Evolution of the ROOT Tree I/O

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CHEP 2019

The TTree I/O

TTree's column-wise format addresses our very problem

- TTree I/O speed and storage efficiency is significantly better than industry products ▸ ACAT'17
- Only few other formats can serialize the complexity of even the simplest event models:
  - Apache Parquet: optimized for sparse collections but HEP data is not sparse
  - Apache Arrow: only in-memory format but not on-disk format
- ROOT's unique feature: **seamless C++ integration**, users do not need to write or generate schema mapping

Nested collections typical in HEP

```
struct Event {
  std::vector<Particle> fPtcls;
};

struct Particle {
  std::vector<Track> fTracks;
};

struct Track {
  int fVertexId;
};
```

We want to ensure that ROOT I/O continues to yield the most efficient analysis I/O

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RNTuple: The New Experimental ROOT I/O Subsystem

Event iteration
`RNTupleDataSource (RDF)`, `RNTupleView`, `RNTupleReader/Writer`

Logical layer / C++ objects
Mapping of C++ types onto columns
e.g. `std::vector<float>` $\mapsto$ index column and a value column
`RField`, `RNTupleModel`, `REntry`

Primitives layer / simple types
"Columns" containing elements of fundamental types (float, int, ...)
grouped into (compressed) pages and clusters
`RColumn`, `RColumnElement`, `RPage`

Storage layer / byte ranges
`RPageStorage`, `RCluster`, `RNTupleDescriptor`

- Improve different parts independently
- Add new storage backends
  - Physical: ROOT file container, raw file, object store, NVRAM
  - Virtual: "friend" and "chain"
- Serialization of simple types and STL collections built-in – can be read without libCore

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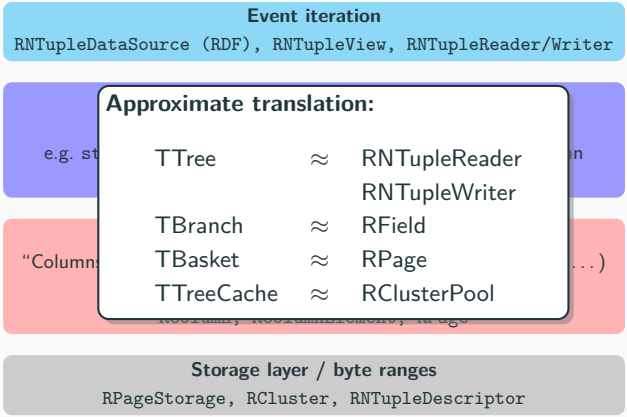

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RNTuple format evolution

Key improvements in RNTuple

- More efficient storage of collections and sub collections
- On disk layout matches most modern in-memory layouts (little-endian)
- Better control of I/O memory utilization
- Boolean values stored as bit field instead of byte array

Goal: slash memory copies and (virtual) function calls in I/O code paths

RNTuple's type system

- `bool`
- Integers (signed and unsigned, 8bit to 64bit)
- `float`, `double`
- `std::string`
- `std::array`
- `std::vector`, `VecOps::RVec`
- `std::variant`
- Whatever other `std` type we want, e. g. `std::chrono`
- Classes with dictionaries

Fully composable within the type system

RNTuple Interface Sketch: Reading Data

Populate User Objects

```
auto model = RNTupleModel::Create();
auto fldPt = model->MakeField<float>("pt");
// Note: there is also a type-unsafe API

auto ntpl = RNTupleReader::Open(
   std::move(model), "Events", "f.root");

for (auto entryId : *ntpl) {
   ntuple->LoadEntry(entryId);
   h.Fill(*fldPt);
}
```

Zero-Copy

```
auto ntpl =
   RNTupleReader::Open("Events", "f.root");
auto viewPt = ntpl->GetView<float>("pt");

for (auto i : ntpl->GetViewRange()) {
   h.Fill(viewPt(i));
}
```

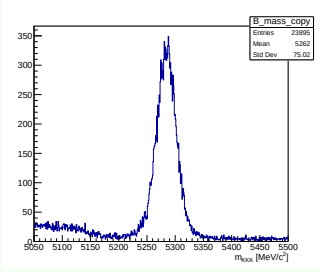
RDataFrame

```
auto df = ROOT::Experimental::MakeNTupleDataFrame("Events", "http://xrootd/f.root");
```

Sample Analyses for Performance Benchmarking

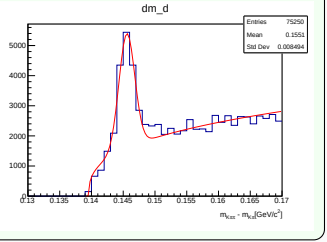
LHCb run 1 open data B2HHH

- Dense reading ($> 75\,\%$): 18/26 branches
- Fully flat data model
- 8.5 million events
- 24 k selected events



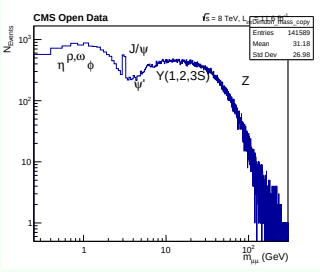
H1 micro dst [$\times 10$]

- Medium dense reading ($\sim 10\,\%$): 16/152 branches
- Event substructure: vector of jets etc.
- 2.8 million events
- 75 k selected events

