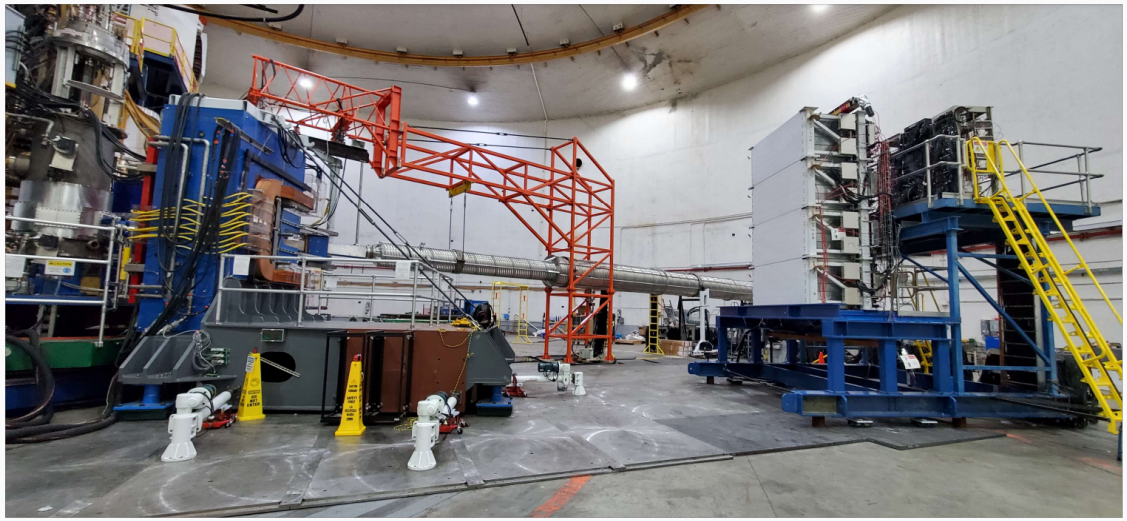
SBS Hadron Calorimeter Commissioning Results

Scott Barcus on behalf of the HCal Working Group

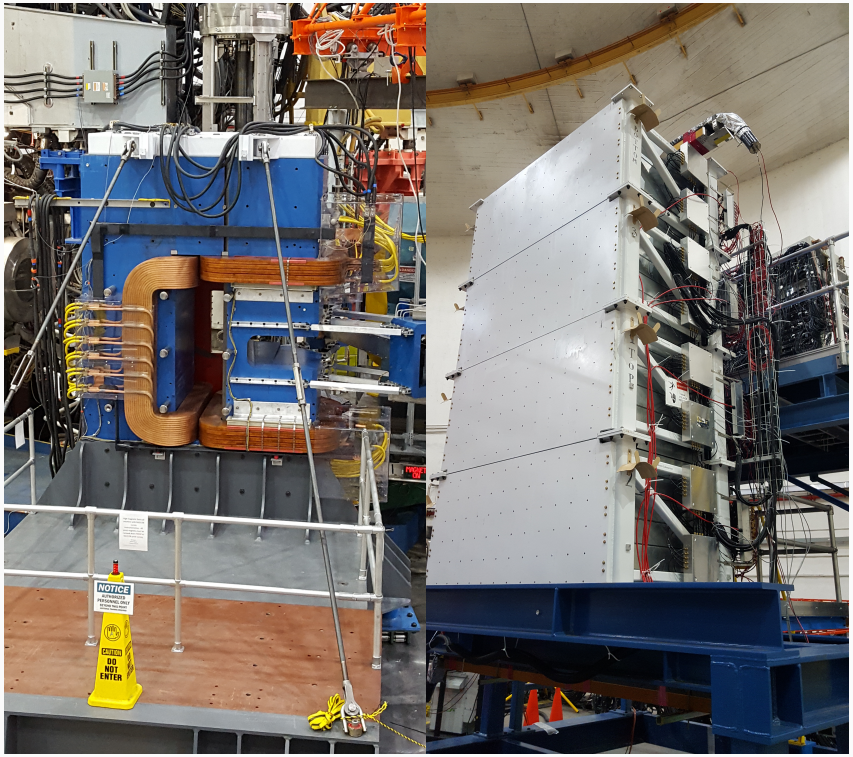
February 11th 2022

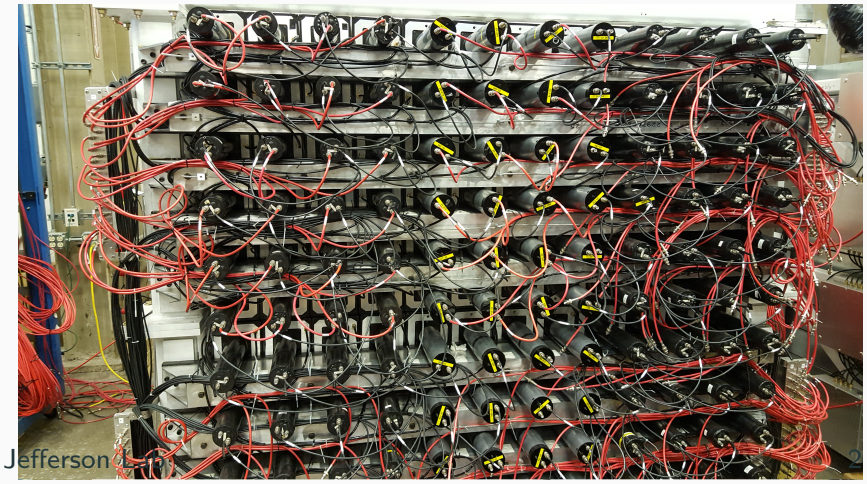
Jefferson Lab



HCal Overview

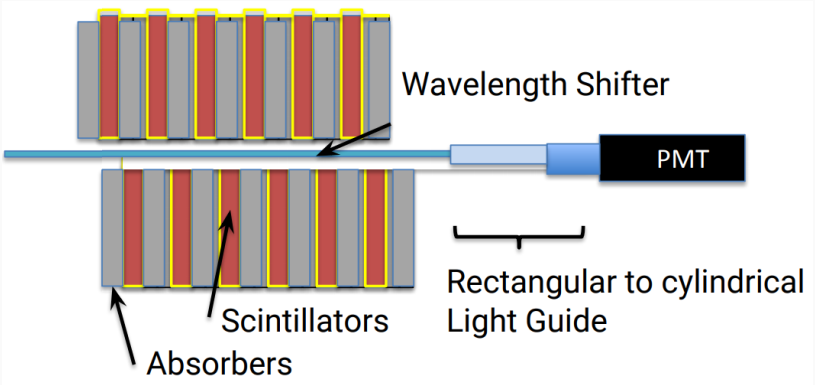
- Design based on COMPASS HCAL1 (Vlasov *et al.* 2006).
- Segmented calorimeter designed to detect multiple GeV protons and neutrons.
  - 288 PMT modules (24×12).
  - LED fiber optics system.
- SBS dipole magnet separates scattered hadrons by charge.
- High time resolution (0.5 ns).
- High position resolution (3-4 cm at 8 GeV).
- Neutron to proton detection efficiency ratio 0.985 at 8 GeV.
- Energy resolution ≈30%.

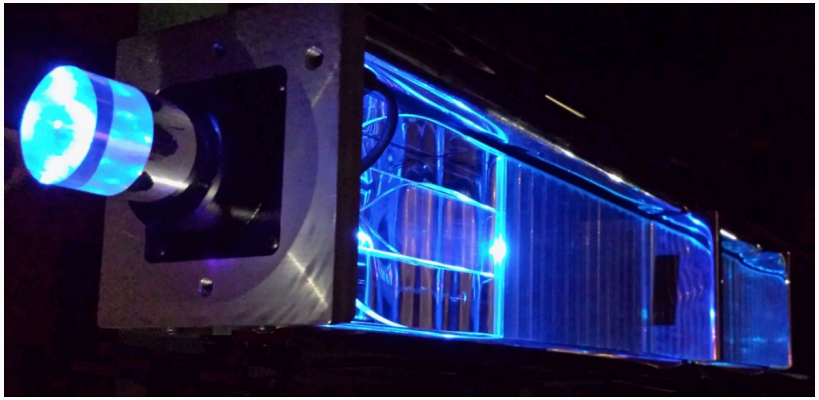




HCal Interior (288 Individual PMT Modules)

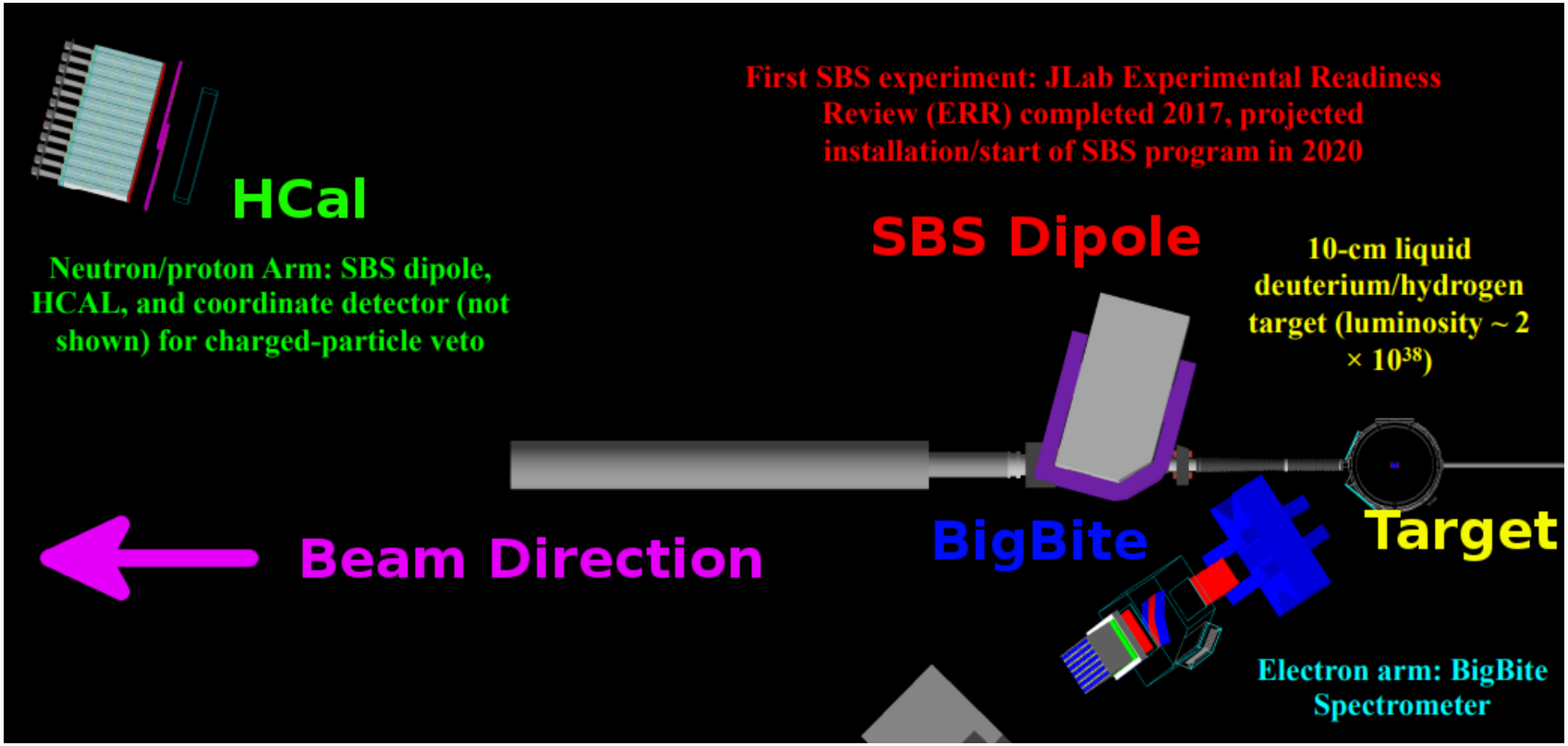
- 40 layers of iron absorbers alternate with 40 layers of scintillator.
- Iron causes hadrons to shower.
- Scintillator layers sample energy.
- Photons pass through a wavelength shifter increasing detection efficiency.
- Custom light guides transport photons to PMTs.
  - 192 12 stage 2" Photonis XP2262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





