ePIC EEEMCal Test Beam Analysis

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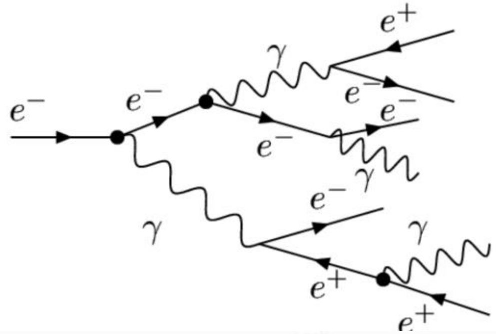
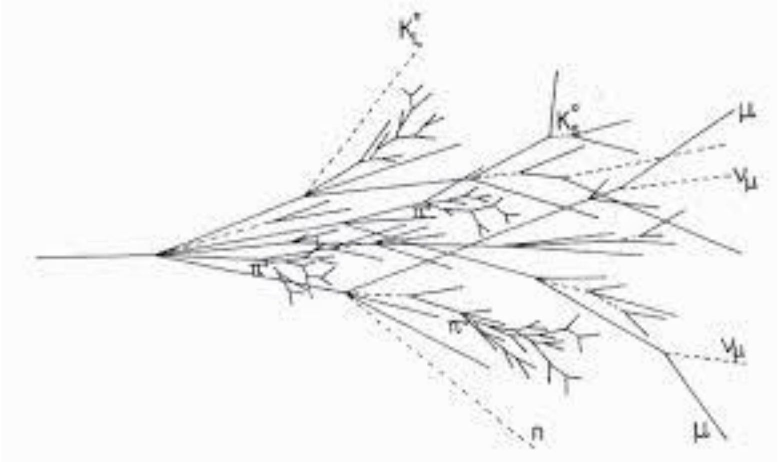
Calorimetry

- Calorimeters measure the energy of particles
  - Convert the particles energy into light or charge, which is measurable
  - Achieved by initiating electromagnetic or hadronic showers
- Electromagnetic and hadronic calorimeters cause showers through different mechanisms

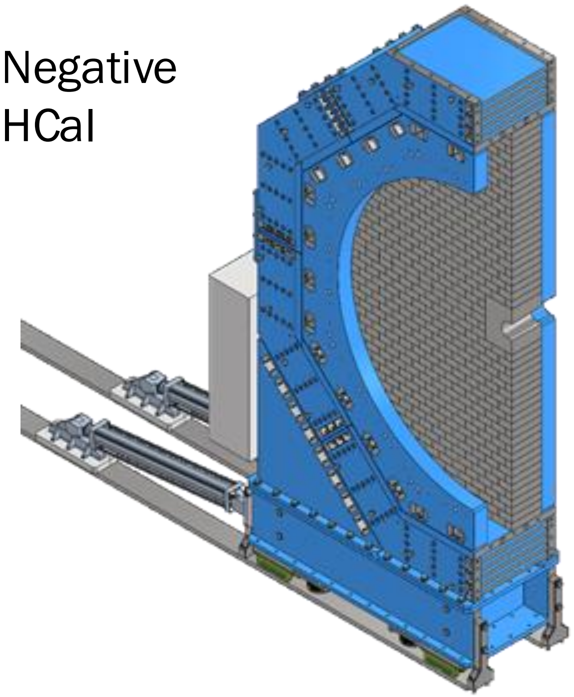
- Electromagnetic
  - Showers through Bremsstrahlung radiation and pair production
  - Produces compact, well described showers
- Hadronic
  - Showers through nuclear interactions
  - Much larger fluctuations in shower size, shape, and electromagnetic fraction





