Status of the Forward Calorimeter System (FCS) Upgrade at STAR

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July 20, 2023

Abstract

The Forward Calorimeter System (FCS), together with the Forward Silicon Tracker (FST) and small Thin Gap Chambers (sTGC), are the most recent upgrades of the STAR detector at RHIC, BNL. This upgrade in the forward $2.8 < \eta < 4$ rapidity region is motivated to explore QCD physics in the low region of x as those related to revealing the nucleon spin structure. The FCS consists of the refurbished PHENIX Shashlyk Lead Scinitillator (Pb/Sc) Electromagnetic Calorimeter (EMCal) followed by an iron - scintillator (Fe/Sc) sampling Hadronic Calorimeter (HCal), with silicon photomultipliers (SiPMs) as readout. The construction of the FCS was completed towards the end of 2020 and started taking data during the 2022 Run Period. This talk will cover the construction and calibration of the FCS with a focus on the radiation damage of the front end electronics, as well as the gain correction factor for each ECal tower for reconstructing neutral pions using the pp Run23 $\sqrt{s} = 510$ GeV data.

1 Introduction

The Relativistic Heavy Ion Collider (RHIC), located at Brookhaven National Laboratory in Upton, New York, is the world's only machine capable of colliding polarized proton beams enabling the study of the proton spin. The Solenoidal Tracker at RHIC (STAR) uses the polarized proton spin beams to measure the different components of the spin of the proton that is estimated to be carried by their constituent quarks and gluons. In recent years, the emergence of various theoretical models to predict the asymmetry of particles produced after polarized proton-proton collisions has sparked an interest in the forward pseudorapidity or low Bjorken x region of the detector. Details on this and many other key results can be found in the RHIC Cold QCD Plan [**1**].The STAR forward upgrade is motivated mainly by exploration of cold QCD physics in the very high and low regions of Bjorken x with pseudorapidity coverage $2.5 < \eta < 4$. It consists of the Forward Calorimeter System (FCS), the Forward Silicon Tracker (FST) and the small Strip Thin Gas Chamber (sTGC). This proceeding will focus on the construction, design and calibration of the FCS.

2 Construction of the FCS

The concept of design of the FCS was first prepared in 2015 in a white paper proposal [**2**]. The construction for the same was finished by the beginning of 2021 and is now currently operational for the latest RHIC Run. The FCS consists of the Electromagnetic Calorimeter (EMCal) followed by the Hadronic Calorimeter (HCal). The EMCal at the FCS consists of the refurbished Shashlyk Lead Scintillator Calorimeters from PHENIX, that last took data in Run16, followed by Iron Scintillator sampling HCal. Both of these calorimeters have symmetric North and South modules placed on a platform beyond the end of the TPC on the west side of STAR There are a total of 1496 EMCal towers with 34 rows and 22 columns in each module. The HCal has a total of 520 towers with 20 rows and 13 columns in each module. Both of the calorimeters cover a transverse area of about 1.2 m in width and 2 m in height.

EMCal Design : The basic PHENIX EMCal modules consisted of 4 independent towers, or a 2x2 EMCal supersector of size 5.52x5.52x33 cm^3 . Each tower has penetrating wavelength shifting (WLS) fibers for light collection. There were several modifications made to these towers which were then used at FCS. Light guides or mixers were glued to the end of the WLS bundles, followed by Silicon Photomultiplier (SiPM) on printed circuit boards (PCB). These PCBs have 4 SiPMs each, so there are a total of 5984 SiPMs in the EMCal, both modules combined, for data taking. Finally, Front End Electronic (FEE) Boards were attached to the SiPM PCBs.

HCal Design : The HCal at FCS is built in a Lego style concept with simple parts which have no interdependencies on each other. It consists of steel absorbers of 20 mm thickness and scintillators of 3 mm. Each tower size is around 10x10x85 cm^3 with 36 layers of scintillators sandwiched between absorber plates. Light is collected by tapered WLS plates placed between two towers, which are in turn attached to SiPM PCBs consisting of 6 SiPMs. Therefore, there are a total of 3120 SiPMs for taking HCal data with the two modules combined. Once the layers of absorbers and scintillators were stacked, and the WLS plates inserted for each tower, the LED plates were attached at the back of the towers to complete the installation of the HCal.

