CMS Patatrack project

A. Bocci[1], V. Innocente[1], **M. Kortelainen**[2], F. Pantaleo[1], M. Rovere[1]

CERN[1], FNAL[2]

2019 Joint HSF/OSG/WLCG Workshop

March 19, 2019

The Patatrack group

- Patatrack was formed by people with common interest and a varied pool of expertise
  - Software optimisation
  - Heterogeneous architectures
  - Track reconstruction
  - High Level Trigger
- Work started in 2016 with the participation to the EuroHack 2016 event, sponsored by NVIDIA
- And continued through 2017 to 2019 with self-organized Hackathons at CERN, collaboration with Openlab, training and working with students, and so on

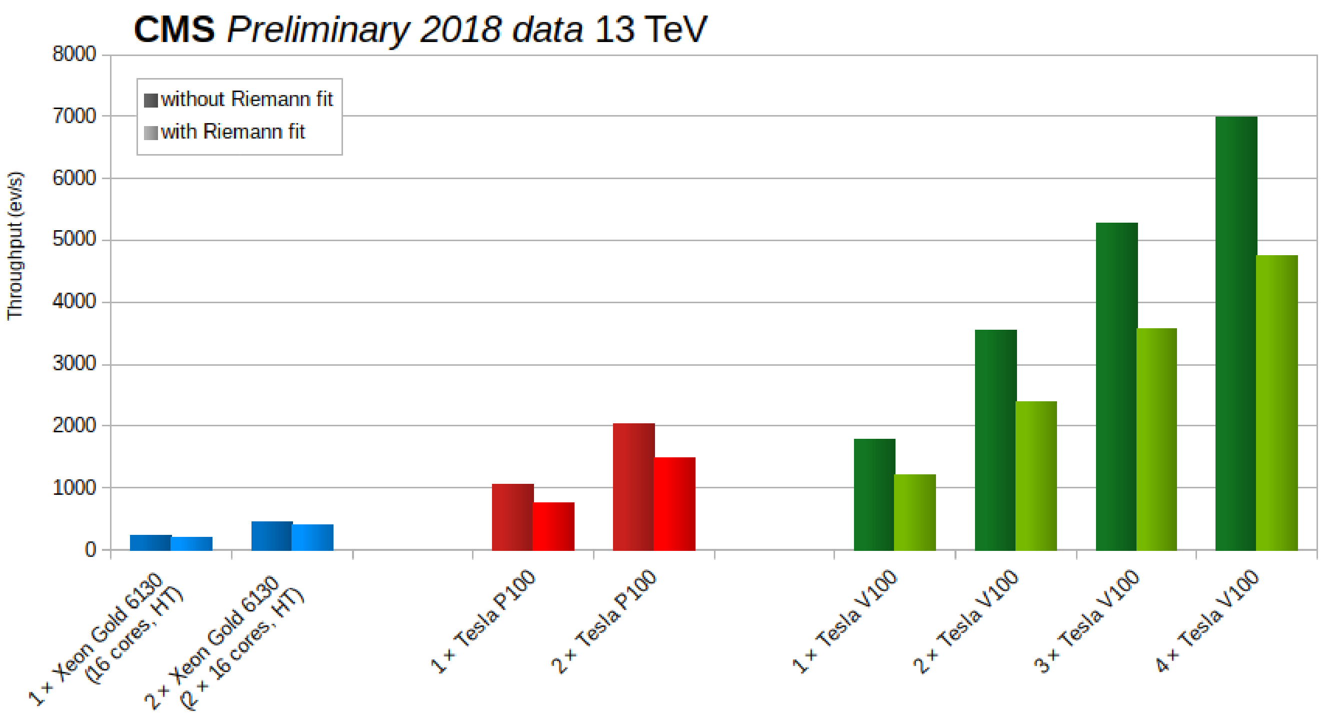
The Patatrack demonstrator

- Goal is demonstrate that part of the HLT reconstruction can be efficienty offloaded
  - Running on a single machine equipped with GPUs
- Focus on a $\sim 10\,\%$ slice of HLT time consumption
  - Pixel local reconstruction
  - Pixel-only track reconstruction
  - Vertex reconstruction
- Other groups have started to work on
  - Calorimeters local reconstruction
  - Full track reconstruction
- For more details see closeby talks in
  - ACAT 2019, 10–15 March, Saas-Fee (Switzerland)
  - CDT/WIT 2019, 2–5 April, Valencia (Spain)