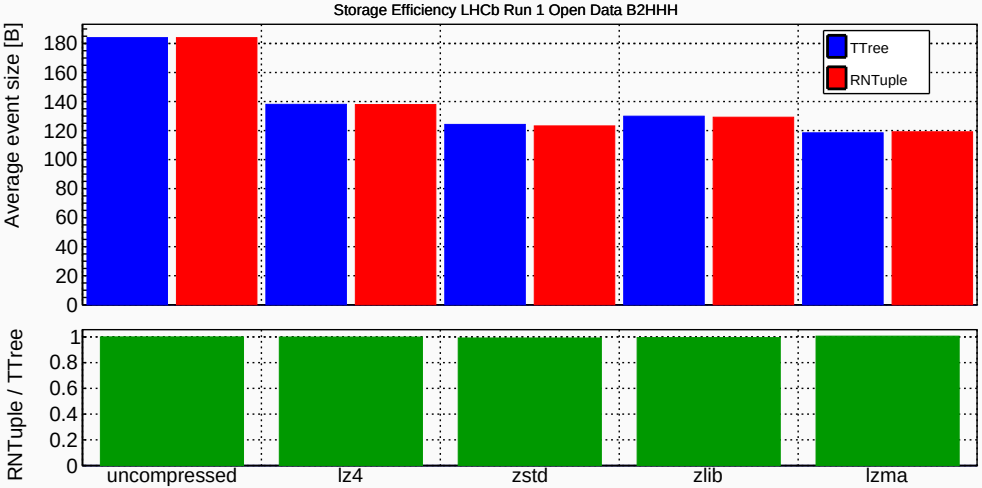


CMS nanoAOD June 2019

- Sparse reading ($< 1\,\%$): 6/1479 branches
- Event substructure: vector of jets etc.
- 1.6 million events
- 141 k selected events



Storage efficiency for very simple data models



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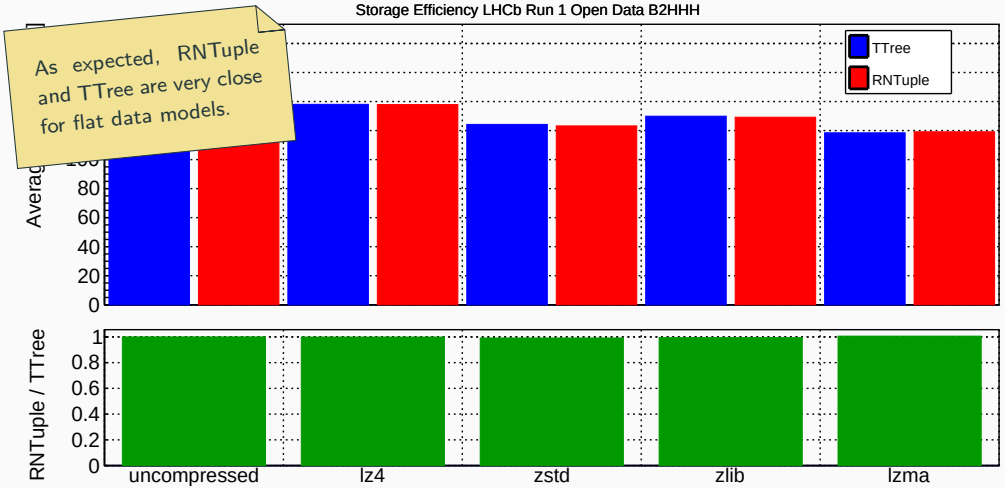

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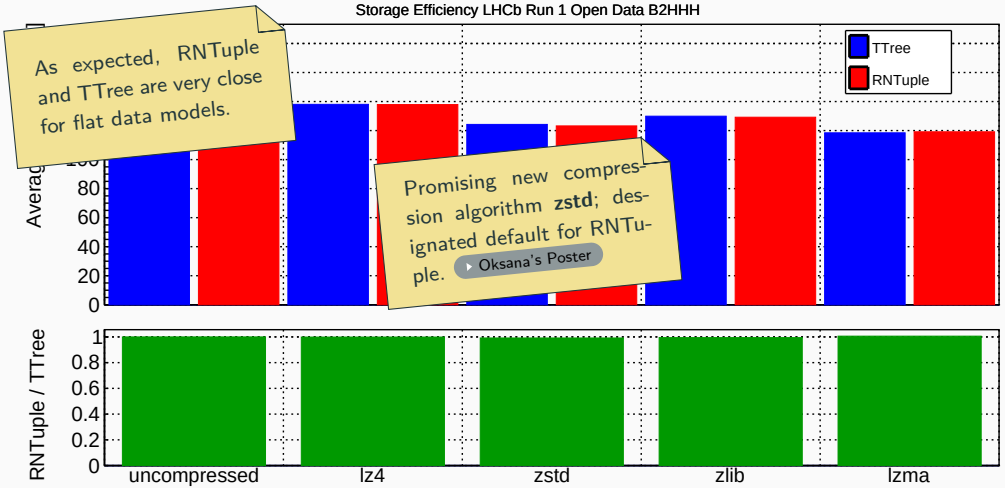
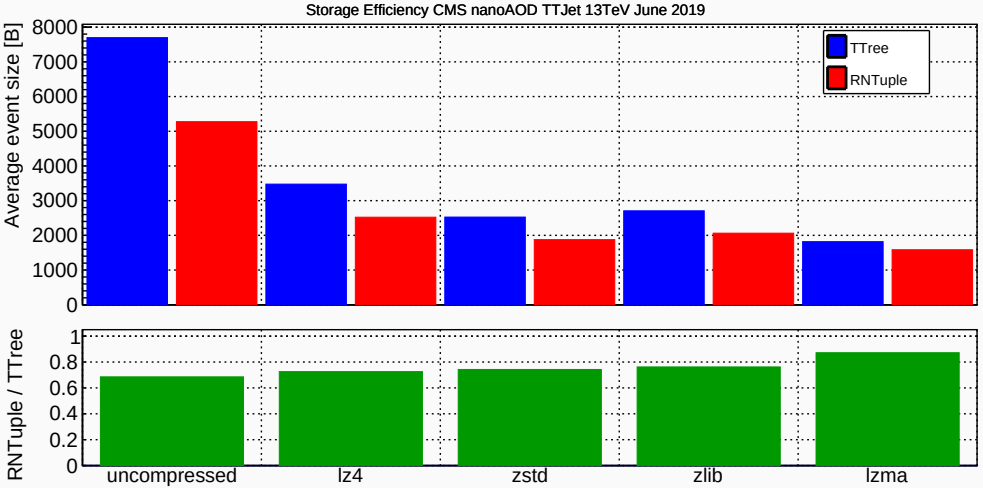


