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HEPnOS: a Specialized Data Service for High Energy Physics Analysis

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Introduction

- Present day HEP analyses map data processing tasks onto computer cores by assigning 1 core : 1 file.
- Each file contains many atomic units of data that can be processed independently
  - these are called events.
- The file-based assignment limits the maximum number of cores that can be used for analyzing a dataset.
- The file-based workflows introduce artificial bottlenecks that make our use of HPC resources inefficient.
- HPC clusters have nodes that are connected by **low latency, high bandwidth interconnects**.
- We propose to **remove this bottleneck** by using a distributed data service, HEPnOS that can **harness the interconnects**.
- In this paper, we demonstrate the reading speed and scalability (both weak and strong) of HEPnOS, using sample from a neutrino physics experiment, NOvA.

Background: Neutrino Physics

- Neutrino: elementary particle which holds no electrical charge, weighs a million times less than the electron and passes through ordinary matter with virtually no interaction!
- Abundance: a thousand trillion pass harmlessly through your body every second!
- There are three flavor states of neutrino: electron, muon and tau (and three mass states formed as a linear superposition of the flavor states).
- As a neutrino travels, it may switch back and forth between the flavors. These flavor “oscillations” confounded physicists for decades.

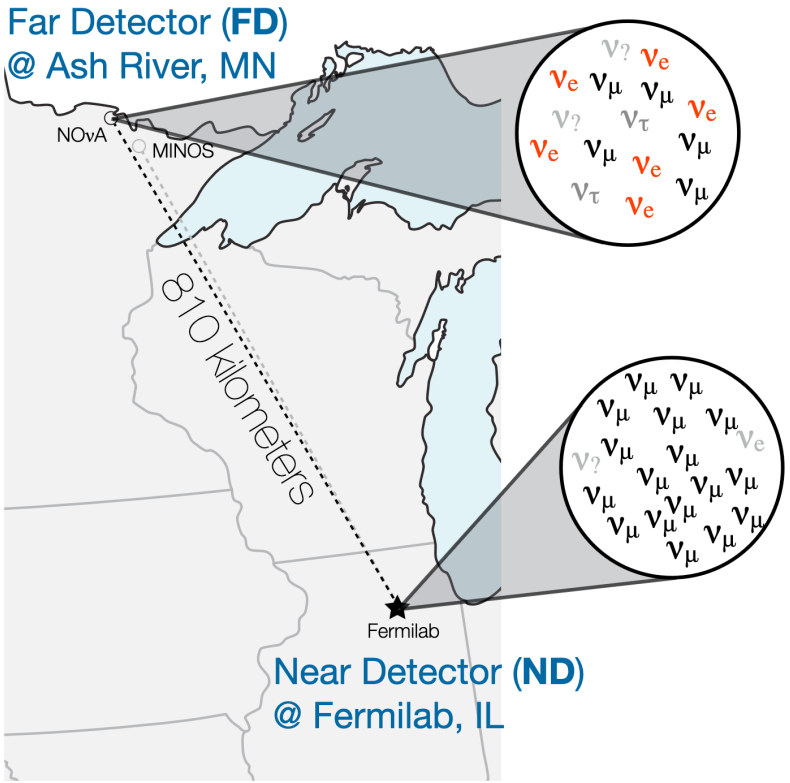
Motivation for NOvA experiment

- The NOvA experiment is constructed to answer the following important questions:
  - What is the relative ordering of the mass states of the neutrinos?
  - Do neutrinos violate charge parity symmetry? (i.e. do anti-neutrinos oscillate the same way as neutrinos)
  - Gather information regarding the oscillation parameters to examine muon-tau symmetry.

- NOvA – (**N**eutrinos from the Main Injector) **O**ff-Axis Electron Neutrino($\boldsymbol{\nu_e}$) **A**ppearance

The NOvA experiment: Overview

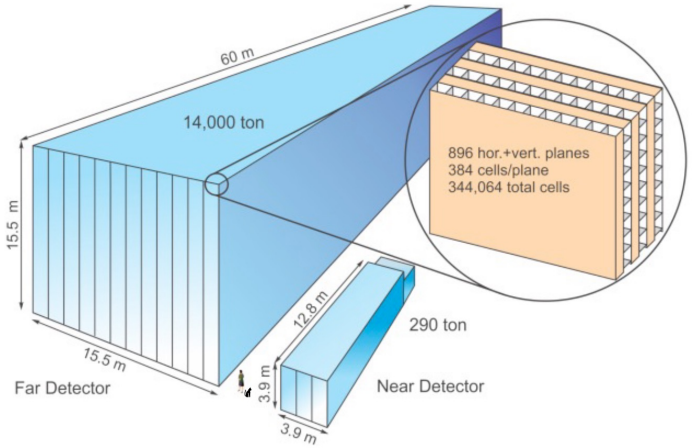
- Fermilab's accelerator complex produces the most intense (muon) neutrino beam in the world and sends it through the earth to northern Minnesota.
- Moving at close to the speed of light, the neutrinos make the 800-km journey in less than three milliseconds.
- When a neutrino interacts in the NOvA detector in Minnesota, it creates distinctive particle tracks.

