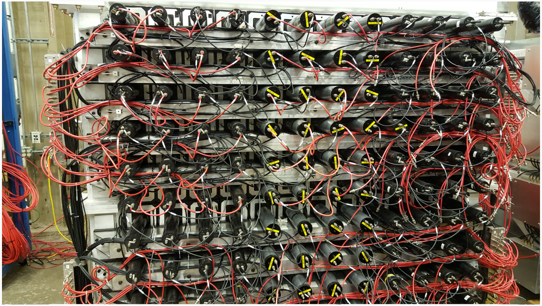
The Hadron Calorimeter for Upcoming SBS Experiments

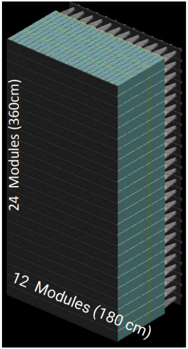
The HCal Working Group
presented by Scott Barcus
January 22nd 2021

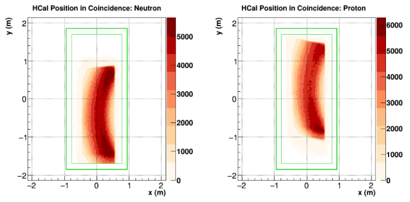
Jefferson Lab



HCal Overview

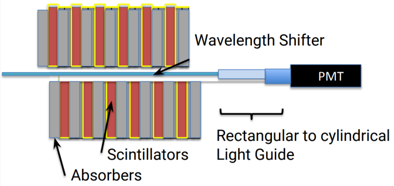
- Design based on COMPASS HCAL1 (Vlasov *et al*. 2006).
- Segmented calorimeter designed to detect multiple GeV protons and neutrons.
  - 288 PMT modules (12×24).
  - Four craneable subassemblies.
  - Weighs ≈40 tons.
  - LED fiber optics system.
- SBS dipole magnet separates scattered hadrons by charge.
- Designed for good time resolution (goal 0.5 ns) and good position resolution.
- Energy resolution ≈30%.

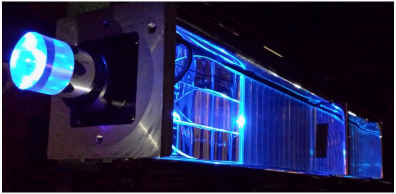




HCal Interior (288 Individual PMT Modules)

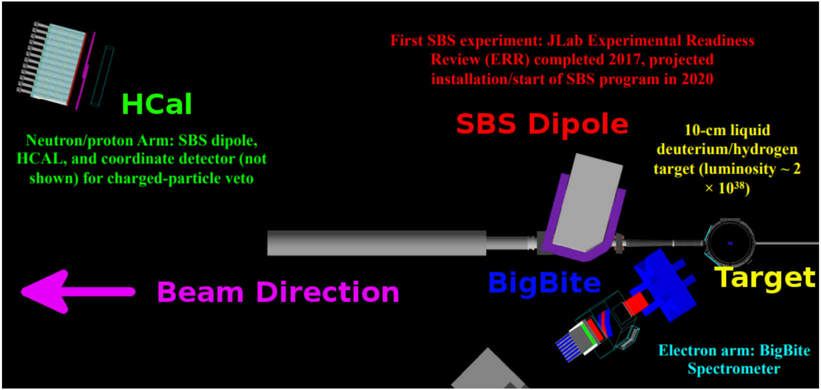
- 40 layers of iron absorbers alternate with 40 layers of scintillator.
- Iron layers cause the hadrons to shower.
- Scintillator layers sample the energy.
- Photons pass through a wavelength shifter increasing detection efficiency.
- Custom light guides transport photons to PMTs.
  - 192 12 stage 2" Photonis XP2262 PMTs.
  - 96 8 stage 2" Photonis XP2282 PMTs.





