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

XXV DAE-BRNS High Energy Physics Symposium

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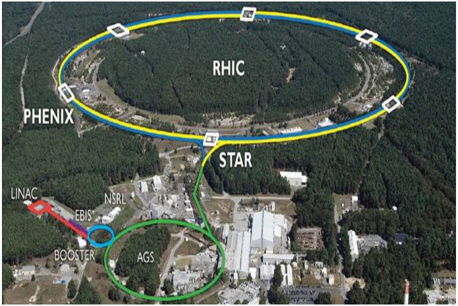
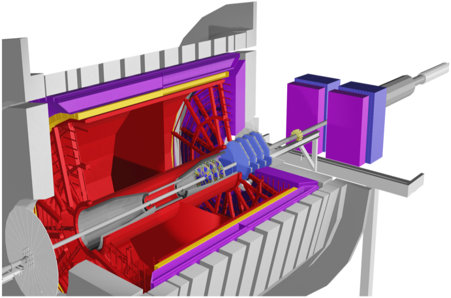
# Contents

# The STAR Detector at BNL



- Relativistic Heavy Ion Collider, located in Brookhaven National Laboratory
- 2.4 mile circumference, two-lane "racetrack"
- World's only machine capable of colliding beams of polarized protons to investigate the 'missing' spin of the proton

- The Solenoidal Tracker at RHIC, located at 6 o'clock at the RHIC Ring
- Several types of detectors, with advanced DAQ system detects final state particles
- Most recent upgrade at Forward Rapidity ($2.5 < \eta < 4$) for better measurements of the proton spin

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# Physics Motivation of the Forward Upgrade at 2.5 $<\eta<$4

## Cold QCD

- p+p 510 GeV (2022) ; p+p and p+Au 200 Gev(2024)
- Sivers asymmetries for hadrons, (tagged) jets and dijets
- Tests of Saturation predictions through di-hadrons, $\gamma$ jets

## Hot QCD

- Au+Au 200 GeV (2023 and 2025)
- Temperature Dependence of viscosity through flow harmonics upto $\eta \approx 4$
- Longitudinal Decorrelation upto $\eta \approx 4$

## Observables

- Charged and Neutral Hadrons
- Inclusive jets and di-jets
- Lambda Polarization
- Mid-forward and forward-forward rapidity correlations

# Contents

# The Forward Upgrade - Tracking and Calorimetry

**Tracking - vertex detection, track discrimination, particle identification, pT measurement**

Forward Silicon Tracker (FST)
Small Strip Thin Gas Chamber (sTGC)

**Calorimetry- Energy Measurement of $\pi^0$, $\gamma$, $e^-$**

Forward Calorimeter System (FCS)
- Electromagnetic Calorimeter (ECal)
- Hadronic Calorimeter (HCal)

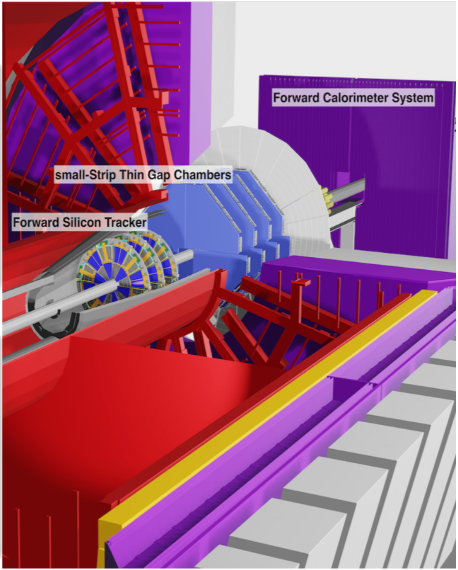


Fig: Calorimeters and Trackers in the Forward Upgrade at STAR

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# Forward Calorimeter System at STAR $2.5 < \eta < 4$

