Results of the 2019 STAR FCS Test Beam at FNAL.

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Abstract

We present measurements of FCS EMcal and Hcal responses for electrons, hadrons and muons from 2019 test beam run. The experimental results are compared to GEANT4 simulations.

Introduction.

STAR Forward Calorimeter System (FCS) consists of EMcal and HCal. EMcal made of refurbished PHENIX shashlyk calorimeter blocks; HCal is Fe/Sc sandwich (20/3 mm sampling). Both calorimeters were readout by HPK SiPMs (S12572-015P). Test Beam setup mockup as close as possible final hardware configuration for STAR FCS, i.e. signal cables lengths, type (FPOST), pre-production Front End Electronics (FEE).

Calibration of EMcal.

All measurements for EMcal performed with attenuator set at 0 at FEE (no attenuation). SiPMs for ECal were preselected according to HPK data. A single SiPM carrying board for ECal has four SiPMs operating at the same bias voltage (within +-10 mV). From sixteen ECal SiPM boards, two had operating voltage 68.53V, seven had nominal voltage 68.50 V, and another seven had nominal bias at 68.55V. For simplicity bias on all ECal SiPM boards was set the same at 68.52V.

EMcal was calibrated with muons. Muon mode at FTBF realized with 30 GeV Low Energy negative Pion mode with one section of steel absorber upstream closed (1.5 meters of steel). ECal and HCal located about 40 feet from the absorber block. Mixed momentum muons illuminate whole front face of calorimeters. FTBF Sc3 counter (~ 10 x 10 cm2) located about 1 meter away from steel absorber was used for triggering DAQ.

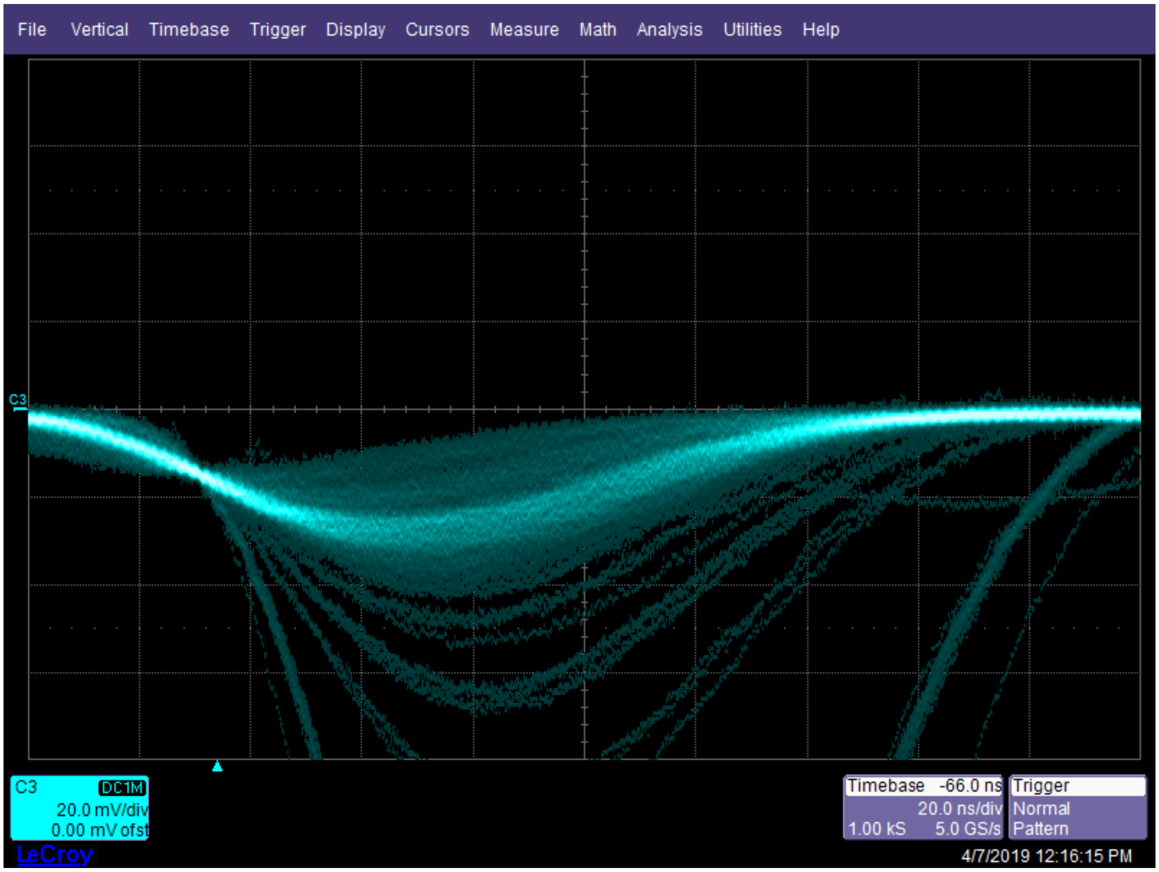

Figure 1. ECal Muon signal shape.

Traces of muons in Ecal shown in Figure 1. MPV amplitude of signals is close 30mV, which is sufficient to perform "MIP" calibration.

Isolated muons spectra for all sixteen towers of ECal shown in Fig.2. A simple Gaussian fit of muon peak used to derive calibration constants for ECal (muon data set taken at medium range of CAMAC CMC080 ADCs, 0.2pC per ADC count).

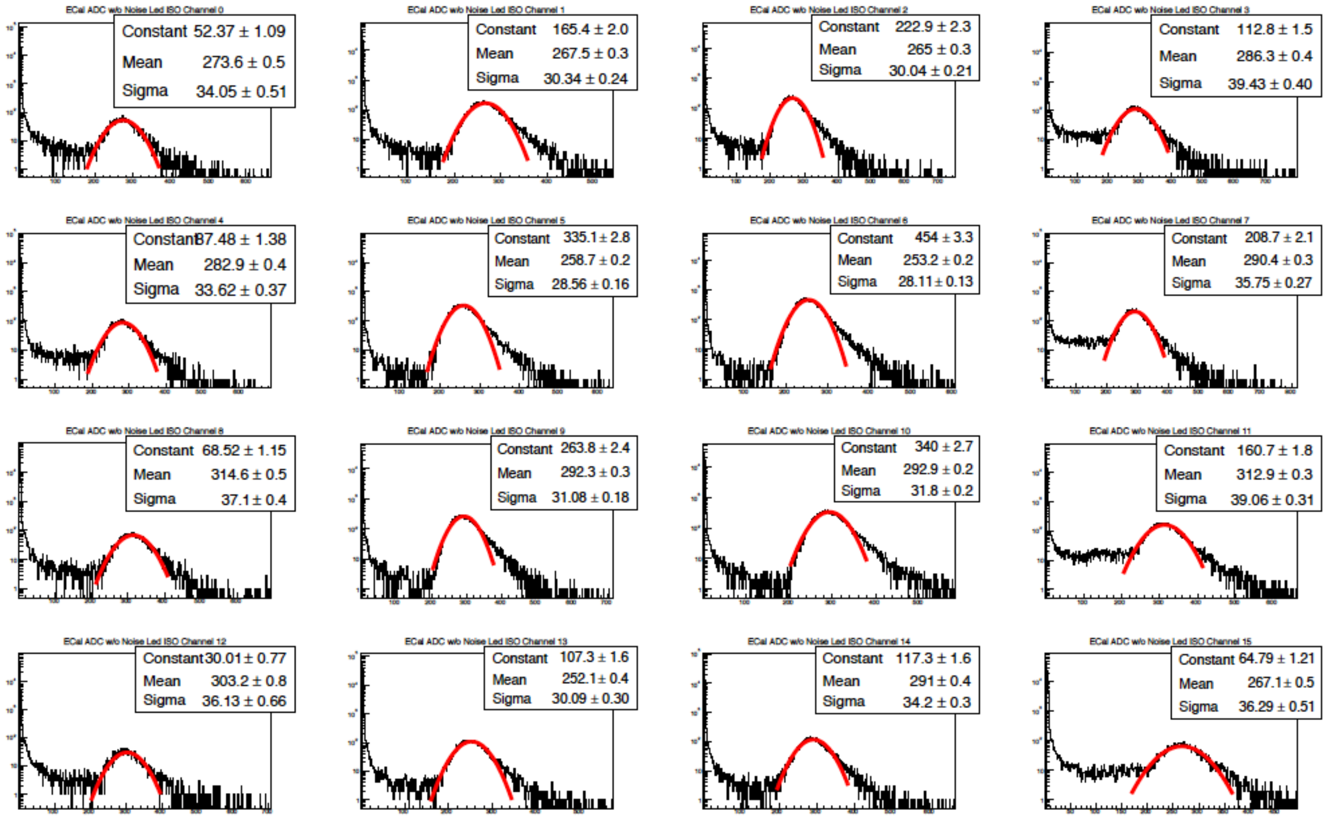

Figure -2. ECal Isoated Muons Spectra.

Uniformity of response of ECal depends on many factors, such as spread in parameters of optical components (scintillation tiles, WLS fibers, light guide mixer), quality of assembly (gluing of light guides to WLS bundles, gluing of SiPM boards to light guides), accuracy of setting of bias voltages (calibration of FEEs) and pre-selection of SiPMs (calibration of SiPM assembly boards).

