Connecting The Dots 2023

Report of Contributions

https://indico.cern.ch/e/CTD2023

Contribution ID: **1** Type: **Mini-workshop plenary**

Standalone track reconstruction and matching algorithms for the GPU-based High Level Trigger at LHCb

The LHCb Upgrade in Run 3 has changed its trigger scheme for a full software selection in two steps. The first step, HLT1, will be entirely implemented on GPUs and run a fast selection aiming at reducing the visible collision rate from 30 MHz to 1 MHz.
This selection relies on a partial reconstruction of the event. A version of this reconstruction starts with two monolithic tracking algorithms, the VELO-pixel tracking and the HybridSeeding on Scintillating-Fiber tracker, which reconstructs track segments in standalone subdetectors. Those segments are then matched through a matching algorithm in order to produce 'long'tracks, which form the base of the HLT1 reconstruction. We discuss the principle of these algorithms as well as the details of their implementation which allows them to run at a high-throughput configuration. An emphasis is put on the optimizations of the algorithms themselves in order to take advantage of the GPU architecture. Finally, results are presented in the context of the LHCb performance requirements for Run 3.

Authors: AGAPOPOULOU, Christina (CERN); HENRY, Louis (EPFL - Ecole Polytechnique Federale Lausanne (CH))

Presenter: HENRY, Louis (EPFL - Ecole Polytechnique Federale Lausanne (CH))

Session Classification: Co-located Real-time Tracking mini-workshop (13 October)

Contribution ID: **2** Type: **YSF Plenary**

Evaluation of Graph Sampling and Partitioning for Edge Classification and Tracking

Thursday 12 October 2023 11:20 (15 minutes)

Graph Neural Network (GNN) models proved to perform well on the particle track finding problem, where traditional algorithms become computationally complex as the number of particles increases, limiting the overall performance. GNNs can capture complex relationships in event data represented as graphs. However, training on large graphs is challenging due to computation and GPU memory requirements. The graph representation must fit into the GPU memory to fully utilize event data when training the GNN model. Otherwise, the graphs must be divided into smaller batches. We evaluate generic sampling methods that modify the conventional GNN training by using the mini-batch scheme to reduce the amount of required memory and facilitate parallel processing. Although splitting graphs may seem straightforward, striking a balance between computational efficiency and preserving the essential characteristics of the graph is challenging.

Through empirical experiments, we aim to test and tune graph sampling and partitioning methods to improve the edge classification performance for track reconstruction. Node, edge, and subgraph sampling methods are explored to divide data into smaller mini-batches for training. Preliminary results on the TrackML dataset show performance similar to full-batch training. These results prove the effectiveness of sampling methods in edge-level GNN classification tasks and the possibility of extending training to event graphs exceeding the top-of-the-line GPU's memory for improved performance.

Authors: LADUTSKA, Ivan (Youngstown State University); LAZAR, Alina; Mr PHAM, Minh-Tuan (University of Wisconsin Madison (US)); MURNANE, Daniel Thomas (Lawrence Berkeley National Lab. (US)); JU, Xiangyang (Lawrence Berkeley National Lab. (US)); CALAFIURA, Paolo (Lawrence Berkeley National Lab. (US)); LAZAR, Alina

Presenters: LAZAR, Alina; LAZAR, Alina

Session Classification: YSF Plenary

Contribution ID: **3** Type: **Plenary**

Downstream: a new algorithm at LHCb to reconstruct Long-Lived particles in the first level of the trigger.

Wednesday 11 October 2023 09:30 (25 minutes)

Long-lived particles (LLPs) are present in the SM and in many new physics scenarios beyond it but they are very challenging to reconstruct at LHC due to their very displaced vertices. A new algorithm, called "Downstream", has been developed at LHCb which is able to reconstruct and select LLPs in real time at the first level of the trigger (HLT1). It is executed on GPUs inside the Allen framework and in addition to an optimized strategy, it uses a Neural Network (NN) implementation to increase the track efficiency and reduce the ghost rates, with very high throughput and limited time budget. Besides serving to calibrate and align the detectors with Ks and L0 particles, the Downstream algorithm will largely increase the LHCb physics potential during the Run3.

Authors: DE OYANGUREN CAMPOS, Arantza (Univ. of Valencia and CSIC (ES)); Mr JASHAL, Brij Kishor (IFIC, Univ. of Valencia, CSIC (ES) and Tata Institute of Fundamental Research (TIFR)); ZHUO, Jiahui (Univ. of Valencia and CSIC (ES))

Presenter: DE OYANGUREN CAMPOS, Arantza (Univ. of Valencia and CSIC (ES))

Session Classification: Plenary

Contribution ID: **4** Type: **Plenary**

Expected tracking performance of the ATLAS Inner Tracker Upgrade for Phase-II

Tuesday 10 October 2023 14:00 (30 minutes)

With its increased number of proton-proton collisions per bunch crossing, track reconstruction at the High-Luminosity Large Hadron Collider (HL-LHC) is a complex endeavor. The Inner Tracker (ITk) is a silicon-only replacement of the current ATLAS Inner Detector as part of its Phase-II upgrade.
It is specifically designed to handle the challenging conditions at the HL-LHC, resulting from greatly increased pile-up.

On the path towards the increased luminosity starting in LHC Run 4, the critical milestone of unifying the ITk and LHC Run 3 reconstruction software releases has been completed. This allows deployment of the software-level improvements added for LHC Run 3. At the same time, improvements to the simulated description of the detector construction, readout and reconstruction of ITk have been implemented.

With the state-of-the-art engineering description of ITk, the performance of the detector can be evaluated, leveraging the aforementioned improvements in simulation and reconstruction. This contribution will report on the updated performance of ITk tracking at high luminosities, which is increasingly representative of the actual expected reconstruction in LHC Run 4.

At the same time, the ATLAS upgrade effort consists as well of a comprehensive software upgrade programme, whose goal is not only to achieve the ultimate physics performance, but at the same time to modernise the software technology, to make best use of upcoming and future processing technologies and ensure maintainability throughout the operation of the experiment. In order to achieve these objectives, the ATLAS Collaboration has decided to extensively use ACTS for the Phase-II reconstruction software.

In this contribution, the current status of the ACTS integration for the ATLAS ITk track reconstruction is presented, with emphasis on the improvements of the track reconstruction software and the implementation of an ATLAS Phase-II EDM, interfaced with the ATLAS xAOD IO infrastructure.

Author: GESSINGER, Paul (CERN)

Presenter: GESSINGER, Paul (CERN)

Session Classification: Plenary

Contribution ID: **5** Type: **Poster**

Heterogeneity in Graph Neural Networks for Track Reconstruction in the ATLAS Upgrade ITk Detector

Tuesday 10 October 2023 19:21 (3 minutes)

The upcoming High Luminosity phase of the Large Hadron Collider (HL-LHC) represents a steep increase in pileup rate ($\langle\mu\rangle = 200$) and computing resources for offline reconstruction of the ATLAS Inner Tracker (ITk), for which graph neural networks (GNNs) have been demonstrated as a promising solution. The GNN4ITk pipeline has successfully employed a GNN architecture for edge classification and showed the competitiveness of this approach in HL-LHC-like pile-up conditions. We present in this study a new heterogeneous GNN architecture that handles the pixel- and strip-subdetectors using separate graph subnetworks, reflecting the naturally differing geometries of these regions. We investigate the impact of varying the degree of heterogeneity in the model and identify the optimal complexity associated with a heterogeneous architecture. In addition, we examine the use of the underlying hit cluster information in model training and demonstrate that cluster-level input is richer and more discriminatory than space point coordinates alone. With this added sophistication, the track reconstruction efficiency and fake rate of the GNN4ITk pipeline using the heterogeneous GNN compares favourably with the results from the homogeneous GNN.

Authors: MURNANE, Daniel Thomas (Lawrence Berkeley National Lab. (US)); CHAN, Jay (University of Wisconsin Madison (US)); Mr PHAM, Minh-Tuan (University of Wisconsin Madison (US)); CALAFIURA, Paolo (Lawrence Berkeley National Lab. (US)); JU, Xiangyang (Lawrence Berkeley National Lab. (US))

Presenter: Mr PHAM, Minh-Tuan (University of Wisconsin Madison (US))

Session Classification: Poster

Contribution ID: **6** Type: **Mini-workshop plenary**

Trigger Level Tracking With Neural Networks on Heterogeneous Computing Systems

The high luminosity upgrade of the LHC aims to better probe the higgs potential and self coupling. The Event Filter task force has been charged with exploring novel approaches to charged particle tracking to be employed in the upgraded ATLAS trigger system, capable of analyzing high luminosity events in real time. We present a neural network (NN) based approach to predicting and identifying hits left by particles at trigger level. In this bottom-up approach, the complexity of and input to the NN are kept minimal to allow the NN to be implemented in a heterogeneous computing system, such as with FPGA or GPU. This hardware based approach allows for increased data throughput, shorter latency and, crucially, flexibility to improve the algorithm in the future.

Author: GEKOW, Alex (Ohio State University (US))

Presenter: GEKOW, Alex (Ohio State University (US))

Session Classification: Co-located Real-time Tracking mini-workshop (13 October)

Contribution ID: **7** Type: **Plenary**

Novel Approaches for ML-Assisted Particle Track Reconstruction and Hit Clustering

Thursday 12 October 2023 10:00 (25 minutes)

Track reconstruction is a vital aspect of High-Energy Physics (HEP) and plays a critical role in major experiments. In this study, we delve into unexplored avenues for particle track reconstruction and hit clustering. Firstly, we enhance the algorithmic design by utilizing a "simplified simulator" (REDVID) to generate training data that is specifically designed for simplicity. We demonstrate the effectiveness of this data in guiding the development of optimal network architectures.

Additionally, we investigate the application of image segmentation networks for this task, exploring their potential for accurate track reconstruction. Moreover, we approach the task from a different perspective by treating it as a hit sequence to track sequence translation problem. Specifically, we explore the utilization of Transformer architectures for tracking purposes. By considering this novel approach, we aim to uncover new insights and potential advancements in track reconstruction.

Through our comprehensive exploration, we present our findings and draw conclusions based on the outcomes of our investigations. This research sheds light on previously unexplored avenues and provides valuable insights for the field of particle track reconstruction and hit clustering in HEP.

Authors: CARON, Sascha (Nikhef National institute for subatomic physics (NL)); ODYURT, Uraz (Nikhef National institute for subatomic physics (NL))

Co-authors: VARBANESCU, Ana-Lucia (University of Twente); FERRER SÁNCHEZ, Antonio (University of Valencia); MARTIN-GUERRERO, José D. (University of Valencia); DOBREVA, Nadezhda (Radboud University); Dr RUIZ DE AUSTRI BAZAN, Roberto (University of Valencia); AAIJ, Roel (Nikhef National institute for subatomic physics (NL)); ZHAO, Yue (SURF); WOLFFS, Zef (Nikhef National institute for subatomic physics (NL))

Presenter: ODYURT, Uraz (Nikhef National institute for subatomic physics (NL))

Session Classification: Plenary

Contribution ID: **8** Type: **Poster**

Flexible Hough Transform FPGA Implementation for the ATLAS Event Filter

Tuesday 10 October 2023 19:03 (3 minutes)

The ATLAS Run3 will conclude as planned in late 2025 and will be followed by the so-called Long Shutdown 3. During this period all the activities exclusively dedicated to Run4 will converge on the closing of the prototyping development and in the start of the production and integration, to reach the data collection in 2029. These upgrades are principally led by the increase of the peak of luminosity up to 5-7.5 x 1034 cm-2 s-1 of LHC expected for the future High Luminosity-LHC operations. One of the major changes ATLAS will face will be an increase in the amount of data to be managed in its Trigger and Data Acquisition system. The triggering operations are targeting to reach from 40 MHz of input event a discrimination in the middle throughput of 1 MHz and finally in the last stage of 10 kHz. The second process will use all the information acquired by the ATLAS detector to complete the event selection, including the study of the tracks of the innermost sub-detector, the Inner Tracker. This tracking operation is planned to be performed with a PC farm because of the need for high precision. The list of the architectures under study to speed-up this process includes the use of a "hardware accelerator"farm, an infrastructure made of interconnected accelerators such as GPUs and FPGAs to speed up the tracking processes. The project described here is a proposal for a tuned Hough Transform algorithm implementation on high-end FPGA technology, versatile to adapt to different tracking situations. The development platform allows the study of different datasets from an ATHENA software simulating the firmware. AMD-Xilinx FPGA has been chosen to test and evaluate this implementation. The system was tested with a ATLAS realistic environment. Simulated 200 pile up events have been exploited to measure the effectiveness of the algorithm. The processing time is averagely in the order of < 10 μs according to internal preliminary estimates, with the possibility to run two events at a time per algorithm instance. Internal efficiency tests have shown conditions that reach > 95 % of the track-finding performance for single muon tracking.

