Columnar Analysis at ATLAS

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on behalf of the ATLAS computing activity

Introduction

- traditional analysis does one event at a time
  - read event data for one event
  - do all processing on that event
  - fill histograms and n-tuples
  - move on to the next event

- columnar analysis does an event loop per operation
  - read a few variables/columns for many/all events
  - do a single (or a couple) operation(s) on those variables
  - can fill histograms, define new variables, etc.
  - move on to the next operation

- will typically do multiple batches of events
  - usually too many events to load all at once
  - allows to split jobs up for a batch system
  - for best performance need to run batches of operations at once

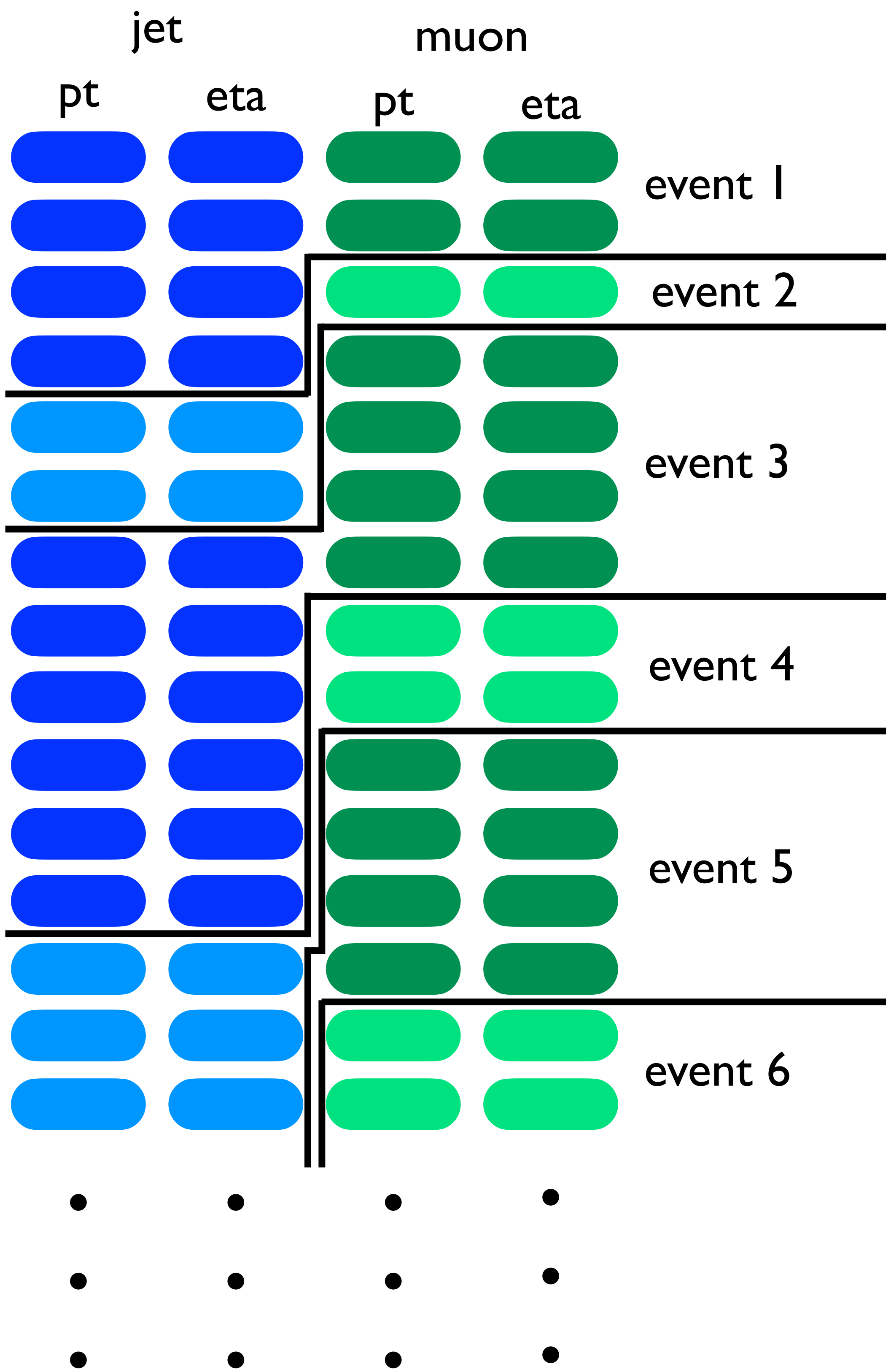
Data Layout

- for columnar analysis process events in batches
  - batches presumed large enough to ignore per-batch overhead
  - want calls to CP tools/algorithms to process entire batches

- data for each variable is a contiguous array in memory, e.g.
  - pt for object 1, followed by pt for object 2…
  - all pts for event 1, followed by all pts for event 2…
- objects are identified by index in array
  - with later events having higher offsets
- event boundaries/offsets are available as a separate array

- **need to know needed columns ahead of time**
  - mostly for loading data into memory
- assume I can pass all buffers by name from python to C++ tools
  - both for input and output variables

Data Layout 2



- each variable has its own column
- can have columns for multiple object types (jets, muons…)
- all (used) columns loaded into memory at the same time

- all variables for one object type share an offset map
- there is a separate offset map for each object type

- all object types have the same events in the same order

CAna Advantages

- hope for a number of advantages
- actual advantages may vary
- still in the early prototyping stage

- easier to teach
- less boilerplate code
- analysis code less spread out/coupled
- automatically disable calculations not used for current study
- can be used with notebooks
- better code performance
- more productive in daily use
- integrate better with industry and ML tools
- experience more relevant for students leaving the field