Calibration of EMcal prototype with muons shows that uniformity of EMcal response is close to 7% (mean 281.5, rms 19.23), which is quite good. MIP calibration of EMcal with minbias events at STAR can be done in few hours. It can probably be done during low energy beam scan in Run 21, prior to 500 GeV pp running. With the spread of response seen in the FNAL Test Beam it is likely we can simply drop requirements to do pre-calibration of ECal using cosmic muons.

Setting of bias voltage on SiPM carrying boards with accuracy +- 25mV is also sufficient. We define this as a requirement for production QA, i.e. calibration of FEEs, and calibration of SiPM carrying boards should allow setting of bias withing +- 25mV.

Gain for ECal FEEs (with bias of SiPMs set at HPK value) is OK for running at STAR in 2021 and relying on MIP calibration from data. But gain is insufficient for 'vertical' muon calibration (vertical muons gives about 40MeV eq/250MeVeq = 0.16 to horizontal, or MPV amplitude of the signal for vertical muons will be close to 30 x 0.16 = 4.8 mV).

To use vertical muons for calibration before we see any beam at RHIC, we need to increase gain at ECal FEEs by factor of 4.

More importantly we will need to operate SiPMs at about 2 V over-voltage at STAR, compare to 4 volt over-voltage during test run at FNAL to decrease effects of neutron radiation damages for SiPMs at STAR. This will decrease gain on SiPMs by about factor of five, which had to be compensated by increasing gain of preamp. Increasing gain of preamp factor of four is sufficient. Table 1, summarizes gain setting discussion.

ECal FEE Gain	SiPM Gain	MIP (250 MeV) Signal Amplitude Peak	120 GeV Signal Amplitude Peak	MIP Vertical (40 MeV)	FEE Attenuator RHIC 2021 DEP -4V Range
x 1 (FNAL)	2.3×10^5	~30 mV	~14.4V	~5 mV	0.3
x 4 (STAR)	4.6×10^4	~24 mV	~11.5V	~5 mV	0.35

Table 1. Amplitudes of signals of interest in ECAl and settings for FEEs.

Isolated 'MIP's were selected in central tower(s) of ECal for all beam energies.

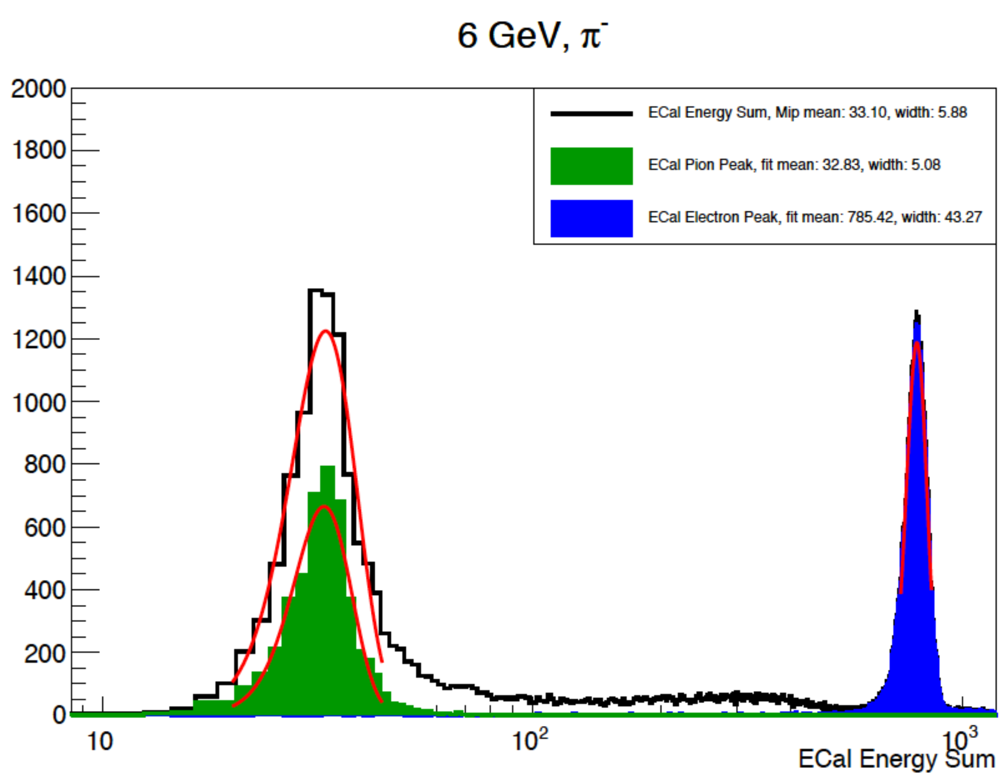

Figure 3. Absolute Calibration of ECal using MIPs.

Isolated MIPs (pions which pass ECal without nuclear interaction) deposit about 250 MeV equivalent energy as shown in Figure 3. The peak position for isolated MIPs and isolated muons (shown in green) is the same.

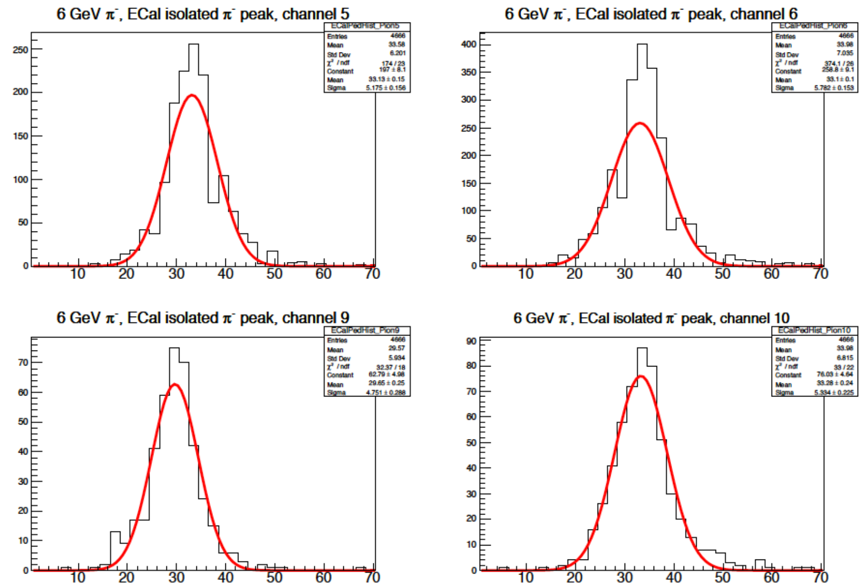

Figure 4. Isolated MIPs in ECal

Isolated MIPs in four central towers of ECal for 6 GeV mixed beam at FTBF.

We do not see relativistic rise in FTBF energy range as shown in Figure 4.

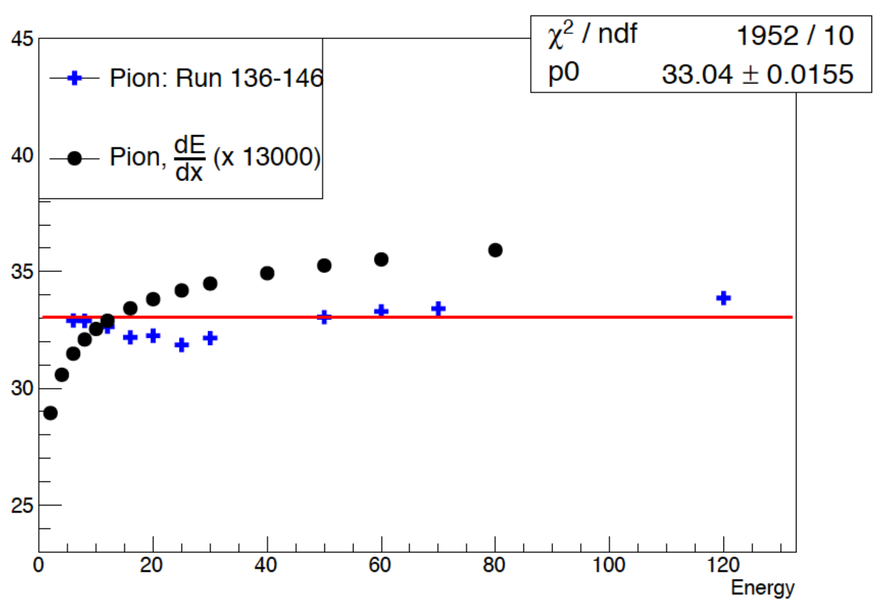

Figure 5. MIP in the ECal vs beam energy.

Calibration of HCal.

Calibration of HCal has to be performed with muons both at FTBF and in STAR. According to Ting's PYTHIA simulations we will see about 4.5k muons in the FCS acceptance from 10M minbias events. Calibration of HCAL was done similar to ECal calibration using FTBF muon beam.

