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Diamond Pixel Luminosity Telescopes

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Current Research Interest and Key contributions to CMS at the LHC

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Abstract

In this document, Halyo summaries her key contributions to CMS at the LHC and provide an explanation of their importance and her role in each project. At the end Halyo describes her recent research interest that includes GPU/MIC Acceleration of the High Level Trigger (HLT) to Extend the Physics Research at the LHC. A description of her work the recent promising results that she accomplished and the deliverable are also elaborated. These contribution were only possible thanks to DOE support of junior faculty research and their clear goal to promote research and innovations.

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1 Summary of Key Contributions to LHC

1.1 Overview

This exciting Large Hadron Collider (LHC) era, brings the hope that we will finally be able to unravel the mystery of electroweak symmetry breaking in the Standard Model (SM) of particle physics and possibly dark matter by a thorough exploration of the TeV scale frontier. Despite the striking success of the SM, There are a lot of reasons why it is not the ultimate theory. Most notably, a few of the unresolved problems include the large hierarchy in energy scales, the presence of dark matter throughout the universe, and the origin of the (many) fundamental parameters. It is hoped that the experimental study of the Higgs mechanism might shed light on the mathematical consistency of the SM at energy scales above about 1 TeV, where various alternatives to the SM invoke new symmetries, new forces or constituents. Furthermore, there are high hopes for discoveries that could pave the way toward a unified theory. These discoveries might take the form of supersymmetry (SUSY), or extra dimensions with implications requiring modification of gravity at the TeV scale, or some entirely new theory that might result from our investigation of the TeV energy scale. While in general we do not know what energy scale is relevant for the solution of the above problems, the electroweak scale is pointing us to new phenomena at the TeV scale. My personal emphasis is to conduct signature based searches, by using my unique knowledge of phenomenology and rigorous experimental new techniques to look for new topological signatures that either were not looked before or could have evaded detection in other experiments.

Significant new challenges are continuously confronting the LHC which does not only drive forward the accelerator but also the theoretical, experimental and detector physics. In order to fully realize the LHC's enormous scientific potential I realized the advantage of close working relationship, between experimentalists and theorists. Catalyzing the interactions between theory and experiment manifested in my work gives me the opportunity to make a broad impact to science and the high energy field of particle physics in particular.

Joining LHC and in particular the CMS experiment at CERN two years before the first collisions allowed me to be part of few critical phases of the experiment. Phase one included the design, development and commissioning of a crucial missing part of the detector operation, the luminosity system, that was still missing at the end of 2006. Phase two allowed me and my group to participate in the data taking and play an essential role in the first precision measurement of the electroweak boson cross sections that proved the excellent performance of both the LHC accelerator and the detector performance. In addition, we were the first to demonstrate the potential use of the Z boson as a standard candle for LHC. The large and clean signature Z boson provides an independent physics channel that will normalize all the physics measurements of LHC.

In the third phase realizing first LHC to be the only game in town for the next 2 decades, second, the invaluable opportunity of the upcoming LHC long shut down and third, the responsibility we got to choose physics program that will extend the physics reach of LHC. I started an extensive research plan towards the quest for new physics based on new topological signature searches that don't exist in the SM and explore those who might have evaded detection. Realizing the enormous significance of the trigger, as part of my plan I proposed a GPU/MIC augmentation of the CMS High Level Trigger that could similarly augment the

ATLAS trigger as well. This upgrade would extend the existing physics program providing reach to new or suppressed physics such as various hidden valley scenarios RPV susy models or other topological models that include displaced vertices or other odd tracks that would have evaded detection to date. In the following a highlight of my various contributions are described. Details on the upgrade proposal and the exsiting current results were described in the end of the ducument 9.

In the following, Halyo's main contributions to LHC are described. An explanation on the importance of the projects and her role are elaborated.

2 CMS Luminosity System:

The reason the Luminosity is important

The high luminosity Figs. 4, 5 (of $10^{33} - 10^{34}$ $cm^{-2}\,s^{-1}$) at the LHC insures that systematic errors will play a dominant role in determining the accuracy of precisions measurements. Therefore, the rich physics program of the LHC require an accurate determination of the luminosity. The luminosity is a measure of the intensity of the accelerator colliding beams and it is needed to calculate the cross sections of observed physics processes.

Responsibility : Luminosity Project manager

Dedicated luminosity measurement devices were not part of the original scope of CMS and were addressed only in recent years. This created a new opportunity for me to make a significant contribution to CMS. I seized this opportunity, which led me being assigned the overall responsibility for measuring and monitoring the luminosity for CMS. I led my group from the system's inception, where CMS luminosity methods were not yet established to actual delivery of luminosity values to the CMS collaboration using the Forward Hadronic Calorimeter. The CMS luminosity measurement is used to monitor the LHC's performance in real time and to provide an overall normalization for all physics analyses.

My main tasks involved the following:

1. Development and quantitative analysis of the candidate methods to be used to extract the instantaneous luminosity on a bunch-by-bunch basis

2. Quantitative analysis of the test beam/collision data used to evaluate the methods chosen and access the systematics uncertainties on the luminosity values.

3. Design and development of the online/offline luminosity readout system based on the existing Hadronic Forward (HF) calorimeter capable of delivering precise ($\sim 1\%$) luminosity information in real time (1 Hz update rate) to various "consumers," such as the LHC and CMS control rooms and the Remote Operations Center at FNAL.

4. Coordination with and incorporation of the information from other detector groups capable of monitoring the luminosity—e.g., the LHC BRAN group and the Pixel Luminosity Telescope (PLT) group.

5. Bookkeeping of the online and offline luminosity information, including the relevant trigger information and providing of the luminosity values to the CMS users.

6. Absolute normalization of the relative luminosity using initially independent measurements of the luminosity from Van der Meer (VdM) scans carried out by the LHC accelerator group, and from the analysis of standard model processes of known cross section. [1]

7. Continuous Readout of the CMS Luminosity during an LHC fill, allowing LHC to optimize the luminosity to CMS [2].

8. Detailed study of the W/Z production cross section and the relevant parton distribution functions, which are likely to be the key to the ultimate determination of the luminosity.

All the milestones I set for HF based luminosity measurement for CMS were completed on time and the luminosity system was ready for the first LHC beam injection on Sep. 10 2008. Under my leadership CMS was the first among LHC experiments to have an automated online readout communicating with LHC. It allowed to optimize the luminosity delivered to CMS and triple its value at these critical start-up moments. Last but not least, while working with the machine group, I led the effort to measure the first absolute normalization of the CMS luminosity using machine parameters. This high impact first measurement was released at the 35th ICHEP conference in 2010 in Paris and was used to normalize all CMS physics results published in 2010 to an accuracy of 4%. This is an unprecedented low value for LHC type bunch pattern. Figs. 4, 5 show our recent CMS integrated and the maximum daily instantaneous luminosity monitoring. The CMS luminosity system continues to successfully to date, monitoring the luminosity, optimizing the beams head on collision and providing normalization to all physics results using the HF based Luminosity results.

2.1 Update on the Diamond Pixel Luminosity Telescopes (PLT) Project

Second effort I am involved include the research and development of advanced detector technologies for the LHC luminosity upgrade project, called "Diamond Pixel Luminosity Telescopes (PLT)". The PLT technique was proposed by a Rutgers-Princeton consortium. It is an independent luminosity measurement for the CMS experiment, complementing the existing online measurement based on the hadronic forward calorimeter (HF) as well as the offline measurement using HF and measurements from the pixel tracker. It consists of sensor planes mounted in sets of three to form a telescope which can detect threefold coincidences corresponding to a particle originating from the interaction point. The total PLT assembly contains sixteen such telescopes, eight mounted in a circular pattern on either side of the CMS detector. The PLT has been in development as a collaboration between Princeton University and Rutgers University.

[1] "CMS Absolute Luminosity Normalization" V. Halyo *et. al.*, HERA and the LHC 4th workshop proceeding V. Halyo *at. al.*

[2] "Continuous Readout of CMS HF based Luminosity" V. Halyo *et. al*

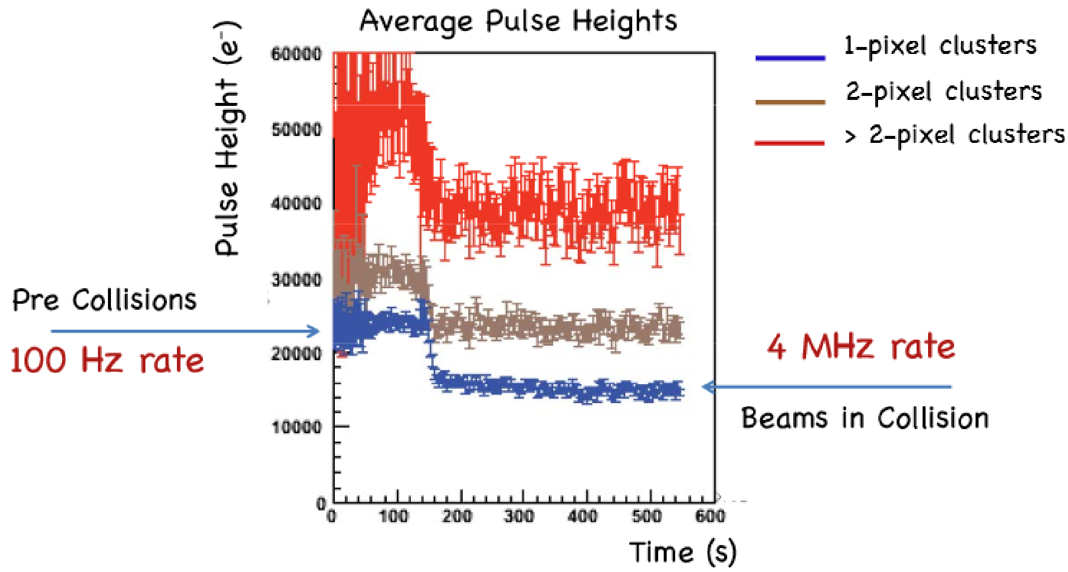


Figure 1: Average pulse heights observed in the diamond PLT for 1-pixel clusters (blue), 2-pixel clusters (brown), and clusters of 3 or more pixels (red) in pre-collision and collision conditions. From S. Schnetzer's review, June 28, 2013.

The PLT was originally designed to use single-crystal diamond sensors for the detector. As part of the initial efforts for this design, the technitian who was paid for a year by this grant developed the procedure to bump bond the readout cheap to the diamond sensor. In parallel a postdoc was hired with this grant. The postdoc participated in the bump-bonding of the first batch of diamond sensors to their backplanes at Princeton. After relocating to CERN, the postdoc worked in adapting the existing code for the HF-based luminosity system to the PLT. This would have allowed for reuse of a large amount of already-tested code for the PLT system. However, the final design of the luminosity DAQ was chosen to use a different architecture and hence the original HF-based code was not used for this purpose.

For the 2012 run, four diamond telescopes, as well as one silicon telescope for comparison, were installed as a pilot installation for the PLT. This pilot installation revealed some issues with the diamond sensors. Specifically, the absorbed dose induced a polarization in the diamond sensor, which decreased the effective electric field, causing a longer charge collection time and reduced charge collection efficiency, as some electrons may end up in traps in the sensor material rather than being collected. Figure 1 shows the change in pulse heights as the beam moves from the pre-collision state (where the PLT rate is approximately 100 Hz) to collisions (where the PLT rate is approximately 4 MHz). A significant decrease in pulse heights is observed.

As a consequence of the polarization developing over time, the efficiency also decreases over the course of time. Figure 2 shows the change in the PLT luminosity measurement relative to the HF luminosity measurement over the course of a single LHC fill. A deviation of approximately 1% per hour can be observed. While this can be corrected for, it created problems for the utility of the PLT as a stand-alone luminosity measurement. Finally, Figure 3 shows the evolution of the pulse heights over the full 20 fb^{-1} of luminosity delivered

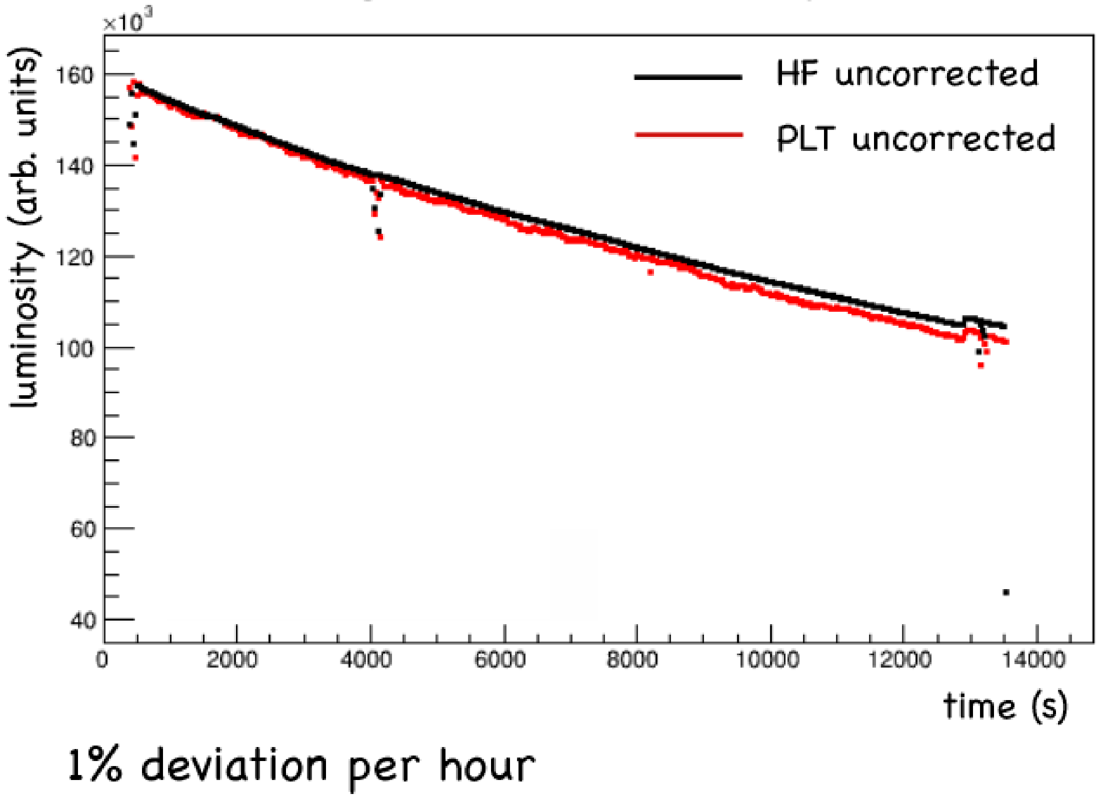


Figure 2: Luminosity measurements from the HF (black) and PLT (red) over the course of a single LHC fill. The PLT measurement decreases relative to the HF by approximately 1% per hour. From S. Schnetzer's review, June 28, 2013.

in the 2012 run. A significant decrease is seen in all cases. The longer charge collection time also resulted in some spillover of the measurement from the diamond sensors into following buckets; while this could be measured and corrected for for the 50 ns bunch spacing in the 2012 run, it posed a significant problem for the 25 ns bunch spacing planned in the 2015 run.

