Vertex reconstruction for tracking in the Inner Tracking System detector of the ALICE experiment at LHC, using GPGPU

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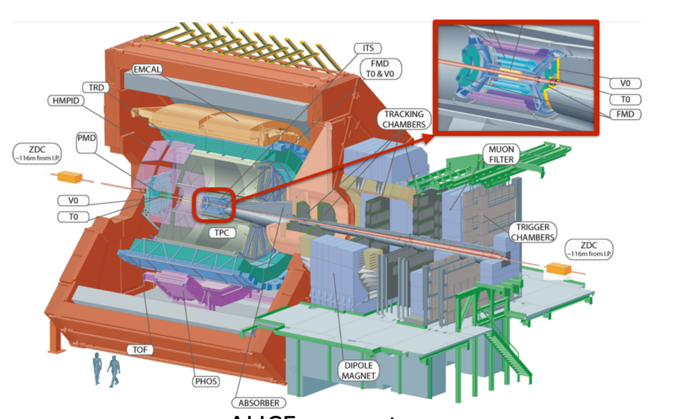
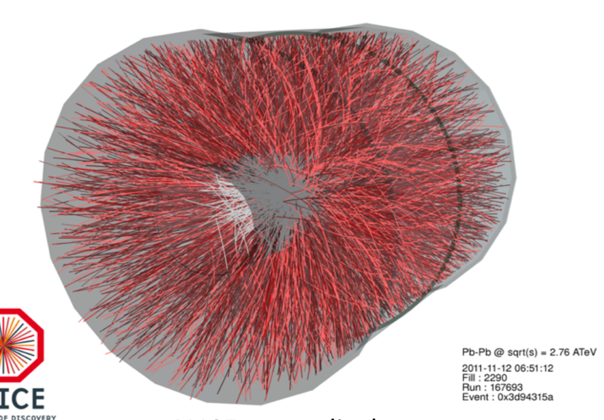
Research context and motivation

- The Large Hadron Collider (LHC) is the largest (27km long) and most powerful proton and heavy nuclei collider in the world. It is located at CERN, the European Organization for Nuclear Research, near Geneva (CH)
- It collides ions at $\sqrt{s}$=13 TeV in pp collisions and $\sqrt{s}$=5.02 TeV per nucleon pair in Pb-Pb collisions (1 eV = 1,602176565 x 10^{-19}J)
- Four major experiments: ALICE, ATLAS, CMS, LHCb along the accelerator ring
- A Large Ion Collider Experiment (ALICE) aims to investigate the state of matter at extreme densities and energies, in particular to study the formation of the Quark Gluon Plasma (QGP)
- This work is carried out within the ALICE Inner Tracking System (ITS) group in Torino, the innermost detector in the ALICE apparatus



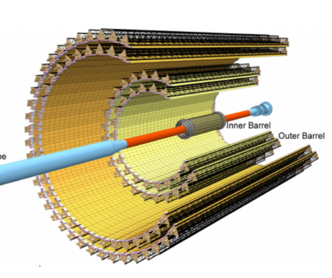
ALICE apparatus

- Physical event: Two counter-rotating ion beams collide detecting area covered by the ITS
- The available energy is "converted" in matter and vice versa: many particles are generated and tracked by many detectors (17 in ALICE)
- Particle reconstruction and identification is a fundamental component in data reconstruction phase

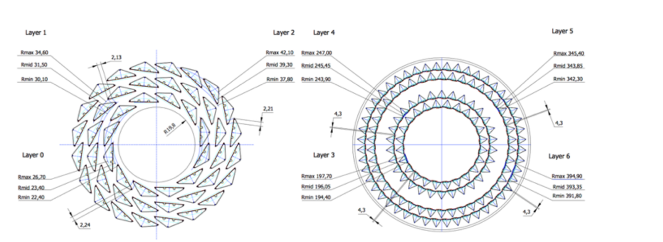


ALICE event display

- In 2018 the LHC will perform a global upgrade on the luminosity leverage (number of ions per bunch-crossing), entering the so-called: Run 3
- To cope with new enhancements and to benefit in term of statistic acquisition (data collected), the ALICE experiment will completely replace the ITS with a brand new one with new hardware and software with improved performances in terms of pointing resolution, tracking efficiency and readout frequency
- Starting from Run3 we expect Pb-Pb collisions at a rate of 50kHz, reaching up to 1.1TB/s of data, an unsustainable value for current data stores
- Need for reducing the amount of data, skimming relevant/healthy to be stored on tape
- Data has to be processed during acquisition (Online)
- Is necessary to track the particle trajectories generated by the collisions



