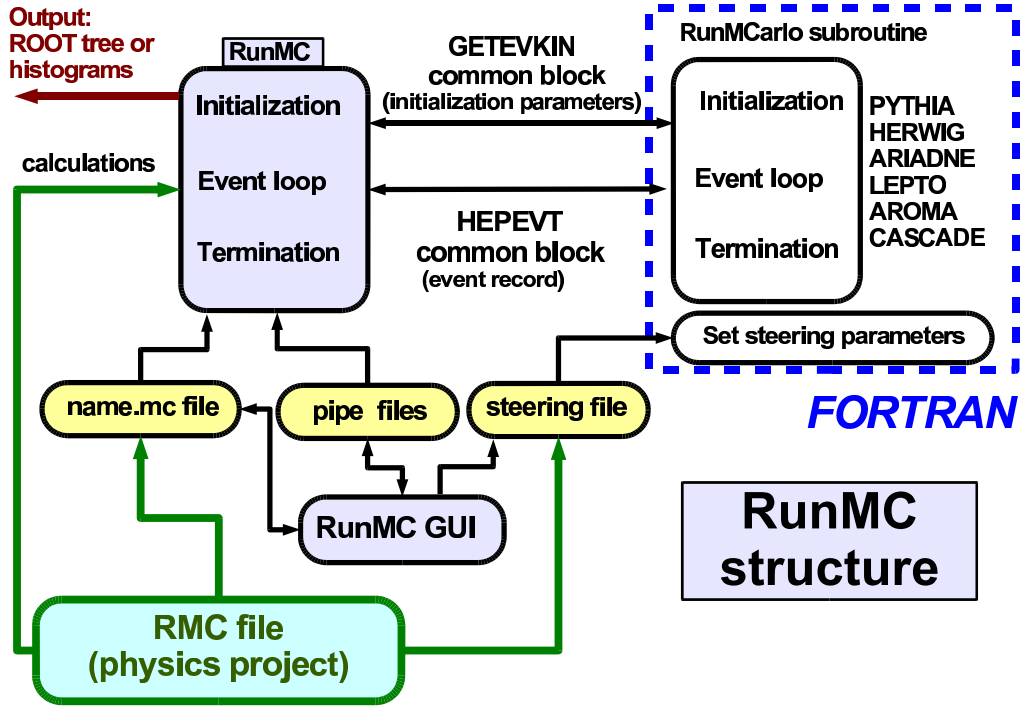


Fig. 1. The diagram shows the structure of the RunMC program.

which can contain external calculations, MC tunings, histogram definitions, etc. can be loaded to RunMC with the same ease as a document can be opened in the Microsoft Word program. Due to such simplicity, the program can be used for educational purposes, since very different aspects of the hadronic final states can easily be studied in a few mouse clicks. The project files are small and platform independent, therefore, it is fairly simple to share complicated physics calculations between scientists in large collaborations.

### 3 The structure of RunMC

The RunMC package consists of the two parts: RunMC GUI and the RunMC MC programs. There are two implementations of RunMC GUI: one is written using the Wide Studio C++ classes [10], and an alternative GUI based on Java.

The RunMC MC programs are based on the ROOT and CLHEP packages integrated with the FORTRAN MC models. A schematic structure of RunMC is illustrated in Fig. 1.

At present, the following MC models are included: PYTHIA 6.2 [11], HERWIG 6.5 [12], ARIADNE 4.12 [13], LEPTO 6.5 [14], AROMA 2.2 [15], CAS-

CADE 1.2 [16], PHOJET 1.05 [17], RAPGAP 3.1 [18]. Thus, there are several executable RunMC MC programs corresponding to each such MC model.

It should be pointed out that many hard processes included in such models come from other authors. In future certain physics algorithms can be replaced, and new processes can be added [19]. The RunMC package should reflect such a modularisation as much as possible. Therefore, an attempt will be made to accommodate this trend.