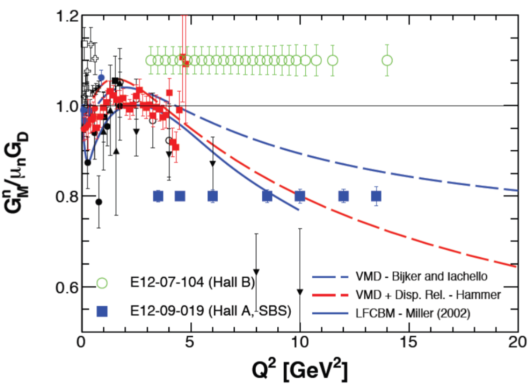
G_M^n Experiment

- G_M^n experiment will extract neutron magnetic form factor.
  - Quasielastic deuterium cross section ratios d(e,e'n)p/d(e,e'p)n (Puckett 2019; Quinn, Wojtsekhowski, Gilman, *et al.* 2008).
- HCal will detect scattered hadrons.
- BigBite spectrometer will detect scattered electrons.



G_M^n Experiment: Science Results

- Flavor decomposition of G_M^n and G_M^p allows extraction of flavor form factors.
- Nucleon form factors constrain GPDs (first moments of H and E).
- High Q^2 G_M^n measurements test lattice QCD, pQCD, VMD models, and effective field theories (Puckett 2019; Quinn, Wojtsekhowski, Gilman, *et al.* 2008).



Geant4 Simulations

- Geant4 simulations model all detectors, the target, and magnets.
  - Full optical photon processes (light yields and backgrounds).
- Require excellent spatial resolution for high Q^2 SBS experiments.
  - $P_N = 8$ GeV: X (horizontal) resolution = 3.2 cm, Y (vertical) resolution = 3.8 cm.
  - $P_N = 2.5$ GeV: X and Y resolution = 6-7 cm.

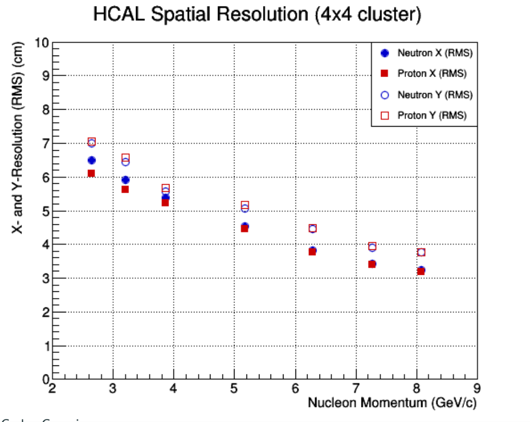


Image image from Juan Carlos Cornejo.

Geant4 Simulations

- HCal also requires nearly identical detection efficiency for protons and neutrons.
  - Ratio of simulated neutron detection efficiency to proton detection efficiency.
  - Ratio $= 0.985$ at 7-8 GeV. Drops to $\approx$0.966 between 2.5-4 GeV.

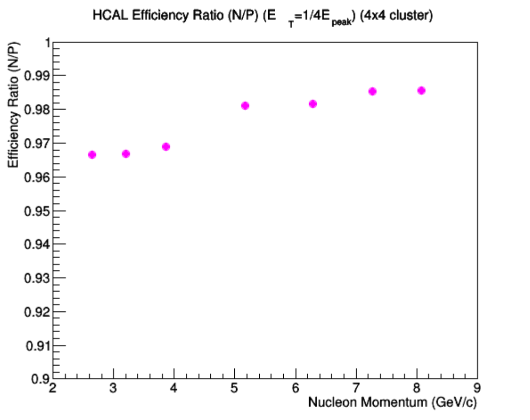
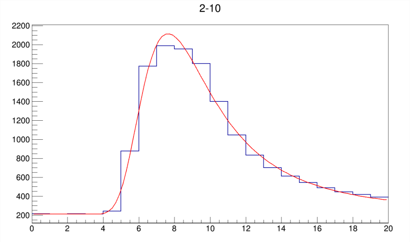
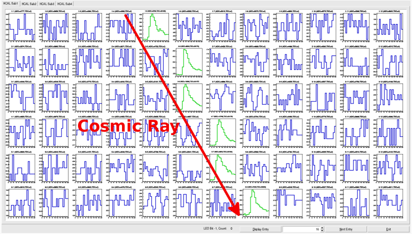


Image image from Juan Carlos Cornejo.