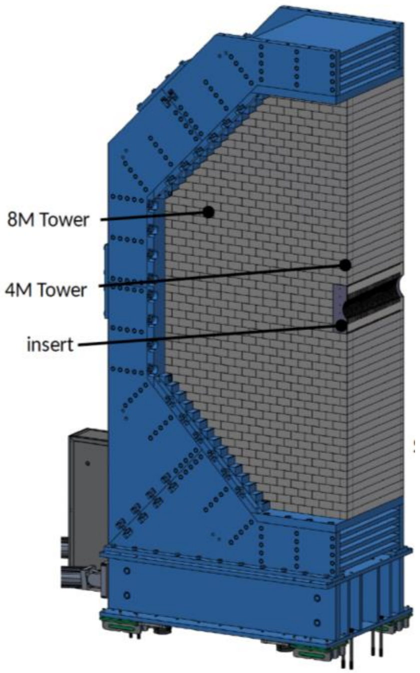
ePIC's calorimeters

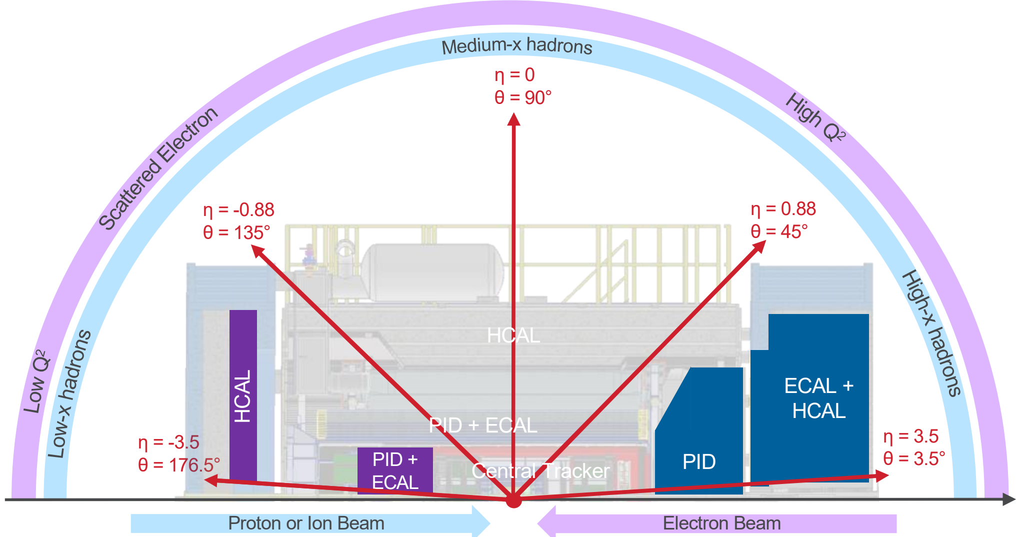
Negative HCal



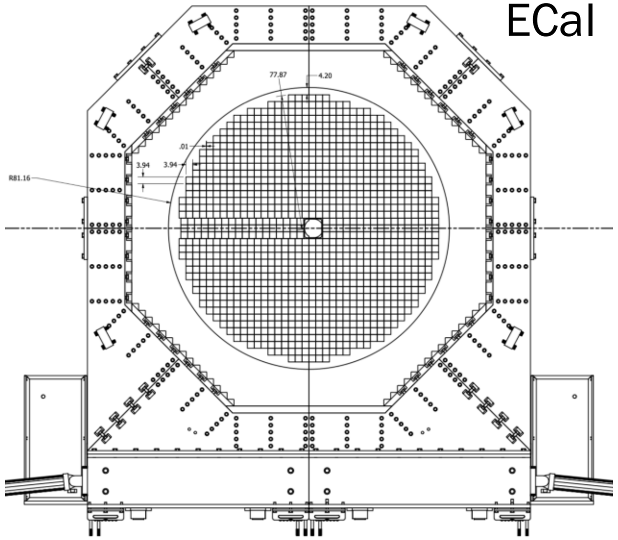
Barrel HCal

LFHCal

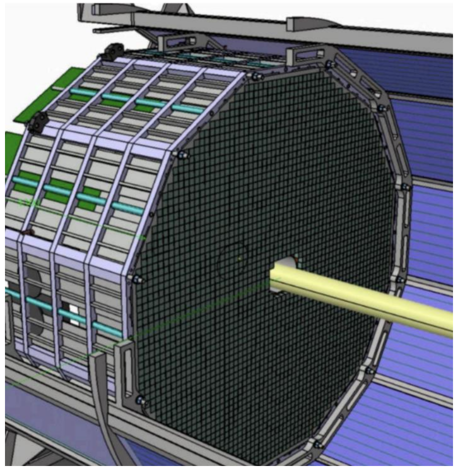


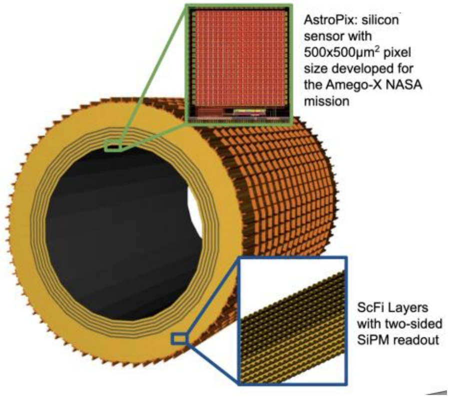


Forward ECal



Electron Endcap EMCal

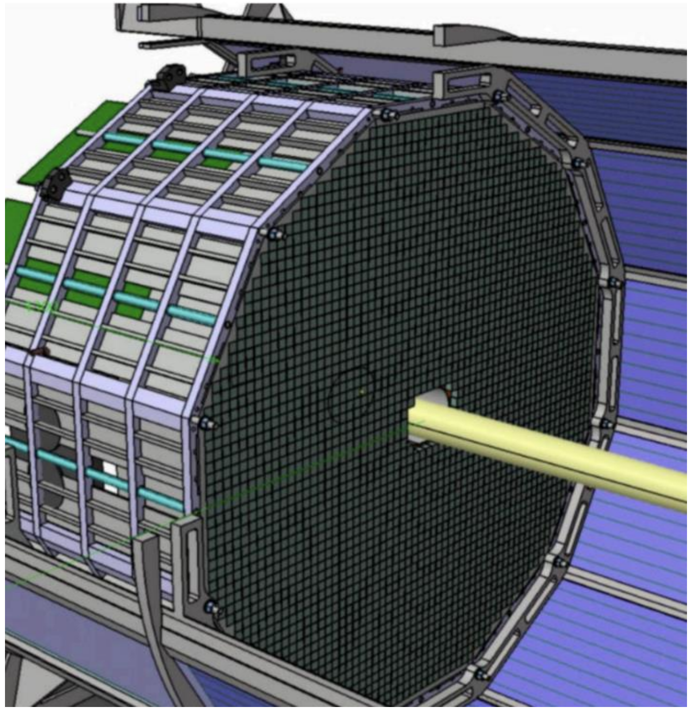




Barrel Imaging Calorimeter

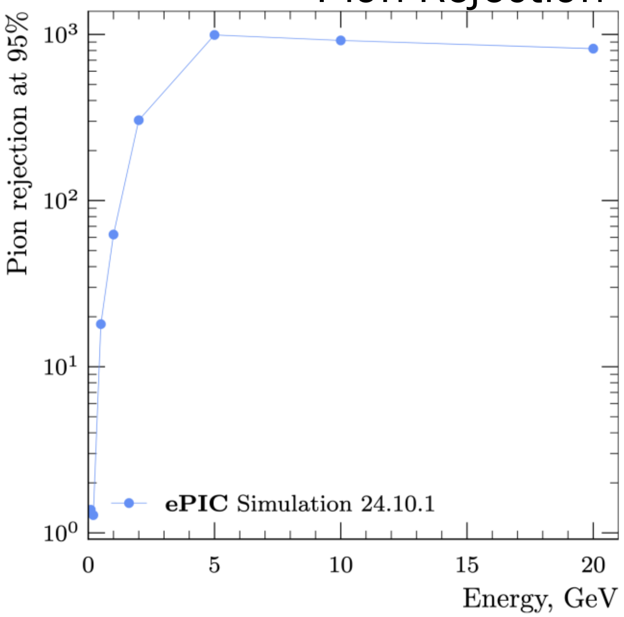
Electron Endcap Electromagnetic Calorimeter

- Captures the scattered electron in low Q^2 events
  - Electron at small angles to beam line
  - Crucial for defining kinematics in DIS events
  - Requires excellent energy and position resolution
    0.5 - 18 GeV dynamic range
  - Target resolution: $\frac{\sigma_E}{E} \approx \frac{2-3\%}{\sqrt{E}} \oplus 1-2\%$



- Separate electrons and pions
  - In low x events, the final hadronic state is in the backwards direction as well as the scattered electron
  - Excellent pion rejection at high energy to identify DIS electron

Pion Rejection



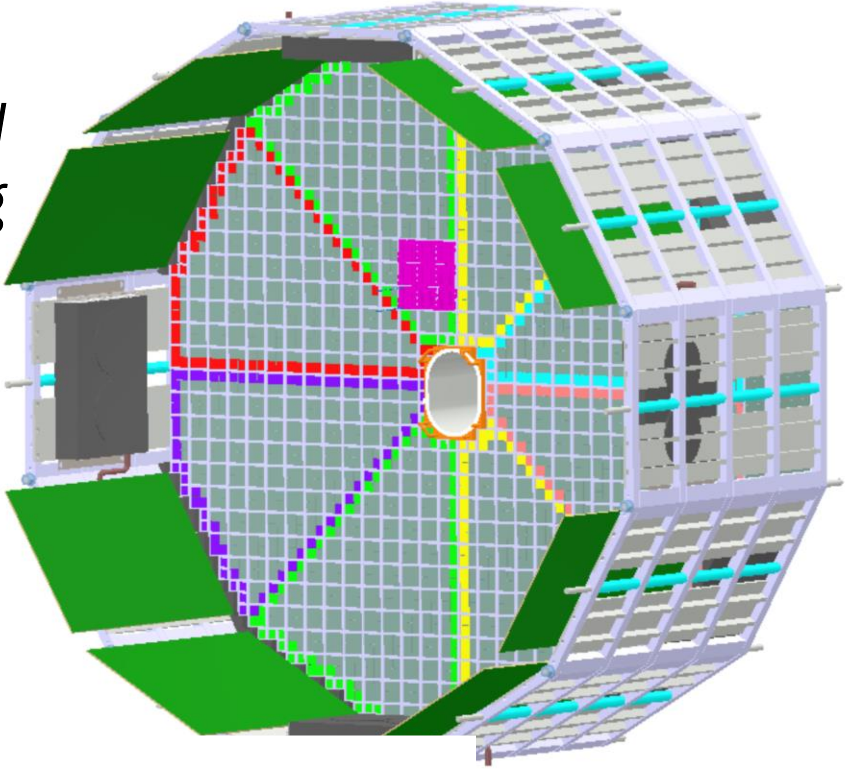
EEEMCal crystals

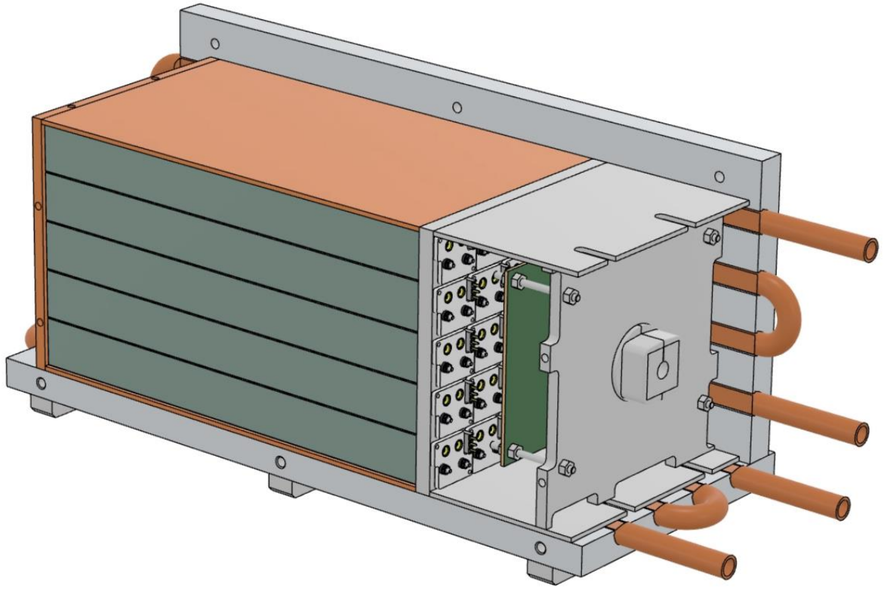
- To maximize the performance, a homogeneous calorimeter was selected
- Composed of lead tungstate (PbWO4) crystals
    - High optical clarity
    - Short radiation length (~0.83 cm)
    - Small Moliere radius (~2 cm)
    - Moderate light yield
- Each crystal is 20 cm long and 2x2 cm on its face
    - 22 radiation lengths in total, and the crystal size matched to the Moliere radius
    - Crystals are individually wrapped in reflective material to maximize the signal and isolate from neighboring crystals
- The light yield of the crystal has a strong temperature coefficient
    - ~2% per degree Celsius

