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The HepMC3 Event Record Library for Monte Carlo Event Generators

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Abstract

In high-energy physics, Monte Carlo event generators (MCEGs) are used to simulate the interactions of high energy particles. MCEG event records store the information on the simulated particles and their relationships, and thus reflects the simulated evolution of physics phenomena in each collision event.

We present the HepMC3 library, a next-generation framework for MCEG event record encoding and manipulation, which builds on the functionality of its widely-used predecessors to enable more sophisticated algorithms for event-record analysis. By comparison to previous versions, the event record structure has been simplified, while adding the possibility to encode arbitrary information. The I/O functionality has been extended to support common input and output formats of various HEP MCEGs, including formats used in Fortran MCEGs, the formats established by the HepMC2 library, and binary formats such as ROOT; custom input or output handlers may also be used. HepMC3 is already supported by popular modern MCEGs and can replace the older HepMC versions in many others.

Keywords: Event generator, Event record, Monte Carlo, MCEG, Particle physics, Collider experiments

PROGRAM SUMMARY

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1. Introduction

During the simulation of elementary particle reactions at high energies by MCEGs it is necessary to store and/or modify information related to the simulation, in the form of calculation elements, intermediate particles, decay cascades, etc. The main purpose of the HepMC3 event record library [1] is to hold this information both on per-event and simulation-run bases, and to facilitate manipulations upon it. In what follows, we first review the design principles of HepMC3 and the challenges which motivated its development, then turn to its technical implementation, and usage.

2. Data and object model

The logical structure of the information in the HepMC3 library follows the typical convention of modern MCEGs, being split into two parts: general information on the conditions during simulation execution (which is typically common for a run of events), and the simulated events themselves. The first part contains the description of used tools and settings applied in MCEG and thus, partially prescribes the interpretation of the simulated events. Here and below we call this data “run information”.

Each event from the second part holds a link to the run information and itself consists of “particles”, “vertices” and additional information about the event or constituent “particles” and “vertices”. In this scheme the “particles” directly correspond to the physical particles and therefore possess physical properties – four momentum, flavour¹, status², etc. The “vertices” do not have a specific physical meaning and simply indicate the elementary transmutation of a set of “incoming” particles into a set of “outgoing” particles: this may be a purely technical operation and hence should not overinterpreted. Typical examples of such a transmutation are $1 \rightarrow 2$ radiative splittings, $2 \rightarrow 2$ scatterings, $1 \rightarrow 1$ momentum-recoil corrections, and $1 \rightarrow n$ decays. Therefore, the vertices hold the lists of pointers to incoming and outgoing particles, the position in space-time of the assumed interaction or decay (if

¹The exact particle-flavour encoding is not enforced in the library code, for reasons of performance and flexibility as the standard continually evolves. However, the examples in this paper, and all known users of the HepMC library, follows the enumeration scheme described in PDG [2].

²See App. A.1 for details.

defined), and the status. The latter is an abbreviated physically meaningful description of the transmutation, see App. A.1 for details.

The described event record structure results in a certain relation between particles and vertices. In a vertex, for each incoming particle the outgoing particles are considered as “children” and for each outgoing particle the incoming particles are considered as “parents”. From these definitions the wider terms “ancestors” and “descendants” are inferred by recursion, e.g. parents of parents of. . . .

The particles that act as graph edges between vertices typically have a “production vertex” where they came from, and an “end vertex”, where they undergo their next modification or interaction: the only exceptions to this rule are the stable final-state particles which have no end vertex, with the (usually two) incoming beam particles which are assigned to a unique “root vertex” without incoming particles.

The HepMC3 event record can hold events with arbitrarily complex relations between the particles and vertices. However, to avoid algorithmic problems, it is expected the event structure will adhere to the following rules:

- All particles and vertices in the event should be connected with each other, e.g. the event should not contain dangling particles or vertices.
- Cyclic relations where a particle can be its own ancestor should be avoided.
- All vertices should have at least one outgoing particle.
- All vertices but root vertex should have at least one incoming particle.
- Vertices should have a meaningful or zero status code³:
 - Particles with no end vertex should be assigned status 1;
 - The incoming particles should be assigned status 4.
- The number of weights in the event should match the number of the names for weights in the run information.

The event’s constituent particles and vertices are collectively referred to as “objects”. Inside the event these are enumerated with non-zero integer

³See App. A.1 for details.

numbers (objects IDs, or OID), while $\text{OID}=0$ is reserved for the event itself. For the correctly composed event the OIDs should be deducible from the event topology, i.e. the particles are sorted according to the event topology and their indices correspond to their position in the sorted list⁴ and are positive. The indexes of vertices correspond to the minimal index of their incoming particles taken with minus sign⁵ and are negative.

Any additional piece of information on the whole event, particles or vertices is called an attribute and can be stored inside the event using character representation and referred object OID. There are some standard physical use case for the attributes: information on the polarisation, color (for particles), type of the interaction (for vertices), information on the used parton density functions (PDFs), process cross-section etc. (for event). As every object can have multiple attributes, these are distinguished by their names, that should be unique within corresponding object. No restrictions are imposed on the number, type or names of the attributes. However, the users should not use for their custom attributes names reserved for the standard attributes. For the events the standard attributes are:

- **GenCrossSection** – an attribute holding the information on the cross-sections on the processes in the event. The description of this attribute is given in App. A.3.
- **GenPdfInfo** – an attribute holding the information on the used PDFs. The description of this attribute is given in App. A.3.
- **GenHeavyIon** – An attribute holding the information on the heavy ions in the incoming beams. The description of this attribute is given in App. A.3.
- **alphaQCD** – an attribute holding the floating point value of QCD coupling constant.
- **alphaQED** – an attribute holding the floating point value of QED coupling constant.

⁴For the ordering to be unique, an ordering rule is needed for topologically identical particles such as e.g. the initial leptons in $e^+e^- \rightarrow \text{hadrons}$. Such a rule cannot cover all potential cases, but, using the particle types, their charge, invariant mass or other quantities it can cover *practically* all physically meaningful cases.

⁵Therefore, the root vertex has no index and all its properties are stored in the event.

- `event_scale` – an attribute holding the floating point value of event hard scale.
- `mpi` – an attribute holding the number of multiparticle interactions integer.
- `signal_process_id` – an attribute holding an integer number that characterises the signal process in the event. As the exact numbering scheme is not defined, the value is generator dependent, see Ref. [3] as an example.
- `signal_vertex_id` – An attribute holding the index of the vertex signal process.
- `random_states1, random_states2 . . . random_statesN` – arbitrary number of attributes holding the integer number states of random number generator in the beginning of event simulation. The numbering should start from one. No gaps in the numbering of these states are allowed.
- `random_states` – vector of integer numbers corresponding to the states of random number generator at the beginning of event simulation.
- `cycles` – an attribute holding an integer number to show the presence of cyclic relations in the event. The events with tree-like structure should have this attribute equal to zero or don't have it at all.

The attributes `alphaQCD`, `alphaQED`, `random_states`, `signal_process_id`, `mpi` and `signal_vertex_id` typically present in the events that were originally produced with the HepMC2 library.

For the vertices the single standard attribute is:

- `weights` – vector of floating point numbers which correspond to the weights assigned to this vertex.

