LHCb's Allen Application and Framework

EIC Software Week 2024

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April 25th, 2024

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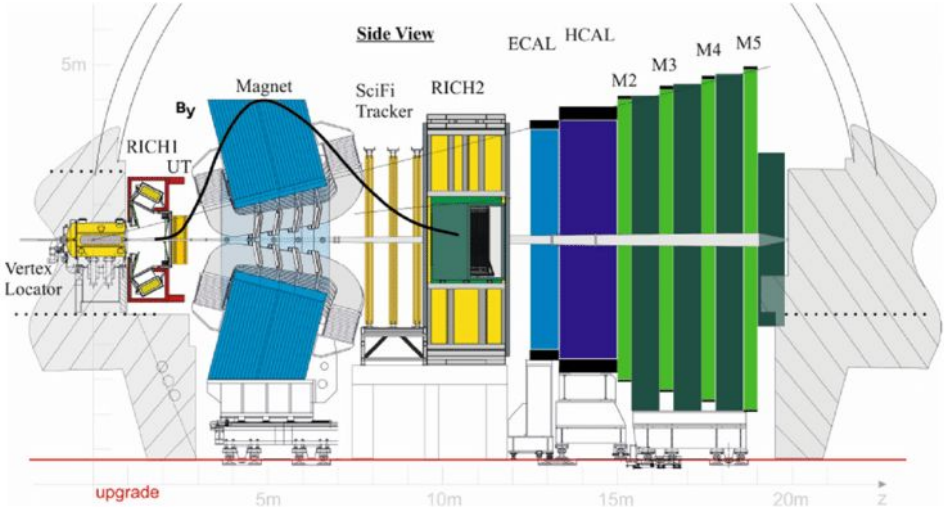
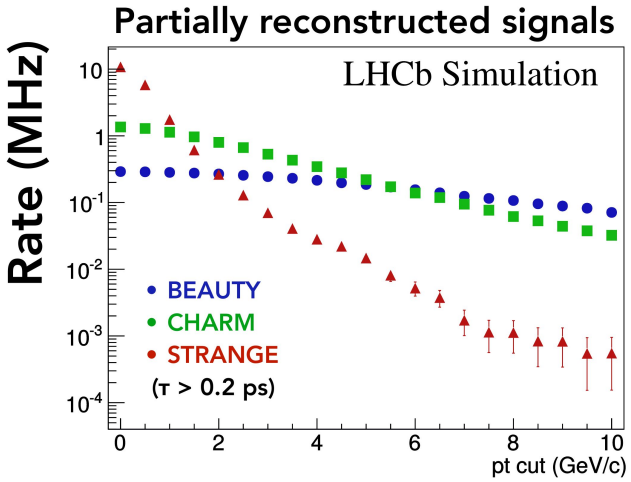
CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