G_M^n Experiment

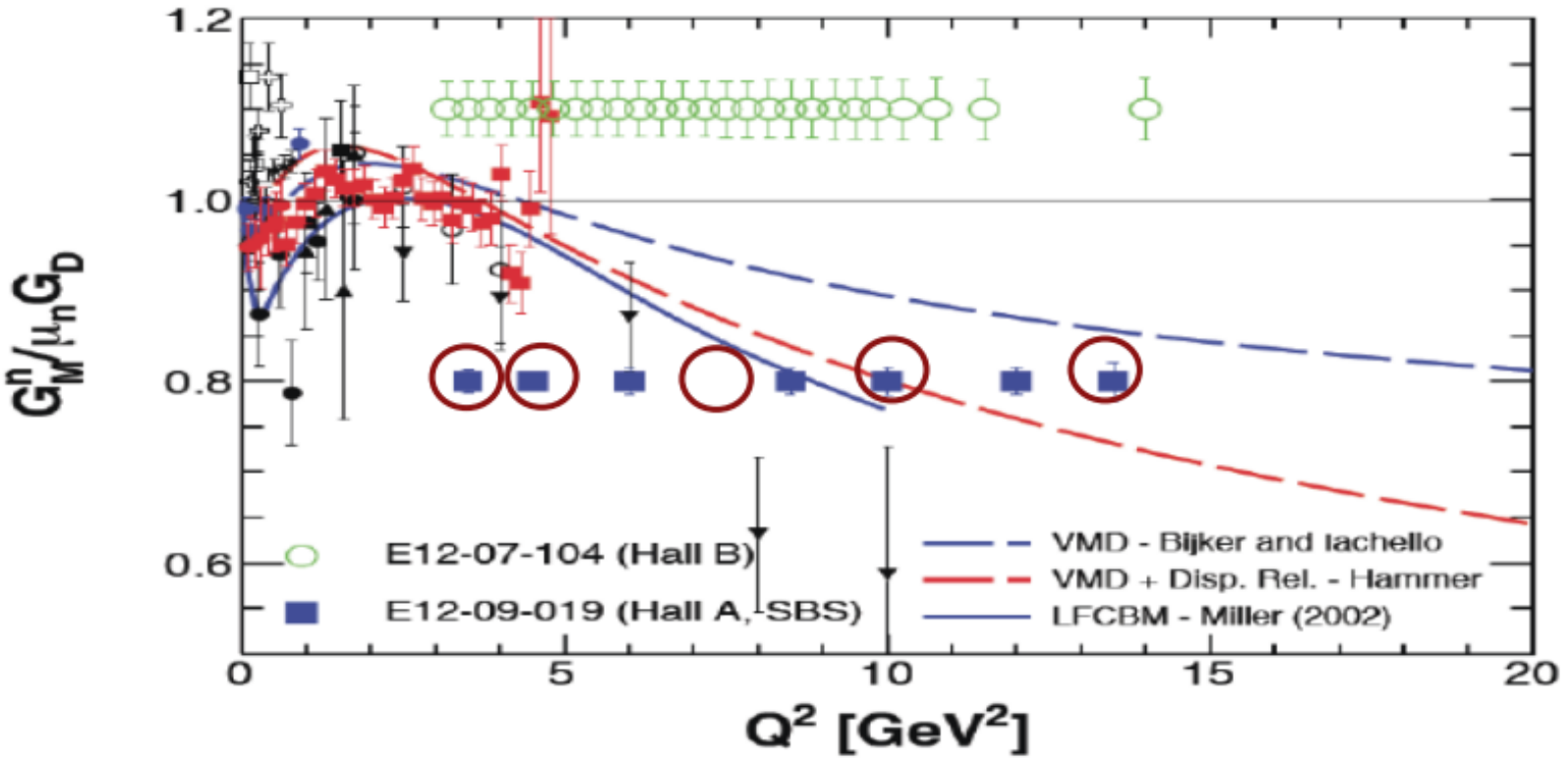
- G_M^n experiment to extract neutron magnetic form factor.
  - Quasielastic deuterium cross section ratios d(e,e'n)p/d(e,e'p)n. (Puckett 2019; Quinn, Wojtsekhowski, Gilman, *et al.* 2008)
- HCal detected scattered hadrons.
- BigBite spectrometer detected scattered electrons.



G_M^n Experiment: Science Results

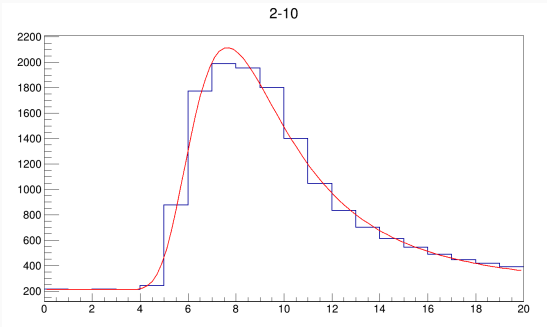
- Flavor decomposition of G_M^n and $G_M^p \rightarrow$ flavor form factors.
- Nucleon form factors constrain GPDs (first moments of H and E).
- High Q^2 G_M^n measurements test lattice QCD, pQCD, VMD models, and effective field theories. (Puckett 2019; Quinn, Wojtsekhowski, Gilman, *et al.* 2008)

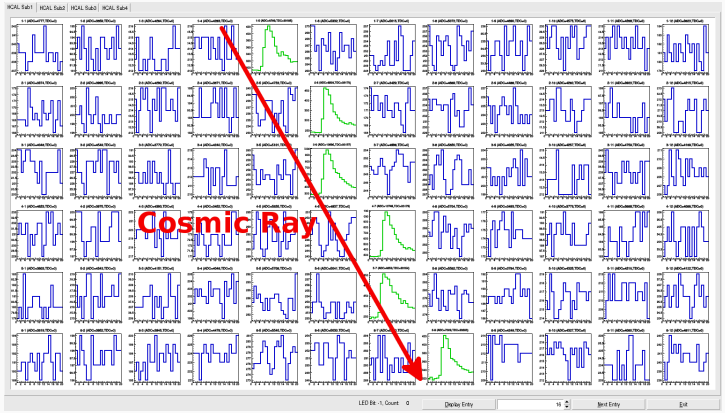
- Completed Q^2 = 3, 4.5, 7.5, 10 and 13.6 GeV^2

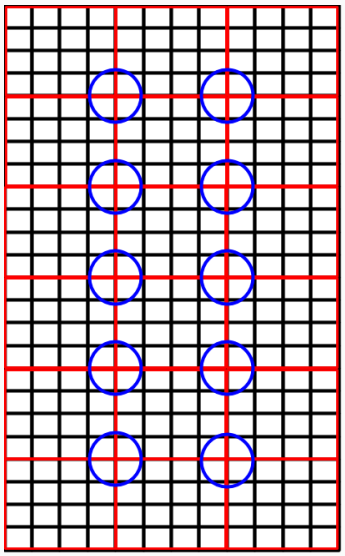


Data Acquisition System

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

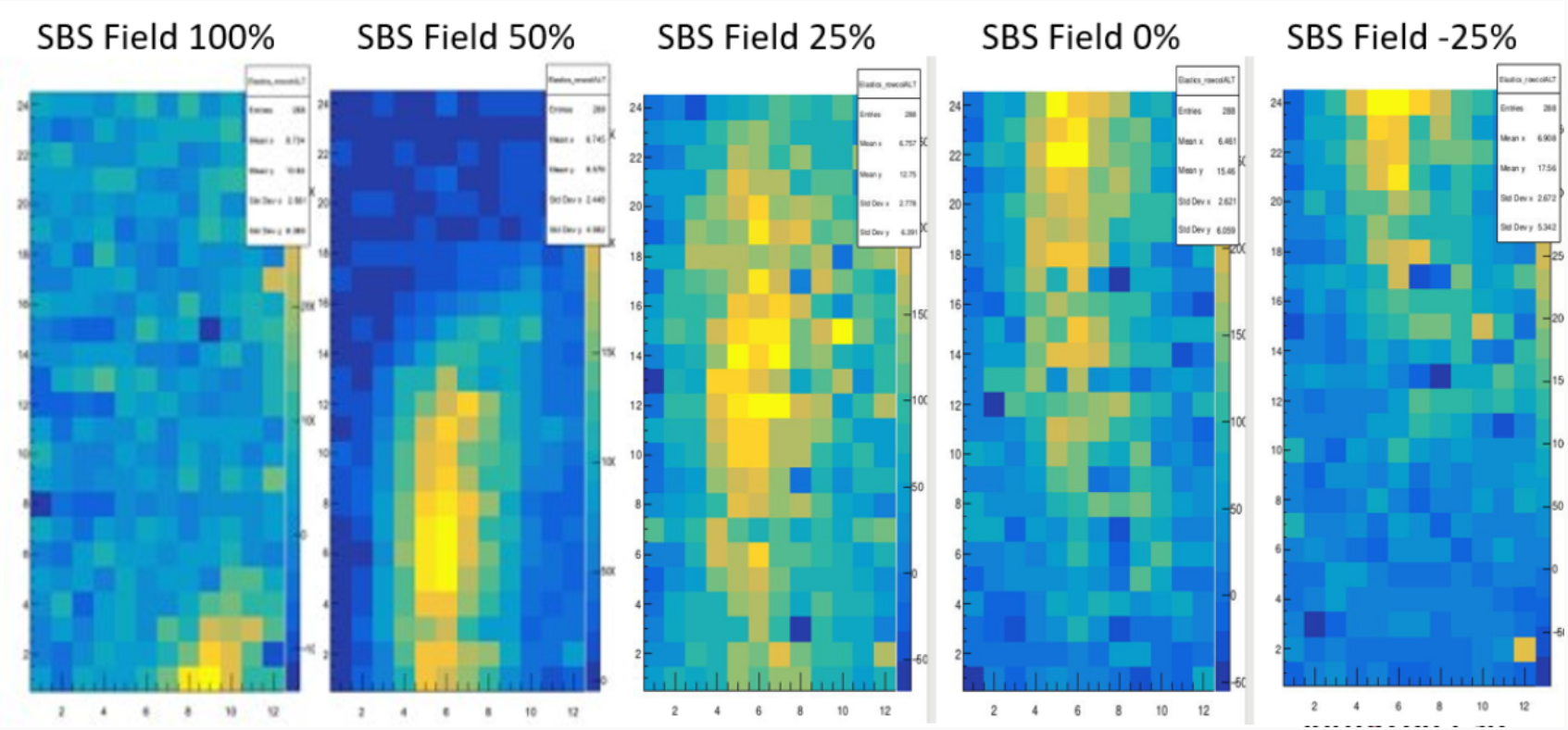






Proton Sweep

- Using a LH_2 target sweep the magnetic field to illuminate all of HCal with elastic protons.
- These elastics are well understood and can be used for calibrations and detector characterization.



Geant4 Simulations Position Resolution

- 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.

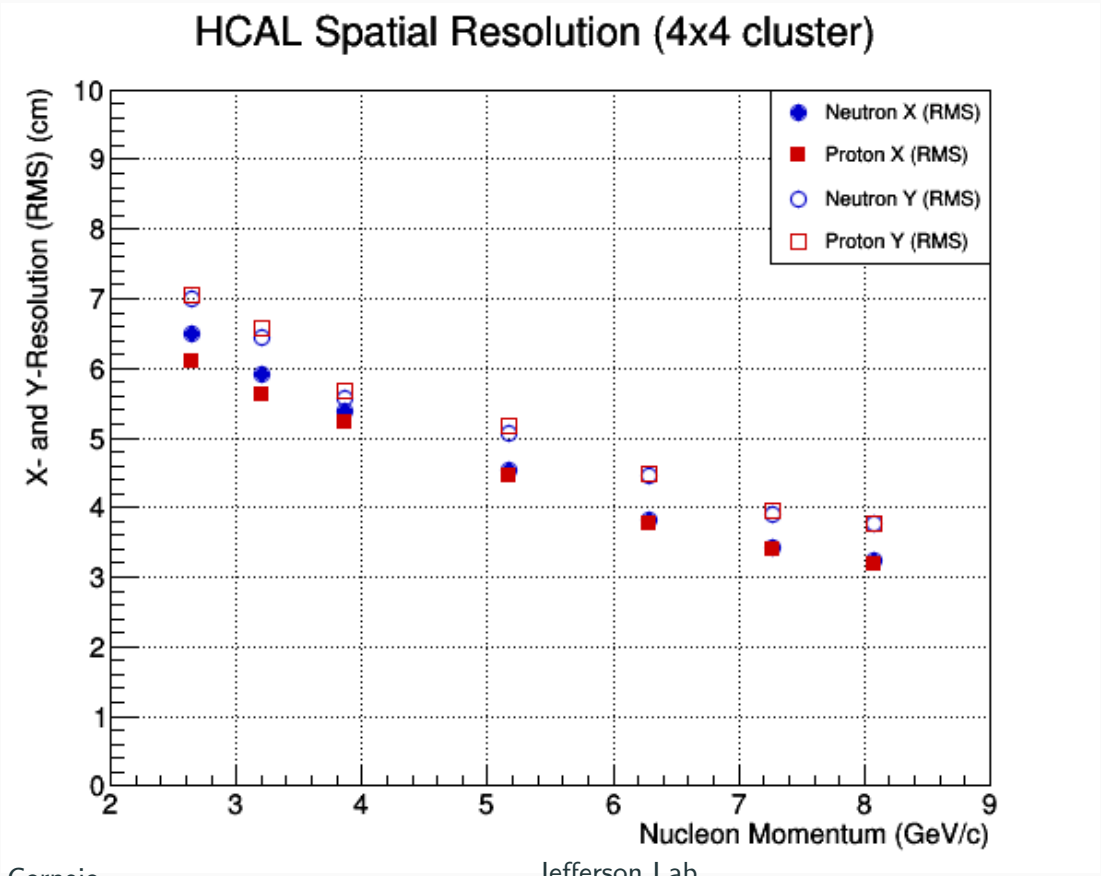
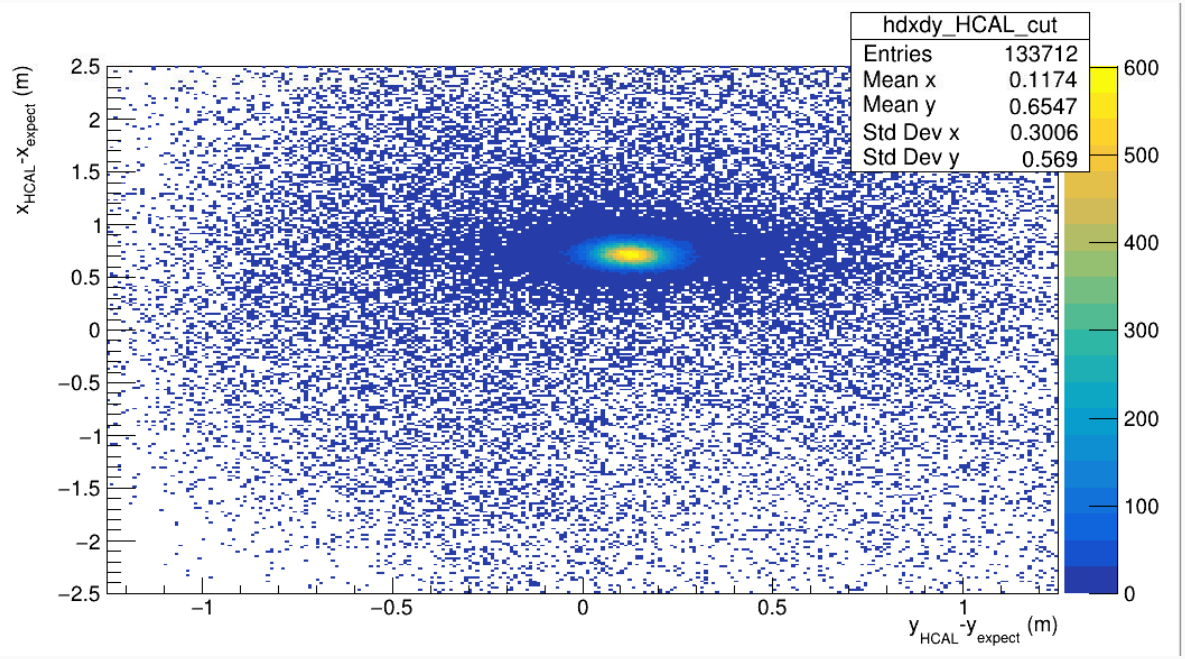


Image from Juan Carlos Cornejo.

