Connecting The Dots / Intelligent Trackers 2019

Tuesday 2 April 2019 - Friday 5 April 2019

Jardí Botànic de València

Book of Abstracts

Contents

6

GPGPU-implemented Tracking in a COMET Phase-I Drift Chamber

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Track finding with GPGPU-implemented fourth order Runge-Kutta (RK) method is investigated to track electrons from muon decay in the COMET Phase-I drift chamber. The COMET Phase-I experiment is aiming for discovering the neutrinoless, coherent transition of a muon to an electron in the field of an aluminium nucleus, $\mu^- N \to e^- N$, with a single event sensitivity of 3×10^{-15} . In the COMET drift chamber, about 30-40 \% of signal events are composed of multiple turns where the correct hit assignments to each turn partition are significant in the track finding. Scanning all possible track seeds can resolve the hit-to-track assignment problem with a high robustness about the noise hits, but requires a huge computational cost; initial track seeds $(\theta, z, p_x, p_y, p_z)$ have broad uncertainties, so many initial seeds should be tried and compared. In this presentation, this problem of massive computations are mitigated with 1) the parallel computing of RK track propagation, which assigns each track to each GPU block unit, 2) a better initial guess on the track seeds using the Hough transform and the geometrical property of the cylindrical drift chamber. The computation speed enhancement compared to CPU-only calculation will also be provided.

7

Triplet Track Trigger for Future High Rate Experiments

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For the post High Luminosity LHC era, several accelerator projects are under study with an aim to increase the discovery potential for new physics at both the high energy and intensity frontier. The hadron-hadron based Future Circular Collider(FCC-hh) is one such project with the goal to collide proton-proton beams at $\sqrt{s} \sim 100$TeV with a bunch crossing rate of 25ns. Some of the major challenges that the FCC-experiments have to tackle are the very large number of pileup events (~ 1000) and the data processing, namely the reduction of the huge data rate of 1 - 2PBytes/s whilst keeping the signal efficiencies high. The required processing power will be extremely challenging even in 20 years time from now. Therefore, we need smart triggering concepts that not only allow for a significant reduction of pileup and rate but also provide high signal acceptance and purity. One such concept is the triplet track trigger based on monolithic pixel sensors.
In this talk, the concept of triplet track trigger using High Voltage Monolithic Active Pixel Sensors(HV-MAPS) is introduced for a generic detector geometry. It is demonstrated that the triplet pixel layer design allows for a very simple and fast track reconstruction, providing excellent track reconstruction efficiencies and very high purity at the same time. Based on a full Geant4 simulation tracking performance studies are presented for a full-scale triplet pixel detector, i.e. three closely spaced pixel layers at a sufficiently large radius, in a FCC like detector environment.
It is shown that the triplet track trigger can be used to trigger efficiently multi-jet signals using track-jets. A significant pileup, and thus data rate reduction is achieved by reconstructing the z-vertex positions of the jet constituents already at the first trigger level. Results obtained for different triplet layer design parameters are compared.

8

Speeding up Particle Track Reconstruction using a Vectorized and Parallelized Kalman Filter Algorithm: Recent Improvements and Applicability to the Software Trigger

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Building particle tracks is the most computationally intense step of event reconstruction at the LHC. With the increased instantaneous luminosity and associated increase in pileup expected from the High-Luminosity LHC, the computational challenge of track finding and fitting requires novel solutions. The current track reconstruction algorithms used at the LHC are based on Kalman-filter methods that achieve good physics performance. By adapting the Kalman-filter techniques for use on many-core SIMD architectures such as the Intel Xeon and Intel Xeon Phi and (to a limited degree) NVIDIA GPUs, we are able to obtain significant speedups and comparable physics performance.

Recent work has focused on integrating the algorithm into the CMSSW environment for use in the CMS High Level Trigger during Run 3 of the LHC. New optimizations including the removal of hits from out-of-time pileup and improvements on the ranking of the hit candidates have further increased the speedup of the algorithm and improved the track-building efficiency. The use of advanced profiling techniques have identified additional areas to target for optimization. The current structure and performance of the code and future plans for the algorithm will be discussed.

11

Comparison of different ML methods applied to the classification of events with ttbar in the final state at the ATLAS experiment

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This contribution describes the experience with application of different ML methods to a physics analysis case. The use case chosen has been the classification of ttbar events coming from BSM or from SM and we have taken the datasets provided in a repository of simulated events. The features of these events are represented by their kinematic observables.

The initial objective was to compare different methods in order to see whether it can lead to an improvement in the classification, but the work has also helped us test many variations in the methods by changing hyperparameters, using different optimizers, ensembles, etc. With this information we have been able to conduct a comparative study that is useful for ensuring as complete control as possible of the methodology.

In the second stage we have incorporated variables from the reconstruction of the events and the substructure of jets in order to evaluate improvements in the classification.

12

Randomized Computer Vision Approaches for Pattern Recognition in Timepix and Timepix3 Detectors

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Timepix and Timepix3 Detectors are 256x256 hybrid active pixel detectors, capable of tracking ionizing particles as isolated clusters of pixels. To efficiently analyze such clusters at potentially high rates, we introduce multiple randomized pattern recognition algorithms inspired by computer vision. Offering desirable probabilistic bounds on accuracy and complexity, the presented methods are well-suited for use in real-time applications, and some may even be modified to tackle trans-dimensional problems. In older Timepix detectors which do not support data-driven acquisition, they have been shown to correctly separate clusters of overlapping tracks. In modern Timepix3 detectors, simultaneous acquisition of ToA+ToT pixel data enables reconstruction of the depth coordinate, transitioning from 2D to 3D point clouds. The presented algorithms have been tested on simulated inputs, test beam data from the Heidelberg Ion therapy Center and the Super-Proton-Synchrotron and were applied to data acquired in the MoEDAL and ATLAS experiments at CERN.

13

Global Track Reconstruction and Data Compression Strategy in ALICE for LHC Run 3

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In LHC Run 3, ALICE will increase the data taking rate significantly to 50 kHz continuous readout of minimum bias Pb-Pb collisions instead of around 1 kHz triggered readout..
The reconstruction strategy of the online offline computing upgrade foresees a first synchronous online reconstruction stage during data taking enabling detector calibration, and a posterior calibrated asynchronous reconstruction stage.
The huge amount of data requires a significant compression to store all recorded events.
We are aiming for a factor of 20 for the TPC, which is one of the main challenges during synchronous reconstruction.
In addition, the reconstruction will run online, processing 50 times more collisions than at present, while thereby yielding results comparable to current offline reconstruction.
All this poses new challenges for the tracking, including the continuous TPC readout, more overlapping collisions, no a priori knowledge of the primary vertex position and of location-dependent

calibration during the synchronous phase, identification of low-momentum looping tracks, and a distorted refit to improve track model entropy coding.
At the last workshop, we presented the fast new TPC tracking for Run 3, which matches the physics performance of the current Run 2 offline tracking.
It leverages the potential of hardware accelerators via the OpenCL and CUDA APIs in a shared source code for CPUs and GPUs for both reconstruction stages.
Porting more reconstruction steps like the remainder of the TPC reconstruction and tracking for other detectors to GPU will shift the computing balance from traditional processors towards GPUs.
This presentation will focus on the global tracking strategy, including the ITS and TRD detectors, on offloading more reconstruction steps onto GPU, and on our approaches to achieving the necessary data compression.