Authors: GABRIELLI, Alessandro (Università e INFN, Bologna (IT)); ALFONSI, Fabrizio (Universita e INFN, Bologna (IT))

Presenter: ALFONSI, Fabrizio (Universita e INFN, Bologna (IT))

Session Classification: Poster

Contribution ID: **9** Type: **Poster**

Obtaining requirements for the future ATLAS Event Filter Tracking system

Tuesday 10 October 2023 19:06 (3 minutes)

The High-Luminosity LHC shall be able to provide a maximum peak luminosity of 5×10^{34} $cm^{-2}s^{-1}$, corresponding to an average of 140 simultaneous p-p interactions per bunch crossing (pile-up), at the start of Run 4, around 2028. The ATLAS experiment will go through major changes to adapt to the high-luminosity environment, in particular in the DAQ architecture and in the trigger selections. The use of the new high-resolution full-silicon inner tracker (ITk) in the high-level-trigger (also called Event Filter) is of paramount importance to improve the trigger selection and purity and reduce the trigger rates against the large background of low-energy pile-up jets. The Event Filter Tracking system is under design as an heterogeneous and flexible system, able to combine algorithms running in CPUs and on accelerators, like FPGAs and/or GPUs, on commodity servers, to allow both a regional reconstruction at the expected 1MHz L1 rate and the full event reconstruction at 150 kHz. The challenge of the Event Filter Tracking design is to maximize the tracking performance of the algorithms while maintaining an adequate data throughput through the processors farm, using reasonable power. In this presentation, the results of studies performed to evaluate the minimal tracking performance required are presented. In particular, the tracking efficiency and the resolution on the track transverse momentum will impact the leptons selections, while the resolution on the track impact parameters will affect the hadronic selections, including b-tagging and multi-jet selections.

Authors: PENN, Gregory; PENN, Gregory

Co-author: CAMPLANI, Alessandra (University of Copenhagen (DK))

Presenters: PENN, Gregory; PENN, Gregory

Session Classification: Poster

Contribution ID: **10** Type: **Mini-workshop plenary**

Track reconstruction for the ATLAS Phase-II High-Level Trigger using Graph Neural Networks on FPGAs

The High-Luminosity LHC (HL-LHC) will provide an order of magnitude increase in integrated luminosity and enhance the discovery reach for new phenomena. The increased pile-up foreseen during the HL-LHC necessitates major upgrades to the ATLAS detector and trigger. The Phase-II trigger will consist of two levels, a hardware-based Level-0 trigger and an Event Filter (EF) with tracking capabilities. Within the Trigger and Data Acquisition group, a heterogeneous computing farm consisting of CPUs and potentially GPUs and/or FPGAs is under study, together with the use of modern machine learning algorithms such as Graph Neural Networks (GNNs).

GNNs are a powerful class of geometric deep learning methods for modeling spatial dependencies via message passing over graphs. They are well-suited for track reconstruction tasks by learning on an expressive structured graph representation of hit data and considerable speedup over CPU-based execution is possible on FPGAs.

The focus of this talk is a study of track reconstruction for the Phase-II EF system using GNNs on FPGAs. We explore each of the steps in a GNN-based EF tracking pipeline: graph construction, edge classification using an interaction network (IN), and track reconstruction. Several methods and hardware platforms are under evaluation, studying optimizations of the GNN approach aimed to minimize FPGA resources utilization and maximize throughput while retaining high track reconstruction efficiency and low fake rates required for the ATLAS Phase-II EF tracking system. These studies include IN model hyperparameter tuning, model pruning and quantization-aware training, and sequential processing of sub-graphs over the detector.

Authors: GUPTA, Sachin; GUPTA, Sachin (Ruprecht Karls Universitaet Heidelberg (DE))

Co-author: CAMPLANI, Alessandra (University of Copenhagen (DK))

Presenters: GUPTA, Sachin; GUPTA, Sachin (Ruprecht Karls Universitaet Heidelberg (DE))

Session Classification: Co-located Real-time Tracking mini-workshop (13 October)

Contribution ID: **12** Type: **Plenary**

The performance of the ATLAS Inner Detector tracking trigger, including new long-lived particle triggers, in high pileup collisions at 13.6 TeV at the Large Hadron Collider in Run-3

Wednesday 11 October 2023 10:00 (25 minutes)

The performance of the Inner Detector tracking trigger of the ATLAS experiment at the Large Hadron Colloder (LHC) is evaluated for the data taken for LHC Run-3 during 2022. Included are results from the evolved standard trigger track reconstruction, and from new unconventional tracking strategies used in the trigger for the first time in Run-3.
From Run-3, the application of Inner Detector tracking in the trigger has been significantly expanded, in particular full-detector tracking is utilized for hadronic signatures (such as jets and missing transverse energy triggers) for the first time. To meet computing resource limitations, several new features, including machine-learning based track seeding, have been developed and are discussed, together with many additional improvements with respect to the trigger tracking used in LHC Run-2. The Large Hadron LHC, as the world's highest energy particle accelerator, provides a unique opportunity for directly searching for new physics Beyond the Standard Model (BSM). Massive long-lived particles (LLPs), which are absent in the Standard Model, can occur in many well-motivated theories of physics BSM. These new massive LLPs can decay into other particles far from the LHC interaction region, resulting in unusual experimental signatures and hence requiring customised and complex experimental techniques for
their identification. Prior to Run-3, the ATLAS trigger did not include dedicated tracking triggers for the explicit identification of massive LLPs decaying in the inner tracking detectors. To enhance the sensitivity of searches, a series of new triggers customised for various unconventional tracking signatures, such as "displaced" tracks, and short tracks which "disappear" within the tracking detector, have been developed for Run-3 data taking, starting from 2022. The high performance of the inner detector trigger remains essential for the ATLAS physics programs in the Run-3 data, in particular for the many precision measurements of the Standard Model and now, in the searches for new physics. For the first time, the development and performance of these new triggers for the 2022 data taking is presented, together with the that from standard tracking.

Author: LONG, Jonathan (Univ. Illinois at Urbana Champaign (US))

Co-author: CAMPLANI, Alessandra (University of Copenhagen (DK))

Presenter: LONG, Jonathan (Univ. Illinois at Urbana Champaign (US))

Session Classification: Plenary

Contribution ID: **13** Type: **Mini-workshop plenary**

Studies on track finding algorithms based on machine learning with GPU and FPGA

Track finding in high-density environments is a key challenge for experiments at modern accelerators. In this presentation we describe the performance obtained running machine learning models studied for the ATLAS Muon High Level Trigger. These models are designed for hit position reconstruction and track pattern recognition with a tracking detector, on a commercially available Xilinx FPGA: Alveo U50, Alveo U250, and Versal VCK5000. We compare the inference times obtained on a CPU, on a GPU and on the FPGA cards. These tests are done using TensorFlow libraries as well as the TensorRT framework, and software frameworks for AI-based applications acceleration. The inference times obtained are compared to the needs of present and future experiments at LHC.

Author: DI BELLO, Francesco Armando (INFN e Universita Genova (IT))

Co-author: CAMPLANI, Alessandra (University of Copenhagen (DK))

Presenter: DI BELLO, Francesco Armando (INFN e Universita Genova (IT))

Session Classification: Co-located Real-time Tracking mini-workshop (13 October)

Contribution ID: **14** Type: **Mini-workshop plenary**

Real time event-level track pattern recognition with Graph Neural Networks in CMS

Detecting the signals of very low-pT muons with traditional track reconstruction algorithms, such as Kalman filters, is very challenging. In case of the decay of a tau lepton decaying into three muons, the signature includes three very low pT muons in the forward region of the CMS detector. Some or all of these muons might not carry enough pT to reach all stations of the CMS muon system. Even for muons reaching the CMS muon system, individual low momentum muon track reconstruction at hardware trigger level is prohibited with the traditional reconstruction algorithms, due to multiple scattering, the nonuniform magnetic field and large combinatorics especially in high pile up environment at the LHC/High-Luminosity LHC. An alternative approach is presented where a Graph Neural Network is trained to make use of the correlation between hits in the muon detectors to detect the presence of the τ -> 3 μ signature. The muon hits form the nodes of the graph and are connected by edges encoding their relative position. Based on this architecture a classifier is developed for use in the upgraded L1 trigger of the CMS detector for the HL-LHC. With this approach, a significant improvement of a factor of 5 to 10 in acceptance for τ -> 3 μ events is achieved compared to previous studies in CMS phase 2 muon system and Level-1 TDR. Support for GNNs designed in pytorch geometric is implemented into the hls4ml toolkit, which enables us to generate a FPGA implementation of the model for use in the L1 trigger.

Authors: SIMON, Benjamin (Purdue University (US)); SCHULTE, Jan-Frederik (Purdue University (US)); LIU, Miaoyuan (Purdue University (US))

Co-authors: GUERRERO, Daniel (Fermi National Accelerator Lab. (US)); YUN, Hyeon-Seo (Purdue University (US)); KONIGSBERG, Jacobo (University of Florida (US)); LI, Pan; MIAO, Siqi (Purdue University)

Presenter: LIU, Miaoyuan (Purdue University (US))

Session Classification: Co-located Real-time Tracking mini-workshop (13 October)

Contribution ID: **15** Type: **Poster**

Real-time long-lived particle reconstruction in LHCb's HLT2

Tuesday 10 October 2023 19:09 (3 minutes)

LHCb is optimised to study particles decaying a few millimetres from the primary vertex using tracks that traverse the length of the detector. Recently, extensive efforts have been undertaken to enable the study of long-lived particles decaying within the magnet region, up to 7.5 m from the interaction point. This approach presents several challenges, particularly when considering real-time analysis within LHCb's trigger system. These include large track combinatorics, a tracker with a low magnetic field and short lever arm, as well as the need to extrapolate tracks through a strong, inhomogeneous magnetic field to find vertices. Several approaches have been developed to tackle these challenges in LHCb's HLT2, including new geometry-based selections, MVA-based vertex finding and modifications to vertex fitting. This talk presents these developments and future prospects.

Author: SANDERSWOOD, Izaac (Univ. of Valencia and CSIC (ES))

Presenter: SANDERSWOOD, Izaac (Univ. of Valencia and CSIC (ES))

Session Classification: Poster

Contribution ID: **16** Type: **Mini-workshop plenary**

A real-time demonstrator of track reconstruction with FPGAs at LHCb

The upgraded LHCb detector has started its Run 3 of data taking in 2022, with a completely overhauled DAQ system, reading out and processing the full detector data at every LHC bunch crossing (30 MHz average rate). At the same, an intense R&D activity is taking place, with the aim of further improving the real-time data processing performance of LHCb, in view of a further luminosity upgrade of the experiment ("Upgrade II").
In this work, we describe the experience gained with a prototype device for a 30 MHz real-time tracking in the LHCb VELO detector, implemented in state-of-art PCIe-hosted FPGA cards interconnected by fast optical links.
The system is capable of processing live LHCb data opportunistically during physics data taking, thanks to a dedicated testbed facility fed by the experiment monitoring system. We describe, amongst other things, the system used to organize and optimize the high-speed distribution of data to the components, and the synchronization with the most updated alignment constants to be used in track reconstruction.

Authors: CONTU, Andrea (INFN); LAZZARI, Federico (Universita di Pisa & INFN Pisa (IT)); TERZUOLI, Francesco (Università di Siena & INFN Pisa (IT)); BASSI, Giovanni (SNS & INFN Pisa (IT)); PUNZI, Giovanni (Universita & INFN Pisa (IT)); TUCI, Giulia (Heidelberg University (DE)); MORELLO, Michael J. (SNS and INFN-Pisa (IT)); FANTECHI, Riccardo (INFN - Sezione di Pisa); KOTRIAKHOVA, Sofia (Universita e INFN, Ferrara (IT)); BALDINI, Wander (Universita e INFN, Ferrara (IT))

Presenter: TERZUOLI, Francesco (Università di Siena & INFN Pisa (IT))

Session Classification: Co-located Real-time Tracking mini-workshop (13 October)

Contribution ID: **18** Type: **Plenary**

Physics Performance of the ATLAS GNN4ITk Track Reconstruction Chain

Wednesday 11 October 2023 16:00 (25 minutes)

Applying graph-based techniques, and graph neural networks (GNNs) in particular, has been shown to be a promising solution [1-3] to the high-occupancy track reconstruction problems posed by the upcoming HL-LHC era. Simulations of this environment present noisy, heterogeneous and ambiguous data, which previous GNN-based algorithms for ATLAS ITk track reconstruction could not handle natively. We present a range of upgrades to the GNN4ITk pipeline that allow detector regions to be handled heterogeneously, ambiguous and shared nodes to be reconstructed more rigorously, and tracks-of-interest to be treated with more importance in training 4. With these improvements, we are able to present detailed direct comparisons with existing reconstruction algorithms on a range of physics metrics, including reconstruction efficiency across particle type and pileup condition, jet reconstruction performance in dense environments, displaced tracking, and track parameter resolutions. By integrating this solution within the offline ATLAS Athena framework, we also explore a range of reconstruction chain configurations, for example by using the GNN4ITk pipeline to build regions-of-interest while using traditional techniques for track cleaning and fitting.

