STAR Forward Upgrade

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2023 RHIC/AGS Annual Users' Meeting
BNL
Aug. 2, 2023

Supported in part by

STAR Forward Upgrade: Overview

Coverage: $2.5 < \eta < 4.0$

- Located on STAR west side
- Similar rapidity coverage as the EIC detector hadron endcap

Requirement:

Detector	pp and pA	AA
ECal	$\sim$10 % / $\sqrt{E}$	$\sim$20 % / $\sqrt{E}$
HCal	$\sim$50 % / $\sqrt{E}$ + 10%	-
Tracking	Charge separation photon suppression	$\delta p_T/p_T$ $\sim$20 - 30% for $0.2 < p_T < 2$ GeV/c

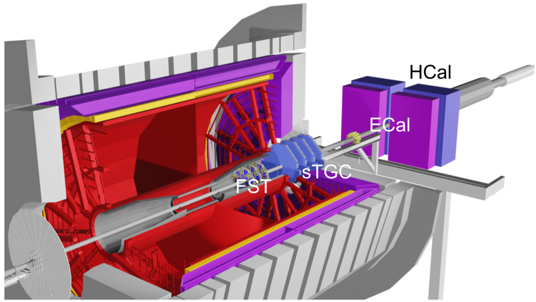
- Good e/h separation
- Good photon, π^0 identification

Status:

- All the forward upgrade detectors were completely installed and commissioned in 2021, and started taking data in 2022 (run 22)

Combines:

1. Forward Tracking System (FTS)
   - Forward Silicon Tracker (FST)
   - small-strip Thin Gap Chambers (sTGC)
2. Forward Colorimeter System (FCS)
   - Electromagnetic Calorimeter (ECal)
   - Hadronic Calorimeter (HCal)



STAR Forward Upgrade: Physics Program

Cold QCD:

- p + p 510 GeV (2022) and p + p , p + Au 200 GeV (2024)
- Sivers asymmetries for hadrons, (tagged) jets, and di-jets
- Collins measurements at high x
- GPD E_g: gluon spin-orbit correlations
- Gluon PDFs for nuclei: R_{pA} for direct photons & DY
- Test of Saturation predictions through di-hadrons, γ-jets

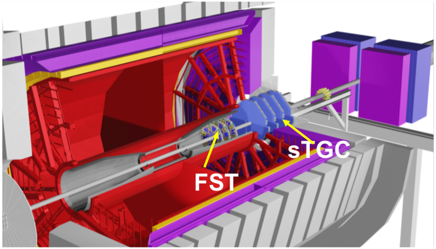
Hot QCD:

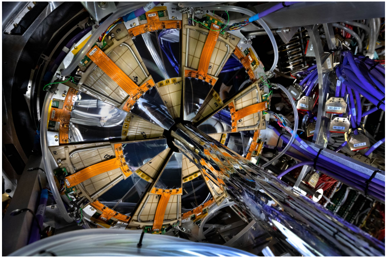
- Au + Au 200 GeV (2023 & 2025)
- Temperature dependence of viscosity through flow harmonics up to $\eta \sim 4$
- Longitudinal decorrelation up to $\eta \sim 4$
- Global Lambda Polarization: test predictions of strong rapidity dependence

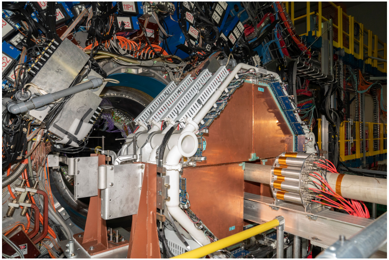
Observables:

- Charged and neutral hadrons
- Inclusive jets and di-jets
- Hadrons in jets
- Photons
- Drell-Yan and J/Ψ di-electrons
- Lambda's
- Mid-forward and forward-forward rapidity correlations

Forward Tracking System (FTS)