14

Towards Fast Displaced Vertex Finding

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Many standard model extensions predict long-lived massive particles that can be detected by looking for displaced decay vertices in the inner detector volume. Current approaches to seek for these events in high-energy particle collisions rely on the presence of additional energetic signatures to make an online selection during data-taking. Enabling trigger-level reconstruction of displaced vertices would strongly enhance the reach of such searches.

A proposed strategy is to exploit machine learning techniques to reconstruct approximate vertex positions from raw detector hits. In particular, a two-step procedure would first reconstruct the primary interaction position and exploit trigger-level objects, such as high energy muons, to define a region of interest. The second step would also use the raw detector hits to search for a displaced vertex.

This work focuses on the first step of approximating the location of the primary vertex in an idealised detector geometry using dense neural networks for regression. Properties of vertex reconstruction, such as position resolution and dependency on pile-up interactions will be discussed. Finally, future work will be tackled, including promising approaches for displaced vertex reconstruction given a limited search area.

15

Estimating data rates for the ATLAS ITk Pixel System

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To ensure particle tracking can be maintained in HEP colliders with high luminosity environments requires increased sensor granularity to keep the occupancies at levels acceptable for pattern recognition In addition the data must be readout fast enough to avoid pile up. Therefore the increase in luminosity and granularity requires read out of large data sets at high rates.
In ATLAS the data from the pixel system is readout via electrical cables due to the high radiation

levels, which preclude the use of optical fibre. Considerations of material budget means this limits the output of the modules to about 5Gbps. Determining the data rates is important to ensure that the system is designed to cope with full collision data and that the number of cables, which are a significant overhead in the material budget of the system, are optimised.
The calculation of data rates starts by calculating the hit rates using simulation of the detector. These are determined by the layout of the system and the geometry of the sensors. In addition, a good understanding of the material distribution is required to ensure that sources of background hits are included. The data rates are then calculated by simulating the output of the readout chip. The readout can be optimised, based on the structure of the hits, to minimise the size of the data.
The estimation of hit rates and data rates for the ATLAS ITk upgrade are presented as an example. The implication of the system layout and pixel geometry, and the uncertainties due to the material distribution are discussed. Different readout algorithms are evaluated based on simulated hit rates and date rate reduction. The subsequent impact on link occupancy is also considered as well as the robustness of these estimates discussed.

16

A novel 4D fast tracking pixel detector

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We present a novel 4D fast tracking system, based on rad-hard pixel detectors and front-end electronics, capable of reconstructing four dimensional particle trajectories in real time using precise space and time information of the hits. The fast track finding system that we are proposing is designed for the high-luminosity phase of LHC and has embedded tracking capabilities. A massively parallel algorithm for fast track reconstruction has been implemented in commercial FPGA using a pipelined architecture. We will present studies of expected tracking performance for a possible pixel detector of a future upgrade of the LHCb experiment and first results based on a FPGA-based hardware prototype.

17

Firmware Upgrade of the CMS Phase-I Pixel Front-End Controller: Impact on Pixel Operation and DAQ

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Pixel Front-End Controller (Pixel FEC) is responsible for programming the front-end chips and distributing the trigger, clock and fast signals to the modules in the CMS Phase-1 Pixel detector. An upgrade of the Pixel FEC firmware was undertaken and was successfully integrated within the online software. It was commissioned and deployed for the operation at the beginning of 2018. The upgrade reduced the configuration programming time of front-end chips dramatically, and also helped towards a more complete and faster recovery of the modules affected by single event upset during data-taking. The details of the implementation, along with the impact on Pixel detector operation and DAQ will be discussed.

18

The CMS High Granularity Calorimeter for HL-LHC - a tracking detector for calorimetry

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The CMS experiment at CERN will undergo significant improvements to cope with a 5-fold increase in instantaneous luminosity for the High Luminosity LHC (HL-LHC) era. In particular the endcap calorimetry will suffer from very high radiation levels and unprecedented event pile-up. The CMS HGCAL is being designed to replace the existing CMS endcap electromagnetic and hadronic calorimeters. It will be a sampling calorimeter, featuring unprecedented transverse and longitudinal readout and trigger segmentation for both electromagnetic (CE-E) and hadronic (CE-H) compartments. This will facilitate particle-flow calorimetry, where the fine structure of showers can be measured and used to enhance pileup rejection and particle identification, whilst still achieving good energy resolution. The CE-E and a large fraction of CE-H will use hexagonal silicon sensors as active detector material. The lower-radiation environment will be instrumented with scintillator tiles with on-tile SiPM readout. An overview of the HGCAL project will be presented, covering motivation, engineering design, readout and trigger concepts, and performance in beams and in simulation.

19

The ATLAS Hardware Track Trigger design towards first prototypes

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In the High Luminosity LHC, planned to start with Run4 in 2026, the ATLAS experiment will be equipped with the Hardware Track Trigger (HTT) system, a dedicated hardware system able to reconstruct tracks in the silicon detectors with short latency. This HTT will be composed of about 700 ATCA boards, based on new technologies available on the market, like high speed links and powerful FPGAs, as well as custom-designed Associative Memories ASIC (AM), which are an evolution of those used extensively in previous experiments and in the ATLAS Fast Tracker (FTK).

The HTT is designed to cope with the expected extreme high luminosity in the so called L0—only scenario, where HTT will operate at the L0 rate (1 MHz). It will provide good quality tracks to the software High-Level-Trigger (HLT), operating as coprocessor, reducing the HLT farm size by a factor of 10, by lightening the load of the software tracking.

All ATLAS upgrade projects are designed also for an evolved, so-called “L0/L1” architecture, where part of HTT is used in a low-latency mode (L1Track), providing tracks in regions of ATLAS at a rate of up to 4MHz, with a latency of a few micro-seconds. This second phase poses very stringent requirements on the latency budget and to the dataflow rates.

All the requirements and the specifications of this system have been assessed. The design of all the components has being reviewed and validated with preliminary simulation studies. After these validations are completed, the development of the first prototypes will start. In this paper we describe the status of the design review, showing challenges and assessed specifications, towards the preparation of the first slice tests with real prototypes.

20

DeepCore: Convolutional Neural Network for high pT jet tracking

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Tracking in high-density environments, such as the core of TeV jets, is particularly challenging both because combinatorics quickly diverge and because tracks may not leave anymore individual "hits" but rather large clusters of merged signals in the innermost tracking detectors. In the CMS collaboration, this problem has been addressed in the past with cluster splitting algorithms, working layer by layer, followed by a pattern recognition step where a high number of candidate tracks are tested. Modern Deep Learning techniques can be used to better handle the problem by correlating information on multiple layers and directly providing proto-tracks without the need of an explicit cluster splitting algorithm. Preliminary results will be presented with ideas on how to further improve the algorithms.

21

A hybrid deep learning approach to vertexing

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In the transition to Run 3 in 2021, LHCb will undergo a major luminosity upgrade, going from 1.1 to 5.6 expected visible Primary Vertices (PVs) per event, and will adopt a purely software trigger. This has fueled increased interest in alternative highly-parallel and GPU friendly algorithms for tracking and reconstruction. We will present a novel prototype algorithm for vertexing in the LHCb upgrade conditions.

We use a custom kernel to transform the sparse 3D space of hits and tracks into a dense 1D dataset, and then apply Deep Learning techniques to find PV locations. By training networks on our kernels using several Convolutional Neural Network layers, we have achieved better than 90% efficiency with no more than 0.2 False Positives (FPs) per event. Beyond its physics performance, this algorithm also provides a rich collection of possibilities for visualization and study of 1D convolutional networks. We will discuss the design, performance, and future potential areas of improvement and study, such as possible ways to recover the full 3D vertex information.