Storage efficiency for events with substructure



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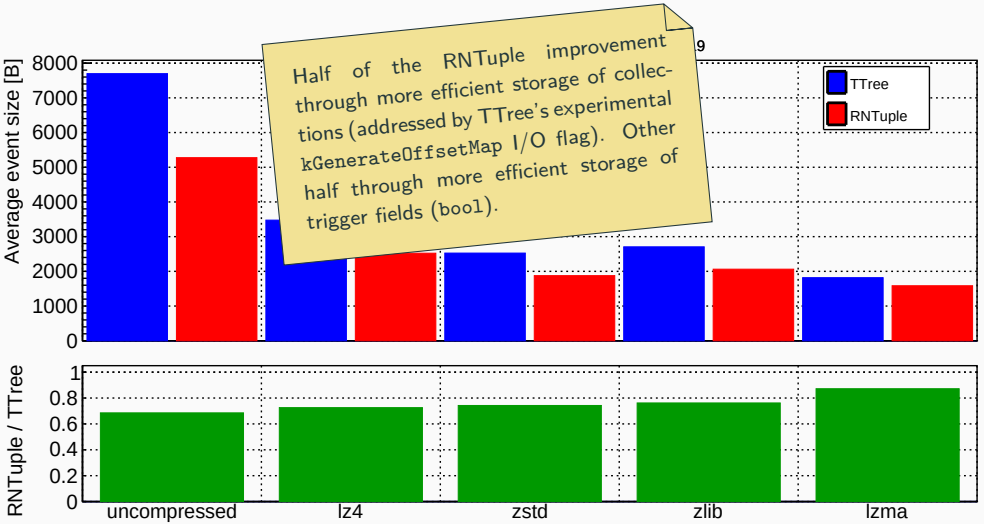

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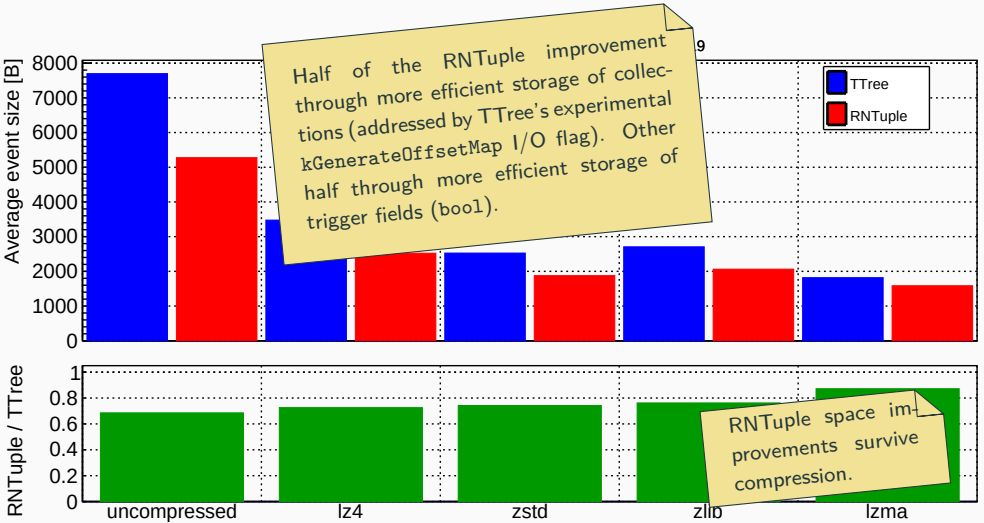
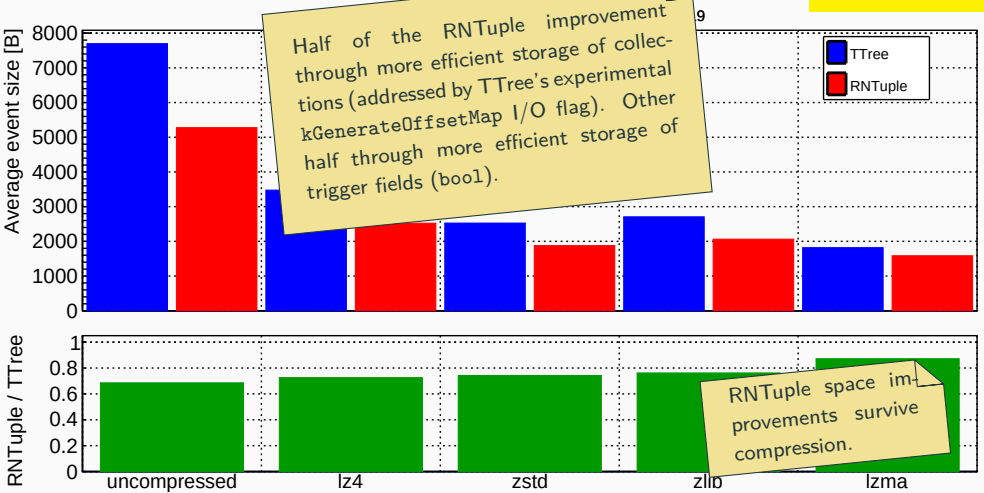