For the particles the standard attributes are:

- `flows` – vector of integer numbers which correspond to the QCD color flow information. No encoding scheme of the colour flows is imposed by the library, but it is expected to comply with the rules in Ref. [2].
- `theta` – an attribute holding the floating point value of the θ angle for polarisation.

- **phi** – an attribute holding the floating point value of the ϕ angle for polarisation.

If these attributes are present in the event they will be handled where it is required, e.g. in the event serialisation or in the interfaces to generators. The implementation of the attributes is slightly different between the HepMC3 version 3.2.0 and the versions 3.1.x. See section Sec. A.2 for details.

3. Implementation

Thanks to the usage of features of recent C++ standards [4], the C++ implementation of the library has been significantly simplified with respect to HepMC2. Many custom types and iterators were removed and the library became more modular, allowing the implementation of custom features without breaking the compatibility with core library components.

For efficient memory management most of the basic types are now used via the smart pointers [5] as implemented in the C++ standard library. In addition, the concept of const-correctness [6] is promoted in the implementation of the library, fixing longstanding problems where traversing the particle–vertex links in the event graph would permit a `const` event to be modified without resorting to use of `const_cast`. Other defects, such as needing to obtain a non-const version of an event in order to perform certain read-only operations have also been fixed in HepMC3. To preserve this consistency, `const` versions of the HepMC3 smart pointers are also implemented.

The main constituent classes of the library are briefly described below.

3.1. C++ storage classes

In HepMC3 the information is represented via C++ objects and can be serialised as C++ structures with plain data types. The main types of objects (plain structures) in HepMC3 are:

- **FourMomentum** – a type that implements four vector in Minkovski space. The class includes some static functions for calculations of distance between vectors, their scalar product and other related quantities.
- **GenRunInfo** – the main bookkeeping type that holds meta-information about the generated events: list of used tools, names of used event

weights and arbitrary attributes. The embedded structure `struct GenRunInfo::ToolInfo` (three `std::string` fields) holds name, version and description of tool used for event generation and/or processing. This object can be serialised into plain data type structure `GenRunInfoData`. The corresponding smart pointer types are `GenRunInfoPtr` and `ConstGenRunInfoPtr`.

- **GenEvent** – the data type that holds the position of the primary interaction, and lists of vertices, particles and attributes. This object can be serialised into the plain data type structure `GenEventData`. The relations between the particles and vertices are implemented in the `GenEventData` structure as two lists of object OIDs. The relations between vertices and particles in `GenEventData` are encoded via members `std::vector<int> links1` and `std::vector<int> links2` in a graph-like structure. The positive elements in `std::vector<int> links1` stand for particles and that have end vertex OID encoded at the same position in `std::vector<int> links2`. The negative elements in `std::vector<int> links1` stand for production vertex with outgoing particle OID encoded in the same position in `std::vector<int> links2`.
- **GenVertex** – type of the objects used to describe decays and interactions, holds its position, list of incoming and outgoing particles, can have multiple attributes stored in the parent `GenEvent`. This object can be serialised into plain data type structure `GenVertexData`. The corresponding smart pointer types are `GenVertexPtr` and `ConstGenVertexPtr`.
- **GenParticle** – type of objects used to describe particles, holds momenta, flavour, status of the particle, can have multiple attributes stored in the parent `GenEvent`. This object can be serialised into plain data type structure `GenParticleData`. The corresponding smart pointer types are `GenParticlePtr` and `ConstGenParticlePtr`.
- **Attribute** – base class used to store arbitrary information. The attribute data is stored as (and can be serialised to) `std::string`, which is used to initialise an object of arbitrary type derived from the `Attribute` class.

The `Attribute` objects allow custom information to be stored in the events. Apart from the attributes used to store plain types (`double`, `int`

, `std::string`) and the corresponding vectors (`std::vector<double>`, `std::vector<int>`, `std::vector<std::string>`) the library provides implementation for the `GenPDFInfo`, `GenCrossSection` and `GenHeavyIon` attributes. These are described in detail in App. A.3.

3.2. Manipulation with objects

The set of orthogonal operations is built in a way that objects manipulates on their constituents/subordinates and not vice versa. The following basic operations are present in the HepMC3

- adding/removing particle to/from event. The particle is added to the list of particles in the event if it is not present there already. While removing the particle attributes are removed as well. It is not checked if particle already belongs to any other event.
These functions are implemented in
`void GenEvent::add_particle(GenParticlePtr)` and in
`void GenEvent::remove_particle(GenParticlePtr)`.
- adding/removing particle to/from vertex. The particle is added to the the list of vertex incoming or outgoing particles. The production/end vertex of the particle is updated. In case the vertex belongs to an event, the particle will be added to the event as well.
These functions are implemented in
`void GenVertex::add_particle_in (GenParticlePtr)`,
`void GenVertex::add_particle_out(GenParticlePtr)`,
`void GenVertex::remove_particle_in (GenParticlePtr)` and
`void GenVertex::remove_particle_out(GenParticlePtr)`.
- adding/removing vertex to/from event. The vertex and all it's particles are added to the list of event vertices/particles. These functions are implemented in `void GenEvent::add_vertex(GenVertexPtr)` and in `void GenEvent::remove_vertex(GenVertexPtr)`.
- adding/removing object attributes.
These functions are implemented in
`bool GenEvent::add_attribute(const std::string&, std::shared_ptr<Attribute>)`,
`bool GenVertex::add_attribute(const std::string&, std::shared_ptr<Attribute>)`,

```

bool GenParticle::add_attribute(const std::string&, std::shared_ptr
<Attribute>),
void GenEvent::remove_attribute(const std::string&),
void GenParticle::remove_attribute(const std::string&) and
void GenVertex::remove_attribute(const std::string&).

```

- setting/getting the properties of run info, event, particles, vertices. For the full list of these functions we refer to the reference manual which is shipped with the library and to the online reference manual [2].

For a more convenient usage multiple basic functions were combined to operate on list of particles or vertices are implemented.

3.3. LHEF classes

Another important innovation in the HepMC3 library is built-in support of routines for the LHEF event record/file format [7, 8]. The Les Houches Event File format (LHEF) is used for passing events from a matrix-element generator program (MEG) to a MCEG implementing parton showers, underlying event models, hadronisation models etc. Previously the standard implementation in C++ of the LHEF routines had already been maintained by Leif Lönnblad. After the merger of the standard LHEF implementation into the HepMC3 library, HepMC3 is a single package for manipulations with event records used in MCEGs and MEGs.