RunMC GUI communicates with the RunMC MC programs using named pipes located in a directory called “\$RUNMC/pipes”. Here, “\$RUNMC” denotes the installation directory of the RunMC project. All the directories to be discussed below are assumed to be located in this directory.

The RunMC MC programs and RunMC GUI can be installed and run independently of each other. These programs are located in the “bin” directory.

### 3.1 *RunMC GUI*

RunMC GUI allows an interaction between the user and RunMC MC programs. At present, two types of RunMC GUI are available: a user interface based on C++ (can be executed with the command “runmc”) and that based on Java (the command “jrunmc”). After the RunMC installation, the Java archive file “JRunMC.jar”, which is called by the “jrunmc” bash script, is located in the “bin” directory. Below we will describe only the C++ RunMC GUI since the Java-based GUI is very similar.

The task of RunMC GUI is to generate the output file “project.mc”, where “project” is a user-defined name of the current calculation. This file contains the most important information for the physics analysis:

- the type of MC model, the number of events to generate, the type of the initial particles, their energy and the structure functions. It also specifies the type of the output final state (partons, stable hadrons, charged hadrons, hadronic jets);
- the type of the output file: ROOT histograms or ROOT event trees. Two types of the ROOT trees can be filled: the complete HEPEVT event record or only the final states selected via RunMC GUI (i.e. partons, stable hadrons etc.). The latter event record, which is called the RunMC ROOT tree, contains the most important variables which are sufficient to do most physics studies (jet reconstruction, event shapes, inclusive particle spectra etc.). The size of the RunMC event record is typically four times smaller than the HEPEVT record;
- the kinematic cuts applied for events or final particles/jets. The cuts can

be set on the transverse energy and/or pseudorapidity of selected particles (or jets). In case of deep inelastic scattering, the range in the kinematic variables  $Q^2$ ,  $x$ ,  $y$  and  $W$  can be set;

- the histogram definitions (the titles, the number of bins, the minimum and the maximum values, histogram dimensions).
- the presentation styles of histograms and the size of the ROOT canvas. The histograms can be filled without normalisations or they can be normalised to the total number of generated events. Also, differential cross sections can be calculated taking into account the predicted luminosity and the histogram bin width (this option is supported for one-dimensional histograms only);
- the named pipes used to communicate with the RunMC MC programs;

RunMC GUI adopts the following strategy to define the histograms: There are two GUI windows, “Variables” and “Histograms”. The first window contains the names of the variables (with some additional comments) defined for a given physics project. The user should select the appropriate variable and copy it to the “Histograms” window by clicking on the corresponding title or icon.

The variable names are divided into the three categories: event-based variables (characterising the event as whole), single-particle densities (filled for each particle/jet; the variable name starts with “@”) and two-particle densities (filled for each particle/jet pair; the name starts with “@@”). Such naming convention is necessary to avoid unnecessary loops over particles or particle pairs if single or two-particle densities are not required by the user.

The histograms can also be filled in the user-defined subroutine “user-run.cpp”; in this case the naming convention for the variables discussed above is unnecessary.

Two-dimensional histograms can also be filled. If two one-dimensional histograms are defined, a two-dimensional histogram can be build from these two histograms using RunMC GUI.

To start the MC run, the command “runmc” should be executed from the project directory “proj” (or “jrunmc” if the user prefers the Java GUI). RunMC GUI allows the selection of the MC models, the initial particles, their energies, the number of events, the output required, the project name. The histograms can be defined by clicking on the “Variable” list and using a spreadsheet-like window “Histograms”. The MC run can be started by executing the command ”Start”. If specific MC settings are required, rather than the default parameters, one can create a steering file (with the extension “.cards”) to change initial MC parameters. This can be done using a spreadsheet-like editor of RunMC GUI. Next, the program performs some basic checks, and in case of problems, reports them. If no errors are found, RunMC GUI performs the following actions:

- creates a file called “project.mc”, where “project” is the name given by the user. This file contains the settings described above. It is always linked to “.analmc.ln” which will be read by the RunMC MC program;
- creates a file called “MCname.cards”, where “MCname” is the name of the current MC model (“pythia6”, “herwig”, “ariadne”, “lepto”, “aroma” “cascade”). This steering file contains initial parameters of the MC models. Note that such file may not be needed if the default MC parameters are required;
- creates a named pipe called “XX.stop”, where “XX” is a unique number assigned by RunMC for the current run. This file, located in the directory “pipes”, contains zero if the MC run is allowed or “1” if the current run should be terminated;
- creates a named pipe called “XX.event”. This file, filled by the RunMC MC programs during the MC run, contains the number of generated MC events. This number will be read by RunMC GUI to display the current status.
- executes one RunMC MC program corresponding to the selected MC model. The executable file has the name “analmc.MCname”, where “MCname” is the name of MC model.

During the event generation, the ROOT canvas can display the output histograms (up to eight in total), as well as how many events have been generated. The output from RunMC MC is written to “.analmc.log” (a symbolic link to the “project.log” file). One can view the log file using the “log” option of RunMC GUI. At the end of the run, an additional window can appear with the run information (the name of MC model, the number of the MC events processed, the luminosity used etc.). Possible errors are redirected to the file “project.err”, which is constantly monitored by RunMC GUI. The output of typical run is given in the Appendix.

The ROOT histograms are automatically modified at the end of the fill if they are required to be normalised to the total number of events or converted to differential cross sections. Note that there is no need to wait until the end of the current run: once the histogram statistics is sufficient, one can terminate the run by clicking “Stop” on the GUI window. Histograms should be saved in the ROOT file “project.root” for further studies. The style of the histograms can further be modified using the ROOT canvas editor.

All user manuals for the MC models and the RunMC user manual can be accessed via RunMC GUI using the “Help” option.

### 3.2 The RunMC MC programs

The RunMC MC programs, which are based on the FORTRAN Monte Carlo models and ROOT, have the generic name “`analmc.MCname`”, where “MCname” is the name of the corresponding MC model. The main function in the file “`analmc.cpp`”, which is located in the directory “`main/src`”, calls the FORTRAN subroutine “`runmcarlo`” to be described below. This main program is based on C++ and ROOT. The C++ code accesses the HEPEVT common block of a given MC program via a C-like structure. The RunMC MC program receives the initial parameters set by RunMC GUI via the symbolic link “`.analmc.ln`” pointing to the file “`project.mc`”.

Each MC model has its own FORTRAN subroutine “`runmcarlo`”, which provides an interface to the FORTRAN code of the given MC program. This interface program (in the file “`RUNMC-MCname.f`”) is located in the directory “`main/mcarlo/MCname`”. The task of the subroutine “`runmcarlo`” is to fill the HEPEVT common block. In addition, some initial settings are done by accessing a C/C++ structure with the initial parameters defined in the “`project.mc`” file. The main function in “`analmc.cpp`” calls this interface subroutine and fills the C/C++ structure which represents the complete HEPEVT event record. Next, this structure was used to select the final state generated by the MC models. The output is copied to the class “`HEPLIST`” which can be accessed by external calculations. The class `HEPLIST` consists of several vectors based on the `LorentzVector` vector class (from the CLHEP library) which represents four-momentum of a particle or a jet. The definition of the `HEPLIST` class, as well as other include files, can be found in the “`main/inc`” directory.

In addition to the FORTRAN subroutine “`RUNMC-MCname.f`”, which communicates with the MC programs, the directory “`main/mcarlo/MCname`” contains an additional FORTRAN subroutine in “`RUNMC-MCname-steer.f`”. It was designed to read the initialisation file (“`MCname.cards`”) located in the user directory “`proj`”.