Storage efficiency for events with substructure

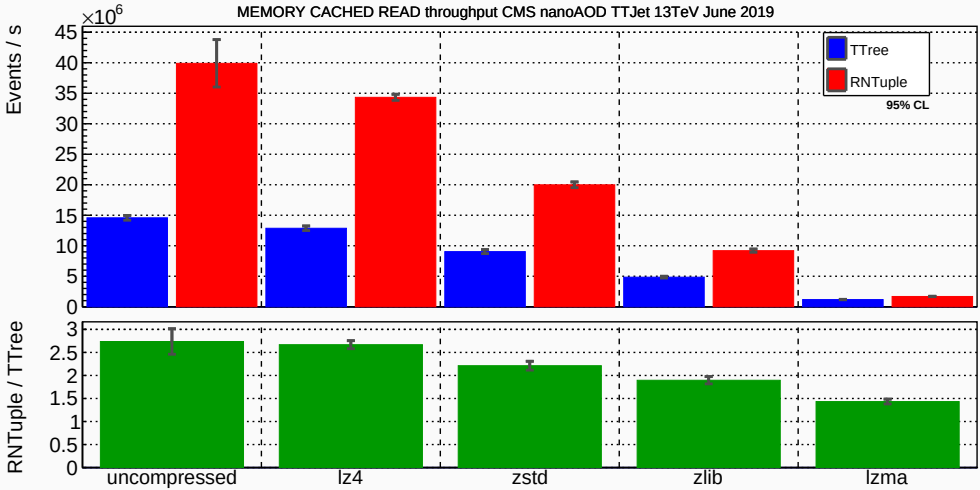
→ see backup slides for "H1" plot



Half of the RNTuple improvement through more efficient storage of collections (addressed by TTree's experimental `kGenerateOffsetMap` I/O flag). Other half through more efficient storage of trigger fields (`bool`).

RNTuple space improvements survive compression.

Read speed for warm file system buffers (kernel memory)



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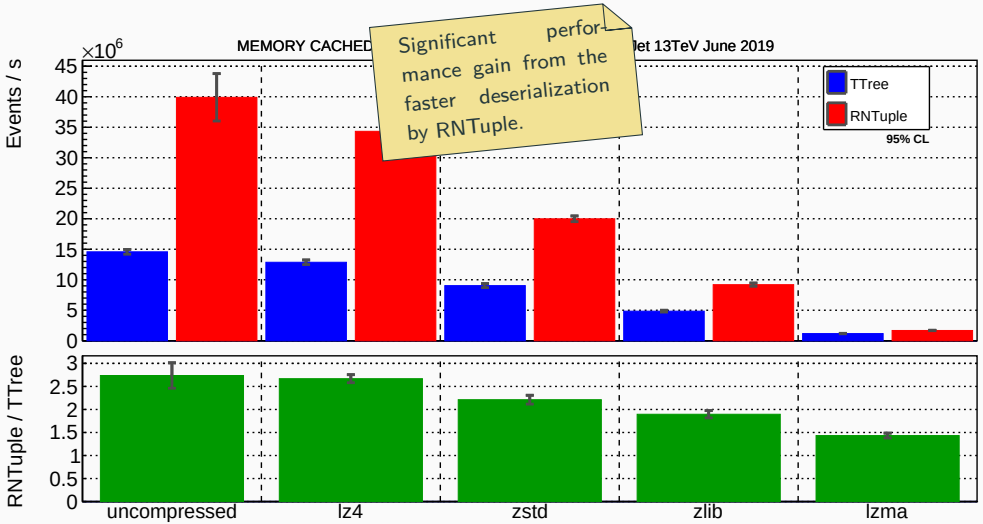
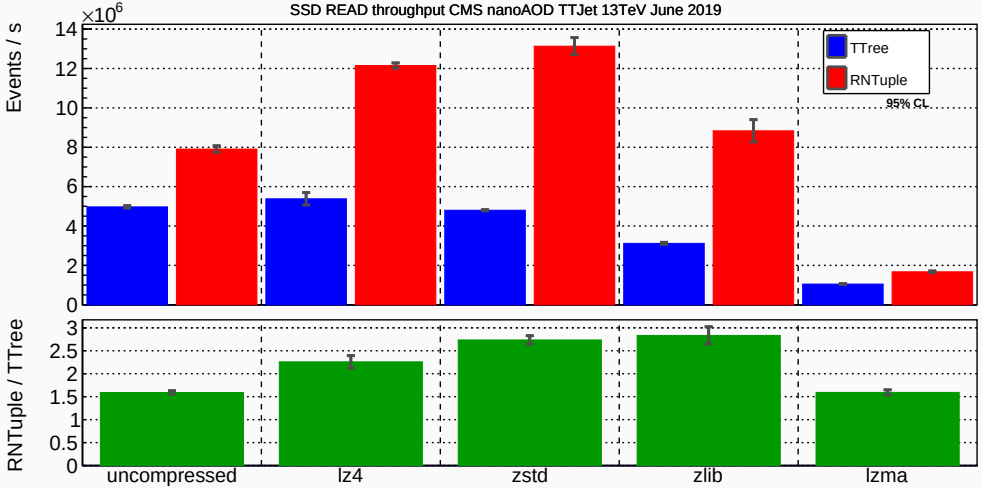