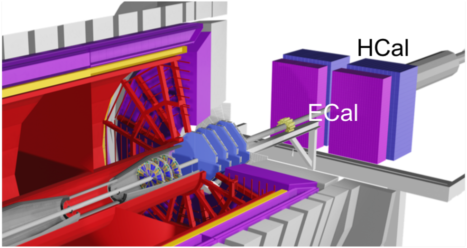






- FTS includes Forward Silicon Tracker (FST) and small-strip Thin Gap Chambers (sTGC)
  - FST: 3 disks (at 152, 165, and 179 cm from the STAR IP), each with 12 modules
  - sTGC: 4 planes (at 307, 325, 343 and 361 cm from IP), each consisting of 4 pentagonal modules
- Details on FTS are in Zhen Wang's talk

Forward Calorimeter System (FCS)



- FCS is located at $\sim$ 7 m from the STAR IP
- Split in 2 movable halves inside and outside of ring
- Slightly projective

Preshower (not shown):

- Split signals off from STAR EPD for triggering

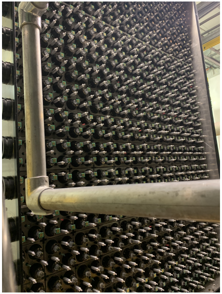
ECal:

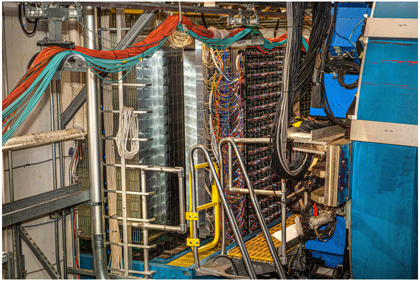
- Reuse PHENIX Pb-Scintillator calorimeter
  - 1496 channels: $5.52 \times 5.52 \times 33\ cm^3$
  - 66 sampling cells with 1.5 mm Pb / 4 mm Sc
  - 36 wavelength-shifting fibers per channel
  - 18 X_0; 0.85 nuclear interaction lengths
- Replaced PMTs with SiPM readout

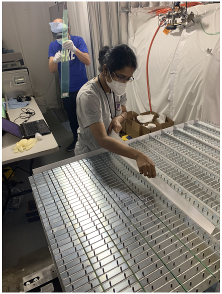
HCal:

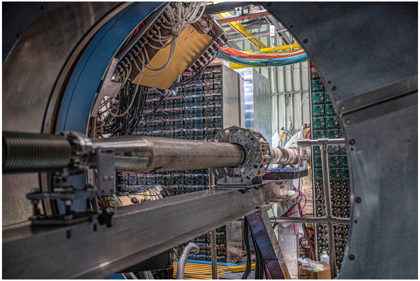
- Fe/Sc (20 mm/3 mm) sandwich
  - 520 channels: $10 \times 10 \times 84\ cm^3$
  - Approximately 4.5 nuclear interaction lengths
- Uses same SiPM readout as ECal
- Developed in collaboration with EIC R&D

FCS Construction



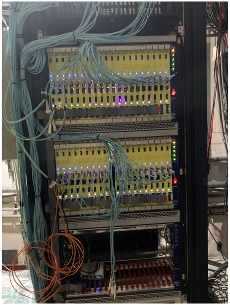






FCS Readout and Commissioning

- FCS constructions were completed in early 2021
- FCS commissioning during run 21:
  - Exercised the on-line data quality monitoring, and slow controls
  - Off-line and Monte Carlo machinery also in place
  - Trigger system was commissioned
- System fully ready at Day-1 for run 22



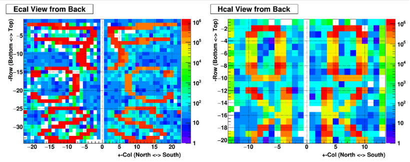


Figure: LED system testing

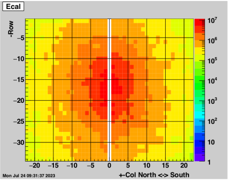


Figure: ECal monitoring plot in run 23

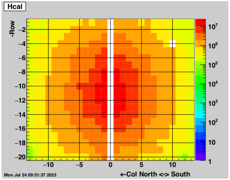


Figure: HCal monitoring plot in run 23

FCS Calibration Status

- The calibration for FCS ECal is done for run 22
- The calibration for FCS HCal is still in progress
- Energy of the ECal tower: E = ADC × Gain × Tower variant gain correction factor