3.4. I/O classes and formats

The serialisation of the MCEG event record is the most important part of the library. Historically the serialisation was implemented in different packages and in different formats. The number of formats led to compatibility problems in the interaction between different simulation packages. For instance, significant technical difficulties arise when the LHC-era MCEGs are used in the simulation and reconstruction chains of older experiments [9]. To overcome such difficulties the reading and writing of events from/to disk was implemented in classes that inherit from the same abstract classes `HepMC3::Reader/HepMC3::Writer`. Both base classes have very similar structure. Apart from constructors and destructors only the following functions are expected to be re-implemented:

- The method to fill next event from input

```

bool Reader::read_event(GenEvent& evt)

```

- The method to write event
`void Writer::write_event(const GenEvent &evt)`
- The methods to get input/output source state
`bool Reader::failed()/bool Writer::failed()`
- The methods to close input/output source
`bool Reader::close()/bool Writer::close()`
- The method to skip full reading some number of events
`bool Reader::skip(const int n)`
- The methods to set/get extra options for the I/O classes `void Reader::set_options(std::map<std::string, std::string>&)`, `std::map<std::string, std::string> Reader::get_options()const`, `void Writer::set_options(std::map<std::string, std::string>&)` and `std::map<std::string, std::string> Writer::get_options()const`

The standard methods to access `GenRunInfo` objects that are used for readers/writers are: `std::shared_ptr<GenRunInfo> run_info()` and `void set_run_info(std::shared_ptr<GenRunInfo> run)`. With such a design the algorithms to read or write events from/to external sources are universal for all event formats, e.g. for reading,

```
#include "MyCustomReader.h"
...
std::shared_ptr<Reader> exemplereader;
exemplereader= std::make_shared<MyCustomReader>(/*...*/);
...
while ( !exemplereader->failed() ) {
    GenEvent evt(Units::GEV,Units::MM);
    exemplereader->read_event(evt);
    if ( exemplereader->failed() ) {
        std::cout << "End_of_file_reached.Exit." << std::endl;
        break;
    }
}
}
```

In addition to the supported standard described formats, the library allows users to implement customised input or output format via implementation of custom `Reader` and/or `Writer` classes inherited from the base classes `Reader`

and `Writer`. The custom `Reader` or `Writer` class can be linked to the user codes directly, either as in the previous code listing, or used at run-time via a plugin mechanism:

```
...
std::shared_ptr<Reader> exemplereader;
exemplereader= std::make_shared<ReaderPlugin>(input,
                                             "libMyReader", "newMyReader");
...
while ( !exemplereader->failed() ) {
    GenEvent evt(Units::GEV, Units::MM);
    exemplereader->read_event(evt);
    if ( exemplereader->failed() ) {
        std::cout << "End of file reached. Exit." << std::endl;
        break;
    }
}
```

The supported formats described were introduced by different groups of people, and for different purposes. Therefore the amount of information they hold is significantly different. The `ROOTTree`, `ROOT`, `LHEF` and `Asciiv3` formats, in addition to the standard content, can hold almost arbitrary information via the attributes mechanism.

IO_GenEvent

`IO_GenEvent` is an outdated text-based format used in the HepMC2 [10] library. The HepMC3 implementation is fully compatible with that in the HepMC2 library. However, unlike HepMC2, the reading ends after the first occurring footer `HepMC::IO_GenEvent-END_EVENT_LISTING`.

The `IO_GenEvent` record has fixed format, i.e. the information is limited to particles, vertices, weights, PDF and heavy-ion information, and no extension is allowed.

The attributes were used to reach compatibility with the HepMC2 software in the I/O `ReaderAsciiHepMC2` and `WriterAsciiHepMC2` classes, e.g. the attributes with names `alphaQCD` and `alphaEM` emulate the corresponding class members of `GenEvent` class in the HepMC2 library. With this emulation the events can be read from `IO_GenEvent` files produced by the HepMC2 library without any loss of information.

The classes that implement I/O in this format are `ReaderAsciiHepMC2`

and `WriterAsciiHepMC2`. The reading of the events by the `ReaderAsciiHepMC2` can be tuned by the options `"vertex_weights_are_separated"`, `"event_random_states_are_separated"` and `"particle_flows_are_separated"` – see Sec. A.2 for details.

Ascii3

`Ascii3` is the HepMC3 native plain text format. While being similar to `IO_GenEvent`, this format is extendable and in comparison to the former requires less storage space, as it does not save meaningless information on particles (e.g. colour flow for hadrons).

The information on events is given between the header lines

```
HepMC::Version X.Y.Z
```

```
HepMC::Ascii3-START_EVENT_LISTING,
```

where X.Y.Z stands for library version and the footer line

```
HepMC::Ascii3-END_EVENT_LISTING.
```

The run information (`GenRunInfo`) is written after the header lines followed by the lines with information on events. Each non-empty line should start from a one letter tag that defines how the content of the line should be interpreted. While reading⁶ all unknown tags are treated as errors. The tags for the run information are “W”, “N” and “T”. These are used as follows:

W number of weights

N name of weight 1 name of weight 2 ...

T name of tool 1 version of tool 1 description of tool 1

The tag “T” can appear multiple times.

Each event starts from line with leading character “E” and ends with the next line with leading character “E” or footer line. The following tags are parsed:

E number of particles number of vertices

W value of weight 1 value of weight 2 ...

U momentum unit length unit

A object OID attribute name string 1 string 2 string 3 ...

P particle OID parent vertex OID PDG I.D. p_x p_y p_z e particle mass status,

where p_x , p_y , p_z and e stand for the particle 4-momentum components. If

⁶In the presented implementation the event might be omitted with `bool Reader::skip(const int)` function without checks for correctness of tags.

the production vertex has only one incoming particle, the outgoing particles can be presented as

P particle OID parent particle OID PDG I.D. p_x p_y p_z e particle mass status
V vertex OID status (comma-separated list of incoming OIDs) @ x y z t ,

where x , y , z and t stand for the correspond position components of the vertex and production time. In case all components of the vertex position are zero, these can be omitted

V vertex OID status (comma-separated list of incoming OIDs).

The tags “E”, “W”, “U” should appear only once per event. Multiple “A”, “P”, “V”, “T” tags per event are allowed. Note that vertex with no position and zero status will not appear in the listing explicitly.

The classes that implement I/O in this format are `ReaderAscii` and `WriterAscii`.

HEPEVT

HEPEVT is an outdated plain text based format used by many MCEGs written in Fortran (e.g. Pythia6). The main purpose of the implementation is to provide a compatibility layer for the MCEGs used in the completed HEP experiments at HERA, LEP and PETRA machines. The HEPEVT is the most restrictive format and holds only the information on the particles without any options for extra information. A more detailed description can be found elsewhere [11]. The classes that implement I/O in this format are `ReaderHEPEVT` and `WriterHEPEVT`. The reading of the events by the `ReaderHEPEVT` can be tuned with an option "`vertices_positions_are_absent`". The option should be present in the list of options of the `ReaderHEPEVT` object to read event record without vertex positions.

ROOTTree

ROOTTree is a binary format based on the ROOT [12] `TTree`. This format is implemented using customisation of ROOT `Streamer` class. Basically, objects of interests (e.g. `GenEvent`, `GenParticle` and others) are serialised as into corresponding data structures (e.g. `GenEventData`, `GenParticleData`) and written in this way as branches of ROOT `TTree`. As a result, the corresponding `TTree` saved to a ROOT file, can be interpreted with standard ROOT without the HepMC3 library itself, i.e. a user with standard ROOT can retrieve all information on the events in a form of simple structures `GenEventData`, `GenParticleData` etc.

This has several advantages in comparison to the other formats: it allows random access, access over network, has the best I/O performance and requires the smallest amount of storage space per event. The classes that implement I/O in this format are `ReaderROOTTree` and `WriterROOTTree`.

ROOT

ROOT is a binary format based on the ROOT [12]. This format is implemented using standard ROOT serialisation and writes the objects to ROOT files “as is”. The classes that implement I/O in this format are `ReaderROOT` and `WriterROOT`.

LHEF

The plain-text Les Houches Event Format, primarily intended for low-multiplicity partonic matrix-element event communication. The class that implement I/O in this format is `ReaderLHEF`. Currently no implementation of `Writer` is provided. The documentation on the LHEF functions can be found elsewhere [8].

