Implicitly Parallel Analysis Tools

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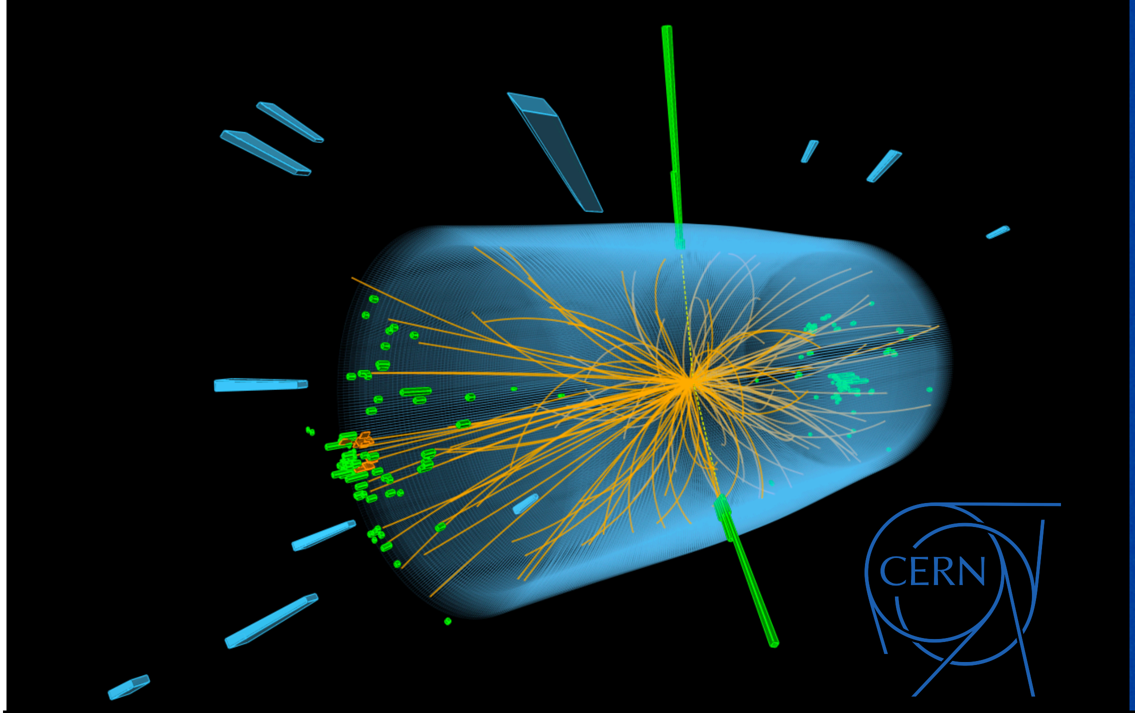