Read speed for NVMe SSD



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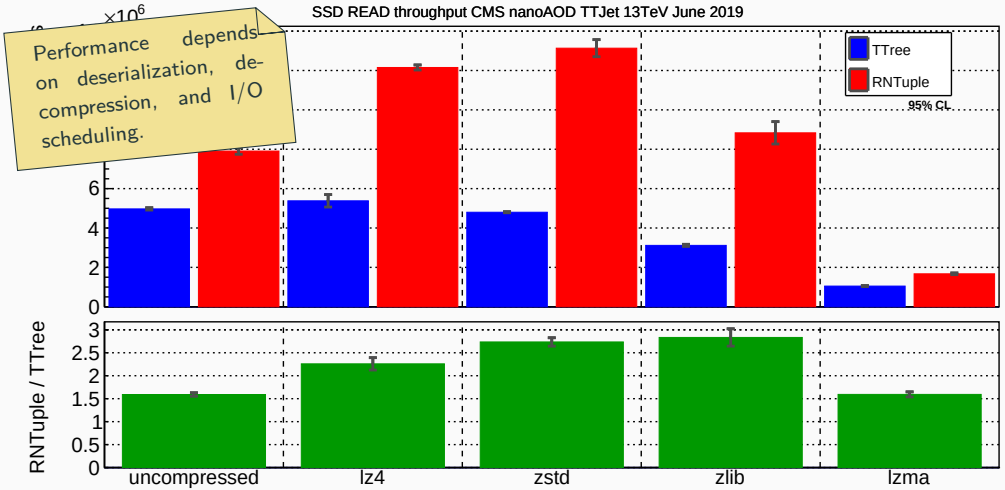

Performance depends on deserialization, decompression, and I/O scheduling.

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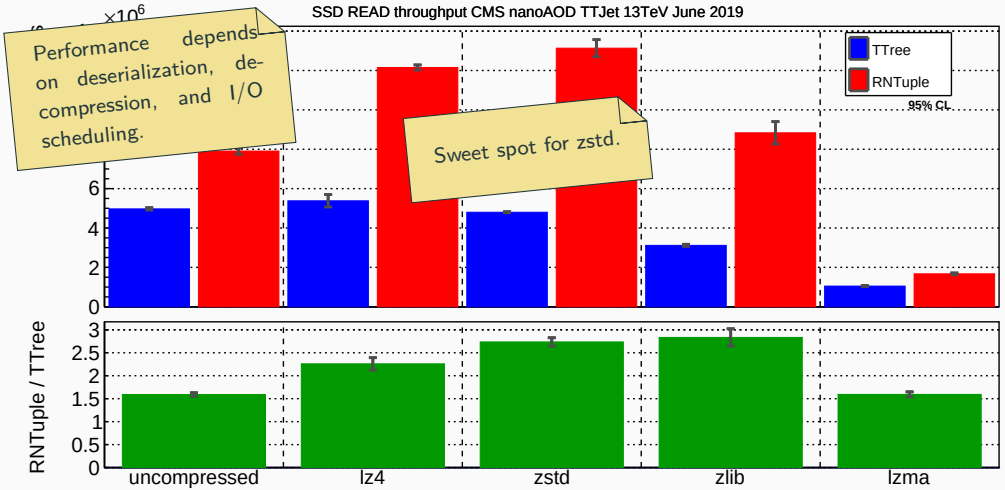
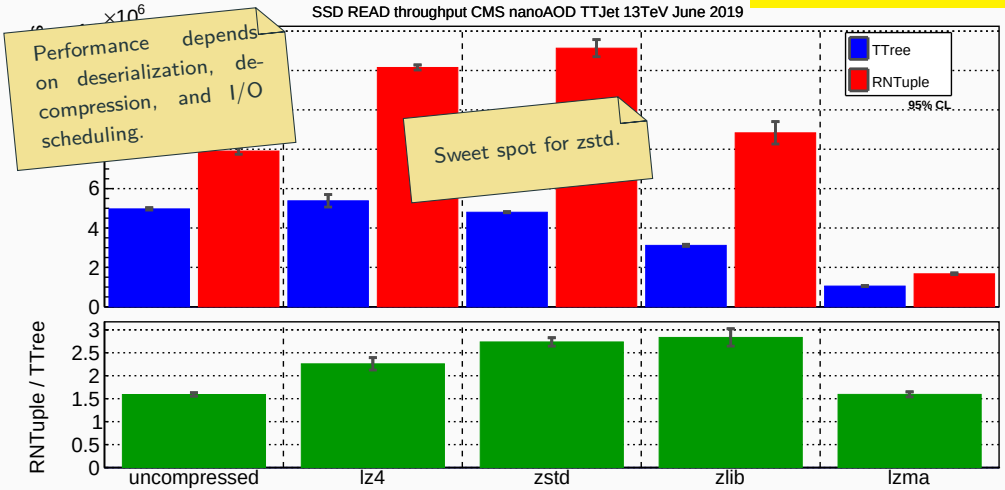
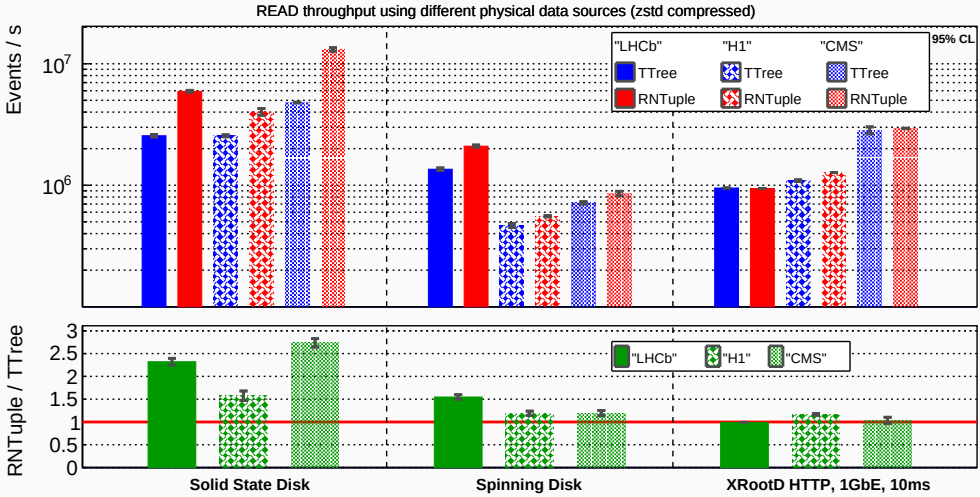


