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The TowerSlope Method: A Relative Calibration Tool for sPHENIX Calorimeter Systems

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Abstract

The new experiment currently under construction at Brookhaven National Laboratory, sPHENIX, will come equipped with three new calorimeter systems - two hadronic and one electromagnetic calorimeter.. To allow a proper tracking and identification, all components of each subsystem must be calibrated on a relative scale, and eventually an absolute one. This technical note presents the development, tools, and results on relative calibrations for each subsystem using the Tower Slope Method.

Introduction

We present in this technical note the development of tools and subsequent studies of the data-driven method ”Tower Slope” for offline calibrations of the sPHENIX calorimeter subsystems: Electromagnetic Calorimeter (EMCal), Inner Hadronic Calorimeter (IHCal), and Outer Hadronic Calorimeters (OHCal). This note includes studies using Mock Data Challenge 2 (MDC2) data with the purpose to test the Tower Slope method's ability to derive gain shift factors at the tower level. The method works in two different modes - gain tracing, and eta slice flattening. To put it briefly, the gain tracing mode determines the gain drift from tower to tower between two points in time, perhaps two runs. The eta slice flattening mode is a new calibration approach that corrects tower energy distributions for each eta bin by using the phi-integrated energy spectrum for said bin. This ”flattens” the phi-dependent energy response in a calorimeter. More details will be given in the analysis section.

Code

There are several key locations for this note to be reproducible. First, the coresoftware needed is located at:

https://github.com/sPHENIX-Collaboration/coresoftware/tree/master/calibrations/calorimeter/calo_tower_slope

This folder contains the source and header file of the method called LiteCaloEval.cc(h). This note will use the abbreviation of LCE to reference the LiteCaloEval analysis module. The key component of the code fits the energy spectrum of a given calorimeter's tower and obtains a gain shift factor. The second key location is:

https://github.com/sPHENIX-Collaboration/macros/tree/master/calibrations/calo/tower_slope_macro

Given in this folder are the macros to run LCE. LCE is modular in the context that each calorimeter has its own macro. More so, the two different modes it can run in produce two sets - six in total. The macros will be described in more detail below.

Implementation of LiteCaloEval.cc

Initialization

The macro to run LCE in the gain tracing mode is named do_eta_fit2_<calotype>.C and takes 3 parameters. The first parameter is a ROOT file who's energy distribution histograms are used as a reference, or what a calorimeter tower will be fit to. The second parameter is a ROOT file that will we call the modified file. For simulation purposes, the modified file has each tower's energy multiplied by a constant value to shift the energy spectrum. This value is actually a set of values that are known before the fitting occurs with the purpose to derive the shift that initially applied. The third parameter is simply an output file. With real data the first two parameters are files with energy spectra at two different time periods, where the oldest time period is used as the reference.

The contents of this macro is straightforward:

- Two LCE objects are created
  - One for "reference", which pertains to the files that do not have modified energy histograms
  - One for the "modified" set of files
- Calorimeter type is set
- Get histograms for each object
- Set minimum and maximum of fit range
- Perform the fit on histograms

The macro to run in the eta flattening only takes two parameters - an input file and and output file. In simulation, the input file would have modified histograms. The contents of this macro is essentially the same as the gain tracing mode with the exception of a parameter being passed when fitting the histograms.

Workflow in Tower Reconstruction

The workflow chart below describes how a single tower calibration is performed within the tower reconstruction process, with the Tower Slope module in the lower right portion.

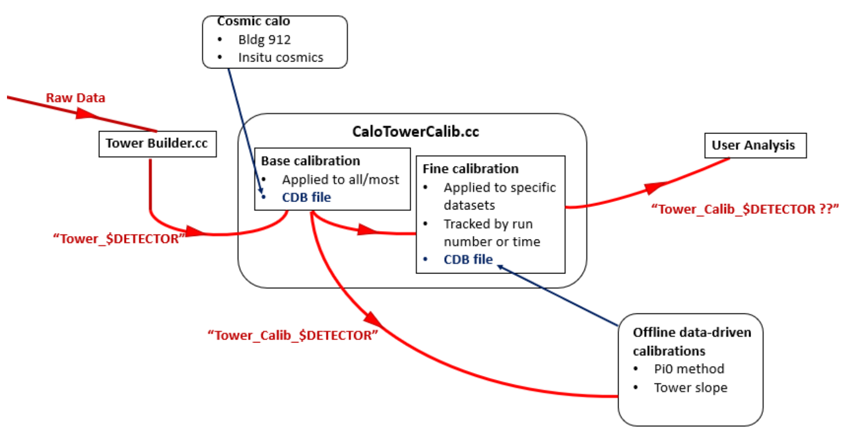

Figure 1: This workflow chart describes how a single tower calibration is performed, with the Tower Slope module in the lower right portion. This chart was used with permission from its author, Blair Seidlitz.

Analysis

Introduction

This section will describe how the Tower Slope module is used to detect gain shifts with the two operating modes.

Simulated Data

We performed this analysis using sPHENIX simulations. Specifically, Run62 Minimum Bias (MB) events were used that amounted to about 1x10^7 events, but only 7.9x106 used due to pileup.

Fitting Modes

Tower-by-Tower Gain Tracing

The gain tracing method holds the purpose to detect a gain shift in an individual tower across time. This method first assumes an initial calibration based on cosmics is applied to the tower. Next, we establish an initial time - t1. This could be the start of a run for instance. Then after a period of time, say at the end of a run, we want to calibrate the towers of a given calorimeter - t2. In this study, towers at t1 are those straight from simulations without any energy modifications made. Towers at t2 are those with an energy modification. The process starts by giving a gain shift, or energy decalibration, in a known pattern to simulated data. Real data will obviously not appear this way, but it's a methodological approach we deemed appropriate versus giving each tower a completely random energy decalibration..

Next, we want to use the LCE module to detect, or re-derive, the decalibration we initially gave. To determine the gain shift factors among towers, each tower from the modified files are fit with a "user-defined" function from its corresponding reference tower (or at towers at t1), and then a parameter describing the fit is extracted - this parameter is the gain.

Input Decalibrations: Gain Tracing Mode

The decalibration mentioned before is the multiplication of the energy value of each tower by a factor in a pattern-like fashion across the detector. The purpose of the pattern is to easily identify the output of the analysis in a qualitative way. A reference plot for the decalibration factors for IHCal and OHCal can be seen in Figure 2. The z-axis are the decalibration factors, ranging from about 0.94 to 1.07. To determine how well the LCE module can pick up these energy shifts, the LCE output plots should look identical to Figure 2. Once the gain shift is returned we determine the relative errors.

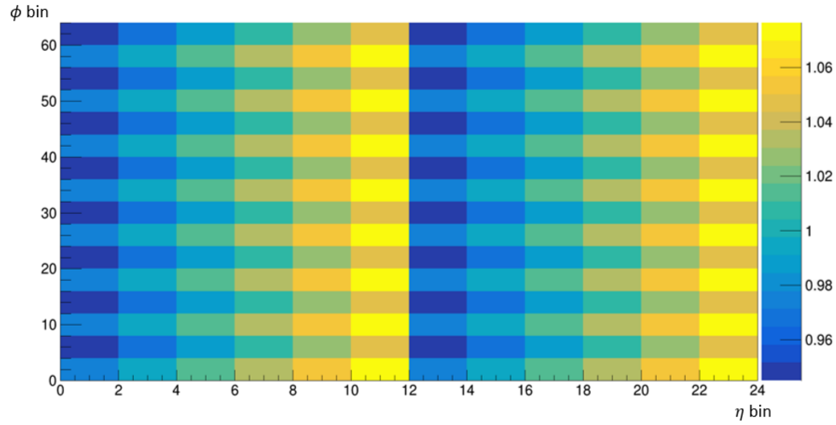

Figure 2: A 2-D histogram of a decalibration pattern for IHCal and OHCal. Each bin has a value corresponding to the size of the energy shift applied to a tower. Note, the colored blocks span several towers.

A similar plot was generated for EMCal as well, with a slight variation of decalibration in phi shown in Figure 3.