3.5. Search module classes

HepMC3 comes with an optional “search” library for finding particles related to other particles or vertices. Two main interfaces are defined: `Relatives`, for finding a particular type of relative, and `Feature`, for generating filters based on Features extracted from particles. In addition, the standard boolean operator on Filters are also defined. A `Filter` is any object that has an operator that takes as input a `ConstGenParticlePtr` and returns a `bool` that reflects whether the input particle passes the filter requirements or not. `Filter` is defined in `Filter.h` as an typedef of `std::function<bool(ConstGenParticlePtr)>`. The filters may use the `Selector` class to extract standard features from a particle and construct relational filters. As an illustrative example the following code will obtain a list of all final state descendants of a particle that has a transverse momentum larger than 0.1 GeV and has a pseudorapidity between -2.5 and 2.5:

```

std::vector<ConstGenParticlePtr>
getDescendants(ConstGenParticlePtr parent) {
    Filter f = (StandardSelector::STATUS == 1 &&
               StandardSelector::PT > 0.1 &&
               StandardSelector::ETA > -2.5 &&
               StandardSelector::ETA < 2.5);
    return applyFilter(f, Relatives::DESCENDANTS(parent));
}

```

3.6. Other classes and free functions

In addition to the classes described above, HepMC3 includes a small number of auxiliary classes.

The `Setup` class controls verbosity of warnings.

The `Units` class holds information on used units. The allowed length units are mm and cm, while the allowed energy units are MeV and GeV. The function `GenEvent::set_units(Units::MomentumUnit, Units::LengthUnit)` performs conversion between different units used in the event. Note that it does not affect the units used in the attributes of event.

The `Print` class provides multiple static functions to produce human-readable printings of objects in the library. The same task is performed with free overloaded operators `<<` in `PrintStreams.h` header.

The functions and macros that help to find out the version of library are located in `Version.h` header.

The header `ReaderFactory.h` provides functions `std::shared_ptr<Reader> deduce_reader(const std::string &filename)` and `std::shared_ptr<Reader> deduce_reader(std::istream &)` that try to open the a file or stream for reading and automatically deduce the appropriate reader.

4. Installation, dependencies, compatibility and usage

HepMC3 supports GNU/Linux, OS X and Windows operation systems and should be able to operate on some other Unix systems. It has been tested on Ubuntu, CentOS, Fedora, openSUSE, Windows 10 and OS X operating systems on Intel-compatible 64-bit processors. Binary packages are available for multiple operating systems, see Tab. 1 for details.

HepMC3 may be installed either from source, or by using precompiled packages from the repositories of corresponding Linux distributions (for Linux users), or from Homebrew-HEP for OS X users. For the Windows, BSD and

Operating system	Repository	ROOT	Version	Credits
Mac OS X	homebrew-hep [13]	no	3.2.0	Enrico Bothmann
Arch Linux	AUR [14]	no	3.1.1	Frank Siegert
Debian 9	Testing [15]	no	3.1.2	Mo Zhou
Ubuntu 19	Universe [16]	no	3.1.1	
Fedora 28+	EPEL [17]	yes	3.2.0	Mattias Ellert
RHEL 7+ and like	EPEL [17]	yes	3.2.0	Mattias Ellert
SUSE/openSUSE	Tumbleweed [18]	no	3.1.1	
Linux	LCG [19]	yes	3.1.2	
Windows 10		no	3.2.0	
BSD 12		no	3.2.0	
Solaris		no	3.2.0	
Multiple	pypi [20]	no	3.2.0	HepMC Devs.
Linux/MacOSX	conda-forge [21]	no	3.2.0	Henry Schreiner

Table 1: Summary on systems where HepMC3 was tested and the availability of HepMC3 precompiled binaries. For the majority of tests only the Intel-compatible 64-bit architecture (x86_64) was considered. The ROOT support was tested only for these systems which provide ROOT packages in the repositories.

Solaris users it is necessary to build the library from sources. Windows 10 users should be able create NSIS [22] installers if needed. Python-based users can install the HepMC3 packages from the CondaForge [21] or PyPI [20] repositories.

The detailed instructions to compile the library from sources are provided in the `README.md` file distributed with the library source codes and are the same for all the supported platforms. Only a short version is given below.

4.1. Dependencies

The only basic dependency for the installation of the library from sources is the availability of a C++ 11 compatible C++ compiler with appropriate run-time and the build tool CMake [23]. It is recommended to use CMake of version 3.9 and newer. The basic features of the package can be extended if additional packages are available, see Tab. 2.

4.2. Installation from sources

The procedure of installation from sources consists of multiple steps⁷. The first step is to get the HepMC3 sources from the git [34] repository:

```
git clone https://gitlab.cern.ch/hepmc/HepMC3.git
```

or from the official site:

```
wget http://cern.ch/hepmc/releases/HepMC3-3.2.0.tar.gz
tar -xzf HepMC3-3.2.0.tar.gz
```

Windows users can use web-browsers and/or proprietary utilities instead. The second step is to create a work-space area on which to perform the builds:

```
mkdir myhepmc3-build
cd myhepmc3-build
```

The third step is to configure, build and install the code with CMake [23]⁸, e.g.

```
cmake -DCMAKE_INSTALL_PREFIX=../
      MyInstallationLocation -DHEPMC3_ENABLE_ROOTIO=
      OFF ../HepMC3
cmake --build ./
cmake --install ./
```

Optionally, after the compilation, it is possible to run the build-in test suite based on CTest [23]:

```
ctest ./
```

⁷Here and below the commands are given assuming POSIX-compatible shell (e.g. GNU bash) and Unix-like OS.

⁸CMake of version 3 could be named as “cmake3” on some systems.

4.3. Compatibility

Starting from version 3.1.0, the HepMC3 and HepMC2 libraries can co-exist in one installation, therefore the migration of user code from HepMC2 to HepMC3 can go as easy as possible.

4.4. Usage

As of end 2019 several MCEGs were interfaced to HepMC3, see Tab. 3 for details.

Package or feature	Used in	Purpose
ROOT 6	ROOT, examples, tests	Provide ROOT I/O
Doxygen [24]	documentation	Generate documentation
Pythia 6	interfaces, examples	Provide Pythia6 example
Pythia 8	interfaces, examples, tests	Pythia8 examples and tests
TAUOLA	interfaces, examples, tests	PHOTOS examples and tests
PHOTOS	interfaces, examples, tests	Tauola examples and tests
HepMC 2	tests	Compare HepMC3 vs HepMC2
threads	tests	Check thread safety
graphviz [25]	examples	Provide GUI event viewer
valgrind [26]	tests	Check for memory leaks
zlib [27]	examples	Access compressed ASCII files
Python [28, 29]	Python, tests	Compile/test Python bindings
binder [30]	Python development	Generate Python bindings
astyle [31]	development	Format the code
cppcheck [32]	development	Do static analysis of the code
NSIS [22]	development	Create Windows installers
gengetopt [33]	development	Create option parsers

Table 2: Summary of the packages that can be used in HepMC3. The packages used for development only are given in the bottom part of the table.