1 EPJ Web Conf. 251 (2021) 03047
2 Eur. Phys. J. C 81 (2021) 876
3 ATL-ITK-PROC-2022-006
4 IDTR-2023-01

Authors: VALLIER, Alexis (L2I Toulouse, CNRS/IN2P3, UT3); ROUGIER, Charline (Laboratoire des 2 Infinis - Toulouse, CNRS / Univ. Paul Sabatier (FR)); Dr COLLARD, Christophe (Laboratoire des 2 Infinis - Toulouse, CNRS / Univ. Paul Sabatier); MURNANE, Daniel Thomas (Lawrence Berkeley National Lab. (US)); TORRES, Heberth (L2I Toulouse, CNRS/IN2P3, UT3); STARK, Jan (Laboratoire des 2 Infinis - Toulouse, CNRS / Univ. Paul Sabatier (FR)); BURLESON, Jared (University of Illinois at Urbana-Champaign); NEUBAUER, Mark (Univ. Illinois at Urbana Champaign (US)); ATKINSON, Markus Julian (Univ. Illinois at Urbana Champaign (US)); Mr PHAM, Minh-Tuan (University of Wisconsin Madison (US)); CALAFIURA, Paolo (Lawrence Berkeley National Lab. (US)); CAILLOU, Sylvain (Centre National de la Recherche Scientifique (FR)); JU, Xiangyang (Lawrence Berkeley National Lab. (US))

Presenter: TORRES, Heberth (L2I Toulouse, CNRS/IN2P3, UT3)

Session Classification: Plenary

Contribution ID: **19** Type: **Plenary**

End-to-end Particle-flow Reconstruction Algorithm for Highly Granular Calorimeters

Tuesday 10 October 2023 15:05 (25 minutes)

We present an end-to-end particle-flow reconstruction algorithm for highly granular calorimeters. Starting from calorimeter hits and reconstructed tracks the algorithm filters noise, separates showers, regresses their energy, provides an energy uncertainty estimate, and predicts the type of particle. The algorithm is trained on data from a simulated detector that matches the complexity of the CMS high-granularity calorimeter (HGCAL) for which it can be retrained in the future. Detector hits and reconstructed tracks are embedded in a dynamic graph. Information between graph nodes is then exchanged between neighbours weighted by their respective distance in a low dimensional latent space. The network is trained using the object condensation loss, a graph segmentation technique that allows to cluster an arbitrary number of showers in every event while simultaneously performing regression and classification tasks. We discuss the network's performance in terms of its shower reconstruction efficiency, its energy resolution and uncertainty estimate, as well as the accuracy of its particle identification. Additionally we discuss the model's jet reconstruction performance and evaluate the model's computational efficiency. To our knowledge this is the first implementation of an end-to-end particle-flow reconstruction algorithm aimed at highly granular calorimeters.

Authors: KIESELER, Jan (CERN); Mr ZEHETNER, Philipp (Ludwig Maximilians Universitat (DE)); QASIM, Shah Rukh (CERN)

Presenter: Mr ZEHETNER, Philipp (Ludwig Maximilians Universitat (DE))

Session Classification: Plenary

Contribution ID: **20** Type: **Plenary**

Track reconstruction with mkFit and developments towards HL-LHC

Tuesday 10 October 2023 14:35 (25 minutes)

MkFit is a Kalman filter-based track reconstruction algorithm that uses both thread- and data-level parallelism. It has been deployed in the Run-3 offline workflow of the CMS experiment. The CMS tracking performs a series of iterations to reconstruct tracks of increasing difficulty. MkFit has been adopted for several of these iterations, which contribute to the majority of reconstructed tracks. When tested in the standard conditions for production jobs, MkFit has been shown to speed up track pattern recognition by an average of 3.5x. This speedup is due to a number of factors, including vectorization, a lightweight geometry description, improved memory management, and single precision. Efficient vectorization is achieved with several compilers and relies on a dedicated library for small matrix operations, Matriplex, which has recently been released in a public repository. The mkFit geometry and material description has been generalized to support the Phase-2 upgraded tracker geometry for the HL-LHC and potentially other detector configurations. The implementation strategy and preliminary results with the HL-LHC geometry are presented. Speedups in track building from mkFit imply that track fitting becomes a comparably time consuming step of the tracking chain. Prospects for an mkFit implementation of the track fit are also discussed.

Authors: REINSVOLD HALL, Allison (Fermilab); YAGIL, Avi (Univ. of California San Diego (US)); RILEY, Daniel Sherman (Cornell University (US)); CERATI, Giuseppe (Fermi National Accelerator Lab. (US)); GIANNINI, Leonardo (Univ. of California San Diego (US)); VOURLIOTIS, Manos (Univ. of California San Diego (US)); MASCIOVECCHIO, Mario (Univ. of California San Diego (US)); TADEL, Matevz (Univ. of California San Diego (US)); KORTELAINEN, Matti (Fermi National Accelerator Lab. (US)); Dr GARTUNG, Patrick (Fermilab (US)); ELMER, Peter (Princeton University (US)); WITTICH, Peter (Cornell University (US)); KRUTELYOV, Slava (Univ. of California San Diego (US)); LANTZ, Steven R (Cornell University (US)); REID, Tres (Cornell University (US))

Presenter: KRUTELYOV, Slava (Univ. of California San Diego (US))

Session Classification: Plenary

Contribution ID: **21** Type: **Mini-workshop plenary**

FPGA-based architecture for a real-time track reconstruction in the LHCb Scintillating Fibre Tracker beyond Run 3

Finding track segments downstream of the magnet is some of the most important and computationally expensive task of the first stage of the new GPU-based software trigger of the LHCb Upgrade I, that has started operation in Run 3. These segments are essential to form all good physics tracks with a very high precision momentum measurement, when combined with those reconstructed in the vertex track detector, and to reconstruct long-lived particles, such as Kshort and strange baryons, decaying after the vertex track detector, largely boosting the physics reach of the experiment. In this talk, we discuss the collaboration plans to install a real-time tracking device based on distributed system of FPGAs, dedicated to the reconstruction of particles trajectories in the forward Scintillating Fibre tracker detector, with the aim to preserve the full physics potential of the experiment in Run 4, and in view of Run 5 (Upgrade II) at higher instantaneous luminosity. This system will enhance the DAQ system of the experiment, and will run in real time during physics data taking, reconstructing tracks on-the-fly at the LHC collision rate, before the software trigger processing begins. The design and the expected performance of this device, with the capability of processing events at the full LHC collision rate of 30 MHz is discussed.

Authors: CONTU, Andrea (INFN); XU, Ao (Universita & INFN Pisa (IT)); DE OYANGUREN CAMPOS, Arantza (Univ. of Valencia and CSIC (ES)); Mr JASHAL, Brij Kishor (IFIC, Univ. of Valencia, CSIC (ES)); MENDOZA, Diego (Instituto de Física Corpuscular - CERN); LAZZARI, Federico (Universita di Pisa & INFN Pisa (IT)); TERZUOLI, Francesco (Università di Siena & INFN Pisa (IT)); BASSI, Giovanni (SNS & INFN Pisa (IT)); PUNZI, Giovanni (Universita & INFN Pisa (IT)); TUCI, Giulia (Heidelberg University (DE)); ZHUO, Jiahui (Univ. of Valencia and CSIC (ES)); HE, Jibo (University of Chinese Academy of Sciences (CN)); PICA, Lorenzo (SNS & INFN Pisa (IT)); MARTINELLI, Maurizio (Universita & INFN, Milano-Bicocca (IT)); MORELLO, Michael J. (SNS and INFN-Pisa (IT)); SHI, Qi (University of Chinese Academy of Sciences (CN)); FANTECHI, Riccardo (Universita & INFN Pisa (IT)); KOTRIAKHOVA, Sofia (Universita e INFN, Ferrara (IT)); BALDINI, Wander (Universita e INFN, Ferrara (IT))

Presenter: MORELLO, Michael J. (SNS and INFN-Pisa (IT))

Session Classification: Co-located Real-time Tracking mini-workshop (13 October)

Contribution ID: **22** Type: **Poster**

Seeding with Machine Learning in ACTS

Tuesday 10 October 2023 19:12 (3 minutes)

To prepare for the High Luminosity phase of the Large Hadron Collider at CERN (HL-LHC), the ATLAS experiment is replacing its innermost components with a full-silicon tracker (ITk), to improve the spatial resolution of the tracks measurements and increase the data readout rate. However, this upgrade alone will not be sufficient to cope with the tremendous increase of luminosity, and significant improvements have to be incorporated into the existing tracking software to keep the required computing resources at a realistic level.

In this poster, we are focusing on the track seeds reconstruction within the ITk detector, and we explore the possibility to use hashing techniques to improve the seed reconstruction efficiency, limit the combinatorics and eventually reduce the computing time. Metric learning is then used to tune our algorithm for the different regions of the detector, and to increase the robustness against time-dependent detector conditions.

The code developments are done within the ACTS framework, an experiment-independent toolkit for charged particles track reconstruction.

Author: COUTHURES, Jeremy (Centre National de la Recherche Scientifique (FR))

Presenter: COUTHURES, Jeremy (Centre National de la Recherche Scientifique (FR))

Session Classification: Poster

Contribution ID: **23** Type: **Plenary**

Application of single-layer particle tracking for radiation field decomposition and interaction point reconstruction at MoEDAL

Tuesday 10 October 2023 16:40 (25 minutes)

In particle physics experiments, hybrid pixel detectors are an integral part of the tracking systems closest to the interaction points. Utilising excellent spatial resolution and high radiation resilience, they are used for particle tracking via the "connecting the dots"method seen in layers of an onion-like structure. In the context of the Medipix Collaborations, a novel, complimentary approach to particle detection has been proposed. This approach relies on analysis of tracks seen in a pixel matrix. Characteristic track features are exploited for the identification of impinging particles, precise particle trajectory, or reaction kinematics reconstruction.

The presented work will concentrates on hybrid silicon detectors of the Timepix3 type 1, which consist of a radiation-sensitive layer typically made of silicon with dimensions 1.408 × 1.408 × 0.05 cm. The active material is then bump bonded to a readout chip at 256 × 256 points with a pitch of 55 μm. Using these detectors, novel algorithms for particle fluence, particle identification, and particle trajectory reconstruction (tracking) are developed mainly for single-layer detectors. These new algorithms were trained and extensively tested with simulation data, then verified with real-world data sets of known particle composition, outperforming state-of-the-art [2,3] in terms of accuracy and stability. In particular, a significant improvement in the tracking resolution was achieved. The capability of proton spectrum determination in compact single-layer detectors was subsequently demonstrated at a hadron therapy facility and using data acquired by the Space Application Timepix Radiation Monitor (SATRAM) in the inner Van-Allen radiation belt.

As a high energy physics application, the methods were applied to data taken at the MoEDAL-MAPP (Monopoles and Exotics Detector At LHCb) [4,5] experiment at the Large Hadron Collider located in CERN, where Timepix3 is at a distance of 1 m from the interaction point. The improved particle tracking algorithms and an unobstructed view allow for the determination of the particle trajectories arising at the point of collisions of opposing beams at the Large Hadron Collider. The improved resolution permits a quantification of structural properties of the field, showing clear variation during lead-lead and proton-proton collision periods (Figure 1). Similarly, the point of interaction and background sources were isolated separately, allowing for the individual classification of the spectral properties of both field contributions.

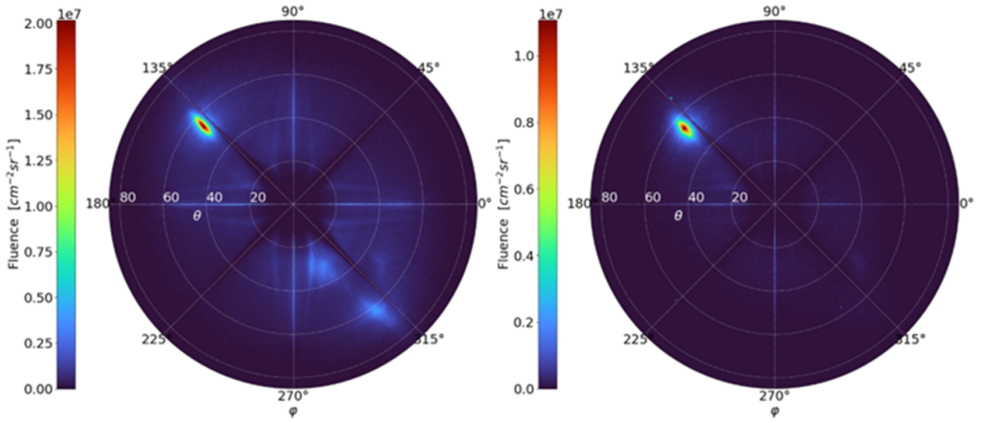

Figure 1: Measured field directionality structure during lead-lead (left) and proton-proton (right) collision periods at MoEDAL using a Random Forrest Regressor combined with particle track line fit methods

1 Poikela, T., et al. "Timepix3: a 65K channel hybrid pixel readout chip with simultaneous ToA/ToT and sparse readout." Journal of instrumentation 9.05 (2014): C05013.

