# HGCal Simulation Analyses for CMS

University of Michigan CERN REU
Caltech CMS Group
Supervisor: Dr. Adolf Bornheim
Sarah Marie Bruno

This summer, I approached the topic of fast-timing detection of photons from Higgs decays via simulation analyses, working under the supervision of Dr. Adolf Bornheim of the California Institute of Technology. My specific project focused on simulating the high granularity calorimeter for the Compact Muon Solenoid (CMS) experiment. CMS detects particles using calorimeters. The Electromagnetic Calorimeter (ECal) is arranged cylindrically to form a barrel section and two "endcaps." Previously, both the barrel and endcap have employed lead tungstate crystal detectors, known as the "shashlik" design. The crystal detectors, however, rapidly degrade from exposure to radiation. This effect is most pronounced in the endcaps. To avoid the high expense of frequently replacing degraded detectors, it was recently decided to eliminate the endcap crystals in favor of an arrangement of silicon detectors known as the "High Granularity Calorimeter" (HGCal), while leaving the barrel detector technology unchanged. The primary aim of my project was to investigate the performance of HGCal using a series of simulations and to compare the performance of the new silicon detectors in the endcap with the traditional crystal detectors in the barrel.

Throughout the summer, I worked with a series of data samples produced by simulations of various mechanisms producing photons, including a gamma gun as well as Higgs to gamma gamma decays. These simulations were primarily produced by researcher Lindsey Gray of Fermi National Accelerator Laboratory. One of the first contributions I made to this investigation was uncovering a mathematical error in the calculation used in the simulation algorithm for reconstructing the collision time of recorded hits. The corrected method is reproduced below:
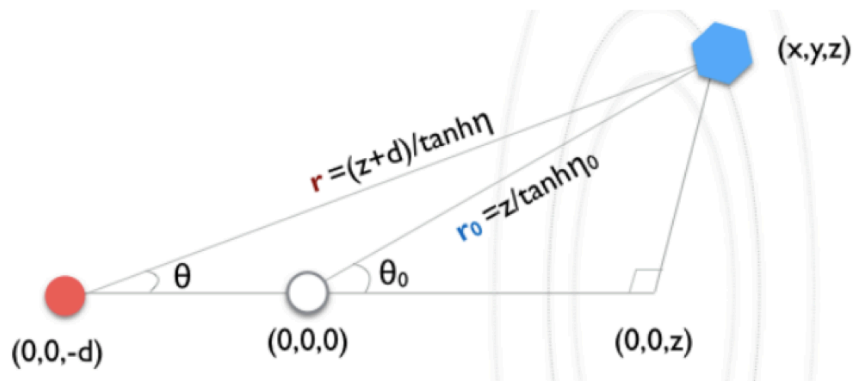
$$\Delta r = r - r_0.$$

$$t_{collision} = t_{rechit} + \frac{\Delta r}{c} = t_{rechit} + \frac{r - r_0}{c}.$$

$$r_0 = r - d\cos\theta.$$

$$\Delta r = r - r_0 = d\cos\theta.$$

$$\eta = -\ln[\tan\tfrac{\theta}{2}].$$

$$\theta = 2\arctan e^{-\eta}.$$

$$\cos\theta = \cos\left(2\arctan\left(e^{-\eta}\right)\right) = \tanh\eta.$$

$$t_{collsion} = t_{rechit} + \frac{\Delta r}{c} = t_{rechit} + \frac{d\tanh\eta}{c}.$$

The second most important step of the summer was the modification of the data processing method such that we can access data in the barrel as well as the endcap in order to compare the performance in both. Once these corrections and modifications were made, we were able to produce and analyze simulations of the calorimeters.