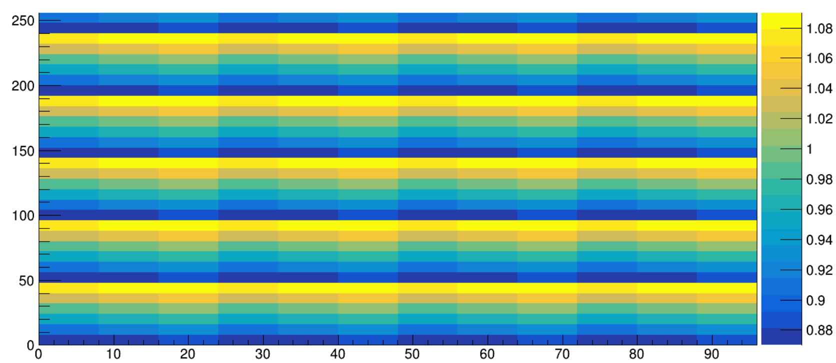

Figure 3: A 2-D histogram of a decalibration pattern for EMCal. Each bin has a value corresponding to the size of the energy shift applied to a tower. Note, the colored blocks span several towers.

The macros to generate these plots can be found in a personal workspace:

/sphenix/user/jbryan1/sphenix_macros/macros/calibrations/calo/tower_slope_macro/
The macros are named make_2D_corrhist.C for I/OHCal and semc_make_2D_corrhist.C for EMCal.

Input Decalibration: Eta Slice Flattening Mode

Tower-by-Eta Slice, is a new technique where we use a phi-integrated eta bin (called an eta slice or eta ring), see Figure 4, as the reference and fit each tower in the slice to the reference. The purpose of this is to simulate how calibrations will be performed in a more realistic scenario. We will not have an initial data set to use as a reference, so we create a reference with the eta slices.

This gives us 63x more statistics than a single tower for the hadronic calorimeters, and 255x more for emcal. One should note that when a tower is fit to an eta slice, that tower is removed from the phi integration so as to avoid inflating the statistical precision in the results, hence the 63 and 255 and not 64 and 256.

The reference plot for this study uses the same exact pattern of values for a decalibration, instead an average energy value is used over all eta bins.

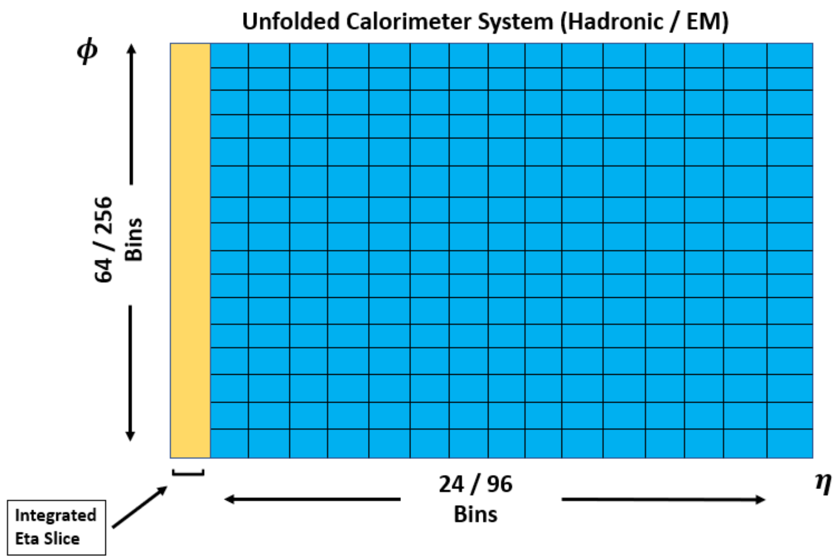

Figure 4: A general, cartoon drawing of an unfolded calorimeter detector system. The figure is for illustrative purposes only, showing what is defined as an eta slice.

Input Decalibrations Because we have kept the same decalibration pattern from the Tower-by-Tower method, we must alter the pattern to reflect the integration over towers in phi. This is shown in Figure 5 for the Hadronic Calorimeters. Shown in Figure 6 is the pattern for EMCal.

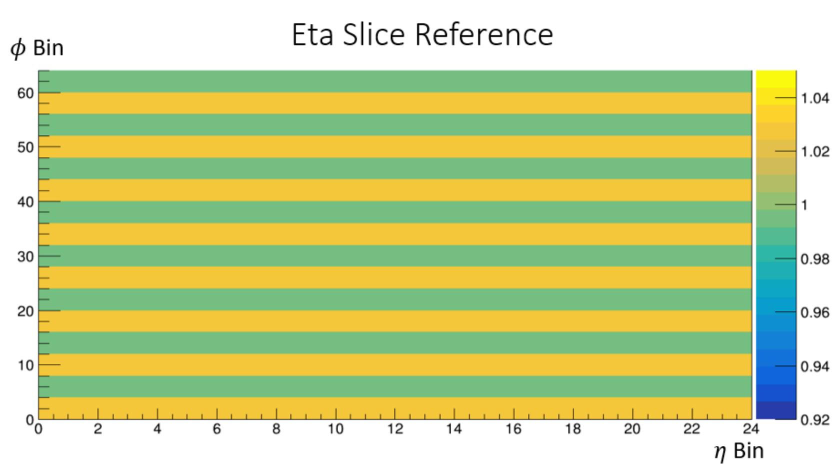

Figure 5: The input decalibration pattern for the Tower-by-Eta Slice method.

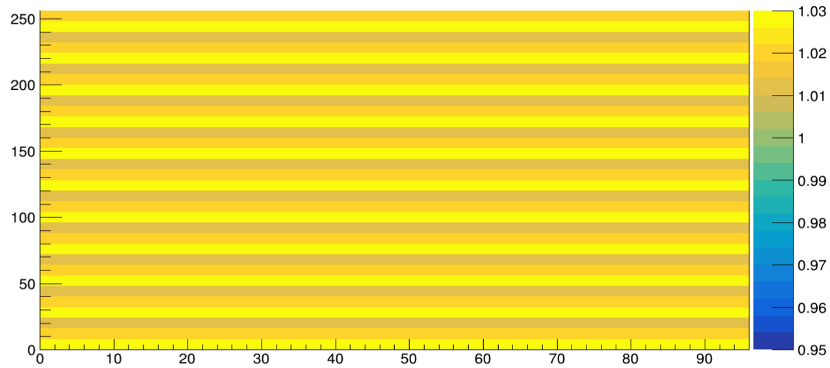

Figure 6: The input decalibration pattern for the Tower-by-Eta Slice method.

Results

We discuss the results for each methodology above in the order of tower-by-tower, and tower-by-eta slice. Each detector will have results shown for thoroughness. More so, we show results with "half-statistics" and "quarter-statistics" (see explanation below). There is a caveat to the results shown below; we could not use the results of full data sets. For example, when we have two sets of files from any MDC2 run, each set has the exact same events - one set is just tower energies while the second is tower energies multiplied by our gain shift pattern. We cannot fit this modified data set with the exact same un-modified set. We must fit together independent data sets, or different events.

Our approach was to take a full data set, say an un-modified one, and split it into two subsets. We did the same with a modified set, resulting in about 3.96x10^6 events. Then we only perform our analysis on the mixture of subsets - see Figure 7. This same idea was then applied to create 4 subsets of data (about 1.98x10^6 events) from a given set of MDC2 files, giving 6 different combinations of file pairs. The purpose of this was to of course use independent data sets, but to also see how well our statistical precision grew when adding more statistics. The process of increasing statistics reflects what will occur during real data taking with sPHENIX over time.

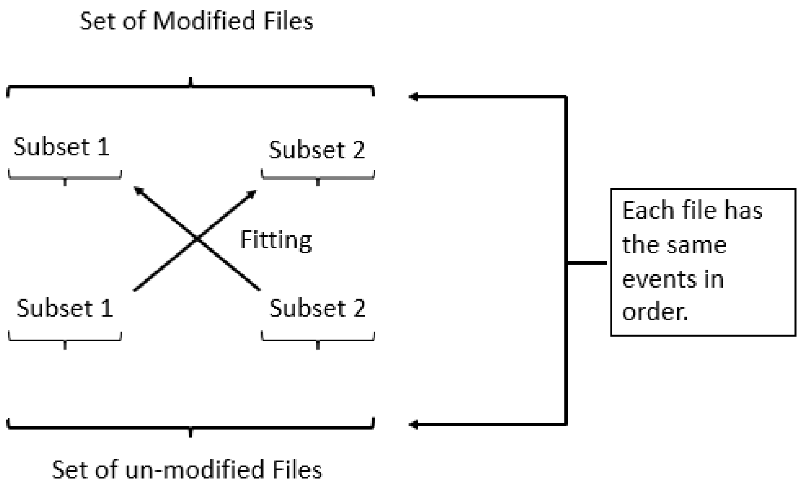

Figure 7: The file system setup used for this analysis note. A similar approach was taken a second time, but making 4 subsets for each file set.