2 Bergmann, B., et al. "Particle tracking and radiation field characterization with Timepix3 in ATLAS." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 978 (2020): 164401.

3 P. Mánek et al. "Improved algorithms for determination of particle directions with Timepix3". In: Journal of Instrumentation 17.01 (Jan. 2022), p. C01062. URL: https://dx.doi.org/10.1088/1748-0221/17/01/C01062

4 M. Fairbairn and J. L. Pinfold, "MoEDAL –a new light on the high-energy frontier", Contemporary Physics, 58:1, pp. 1-24 (2017). doi: 10.1080/00107514.2016.1222649

[5] J. Pinfold (MoEDAL collaboration), "MoEDAL-MAPP –an LHC Dedicated Detector Search Facility"URL: https://arxiv.org/abs/2209.03988

Authors: GARVEY, Declan (Institute of Technical and Experimental Physics CTU in Prague); Mr GARVEY, Declan (Institute of Experimental and Applied Physics, Czech Technical University in Prague)

Co-authors: Dr BERGMANN, Benedikt (Institute of Experimental and Applied Physics, Czech Technical University in Prague); Mr MÁNEK, Petr (Department of Physics and Astronomy, University College London); Dr SMOLYANSKIY, Petr (Institute of Experimental and Applied Physics, Czech Technical University in Prague); Dr POSPÍŠIL, Stanislav (Institute of Experimental and Applied Physics, Czech Technical University in Prague)

Presenters: GARVEY, Declan (Institute of Technical and Experimental Physics CTU in Prague); Mr GARVEY, Declan (Institute of Experimental and Applied Physics, Czech Technical University in Prague)

Session Classification: Plenary

Contribution ID: **24** Type: **Plenary**

Improving tracking algorithms with machine learning: a case for line-segment tracking at the High Luminosity LHC

Thursday 12 October 2023 09:30 (25 minutes)

In this work, we present a study on ways that tracking algorithms can be improved with machine learning (ML). We base this study on a line-segment-based tracking (LST) algorithm that we have designed to be naturally parallelized and vectorized in order to efficiently run on modern processors. LST has been developed specifically for the Compact Muon Solenoid (CMS) Experiment at the LHC, towards the High Luminosity LHC (HL-LHC) upgrade. Moreover, we have already shown excellent efficiency and performance results as we iteratively improve LST, leveraging a full simulation of the CMS detector. At the same time, promising deep-learning-based tracking algorithms, such as Graph Neural Networks (GNNs), are being pioneered on the simplified TrackML dataset. These results suggest that parts of LST could be improved or replaced by ML. Thus, a thorough, step-by-step investigation of exactly how and where ML can be utilized, while still meeting realistic HL-LHC performance and efficiency constraints, is implemented as follows. First, a lightweight neural network is used to replace and improve upon explicitly defined track quality selections. This neural network is shown to be highly efficient and robust to displaced tracks while having little-to-no impact on the runtime of LST. These results clearly establish that ML can be used to improve LST without penalty. Next, exploratory studies of GNN track-building algorithms are described. In particular, low-level track objects from LST are considered as nodes in a graph, where edges represent higher-level objects or even entire track candidates. Then, an edge-classifier GNN is trained, and the efficiency of the resultant edge scores is compared with that of the existing LST track quality selections. These GNN studies provide insights into the practicality and performance of using more ambitious and complex ML algorithms for HL-LHC tracking at the CMS Experiment.

Authors: GUIANG, Jonathan (Univ. of California San Diego (US)); SILVA, Mayra (University of Florida); VOURLIOTIS, Manos (Univ. of California San Diego (US)); KRUTELYOV, Slava (Univ. of California San Diego (US)); GU, Yanxi (Univ. of California San Diego (US)); NIENDORF, Gavin (Cornell University (US)); CHANG, Philip (University of Florida (US)); WITTICH, Peter (Cornell University (US)); YAGIL, Avi (Univ. of California San Diego (US)); REID, Tres (Cornell University (US)); SATHIA NARAYANAN, Balaji Venkat (Univ. of California San Diego (US)); TADEL, Matevz (Univ. of California San Diego (US)); ELMER, Peter (Princeton University (US))

Presenter: GUIANG, Jonathan (Univ. of California San Diego (US))

Session Classification: Plenary

Contribution ID: **25** Type: **Plenary**

Application of Quantum Annealing with Graph Neural Network Preselection in Particle Tracking at LHC

Thursday 12 October 2023 15:10 (25 minutes)

Quantum computing techniques have recently gained significant attention in the field. Compared to traditional computing techniques, quantum computing could offer potential advantages for high-energy physics experiments. Particularly in the era of HL-LHC, effectively handling large amounts of data with modest resources is a primary concern. Particle tracking is one of the tasks predicted to be challenging for classical computers in the HL-LHC. Previous studies have demonstrated that quantum annealing (QA), an optimization technique with quantum computer, can achieve particle tracking with an efficiency of over 90%, even in dense environments. To execute the QA process, a Quadratic Unconstrained Binary Optimization (QUBO) object is required. In order to apply the QA technique in particle tracking, hits are pairing up and form a QUBO object. Recent research has implemented and tested a graph neural network (GNN) using simplified samples in the preselection stage of the QA-based tracking algorithm. The current study aims to generalize the dataset and construct a GNN to classify hit pairs within a dense environment. Furthermore, the tracking performance of the standard QA-based tracking algorithm will be compared with that of the GNN-QA tracking algorithm.

Authors: TANAKA, Junichi (University of Tokyo (JP)); TERASHI, Koji (University of Tokyo (JP)); SAWADA, Ryu (University of Tokyo (JP)); GANGULY, Sanmay (University of Tokyo (JP)); Dr CHAN, Wai Yuen (University of Tokyo (JP))

Presenter: Dr CHAN, Wai Yuen (University of Tokyo (JP))

Session Classification: Plenary

Contribution ID: **27** Type: **YSF Plenary**

Combined track finding with GNN & CKF

Thursday 12 October 2023 11:00 (15 minutes)

The application of graph neural networks (GNN) in track reconstruction is a promising approach to cope with the challenges that will come with the HL-LHC. They show both good track-finding performance in high pile-up scenarios and are naturally parallelizable on heterogeneous compute architectures.

Typical HEP detectors have have a high resolution in the innermost layers in order to support vertex reconstruction, but then lower resolution in the outer parts. GNNs mainly rely on 3D space-point information, so this can cause reduced track-finding performance in these regions.

In this contribution we present a novel combination of GNN-based track finding with the classical Combinatorial Kalman Filter (CKF) algorithm to circumvent this issue: The GNN resolves the track candidates in the inner pixel region, where 3D space points can represent measurements very well. These candidates are then seamlessly picked up by the CKF in the outer regions, which performs well even for 1D measurements, where a space point definition is not clearly given.

With the help of the infrastructure of the ACTS project, we will show both a proof-of-concept based on truth tracking in the pixels, that allows to estimate achievable improvements for duplicate and fake rate, as well as a dedicated GNN pipeline trained on ttbar events with pileup 200 in the OpenDataDetector.

Authors: SALZBURGER, Andreas (CERN); HUTH, Benjamin (CERN); HEINRICH, Lukas Alexander (Technische Universitat Munchen (DE)); WETTIG, Tilo (University of Regensburg)

Presenter: HUTH, Benjamin (CERN)

Session Classification: YSF Plenary

Contribution ID: **28** Type: **Plenary**

High Pileup Particle Tracking with Object Condensation

Tuesday 10 October 2023 09:20 (25 minutes)

Recent work has demonstrated that graph neural networks (GNNs) can match the performance of traditional algorithms for charged particle tracking while improving scalability to meet the computing challenges posed by the HL-LHC. Most GNN tracking algorithms are based on edge classification and identify tracks as connected components from an initial graph containing spurious connections. In this talk, we consider an alternative based on object condensation (OC), a multi-objective learning framework designed to cluster points (hits) belonging to an arbitrary number of objects (tracks) and regress the properties of each object. Building on our previous results, we present a streamlined model and show progress toward a one-shot OC tracking algorithm in a high-pileup environment.

Authors: DEZOORT, Gage (Princeton University (US)); LIERET, Kilian (Princeton University)

Presenters: DEZOORT, Gage (Princeton University (US)); LIERET, Kilian (Princeton University)

Session Classification: Plenary

Contribution ID: **29** Type: **YSF Plenary**

On-the-fly measurement calibration with ACTS

Wednesday 11 October 2023 11:00 (15 minutes)

Kalman Filter (KF)-based tracking algorithms are used by many collider experiments to reconstruct charged-particle trajectories with great performance. The input to such algorithms are usually point estimates of a particle's crossing on a detector's sensitive elements, known as measurements. For instance, in a pixel detector, connected component analysis is typically used to yield two-dimensional pixel clusters on which shape analysis is performed to obtain a position estimate. Such estimates can usually be made more precise if some information about the the fitted track's direction is available. Kalman Filter-based pipelines can thus readily benefit from on-the-fly measurement calibration, since the KF always makes a prediction of the current track state, which includes track angles, before incorporating each measurement. Measurement calibration can also be used to correct for detector effects such as wire sagging or module deformation, and may also be used to improve convergence when performing track finding and fitting with misaligned detector geometries. All of these calibrations are well suited to machine learning applications.

ACTS is an experiment-independent toolkit for charge particle tracking which includes implementations of Kalman Filter track finding and fitting algorithms. This contribution will focus on the measurement calibration infrastructure implemented in ACTS and will present results from actual applications of realistic measurement calibration methods, from simple scale-and-offset schemes to sophisticated neural network-based techniques.

Author: GAGNON, Louis-Guillaume (University of California Berkeley (US))

Presenter: GAGNON, Louis-Guillaume (University of California Berkeley (US))

Session Classification: YSF Plenary

Contribution ID: **31** Type: **Plenary**

k4Clue: the CLUE Algorithm for Future Collider Experiments

Tuesday 10 October 2023 11:30 (25 minutes)

CLUE is a fast and innovative density-based clustering algorithm to group digitized energy deposits (hits) left by a particle traversing the active sensors of a high-granularity calorimeter in clusters with a well-defined seed hit. It was developed in the context of the new high granularity sampling calorimeter (HGCAL) which will be installed in the forward region of the Compact Muon Solenoid (CMS) experiment as part of its HL-LHC upgrade. Its outstanding performance in terms of high efficiency and excellent computing timing has been proven in the context of the CMS Phase-2 upgrade using both simulated and test beam data.

Initially, CLUE was developed in a standalone repository to allow performance benchmarking with respect to its CPU and GPU implementations, demonstrating the power of algorithmic parallelization in the coming era of heterogeneous computing. In recent years, CLUE's capabilities outside CMS and, more specifically, at experiments at future colliders, were tested by adapting it to run in the Turnkey Software Stack (key4hep) framework. The new package, k4Clue, is now fully integrated into the Gaudi software framework and it now supports EDM4hep data format for inputs and outputs.

This contribution will start from CLUE's state-of-the-art in the CMS software reconstruction context, to then move to describe the enhancements needed for the algorithm to run on several detector geometries and for both the barrel and the forward region of the detector. The preliminary performance will also be presented for several types of high-granularity calorimeters proposed at linear and circular e+e− colliders.

Authors: BRONDOLIN, Erica (CERN); PANTALEO, Felice (CERN); ROVERE, Marco (CERN)

Presenter: BRONDOLIN, Erica (CERN)

Session Classification: Plenary

Contribution ID: **33** Type: **YSF Plenary**

A Generalist Model for Particle Tracking

Wednesday 11 October 2023 11:40 (15 minutes)

The application of deep learning models in particle tracking is pervasive. Graph Neural Networks are applied in track finding, Deep learning models in resolving merged tracks, Transformers in jet flavor tagging, and GravNet or its variations in one-short track finding. The current practice is to design one deep learning model for one task. However, these tasks are so deeply intertwined that factorizing them will inevitably lose information and hurt overall performance. We propose to design an intermediate generalist model that offers learned detector encodings for various particle tracking tasks.

Inspired by the BERT model, which is the pre-training of deep bidirectional transformers for language understanding, we propose to train deep bidirectional transformers to encode the detector modules for particle tracking. Similarly, we define two surrogate tasks for the training. One task is to predict masked hits in a particle track, and the other is to predict if track A has higher momentum than track B. The goal is to obtain novel representations of detector modules and to use those representations for various downstream tasks, including outlier/hole detection and track generation.

In this talk, we will present the preliminary results of training the BERT model for particle tracking and show the first application of the novel detector module representations for hole detection and track extrapolation. This study can be potentially extended to encode the whole particle detectors, including calorimeters and muon spectrometers, for more downstream particle reconstruction tasks.