The main function tries to determine which loop is necessary to use for filling the histograms. This decision is based on the naming convention for the RunMC variables described in Section 3.1. Note that the RunMC MC programs do not require recompilations, since the histograms are set via the input file. For a larger flexibility, the histograms can also be filled manually in the user-defined file “`user-run.cpp`” (see Section 4).

Several physics packages are available inside RunMC MC to transform the original four-momentum vector of particles/jets to the required observable:

- the transformations provided by the physics vector class “`LorentzVector`” from CLHEP can be used, since a particle or a jet is represented as a general



- four-vector based on this class;
- the event-shape calculations are available using the package developed by M. Iwasaki [20];
- the longitudinally-invariant  $k_T$  algorithm as implemented in C++ [21] can be used for the jet reconstruction. In addition to this package, the JADE and Durham jet algorithms are implemented according to M. Iwasaki [20];
- the Breit frame was implemented for  $ep$  deep inelastic scattering.

The physics packages with the corresponding documentation are located in the directory “main/physics”.

The transformations based on the LorentzVector class belong to a high-level layer of the RunMC event record. The user still can access more elementary event records which can be used to transform them to other event classes and physics calculations<sup>1</sup>. For example, the FORTRAN HEPEVT common block can directly be accessed using a C++ structure inside the RunMC package.

## 4 User calculations

For a new physics calculation, the directory “proj” should be modified. This user directory can contain external calculations, steering cards for MC initialisations, as well as the standard RunMC functions which are necessary to initialise and fill the histograms.

The user directory should always contain the file “project.mc” created by RunMC GUI. This file can be edited manually without the RunMC GUI program using any text editor. One can load this file to RunMC GUI by executing the command “runmc project.mc” from the bash shell (or using the option “Projects→read MC” of RunMC GUI). This updates the RunMC GUI program according to new project settings.

The directory “proj” can contain steering files “MCname.cards” to redefine initial MC parameters. Such files can be created via RunMC GUI (“MC settings” option). For more flexibility, the MC initialisation parameters can also be overwritten by FORTRAN-coded subroutines located in the directory “proj/ini”. If this is not done, the default MC parameters will be selected according to the RunMC option.

The histograms can be defined in the two steps: First, a necessary variable should be calculated in the file “user\_afill.cpp”. The output of this function is a pointer. The output variable name should always be associated with this

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<sup>1</sup> This can be done in the user directory “proj”, and packed in a physics-project module, see Sections 4 and 5.

pointer. As was explained above, three types of the variables can be defined (for each event, for each particle/jet, for each particle/jet pairs). Next, the variable names should be specified in the file “user-name.txt”. It includes the variable names to the list “Variables” accessed by RunMC GUI. Finally, to compile the source codes in the directory “proj” and to rebuild all RunMC MC programs to take into account changes made in the project source files, one should type “make” in the “proj” directory. All MC programs will be recompiled and RunMC GUI will be updated with new histograms. Then, the “runmc” command should be executed in the user directory to start RunMC GUI. The main advantage of this approach is that once a necessary variable is defined, new histogram definitions do not require the recompilation of all MC models.

However, the approach discussed above has some limitations since histograms for more complicated observables cannot be filled (for example, if they are constructed from three or more particle densities). Therefore, to avoid this restriction, the RunMC histograms can also be filled using the conventional method, i.e. in the function located in “user-run.cpp”. In this case, the initialisation of histograms is not required, as long as the file “project.mc” defines which histograms should be filled and what presentation style should be used to fill the histograms.

To have even more flexibility, the histograms can be initialised in the file “user-init.cpp” according to the standard ROOT procedure. In this case, each redefinition of the histograms (the bin size, the title etc.) requires recompilation of all RunMC MC programs, i.e. it is necessary to run “make” from the “proj” directory.

All RunMC MC histograms and the ROOT canvas can be accessed by the user using the C/C++ “extern” statement.