Tower-by-Tower with Run4 Simulated Data

Inner Hadronic Calorimeter

The energy spectra of IHCal were fit over a range of 0.1-0.4 GeV for both eta slice histograms and individual tower histograms - see Figure 8. The main criteria to establishing a fit range is to capture as much statistics as possible, while also avoiding bins that don't have as smooth of distribution (i.e. the higher energy bins). The low energy bins are also avoided simply do to trial and error. We found the low energy bins didn't result in a better fit, even though there are more statistics.

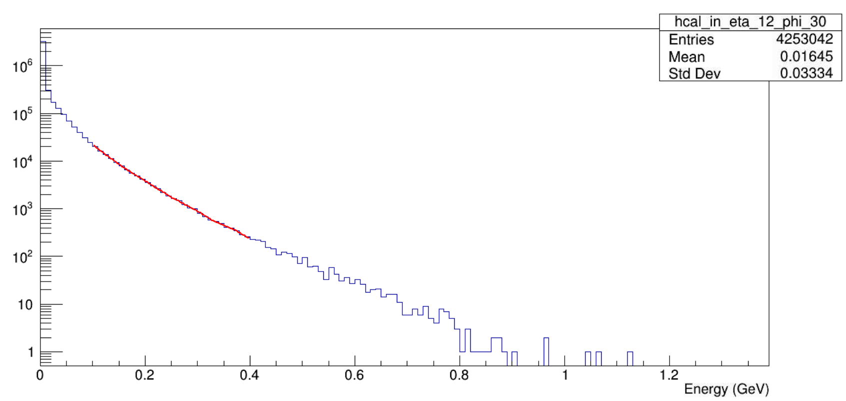

Figure 8: Example fitting on a single tower in IHCal. The spectrum is fit with the solid red line. The x-axis is units of energy in GeV.

An optimal fit range had been explored extensively with IHCal, and the range presented here gave the best RMS after evaluating the relative error using Figure 2 as a reference. The relative error results are shown in Figure 9 on the right. In this figure note the relative error is not multiplied by 100, and the box within the figure shows the percentage of towers and the number of towers in parentheses that fell below a certain error threshold. These categories were chosen arbitrarily to a small degree, but the most important one is the $< 1\%$. Quantitatively, we want the LCE module to detect the gain shifts and return said shifts at, or below the 1% level. For IHCal with half-statistics 1203 towers (78.3%) had the input decalibration detected within 1% accuracy.

Inside the box of Figure 9 one can also see the maximum error of 3.28%. This reflects the largest relative error among all towers. The 1% error has not been achieved among all towers, but this likely stems from the fact that this is from a data sample that had been halved as mentioned before ($\sim$3.96x10^6 events). The RMS is 0.00818 and we expect it to decrease as the number of statistics increases. A similar result in the RMS was attained for its data sample counterpart.

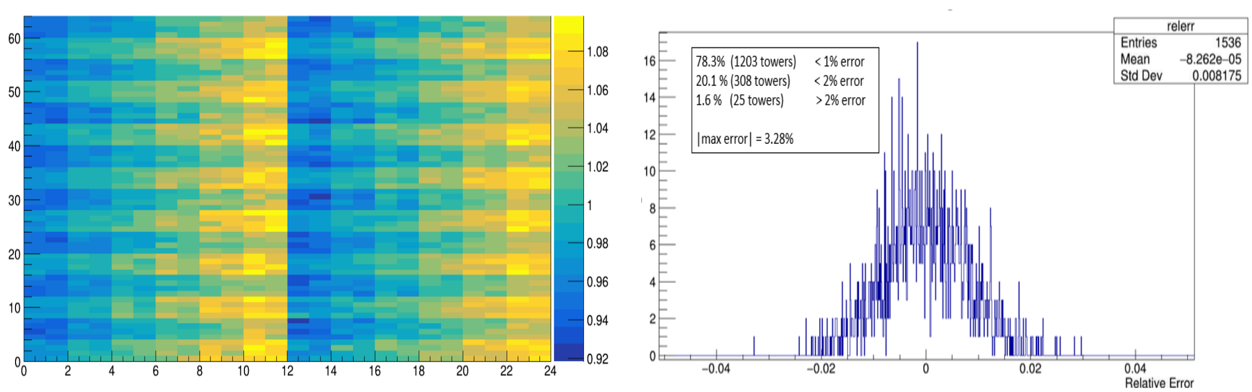

Figure 9: Left: A 2D histogram of the returned fit parameter over the range of 0.1-0.4 GeV. The y-axis are the phi bins and the x-axis are the eta bins. Right: The resulting relative error using Figure 2 as a "theoretical" value.

We show next the results when we took the original data set and split it into four subsets ($\sim$1.98x10^6 events). We expect the RMS to become larger by a factor of $\frac{1}{\sqrt{N}}$ where N is the number of statistics (or events). Only one of the six subset combinations will be shown.

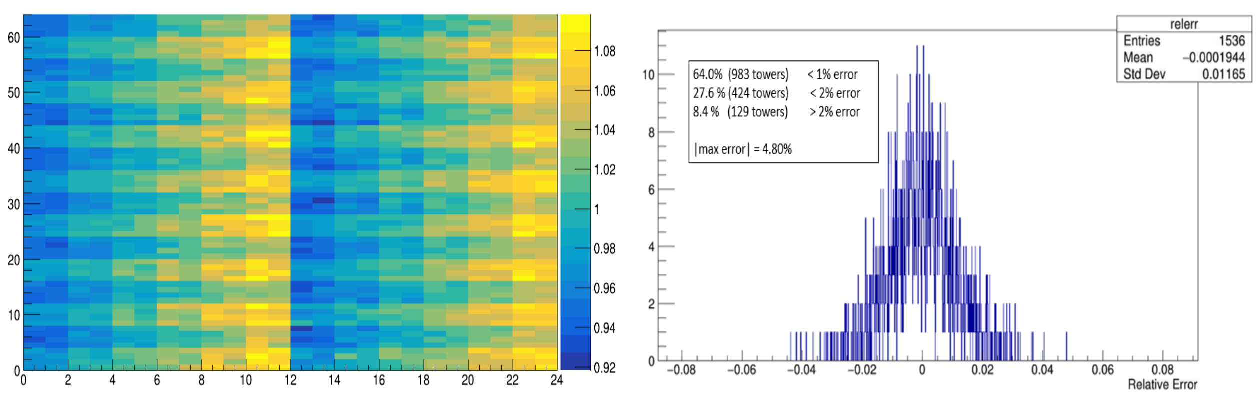

Figure 10: Left: A 2D histogram of the returned fit parameter over the range of 0.1-0.4 GeV. The y-axis are the phi bins and the x-axis are the eta bins. Right: The resulting relative error using Figure 2 as a "theoretical" value.

The RMS in Figure 10 is 0.01165. Results were similar with the other five subsets of data. There were 983 towers (64.0%) had a relative error below 1%. To ensure the $\frac{1}{\sqrt{N}}$ is satisfied Figure 11 shows the average RMS from the "half-statistics" and "quarter-statistics" with a power law fit. The expected returned parameter value should be 0.5, and we see it follows an inverse square root form with -0.52. [point about only 2 data points?]. For future data taking, when we begin to add statistics from different runs or time periods at RHIC, we can be sure the RMS on returned fits will become narrower as more statistics are added.