Feature	ITS	ITS Upgrade
# Layers	6	7
Acceptance	$\lvert\eta\rvert<0.9$	$\lvert\eta\rvert<1.5$
Material budget/layer	1.1% X_0	0.3-1% X_0
Spatial resolution	12 x 100 μm^2 35 x 20 μm^2 20 x 830 μm^2	5 x 5 μm^2
Max Pb-Pb readout rate	1 kHz	50 kHz
Technology	Hybrid Silicon Pixels, Silicon drift detectors, Silicon strip	Monolithic Active Pixel Sensors (MAPS)



ITS new design and specifications

- Most tracking algorithms rely on the previous reconstruction of the interaction point (vertex)
- During the Run3 in ALICE will start to track particles even from the ITS data (results later refined with the rest of the tracking detectors)

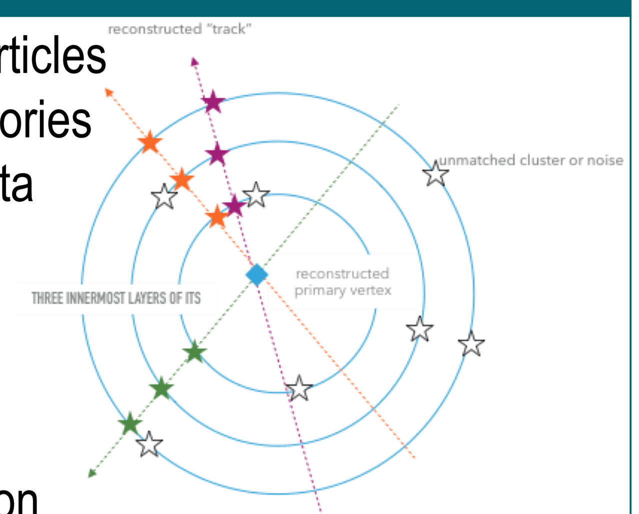
Addressed research questions/problems

- Two main steps in event reconstruction in ITS. "Vertexing": find the interaction point. "Tracking": reconstruct path of particles in space
- The O^2 (Online-Offline) project aims to merge in a single framework the Data AcQuisition (DAQ), the High Level Trigger (HLT) and the Offline data reconstruction for Run 3
- This work integrates within the O^2 software stack, implementing a vertexing algorithm to:
  - process a continuous stream of data sliced in "ReadOut Frames (ROF)"
  - reconstruct more than one vertex in the same acquisition frame *(pile up)*
  - effectively cope with large combinatorial and computing-intensive loads
  - achieve data reduction through effective decision-making based on reconstructed data
- Need to create a performant, efficient and precise software relying on the best available technologies both in terms of hardware architectures and software, exploiting GPGPU approach which offers many advantages in terms of speed and energy consumption

Submitted and published works

- M. Aldinucci et al. *"Managing a heterogeneous scientific computing cluster with cloud-like tools: ideas and experience"*, EPJ Web Conf. , vol 214 pp. 1-9.
- ALICE Collaboration (S.Acharya et al.) *"Linear and non-linear flow mode in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV"*, Phys. Lett. B, vol. 773 pp. 68-80.
- ALICE Collaboration (S.Acharya et al.) (2017, May) *"Production of π^0 and η mesons up to high transverse momentum in pp collisions at 2.76 TeV"* Eur. Phys. J. C, vol. 77(339)
- ALICE Collaboration (S.Acharya et al.) *"Production of muons from heavy-flavour hadron decays in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV."* Phys. Lett. B, vol. 770 pp. 459-472
- ALICE Collaboration (S.Acharya et al.) (2017, August) *"Measurement of D-meson production at mid-rapidity in pp collisions at $\sqrt{s}$=7 TeV"* Eur. Phys. J. C, vol. 77(550)
- ALICE Collaboration (S.Acharya et al.) (2017, June) *"Energy dependence of forward-rapidity J/ψ and ψ(2S) production in pp collisions at the LHC."* Eur. Phys. J. C, vol. 77(392)