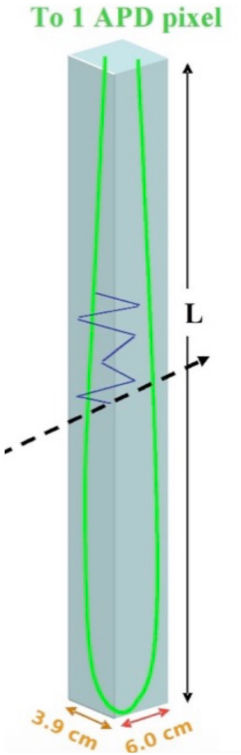


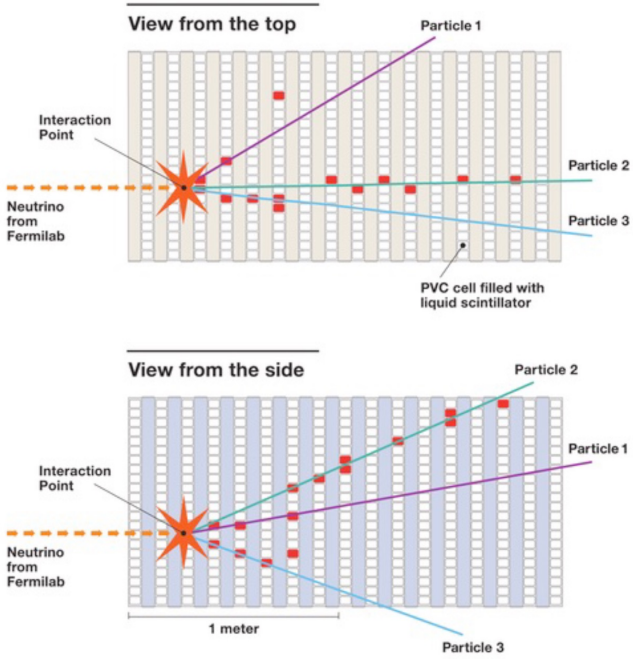
Credit: Maria Manrique Plata, NOvA in 10 minutes, New Perspectives 2022