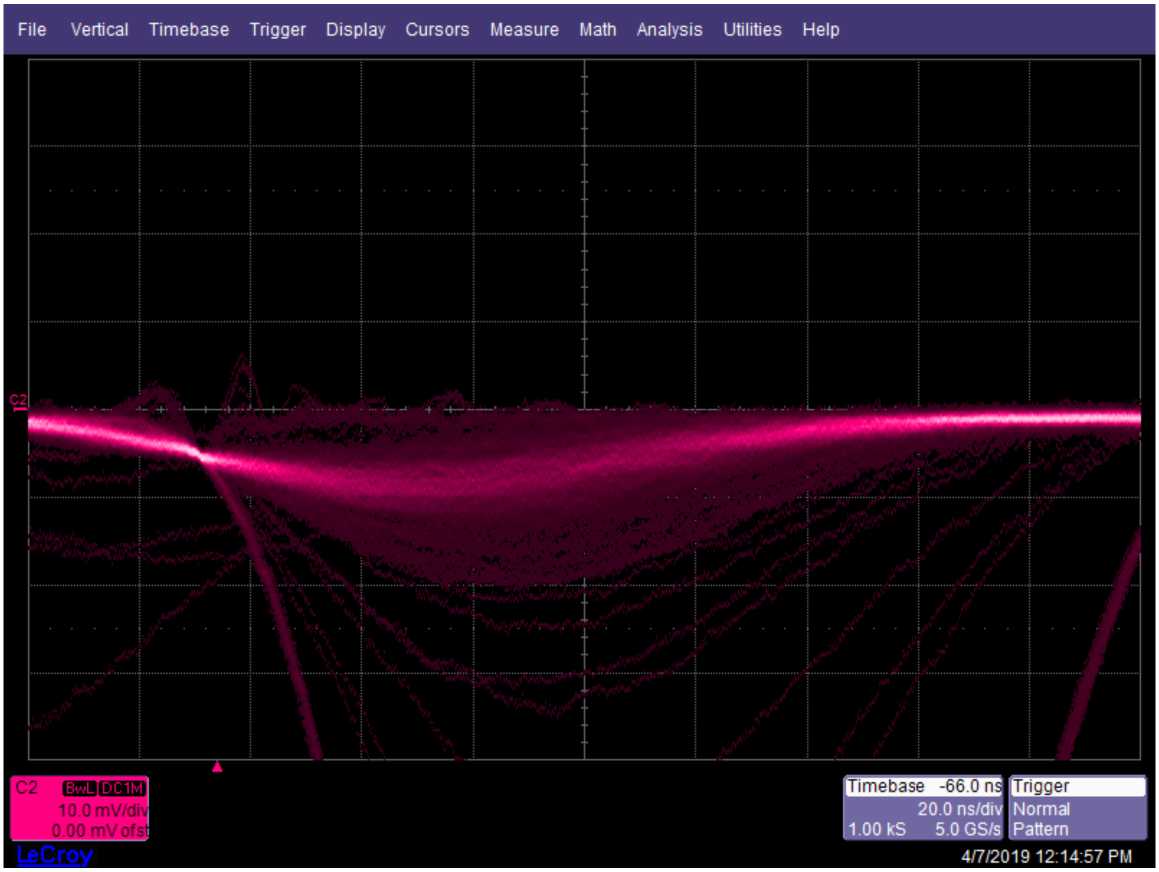

Figure -6. Oscilloscope traces of muon signals in HCal

Figure 6 shows oscilloscope traces of HCAL signals from muons. The amplitude of MPV for muons is about 8 mV.

A simple Gaussian fit of muon peak used to derive calibration constants for HCal (muon data set taken at most sensitive range of CAMAC CMC080 ADCs, 0.025pC per ADC count).

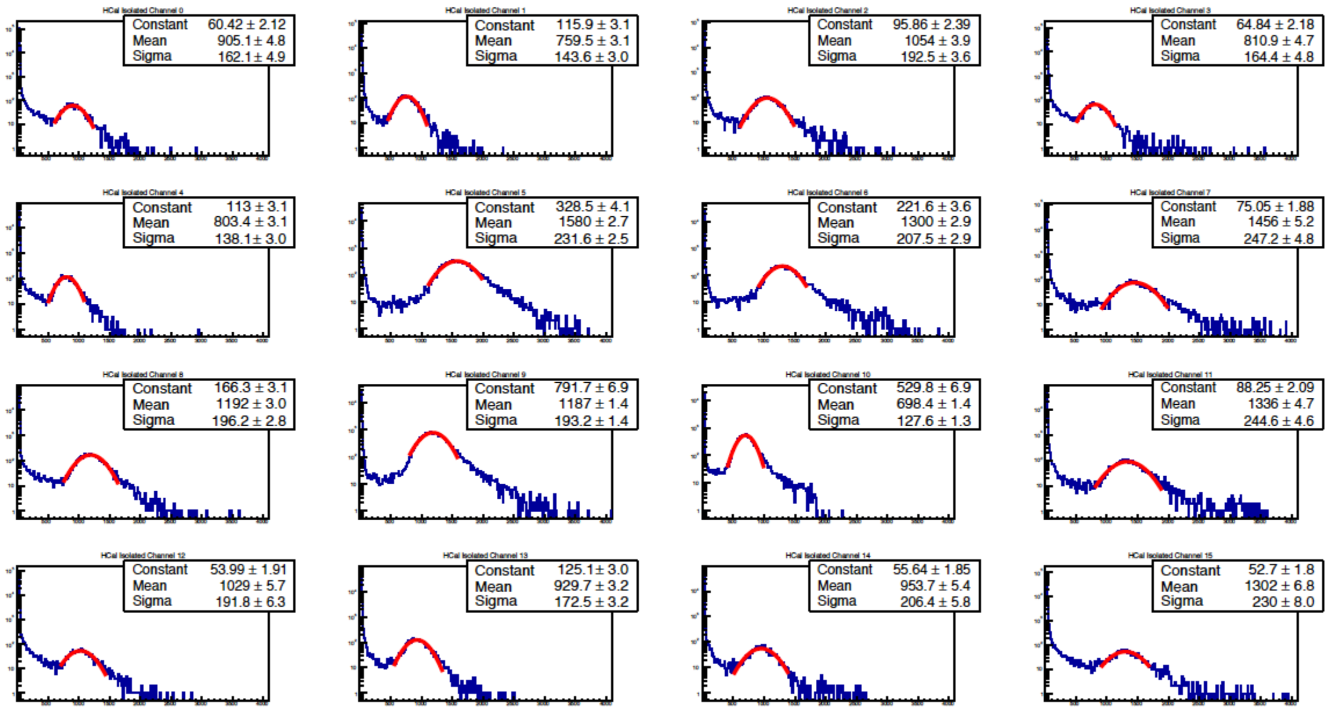

Figure -7. Isolated muons in HCal towers.

Figure 7 shows spectra of isolated muons for HCAL towers. Simple gaussin fit of muon peak gives same peak position compare to more complicated fitting procedure (exponential + Gauss + Gauss) as was checked later.

Uniformity of response of HCAL depends on same factors mentioned earlier for ECAL case. In case of HCAL, uniformity is close to 20% (mean 1048, rms 228) as shown in Figure 8.

The spread of light yield of HCal WLS/SiPM board assemblies was measured in the lab at UCLA prior to the test run. Each WLS/SiPM assembly (after SiPM board was glued to WLS bar) was illuminated by 405 nm blue laser in the middle (transversely and longitudinally) of the WLS bar. White diffusive reflector surrounded WLS bar. Current from SiPMs measured with picoammeter. There is very good correlation between muon peak position and current measured in the lab as shown in figure 9.

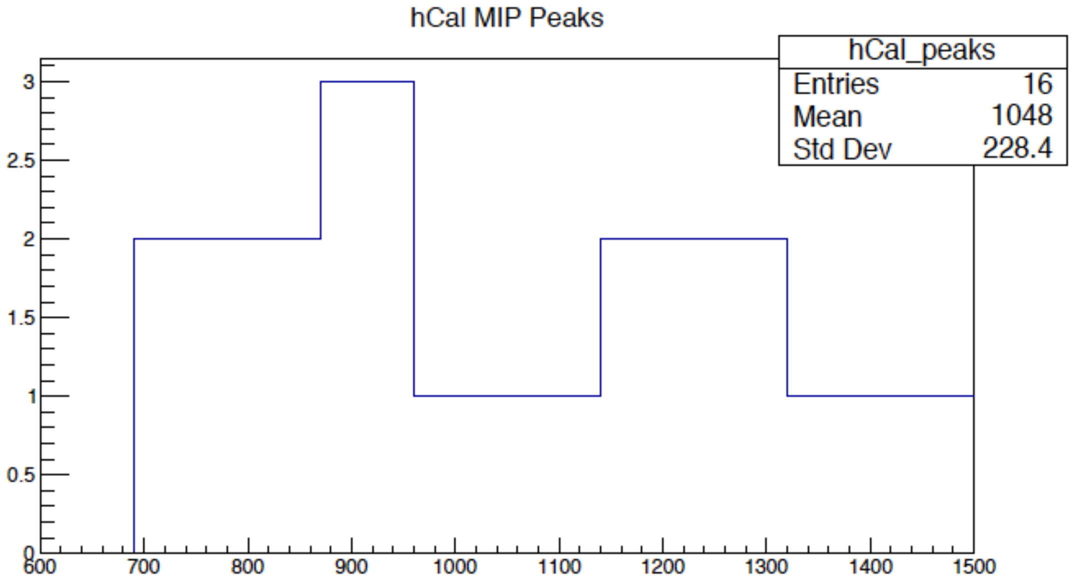

Figure 8. Position of muon peak in HCal towers.

