# Upcoming Storage Features in ROOT

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ROOT
Data Analysis Framework
https://root.cern

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# ROOT Foundation Upgrade for HL-LHC

**Major I/O upgrade** of the event data file format and access API: TTree → RNTuple

# ROOT Foundation Upgrade for HL-LHC

- **Major I/O upgrade** of the event data file format and access API: TTree → RNTuple
    - Target an **order of magnitude higher event throughput** (storage to compute)
    - Give access to **novel and future storage technologies**

- **Generation hand-over** of I/O experts to ensure availability of I/O expertise compatible with the HL-LHC lifetime

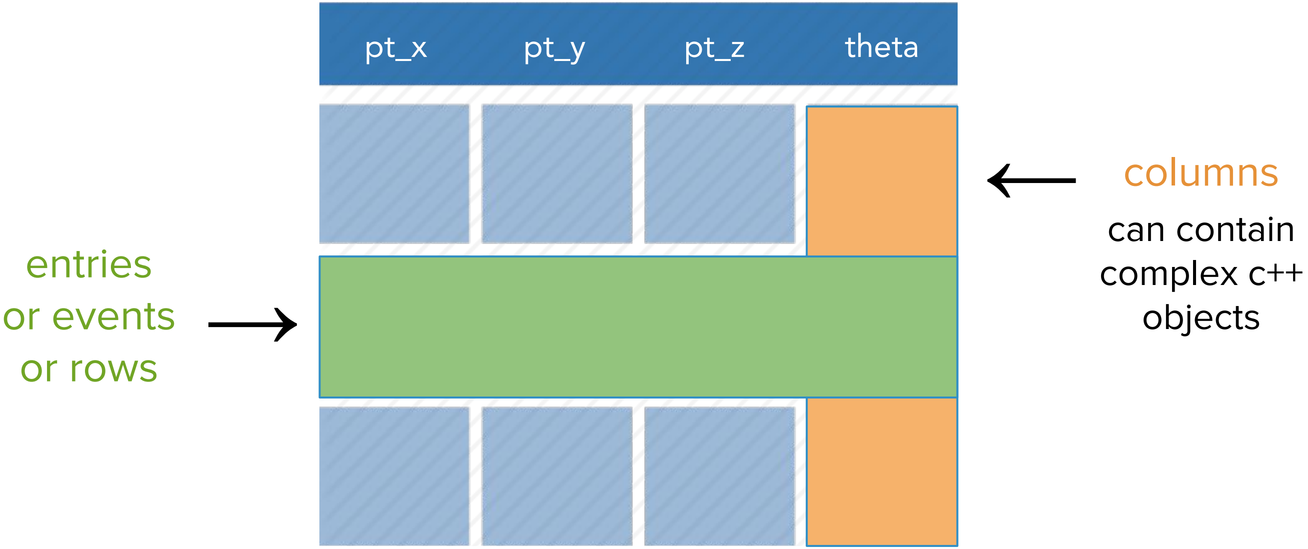
- Est. 50 MCHF/year on storage in WLCG
→ strong incentive for common, highly efficient I/O layer

- **New** generation of **hardware architecture** (GPU, HPC, Object Stores, etc.)

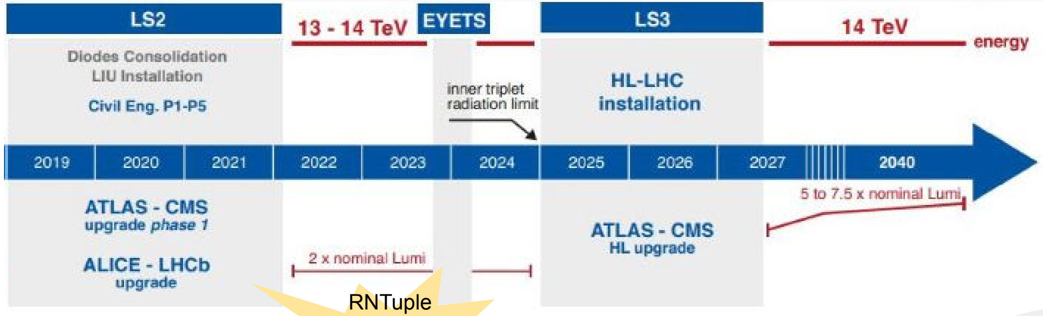
# Data Storage in ROOT

- TTree and RNTuple: ROOT classes for **columnar storage** of event data
    - Optimized for selective reads as is typical in analysis
    - Since 25 years in ROOT, today a common standard in Big Data tools

- Support for **complex objects and nested collections** within events
- Assisted by cling: **Seamless C++ and Python integration:** no hand-coded data schema



# Overview of Foundation Components



**Plus**: compression schemes, caching, merging, data movement

RNTuple PoC, first exposure to experiments

Large-scale format transition

e.g. to develop readers in Go, Julia, ...

**RNTupleLite:** low-level C API for reading

**TTree**: O(1EB) Run 1 to Run 3 data

**RNTuple**: O(10EB) Run 4-6 data

ROOT File (local and remote): **TFile** container format hosting data (TTree, RNTuple) and summary objects (TH1 etc.)

**Cling**: C++ and Python reflection for user-defined object, common AoS ➔ SoA object mapping

Remote file access: **XRootD**, **Davix** for HTTP, X.509 and SciToken authentication

**Object store adapters** for cloud and HPC (e.g., DAOS, S3)

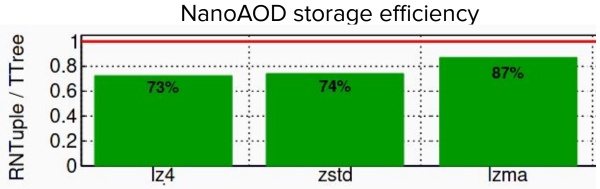
**In-memory adapters** (e.g., numpy, Arrow)