Data Acquisition System

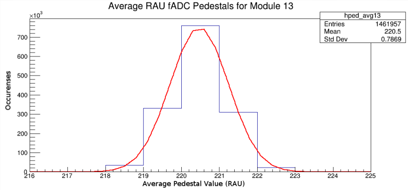
- Two VXS crates.
- 18 16-channel fADC250 flash ADCs measure energy.
  - Takes numerous samples (250 MHz, 4ns).
  - Time over threshold measurements extract timing (CFD removes time walk).
- 5 64-channel F1TDCs for timing.
- VXS Trigger Processors (VTPs) contain FPGAs to form triggers.
- Triggers:
  - Scintillator paddle (cosmics).
  - Summing module trigger.
  - LED pulser trigger.
  - BigBite coincidence trigger.

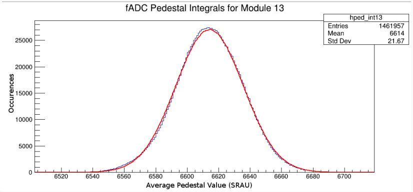


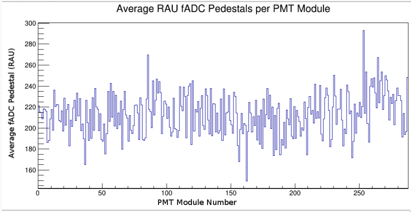


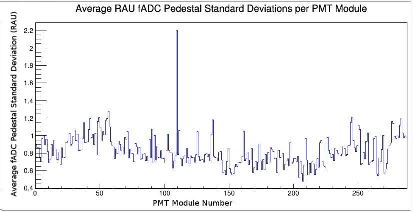
fADC Pedestals

- Typical fADC pedestal results using raw ADC units (RAU) and summed raw ADC units (SRAU).
  - RAU pedestal std. dev. ≈1 and SRAU std. dev. ≈30.









TDC Timing Resolution

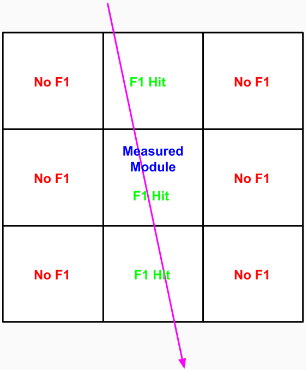
- High time resolution allows separation of elastic and inelastic events.
- Require cosmic to be nearly 'vertical'.
  - Vertical F1 signals (no surrounding).
- TDC time:

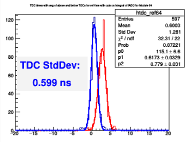
$$T_{\mathrm{cor}} = T_{\mathrm{PMT}} - T_{\mathrm{ref}},$$

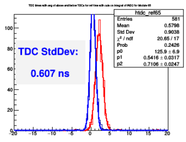
$$T_{\mathrm{ref}} = \frac{\mathrm{TDC}\ 1 + \mathrm{TDC}\ 2}{2}.$$

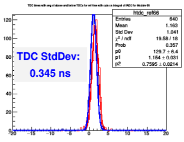
- Standard deviation of single PMT:

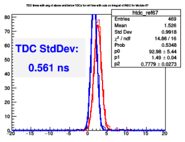
$$\sigma_{PMT} = \sqrt{|\sigma_{cor}^2 - \sigma_{ref}^2|}.$$







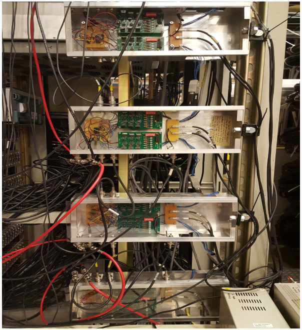




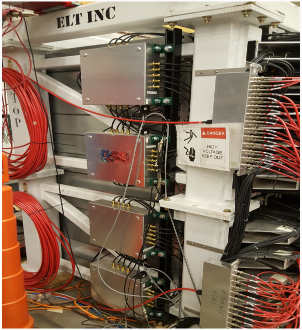
HCal LED System

- All 288 PMT modules can observe 6 different LEDs via fiber.
- Each successive LED is roughly twice as bright as the previous LED.
- Powered by 8 LED power boxes on front-end (4 completed).
- Each LED power box controls 2 LED boxes on the sides of HCal (all 16 completed).