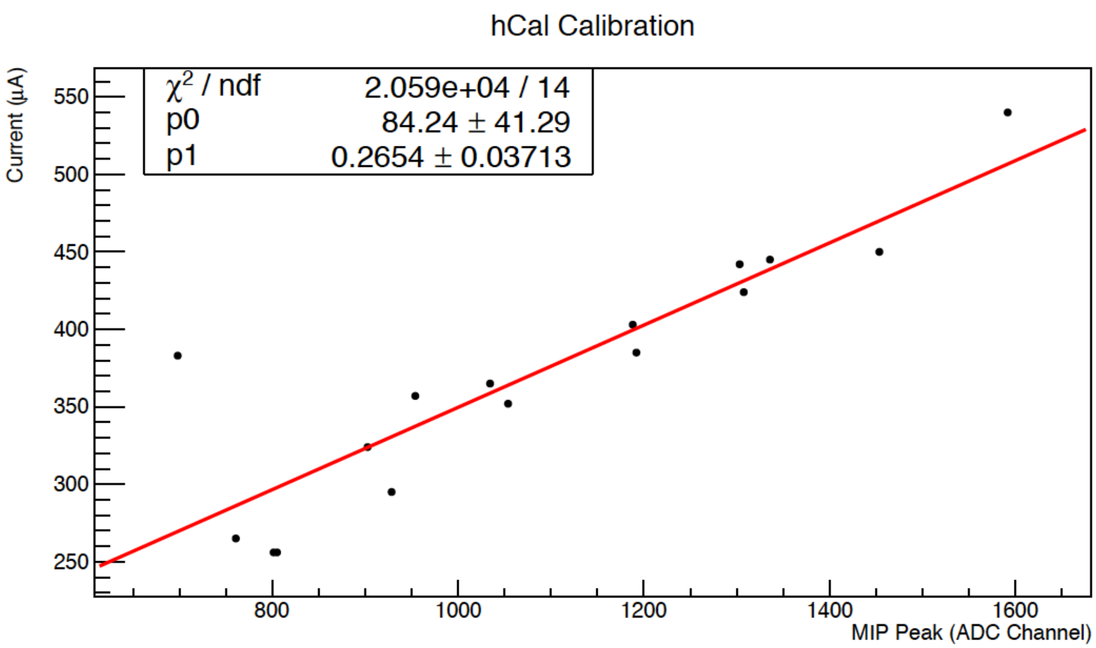

Figure 9. Correlation between muon peak position and LY measured in the lab.

A very simple QA during production of HCAL WLS/SiPM board assemblies will allow equalizing HCal channels prior data taking.

A large spread in response of HCal towers was observed during test run 2014 as well. It is an indication that some variations in WLS bars responsible for such large variations of responses in Hcal towers. We need to discuss with EJ how to minimize such variations.

Similar to ECal, we want to operate SiPMs for HCal at reduced bias (3V over-voltage) to reduce effects of neutrons damages. This will require increasing gain on preamplifier by factor of 4.

HCAL FEE Gain	SiPM gain	Muons MPV Signal Peak	120 GeV
FNAL 2019	2.3 x 10^5	8 mV	610 mV
x4 for STAR 2021	1 x 10^5	16 mV	1200 mV

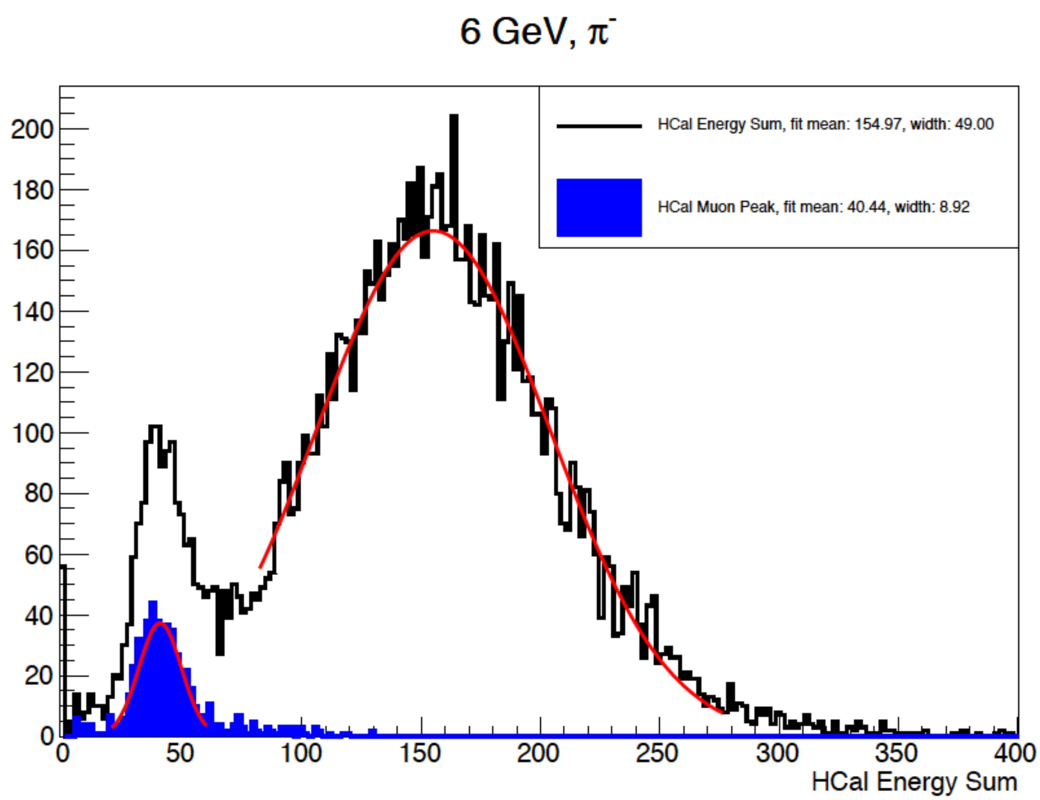

Figure 10. Absolute calibration of HCal with muons.

Figure 10 shows relation between isolated muon peak position and energy deposited in HCal by 6 GeV pions. In this analysis it was required that ECal energy deposition should be MIP like, i.e. almost all energy of pions were deposited in HCal cells. Isolated muon deposit same energy as 1.566 GeV pion in HCal. (Data taken at low resolution scale 1.5 pC per count)

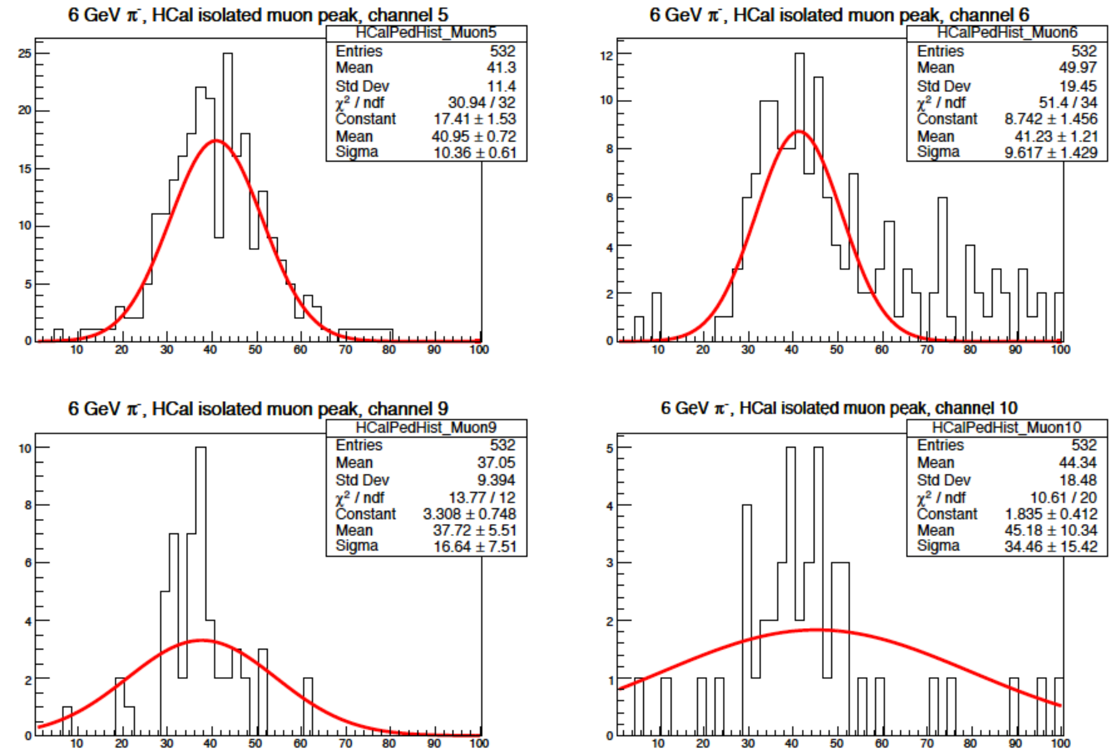

Figure 11 Isolated muon in HCal for 6 GeV pion beam.

Position of isolated muon peak in HCal tower(s) vs energy shown in Figure 11. Similar to EMcal we do not see changes in peak position with increased energy of the beam as shown in Figure 12.