Elastic Hadrons on HCal

- Using track reconstruction from GEMs and BB project the hadron path onto HCal.
  - Assume no SBS field → proton measured position is higher than expected.
  - Find cluster X,Y position and subtract off the expected position.
  - See elastic proton spots from hydrogen.



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- May have replayed SBS8 before optics were well calibrated.

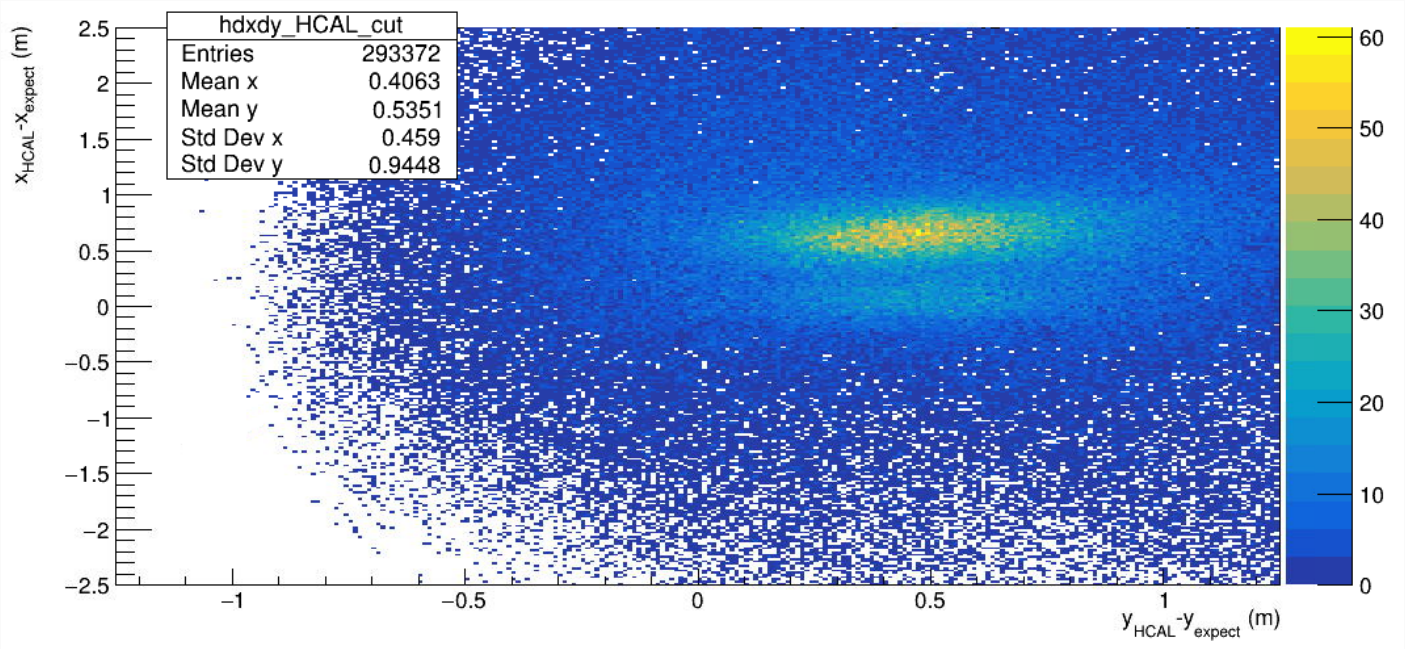
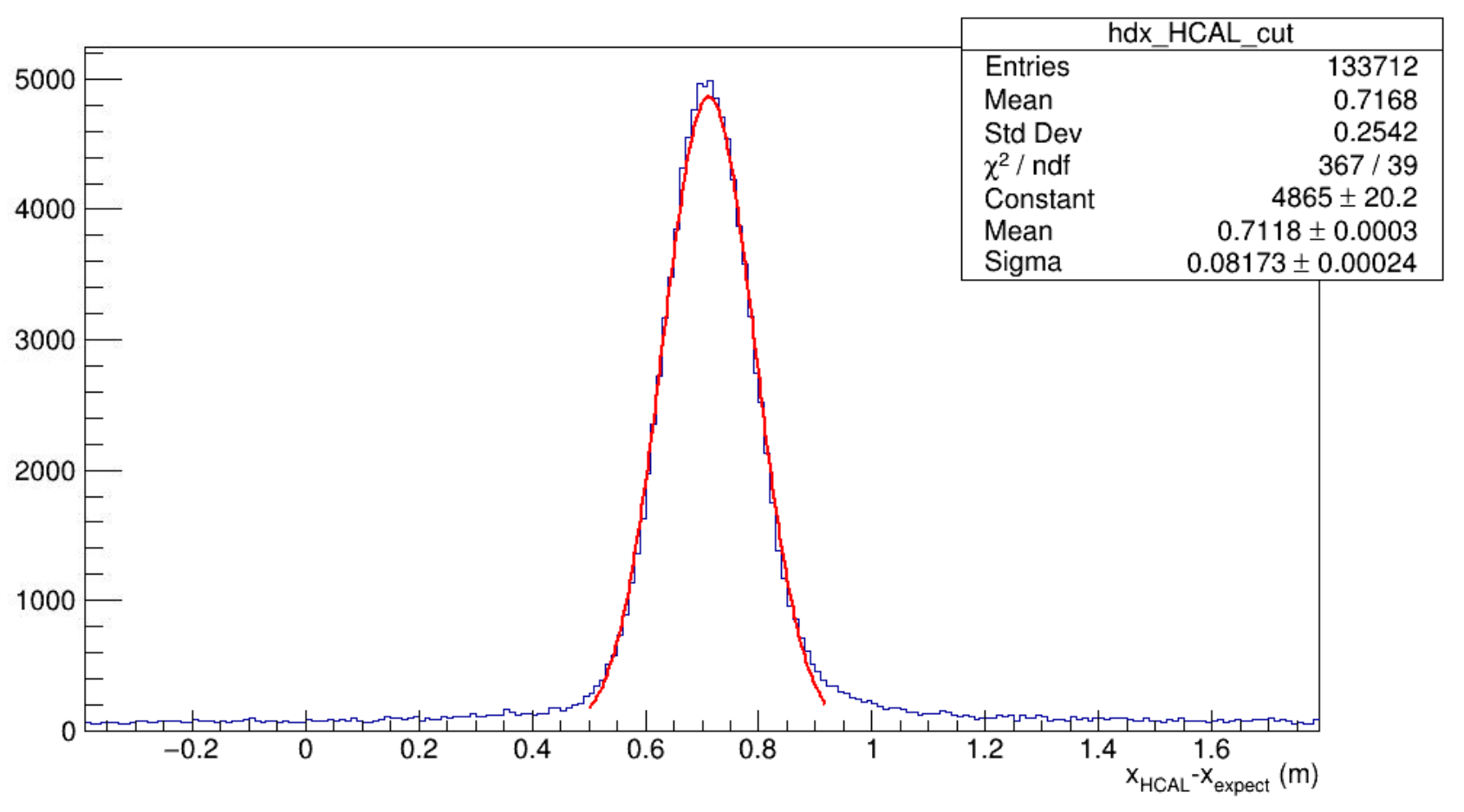


Image from Sebastian Seeds.

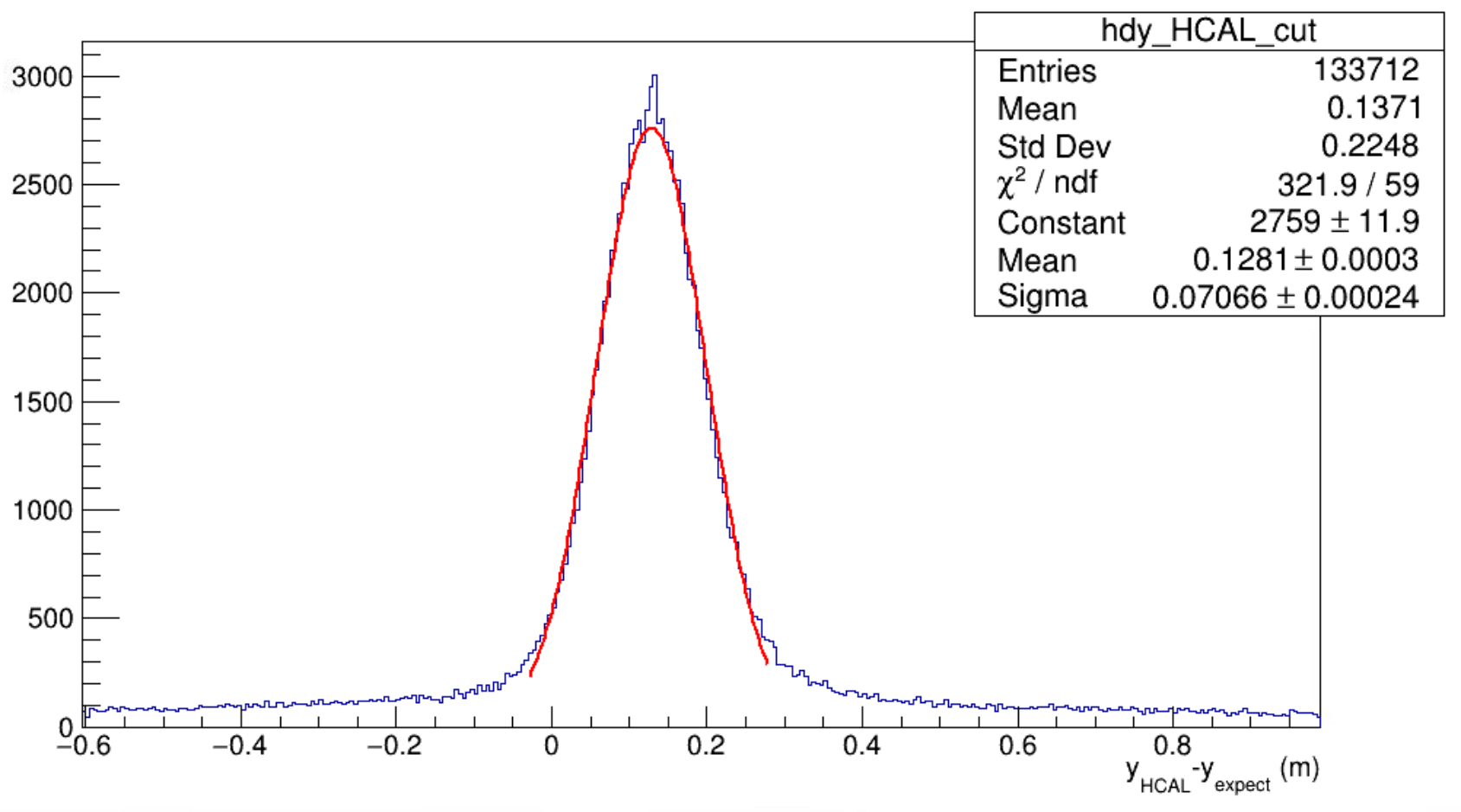
Measured Position Resolution

- SBS4 X-direction (vertical) position resolution $\approx$ 8.2 cm.
  - $E_{beam} \approx 3.7 GeV$ and $Q^2 \approx 3 GeV^2$.



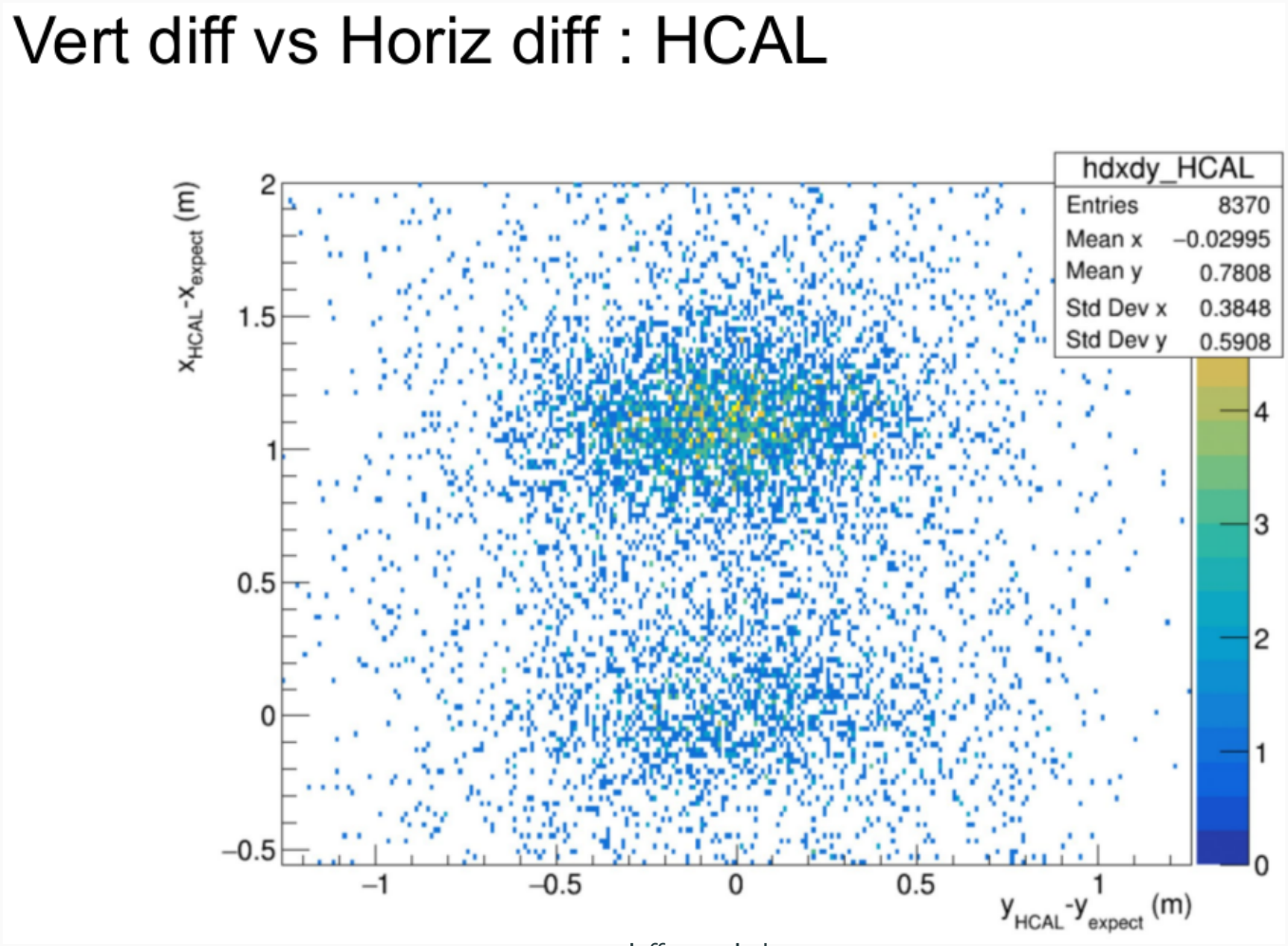
Measured Position Resolution

- SBS4 Y-direction (horizontal) position resolution $\approx$ 7.1 cm.
  - $E_{beam} \approx 6 GeV$ and $Q^2 \approx 4.5 GeV^2$.