LED Power Boxes

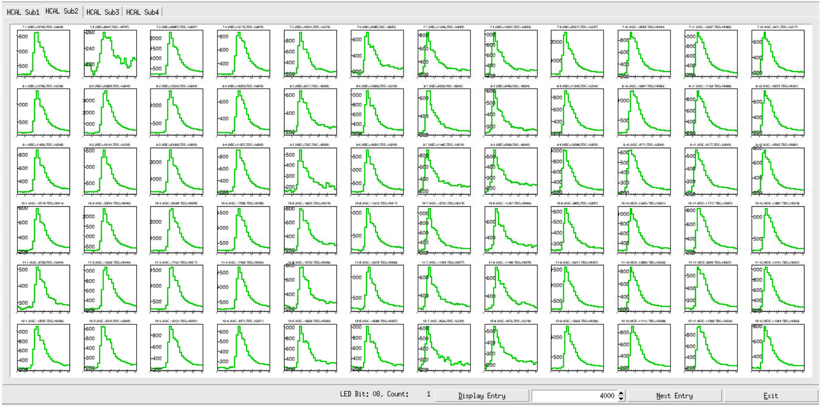


LED Boxes



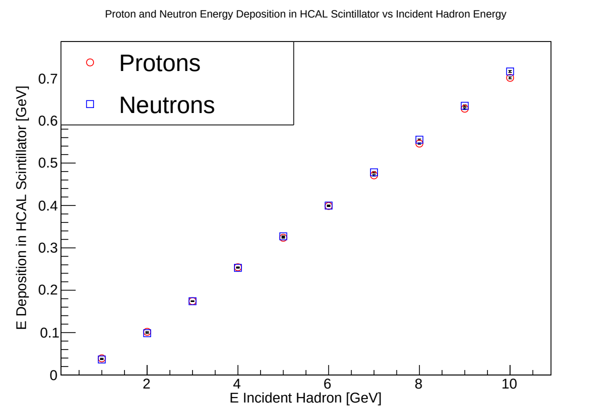
LED Event Display

- Gives a fast stable signal to work with.
- LED cycles programmable (i.e. turn LED1 on for 1000 triggers then LED2 for 1000).



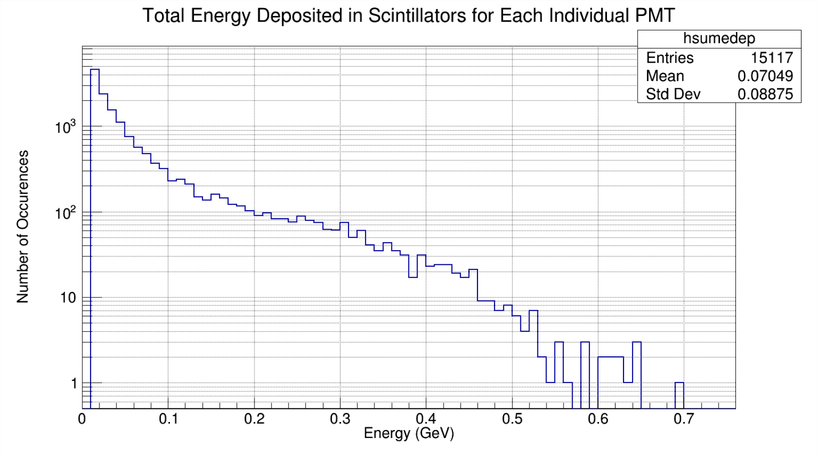
Cosmic Ray HV Calibration

- Calibrate the HV using cosmic rays (match fADC signals).
- Set cosmic ray signals so a hadron depositing the maximal energy during G_M^n won't saturate electronics.
- Use G4SBS to determine energy deposited by hadrons and cosmics.
  - Plot of energy deposited in scintillators vs. incident hadron energy. (Plot thanks to Sebastian Seeds.)



