

# New discoveries at the LHC

**Dr Valerie Halyo** explains how advances in scientific computing, and the integration of massively parallel architecture in the trigger, might further advance the possibilities of new scientific discovery at the LHC



## Could you begin by outlining the primary objectives of your research?

I believe the key to an era of new discoveries at the Large Hadron Collider (LHC) might lie in recent innovations focused around parallel processing. Computational accelerators such as Nvidia's Graphics Processing Unit (GPU) or Intel's Xeon-Phi and multi core CPUs are capable of running massively parallel algorithms to enhance the performance of the trigger system that is responsible for selecting, for further rigorous study, the most interesting particle events emanating from the proton-proton (pp) collisions.

## What led you to develop an interest in this area?

While working as a postdoc in the BaBar experiment at the SLAC National Accelerator Laboratory in the US, I was heavily involved in the trigger upgrade, which helped me realise the importance of the trigger system in collider experiments. Moving to the LHC, I initially set myself two goals: to try to look for final state

topologies that can differentiate themselves from the Standard Model (SM) of particle physics we know today, and to keep a note of all corresponding events the trigger system suppressed or designated non-important, for archiving and further analysis. My goal was to investigate how we can improve the performance of the trigger at the LHC and pave the way for great expansion in the search for new physics.

## How does this work tie in with your investigations into physics beyond the SM?

In our recent publications, we demonstrated promising preliminary results in our attempt to extend the search at the LHC. We chose to develop a tracking algorithm based on the Hough Transform to run on the GPUs in order to reconstruct the trajectory of the particles created after the collisions. The parallel algorithm not only permits simultaneously finding, in real time, any combination of prompt and non-prompt tracks at LHC conditions where the number of pp interactions in a collision is very large, but it also allows development of new trigger algorithms that could select exotic final state topologies which include new highly displaced black holes or jets. If found, these new topologies would represent a smoking gun for new physics, and hence increase the reach of new physics at the LHC. The new algorithm still needs to be compared to the conventional implementation of the tracking algorithm on the GPU or Xeon-Phi, and extensive work has to be done to bring it to final production. However, these preliminary results on the impact of the potential discovery reach are encouraging.

## Could you summarise some of your most exciting or significant professional highlights to date?

As co-manager of the CMS Luminosity effort (February 2006 – December 2010), I led my

group to provide the sole online luminosity system for the CMS collaboration based on the Hadronic Forward Calorimeter. I was responsible for the design, development, commissioning and deployment of the online/offline CMS luminosity system readout. With my magnificent group we were able to complete all the milestones on time before LHC started running. The system not only delivers the LHC with real-time bunch-by-bunch luminosity at the CMS interaction point, but also – through its collaborative work with LHC – provides the absolute luminosity measurement via the Van der Meer calibration. In 2010, and for the first time at the LHC, my graduate student Jeremy Werner compared the latter measurement to the absolute Luminosity measurement obtained by measuring the yield of Z bosons.

My latest effort was to lead searches for long-lived particles decaying either leptonically or to heavy flavour hadrons, which also led us to investigate new ways of improving the trigger performance for this type of search. My goal is to integrate the new GPU/Xeon-Phi technology into the trigger to enhance its performance and extend the scope of the physics reach at the LHC, and at the same time empower students and postdocs with new cutting edge skills.

## Has a collaborative approach proved important to the success of the project?

I am collaborating with experts from Nvidia and Colfax who are specialising on GPU and MIC architecture respectively. They are not only very knowledgeable and competent, but also share the enthusiasm to contribute to fundamental science. Scientific computing is playing a significant role in the operation of the LHC. It takes an interdisciplinary attitude to obtain the optimal hardware and software design and impact the physics of tomorrow.

# Pushing energy frontiers

As the LHC enters its fifth year of operation, pioneering research led by Dr Valerie Halyo at **Princeton University** in the US is beginning to show how accelerated parallel processing could be the key to new scientific discoveries

**THE LARGE HADRON COLLIDER (LHC)** is the world's largest and most powerful particle accelerator, situated 175 m beneath the Franco-Swiss border near Geneva. Capable of the largest currently known centre-of-mass energy collisions, it is enabling researchers to probe new physics at a level of  $10^{-19}$  m and recreate conditions similar to those a picosecond after the Big Bang at temperatures eight orders of magnitude higher than the core of the sun. With such a powerful machine at their disposal, scientists like Professor Valerie Halyo are keen to extend possibilities of discovery as far as they can. Drawing inspiration from recent innovations led by Nvidia and Intel, Halyo and her collaborators have been investigating how parallel processing – either through systems containing multiple processors, or processors containing multiple cores – could allow an architectural overhaul of the LHC's computing system, in particular the trigger system, and open up the availability of additional computing power.