Code	Type	Matched versions		Interface location
		Code	HepMC3	
SHERPA-MC [35]	MCEG	>2.2.8	3.1+	SHERPA-MC
		>2.2.6	3.0	SHERPA-MC
JetScape [36]	MCEG	1.0	3.0	JetScape
ThePEG 2 [37]	MCEG toolkit	2.2.0	3.1+	ThePEG2
Herwig 7 [38]	MCEG	7.2.0	3.1+	ThePEG2
Pythia 8 [39]	MCEG	8.2+	3.X	HepMC3
Pythia 6 [3]	MCEG	6.4	3.1+	HepMC3
Tauola [40]	MCEG	1.1.6c	3.X	HepMC3
Photos [41]	MCEG	3.61	3.X	HepMC3
WHIZARD [42]	MCEG	>2.8.1	3.1+	WHIZARD
Rapgap [43]	MCEG	>3.303*	3.1+	Rapgap
Cascade [44]	MCEG	>3.00*	3.1+	Cascade
EvtGen [45]	MCEG	master*	3.1+	EvtGen
Geant V [46]	Simulation	master	3.0	GeantV
MC-TESTER [47]	Testing	1.25	3.X	HepMC3
Rivet [48]	Testing	3.0.3	3.1+	Rivet

Table 3: Summary on the usage of HepMC3 in external projects. “master” stands for the latest version in the used version control system of the official repository, e.g. for master branch of git repository. If known, the versions where support is expected to be released are given in brackets. The * symbols denote support implemented in non-official versions of the codes.

5. External codes

The library itself embeds some external codes. These are:

- pybind11 [49], a header-only library used for python bindings.
- Pythia6 [3], a MCEG generator used in the examples.
- gzstream [50], a set of C++ classes wrapping the zlib compression library.
- Codes from examples of the binder [30] package.
- Various cmake modules were taken from the cmake distribution, see details in the corresponding modules.

The initial version of the Pythia8 HepMC3 interface was committed by Mikhail Kirsanov, who created the HepMC2 interface for the Pythia8 package [39]. The later versions were improved by Philip Ilten.

6. Performance

During the event generation by the MCEGs the speed of event construction typically is not of great concern. Moreover, it strongly depends on the type of generator, its settings and therefore is not well defined. Therefore, we concentrate on a better defined characteristics of I/O performance while using already generated events. The input samples [51] consist of multiple event samples with various signal processes saved in HepMC2 files. These include the $e^+e^- \rightarrow$ hadrons processes for $\sqrt{s} = 10\text{--}206$ GeV, $e^+e^- \rightarrow \Upsilon$, $e^\pm p$ deep-inelastic scattering, $pp \rightarrow$ jets for $\sqrt{s} = 7$ and 13 TeV, and more.

With these samples series of tests were performed with HepMC2 and HepMC3 libraries. All tests were performed on CentOS 7 x86_64 with ROOT version 6.18, zlib version 1.27, HepMC2 version 2.06.10, gcc version 4.8.5 and default settings for ROOT compression level, ROOT compression algorithm and the precision of `Asciiv3` output. Before the tests all the files were loaded into memory.

The measurements of relative samples sizes are given in Fig. 1.

The Fig. 1 shows that `Asciiv3` with default precision has the same size as `IO_GenEvent`, and the `ROOTTree` format provides the most efficient packing of events ahead of compression with `zlib`. The measurements of total reading

time for the samples are given in Fig. 2. The same measurements as described above were corrected for the time of opening of files are given in Fig. 3.

The Fig. 3 shows that reading from `Asciiv3` is typically faster than from `IO_GenEvent` in HepMC3. The reading from `Asciiv3` in HepMC3 is sometimes slightly slower than reading from `IO_GenEvent` in HepMC2. The small difference can be explained with extra time needed to assure thread safety.

The `ROOTTree` format provides the most efficient reading of events for almost all cases.

7. Interfaces, examples and documentation

7.1. Interfaces

The presented library contains some interfaces to the MCEGs, which do not ship the interfaces to HepMC3, see Tab. 3. These interfaces can be used instantly in the production or tests to generate the Monte Carlo simulated events. One important difference between the HepMC2 and HepMC3 is that the later delivers only it's interface for the Pythia6 generator, while the former provided C++ wrappers to the Pythia6 functions.

7.2. Examples

For the users convenience, numerous example programs are provided with the library. A brief overview of these codes is given in Tab. 4.

These examples can be modified and/or compiled using with external HepMC3 installation. For instance, with an installed HepMC3 it is possible to compile examples only:

```
mkdir -p myexamples
cd myexamples
git clone https://gitlab.cern.ch/hepmc/HepMC3
...
cd HepMC3/examples/
cmake -DUSE_INSTALLED_HEPMC3=ON CMakeLists.txt
cmake --build .
```

7.3. Documentation

The online documentation is available on the HepMC3 home page [1]. It includes the automatically generated documentation on the codes as well as

Example location	Requires	Purpose
BasicExamples/ basic_tree.cc		Build event from scratch
hepevt_wrapper_example_fortran.f	FORTRAN	Use HEPEVT wrapper
HepMC2_reader_example.cc		Read HepMC2 IO_GenEvent files
HepMC3_fileIO_example.cc		Read HepMC3 AsciiV3
ConvertExample/	(ROOT,zlib)	Convert files from one format into another
LHEFExample/		Manipulate LHEF events
Pythia6Example/	FORTRAN	Use Pythia6 interface
Pythia8Example/	Pythia8	Use Pythia8 interface
ViewerExample/	ROOT, graphviz	Use GUI event browser
RootIOExample/	ROOT	Use ROOT format
RootIOExample2/	ROOT	Use ROOT format with own class
RootIOExample3/	ROOT	Use ROOTTree format

Table 4: List of examples in HepMC3. The optional dependencies are given in brackets.

extra material on specific topics, e.g. the LHEF format. The same documentation can be generated from the sources using the doxygen [24] utility and appropriate configuration options, e.g.

```
cmake -DHEPMC3_BUILD_DOCS=ON <other options>
      CMakeLists.txt
```

7.4. Python bindings

HepMC includes C++ codes for Python [52] language bindings. The codes are suitable for compilation of Python modules for Python2.7 [28] and Python3 [29]. These codes were generated automatically using the binder [30]

utility and depend on the pybind11 [49] header-only library included in the HepMC3 codes. So far the binding codes are available for all classes in HepMC3 and LHEF name spaces but some in Search engine. For usage examples please look into the tests. To turn on the compilation of bindings use

```
cmake -DHEPMC3_ENABLE_PYTHON=ON <options> CMakeLists
.txt
```

By default the Python modules will be generated for Python2 and Python3 if these are found in the system. The exact desired Python version can be specified appropriate configuration options, e.g.

```
cmake -DHEPMC3_PYTHON_VERSIONS=2.7,3.4,3.6 <other
options> CMakeLists.txt
```

In case the test suite is enabled, tests of python bindings with all the enabled versions will run as well. In the automatically generated codes it was assumed that `std::ostream` will be mapped onto `io.stringIO()` and similar objects. The constructors of classes derived from `Reader/Writer` with `std::ifstreams/std::ostreams` were omitted. To benchmark the implemented capabilities, the Pythia8 HepMC3 interface was re-implemented in Python and tested together with Python bindings of Pythia8, see Fig.??.

Despite not being recommended, it should be possible to compile the Python bindings using the installed version of HepMC3. To do this, copy the `python` directory outside the source tree, uncomment the line

```
project(pyHepMC3 CXX)
```

in `python/CMakeLists.txt` and run CMake inside the `python` directory with the option `-DUSE_INSTALLED_HEPMC3=ON`.