Hadron X-Position LD_2

- SBS4 HCal X-position expected vs. measured with zero SBS field.
  - Proton peak deflected upwards ≈110 cm on HCal.
  - See clear neutron peak below the proton peak.



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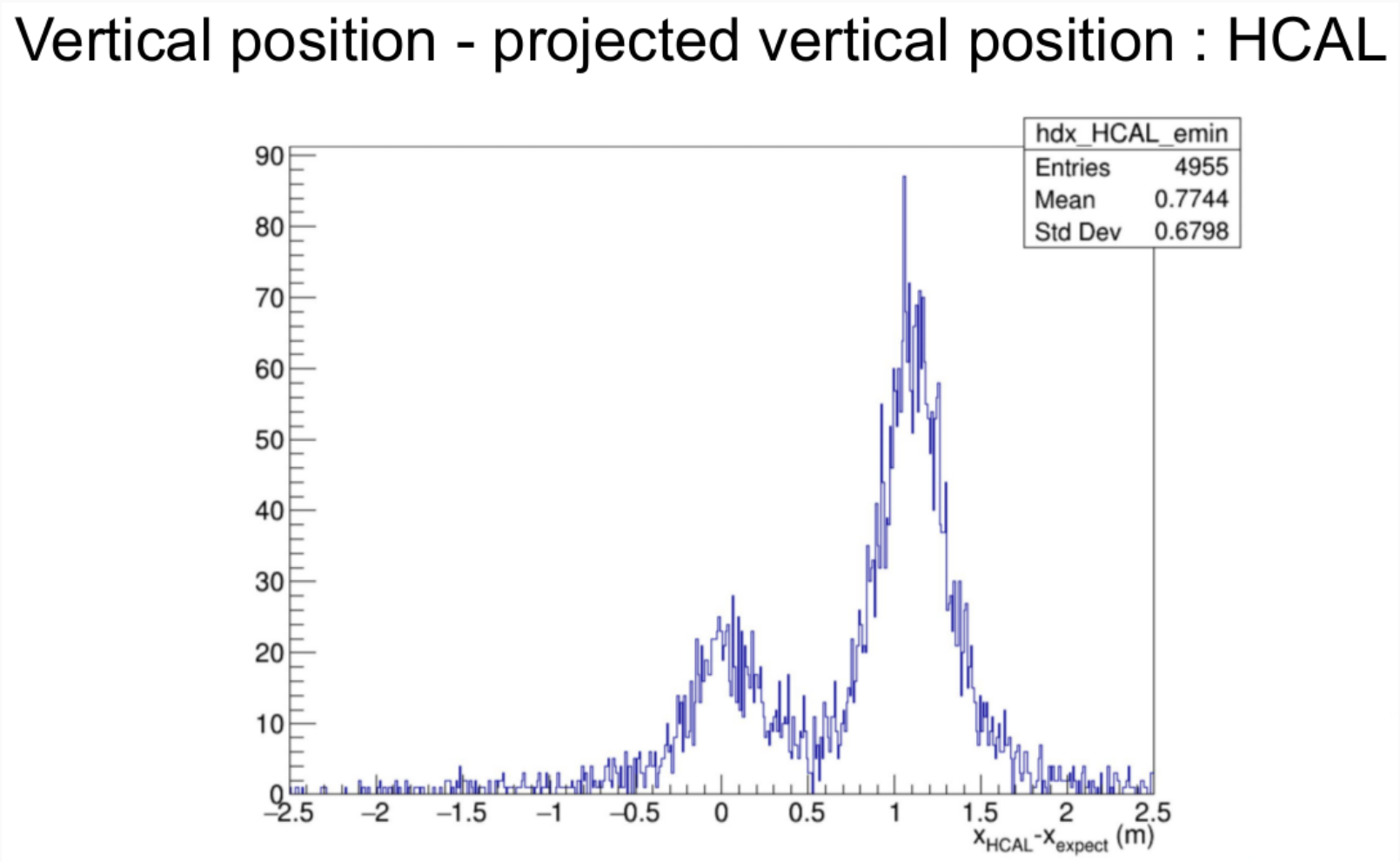


Geant4 Simulations Detection Efficiency

- HCal requires comparable detection efficiency for protons and neutrons.
  - Ratio of simulated neutron detection efficiency to proton efficiency.
  - Ratio = 0.985 at 7-8 GeV. Drops to ≈0.966 between 2.5-4 GeV.

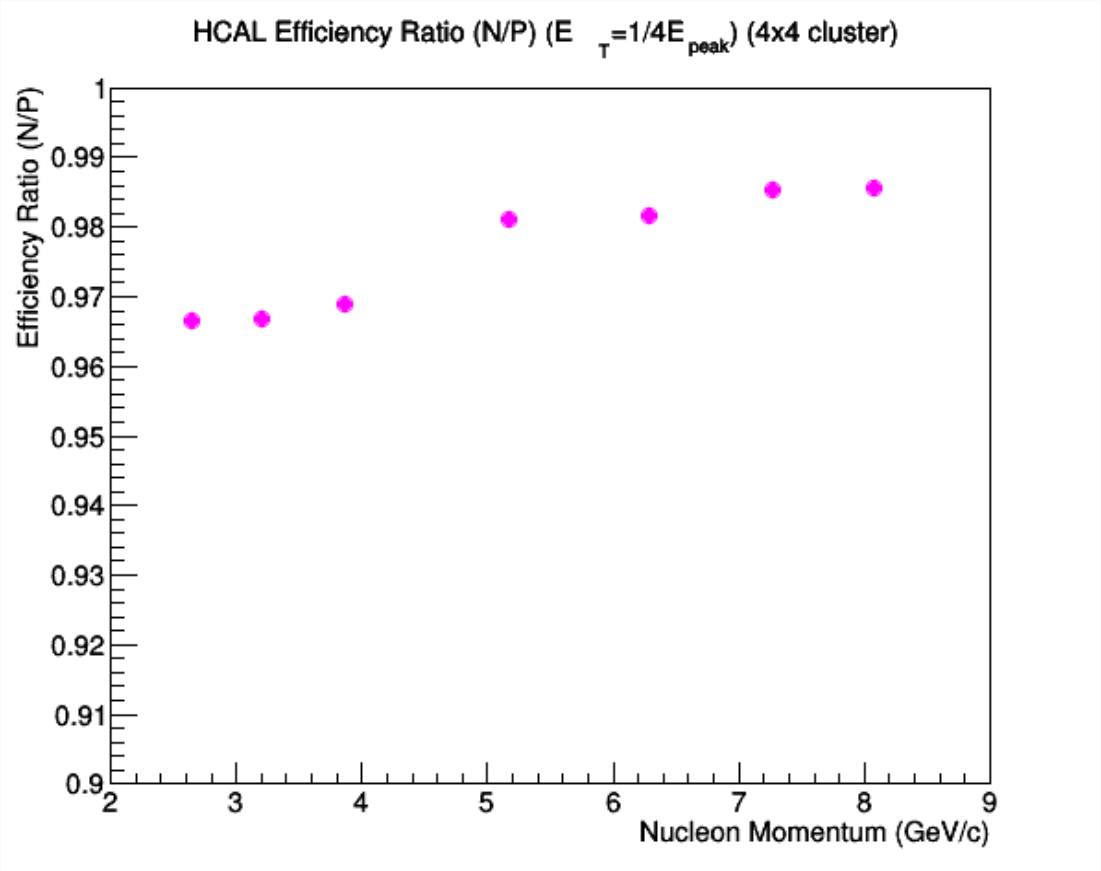


Image from Juan Carlos Cornejo.

Detection Efficiency Uniformity

- Important to detect protons and neutrons with the same efficiency.
  - If detection efficiency differs the p/n cross section ratio becomes less accurate.
- Proton elastic spot separated from neutrons by SBS magnet.
  - Need the detection efficiency at the proton spot and neutron spots to be the same.
- Using elastic electron information from BB and GEMs calculate expected hadron energy.
  - Measured HCal cluster energy for elastic hadrons represents the sampling fraction of the expected energy detected.
  - This sampling fraction should be uniform across the surface of HCal.
  - Predicted by Geant4 to be on the order of $\approx$7.5%.

Detection Efficiency Uniformity SBS4 & SBS8

- SBS4: $E_{beam} \approx 3.7 GeV$ and $Q^2 \approx 3 GeV^2$. Sampling fraction ≈4.76%.

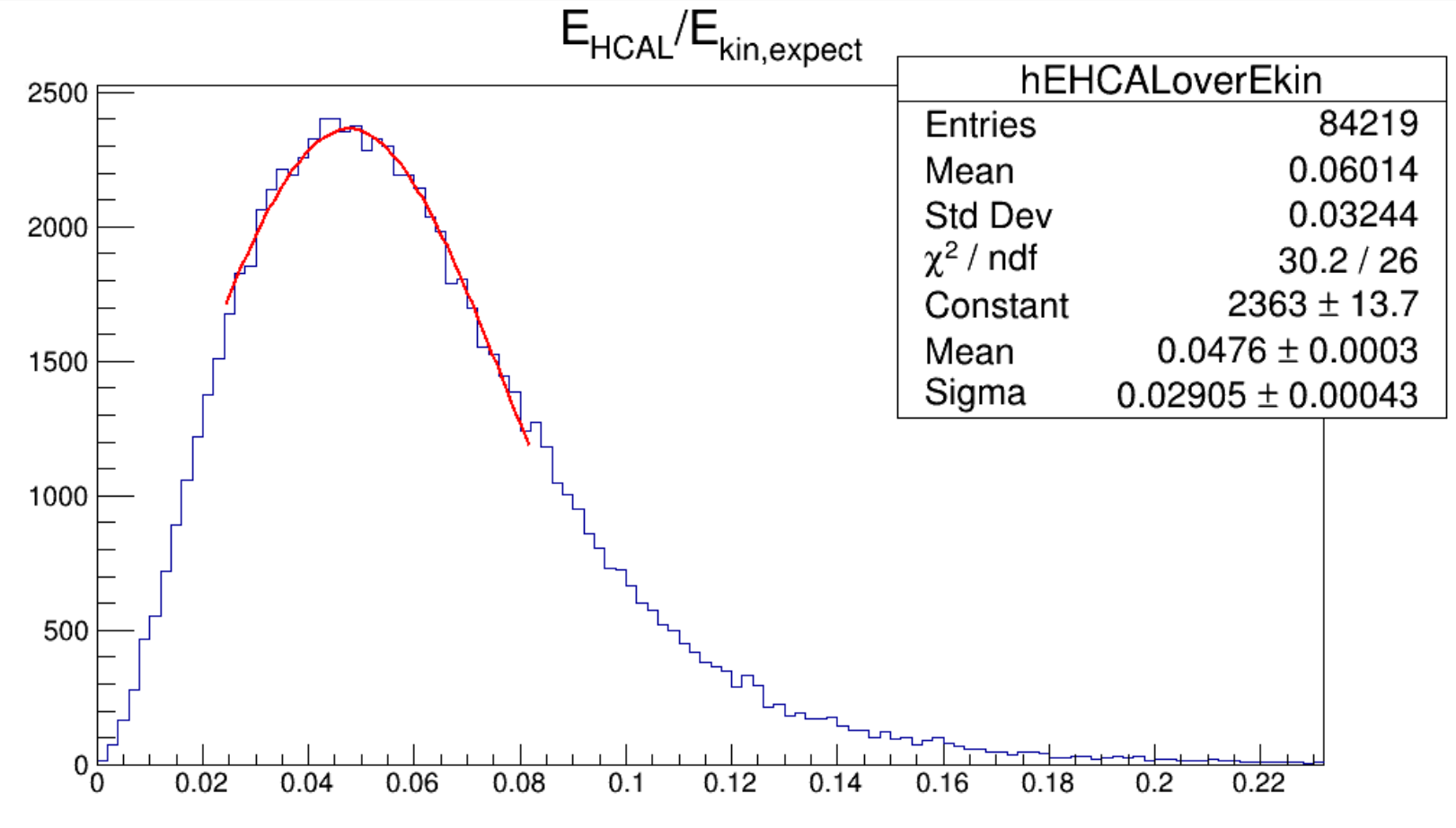


Image from Sebastian Seeds.

Detection Efficiency Uniformity SBS4 & SBS8

- SBS8: $E_{beam} \approx 6 GeV$ and $Q^2 \approx 4.5 GeV^2$. Sampling fraction ≈3.63%.