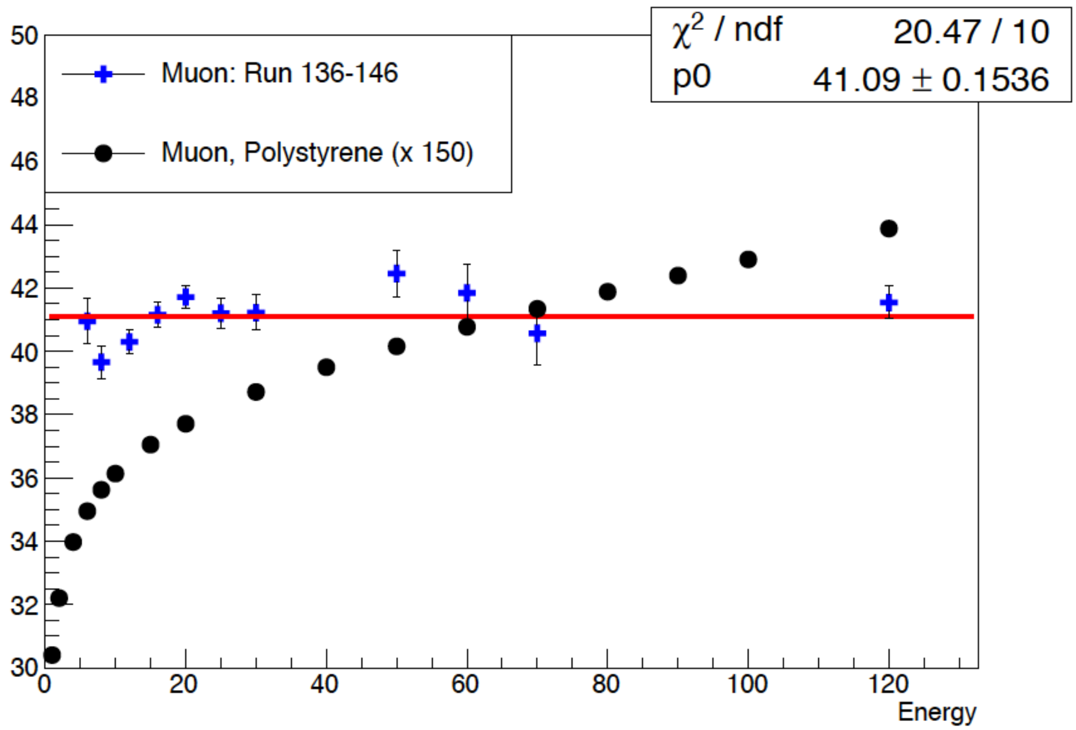

Figure 12. Position of the peak of isolated muons in HCal vs beam energy.

EMcal Response to Electrons.

ECal analysis. Identification of electrons performed with Inner Cherenkov PMT signal (threshold Cherenkov counter). Impact point at EMcal face defined by trigger counter, 4 cm x 4 cm. Sc. hodoscope information was not used in any analysis. Figure 13 shows typical amplitude spectra for electrons (12 GeV). Green histogram shows sum of all 16 EMcal channels prior applying "MIP" calibration. Blue represents same sum after calibration. Red histogram shows summed calibrated channels for electrons selected with Cherenkov counter.

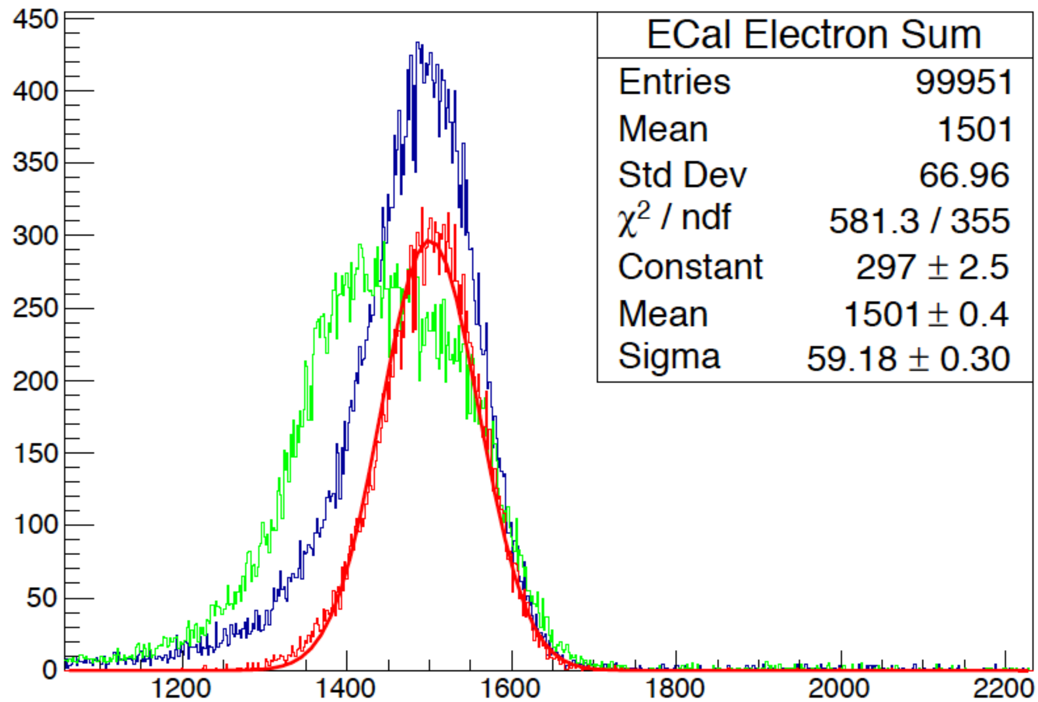

Figure 13 Response of EMcal to 12 GeV electrons.

Linearity. Fit range was restricted to lower energy points, due to relatively short EMcal length we expect some leakage from the back side.

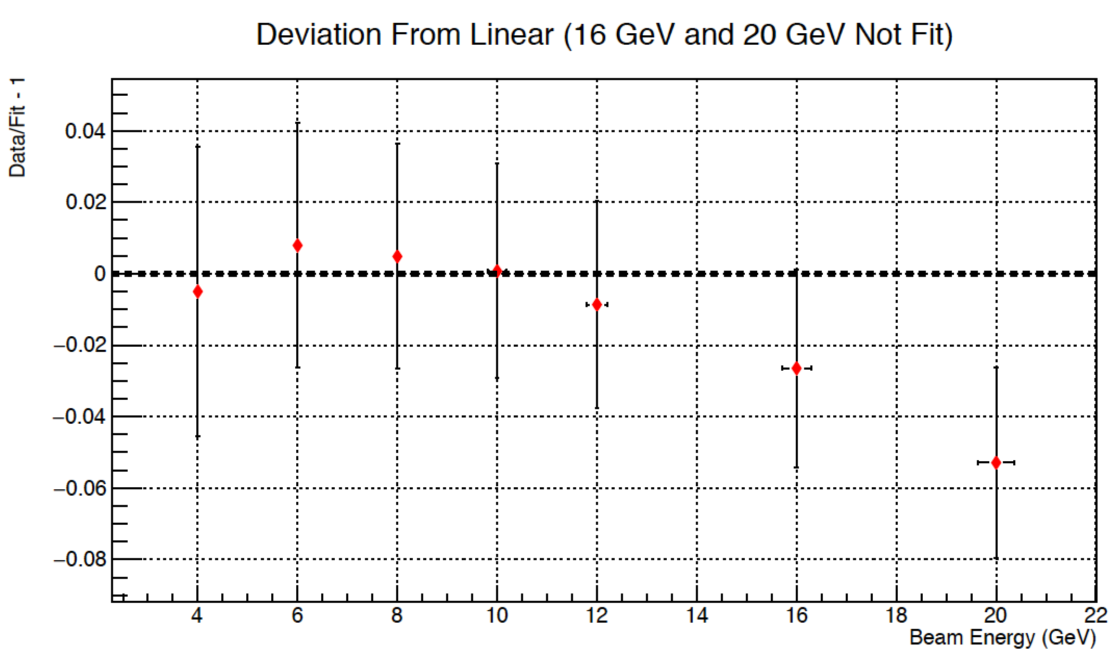

Figure 14. Linearity of EMcal.

In previous test runs at FTBF we have seen deviation from linearity at higher beam momentum for different type of calorimeters, which depends on beam line parameters setting (like collimators) and is not well reproducible from year to year.

For reference deviation from linearity shown for different calorimeters tested in 2016 in Figure 15.

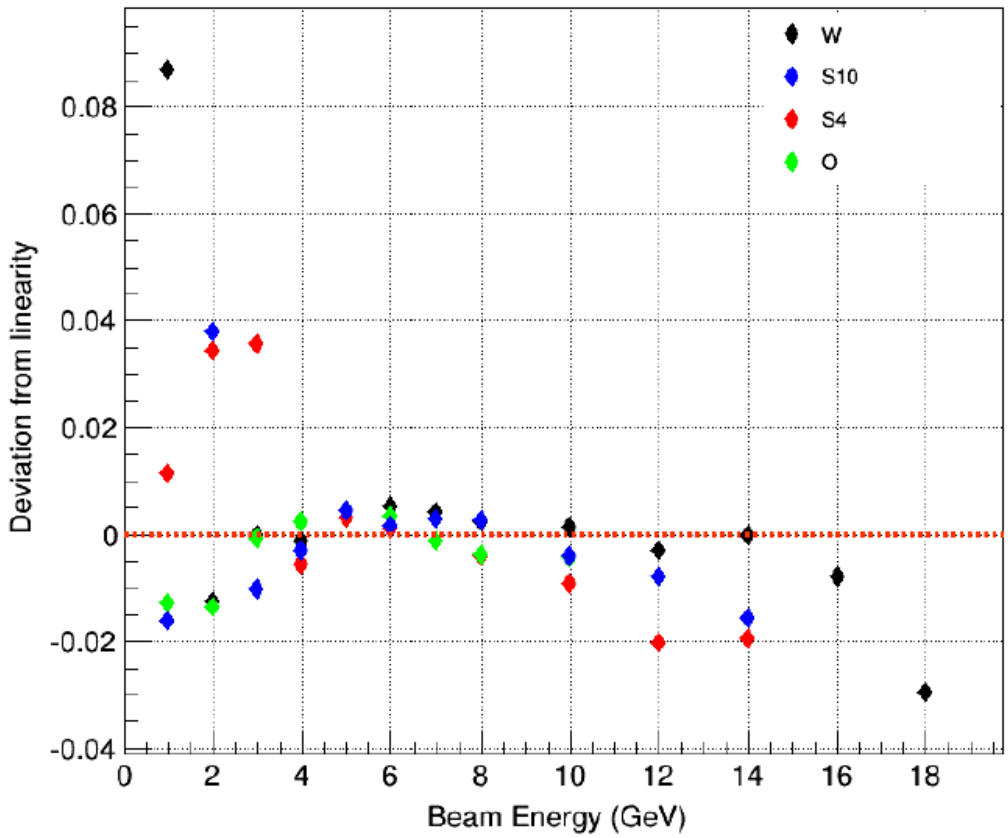

Figure 15. Deviation from linearity for different EMcals tested in 2016.