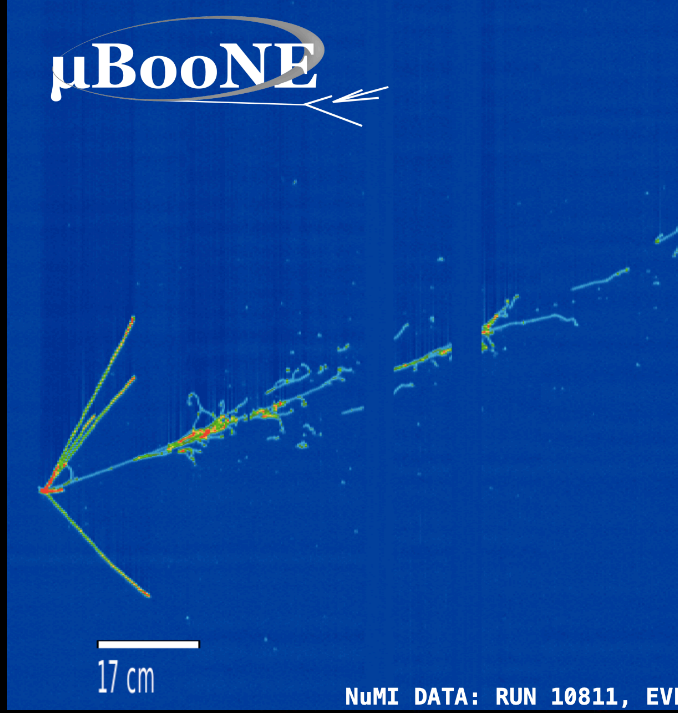
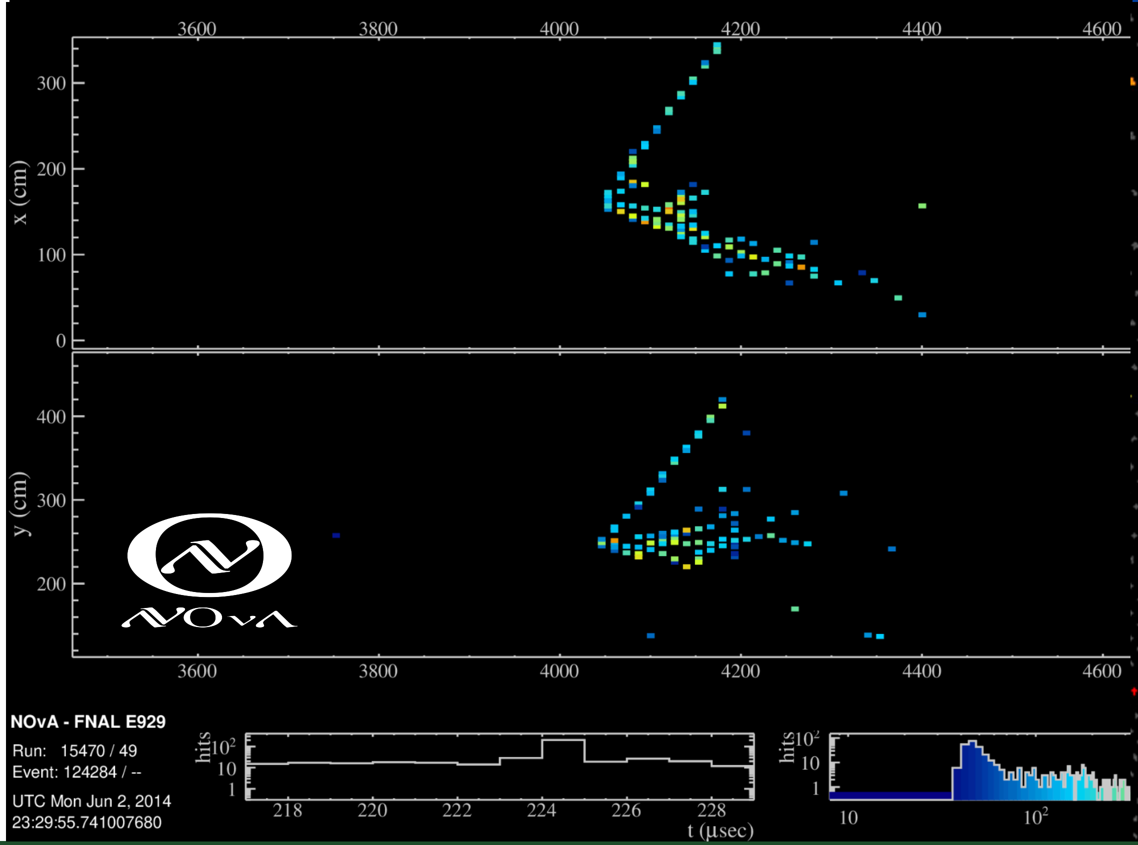
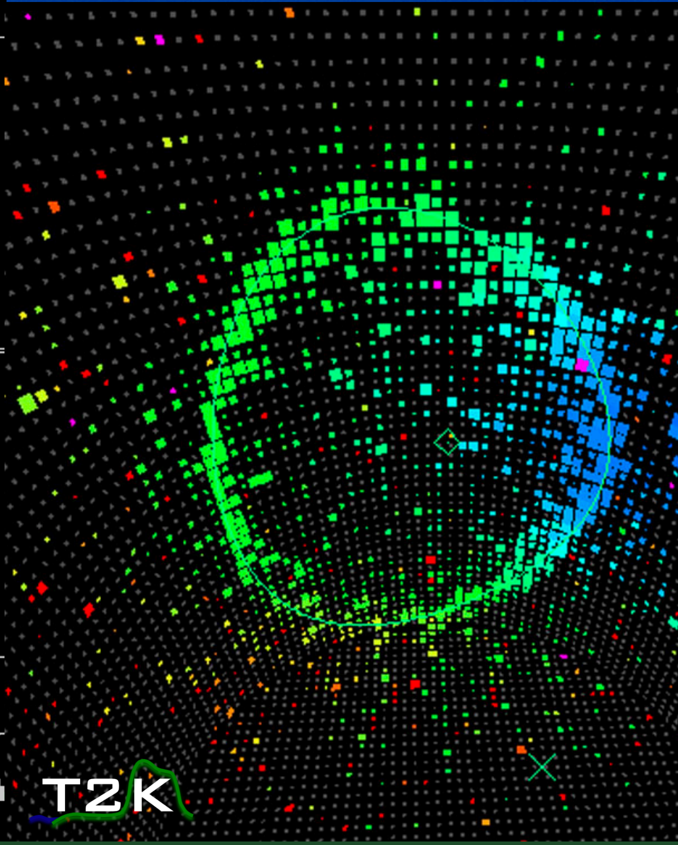
High Energy Physics Data