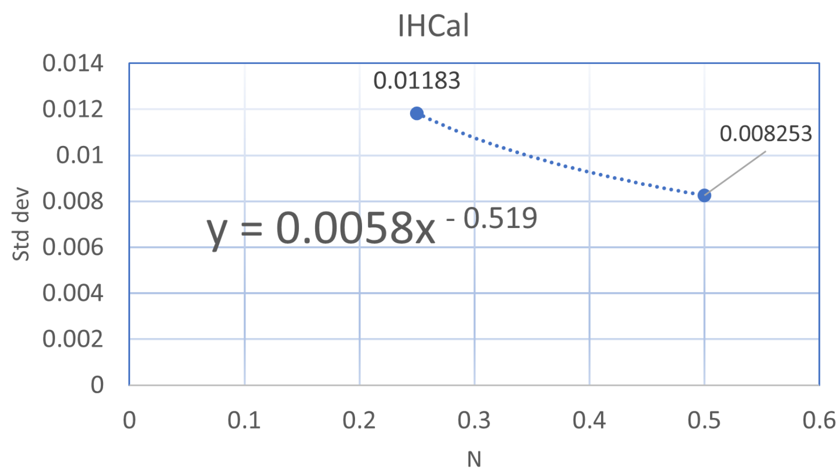

Figure 11: A power-law fit to the averaged RMS with the half subsets of data and quarter subsets of data. The left-most data point is from the quarter subset. The x-axis represents what fraction of the full data set was used.

Outer Hadronic Calorimeter

The outer hadronic calorimeter had a fit range of 0.12-0.7 GeV for both eta slice histograms and individual tower histograms - see Figure 12. Other ranges were also explored but again, the RMS was smallest with the range above. OHCal does have more statistics in the higher energy bins that wouldn't appear to be problematic for the fit process, but the analysis had shown otherwise. The chimney was not removed for the Run4 analysis.

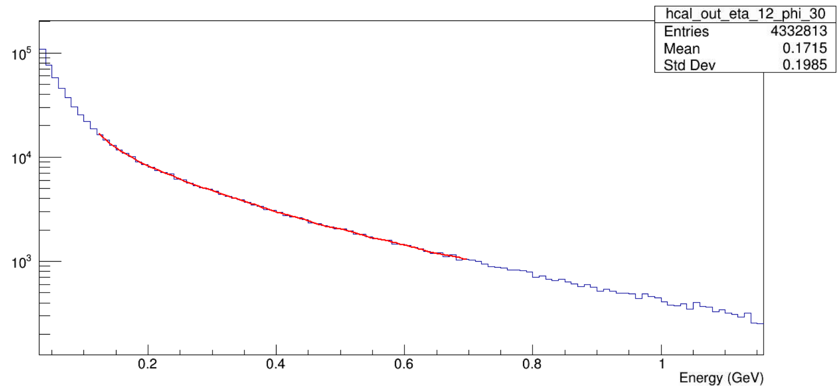

Figure 12: Example fitting on a single tower in OHCal. The spectrum is fit with the solid red line. The x-axis is units of energy in GeV.

The half statistics results show an RMS of 0.02355 in the relative error with the largest error in the returned fits of 9.23%. 549 towers (35.7%) had the input decalibration at or below 1%. The other half statistic result was similar with a mean RMS of 0.02353.

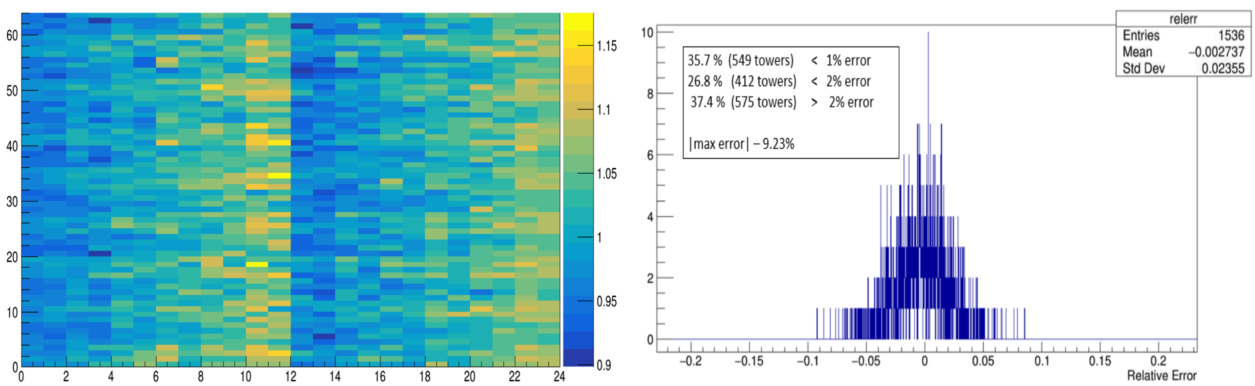

Figure 13: Left: A 2D histogram of the returned fit parameter over the range of 0.12-0.7 GeV. The y-axis are the phi bins and the x-axis are the eta bins. Right: The resulting relative error using Figure 2 as a "theoretical" value.

The quarter statistics are shown next. The RMS of the error distribution is 0.03285 and only 416 towers (27.1%) have an error of 1% or lower. Again, this data set is a quarter of the full data set so there are only $\sim$1.96x10^6 events, hence the decrease in performance. Though we see an increase in performance as statistics increase. The other 5 combinations of results were similar to those in Figure 14. Over the 6 results the mean RMS was 0.03453. Figure 15 shows the power fit law between the two data sets. The returned exponent parameter was -0.553.

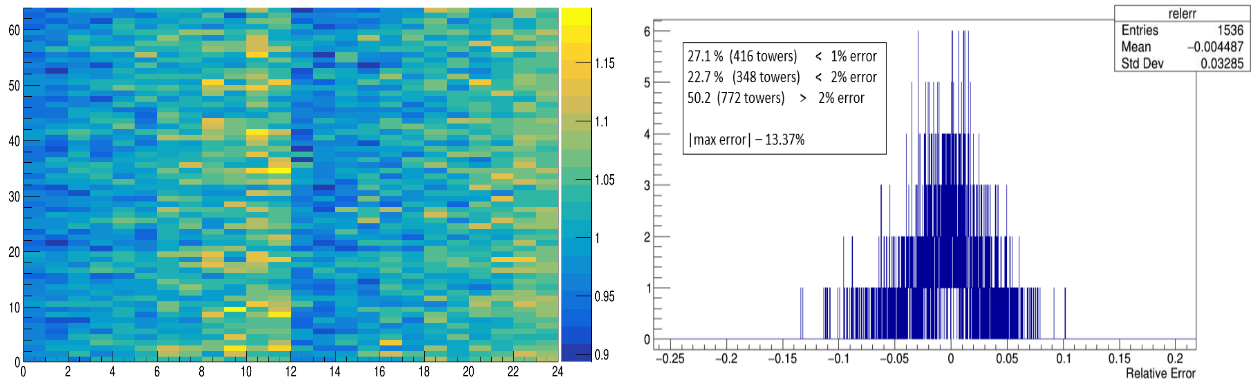

Figure 14: Left: A 2D histogram of the returned fit parameter over the range of 0.12-0.7 GeV. The y-axis are the phi bins and the x-axis are the eta bins. Right: The resulting relative error using Figure 2 as a "theoretical" value.

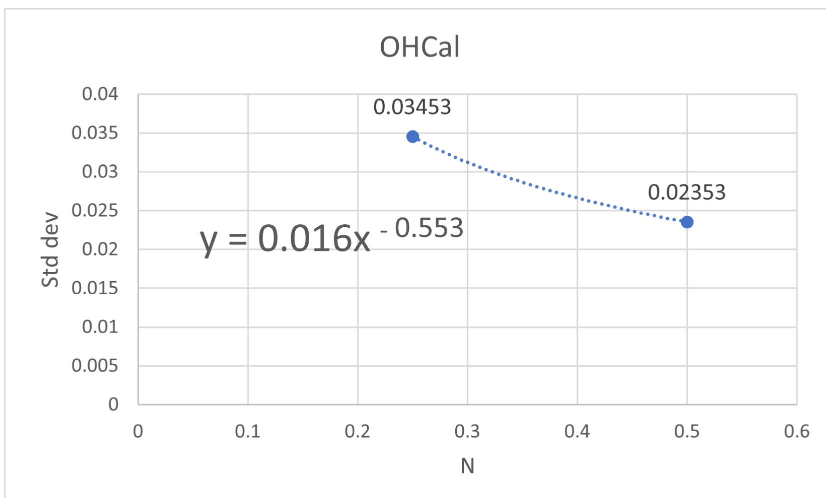

Figure 15: A power-law fit to the averaged RMS with the half subsets of data and quarter subsets of data. The left-most data point is from the quarter subset. The x-axis represents what fraction of the full data set was used.