EEEMCal infrastructure

- Support structure include integrated copper cooling plates to maintain crystal temperature
- Carbon fiber spacers used between crystals to define the structure
- Cooling water connected to a chiller unit kept the temperature constant 19 ± 0.1°C
- Monitored throughout the test beam campaign at multiple points throughout the calorimeter to ensure stability

ePIC mechanical drawing

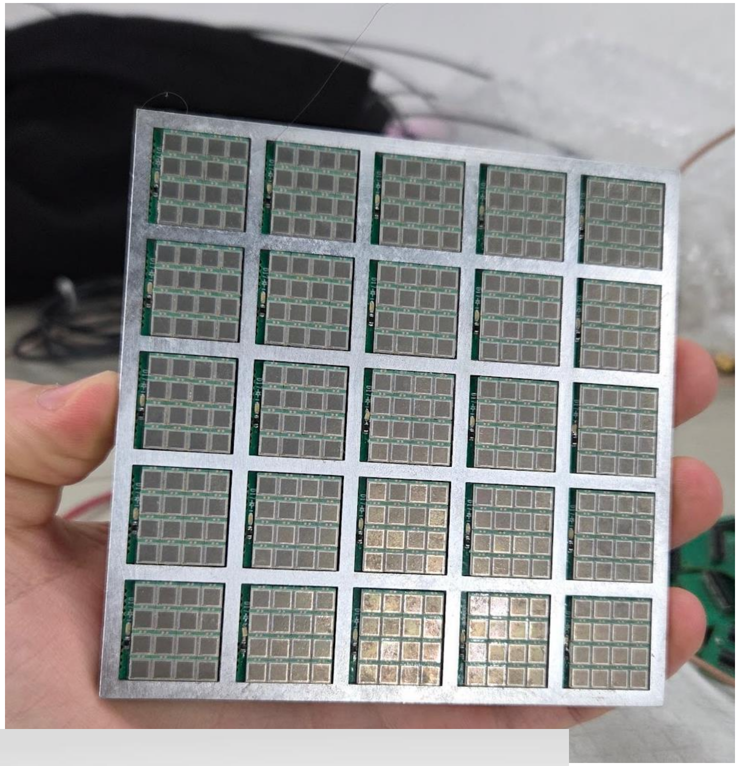


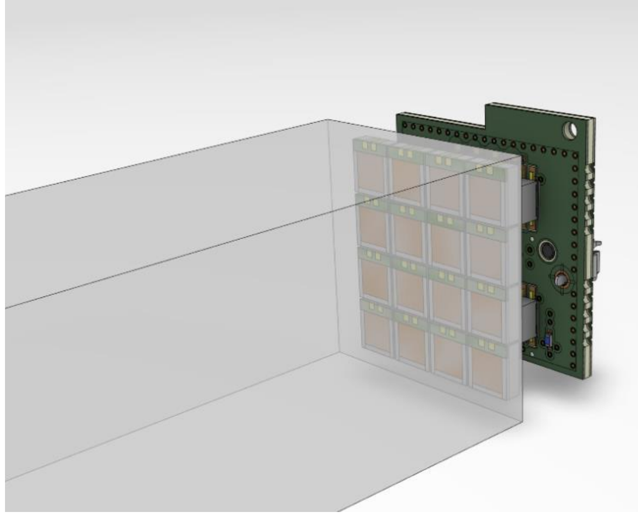


EEEMCal test beam prototype

EEEMCal readout

- To cover the wide dynamic range and sensitivity to small signals, SiPMs have been selected for the readout
  - Hamamatsu S14160-3015PS
  - 3x3 mm with 15 μm pixels
  - Work in strong magnetic fields
  - Test bean done at 42 V bias
- Coupled directly to face of crystals with an optical grease
- Multiple readout configurations are being investigated
  - Tradeoff between capacitance and channel count



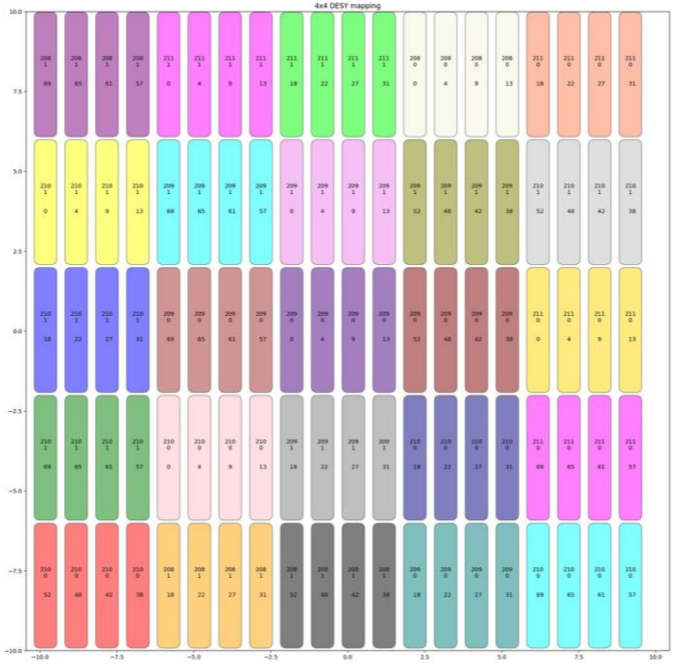


EEEMCal readout

16 Individual

- 400 total channels
- 530 pF per channel

4 in parallel



- 100 total channels
- 2120 pF per channel

16 in parallel

- 25 total channels
- 8480 pF per channel

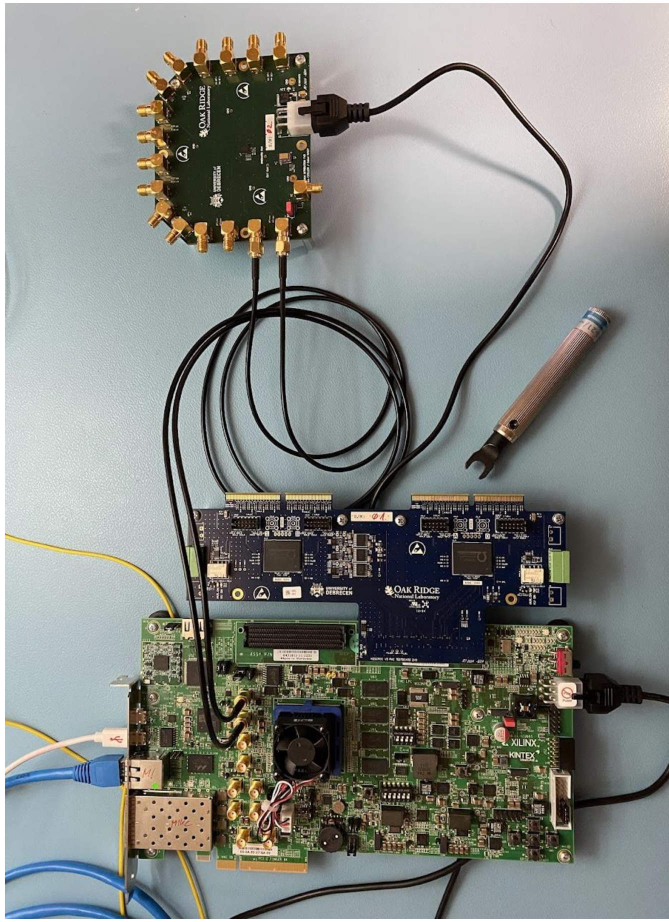
EEEMCal digitization

- ePIC digitization is based around the streaming readout concept
  - Recording constantly, not triggered!
- The EEEMCal as well as many other calorimeters will make use of the EICROC readout ASIC
  - ePIC specific implementation of HGCROC developed for CMS HGCal
  - 40 MHz digitization
  - Large dynamic range through through combination of ADC and time-over-threshold measurement
- A prototype utilizing a Xilinx KCU for readout was used for the EEEMCal test beam as well as several other