A variety of methods were investigated for mitigating these issues. Increasing the bias voltage of the sensors decreased the polarization effects, but was not viable as a long-term solution. Reactive Ion Etching (RIE) was tried to remove material from the surface of the diamond sensors, on the theory that surface traps had been created by the mechanical polishing of the sensors which were decreasing the charge collection efficiency; removing a few microns of material from the surface might then remove these traps and restore the original efficiency. Unfortunately, RIE failed to increase the efficiency for the diamonds that had been in the pilot run. Illumination by lasers was also attempted to ionize the traps. This improved the pulse heights at lower rates, but failed to provide an improvement at higher rates.

As a consequence of these issues, over concern that the PLT installation might not be successful with the single-crystal diamond design, the decision was made in 2013 to switch to a design based on silicon sensors instead. As the silicon sensors are the same as used in the CMS pixel detector, this allowed for a significant amount of reuse of components,

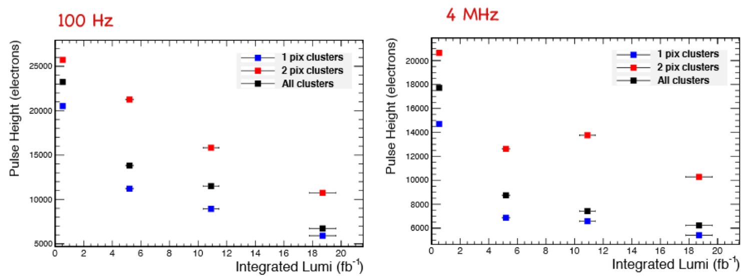


Figure 3: Observed pulse heights as a function of integrated luminosity during non-collision conditions (100 Hz, left) and collision conditions (4 MHz, right). From S. Schnetzer's review, June 28, 2013.

software, and expertise. However, it also necessitated changes to the design of the PLT detector to account for the additional cooling necessary for the operation of the silicon sensors. Fortunately, this was the only major change necessary for the switch from diamond to silicon.

At the end of 2013 the postdoc has been working on the testing and installation of the silicon PLT. As the silicon planes were shipped to CERN, he was part of the group performing the testing and quality control of the planes. We ended up with a total of 68 planes successfully tested and identified as good, more than sufficient for the requirements of 48 for installation and 16 spares.

The postdoc then aided in setting up the testing environment for pre-installation testing and burn-in, consisting of a humidity- and temperature-controlled dry box providing a light-proof testing stand with full cooling, power, and control and data connections, so we could test up to a full half of the detector at a time in continuous running to ensure that no unexpected issues arise over the course of the several months of time before the actual PLT installation.

Finally, while waiting for the installation (currently scheduled for January 2015), the postdoc has been working on developing code for calibration of the PLT system. This will also allow us to quickly test and verify that the PLT is working correctly after installation, so we can quickly identify and fix any potential problems that may occur during the installation process.

3 The Z boson production cross section measurement and its leverage as the first "Standard Candle" for LHC absolute Luminosity:

Responsibility: Led the first result using a physics signal (Leptonic Z boson decay to electrons) to measure the absolute luminosity for CMS

The responsibility included initially crucial role in the precision measurement of the Z boson production cross section decaying to leptons. Later these measurement were leverage

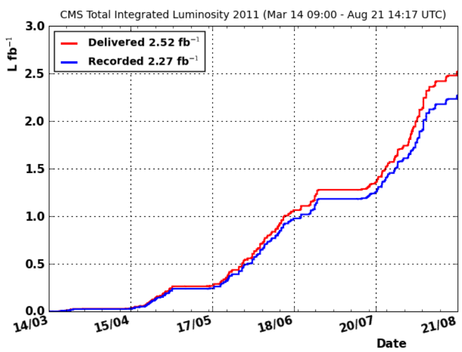


Figure 4: Integrated luminosity versus time delivered to (red), and recorded by CMS (blue) during stable beams at 7 TeV centre-of-mass energy.

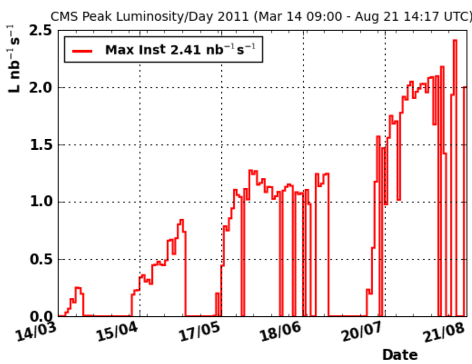


Figure 5: Maximum Instantaneous luminosity per day delivered to (red) CMS during stable beams at 7 TeV centre-of-mass energy.

as standard candle for LHC as I proposed in HERA and the LHC 4th workshop in 2008. The production cross section measurements were the first results presented in ICHEP 2010 in Paris. These results led to 2 physics journal publications in PRL. Preliminary results that demonstrate the use of the Z boson production to measure the absolute luminosity were presented in the LHC workshop in 2010

My graduate, Jeremy Werner thesis is the first thesis in LHC that proposes and provide the Z boson production cross section results and the first results that demonstrate the use of the Z boson production as a "Standard Candle" to measure the absolute luminosity for LHC.

Reason it is important

Clear understanding of the need to demonstrate the feasibility of utilizing signals from existing sub-detectors, using physics processes is crucial. The reason is that these processes are independent of the Hadronic Forward calorimeter based luminosity methods I developed. The electroweak bosons which are copiously produced at the LHC have large cross section, are cleanly reconstructed and have relatively small systematic uncertainty that could be improved with larger amount of data is one of the obvious choices to be used in order to test their feasibility to be employed as luminosity monitors for LHC. These physics processes will provide a better understanding of the luminosity that is critical to managing the systematic errors on LHC precision measurements, providing more stringent tests of the underlying theory. This method will eventually be the ultimate way to calibrate all the physics measurements in LHC.

A summary of the measurements result using different methods to measure the signal efficiency and its comparison to the theoretical prediction is given in Fig. 6. This excellent agreement allowed us to try and Leverage $Z \rightarrow e^+e^-$ decays as "standard candles" for measuring the absolute luminosity at the LHC by simply inverting the measurement to instead use the $Z \rightarrow e^+e^-$ signal yield to measure the luminosity. We found as shown in

Fig. 7 that this result based on a physics process agreed to about 1% with the primary relative CMS luminosity measurement we performed in parallel and calibrated with LHC. Our results is found to be not only the most precise absolute luminosity measurement performed to date (2010) at a hadron collider but also the first one based on a physics signal at the LHC.

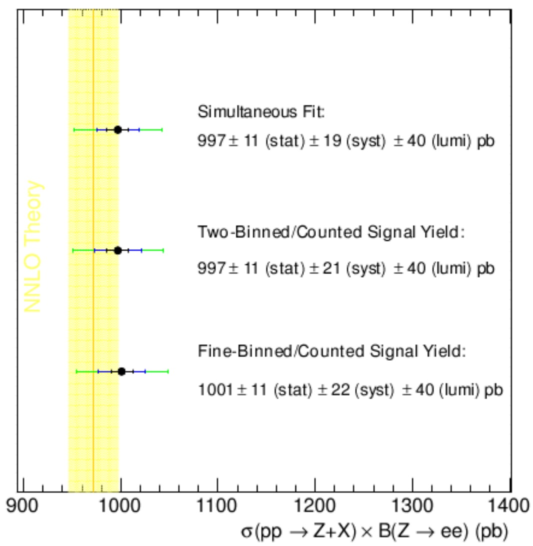


Figure 6: A summary the $Z \to e^+e^-$ production cross section measurement results using different methods to measure the signal efficiency and its comparison to the theoretical prediction calculated to NNLO in QCD.

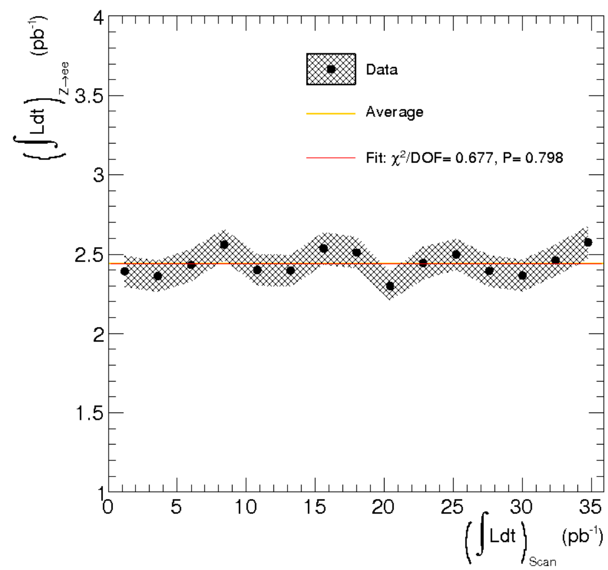


Figure 7: The $Z \to e^+e^-$ absolute luminosity is profiled in terms of the HF based calibrated luminosity (we both measured). Each luminosity blocks to 2.4 pb^{-1}. The data profile is shown in black. The corresponding errors are represented by a hatched band. The average of the profile is represented by an orange line. The fit of the profile to a constant is represented by a red line.

4 Main Contributions during the LHC Commissioning Period:

Responsibility: Co-convener of the di-lepton topological group in USCMS

During the pre-collision time, I had the privilege to be elected as the convener of the USCMS di-lepton signature topological group which consist responsibility on the leptonic decay of the Z as well.

The Reason it is important

This allowed me to make an important impact on CMS and lead the analysis working group to develop the technical infrastructure common to various dilepton analyses which had to be ready before LHC collisions. I led the effort to develop data driven tools that are widely used in CMS and that were crucial to insure our readiness before first data taking.

Few of these tools included:

1. Data driven method called Tag&Probe, originally developed in the Tevatron to measure the physics signal efficiency -
   This is the only tool that allows data driven technique to measure the efficiency of a physics channel to provide the corrected yield for cross section measurements or others

2. Multiple data driven method to estimate the background for di-lepton analysis
   These are critical for evaluating correctly the yield of our signal based on data

3. Proposed , developed and deployed low P_T di-elerton triggers
   This is important for electron calibration and crucial for the Higgs or SUSY cascades decay searches that include a non negligible contribution of soft electrons

4. I created with Prof. I. Shipsey the first low mass resonances groups in USCMS which served as a benchmark for the performance of the CMS detector and shed first light on results from the Tevatron.

5 New Approach; New of Era with Strong Theory-Experiment Interface

Unlike recent discoveries at colliders, which were of particles and forces with properties predicted in advance, there is no clear consensus on what will be seen at the LHC. Searches for new physics must prepare for every eventuality and cover a vast spectrum of possibilities. A new strategy is clearly needed, one that will require a much more intense interaction between all facets of theory and experiment than has existed before. Adapting this approach to the new LHC era helped me initiate various fruitful collaborations with experts in Monte-Carlo simulation and SM phenomenology, to QCD theorists, model-builders and string theorists.

1. A few of the important published results included assessments of the theoretical systematic uncertainty that contributes to key measurements such as the inclusive production of the W/Z cross section and the use of the W/Z boson production to measure the absolute luminosity at the LHC. This work was done in collaboration with Prof. S. Yost [3] and my postdoc N. Adam, graduate-student W. Zhu. The systematic errors in both the total cross-section and acceptance for anticipated experimental cuts to be used by both CMS/ATLAS were evaluated using the state of the art theoretical tools and they clarified where improvements are needed. We included the best available analysis of QCD effects at NNLO in assessing the effect of higher order corrections and PDF and scale uncertainties on the theoretical acceptance. In addition, we evaluated the error due to missing NLO electroweak corrections and proposed which MC generators and computational schemes should be implemented to best simulate the events. The systematic uncertainties were evaluated for the production cross section

[3] Permanent address: Department of Physics, The Citadel, Charleston, SC 29409, USA

of the Z boson decay to leptons using the 2010/2011 data. In addition, my inverting these results it allowed us to evaluate the the systematic uncertainty on the absolute luminosity delivered to CMS based on the Z boson standard candle.

2. Another collaboration was initiated during the period I served as the convener of the di-lepton topological signature group. I noticed the lack of an event based MC generator that includes both NLO QCD and EWK corrections that is able to describe well the invariant mass of the di-leptons in the few TeV regions for Z' boson searches. It is important to realize that the leading edge understanding of the theory which we can be translated to an event based Monte Carlo simulation used by experimentalists is critical to managing some of the systematic errors on these measurements and can provide stringent test of the underlying theory. Understanding the problem shared by both LHC experiments and the importance of the progress towards its solution initiated a natural collaboration between my graduate student at the time Miroslav Hejna, myself and my theorist colleagues Prof. S. Yost, Prof. B. Ward, [4] who are Monte Carlo experts that have been advocating the need for an event generator with NLO QCD and EWK corrections for several years and worked out a theoretical construct to support such a generator, named "QCDxQED exponentiation". [5] Miroslav joined us on a project to try help initially to combine EWK calculation to Next Leading Order (NLO) into Herwig a LO QCD event based generator. Miroslav's task was aimed at including both the theoretical part of trying to understand the higher order corrections and to improve the existing MC event generator and also to validate the MC and compare it to data with various CMS cuts. Extending existing programs to this level is difficult, in part because the algorithm in MC@NLO cannot be easily extended to multiple gluon emission, and in part because combining existing tools for electroweak corrections with MC@NLO by traditional means requires subtractions that can lead to negative-weight events. Thus we started working on a new method that was originally used a LEP and tried to incorporate it with existing LHC generator such as Herwig. The new event generator for W and Z production at the LHC would include initially exact LO QCD and NLO electroweak corrections with resummation of the large QED IR effects. Results of this work will soon be released in a program called HERWIRI2.0. The theoretical idea on how to deal with the higher order corrections relied on Prof. S. Yost and Prof. B. Ward's previous work from LEP and partially implements their QED $\otimes$ QCD resummed theory in which all IR singularities are canceled to all orders in α_s and α. Progress on our work was reported at Loopfest VIII, Madison, WI, May 8, 2009, RADCOR 2011 in Mamallapuram, India and in ICHEP 2012 in Melboune AUS.