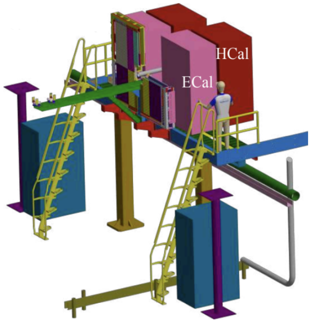



Fig1. FCS Physical Layout

Fig2a. HCal N fully stacked

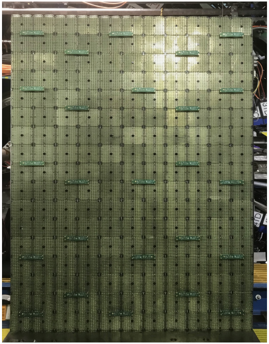


Fig2b. ECal S LED Panels installed

- Refurbished PHENIX Shashlyk Pb/Sc EMCal, followed by Fe/Sc sampling HCal
- **1496** EMCal towers and **520** HCal towers - North/South symmetric modules
- Each module of EMCal has **34 rows** and **22 columns**
- Each module of HCal has **20 rows** and **13 columns**
- Transverse area $\approx$ **1.2 m W x 2 m H**

# ECal Scope - Refurbished PHENIX EM Module

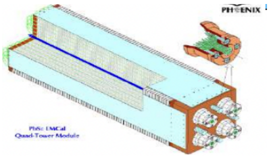
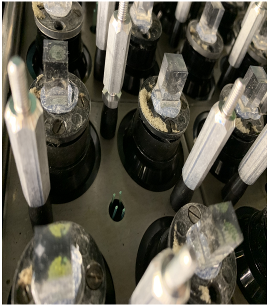



Fig3: 1 Ecal supersector - 2x2 towers

## EM Module

- 4 independent towers
- Each tower 5.52 x 5.52 x 33 $cm^3$
- Penetrating WLS fibers for light collection

## Modifications



Step A: Gluing four light guides/ mixers at the end of WLS bundles

Step B: Gluing SiPM currying boards to LG **(4 SiPM/tower, 5984 total)**

Step C: Attaching FEE (Pogo Pins, utilizing existing holes in EM Module)

# HCal RD and Design - Lego Style Concept

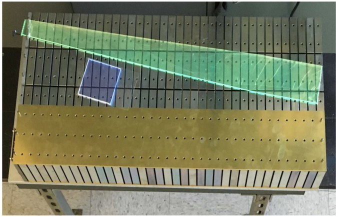


Fig: Absorber, Scintillator, WLS Bars, Interlink Plates

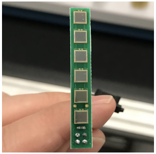
## HCal module - simple parts, no interdependencies

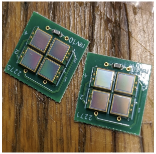
- Absorber 20 mm steel, Scintillator 3 mm
- Tower size 10 x 10 x 85 $cm^3$
- Number of layers - 36
- Light collection - tapered WLS
- Number of **SiPMs - 6**

Fig : Stacking layers of absorbers with scintillators sandwiched (left), Installing WLS bars (middle), Installing LED (right)

# Silicon Photomultiplier - SiPM

SiPM - solid state photodetector consisting of arrays of integrated single photon avalance diodes, squares of size 15 $\mu$m - operating in reverse bias above the breakdown voltage ($V_{bd}$)





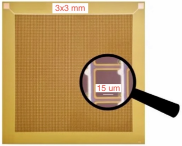



Fig: SiPM used in HCal (left),

SiPM used in ECal (middle),

SiPM structure (right)

## Pros

- High Photon Detection Efficiency (PDE)
- Mechanical and electrical robustness
- Low bias voltage
- Insensitive to magnetic fields

## Cons

- High Dark Current Rate (DCR)
- Loss in performance characteristics on exposure to high neutron radiation

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# Calibration : $\pi^0$ reconstruction for the ECal

## Steps for $\pi^0$ reconstruction:

- $\pi^0$s are reconstructed using 2 photon clusters i.e. a group of ECal towers fired from Electromagnetic Photon Shower
- Data Sample : 8.5 M Events from *pp* collisions at $\sqrt{s} = 510$ GeV

## Cluster Pair Selection :

- Each Cluster Energy $E_1$ ($E_2$) $>$1 GeV
- Energy Asymmetry $Z_{\gamma\gamma} = \frac{|E_1 - E_2|}{E_1 + E_2} < 0.7$
- For each event, only keep the pair with highest summed Energy ($E_1 + E_2$)