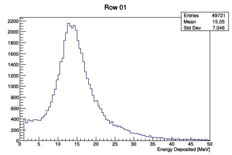
G4SBS for HV Calibration

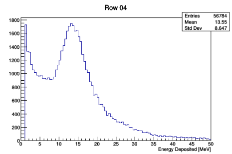
- Plot of maximum energy deposited in scintillators seen by a single PMT for G_M^n max kinematic.
  - Max energy deposited in single PMT $\approx$ 700 MeV.

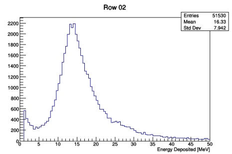


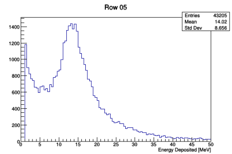
G4SBS for HV Calibration

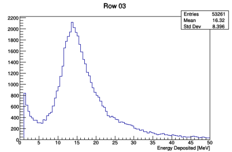
- Plots show average energy deposited in a single PMT's scintillators for a vertical cosmic ray. (Plots from Juan Carlos Cornejo.)
  - Average energy $\approx$ 14 MeV. (700 MeV/14 MeV = 50)
  - Set HV such that cosmics reach 1/50th electronics saturation.

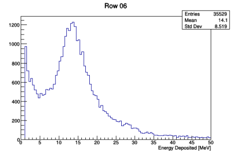






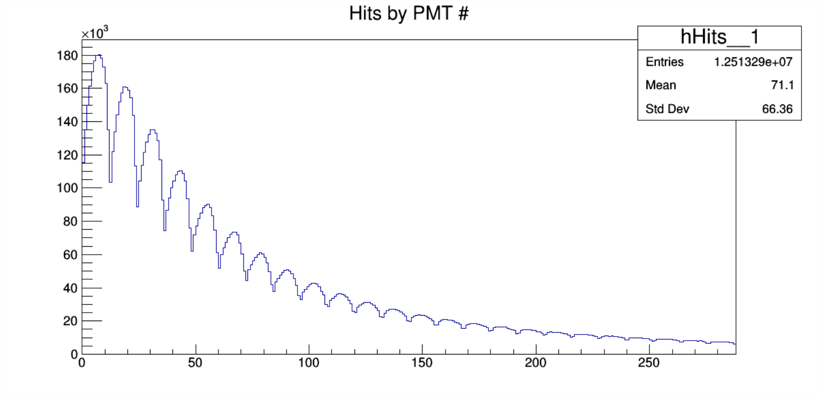






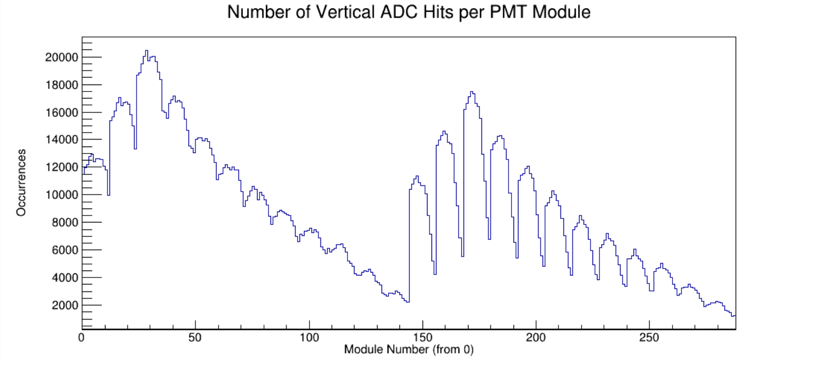
G4SBS Cosmics

- Cosmic runs are currently being taken to calibrate the HV based on fADC signal.
- Plot shows what G4SBS predicts cosmics will look like in HCal. (Plot from Juan Carlos Cornejo.)



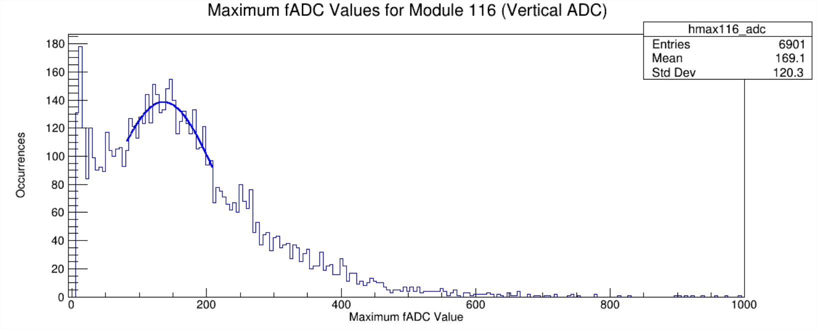
Cosmic Results

- Plot shows vertical (three consecutive) PMT fADC hits for HCal.