ADC

- Optimize the methods to extracting ADC
- Save computation time

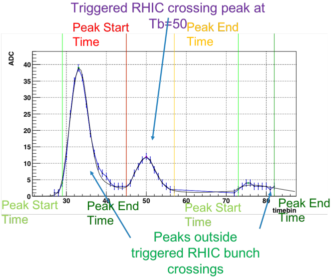
Tower variant gain correction factor

- Deal with the tower variant radiation damage
- Extrapolate the gain correction factor for the entire run 22

ADC Values: Gaussian Integral vs. Time Bin Sum

- Signals from STAR are digitized 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 $\approx$ 13.5 ns $\Rightarrow$ 1 Time Bin (Tb)
  - 8 Tb in 1 RHIC bunch crossing $\approx$ 100 Tb of data for every channel in every event

Sample Signal from DEP showing multiple RHIC bunch crossings



2 methods for measuring ADC value:

1. Gaussian Fit signal integral

- Fit signal to all peaks shown in black with Gaussian function
- Amplitude of Gaussian $\sim$ Gaussian integral
- Challenge: Time Consuming; Might identify noise as signal; Lots of computation time for overlapping signals

2. Summing over Time Bins (Sum8)

- Sum over ADCs in 8 Tb of RHIC Bunch crossing
- Challenge: Might overestimate low side of energy compared to fitting

New Algorithm for reading ADCs

- Differentiate cases to apply either Gaussian fitting or Sum8 method
- Accurate determination of peaks ⇒ less computation time
- Aid in fitting overlapping peaks and eliminating peaks from noise ⇒ correctly determine the energy

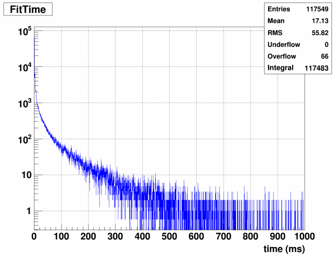


Figure: Time taken by Fit Method

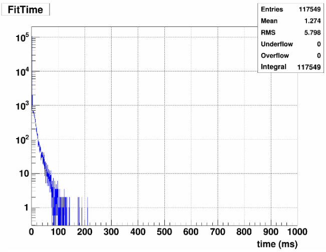


Figure: Time taken by New Algorithm

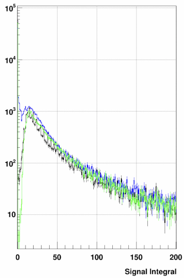
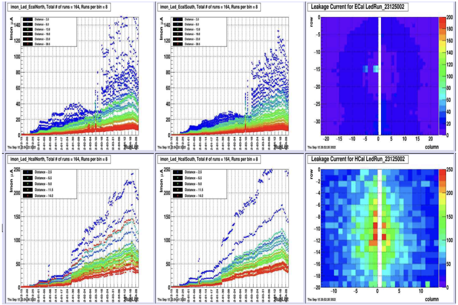
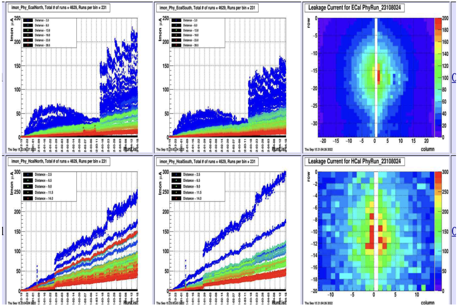


Figure: Energy Peaks (Blue Curve) sum8 Method (Green Curve) Fitting all peaks (Black Curve) Result with cuts



History Plots and 2D Plots of Leakage Currents for LED runs



History Plots and 2D Plots of Leakage Currents for Physics runs

- Radiation plots are set up to monitor and qualify the radiation damage
- Plots for every tower throughout the run 22 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)
- Towers closer to beam pipe show higher radiation damage than towers far away from beam pipe