- High energy physics experiments collect massive amounts of data
  - Complicated event structure/ features
  - High intensity beams
- The first step of many analyses is often event selection and feature extraction
  - Highly-parallel task
  - Leverage high-speed interconnect and data storage at HPC facilities

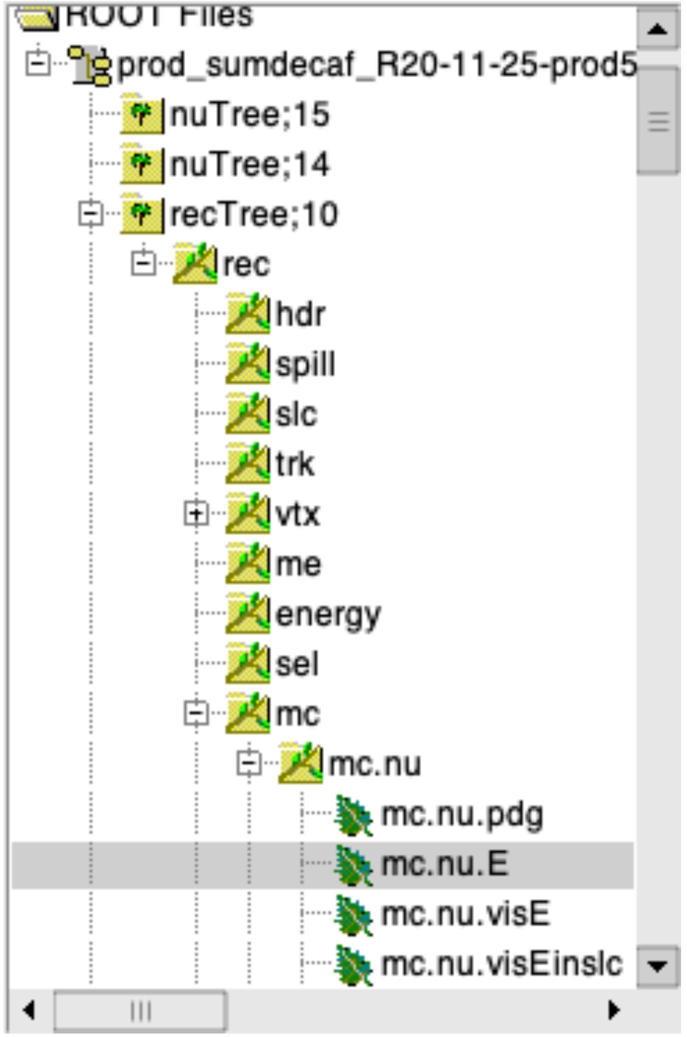








HDF5 Data Organization



- ROOT Files
  - prod_sumdecaf_R20-11-25-prod5
    - nuTree;15
    - nuTree;14
    - recTree;10
      - rec
        - hdr
        - spill
        - slc
        - trk
        - vtx
        - me
        - energy
        - sel
        - mc
          - mc.nu
            - mc.nu.pdg
            - mc.nu.E
            - mc.nu.visE
            - mc.nu.visEinslc

- HDF5 is the foundation of our Python analysis ecosystem
  - Can leverage highly optimized MPI implementations on HPC platforms
  - Large industry investment
- Data are store column-wise for efficiency columnar processing
- Flat tables, event indices associate features across tables
- From ROOT…
  - Nested tuples are flattened into separate groups (HDF5 Group)
  - Leaves compose the table's columns (HDF5 Dataset)

/rec.mc.nu (HDF5 Group)