# RNTuple Targets

**Based on 25+ years of TTree experience**, redesign of the I/O subsystem for

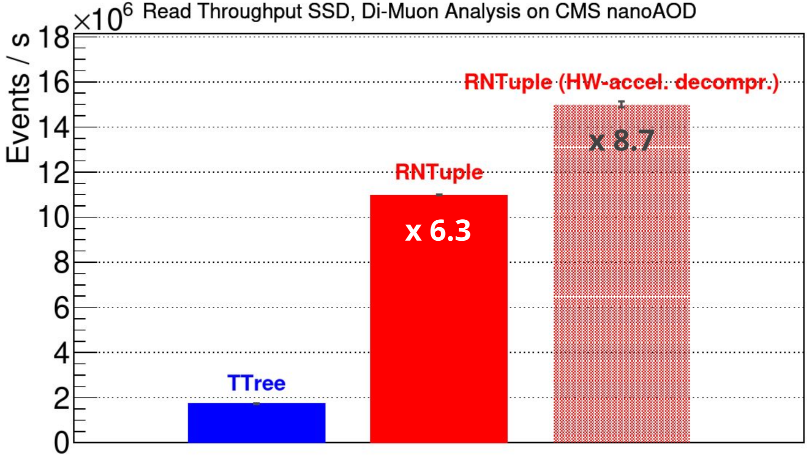
- Less disk and CPU usage for same data content
  - **10-20% smaller** files, **at least x3-5 better single-core performance**
  - 10 GB/s per node and 500 MB/s per core sustained end-to-end throughput (compressed data to histograms, based on current HW generation)
- Native support for HPC and cloud object stores
- Lossy compression
- Systematic use of checksumming and exceptions to prevent silent I/O errors

**RNTuple compatibility break warranted by a leap in performance and access to upcoming hardware choices**



**Full control of the I/O layer enables fast adaptation to HEP-specific needs**, such as

- Tight RDataFrame integration
- Support for rich event data models (EDMs)
- Rich metadata: e.g., scale factors, data management information
- Vertical and horizontal joins (“friends”, “chains”, …)
- Fast merging of data streams
- Good integration with multi-threaded frameworks
- Support for code & data evolution over decades



Comparison of TTree and RNTuple defaults

**Performance and functionality unmatched by any other available data format / API**

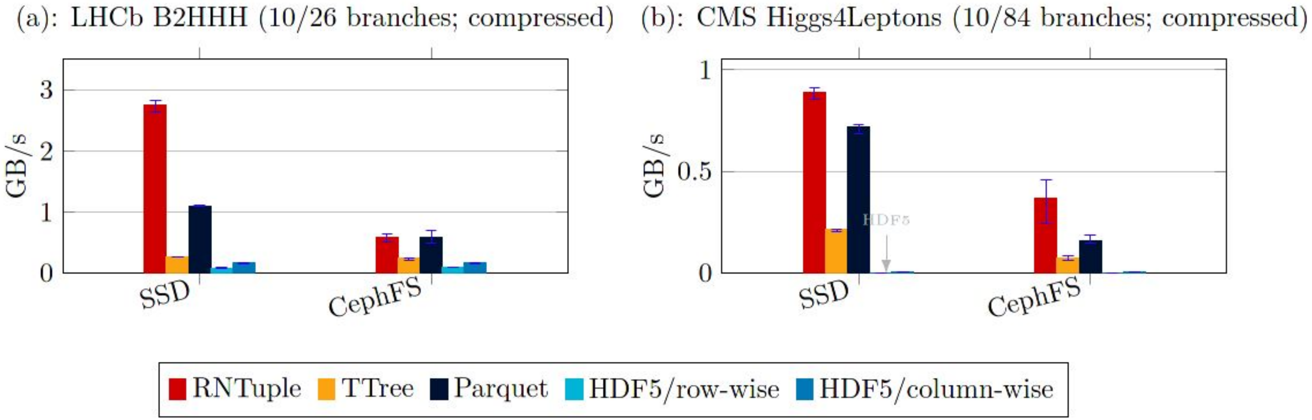
# RNTuple: Current performance snapshot

RNTuple is both **significantly faster** and has **best data compression efficiency**

RDF ***Analysis Prototype***:

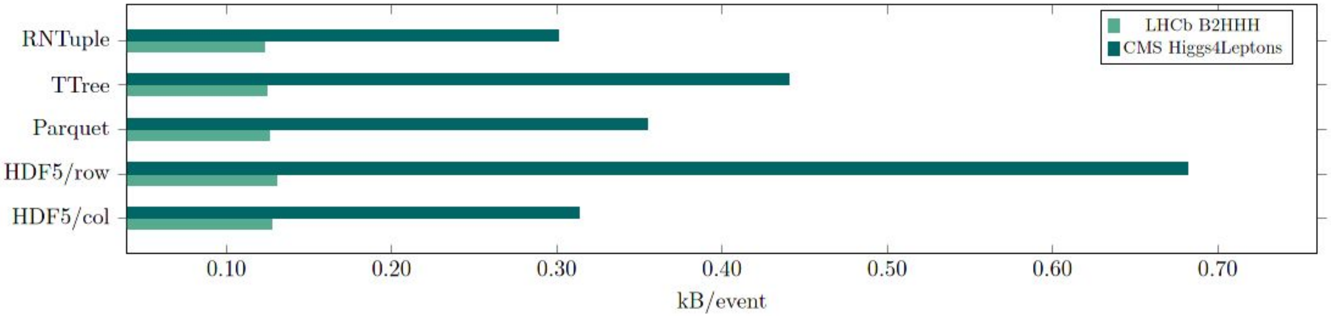
With Distributed RDF reached **50 GB/s** using 1024 core of CERN HPC

With DAOS reached 70% of theoretical bandwidth of the cluster ( 36.5GB/s out of 48 GB/s )


(a): LHCb B2HHH (10/26 branches; compressed)

(b): CMS Higgs4Leptons (10/84 branches; compressed)

(a) Average size per event in kB (compressed dataset)



# RNTuple Development Plan

~2018-19 **Proof of concept**

- ✅ Architecture
- ✅ Review on state-of-the-art
- ✅ First prototypes

~2019-20 **Prototype**

- ✅ Adoption in ROOT::Experimental
- ✅ I/O scheduler for local and remote access
- ✅ Performance validation