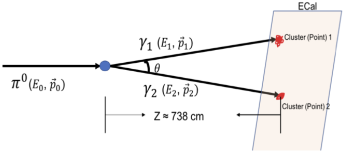



Fig: $\pi^0$ reconstruction from 2 photon clusters

Energy is calculated as
**E = Gain×Gain Corr.×ADC**

# Calibration : Monitoring the Radiation Damage

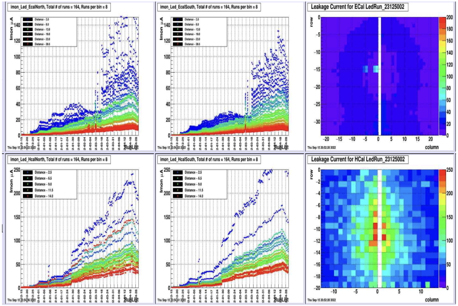



Fig: History Plots and 2D Plots of Leakage Currents for LED Runs

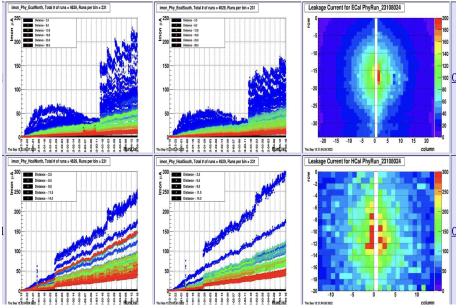



Fig: History Plots and 2D Plots of Leakage Currents for Physics Runs

- History Plots for every tower throughout the run period shows that Leakage Current increases drastically towards the end of the run
  (Red Points - Far from the Beam Pipe, Blue Points - Near the Beam Pipe)
- Normalised 2D Plots of the Calorimeters for a particular run show that Maximum Radiation Damage occurs at towers closer to the Beam Pipe

# Calibration: Estimating the Gain Correction Factor

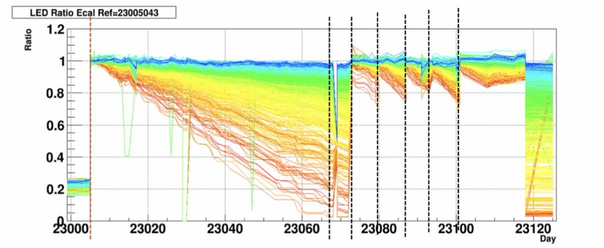



Fig: LED Ratio for all towers during RHIC Run 2022; Data has been divided into periods

- Gain loss due to Radiation Damage to FEE Boards can be observed through the LED system
- The attenuator and SiPM bias set voltage on FEE Boards was changed to adjust the LED readout between periods
- Ratio of LED readout between each LED test run and the reference test run in a period (dashed line) was calculated
- LED Ratio drops for each tower → Radiation Damage at the tower
- Higher LED Ratio drop Rate → more serious Radiation Damage

# ADC Values - Gaussian Integral vs. Time Bin Sum

- Signals from STAR are digitised by time integrating the voltage (ADC) of the signal over the trigger window i.e. the time between RHIC bunch crossings
- DEP boards digitize signal every ≈ 13.5 ns $\implies$ 1 Time Bin (Tb)
- 8 Tb in 1 RHIC bunch crossing ≈ 100 Tb of data for every channel in every event

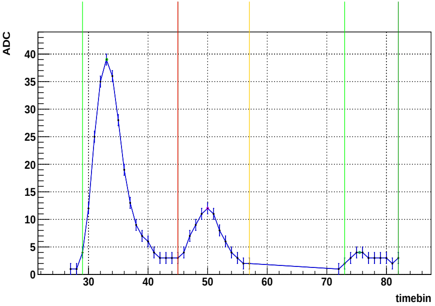



Fig: Detector Signal Waveform ; Triggered RHIC Crossing Peak at Tb = 50; peak start time peak end time

## Energy = gain × gain correction factor × ADC

Two methods to measure the ADC value :

**Gaussian Fit signal integral**

◦ Fit Signal to Gaussian (Fit shown in black)

◦ Amplitude of Gaussian ∼ integral of wavefcn.