We need to model EMcal response to electrons with GEANT4 and also get FEE calibrated in terms of single pixel response, to be sure EMcal linearity is not limited by finite number of pixels. (Indication it is not as can be seen in correlation plots ECal vs HCal for 120 GeV proton beam).

Energy resolution for EMcal.

Assumption, beam momentum spread is flat 1.8% for all energies. (FTBF site quote 2%, but we used 1.8% based on our own estimates in 2016). Energy resolution for EMcal is shown in Figure 16. Energy deposition in all 16 towers was summed to determine energy resolution.

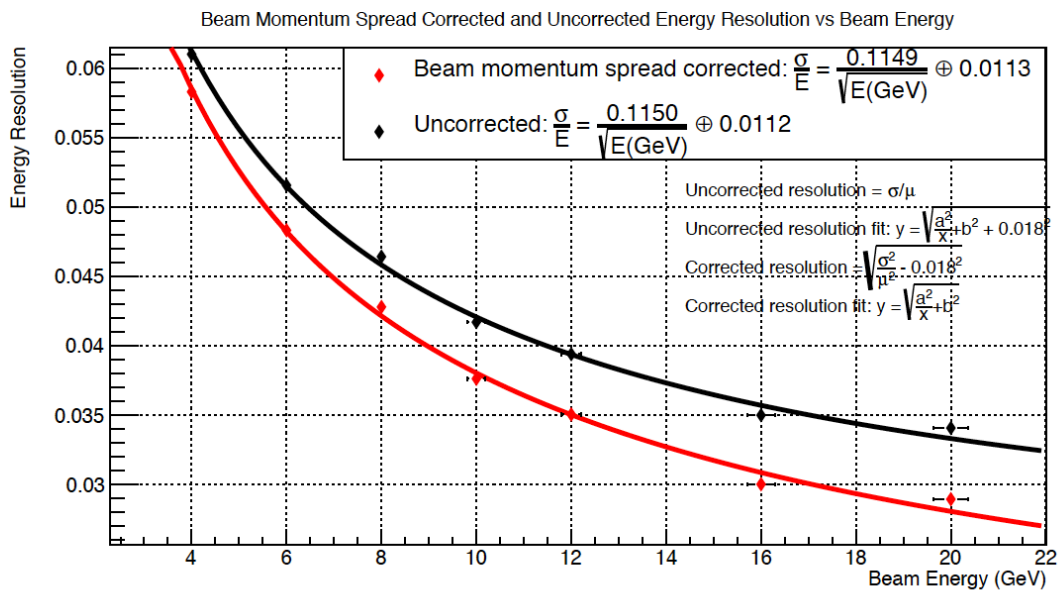

Figure 16. Energy resolution for EMcal, raw and beam momentum spread corrected.

In 2016 test run we tested a single PHENIX block readout by a single PMT (light from four towers was collected by a single PMT). For that block stochastic term was ~8.8% and constant term 2.7%. Because beam momentum spread is not well known and it has large effect for higher energies (16 GeV and 20 GeV) we may somewhat underestimating constant term for 2019 data.

HCal, Linearity and energy resolution.

ECal and HCal has different responses to electrons and hadrons. For each energy point we calculated optimal weight for ECal to sum its energy with HCal energy to get best result in reconstructing energy of incoming hadron. Increase in optimal weight for ECal for low energy hadrons shown in Figure 17 seemingly related to transverse leakages from ECal, probably due to position of shower max for hadronic shower, which is gradually shifting with energy deeper in the apparatus. This is seen for both experimental and GEANT4 data. For STAR configuration, i.e. no transverse leakages ECal weight is energy independent. Figure 18 shows correlations between energy depositions in HCal and ECal for 30 GeV pions seen in the FNAL test run.

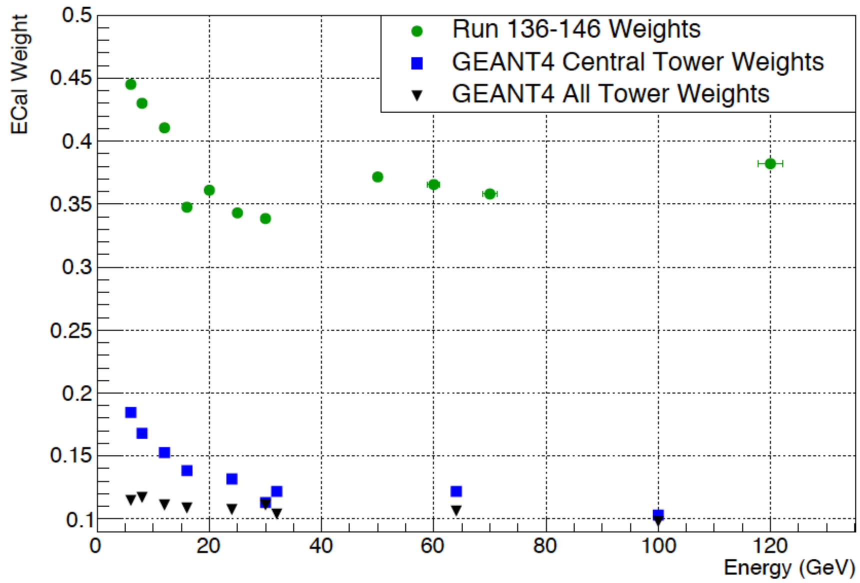

Figure 17. Optimal weighting of ECal vs energy.

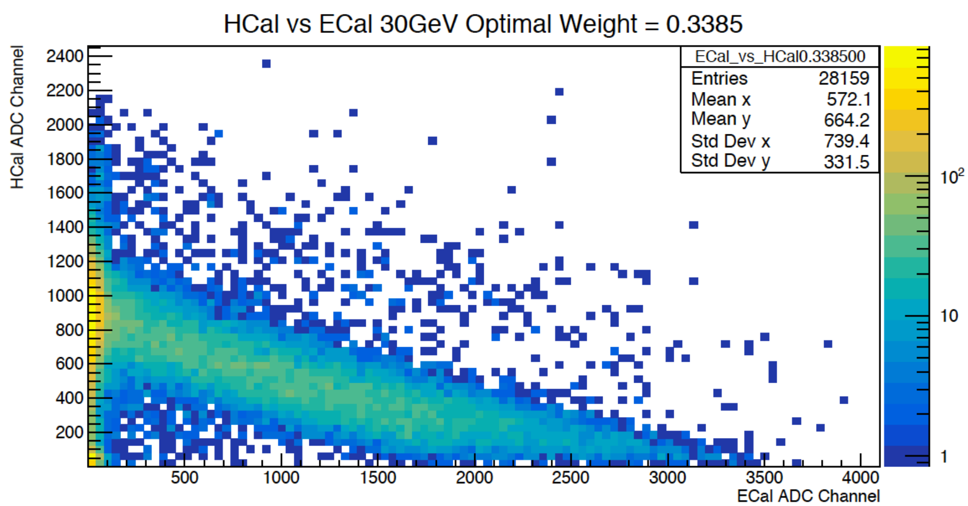

Figure 18. Correlations between energy deposited in HCal and ECal for 30 GeV pions.

Response of FCS prototype to hadrons was measured with two different light collection schemes for HCal (Runs 76-85 – tapered WLS bar with SiPMs, Runs 136-146 WLS Bar with filter (2014 version) readout with PMTs). In both cases linearity of FCS is good.