~2021-22 **First exploitation**

- ⛅ Object store support
  - ✅ DAOS (HPC)
  - ⛅ S3 (Cloud)
- ⛅ RNTuple version 1 spec
- ⛅ RNTupleLite
- ⛅ Schema evolution
- ⛅ Disk-to-disk conversion
- ☐ Virtual data sets for skims and selections
- ✅ First exposure to frameworks:
  - ✅ CMSSW nanoAOD output module
  - ✅ Prototyping by ATLAS, CMS, LHCb I/O experts

~2022-23 **Pre-production**

- ☐ RDataFrame bulk processing
- ☐ Debugging and inspection tools
- ☐ Metadata API
- ☐ Special use case support: e.g. backfill, in-memory adapters
- ⛅ XRootD support
- ☐ Validation of feature coverage
- ☐ Training experiments' core developers
- ☐ Large-scale experiment benchmarks

~2023-24 **Production**

- ☐ PB scale tests
- ☐ Automatic optimization features
- ☐ Low-precision floats
- ☐ ML Training: direct GPU transfer
- ☐ End-user training
- ☐ Training and support for code and data migration

Expecting stable, if not increasing, I/O workload well into Run 4

✅ = available
⛅ = under development
☐ = programme of work
— = in collaboration with users/experiments

**Growing importance of coordination & collaboration with experiment I/O experts**

# TTree Development

1. Support
2. **Thread-safety** and performance improvements
3. TBufferFile larger than **1GB**
4. Schema Evolution Improvement
5. Incorporate **lossy** compression engine (Accelogic)

# Key Challenges and Risks I/II

☐ Challenge
☐ Risk if challenge unmet
☐ Mitigation

1. Keeping the schedule of the RNTuple implementation plan
   - **Risks fractured I/O landscape of ad-hoc solutions, likely resulting in increased storage needs, reduced compute efficiency, and failure in long-term data preservation**
   - Stable support for 2.5 FTEs until 2025 on TTree, RNTuple, and experiment framework expertise
   - Gradual RNTuple rollout from AODs to RAW for agile adjustment of development efforts

2. Long-term retention of TTree and RNTuple I/O experts
   - **Risks trust erosion and inefficiencies due to work-arounds**
   - Mitigated by thorough development and documentation discipline
   - Mitigated by existing permanent positions in I/O

3. Design of RNTuple meeting the Run 4 hardware and software requirements
   - **Risks limitation of HL-LHC computing workflows, in the worst case partial loss of data**
   - Mitigated by early involvement of experiments in the RNTuple design and format specification
   - RNTuple designed informed by years of TTree experience
   - Large-scale validation tests

# Key Challenges and Risks II/II

☐ Challenge
☐ Risk if challenge unmet
☐ Mitigation

4. Continued support of 3rd party libraries
    - **Risks limitations of computing workflows involving remote I/O and AuthX**
    - Continued community funding for XRootD and Davix (HTTP) library developers

5. Adoption of RNTuple through experiment and analysis framework adaptations and optimized data models
    - **Risks mismatch between experiments' data model and RNTuple main format and API, thus fractured landscape with significant maintenance support for both RNTuple and TTree**
    - Mitigated by investment on both ROOT side and experiment side for close feedback loops
    - Seamless analysis code migration through RDataFrame
    - We believe that the benefits of RNTuple warrant transition with high priority

6. Evolving ROOT reflection support (cling)
    - **Risks limitations in the EDMs due to lack of I/O support for language features**
    - Mitigated by stable positions for experts on clang/cling and llvm

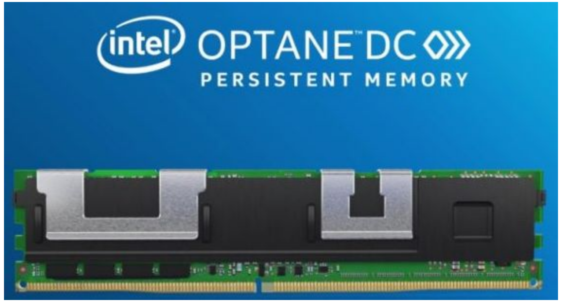
# Backup slides

# Motivation for Investment in I/O

1. HL-LHC data challenge:
    - From 300fb$^{-1}$ in run 1-3 to 3000fb$^{-1}$ in run 4-6
    - 10B events/year to 100B events/year
    - Real data challenge depends on several factors: number of events, analysis complexity, number of reruns, etc.
        - **As a starting point, preparing for ten times the current demand**

2. Full exploitation of modern storage hardware
    - Ultra fast networks and SSDs: 10GB/s per device reachable (HDD: 250MB/s)
    - Flash storage is inherently parallel → asynchronous, parallel I/O key
    - Heterogeneous computing hardware → GPU should be able to load data directly from SSD, e.g. to feed ML pipeline
    - Distributed storage systems move from POSIX to object stores

**Blurring between I/O and compute**



# File Format Essential Properties

| | |
|---|---|
| Robustness | Protection against media failure & API misuse |
| Expressiveness | Support for events with nested variable length collections |
| Speed | Columnar layout, merge-friendly, sophisticated I/O scheduling |
| Stability | Backwards and forwards compatibility, hooks for schema evolution |
| Usability | Accessible to novice and expert programmers |
| Concurrency | Facilitate concurrent reading/writing (merging) and (de-)compression |
| Integration | Support for HEP-specific, HPC, and Cloud storage and data mgmt systems |

# Facets of a full I/O system

In addition to deserializing file contents, the full I/O system has many more aspects, such as

- Parallel and distributed reading & writing
- I/O scheduling (read-ahead, request coalescing, etc)
- Beyond file system I/O: HTTP, XRootD, object stores
- Schema evolution
- Data set combinations: chains, friends, indexes, merging
- Complex object hierarchies (e.g. for ESD EDMs)
- User customizations
  - E.g. skip “transient data members”
  - I/O customization rule (transformation of data)