24

Tracking performance for long living particles at LHCb

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The LHCb experiment is dedicated to the study of the c- and b-hadrons decays, including long living particles such as Ks and strange baryons (Lambda, Xi, etc…). These kind of particles are difficult to reconstruct from LHCb tracking systems since they escape the detection in the first tracker. In this talk the performance of the tracking algorithms for detecting long living particles are studied and compared with other methods. Special emphasis is laid on the tracking reconstruction achievements with the new LHCb upgrade detector.

26

A GPU High Level Trigger 1 for the upgraded LHCb detector

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Beginning in 2021, the upgraded LHCb experiment will use a triggerless readout system collecting data at an event rate of 30 MHz. A software-only High Level Trigger will enable unprecedented flexibility for trigger selections. During the first stage (HLT1), a sub-set of the full offline track reconstruction for charged particles is run to select particles of interest based on single or two-track selections. After this first stage, the event rate is reduced by at least a factor 30. Track reconstruction at 30 MHz represents a significant computing challenge, requiring a renovation of current algorithms and the underlying hardware. In this talk, we present the approach of executing the full HLT1 chain on GPUs. This includes decoding the raw data, clustering of hits, pattern recognition, as well as track fitting. We will discuss the infrastructure of our software project and the design of HLT1 algorithms optimized for many-core architectures. Both the computing and physics performance of the full HLT1 chain will be presented. Ses. 2

27

Level-1 track finding with an all-FPGA system at CMS for the HL-LHC

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The CMS experiment at the LHC is designed to study a wide range of high energy physics phenomena. It employs a large all-silicon tracker within a 3.8T magnetic solenoid, which allows precise measurements of transverse momentum (pT) and vertex position.

This tracking detector will be upgraded to coincide with the installation of the High-Luminosity LHC, which will provide luminosities of up to about 10ˆ35 cmˆ2 /s to CMS, or 200 collisions per 25 ns bunch crossing. This new tracker must maintain the nominal physics performance in this more challenging environment. Novel tracking modules that utilise closely spaced silicon sensors to discriminate on track pT have been developed and allow the readout of only hits compatible with pT > 2-3 GeV tracks to off-detector trigger electronics. This would allow the use of tracking information

at the Level-1 trigger of the experiment, a requirement to keep the Level-1 triggering rate below the 750 kHz target, while maintaining physics sensitivity.

This talk presents a concept for an all FPGA based track finder using a fully time-multiplexed architecture. Hardware demonstrators have been assembled to prove the feasibility and capability of such a system. The performance for a variety of physics scenarios will be presented, as well as the proposed scaling of the demonstrators to the final system and new technologies.

28

Identifying merged tracks in Dense Environments using multivariate analysis

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Tracking in high density environments, particularly in high energy jets, plays an important role in many physics analyses at the LHC. In such environments, it is possible that two highly collinear particles contribute to the same hits as they travel through the ATLAS pixel detector and semiconductor tracker. If the two particles are sufficiently collinear, it is possible that only a single track candidate will be created, denominated a "merged track", leading to a decrease in tracking efficiency. This study details a novel technique based on multivariate analysis to classify reconstructed tracks as merged. An application of this new method is the recovery of the number of reconstructed tracks in high transverse momentum three-pronged tau decays, leading to an increased tau reconstruction efficiency. The technique is also applied to simulated boosted jets for validation.

29

Primary Vertex Selection in VBF Higgs to Invisibles at mu 200 with the ATLAS Experiment

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Vertex selection algorithms at the LHC have thus far relied primarily upon the hardness of the hard-scatter (HS) vertex relative to vertices from pileup (PU). The high PU environment at the HL-LHC will, however, introduce major experimental challenges for the correct selection of the HS vertex. In particular, the expected average PU vertex density of $2\ vtx/mm$ at $z = 0$ can often lead to the merging of nearby PU vertices resulting in PU vertices with very large summed transverse momentum (p_{T}) that can be incorrectly identified as HS by the standard algorithm.

This is especially relevant for vector boson fusion (VBF) invisible final state topologies where the HS process does not have very high visible p_{T} activity, resulting in a low selection efficiency as a function of pileup density when using the standard algorithm.
ATLAS has developed a new approach for vertex selection in VBF invisible events at HL-LHC conditions, exploiting its new forward tracking capabilities, integrating calorimeter and tracking information to mitigate the impact of pileup vertex merging, and introducing a new way to apply pile-up jet suppression methods for the selection of VBF jets. The new algorithm is insensitive to pileup density and improves the average vertex selection efficiency from 80% to 94-96%.

30

Firmware oriented trigger algorithm for CMS Drift Tubes in HL-LHC

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A full replacement of the muon trigger system in the CMS (Compact Muon Solenoid) detector is envisaged for operating at the maximum instantaneous luminosities expected in HL-LHC (High Luminosity Large Hadron Collider) of about $5 - 7.5x10^{34}cm^{-2}s^{-1}$. Under this scenario, the new on detector electronics that is being designed for the DT (Drift Tubes) detector will forward all the chamber information at its maximum time resolution. A new trigger system based on the highest performing FPGAs is being designed and will be capable of providing precise muon reconstruction and Bunch Crossing identification. An algorithm easily portable to FPGA architecture has been designed to implement the trigger primitive information from the DT detector. This algorithm has to reconstruct muon segments from single wire DT hits which contain a time uncertainty of 400 ns due to the drift time in the cell. This algorithm provides the maximum resolution achievable by the DT chambers, bringing closer to the hardware system the offline performance capabilities. The results of the simulation and of the first implementations in the new electronics test bench will be shown.

31

Tracking performance with the HL-LHC ATLAS detector

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The High Luminosity LHC (HL-LHC) aims to increase the LHC data-set by an order of magnitude in order to increase its potential for discoveries. Starting from the middle of 2026, the HL-LHC is expected to reach the peak instantaneous luminosity of $7.5 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ which corresponds to up to about 200 inelastic proton-proton collisions per bunch crossing. To cope with the large radiation

doses and high pileup, the current ATLAS Inner Detector will be replaced with a new all-silicon Inner Tracker. In this talk the expected tracking performance of the HL-LHC tracker is presented. Impact of tracking on physics object reconstruction is discussed.

32

Increasing track reconstruction efficiency in dense environments at ATLAS

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In the ATLAS experiment at the LHC, the primary-track reconstruction algorithm utilizes iterative track-finding seeded from combinations of silicon detector measurements. As all realistic combinations of space-points have been made, there are a number of track candidates where space-points overlap, or have been incorrectly assigned. This necessitates an ambiguity-solving stage. In the ambiguity solver, track candidates considered to create the reconstructed track collection are processed individually in descending order of a track score, favouring tracks with a higher score. The scoring algorithm depends on simple measures of the track quality, which includes the χ^2 of the track fit, cut on hits and holes on track and merged clusters. In this talk, modifications to the ambiguity solver aimed at improving track reconstruction in the dense core of high pT jets will be discussed. These modification include application of machine learning techniques to the scoring function and for classification of merged tracks.

