I/O Performance trade-offs among RNTuple's persistent layouts for DUNE Data Products

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Outline

Introduction

Introduction

- The Deep Underground Neutrino Experiment (DUNE) is projected to record roughly 30 PB of liquid-argon TPC data per year [1]—far beyond the scale of previous neutrino experiments.
- DUNE is developing a new framework: **Phlex** stands for **P**arallel, **h**ierarchical, and **l**ayered **ex**ecution of data-processing algorithms.
- ROOT's new `RNTuple` storage container is a candidate for the long-term DUNE data model, promising faster compression, cluster-aware reads, and thread-safe writes.
- This study benchmarks alternative RNTuple *persistent layouts* (AOS/SOA, vertical splits, granularity levels) for realistic data products.
- Focus data products: `recob::Hit` (charge deposits) and `recob::Wire` (ROI-compressed waveforms).

Motivation

- A single DUNE far-detector module streams about 1.2 TB/s of raw data before compression [2]; naive storage could potentially overwhelm the archival budget.
- Efficient layout choice can cut file size and accelerate cluster reads needed for GPU/CPU reconstruction farms.

Problem Statement

- Which RNTuple persistent layout minimises read time, write time and on-disk footprint for DUNE Hit/Wire data products?
- How does vertical splitting such as one RNTuple for all data products or one of each data products interact with horizontal granularities (event, spill, element)?
- How does the choice of persistent layout affect the performance of the read and write operations?

Objectives

- Benchmark seven layout variants on a 1 M-event (35 GB) Phlex dataset (`recob::Hit`, `recob::Wire` with ROIs).
- Measure: write throughput, cold/warm read latency, compressed file size.
- Quantify trade-offs of ROI flattening, vertical split depth, and SOA vs. AOS.

Persistent Layouts

Data Layouts: AOS vs. SOA

Array of Structures (AOS)

Stores complete objects in an array.

```
struct Hit {
  long long EventID;
  unsigned int fChannel;
  float fPeakTime;
};
// Array:  [Hit1, Hit2, ...]
```

Example: Hit, Wire (per-item entries).

Structure of Arrays (SOA)

Separate arrays per field.

```
struct Hits {
   vector<long long> EventID;
   vector<unsigned int> fChannel;
   vector<float> fPeakTime;
};
// Columns:  EventID[ ],
//fChannel[ ], fPeakTime[ ], ...
```

Example: Hits, Wires (per-event vectors).

Layout Strategies

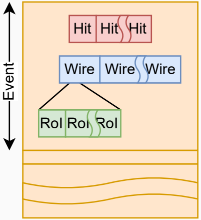


Figure 1: AOS Layout

Layout Strategies

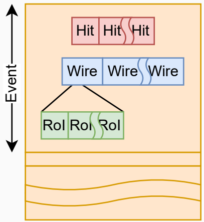


Figure 1: AOS Layout

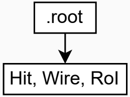


Figure 2: 1 RNTuple for all data products

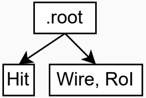


Figure 3: 1 RNTuple per data product

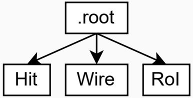
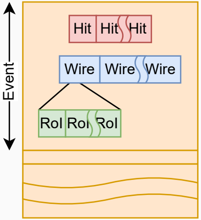


Figure 4: 1 RNTuple per group

Layout Strategies



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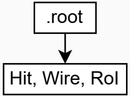