## 5 Physics projects

In order to share complicated analysis calculations and store them for further use in a future, the directory “proj” can be packed into an external file. Such a file, which contains the zipped directory “proj”, is called the RMC project file. It has the extension “rmc”. For example, “project.rmc” is the RMC file which has a user-defined name “project”. The “proj” directory inside of this RMC file has one and only one file “project.mc” with RunMC GUI settings. As was discussed in Section 4, this directory may contain some user-defined external functions, libraries, make files and MC steering files.

RunMC GUI can read such project RMC file automatically using the option.

“Projects→load RMC”. The RunMC GUI program does this in a few steps:

- unzips this file and replaces the content of the directory “proj” with new files from “project.rmc”. The old user directory is zipped and copied to the directory “main/tmp”;
- recompiles the project (i.e. it executes “make” from the directory “proj”). RunMC GUI displays the status bar indicating the compilation process;
- updates the GUI window with new variables, histograms and options.

After a short time (typically 30-60 sec depending on the CPU), the new project is loaded into RunMC GUI. To run it, the user should select “Start→Run”, and after making sure that the project can successfully be executed, make necessary modifications via RunMC GUI or in the source files.

To save the project, one should select “Projects→archive RMC”. This creates the file “project.rmc” from the content of the directory “proj”. Then this file will be copied to the directory “archive”.

At present, several RunMC project files are available on the Web [22] (they are also included in the directory “archive” of RunMC):

- the default project. Only pre-installed variables can be included in the calculations. All user-defined functions in the directory “proj” are dummy routines;
- HERA kinematic variables calculated in user-defined functions ( $Q^2$ ,  $x$  etc.);
- jets at HERA using the longitudinally-invariant  $k_T$  algorithm in the Breit frame;
- jets at LHC. As for the previous module, the jet cross sections are reconstructed using the longitudinally-invariant  $k_T$  algorithm;
- jet cross sections at LHC on the parton and hadron level. This project contains the calculation of hadronisation corrections by taking the ratio of these cross sections. It also illustrates how to initialise and to fill histograms in the function “user-run.cpp”;
- calculations of the  $D^*$  cross sections in  $ep$  collisions at HERA;
- calculations of the cross sections for strange-particle production in  $ep$  collisions at HERA;
- the HZTOOL package [23];
- the event-shape variables in  $e^+e^-$  at NLC energies;
- several examples of how to visualise tracks and  $k_T$  jets in 3D for a single MC event ( $e^+e^-$ ,  $ep$ ,  $pp$  collisions). They use a simple imitation of the magnetic field using the example taken from the ROOT project [7, 8].

The RMC project files discussed above only illustrate how to set up and to develop new physics calculations in the RunMC framework. For practical applications, these examples should be modified.

## 6 Running in the background

Due to a complete independence of RunMC GUI and RunMC MC programs, one can run jobs in the background without any GUI or pop-up window. This can be done using the following steps:

- edit the source files in the directory “proj”, or unzip a RMC project file to this directory. Recompile the project by typing “make” from the directory “proj”;
- make sure that the file “project.mc” is linked to “.analmc.ln”. If you do not want ROOT pop-up canvas with histograms, a corresponding option should be set in the file “project.mc” (see the line “OPTIONS” in “project.mc”, you may use RunMC GUI first to find out which RunMC parameter should be modified);
- execute the file “analmc.MCname” corresponding to the particular MC model. Normally, the program should ask first to create a named pipe with “0” in the directory “pipes” which allows this run.

The MC run can be terminated at any time by setting “1” in the named pipe. All histograms should be saved in the file “project.root”.

## 7 RunMC ROOT tree analyser

In addition to the standard functionality of the MC event simulation, RunMC GUI can also use ROOT trees as the input for physics calculations.