Electromagnetic Calorimeter

Like OHCal, EMCal histograms were fitted over 0.12-0.7 GeV - see Figure 16 for an example. This analysis did not entail removing the TPC supports.

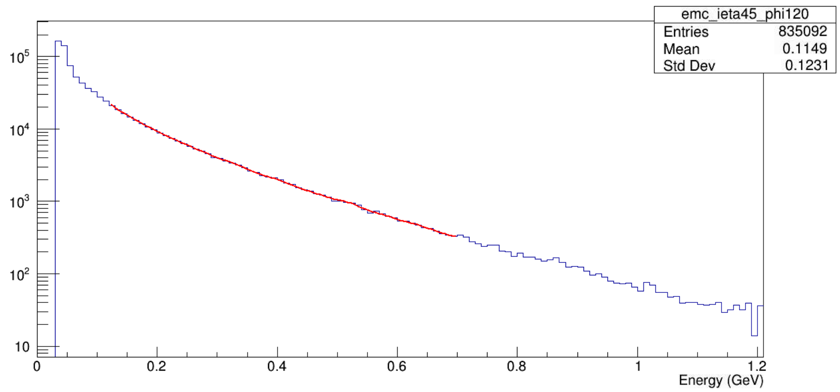

Figure 16: Example fitting on a single tower in EMCal. The spectrum is fit with the solid red line. The x-axis is units of energy in GeV.

The half statistics results are shown first. The first pair of files had a RMS of 0.01041 with 16,471 towers (67.0%) having their input decalibration found within a 1% accuracy. The second result from the half data set was similar.

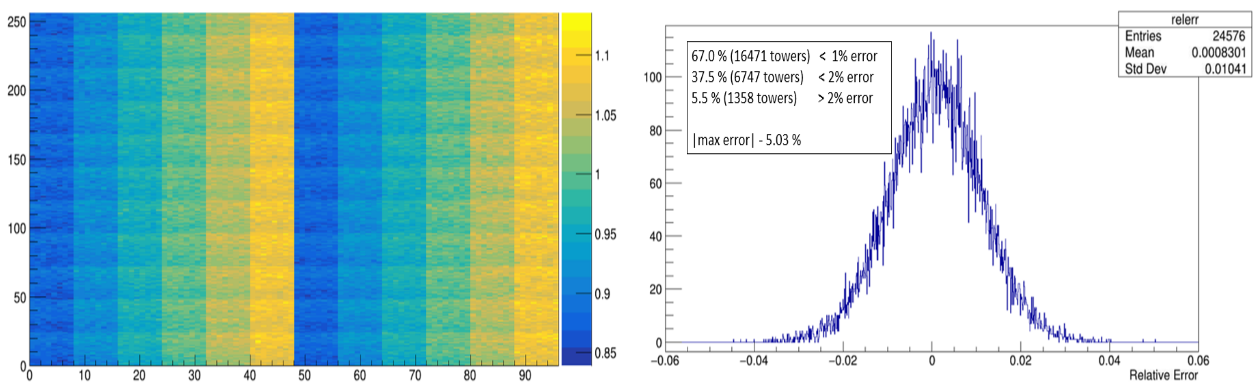

Figure 17: Left: A 2D histogram of the returned fit parameter over the range of 0.12-0.7 GeV. The y-axis are the phi bins and the x-axis are the eta bins. Right: The resulting relative error using Figure 2 as a "theoretical" value.

An example of the quarter statistics results are shown next in 18 with 10,731 (43.7%) towers having a relative error less than 1%. The other 5 comibinations were similar. The average RMS on the relative error was 0.0176 among all 6 file comibations.

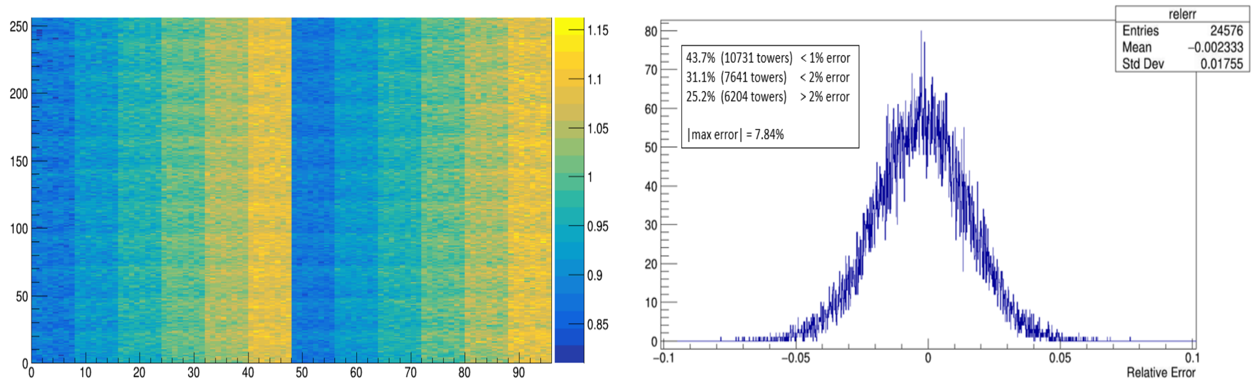

Figure 18: Left: A 2D histogram of the returned fit parameter over the range of 0.12-0.7 GeV. The y-axis are the phi bins and the x-axis are the eta bins. Right: The resulting relative error using Figure 2 as a "theoretical" value.

The final result to show for the EMCal, and the tower-by-tower fitting, is the $\sqrt{N}$ fitting of the average RMS of the half and quarter data statistics. The exponent parameter had a value of -0.755, which has a relative error of 51% from the expected value of -0.5.

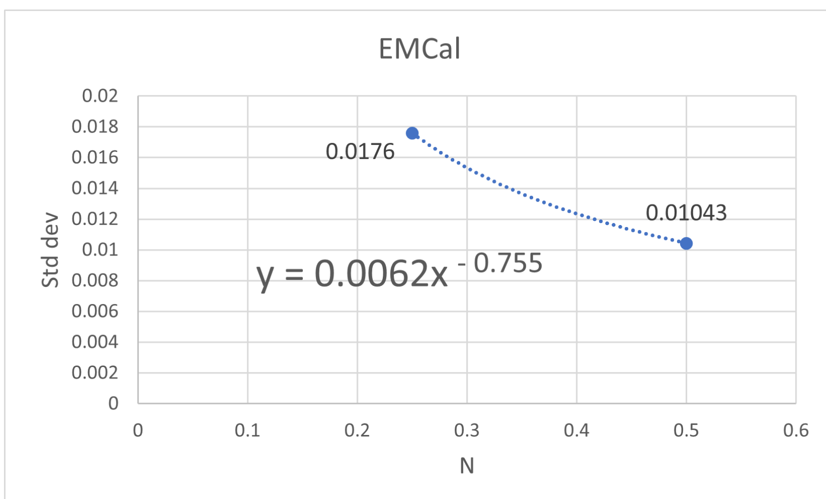

Figure 19: Example fitting on a single tower in EMCal. The spectrum is fit with the solid red line. The x-axis is units of energy in GeV.

Fitting Tower to Eta Slice with Run4 Simulated Data

We show in the following sections the results of fitting a tower with a modified energy to a phi-integrated eta slice. This method required only a single data set of modified files (with the decalibration pattern). This is because the eta slice is used as a reference. There is a large advantage to this because we can use the full MDC2 data set of Run4, which has about 7.86×10^{6} events, and not have to run the analysis with half or quarter statistics. Each calorimeter has the same fit range as its tower-by-tower counterpart.