Figure 2: 1 RNTuple for all data products

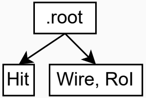


Figure 3: 1 RNTuple per data product

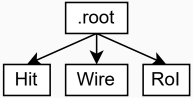


Figure 4: 1 RNTuple per group

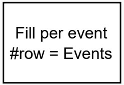


Figure 5: 1 fill/row per event

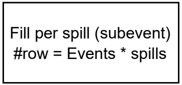


Figure 6: 1 fill/row per spill

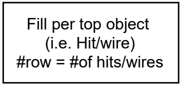


Figure 7: 1 fill/row per top object

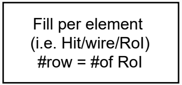


Figure 8: 1 fill/row per element

Layout Strategies: AOS vs SOA

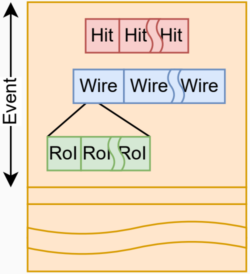


Figure 9: AOS Layout

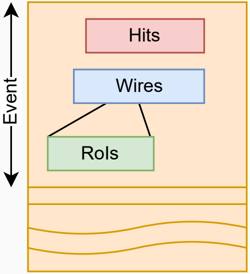


Figure 10: SOA Layout

Granularity vs. Vertical Split Matrix

Horizontal Granularity	1 NTuple (all DP)	1 NTuple / DP	1 NTuple / group
Event-wise	`event_allDP()`	`event_perDP()`	`event_perGroup()`
Spill-wise	`spill_allDP()`	`spill_perDP()`	`spill_perGroup()`
Top-object-wise	–	`topObject_perDP()`	`topObject_perGroup()`
Element-wise	–	`element_perDP()`	`element_perGroup()`

DP = Data Product

Parallel Optimizations

Write Optimization: Multi-Threaded Chunking

Parallel Chunking Divide events into thread-specific ranges for concurrent filling.

```
std::vector<unsigned int> seeds = generateSeeds(nThreads);
for (int th = 0; th < nThreads; ++th) {
    int first = th * chunkSize;
    int last = std::min(first + chunkSize, totalEvents);
    futures.emplace_back(std::async(
        std::launch::async, thinWorkFunc, first, last, seeds[th], th ));
}
```

Example: `executeInParallel` writers.

Project Use: Scales writes with cores for large datasets.

Read Optimization: Cluster-Aware Splitting

Cluster Splitting Split read ranges by cluster boundaries to avoid duplicates.

```
auto clusters = split_range_by_clusters(*reader, nChunks);
for (auto& chunk :  clusters) {
    futures.push_back(std::async(
        &processChunk, chunk.first, chunk.second
    ));
}
```

Helper Function Defines cluster-based splits.

```
std::vector<std::pair<size_t, size_t>>
split_range_by_clusters(ROOT::RNTupleReader& reader, int nChunks)
```

Project Use: Enhances read efficiency by reducing redundant reads.

Challenges

Challenge: Corrupted ROOT Files

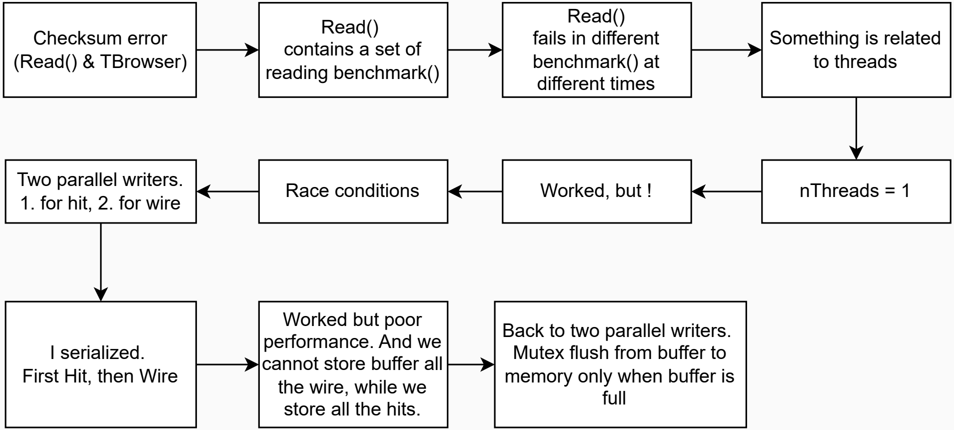


Figure 11: Challenge: Addressing corrupted ROOT files in parallel write operations.

Parallel Write Challenge: File Corruption Solution

Problem: Concurrent Flushes
Unsynchronized cluster flushes cause file corruption in multi-threaded writes. **Example Issue**: Threads overwriting shared file regions.