**Summing over Time Bins (Sum8)**

◦ Sum over ADCs in 8 Tb of RHIC Bunch crossing

◦ Introduces a factor of ≈ 1.2 to the Gaussian Fit, very little difference

# ADC Values - Gaussian Integral vs. Time Bin Sum

## Gaussian Fit Signal - Challenges

- ◦ Time Consuming, Might identify noise as signal (fir single peak)
- ◦ Overlapping Signals → More Fit Parameters → More Computation time

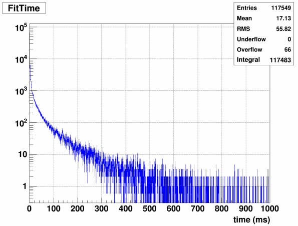



Fig: Time taken by Fit Method

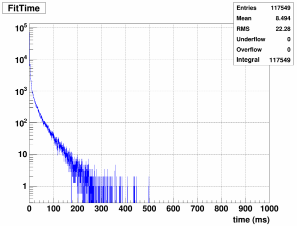



Fig: Time taken with new algorithm

## New Algorithm for reading ADCs

- ◦ Differentiates cases - Fitting Method or Summing Bins (Sum8) Method → optimization
- ◦ Accurate determination of peaks → less computation time
- ◦ Aid in fitting overlapping peaks → correct Energy determined

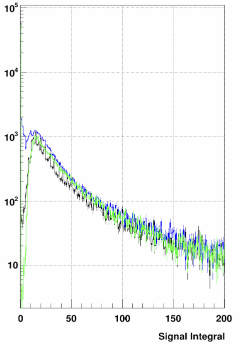



Fig: Energy Peaks Blue Curve sum8 Method Green Curve Fitting all peaks Black Curve Result with cuts

# Extracting Gain Correction Factor by Invariant Mass Peak

Our Goal is to develop the **Gain Correction Factor for each tower** that changes due to radiation damage. This is done iteratively as follows:

## Iterative Tower-by-Tower Gain Correction Factor Calculation

- Extract invariant mass peak for the invariant mass plot of each tower
- Corrected Gain Correction Factor for each tower:
  $G_{corr} = G_{org} \text{ X } \frac{\pi^0 \text{inv mass}}{\text{inv mass peak}}$
- Apply corrected gain correction values for another iteration of $\pi^0$ reconstruction
- After several iterations, most of the invariant mass peaks converge at $\pi^0$ invariant mass

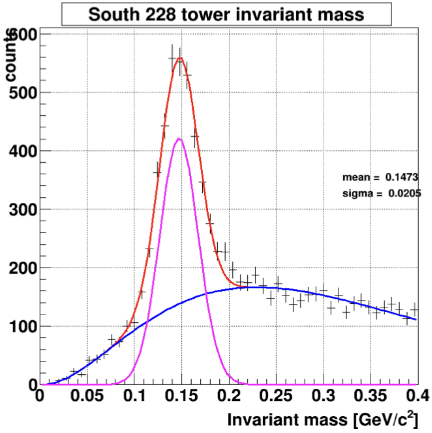



Fig: $\pi^0$ invariant mass plot for each tower - Gaussian Signal Fit , with Exponential Background Fit

# Iterative Invariant Mass Plot Results

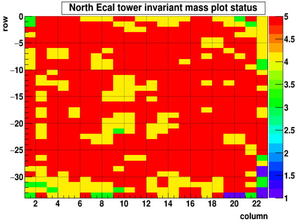



Fig: Invariant mass peak status plot before iterations

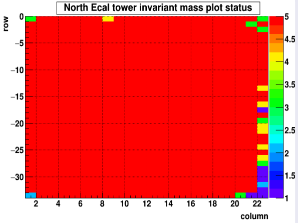



Fig: Invariant mass peak status plot after 2 iterations

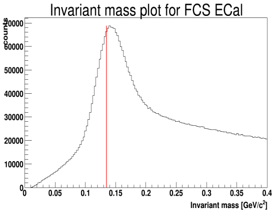



Fig: $\pi^0$ invariant mass plot for all towers before iterations

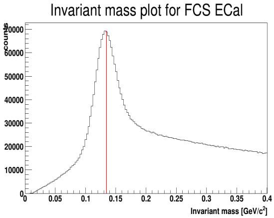



Fig: $\pi^0$ invariant mass plots for all towers after iterations

**Red color**: Invariant Mass Peak <10% difference of $\pi^0$ invariant mass

**Other colors** : Invariant Mass Peak is far from $\pi^0$ invariant mass and need iterations to fix

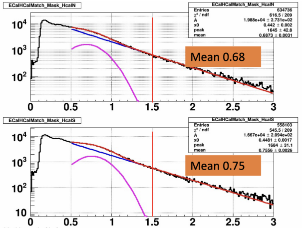
**Successful $\pi^0$ reconstruction for FCS ECal after 2 iterations**

