

# Next generation input-output data format for HEP using Google's protocol buffers

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## Abstract

We propose a data format for Monte Carlo (MC) events, or any structural data, including experimental data, in a compact binary form using variable-size integer encoding as implemented in the Google's Protocol Buffers package. This approach is implemented in the so-called PROMC library which produces smaller file sizes for MC records compared to the existing input-output libraries used in high-energy physics (HEP). Other important features are a separation of abstract data layouts from concrete programming implementations, self-description and random access. Data stored in PROMC files can be written, read and manipulated in a number of programming languages, such C++, Java and Python.

# 1 Introduction

A crucial requirement for many scientific applications is store, retrieve and process large-scale numeric data with a small signal and large background (or “noise”). Information on background objects is not required to be stored with the same numeric precision as that for signal objects. An input/output library which dynamically compresses data depending on the content of information becomes important for effective data storage and analysis.

A typical example is the Large Hadron Collider (LHC) experiments designed to investigate proton-proton and heavy-ion collisions in order to understand the basic structure of matter. The LHC experiments are currently involved in event processing and physics analysis of petabytes of data. A single analysis requires a processing of tens of terabytes of data located on the grid storage across the glob. For example, the number of collisions recorded by the ATLAS experiment since 2009 exceeds 20 billion. The number of particles in a single collision will increase by a factor 5-10 for future high-luminosity LHC runs. Currently, the LHC experiments store more than 100 petabytes of data and this number will increase by a factor 10 over the next 10 years. A large fraction of stored data has a small fraction of “signal” particles, while most of low-energetic particles from other events are less interesting and represent “pileup” background. It is important to store pileup particles to derive corrections, but to store such particles with the same numeric precision as signal particles is inefficient.

In this paper we will discuss an input-output library which has a content dependent compression. It stores less energetic particles with a reduced numerical precision and smaller numbers of bytes. The library is designed for Monte Carlo (MC) simulation events, but it can naturally be extended to store any information. The library was created during the Snowmass Community Studies [1] with the goal to store MC simulations in a compact form on public web pages.

## 2 The proposal

This paper discusses an input/output persistent framework which:

- streams data into a binary form and dynamically writes less interesting, low-energetic particles with reduced precision compared to more energetic signal particles. For example, we expect that such content-dependent compression will decrease the LHC data volume by 30% or more. Although we use the word “compression”, it should be noted that no standard compression algorithms (gzip, zip, bunzip2) are used since the file-size reduction is achieved using a highly efficient binary format.
- is multiplatform. Data records can be manipulated in C++, Java and Python. This opens the possibility to use a number of “opportunistic”

platforms for data analysis, such as Windows or Android, which have not been used widely in HEP.

- is a self-describing data format based on a template approach to encode complex data structures. One can generate C++, Java and Python analysis codes from a PROMC file itself.
- has random access capabilities. Events can be read starting at any index. Individual events can be accessed via the network without downloading the entire files. Metadata can be encoded for each record, allowing for a fast access to interesting events.
- is implemented as simple, self-containing library which can easily be deployed on a number of architectures including supercomputers, such as IBM Blue Gene/Q system.

The proposed input-output framework is expected to be used in many scientific areas. In particular, it is useful for (a) data reduction for large general-purpose detectors at colliders and other experiments; (b) effective data preservation; (c) effective data analysis without CPU overhead due to the standard decompression algorithms.

### 3 Existing approaches

The LHC experiments store data and experiment-specific MC events in compressed ROOT format [2]. To store events generated by MC models in a more generic and exchangeable way, HEPMC [3], STDHEP [4], HepML [5] and the Les Houches event format (LHEF) [6] file formats have been developed. For example, the HEPMC library is interfaced with all major Monte Carlo models and is widely used by the HEP community due to its simplicity, platform independence, exchangeability and reusability. However, the HEPMC format stores data in uncompressed ASCII files, which are typically ten times larger than ROOT files with the default compression.