Authors: Mr HUANG, Andris (Berkeley Lab); JU, Xiangyang (Lawrence Berkeley National Lab. (US)); Mr MELKANI, Yash (Berkeley Lab)

Co-authors: LAZAR, Alina; MURNANE, Daniel Thomas (Lawrence Berkeley National Lab. (US)); Mr PHAM, Minh-Tuan (University of Wisconsin Madison (US)); CALAFIURA, Paolo (Lawrence Berkeley National Lab. (US))

Presenter: JU, Xiangyang (Lawrence Berkeley National Lab. (US))

Session Classification: YSF Plenary

Contribution ID: **34** Type: **Plenary**

High-throughout GNN track reconstruction at LHCb

Tuesday 10 October 2023 16:10 (25 minutes)

Over the next decade, increases in instantaneous luminosity and detector granularity will increase the amount of data that has to be analyzed by high-energy physics experiments, whether in real time or offline, by an order of magnitude. The reconstruction of charged
particles, which has always been a crucial element of offline data processing pipelines, must increasingly be deployed from the very first stages of the real time processing to enable experiments to achieve their physics goals. Graph Neural Networks have received a great deal of attention in the community because their computational complexity scales linearly with the number of hits in the detector, unlike conventional algorithms which often scale quadratically or worse. We present a first implementation of the vertex detector reconstruction for the LHCb experiment using GNNs, and benchmark its computational performance in the context of LHCb's fully GPU-based first-level trigger system, Allen. As Allen performs charged particle reconstruction at the full LHC collision rate, over 20˜MHz in the ongoing Run˜3, each GPU card must process around one hundred thousand collisions per second. Our work is the first attempt to operate a GNN charged particle reconstruction in such a high-throughput environment using GPUs, and we discuss the pros and cons of the GNN and classical algorithms in a detailed like-for-like comparison.

Authors: CORREIA, Anthony (Centre National de la Recherche Scientifique (FR)); GIASEMIS, Fotis (Centre National de la Recherche Scientifique (FR)); GARROUM, Nabil (Centre National de la Recherche Scientifique (FR)); GLIGOROV, Vladimir (Centre National de la Recherche Scientifique (FR))

Co-author: GRANADO, Bertrand (sorbonne universite)

Presenter: CORREIA, Anthony (Centre National de la Recherche Scientifique (FR))

Session Classification: Plenary

Contribution ID: **35** Type: **Plenary**

Study of a new algorithm for tracker alignment using Machine Learning

Wednesday 11 October 2023 14:30 (25 minutes)

For the tracker systems used in experiments like the large LHC experiments, a track based alignment with offline software is performed. The standard approach involves minimising the residuals between the measured and track-predicted hits using the χ^2 method. However, this minimisation process involves solving a complex and computationally expensive linearised matrix equation. A new approach utilising modern Machine Learning frameworks such as TensorFlow and/or PyTorch is being studied. In this study, the problem is addressed by leveraging these frameworks' implemented stochastic gradient descent and backpropagation algorithms to minimise the χ^2 as the cost function. A proof-of-principle example with a generic detector setup is presented.

Author: Mr BRUNNER, David (Stockholm University (SE))

Co-authors: BRUCKMAN DE RENSTROM, Pawel (Polish Academy of Sciences (PL)); KUHL, Thorsten (Deutsches Elektronen-Synchrotron (DE))

Presenter: Mr BRUNNER, David (Stockholm University (SE))

Session Classification: Plenary

Contribution ID: **36** Type: **Plenary**

Simultaneous multi-vertex reconstruction with a minimum-cost lifted multicut graph partitioning algorithm

Wednesday 11 October 2023 15:00 (25 minutes)

Particle physics experiments often require the simultaneous reconstruction of many interaction vertices. This task is complicated by track reconstruction errors which frequently are bigger than the typical vertex-vertex distances in physics problems. Usually, the vertex finding problem is solved by ad hoc heuristic algorithms. We propose a universal approach to address the multiple vertex finding in a dense environment through a principled formulation as a minimum-cost lifted multicut problem. The suggested algorithm is tested in a typical LHC environment with multiple pileup vertices produced by proton–proton interactions. The amount of these vertices and their significant density in the beam interaction region make this case a challenging testbed for the vertex-finding algorithms. To assess the vertexing performance in a dense environment with significant track reconstruction errors several dedicated metrics are proposed. We demonstrate that the minimum-cost lifted multi-cut approach outperforms heuristic algorithms and works well up to the highest pileup vertex multiplicity expected at the HL-LHC.

Author: KOSTYUKHIN, Vadim (Universitaet Siegen (DE))

Presenter: KOSTYUKHIN, Vadim (Universitaet Siegen (DE))

Session Classification: Plenary

Contribution ID: **37** Type: **Mini-workshop plenary**

Accelerated Large Graph Creation with CUDA: Empowering Graph Neural Networks in Particle Physics

Graph neural networks have emerged as a powerful tool in various physics studies, particularly in the analysis of sparse and heterogeneous data. However, as the field of particle physics advances towards utilizing graphs in high-luminosity scenarios, a new challenge has emerged: efficient graph creation. While GNN inference is highly optimized, graph creation has not received the same level of attention. This becomes a significant bottleneck when working with graphs that have a large number of nodes such as those arising from HL-LHC collisions.
In this talk, we will delve into the specifics of this issue and explore the impact of graph creation on performance. We will highlight that even for graphs with a specific structure in mind, the process of creating them can be several orders of magnitude slower on a CPU compared to running inference with a network. To overcome this limitation, we will investigate how hardware-based acceleration, specifically utilizing CUDA on GPUs, can address these challenges.
By leveraging CUDA acceleration, we can unlock the full potential of graph neural networks without being hindered by inefficient graph creation. This talk aims to highlight the importance of fast and efficient graph creation in the context of large-scale graphs in particle physics and how leveraging hardware acceleration can propel research in this exciting field.

Authors: SHIELDS, Edward; KAKATI, Nilotpal (Weizmann Institute of Science (IL))

Presenter: KAKATI, Nilotpal (Weizmann Institute of Science (IL))

Session Classification: Co-located Real-time Tracking mini-workshop (13 October)

Contribution ID: **38** Type: **Poster**

Improvement of event-building for data-driven hybrid pixel detector data

Tuesday 10 October 2023 19:15 (3 minutes)

Hybrid pixel detectors like Timepix3 and Timepix4 detect individual pixels hit by particles. For further analysis, individual hits from such sensors need to be grouped into spatially and temporally coinciding groups called clusters. While state-of-the-art Timepix3 detectors generate up to 80 Mio hits per second, the next generation, Timepix4, will provide data rates of up to 640 Mio hits (data bandwidth of up to 164 Gbps), which is far beyond the current capabilities of the real-time clustering algorithms, processing at roughly 3 MHits/s. We explore the options for accelerating the clustering process, focusing on its real-time application. We developed a tool that utilizes multicore CPUs to speed up the clustering. Despite the interdependence of different data subsets, we achieve a speed-up scaling with the number of used cores. Further, we exploited options to reduce the computational demands of the clustering by determining radiation field parameters from raw (unclustered) data features and self-initiating further clustering if these data show signs of interesting events. This further accelerates the clustering while also reducing storage space requirements. The proposed methods were validated and benchmarked using real-world and simulated datasets.

Author: CELKO, Tomas (Czech Technical University in Prague (CZ))

Co-authors: BERGMANN, Benedikt; MRÁZ, František (Charles University); MÁNEK, Petr (Department of Physics and Astronomy, University College London)

Presenter: CELKO, Tomas (Czech Technical University in Prague (CZ))

Session Classification: Poster

Contribution ID: **40** Type: **Plenary**

FASER tracking system and performance

Wednesday 11 October 2023 17:00 (25 minutes)

FASER, the ForwArd Search ExpeRiment, is an LHC experiment located 480 m downstream of the ATLAS interaction point along the beam collision axis. FASER is designed to detect TeV-energy neutrinos and search for new light weakly-interacting particles produced in the pp collision at the LHC. FASER has been taking collision data since the start of LHC Run3 in July 2022. The first physics results were just presented in March 2023 [1,2], including the first direct observation of collider neutrinos. FASER includes four identical tracker stations constructed from silicon microstrip detectors, which play a key role in the physics analysis. Specifically the tracker stations are designed to separately reconstruct the pair of charged particles arising from the new particle, as well as high-energy muons from the neutrino interactions. This talk will present the performance study for track reconstruction and detector alignment using the first collision data.

1 https://arxiv.org/abs/2303.14185
2 https://cds.cern.ch/record/2853210

Author: LI, Ke (University of Washington (US))

Presenter: LI, Ke (University of Washington (US))

Session Classification: Plenary

Contribution ID: **41** Type: **YSF Plenary**

Kalman filter for muon reconstruction in the CMS Phase-2 endcap calorimeter

Thursday 12 October 2023 14:00 (15 minutes)

At the High Luminosity phase of the LHC (HL-LHC), experiments will be exposed to numerous (approx. 140) simultaneous proton-proton collisions. To cope with such harsh environments, the CMS Collaboration is designing a new endcap calorimeter, referred to as the High-Granularity Calorimeters (HGCAL).
As part of the detector upgrade, a novel reconstruction framework (TICL: The Iterative CLustering) is being developed. The framework uses a hierarchical approach to build physics objects out of energy deposits and employs a wide range of both classical and machine learning algorithms, for different tasks in the reconstruction chain. Even though TICL is under continuous development, it has already shown outstanding performance in particle shower reconstruction.
In this contribution, the development of a dedicated muon reconstruction within TICL is discussed. Such dedicated reconstruction is crucial for HGCAL, especially for inter-cell calibration and for expanding the global muon reconstruction to regions with pseudorapity >2.4. The Kalman Filter (KF) algorithm is particularly suited to tackle this challenge, and it has already been tested and used extensively in many particle physics experiments for track reconstruction, including CMS. The performance of the KF algorithm for muon reconstruction in HGCAL under various conditions will be presented for the first time, as well as its capabilities and limitations as a tool for inter-cell calibration.

Author: MATTHEWMAN, Mark Nicholas (HEPHY)

Co-authors: BRONDOLIN, Erica (CERN); ROVERE, Marco (CERN); WALTENBERGER, Wolfgang (Austrian Academy of Sciences (AT))

Presenter: MATTHEWMAN, Mark Nicholas (HEPHY)

Session Classification: YSF Plenary

Contribution ID: **42** Type: **YSF Plenary**

Studying a new Primary Vertex (PV) identification algorithm within ACTS framework

Thursday 12 October 2023 14:20 (15 minutes)

We present a project proposal aimed at improving the efficiency and accuracy of Primary Vertex (PV) identification within the 'A Common Tracking Software'(ACTS) framework using the deep learning techniques. Our objective is to establish a primary vertex finding algorithm with enhanced performance for the LHC like environments. This work is focused on finding PVs in simulated ACTS data using a hybrid approach that started with the Kernel Density Estimators (KDEs), analytically derived from the ensemble of charged track parameters, which are then fed to a UNet/UNet++ neural network along with truth PV information. The neural network is trained using a large training dataset and the performance is evaluated on an independent test dataset. By leveraging KDEs and neural networks, our aim is to enhance pattern recognition and feature detection in High Energy Physics (HEP) data. We also plan to conduct a comparative analysis to assess the performance of the newly implemented algorithm against established results from ACTS Adaptive Multi-Vertex Finder (AMVF) algorithm. This work aims to contribute to the ongoing development of data analysis and machine learning techniques in the field of HEP.

Authors: TOMPKINS, Lauren Alexandra (Stanford University (US)); Ms ALSARAYRA, Layan; GARG, Rocky Bala (Stanford University (US))

Presenter: Ms ALSARAYRA, Layan

Session Classification: YSF Plenary

Contribution ID: **43** Type: **Plenary**

An application of HEP track reconstruction methods to Gaia EDR3

Tuesday 10 October 2023 12:00 (25 minutes)

Utilization of machine learning for pattern recognition and track reconstruction in HEP sets promising precedents of how novel data science tools can aid researchers in other fields of physics and astronomy in conducting statistical-inference on large datasets. We present our work in progress on the applications of fast nearest-neighbor search (kNN) to Gaia EDR3—one of the most extensive catalogs of astronomical objects and their properties, including their position and motion in the sky. Mapping positions of stars that are gravitationally bound to Milky Way (MW), but that have not originated in our galaxy could reveal crucial insights about its dark matter halo, which played a fundamental role in its formation. Motions of such stars are modeled differently from MW stars, which allows us to track them across the galaxy. "Tracking" in this context amounts to connecting stars that have a common origin based on their position and motion. The most literal analogy to HEP tracking is given by stellar streams, which are populations of stars that follow a distinct path in the sky, almost like a particle track, but this is not the only possibility. Parallel to the seeding stage of track reconstruction inside colliders, our method identifies potential regions of the galactic halo where stars from different populations may reside, based on their average angular motions over time. This enables us to generically identify any astronomical structure or clustering among stars with similar kinematics that stand out from a group of background objects; thus providing opportunities for our method to not be limited to identification of formally defined star clusters. We will present examples of known star clusters that our method successfully located and discuss the accuracy of their characterization, as well as the robustness of our algorithm given various algorithmic choices.