Read speed for NVMe SSD

→ Same trend for "LHCb" and "H1" samples



Read speed with different bandwidth and latency profiles



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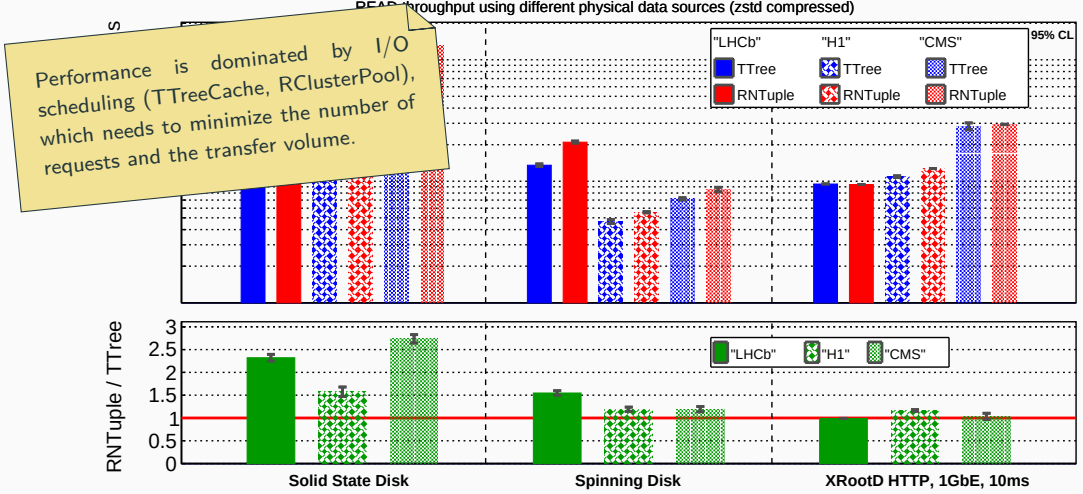
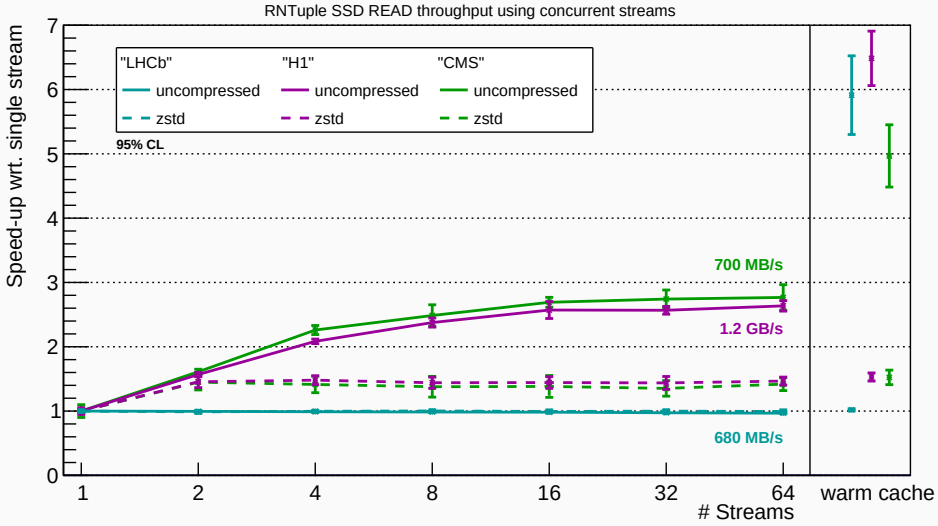


Performance is dominated by I/O scheduling (TTreeCache, RClusterPool), which needs to minimize the number of requests and the transfer volume.