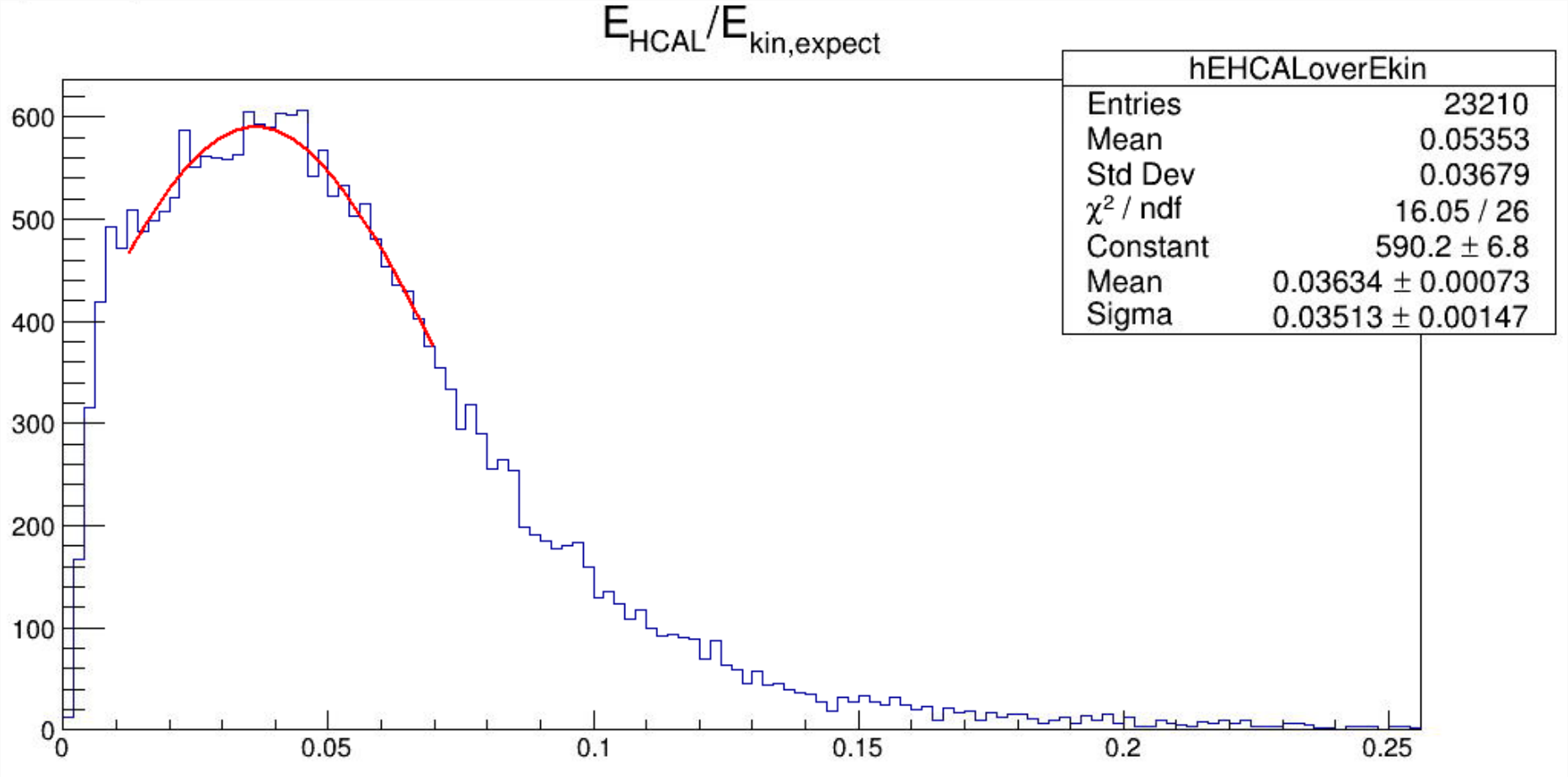


Image from Sebastian Seeds.

Detection Efficiency Uniformity SBS4 & SBS8

- SBS4: $E_{beam} \approx 3.7 GeV$ and $Q^2 \approx 3 GeV^2$. Sampling fraction by row.

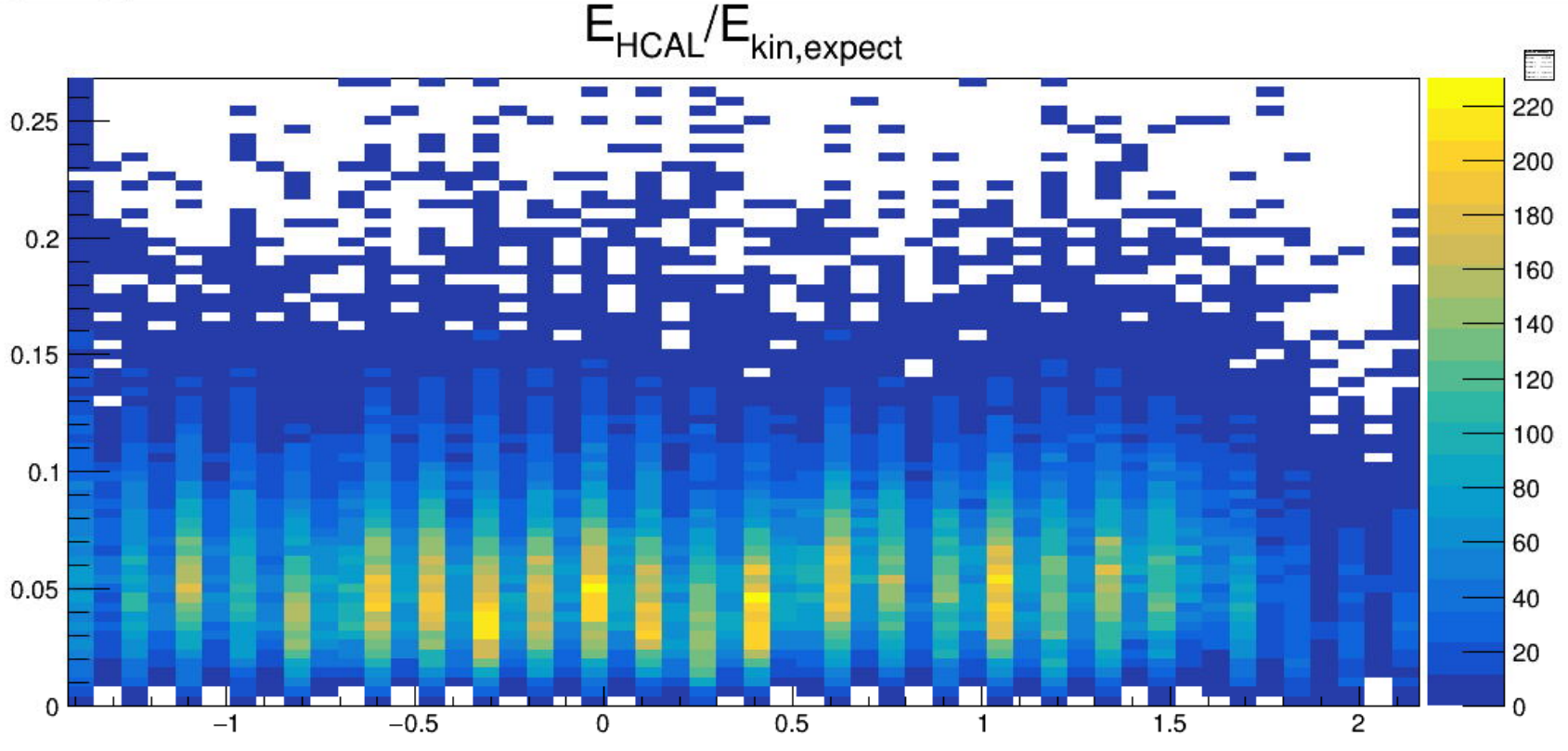
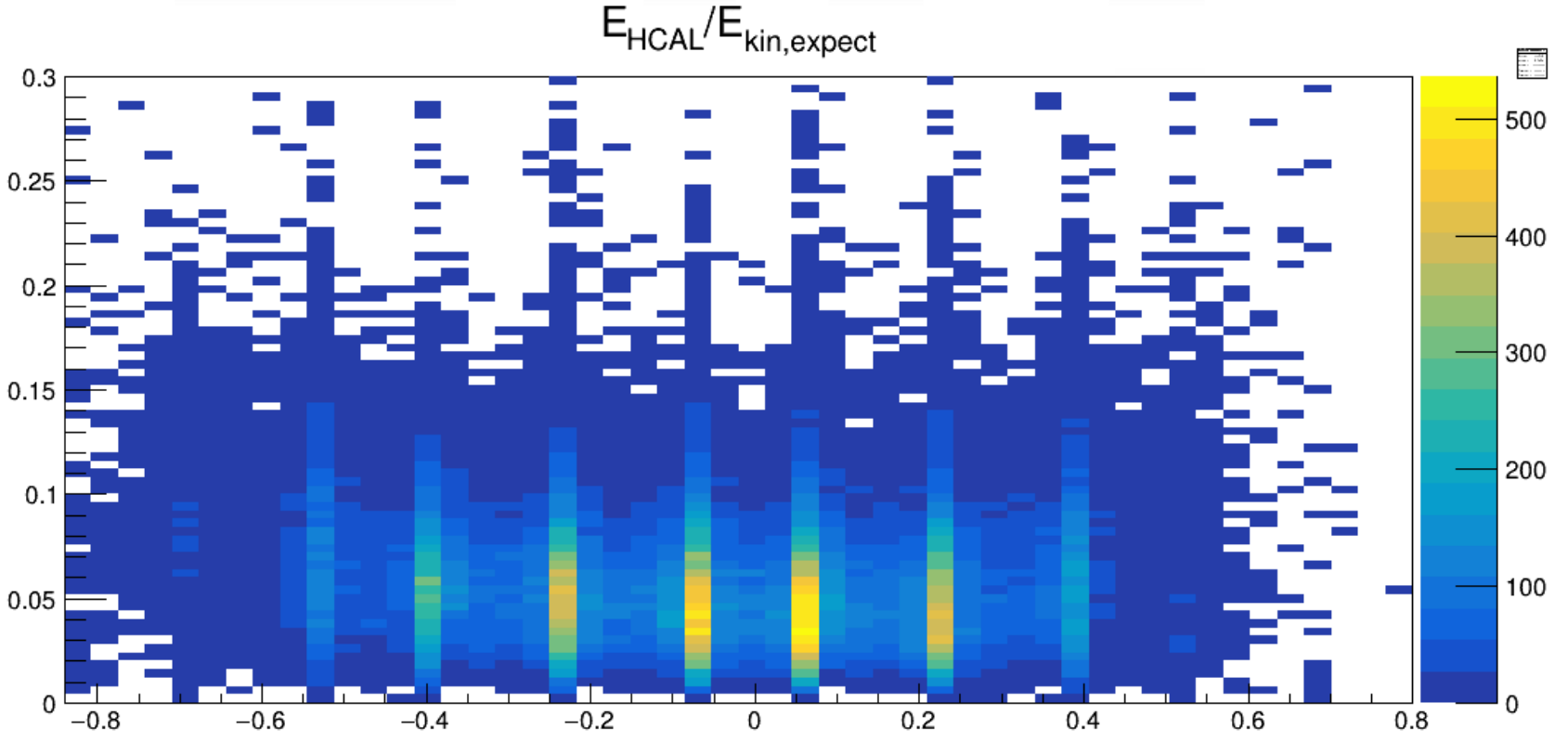


Image from Sebastian Seeds.

Detection Efficiency Uniformity SBS4 & SBS8

- SBS4: $E_{beam} \approx 3.7 GeV$ and $Q^2 \approx 3 GeV^2$. Sampling fraction by column.



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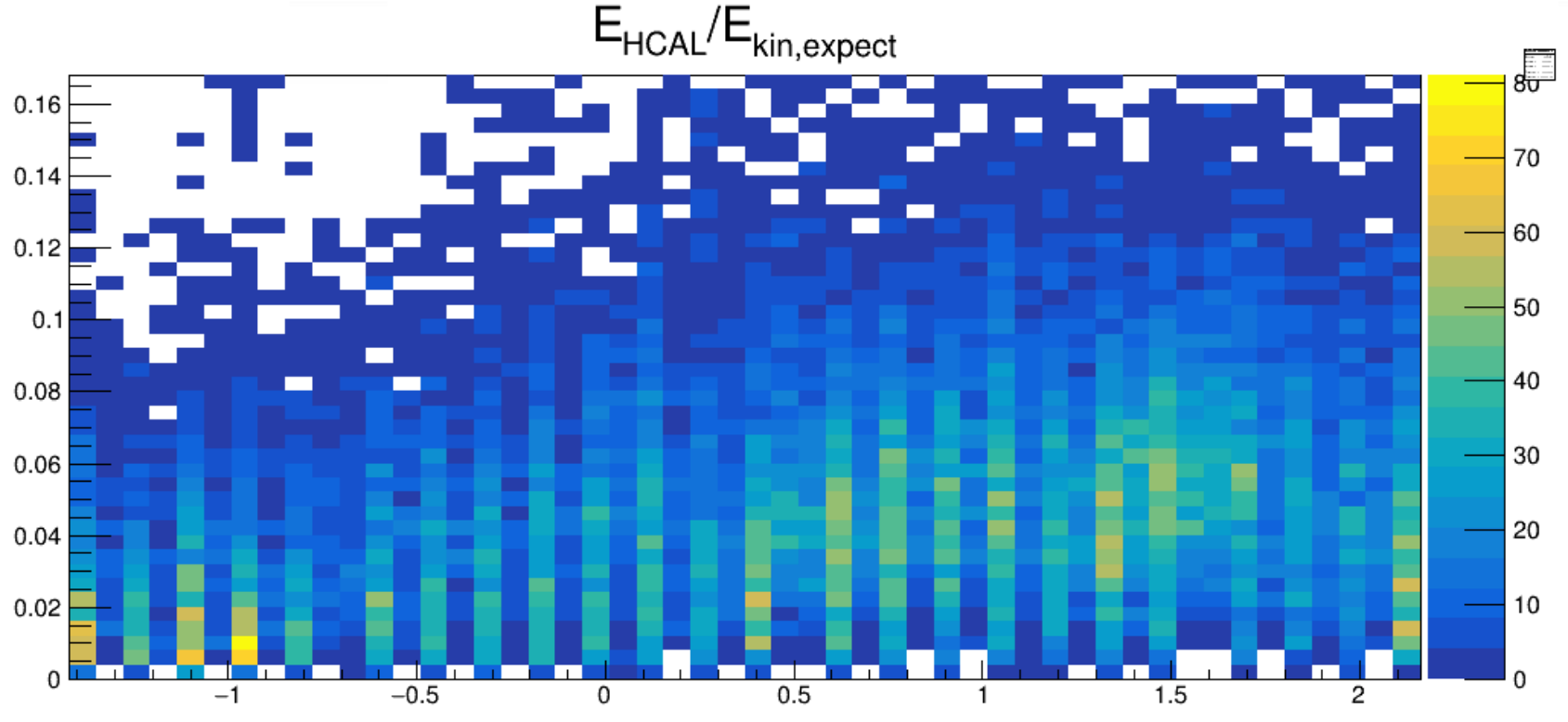
Detection Efficiency Uniformity SBS4 & SBS8

- SBS8: $E_{beam} \approx 6 GeV$ and $Q^2 \approx 4.5 GeV^2$. Sampling fraction by row.