LHCb Detector

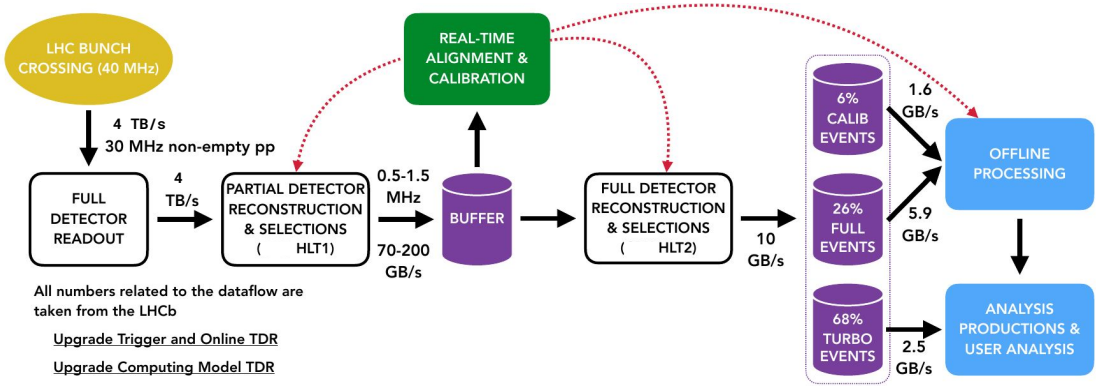


LHCb Upgrade Physics in a Single Slide



30 MHz (4 TB/s) of input contains a MHz of signal, while we can only store 10 GB/s long-term

LHCb Upgrade Dataflow



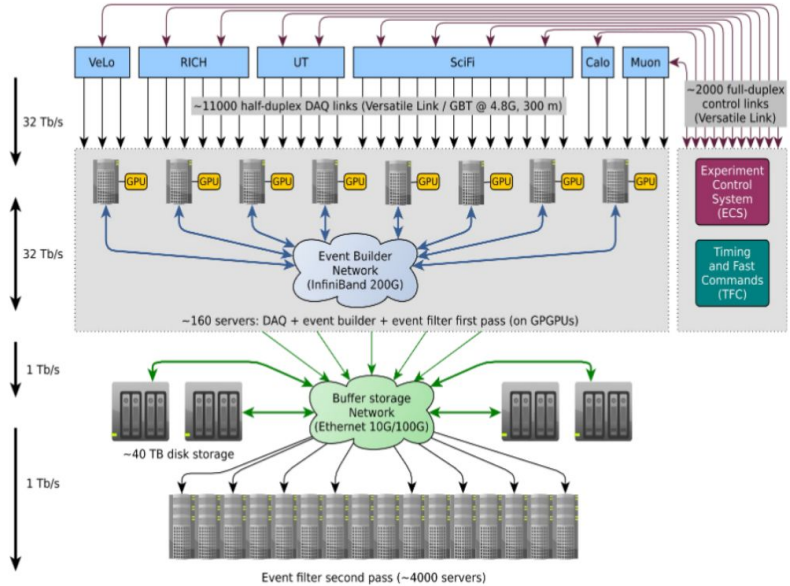
All numbers related to the dataflow are taken from the LHCb

Upgrade Trigger and Online TDR

Upgrade Computing Model TDR

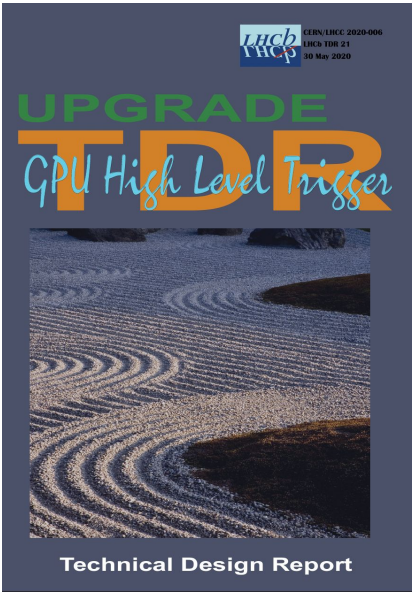
HLT1 challenge: reduce ~4 TB/s to 100 GB/s in real-time with high physics efficiency

LHCb Upgrade Trigger and DAQ



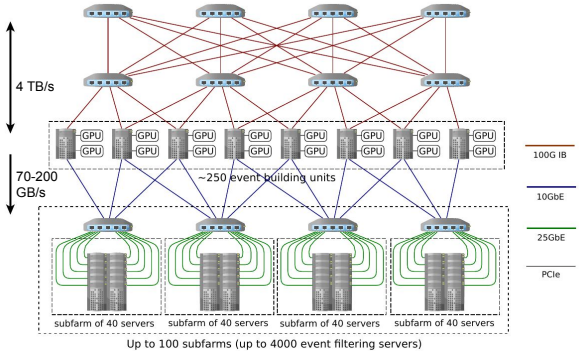
LHCb HLT1

- Inclusive trigger
- Reduce rate from 30 MHz to 1 MHz
- Need to reconstruct:
  - Velo tracks
  - Primary Vertices
  - “Long” tracks (Velo->UT->SciFi)
  - Muon ID
- Optional ingredients
  - ECal reconstruction
  - Electron ID
  - Photons
  - “T-Tracks” (SciFi)
  - “Downstream” tracks (UT-SciFi)
  - RICH PID
- Avoid global event cuts if possible