Common clock

Protoboard 2.0 with two H2GROC3A

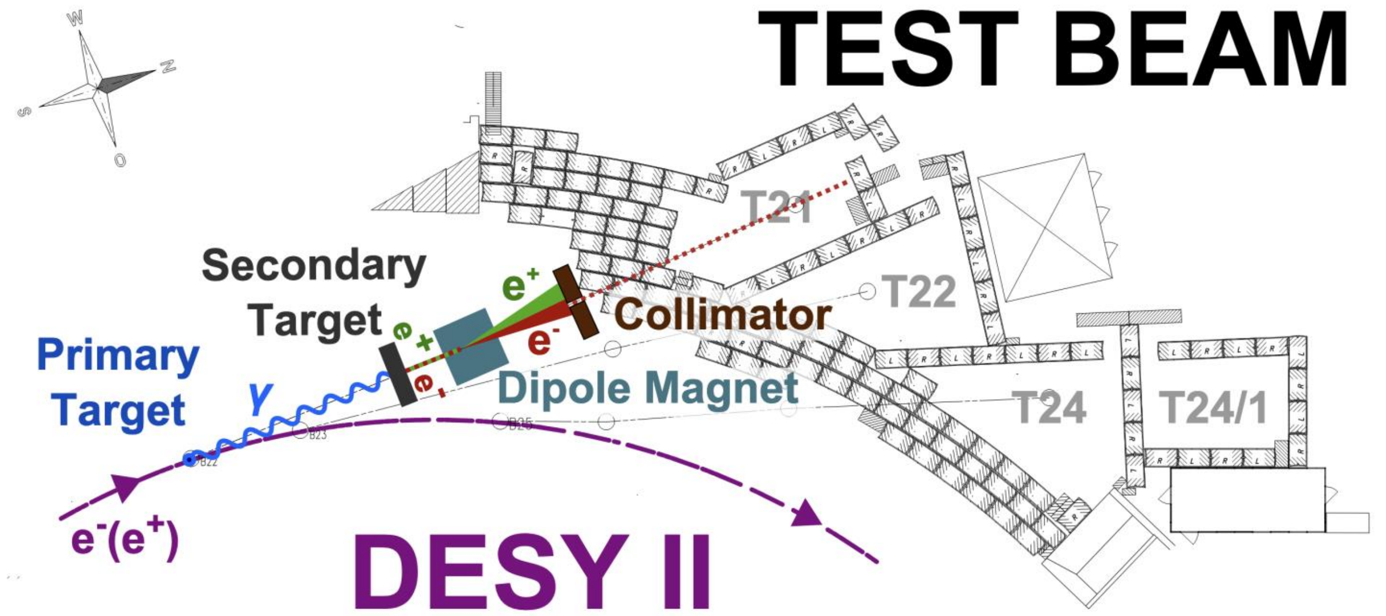
Xilinx KCU

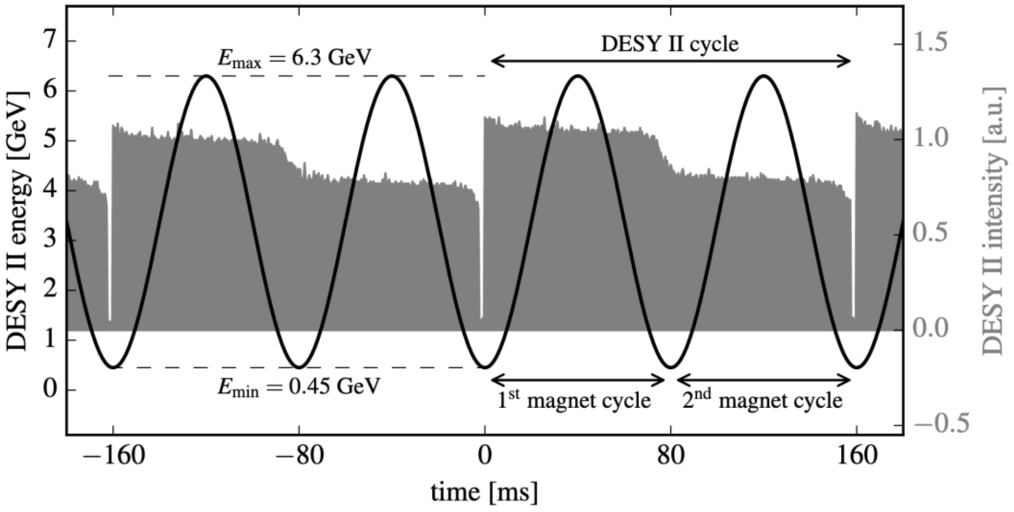


Test beam prototype

DESY II test beam

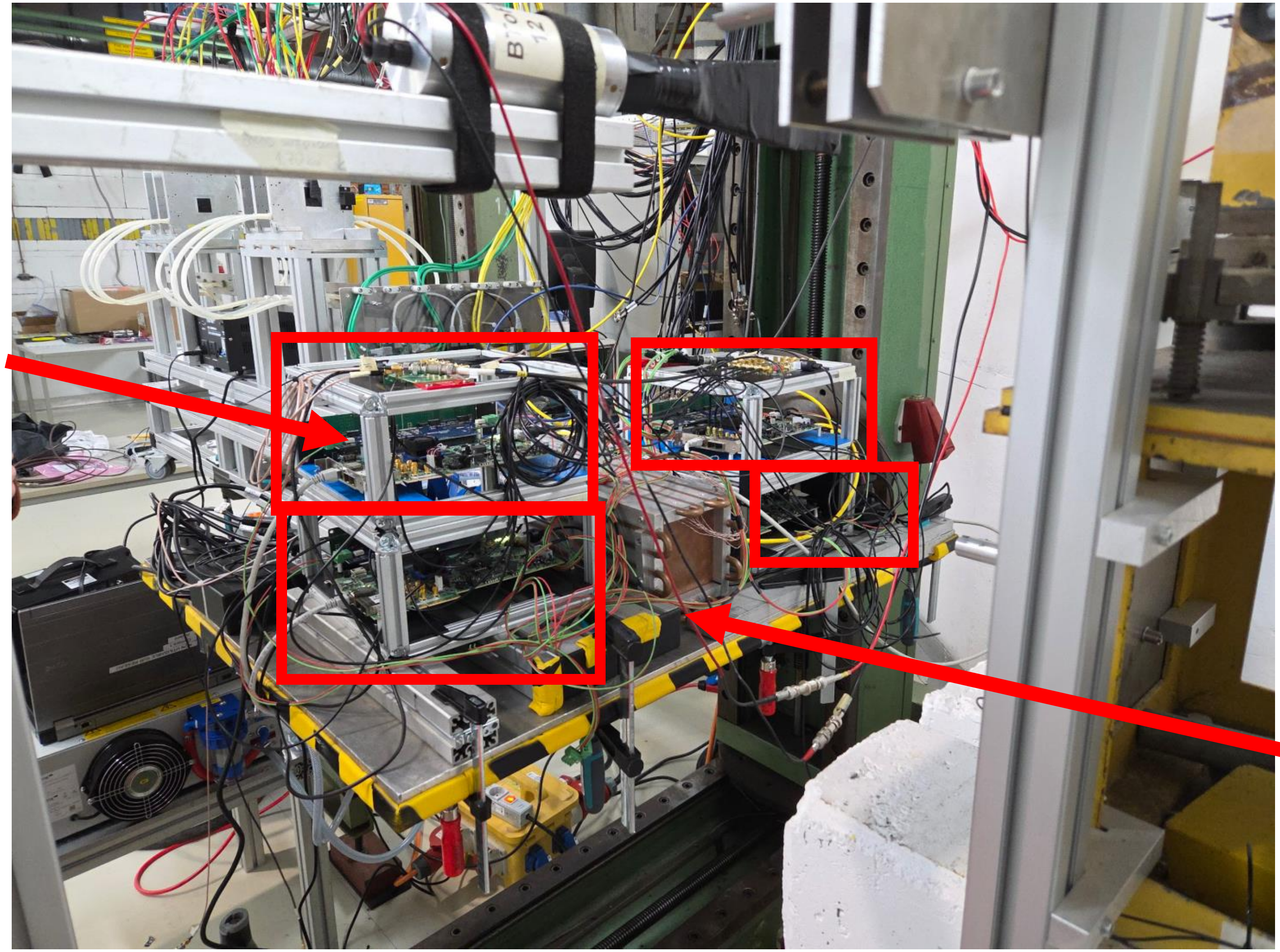
- DESY II is the electron synchrotron used as an injector in to the PETRA light source
- Three test beam lines exit off it through a pair of conversion targets
- Dipole magnets allow the selection of electrons from 1 to 6 GeV





