Parallel Writing of Nested Data in Columnar Formats

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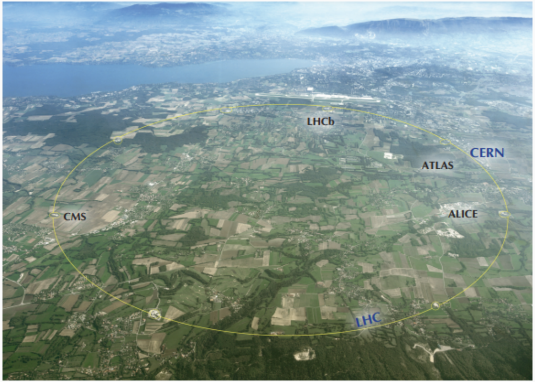
Motivation

- Large Hadron Collider at CERN
  - More than 2 exabytes since 2010
  - Stored in binary columnar format



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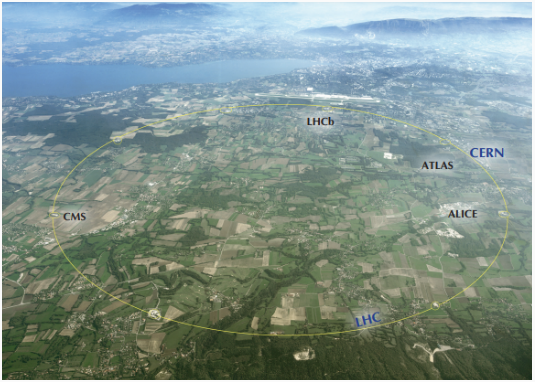

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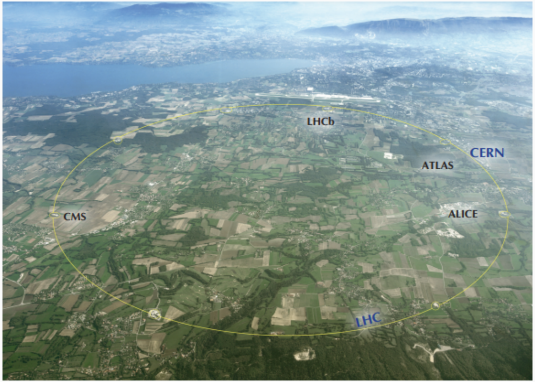
- High-Luminosity LHC (from 2029)
  - Further increase of data rate
- RNTuple: evolution of the currently used TTree columnar format
  - Opportunity to include parallel writing from the start



Outline

RNTuple Overview

Concepts for Parallel Writing of Columnar Data

Evaluation of Parallel RNTuple Writing

Conclusions and Future Work

RNTuple Overview

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- Serialize acyclic C++ data structures into a columnar format
  - Important to support nested collections for HEP use cases

```
struct Event {
  int fId;
  std::vector<Track> fTracks;
};
```

```
struct Track {
  float fEnergy;
  std::vector<int> fIds;
};
```

Figure 1: Simplified example of nested data structures. Real-world HEP data models often have thousands of fields.

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  - *Columns* at leafs of field tree: primitive, fixed-size types
- Columns partitioned into *pages*
  - Transparently compressed (default for RNTuple: Zstandard)
- *Cluster:* all pages of a consecutive range of rows, or *entries*

RNTuple Overview

Table 1: Example of columnar representation for the nested data structure shown in Figure 1.

fId	fTracks	fTracks._0.fEnergy	fTracks._0.fIds	fTracks._0.fIds._0
6873	2	25.4f	2	42
				27
		32.8f	3	16
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- Metadata updated in critical section

Concepts for Parallel Writing of Columnar Data

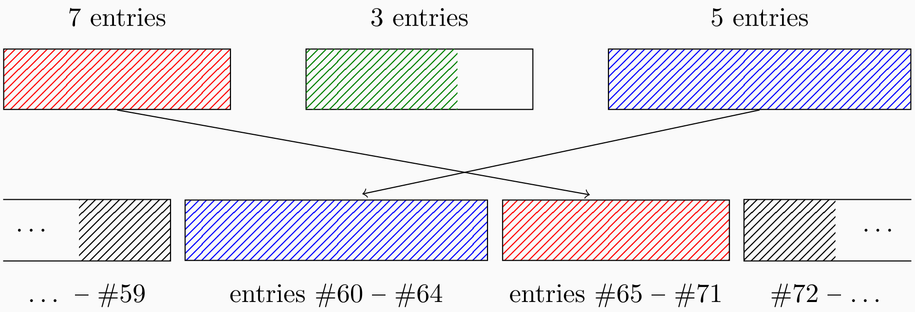

Figure 2: Illustration of filling three RNTuple clusters in parallel. After buffering in memory (top), entries are appended into a sequential file (bottom).