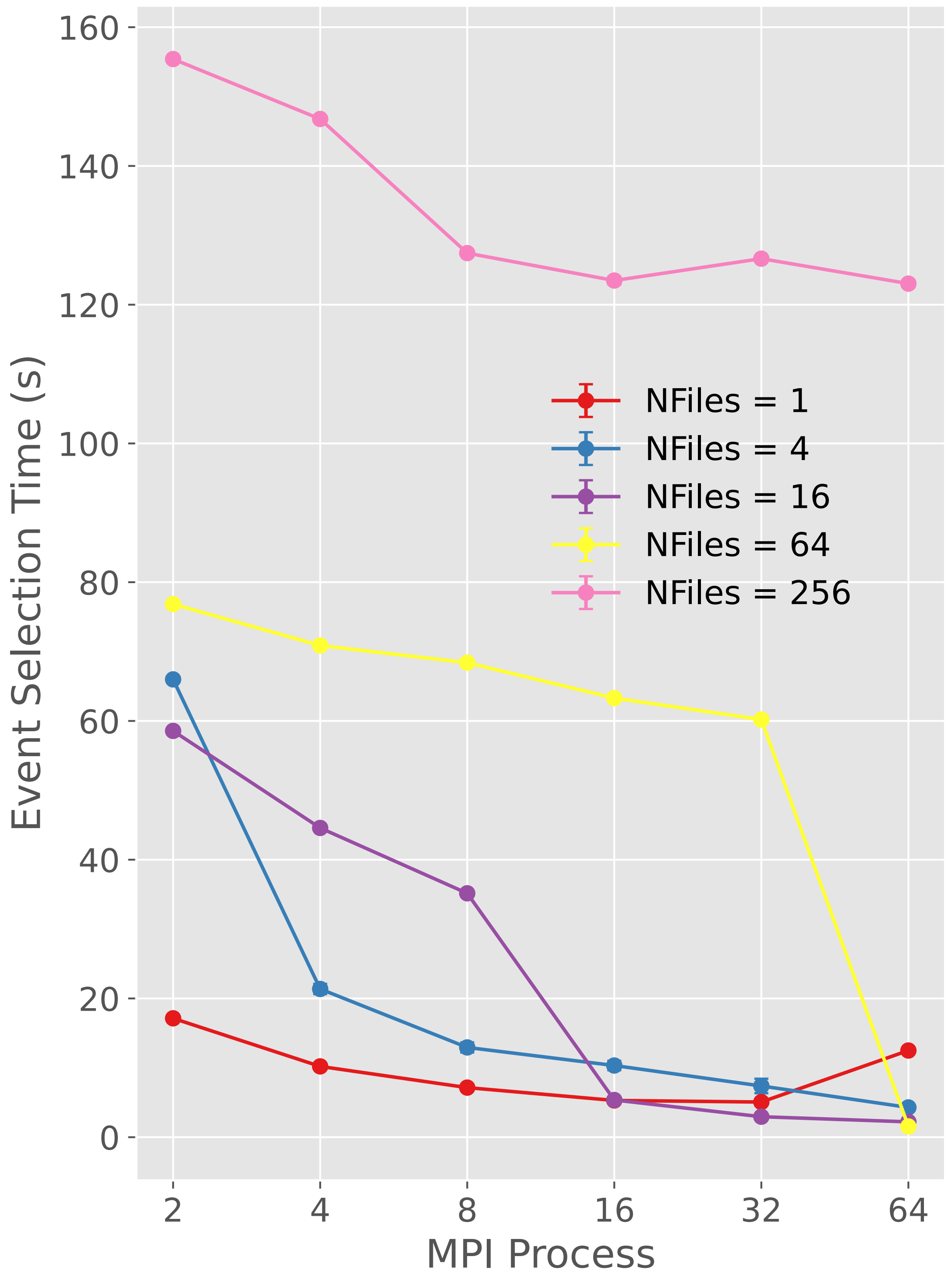
Event Index	pdg	E	visE	visEinslc	…
0	-14	1.6	0.89	0.79	
1	-14	2.3	0.92	0.91	
2	-14	2.07	1.26	1.23	
3	-14	2.00	1.04	0.98	

HDF5 Concatenation

https://github.com/NU-CUCIS/ph5concat

- HDF5 Chunking allows us to scale file size with little overhead
- Demonstrate scaling compression and improved event-selection time at various levels of concatenation of NOvA Monte Carlo dataset

- Monolithic dataset provides most flexibility
  - Consistent x10 speedup in event selection time
  - 11x compression
  - Self-contained
- Concatenated almost 3TB of uncompressed data using only 985 CPU hours (NERSC Cori)
  - $\mathcal{O}(10^2)$ GB file size enables laptop analyses