3. Last but not the least is my recent project in collaboration with Prof. G. P. Salam, Prof. M. Strassler, and my graduate student W. Zhu. In our paper we proposed a new search channel in LHC for the Higgs Boson decaying into two long lived neutral particles, each of which decays to bb at a displaced vertex inside the beam pipe. We demonstrated how to discriminate the signal from the QCD background by looking at

[4] Department of Physics, Baylor University, Waco, TX, USA,

[5] Other theorists have also considered this to be a priority, including the authors of "HORACE",a MC event generator using a different technique to add NLO EWK corrections to LO QCD.

properties of the tracks from the highly-displaced vertices. Figs. 8, 9 shows how by using our selection criteria we are able to suppress the background significantly. It appears that a 120 GeV/c^2 Higgs decaying always in this mode, for a long-lived neutral particle with mass in the range of 15-30 GeV/c^2 and a decay length inside the beam pipe, can be readily observed with an integrated luminosity of 1 fb^{-1}. This collaboration is another classic example how the invaluable theoretical input that includes among many other, the QCD background modeling, QCD jets algorithms and model building combined with the rich experience by experimentalist on the detector resolution effects, triggers and data driven methods to estimate the background are necessary to evaluate the feasibility of the new proposed search in LHC. This study allowed us to propose a realistic search experimentalist can look for immediately with the current data recorded. The triggers for this analysis resulting from the phenomenological study were implemented by my group in the CMS trigger menu for the 2012 data analysis and the analysis is currently work in progress.

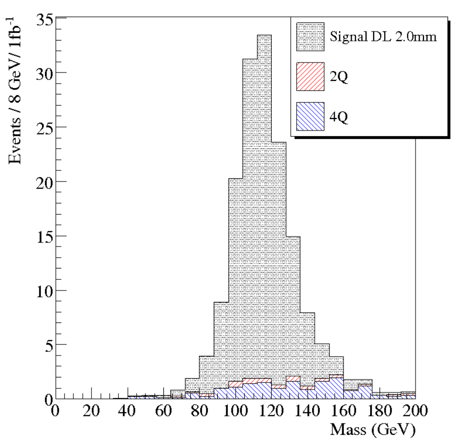


Figure 8: The mass spectrum of the Higgs boson candidate, is shown for the backgrounds and the signal with (pseudo-)scalar Decay Length (DL) of 2.0 mm.

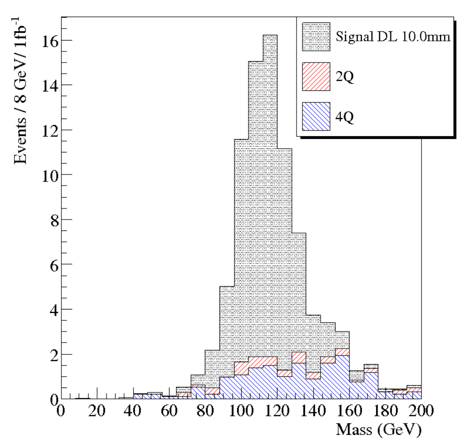


Figure 9: The mass spectrum of the Higgs boson candidate, is shown for the backgrounds and the signal with (pseudo-)scalar Decay Length (DL) of 10.0 mm.

6 New topological based Signatures Searches:

One of the fascinating advantages that LHC provides is the opportunity to look above the TeV energy scale for new processes that include new particles or interactions. My approach is to embark on new types of topological based signature searches expanding the original CMS physics program in the quest for physics beyond the SM. These topological searches include processes that could have evaded discoveries in previous experiments or new ones that depends on the high energy scale. However, expending the physics scope requires at least, the development of new or the improvements current reconstruction algorithms. In addition to significantly improve its potential discovery search I suggested a new augmentation of the CMS High Level Trigger that would be briefly described.

6.1 The main searches and activities I have been leading in CMS.

In the following I describe few proposals for new searches I initiated in CMS and I am leading as well.

6.1.1 Search for Higgs Bosons decaying to Long-Lived Exotica in the Displaced Lepton Channel

The Higgs sector is one of the great unknowns in our current understanding of particle physics, and is the primary target of the current Tevatron and LHC programs. Within the SM, the mass of its single Higgs boson is undetermined, but for a given mass the Higgs bosons decay modes are precisely predicted. However, beyond the Standard Model (BSM), the number of neutral Higgs bosons (and other scalars or pseudoscalars) and their decay modes can vary widely. It is essential, even if the SM Higgs boson is confirmed to do a very wide variety of analyses that cover all decay/production possibilities, until more light is shed on the scalar sector.

In recent years I published few proposals for few new Higgs searches with new topological signatures. The first one proposed is $h^0 \to A^0 A^0 \to b\bar{b}\tau^+\tau^-$ in 2007 in collaboration with N. E. Adam, M. Herquet, and S. Gleyzer and the most recent proposal to be published soon is $gg \to h \to (a \to b\bar{b})(a \to b\bar{b})$ in collaboration with my theorist colleagues Prof. G. P. Salam, Prof. M. Strassler and my student W. Zhu. In the last proposal, the Higgs Boson decays into two long lived particles, each of which decays to bb at a displaced vertex inside the beam pipe. As can evidently be seen, my interest gradually shifted to investigate the possibility that the SM Higgs or some scalar has been missed in previous searches. Namely it may have been copiously produced at LEP and the Tevatron but has evaded detection due to non-standard decays that were not targeted before. One of the important new search topology I proposed to look for in CMS includes the decay of the "Higgs" (Heavy Resonance) to long lived neutral and boosted particles that have never been searched before.

Following the excellent performance of the LHC, delivering the highest instantaneous luminosity so far ($\sim 3^{33}\mathrm{cm}^2\mathrm{s}^-1$ and the excellent performance of the CMS detector that was repeatedly proven during 2010 first physics data. It was a good time for me this year to embark and lead a new search in CMS for a new topological signature of the Higgs boson. The main search I led was in collaboration with members from RAL and Purdue university is the

"Search for Heavy Resonance decaying to Long-Lived Neutral Particles in the Displaced Lepton Channel".

In this search, for simplicity, the massive resonance was taken to be a Higgs boson H^0 who subsequently decays to two long-lived, spinless, neutral particles, which then each have a finite branching ratio to decay to dileptons, i.e. $H^0 \to 2X$, $X \to \ell^+\ell^-$. The signature of these events is one or two displaced vertices within the CMS tracker volume, formed by a pair of oppositely charged reconstructed leptons (electrons or muons). The mass range of the Higgs was first chosen to be between $M_{H^0} = 200 - 1000$ GeV/c^2 and $M_X = 20 - 350$ GeV/c^2 with life times $c\tau_X = 2 - 40$ cm. The reason these parameters were initially chosen is due to the high transverse momentum thresholds required by the CMS trigger algorithms which highly suppress the decay to low mass Higgs. Hence this search has a dual purpose, first to look for this Higgs decay topology at mass ranges feasible by the CMS detector and second to help me evaluate the performance of the CMS detector for this type of topological signature where the Higgs decay to 1 or 2 displaced vertices.

Performing the analysis we found various limitations that impact the search for long lived leptons in CMS. Few of this limitations include the ability to reconstruct tracks only up to 20-40cm from the interaction point, or the limitation to select events by the trigger if the muons are collimated at angular distance less than $\sqrt{\eta^2 + \phi^2} < 0.2$. An extensive work was also done with the group from RAL and Purdue to improve a dedicated trigger for the leptonic channel. The results of this analysis yield upper limits on the cross section typically in the range 0.7-10 fb, for X bosons whose lifetime is such their mean transverse decay length is less than about 1 metre. The 95% confidence level upper limits on σB for the electron and muon channel for one of the Higgs masses we looked for is given in Figs. 10 using and integrated luminosity $\sim 5.1\text{fb}^{-1}$ in the muon channel and $\sim 4.1\text{fb}^{-1}$ due to the raise of the p_T threshold in the electron channel. This result was the best result in LHC in 2011 the year it was published.

For the 2012 update to the displaced lepton search (currently submitted to PRD and available at arXiv:1411.6977), we implemented a variety of improvements to extend the sensitivity of our search above and beyond the improvement from the increased luminosity available in the 2011 run. In particular, we used a new technique for identifying candidate events, which allowed me to implement an entirely data-driven background estimation which was valid for a wide variety of possible signal models. This allowed us to set limits on an entirely new signal model featuring a squark decaying to a quark and a long-lived neutralino, which then decayed to two leptons and a neutrino, in addition to the signal model used in 2011 featuring a neutral long-lived boson, which decayed to a pair of leptons, produced from an exotic Higgs decay. We also produced an additional set of limits correcting for the CMS acceptance, allowing them to be used in a more model-independent way, which could be used by theorists to quickly evaluate the feasibility of new models. The postdoc also worked extensively on the displaced lepton triggers for the 2012 run which allowed us to maintain a good efficiency for our signal models despite the necessity of reducing the rate due to the increasing luminosity. The results for 2012 are summeried are in figs 11

Importance of the analysis

This analysis is the first search in LHC to look for topological signature that manifest itself as 1 or 2 displaced vertices within the tracker volume, formed by a pair of oppositely charged reconstructed leptons. In particular a decay of the Higgs boson to two long lived

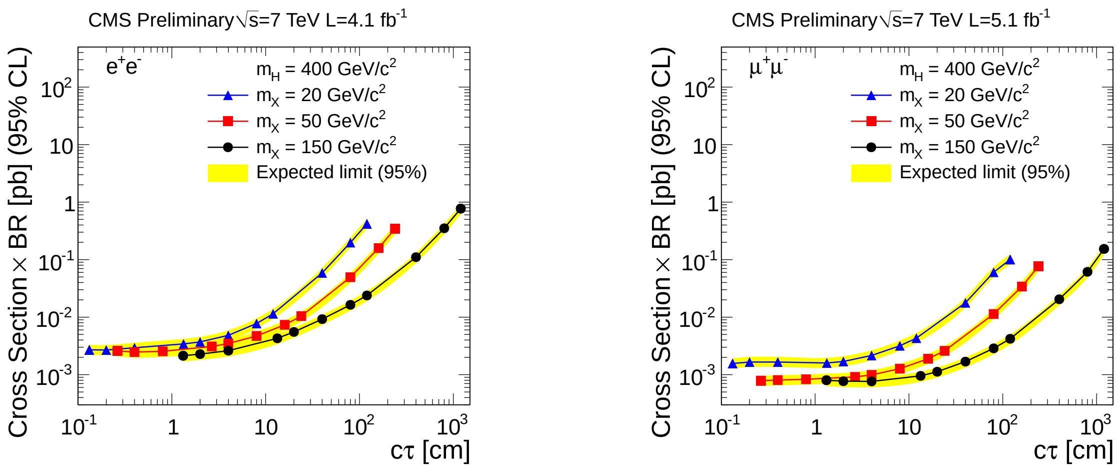


Figure 10: 95% confidence level upper limits on σB for the muon channel for a Higgs mass of 400 using 2011 data

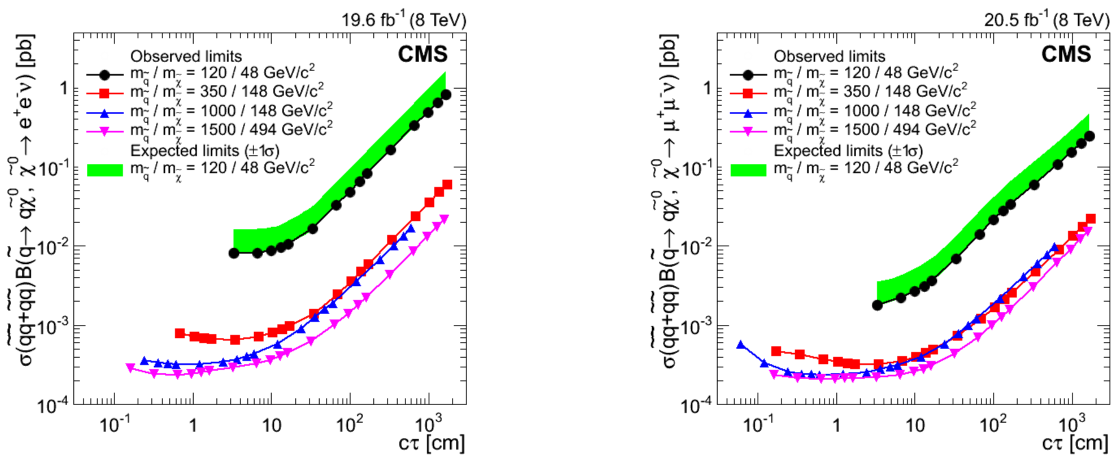


Figure 11: 95% confidence level upper limits on σB for the muon channel 2012 data

particles decaying each to two leptons. Based on what I learned in this analysis and various trigger and track reconstruction studies I investigated with my group (some are internally published in CMS). We developed new triggers for new type of spectacular topologies never looked before and 2 of our triggers were deployed and will be used for our 2012 search for long lived particles decaying to heavy flavor jets with or with out displaced leptons in the final states. My plan is not only to look for "Higgs" which decays to non boosted long lived particles but also to lead a search to searches for "Higgs" decay to long lived and boosted particles that have never being look at before. The experimental signature will be collimated leptons, pions or QCD jets originating from displaced vertices. Previous studies considered decays that produce very displaced vertices. While it is conceivable that such a scenario can accommodate a light Higgs boson, this possibility was not explored before. Similarly studies of Higgs boson decays to lepton jets were considered; however the possibility of a scenario with non-prompt lepton jets, even though it could be accommodated, was not studied.

6.1.2 Signature based search for lepton jets in CMS which led to new observation

Similarly to the SM Higgs like boson, a hidden Higgs boson can exist in a SUSY model with a light hidden sector and provide spectacular signatures of displaced lepton jet decays of the Minimally Supersymmetric SM (MSSM) Higgs boson [6]. It can exist in hidden valley models [7] , various SUSY scenarios such as split SUSY [8] or SUSY with very weak R-parity violation [9]. However no matter what the theory is my search is motivated by the quest for new topological signature decays of the "Higgs" that were not search before and could evaded detection in previous experiments. One should note, even tough I chose to discuss the Higgs this topological search is sensitive to various heavy resonances. This is a very challenging process that will be one of the beneficiary of my higher level trigger upgrade proposal submitted to NSF and will be presented in a nut shell in the following. To conclude, my proposed searches will search and reach new regions of phase space never reach before in a quest for better understanding of the mysterious Higgs sector and finding finally the Higgs boson.