Solution: Mutex Synchronization Lock during flushes to serialize access per cluster.

```
for (int idx = first; idx < last; ++idx) {
    // Generate data for hits/wires
    if (hitStatus.ShouldFlushCluster()) {
        hitContext.FlushColumns();
        {
          std::lock_guard<std::mutex> lock(mutex);
        }
        hitContext.FlushCluster();
    }
}
```

Project Use: Ensures thread-safe parallel writes without corruption.

ROI Flattening vs. Custom Dictionary

ROI Flattening (Non-Dictionary)

Flattens hierarchical ROI data into vectors for efficient storage without custom classes.

```
struct Wires {
    vector<unsigned int> fSignalROI_nROIs;
    vector<size_t> fSignalROI_offsets;
    vector<float> fSignalROI_data;
};
```

Example: Used in non-dictionary experiments for raw vector-based I/O.

Custom Dictionary (ROOT Classes)

Uses structured classes of ROOT's dictionary system, enabling object-oriented I/O.

```
struct RegionOfInterest {
    size_t offset;
    vector<float> data;
};
```

Example: Used in dictionary experiments for type-safe, hierarchical data handling.

Results

Evaluation Metrics

- **Write Throughput:** Total events per second during RNTuple serialization.
- **Cold Read Time:** Latency for first access after file creation, reflecting raw I/O.
- **Warm Read Time:** Latency when data is cached, measuring memory locality effects.
- **Compressed File Size:** Total on-disk footprint post-write, accounting for RNTuple's column-wise compression.

AOS: Write Performance

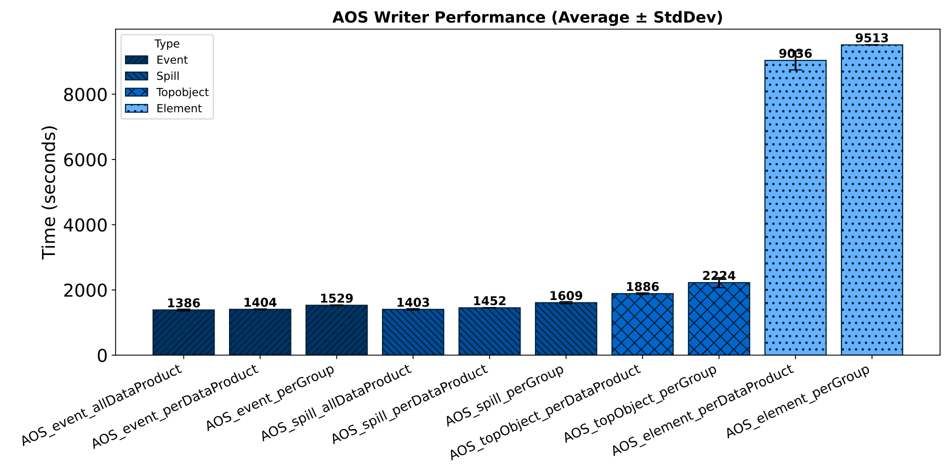
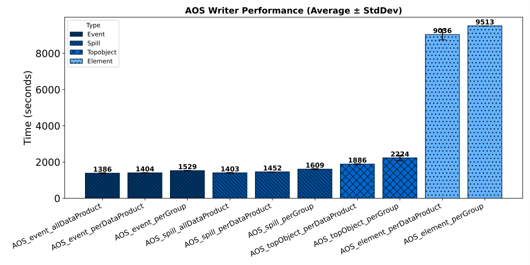


Figure 12: AOS (Array of Structures) Write performance across different persistent layouts.

AOS: Write Performance



Key Takeaways:

- Higher granularity leads to slower write performance due to thread contention.
- For horizontal persistent layouts, slow down is upto 6.9×, although it is marginal for vertical persistent layouts.