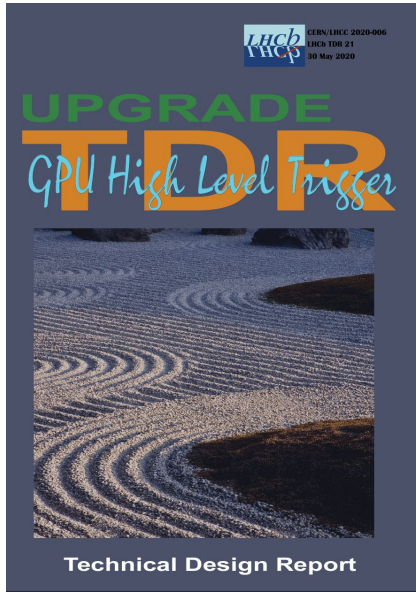


GPU HLT1 TDR

HLT1 on GPUs: Allen

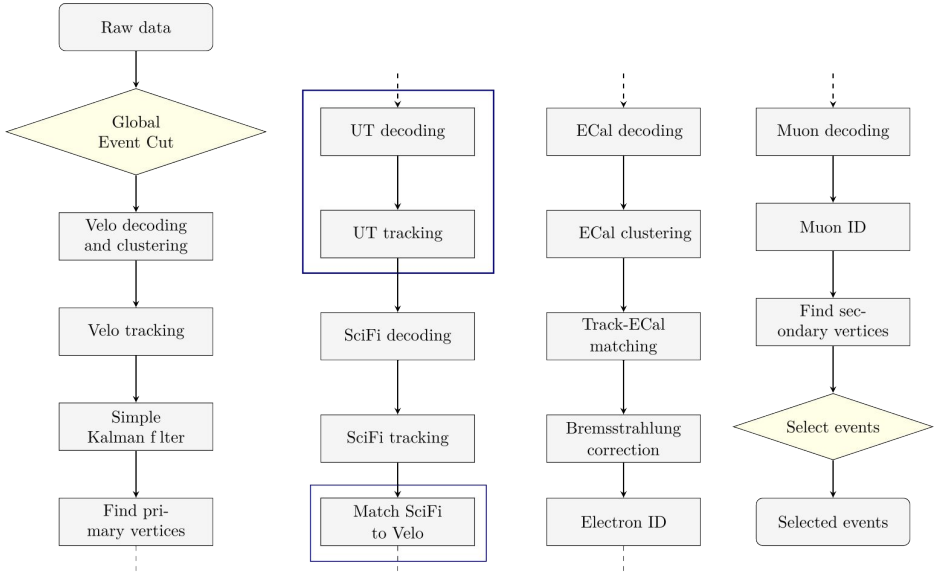


Allen implements HLT1 as a GPU application; currently 2 GPUs installed in each event builder server



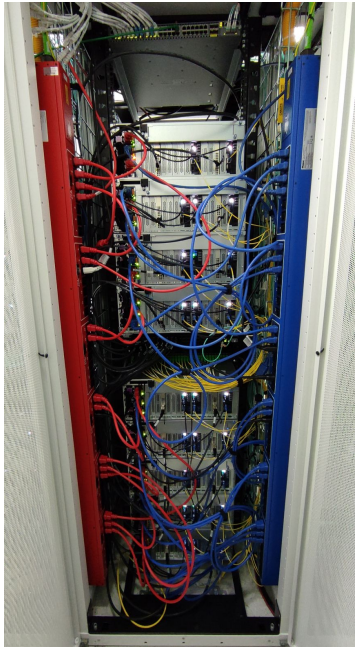
GPU HLT1 TDR

Allen Kernels



DAQ with GPUs

- 400 GPUs installed in Event Builder servers
- Input data copied to GPUs in EB format: ~1000 multi-fragment-packets in multi-event-packets of 30000 events
- 20-25 GB/s per server
- Event data memory layout “transposed” with respect to event-by-event
- Input data directly from shared memory
- Output in custom binary format to DAQ
- Experiment Control System steers HLT1
- Obtain geometry and conditions from LHCb software on-the-fly



