Adapting HLT tracking algorithms to run on heterogenous computing resources

During Run 2 of the LHC the CMS experiment has recorded about 140 fb^{-1} of data that has allowed the CMS collaboration to explore a wide range of particle physics phenomena. Run 3 of the LHC is expected to start in 2021 and will deliver about 300 fb^{-1} of data. After Run 3 an upgrade of the accelerator is planned, called the High Luminosity Large Hadron Collider (HL-LHC), which is expected to achieve instantaneous luminosities of $5 \times 10^{34}\,cm^{-2}s^{-1}$ and is planned to run for a decade. Correspondingly, the number of simultaneous proton-proton (pp) interactions per bunch crossing (pileup) in the CMS detector will significantly increase, from about 35 observed during the data taking in 2018 to 140-200. The HL-LHC will allow to collect enormously large data samples (about 3000 fb^{-1} of pp collision data), however, the ability to record, reconstruct and ultimately analyze these huge data samples is severely impacted by the availability of computing resources.

The Phase-2 upgrades to the CMS detector, especially the upgraded silicon tracker, are designed to maintain or improve the detector performance to allow a precise reconstruction of all particles despite the significant increase in particle multiplicity caused by the additional pp interactions. However, upgraded detectors will not be sufficient to overcome the challenges posed by these extreme pileup conditions. As the available computing resources will continue to be limited during the HL-LHC period, it is not feasible to rely on the same reconstruction algorithms currently used in the CMS software. For example, the time per event spent on track reconstruction in the offline data processing increases by more than a factor of 10 going from 40 to 140 pileup interactions. While an increase in computing power due to technological progress will alleviate some fraction of this increase, novel algorithms running on heterogenous computing resources are needed to cope with the computing challenge posed by the pileup conditions at the HL-LHC.

Significant efforts are necessary to upgrade all parts of the CMS track reconstruction software – track seeding, pattern recognition, track fitting, and track selection – in order to meet the challenges outlined above. Development projects are ongoing to ensure the necessary improvements will be available in time for the HL-LHC. Track seeding has already been improved by the development of a Cellular Automaton (CA) algorithm that has significantly sped up seed finding since 2017 and is highly parallelizable, making it suitable to run on architectures optimized for parallel computing. The MkFit project has developed a highly parallelizable implementation of the pattern recognition using a Kalman Filter technique, which promises significant speedup of the most resource intensive step of the track reconstruction. New approaches to track selection based on deep learning are also being developed.

It has been demonstrated that for sufficiently parallelizable algorithms, computing architectures other than the conventionally used CPUs are advantageous. Currently, GPUs are the favorite alternative architecture as they are designed to efficiently execute instructions in parallel on many computing cores. This make them especially interesting for track reconstruction, where for example the same algorithms for pattern recognition are executed concurrently using different track seeds as inputs.

As not all algorithms will be suited for these new architectures, and as not all computing resources where the CMSSW code might be executed will contain GPUs, it is important that the CMS software is optimized for heterogenous computing environments where different kinds of resources will be available and optimized versions of the reconstruction algorithms are available to be used accordingly. For example, for Run 3 the CMS high-level trigger (HLT) computing farm will be upgraded so that each computing node will contain a GPU together with a number of CPUs.

Given the limited computing resources and the need to make fast decisions if an event is to be kept, efficient reconstruction algorithms are of even greater importance in the HLT. As track reconstruction contributes significantly to the overall HLT computing needs, an optimized implementation of these algorithms is crucial to overcome the computing challenges in the HL-LHC environment. Tracking performance in the HLT will be constrained by the time taken per event, and several interesting strategies are being developed to overcome this. Using GPUs for parallel processing within each event will assist with latency constraints.

Currently, significant efforts are underway to port the CMS HLT reconstruction software to run on GPUs. The Patatrack project has implemented GPU-compatible versions of the pixel detector local reconstruction and the reconstruction of pixel tracks. Work is ongoing to similarly improve the local reconstruction of the silicon strip detector. The parallelized implementation of the pattern recognition developed by the MkFit project is so far based on CPU architectures, but a similar GPU-compatible implementation is expected to be developed in the near future.