The ROOT tree can be generated by selecting an appropriate option via RunMC GUI, either “HEPEVT” or “RUNMC”, in addition or instead of the ROOT histogram option. Then, the MC events should be generated as usual, but this time a ROOT tree with the extension “.rtup” or “.htup” will be created. Then, RunMC can run over this ROOT tree if, instead of the MC model, the option “RUNMC” or “HEPEVT” is selected. Several ROOT trees can automatically be included in the analysis as long as they are of the same type and located in the same directory.

The analysis of the ROOT trees is very similar to the standard run over MC events. The external RMC files can be used to define new variables and to specify the output histograms. The only difference is that cross section calculations are not possible at present.

The main advantage of the ROOT tree analyser is that physics calculations and histograms can be produced significantly faster than when MC models

are used to generate events and to fill histograms at the same time. In case of the ROOT tree, RunMC can fill histograms by a factor of  $\sim 10\text{--}15$  faster, thus the RMC project files can be validated and analysed more efficiently.

With this additional feature, RunMC can also be used to analyse experimental data if the event record is converted to the appropriate ROOT tree. As for the Monte Carlo models, the data analysis can be performed using the RMC project files.

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## A Appendix A. Test run

After installation as described in the "INSTALL" file, execute "runmc default.mc" (or "jrunmc default.mc") from the "proj" directory. The user should see a window which can be used to start the run. Use the option "Start" to start generation of  $e^+e^-$  collisions. In 1 – 2 seconds, another window should appear with 3 histograms. A status bar on RunMC will indicate the number of processed events.

## B Appendix B. Test run output

The output could also be monitored using the option "Log" which opens the file "proj/default.log". This file should contain:

```
RUNMC: Log      file is default.log
RUNMC: Error    file is default.err
RUNMC: PID OF THE PROCESS = 6287
RUNMC: renice 10      6287
6287: old priority 0, new priority 10
RUNMC: RUNMC: execution time      = Tue Mar 22 09:49:33 2005
RUNMC: random seeds for this run = 503631 62875253
RUNMC: output file: default
RunMC: the following order was set to show the histograms=
      1D 1D 2D 2D 1D 1D 1D 1D
RUNMC: total number of 1D histograms          =2
      number of 1D histograms for events      =0
      number of 1D histograms for 1-particle density=2
      number of 1D histograms for 2-particle density=0
RUNMC: title of 1D histogram=1  Perp
RUNMC: title of 1D histogram=2  Rapidity
RUNMC: number of 2D histograms              =1
RUNMC: title of 2D histogram=1  Eta-N(tot) build from Eta and N(tot)
      number of 2D histograms for events      =0 and 1
      number of 2D histograms for 1-particle density=1 and 0
      number of 2D histograms for 2-particle density=0 and 0
-----
Call to user initialisation: userInit()
-----
RUNMC: Total number of events to generate = 1000
PYTHIA: Minimal W to set minimum photon energy fractions!
PYTHIA 6: Beam 1 11 e-
PYTHIA 6: Beam 2 -11 e+
```

*more messages from the PYTHIA 6.2 model*

```
Advisory warning: maximum violated by 1.063E+00 in event      154
XSEC(1,1) increased to 1.239E-07
No events= 200 time passed=0 s
No events= 300 time passed=1 s
No events= 400 time passed=1 s
No events= 500 time passed=2 s

Advisory warning: maximum violated by 1.069E+00 in event      541
XSEC(1,1) increased to 1.324E-07
No events= 600 time passed=2 s
No events= 700 time passed=3 s
No events= 800 time passed=3 s
No events= 900 time passed=4 s
No events= 1000 time passed=4 s

RUNMC-PYTHIA6: total cross section is (pb): 17.1710949
RUNMC-PYTHIA6: ALL done!
All done by analmc, call RUNMCARLO with itake=3
Int. Lumi=58.2374 pb-1 for 1000 MC events
-----
Call to user termination: userEnd()
-----
```

Similarly, one can test other RMC project files. Use the option “RMC project→Open” to compile a new project.

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