Calorimeter setup

4x KCUs with 2 HGCROC ASICS each

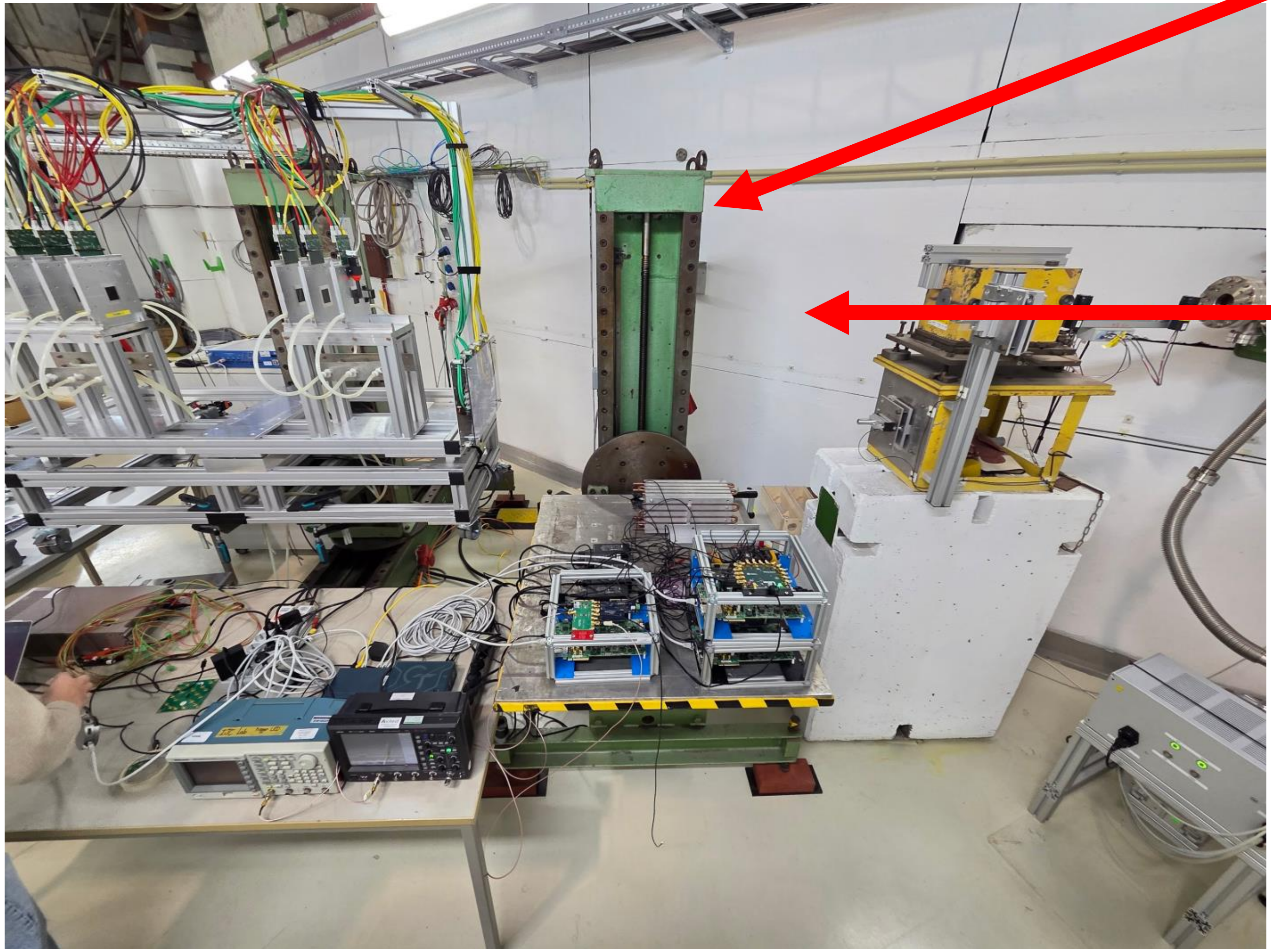


5x5 calorimeter

Calorimeter setup

XY table for positioning

Electron beam

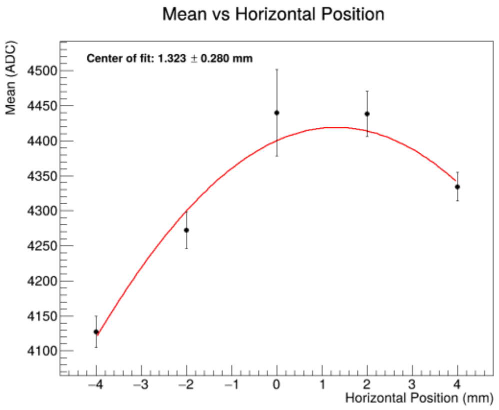


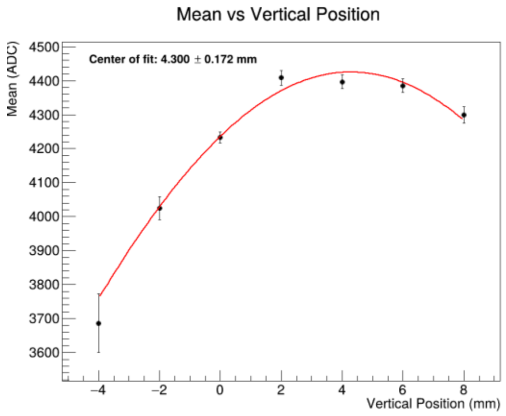
Run plan

- We had access to the beam line from Feb 17th through March 2nd
- Goals:
  - Operate the calorimeter in a test beam
  - Test multiple configurations of SiPM readouts
  - Measure the energy resolution of the calorimeter
- Utilized electron beams between 1 and 5 GeV
- 2 mm x 2 mm collimator used to produce a narrow beam
- Triggered with the coincidence of a pair of scintillators
- Rate limited to 100 Hz, with lower available rates at high energies

Run Type	Runs
Testing	158
Gain Matching	120
Position Scan	89
Energy Scan	77
Alignment	15
Phase Scan	214
Other	163

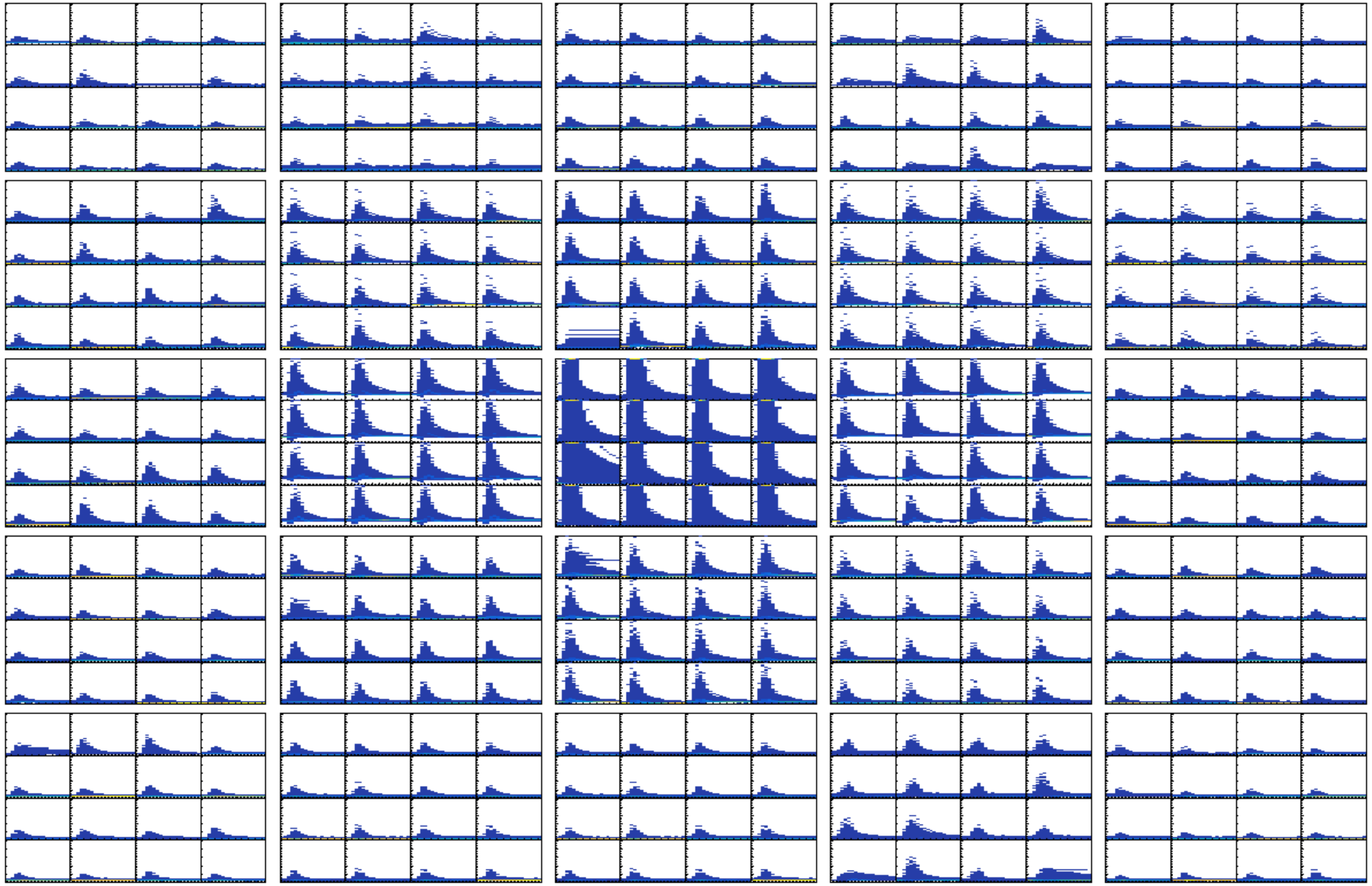
Alignment scan results





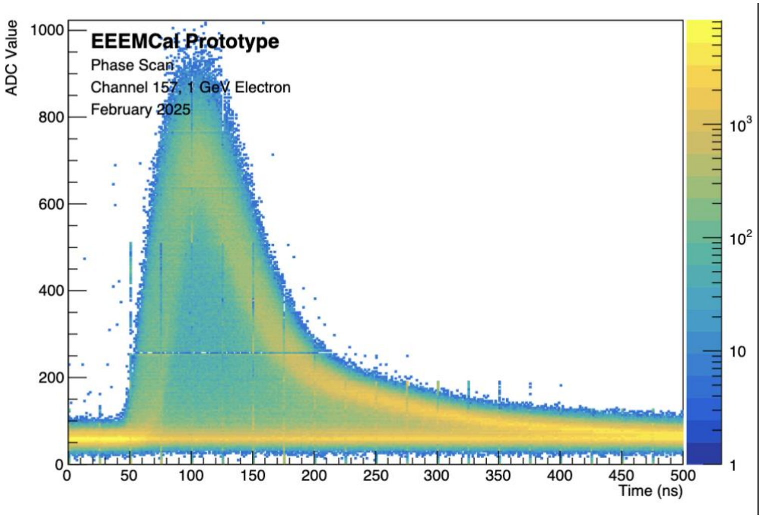
Online monitoring

- Real time decoding of events
- Implemented as webserver accessible from any browser
- ADC, ToA, ToT spectra
    - Very helpful to make sure pedestals look correct
- Tracks events and packets from each ASIC