The Patatrack demonstrator workflow

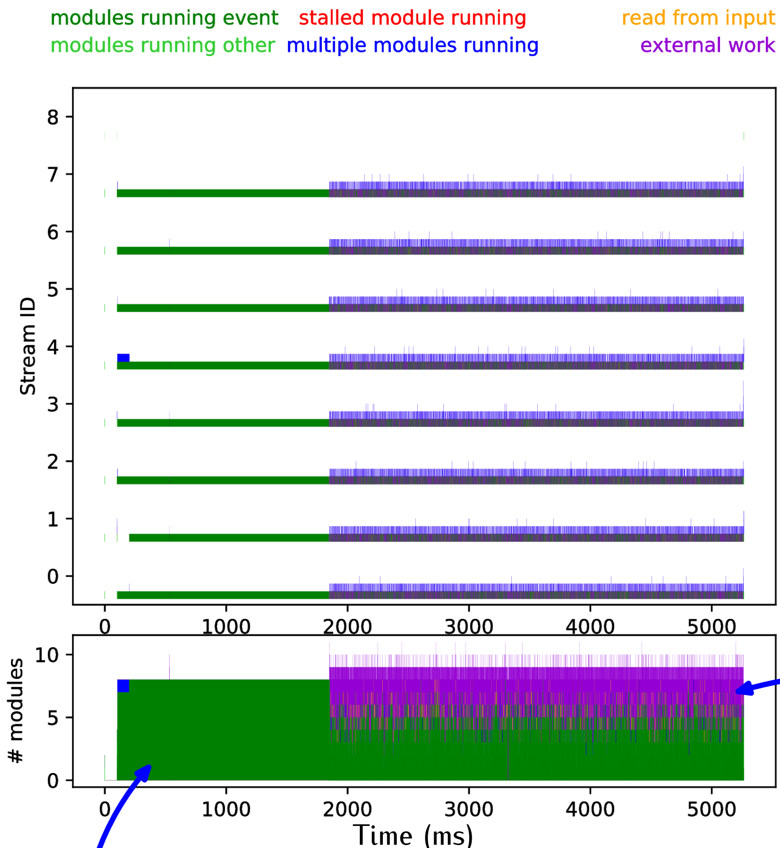
- Copy the pixel raw data to the GPU
- Pixel local reconstruction
  - Decode the raw data
  - Clustering
  - Calibrations
- Pixel-only tracking
  - Form hit doublets
  - Form hit quadruplets with Cellular automaton algorithm
- Optionally
  - Full track fit (Riemann, Broken-line fits)
- Some GPU algorithms are same, others different wrt. (legacy) CPU
  - Implementations are currently different
  - Bitwise or statistically identical physics performance
- Organized as a chain of 3 GPU producer modules
  - Pass GPU data from one producer to the next
  - Use the CMSSW's "external worker" mechanism

The Patatrack demonstrator (2018)



- 2018 data: average pileup 50
- HLT-like configuration, optimised for maximal throughput
- One Tesla V100 is 5×–7× faster than one Xeon Gold 6130