Authors: GOKCEN, Mine; GARCIA-SCIVERES, Maurice (Lawrence Berkeley National Lab. (US)); JU, Xiangyang (Lawrence Berkeley National Lab. (US))

Presenter: GOKCEN, Mine

Session Classification: Plenary

Contribution ID: **44** Type: **Plenary**

Seed finding in the Acts Software Package: Algorithms and Optimizations

Wednesday 11 October 2023 14:00 (25 minutes)

Seed finding is an important and computationally expensive problem in the reconstruction of charged particle tracks; finding solutions to this problem involves forming triples (seeds) of discrete points at which particles were detected (spacepoints) in the detector volume. This combinatorial process scales cubically with the number of spacepoints, which in turn is expected to increase in future collision experiments as well as in upgrades to current experiments such as the HL-LHC (High-Luminosity Large Hadron Collider). The Acts (A Common Tracking Software) software package provides a broad range of algorithms –including seeding –for the reconstruction of charge particle tracks in a broad range of detectors. In order to provide competitive performance –in terms of computation as well as physics –for future experiments, the Acts software provides highly optimized seed finding algorithms which can be configured for different detector geometries. In this talk, we describe the seeding algorithms in traccc which reduce the combinatorial explosion problem through the use of structured grids and k -dimensional search trees. We compare the performance of these algorithms in CPU- and GPU-based environments. Finally, we discuss strategies for reducing the volume of output seeds –which impacts the performance of other algorithms such as combinatorial Kalman filtering –such as seed filtering and seed merging. In particular, we propose to combine a clustering algorithm –such as DBSCAN –and a neural network with Margin Ranking Loss for an efficient and performant seed selection.

Authors: CALACE, Noemi (CERN); FALDA COELHO, Luis (CERN); SALZBURGER, Andreas (CERN); SWATMAN, Stephen Nicholas (University of Amsterdam (NL)); VARNI, Carlo (University of California Berkeley (US)); ROUSSEAU, David (IJCLab-Orsay); ALLAIRE, Corentin (IJCLab, Université Paris-Saclay, CNRS/IN2P3); GRASLAND, Hadrien Benjamin (IJCLab - CNRS); BOUVET, Françoise

Presenters: FALDA COELHO, Luis (CERN); ALLAIRE, Corentin (IJCLab, Université Paris-Saclay, CNRS/IN2P3)

Session Classification: Plenary

Contribution ID: **45** Type: **YSF Plenary**

GNN Track Reconstruction of Non-helical BSM Signatures

Thursday 12 October 2023 11:40 (15 minutes)

Accurate track reconstruction is essential for high sensitivity to beyond Standard Model (BSM) signatures. However, many BSM particles undergo interactions that produce non-helical trajectories, which are difficult to incorporate into traditional tracking techniques. One such signature is produced by "quirks", pairs of particles bound by a new, long-range confining force with a confinement scale much less than the quirk mass, leading to a stable, macroscopic flux tube that generates large oscillations between the quirk pair. The length scale of these oscillations is dependent on the confinement scale, and in general can be shorter than a micron, or longer than a kilometer. We present a version of the ML-based GNN4ITk track reconstruction pipeline, applied to a custom detector environment for quirk simulation.

We explore the ability of an SM-trained graph neural network (GNN) to handle BSM track reconstruction out-of-the-box. Further, we explore the extent to which a pre-trained SM GNN requires fine-tuning to specific BSM signatures. Finally, we compare GNN performance with traditional tracking algorithms in the simplified detector environment, for both helical SM and non-helical BSM cases.

Authors: MURNANE, Daniel Thomas (Lawrence Berkeley National Lab. (US)); WHITESON, Daniel (University of California Irvine (US)); CONDREN, Levi Harris Jaxon (University of California Irvine (US)); FIEG, Max; SHA, Qiyu (Chinese Academy of Sciences (CN))

Presenter: SHA, Qiyu (Chinese Academy of Sciences (CN))

Session Classification: YSF Plenary

Contribution ID: **46** Type: **Plenary**

Neural-Network-Based Event Reconstruction for the RadMap Telescope

Wednesday 11 October 2023 16:30 (25 minutes)

Detailed knowledge of the radiation environment in space is an indispensable prerequisite of any space mission in low Earth orbit or beyond. The RadMap Telescope is a compact multi-purpose radiation detector that provides near real-time monitoring of the radiation aboard crewed and uncrewed spacecrafts. A first prototype is currently deployed on the International Space Station for an in-orbit demonstration of the instrument's capabilities.
RadMap's main sensor consists of a stack of scintillating-plastic fibres coupled to silicon photomultipliers. The perpendicular alignment of fibres in the stack allows the three-dimensional tracking of charged particles as well as the identification of cosmic ray ions by reconstruction of their energy-loss profiles. We implemented artificial neural networks trained on simulated detector data in the instrument's flight computer to reconstruct the tracks from raw detector data in real time and determine the particles'types and energies without requiring the transmission of raw data to Earth for offline reconstruction.
In this contribution, we will describe our neural-network-based reconstruction methods and the results achieved for the different reconstruction tasks. We show the performance of different network architectures constituted of fully-connected and convolutional layers and present early results using transformer networks that further improve the reconstruction performance of RadMap.

Authors: MEYER-HETLING, Luise (Technical University of Munich); HINDERBERGER, Peter (Technical University of Munich); LOSEKAMM, Martin Jan (Technical University of Munich); Prof. PAUL, Stephan (Technical University of Munich); Mr POESCHL, Thomas (Technical University of Munich); RUECKERL, Sebastian (Technical University of Munich)

Presenter: MEYER-HETLING, Luise (Technical University of Munich)

Session Classification: Plenary

Contribution ID: **47** Type: **Plenary**

Track Finding-and-Fitting with Influencer Object Condensation

Tuesday 10 October 2023 09:50 (25 minutes)

ML-based track finding algorithms have emerged as competitive alternatives to traditional track reconstruction methods. However, a major challenge lies in simultaneously finding and fitting tracks within a single pass. These two tasks often require different architectures and loss functions, leading to potential misalignment. Consequently, achieving stable convergence becomes challenging when incorporating both finding and fitting in a multi-task loss framework.

To address this issue, we propose to use a solution called object condensation, which aims to find a representative point for track building while serving as the target for parameter regression. Specifically, we leverage the recently-introduced Influencer approach, where each hit can act as both a representative and a representee, which has been shown to allow robust track building. In this work, we present the results obtained by utilizing the Influencer model for the combined track finding-and-fitting task. We evaluate the performance benefits of treating fitting as an auxiliary task to enhance track finding and compare the physics performance and resource utilization against the typical sequential finding-then-fitting pipeline.

Author: MURNANE, Daniel Thomas (Lawrence Berkeley National Lab. (US))

Presenter: MURNANE, Daniel Thomas (Lawrence Berkeley National Lab. (US))

Session Classification: Plenary

Contribution ID: **48** Type: **Plenary**

Belle II track finding and hit filtering using precise timing information

Thursday 12 October 2023 09:00 (25 minutes)

The SuperKEKB accelerator and the Belle II experiment constitute the second-generation asymmetric energy B-factory. SuperKEKB has recently set a new world record in instantaneous luminosity, which is anticipated to further increase during the upcoming run periods up to $6 \times 10^{35} cm^{-2} s^{-1}$. An increase in luminosity is challenging for the track finding as it comes at the cost of a significant increase of the number of background hits. The Belle II experiment aims at testing the Standard Model of particle physics and searching for new physics by performing precision measurements. To achieve these physics goals, including e.g. time-dependent measurements, the track finding and fitting has to deliver tracks with high precision and efficiency. As the track reconstruction is part of the online high level trigger system of Belle II there are also stringent requirements on the resource usage.

The Belle II tracking system consists of 2 layers of pixelated silicon detectors, 4 layers of double sided silicon strip detectors (SVD), and the central drift chamber. We will present the general performance and working of the track reconstruction algorithm of Belle II. In particular we will focus on the usage of hit time information from the silicon strip detector. The SVD has a very precise determination of the hit time, which will be used for the first time in the Belle II track finding in the next data taking period. These hit times are used for hit filtering, estimation of the time of collision, and the determination of the time of individual tracks. All of these are important tools to help to cope with the anticipated increase in background hits caused by the increase in luminosity.

Authors: WESSEL, Christian (DESY); Dr LÜCK, Thomas

Presenter: WESSEL, Christian (DESY)

Session Classification: Plenary

Contribution ID: **49** Type: **YSF Plenary**

Reconstruction performance with ACTS and the Open Data Detector

Wednesday 11 October 2023 11:20 (15 minutes)

Over the last years, the ACTS software has matured in functionality and performance while at the same time the Open Data Detector (ODD), a revision and evolution of the TrackML detector, has been established. Together they form a foundation for algorithmic research and performance evaluation also for detectors with time measurements, like the ODD. In this contribution we present the performance for reference physics samples as a baseline for a reconstruction chain implemented with ACTS for silicon based detectors. This serves as a validation for both the ODD geometry and the ACTS reconstruction algorithms. At the same time it is a reference for experiments looking into ACTS reconstruction performance. Additionally, we use it to validate the ACTS intrinsic fast track simulation (ActsFatras) and present a coherent continuous integration testing suite to monitor performance changes over time.

Authors: SALZBURGER, Andreas (CERN); STEFL, Andreas (Technische Universitaet Wien (AT)); CALACE, Noemi (CERN); BUTTI, Pierfrancesco (SLAC National Accelerator Laboratory (US))

Presenter: STEFL, Andreas (Technische Universitaet Wien (AT))

Session Classification: YSF Plenary

Contribution ID: **50** Type: **Plenary**

CEPC tracking performance with ACTS

Tuesday 10 October 2023 11:00 (25 minutes)

The Circular Electron Positron Collider (CEPC) is a physics program proposal with the goal of providing high-accuracy measurements of properties of the Higgs, W and Z bosons, and exploring new physics beyond the SM (BSM). The CEPC is also an excellent facility to perform precise tests of the theory of the strong interaction.
To deliver those physics programs, the CEPC detector concepts must meet the stringent performance requirements. The majority of the visible particles at CEPC are charged particles whose multiplicity can be as high as 100. An efficient separation of these particles provides a solid basis for the reconstruction and identification of physics objects, the high-level objects such as leptons, photons and jets that are input to physics analyses. Therefore, the CEPC detector should have excellent track finding efficiency and track momentum resolution. For example, for tracks within the detector acceptance and transverse momenta larger than 1 GeV, a track finding efficiency better than 99% is required.

A Common Tracking Software (ACTS) project aims to provide an open-source experiment-independent and framework-independent software designed for modern computing architectures based on the tracking experience at LHC. It provides a set of high-level performant track reconstruction tools which are agnostic to the details of the detection technologies and magnetic field configuration, and tested for strict thread-safety to support multi-threaded event processing. ACTS has been used as a tracking toolkit at experiments such as ATLAS, sPHENIX, ALICE, STCF etc. and has shown very promising tracking performance in terms of both physics performance and time performance. In particular, recently, implementation of ACTS for STCF, which is the first application of ACTS for a drift chamber, is made and promising performance is achieved.

In this talk, we will report on development of the CEPC track reconstrcon software based on the detection information from Silicon Trackers and a Main Drift Chamber using the Kalman Filter based track finding and fitting algorithms of ACTS. The tracking performance for a tracking system with a drift chamber and a track mulplicity of 100 (which is much higher than that at STCF) will be presented.

Authors: LIU, Mengyao; AI, Xiaocong (Zhengzhou University); HUANG, Xingtao; Mr QIN, Zuyin

Presenter: AI, Xiaocong (Zhengzhou University)

Session Classification: Plenary

Contribution ID: **51** Type: **Plenary**

First experiences with the LHCb heterogeneous software trigger

Wednesday 11 October 2023 09:00 (25 minutes)

Since 2022, the LHCb detector is taking data with a full software trigger at the LHC proton proton collision rate, implemented in GPUs in the first stage and CPUs in the second stage. This setup allows to perform the alignment & calibration online and to perform physics analyses directly on the output of the online reconstruction, following the real-time analysis paradigm.
This talk will discuss challenges of the heterogeneous trigger implementations, the first running experiences, and show preliminary performance results of both stages of the trigger system.

Author: MORRIS, Andy (Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France)

Presenter: MORRIS, Andy (Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France)

Session Classification: Plenary

Contribution ID: **52** Type: **Plenary**

A Multipurpose Graph Neural Network for Reconstruction in LArTPC Detectors

Tuesday 10 October 2023 17:10 (25 minutes)

The Exa.TrkX Graph Neural Network (GNN) for reconstruction of liquid argon time projection chamber (LArTPC) data is a message-passing attention network over a heterogeneous graph structure, with separate subgraphs of 2D nodes (hits in each plane) connected across planes via 3D nodes (space points). The model provides a consistent description of the neutrino interaction across all planes.

The GNN initially performed a semantic segmentation task, classifying detector hits according to the particle type that produced them. Performance results will be presented based on publicly available samples from MicroBooNE. These include both physics performance metrics, achieving ˜95% accuracy when integrated over all particle classes, and computational metrics for training and for inference on CPU or GPU.