Being motivated by signature based searches I also investigated the feasibility of the CMS detector to reconstruct prompt collimated lepton jets which contain muons. I should note, that these topological signature were originally motivated in the literature [10] by various astrophysical observations which might suggest the annihilation of a TeV scale dark matter in the galactic halo accounts for the anomalous excess of cosmic ray leptons. However, one should emphasize that even a minimal extensions of the SM, such as with an extra U(1) gauge symmetry, can lead to these interesting, new, topological signatures including "lepton jets". Using the data collected in CMS in 2010 we started investigating the feasibility of the CMS detector to reconstruct prompt lepton jets which contain muons. The reason reconstruction of collimated muons is challenging is that they will usually fail due to single muon isolation requirements or clean up of spurious hits imposed during muon reconstruction. In addition, if isolation is loosened, it will be hard to differentiate the signal from heavy QCD jets. Therefore, collimated muons required a dedicated muon identification to be developed. Similar but simpler improvements are needed for collimated electrons and pions. For the clustering of the leptons, I chose to use the anti-kt jet algorithm which I adapted to our analysis. For this interesting effort I assembled a small CMS group [11] to study these new signatures. The new muon identification selector we developed recovered most of the efficiency lost by the standard muon reconstructions. However the current standard muon reconstruction at the High Level Trigger (HLT) is not optimal for highly collimated lepton searches ($\Delta R \approx 0.1$) as can be seem in Fig. 14. Hence, in the case of muons, a combination of the L1 and HLT trigger improvements may be required to cope with the high luminosity data. On the L1 trigger, one may impose a geometrical separation requirement between the muons. On the high level trigger, an improvement on the muon reconstruction similar

[6] A. Falkowski, J. T. Ruderman, T. Volansky, J. Zupan , L. Tao, Y. Yavin *et al*

[7] Han, T. and Si, Z. and Zurek, K. M. and Strassler, M. J.

[8] J. L. Hewett, B. Lillie, M. Masip, T. G. Rizzo,

[9] R. Barbier *et al.*

[10] N. Arkani-Hamed, D. P. Finkbeiner, T. R. Slatyer, N. Weiner and D. Tucker-Smith *et. al.*

[11] including a student from Florida State University and two postdoctoral fellows, C. Boulahouache from Rice University and N. Adam (Princeton)

to the one done offline may recover some of the efficiency loss seen in Fig. 14 and allow a dedicated collimated muon trigger fitted for lepton jet searches at higher luminosity. The improvement of the current HLT algorithm or a new dedicated HLT trigger which will select multiple muons will allow us to easily select these rare events.

New Observation of Prompt Double Jpsi at CMS Resulting from 2010 Lepton Jets Background Study

A careful lesson that repeats itself in this analysis arise due to a careful and through analysis. Excess around the Jpsi mass distribution in our background control samples in the lepton jets search in 2010 lead to an interesting and surprising outcome. First observation of prompt Double Jpsi in CMS 2010 data by our group which was composed of the following members V. Hagopian, S. Glayzer,N. Adam, P. Lujan, V. Halyo. Indeed, the large data volume delivered by LHC in 2011 allowed us, together with the Beijing and Tennessee group, to joined our effort to measure the production cross section of prompt Jpsi and estimate the fraction of double and single parton scattering. The measurement of the simultaneous production of prompt double jpsi mesons in the collision of protons at $\sqrt{s} = 7$TeV provides general insight into how particles are produced during proton collisions in the LHC shedding light on multiple parton interaction processes. Using the 2011 data were able to also measure the fraction single to double patron processes yielding double prompt This results (see 12) was published in JHEP 2014.

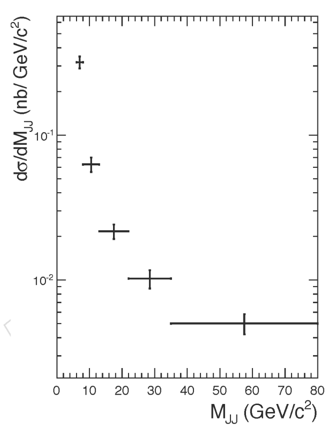


Figure 12: Preliminary result summarizing the measured differential cross section $d\sigma/dM$ for double J/ψ production. The error bars only represent statistical error.

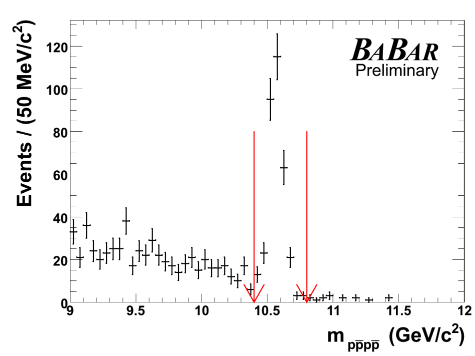


Figure 13: First observation of the process $e^+e^- \rightarrow p\bar{p}p\bar{p}$ and a study of its structure at 10.6 GeV. Using 427.2fb^{-1} of data collected using the BABAR detector Runs 1˘6 at the PEP-II e^+e asymmetric storage rings. In the plot one sees a a sample of 365 events we isolated in our signal region indicated by red arrows between $10.4 - 10.8$ GeV$/c^2$.

7 First observation of $e^+e^- \rightarrow pppp$ in Babar

Responsibility: played essential with my senior thesis student in the new observation of a new physics channel

Following the successful search I led in Babar for “Pentaquark”. Even tough we ended us proving that “Pentquark” could not be produced at the rate claimed by other experiments hence using the Babar data to falsify the observation “Pentquark” in 2004. I recognized the immense potential of the large Babar data to look for new physics. In Aug. 2008 I found an opportunity to split my time with CMS, which did not start to collect data yet and play a crucial role with my senior student Joel Thompson to look for new resonances in collaboration with D. Miller, S. Dong and K. Yi from SLAC. We found the first observation of the process $e^+e^- \rightarrow pppp$ using 427.2fb$^-$1 of data collected with the Babar detector. We isolated 365 events in our signal region with a background of about 19 events as can be seen in fig. 13. The observed events are characterized by two low mass $p\bar{p}$ pairs recoiling against each other which is consistent with expectations from both hadronization models and resonance models involving pair production of a sub-threshold or near sub-threshold resonance models decaying to $p\bar{p}$. We perfumed full angular analysis of these events and found that they are consistent with hadronization models even though these models are not expected to reproduce the rate or structure of such low multiplicity events in the observed kinematical region in detail. We observe a correlation between the helicity angles of the two $p\bar{p}$ pairs which are expected in jet-like events but not in resonance pair production. Taking into account the measured angular distribution we measured a model independent visible production cross section of 2.9 ± 0.2(stat) $\pm$ 0.2(sys)fb Assuming $1/s^2$ ISR dependence we reported a Born cross section of 4.0 ± 0.2(stat) $\pm$ 0.2(sys)fb. These results will help tune hadronization models. Preliminary results were released at 2008 Recontres de Moriond QCD Conference.

8 Development of New and Improvement of Exiting Exotic Triggers

Realizing the invaluable importance of the trigger to select the events that will be used for commissioning, calibration and discoveries. I used the opportunity before the LHC started running to propose the missing, at that time, low pt di-electron trigger. The importance of this trigger was foreseen not only for the commissioning period but for various searches for physics beyond the SM that consist of low pt electrons. Improving the understanding of the electromagnetic calorimeter systematic uncertainties and provide a compliment calibrations using other resonances is a necessary condition to perform these exotic searches that include decays to low pt electrons.

In order to guaranty the inclusion of these triggers already at start-up we demonstrated that it is possible to obtain a reasonable, albeit low, L1$\otimes$ HLT signal efficiency (within geometric acceptance) of about 10% for $\Upsilon(1\mathrm{S}) \rightarrow ee$ and 0.1% for J/ψ while sufficiently suppressing the background. For Υ, we maintain a manageable trigger rate of about 10Hz through the HLT at $\mathcal{L} = 1E31\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. For $J/\psi \rightarrow ee$ the rate through the HLT is only 2Hz at $\mathcal{L} = 1E31\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The proposed trigger work was done in collaboration with

CERN, Wisconsin and FNAL required events to consist two electromagnetic trigger objects at both L1 and HLT, with the additional requirement that either one or both of the legs be pixel-track-matched in the HLT. We demonstrated that the HLT time performance of the proposed paths are well within design specifications, and that inclusion of the paths in the trigger menu only results in an addition of 0.9ms to the event processing time on average. Finally, the 2 proposed low p_{T} di-electron triggers lead to more than 1 order of magnitude improvements in signal yield compared to their nominal counterparts in the trigger menu.

Aside from improving the yield for $\Upsilon(1S) \to ee$ and $J/\psi \to ee$ cross-section measurement, the improved triggers opened up a whole new region of phase space for understanding ECAL systematics that would otherwise be lost. This triggers were accepted and included in the trigger menu yielding crucial information for start-up and for future searches for physics processes that include low pt electrons such as susy cascade decays.

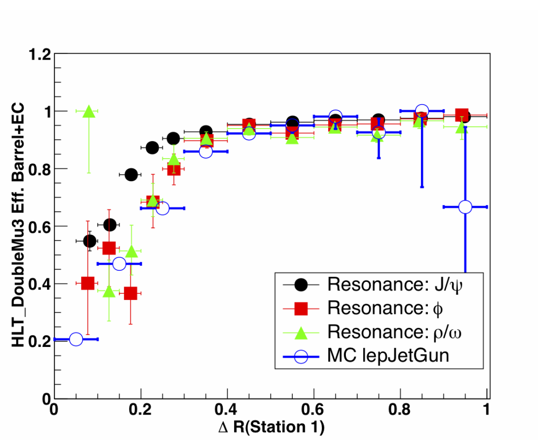


Figure 14: Single leg efficiency for dimuon pairs
versus the angular separation ΔR of the two muons. Data measurements from J/ψ (black circles), ϕ (red squares) and ρ/ω (green triangles) are compared with simulation.

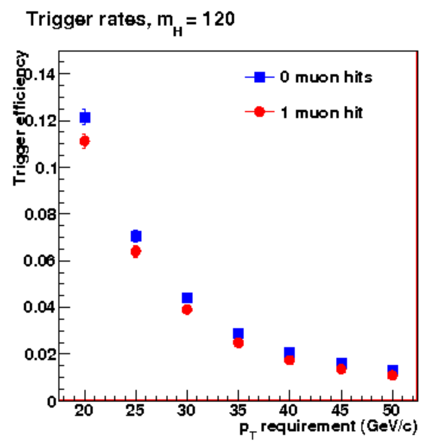


Figure 15: Trigger efficiencies in signal Monte Carlo. $m_{H^0} = 120$ GeV/c^2

In addition to triggers that had to be included already from the start-up of LHC My main concern was the existence of triggers to select new topological signatures that dont exist in the SM such as the search I was leading for heavy resonance that decay to long lived particles in the CMS tracker. The analysis necessitated a new trigger that required a di-muon with a transverse momentum larger than 20 GeV and without an Interaction Point (IP) constraint was added to the trigger menu (1.5 Hz at $6^{31}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$).

However, one of the concerns to this trigger is that significant increase in luminosity will require an increase in the trigger threshold or prescaling, hence reducing the trigger signal efficiency. Hence, our first task was to modify the trigger to cope with the luminosity increase as demonstrated in Fig. 15. In addition, I realized that this trigger is not optimized for collimated muons or multiple low pt muons with $P_T < 20$ GeV/c preventing us to look for topological signatures that include lepton jets or low mass resonances decaying to displaced vertices.

Therefore since the beginning of 2011, I am designing new dedicated triggers for these kind of searches never done before in LHC. The triggers have to face interesting obstacles such as simply the Poisson life time distribution of the long-lived particles or a source that shower collimated fermions reducing the signal efficiency if dedicated triggers are not designed. Other trigger challenges I pursue include the selection of collimated non-prompt fermions or non collimated heavy flavor jets or boosted jets.

Following these plan, I developed with my postdoc Paul Lujan 2 new triggers deployed in the 2012 that would select displaced heavy flavor jets possibly including displaced leptons originating from long lived particles decaying in the CMS tracker.

The successful run of the LHC, as expected, makes it possible to look for spectacular new signatures not yet explored by either the ATLAS/CMS collaborations. Great efforts should be made to come up with new triggers which are key to the detection of new physics.

9 Current Research Interest :Research into Many-Core Computing Accelerators for CMS High Level Trigger

Massively parallel computing at the LHC could be the next leap necessary to reach an era of new discoveries at the LHC after the Higgs discovery. One way to improve the physics reach of the LHC is to take advantage of the exibility of the trigger system by integrating coprocessors based on Graphics Processing Units (GPUs) or the Many Integrated Core (MIC) architecture into its server farm. This cutting edge technology provides not only the means to accelerate existing al- gorithms, but also the opportunity to develop new algorithms that select events in the trigger that previously would have evaded detection. In the following, Halyo's currect research interest is described.

9.1 Overview

Scientific computing is a significance component of the LHC experiment, affecting detector operations, trigger, simulation, analysis, and the LHC computing grid. The trigger systems are especially sensitive to computing performance, as they must balance the physics goals of the experiment with the need to be able to process events in real time. Improvements in the speed with which the trigger system can reconstruct events can thus extend the physics reach of the LHC. One way this can be achieved is to take advantage of the flexibility of the trigger system by integrating coprocessors based on Graphics Processing Units (GPUs) or the Many Integrated Core (MIC) architecture into its server farm. Parallel processing will provide means not only to accelerate existing algorithms, but also the opportunity to develop new algorithms that select events that could have previously evaded detection[1, 2].

One of the application that can take advantage of parallel processing is the tracking algorithm. It is well-known that the problem of track reconstruction becomes exponentially more difficult using traditional reconstruction algorithms as the number of hits in the detector increases due to high pileup. Halyo demonstrated a preliminary version of a fast parallel algorithms complimentary to the Combinatorial Track Finder used in CMS that allows to reconstruct in real time all prompt and non prompt charged particles trajectories in the silicon tracker [3, 1, 4, 5]. The new tracking can not only overcome the challenges faced by the trigger at high pileup, but it allows us to develop complex triggers that could select in real time final state topologies not possible before [1]. This example is one among many that needs to be rethought and designed using the parallel software and hardware architecture available today.