As an example, I include some of my results for an extremely large (8020 event) pile-up free Higgs to gamma gamma sample. I produced the following two eta-phi plots illustrating the differences in the detector technologies in the barrel as opposed to the endcap for a single event.
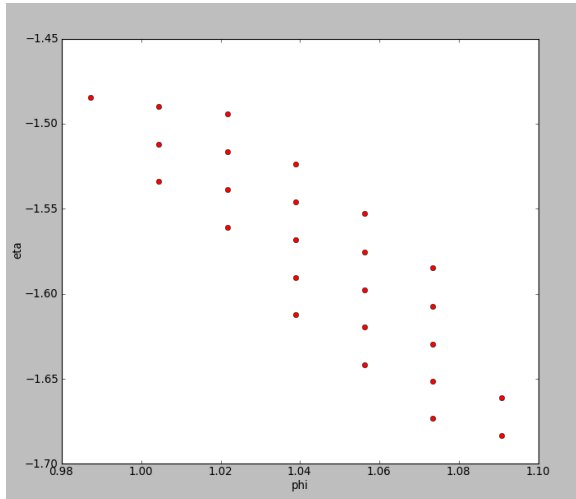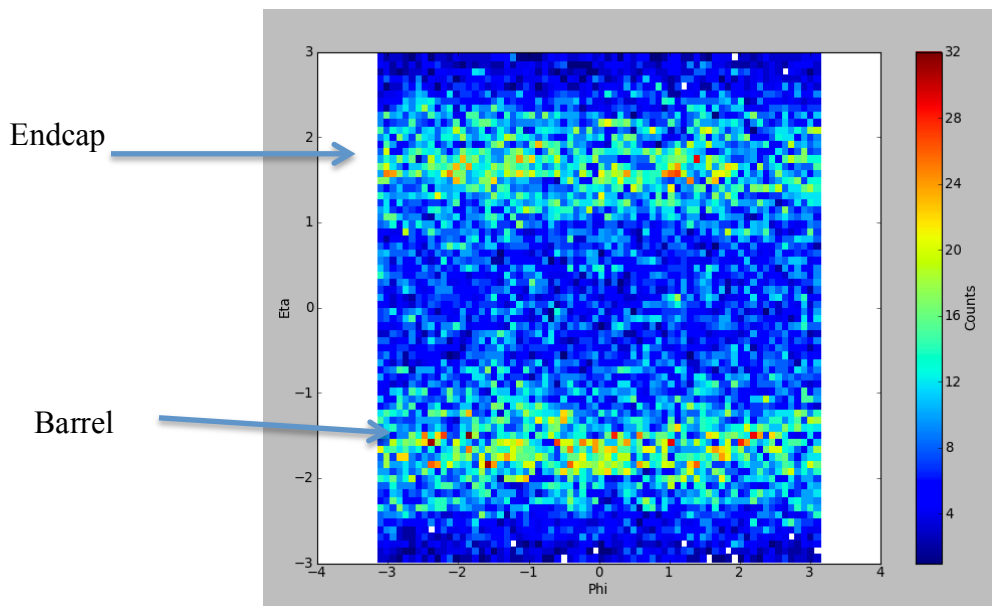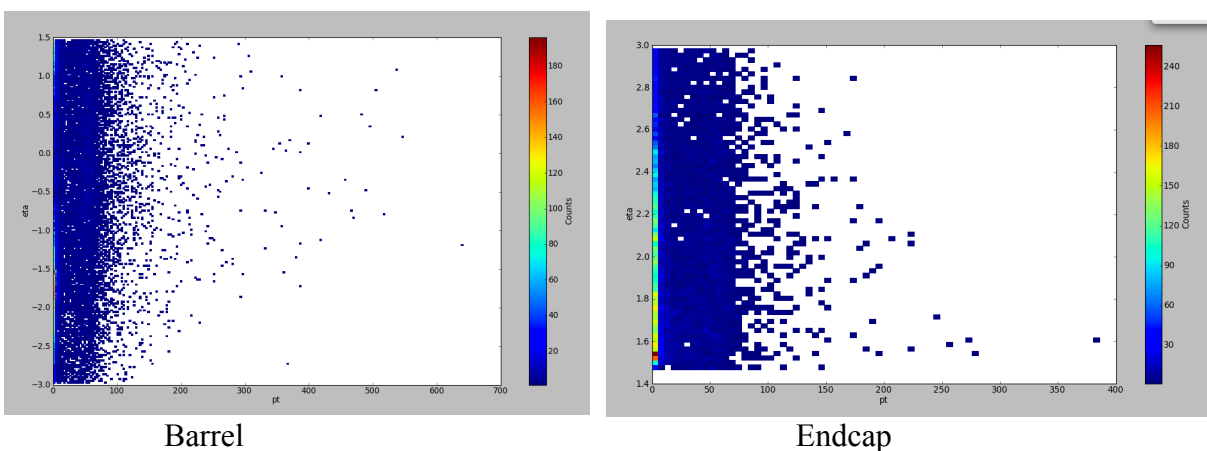