The ROOT IO is an integrated part of the C++ ROOT analysis framework [2] developed at CERN. This framework is heavily integrated to the Linux platform. Despite its popularity to store experiment-specific data, it uses the GZIP compression which is CPU intensive and lacks flexibility in store particles depending on their importance. As discussed before, the current and future LHC experiments will collect events with only a small fraction of signal particles that are important for analyzers, while most of low-energetic particles from other (overplayed) events represent “pileup” background. For high-luminosity LHC runs, one “signal” event (for example, event with a Higgs particle) will contain 50-140 pileup events, with up to 10,000 low-energy particles that are not important for analysis of the signal itself. Still, such particles (or a fraction of such particles)

should be kept to derive corrections to signals. Therefore, to store low-energetic particles with a smaller numeric precision becomes crucial in effective data storage and analysis. The fixed-number of bytes to represent numeric data used by ROOT and by other data formats does not allow to implement a compression that depends on particle content (particle energy, mass, origin, etc.). Another crucial aspects that can be improved is the ability to identify interesting events and particles without reading entire files. This requires random access, effective metadata model, and the ability to process files on multiple cores of high-performance multicore computers.

## 4 Varint data encoding

A possible solution for data reduction is to use “varints” which can encode integer (int32, int64 etc.) values using variable number of bytes. Such algorithm is implemented in the Google’s Protocol Buffers library [7]. This library encodes complex data in the form of platform-neutral “messages” which can include the varint representation of data. Smaller integer numbers represented by varints in such messages take a smaller number of bytes. For HEP applications, this implies that four-momenta of low-energetic particles encoded using the integer representation can be represented with a smaller number of bytes. In addition, many particle characteristics (such as particle status, particle ID, etc.) should be represented by integer values anyway and thus are well suited to the varint representation.

Although the varint data encoding is available in the Protocol Buffers library publicly released by Google, this library alone is not sufficient to pursuit the goal of creating large files with multiple logically-separated records. The Protocol Buffers approach is most effective if each separate Protocol Buffers message has a size less than 1MB (as recommended by Google). The major problems that need to be addressed are: 1) to design Protocol Buffers message to store particles in a single event to allow for the varint representation; 2) to find a method of serialization of multiple messages (“events”) into a file which can keep many events; 3) how to implement metadata model for fast access of interesting events and particles. While (1) is rather specific to HEP, (2) and (3) are very general issues that have to be solved in any research area where logically-separated event records with varint-based information is an attractive option for data storage and processing. Because of such problems, the usage of Google’s Protocol Buffers to keep large numeric data is still limited in science and technology.

### 4.1 Current implementation

The PROMC library [8] is designed to store HEP collision events using the Google’s Protocol Buffers library as a backend. The data are stored in a file

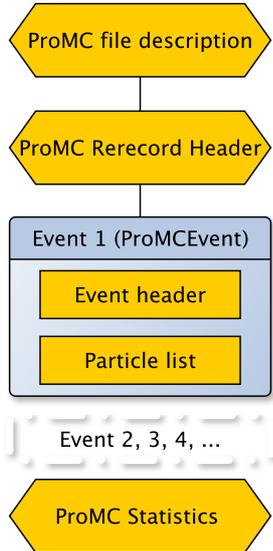


Figure 1: A schematic representation of the PROMC file format. All records are encoded using the Protocol Buffers messages. In addition, some metadata information is stored as text files inside the ZIP file for easy access on platforms without installed PROMC library.

with the file headers and multiple logically-separated messages. Each separate message leverages the varint encoding for representing a single MC event. Figure 1 shows a schematic representation of a PROMC file. All Protocol Buffers messages are stored as ZIP entries inside the PROMC file.

To work with the PROMC files, the PROMC library does not need to be installed. This C++ library has to be installed if events will be written or read in C++. PROMC files can also be read and created using Java or Python, without the platform-dependent PROMC library.