1-Slide Framework

- gitlab: gitlab.cern.ch/lhcb/Allen
- C++17 (soon 20), CUDA (12.X), HIP (5.X)
- Built with CMake and runs on CPU and GPU (NVIDIA and AMD)
- Standalone builds and “stack” builds

- Single precision throughout
- Batches of ~1000 events (~100 kb/event)
- GPUs have their own memory; framework provides functions to copy data
- ~10 batches in parallel using CUDA/HIP streams (1 CPU thread per stream)
- No dynamic allocations
- Configurable (in Python) sequence of algorithms
- Asynchronous event loop
- All algorithms written from scratch for good performance on GPUs
- documentation: https://allen-doc.docs.cern.ch/

Philosophy

- Must not interfere with event building
- Do everything on the GPU: raw data in, decisions and candidates out
- Maximise (GPU) algorithm performance
- Start with barebones framework and write kernels in CUDA
- Implement performant reconstruction algorithms,
  i.e. significantly faster/$ than on CPU
- Batches of ~1000 events with control flow
- Event model **will** evolve so keep it simple
  - little to no dynamic memory allocation
  - SOA containing (small structs of) PODs
  - Count first, write later
- Minimise serialization of event data
- Opportunistic use of the CPU
  - Prefix sums
  - Monitoring
  - Low IPC algorithms that require little data

Portability

- No portability frameworks, just write CUDA
- `#ifdef` and a tiny middleware (1400 LoC) to allow running on CPU (x86, ppc64le, ARM) and AMD GPUs
- Port to Intel GPUs nearly ready
- Allow dispatching to architecture-specific functions for extra performance
- No performance penalty due to portability

Configuration

- Database of algorithms, inputs, outputs and properties built using code parsing with `libclang`
- Allow configuration of the sequence of algorithms/kernels
- Allow properties of algorithms to be set
- Multiple instances of an algorithm with separate inputs and outputs
- Configuration in Python using LHCb's PyConf package

Memory Management

- Memory allocations on the GPU are very slow
- Allocate memory for event data up front
- Chunk of memory allocated per stream
  ~1 MB per event

- Each algorithm proceeds in two steps:
  - Request memory for outputs
  - Run kernel
- Strong preference for “Count First, Write Later”
- Sequence uses data dependencies to track lifetime
- Device Memory is released as soon as possible
- Failure to reserve memory aborts the batch ->
  Split in two and try again
- Host memory done analogously, but not released until after data is output from the application

Event Loop

- 150 kHz of events per server
- 20-25 GB/s per server
- Low overhead
- Batches of ~1000 events

- Based on ZeroMQ
- Initial use case was a benchmark for performance measurement
- Asynchronous event processing added later
- Support four data flow models:
  - Benchmark with single batch of events
  - Process all input in a set of files (simulation, development)
  - Externally controlled, i.e. wait for data and process whatever arrives and stop/exit when told
  - Benchmark with multiple (preloaded) batches
- All of this is currently mixed together in the same code
- It works, but is not very pretty and needs refactoring

Integration with LHCb stack

- Need geometry and conditions data
- LHCb conditions change slowly (a 10 minute runs is considered short)
- All required geometry and conditions data are converted to blobs that can be memcpy'd to the device and are fast to use
- Use parameterisations when possible,
  e.g. currently no magnetic field map on the device
- Setup a Gaudi/LHCb application with a fake event loop "on the side"
- When data with a new run number arrives:
  - Finish processing data of previous run
  - Trigger a single event in the fake event loop to update blobs
  - Copy new blobs to the device
  - Restart processing
- A derived Gaudi::Application handles interaction with control system
- Input and output to the DAQ are Gaudi Services with an extra ABC

Development

- Standalone build has helped developers
  - Easy to build anywhere
  - Fast turnover
- Getting into CUDA is not harder than C++
  - Parallel programming requires a different mindset
  - Good docs and examples are very important
  - Making it performant is hard
- A good and fast CI pipeline is a huge asset
  - Allen CI runs CPU and GPU builds and a representative set of tests in about 10 minutes on every push to every MR
  - More extensive pipeline takes another 20 minutes
  - Fast feedback for developers
- Very agile development in the first years
  - Helped test new ideas
  - Great motivation for contributors