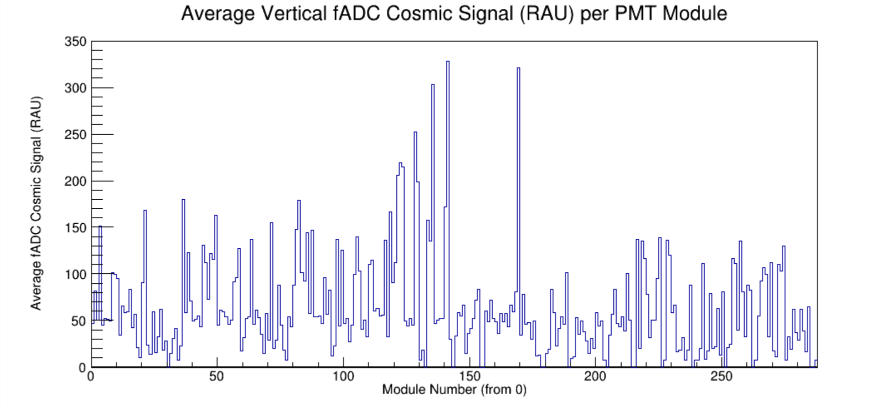
Finding Average Cosmic Amplitude

- Cosmic hit defined as fADC signals above threshold above and below PMT module.
  - fADC threshold applied to central module as well to cut out pedestal.
- Fit signal peak with Gaussian (skewed).



Cosmic Calibration Progress

- Plots display the average fADC signal (RAU) during a cosmic event versus PMT module for three runs.
  - Each successive run calibrates signals closer to goal of 61 RAU by adjusting HV.



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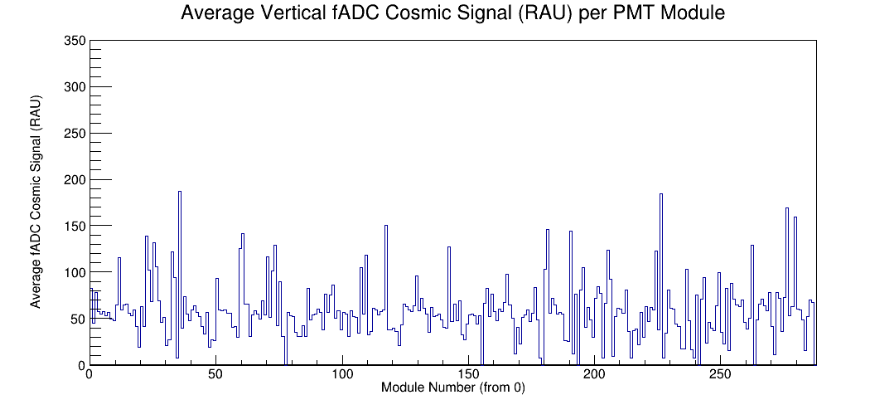