Tower by Tower Radiation Damage

- Gain loss due to the radiation damage to FEE boards can be observed from the LED system
  - LED ratio: ratio of LED readout between each LED test run and the reference test run in a period (between dash line)
    - Change the attenuator and SiPM bias set voltage on FEE boards to adjust the LED readout between periods
  - For each tower, LED ratio drops → the tower suffers radiation damage
  - Higher LED ratio drop rate → more serious radiation damage
- Calibration for each tower is necessary to deal with such radiation damage
- Extrapolate the gain correction for each tower for each physics run based on the calibration for the beginning and end of period run

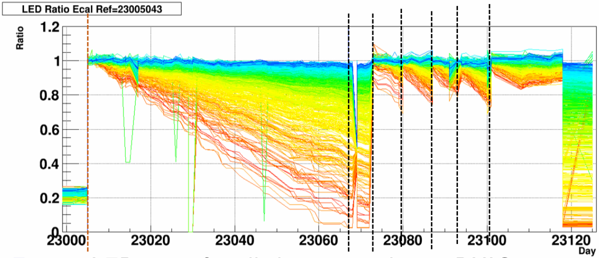


Figure: LED ratio for all the towers during RHIC run in run 22

ECal Calibration: π^0 reconstruction

- π^0 reconstruction method is used to calibrate the ECal
  - $\pi^0 \to \gamma + \gamma$
  - ECal cluster is the photon candidate
- Gain correction factor for each ECal tower is obtained from π^0 reconstruction iteration

Iterative tower-by-tower gain correction factor calculation:

- Extract the invariant mass peak for the invariant mass plot of each individual tower
- Gain Correction Factor for each tower $=$ $\textit{gain corr}_{org} \times \frac{\pi^0 \textit{ inv mass}}{\textit{inv mass peak}}$
- Apply corrected gain correction values for another iteration of π^0 reconstruction
- Repeat the iterations until most of the tower invariant mass peaks converge at π^0 invariant mass

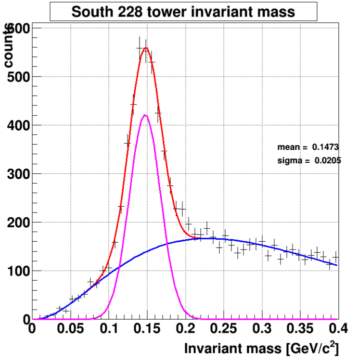


Fig: Invariant mass plot for each tower - Signal fit: Gaussian; Background fit: power * exponential

ECal Calibration: Results

Successful π^0 reconstruction for FCS ECal with iterations

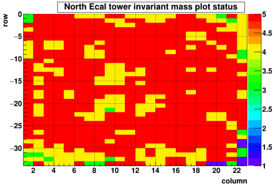


Figure: Invariant mass peak status plot before iterations

- Invariant mass peak status for every tower
- Red color: the invariant mass peak is less than 10% difference to π^0 invariant mass
- Other color: the invariant mass peak away from π^0 invariant mass and need iterations to fix

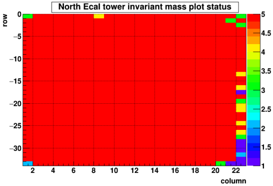


Figure: Invariant mass peak status plot after 2 iterations

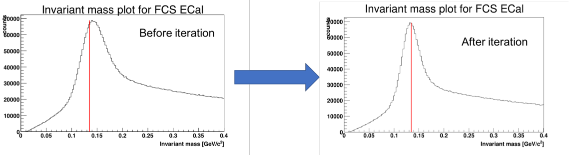


Figure: Invariant mass plot before (left) and after (right) iterations

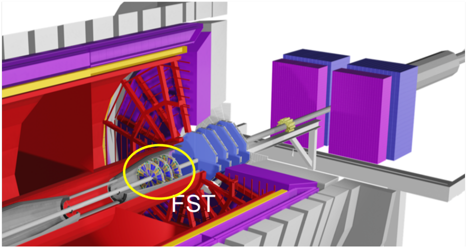
- The invariant plot for after 2 iterations shows an obvious peak right at π^0 invariant mass and with smaller width