The package `pyhepmc/pyhepmc-ng` [53] provides bindings to some core functions of HepMC3.

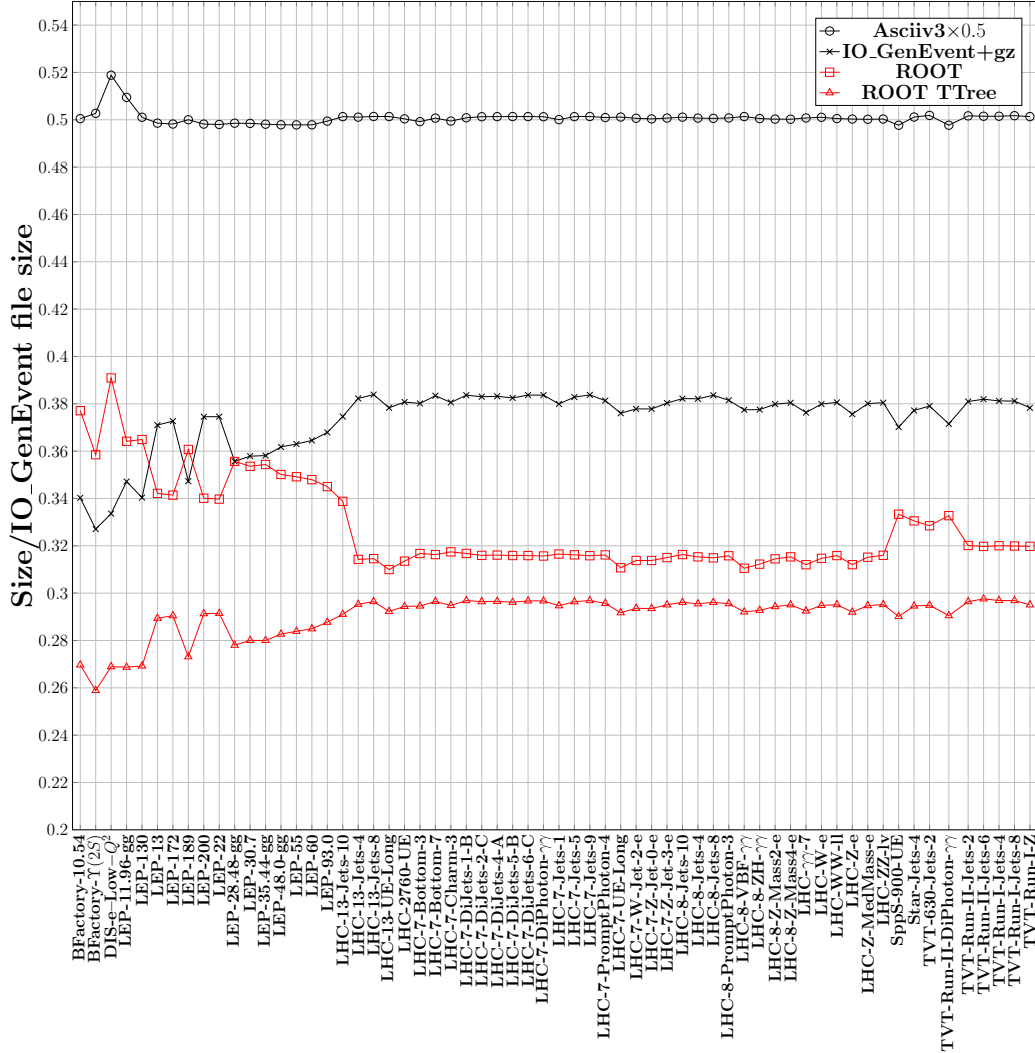


Figure 1: Size of events samples in different formats relatively to the size of same sample in HepMC2 IO_GenEvent format. The physical content of the files with simulated events is encoded in the name of file. “BFactory” and “LEP” in the file names indicate simulation of e^+e^- collisions at B -factories and PETRA/TRISTAN/LEP colliders. The main simulated processes are $e^+e^- \rightarrow$ hadrons for “LEP” and $e^+e^- \rightarrow$ resonances \rightarrow hadrons. “DIS” in the file name indicates the simulation of deeply-inelastic $e^\pm p$ scattering at HERA collider. “LHC”, “SppS” and “TVT” in the file name indicate the simulation of pp collisions at LHC, SppS or Tevatron colliders. The numbers following the collider name abbreviate the centre-of mass energy of the collision in GeV or TeV. In addition, the names of files with pp simulated events include the abbreviated in the main process name, e.g. “LHC-8-Jets” abbreviates the inclusive jet production.

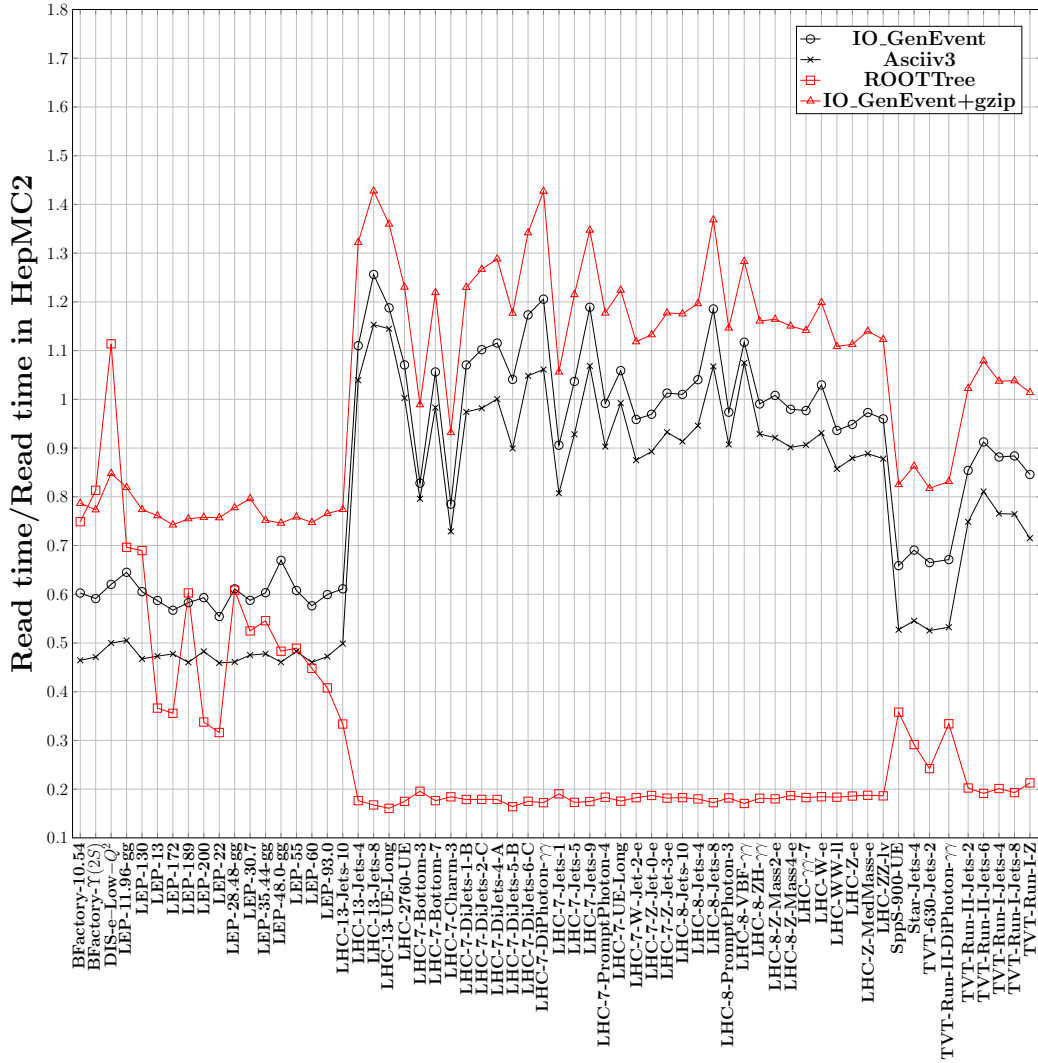


Figure 2: Total reading time of events samples in different formats relatively to the total reading time of same sample in HepMC2 IO_GenEvent format. See Fig. 1 for details.