While these developments will allow the majority of the general track reconstruction to be executed on GPUs, additional developments are needed to fully support more specialized reconstruction steps, for example the reconstruction of muons, on GPUs.

The CMS HLT computing farm will be equipped with GPUs already for Run 3. This presents a unique opportunity to use it as a testbed for algorithmic improvements developed in preparation for the HL-LHC while allowing CMS to profit from these developments already in the next few years of data taking. Therefore, there is benefit in developing GPU-optimized versions of the HLT reconstruction for the current detector that can subsequently be extended to make use of the improvements planned for the Phase-2 detector upgrade.

To select events containing muons with high efficiency is of utmost importance for the success of the CMS physics program. Muons are reconstructed in the CMS trigger system in three steps. The first reconstruction step is using information from the muon system only and is performed in the Level-1 (L1) trigger using custom electronics. In the software high-level trigger, a more precise reconstruction of the muon trajectory in the muon system is performed, resulting in so called Level-2 (L2) muons. Finally, the muon trajectory is reconstructed in the full detector (L3), including the inner tracking detectors. The reconstruction of muon tracks in the inner tracking detectors (L3 muons) currently uses two complementary approaches to start the track reconstruction (track seeding). In both cases, the information from the muon system in form of

L1 or L2 muons is used to create regions of interest in the detector in which track seeds are formed. In the first case, the track state vector from the L2 muon is propagated to the outer layers of the silicon strip detector to search for compatible hits, which are used to create the track seed (outside-in reconstruction). In the second case, the track state from the muon system is extrapolated to the interaction region instead and used to define a search window in which pixel detector hits are used to create track seeds (inside-out reconstruction).

These two complementary approaches ensure optimal performance for a wide range of signatures. Particularly the outside-in step is of critical importance to reconstruct displaced muons, which would be missed in a purely pixel-seeded reconstruction. This is especially important for long-lived particles signatures which are currently a focal point of LHC searches.

With the developments for GPU-based track reconstruction already in place or planned by the Patatrack and MkFit groups, significant portions of the HLT muon reconstruction will be empowered to be executed on GPUs. However, for a fully GPU-based muon reconstruction, two significant pieces are missing:

- The muon system information used to seed the reconstruction of muon tracks in the inner detector is not optimized to be used on the GPUs yet. The minimal approach to solve this problem would be to develop a conversion of the L1 and L2 muon object collections into data formats suited to be used on GPUs. A full solution would consist of an unpacker of the L1 muon information optimized for GPUs as well as a similarly optimized implementation of the L2 reconstruction.
- While the inside-out reconstruction of muon tracks will be possible to a large degree with the track reconstruction code that is optimized for GPUs or is planned to be ported already, the outside-in reconstruction is lacking a similar implementation of the seed generator to create the track seeds on the outermost layers of the outer tracker.

These developments would allow to perform the full current muon reconstruction at HLT on GPUs, profiting from the efficient parallelization of the track seeding and reconstruction while minimizing the number of data format conversion and copying of data between the CPU and GPU.

With the introduction of a track trigger at L1 level in the Phase-2 tracker, the upgraded detector will allow for significant further improvements of the muon HLT. The new high-momentum track stub information provided by the L1 track trigger can be used to seed muon track reconstruction. In addition, the new precision timing detector (MTD), which can assign times to tracks, if added to L1 information would enable the development a trigger based solely on an isolated, high p_T, delayed track. Possibilities at the HLT will vary depending on the tracking available, but if reconstruction is sufficiently fast CMS's sensitivity to displaced muons will significantly increase and even more exciting options become available.

Therefore, we propose to work on these crucial developments to adopt the CMS muon HLT software to run on heterogenous computing resources, focusing on making tracking maximally efficient and using all available information to develop new triggers for LLPs. The proposed work will proceed in close collaboration with both the Patatrack team, which developed the existing tracking algorithms on GPUs, as well as the MkFit team, which will develop a GPU-optimized version of their pattern recognition algorithm.