SOA: Write Performance

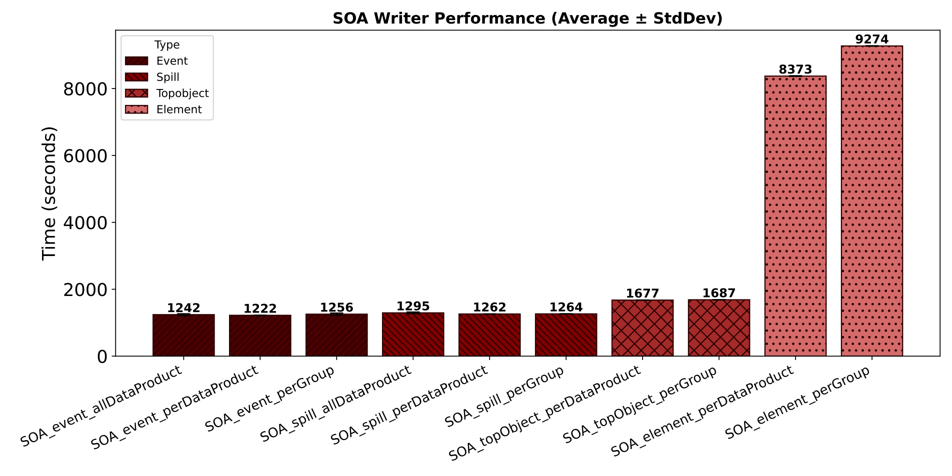
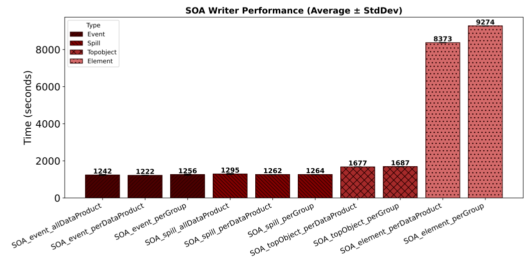


Figure 13: SOA (Structure of Arrays) Write performance across different persistent layouts.

SOA: Write Performance



Key Takeaway:

- SOA writer performance is overall similar to AOS writer performance.

AOS vs SOA: Write Performance

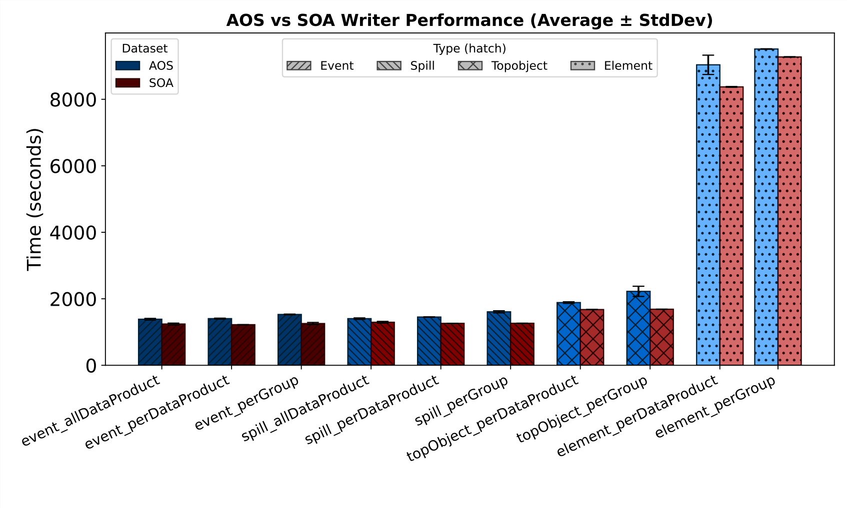
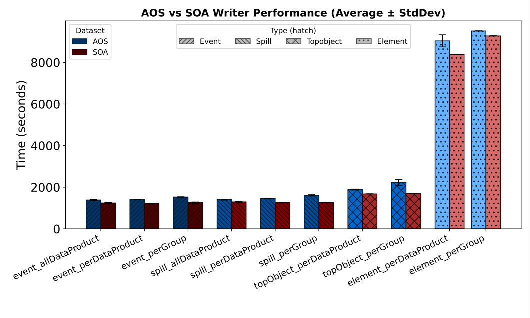


Figure 14: AOS vs SOA write performance across different persistent layouts.

AOS vs SOA: Write Performance



Key Takeaway:

- SOA writer is on average 3.65% faster than AOS writer for all persistent layouts.