Scintillator detectors

Detector Overview

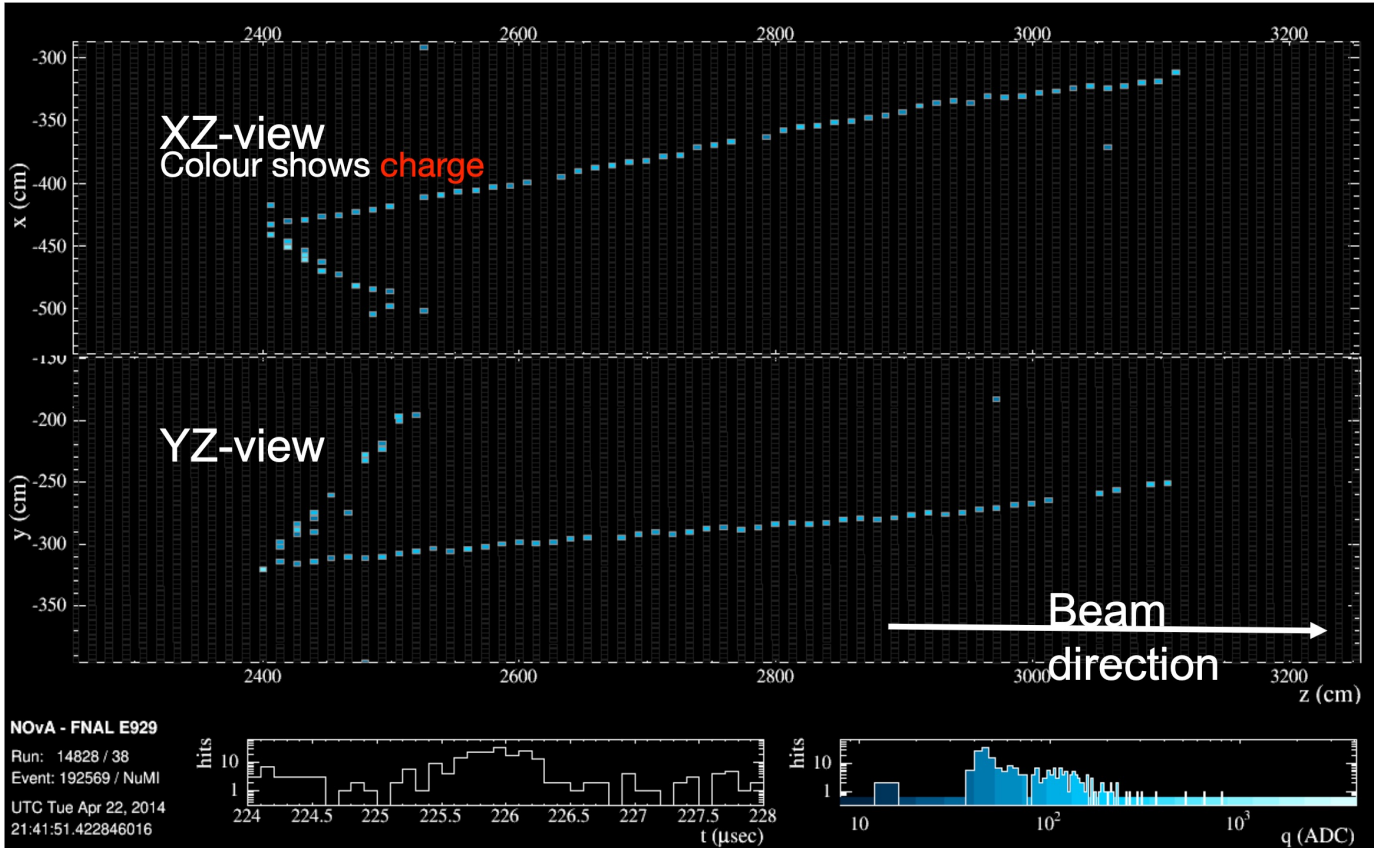




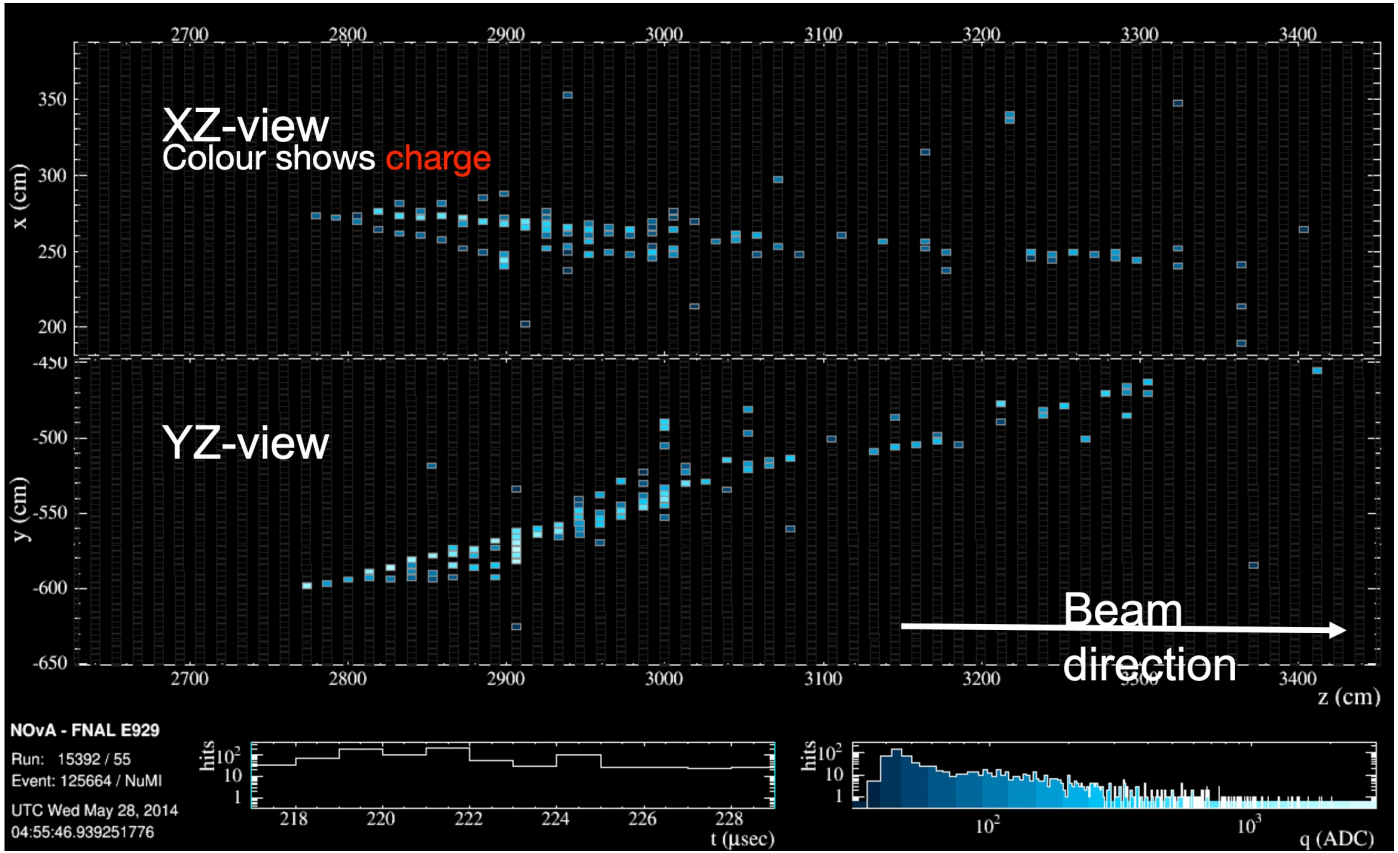


Credit: Maria Manrique Plata, NOvA in 10 minutes, New Perspectives 2022

Muon-neutrino Charged-Current Candidate



Electron-neutrino Charged-Current Candidate



Physics task at hand

- Classify types of interactions based on patterns found in the detector:
  - Is it a muon or electron neutrino?
  - Is it a charged current or a neutral current interaction?

- Classify a detector event by comparing its cell energy pattern to a library of 77M simulated events cell energy patterns, choosing 10K that are “most similar”.