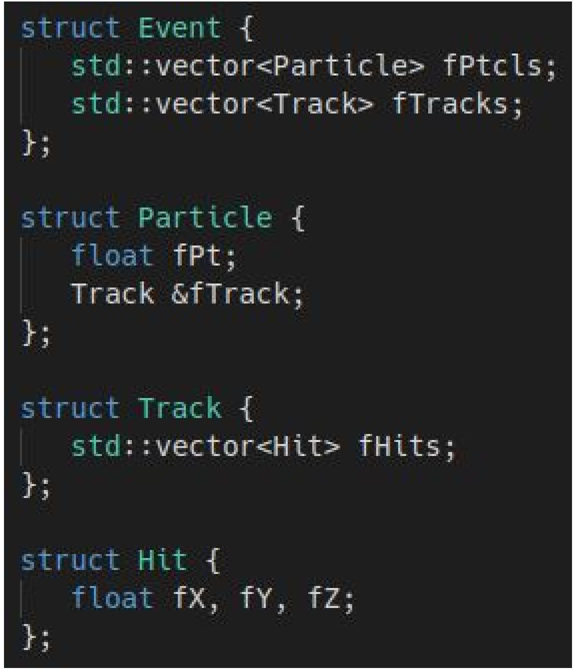
# HEP Event Data I/O

Why invest in a **tailor-made I/O system**

**TTree & RNTuple**

- Capable of storing the **HEP event data model**: nested, inter-dependent collections of data points
- **Performance-tuned** for HEP analysis workflow (columnar binary layout, custom compression etc.)
- **Automatic schema** generation and evolution for C++ (via cling) and Python (via cling + PyROOT)
- Integration with **federated data management** tools (XRootD etc.)
- Long-term **maintenance** and support

Example EDM

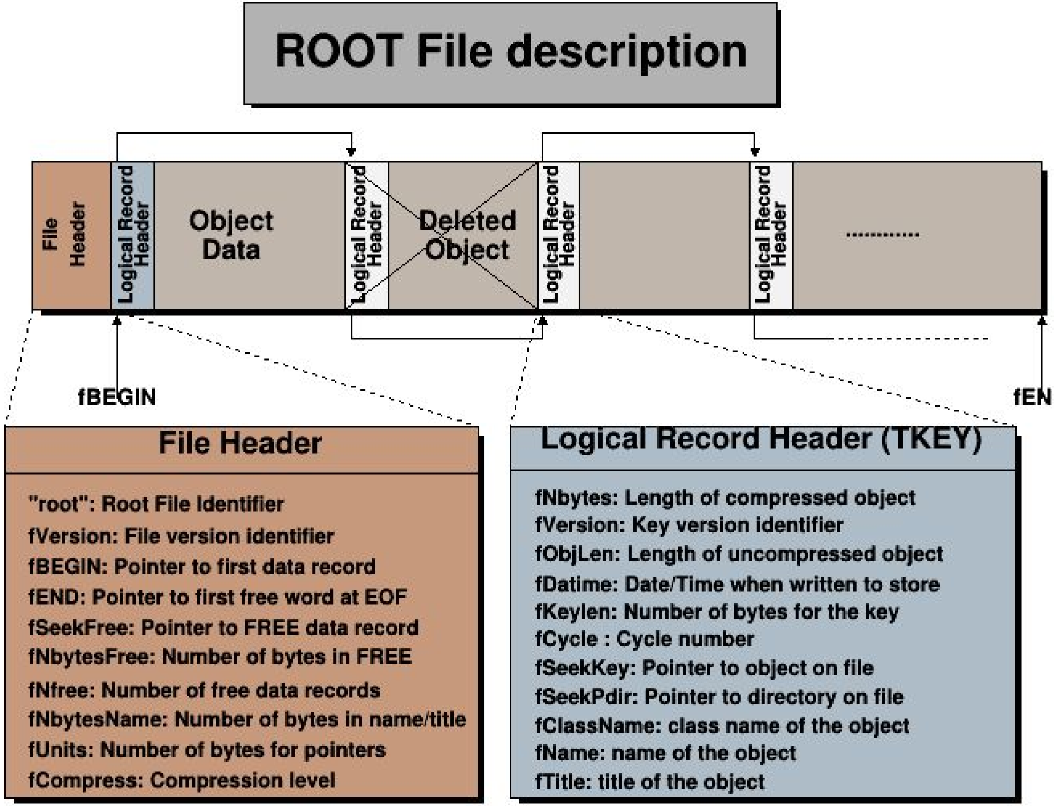


```
struct Event {
    std::vector<Particle> fPtcls;
    std::vector<Track> fTracks;
};

struct Particle {
    float fPt;
    Track &fTrack;
};

struct Track {
    std::vector<Hit> fHits;
};

struct Hit {
    float fX, fY, fZ;
};
```

# The ROOT File

- In ROOT, objects are written in files (“TFile”)
- TFiles are *binary* and have: a *header*, *records* and can be compressed (transparently for the user)
- TFiles have a logical “file system like” structure
  - e.g. directory hierarchy
- TFiles are self-descriptive:
  - Can be read without the code of the objects streamed into them
  - E.g. can be read from JavaScript