The time to embrace parallel computing in HEP is now. About a decade ago, power limits for processor sockets stalled the Moore's Law-like growth in the performance/cost of single processor systems and the throughput performance obtainable for sequential (single-threaded) applications. This led to the introduction of multi-core CPUs. Although the single-core performance is no longer significantly increasing, the aggregate throughput/cost through many-core CPUs has continued to increase. The underlying power limits have not gone away, however, and indeed the growth in the number of large x86-64 over time has been closer to linear than exponential. To achieve better performance growth, it appears that the next step for the market of general server processors will be to move away from large aggressive cores like the current x86-64 cores and towards larger numbers of lighter-weight cores such as those found in ARM processors or in accelerators such as GPGPUs or Intel MIC. These cores have recently not only had better performance growth (in gflops/year), but also better performance/watt. However, our current software algorithms and tools in LHC do not run "out of the box" on this hardware architecture. V. Halyo research proposal is to incorporate these new technologies into the CMS High Level Trigger (HLT) in order to extend the physics reach at the LHC.

The main players in this area of computational accelerators are NVIDIA (with their CUDA language extensions and extensive GPU families), AMD (with their GPU families and support for the open-standard OpenCL platform), and Intel (with their Xeon Phi and associated toolsets.) Additional platforms, such as ARM, are also of interest, but not covered in this proposal. Currently, it is unclear which architecture is best suited for HEP. The CUDA language extensions are the most mature but only supported by NVIDIA. On the software side, the MIC architecture promises easier integration but it is unclear if this promise holds up under scrutiny when trying to achieve comparable performance to GPGPU. OpenCL, as an open standard, promises heterogeneous processor support and open hardware standards but as of today the open standard does not yet translate to hardware portability. This complex landscape of possibilities means CMS must keep its options open.

Leveraging processors derived from consumer products helps minimize costs associated with purchasing and operating large computing installations, such as those required for the LHC, but there is also a software aspect that needs to be considered. Parallel processors, in the form of multi-core CPUs and, more recently, highly programmable Graphics Processing Units (GPUs), requires a significant rethinking of our software. This process will allow us to develop new algorithms that execute faster than the existing HLT applications. In addition, in order to search for beyond the Standard Model (BSM) physics, it will require development of advanced algorithms [3, 1, 4, 2] for detecting rare new physics phenomena, and these new algorithms will need to be designed and implemented based on knowledge of the current state and likely future directions for processor architecture.

Halyo's goal is to study the feasibility of integrating accelerators cards into the HLT farm and developing applications that would be used in the HLT. Halyo's primary application will be to develop fast complimentary tracking algorithm that could be used to identify not only prompt charged tracks in real time but also improve the identification of electrons, muons or non-prompt tracks. These particles are topological signatures that could have easily evaded detection to date.

10 Technical Description and Deliverables of the Current Project

In the past decade, it has become apparent that it is no longer possible to rely solely on increases in 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, processors containing multiple cores and introducing computation accelerators such as GPUs and Xeon-Phi. Taking advantage of these massively parallel-processing resources Halyo will broaden the range of its computing applications to hep experiment to accelerate the selection algorithm running in the HLT and extend the physics reach at the LHC.

10.0.1 Proposed Hardware integration of GPU/ Xeon Phi in the High Level Trigger

The implementation of a proposed GPU/coprocessor based HLT tracking trigger upgrade requires to upgrade the HLT commercial computing farm. In the next half a year CMS plans to decide on the next generation of servers that will replace the 720 nodes with the Harpertown processors architecture. The goal is to replace these nodes with either similar number of cores or sockets and purchasing processors with the Haswell architecture. Multiple options are possible and they have to be compiled with the performance goals, power consumptions, server rack space , hardware cost and etc. Halyo plans to continue to study the Haswell architecture performance and evaluate the computational accelerators such as the Nvidia Tesla K20 and K40 GPU cards (Kepler architecture) and Xeon Phi coprocessors of 3000, 5000 and 7000 series (Knights Corner architecture) to see which is most suitable for the experiment during RunII. The K20 and K40 Tesla GPU has 6/12 GB of memory (GDDR5) memory bandwidth of 250/288 GB/sec and 2688/2880 CUDA cores. Similarly Xeon Phi coprocessors are equipped with 6 to 16 GB of on-board GDDR5 memory with a theoretical peak bandwidth up to 384 GB/sec and up to 60 cores. Each core contains a vector processing unit (VPU) with 512-bit SIMD vectors supporting a new instruction set called Intel Initial Many-Core Instructions. The architecture of Xeon Phi coprocessors allows to use the same application code on coprocessors as on processors, which is conducive to developer productivity and heterogeneous processing. Both the GPU/Xeon Phi accelerators will be tested to comply with the performance requirements set by the LHC conditions at least until Run III.

10.0.2 Current Tracking Algorithm

The CMS track reconstruction, known as the Combinatorial Track Finder (CTF), uses an iterative algorithm, with earlier iterations searching for tracks that are more easily found (relatively higher p_T tracks close to the interaction region). The hits in these tracks are then removed, allowing later iterations to search for lower momentum or highly displaced tracks without the combinatorial possibilities becoming too large. Each iteration consists of four steps: a seeding step, a track finding step, a track fitting step, and a selection step.

In the first step, a seed, consisting of two or three hits and a primary vertex constraint, is constructed to create an initial estimate of the trajectory parameters for the track. Second, the track finding is performed using a global Kalman filter [6]. This step performs a fast propagation of the track candidate to propagate the track through the layers of the detector, search for compatible nearby hits, and attach them to the candidate. After all candidates in this step have been found, the track candidate collection is then cleaned to remove duplicate tracks or tracks which share a large number of hits. The third step is to perform a full Kalman fit over the whole track to obtain the best estimate of the track parameters at all points along the trajectory. The filter begins at the innermost hits, and then iterates outward through each hit to update the track trajectory estimate and its uncertainty. After this first fit is complete, a smoothing stage is then performed running backwards from the last hit to apply the information from the later hits to the earlier ones. This step uses a Runge-Kutta propagator to account for the effect of material interactions and an inhomogeneous magnetic field. Finally, track selection requirements are applied to reduce the fake rate of the resulting track candidates.

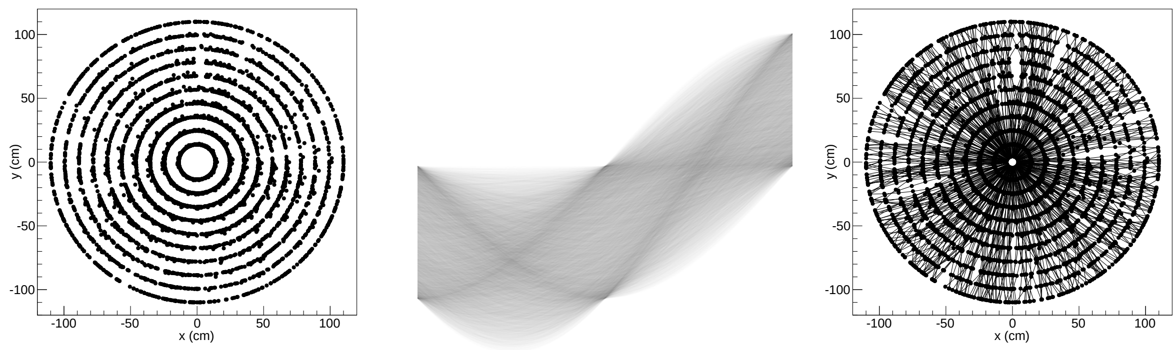
10.0.3 Proposed Fast Tracking based on Hough Transform Algorithm

One possible application of the GPU/Xeon Phienabled parallelism would be to accelerate the performance of the existing combinatorial track finder. Since the finding and fitting process for each track is largely independent of the other tracks, parallelization should not be conceptually difficult. However, the use of GPU/Xeon Phibased computing in the HLT also enables the possibility of running tracking algorithms which are dramatically and qualitatively different in nature to the current Combinatorial Track Finder commonly used in hep experiment, thus enhancing the discovery potential.

As a demonstration of how computationally intensive 2D tracking algorithms can take advantage of massively parallel GPU processing, Halyo developed an implementation of the Hough transform using CUDA [3] in order to measure in real time the transverse momentum of prompt or non-prompt tracks. The Hough transform [7, 8, 9] is an image processing algorithm for feature detection that considers all possible instances of a parameterized feature such as a line or circle. Each possible instance of a feature starts with zero votes in the parameter space, and then for each piece of input data votes are added to the feature instances that would include that input data. After all input data has been processed the votes in the parameter space are processed. Locations in the parameter space with more votes are likely to be actual features in the input data so this step amounts to looking for local maxima in the parameter space. Once candidate features have been identified, more expensive computations can be applied to confirm the existence of the feature. One should note that the Hough transform approach as presented above is computationally expensive. Hence, simplification of the standard Hough transform method [10, 11] had to be used in the past for the purpose of track finding in high energy physics [12].

Figure 16 shows the algorithm in operation for a simple case with 500 curved tracks. The simulated curved track data shown in Figure 16(a), can correspond to many different possible tracks in parameter space as shown in Figure 16(b). When integrated over the entire data set, peaks appear in parameter space at the values corresponding to the actual, physical trajectories as shown in Figure 16(c).

One clear advantage of the Hough transform over the combinatorial track finding algorithms that are currently standard is that the execution time is linear with respect to the number of hits present in the event, while combinatorial algorithms, as the number of combinations increases much more rapidly with respect to the number of hits, show a worse dependence on the number of hits. In addition, the Hough transform is naturally tolerant of missing hits or hits that do not exactly fit the candidate features, due to limited resolution or the discretization used in computing the parameter space. While the Hough transform is more expensive to implement for a small number of hits, the ability to take advantage of multithreading offers the chance of significantly improved performance for events with a large number of tracks.



(a) (b) (c)

Figure 16: 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.

One should note that this proposal does not imply that executing machine vision and pattern recognition algorithms is necessarily more appropriate for parallel processing compared to the conventional combinatorial algorithms used in high energy physics. Rather, it is a complementary way that was first studied by Halyo due to the similarity of the problem with computer image analysis. These techniques have proven successful in image processing using the Hough transform on GPUs.

For her studies Halyo's input data was generated using a Monte Carlo simulation of a simple detector model where only the transverse plane is considered. The model contains a simulated beam pipe with a radius of 3.0 cm surrounded by ten concentric, evenly-spaced tracking layers with an overall radius of 110.0 cm. A hit resolution of 0.4 mm in each direction is used, corresponding to a relative p_T resolution of approximately 7% at 100 GeV/c. In order to obtain a relative momentum resolution similar to the one obtained using current HEP tracking, one would need to approximately double the time performance results obtained in Figure 17.

In her previous studies Halyo presented preliminary results of the fast tracking using a GPU implementation of the Hough transform [1, 3]. She also demonstrated for the first time results of an implementation of her algorithm on the Xeon CPU and Xeon Phi architecture, along with improvements in the GPU implementation as see in Fig. 17.

Fig 17 demonstrate an optimization of a real time fast parallel tracking algorithm based on Hough transform algorithm on four different architectures Tesla GPU, Xeon and i7 CPUs, and Xeon Phicoprocessor. The outcome provides a benchmark that may be used to identify the optimal computing system configuration for the required throughput, cost and other compliance factors of the Hough transform based tracking detector. The results obtained suggest that using an optimized algorithm on hybrid systems with add on coprocessors could be the leap necessary to discover new physics at the LHC. One should note however, that the results obtained reflect the performance of a particular algorithm, a different algorithm might have different behavior. This demonstrate the extensive work needed to study the various architectures and the serious rethink necessary to design the optimal algorithm for each parallel processing application. Detail discussion on the results shown in Fig. 17 appear in paper [4]

10.0.4 Proposed Displaced Jet and Black Hole Detection at the HLT

The overall data processing pipeline for detection of displaced jets and black holes builds on the existing components of the tracking algorithm described in the previous section. This is an example of how a new parallel tracking algorithm can be extended on a computational accelerator to develop an advanced trigger to look for new physics. With candidate tracks identified the corresponding parameter space representation of these tracks is processed by a second application of the Hough transform. In this case the goal is to identify not straight lines but sinusoids which contain a significant number of tracks, indicating that this is a location of a displaced jet or black hole. Again, the location of features of interest correspond to local maxima, or peaks, in the parameter space so the same peak finding algorithm is applied to the parameter space of this second Hough transform. The output of the peak finding can be used directly, as shown here, or if necessary after application of the Kalman filter.

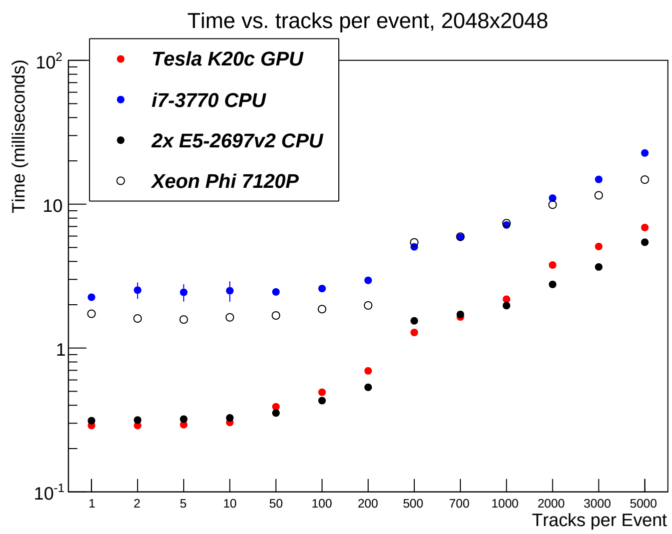


Figure 17: Performance of the Hough transform algorithm on four platforms [4]: (i) NVIDIA Tesla K20c GPU, (ii) Intel i7-3770 CPU, (iii) dual-socket Intel Xeon E5-2697v2 CPU, and (iv) Intel Xeon Phi 7120P coprocessor, as a function of the number of simulated tracks in the event.

It should be noted that the large number of tracks originating from the interaction point will also be identified as a jet. These false positives can be excluded by filtering out features that are at or extremely close to the known interaction point. This filtering could be done within the Hough transform process itself by setting a lower bound on the radius, or at the downstream peak finding step.

Figure 18 illustrates the detection process for a simple event with four displaced jets. The initial hit data is used to identify tracks as shown on the left in x–y space and in the center in parameter space. Applying a second Hough transform to the tracks in parameter space identifies four sinusoids in the second parameter space shown on the right. These four sinusoids correspond to the four vertices of the displaced jets in the original x–y space.

