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GPU Enahncement of the Trigger to Extend Physics Reach at the LHC

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ABSTRACT: Significant new challenges are continuously confronting the High Energy Physics (HEP) experiments in particular the Large Hadron Collider (LHC) at CERN who at nominal conditions will deliver proton-proton collisions to the detectors at a rate of 40 MHz. This rate must be significantly reduced to comply with the performance limitations of the mass storage hardware, and the capabilities of the computing resources to process the collected data in a timely fashion for physics analysis. At the same time, the physics signals of interest must be retained with high efficiency.
The quest for rare new physics phenomena at the LHC and the flexibility of the trigger system allows to evaluate a GPU enhancement of the conventional computer farm to not only provide faster and more efficient events selection but also include new complex triggers that were not possible before. A new tracking algorithm is evaluated on the hybrid a K20 Inter multi core processor allowing for example for the first time to reconstruct long lived particles at the tracker system in the trigger. Preliminary time performance and efficiency will be presented.

KEYWORDS: ATLAS; CMS; Level-1 trigger; HLT; Tracker system; .

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1. Introduction

The stunning performance of the LHC, the successful physics results and the discovery of a new Higgs like particle will mark in history the first LHC running period not as the beginning of the end but rather the end of the beginning. The first LHC shut down scheduled for 2 years provides a remarkable opportunity improve our detector performance even further. In particular to enahnce and extend the physics reach that would be selected and recorded by the trigger .

The Trigger and Data Acquisition (DAQ) systems [**?**] in a modern collider experiment provide the essential preliminary online analysis of the raw data for the purpose of filtering potentially interesting events into the data storage system. At the design luminosity of 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, this is a formidable task, which requires real time handling of raw data with beam crossings at 40 MHz, each yielding on average $\sim$20 inelastic pp events, producing approximately 1 MB of zero-suppressed data. In order to keep the overall data rate within the current capability of the archival storage system of $\sim$100 MB/s, the trigger system must achieve a rejection ratio for background events of at least $\sim 400,000 : 1$.

The required level of performance can be achieved, by implementing a typical trigger system with a hierarchy of multiple levels, ranging from fast and relatively simple criteria implemented entirely in hardware and firmware, to more sophisticated software based analysis. The CMS trigger is implemented in 2 levels, with a hardware Level-1 trigger reducing the event rate to less than 100 kHz, followed by further processing in the High-Level Trigger (HLT), designed to reduce this maximum Level-1 accept rate of 100 kHz to a final output rate of 100 Hz. A significant component of the HLT is to evaluate a specific set of physics selection algorithms on the events read out, in order to accept the events with the most interesting physics content. This computing-intensive event selection is executed on a farms of commercial processors that constitute the CMS HLT hardware.

By its very nature of being a computing system, the HLT relies on technologies that have evolved extremely rapidly. For 30 years, one of the important methods for improving the performance of computing devices has been to increase the speed at which the processor's clock operated. Indeed, during this period, the typical CPU clock speed has increased nearly by a factor of a 1000.

In recent years, however, it has been observed that it is no longer possible to rely solely on the increase of processor clock speed as a means for extracting additional computational power from existing architectures. The underlying reasons are complex, but center around reaching what may be fundamental limitations in semiconductor device physics. For this reason, recent innovations have focused around *parallel* processing, either through systems containing multiple processors, or processors containing multiple cores, etc.

One interesting technology which has continued to see exponential growth is graphics processing. A modern graphics card contains multiple graphics processing units (GPU), in order better handle the highly parallel workloads related to computer graphics. By making these cores flexibly configurable and programmable, manufacturers have made the massive floating-point computational power of a modern graphics accelerator's rendering pipeline available as general-purpose computing power, as opposed to being hard wired for specific graphical operations. In certain applications requiring massively parallel vector operations, this can yield several orders of magnitude higher performance than a conventional CPU.

Furthermore, leading technology vendors have recently released supported development APIs, such as Nvidia's CUDA ("Compute Unified Device Architecture") [**?**], which allows rapid development of code libraries in nearly standard C code, with the ability to leverage a GPU's stream processors. CUDA is the first API to allow CPU-based applications to access directly the resources of a GPU for more general purpose computing without the limitations of using a graphics API. A modern GPU (e.g. 8800 GTX or later) can readily simultaneously execute hundreds of thousands of very small programs in parallel, and an application using effective collaboration between the GPU and the CPU can see dramatic acceleration in algorithm execution for parallel tasks.