# ROOT File Description



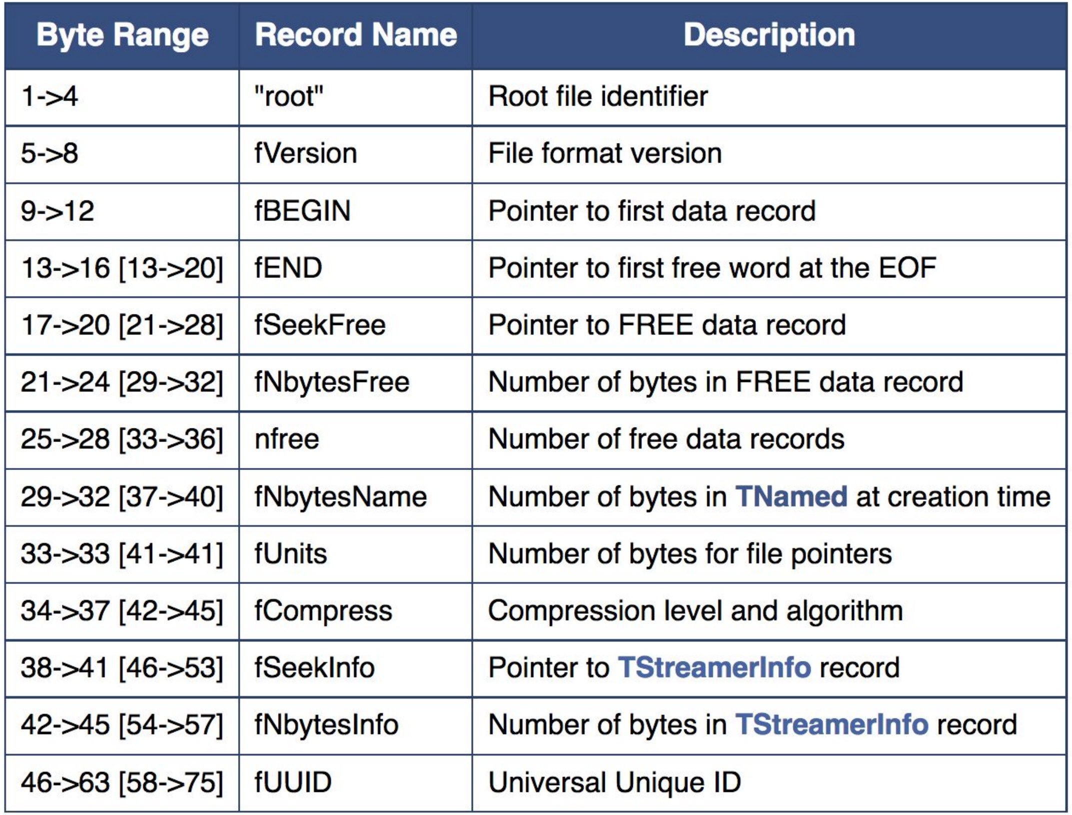
**File Header**

"root": Root File Identifier
fVersion: File version identifier
fBEGIN: Pointer to first data record
fEND: Pointer to first free word at EOF
fSeekFree: Pointer to FREE data record
fNbytesFree: Number of bytes in FREE
fNfree: Number of free data records
fNbytesName: Number of bytes in name/title
fUnits: Number of bytes for pointers
fCompress: Compression level

**Logical Record Header (TKEY)**

fNbytes: Length of compressed object
fVersion: Key version identifier
fObjLen: Length of uncompressed object
fDatime: Date/Time when written to store
fKeylen: Number of bytes for the key
fCycle : Cycle number
fSeekKey: Pointer to object on file
fSeekPdir: Pointer to directory on file
fClassName: class name of the object
fName: name of the object
fTitle: title of the object