At first glance the proposed enhancement for detecting displaced jets and black holes would seem to double the computational cost due to the need to perform a second expensive Hough transform. However, it is important to note that the first application of the Hough

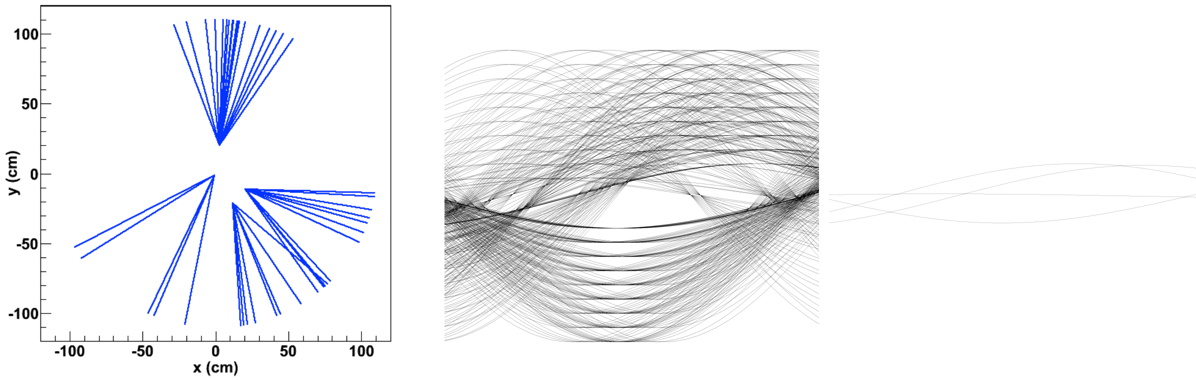
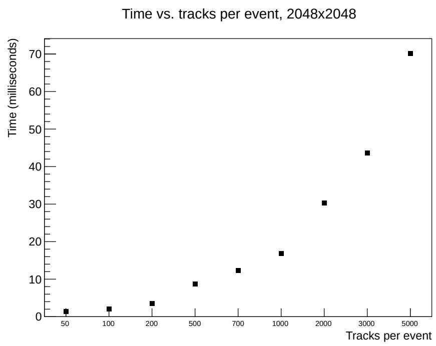


Figure 18: The Hough transform algorithm applied to an event with multiple displaced jets. Left: The simulated tracks present in the event. Center: The parameter space after applying the first Hough transform is still very cluttered. Right: The second Hough transform identifies the sinusoids corresponding to the jet vertices.

transform and associated peak finding and Kalman filtering results in a significant data dimensionality reduction. Where the first application of the transform has a cost proportional to the number of hits, the second application of the transform has a cost proportional to the number of tracks. For example, with an average of 10 hits per track, and in the limit of 100% efficiency and purity, the dimensionality of the data is reduced by a factor of 10. Figure 19 shows a time comparison of the baseline tracking algorithm and the enhancement for detecting displaced jets and black holes. Ten percent of the tracks are associated with a displaced jet. So, in practice, the computational cost increases by approximately 30% compared to the baseline tracking algorithm. This time includes the time for the data transfer and computational time of the Kalman filter running on the CPU and represents an additional opportunity for performance optimization if the Kalman filter were to be moved to the GPU.

In Figure 20 results for the efficiency of detecting a single jet with a varying number of tracks and 10 hits per track are shown. Efficiency is defined as the fraction of simulated jets successfully identified by the algorithm divided by the number of jets known to be present. The efficiency is relatively low for a small number of tracks but quickly rises for 10 tracks and beyond. Because the peak finding has been optimized for track detection where 7 or more hits per track are expected, simple reuse of this code explains the efficiency results. Separate tuning of the peak detection for a fewer number of votes per feature could improve the jet finding efficiency.

These results demonstrate only few of the performance results obtained by Halyo more details could be found in [1]. A natural extension of a computationally intensive 2D tracking algorithm using the Hough Transform algorithm was developed to enhance the LHC trigger performance. The GPU based algorithm has been extended to detect displaced jets and black holes; the signature of these events would be a smoking gun for the presence of physics beyond the Standard Model. The proposed extension uses a second application of the Hough transform to identify tracks originating from a vertex displaced from the interaction point.



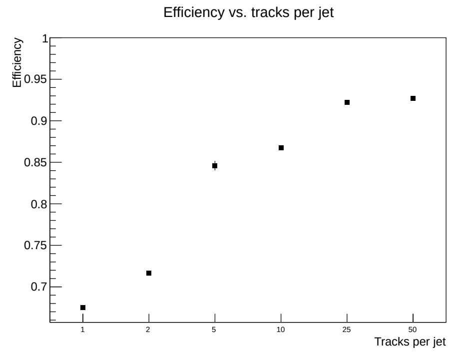


Figure 19: Time performance of the tracking plus displaced jet detection algorithm using an NVIDIA Tesla K20c GPU. Ten percent of the tracks are associated with a displaced jet.

Figure 20: Efficiency of displaced jet detection with varying number of tracks per displaced jet.

Although the Hough transform is a computationally expensive algorithm an implementation on a massively parallel processor such as a GPU is significantly faster than implementations on conventional CPUs. Recent work to incorporate additional CPU optimizations yielded approximately a 40% improvement in GPU performance. The computational cost increase when performing the second Hough transform is mitigated by the data reduction of the first application of the transform, which reduces the data dimensionality from the number of hits to the number of tracks. Benchmarks using data from Monte Carlo simulations showed that the implementation of this proposed trigger enhancement for displaced jets and black holes only increased the runtime by 30%. Hence, the promising results of this trigger algorithm suggest that massively parallel computing at the LHC could be the next leap necessary to reach an era of new discoveries at the LHC post the Higgs-like discovery.

As can be seen in Fig. 19 only part of the displaced jet trigger is tested on all three parallel processing architectures. To evaluate the new trigger path on all parallel architectures it remains to complete the development of the displaced jet and black hole trigger on the Xeon PhiḢalyo plans to complete the development of the new physics trigger on the Xeon Phi and optimize the algorithm to cope with the various LHC conditions. Optimizing its purity which is currently at 86% and doubling its resolution which will probably increase the processing time by about 40% which is away from the trigger time budget constraint by almost 2 orders of magnitude. Succeeding to commission this displaced trigger selection during the upcoming RunII will allow to extend the physics reach of CMS at the LHC and potentially provide answers to important questions such as why did not we see any WIMPS or sparticles at the LHC yet. Parallel processing provide the opportunity to develop advanced algorithms for detecting rare new physics phenomena never possible before in real time.

11 Conclusion of Current Research Interest Section

To conclude, Halyo recent work [3, 1, 4, 2] demonstrates one of the advantages of massively parallel computing at the LHC as a means to reach an era of new discoveries at the LHC after the Higgs discovery. However, the proposed use of the massively parallel processing which integrates computational accelerators goes far beyond the proposed parallel HLT tracking upgrade. It can address parallel offline event reconstruction for the purpose of Monte Carlo generation or user analysis, and evidently impact the the LHC computing GRID who uses its computer resources in order to store and process data or simulate MC events. The use of parallel processing will result in efficiency and cost effective operation that will end up saving money. Last but not least, postdoc, graduate students and undergrade will improve not only their physics or programming skills but most important learn to develop inter-disciplinary solutions that addresses today's demanding complex problems.

References

[1] V. Halyo *et al. Massively Parallel Computing and the Search for Jets and Black Holes at the LHC*, [arXiv:1309.6275].

[2] V. Halyo,*et al. Data Driven Search in the Displaced $b\bar{b}$ Pair Channel for a Higgs Boson Decaying to Long-Lived Neutral Particles*, [arXiv:1308.6213].

[3] V. Halyo *et al. GPU Enhancement of the Trigger to Extend Physics Reach at the LHC*, JINST **1310**, P10005 (2013) [arXiv:1305.4855].

[4] V. Halyo, *et al. First Evaluation of the CPU, GPGPU and MIC Architectures for Real Time Particle Tracking based on Hough Transform at the LHC*, [arXiv:1310.7556].

[5] V.Halyo,*et al. GPU Enhancement of the Trigger to Extend Physics Reach at the Large Hadron Collider*, in Proceedings for the 20th International Conference on Computing in High Energy and Nuclear Physics (CHEP), Amsterdam (2013). [arXiv:1311.2769].

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[8] P. Hough, *Method and mean for recognizing complex patterns*, United States Patent 3069654, 1962

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[10] M. Ohlsson, C. Peterson. *Track finding with deformable templates*, Computer Physics Communication, v. 71, pp. 77-98, 1992.

[11] J. Illingworth. *The adaptive Hough transform*, Trans. Pattern Analysis and Machine Intelligence, v. 9, 5 pp.. 690-697, 1987

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1 List of Publications of Valerie Halyo Benefiting from ARRA Award

My full list of publications is:
`http://www.slac.stanford.edu/spires/find/hep/www?rawcmd=FIND+AU+V.+HALYO+OR+VALERIE+HALYO+or+ben+hamo\&FORMAT=www\&SEQUENCE=`

In the following, I list the publications in which I was either the leading author or played a crucial role.

References

[1] "First Evaluation of the CPU, GPGPU and MIC Architectures for Real Time Particle Tracking based on Hough Transform at the LHC," V. Halyo, P. LeGresley, P. Lujan, V. Karpusenko, A. Vladimirov arXiv:1310.7556v1 [physics.comp-ph]. 2014 JINST **9** P04005

Recent innovations focused around *parallel* processing, either through systems containing multiple processors or processors containing multiple cores, hold great promise for enhancing the performance of the trigger at the LHC and extending its physics program. The flexibility of the CMS/ATLAS trigger system allows for easy integration of computational accelerators, such as NVIDIA's Tesla Graphics Processing Unit (GPU) or Intel's Xeon Phi, in the High Level Trigger. These accelerators have the potential to provide faster or more energy efficient event selection, thus opening up possibilities for new complex triggers that were not previously feasible. At the same time, it is crucial to explore the performance limits achievable on the latest generation multicore CPUs with the use of the best software optimization methods. In this article, a new tracking algorithm based on the Hough transform will be evaluated for the first time on a multi-core Intel Xeon E5-2697v2 CPU, an NVIDIA Tesla K20c GPU, and an Intel Xeon Phi 7120 coprocessor. Preliminary time performance will be presented.

[2] "Massively Parallel Computing and the Search for Jets and Black Holes at the LHC," V. Halyo, P. LeGresley and P. Lujan, arXiv:1309.6275 [physics.comp-ph]. Nuclear Inst. and Methods in Physics Research, NIM A, (2014) 744 pp. 54-60

Massively parallel computing at the LHC could be the next leap necessary to reach an era of new discoveries at the LHC after the Higgs discovery. Scientific computing is a critical component of the LHC experiment, including operation, trigger, LHC computing GRID, simulation, and analysis. One way to improve the physics reach of the LHC is to take advantage of the flexibility of the trigger system by integrating coprocessors based on Graphics Processing Units (GPUs) or the Many Integrated Core (MIC) architecture into its server farm. This cutting edge technology provides not only the means to accelerate existing algorithms, but also the opportunity to develop new algorithms that select events in the trigger that previously would have evaded detection. In this article we describe new algorithms that would allow to select in the trigger new topological signatures that include non-prompt jet and black hole–like objects in the silicon tracker.

[3] "GPU Enhancement of the Trigger to Extend Physics Reach at the LHC," V. Halyo, A. Hunt, P. Jindal, P. LeGresley and P. Lujan, arXiv:1305.4855 [physics.ins-det]. 2013 JINST **8** P10005

Significant new challenges are continuously confronting the High Energy Physics (HEP) experiments, in particular the two detectors at the Large Hadron Collider (LHC) at CERN, where nominal conditions deliver proton-proton collisions to the detectors at a rate of 40 MHz. This rate must be significantly reduced to comply with both 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 leads us to evaluate a Graphics Processing Unit (GPU) enhancement of the existing High-Level Trigger (HLT), made possible by the current flexibility of the trigger system, which not only provides faster and more efficient event selection, but also includes the possibility of new complex triggers that were not previously feasible. A new tracking algorithm is evaluated on a NVIDIA Tesla K20c GPU, allowing for the first time the reconstruction of long-lived particles at the tracker system in the trigger. Preliminary time performance and efficiency will be presented.

[4] "Data Driven Search in the Displaced $b\bar{b}$ Pair Channel for a Higgs Boson Decaying to Long-Lived Neutral Particles," V. Halyo, H. K. Lou, P. Lujan and W. Zhu, arXiv:1308.6213 [hep-ph]. JHEP **01**, 140 (2014)

This article presents a proposal for a new search channel for the Higgs boson decaying to two long-lived neutral particles, each of which decays to b$\bar{b}$ at a displaced vertex. The decay length considered is such that the decay takes place within the LHC beampipe. We present a new data-driven analysis using jet substructure and properties of the tracks from the highly-displaced vertices. We consider a model with a 125 GeV Higgs boson with a significant branching fraction to decay via this mode, with the long-lived neutral particle having a mass in the range of 15–40 GeV and a decay length commensurate with the beam pipe radius. Such a signal can be readily observed with an integrated luminosity of 19.5 fb^{-1} at 8 TeV at the LHC.

[5] "Search in leptonic channels for heavy resonances decaying to long-lived neutral particles," S. Chatrchyan *et al.* [CMS Collaboration],CERN-PH-EP-2012-304 ; CMS-EXO-11-101-003, JHEP **1302**, 085 (2013) [arXiv:1211.2472 [hep-ex]].

A search is performed for heavy resonances decaying to two long-lived massive neutral particles, each decaying to leptons. The experimental signature is a distinctive topology consisting of a pair of oppositely charged leptons originating at a separated secondary vertex. Events were collected by the CMS detector at the LHC during pp collisions at $\sqrt{s}$ = 7 TeV, and selected from data samples corresponding to 4.1 (5.1) inverse femtobarns of integrated luminosity in the electron (muon) channel. No significant excess is observed above standard model expectations, and an upper limit is set with 95% confidence level on the production cross section times the branching fraction to leptons, as a function of the long-lived massive neutral particle lifetime.

[6] "Search for Displaced Leptons in pp Collisions at sqrt(s) = 7 TeV" CMS-PAS-EXO-11-004, The CMS Collaboration, *http://cms-physics.web.cern.ch/cms-physics/public/EXO-11-004-pas.pdf*

A search is performed for a heavy resonance decaying to two long-lived massive neutral particles. The process would manifest itself as a distinct topological signature appearing as a pair of leptons originating from a vertex far displaced from the LHC beam spot. The events were selected during pp collisions at 7 TeV using approximately 1.1 fb^{-1} of integrated luminosity collected by the CMS detector at the LHC. No significant excess is observed above Standard Model background, and a 95% CL upper limit is set on the production cross section times the branching ratio as a function of the long-lived particle lifetime.