As for the existing GPU implementations, Nvidia's CUDA interface will be used to develop the GPU-optimized algorithms described above. Heterogeneous computing architecture for HLT developments already exists at CERN and will be used for this project. In addition, a dedicated GPU cluster is available at Purdue University to test the implementation.

Timeline and deliverables

The goal of the project is to deliver a GPU based muon reconstruction for the CMS HLT using the current reconstruction algorithms as a baseline. This can then be extended to the Phase-2 geometry and be further improved using track trigger and MTD information. The results of the first phase of the proposed development can be broken down into three sub-deliverables:

- An unpacking of the L1 muon information that is optimized to be run on GPUs. Together with a module capable of creating regions of interests that can run on GPUs, this will allow to run part of the inside-out reconstruction on GPUs with limited development challenges.
- A seed generator capable of extrapolating the trajectory state of an L1 or L2 muon to the outer layer of the silicon strip detector and creating track seeds there. This will enable out-side reconstruction on GPUs at HLT level.
- A reimplementation of the L2 reconstruction optimized for GPUs which will reduce the need for data conversion from the CPU to the GPUs and will further speed up the reconstruction.
- First steps to integrate L1 track trigger information into the HLT muon reconstruction.

The expected start date for this project is June 2020. Given the need of the postdoc to familiarize himself with the CUDA interface and programming of GPUs, the first deliverable is expected to be completed after about six months. With the experience gained during that time, faster progress is expected on the remaining deliverables, with an estimated development time for the seed generator of two months and the remaining two items being developed concurrently within the remaining four months of the project. The resulting timeline is:

- June 2020: Start of the program
- November 2020: L1 unpacking and region-of-interest producer to allow seeding for inside-out reconstruction
- January 2021: Seed generator for the outside-in reconstruction
- May 2021: GPU based L2 reconstruction and first steps towards inclusion of track trigger information

The projected timeline overlaps with the preparation of the HL-LHC HLT TDR that is being finalized during 2020, opening up the possibility of including first results of the project in this document already.

Personpower

The project will be executed by Jan-Frederik Schulte. He has been a member of the CMS collaboration since 2011, working on his Master's and PhD theses at RWTH Aachen University. After finishing his PhD he joined the CMS group at Purdue University as a postdoc in 2016, working with Prof. Norbert Neumeister. In the Purdue group, developments towards the Phase-2 muon HLT reconstruction will be supported by the work of one PhD student.

Jan-Frederik is stationed at the Fermilab LPC. This allows for close collaboration with the experts on Phase-2 software, whose expertise will be of tremendous help in ensuring the success of the project.

He has worked on several searches for new physics in CMS, focusing on signatures including leptons, such as searches for W' in the lepton + neutrino final state, for SUSY in final states with opposite-sign same-flavor leptons, and most recently for new physics in the high-mass dilepton final state.

Since 2016, Jan-Frederik has made significant contributions to the CMS HLT and offline track reconstruction software, serving as the L3 convener for tracking in the HLT from 2016-2018 and is currently one of the L2 conveners of the CMS tracking POG. During this time, he worked to adapt the HLT tracking to make use of the upgrade Phase-1 pixel detector and later implemented strategies to adapt the tracking algorithms to deal with the loss of pixel detector modules experienced during the data taking in 2017.

Jan-Frederik was part of a Task Force that significantly improved the muon reconstruction in the HLT after it was found to be underperforming during the data taking in 2017, helping to assure optimal performance in 2018. He is currently preparing a detector performance paper documenting these achievements.

As tracking POG convener, Jan-Frederik is coordinating the improvements and modifications of the CMS tracking software for Run 3 and the long-term developments for the HL-LHC. Currently he is developing improvements for the track seeding in the outer tracker for the Phase-2 upgrade of the CMS detector.

During this work, Jan-Frederik became closely familiar with general track as well as muon reconstruction in CMS, both for the offline reconstruction and in the HLT. He has demonstrated the ability to efficiently develop software within the CMSSW framework. This makes him well suited to the proposed development project, which will allow him to extend his development experience to the new subject of programming for heterogeneous computing architectures.