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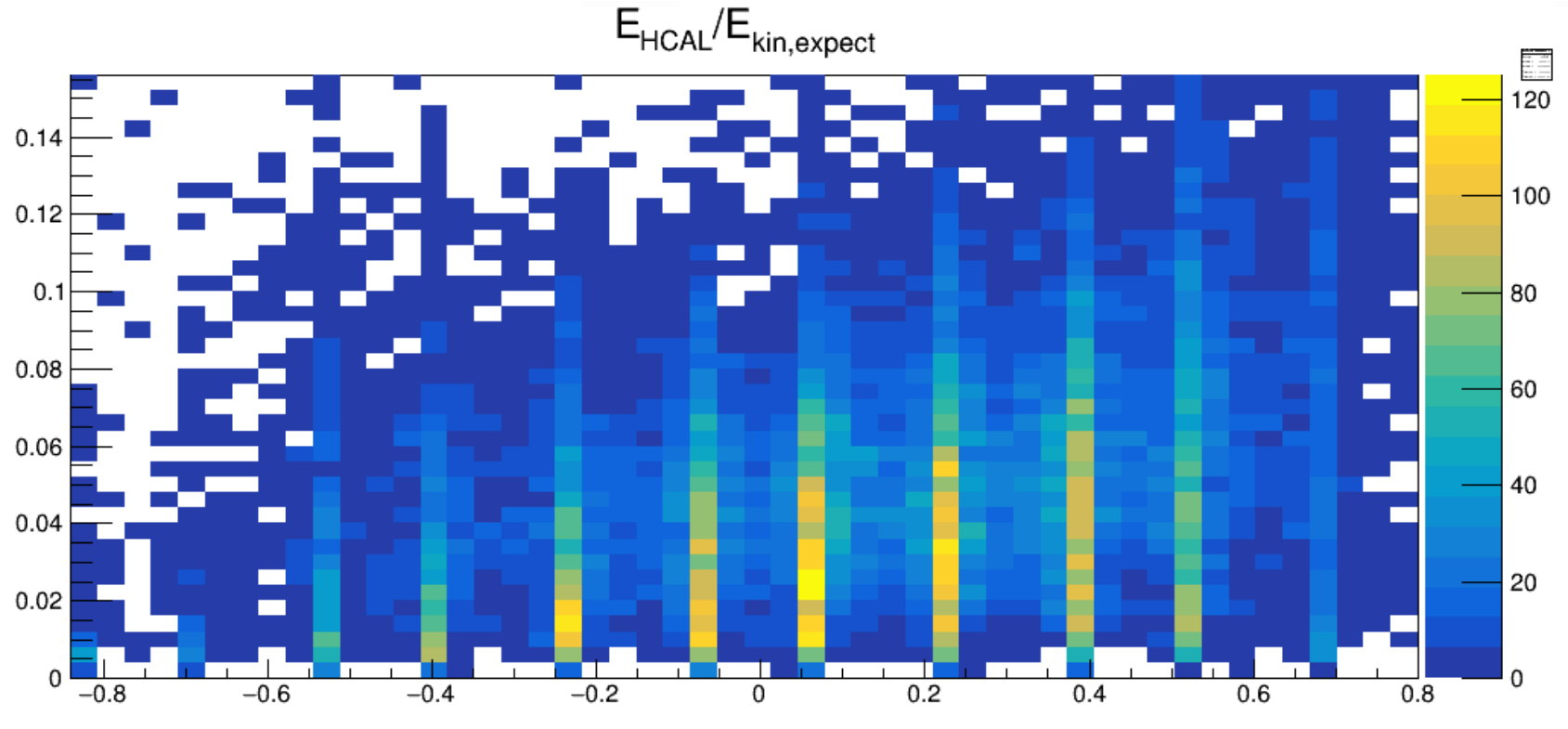
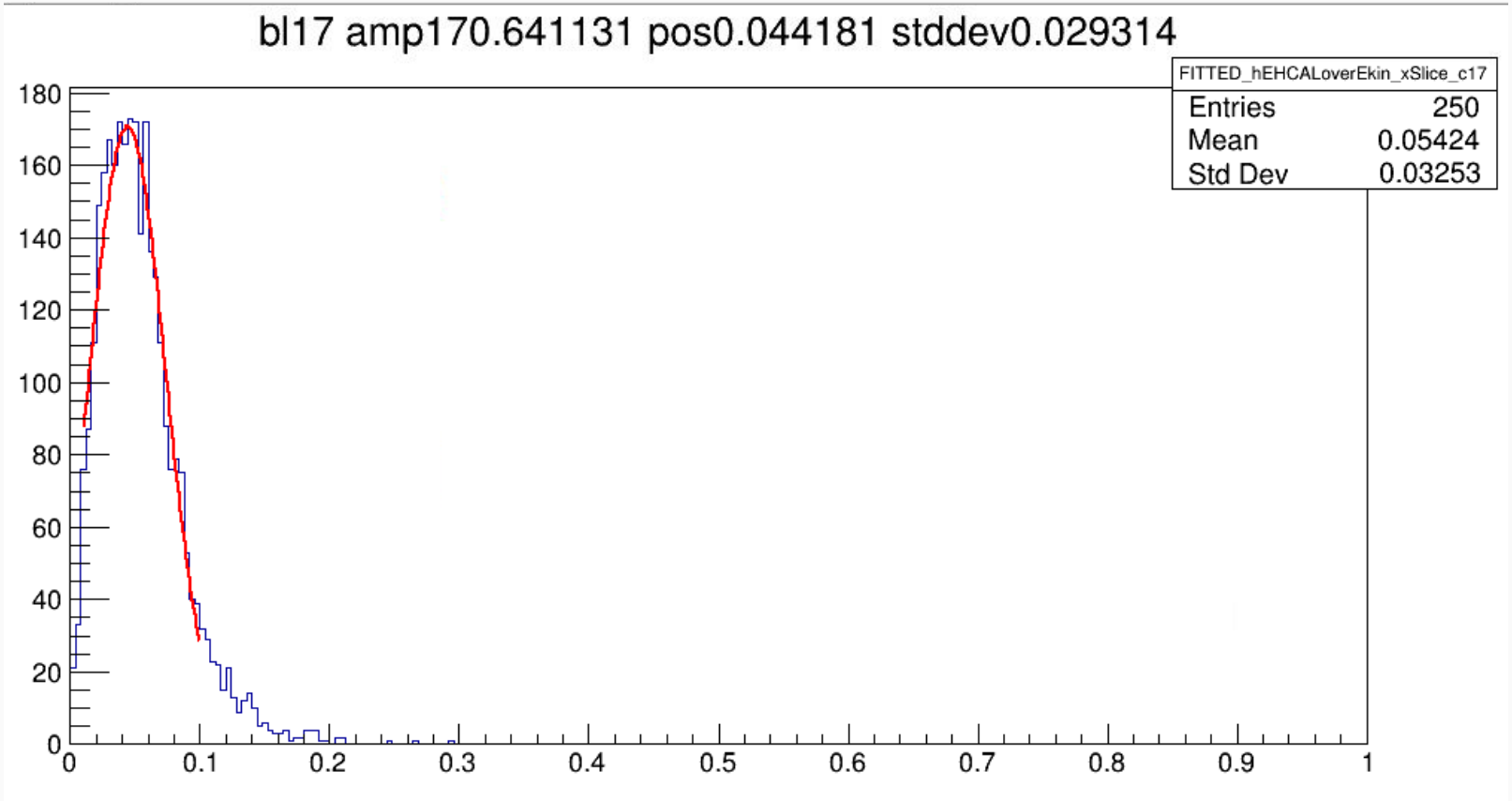


Image from Sebastian Seeds.

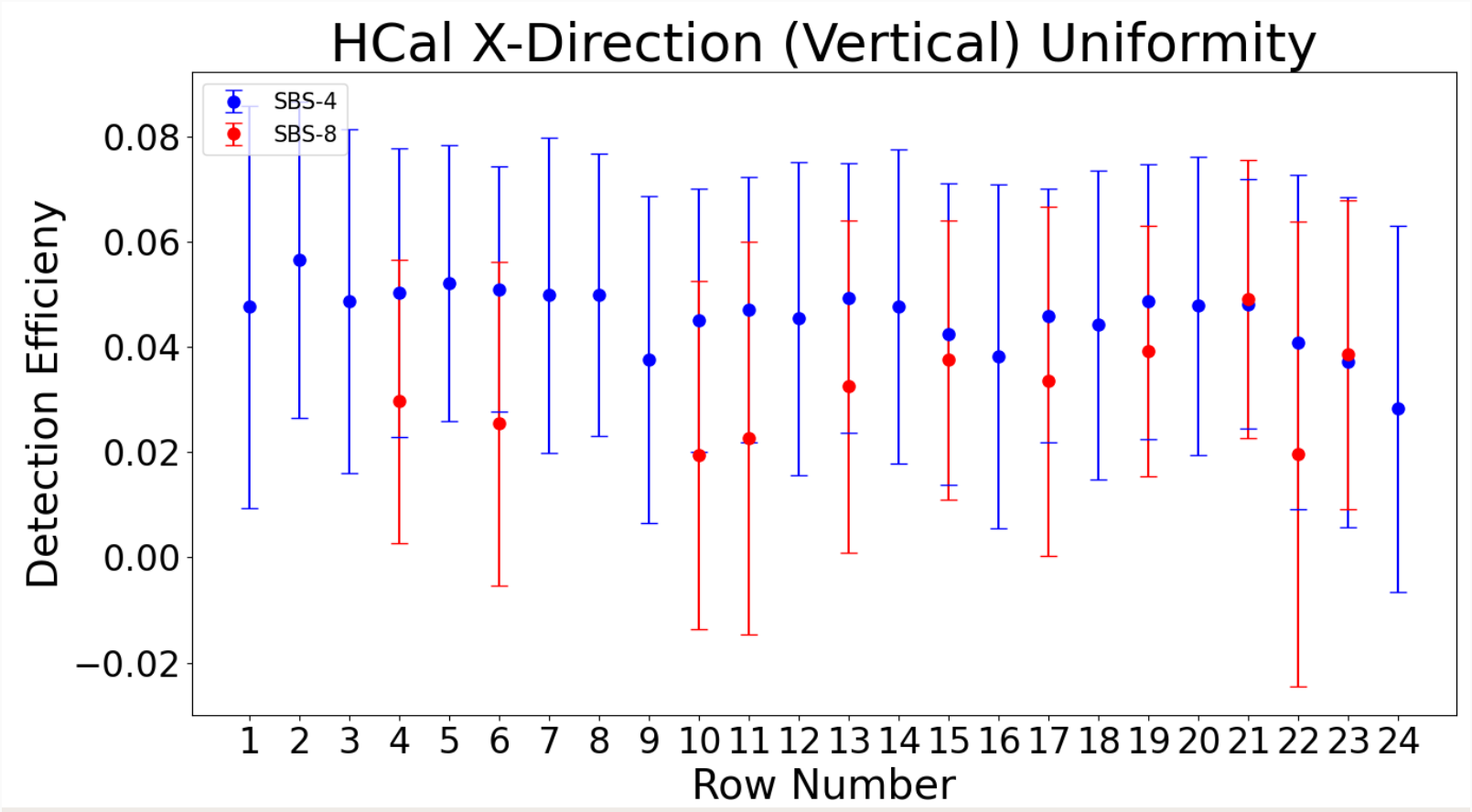
Detection Efficiency Uniformity SBS4 & SBS8

- Project individual rows and columns and fit sampling fractions for SBS4/8.



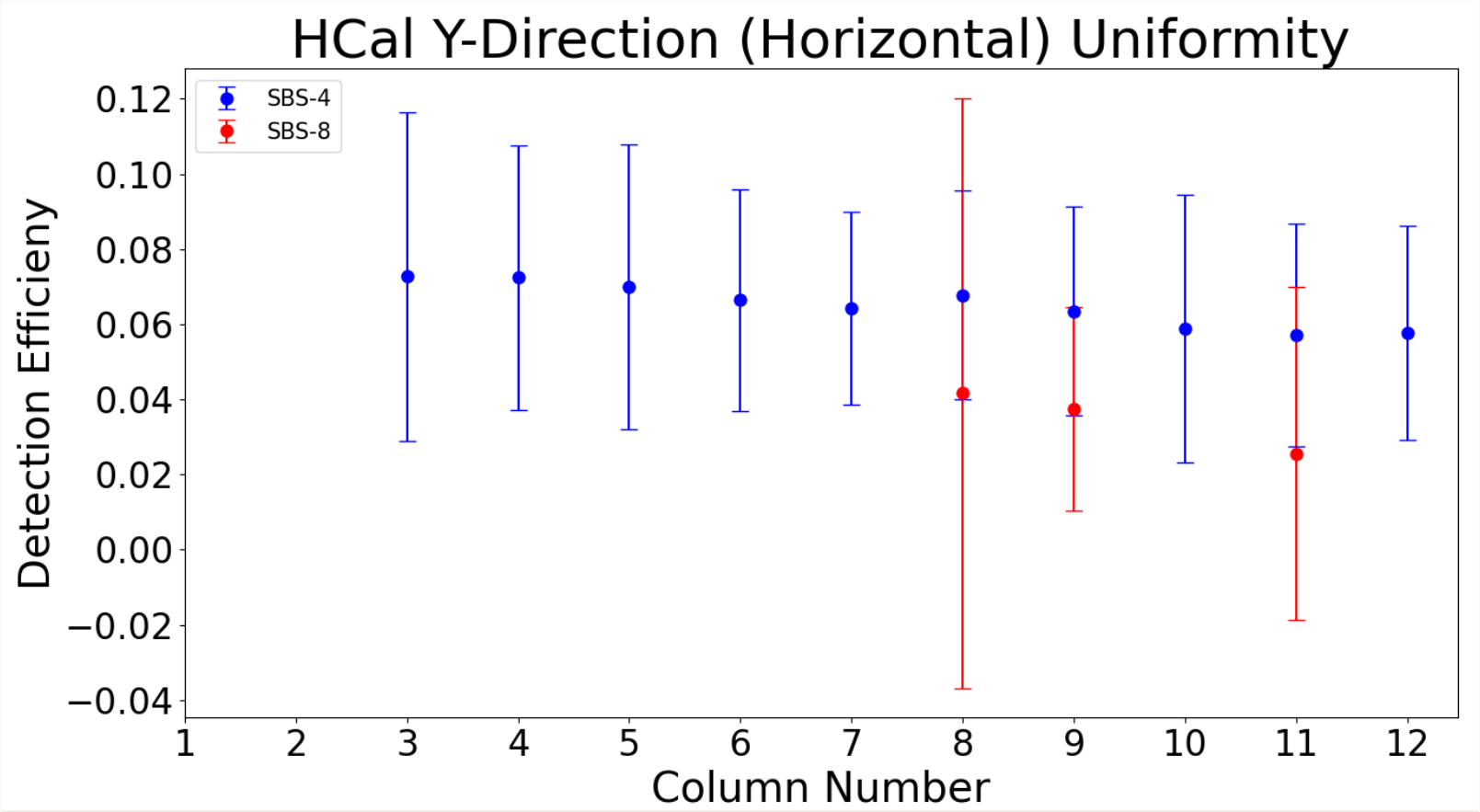
Detection Efficiency Uniformity SBS4 & SBS8

- X-direction (vertical) uniformity. Sampling fraction fit by row.