CPU utilization

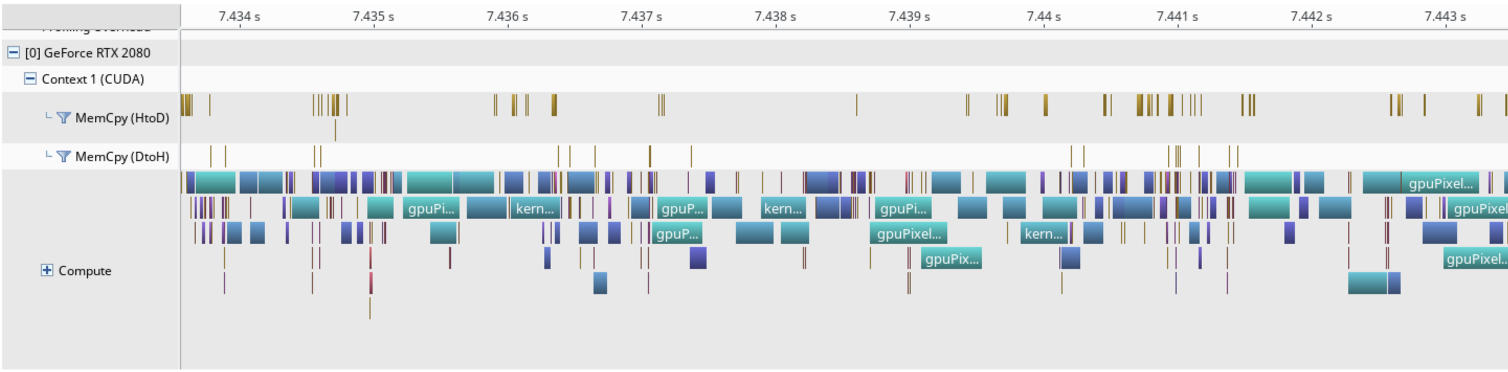


Number of running modules

Number of scheduled external workers

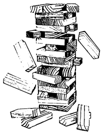
- Caveat: different machine (i7-4771, GeForce RTX 2080)
  - 8 threads and 8 concurrent events
- After the initialization
  - CPU utilization is roughly 50 %
  - There are roughly 4–5 external workers scheduled in parallel
- NB: this workflow is "artificially" tuned to minimize the CPU utilization

GPU utilization



- Screenshot of NVIDIA Visual Profiler for a random 10 ms period
- Kernels and data transfers being run in parallel

Lessons learned: design principles



- For optimal performance, follow a Data Oriented Design
  - Memory operations are costly, computations are almost free
  - Design the data structure for maximal efficiency (SOA vs ... vs. AOS)
  - Implement the algorithms around the data structure
  - Avoid object-oriented patterns in critical code e.g. data formats
    - ⋆ inheritance, virtual functions, etc
- Most (all?) GPU operations (memory copies, running “kernels”, etc) should be asynchronous
  - The “kernels” run on the GPU while the CPU is doing other work
  - The GPU can transfer data to and from the host while both the CPU and the GPU are working
- Memory transfer, and especially data format conversions, between CPU and GPUs are costly
  - In some cases, almost as much as running the original algorithm itself

Lessons learned: tools and architectures

- CUDA and CMSSW support different sets of compilers and C++ features
  - CUDA 10.1 supports
    - C++ 14
    - GCC 8, CLANG 7
      - CUDA 10.0 supported GCC 7, CLANG 6
  - CMSSW 10.6.X supports
    - C++ 17
    - GCC 7 and GCC 8, CLANG 7
    - CUDA 10.1 in latest pre-release (was 10.0 before)
- Unfortunately, we need to keep the host and device code somewhat separate
  - Host code can use C++ 17 features
  - Device code (and common code) is limited to C++14 features
  - You do not want to `#include` framework (or ROOT) headers in device code!

Lessons learned: what about CMSSW?