3 Calibration of the FCS

The calibration of the FCS consists of several steps and is an ongoing process. One of the very first steps for calibration is to monitor the leakage current from the SiPMs at ECal and HCal. The ADC values of currents read from the FEEs need to be converted to SI units of current, μA for every day of data taking and plotted for each run number for monitoring. The bias voltage is reduced manually in case an increased amount of leakage current is observed in the monitoring history plots. This usually occurs towards the end of the run period due to increased irradiation of the SiPMs by high luminosity beams. Additionally, normalized 2D plots for each run show that there is more radiation damage done to SiPMs closer to the beam pipe than the ones further away, as expected (Figure 1a and 1b). This kind of damage done to SiPMs reduces their gain correction factor for converting ADC values to Energy. Different amounts of radiation damage done to the different SiPMs, based on their location on the FCS result in different corresponding gain correction factors which need to be calibrated to get the correct particle invariant mass peaks. The calibration methods for the EMCal and HCal are described below.

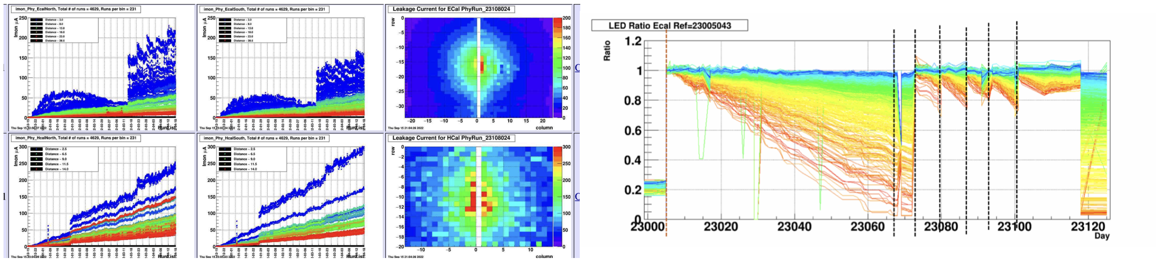


Figure 1a: History plots of leakage current for Run23 Physics Runs; Figure 1b: 2D plots of EMCal and HCal for a particular Physics Run; Figure 1c: Led Ratio plots with dashed lines showing periods for calibrating the Gain Correction Factor

3.1 Calibration of the EMCal

Calibrating the different EMCal towers involves reconstructing neutral pions using two photon clusters. A cluster is defined as a group of neighbouring non-zero energy EMCal towers fired from an electromagnetic photon shower. The neutral pion decays into two photons ($\pi^0 \rightarrow \gamma\gamma$) at a certain opening angle from each other. Each of those photons are expected to shower and form a cluster at the EMCal. The neutral pions are reconstructed as :

$$m_{\pi^0}^2 = 4E_1E_2sin^2(\frac{\alpha}{2}) \tag{1}$$

where E_1 and E_2 are the energies of the two photon clusters and α is the opening angle between them. The data sample used for this calibration included 8.5 M events from pp collisions at $\sqrt{s} =$ 510 GeV from the Run23 period.

Cluster Selection Cuts : The first step for selecting a photon cluster pair is to set a lower energy cut of 1 GeV to both clusters. Only the pairs with energy asymmetry less than 0.7 are taken into account i.e. $\frac{E_1-E_2}{E_1+E_2} < 0.7$. Furthermore, for each event, only the pairs with highest summed energy $(E_1 + E_2)$ are considered. The energy for each tower is then given as :

$$\text{Energy} = \text{Gain} \times \text{Gain Correction Factor} \times \text{ADC} \tag{2}$$

where, ideally, the gain is what needs to be determined from the radiation damages iteratively, while the gain correction factor is the tower variant factor which accounts for the effect from the radiation damage for each individual tower, and the ADC values are determined from the DAQ system through proper algorithm.