- Compare the pattern of energy (hit) deposited in the cells of one event with the pattern in another event.

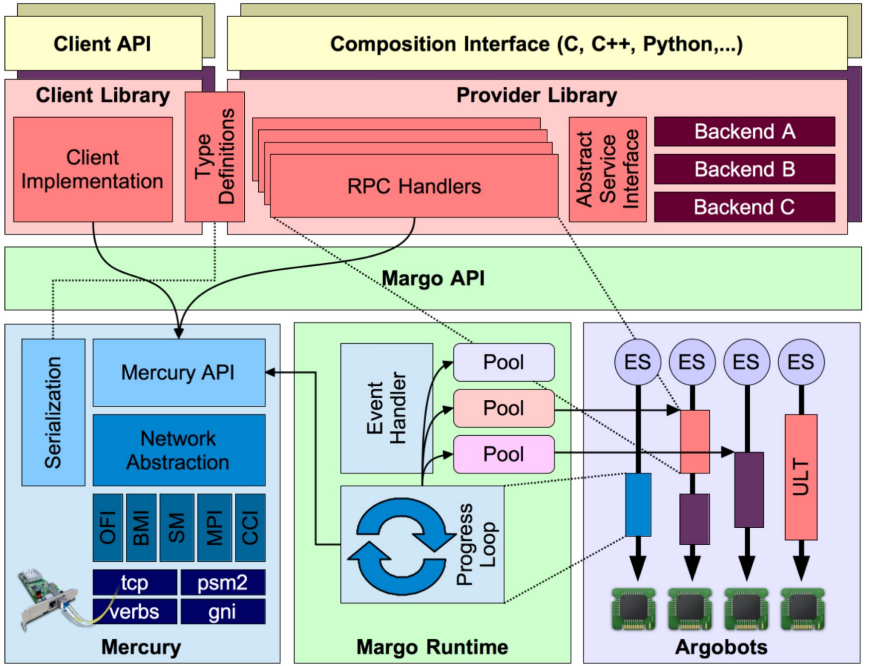
- The “most similar” metric is motivated by an electrostatic analogy: energy comparison for two systems of point charges laid on top of each other.

Goals: Harness HPC resources

- Present day analysis maps the work onto computer cores by assigning each core one ROOT file (which contains many events).
- This limits the maximum number of cores that can be used for analyzing a dataset.
- The goal is to **remove this bottleneck** and allow for faster processing of datasets by **harnessing HPC resources**.
- HPC clusters have nodes that are connected by **low latency, high bandwidth interconnects**.