Conclusion

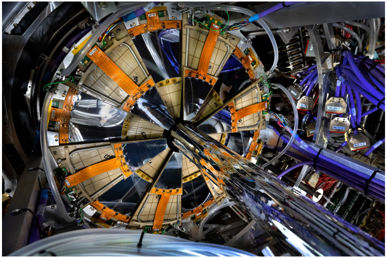
- The STAR Forward Upgrade were constructed and commissioned successfully in 2021, and were ready to take physics data in run 22
- The calibration for FCS ECal was done for run 22
- The new algorithm for reading ADCs can allow less computation time
- The radiation damages are monitored in place. They are varied in different towers
- The π^0 reconstruction is applied for calibrating the ECal
- FST and sTGC tracking algorithm is ongoing (see Zhen Wang's talk)

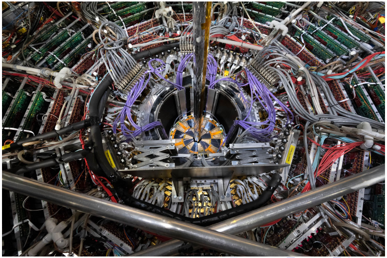
Back up

Forward Silicon Tracker (FST)

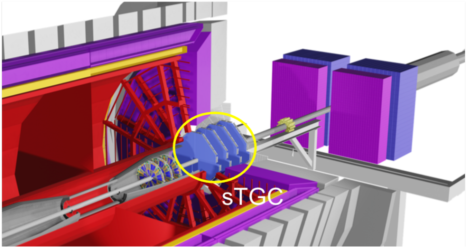


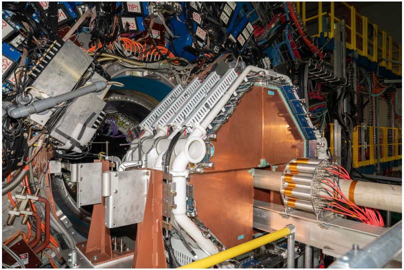
- 3 disks (at 152, 165, and 179 cm from the STAR IP), each with 12 modules
- Each module includes 3 single-sided double-metal mini-strip sensors (Si from Hamamatsu)
  - Fine granularity in ϕ and coarse in R
- Material budget $\sim 1.5\%\ X_0$ per disk
- Technology is similar to STAR Intermediate Silicon Tracker
  - Same APV25-S1 front-end chip
  - Reusing the IST data acquisition and cooling systems



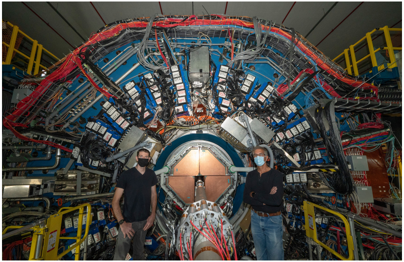


Small-strip Thin Gap Chambers (sTGC)





- 4 planes (at 307, 325, 343 and 361 cm from IP), each consisting of 4 pentagonal modules
  - Double-sided sTGC with diagonal strips give x, y, u in each layer
  - Position resolution $< 200\ \mu$m
- Material budget $\sim 0.5\%\ X_0$ per layer
- Readout based on VMM chips
  - Similar to the ATLAS sTGC system



FCS ECal module and LED system

- 4 independent towers in each module
- Penetrating WLS fibers for light collection

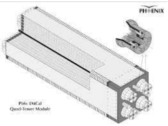


Figure: PHENIX ECal Module

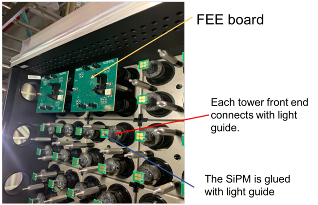


Figure: Refurbished ECal tower front end display

- There are blue LED at the back side of ECal stack, which shine light to enclose cover. Some light will be absorbed by exposed loops of Wavelength Shifting fibers at the back side