33

Unconventional Tracking Techniques for Long-Lived Particle Searches in ATLAS

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A variety of Beyond the Standard Model (BSM) theories predict new particles with macroscopic lifetimes of $c\tau \geq calO(1\ \mathrm{mm})$ that could be created in proton-proton collisions at the Large Hadron Collider (LHC). Such theories often give rise to signatures that require dedicated tracking and vertexing techniques beyond conventional tracking algorithms. In this talk, a variety of unconventional tracking and vertexing techniques for long-lived particle searches in ATLAS will be discussed, including a secondary vertex algorithm for heavy neutral particles decaying to hadronic and leptonic final states within the ATLAS Inner Detector, a disappearing charged track reconstruction technique, which extends to trajectories with as few as three position measurements in the ATLAS pixel detector, and a new region-of-interest track seeding technique for low momentum tracking to target tracks originating from the long-lived charged particle decays within the Inner Detector. The performance of these unconventional tracking techniques will be discussed in the context of a variety of BSM theories in preparation for full Run 2 analyses with the ATLAS detector.

34

HEP.TrkX Charged Particle Tracking using Graph Neural Networks

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To address the unprecedented scale of HL-LHC data, the HEP.TrkX project has been investigating a variety of machine learning approaches to particle track reconstruction. The most promising of these solutions, a graph neural network, processes the event as a graph that connects track measurements (detector hits corresponding to nodes) with candidate line segments between the hits (corresponding to edges). This architecture enables separate input features for edges and nodes, ultimately creating a hidden representation of the graph that is used to turn edges on and off, leaving only the edges that form tracks. Due to the large scale of this graph for an entire LHC event, we present new methods that allow the event graph to be scaled to a computationally reasonable size. We report the results of the graph neural network on the TrackML dataset, detailing the effectiveness of this model on event data with large pileup. Additionally, we propose post-processing methods that further refine the result of the graph neural network, ultimately synthesizing an end-to-end machine learning solution to particle track reconstruction.

35

Optimization of the Adaptive Multi Vertex Finder in ATLAS

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The increasing track multiplicity in ATLAS poses new challenges for primary vertex reconstruction software, reaching to over 70 inelastic proton-proton collisions per beam crossing during Run-2 of the LHC and even more extreme vertex density in the next upcoming Runs. One way to get around these challenges, is to take a global approach to the track assignment to primary vertices, as opposed to the Iterative Vertex Finder procedure that was used in Run-2.
The Adaptive Multi Vertex Finder, a true multi-vertex implementation of the adaptive vertex finder algorithm is one such approach, which deploys the same adaptive vertex fitting technique as the Iterative Vertex Finder procedure, but fits for N vertices in parallel to take into account the vertex structure of the event.

This talk summarises the optimization and expected performance of the Adaptive Multi Vertex Finder for conditions foreseen for Run-3 of the LHC. These studies are coupled to a newly optimised vertexing seeder and further performance studies in the ITk scenario.

36

Tracking Performance of the ATLAS Fast TracKer (FTK)

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Particle physicists at the Large Hadron Collider (LHC) investigate the properties of matter at length scales one million times smaller than the atom by colliding together high-energy protons 40 million times per second and observing the decay products of the collisions. ATLAS is one of two general-purpose detectors that reconstruct the interactions and as part of a wide range of physics goals measures production of Higgs bosons and searches for exotic new phenomena including supersymmetry, extra dimension and dark matter.

Selecting the interesting collision events using hardware- and software-based triggers is a major challenge as reconstructing these collisions will only become more challenging as the LHC luminosity increases in future data. The ATLAS Fast TracKer (FTK) is a custom electronics system that performs fast FPGA-based tracking of charged particles for use in trigger decisions. In 2018, an FTK "Slice" covering a portion of the ATLAS detector was installed and commissioned using proton-proton collisions. This presentation will review the track-finding and track-fitting strategies employed by the FTK hardware and present the first tracking performance results for the FTK Slice in 2018 pp collisions data, including hit- and track-finding efficiencies, track parameter resolutions, and track purities.

37

Registration

38

Introduction

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53

Talk Botanic Garden

78

Discussion on the TrackML challenge

80

Free

87

Workshop Summary

88

The CMS Tracker Upgrade for the High-Luminosity LHC

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The LHC machine is planning an upgrade program, which will smoothly bring the luminosity at about $5-7.5x10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in 2028, to possibly reach an integrated luminosity of 3000-4500 fb^{-1} by the end of 2039. This High-Luminosity LHC scenario, HL-LHC, will require a preparation program of the LHC detectors known as Phase-2 upgrade. The current CMS Outer Tracker, already running beyond design specifications, and recently installed CMS Phase-1 Pixel Detector will not be able to survive the HL-LHC radiation conditions. Thus, CMS will need completely new devices in order to fully exploit the high-demanding operating conditions and the delivered luminosity. The new Outer Tracker should also have trigger capabilities. To achieve such goals, the R&D activities have investigated different options for the Outer Tracker and for the pixel Inner Tracker. The developed solutions will allow including tracking information at the Level-1 trigger. The design choices for the Tracker upgrades are discussed along with some highlights on the technological choices and the R&D activities.

89

New developments in conformal tracking for the CLIC detector

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Conformal tracking is the innovative track reconstruction strategy adopted for the detector designed for CLIC.
It features a pattern recognition in a conformal-mapped plane, where helix trajectories of charged particles in a magnetic field are projected into straight lines, followed by a Kalman-Filter-based fit in global space.
The nearest neighbour search is optimized by means of fast kdtrees and a cellular automaton is used to reconstruct the linear paths.
Being based exclusively on the spatial coordinates of the hits, this algorithm is adaptable to different detector designs and beam conditions. In the detector at CLIC, it also profits from the low-mass silicon tracking system, which reduces complications from multiple scattering and interactions.
Full-simulation studies are performed with the iLCSoft framework developed by the Linear Collider Community, in order to validate the algorithm and assess its performances, also in the presence of beam-induced backgrounds expected at 3 TeV CLIC.
In this talk, recent developments and new features of the track reconstruction chain will be discussed. Results will be shown for isolated tracks and di-jet events.

90

Track seed classification with DNNs

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In the next decade, high-luminosity upgrades to the LHC will confront detectors with an order of magnitude increase in particle collisions. This will push track reconstruction software and hardware beyond current capabilities. The current track reconstruction approaches based on track seeding and track following allow for large contingency and hence are not optimal in terms of computational efficiency. Early fake classification, especially during the first stages of track reconstruction offer viable opportunities for a faster, more efficient reconstruction. In an attempt to harness multiple advantages in a single approach, we investigate the applicability of Deep Neural Networks (DNNs) to the classification of track seeds. A DNN offers not just inherent parallelizability and execution on dedicated hardware, but also the possibility to improve rejection rates for improper seeds and thereby free up time for any actual track reconstruction. This approach is underpinned by the surge of high performance and free to use deep learning frameworks, which have matured over the last years.

91

Machine Learning For Track Finding

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The $\bar{\text{P}}$ANDA (anti$\bar{\text{P}}$roton ANnihilation at Drmstadt) experiment at the future Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany, will investigate the behavior of QCD in the mass range of the charmonium. As a fixed target experiment, most of the generated particle will have a forward boost. Therefore, the PANDA detector consists of a Central Spectrometer (CS), directly around the interaction point and a Forward Spectrometer (FS) measuring the forward going particles. The FS is located downstream of the interaction region and measures particles at small polar angles θ below 5° in the vertical and 10° in the horizontal plane. Its magnetic field with a maximum bending power of 2 Tm is provided by a dipole magnet. For the measurement of particle momenta based on the deflection of their trajectories in the magnetic field of the FS dipole magnet, Forward Tracker Stations (FTS) are foreseen. The design of the FTS is based on self-supporting straw tubes arranged in three pairs of planar stations. One pair (FT1, FT2) is placed upstream of the FS dipole magnet, the second pair (FT5, FT6) downstream of the magnet, and the third pair (FT3, FT4) is placed inside the gap of the magnet. Each tracking station consists of four double layers of straws: the first and the fourth one are vertical straws and the two intermediate are composed of straws tilted at +5° and −5°, respectively.