A particularly good application for this technology would be in executing machine vision and pattern recognition algorithms on detector data. These algorithms are often parallel by their very nature, and the highly controlled data produced by a particle physics detector reduces the pattern recognition task to it's purest form. From the physics perspective, such an enhancement of the trigger capabilities would allow inclusion in the trigger menu new tracking triggers, for example selection of events with multiple displaced vertices at any location in the silicon tracker, which could be a smoking gun for new topological signatures not predicted by the Standard Model. The proposed tracking upgrade will serve to augment the existing trigger with new types of trigger filter to select events with topological signatures that are currently suppressed.

In the following, a description of the physics motivation behind GPU enhacment of the HLT. A description of the existing High Level Trigger, the GPU and CUDA architecture and the additional capabilities which would be enabled by a hybrid GPU/CPU computing farm on the HLT. The authors proposed tracking reconstruction algorithm, preliminary results and a disucusion of proposed new triggers that could be trigger on new physics that would be a smoking gun for new physics at the LHC.

2. Physics Motivation

The enhancement of the HLT might permit the processing the tracking reconstruction on the full event at Level-1 event rate up to design luminosity. The new HLT tracking has far reaching impact on the physics program set by the HLT who its ultimate goal is to select the event of interest for CMS. The new tracking algorithm will introduce new possible trigger paths that are currently not possible due to the extensive processing time. The robust parallel processing of the tracking on the hybrid CPU/GPU system will allow to reconstruct not only charged prompt tracks from the interaction point it will allow to reconstruct displaced vertices in the tracker far beyond what is possible in both CMS/ATLAS. Therefore the tracking algorithm using the GPU will enrich the physics program and allow to search easily for new topological signatures not possible or suppressed before.

Only few of the large selection of topological models could be described here. An example of an interesting class of models which would benefit from such triggers are âĂIJhidden-valleyâĂİ models [4], in which a new confining gauge group is added to the standard model. The resulting (electrically-neutral) bound states can have low masses and long lifetimes, and could be observed at the LHC. The production multiplicities are often large and events with final states with heavy flavor are common. In addition, displaced vertices and missing energy are possible. Accounting for LEP constraints, LHC production cross-sections were estimated to be typically in the 1-100 fb range, though they can be larger.

New tracking triggers would permit to select on the HLT Higgs like decays with a substantial branching fraction to long-lived neutral particles that may decay at macroscopic distances from the primary vertex [4] in the tracker. The limited experimental constraints on light neutral long-lived particles, argues that we probably should not be surprised if a Higgs like reveals itself through such decays. The lifetimes of these resonances are not constrained; decays at centimeter and meter scales are equally possible. Each Higgs decay may produce two or more resonances, with the multiplicity possibly varying from event to event. In many models, the resonances will decay to the heaviest fermion pair available, with branching fractions similar to those of the standard model Higgs.

There are various models that predict these unusual signatures [4]-[**?**]. It include either simple models where a scalar was added to the Higgs potential or supperpotetial depending whether a nonsupersymetric or supersymetric framework was used to build the model. Or other models that include conïňĄning hidden valley models which showed qualitatively similar signals though the origin of the signals is quite different. A complex Higgs decay in a hidden-valley model could produce, say, four resonances, one decaying promptly to jets, one escaping the detector giving missing energy, and two decaying to bb, each with a displaced vertex.

Other obvious channels that would benefit from the new tracking algorithm or displaced jets or vertex triggers are inclusive and exclusive b decay channels or various topologies with boosted jets that will be more frequent as we increase our center of mass of the collision at desgin luminosity. These new triggers will allow us to be sensitive to a larger parameter space including lower mass Higgs that could have evaded detection in previous experiments.