Evaluation of Parallel RNTuple Writing

Writing to SSD

- Evaluate weak scaling behavior for a synthetic benchmark
  - Fixed number of 20 million entries per thread
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- Write data on Samsung PM1733 NVMe SSD formatted with `ext4`
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  - Possible optimization: pre-allocate file with `fallocate`
  - Increases bandwidth to 1062 MB/s

Writing to SSD

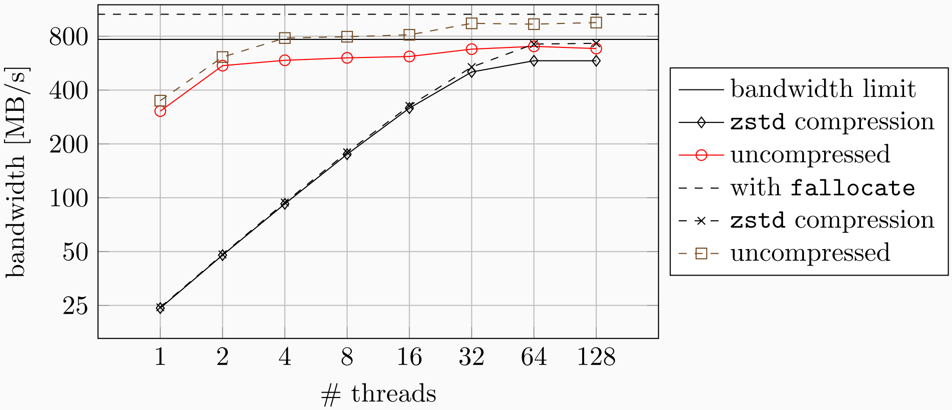

Figure 4: Bandwidth measured with the synthetic benchmark writing on a server SSD.[1]

[1] Figure adapted from the paper, see Backup Slide 3 for the original plot.

Dataset Skimming of the Analysis Grand Challenge

- Analysis Grand Challenge: test workflows at scales required for HL-LHC
  - "ttbar" analysis, input dataset derived from 2015 Open Data of the CMS experiment
  - Conversion to RNTuple: 969 GB across 787 files, divided into nine partitions

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  - "ttbar" analysis, input dataset derived from 2015 Open Data of the CMS experiment
  - Conversion to RNTuple: 969 GB across 787 files, divided into nine partitions

- Evaluation benchmark: reduce size of the dataset by *skimming*
  - Retain only fields used by analysis, filter events (entries) based on coarse cuts
  - Output: nine files, total size of 19 GB

Dataset Skimming of the Analysis Grand Challenge

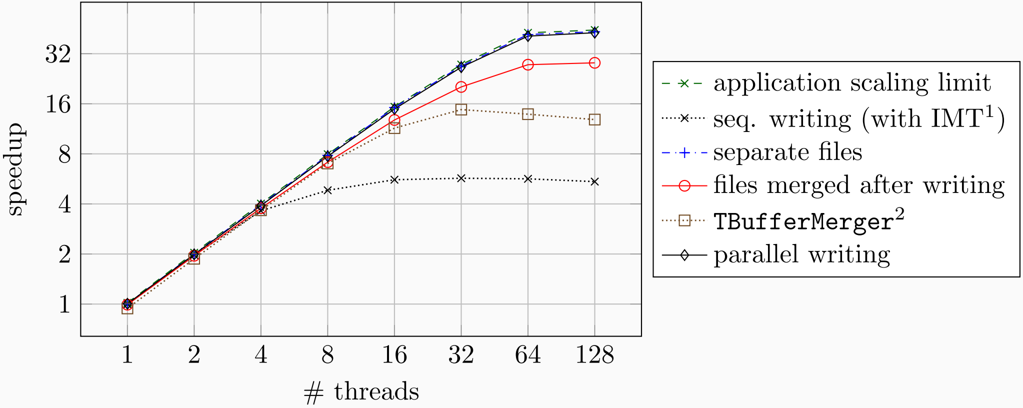

Figure 6: Speedup of the AGC dataset skimming benchmark compared to a full sequential run.

[1] ROOT's *implicit multithreading* (IMT) used to parallelize compression of pages.
[2] `TBufferMerger` merges files in memory. It is the current way of parallel writing in ROOT.

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  - Plan to investigate usage of Direct I/O

