The SBS Hadronic Calorimeter

Design, Calibration, and Performance

Sebastian Seeds

On behalf of the HCal working group

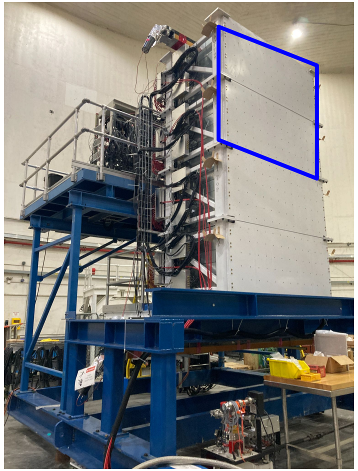
August 6, 2022

Jefferson Lab

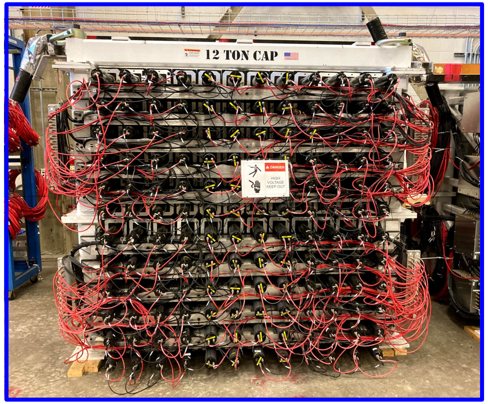
Jefferson Lab UCONN

Design - Overview

- Segmented calorimeter designed to detect hadrons via electromagnetic showers
- Energy from incoming hadrons sampled by calorimeter
  - Simulated energy sampling fraction: 6.6%
  - Simulated energy resolution: ~30%
- 288 individual showering **modules** (12 columns, 24 rows)
  - Detected hadron from target located by clusters of signals from modules
  - Each module equipped with fADC and TDC readout and pulsed LED array
  - Full Acceptance: 180cm x 360cm
  - Simulated position resolution: 3-4cm at 8 GeV
  - Simulated timing resolution (TDC): 0.5ns
- Particle ID via SBS magnet between HCal and target chamber
  - Neutrons unaffected, protons bent by magnetic field
  - Simulated Neutron/Proton detection ratio: 0.985 at 8 GeV



HCal, Target-facing-side, Hall A



HCal, PMT-side, Test Lab

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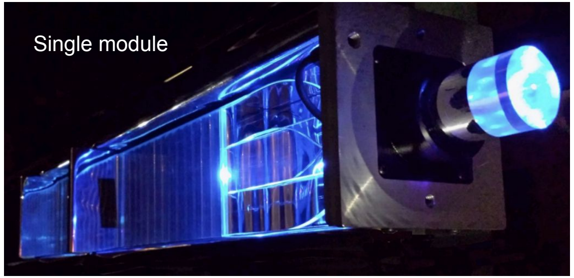
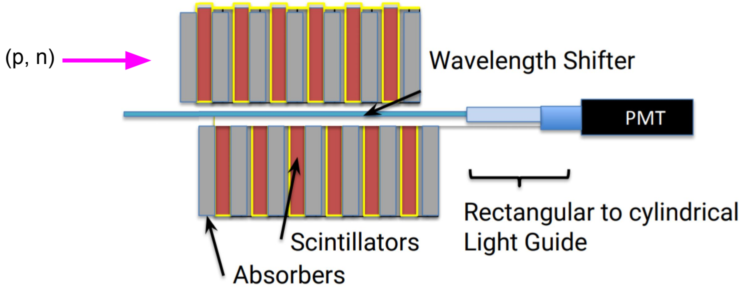
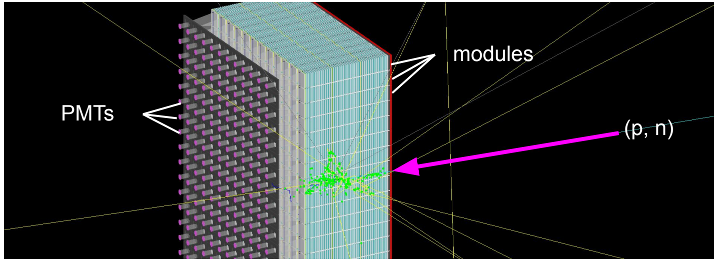
Design - Module