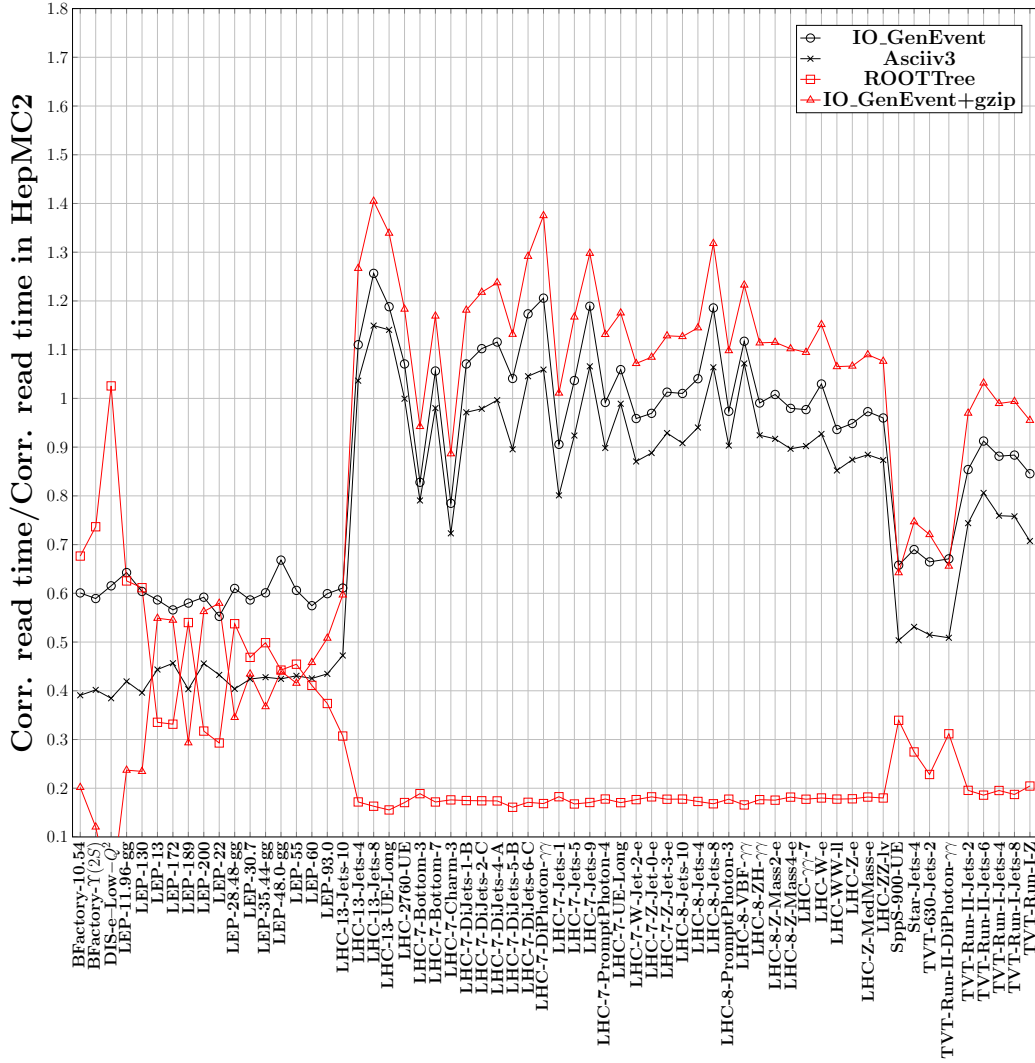


Figure 3: Corrected reading time of events samples in different formats relatively to the corrected reading time of same sample in HepMC2 IO.GenEvent format. The correction is done subtracting the time needed to read the first event in the file. See Fig. 1 for details.