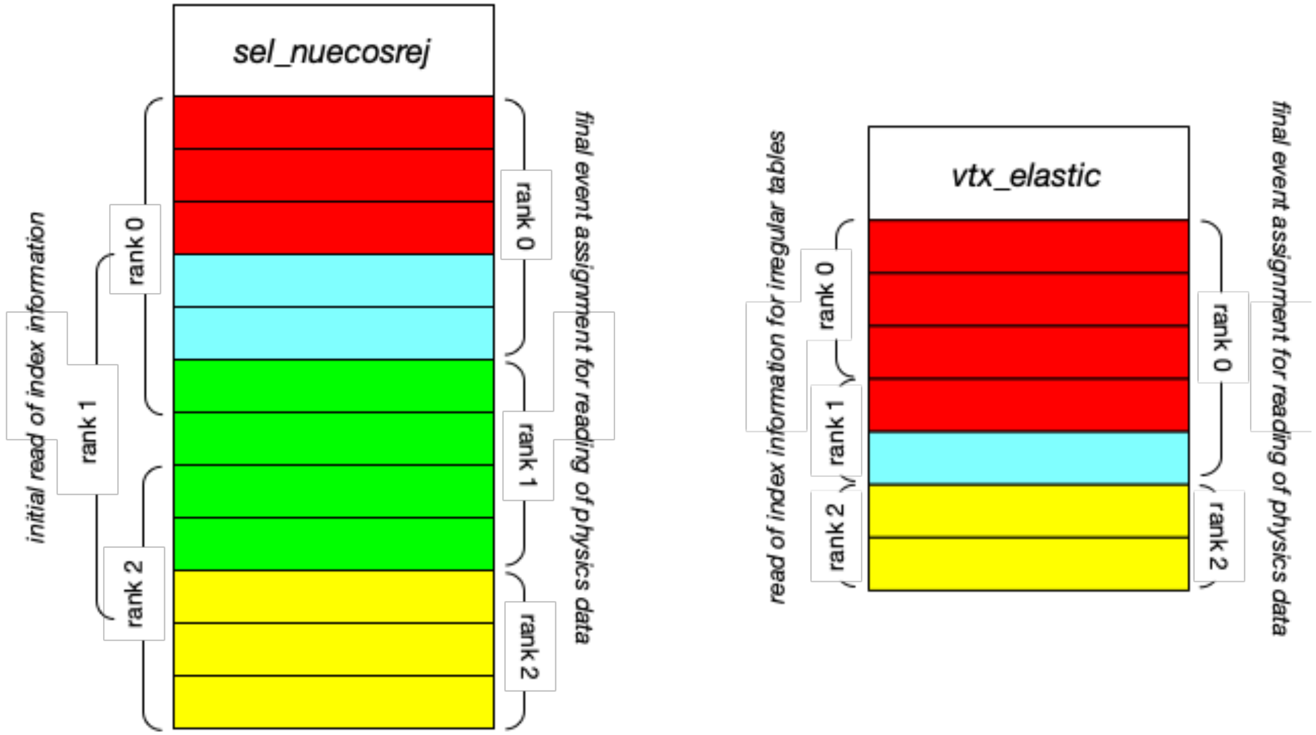


PandAna

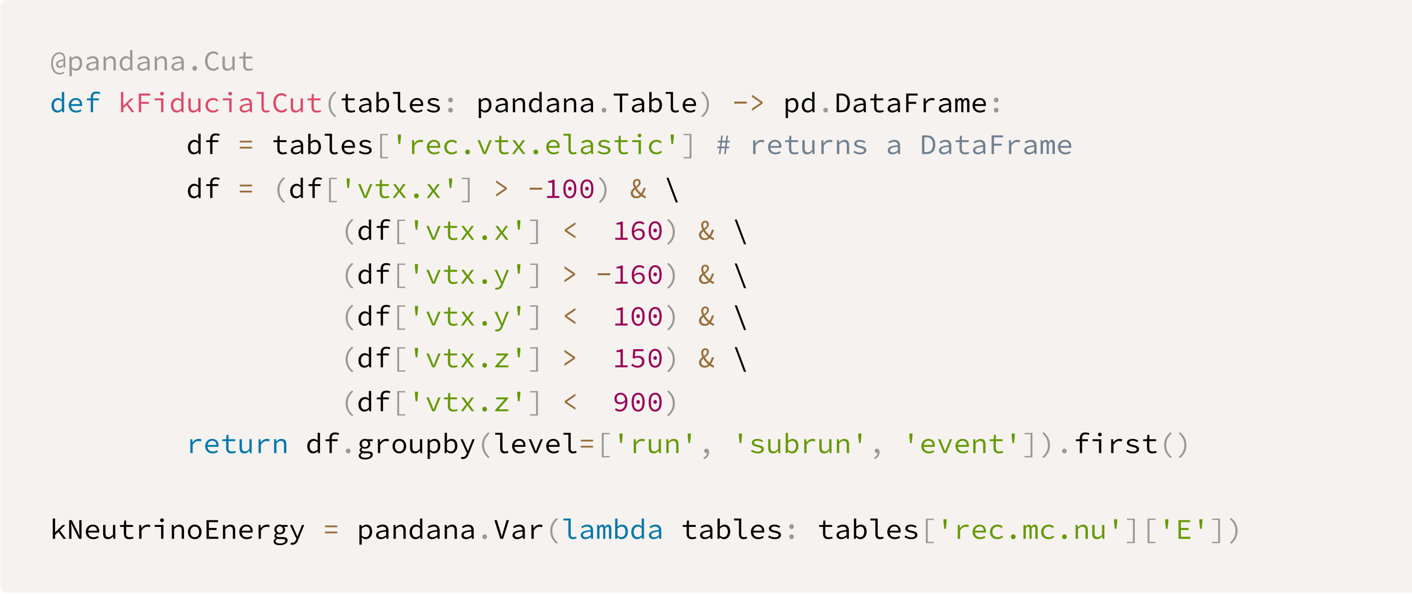
https://github.com/HEPonHPC/pandana

- PandAna is an implicitly parallel event selection framework
- Event indexing is used to distribute event selection workload among MPI ranks
  - Leverages parallel HDF5 I/O
  - Scalability limited by number of events
  - Handles irregular group sizes
- Easy to write, Pandas operations

- Possible improvements
  - Reduce event index redundancy requirements
  - Optimized data-flow using abstract syntax trees


sel_nuecosrej
initial read of index information
rank 0
rank 1
rank 2
rank 0
rank 1
rank 2
final event assignment for reading of physics data
read of index information for irregular tables