[7] "Measurement of the Prompt Double J/psi Production Cross Section in pp Collisions at $\sqrt{s}$ = 7TeV" CMS-PAS-BPH-11-021 The CMS Collaboration, *http://cds.cern.ch/record/1633400/files/BPH-11-021-pas.pdf* JHEP **09**,094 (2014)

Production of prompt J/ψ meson pairs in proton-proton collisions at $\sqrt{s}$ = 7is measured with the CMS experiment at the LHC in a data sample corresponding to an integrated luminosity of about 4.7fb^{-1}. The two J/ψ mesons are fully reconstructed via their decays into $\mu^+\mu^-$ pairs. This observation provides for the first time access to the high-transverse-momentum region of J/ψ pair production where model predictions are not yet established. The total and differential cross sections are measured in a phase space defined by the individual J/ψ transverse momentum ($p_T^{\mathrm{J}/\psi}$) and rapidity ($|y^{\mathrm{J}/\psi}$): $|y^{\mathrm{J}/\psi} < 1.2$ for $p_T^{\mathrm{J}/\psi} > 6.5$GeV/$c$; $1.2 < |y^{\mathrm{J}/\psi} < 1.43$ for a p_T threshold that scales linearly with $|y^{\mathrm{J}/\psi}$ from 6.5 to 4.5GeV/c; and $1.43 < |y^{\mathrm{J}/\psi} < 2.2$ for $p_T^{\mathrm{J}/\psi} > 4.5$GeV/$c$. The total cross section, assuming unpolarized prompt J/ψ pair production is $1.49 \pm 0.07 \pm 0.13$nb. Different assumptions about the J/ψ polarization imply modifications to the cross section ranging from −31% to +27%.

[8] "Jet Substructure at the Tevatron and LHC: New results, new tools, new benchmarks," A. Altheimer, *et al.*, J. Phys. G **39**, 063001 (2012), [arXiv:1201.0008 [hep-ph]].

In this report we review recent theoretical progress and the latest experimental results in jet substructure from the Tevatron and the LHC. We review the status of and outlook for calculation and simulation tools for studying jet substructure. Following up on the report of the Boost 2010 workshop, we present a new set of benchmark comparisons of substructure techniques, focusing on the set of variables and grooming methods that are collectively known as "top taggers". To facilitate further exploration, we have attempted to collect, harmonise, and publish software implementations of these techniques.

[9] "Measurements of inclusive W and Z Cross sections in pp collisions at s=7 TeV" (36pb-1) [arXiv:1106.5393] CMS-PAS-EWK-10-005, The CMS Collaboration, *http://cms-physics.web.cern.ch/cms-physics/public/EWK-10-005-pas.pdf JHEP* **10** (2011) 132

We present the measurements of inclusive W and Z production cross sections in electron and muon decay channels at $\sqrt{s} = 7TeV$, obtained using 36 pb^{-1} of pp collisions in the Compact Muon Solenoid (CMS) detector at the Large Hadron Collider (LHC). The measured inclusive cross sections are $\sigma(ppWX)xBF(W \rightarrow ln) = 10.31 \pm 0.02(stat.) \pm 0.09(syst.) \pm 0.10(th.) \pm 0.41(lumi.)$ nb and $\sigma(pp \rightarrow ZX)xBF(Z \rightarrow l+l-) = 0.975 \pm 0.007(stat.) \pm 0.007(syst.) \pm 0.018(th.) \pm 0.039(lumi.)$ nb limited to the di-lepton invariant mass range [60, 120] GeV. The luminosity-independent cross section ratios are $(\sigma(pp \rightarrow WX)xBF(W \rightarrow ln))/(\sigma(pp \rightarrow ZX)xBF(Z \rightarrow l+l-)) = 10.54 \pm 0.07(stat.) \pm 0.08(syst.) \pm 0.16(th.)and(\sigma(pp \rightarrow W+X)xBF(W+ \rightarrow l+n))/(\sigma(pp \rightarrow W-X)xBF(W- \rightarrow l-n)) = 1.421 \pm 0.006(stat.) \pm 0.014(syst.) \pm 0.030(th.)$. The measured values agree with NNLO QCD cross section calculations and current parton distribution functions.

[10] "Measurements of Inclusive W and Z Cross Sections in pp Collisions at sqrt(s) =7 TeV" (2.9pb-1) *JHEP* **01** (2011) 080, [arXiv: 1012.2466] PAS-EWK-10-002, The CMS Collaboration, *http://cms-physics.web.cern.ch/cms-physics/public/EWK-10-002-pas.pdf* , CERN-PH-EP-2010-050 .

Measurements of inclusive W and Z boson production cross sections in pp collisions at sqrt(s)=7 TeV are presented, based on 2.9 inverse picobarns of data recorded by the CMS detector at the LHC. The measurements, performed in the electron and muon decay channels, are combined to give sigma(pp to WX) times B(W to muon or electron + neutrino) = 9.95 $\pm 0.07(stat.) \pm 0.28(syst.) \pm 1.09(lumi.)nband\sigma(pp \rightarrow ZX)$times B(Z to oppositely charged muon or electron pairs) = $0.931 \pm 0.026(stat.) \pm 0.023(syst.) \pm 0.102(lumi.)$ nb. Theoretical predictions, calculated at the next-to-next-to-leading order in QCD using recent parton distribution functions, are in agreement with the measured cross sections. Ratios of cross sections, which incur an experimental systematic uncertainty of less than 4%, are also reported.

[11] "Evaluation of the Theoretical Uncertainties in the Z to ll Cross Sections at the LHC" N.E. Adam, V. Halyo, and S.A. Yost, *JHEP* **05** (2008) 062, [arXiv:0802.3251] .

We study the sources of systematic errors in the measurement of the Z to ll cross-sections at the LHC. We consider the systematic errors in both the total cross-section and acceptance for anticipated experimental cuts. We include the best available analysis of QCD effects at NNLO in assessing the effect of higher order corrections and PDF and scale uncertainties on the theoretical acceptance. In addition, we evaluate the error due to missing NLO electroweak corrections and propose which MC generators and computational schemes should be implemented to best simulate the events.

[12] "Evaluation of the Theoretical Uncertainties in the W to Lepton and Neutrino Cross Sections at the LHC", N. E. Adam, V. Halyo, S. Yost, W. Zhu *JHEP* **09** (2008) 133, [arXiv:0808.0758].

We study the sources of systematic errors in the measurement of the W to lepton and neutrino cross-sections at the LHC. We consider the systematic errors in both the total cross-section and acceptance for anticipated experimental cuts. We include the best available analysis of QCD effects at NNLO in assessing the effect of higher order corrections and PDF and scale uncertainties on the theoretical acceptance. In addition, we evaluate the error due to missing NLO electroweak corrections and propose which

MC generators and computational schemes should be implemented to best simulate the events.

[13] "Theoretical Uncertainties In Electroweak Boson Production Cross Sections at 7, 10, and 14 TeV at the LHC", Nadia Adam, Valerie Halyo, Scott A. Yost, *JHEP* **11** (2010) [arXiv:1006.3766].

We present an updated study of the systematic errors in the measurements of the electroweak boson cross-sections at the LHC for various experimental cuts for a center of mass energy of 7, 10 and 14 TeV. The size of both electroweak and NNLO QCD contributions are estimated, together with the systematic error from the parton distributions. The effects of new versions of the MSTW, CTEQ, and NNPDF PDFs are considered.

[14] "Results from a Beam Test of a Prototype PLT Diamond Pixel Telescope", R. Hall-Wilton, *et. al*, Nucl. Instrum. Meth. A636: S130-S136 (2011).

We describe the results from a beam test of a telescope consisting of three planes of single-crystal, diamond pixel detectors. This telescope is a prototype for a proposed small-angle luminosity monitor, the Pixel Luminosity Telescope (PLT), for CMS. We recorded the pixel addresses and pulse heights of all pixels over threshold as well as the fast-or signals from all three telescope planes. We present results on the telescope performance including occupancies, pulse heights, fast-or efficiencies and particle tracking. These results show that the PLT design concept is sound and indicate that the project is ready to proceed with the next phase of carrying out a complete system test, including full optical readout.

[15] "Studies of PLT-type single-crystal diamond pixel detectors", R. Hall-Wilton, *et. al*, Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), (2011) IEEE

The Pixel Luminosity Telescope (PLT) is a dedicated luminosity monitor, presently under construction and planned for installation during the next CMS opening, for the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC). It measures the particle flux in an array of sixteen telescopes each consisting of three layers of pixel diamond detectors. The PLT's single-crystal CVD diamonds are bump-bonded to the PSI46 pixel readout chip - the same readout chip used in the silicon pixel system in CMS. Final hardware and software components have been assembled at CERN. The performance with has been measured this year in beams at the CERN PS, as well as the test beam facility at Fermilab. With respect to charged particle tracking, we also measured the Lorentz angle in a magnetic field at the CERN SPS. We present the results of these studies for the final system.

[16] "A CMS luminosity monitor using single-crystal CVD diamond pixel detectors," E. Bartz, J. Doroshenko, V. Halyo, B. Harrop, D. A. Hits, A. Macpherson, D. Marlow and L. Perera *et al.*, JINST **4**, P04015 (2009).

The Pixel Luminosity Telescope (PLT) is an innovative luminosity monitor which is planned as an upgrade for the CMS detector at the LHC. It uses pixelated single-crystal diamonds as the active sensor material bumpbonded to standard CMS pixel readout electronics. The PLT makes use of a presently unused feature of the pixel readout chip which was designed to provide a hit-over-threshold signal to a hardware trigger processor. This feature will produce a bunch crossing (25 ns) 'hit' signal that can form the basis of luminosity information at the hardware level. We will report on the first successful use of this 'Fast-Or' signal to self-trigger on beta particles from a source using a diamond pixel detector. Expected performance of the PLT based on Pythia simulations is also detailed.

[17] " $\Upsilon(nS)$ Production Cross-Section Measurement with 1pb^{-}1 of Integrated Luminosity", CMS AN-2009/119 N. Adam *et al.*, "Upsilon Production Cross Section in pp Collisions at sqrt(s) = 7 TeV" BPH-10-003 *http://cms-physics.web.cern.ch/cms-physics/public/BPH-10-003-pas.pdf* , Phys. Rev. D 83, 112004 (2011), CERN-PH-EP-2010-055.

The Upsilon production cross section in proton-proton collisions at sqrt(s) = 7 TeV is measured using a data sample collected with the CMS detector at the LHC, corresponding to an integrated luminosity of 3.1 +/- 0.3 inverse picobarns. Integrated over the rapidity range —y—¡2, we find the product of the Upsilon(1S) production cross section and branching fraction to dimuons to be $\sigma(pp \to Upsilon(1S)\times)B(\Upsilon(1S)tomu+mu-) = 7.37 \pm 0.13^{+0.61}_{-0.42} \pm 0.81nb$, where the first uncertainty is statistical, the second is systematic, and the third is associated with the estimation of the integrated luminosity of the data sample. This cross section is obtained assuming unpolarized Upsilon(1S) production. If the Upsilon(1S) production polarization is fully transverse or fully longitudinal the cross section changes by about 20%. We also report the measurement of the Upsilon(1S), Upsilon(2S), and Upsilon(3S) differential cross sections as a function of transverse momentum and rapidity.

[18] "First CMS Results", contribution to the Physics at the LHC 2010 proceeding, DOI:10.3204/DESY-PROC-2010-01/267

Already in 2006 with 25M muons accumulated during the Magnet Test and Cosmic Challenge with only a small fraction of the sub detector installed on the surface, CMS worked towards its first measurement of charge asymmetry of atmospheric muons that was published once combined with the 270M muons accumulated during Cosmic Run at four Tesla (CRAFT) in 2008. This result was followed by the first CMS measurements of dN/dη, dN/dp_T, the underlying event activity, two particle correlation, Bose-Einstein Correlations (BEC), and the observation of diffractive events presented in the talk. These first measurements were based on collision data taken during the successful startup at 2009 where LHC delivered about 15 μb^1/ 1 μb^{-1} at collision energy of 0.9 TeV /2.36 TeV correspondingly and followed at 2010 with the first proton-proton collisions at center of mass energy at 7 TeV.

[19] "Measurement of CMS Luminosity", The CMS Collaboration, CMS-PAS-EWK-004 *http://cms-physics.web.cern.ch/cms-physics/public/EWK-10-004-pas.pdf*

The CMS luminosity system is used to monitor the performance of the LHC in real time, to provide an overall normalization for physics analyses, and to produce bunch-by-bunch luminosities useful for accelerator diagnostics and optimization. Horizontal and vertical separation scans were used to optimize the delivered luminosity and to measure the beam sizes in the interaction regions. Combined with the measured beam currents, the beam sizes are used to determine the luminosity of the LHC to an accuracy of 11%. This paper describes the methods used to measure the online and offline luminosity in CMS, and presents preliminary analysis on the absolute luminosity calibration.

[20] "LHC BUNCH CURRENT NORMALISATION FOR THE APRIL-MAY 2010 LUMINOSITY CALIBRATION MEASUREMENTS" G. Anders *et. al.*, CERN-ATS-Note-2011-004

In April-May 2010, a series of experiments were done to perform first luminosity calibration measurements for each LHC Interaction Point at the zero-momentum frame energy sqrt(s)=7 TeV. In this note, the results are presented of the LHC bunch current normalization analysis for these experiments. The uncertainties, and the prospects to reduce these for future experiments, are discussed in detail.

Ph.D. Thesis

[21] J. Werner, "Measurement of the Inclusive $Z \to ee$ Production Cross Section in Proton-Proton Collisions at $\sqrt{s} = 7$TeV and $Z \to ee$ Decays as Standard Candles for Luminosity at the Large Hadron Collider," CERN-THESIS-2011-043.

This thesis comprises a precision cross section measurement of inclusive Z → ee production in proton-proton collisions provided by the Large Hadron Collider (LHC) at a center-of-mass energy of $\sqrt{s}$=7TeV. The data was collected by the Compact Muon Solenoid (CMS) detector near Geneva, Switzerland during the year of 2010 and corresponds to an integrated luminosity of Ldt=35.9pb^1. Electronic decays of Z bosons provide one of the first electroweak measurements at the LHC, making this analysis a benchmark of physics performance after the first year of CMS detector and LHC machine operations. It is the first data-driven, systematic uncertainty limited, inclusive Z → ee production cross section measurement performed at $\sqrt{s} = 7TeV$.

$$\sigma(pp \to Z + X) \times \mathcal{B}(Z \to ee) = 997 \pm 11(\text{stat}) \pm 19(\text{syst}) \pm 40(\text{lumi})\ \text{pb} \tag{1}$$

which agrees with the theoretical prediction of:

$$\sigma(pp \to Z + X) \times \mathcal{B}(Z \to ee)_{\text{NNLO Theory}} = 970 \pm 40\ \text{pb} \tag{2}$$

calculated to next-to-next-to-leading-order in QCD using recent parton distribution functions. Leveraging $Z \to ee$ decays as "standard candles" for measuring the luminosity at the LHC is examined; they are produced copiously at the LHC, are well understood, and have clean detector signatures. Thus the consistency of the measurement with the theoretical prediction suggests inverting the result to instead use the $Z \to ee$ signal yield to calibrate the luminosity.