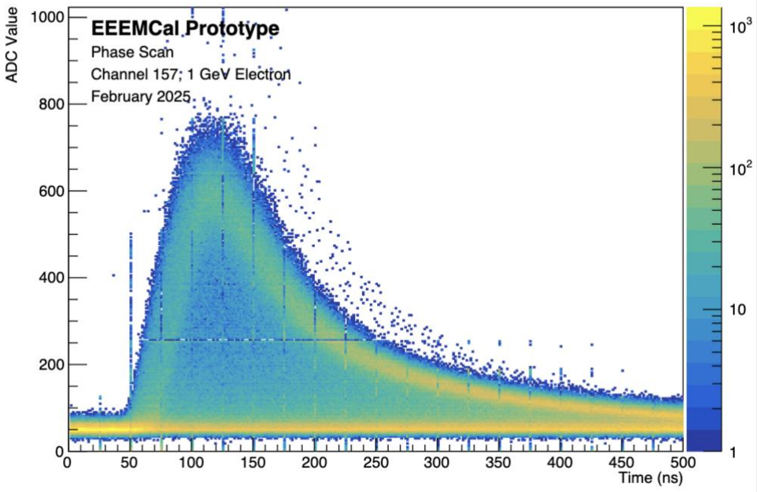


Signal shape

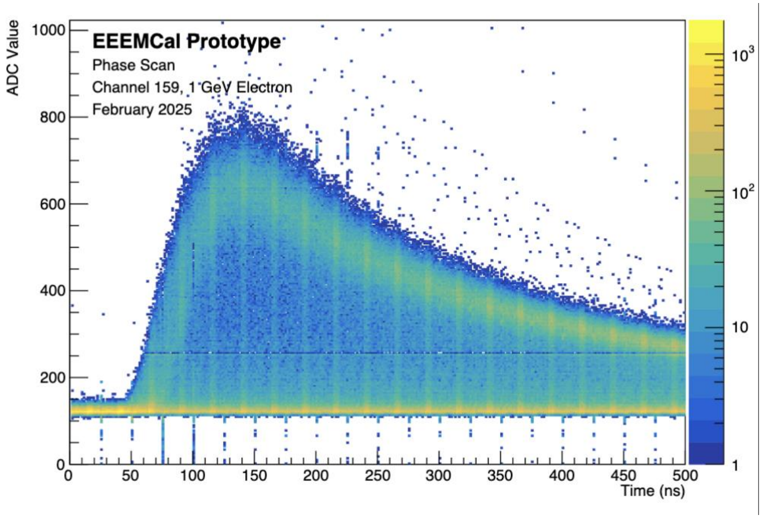
- HGCROC readout samples at 40 MHz, every 25 ns
- The phase of the readout can be stepped in increments of 1/16th to build a finer picture of the signal
- Demonstrates the effect that increased SiPM capacitance has



16 Individual



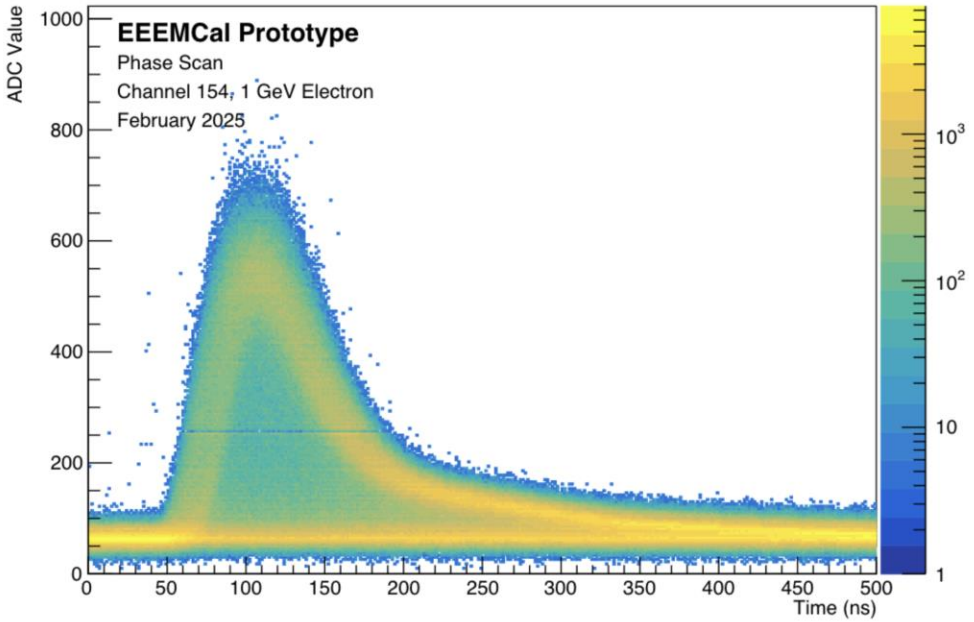
4 in parallel

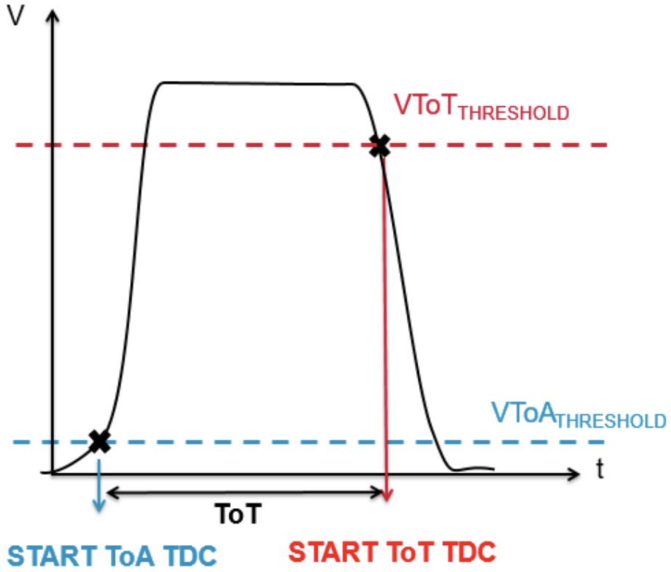


16 in parallel

Signal extraction

- Two types of signals to process
- ADC
  - Higher sensitivity to low energy events
  - Samples signal every 25 ns
  - Signal from $\mathrm{ADC}_{max} - \mathrm{ADC}_{ped}$, waveform fit, any number of strategies
- ToA/ToT
  - Expands dynamic range by measuring the time the signal is over some threshold
  - One value per "waveform" – most samples are 0
  - If there is a ToT measurement, the ADC measurement is invalid