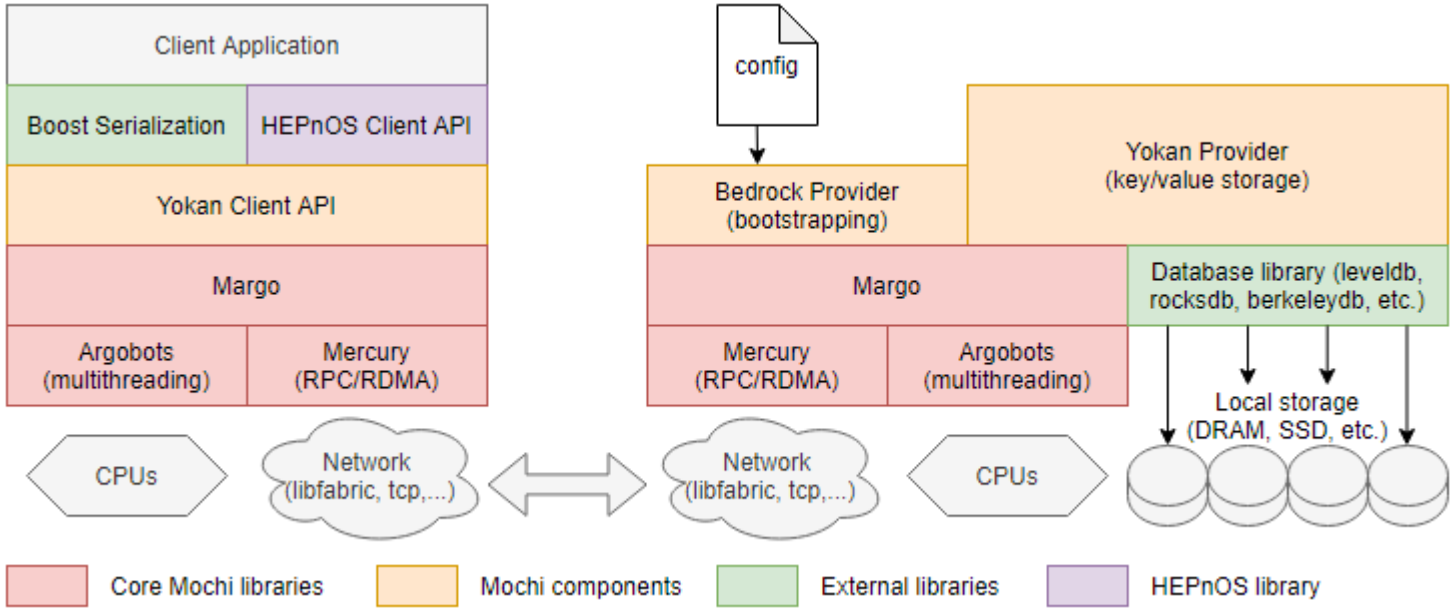
Background: Custom data services with Mochi

- Mochi microservices: a suite of re-usable components for building data services including:
  - *Mercury*: RPC framework that can use a variety of transports, which supports bulk data transfers.
  - *Argobots*: Lightweight user level threads to run tasks in execution streams.
  - *Margo*: Utilities for argobots aware mercury requests.



Anatomy of a data service backed by mochi microservices. Illustration by Matthieu Dorier. J Comput Sci Technol. 35, 121–144 (2020).

High-Energy Physics's new Object Store: Architecture

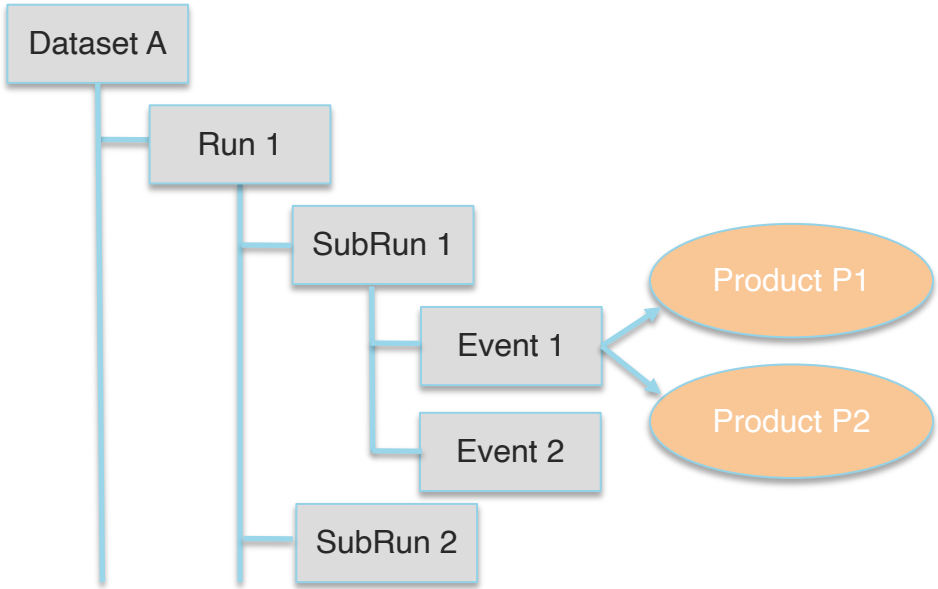


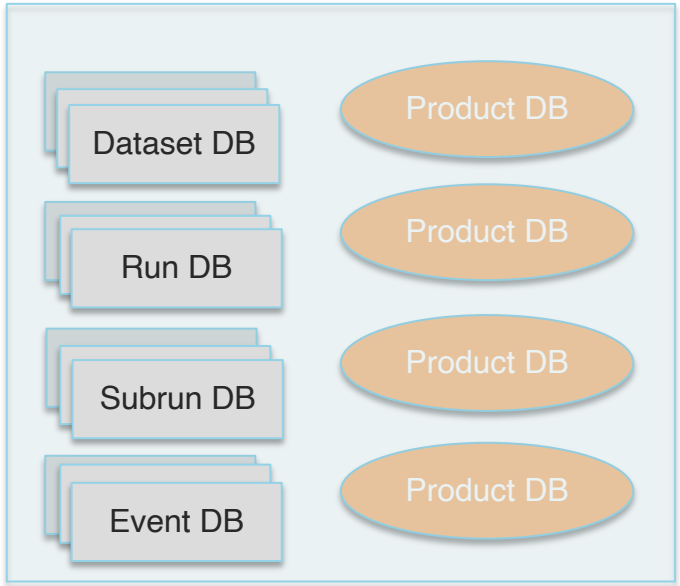
Architecture of HEPnOS: (Left) Client stack, (Right) Server stack. Illustration by Matthieu Dorier.