File Size Analysis: AOS vs SOA

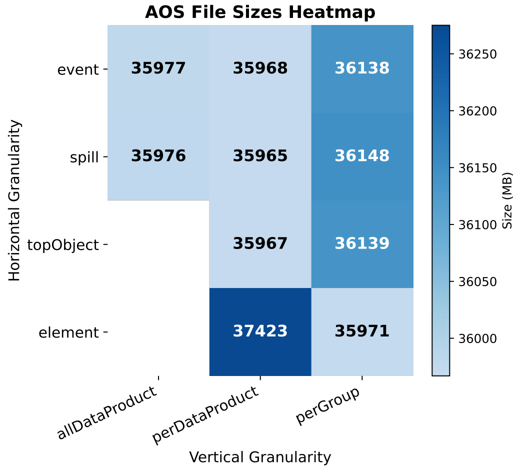


Figure 15: AOS file size across persistent layouts

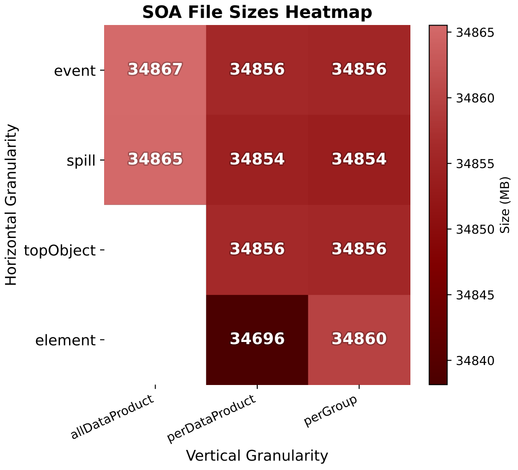
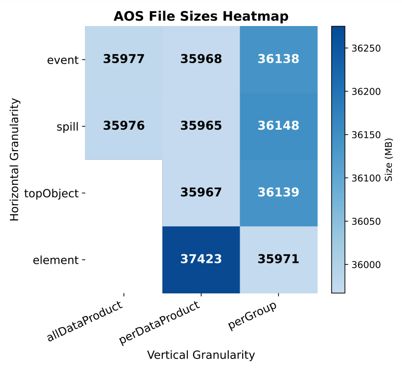
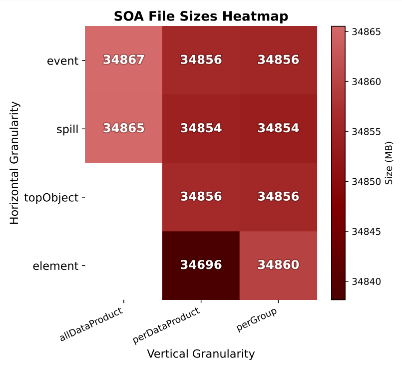


Figure 16: SOA file size across persistent layouts

File Size Analysis: AOS vs SOA





Inconclusive observations:

- The variability in file size is higher for AOS than SOA.
- Element_perDataProduct layout for AOS leads to higher file size due to additional information storage of EventID and WireID.

Fields Read in Benchmarks

- **Hits**: `PeakAmplitude`.
- **Wires**: `Channel`.
- **ROIs**: ROI `data vector data`.

- **Note**: We do not reconstruct full objects from the fields; we only read the fields through RNTuple views, using `volatile` to prevent the compiler optimization.