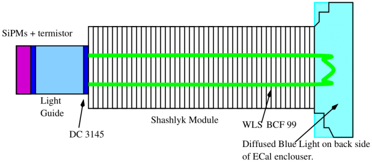
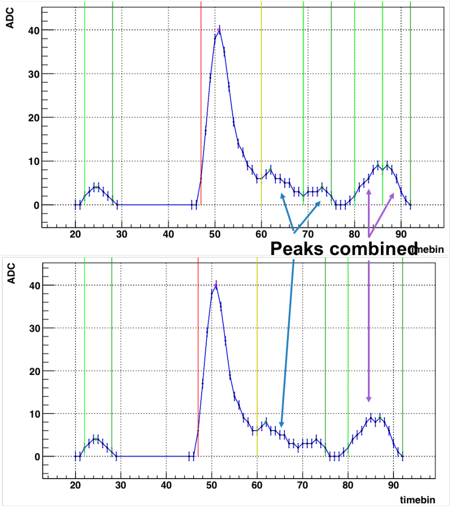


Figure: LED system

Eliminating Peaks Coming From Noise

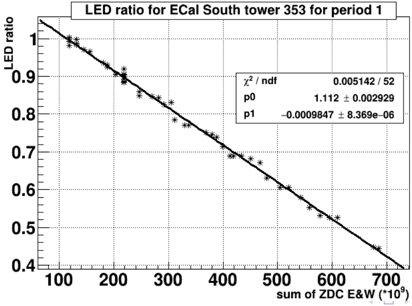
- Compute the probability a peak is a real peak or noise
  - Call this method peak tunnelling as it was inspired by quantum tunneling
- Assumes noise follows a Normal distribution
  - Parameters need to be tuned to data set
- Merge peaks that have low probabilities together
  - Higher probability peak is identified as peak position when merging



LED ratio and gain correction study

- Plot the LED ratio as a function of RHIC ZDC rate (related to the integrated luminosity) for each period, and use linear fit to estimate the LED ratio change
- Predict the LED ratio of each tower for every run

* Calibrate the ECal tower and obtain the corrected gain correction from π^0 reconstruction iteration
* Investigate the possible relation between LED ratio difference and gain correction difference between 2 different runs in the same period
    - Possible relation: Gain correction $\times$ LED ratio $=$ Constant



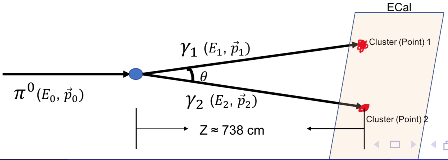
Calibration method: π^0 reconstruction

π^0 reconstruction

- π^0 reconstruction using 2 photons (clusters)
- Cluster: a group of towers fired on ECal from EM shower of photon
- Data set sample used: 8.5 M events from $p + p$ collision data at $\sqrt{s} = 510$ GeV
- Energy = ADC × gain × gain correction

Cluster pair selection:

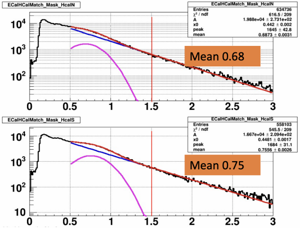
- Each cluster energy E_1 (E_2) > 1 GeV
- Energy asymmetry $Z_{\gamma\gamma} = \frac{|E_1 - E_2|}{E_1 + E_2} < 0.7$
- For each event, only keep the pair with highest sum energy $(E_1 + E_2)$



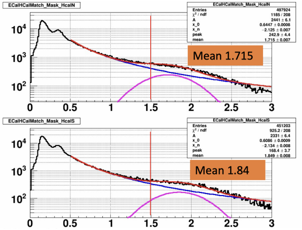
HCal Calibration : MIP

Similar iterative method followed for calibrating the HCal with MIPs

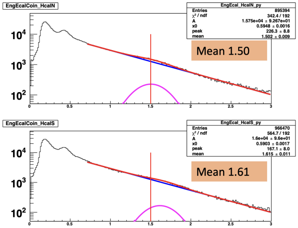
- ≈ 1 % of hadrons leave MIP (Minimum Ionizing Particles) at HCal
- MIP peaks in HCal observed in isolated 1-2 towers



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