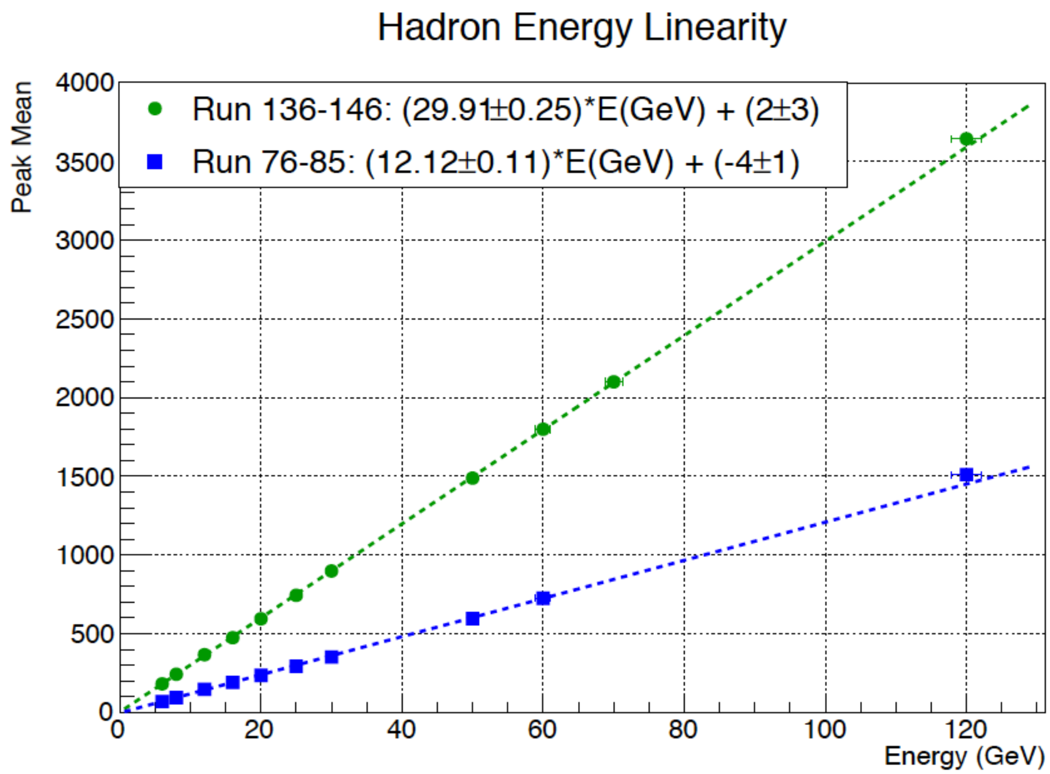

Figure 19. Liearity of FCS for hadrons.

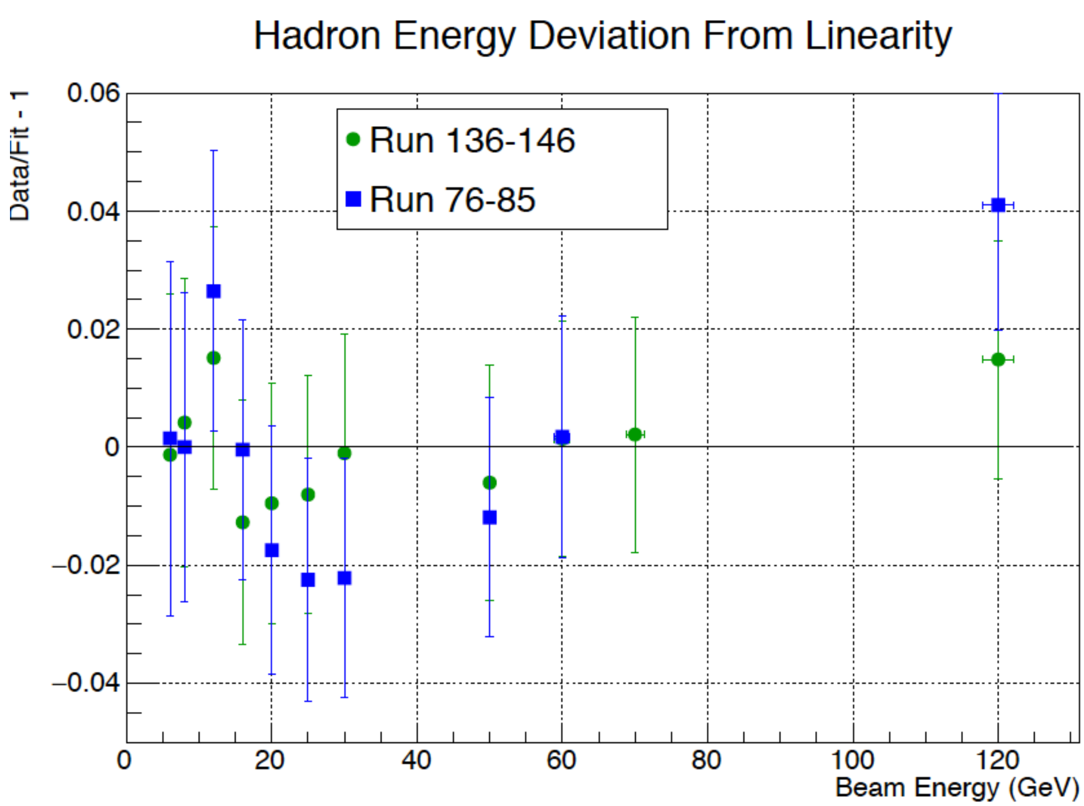

Figure 20. FCS , Hadrons. Deviation from linearity vs energy.

FCS prototype is small to contain hadronic shower. Transverse leakages significantly degrade energy resolution of FCS prototype. GEANT4 simulations for configuration of the FNAL test run prototype and STAR FCS (no transverse leakages) shown in in Figure 21. These simulations used to estimate performance of STAR FCS using FNAL test run data, i.e. scaling factor between blue and green points.

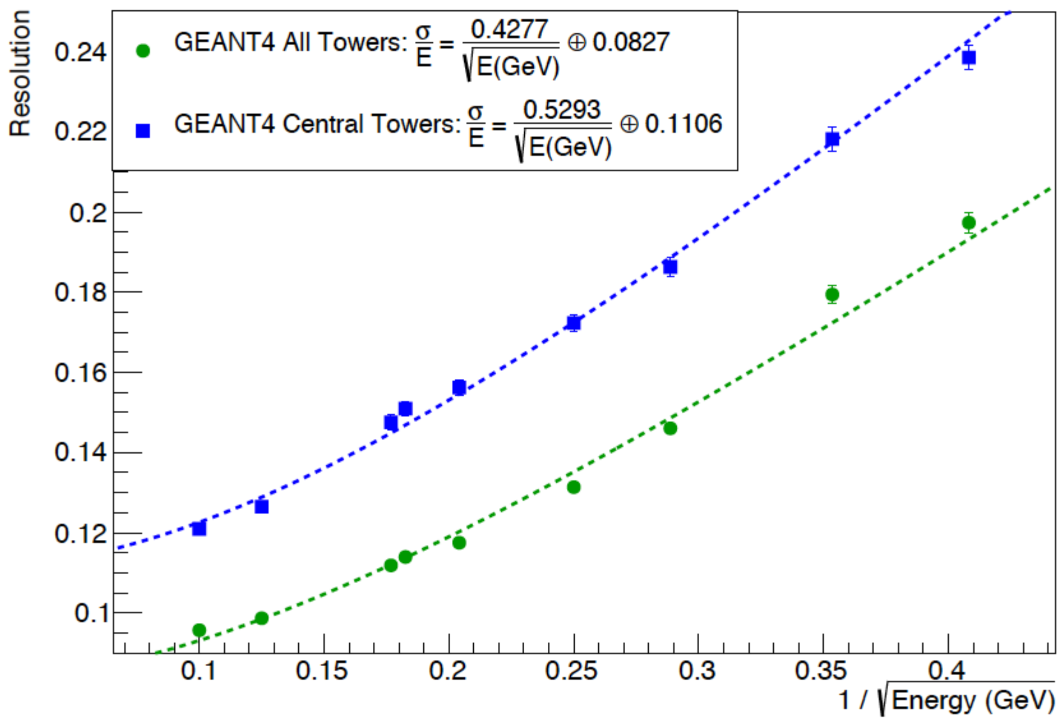

Figure 21. GEANT4 predictions for FNAL test run configuration and STAR.

Energy resolution of FCS was measured with two different light collection system for HCal. A tapered WLS bars and SiPM sensors have been used for energy scan runs 76-85. A WLS bars with filters (2014 configuration) with PMTs used for scans 136-146. Tapered WLS bars introduced transverse non-uniformities in light collection, which degrades energy resolution. This need to be corrected for final production of WLS bars for HCal. Typical amplitude spectra of FCS for 30 GeV pions shown in Figure 22. Comparison of performance of FCS with two different schemes of light collection is shown in Figure 23. Comparison of experimental results and GEANT4 simulations shown in Figure 24.

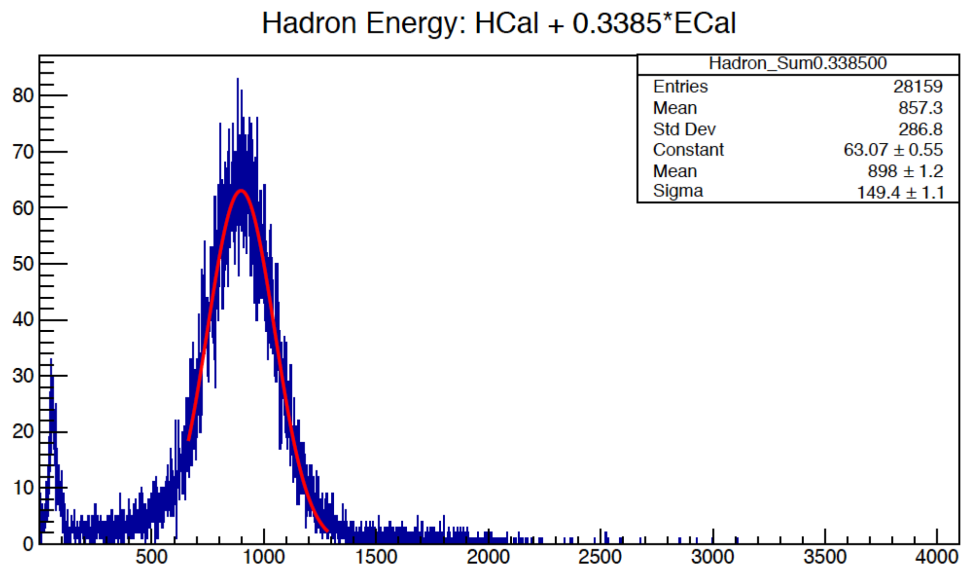

Figure 22. FCS 30 GeV pions.