AOS vs SOA: Cold Read Performance Comparison

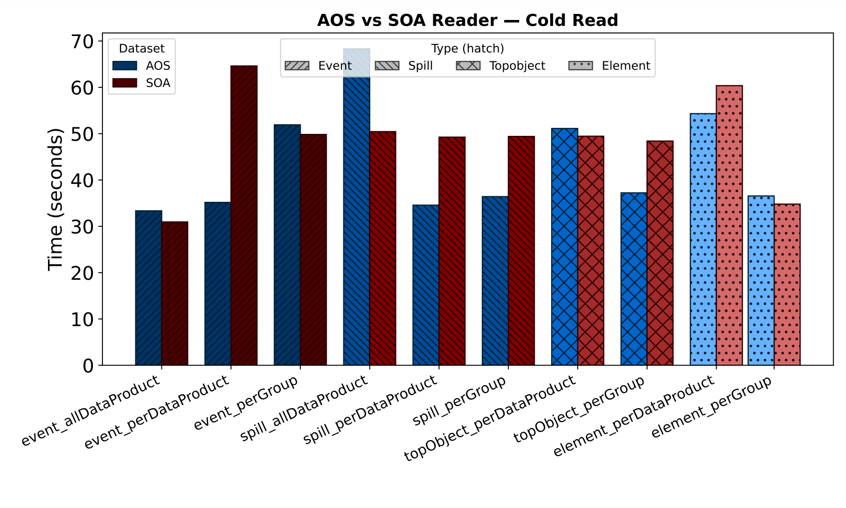


Figure 17: Cold Read Performance Comparison: Initial read times for AOS vs SOA implementations.

AOS vs SOA: Warm Read Performance Comparison

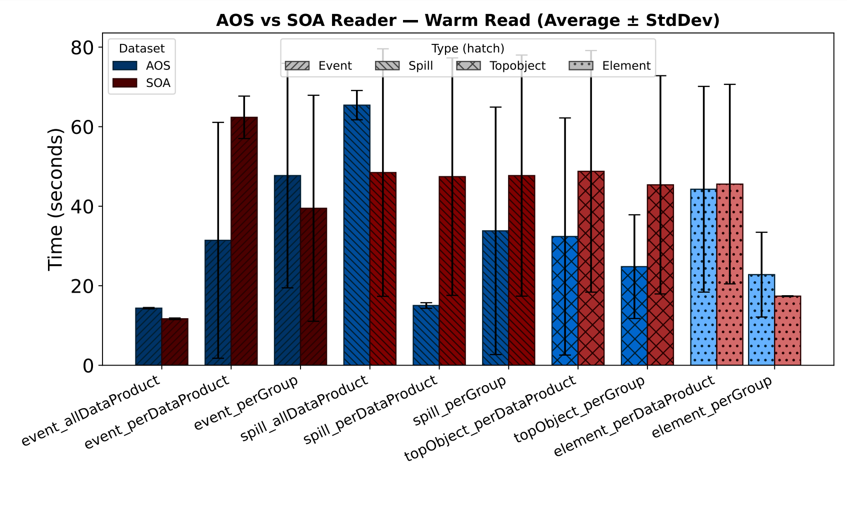
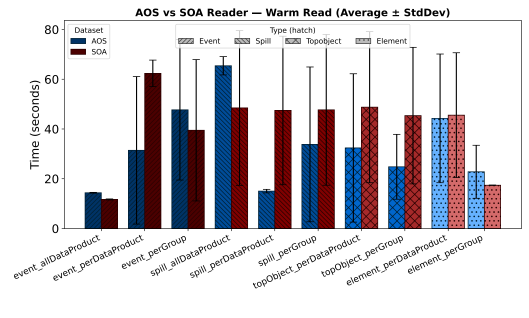


Figure 18: Warm Read Performance Comparison: Subsequent read times for AOS vs SOA implementations.

AOS vs SOA: Warm Read Performance Comparison



Limitations:

- No visible pattern in both cold and warm read performance.
- The StdDev of warm read performance is higher because we are yet to utilize the flushing of cache.

Future Considerations

- **Uniformity in Data Storage:** Deterministic approach to store exactly same data for each of the root files.
- **Thread Scaling Analysis:** Rigorous testing across 1–128 threads to evaluate layout performance scaling and optimal configurations.
- **Extensible Framework:** Develop scalable architecture for arbitrary data products beyond Hits and Wires with configurable layouts.
- **Advanced Layout Testing:** Explore N-tuple groupings and clustering strategies for improved read/write efficiency and storage optimization.

References i

[1] DUNE Collaboration, “Deep Underground Neutrino Experiment Technical Design Report–VolumeII: DUNE Physics,” 2020, Sec.2.6.

[2] DUNE Collaboration, “Data Acquisition System for the DUNE Far Detector,” IEEE NSS/MIC Proc., 2023.

Thank you!

Questions?