We apply machine/deep learning methods as a track finding algorithm at the FTS.
The problem is divided into two steps:

The first step is to build track segments in three different parts of the FTS, namely FT1, FT2, and FT3. Two models were tested in this step so far, the first model relies on unsupervised clustering algorithm to find track segments, and the second model relies on supervised learning to combine hit pairs/triplets to form track segments in the three different parts of the FTS.

The second step is to join the track segments from the different parts of the FTS to form a full track, and is based on Recurrent Neural Network (RNN). The RNN is used as a binary classifier that outputs

1 if the combined track segments are a true track, and 0 if the track segments do not match. The performance of the algorithm is judged based on the purity, efficiency and the ghost ratio of the reconstructed tracks. The purity specifies which fraction of hits in one track come from the correct particle. The correct particle is the particle, which produces the large majority of hits in the track. The efficiency is defined as the ratio of the number of correctly reconstructed tracks to all generated tracks present. The ghost ratio is defined as the number of impure tracks (which have a large fraction of hits from more than one track) to all tracks present.

92

QUBO for Track Reconstruction on D-Wave

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D-Wave Systems Quantum Annealer (QA) finds the ground state of a Hamiltonian expressed as:

O(a;b;q)= $\sum_{i=1}^{N} a_i q_i + \sum_{i}^{N} \sum_{j<i}^{N} b_{ij} q_i q_j$
$This Quantum Machine Instruction (QMI) is equivalent to a Quadratic Unconstrained Binary Optimization (Q$

Following Stimpfl-Abele[1], we expressed the problem of classifying track seeds (doublets and triplets) as a QUBO, where the weights depend on physical properties such as the curvature, 3D orientation, and length.

We generated QUBOs that encode the pattern recognition problem at the LHC using the TrackML dataset[2] and solved them using qbsolv[3] and the D-Wave Leap Cloud Service[4]. Those early experiments achieved a performance in terms of purity, efficiency, and TrackML score that exceeds 95%.

Our goal is to develop a strategy appropriate for HL-LHC track densities by using techniques including improved seeding algorithms and geographic partitioning. We also plan to refine our model in order to reduce execution time and to boost performance.

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93

Patatrack: accelerated Pixel Track reconstruction in CMS

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The upgraded CMS Pixel Tracker Detector installed during the 2016-2017 extended year-end technical stop consists of four layers in the barrel region and three disks on both sides in the forward region. This made it possible to perform a real fit on quadruplet of hits selected by a Cellular Automaton algorithm to form the pixel tracks. Pixel tracks are an important component of the CMS High-Level Trigger(HLT) reconstruction since they are also used as seeds for additional tracking iterations that make use of the full tracker information. Having a good knowledge of the parameters of the tracks allows a better cleaning and reduces the fake tracks saving CPU time. In this talk, we will describe our experience in implementing two non-iterative and multiple scattering aware fit techniques in the CMS Experiment: the Riemann Fit and Broken Line Fit. We will compare their performances against the standard Run-2 reconstruction both in terms of timing and track-parameter resolution. We will also illustrate our experience in implementing both algorithms on GPU architectures, with a particular emphasis on the engineering work that has been necessary to make the integration.

94

Time based reconstruction of hyperons with PANDA at FAIR

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The upcoming PANDA (anti-Proton ANnihilation at DArmstadt) experiment at FAIR (Facility for Anti-proton and Ion Research) offers unique possibilities for performing hyperon physics such as extraction of spin observables. Due to their relatively long-lived nature, the displaced decay vertices of hyperons impose a particular challenge on the track reconstruction and event building. The foreseen high luminosity and high beam momenta at PANDA requires new advanced tracking algorithms for successfully identifying the hyperon events. The purely software based event selection of PANDA puts high demands on the online reconstruction algorithms. A fast, versatile, modular and dynamic approach to track reconstruction and event building is required. Such a scheme is currently under development in Uppsala. This talk will address the reconstruction algorithms used in the scheme such as the cellular automaton and the Riemann fit. The computing requirements and challenges will also be discussed.

95

Tracks Reconstruction with Similarity Hashing and Learning

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At the LHC, many proton-proton collisions are happening at a single beam crossing which leads to thousands of particles emerging from the interaction region and vast amount of data to be analyzed by the reconstruction software.

The finding of trajectories from charged particles in the tracking devices is a particularly challenging task due to two main factors. Firstly, deciding whether a given set of hits belong to the same trajectory is an under-specified task and state of the art models discard combinations only at a later stage when adding more hits (track following). Secondly, assuming a nearly perfect decision function, the construction of combinatorics to check hits compatibility using this decision function is computationally intensive and will grow exponentially in the HL-LHC.

We propose a framework for Similarity Hashing and Learning for Tracks Reconstruction (SHLTR) where multiple regions of the detector are reconstructed in parallel with minimal fake rate. We consider hashing to reduce the detector search space into "buckets" where the purity of the sub-regions is increased using locality sensitivity in the feature space. A neural network selects the valid combinations in the buckets and builds up full trajectories by connected components search independently of global positions of the hits and detector geometry. The whole process occurs simultaneously in the N regions of the detector and curved particles are found by allowing buckets overlap.
The framework succeeds in addressing the two main tracking challenges : decision making and computation scale in mu 200 datasets. We present first results of such a track reconstruction chain including efficiency, fake estimates and computational performances.

96

Performance of Belle II tracking in central drift chamber

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The tracking system of the Belle II consists of the silicon vertex detector and cylindrical drift chamber, both operating in a magnetic field created by the main solenoid of 1.5 T and final focusing magnets. The drift chamber consists of 56 layers of sense wires, arranged in interleaved axial and stereo superlayers, to assist track finding and provide full 3D tracking. The drift chamber serves as the main detector for track finding in Belle II. Two distinct track finding algorithms, local and global, are employed for this purpose and the found track candidates are combined, fitted and extrapolated into the silicon vertex detector using the combinatorial Kalman filter algorithm. A distinct feature of the Belle II tracking is its modularity allowing for changes in the algorithm sequence, to optimize the overall performance. Another feature is a use of multivariate estimators, for noise filtering and track-candidate selection. The reconstruction is tested on e+ and e- collision data collected in phase 2 operation during spring 2018. The good performance of the drift chamber and tracking reconstruction allowed rediscovery of many physics channels and was essential for tuning of the accelerator parameters

97

Performance of the Belle II Silicon Vertex Detector stand alone track finder

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The performances on data of the silicon standalone track finder based on the Sector Map concept developed for the Belle II vertex detector (VXD) will be presented.
The Belle II VXD is a combined tracking system composed by two layers of DEPFET pixel detectors married with four layers of double sided silicon strip sensors (SVD).
The VXD is recording e+ e- collisions occurring at the interaction points of SuperKEKB, the asymmetric e+ e- collider operating at Y(4S) mass peak. The track finder algorithm must operate in a very harsh environment characterized by very high occupancy stemming from beam background and it must be very efficient in finding very soft charged tracks (total momentum around 50 MeV/c) that are in the lowest range of the momentum spectrum of the B mesons decay products. To achieve this demanding goal a set of novel algorithms that are fully exploiting the excellent time and spatial resolution of the SVD had been developed and tuned. The experience gained so far on a sample of half an inverse femtobarn collected on 2018 with a section of the full VXD will be presented together with the very first results from the phase 3 run that will start on March 2019.