3. The Trigger System

The Large Hadron Collider (LHC) at CERN delivers protonâĂŞproton collisions to the CMS [**?**] detector at a rate of 40 MHz. This rate must be significantly reduced to comply with the performance limitations of the mass storage hardware, and the capabilities of the offline computing resources to process the collected data in a timely fashion for physics analysis. At the same time, the physics signals of interest must be retained with high efficiency. CMS features a two-level trigger system to reduce the rate to approximately 100 Hz. The Level-1 trigger [**?**] is based on custom hardware and designed to reduce the rate to about 100 kHz, corresponding to 100 GBs, assuming an average event size of 1 MB. The High Level Trigger (HLT) [**?**],[**?**] is purely software-based and must achieve the remaining rate reduction by executing sophisticated offline-quality algorithms. HLT algorithm sequences consist of algorithms that are executed in order of increasing complexity, and the execution of a path is stopped unless evidence for the signal of interest is found. This optimization causes more sophisticated and time consuming reconstruction algorithms to be seldomly applied. The ability to select the events of interest is the foundation of our quest for rare new physics phenomena, and thanks to the flexibility of the CMS HLT software and hardware computing farm the PI is able to propose an enhancement for the HLT a few years down the road after startup.

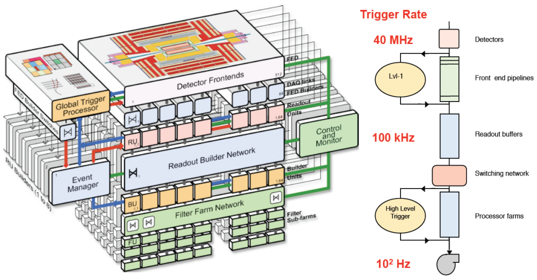

Figure 1. CMS DAQ Architecture. The size of the event builder (72 Readout Units, 288 Builder Units) represents one âĂIJsliceâĂİ; the system can be equipped with up to eight slices.

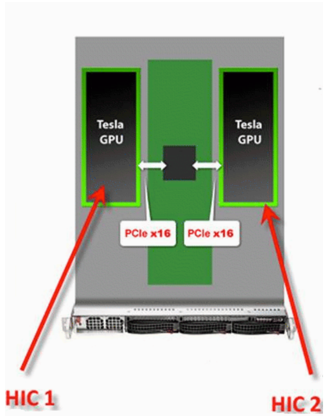

Figure 2. Schematic of an integrated GPU/CPU 1U server.

The architecture of the CMS HLT [**?**],[**?**], combines the flexibility gained by using the offline reconstruction [**?**] with the robustness required for reliable online operation of the DAQ. Fig. 10 shows a schematic of the architecture of the CMS DAQ system. Event fragments are read out and stored in Readout Units (RU) for each event accepted by the Level-1 trigger. The fragments are subsequently assembled into complete events by an Event Builder through a complex of switched networks into âĂIJevent buffersâĂİ (BU). The full event content is then handed to one of the HLT Filter Units (FU). The FU execute a series of physics reconstruction and filter algorithms, and events that are found to be sufficiently interesting for offline analysis are forwarded to the Storage Manager (SM). The decoupling of physics algorithm execution from data flow allows each FU to continue operation, recover the content of the problematic event, and forward it to be stored unprocessed. The FU architecture consists of two separate applications, the ResourceBroker, which exchanges data with the DAQ, and the EventProcessor, which integrates the reconstruction software. Given the involved event sizes and rates, reformatting raw events consisting of a large number of small data fragments into the physical memory of a Filter Unit requires high bandwidth I/O, while the subsequent HLT processing is mostly CPU intensive. The EventProcessor previously mentioned, encapsulates the event processing machinery of the CMS reconstruction, providing the full flexibility required to execute complex physics algorithms.

The farms of commercial processors where these event selection are executed is a natural place where the GPU cards could be integrated. A simple prototype solution is shown in Fig. 2, where a 1U server that constitute a motherboard with two PCI-e x16 slots, that would allow installation of both GPU Host Interface Cards (HIC) onto the system without using additional hardware/system to host the GPU server. While this would provide a single, integrated 1U GPU/CPU server, this of course implies replacing the existing servers evaluating the new power consumtion and cost of these servers relative to any other multi core option.