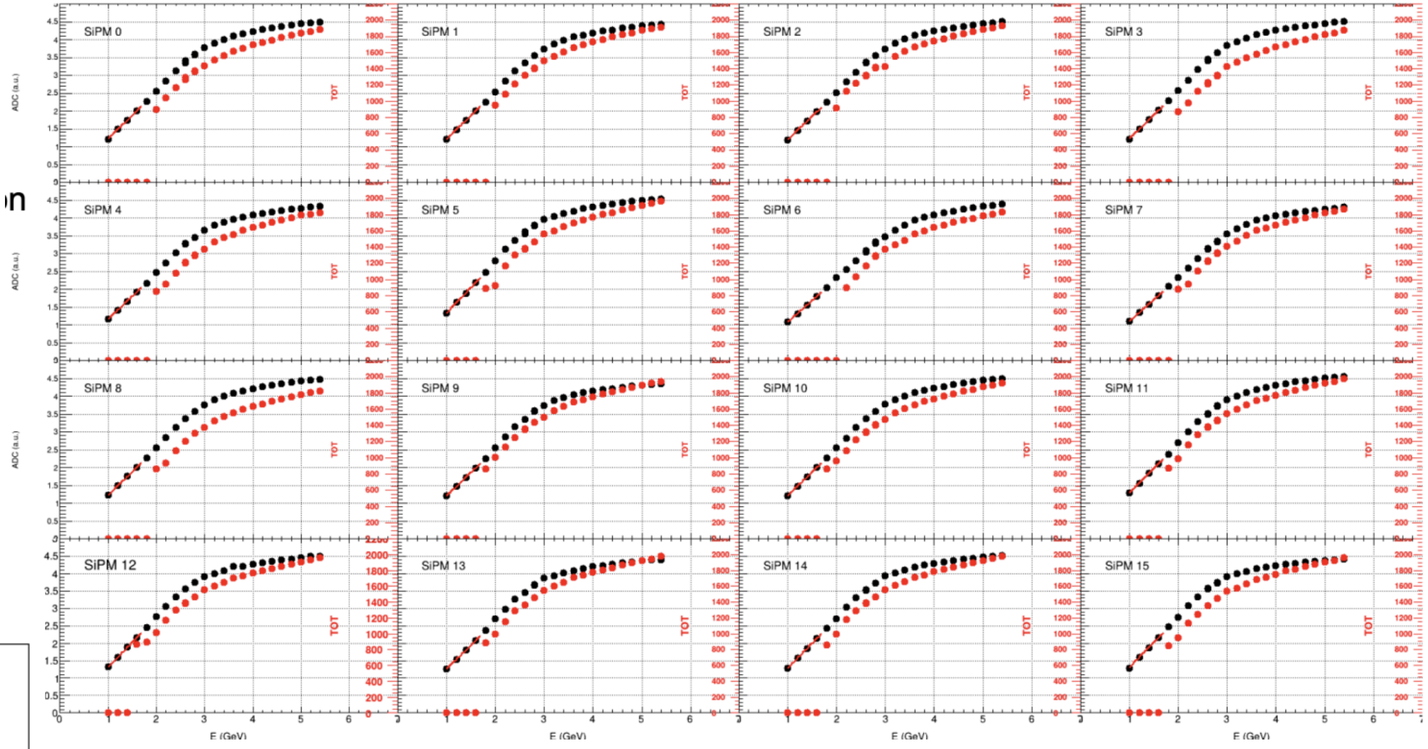


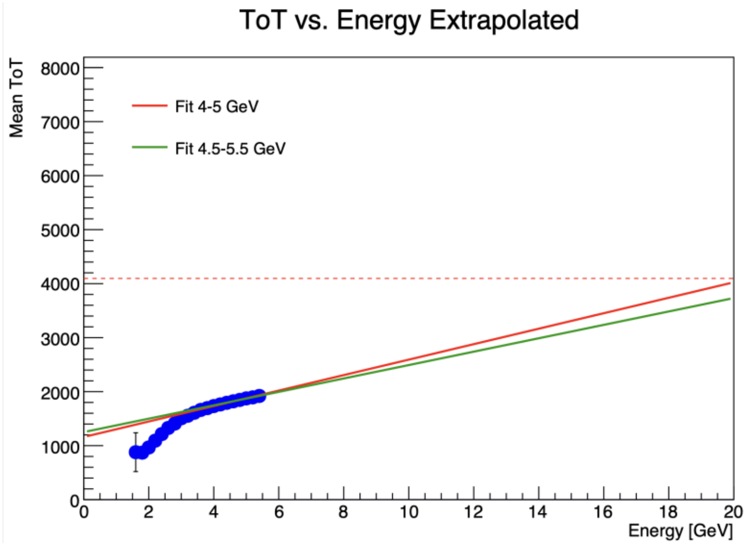


Linearity and dynamic range

- Measuring the detector response at many different energies allows us to measure linearity
- ADC scales linearly with energy until saturation
- ToT requires further correction and study
- ToT dynamic range extends out to 18 GeV!