Estimating the Gain Correction Factor : Radiation damages done to the SiPMs and FEE boards are the main causes for reduction in the gain. These damages are directly observed through the LED system, whence the attenuator and SiPM bias set voltage on FEE boards are changed manually to adjust the LED readout between periods. The ratio of the LED readout between each LED test run and the reference test run in a period (dashed line, Figure 1c) is calculated. It is observed that the ratio drops for each tower along the time, but the slope of ratio drop for each tower is different, depending on the distance to the beam pipe. The higher the drop rate, the more serious is the radiation damage done on those towers.

Iterative tower-by-tower Gain Correction Factor Calculation : The invariant mass peak has been extracted from the mass plots of each tower for this calculation. For each best pair of clusters, the tower with the highest energy inside each cluster is selected. The two next highest energy towers are filled with the invariant mass of this pair. For each tower invariant mass plot, a Gaussian Function is used to fit the signal and an exponential fit is used to fit the background. The invariant mass peak is then obtained from the Gaussian mean of each tower. The corrected Gain Factor for each tower is calculated as

$$\text{G}_{\text{corr}} = \text{G}_{\text{org}} \times \frac{\pi^0 \text{ inv. mass peak } (0.135\text{Gev/c}^2)}{\text{obs. inv. mass peak}} \tag{3}$$

The calculated gain correction factor is then applied for another iteration of π^0 reconstruction. This process is repeated until the invariant mass peak converges at the π^0 invariant mass. The diagram on the left below shows the π^0 invariant mass plot for all towers before iteration and the one on the right shows the peak after iteration. The invariant mass plot after 2 iterations shows an obvious peak right at π^0 invariant mass with smaller width

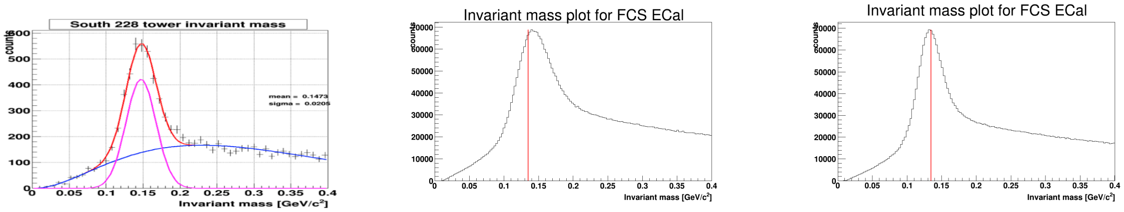
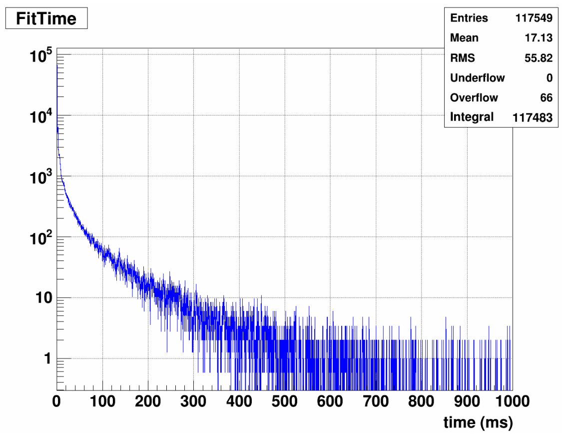


Figure 2: Fit functions for signal and background for neutral pion invariant mass histogram (left) Neutral pion peak before iteration (middle) Neutral pion peak after iteration, at the expected value of pion mass (right)

Conversion of ADC Values : Proper algorithms are required to compute that ADC values in eq. (2) from the raw data with fast computation speed and high accuracy. In STAR, analog signals are digitized by time integrating the voltage (ADC) of the signal over the trigger window i.e. the time between the RHIC bunch crossings. DEP Boards digitize signals every 13.5 nanoseconds; this time interval is considered 1 Time Bin (Tb) at STAR. There are exactly 8 time bins in 1 RHIC bunch crossing, so there can be as many as 100 Tb of data for every channel in every event. There are two methods to calculate the ADC Values. *Method A :* The Gaussian Fit Signal Integration Method, where the signal is fit to a Gaussian function and the amplitude of the function gives the integral of the signal wavefunction. This method, however, is quite time consuming and is only needed in cases where multiple overlapping peaks appear. The more peaks there are to fit the longer it will take. *Method B :* The Sum8 method, where the time bins are summed over the 8 time bins of the RHIC Bunch Crossing. This method introduces a factor of 1.2 to the previous method, which has some difference, albeit negligible to the proper signal wavefunction.