Barrel
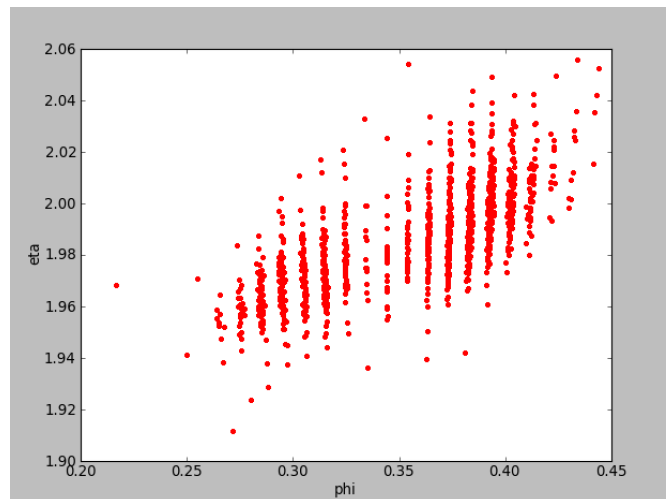
Endcap

One can see that in the barrel all hits are detected at the same depth and significantly less hits are detected, whereas we see many more hits boosted into the endcap.

Similarly, I include an eta-phi plot for all events. The two horizontal regions of high density correspond to clusters of hits in the barrel and endcap.


Now, looking at the relationship between pT and eta rather than phi and eta, we see the following plots for all events:


Barrel   Endcap

Here, we see that events with higher pT are shifted towards lower eta in the endcap and higher eta in the barrel. This is as expected, because the samples are flat in energy.

Next, I looked specifically at the timing of the hits, the main point of interest in assessing the performance of HGCal. Below are histograms displaying the distribution of times among hits in both the barrel and the endcap for one single event.
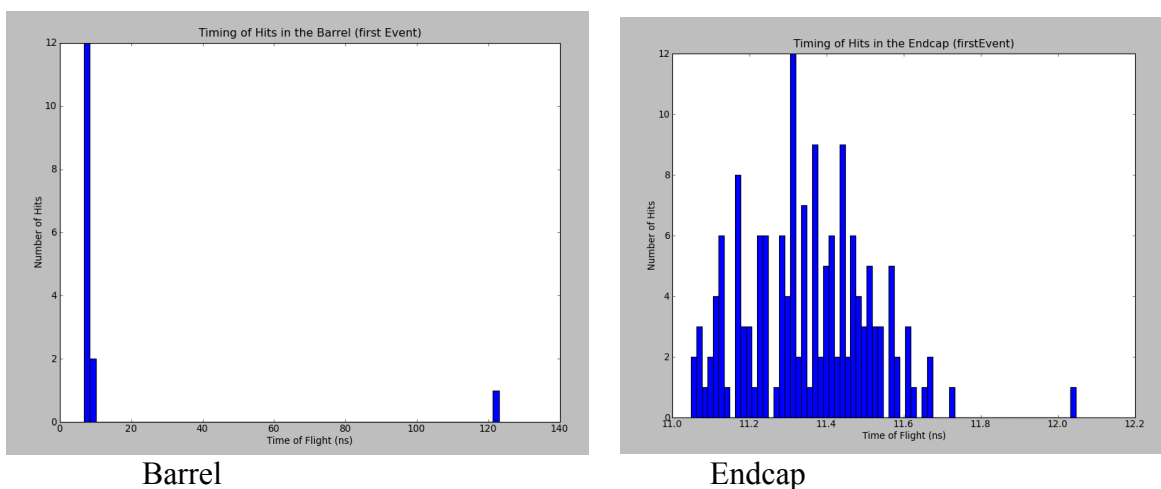
Barrel   Endcap

Aside from the one late hit in the barrel, there is significantly more spread in the endcap. This corresponds to the length of the shower. In the barrel, there is only one sampling of the time, so we always sample at the same depth, as was seen in the eta-phi plot. Thus, there is minimal spread.