rank 0
rank 1
rank 2
vtx_elastic
rank 0
rank 2
final event assignment for reading of physics data

User code for defining data-filtering operation (Cut)



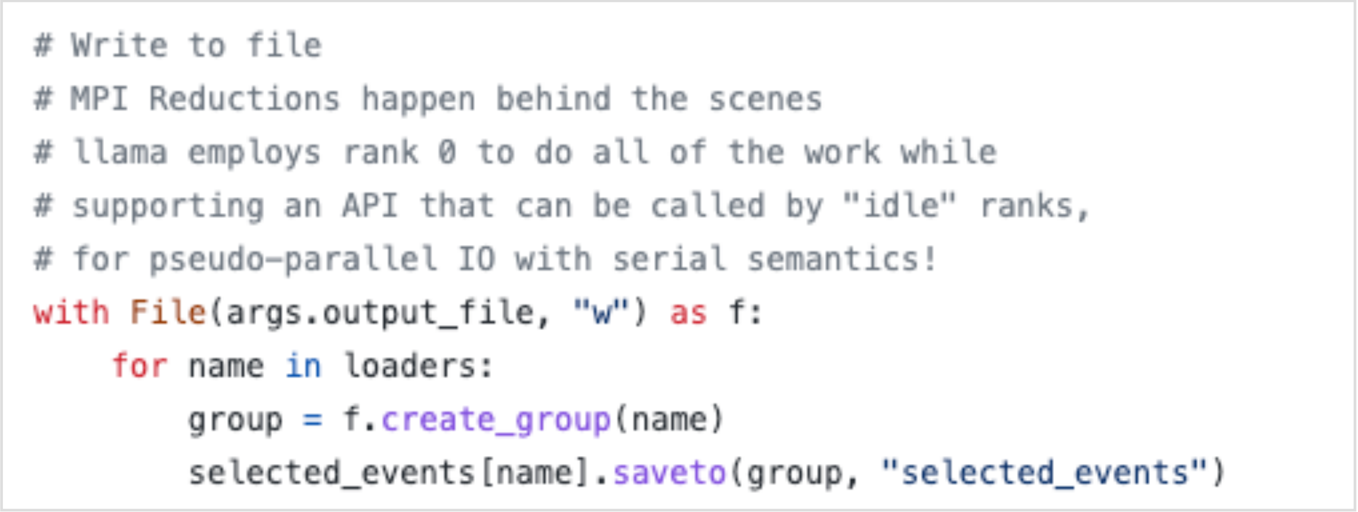
```
@pandana.Cut
def kFiducialCut(tables: pandana.Table) -> pd.DataFrame:
        df = tables['rec.vtx.elastic'] # returns a DataFrame
        df = (df['vtx.x'] > -100) & \
                 (df['vtx.x'] <  160) & \
                 (df['vtx.y'] > -160) & \
                 (df['vtx.y'] <  100) & \
                 (df['vtx.z'] >  150) & \
                 (df['vtx.z'] <  900)
        return df.groupby(level=['run', 'subrun', 'event']).first()

kNeutrinoEnergy = pandana.Var(lambda tables: tables['rec.mc.nu']['E'])
```