- Iron absorbers create electromagnetic showers via collisions with incoming protons and neutrons.
- Scintillators sample the energy from these showers and emit photons proportional to energy sampled into wavelength shifter
- Wavelength shifter converts photons to optimal wavelength range for PMTs, improving detection efficiency
- Light guide directs photons to PMT with minimal light loss where photons are converted to electrical signal
  - 192 12-stage “CMU” Photonis XP2262 PMTs
  - 96 8-stage “JLAB” Photonis XP2282 PMTs







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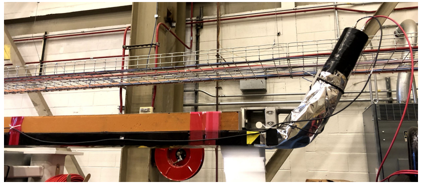
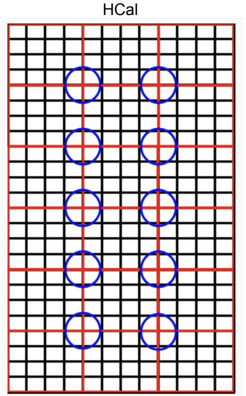
Front End (FE) and Data Acquisition (DAQ)

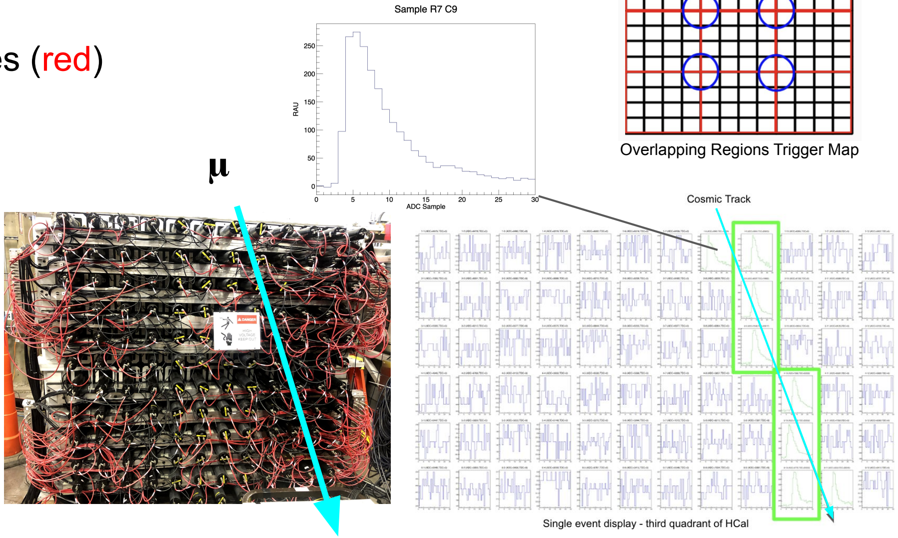
- (FE) Signal 10x amplified with two outputs from amp.
  - One to fADC
  - One split from module (50:50), half to trigger logic and half to TDC
- (FE) Cosmic Trigger: 2x coincidence paddles, one above and one below HCal
- (FE) Overlapping Regions Trigger: Sums of 4x4 modules (red) summed into 8x8 (blue circles), trigger over threshold
- (FE) LED Pulser Trigger
- (DAQ) 2x VXS Crates
  - 19 16-channel fADC250 configured mode 1 (recording full waveforms)
    - 4ns samples, 250 MHz sample rate Analog-to-Digital Converter
  - 5 64-channel F1TDCs
    - Multi-hit rolling Time-to-Digital Converter referenced to BigBite Trigger