Finally, I looked for time of flight (TOF) bias in eta.
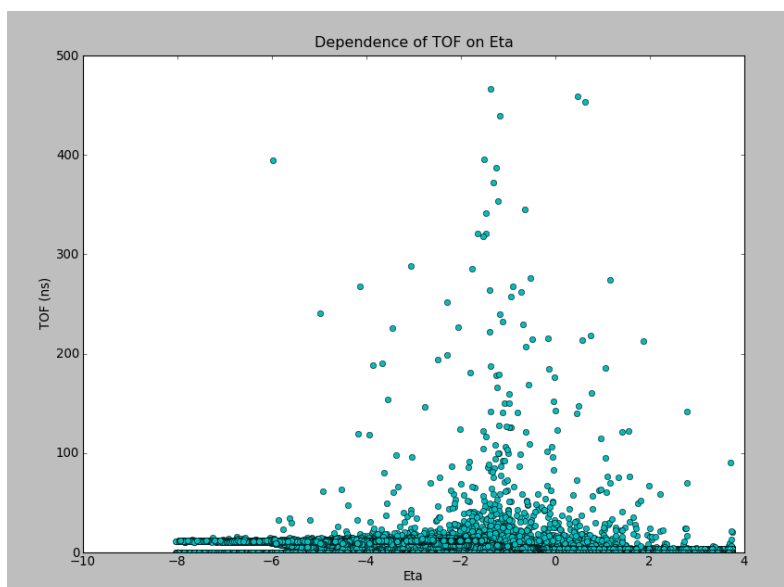
While I did not expect the TOF distribution in eta to be entirely flat, I was initially surprised by the extreme lateness of some of the hits. However, the late outliers are the result of low pT secondary particles. These particles make several loops in the detector before the hit is registered, resulting in hits near 500ns.

Ultimately, we want to be able to use the energy of the hits to reconstruct the invariant mass of the Higgs. This can be done using the two highest energy clusters of any given event, which

correspond to the two photons produced. For the first event, for instance, the combined energies of the two most energetic clusters are ~245GeV. This is greater than the Higgs mass, ~125GeV due to additional energy from forward boosting.

Remaining topics of investigation include determining the best way to measure the energy and reconstruct the Higgs mass. Counting the sensors may be a reasonable method for calculating the energy of the system, but may be less effective than adding all of the energies in the sensors or applying a method of energy weighting. We must also determine the correlation between the sensor reading and the energy deposited in the absorber in front of the sensors. Finally, we can calculate the difference between the true energy and the reconstructive energy and investigate whether this difference is consistent among various events.

In addition to the simulation analyses, I also had the opportunity to work several shifts at the test beam site in Prevessin, assisting in the collection of data to test the performance of the Shashlik detector in both electron and muon beams. Below can be seen an example of the detected muon signal. The yellow curve is the signal detected by the Shashlik.
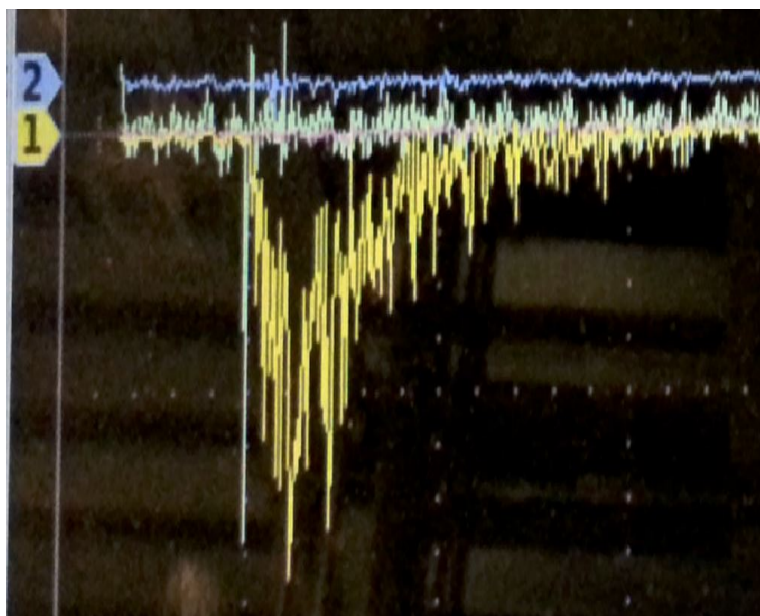
I am grateful for the opportunity to participate in research at CERN. I greatly expanded my knowledge in particle physics and enjoyed engaging in both the hands-on work with our detector apparatus at the test beam site as well as the analytic simulation work. Thank you for the opportunity.