In order to reduce systematic effects, the tower that is being fit has its respective energy distribution histogram removed from its respective eta slice reference histogram (which, again, is the phi-integrated histogram). After a fitting has been complete, the tower histogram is added back to the reference, and the cycle repeats. More so, in the OHCal, the chimney sector must be accounted for in a similar fashion. The towers corresponding to the chimney are removed from its corresponding eta slice histogram, but not added back. So, for example, the first eta slice (which corresponds to the first bin, or tower in eta) has six towers removed from the phi-integrated histogram, and the seventh when a fit is performed on a tower. The same process is applied to EMCal and the TPC support structures.

Inner Hadronic Calorimeter

We show in this section the results of detecting the input decalibrations, or the gain shifts. The figure below shows the retrieved gain shifts to qualitatively show the similarity to the input decalibration pattern from Figure 5.

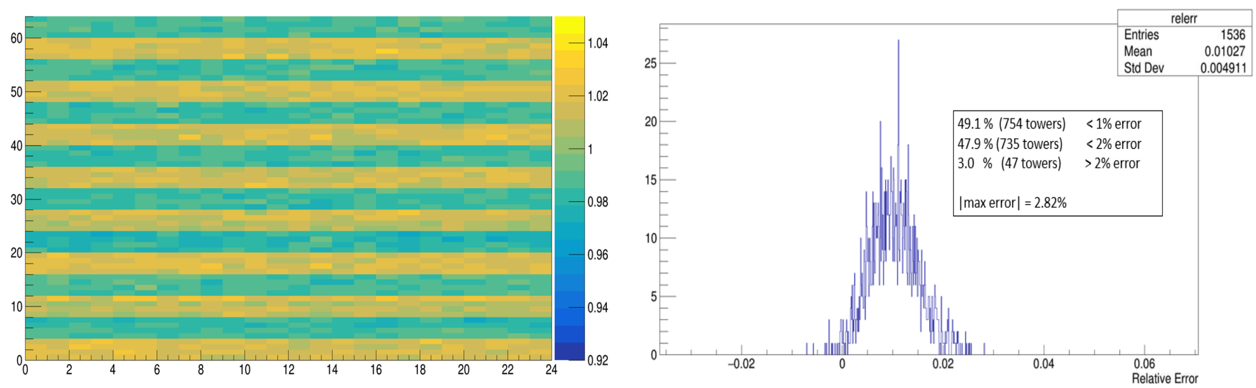

Figure 20: Caption

Next, we derive the relative errors on the detected gain shifts. The expectation when deriving the relative error plot is a single bin centered at zero, implying every detected gain shift was exactly what was initialized to, but this is naive. We do expect a narrow distribution to be centered at zero. In Figure **??**, the relative error is displayed using the input decalibration as the ”theoretical” value and the detected gain shift as the ”experimental” value, which is the strongest quantitative test of the LCE analysis module. The mean of the distribution is not centered about zero, which may likely be due to lower energy responses, becuase IHCal tiles are tilted in the radial direction. The tilt reduces the energy deposited after the particle hits the inner most tile (see REF). The RMS is 0.0049, which denotes our analysis is capable of detecting gain shifts on the sub-percent level. Furthermore, the number of towers that detected the input decalibration at a 1% or better level was 754 towers - nearly fifty percent of the 1,536 towers.

Outer Hadronic Calorimeter

OHCal results are shown next, with the same type of plots as IHCal. For OHCal, there is an area where towers have been altered to accommodate for a cryogenic stack for detector cooling, called the chimney. Because of this, the associated energy in each tower is lower and we do not want to include such towers in this analysis. Note, we did include such towers in the tower-by-tower analysis because we were exactly looking at gain shifts in towers. In fitting towers to an eta slice, the lower tower energy response contributes to the lower energy bins in an eta slice histogram, a potential systematic error contribution we do not want. The chimney region spans four towers in η and six towers in ϕ, this can be seen in Figure **??** as the white rectangular region. So, we skip over fitting towers associated with the chimney.

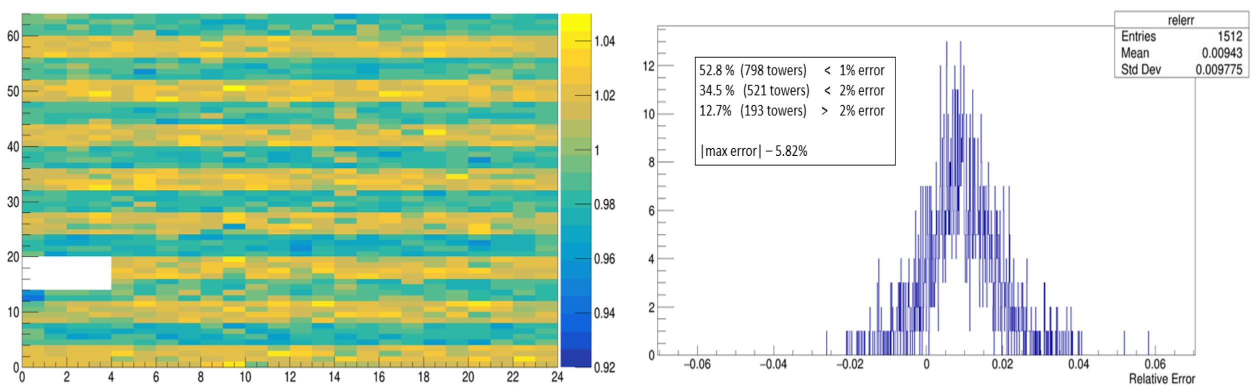

Figure 21: Caption

Upon skipping the fitting process of the chimney towers we excluded said towers from the relative error plot. In Figure **??** the relative error on detecting gain shifts is presented. The mean of the distribution is 0.009, which can likely be explained like that of IHCal. The RMS though is good, 0.0098. This figure tells us again that the LCE module is detecting gain shifts within a precision of 1%. Over fifty percent of the towers had a relative error at or below 1%, and a max error of 5.82%

Electromagnetic Calorimeter

The EMCal detector system appears to have more systematic effects that need to further addressed, but for now we will show the same results as the hadronic calorimeters.

The two white sections in Figure 22 are the designated TPC supports. We are skeptical the 8 sections in the same figure between 100 and 150 on the y-axis belong to the TPOT detector. The qualitative result of detected energy shifts shows the LCE module had a poor precision.

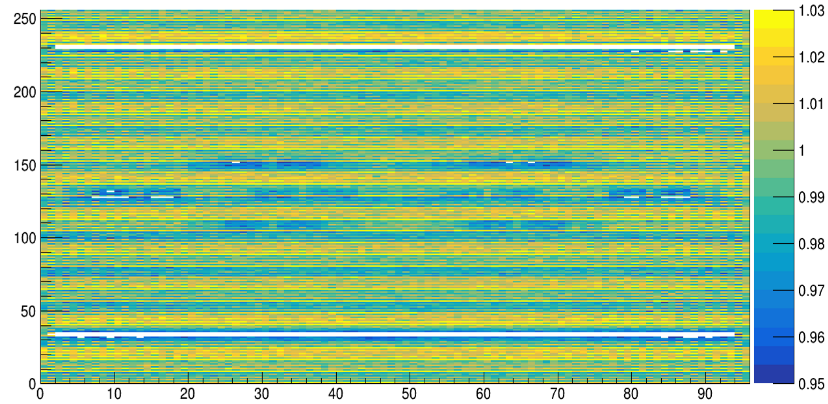

Figure 22: Caption

In Figure 23 on the left, there are three separate distributions. The same image is re-binned (Rebin(2) four times) on the right, to get a clearer image of the distributions. The peak closest to zero is what we would typically expect to see, but the two bumps to the left currently cannot be explained, or what the contributing the factors are precisely. It may be that tower or sector boundaries are causing this. The boundaries would cause a lower energy response, changing the shape of the tower energy distributions, causing the parameter describing the distribution to change. The sector boundaries are easy to conceptualize as there is literally a boundary of material that encapsulates each sector. In a block, where the towers located, there are