We will also present recent work extending the network application to additional LArTPC reconstruction tasks, such as cosmic background and noise filtering, interaction vertex position identification, and particle instance segmentation. Early results indicate that the network achieves excellent filtering performance without increasing the network size, thus demonstrating that the set of learned features are somewhat general and relevant for multiple tasks.

Prospects for the integration of the network inference in the data processing chains of LArTPC experiments will also be presented.

Author: CERATI, Giuseppe (Fermi National Accelerator Lab. (US))

Presenter: CERATI, Giuseppe (Fermi National Accelerator Lab. (US))

Session Classification: Plenary

Contribution ID: **54** Type: **Plenary**

Reconstructing charged particle track segments with a quantum-enhanced support vector machine

Thursday 12 October 2023 14:40 (25 minutes)

Reconstructing the trajectories of charged particles from the collection of hits they leave in the detectors of collider experiments like those at the Large Hadron Collider (LHC) is a challenging combinatorics problem and computationally intensive. The ten-fold increase in the delivered luminosity at the upgraded High Luminosity LHC will result in a very densely populated detector environment. The time taken by conventional techniques for reconstructing particle tracks scales worse than quadratically with track density. Accurately and efficiently assigning the collection of hits left in the tracking detector to the correct particle will be a computational bottleneck and has motivated studying possible alternative approaches. This paper presents a quantum-enhanced machine learning algorithm that uses a support vector machine (SVM) with a quantum-estimated kernel to classify a set of three hits (triplets) as either belonging to or not belonging to the same particle track. The performance of the algorithm is then compared to a fully classical SVM. The quantum algorithm shows an improvement in accuracy versus the classical algorithm for the innermost layers of the detector that are expected to be important for the initial seeding step of track reconstruction. (arXiv:2212.07279)

Authors: FACINI, Gabriel (University College London); JASTRZEBSKI, Marcin (University College London); DUCKETT, Philippa (University College London); MALIK, Sarah (University College London); RETTIE, Sebastien (University College London & CERN); SCANLON, Tim (University College London)

Co-author: HASSANSHAHI, Mohammadhassan

Presenters: JASTRZEBSKI, Marcin (UCL); JASTRZEBSKI, Marcin (University College London)

Session Classification: Plenary

Contribution ID: **55** Type: **YSF Plenary**

Developing Novel Track Reconstruction Algorithms for the Mu2e Experiment

Wednesday 11 October 2023 12:00 (15 minutes)

The Mu2e experiment plans to search for neutrinoless muon to electron conversion in the field of a nucleus. Such a process violates lepton flavor conservation. To perform this search, a muon beam is focused on an aluminum target, the muons are stopped in the field of the aluminum nucleus, and electrons emitted from subsequent muon decays in orbit are measured. The endpoint energy for this process is 104.97 MeV; an excess of measured electrons at this energy signifies neutrinoless muon to electron conversion has occurred. Currently under construction at the Fermilab Muon Campus, Mu2e will stop 10^{18} muons on target in 3 years of running, with the goal of reaching a single event sensitivity of 3×10^{-17} on the branching ratio. In order to reach such a sensitivity, one must write software that efficiently reconstructs the tracks of conversion electrons that pass through the Mu2e tracker. This has been achieved by breaking the reconstruction process down into four successive steps: hit reconstruction, time clustering, helix finding, and a final track fitting. One shortcoming of the current code is that the time clustering and helix finding stages make various assumptions that make them highly tuned to conversion electrons at the endpoint energy. This limits the collaboration's ability to constrain some backgrounds, and search for a larger range of physics. The work presented here details the development of novel time clustering and helix finding algorithms, and how they fit into the Mu2e trigger system.

Author: STORTINI, Matthew

Presenter: STORTINI, Matthew

Session Classification: YSF Plenary

Contribution ID: **56** Type: **Poster**

Graph Neural Network-based Tracking as a Service

Tuesday 10 October 2023 19:18 (3 minutes)

Recent studies have shown promising results for track finding in dense environments using Graph Neural Network (GNN)-based algorithms. These algorithms not only provide high track efficiency but also offer reasonable track resolutions. However, GNN-based track finding is computationally slow on CPUs, necessitating the use of coprocessors like GPUs to accelerate the inference time. Additionally, due to the substantial graph size typically involved (consisting of approximately 300k nodes and 1M edges), significant GPU memory is required to ensure efficient computation. Not all computing facilities used for particle physics experiments are equipped with high-end GPUs such as NVIDIA A100s or V100s, which can meet the computational requirements. These computing challenges must be addressed in order to deploy GNN-based track finding into production. We propose addressing these challenges by establishing the GNN-based track finding algorithm as a service hosted either in the cloud or high-performance computing centers.

In this talk, we will describe the implementation of the GNN-based track finding workflow as a service using the Nvidia Triton Inference Server. The pipeline contains three discrete deep-learning models and two CUDA-based algorithms. Because of the heterogeneity in the workflow, we explore different server configurations? to maximize the throughput of track finding and the GPU utilization. We also study the scalability of the inference server using the Perlmutter supercomputer at NERSC and cloud resources like AWS and Google Cloud.

Authors: ZHAO, Haoran (University of Washington (US)); JU, Xiangyang (Lawrence Berkeley National Lab. (US))

Co-authors: NAYLOR, Andrew (Lawrence Berkeley National Lab); RANKIN, Dylan Sheldon (University of Pennsylvania (US)); KHODA, Elham E (University of Washington (US)); CALAFIURA, Paolo (Lawrence Berkeley National Lab. (US)); HARRIS, Philip Coleman (Massachusetts Inst. of Technology (US)); HSU, Shih-Chieh (University of Washington Seattle (US)); FARRELL, Steven (Lawrence Berkeley National Laboratory); MCCORMACK, William Patrick (Massachusetts Inst. of Technology (US)); FENG, Yongbin (Fermi National Accelerator Lab. (US))

Presenter: JU, Xiangyang (Lawrence Berkeley National Lab. (US))

Session Classification: Poster

Contribution ID: **57** Type: **Poster**

The Layer-1 Barrel Muon Filter for the Level-1 muon trigger upgrade of the CMS experiment at the HL-LHC

Tuesday 10 October 2023 19:00 (3 minutes)

In view of the HL-LHC, the Phase-2 CMS upgrade will replace the entire trigger and data acquisition system. The detector readout electronics will be upgraded to allow a maximum L1 accept rate of 750 kHz, and a latency of 12.5 μs. The muon trigger is a multi-layer system that is designed to reconstruct muon stubs on each muon station and then to measure the momenta of the muon by correlating information across muon chambers on the so-called muon track finders and by matching the reconstructed stubs with the L1 tracker tracks sent by the track trigger. This is achieved with sophisticated pattern recognition algorithms that run on Virtex UltraScale+ FPGA processors. The Layer-1 Barrel Muon Filter is the second layer of this system, it concentrates the stubs and hits from
the barrel muon stations and runs dedicated algorithms to refine and correlate the information of multiple chambers before sending the information to the track finders for momentum estimation. One of the proposed algorithms is meant to detect and identify muon showers allowing for tagging both hadronic showers in the muon system as well as highly-energetic muons that will be missed otherwise. We review the current status of such an algorithm, its demonstration in firmware and its measured physics performance.

Authors: VICO VILLALBA, Carlos (Universidad de Oviedo (ES)); PRADO PICO, Javier (Universidad de Oviedo (ES)); FOLGUERAS, Santiago (Universidad de Oviedo (ES))

Presenter: PRADO PICO, Javier (Universidad de Oviedo (ES))

Session Classification: Poster

Contribution ID: **58** Type: **Mini-workshop plenary**

Level-1 Tracking at CMS for the HL-LHC

The success of the CMS physics program at the HL-LHC requires maintaining sufficiently low trigger thresholds to select processes at the electroweak scale. With an average expected 200 pileup interactions, critical to achieve this goal while maintaining manageable trigger rates is in the inclusion of tracking in the L1 trigger. A 40 MHz silicon-tracker based track trigger on the scale of the CMS detector has never before been built; it is a novel handle, which in addition to maintaining trigger rates can enable entirely new physics studies.

The main challenges of reconstructing tracks in the L1 trigger are the large data throughput at 40 MHz and the need for a trigger decision within 12.5 μs out of which 4 μs is for track finding. The CMS outer tracker for HL-LHC uses modules with closely-spaced silicon sensors to read out only hits compatible with charged particles with pT above 2 GeV (”stubs”). These are used in the backend L1 track finding system, based on commercially available FPGA technology. The ever-increasing capability of modern FPGAs combined with their programming flexibility is ideal for a fast track finding algorithm. The L1 tracking algorithm forms track seeds (”tracklets”) from pairs of stubs in adjacent layers of the outer tracker. These seeds provide roads where consistent stubs are included to form track candidates. Track candidates sharing multiple stubs are combined prior to being fitted. A Kalman Filter track fitting algorithm is employed to identify the final track candidates and determine the track parameters. The system is divided into nine sectors in the r-phi plane, where the processing for each sector is performed by a dedicated track finding board.

This presentation will discuss the latest status of the CMS L1 track finding and its implementation, present simulation studies of the estimated performance, and discuss the developments of hardware demonstrators.

Author: FIORENDI, Sara (University of Tennessee (US))

Presenter: FIORENDI, Sara (University of Tennessee (US))

Session Classification: Co-located Real-time Tracking mini-workshop (13 October)

Contribution ID: **61** Type: **not specified**

Welcome & Introduction

Tuesday 10 October 2023 09:05 (15 minutes)

Presenter: VALLIER, Alexis (L2I Toulouse, CNRS/IN2P3, UT3)

Session Classification: Plenary

Contribution ID: **62** Type: **Poster**

Clustering and tracking in dense environments with the ITk

Tuesday 10 October 2023 19:24 (20 minutes)

Dense hadronic environments encountered, for example, in the core of high-transverse-momentum jets, present specific challenges for the reconstruction of charged-particle trajectories (tracks) in the ATLAS tracking detectors, as they are characterised by a high density of ionising particles. The charge clusters left by these particles in the silicon sensors are more likely to merge with increasing particle densities, especially in the innermost layers of the ATLAS silicon-pixel detectors. This has detrimental effects on both the track reconstruction efficiency and the precision with which the track parameters can be measured. The new Inner Tracker (ITk), which will replace the ID for the High-Luminosity LHC programme, features an improved granularity due to its smaller pixel sensor size, which is expected to reduce cluster merging rates in dense environments. In this contribution, the cluster and track reconstruction performance in dense environments is studied with the most 23-00-03 ITk layout. Different quantities are studied to assess the effects of cluster merging at the cluster-, track-, and jet-level.

Presenter: DE BIASE, Nicola (Deutsches Elektronen-Synchrotron (DE))

Session Classification: Poster

Contribution ID: **63** Type: **not specified**

Welcome from L2IT Director

Tuesday 10 October 2023 09:00 (5 minutes)

Presenter: STARK, Jan (Laboratoire des 2 Infinis - Toulouse, CNRS / Univ. Paul Sabatier (FR))

Session Classification: Plenary

Contribution ID: **64** Type: **Poster**

Flash Talk: Heterogeneity in Graph Neural Networks for Track Reconstruction in the ATLAS Upgrade ITk Detector

Tuesday 10 October 2023 17:40 (3 minutes)

The upcoming High Luminosity phase of the Large Hadron Collider (HL-LHC) represents a steep increase in pileup rate ($\langle\mu\rangle = 200$) and computing resources for offline reconstruction of the ATLAS Inner Tracker (ITk), for which graph neural networks (GNNs) have been demonstrated as a promising solution. The GNN4ITk pipeline has successfully employed a GNN architecture for edge classification and showed the competitiveness of this approach in HL-LHC-like pile-up conditions. We present in this study a new heterogeneous GNN architecture that handles the pixel- and strip-subdetectors using separate graph subnetworks, reflecting the naturally differing geometries of these regions. We investigate the impact of varying the degree of heterogeneity in the model and identify the optimal complexity associated with a heterogeneous architecture. In addition, we examine the use of the underlying hit cluster information in model training and demonstrate that cluster-level input is richer and more discriminatory than space point coordinates alone. With this added sophistication, the track reconstruction efficiency and fake rate of the GNN4ITk pipeline using the heterogeneous GNN compares favourably with the results from the homogeneous GNN.