Therefore, a new algorithm is developed for reading ADCs to correctly determine the number of peaks and then decide whether to apply method A or B depending on the number of peaks found. This optimizes the computation time by accurate determination of the peaks, hence determining the energy correctly.



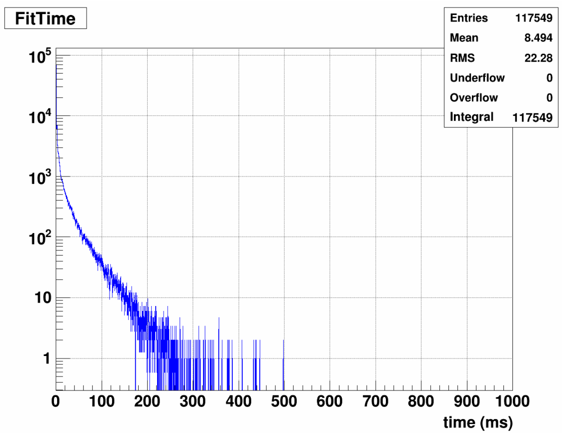


Figure 3a: Computation time taken by Gaussian Fit method. Figure 3b : Computation time taken by new algorithm

3.2 Calibration of the HCal

At the HCal, nearly 1% of the hadrons and all muons leave behind Minimum Ionizing Particles (MIPs), which are usually observed at 1-2 isolated HCal towers. Hence, these MIPs are considered good calibrating particles for HCal. A histogram of ADCs using this isolation cut of 1 or 2 tower clusters is assessed to find a peak that could be the MIP peak. There appears in some towers a nice peak where it is expected but in others it is dominated by backgrounds coming from potentially noise. The MIP peaks calculated from those plots are then found to be in agreement with the expected values of MIP peak locations. This method works for most of the towers of HCal, however, the calibration is ongoing with the search for better methods to eliminate huge backgrounds in the MIP Peaks.

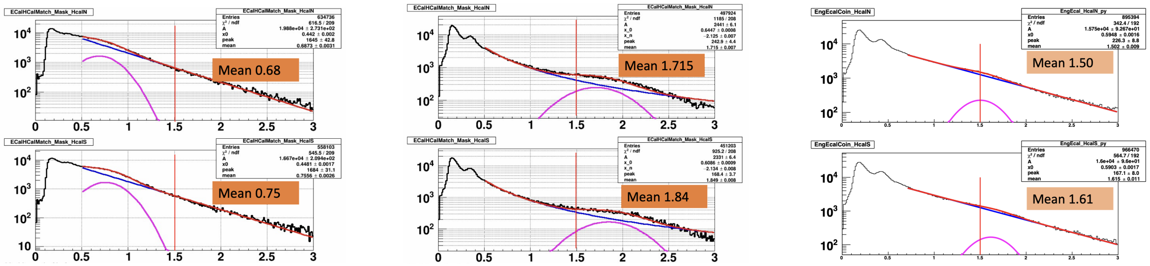


Figure 4 : Calibrating HCal towers with MIP peaks by varying the Gain Correction Fcators and ADC Values. Huge background observed for most HCal towers.

4 Conclusion

Currently, the software for continuous monitoring of the leakage current from SiPMs for both ECal and HCal is in place. Gain correction factors have been calculated for the EMCal using π^0 reconstruction. This will be continued for each run period. Calibrating with MIPs works for most of the HCal towers, however, better algorithms are being developed to eliminate MIP backgrounds. Once this is done, the data from the FCS for Run21 onwards will be ready for physics analysis.

References

[1] Elke-Caroline Aschenauer (BNL), Christine Aidala (U. Michigan), Alexander Bazilevsky (BNL), Markus Diehl (DESY), Renee Fatemi (Kentucky U.), Carl Gagliardi (Texas AM) et. al. *The RHIC Cold QCD Plan for 2017 to 2023: A Portal to the EIC*, arXiv:1602.03922.

[2] STAR Collaboration *FCS MRI narrative*, https://drupal.star.bnl.gov/STAR/files/FCS