High-Energy Physics's new Object Store: Features

- Write-once, read-many access.
- Bulk ingest and iterative access.
- Eliminates software artifacts related to the filesystem and grid computing.
- Parallelism expressed at the event level instead of file level, allowing for better load balancing.

High-Energy Physics's new Object Store: Organization





Yokan providers in a HEPnOS server instance

Stored with lexicographic ordering

Stored without ordering

Background on dataset used

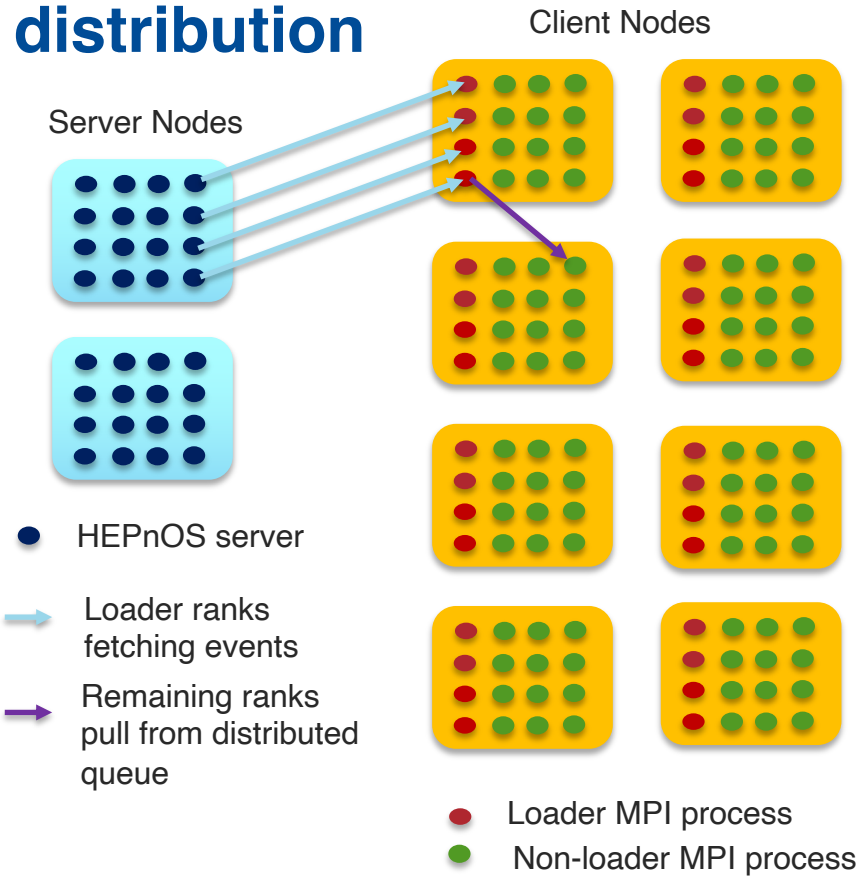
- Data collected from NOvA detectors, where each “spill” of the accelerator is called an “event”. These “events” are further split into “slices” associated with neutrino candidates.
- Performing neutrino candidate selection on these slices as a precursor to fitting model parameters.
- Input data is a collection of ROOT files using the “Ttree” format, also known as the “Common Analysis Format”.
- Using a dataset of 1929 ROOT files, that contain 4,359,414 events and 17,878,347 slices; size: ~0.2TB, representing ~1.1% of the total data (duplicated 4x for scaling studies).

New workflow with HEPnOS

- Set aside some of the compute nodes to run the HEPnOS Server.
- Load the data into the HEPnOS server.
- Call the processing function on “events” on the client nodes, with the HEPnOS Parallel Event Processor.
- Re-run the analysis as needed, without needing to reload data into the server!