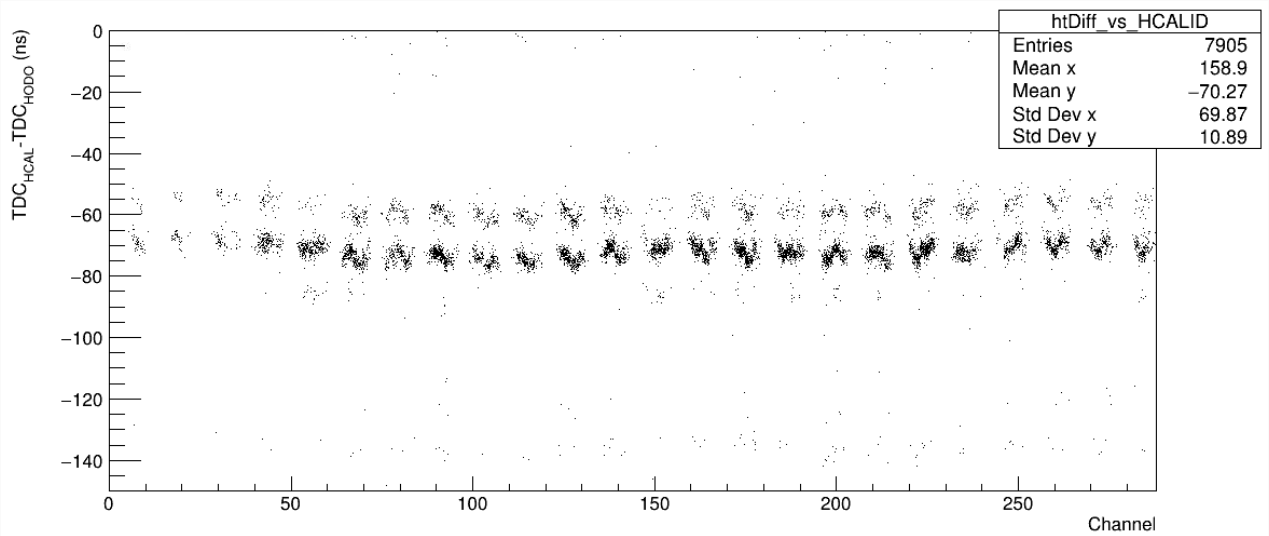
Detection Efficiency Uniformity SBS4 & SBS8

- Y-direction (horizontal) uniformity. Sampling fraction fit by column.



Preliminary Timing Resolution

- Isolate elastic proton events and find the HCal TDC time of the highest energy PMT in the largest energy cluster for each event.
- This time has significant jitter and requires a reference time which is taken as the hodoscope time for these events.
- Plot these times for every channel.
  - Needs time walk correction (work in progress).
  - Secondary peaks thought to be light reflected to back of PMT module before entering PMT (can remove with time cut).



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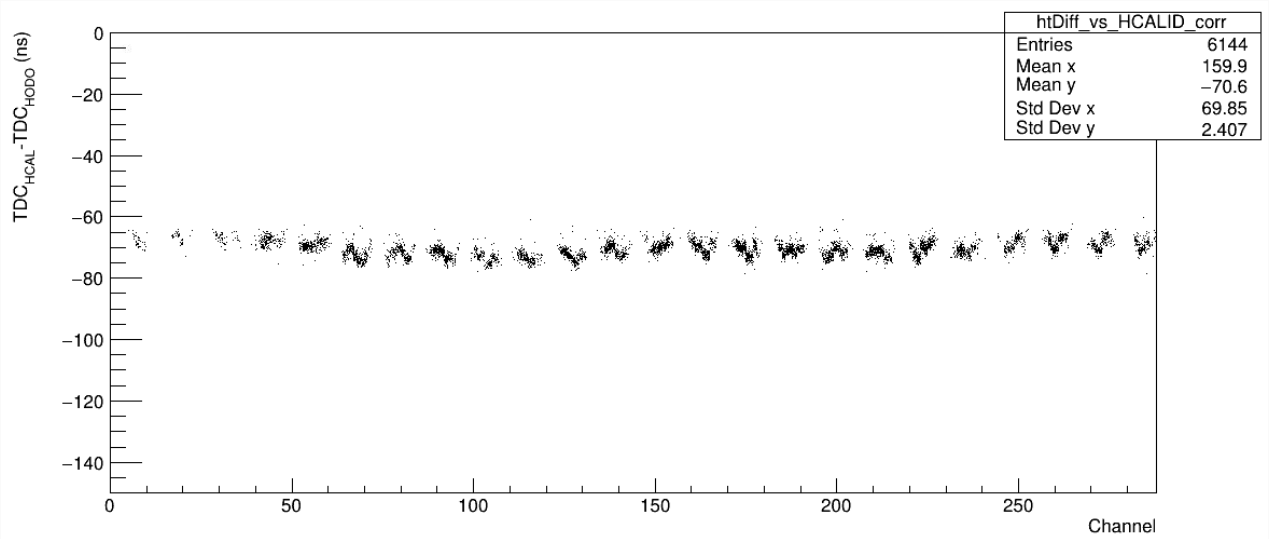
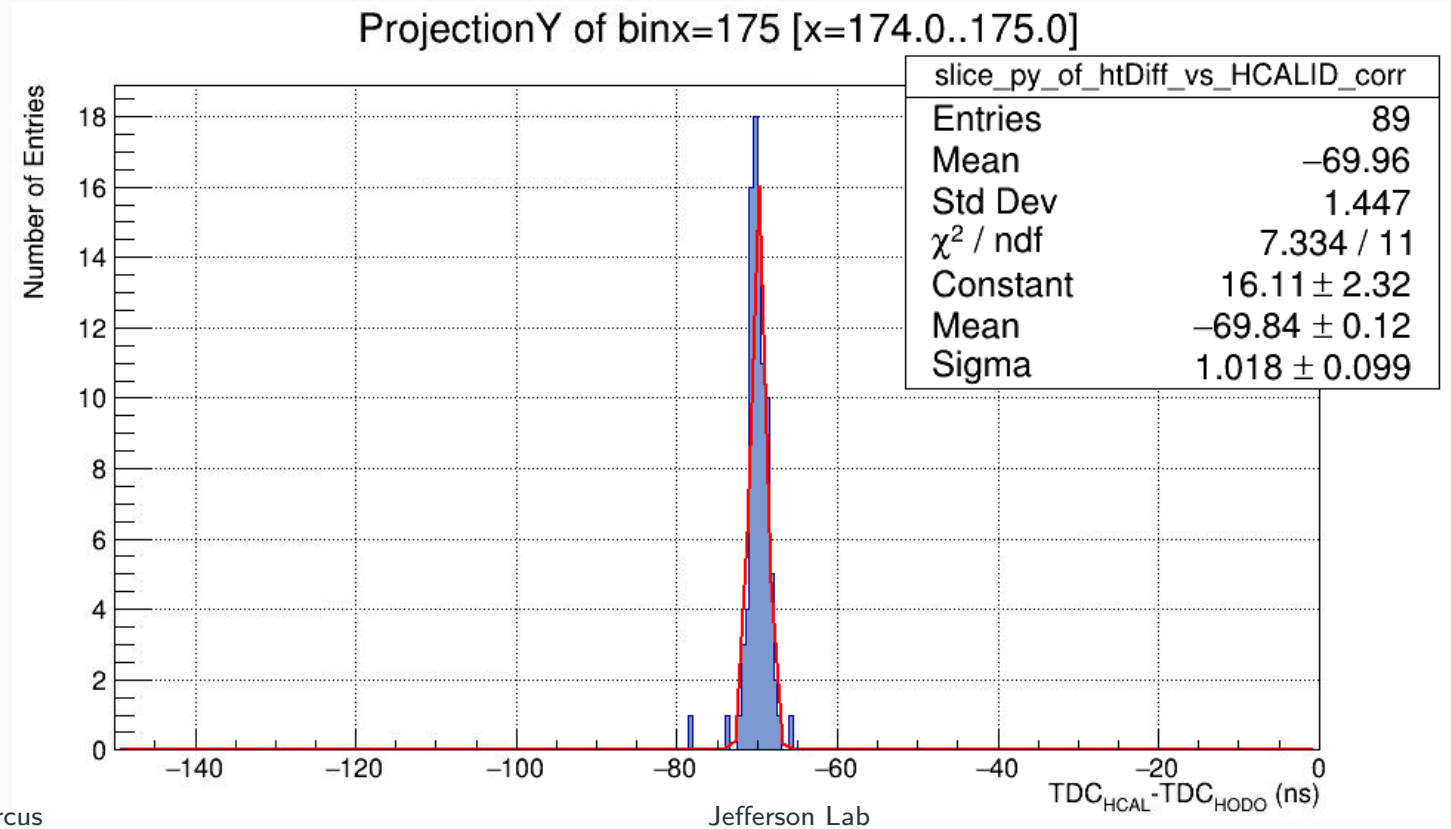


Image from Sebastian Seeds.

Preliminary Timing Resolution

- Project out timing of a single PMT with more statistics to find individual timing resolution.
- Apply time walk correction.
- Timing resolutions for individual PMTs ≈1 ns (with better time walk correction as low as 0.6 ns).
- Need more statistics replayed.



HCAL-J Summary

- The SBS HCal has successfully been commissioned collecting elastic hadrons during the G_M^n run!
- Preliminary analyses indicate detector is performing as expected.
  - Position resolution at low hadron energy $\approx$7-8 cm.
  - Detection efficiency uniformity looks constant over HCal's surface.
  - Timing resolutions for individual PMTs $\approx$1 ns (can likely improve).
- Upcoming Work:
  - Finalize calibrations and DB geometry then mass replay data.
  - High statistics analyses and extraction of the p/n cross section ratio.
  - Integrate VTP software trigger for upcoming experiments.
  - Study performance of individual modules to make improvements.
  - Test software fixes for LED pulser sequences.

Acknowledgments

Many people and institutions were involved in HCal's development:

- Special thanks to Juan Carlos Cornejo and Sebastian Seeds for getting HCal where it is today.
- Thanks to the many students who have worked on HCal including Alexis Ortega, So Young Jeon, Jorge Peña, Carly Wever, Vanessa Brio, Sebastian Seeds, and Provakar Datta.
- Thanks to Gregg Franklin, Brian Quinn, and the Carnegie Mellon team for design, overseeing construction, and ongoing guidance.
- Thanks to Universitá di Catania for major financial contributions.
- Thanks to Vanessa Brio, Cattia Petta, and Vincenzo Bellini for their cosmic commissioning efforts.
- Thanks to Alexandre Camsonne and Bryan Moffit for DAQ work.
- Thanks to Chuck Long for all his help fixing and acquiring things.
- Thanks to Bogdan Wojtsekhowski for his guidance and advice.
- Thanks to the rest of the HCal Working Group as well:Dimitrii Nikolaev, Jim Napolitano, and Donald Jones.

Questions?

References

Vlasov, N. V. *et al.* (2006). "A Calorimeter for Detecting Hadrons with Energies of 10-100 GeV". In: *Instruments and Experimental Techniques* 49, pp. 41–55.

Puckett, A. (2019). *SBS Physics Program Proposed and New*. URL: https://hallaweb.jlab.org/12GeV/SuperBigBite/meetings/col_2019feb26/talks/PuckettSBSphysics.pdf.