Authors: MURNANE, Daniel Thomas (Lawrence Berkeley National Lab. (US)); CHAN, Jay (University of Wisconsin Madison (US)); Mr PHAM, Minh-Tuan (University of Wisconsin Madison (US)); CALAFIURA, Paolo (Lawrence Berkeley National Lab. (US)); JU, Xiangyang (Lawrence Berkeley National Lab. (US))

Presenter: Mr PHAM, Minh-Tuan (University of Wisconsin Madison (US))

Session Classification: Poster Flash Talk

Contribution ID: **65** Type: **Poster**

Flash Talk: Flexible Hough Transform FPGA Implementation for the ATLAS Event Filter

Tuesday 10 October 2023 17:43 (3 minutes)

The ATLAS Run3 will conclude as planned in late 2025 and will be followed by the so-called Long Shutdown 3. During this period all the activities exclusively dedicated to Run4 will converge on the closing of the prototyping development and in the start of the production and integration, to reach the data collection in 2029. These upgrades are principally led by the increase of the peak of luminosity up to 5-7.5 x 1034 cm-2 s-1 of LHC expected for the future High Luminosity-LHC operations. One of the major changes ATLAS will face will be an increase in the amount of data to be managed in its Trigger and Data Acquisition system. The triggering operations are targeting to reach from 40 MHz of input event a discrimination in the middle throughput of 1 MHz and finally in the last stage of 10 kHz. The second process will use all the information acquired by the ATLAS detector to complete the event selection, including the study of the tracks of the innermost sub-detector, the Inner Tracker. This tracking operation is planned to be performed with a PC farm because of the need for high precision. The list of the architectures under study to speed-up this process includes the use of a "hardware accelerator"farm, an infrastructure made of interconnected accelerators such as GPUs and FPGAs to speed up the tracking processes. The project described here is a proposal for a tuned Hough Transform algorithm implementation on high-end FPGA technology, versatile to adapt to different tracking situations. The development platform allows the study of different datasets from an ATHENA software simulating the firmware. AMD-Xilinx FPGA has been chosen to test and evaluate this implementation. The system was tested with a ATLAS realistic environment. Simulated 200 pile up events have been exploited to measure the effectiveness of the algorithm. The processing time is averagely in the order of < 10 μs according to internal preliminary estimates, with the possibility to run two events at a time per algorithm instance. Internal efficiency tests have shown conditions that reach > 95 % of the track-finding performance for single muon tracking.

Authors: GABRIELLI, Alessandro (Università e INFN, Bologna (IT)); ALFONSI, Fabrizio (Universita e INFN, Bologna (IT))

Presenter: ALFONSI, Fabrizio (Universita e INFN, Bologna (IT))

Session Classification: Poster Flash Talk

Contribution ID: **66** Type: **Poster**

Flash Talk: Obtaining requirements for the future ATLAS Event Filter Tracking system

Tuesday 10 October 2023 17:46 (3 minutes)

The High-Luminosity LHC shall be able to provide a maximum peak luminosity of 5×10^{34} cm^{-2}s^{-1}, corresponding to an average of 140 simultaneous p-p interactions per bunch crossing (pile-up), at the start of Run 4, around 2028. The ATLAS experiment will go through major changes to adapt to the high-luminosity environment, in particular in the DAQ architecture and in the trigger selections. The use of the new high-resolution full-silicon inner tracker (ITk) in the high-level-trigger (also called Event Filter) is of paramount importance to improve the trigger selection and purity and reduce the trigger rates against the large background of low-energy pile-up jets. The Event Filter Tracking system is under design as an heterogeneous and flexible system, able to combine algorithms running in CPUs and on accelerators, like FPGAs and/or GPUs, on commodity servers, to allow both a regional reconstruction at the expected 1MHz L1 rate and the full event reconstruction at 150 kHz. The challenge of the Event Filter Tracking design is to maximize the tracking performance of the algorithms while maintaining an adequate data throughput through the processors farm, using reasonable power. In this presentation, the results of studies performed to evaluate the minimal tracking performance required are presented. In particular, the tracking efficiency and the resolution on the track transverse momentum will impact the leptons selections, while the resolution on the track impact parameters will affect the hadronic selections, including b-tagging and multi-jet selections.

Authors: PENN, Gregory; PENN, Gregory

Co-author: CAMPLANI, Alessandra (University of Copenhagen (DK))

Presenters: PENN, Gregory; PENN, Gregory

Session Classification: Poster Flash Talk

Contribution ID: **67** Type: **Poster**

Flash Talk: Real-time long-lived particle reconstruction in LHCb's HLT2

Tuesday 10 October 2023 15:38 (3 minutes)

LHCb is optimised to study particles decaying a few millimetres from the primary vertex using tracks that traverse the length of the detector. Recently, extensive efforts have been undertaken to enable the study of long-lived particles decaying within the magnet region, up to 7.5 m from the interaction point. This approach presents several challenges, particularly when considering real-time analysis within LHCb's trigger system. These include large track combinatorics, a tracker with a low magnetic field and short lever arm, as well as the need to extrapolate tracks through a strong, inhomogeneous magnetic field to find vertices. Several approaches have been developed to tackle these challenges in LHCb's HLT2, including new geometry-based selections, MVA-based vertex finding and modifications to vertex fitting. This talk presents these developments and future prospects.

Author: SANDERSWOOD, Izaac (Univ. of Valencia and CSIC (ES))

Presenter: SANDERSWOOD, Izaac (Univ. of Valencia and CSIC (ES))

Session Classification: Poster Flash Talk

Contribution ID: **68** Type: **Poster**

Flash Talk: Seeding with Machine Learning in ACTS

Tuesday 10 October 2023 10:26 (3 minutes)

To prepare for the High Luminosity phase of the Large Hadron Collider at CERN (HL-LHC), the ATLAS experiment is replacing its innermost components with a full-silicon tracker (ITk), to improve the spatial resolution of the tracks measurements and increase the data readout rate. However, this upgrade alone will not be sufficient to cope with the tremendous increase of luminosity, and significant improvements have to be incorporated into the existing tracking software to keep the required computing resources at a realistic level.

In this poster, we are focusing on the track seeds reconstruction within the ITk detector, and we explore the possibility to use hashing techniques to improve the seed reconstruction efficiency, limit the combinatorics and eventually reduce the computing time. Metric learning is then used to tune our algorithm for the different regions of the detector, and to increase the robustness against time-dependent detector conditions.

The code developments are done within the ACTS framework, an experiment-independent toolkit for charged particles track reconstruction.

Author: COUTHURES, Jeremy (Centre National de la Recherche Scientifique (FR))

Presenter: COUTHURES, Jeremy (Centre National de la Recherche Scientifique (FR))

Session Classification: Poster Flash Talk

Contribution ID: **69** Type: **Poster**

Flash Talk: Improvement of event-building for data-driven hybrid pixel detector data

Tuesday 10 October 2023 10:23 (3 minutes)

Hybrid pixel detectors like Timepix3 and Timepix4 detect individual pixels hit by particles. For further analysis, individual hits from such sensors need to be grouped into spatially and temporally coinciding groups called clusters. While state-of-the-art Timepix3 detectors generate up to 80 Mio hits per second, the next generation, Timepix4, will provide data rates of up to 640 Mio hits (data bandwidth of up to 164 Gbps), which is far beyond the current capabilities of the real-time clustering algorithms, processing at roughly 3 MHits/s. We explore the options for accelerating the clustering process, focusing on its real-time application. We developed a tool that utilizes multicore CPUs to speed up the clustering. Despite the interdependence of different data subsets, we achieve a speed-up scaling with the number of used cores. Further, we exploited options to reduce the computational demands of the clustering by determining radiation field parameters from raw (unclustered) data features and self-initiating further clustering if these data show signs of interesting events. This further accelerates the clustering while also reducing storage space requirements. The proposed methods were validated and benchmarked using real-world and simulated datasets.

Author: CELKO, Tomas (Czech Technical University in Prague (CZ))

Co-authors: BERGMANN, Benedikt; MRÁZ, František (Charles University); MÁNEK, Petr (Department of Physics and Astronomy, University College London)

Presenter: CELKO, Tomas (Czech Technical University in Prague (CZ))

Session Classification: Poster Flash Talk

Contribution ID: **70** Type: **Poster**

Flash Talk: Graph Neural Network-based Tracking as a Service

Tuesday 10 October 2023 10:20 (3 minutes)

Recent studies have shown promising results for track finding in dense environments using Graph Neural Network (GNN)-based algorithms. These algorithms not only provide high track efficiency but also offer reasonable track resolutions. However, GNN-based track finding is computationally slow on CPUs, necessitating the use of coprocessors like GPUs to accelerate the inference time. Additionally, due to the substantial graph size typically involved (consisting of approximately 300k nodes and 1M edges), significant GPU memory is required to ensure efficient computation. Not all computing facilities used for particle physics experiments are equipped with high-end GPUs such as NVIDIA A100s or V100s, which can meet the computational requirements. These computing challenges must be addressed in order to deploy GNN-based track finding into production. We propose addressing these challenges by establishing the GNN-based track finding algorithm as a service hosted either in the cloud or high-performance computing centers.

In this talk, we will describe the implementation of the GNN-based track finding workflow as a service using the Nvidia Triton Inference Server. The pipeline contains three discrete deep-learning models and two CUDA-based algorithms. Because of the heterogeneity in the workflow, we explore different server configurations? to maximize the throughput of track finding and the GPU utilization. We also study the scalability of the inference server using the Perlmutter supercomputer at NERSC and cloud resources like AWS and Google Cloud.

Authors: ZHAO, Haoran (University of Washington (US)); JU, Xiangyang (Lawrence Berkeley National Lab. (US))

Co-authors: NAYLOR, Andrew (Lawrence Berkeley National Lab); RANKIN, Dylan Sheldon (University of Pennsylvania (US)); KHODA, Elham E (University of Washington (US)); CALAFIURA, Paolo (Lawrence Berkeley National Lab. (US)); HARRIS, Philip Coleman (Massachusetts Inst. of Technology (US)); HSU, Shih-Chieh (University of Washington Seattle (US)); FARRELL, Steven (Lawrence Berkeley National Laboratory); MCCORMACK, William Patrick (Massachusetts Inst. of Technology (US)); FENG, Yongbin (Fermi National Accelerator Lab. (US))

Presenter: JU, Xiangyang (Lawrence Berkeley National Lab. (US))

Session Classification: Poster Flash Talk

Contribution ID: **71** Type: **Poster**

Flash Talk: The Layer-1 Barrel Muon Filter for the Level-1 muon trigger upgrade of the CMS experiment at the HL-LHC

Tuesday 10 October 2023 15:35 (3 minutes)

In view of the HL-LHC, the Phase-2 CMS upgrade will replace the entire trigger and data acquisition system. The detector readout electronics will be upgraded to allow a maximum L1 accept rate of 750 kHz, and a latency of 12.5 μs. The muon trigger is a multi-layer system that is designed to reconstruct muon stubs on each muon station and then to measure the momenta of the muon by correlating information across muon chambers on the so-called muon track finders and by matching the reconstructed stubs with the L1 tracker tracks sent by the track trigger. This is achieved with sophisticated pattern recognition algorithms that run on Virtex UltraScale+ FPGA processors. The Layer-1 Barrel Muon Filter is the second layer of this system, it concentrates the stubs and hits from
the barrel muon stations and runs dedicated algorithms to refine and correlate the information of multiple chambers before sending the information to the track finders for momentum estimation. One of the proposed algorithms is meant to detect and identify muon showers allowing for tagging both hadronic showers in the muon system as well as highly-energetic muons that will be missed otherwise. We review the current status of such an algorithm, its demonstration in firmware and its measured physics performance.

Authors: VICO VILLALBA, Carlos (Universidad de Oviedo (ES)); PRADO PICO, Javier (Universidad de Oviedo (ES)); FOLGUERAS, Santiago (Universidad de Oviedo (ES))

Presenter: PRADO PICO, Javier (Universidad de Oviedo (ES))

Session Classification: Poster Flash Talk

Contribution ID: **72** Type: **not specified**

Social Dinner

Wednesday 11 October 2023 19:30 (4h 30m)

https://maps.app.goo.gl/QUqqxbgH1y3rGKqR7

Contribution ID: **73** Type: **Poster**

Flash Talk: Clustering and tracking in dense environments with the ITk

Tuesday 10 October 2023 15:41 (3 minutes)

Dense hadronic environments encountered, for example, in the core of high-transverse-momentum jets, present specific challenges for the reconstruction of charged-particle trajectories (tracks) in the ATLAS tracking detectors, as they are characterised by a high density of ionising particles. The charge clusters left by these particles in the silicon sensors are more likely to merge with increasing particle densities, especially in the innermost layers of the ATLAS silicon-pixel detectors. This has detrimental effects on both the track reconstruction efficiency and the precision with which the track parameters can be measured. The new Inner Tracker (ITk), which will replace the ID for the High-Luminosity LHC programme, features an improved granularity due to its smaller pixel sensor size, which is expected to reduce cluster merging rates in dense environments. In this contribution, the cluster and track reconstruction performance in dense environments is studied with the most 23-00-03 ITk layout. Different quantities are studied to assess the effects of cluster merging at the cluster-, track-, and jet-level.

Presenter: DE BIASE, Nicola (Deutsches Elektronen-Synchrotron (DE))

Session Classification: Poster Flash Talk

Contribution ID: **74** Type: **not specified**

Closeout

Thursday 12 October 2023 15:40 (20 minutes)

Presenter: VALLIER, Alexis (L2I Toulouse, CNRS/IN2P3, UT3)

Session Classification: Summary & Wrap-up