98

Calibration and alignment of the Belle II tracker

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The physics goals the Belle II experiment require an exceptionally good alignment of all the components of the Belle II tracker. The Belle II tracker is composed of the DEPFET based pixel silicon detector, four layers of double sided silicon strip detector, a low material budget drift chamber, all three operating in a solenoidal 1.5 T B field, which is affected by the final focusing system of the accelerator. Each component of these three components must be aligned with an accuracy significantly better than the point resolution of the detector that for the PXD is order of 10 microns. The Belle II alignment software is based on the Millepede II package and uses cosmics and collision data to constrain the weak modes. The performance of the alignment algorithms was tested on the phase 2 collision data collected during spring 2018. Good alignment of the vertex detector was essential to demonstrate the nano-beam collision scheme of the accelerator and check the quality of the impact parameter resolution, which is essential for time-dependent CP violation studies at the B factory.

99

Machine Learning approaches to Track Reconstruction in the Upgraded LHCb VELO

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The LHC Run-III, scheduled to start taking data in 2021, will pose new challenges to event reconstruction as experiments are forced to move to more sophisticated software-based event filters to exploit the physics potential offered by the upgraded accelerator.

In particular, the LHCb experiment will install a new Vertex Locator (VELO), moving to pixel sensors with a trigger-less readout. The particle tracks and decay vertices provided by the upgraded VELO comprise a large fraction of the background suppression power of the LHCb software event filter. It has become clear that the speed of conventional approaches to track and vertex reconstruction would limit the physics potential of the upgraded LHCb experiment. Exploring novel approaches is therefore necessary.

Recent developments in Deep Learning and parallel processing enable radically new approaches to event reconstruction. We have explored a number of approaches to track reconstruction using various machine learning techniques: layer-to-layer connection FCNN classifiers, graph neural networks and so on. The input data for all approaches is fully simulated minimum bias data, ie. we do not use toy models. We always compare the performance in terms of reconstruction quality to conventional algorithms using the criteria agreed on by the LHCb collaboration. The very promising results obtained so far as well as ideas for further improvements will be presented.

100

Sensor shapes and weak modes of the ATLAS Inner Detector track based alignment

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The alignment of the ATLAS Inner Detector is performed with a track-based algorithm. The aim of the detector alignment is to provide an accurate description of the detector geometry such that track parameters are accurately determined and bias free.

A new analysis with a detailed scrutiny of the track-hit residuals allows to study the deformation shape of the Pixels and IBL modules. The sensor distortion can result in track-hit residual biases of up to 10 microns within a given module. Their shape is parametrized with Legendre polynomials and used to correct the hit positioning in the track fitting procedure.

The detector alignment is validated and improved by studying resonance decays (J/psi, Upsilon and Z to mu+mu-), as well as using information from the calorimeter system with the E/p method from electrons. The detail study of these resonances (together with the properties of the tracks of their decay products) allows to detect and correct for alignment weak modes such as detector curls and radial deformations that may bias the momentum and/or the impact parameter. The weak mode correcting maps and their magnitude are then used to realign the detector with increased accuracy.

101

Charged Particle Tracking as a QUBO problem solved with Quantum Annealing-Inspired Optimization

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With the upgrade of the LHC to high luminosity, an increased rate of collisions will place a higher computational burden on track reconstruction algorithms. Typical algorithms such as the Kalman Filter and Hough-like Transformation scale worse than quadratically. However, the energy function of a traditional method for tracking, the geometric Denby-Peterson (Hopfield) network method, can be described as a quadratic unconstrained binary optimization (QUBO) problem. Quantum annealers have shown shown promise in their ability to solve QUBO problems despite being NP-hard. We present a novel approach for track reconstruction by applying a quantum annealing-inspired algorithm to the Denby-Peterson method. We propose additional techniques to divide an LHC event into disjoint subgraphs in order to allow the problem to be embeddable on existing quantum annealing hardware, using multiple anneals to fit tracks to a single event. To accommodate this dimension reduction, we use Bayesian methods and further algorithms to pre- and post-process the data. Results on the TrackML dataset are presented, demonstrating the successful application of quantum annealing-inspired algorithms to the track reconstruction problem.

102

Low Latency Neural Networks using Heterogenous Resources on FPGA for the Belle II Trigger

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One of the major components of the Belle II trigger system is the neural network trigger. Its task is to estimate the z-Vertex particle tracks observed in the experiments drift chamber. The trigger is implemented on FPGAs to ensure flexibility during operation and leverage their IO capabilities. Meanwhile the implementation has to estimate the vertex in a few hundred nanoseconds to fulfill the requirements of the experiment. A first version of that trigger was operational during the first collisions. While it was able to estimate the vertex, it had some drawbacks regarding the possible throughput and timing closure. These are the focus of this work, which modifies the original design to allow two networks running in parallel and less routing congestion. We conducted a rescheduling of multiply and accumulate which are the basic operations in such networks. While the original design tried to parallelize as much as possible, the rescheduling tries to reduce the number of parallel data transmission by reusing processing modules. This way resource consumption was reduced by 40% for DSPs. To further increase the throughput by operating an additional network in parallel, we investigated the balanced use of SRAM-LUTs and DSPs for multiply and accumulate operations. With the found balancing ratio the trigger is able to operate two neural networks in parallel on the targeted FPGA within the required latency.

103

Another approach to track reconstruction: cluster analysis

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A novel combination of data analysis techniques is proposed for the reconstruction of all tracks of primary charged particles, as well as of daughters of displaced vertices (decays, photon conversions, nuclear interactions), created in high energy collisions. Instead of performing a classical trajectory building or an image transformation, an efficient use of both local and global information is undertaken while keeping competing choices open.

The measured hits of adjacent tracking layers are clustered first with help of a mutual nearest neighbor search in angular distance. The resulted chains of connected hits are used as initial clusters and as input for cluster analysis algorithms, such as the robust k-medians clustering. This latter proceeds by alternating between the hit-to-track assignment and the track-fit update steps, until convergence. The calculation of the hit-to-track distance and that of the track-fit χ^2 is performed through the global covariance of the measured hits. The clustering is complemented with elements from a more sophisticated Metropolis-Hastings MCMC algorithm, with the possibility of adding new track hypotheses or removing unnecessary ones.

Simplified but realistic models of today's silicon trackers, including the relevant physics processes, are employed to test and study the performance (efficiency, purity) of the proposed method as a function of the particle multiplicity in the collision event.

104

Use of R-trees to improve reconstruction time in pixel trackers

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Computing time is becoming a key issue for tracking algorithms both online and off-line. Programming using adequate data structures can largely improve the efficiency of the reconstruction in terms of time response. We propose using one such data structure, called R-tree, that performs a fast, flexible and custom spatial indexing of the hits based on a neighbourhood organization. The overhead required to prepare the data structure shows to be largely compensated by the efficiency in the search of hits that are candidate to belong to the same track when events present a large number of hits. The study, including different indexing approaches, is performed for a generic pixel tracker largely inspired in the upgrade of the LHCb vertex locator with a backwards reconstruction algorithm of the cellular automaton type.