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

Backup Slides

TDC Timing Resolution

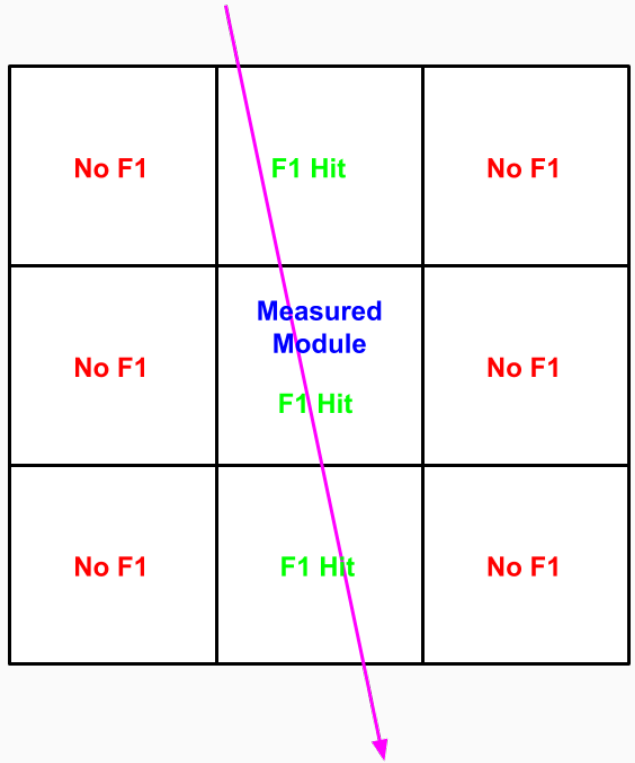
- Require cosmic to be nearly 'vertical'.
  - Vertical F1 signals.
  - No surrounding F1 signals.
- TDC time:

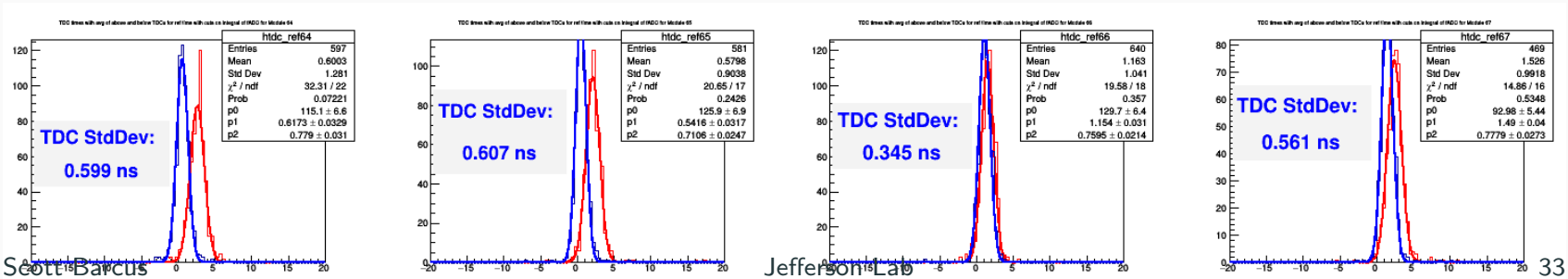
$$T_{cor} = T_{PMT} - T_{ref},$$

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

- Extract standard deviation of single PMT.

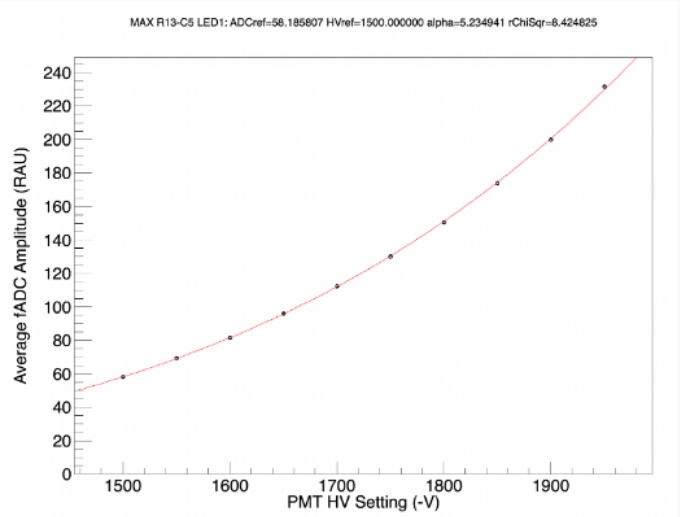
$$\sigma_{PMT} = \sqrt{|\sigma^2_{cor} - \sigma^2_{ref}|}.$$

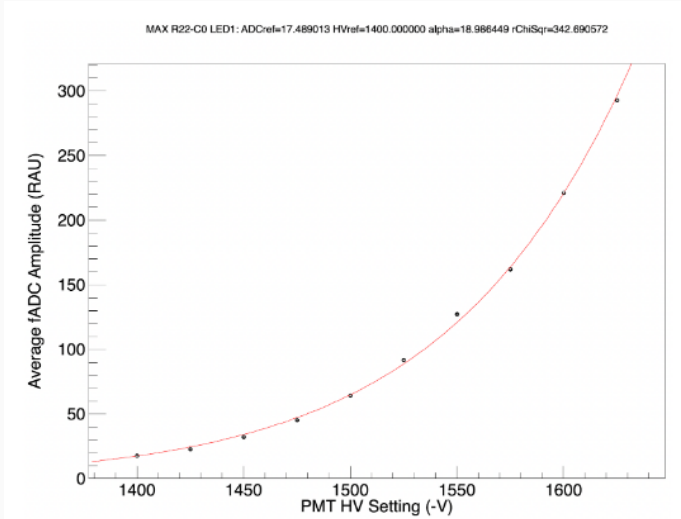


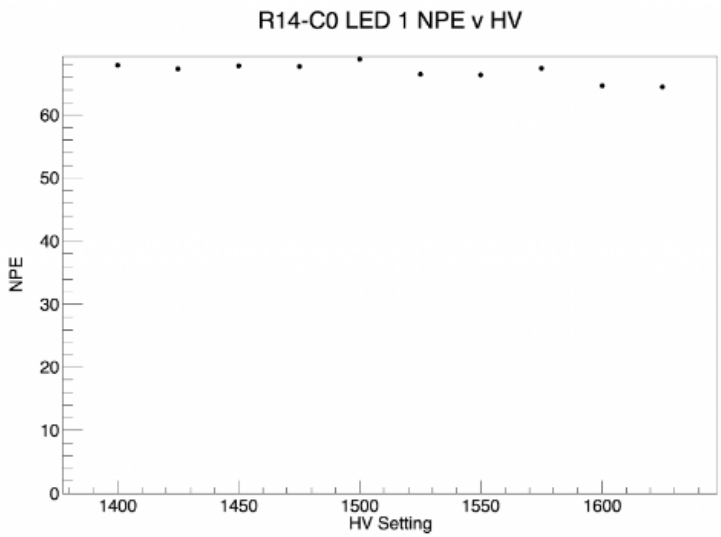


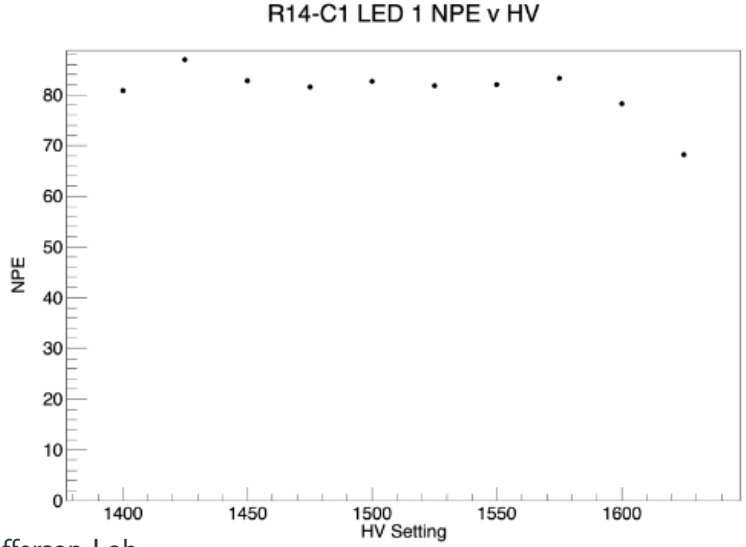
LED HV Calibration

- Plots of PMT gain curves and measured number of photoelectrons from LEDs.
  - Images from Sebastian Seeds.



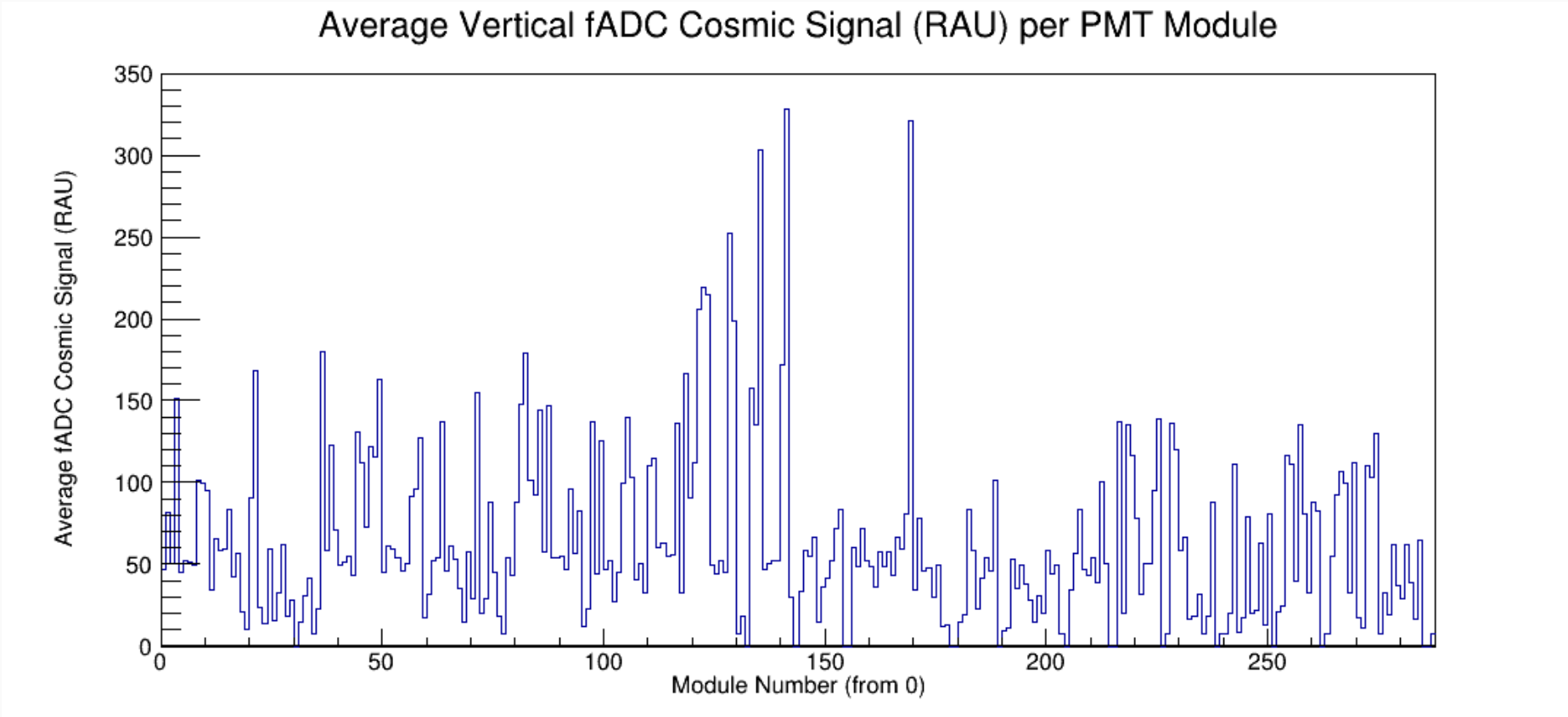






Cosmic Calibration Progress

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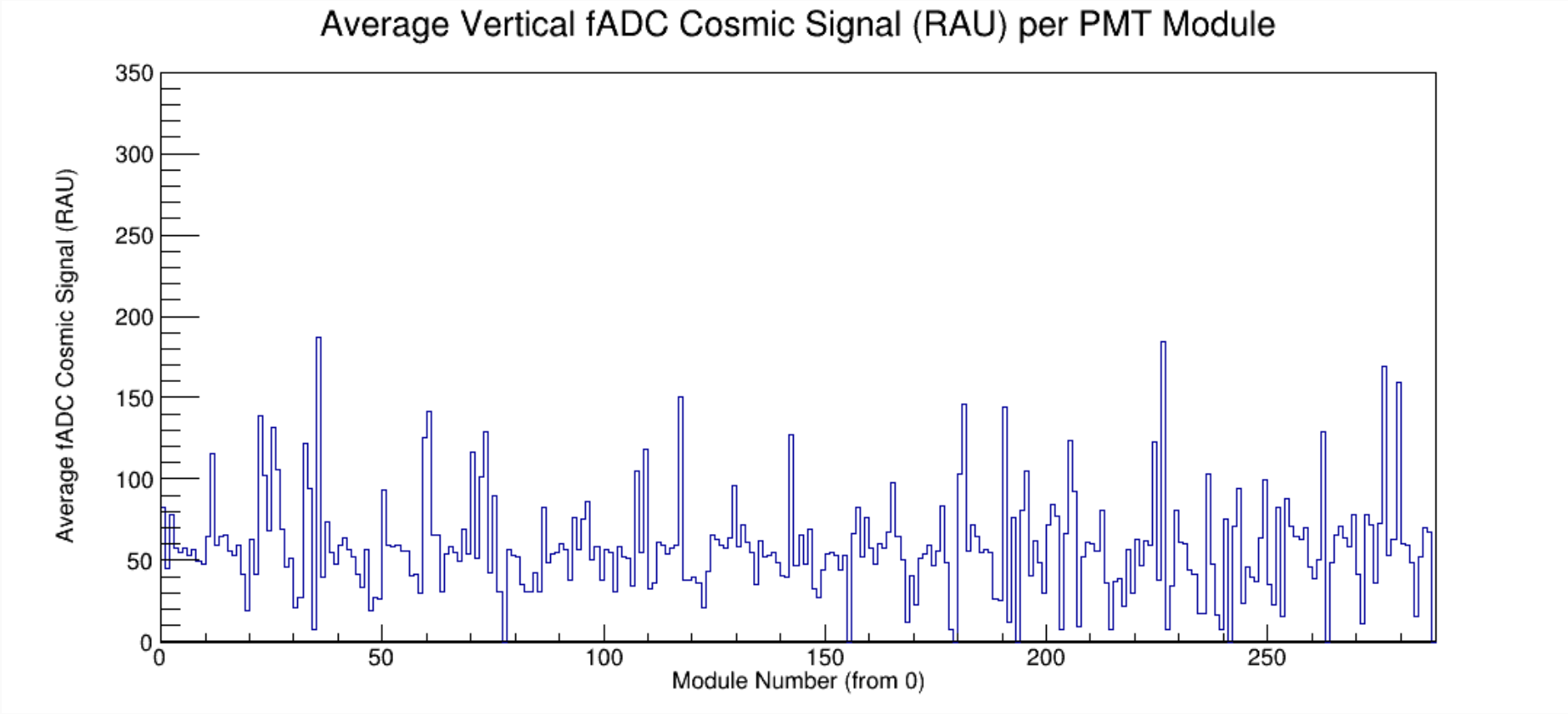
- Plots display the average fADC signal (RAU) during a cosmic event versus PMT module for three runs.
  - Each successive run calibrates signals closer to goal of 61 RAU by adjusting HV.



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.