[22] W. zhu, “Topics in Collider Physics” Ph.D Thesis *http://www.princeton.edu/physics/graduate-program/theses/Wenhan-Zhu$_t$hesis.pdf*

The Large Hadron Collider (LHC), the world’s largest and highest-energy particle accelerator, is leading particle physics into a new era. This experiment will very likely to discover the mechanism responsible for electroweak symmetry breaking and also possibly new particles at the TeV scale.

This thesis addresses some topics which we may hope to probe at the LHC. Chapter 1 serves an an introduction, reviewing the Standard Model and introducing all the topics covered in this thesis. In Chapter 2, we discusses the evaluation of PDF uncertainty of W $\rightarrow \ell\nu$ cross section at the LHC with the Hessian Method. In Chapter 3, we discusses the search channel for boosted Higgs boson produced with a vector boson using Jet Trimming Technique. In Chapter 4, we discusses a new collider based probe of electroweak symmetry breaking, designed to look for models that approximate the Standard Model at the electroweak scale, but which deviate from it at higher energies. In Chapter 5, we discusses the feasibility of seeing a Higgs boson which decays to four bottom quarks through a pair of long-lived (pseudo-)scalars. In Chapter 6, we investigates various sources of the systematic uncertainty in the dijet mass distribution of W+jets at Tevatron. Chapter 7 contains the conclusions.

CMS Analysis Notes

In the following, I list the internal CMS publications that are based on work I was leading or played a crucial role.

[23] CMS AN-2012/222 – “Measurement of Double J/ Production Cross-section in pp Collisions at 7 TeV” A. York, Z. Yang, G. Cerizza, S. Spanier, J. Bian,G. Chen, V. Halyo P. Jindal, P. Lujan,D. Bandurin, S. Gleyzer, and V. Hagopian

The cross section for the simultaneous production of two J mesons in proton-proton collisions at sqrt(s) = 7 TeV at LHC from a sample corresponding to an integrated luminosity of 4.968 /fb has been measured with the CMS detector. The two J mesons are fully reconstructed in the mu+mu- decay. The signal yield is extracted with a extended maximum likelihood fit based on four event variables, and the trigger and reconstruction efficiencies are derived from data. Data are compared to theory predictions. The measurement is performed in the following acceptance regime defined by the individual J transverse momentum, pT and rapidity, y: pT¿6.5 GeV/c for y¡1.2, pT¿6.5-3 GeV/c (where the pT threshold scales linearly) in the region 1.2¡y¡1.6, and pT¿3 GeV/c for 1.6¡y¡2.2 . The total cross section is found to be sigma = 1.51 +- 0.07 +- 0.26 +- 0.06 nb, where the first uncertainty is statistical, the second systematic, and the third due to the luminosity measurement. Based on the differential cross section dsigma/dy using production models we estimate that double parton scattering contributes 29% (0.44 nb) to the double J production.

[24] CMS AN-2011/528 – " Observation of Double J/ Production in pp Collisions at 7 TeV",Jianguo Bian, Guoming Chen, Jian Wang, D. Bandurin, S. Gleyzer, V. Hagopian, V. Halyo, P. Lujan, M. Wu

Copious production of double J/ψ with very small background has been observed in pp collisions at a mass center energy $\sqrt{s} = 7$ TeV using data collected by the CMS experiment at the LHC. The data sample corresponds to an integrated luminosity of 5.0 fb^{-1}. A 4 dimension fit to two J/ψ invariant masses and two J/ψ proper decay lengths is used to separate the prompt double J/ψ from the non-prompt double J/ψ. The production cross section of prompt double J/ψ for both J/ψ with the transverse momentum $3 < p_T^{J/\psi} < 25$ GeV for the rapidity $1.2 <| y^{J/\psi} |< 2.1$ or $6 < p_T^{J/\psi} < 25$ GeV for $0 <| y^{J/\psi} |< 1.2$ has been measured to be

$$\sigma_p(J/\psi J/\psi) = 1.641 \pm 0.107 \pm 0.288 \text{ nb},$$

where 0.107 is a statistical uncertainty, and 0.288 is a systematic uncertainty.

[25] CMS AN-2011/488 – "Triggers to find Displaced Fermions from Long Lived Resonances", M. Baber, E. Clement, K. Harder, I. Tomalin, V. Halyo, A. Hunt, P. Lujan, J.Werner, A. Zuranski, Z. Hu, M. Jones, N. Leonardo, M. de Mattia, I. Shipsey, D. Silvers, Y. Zheng, A. Gay, C. Boulahouache, and M. Gouzevitch

This trigger describes the improvements made to the CMS trigger menu for the 2012 run, to select events in which long-lived exotic particle(s) are produced and then decay to give displaced fermions within the volume of the CMS detector.

[26] CMS AN-2011/487 – "Stand Alone Muon Reconstruction", M. Baber, E. Clement, K. Harder, I. Tomalin, V. Halyo, A. Hunt, P. Lujan, J.Werner, Z. Hu, M. Jones, N. Leonardo, M. de Mattia, I. Shipsey, D. Silvers, Y. Zheng, A. Gay, C. Boulahouache, and M. Gouzevitch

A study of the performance of stand-alone muon reconstruction for displaced muons is presented. The default algorithm shows a substantial bias of the reconstructed muon trajectory towards the beamspot. A small change in the reconstruction sequence significantly reduces this bias.

[27] CMS AN-2011/486 – "Search for Heavy Resonances Decaying to Long-Lived Neutral Particles in the Displaced Lepton Channel", M. Baber, E. Clement, K. Harder, I. Tomalin, V. Halyo, A. Hunt, P. Jindal,P. Lujan, J. Werner, A. Zuranski, Z. Hu, M. Jones, N. Leonardo, M. de Mattia, I. Shipsey, D. Silvers, Y.Zheng, A. Gay, M. Gouzevitch, C. Boulahouache

A search is performed for heavy resonances decaying to two long-lived massive neutral particles, each decaying to dileptons. The experimental signature is a distinctive topology consisting of a pair of oppositely charged leptons originating at a separated secondary vertex. Events were collected by the CMS detector at the LHC during pp collisions at sqrt(s) = 7 TeV, and selected from data samples corresponding to 4.1 (5.1) /fb of integrated luminosity in the electron (muon) channel. No significant excess is observed above standard model expectations, and an upper limit is set with 95% confidence level on the production cross section times the branching fraction to leptons, as a function of the long-lived massive neutral particle lifetime.

[28] CMS AN-2011/348 – "Z ee Decays as Standard Candles for Luminosity at the LHC in 2011", Valerie Halyo, Tim Lou, and Jeremy Werner

$Z \rightarrow ee$ decays have clean detector signatures and are produced copiously at the LHC. This channel also has a well-known theoretical cross section, suggesting it may be leveraged for absolute luminosity calibration at the LHC. We present such a calibration using data collected at the CMS detector during 2011. Future prospects for vector boson based luminosity monitoring and calibration at the LHC are also discussed.

[29] CMS AN-2011/344 – "Observation of double Jpsi production in proton-proton collisions at a center-of-mass energy of sqrt(s) = 7 TeV with the CMS detector", D. Bandurin, S. Gleyzer, V. Hagopian 1 and V. Halyo, P. Lujan, M.Wu

The production of prompt double Jpsi pairs in proton-proton collisions at a center of mass energy of sqrt(s)=7 TeV has been observed with the CMS detector with an integrated luminosity of 1.2 invfb.

[30] CMS AN-2011/112 – "Triggers to find Displaced Fermions from Exotica in the 2011 Run", Valerie Halyo, Sam Harper, Paul Lujan, Ian Tomalin

Long-lived, massive, exotic particles that decay to displaced leptons or jets inside CMS are predicted by many physics models. Examples include hidden valley models or SUSY with weak R-parity violation. This paper describes the improvements made to the high-level trigger menu for the 2011 run to increase the acceptance for these signals.

[31] CMS AN-2011/093 – "Absolute Calibration of Luminosity Measurement at CMS", Nadia Adam, Nicola Bachetta, Seth Cooper, Giovanni Franzoni, Valerie Halyo, Adam Hunt, Yuichi Kubota, Daniel Marlow, Marco Zanetti, Andrzej Zuranski

A series of transverse beam scans in the LHC in October 2010 has been used to determine the effective crossing area of the beams at the CMS intersection point. Taken together with the measurement of the beam currents provide, these measurements provide an absolute calibration of the luminosity delivered to CMS by the LHC. This paper describes the analysis of the data taken during these scans.

[32] CMS AN-2010/423 – "Inclusive Search for at least 1 or 2 Collimated Muon Jets + 2 QCD Jets + MET using pp collisions data collected at sqrt s = 7 TeV with CMS detector at LHC", N. Adam, B. Chaouki, V. Halyo, S. Glayzer, D. Marlow, B. P. Padley

Physics beyond the Standard Model could manifest itself by highly collimated leptons that result from the decay of these highly boosted decay of GeV-scale, highly-boosted, hidden sector particles. We present a search for isolated muon jet, 2 QCD jets and with a large imbalance in transverse energy in p p collisions using 38.4of integrated luminosity collected by the CMS detector at the LHC. No excess is observed above Standard Model background, and the result is used to set limit on the colored SUSY production, where squarks are the lightest standard model super-partners. An upper limits is set with

95% C. L. on the production cross section times the branching ratio as a function of the squark mass and dark photon mass constraining the color SUSY prodcution with squark masses up to 750GeV/c

[33] CMS AN-2010/349 – "Electron Efficiency Measurements with 2.88pb-1 of pp Collision Data at sqrt(s) = 7 TeV", Jeffrey Berryhill, Kalanand Mishra, Georgios Daskalakis, Valerie Halyo, Jeremy Werner, Si Xie.

We present the first data driven electron efficiency measurements performed at CMS. These measurements were performed as part of the W/Z analysis, and use 2.88 pb^{-1} of pp collision data at $\sqrt{s} = 7$ TeV.

[34] CMS AN-2010/323 – "Electron Efficiency Measurements with 2.88pb-1 of pp Collision Data at sqrt(s) = 7 TeV", Jeff Berryhill, Georgios Daskalakis, Valerie Halyo, Kalanand Mishra, Jeremy Werner, Si Xie.

We present the first systematics limited data driven electron efficiency measurements performed at CMS. These measurements were performed as part of the W/Z analysis, and use 36.1pb$^{-1} of pp collision data at \sqrt{s} = 7$ TeV.

[35] CMS AN-2010/277 – "Data Driven Techniques to Estimate the Background in the Zee Events", D. Bandurin, V. Halyo, J. Werner.

We present 2 data driven methods to estimate the background underneath the Z peak. We also provide the results of the methods on the first $\sqrt{s} = 7$ TeV proton-proton collision data corresponding to $\int \mathcal{L}dt = 1.34$ pb^{-1}.

[36] CMS AN-2010/264 – "Updated Measurements of the Inclusive W and Z Cross Sections at 7 TeV", Authors: J. Alcaraz Maestre, S. Baffioni, D. Bandurin, J. Bendavid, J. Beryhill, J. Branson, C. Broutin, R. Castello, C. Charlot, M. Cepeda, A. de Costa, B. de la Cruz, B. Dahmes, G. Daskalakis, C. Firz Pardos, A. Drozdetskiy, D. Evans, P. Everaerts, F. Fabozzi, D. Futyan, G. Gomez-Ceballos, M. Grothe, M. de Gruttola, K. Hahn, V. Halyo, G. Hamel de Monchenault, P. Harris, J. Hays, J. M. Hernandez, A. Ivanov, M. I. Josa, S. Kesisoglou, S. Khalil, M. Klute, I. Kravchenko, C. Lazaridis, M. LeBourgeouis, P. Lenzi, L. Lista, M. Makouski, E. di Marco, M. de Mattia, P. Meridiani, K. Mishra, R. Nandi, P. Paganini, R. Paramatti, C. Paus, C. Plager, I. Puljak, N. Rompotis, C. Rovelli, L. K. Saini, M. Sani, J. Santaolalla, M. Schmitt, C. Seez, M. Soares, S. Stoynev, E. Sudano, K. Sung, N. Wardle, D. Wardrope, J. Werner, S. Xie, H. Yoo, A. Zabi, M. Zeise.

We present updated measurements of the inclusive W and Z cross sections for pp collisions at 7 TeV, based on approximately 2.9 pb^{-1} of data. Analyses with electrons and muons are described in detail. This analysis note serves as support for publication EWK-10-002, and supersedes AN-10-116.

[37] CMS AN-2010/175 – "Measurement of CMS Luminosity in the 2010 Run", N. Adam, V. Halyo, A. Hunt, D. Marlow.

This note provides details on the first 7 TeV luminosity measurements made in CMS.

[38] CMS IN-2010/007 – "Low Pt Double Electron Trigger Proposal for CMS", R. Covarelli, D. Bandurin, N. Adam, V. Halyo, J. Werner, A. Ghezzi, S. Dasu, J. Leonard, M. Grothe, P. Klabbers, A. Savin, W. Smith.

This note details the formulation and performance of a low PT double electron trigger proposal for LHC start-up conditions at $\sqrt{s} = 10$ TeV. An order of magnitude improvement of the L1$\otimes$ HLT $\Upsilon(1S) \rightarrow ee$ and J/ψ signal efficiency (10% and 0.1% correspondingly within geometric acceptance) is achieved while sufficiently suppressing the background to about 2Hz at $\mathcal{L} = 1E31\text{cm}^{-}2s^{-1}$ $\text{cm}^{-2}\text{s}^{-1}$. The proposed triggers are double EM object trigger at both L1 and HLT, with the additional requirement that either one or both of the legs be pixel-track-matched in the HLT. We demonstrate that the HLT time performance of the proposed paths are well within design specifications, and that inclusion of the paths in the trigger menu only results in an addition of 0.9ms to the event processing time on average. Aside from improving the yield of the low mass resonances for any cross-section measurement, The additional new mass points (eg, Upsilon) will add more information that can go into the overall inter-regional ECAL calibration providing a handle on the systematics of the ECAL at very low pt which may be relevant for fully understanding the detector.