People

- Project grew quite fast from the start
- Good core team with complementary skills
  - GPU performance and parallel programming
  - Knowledge of the experiment and existing stack
  - Project management
  - Modern C++/CUDA
  - Mixed CS/HEP background
- Political support
- Support from DAQ/Online

- Most contracts are short, so bringing new people and skills on board has to happen all the time
- Knowledge transfer is hard
- Skilled people are few.
  - They are highly motivated, but career prospects matter
  - Allen has already contributed to at least 4 people getting a big grant or a permanent position.

Commissioning 1/2

- Running in production since 2022
- Overall good performance, Allen has rarely been a bottleneck
- Many moving targets
  - DetDesc -> DD4hep
  - Quickly changing detector conditions
  - Different sets of detectors participating in data taking
  - Evolving sub-detector geometries and data formats
- Additional features requested and implemented with very fast turnover
  - Output of short trains of bunch crossings
- Minimal monitoring was a serious issue
  - Slowed-down iteration between detector experts and reconstruction experts

Commissioning 2/2

- Performance has been good, 2nd GPU available since 2023
- Running at target pile-up
- Currently about 100 kHz of events per GPU
  - “matching” tracking sequence
  - ECal reconstruction
  - Fast MLPs for ghost rejection
  - electron ID, improved muon ID
  - nearly 90 selections
  - fixed-target experiment in parallel (SMOG)
  - luminosity measurement
- Monitoring improved for 2024
  - easy histograms on the device
  - double buffering
- Configuration provenance implemented for 2023
  - each configuration has unique identifier
  - stored in each event

Framework Issues

- Too little protection against memory errors
  - Pool allocations make it worse
  - Move to span instead of raw pointers
  - Have tools to assist with debugging
- Two memory layouts of raw data supported
- Event loop code is very messy
- Complex application, many threads
- Too tight coupling between input handling, output handling, sequence and overarching data-flow mode
- No Service equivalent, e.g. detector data store is a `struct`
- (Physics) Monitoring came quite late
  - Very important during commissioning
  - Device-side monitoring more important than we thought
- Glue-like interface to LHCb stack is not very elegant
- Need more tests

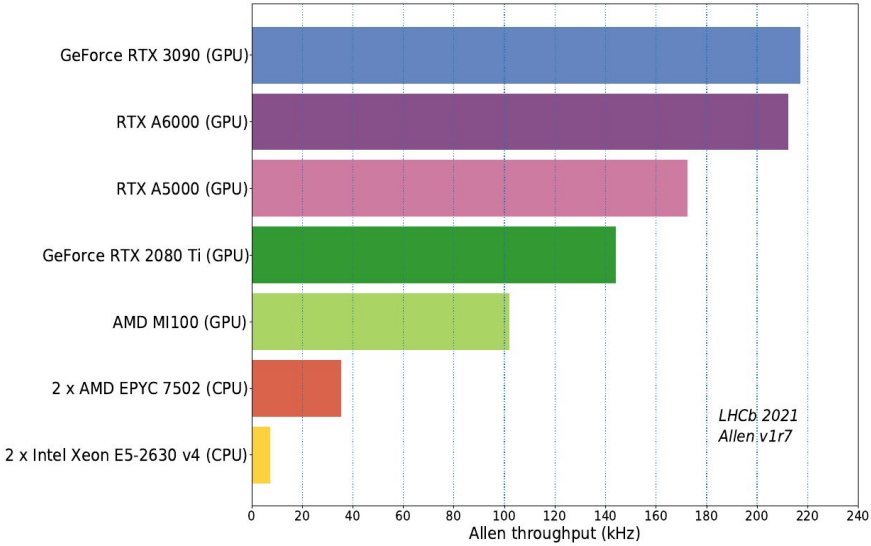
Future (IOHO)