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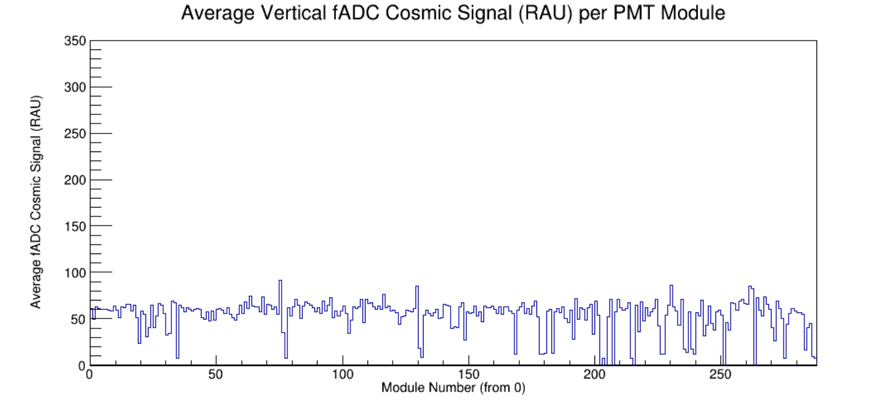
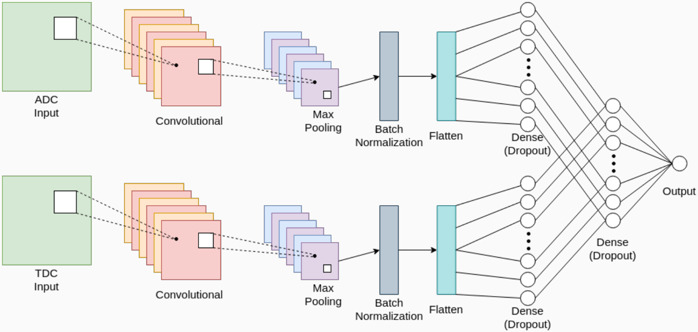


Machine Learning Detector Trigger for HCal

- Motivation:
  - High background rates obscure physics signals.
- Traditional Solutions:
  - Energy threshold cuts.
  - Prescaling the data.
  - Decreasing the beam current.
- Machine Learning Solution:
  - Train a neural network to classify detector events (e.g. p, n, π).
  - Use data from G4SBS converted to detector output to train NN.
  - Load trained NN onto VTP FPGA (fast) to use as HCal trigger.
- Goal:
  - Demonstrate that NNs can be loaded onto VTPs for triggering JLab detectors.
  - Allow HCal to run at higher current with a cleaner trigger.

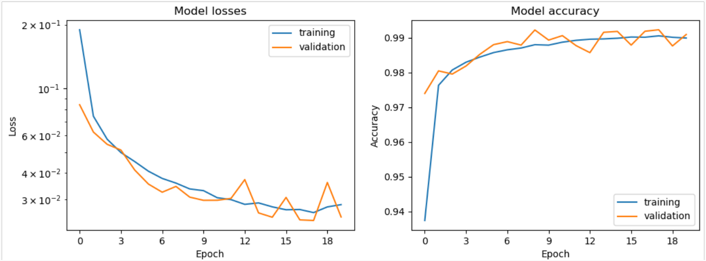
Proposed Convolutional Neural Network Architecture



- PMT pulse shapes are essentially images.
  - Each event every PMT has several fADC samples and a TDC value.
- CNN scans across the image with a kernel creating filters which identify localized features (like hits).
  - Detector geometry preserved.
  - Pooling decreases dimensionality by merging adjacent signals.
  - Batch normalization improves speed and regularization.
  - Dropout helps reduce overfitting.

Toy Example HCal Neural Network

- Create CNN to identify events with large cosmic signals.
  - Input: PMT fADC integrals.
  - Note: Traditional methods work better than this illustrative example.
- Tools: ROOT, Python, Numpy, Scikit-learn, Tensorflow, Keras, Google Colaboratory (GPUs).
- 99% accuracy with small amount of optimizing!



HCAL-J Summary

- Detects protons and neutrons for future JLab Hall A SBS experiments.
  - Measure nucleon form factors up to high Q^2.
- Energy resolution ≈30%.
- High time resolution (≈0.5 ns).
- Excellent position resolution (as low as 3-4 cm).
- Similar detection efficiency for protons and neutrons.
- LED system for calibrations (currently studying HV vs. gain).
- Cosmic ray testing and calibrations in progress.
- ML particle ID detector trigger research ongoing.
  - Serve as test bed for FPGA based ML detector triggers at JLab and hopefully create a cleaner HCal trigger.