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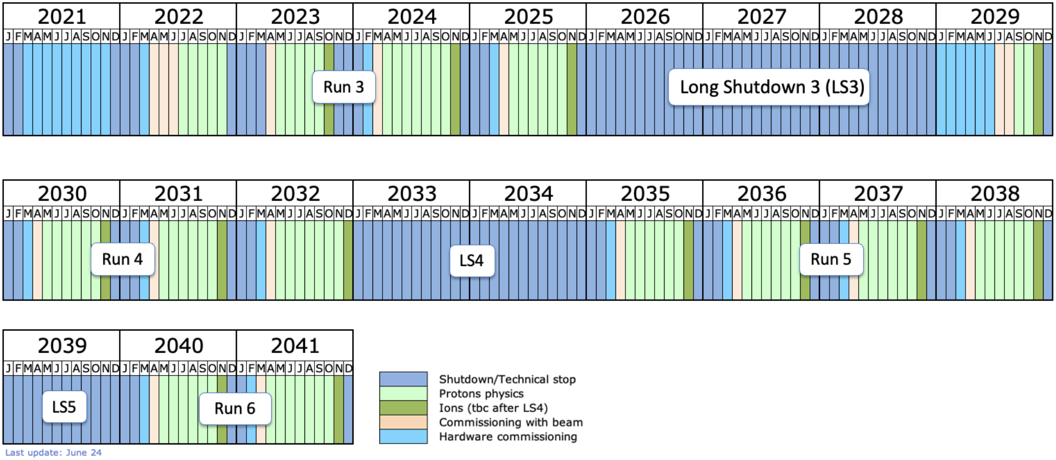
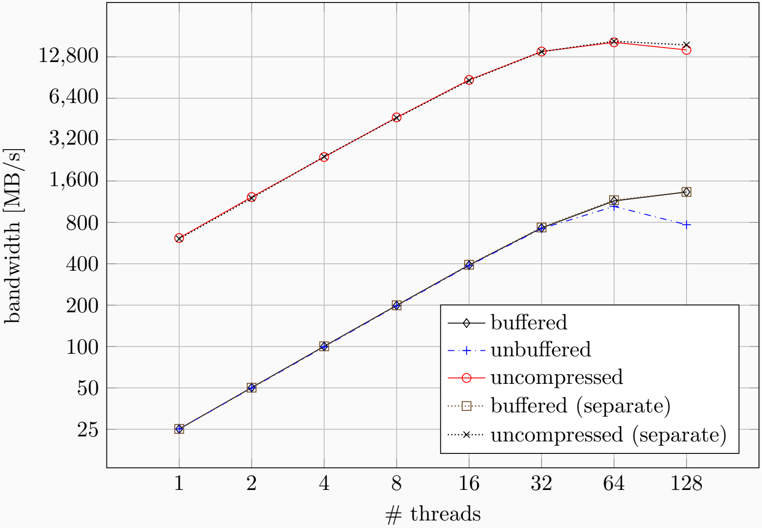
- Extend parallel writing to process-level parallelism
- Distributed parallelism with MPI and writing to cluster filesystems

Backup Slides

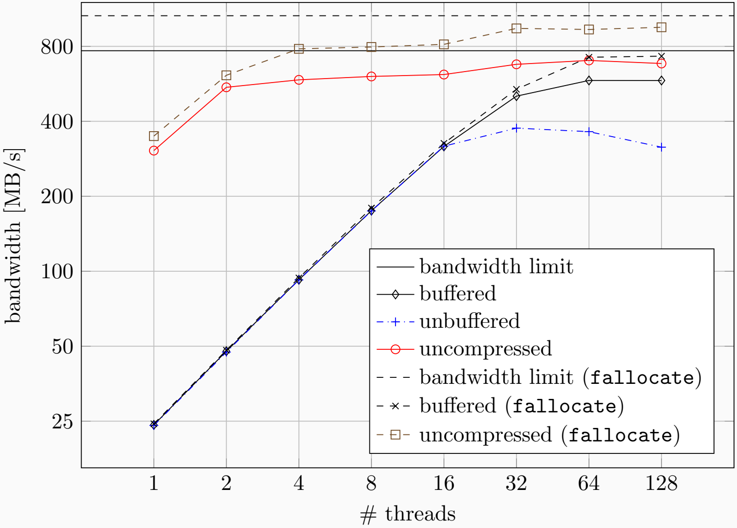
LHC Long Term Schedule



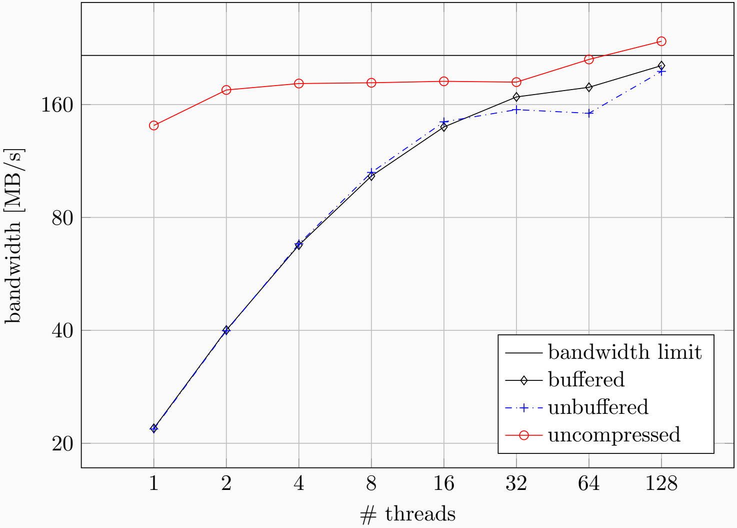
Writing to /dev/null



Writing to SSD (original plot from the paper)



Writing to HDD



Direct I/O – Writing to SSD, no compression – preliminary