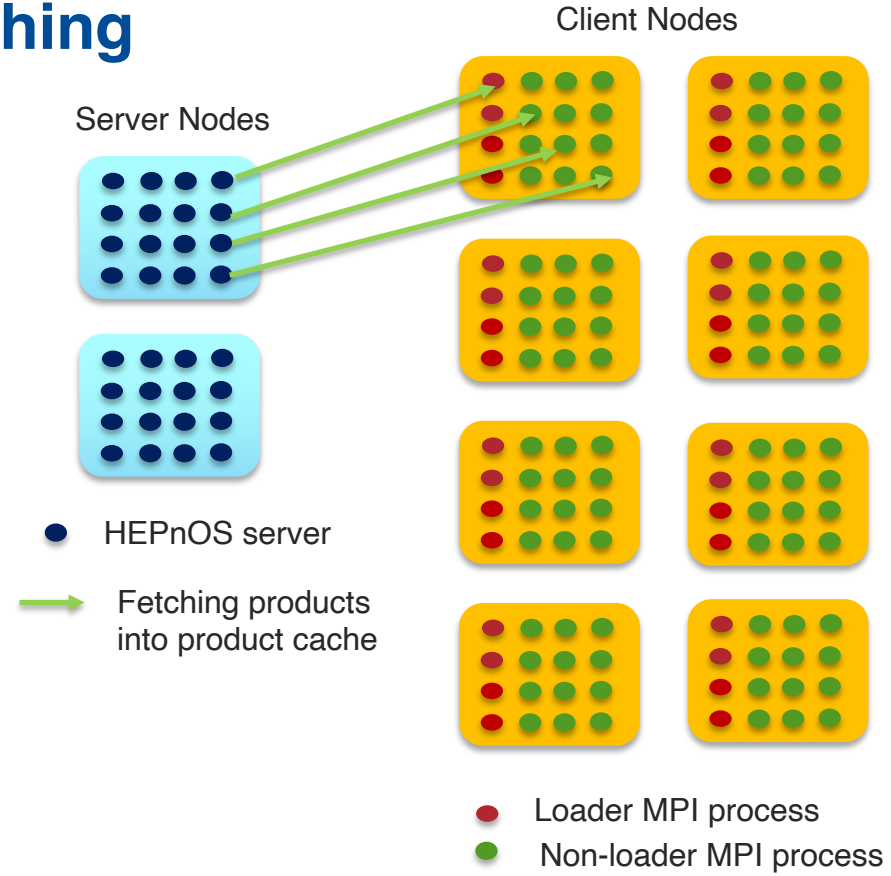
Parallel Event Processor: Task distribution

- Subset of the MPI ranks are designated as “loader” ranks.
- Loader ranks fetch the “events” from the datastore (in batches) and collectively provide a distributed queue.
- All MPI ranks fetch events (in batches) to process.
- This allows for implicit load-balancing at the event level.



Parallel Event Processor: Caching

- Can optionally indicate which product labels need to be pre-fetched into a “product cache” asynchronously.
- The user-function is then called on the events, with the “product cache” used to look up required products before searching for it on the servers.



Experimental Setup

- We tested the conventional file-based workflow with the Python multiprocessing module being used to map files to cores, with cores being idle at larger node counts.

- For the HEPnOS based workflow, we used two storage backends via the Yokan provider:
  - An in-memory backend using the C++ std::map
  - SSD backend utilizing the node-local SSDs via the RocksDB library

- Server configurations for the two backends:
  - In-memory backend: 1 MPI rank per node accessing 64 cores with HT disabled.
  - Node-local SSD backend: 16 MPI ranks per node, each accessing 4 cores with HT disabled.

- Quantity of interest: throughput, measured by number of slices processed per unit time.

Experimental Setup

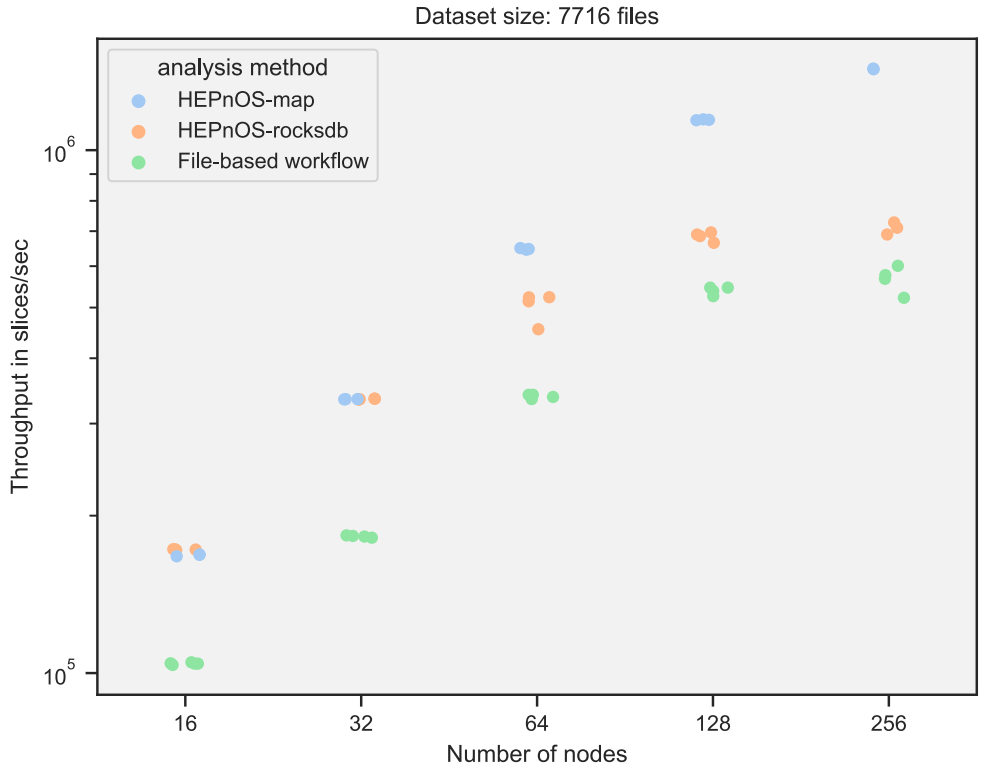
- We use the “theta” cluster at ALCF that consists of Intel Knights Landing nodes connected via a Cray Aries interconnect.