105

Real-time Timepix3 data clustering, visualization and classification with a new Clusterer framework.

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With the next-generation Timepix3 hybrid pixel detector, new possibilities and challenges have arisen. The Timepix3 segments active sensor area of 2cm² into a square matrix of 256 x 256 pixels. In each pixel, the ToA (Time of Arrival, with a precision of 1.56 ns) and ToT (Time over Threshold, energy) are measured simultaneously in data-driven, self-triggered, read-out scheme.

This contribution presents a framework for data acquisition, real-time clustering, visualization, classification and data saving. All of these tasks can be performed online directly from multiple readouts via UDP protocol. Clusters are reconstructed on a pixel-by-pixel decision from the stream of not-necessarily chronologically sorted pixel data. To achieve quick spatial pixel-to-cluster matching, non-trivial data structures were utilized (e.g. Quadtree). Furthermore, parallelism (i.e. multithreaded architecture) is used to further improve the performance of the framework. Such real-time clustering offers the advantages of an online filtering and classification of events. Versatility of the software is ensured by supporting all major operating systems (macOS, Windows and Linux) with both graphical and command-line interface.

Using plug-in architecture, most efficient cluster features were selected and multiple approaches to artificial intelligence classification, such as neural networks and semi-labeled data learning, were applied to data measured in test beam campaigns. The performance of the real-time clustering and the applied classification methods are demonstrated using data from the Timepix3 network installed in the ATLAS and MoEDAL experiments at CERN.

107

Convolutional Neural Network for Track Seed Filtering at the CMS HLT

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Starting from 2020, future development projects for the Large Hadron Collider will constantly bring nominal luminosity increase, with the ultimate goal of reaching a peak luminosity of 5 ·1034 cm−2 s−1 for ATLAS and CMS experiments planned for the High Luminosity LHC (HL-LHC) upgrade. This rise in luminosity will directly result in an increased number of simultaneous proton collisions (pileup), up to 200, that will pose new challenges for the CMS detector and, specifically, for track reconstruction in the Silicon Pixel Tracker.

One of the first steps of the track finding workflow is the creation of track seeds, i.e. compatible pairs of hits from different detector layers, that are subsequently fed to to higher level pattern recognition steps. However the set of compatible hit pairs is highly affected by combinatorial background resulting in the next steps of the tracking algorithm to process a significant fraction of fake doublets.

A possible way of reducing this effect is taking into account the shape of the hit pixel cluster to check the compatibility between two hits. To each doublet is attached a collection of two images built with the ADC levels of the pixels forming the hit cluster. Thus the task of fake rejection can

be seen as an image classification problem for which Convolutional Neural Networks (CNNs) have been widely proven to provide reliable results.

In this work we present our studies on CNNs applications to the filtering of track pixel seeds. We will show the results obtained for simulated event reconstructed in CMS detector, focussing on the estimation of efficiency and fake rejection performances of our CNN classifier. The results from a first integration within the CMS tracking software will be also discussed.

108

Optimization of a First Level Neural Network z-Trigger for the Drift Chamber at the Belle II Experiment

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For the Belle II experiment at the SuperKEKB asymmetric electron-positron collider (KEK, Japan) the concept of a first level track trigger, realized by neural networks, is presented. Using the input from a traditional Hough-based 2D track finder, the stereo wire layers of the Belle II Central Drift Chamber are used to reconstruct by neural methods the origin of the tracks along the beam ("z") direction. A z-trigger for Belle II is required to suppress the dominating background of tracks from outside of the collision point. Extensive training and testing using simulated tracks achieve resolutions below 2 cm in the high Pt region, and below 5 cm in the low Pt region, sufficient for efficient background rejection. The importance of the correct drift time input from Belle's Event Time Finder on the optimal spatial resolution of the z-trigger is discussed. Background distributions from first data taking with Belle II are analyzed to optimize suitable z-cuts for an efficient background suppression.

110

RecPack: a general reconstruction tool-kit

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In High Energy Physics (HEP), as in other fields, one frequently faces the problem of reconstructing the evolution of a dynamic system from a set of experimental measurements. Most of reconstruction programs use similar methods. However, in general they are reimplemented for each specific experimental setup. Some examples are fitting algorithms (i.e. Kalman Filter), equations for propagation, random noise estimation (i.e. multiple scattering), model corrections (i.e. energy loss, inhomogeneous magnetic field, etc.), etc. Similarly, the data structure (measurements, tracks, vertices, etc.), which can be generalised as well, is not reused in most of the cases.

RecPack tries to avoid that by providing a setup–independent data structure and algorithms, which can be applied to any dynamic system. The package follows an "interface"strategy, that is, all the classes that could have a different implementation have their own interface, in such away that the rest of the classes do not depend on such a specific implementation. This modular structure allows a great flexibility and generality.

RecPack was born in the HARP experiment at CERN-PS and is currently being developed mainly for T2K. Other experiments using it are MICE, MuScat, MIPP, NEMO and SuperNemo.

111

LHCb phase 2 upgrade program

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The LHCb Collaboration is planning an Upgrade II, a flavour physics experiment for the high luminosity LHC era. This will be installed in LS4 (2030) and targets an instantaneous luminosity of 1 to $2 \times 10^{34}\}$ cm^{-2} s^{-1} so as to collect an integrated luminosity of at least 300fb^{-1}. Modest consolidation of the current experiment will also be introduced in LS3 (2025).

The higher luminosity increases the detector occupancy considerably giving a challenging environment for track reconstruction which is done in Real Time in the trigger at the visible crossing rate of 30 MHz. To meet this challenge two major upgrades to the tracking system are forseen. First a "4D"vertex detector is proposed, which exploits both spatial and time information. The addition of timing information is beneficial both in the assignment of hits to tracks but also allows to separate primary vertices using both spatial and time information. The second major change is to replace the inner part of the downstream tracking stations (which utilize fibers) with silicon technology. For this purpose CMOS and HVCMOS technologies are considered. The new 'Mighty' Tracker will cover an area of 20 square meters, much larger than any silicon detector previously constructed by LHCb.

In this talk the challenges of the LHCb phase 2 upgrade program will be discussed and first results of performance studies presented.

112

Silicon Detectors for the LHC Phase-II Upgrade and Beyond – RD50 Status Report

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It is foreseen to significantly increase the luminosity of the LHC by upgrading towards the HL- LHC (High Luminosity LHC) in order to harvest the maximum physics potential. Especially the Phase-II-Upgrade foreseen for 2023 will mean unprecedented radiation levels, significantly beyond the limits of the silicon trackers currently employed. All-silicon central trackers are being studied in ATLAS, CMS and LHCb, with extremely radiation hard silicon sensors to be employed on the innermost layers. Within the RD50 Collaboration, a large R&D program has been underway for more than a decade across experimental boundaries to develop silicon sensors with sufficient radiation tolerance for HL-LHC trackers.
Key areas of recent RD50 research include new sensor fabrication technologies such as High-Voltage (HV) CMOS, exploiting the wide availability of the CMOS process in the semiconductor industry at very competitive prices compared to the highly specialised foundries that normally produce particle detectors on small wafers. We also seek for a deeper understanding of the connection between the macroscopic sensor properties such as radiation-induced increase of leakage current, doping concentration and trapping, and the microscopic properties at the defect level. Another strong activity is the development of advanced sensor types like 3D silicon detectors, designed for the extreme radiation levels expected for the vertexing layers at the HL-LHC. A further focus area is the field of Low Gain Avalanche Detectors (LGADs), where a dedicated multiplication layer to create a high field region is built into the sensor. LGADs are characterised by a high signal also after irradiation and a very fast signal compared to traditional silicon detectors with make them ideal candidates for ATLAS and CMS timing layers in the HL-LHC.
We will present the state of the art in several silicon detector technologies as outlined above and at radiation levels corresponding to HL-LHC fluences and partially beyond. As an example, Figure 1 shows a summary of signal measurement results for irradiated LGAD silicon detectors (left), indicating a good radiation tolerance at high bias voltages, and efficiency measurements for 3D detectors (right) irradiated to 1015neq/cm2, demonstrating a high efficiency even at moderate bias voltages.
Fig. 1: Signal measurements on LGAD detectors irradiated to a range of fluences (left) and efficiency measurements for irradiated 3D detectors (right)