CAna at ATLAS

- can use CAna at ATLAS already
  - analysis generally done on user-generated n-tuples
  - n-tuples incorporate corrections, systematics, etc.
  - n-tuples normally readable without extra software
  - can do analysis in either event-wise or columnar analysis
- not what this talk is about

- main goal: run directly on centrally produced PHYSLITE files
  - incorporate object corrections (Jana Schaarschmidt's talk)
  - need "on-the-fly" calculation of systematics, scale factors, etc.
  - code needs to be callable from CAna frameworks

- requirement: performance competitive with n-tuple analysis
  - otherwise users may continue using n-tuples
  - also: don't have infinite resources for analysis
  - currently 1-2 orders of magnitude slower

CP Tools

- mentioned CP tools in earlier talk
  - all analysis recommendations/recipes provided via CP tools
  - very successful system for event-wise analysis
  - CP tools shared with production and online
- can not break CP tool infrastructure
  - want to maintain ability to do event-wise analysis
  - should also not duplicate recommendation code
  - can rewrite the tools and infrastructure though
  - at the very least will need to wrap existing tools
- will need a fair rework of current CP tools for CAna
  - need to get a lot faster to meet performance goals
  - want to be as fast or faster than reading results from disk
  - need across the board improvements for that
  - already found substantial improvement potential for some tools

Types of Tools

- most tools involve a simple lookup from histogram
  - used for scale factors and most systematics
  - conceptually all very similar
  - inherently fairly simple and fast

- most other tools involve fairly simple calculations
  - e.g. object selection tools
  - fairly easy to transcribe to most formalisms
  - can incorporate some into PHYSLITE production

- a few tools involve fairly complex calculations
  - e.g. full reconstruction of missing transverse energy
  - generally need custom C++ implementations
  - process full events instead of single objects
  - harder to integrate with columnar analysis

Proposed Solutions

- several proposed solutions for columnar tools
  - change existing tool to work directly in RDataFrame (RDataFrame can handle ATLAS EDM)
  - wrap existing tools for columnar analysis (make EDM objects wrap data columns)
  - use ServiceX to create n-tuples on-the-fly (straightforward, prototype exists)
  - extend CP tools with separate columnar mode (see later slides)
  - use correctionlib [initially developed at CMS] (allows abstract description of object corrections)
  - rewrite tools in numpy
  - some combination of the above

Design Criteria

- main criteria for choosing solutions:
  - support both columnar environments: uproot & RDataFrame
  - also support event-wise analysis and production jobs
  - support calculations that operate one-event-at-a-time
  - need C++ implementations for at least some calculations
  - match/exceed performance of reading from n-tuple
  - minimize rewriting of tools
- most solutions fail on one or more points
  - no solution is fulfilling all requirements
- can have different solutions for different classes of tools

- investigating two solutions right now:
  - correctionlib: well-established at CMS for single object tools
  - triple-use tools: custom solution to match above criteria

Triple-Use Tools

- current recommendations are provided via dual-use CP tools
  - can be used in both the analysis and production framework
  - uses conditional compilation to select one or the other
- plan to extend that to triple-use tools
  - add columnar analysis as a third usage mode
  - provide zero-overhead, vectorizable access to data columns

- design centers heavily around data handles
  - handles are member objects for each CP tool
  - all data access happens through handles
    - regular mode: handles access event data from whiteboard
    - columnar mode: data columns get loaded into handles
  - handles also declare inputs/outputs
- objects identified via ObjectId objects
  - regular mode: pointer to EDM objects
  - columnar mode: simple index into data column

Mock Code

- simplified mock-up of what code would look like
- C++ side inspired by current tool design
- buffers managed purely on the python side
- python buffers get connected to C++ handles

```
class MuonTool {
 ObjectHandle muons;
 ReadHandle pt;
 ReadHandle eta;
 WriteHandle output;

 void apply (MuonId muon) {
  output[muon] =
   calc (pt[muon], eta[muon]);
 }
 ...
};
```

```
import uproot as up
tool = MuonCPTool ()
for batch in up.iterate_batches(...):

 for var in tool.inputs() :
  tool.setBuffer (var, batch[var]...)
 for var in tool.outputs() :
  buffer = ...
  tool.setBuffer (var, buffer)
 tool.apply_batch()

 # user code here
```

Anticipated Rollout

- mostly talked about plans today
  - have a prototype for triple-use tools
- did benchmarking for correctionlib and triple-use tools, results:
  - correctionlib is not faster than existing CP tool
  - no overhead passing data from python into triple-use tools

- ultimate goal: run directly on PHYSLITE
  - requires full suite of tools available
  - requires all tools to be fast enough
  - allows elimination of user n-tuples

- stepping stone: run on user n-tuples
  - can be done one tool at a time
  - allows to gain experience with simple tools first
  - replace n-tuple variables with on-the-fly calculations
  - immediate benefit: smaller user n-tuples

Summary & Outlook

- columnar analysis still in early stages at ATLAS
  - can do CAna on current user n-tuples
  - hope to replace n-tuple variables with "on-the-fly" calculations

- ultimate goal: running directly on PHYSLITE files
  - would avoid the need for intermediate n-tuples
  - aim to be ready for Run 4
  - partial solutions would already be useful for n-tuple analysis

- main issue: how to do "on-the-fly" calculations
  - need columnar interface for CP tools
  - need substantial performance improvements
  - need some rework of algorithms and PHYSLITE content
  - prototyping and benchmarking multiple solutions
  - still in the early stages