4. The Inner Tracker

Both CMS and ATLAS inner tracker include a silicon pixel detector and a silicon strip detector. All tracker layers provide two-dimensional hit position measurements, but only the pixel tracker and a subset of the strip tracker layers provide three dimensional hit position measurements. In the following only the CMS tracker would be considered however the detector perfromances are comparable in CMS/ATLAS experiements and the tracking algorithm and results discused are applicable for both of these expereiments as well. The CMS pixel detector includes three barrel layers and two forward disks on either end of the detector surrounded by ten strip detectors barrel layers plus three inner disks and nine forward disks at each end of the detector. Owing to the strong magnetic field and the high granularity of the silicon tracker, promptly produced charged particles with transverse momentum $pT = 100$ GeV/c are reconstructed with a resolution in pT of 1.5% and in transverse impact parameter d0 of 15 mm. The track reconstruction algorithms are able to reconstruct displaced tracks with transverse impact parameters up to 25 cm from particles decaying up to 50 cm from the beam line. The performance of the track reconstruction algorithms has been studied with data [11]. The silicon tracker is also used to reconstruct the primary vertex position with a precision of $\sigma_d 20$ mm in each dimension.

5. Fast Tracking Algorithm

One possible obvious application of the GPU enabled parallelism would be to accelerate the performance of the existing Kalman fitter used for tracking reconstruction. Since the iterative Kalman process for each track is largely independant of the other tracks, parallelization should not be conceptually difficult. However, an additional motivating force behind the use of GPU in the HLT is to be able to investigate the possibility of running trigger algorithms which are dramatically and qualitatively different in nature to enhance the discovery potential.

As an example, the Hough Transform, is well known algorithm used in various machine vision applications, differs from the Kalman approach in that it does not operate on localized features of a data set. Rather the technique is in some sense more holistic, operating on an entire image as a whole. The technique is described at length in existing literature, but the concept as it would be applicable to the tracking problem, is to consider the parameterization of any given track. Any given hit observed in the detector can correspond to many different possible tracks in parameter space, but when integrated over the entire data set, peaks appear in parameter space at the values corresponding to the actual, physical trajectories. As was briefly described previously, the traditional Kalman approach implicitly depends on various assumptions and constraints on the phase space of the seed tracks, with one of the most significant results being suppression of displaced vertices. It is hoped that a more holistic algorithm can be used to supplement the existing tracking algorithm in a significant way. As a demonstration of this, a simple tracking algorithm was developed and run against a stand alone Monte Carlo simulation with a simple tracker geometry file. The preliminary investigation was performed on a modest testbench consisting XXX Machine with Tesla C2075 and K20 GPU cards........

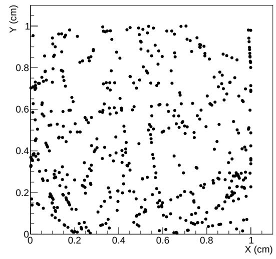

Figure 3. CMS DAQ Architecture. The size of the event builder (72 Readout Units, 288 Builder Units) represents one âĂIJsliceâĂİ; the system can be equipped with up to eight slices.

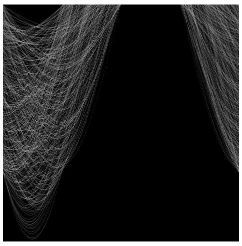

Figure 4. CMS DAQ Architectur. The size of the event builder (72 Readout Units, 288 Builder Units) represents one âĂIJsliceâĂİ; the system can be equipped with up to eight slices.

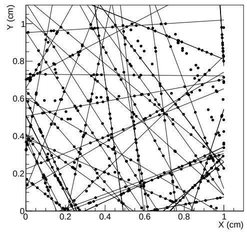

Figure 5. Filter Unit architecture: the responsibilities to receive, reformat, and send accepted events (ResourceBroker), and to reconstruct the physics content (EventProcessor) are split.

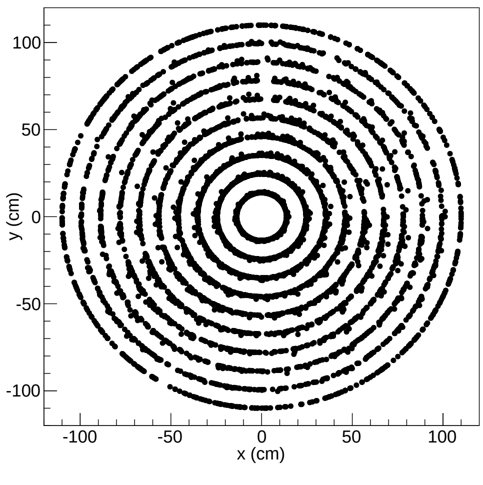

Figure 6. CMS DAQ Architecture. The size of the event builder (72 Readout Units, 288 Builder Units) represents one âĂIJsliceâĂİ; the system can be equipped with up to eight slices.