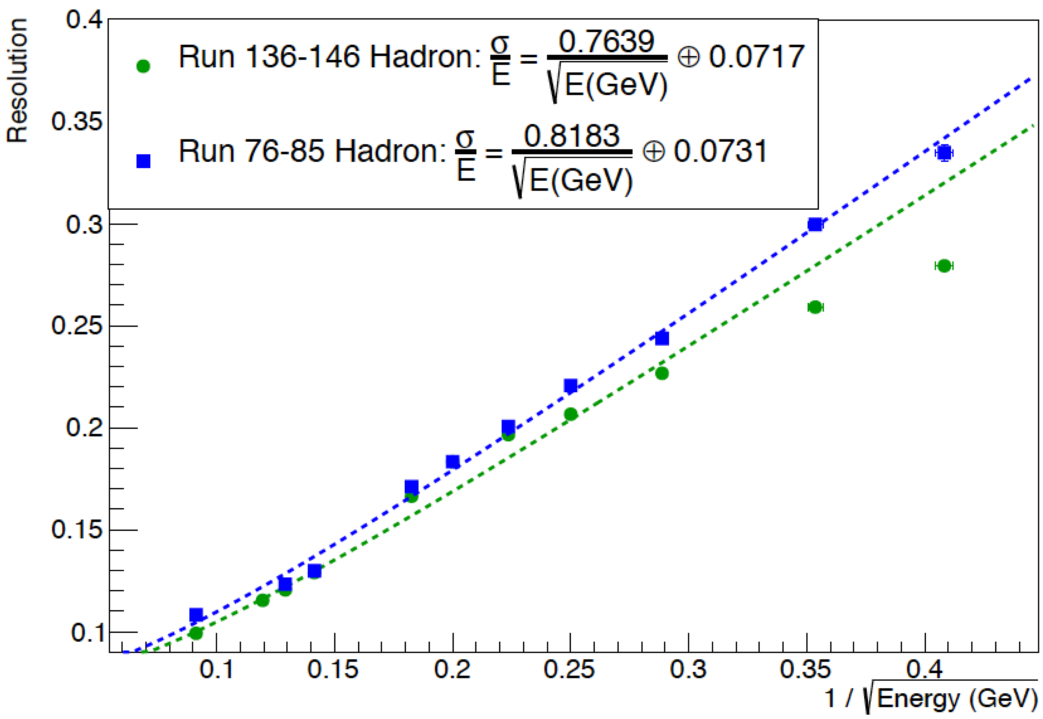

Figure 23. Comarison of energy resolution of FCS prototypes with different light collection schemes for HCAl.

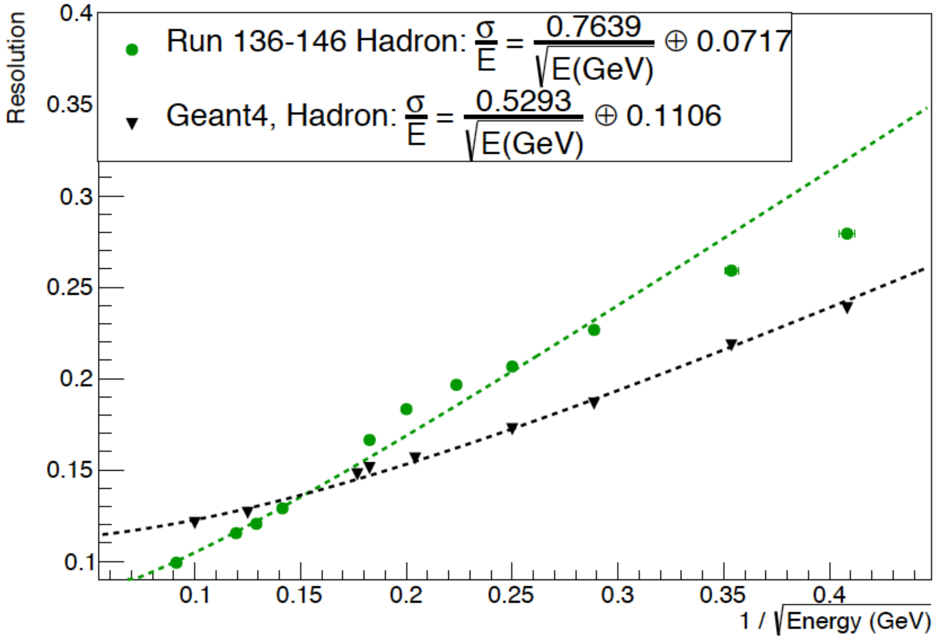

Figure 24. Comparison of experimental and GEANT4 predicted energy resolution

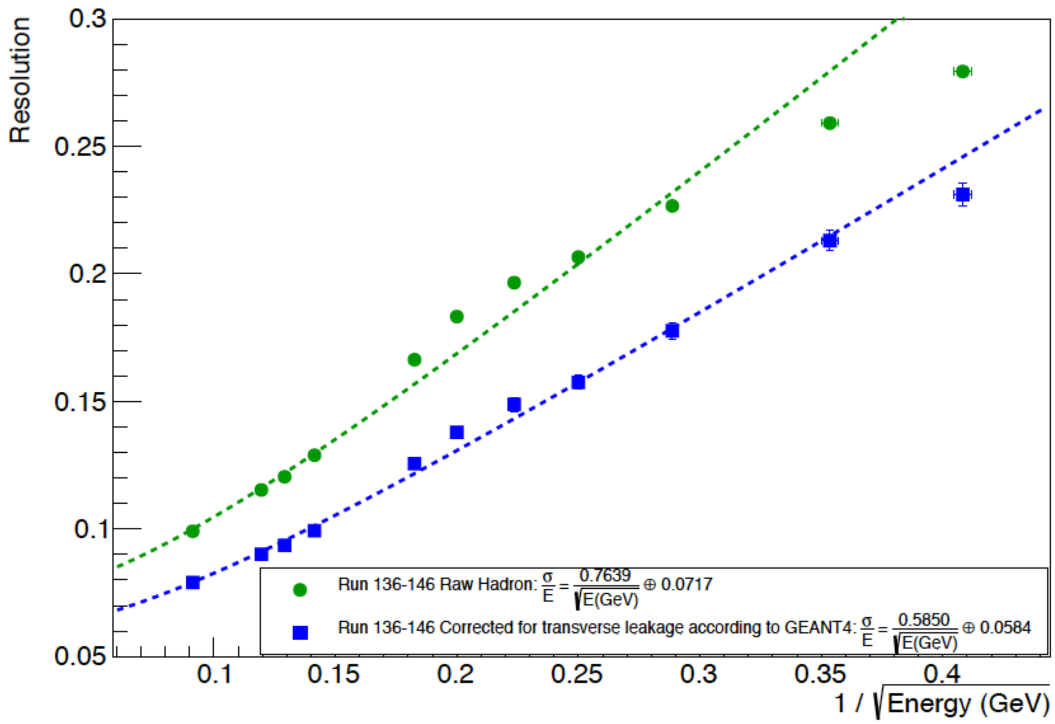

Figure 25. Raw and corrected for transverse leakages energy resolution of FCS prototype.

Energy resolution of FCS prototype corrected for transverse lekages according to GEANT4 MC shown in Figure 25.

Energy resolution for hadrons of FCS prototype is somewhat worse than expectation. Measurements with two different light collection schemes shows that transverse non-uniformities in light collection with tapered WLS bars responsible for degradation in performance. With light collection scheme providing uniform light collection (WLS/Filter 2014 version) energy resolution of FCS is close to required.

Discussion and Conclusions:

- Performance of FCS EMcal prototype is close to required for STAR forward upgrade.
- Gain on FEEs need to be increased by factor of four for final production.
- Simple QA followed during construction of prototype sufficient to have detector uniform enough for day one data taking at RHIC.
- There is no need for cosmic muon pre-calibration of ECal prior data taking.
- Current FEEs need to be calibrated in terms of single pixel response.
- Need to perform GEANT4 simulation for muons.
- Performance of FCS HCal prototype is close to required with 2014 light collection scheme.
- A single tapered WLS plate to collect light from Scintillation tiles introduced significant variations in light collection efficiency, degrading energy resolution.
- FEE gain need to be increased same factor of four as for EMcal.
- Simple lab QA used during construction of HCal prototype sufficient to have detector uniform enough for data taking.
- Need to optimize light collection by reading out Scintillation tile from both sides. This requires having two edges of scintillation tiles be polished.
- Need to discuss with EJ QA steps during production of WLS bars, i.e. large spread in light collection efficiency observed in test runs 14 and 19.
- There were no mechanical issues during assembly/dis-assembly of HCAL at FNAL.
- A simplified version of LED monitoring system for HCal worked better than initially proposed (leaking bar system).
- Mechanical integration of FEEs for both HCal and EMcal is good as it is.