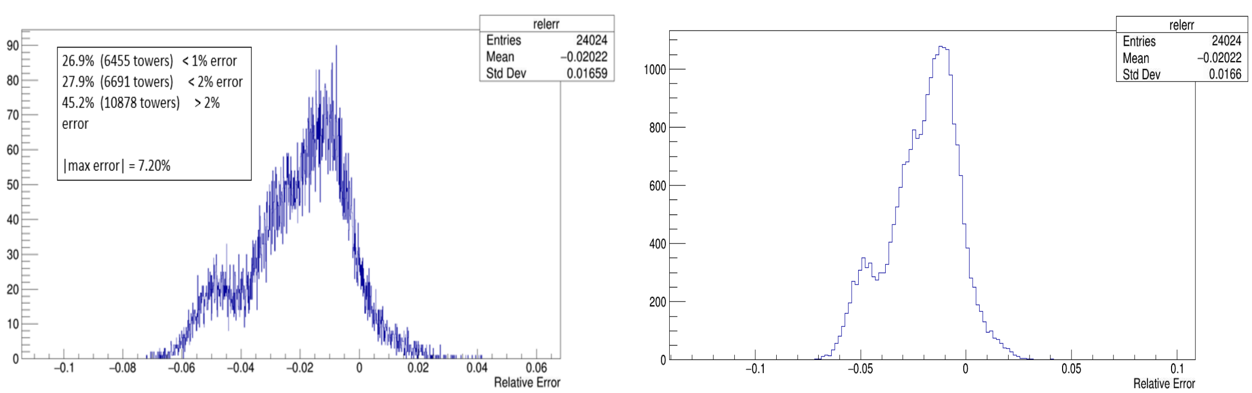

Figure 23

Updated Results: Tower-by-Tower with Run5 Simulated Data

At the time studies using Run4 data were being performed, Run5 simulations were underway. This prompted another study of the exact same type using Run5 data. The main reason why we duplicated the study is because of updates with regards to detector geometries, change of materials used such as the Time Projection Chamber supports that partly block the EMCal, or adding in a support ring for the IHCal. Below we show results of the Tower-by-Tower and Eta Slice studies, but neglect the "quarter-statistics" studies.

Inner Hadronic Calorimeter

The IHCal has seen an improvement over the previous simulation study. The most important figure that has improved is the RMS of the relative error distribution, which has decreased by a factor of about 1.5, and the total number of towers detecting the gain shift at 1% or lower (see Figure 24).

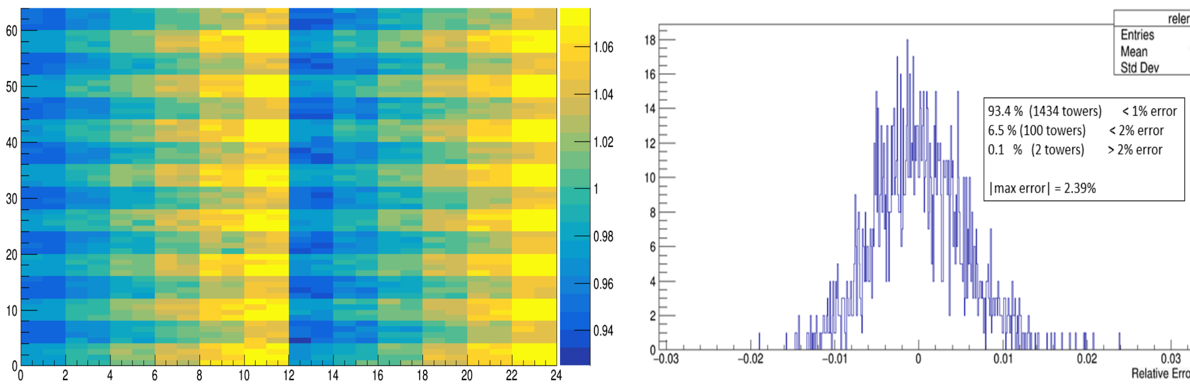

Figure 24: Run5 relative error results (right).

Outer Hadronic Calorimeter

The OHCal has also seen improvements in the tower-by-tower gain mode. The RMS has decreased by a factor of 1.6 (see Figure 25).

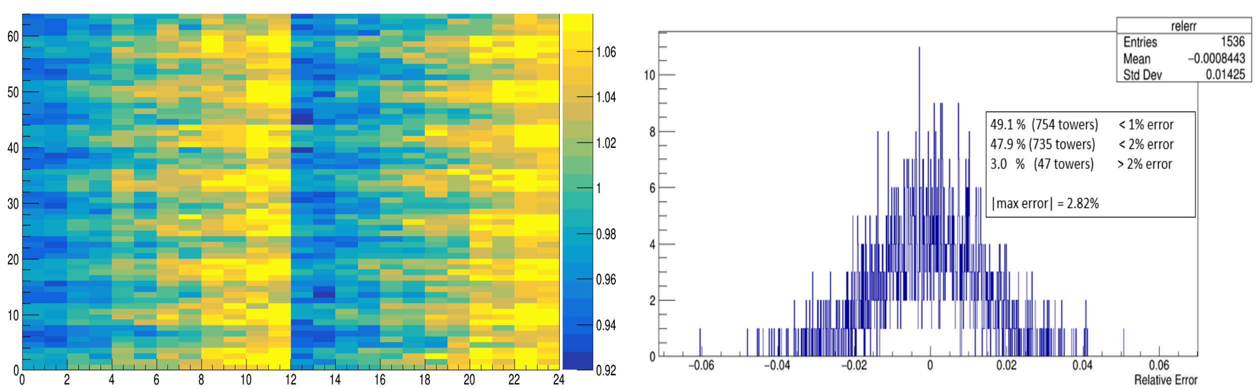

Figure 25

Electromagnetic Calorimeter

For Run5 simulations, the pattern for EMCal was swapped with respect to η and ϕ (see Figure 26). This was done to see if the Tower Slope method was consistent in determining a gain shift independent of the same shift that has been given. The method has shown to obtain shift with sub-percent precision, a further improvement over the previous simulation data. The RMS here has decreased by a factor of 1.4, going from 0.01041 to 0.00731 (see Figure 27).

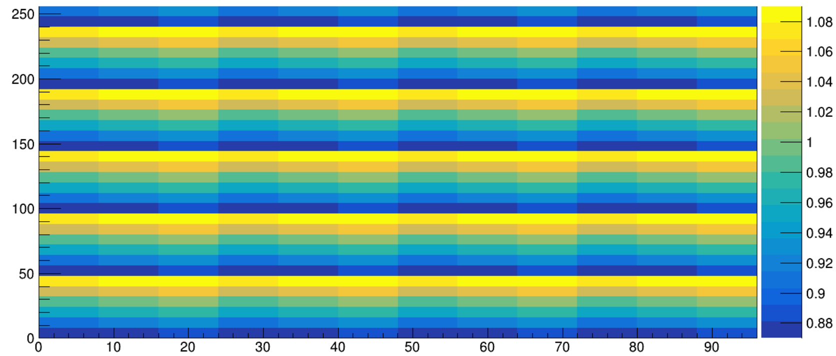

Figure 26: Caption

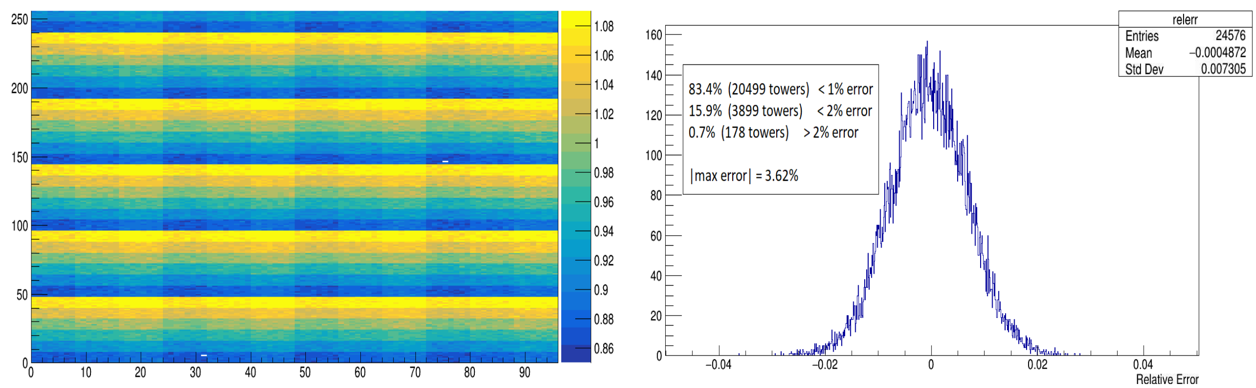

Figure 27

Fitting Tower to Eta Slice with Run5 Simulated Data

Inner Hadronic Calorimeter

With new simulations and a slight improvement of the Tower Slope method, the relative errors for the IHCal have improved noticeably. The mean of the distribution is now properly peaked around zero, which still indicates the method has recovered the input decalibrations near perfectly, but the width of the distribution has decreased by a factor of 1.2, going from 0.004911 to 0.003881 (see Figure 28).