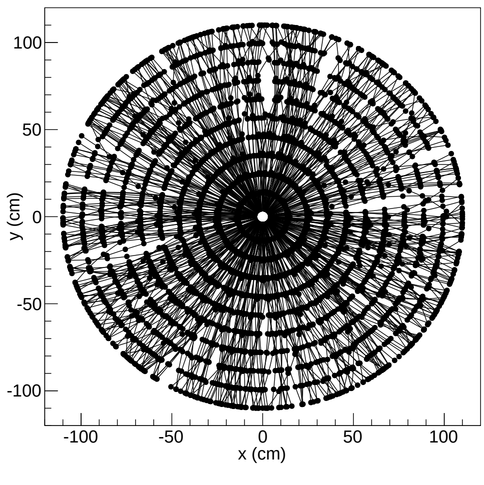

Figure 7. Filter Unit architecture: the responsibilities to receive, reformat, and send accepted events (ResourceBroker), and to reconstruct the physics content (EventProcessor) are split.

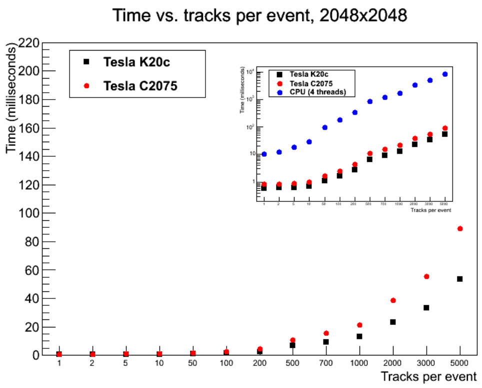

Figure 8. CMS DAQ Architecture. The size of the event builder (72 Readout Units, 288 Builder Units) represents one âĂIJsliceâĂİ; the system can be equipped with up to eight slices.

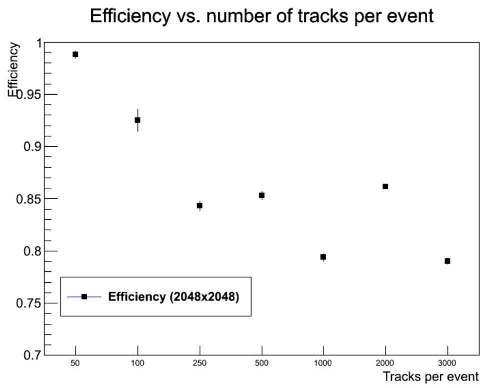

Figure 9. Filter Unit architecture: the responsibilities to receive, reformat, and send accepted events (Resource-Broker), and to reconstruct the physics content (Event-Processor) are split.

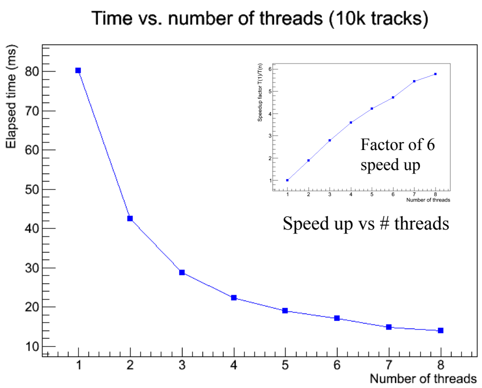

Figure 10. CMS DAQ Architecture. The size of the event builder (72 Readout Units, 288 Builder Units) represents one âĂIJsliceâĂİ; the system can be equipped with up to eight slices.

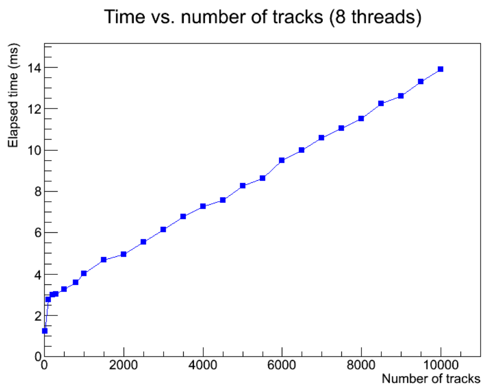

Figure 11. Filter Unit architecture: the responsibilities to receive, reformat, and send accepted events (Resource-Broker), and to reconstruct the physics content (Event-Processor) are split.

6. Preliminary Results

7. Summary

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