Full exploitation of SSDs by concurrent streams



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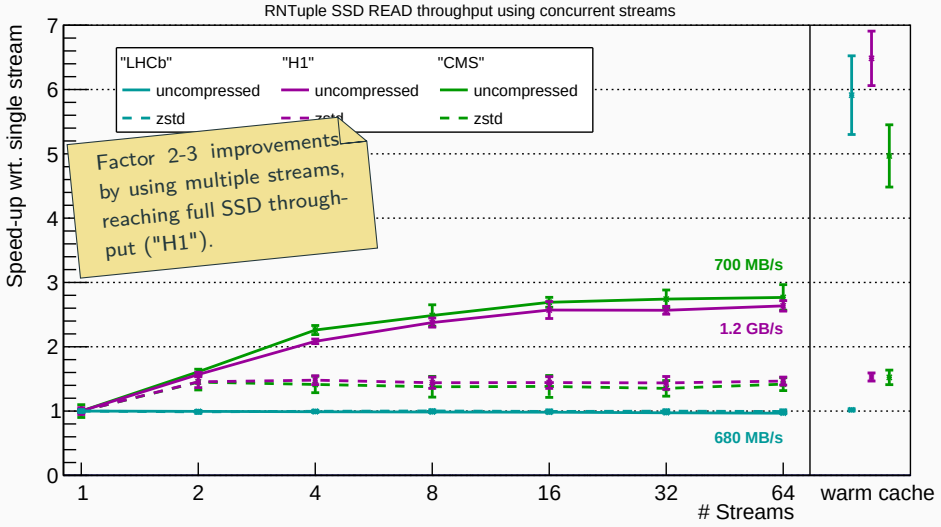

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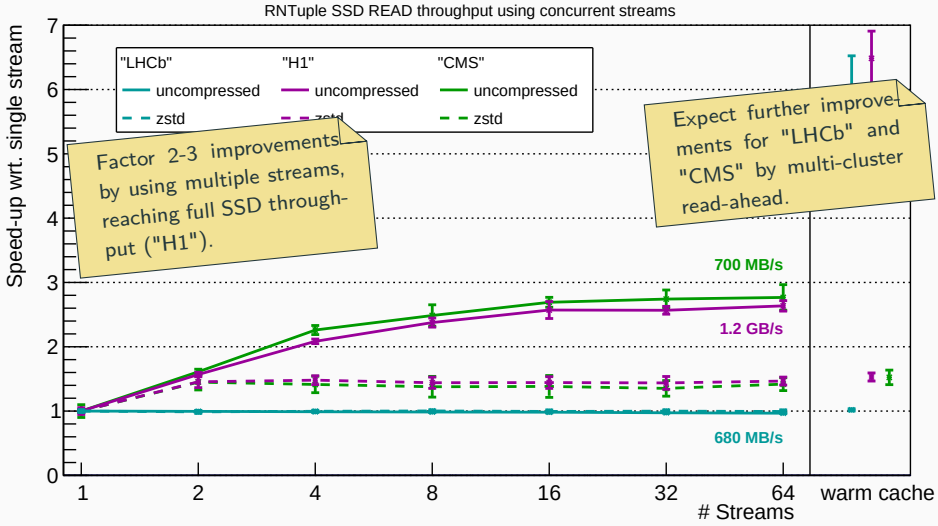
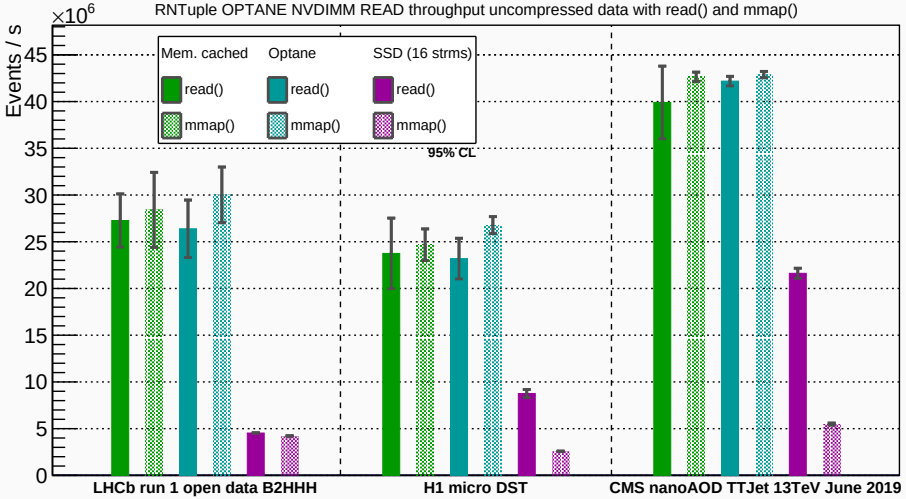


First measurements with Optane NVDIMMs (“App Direct” mode)