# ROOT File Specification

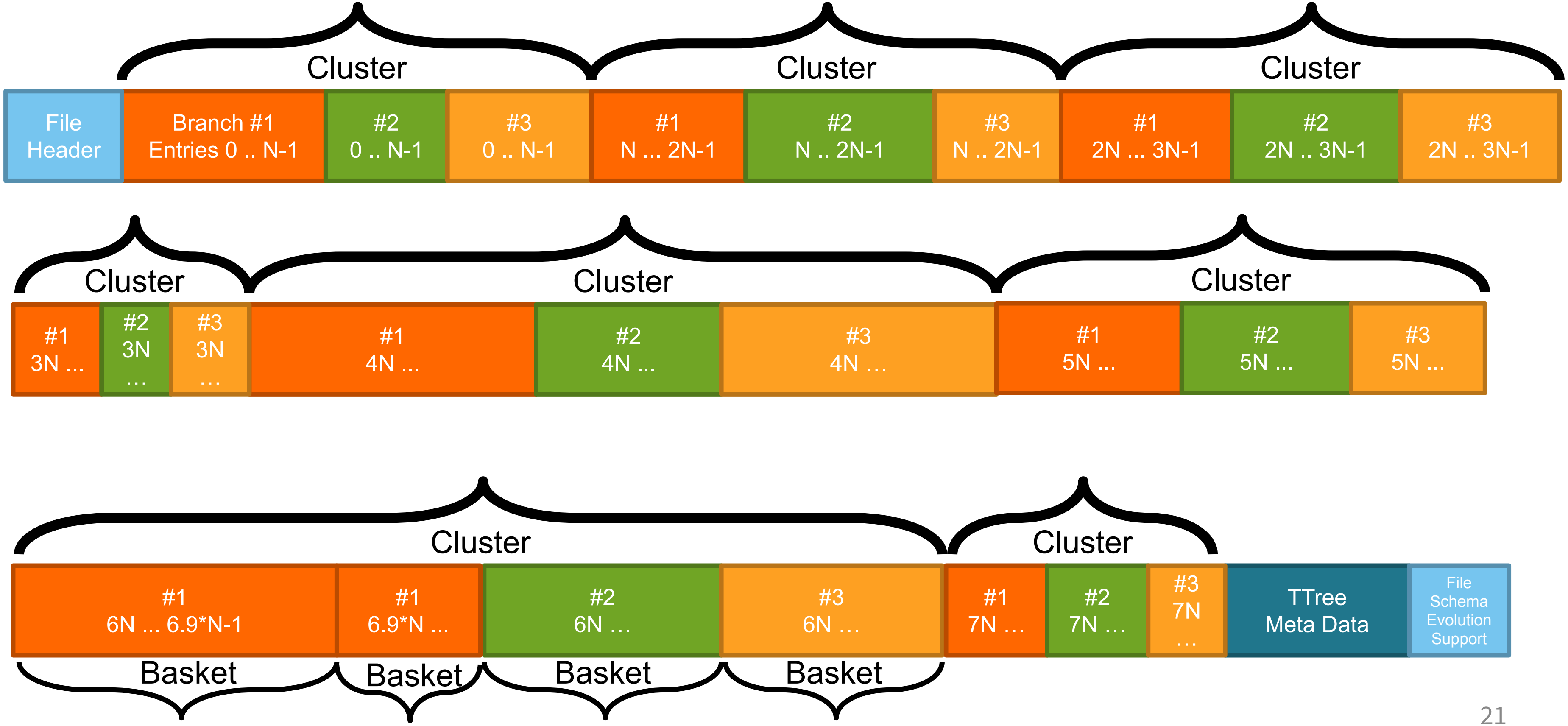


| Byte Range | Record Name | Description |
|---|---|---|
| 1->4 | "root" | Root file identifier |
| 5->8 | fVersion | File format version |
| 9->12 | fBEGIN | Pointer to first data record |
| 13->16 [13->20] | fEND | Pointer to first free word at the EOF |
| 17->20 [21->28] | fSeekFree | Pointer to FREE data record |
| 21->24 [29->32] | fNbytesFree | Number of bytes in FREE data record |
| 25->28 [33->36] | nfree | Number of free data records |
| 29->32 [37->40] | fNbytesName | Number of bytes in **TNamed** at creation time |
| 33->33 [41->41] | fUnits | Number of bytes for file pointers |
| 34->37 [42->45] | fCompress | Compression level and algorithm |
| 38->41 [46->53] | fSeekInfo | Pointer to **TStreamerInfo** record |
| 42->45 [54->57] | fNbytesInfo | Number of bytes in **TStreamerInfo** record |
| 46->63 [58->75] | fUUID | Universal Unique ID |

# Event Data and ROOT Files

- A ROOT file can be seen as a hierarchically organized container of objects
  - E.g. a file can contain directories with histograms
- In addition, ROOT files can also contain event data
  - E.g., a series of `TEvent` objects for a user-defined `TEvent` class
- Event data stored in a TTree (or RNTuple, see later) is usually written as a set of many objects
- TTree and RNTuple have a custom, internal serialization format (columnar layout)
- A binary format within the TFile binary format

# Anatomy of a Tree



Cluster
Cluster
Cluster

File Header
Branch #1 Entries 0 .. N-1
#2 0 .. N-1
#3 0 .. N-1
#1 N ... 2N-1
#2 N .. 2N-1
#3 N .. 2N-1
#1 2N ... 3N-1
#2 2N .. 3N-1
#3 2N .. 3N-1

Cluster
Cluster
Cluster

#1 3N ...
#2 3N …
#3 3N …
#1 4N ...
#2 4N ...
#3 4N …
#1 5N ...
#2 5N ...
#3 5N ...

Cluster
Cluster

#1 6N ... 6.9*N-1
#1 6.9*N ...
#2 6N …
#3 6N …
#1 7N …
#2 7N …
#3 7N …
TTree Meta Data
File Schema Evolution Support

Basket
Basket
Basket
Basket

# ROOT Data Access Options

- ROOT can read, write, and represent data in C++
- ROOT can read, write, and represent data in Python through pyROOT (dynamic binding between C++ and Python)
    - Can also export ROOT trees to numpy arrays
- ROOT can read and represent trees and the most common classes (histograms, graphs, etc.) in JavaScript with JSROOT
    - Can also export objects in JSON

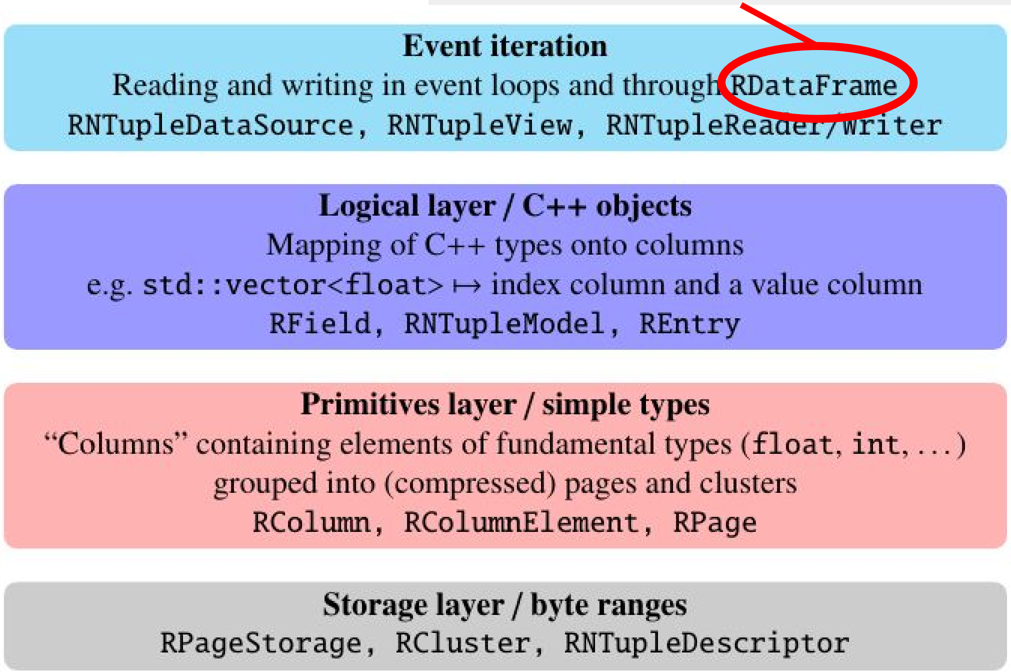
# 3rd Party Implementations of ROOT I/O

- There are several projects that re-implement parts of the ROOT file format
  - Julia: unroot
  - Python: uproot
  - Go: hep/groot
  - Java/Scala: FreeHEP rootio
  - Rust: alice-rs/root-io

- Typically supported features: reading of simple objects (histograms) and trees with a simple structure (numerical types and vectors thereof)

# RNTuple Class Design

Seamless transition from TTree to RNTuple



**Event iteration**

Reading and writing in event loops and through `RDataFrame`

`RNTupleDataSource, RNTupleView, RNTupleReader/Writer`

**Logical layer / C++ objects**

Mapping of C++ types onto columns

e.g. `std::vector<float>` ↦ index column and a value column

`RField, RNTupleModel, REntry`

**Primitives layer / simple types**

"Columns" containing elements of fundamental types (`float`, `int`, ...)