- The server software stack is installed using the *spack* package manager.

- The client stack comes from a SL6 contained image, into which we inject the networking libraries to enable the use of the GNI transport fabric.

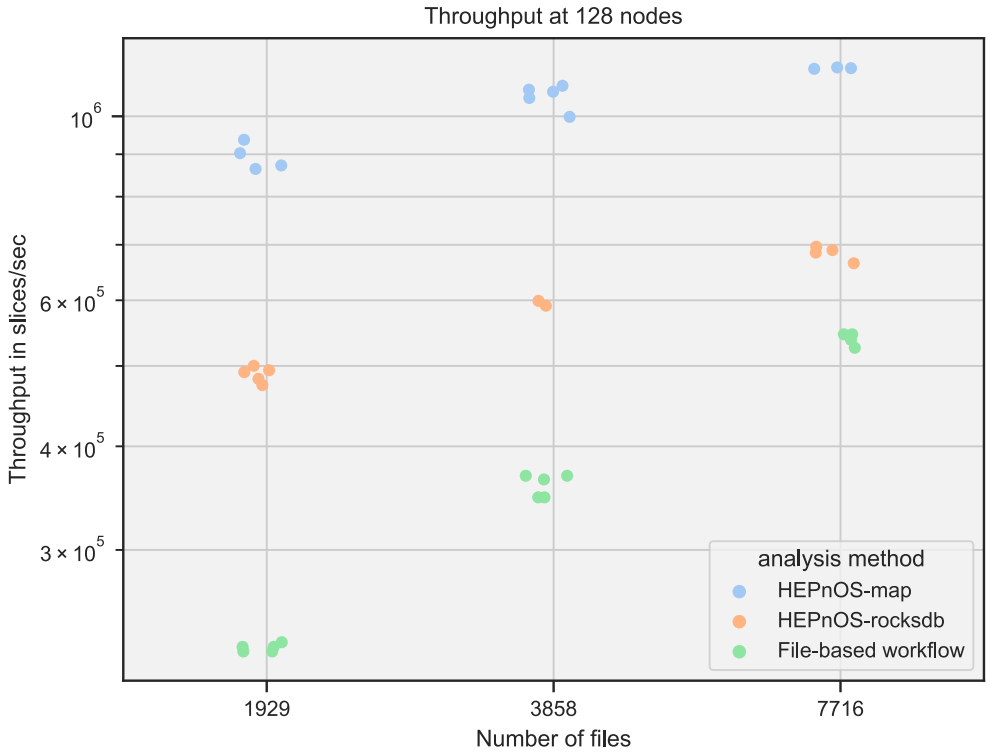
Throughput as a function of # nodes

- Performance of HEPnOS with either backend is better than the file-based workflow.
- In-memory backend of HEPnOS achieves ~85% scaling efficiency at 128 nodes.
- Typical data sizes for this workflow in production would allow for the usage of the in-memory backend.



Throughput as a function of # files

- File-based workflow is unable to harness all the available cores with 1929 files where only ~24% of cores are used.
- By using the HEPnOS-based workflow, we are better able to utilize compute resources.



Summary

- Benchmarked a novel HEP data store for the NOvA neutrino candidate selection workflow.
- Improved throughput for processing slices demonstrated at any number of nodes by **harnessing the interconnects on a HPC system**.
- Demonstrated the ability to **harness workflow parallelism at the event-level** with *HEPnOS*.

SciDAC team

- HEP and ASCR Collaboration
  - LHC and neutrino physics: N. Buchanan (CSU, NOvA/DUNE), P. Calafiura (LBNL, LHC-ATLAS), Z. Marshall (LBNL, LHC-ATLAS), S. Mrenna (FNAL, LHC-CMS), A. Norman (FNAL, NOvA/DUNE), A. Sousa (UC, NOvA/DUNE)
  - FASTMath Optimization: S. Leyffer (ANL), J. Mueller (LBNL)
  - RAPIDS Workflow, Data Modeling: T. Peterka (ANL), R. Ross (ANL)
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  - J. Kowalkowski – PI (FNAL)
- Research Associates and Graduate students
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- http://computing.fnal.gov/hep-on-hpc/

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