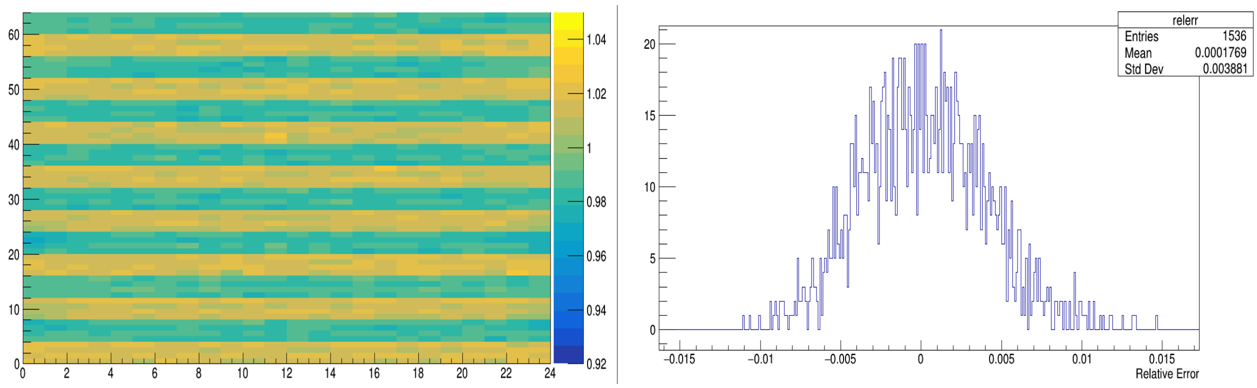

Figure 28

Outer Hadronic Calorimeter

The OHCal has seen a slight improvement with the addition of not removing the chimney (see Figure 29. This was due to the sPHENIX calibrations framework not skipping the chimney section either. When attempting to recover the decalibration factor in the chimney region the relative errors were very large - ranging from several percent to just over twenty percent. Further studies will be needed to assess how we can improve the fitting of towers in this region, and possibly re-iterate the fitting.

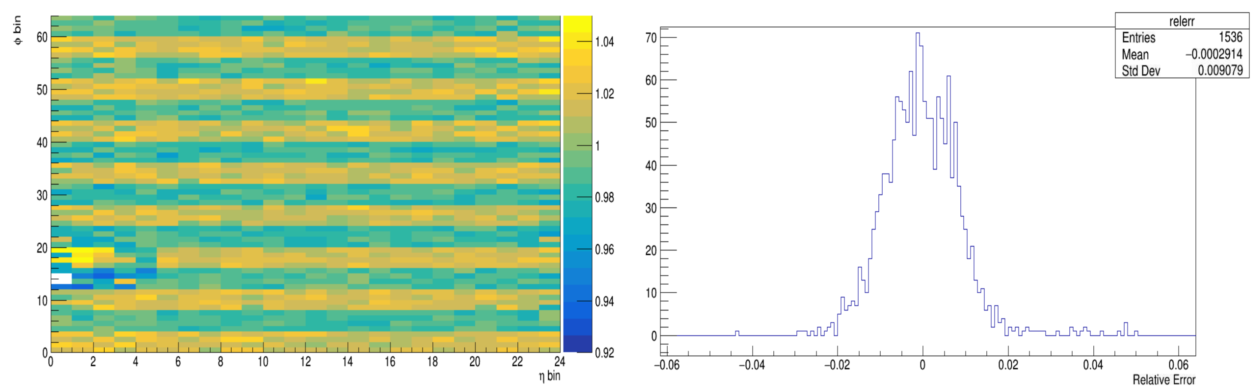

Figure 29

The improvement in the method is noticed in the number of towers that have a certain percent error. For example, from Run4 the number of towers that were able to detect the gain shift with an accuracy at or below 1% was 798, and to Run5 we saw (excluding the chimney now) was 1,207.

Electromagnetic Calorimeter

Given the tower-by-tower method used a different input decalibration on the towers, that same pattern was utilized for the eta flattening mode (see Figure 30). The left plot shows the input values, and the right shows the recovered shifts.

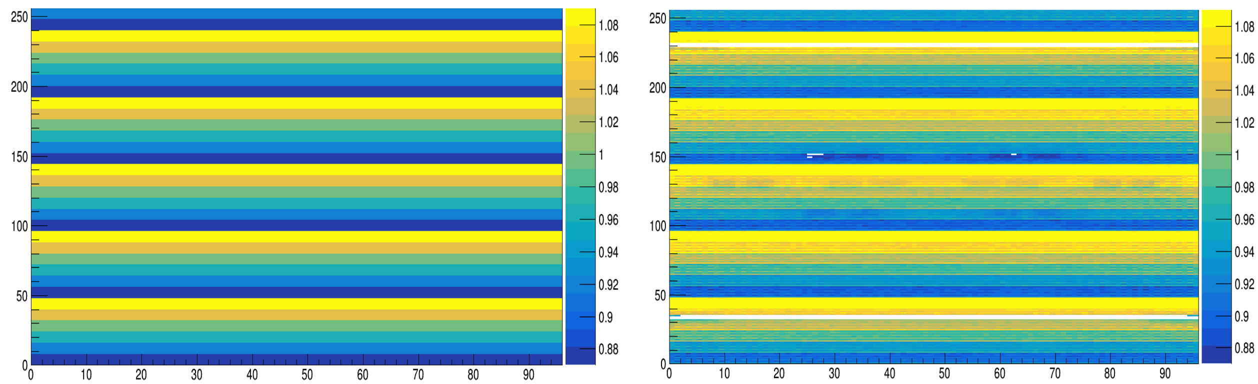

Figure 30

The relative error distribution shown in Figure 31 has revealed the phi-dependent energy responses in the EMCal. This is apparent in the three different mini distributions where the left-most is most correlated with sector boundaries. The middle mini distribution has not been associated with any region yet within the EMCal itself, but is likely due to the phi-dependent response at the tower level. The right-most distribution appears to be the main distribution but with an overall shift.

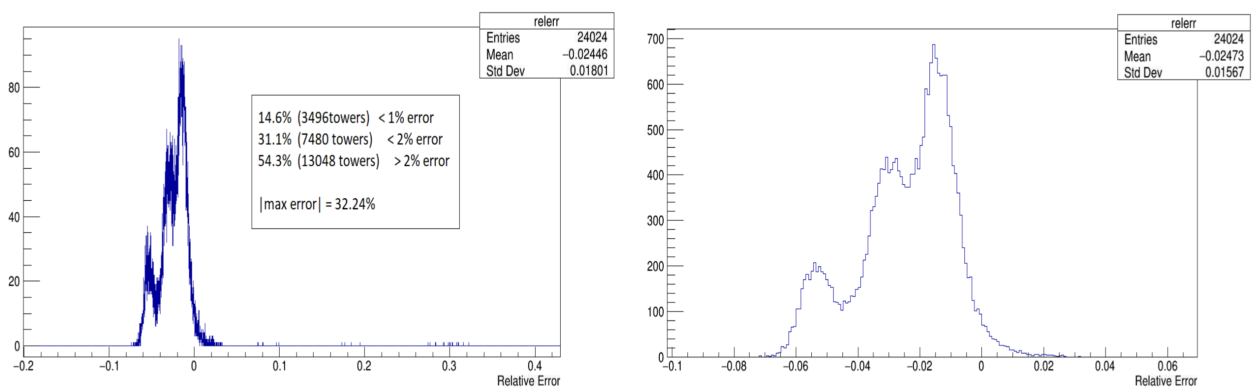

Figure 31

Future Work & Conclusion