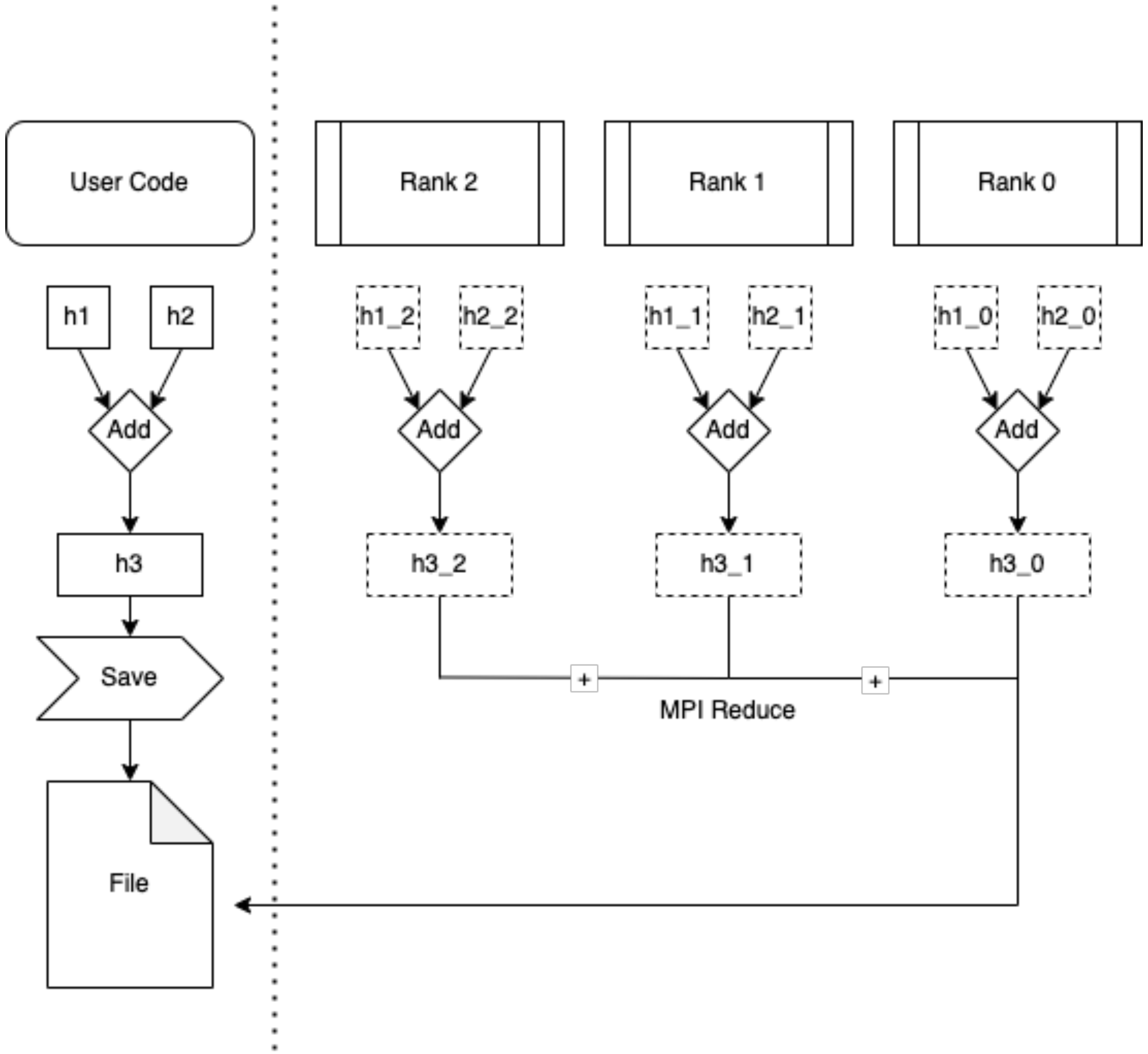
Llama — Llama does Lazy Mpi Aggregation

https://github.com/HEPonHPC/llama

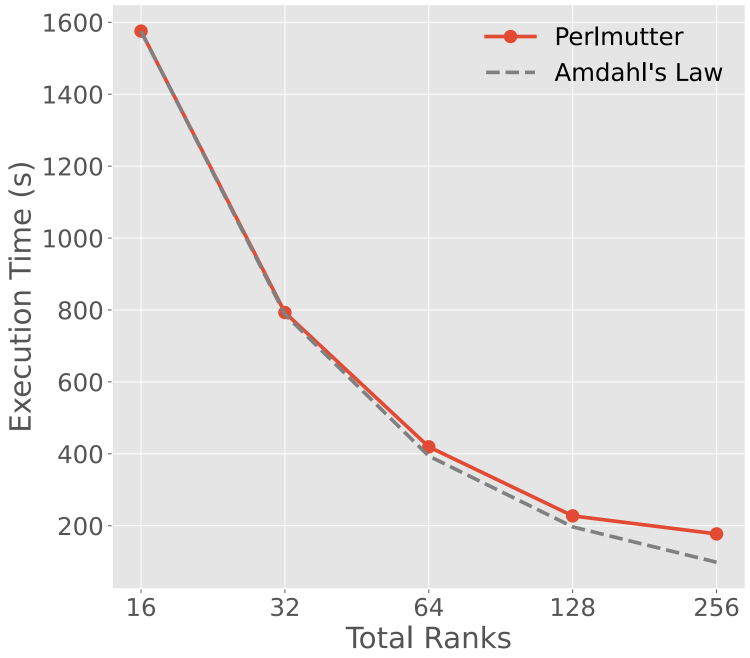
- Implicitly parallel histogram package
- Wraps boost_histogram for performance and uncertainty accumulation
- Lazy aggregation of common histogram operations
- Implements the Unified Histogram Interface for plotting



```
# Write to file
# MPI Reductions happen behind the scenes
# llama employs rank 0 to do all of the work while
# supporting an API that can be called by "idle" ranks,
# for pseudo-parallel IO with serial semantics!
with File(args.output_file, "w") as f:
    for name in loaders:
        group = f.create_group(name)