Description of the Scenario



Vertex reconstruction schema: transverse plane section

- Seven cylindrical concentric pixel detectors for charged particles originated in ion collisions. Need to reconstruct their trajectories
- Frontend electronics preprocesses signals and streams data to digitization and then to the tracking workflow
- Track reconstruction combines *vertexing* and *tracking*
- Vertexing uses data from three innermost layers (Fig.), the actual tracking requires whole dataset from detector
- Vertex finding is a primary phase, it estimates vertex position using selections on physical observables and efficiencies
- Eventually it is used as seed for the tracking Cellular Automata (CA) in track fitting
- The entire collision must be reconstructed in less than one second
- Goal of my research: use natively parallel accelerators (Co-processors, GPUs, …) to offload computing-intensive algorithms dominated by combinatorial matches
- CPU version is developed as well for portability (not every machine where the code will run will have a GPU)

Novel contributions (w.r.t. last year)

- CPU version is now fully operational, integrated in the reconstruction workflow, well-performing in terms of reconstruction efficiency and time performances
- Two different collision systems tested: *pp* and *PbPb*, with parameters and selection
- Implemented parallel CPU version of DBSCAN for cluster identification meant to be used in the reconstruction of multiple vertices. Not fast enough still useful in other contexts: anomaly detection in quality control for pixels construction
- GPU version has been completely revamped and organically re-integrated in the O^2, also using new software interface available in the hosting code-base
- The algorithm has been improved in terms of performances and resource management, also considering form what I learned form CPU
- Results:
  GPU combinatorics-dominated parts are faster on GPU, average results for PbPb *minimum bias* events:
  - **Tracklet finder**: ~2.3ms on CPU, ~1.28ms on GPU, ratio: 1.87. Std deviation: 11ms
  - **Tracklet selection**: ~0.2ms on CPU, ~0.04ms on GPU, ratio: 5. Std deviation: 1.3ms
  - **Results are consistent** across {C,G}Pus versions

[1]Unsupervised learning algorithm capable to find multiple accumulation points in a N-dimensional space under some definition of distance

Adopted methodologies

- CPU version is written in C++17, integrated natively with the final Software framework
- Two implementations of the vertexing algorithm on GPU using HIP and CUDA™
  - Combinatorial is faced by using high thread density to split work
  - Each reconstruction phase will eventually be represented by routine on GPU (kernel)
  - Need to cope with diverse hardware availability leads to different implementations
- Organize data in ordered structures accessed via index tables → easy to partition data and smart access them also in a parallel fashion
- Continuous integration, unit testing, collaborative development, debug, benchmarking and versioning tools, pair programming
- Development workstation equipped with both Nvidia Titan XP and AMD WX 9100, Linux environment

Future work

- Multiple vertex finding based on clusterization algorithm on GPU (atm still using CPU for last part) is in development already
- Finalise the HIP translation as well
- Investigate more exotic reconstruction scenario in colliding systems with very low multiplicity of generated tracklets or mixed events, possibly adding some further refining step with different selections
- Exhaustive benchmarking, profiling and characterization of the implementations (prove consistency between divers implementations)

List of attended classes

- 01MNFIU – Parallel and distribute computing (07/07/2017, 5 CFU)
- 01RQXRV – Pattern Recognition and Neural Networks (05/05/2017, 8 CFU)
- 01QORRV – Writing Scientific Papers in English (23/03/2017, 3 CFU)
- 01SHCRV – Unsupervised Neural Networks (09/04/2018, 6 CFU)
- 9th INFN ESC17 School on "Architectures, tools and methodologies for developing efficient large scale scientific computing applications"
- 41st CERN School of Computing (CSC 2018) at Tel Aviv from 1 to 14 October 2018

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PhD program in
Electrical, Electronics and Communications Engineering