- Redesign dedicated data formats for use on GPUs
  - In fact, they might be more efficient also on traditional CPUs
- Design a chain of algorithms (framework modules) that work on the GPU
  - Without copying data back and forth
- Take advantage of the “external worker” approach in CMSSW
  - Launch the work on the GPU, schedule other work in parallel on the CPU
- Split GPU modules in two parts
  - The part that deals with the framework and the rest of the CMSSW
  - The part that deals with the GPU data structures and kernels
- Split the GPU-related work in two (or more) modules, e.g.
  - Copy data from CPU to GPU, launch kernels
  - Copy data from GPU to CPU
    - ⋆ ran only if another modules consumes the CPU SOA
  - Transform CPU SOA to CPU legacy data format
    - ⋆ ran only if another module consumes

Model for CUDA Producers

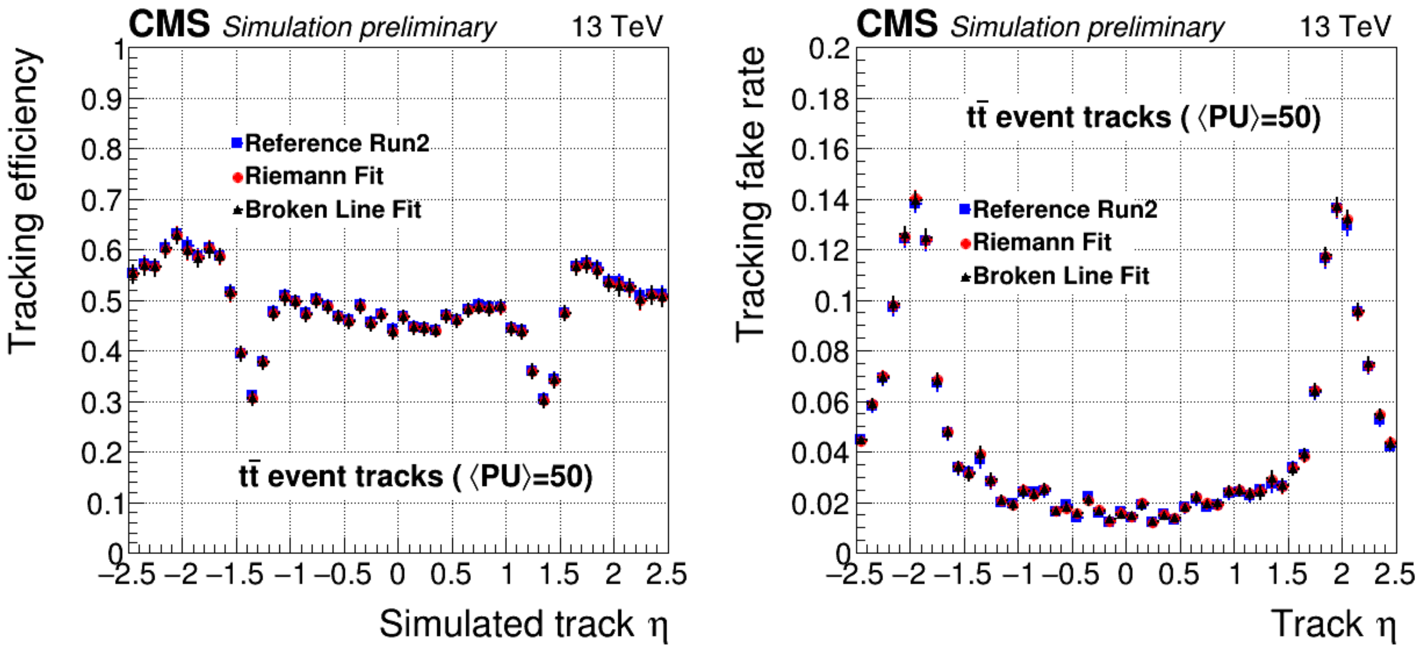
- Aim to avoid blocking synchronization as much as possible
- A helper object gives the CUDA device and stream to use for the algorithms
- Memory management
  - Raw CUDA allocations and frees should be avoided within the event loop
  - Preallocating memory buffers as module member data leads to unnecessarily high GPU memory use
  - We went for a caching allocator for device and pinned-host memory that amortizes the cost of raw CUDA allocations
    - ⋆ Currently based on the caching allocator of `cub`
- GPU event products are like regular EDM products, but enclosed in a wrapper that holds also the CUDA device and the CUDA stream
  - Allows the consumer to set the device, and queue more work to the same CUDA stream
  - Allows also the TBB-flowgraph `streaming_node` style operation
    - ⋆ Module in the middle of the chain may only queue more asynchronous work
    - ⋆ Later module in the chain synchronizes (with "external worker")