113

FPGA-accelerated machine learning inference for particle physics computing challenges

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The growing exploration of machine learning algorithms in particle physics offers new solutions to simulation, reconstruction, and analysis. These new machine learning solutions often lead to increased parallelization and faster reconstructions times on dedicated hardware, here specifically Field Programmable Gate Arrays (FPGAs). We explore the possibility that applications of machine learning simultaneously also solve the increasing computing challenges. Employing machine learning acceleration as a web service, we demonstrate a heterogeneous compute solution for particle physics experiments that requires minimal modification to the current computing model. First results with Project Brainwave by Microsoft Azure, using the Resnet-50 image classification model as an example, demonstrate inference times of approximately 50 (10) milliseconds with our experimental physics software framework using Brainwave as a cloud (edge) service. We also adapt the image classifier, for example, physics applications using transfer learning: jet identification in the CMS experiment and event classification in the Nova neutrino experiment at Fermilab. Solutions explored here are potentially applicable sooner than may have been initially realized. We will also briefly present a short status on real-time machine learning inference on FPGAs for the hardware trigger.

124

The RD53 data format and communication efficiency

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The RD53 Collaboration was established in 2013 to develop the next generation of pixel readout chips for the High Luminosity LHC detector upgrades. This proposal is to extend the scope of the collaboration to design the final pixel readout chip for the ATLAS and CMS upgrade detectors. A common design is proposed that can be fabricated with different pixel matrix sizes. The proposed work plan and resources are presented.

125

High Precision Timing Distribution for HL-LHC

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Study the HL-LHC pile-up impact on clock distribution systems and analysing the needs and requirements from experiments in terms of timing distribution in order to fight high pile-up effects of High Luminosity LHC. For this, one needs to define a common set of Figures of Merits (FoMs) allowing the characterization of a timing distribution system per application in the framework of LHC experiments. Review the proposed equipment references and methodologies to assess timing distribution systems against each HPTD FoM in a systematic and comparable way. Characterize and optimize existing components and clock distribution systems against these procedures. Provide tools or methods to help experiments optimize their systems and a framework to experiments to assess their systems against these methods

126

Precision timing detectors for the upgrade of the LHC experiments

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For the HL-LHC, the CMS and ATLAS collaborations have defined the detector geometry of their respective timing layers. Even though both collaborations have selected UFSD in their baseline design, the requirements for the two experiments differ in key aspects such as with pixel size, radiation hardness, number of layers. In this contribution we review the requirements and challenges in the design and production of the sensors for CMS and ATLAS, outlining similarities and differences.

127

Review of the TrackML challenge

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To explore what our universe is made of, scientists at CERN are colliding protons, essentially recreating mini big bangs, and meticulously observing these collisions with intricate silicon detectors.

While orchestrating the collisions and observations is already a massive scientific accomplishment, analyzing the enormous amounts of data produced from the experiments is becoming an overwhelming challenge.

Event rates have already reached hundreds of millions of collisions per second, meaning physicists must sift through tens of petabytes of data per year. And, as the resolution of detectors improve, ever better software is needed for real-time pre-processing and filtering of the most promising events, producing even more data.

To help address this problem, a team of Machine Learning experts and physics scientists working at CERN (the world largest high energy physics laboratory), has partnered with Kaggle and prestigious sponsors to answer the question: can machine learning assist high energy physics in discovering and characterizing new particles?

Specifically, in this competition, you're challenged to build an algorithm that quickly reconstructs particle tracks from 3D points left in the silicon detectors. This challenge consists of two phases:

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The Accuracy phase has run on Kaggle from May to 13th August 2018 (Winners to be announced by end September
The Throughput phase will run on Codalab starting in September 2018. Participants will submit their softwa
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All the necessary information for the Accuracy phase is available here on Kaggle site. The overall TrackML challenge web site is there.

128

The FCC pp, ep and ee tracking detector concepts and their projected performance

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As a part of the future circular collider conceptual design study for hadron–hadron physics (FCC-hh), conceptual designs of the tracking detectors are being developed to facilitate the accurate measurement of particle products resulting from the 100-TeV collisions.

129

Report from RAMP challenge November on fast vertexing

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Report from RAMP challenge November on fast vertexing

130

The Phase 2 run of the Belle II experiment

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Having started data taking at the beginning of 2018, the Belle II experiment is a substantial upgrade of the Belle detector, operating at the SuperKEKB collider at the KEK laboratory in Japan. The experiment represents the cumulative effort from the collaboration of experimental and detector physics, computing, and software development. Taking everything learned from the previous Belle experiment, which ran from 1998 to 2010, Belle II aims to probe deeper than ever before into the field of heavy quark physics. By achieving an integrated luminosity of 50 ab-1 and accumulating 50 times more data than the previous experiment across its lifetime, the Belle II experiment will push the high precision frontier of high energy physics. Both, accelerator and detector, have already successfully completed the commissioning phase, recording the first electron versus positron collisions in April 2018. This presentation will give an overview of the key accelerator and detector components that make the Belle II experiment possible, with emphasis on the achieved pixel detector performance during the Phase 2 commissioning stage.

133

Big data challenges for Earth observation imaging

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Remote sensing for earth observation is a tool that provides large information to monitor the vegetation, ice, water, sea levels, atmosphere temperature and wind, among other physical phenomena. This information comes in the form of multi and hyper spectral images covering the whole spectrum of emission of the sun. This information needs to be prepared and accommodated to be used, needs to be optically corrected, thermally calibrated, and co-registered to localisation coordinates in order to be used for physical parameter extraction. Computing model and processing steps has large similarities to those in particle physics.

134

Overview of CMOS sensors for future tracking detectors

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The CMOS sensors are emerging as one of the main candidate technologies for future tracking detectors in high luminosity colliders. Its capability of integrating the sensing diode into the CMOS wafer hosting the front-end electronics allows for reduced noise and higher signal sensitivity. They are suitable for high radiation environments due to the possibility of applying high depletion voltage and the availability of relatively high resistivity substrates. The use of a CMOS commercial fabrication process leads to their cost reduction and allows faster construction of large area detectors. A general perspective of the state of the art of these devices will be given in this contribution as well

as a summary of the main developments carried out with regard to these devices in the framework of the CERN RD50 collaboration.

135

CTD 2020 Proposal: Princeton

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136

CTD 2020 Proposal: LNF - Frascati National Laboratory

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137

Closing

138

City Center Guided Tour Information

139

Day 2 Introduction

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140

Day 3 Introduction

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141

Bus pickup