Acknowledgments

Thanks to Gregg Franklin for his many dedicated years designing and overseeing the construction of HCal. Thanks to Universitá di Catania for their major financial contributions. Many other people and institutions were involved in making HCal possible, including, but not limited to:

- Thanks to the many students who have worked on HCal including Alexis Ortega, So Young Jeon, Jorge Peña, Carly Wever, and Dimitrii Nikolaev.
- Thanks to our current students Vanessa Brio and Sebastian Seeds.
- Thanks to Alexandre Camsonne for helping us get the DAQ working.
- Thanks to Chuck Long for all his help fixing and acquiring things.
- Thanks to Bryan Moffit for DAQ help.
- Thanks also to Brian Quinn and Bogdan Wojtsekhowski.
- Thanks to Vanessa Brio, Cattia Petta, and Vincenzo Bellini for their cosmic commissioning efforts.

References

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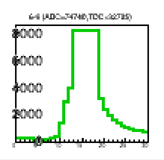
Quinn, B., B. Wojtsekhowski, R. Gilman, *et al.* (2008). *Precision Measurement of the Neutron Magnetic Form Factor up to $Q^2 = 18.0\ (\mathrm{GeV}/c)^2$ by the Ratio Method*. URL: https://hallaweb.jlab.org/collab/PAC/PAC34/PR-09-019-gmn.pdf.

LED High Voltage Calibration

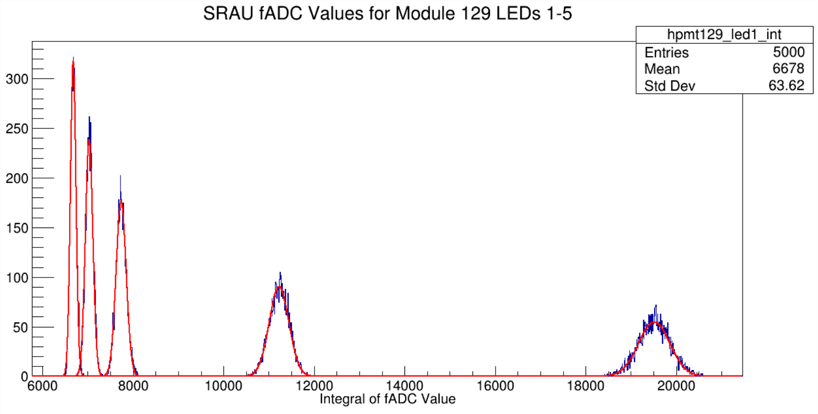
- Want to know fADC signal to HV calibration (gain calibration).
- Program LEDs to cycle during run in 1000 event increments.
  - Off→LED1→LED2→LED3→LED4→LED5→Repeat
- Data was taken on the left half of HCal at eight voltages.
  - -1200 V, -1250 V, -1300 V, -1350 V, -1375 V, -1400 V, -1425 V, -1450 V.
  - Five full cycles of data were taken (5k events/setting).

- At low voltages and dimmer LEDs sometimes there is no PMT response.
- At high voltage and brighter LEDs sometimes the fADC saturates.



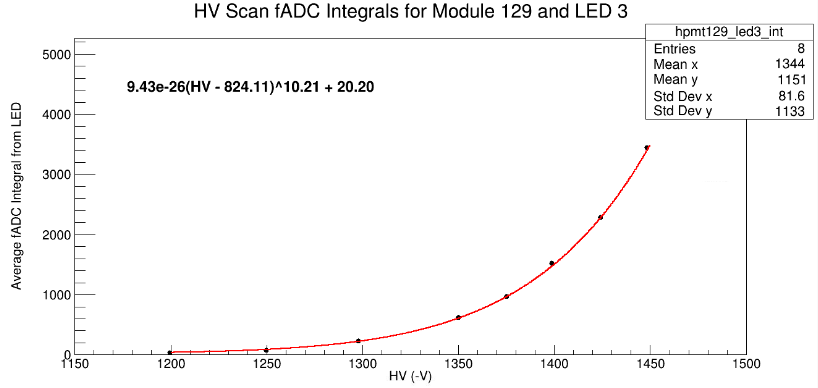
SRAU for 5 LEDs

- Fit each LED fADC signal histogram for each HV setting.
- Pictured below PMT 129 at a single voltage looking at 5 different LEDs.
  - Each LED roughly doubles in brightness as expected.
  - Plot is not pedestal subtracted.



Selected Results

- The CMU PMTs have exponents ≈ 10-11.



Selected Results

- The JLab PMTs have exponents ≈ 8.