Conclusions

- We have demonstrated that GPUs are an efficient alternative to traditional CPUs
  - For complex tasks like track reconstruction
- Next steps
  - Integrate the developments in the official CMSSW
  - Continue evolving the framework to make it easier to leverage GPUs
  - Focus on code portability and avoiding code duplication as much as possible
  - Study how more algorithms and data structures could benefit from GPUs
  - Study local vs. remote offloading to GPUs

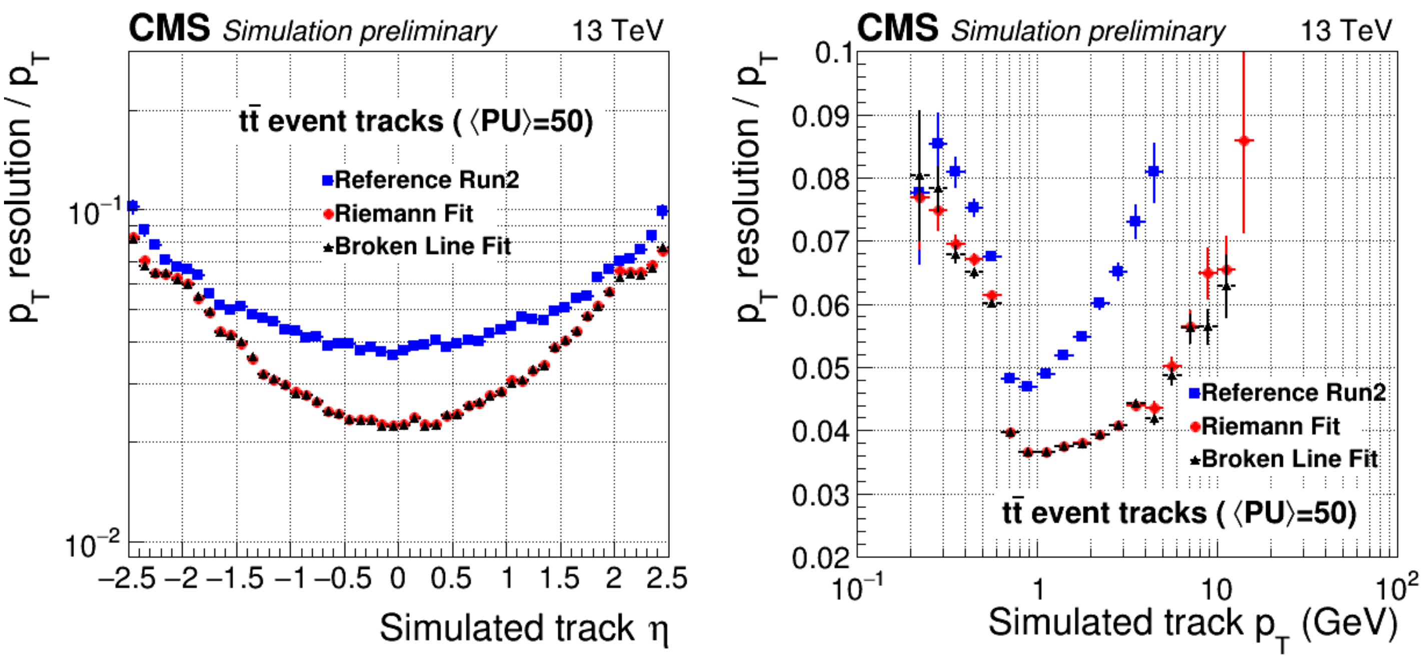
BACKUP MATERIAL

The Patatrack demonstrator (2018)



- Similar efficiency and fake rate as with legacy CPU algorithm
- More information: CMS Detector Performance Note DP-2018/059

The Patatrack demonstrator (2018)



- Proper fits improve resolution significantly
- More information: CMS Detector Performance Note DP-2018/059