## THE BRAIN OF THE EXPERIMENT

High-energy physics (HEP) is fraught with many challenges and variables that make the obtaining of physically interesting data a difficult task. Developments in scientific computing at the LHC could have important implications on the particle physics being studied there.

The 'trigger' performs the first quick real-time analysis on data observed from the LHC's four particle detectors (ATLAS, CMS, ALICE, and LHCb), and as such has been dubbed 'the brain' of the experiment by scientists working at CERN. The trigger is programmed to decide whether the data observed should be kept for further analysis or disregarded. Accelerating and enhancing its performance could impact the discovery of potential New particles and their interactions.

## FURTHER ADVANCES

Halyo believes the benefits of scientific computing advances are not limited to improved function of the trigger. The benefits of computational accelerators such as the Graphics Processing Unit (GPU) or Xeon-Phi could have a significant impact on the Worldwide LHC Computing Grid. In order to test new ideas and evaluate our understanding of the data, billions of events need to be simulated; all must match LHC running conditions. Improving the speed of event reconstruction will allow higher productivity, whilst also optimising the efficiency of the computing resources and saving the project money.

The challenges facing both students and researchers involve conducting a careful and thorough analysis whilst delivering new results at a sufficiently fast rate to stay relevant and competitive. The parallel programming techniques will allow young scientists to achieve seemingly competing requirements while acquiring new skills at the cutting-edge of scientific computing. It will improve the turnover time for analysing results, thereby affording young investigators the opportunity to test

new theories and ideas. "These computation accelerators could be the necessary final leap the LHC has waited for to become the discovery machine after the Higgs era," Halyo states.

## ENHANCING THE HIGH LEVEL TRIGGER WITH GPUS

Initial studies conducted by Halyo and her team already suggest that the additional functionality achieved by adding computing accelerators to the high-level trigger (HLT) could make significant improvements to the study of HEP at the LHC. The accelerated execution speed of algorithms alleviates various issues that researchers had previously encountered, while simultaneously providing the opportunity to broaden physics research. The flexible software and hardware architecture of the HLT will allow simple integration of new hardware into the trigger without causing substantial disruption to operation flow.

Results also show the algorithm the team has chosen easily satisfy the processing time constraints set by the trigger system up to luminosities where 250 proton-proton interactions occur at the same collision. At these



Hough transform algorithm applied to a simple example. **Left:** Hits in a simulated event with curved tracks. **Centre:** Each hit results in a curve of votes in parameter space. Locations with many votes are likely to be tracks in the original data. **Right:** Candidate tracks identified from finding local maxima in the parameter space.

## INTELLIGENCE

### ACCELERATED PARALLEL PROCESSING THE KEY TO NEW DISCOVERIES AT THE LARGE HADRON COLLIDER (LHC)

#### OBJECTIVES

Scientific computing is a critical component of the LHC experiment, including operation, trigger, LHC computing GRID, simulation, and analysis. The goal is to extend the physics reach at the LHC by enhancing the performance of the multi-level trigger system in the CMS/ATLAS experiments. The new hardware developed by Nvidia/Intel can, in the next two years, revolutionise the field.

#### KEY COLLABORATORS

**Colfax International:** leading provider of innovative and expertly engineered computing systems, and personal supercomputing solutions.

**Nvidia:** a pioneer in visual computing for two decades and inventor of GPUs used for video games, medical diagnosis and scientific research etc.

**Palix Technologies LLC**

#### FUNDING

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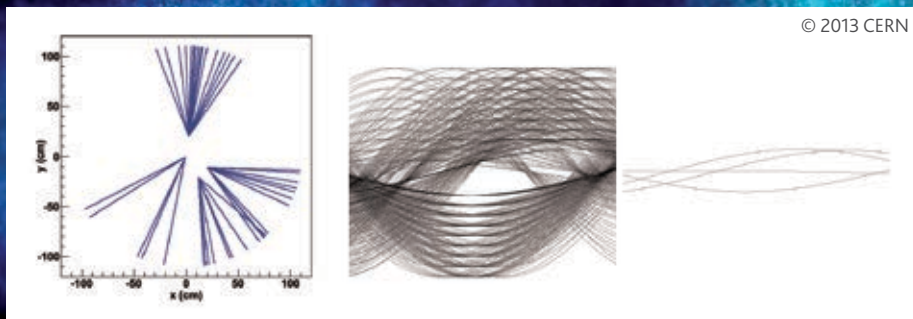
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**VALERIE HALYO** received her BSc in Physics and Mathematics from the Hebrew University and her MSc in Theoretical Physics from the Weizmann Institute of Science in Israel. In 2001 Halyo received her PhD in Physics at Stanford University under the supervision of Nobel laureate Professor Martin L Perl and became a Research Associate at Stanford Linear Accelerator Center working on the BaBar experiment. She was heavily involved in the trigger upgrade. She looked for rare B decays and led the pentaquark search effort. In 2006 she became Assistant Professor at Princeton and a member of the CMS collaboration at the LHC. She led her group to provide the sole online luminosity system for CMS and then focused her analysis and efforts on integrated massively parallel computing to enhance the trigger and extend the physics reach at the LHC.