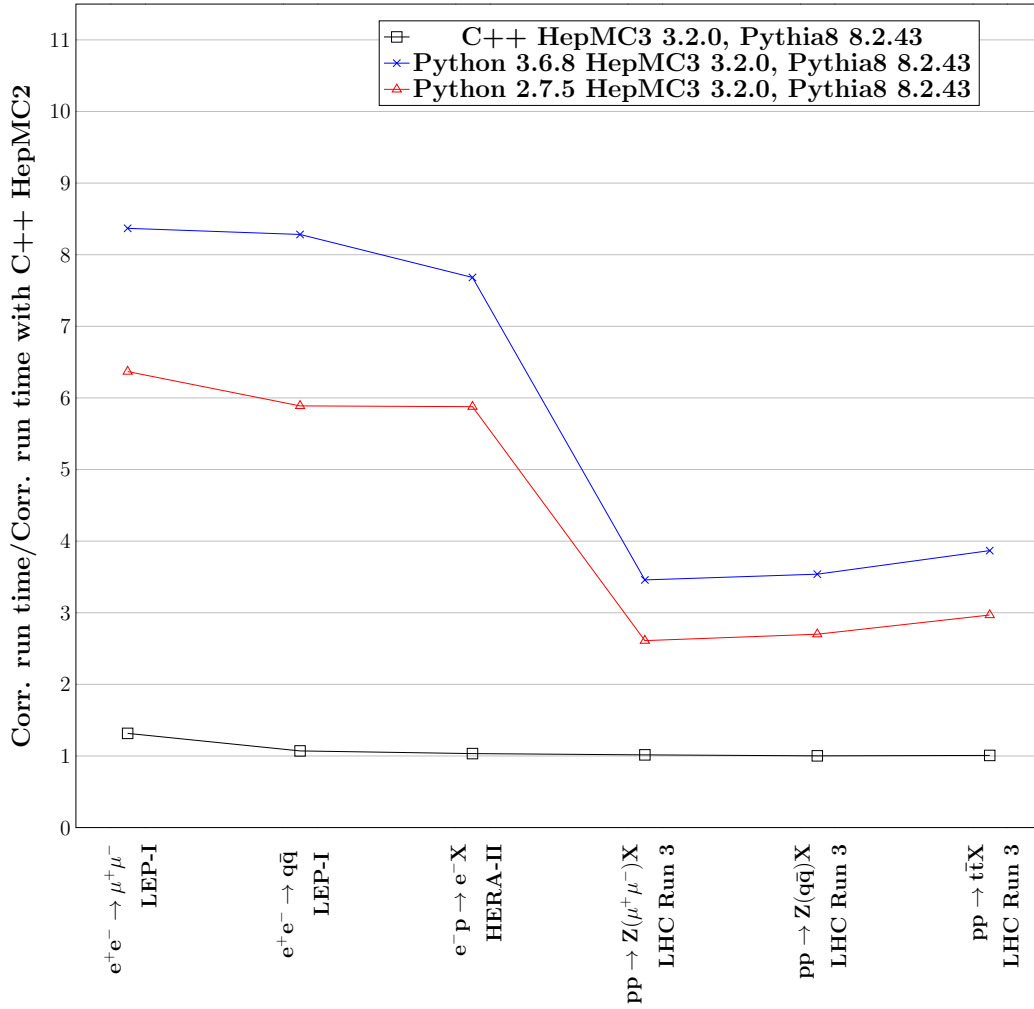


Figure 4: Time needed to produce a sample of simulated events using different Pythia8 interfaces to event record libraries relatively to the time needed to produce a sample of same size using Pythia8 HepMC2 C++ interface. The ratios were obtained from the measurements of time needed to produce $\mathcal{O}(10^4 - 10^5)$ events and were corrected for the effects of start-up in the same way as the ratios in Fig. 3. The measurements were provided using the HepMC2, HepMC3, Pythia8 and python packages from the EPEL repository on x86.64 machine running CentOS7. The C++ codes were compiled with standard options for this platform using the gcc compiler of version 4.8.5.

8. Conclusions

The HepMC3 library is designed to perform manipulations with event records of High Energy Physics Monte Carlo Event Generators (MCEGs). The library version 3.2.0 has been released in November 2019.

The I/O functionality of the library has been extended to support common input and output formats of HEP MCEGs, including formats used in Fortran HEP MCEGs, formats used in HepMC2 library and ROOT. The library is already supported by many MCEGs (e.g. Herwig, Sherpa, WHIZARD), provides interfaces to others (Pythia8, TAUOLA and PHOTOS) and can replace the older HepMC versions in various applications dealing with Monte Carlo event records (e.g. in Rivet).

Acknowledgements

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Appendix A

A.1 Status codes

Status code	Meaning	Usage
0	Not defined (null entry)	Not a meaningful status
1	Undecayed physical particle	Recommended for all cases
2	Decayed physical particle	Recommended for all cases
3	Documentation line	Often used to indicate in/out particles in hard process
4	Incoming beam particle	Recommended for all cases
5–10	Reserved for future standards	Should not be used
11–200	Generator-dependent	For generator usage
201–	Simulation-dependent	For simulation software usage

Table 5: Status codes for particles.

Status code	Meaning	Usage
0	Not defined (null entry)	Vertex with no meaningful status
1-	Generator-dependent	For generator usage

Table 6: Status codes for vertices.

A.2 Compatibility with earlier version of HepMC3

Prior to version 3.2.0, the following attributes were handled during the reading of `IO_GenEvent` files in a different way. The differences are:
For the particles:

- The particle flows were added to the event as multiple `IntAttribute` attributes with names “flow1” and “flow2”.

- The vertex weights were added to the event as multiple `DoubleAttribute` attributes with names “weights1”, “weights2” ... “weightsN”.
- The event random number generator states were added to the event as multiple `IntAttribute` attributes with names “random_state1”, “random_state2” ... “random_stateN”.

The old behaviour during the event reading can be restored setting the options `"particle_flows_are_separated"`, `"vertex_weights_are_separated"` and `"event_random_states_are_separated"`.

A.3 Attributes

The attributes described below have a simple structure with all important members being public. Therefore, the functions like `void GenPDFInfo::set(...)` are provided only for convenience and are not described in detail below.

A.3.1 *GenPdfInfo*

The `GenPDFInfo` contains the following data members:

- `int parton_id[2]` – array with two elements holding PDG I.D. for the first and second interacting parton.
- `int pdf_id[2]` – array with two elements holding I.D.s of PDF distributions as encoded in the LHAPDF [54] library.
- `double scale` – value of factorisation scale (in GeV).
- `double x[2]` – array with two elements holding fractions of interacting partons momentum with respect to the momentum of their beams.
- `double xf[2]` – array with two elements holding the values of PDF.

The representation of `GenPDFInfo` as `std::string` is structured as

`parton_id[0] parton_id[1] x[0] x[1] scale xf[0] xf[1] pdf_id[0] pdf_id[1]`

A.3.2 *GenCrossSection*

The `GenCrossSection` contains the following data members:

- `long int accepted_events` – the number of generated events.
- `long int attempted_events` – the number of attempted events.
- `std::vector<double> cross_sections` – values of cross-sections.
- `std::vector<double> cross_section_errors` – values of cross-section uncertainties.

The representation of `GenCrossSection` as `std::string` is structured as

cross_sections[0] cross_section_errors[0] accepted_events attempted_events
cross_sections[1] cross_section_errors[1] ...

A.3.3 *GenHeavyIon*

The `GenHeavyIon` contains the following data members:

- `int Ncoll_hard` the number of hard nucleon-nucleon collisions.
- `int Npart_proj` the number of participating nucleons in the projectile.
- `int Npart_targ` the number of participating nucleons in the target.
- `int Ncoll` the number of inelastic nucleon-nucleon collisions.
- Deprecated `int spectator_neutrons` Total number of spectator neutrons.
- Deprecated `int spectator_protons` Total number of spectator protons.
- `int N_Nwounded_collisions` Collisions with a diffractively excited target nucleon.
- `int Nwounded_N_collisions` Collisions with a diffractively excited projectile nucleon.
- `int Nwounded_Nwounded_collisions` Non-diffractive or doubly diffractive collisions.
- `double impact_parameter` The impact parameter.

- `double event_plane_angle` The event plane angle.
- `Deprecated double eccentricity` The eccentricity.
- `double sigma_inel_NN` The assumed inelastic nucleon-nucleon cross section.
- `double centrality` The centrality.
- `double user_cent_estimate` A user defined centrality estimator.
- `int Nspec_proj_n` The number of spectator neutrons in the projectile.
- `int Nspec_targ_n` The number of spectator neutrons in the target.
- `int Nspec_proj_p` The number of spectator protons in the projectile.
- `int Nspec_targ_p` The number of spectator protons in the target.
- `std::map<int,double> participant_plane_angles` Participant plane angles.
- `std::map<int,double> eccentricities` Eccentricities.

The `std::string` representation of `GenHeavyIon` can be built in two ways:

- The “old” version is structured as:

```
v0 Ncoll_hard ... Nspec_targ_p
participant_plane_angles.size()
participant_plane_angles[0].first participant_plane_angles[0].second ...
eccentricities.size()
eccentricities[0].first eccentricities[0].second ...
```

With all other members described above listed between `Ncoll_hard` and `Nspec_targ_p`.

- The “new” version is structured as:

```
v1 Ncoll_hard ... Nspec_targ_p
participant_plane_angles.size()
participant_plane_angles[0].first participant_plane_angles[0].second ...
eccentricities.size()
eccentricities[0].first eccentricities[0].second ...
```

With all non-deprecated members described above listed between Ncoll_hard and Nspec_targ_p.

The “new” should comply to the Lisbon Accord [55] and is aimed to be helpful for the groups performing heavy-ion physics studies.

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