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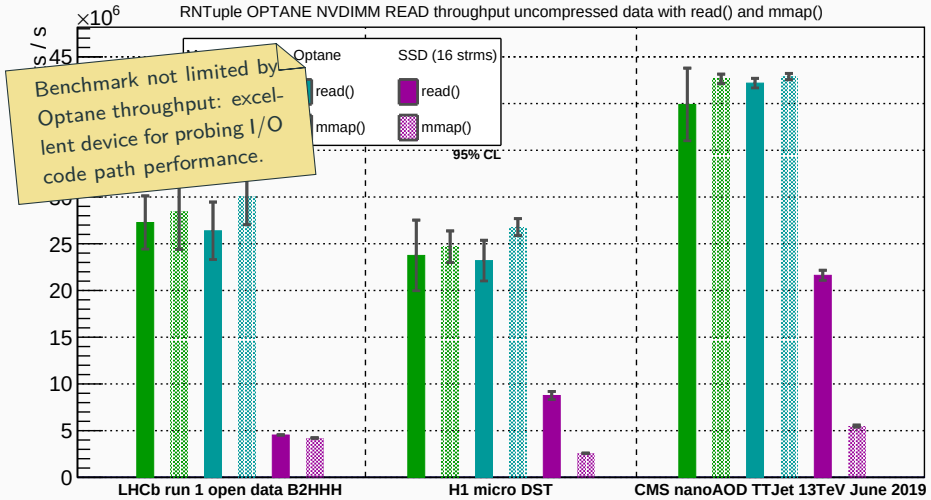

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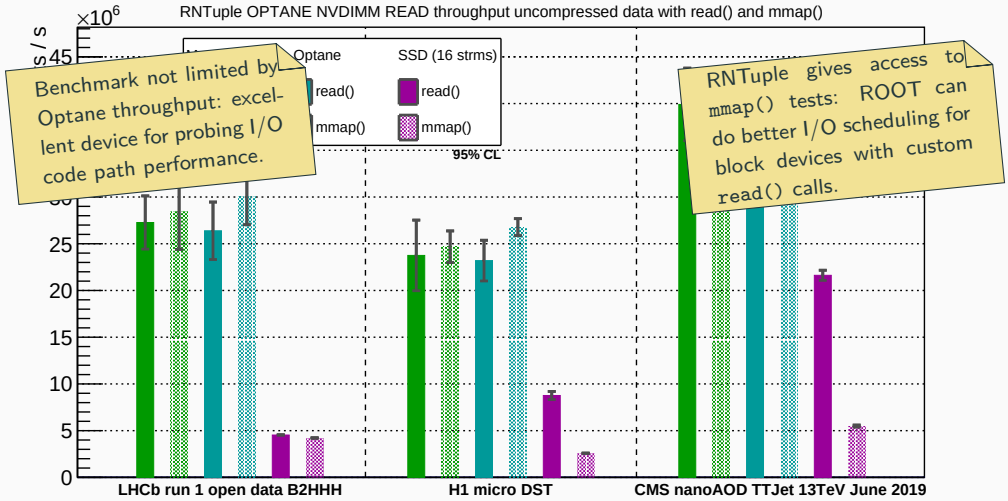
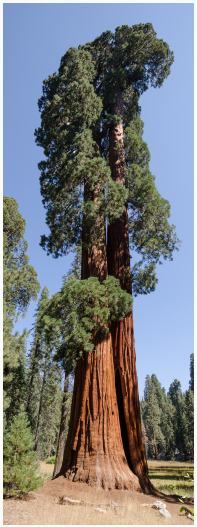


Summary & Outlook

- RNTuple is **exploring the I/O performance frontiers**
- Optimized throughput starting from a blank piece of paper plus 25 years of experience
- Simple, robust, intuitive ROOT7 user interface
- Significant speed-ups for simple event models
- Sneak preview released with ROOT 6.18
  lots of exciting work ahead towards a production-ready I/O subsystem!



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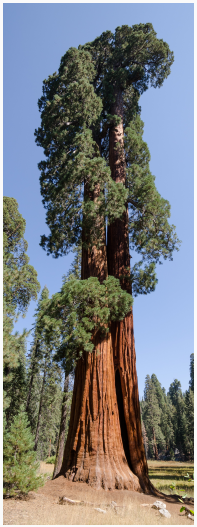
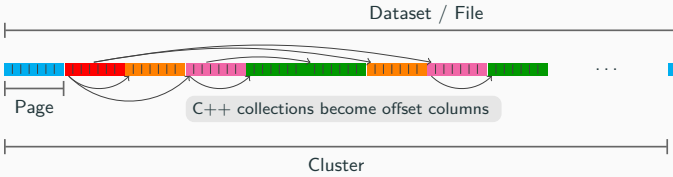


Many thanks to CERN openlab and CERN IT for providing test hardware!

Backup Slides

Breakdown of the RNTuple Data Format




```
struct Event {
  int fId;
  vector<Particle> fPtcls;
};
struct Particle {
  float fE;
  vector<int> fIds;
};
```

Cluster

- Block of consecutive complete events
- Unit of thread parallelization (read and write)
- Unit of reading when seeks are expensive
- Typically tens of megabytes

Page

- Unit of memory mapping
- Unit of (de-)compression and (un)packing
- Unit of reading when when seeks are cheap
- Typically tens of kilobytes