- LHCb Upgrade 2 baseline is all of HLT1 and all HLT2 reconstruction on GPUs; particle combinatorics better done on CPUs
- Amount of preprocessing and reconstruction on FPGAs to be decided
- Gaudi has already solved many of the issues that Allen has
- Maintaining two frameworks makes little sense
- Impedance mismatch is actually rather small

- Put batched input data on the event data whiteboard
- `DeviceAlgorithm` that implements the two-step approach of Allen
- `DeviceDataHandles` to interact with the memory pool manager and handle copying of data between host and device
- `DeviceConditionAccessor` to manage device geometry data using derived conditions
- `DeviceBatchContext` to propagate the GPU stream
- No need for an additional portability framework
- Use LHCb's CPU scheduler to schedule batches
- Static balancing of GPU/CPU load, i.e. as different sequences/applications

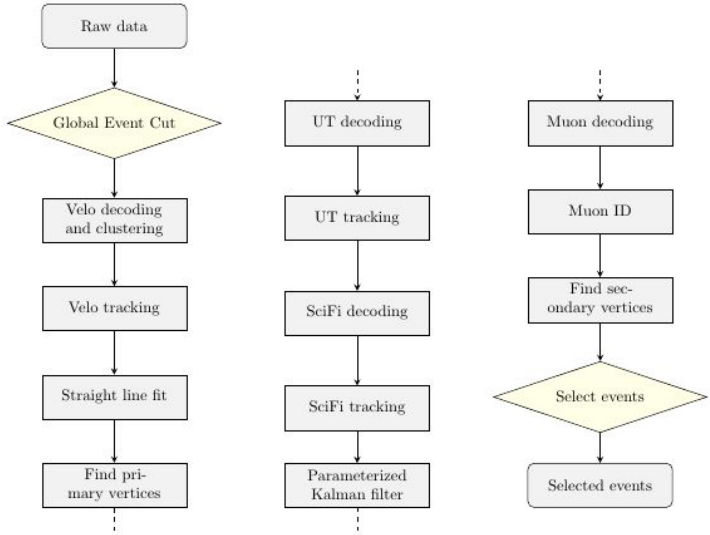
BACKUP

Throughput



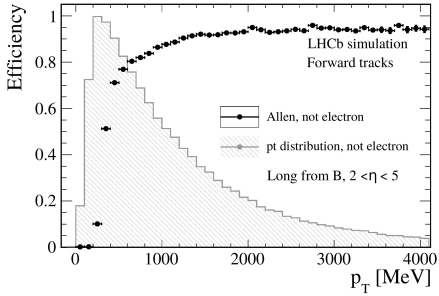
LHCb-FIGURE-2020-014

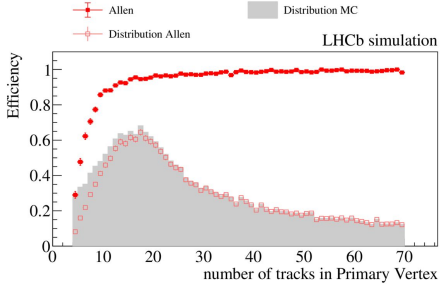
Reconstruction Sequence

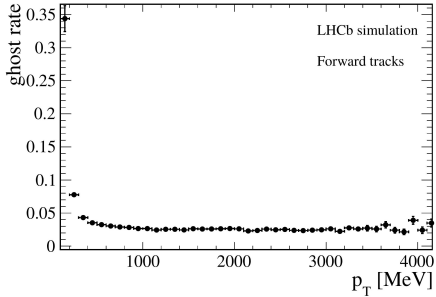


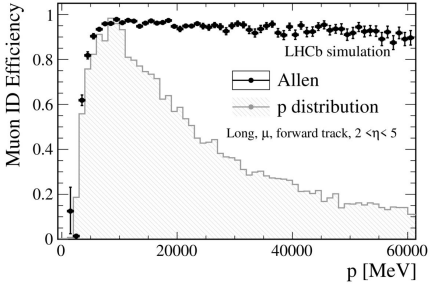
GPU HLT1 TDR

Reconstruction Performance









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