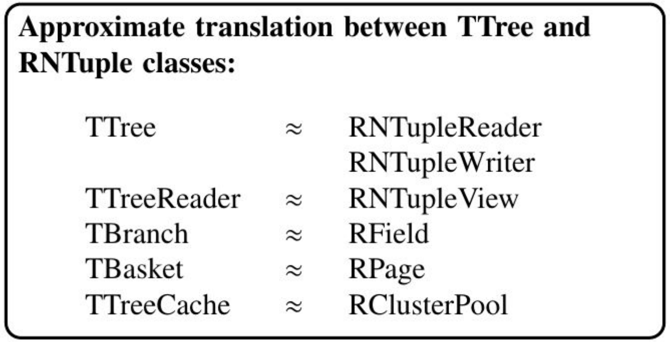
grouped into (compressed) pages and clusters

`RColumn, RColumnElement, RPage`

**Storage layer / byte ranges**

`RPageStorage, RCluster, RNTupleDescriptor`

Modular storage layer that supports files as data containers but also file-less systems (object stores)



**Approximate translation between TTree and RNTuple classes:**

| | | |
|---|---|---|
| TTree | ≈ | RNTupleReader<br>RNTupleWriter |
| TTreeReader | ≈ | RNTupleView |
| TBranch | ≈ | RField |
| TBasket | ≈ | RPage |
| TTreeCache | ≈ | RClusterPool |

→ RNTuple v1 Format Specification

# RNTuple Format Evolution

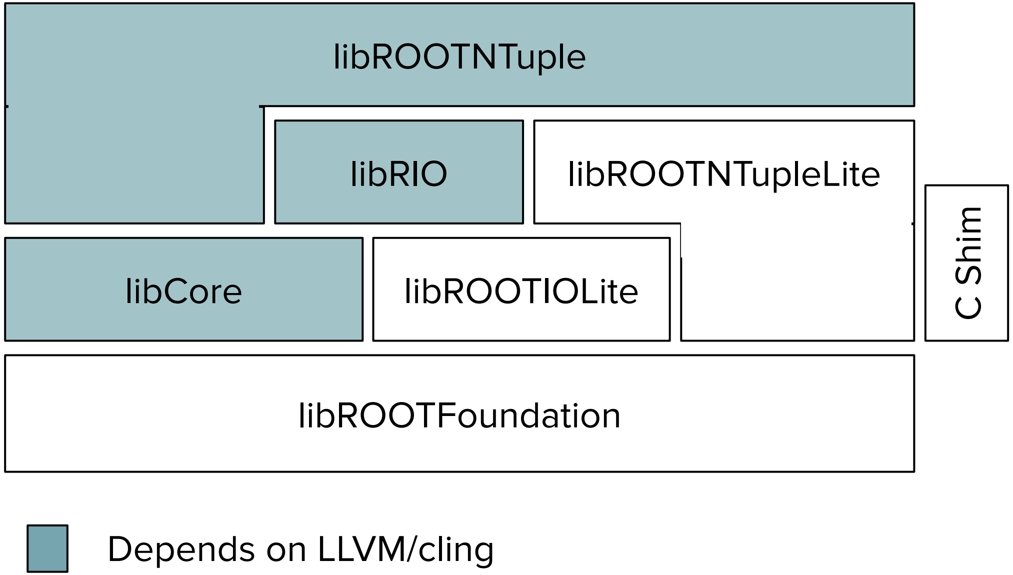
- Key binary layout changes wrt. TTree
  - More efficient nested collections
  - More efficient boolean values (bitfield), interesting for trigger bits
  - experimenting with “split floats”
  - Little-endian values (allows for mmap())

Implementation uses templates to slash memory copies and virtual function calls in common I/O paths

- Supported types
  - Boolean
  - Integers, floating point
  - std::string
  - std::vector, std::array
  - std::variant
  - User-defined classes
  - More classes planned (e.g. std::chrono timepoints)

Fully composable (including aggregation, inheritance) within the supported type system

# libRNTupleLite (under development)


libROOTNTuple

libRIO

libROOTNTupleLite

C Shim

libCore

libROOTIOLite

libROOTFoundation

🟦 Depends on LLVM/cling

- The libRNTupleLite library is built just like any other ROOT libraries in ROOT proper (including modules, dictionaries etc)
- The libRNTupleLite does not use any infrastructure from libCore but only from libROOTFoundation
- Functionality:
  - RIOLite: RRawFile without support for plugins, i.e. only local files
  - ROOTNTupleLite: Provide access to meta-data (schema etc.) and data pages

# libRNTupleLite C API

- C API header and dynamic library libROOTNTupleLite.so
  - Header files will be in
    - io/iolite/inc/ROOT/IOLite.h
    - tree/ntuplelite/inc/ROOT/NTupleLite.h

- Provides a C wrapper to the C++ libROOTRNTupleLite.so

- Provided functionality:
  - Open an RNTuple that is stored in a local ROOT file
  - Read the schema: fields, columns, pages, and their relationships
  - Read pages into void * memory areas given column id and page id
    - Takes care of decompressing and unpacking pages along the way

- Aims at being a building block for 3rd party tool builders

# ROOT I/O: Support

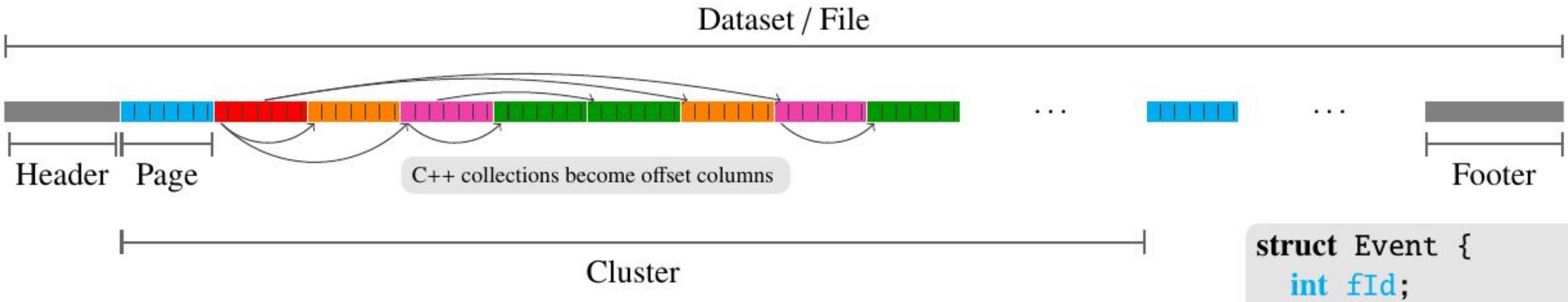
Full support by the ROOT Team:

- I/O through the ROOT C++ library
- pyROOT
- Conversion of simple structures to numpy arrays
- JSROOT
- JSON serialization of objects
- In the future: C API provided by RNTupleLite

Indirect support (“support the maintainers”)

- Third-party implementation of the binary format (uproot, unroot, Java, Go, ...)

# RNTuple Format Breakdown



**Approximate translation between TTree and RNTuple concepts:**

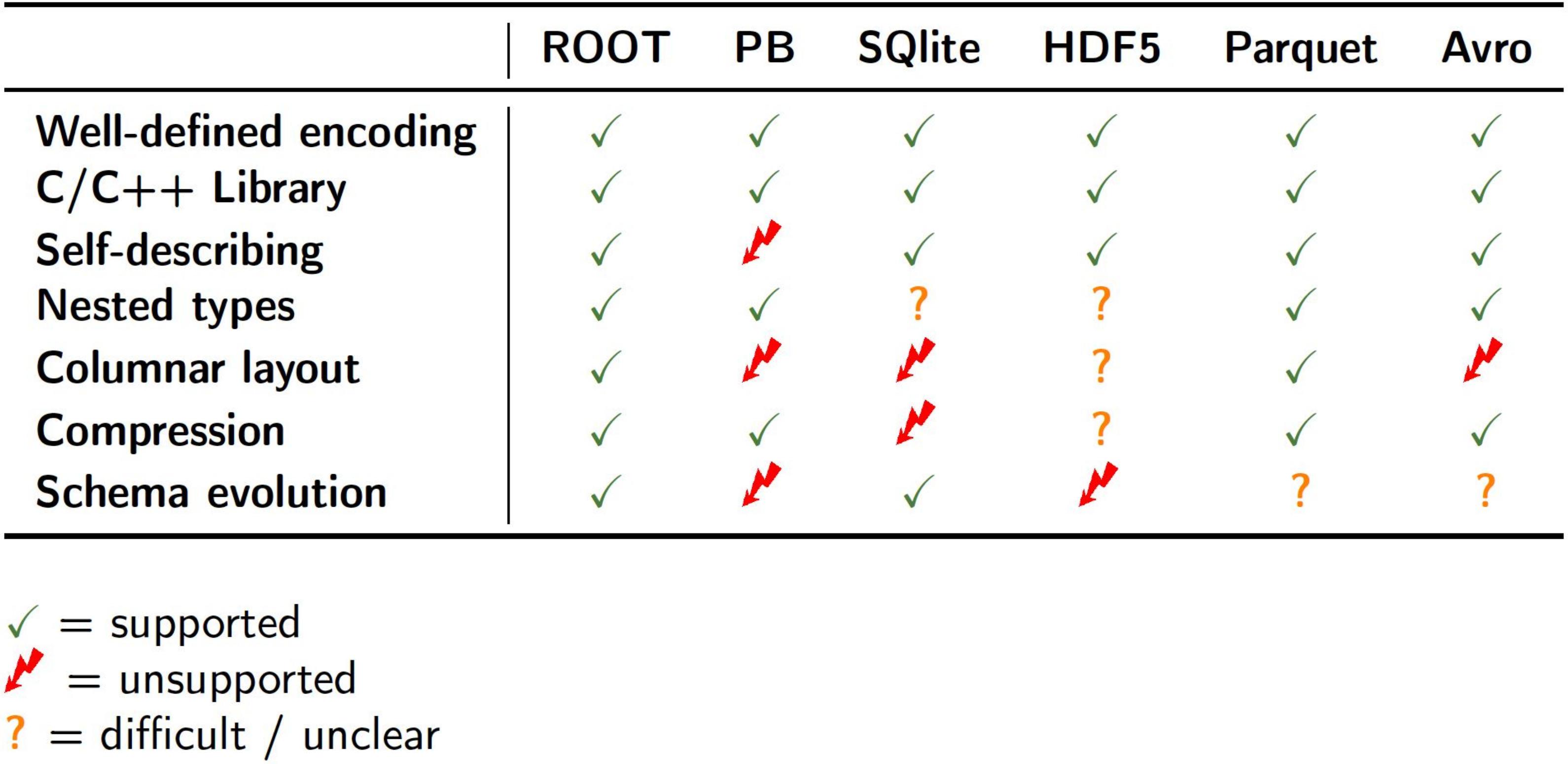
| | | |
|---|---|---|
| Basket | ≈ | Page |
| Leaf | ≈ | Column |
| Cluster | ≈ | Cluster |

```
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 & write)
- Typically tens of megabytes

**Page/Basket:**
- Unit of memory mapping or (de)compression
- Typically tens of kilobytes

# Comparison With Other I/O Systems



| | ROOT | PB | SQlite | HDF5 | Parquet | Avro |
|---|---|---|---|---|---|---|
| Well-defined encoding | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| C/C++ Library | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Self-describing | ✓ | ↯ | ✓ | ✓ | ✓ | ✓ |
| Nested types | ✓ | ✓ | ? | ? | ✓ | ✓ |
| Columnar layout | ✓ | ↯ | ↯ | ? | ✓ | ↯ |
| Compression | ✓ | ✓ | ↯ | ? | ✓ | ✓ |
| Schema evolution | ✓ | ↯ | ✓ | ↯ | ? | ? |

✓ = supported
↯ = unsupported
? = difficult / unclear

J. Blomer, [A quantitative review of data formats for HEP analyses] ACAT 2017