The invariant mass plot after 2 iterations shows an obvious peak right at $\pi^0$ invariant mass and with smaller width

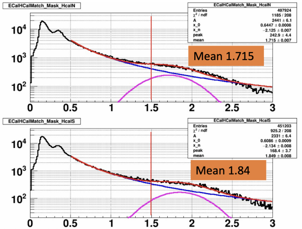
# Calibration : MIP peaks for HCal

## Similar iterative method followed for calibrating the HCal with MIPs

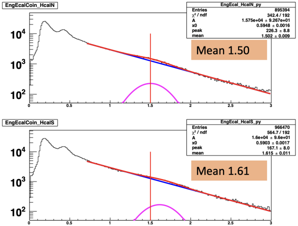
- $\approx$ 1 % of hadrons leave MIP (Minimum Ionizing Particles) at HCal
- MIP peaks in HCal observed in isolated 1-2 towers




**Period 1**
**Gain:** 0.0053Gev/ch $\times$ 1.3 (Initial Gain $\times$ Electronic Gain)
**MIP Peak:** $\sim$ 0.5 of expected, need to increase gain by a factor $\sim$ 2




**Period 2**
**Gain:** 0.0053Gev/ch $\times$ 1.3 (Initial Gain $\times$ Electronic Gain)
**MIP Peak:** Overshoot by a factor of $\sim$ 2.5




**Period 3**
**Gain:** 0.0053Gev/ch $\times$ 1.3 $\times$ 1.21 (Initial Gain $\times$ Electronic Gain $\times$ sum8 Fit)
**MIP Peak:** as expected

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# Current Status and Future Plans

## Current Status

- Software for continuous monitoring for Leakage Current is in place
- Radiation Damage caused by Leakage current varies from tower to tower
- Gain correction ratios have been developed for each tower to estimate such damage
- Iterative $\pi^0$ reconstruction has been successfully applied to calculate the Gain Correction for each tower
- Iterative MIP reconstruction for HCal also works for most of the HCal towers

## Future Plans

- Data has been divided into periods for whole of Run22
- Based on LED ratio drop rate of every tower, study the relation between LED ratio and gain correction for each period
- Use $\pi^0$ reconstruction to calibrate FCS ECal for each period
- Better Clustering algorithms being developed for HCal to enhance MIPs over background

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# Conclusion

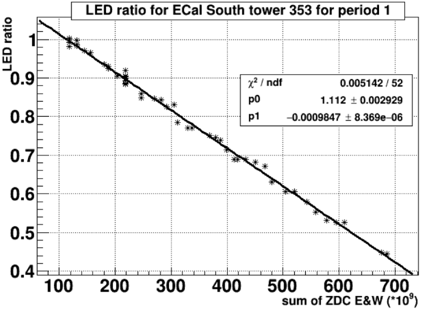
The $\pi^0$ reconstruction for calibrating the FCS ECal for each period will be completed soon.
Work on developing the clustering algorithm for HCal is in progress
Data from the FCS will then be ready for physics analysis

**Thank You!**

# Contents

# Back Up Slides: LED Ratio and Gain Correction Study

- Plot the LED ratio as a function of RHIC ZDC Rate (related to integrated luminosity) for each period, use linear fit to estimate the LED ratio change
- Predict the LED Ratio for each tower for every run
  ◦ Calibrate the ECal tower and obtain the corrected gain from $\pi0^0$ reconstruction iteration
  ◦ Investigate possible relation between LED ratio difference and gain correcrtion difference between 2 different runs in the same period
- Possible relation : LED Ratio $\times$ Gain Correction $=$ Constant



# Back Up Slides: Invariant Mass Peak Extraction

## Extract the $\pi^0$ Invariant mass peak for the invariant mass plots of each tower

- For each best pair of clusters, find out the tower with the highest energy inside each cluster (highest energy tower selection) and fill the 2 highest energy towers with invariant mass of this pair
- For each tower invariant mass plot, use a Gaussian to fit the signal and use power $\times$ exponential to fit the background
- Obtain the invariant mass peak from the Gaussian mean for each tower.