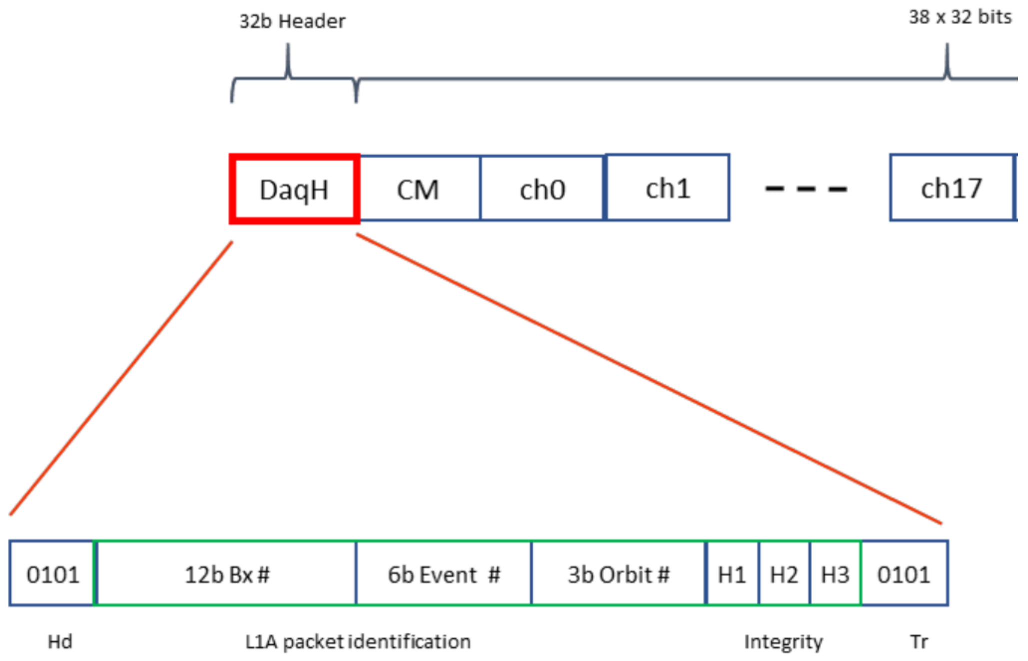
ADC ToT





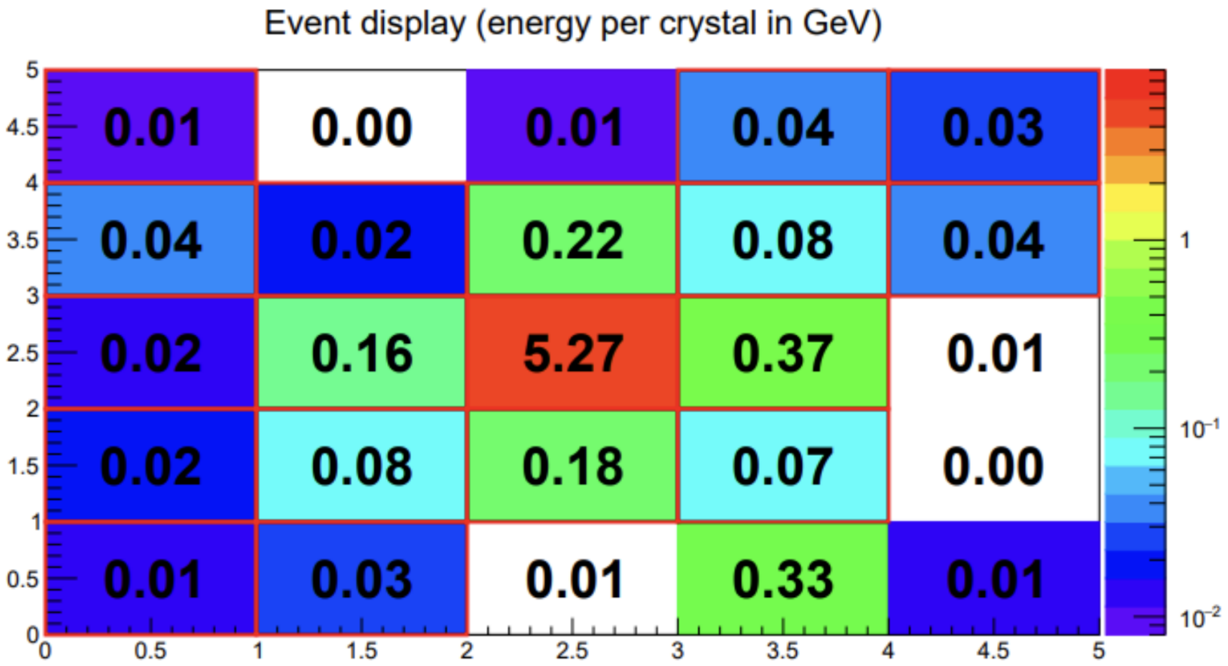
Event alignment

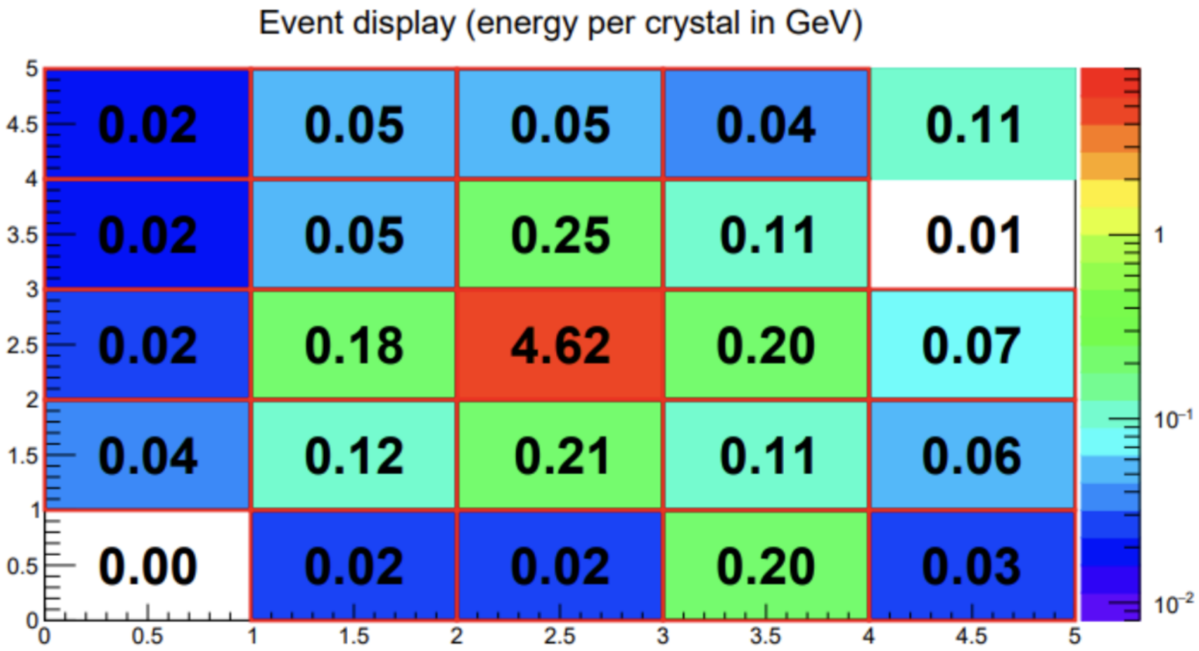
- Waveforms from multiple H2GCROC need to be aligned to process the full event
  - Within a FPGA: Waveform share a common timestamp
  - Alignment between FPGAs requires a different approach
- FPGA streams data to DAQ over UDP
  - Packets out of order, lost
- Each H2GCROC contains an event counter, bunch crossing counter, and orbit counter
- Multiple FPGAs are synchronized by keeping the gap between event numbers equivalent
  - Counters not yet reset synchronously
  - Allows incomplete events to be skipped without losing alignment between FPGAs



Results

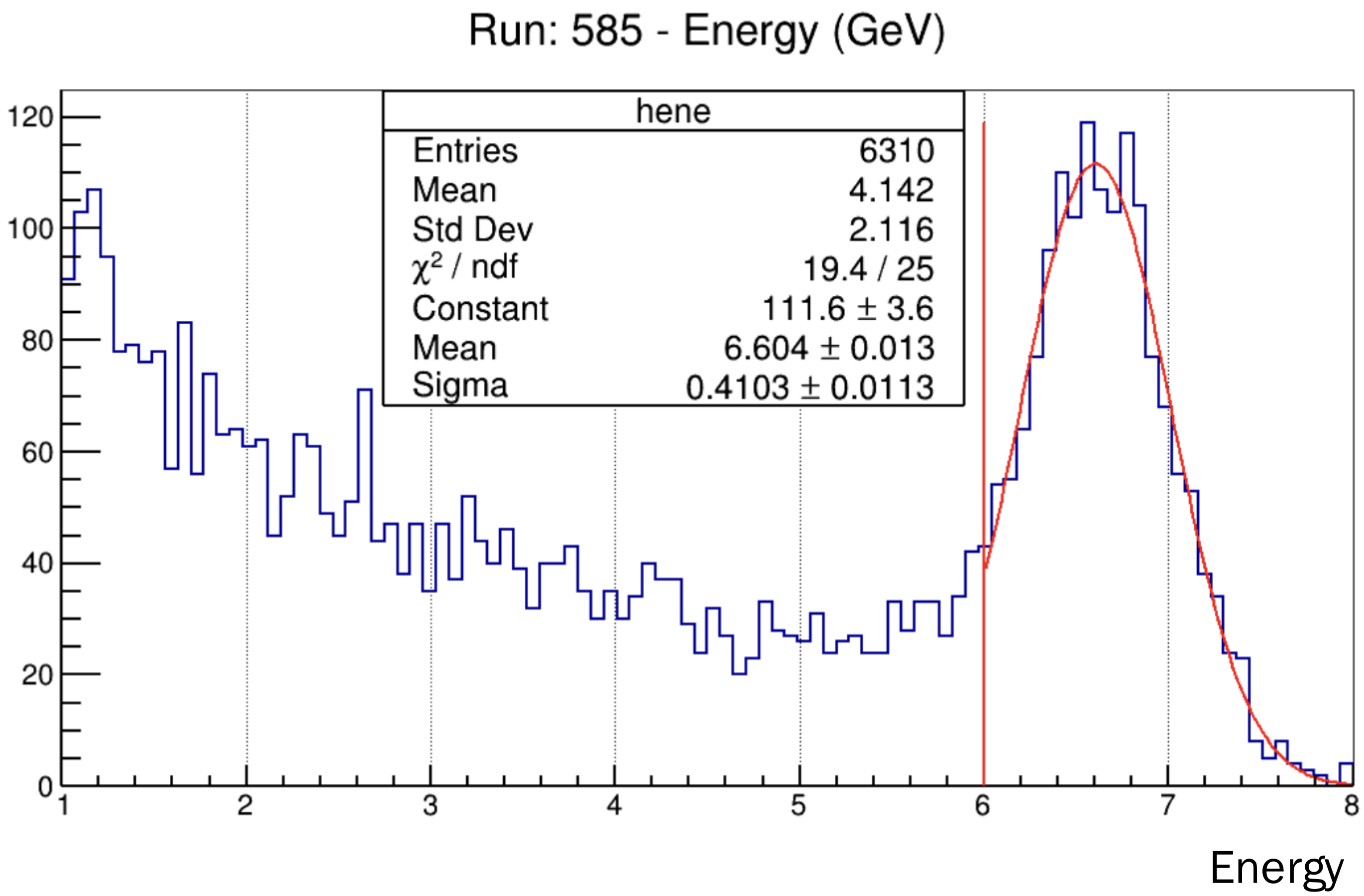
- Event displays show us how energy is distributed amongst the 25 crystals
- 5 GeV electron event
- Calibrations are still a work in progress





Energy resolution

- Current best energy resolution at 5 GeV is 6.2%
  - Far from the required 2%
- Very large low energy tail observed and under investigation
- Since the test beam, some improvements have been found
- A grounding issue between the HGCROC Protoboard and EEMCal backplane has been discovered
- A large ripple in the SiPM bias with the utilized power supply is observed



Conclusions

- A successful test beam at DESY was completed
- The analysis is still ongoing to understand the results
- Several improvements to come include better channel by channel signal shape and calibration and masking of bad channels
- The sources of the low energy background are being investigated and remedied
- Preparations are underway for a second test beam campaign later in the year

EEEMCal team

J. Bettane[1], E. Cline[8,9], J. Crafts[10], V. Chaumat[1], M. Czeller[4], C. Delafosse[1], P. Dinaucourt[6], C. Domingues Goncalves[1], F. Dulucq[6], P. Dumas Ziehlmann[6], R.H. Fatemi[14], J. Frantz[13], B. Geoffroy[1], A. Hoghmrtsyan[15], C. de La Taille[6], O. Le Dortz[5], D.K. Hasell[8], T. Horn[10,16], M. Imre[1], L.D. Isenhower[12], S. Jia[7], B. Mathon[1], H. Mkrtchyan[15], A. Migayron[1], R.G. Milner[8], C. Muñoz Camacho[1], G. Nagy[4], M. Nguyen[5], T. Nguyen Trung[1], N. Novitzky[3], S. Obraztsov[5], S. Olmo[1], T. Protzman[2], R. Reed[2], A. Shatat[5], D. Thienpont[6], G. Visser[11]