        selected_events[name].saveto(group, "selected_events")
```



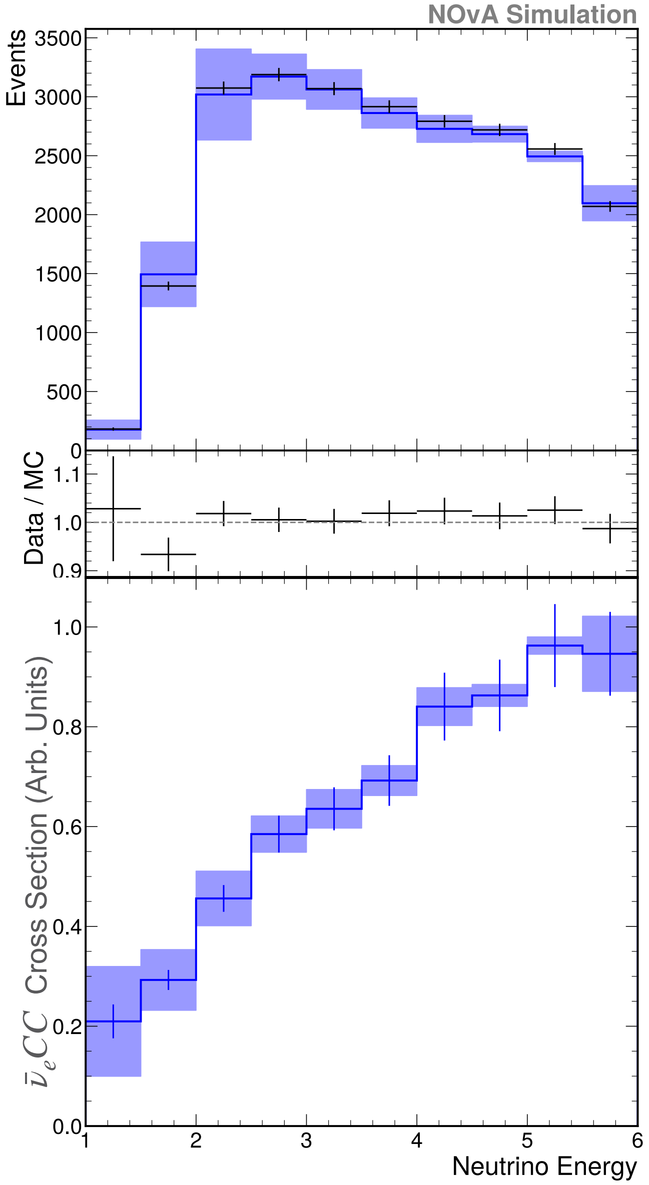
Case Study: A Realistic Analysis



Datasets	Beam Spills (million)	Size (GB)
Dataset 0	104	432
Dataset 1	25	74
Dataset 2	25	74
Dataset 3	25	76

*We demonstrate **near-perfect scalability** of our implicitly-parallel analysis workflow on a realistic sample size*

- NERSC's Perlmutter system
- $\bar{\nu}_e CC$ Inclusive cross-section measurement in the NOvA near detector
  - ~10,000 signal events
  - 12e20 Protons on Target (integrated luminosity) of data per Dataset
- Number of unique H5groups accessed = 16
- Number of unique H5datasets read = 54



Thank you

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