The current PROMC library is built on the assumption that the new data format should be self-describing. The current implementation allows to generate analysis source codes (in C++, Java, Python) from a PROMC file itself without knowing how it was originally created. Another notable features are random access to any given event and a possibility to stream individual events through the network without reading or downloading entire files.

Several benchmarks have shown that the PROMC files are rather compact, typically 40% smaller than ROOT files (See Table 1). The PROMC file size depends on many factors, but there are two major factors that should be mentioned: 1) energy spectra of stored particles; 2) what exactly information is stored; 3) how the information is represented using integer values and what are their values. In the first case, particle spectra with large fraction of low-energy (“soft”) particles

File format	File size (in MB)
ASCII HEPMC file	346
ASCII HEPMC (after gzip compression)	138
ROOT file (using Double32_t)	158
PromC file	112

Table 1: Typical file sizes for a benchmark included into the PROMC package.

Energy	int64 representation	Nr of bytes
0.01 MeV	1	1
0.1 MeV	10	1
1 MeV	100	2
1 GeV	100 000	4
1 TeV	100 000 000	8
20 TeV	2000 000 000	8

Table 2: The default PROMC mapping between energy units and int64 (varint) representation, together with the number of bytes used for the encoding.

will be stored more effectively than particles with large values of four-momenta. The file size depends on a conversion factor which converts float values to integer representation. The default mapping between the energy units used in HEP and int64 varints is given in Table 2. This layout can be changed since the conversion factor is included into the metadata section of the PROMC file format. In case of events with large pileup (i.e. a large fraction of soft particles), PROMC files can lead to almost a factor two smaller files compared to ROOT files with the same information based on the Double32\_t data types.

The second factor that determines data reduction depends on the fraction of information which can be presented using integer values (int32, int64, etc.). For a typical MC truth event record, several particle characteristics can be represented using varints without losing numeric precision. The examples include particle ID, status code, 1st and 2th daughter and mother particles. In many cases, their values are small and thus can be represented by only a few bytes.

The PROMC library includes several packages and tools to work with stored information:

- a Java browser to open PROMC files in order to study data layout of data, as well as the stored data. Currently, the latter feature supports only truth MC records. Files can be streamed using the network.
- A number of tools to work with PROMC files implemented in Python. Some of them are described below:

- *promc\_info file.promc* - displays the information on the PROMC file
- *promc\_proto file.promc* - extracts the file layouts in the form of Protocol Buffers data templates
- *promc\_code* - generates analysis code in C++, Java and Python.
- *promc\_log file.promc* - extracts a log file (if attached).
- *promc\_extract file.prom out.promc N* - extracts first “N” events and save them in the file “out.promc”
- *hepmc2promc file.hepmc file.promc “description”* - converts a HEPMC file [3] to the PROMC file
- *stdhep2promc file.stdhep file.promc “description”* - converts a STD-HEP file [4] to the PROMC file

## 4.2 Tutorials and examples

The PROMC library was used for the Snowmass 2013 community studies in order to store truth and DELPHES [9] MC events in a compact binary form on the web servers for HEP community. The DELPHES fast simulation can read the PROMC files [10] with the truth records and convert such files to reconstructed events. A number of examples illustrating how to read and write the PROMC files is given on the PROMC web page [8]. The web page includes several examples of how to read, write and manipulate with PROMC files using several programming languages: C++, Java and Python. Some basic information on stored data can also be extracted using PHP.

For C++/Python examples of reading and writing data, ROOT/PyROOT can be used for graphical visualization. There are also examples which illustrate how to read data using Jython, the Python language implemented in Java. In this case, no platform specific libraries are used to read and display the data. In case of Java or Jython, SCAVIS [11, 12] and JAS [13] Java-based analysis environments can be used for visual representation of data (histograms, scatter plots etc.). There is also an example which shows the random access capability of the PROMC format and how to access certain events from a network without reading the entire PROMC file. In addition, a few examples are given which illustrate how to fill PROMC files directly from the PYTHIA8 [14] MC program or from HEPMC files.

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