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The Hough transform algorithm applied to an event with multiple displaced jets. **Left:** The simulated tracks present in the event. **Centre:** The parameter space after applying the first Hough transform is still very cluttered. **Right:** The second Hough transform identifies the sinusoids corresponding to the jet vertices.

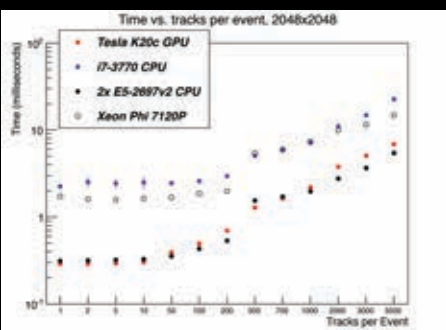
extreme conditions, the algorithm requires on average about 4.5 MB of memory using double precision, compared to the 6 GB of available memory on the current K20c GPU. With these generous memory margins, the need to move data back and forth between the CPU and GPU over PCI Express during the processing of an event is negated. Thus parallel processing using heterogeneous systems sharing work between the CPU and the GPU/Xeon-Phi coprocessors offers a faster algorithm and cost-effective system.

#### TRACKING NEW PHYSICS

The tracking algorithm developed by Halyo and her collaborators has made it possible to identify any combination of charged particles in the silicon tracker that originate either close to the interaction point or at some distance away from it. This is significant, as it allows for the use of new algorithms in the trigger designed to select phenomena including black holes and highly-displaced jets, boosted jets or simply heavy flavour jets that could not be selected efficiently before or even totally evade detection. This marks a significant advancement in the study of new physics, which is the primary objective of the LHC. Developing fast and efficient parallel algorithms will allow students and researchers the chance to test their ideas and pioneer new searches in areas previously unexplored or highly suppressed.

#### UNDERSTANDING LUMINOSITY

A strong understanding of luminosity is critical in an experiment like the LHC, as it is used to monitor the LHC's performance in real time and to provide an overall normalisation for



Time performance of CPU, GPU, and Xeon Phi implementations as a function of the number of simulated tracks in the event showing the advantage of adding multiple co-processors to the system.

physics analyses. Real-time luminosity monitors measure interaction rates for the setup, optimisation and equalisation of the beams at the interaction regions. Bunch-by-bunch effects are detected and corrected using a bunch-by-bunch luminosity measurement. The absolute luminosity measurement also provides an overall normalisation for physics analysis.

Understanding luminosity is vital to managing systematic errors on precision measurements, and can also provide the pathway to more rigorous testing of the underlying theories. The absolute luminosity value allows for normalisation of all the measurements taken during the experiment(s), and thus a significant comparison of results from other similar studies.

#### THE FUTURE OF HEP

Studies at the LHC have already resulted in the fantastic discovery of the Higgs particle. If confirmed as the Standard Model Higgs, it completes the discovery of the last unknown parameter in the Standard Model of particle physics and the key to understanding the origin of mass of fundamental particles in the universe.

It is difficult to anticipate where the next step in HEP progress will take the team after such a significant milestone. Certainly for the foreseeable future, the LHC will remain the only machine at the frontier of HEP advancement. The task for the researchers now is to continue to revise the questions they ask of themselves in HEP and check whether new technologies can facilitate the search for an answer to one of them. This is one of the reasons why Halyo greatly appreciates the valuable discussions with the scientific non-academic community: "I think today, many large scale projects can only be achieved if you have an interdisciplinary attitude," she expresses.

One cannot overlook the developments in the past decade and ignore the current solitude of the LHC in the experimental HEP landscape. One major concern amongst the scientific community is whether governments will be willing to fund major new particle physics facilities such as the International Linear (ILC) Collider or a muon collider.

Whilst recent accomplishments at the LHC include the discovery of the Higgs boson, Halyo is confident that this is not the beginning of the end but rather the end of the beginning.