Cosmic paddle

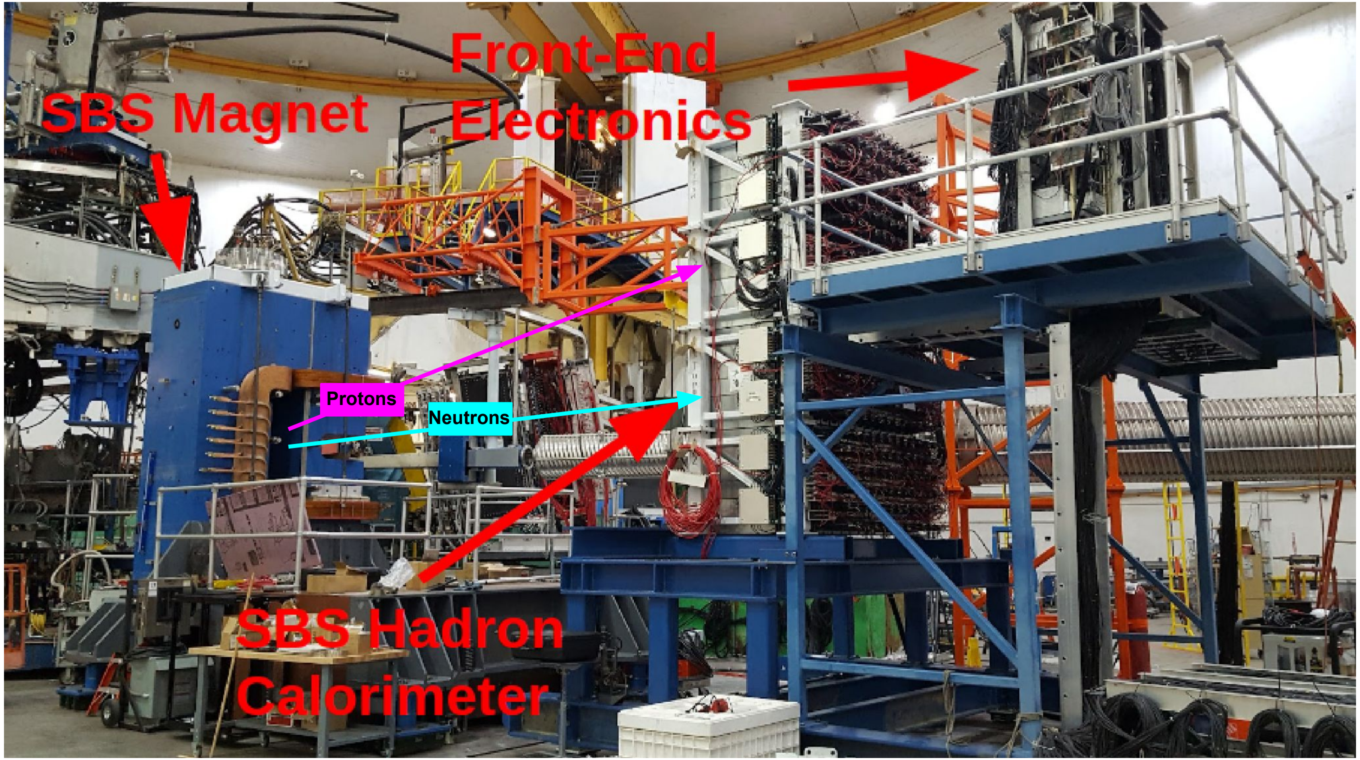


Overlapping Regions Trigger Map



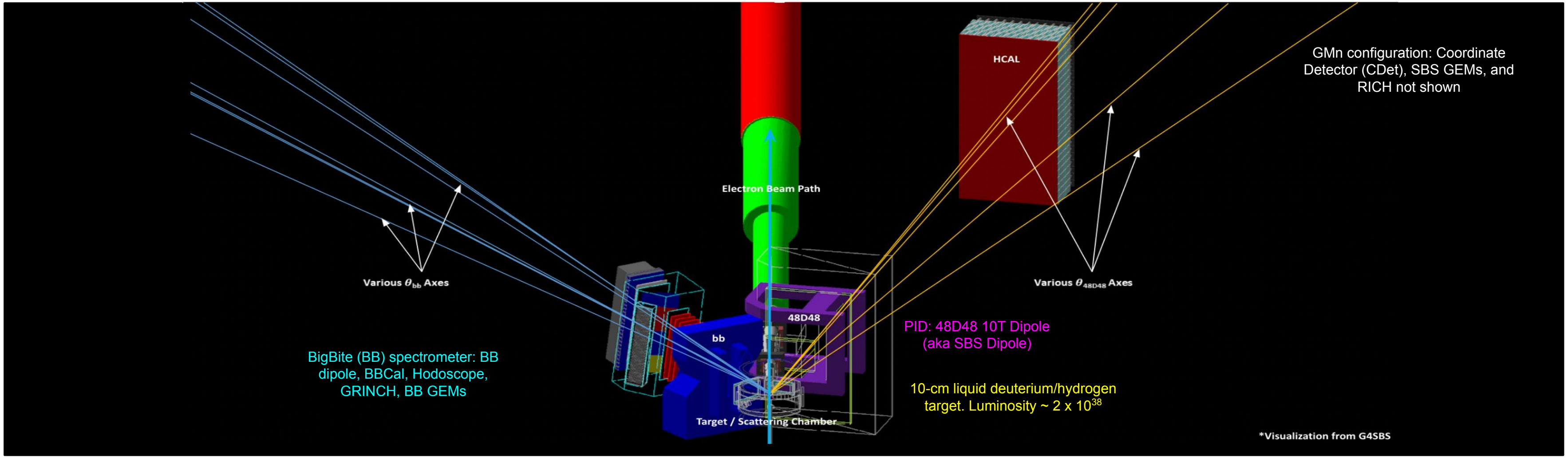
Single event display - third quadrant of HCal

HCal Broad View



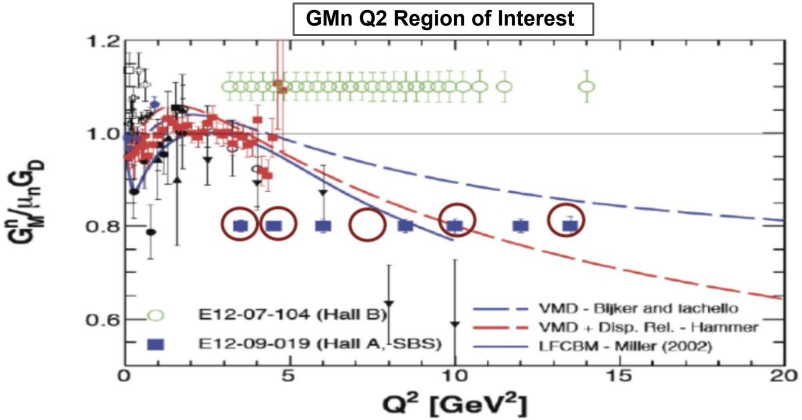
SBS Program

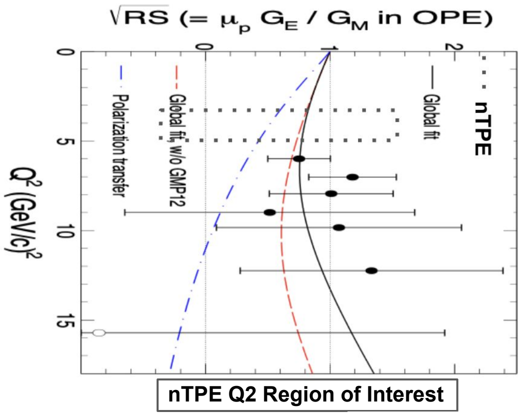
- PAC approved experiments (**6** over several years)
  - Nucleon Form Factors: G_M^n (E12-09-019), G_E^n (E12-17-004), and G_E^p / G_M^p (E12-07-109).
  - nTPE (E12-09-010), GEn-rp (E12-17-004), SIDIS (E12-09-018)
- G_M^n and nTPE ran in the winter of 2021-2022, the first two in the SBS program
  - (G_M^n) Via the ratio method to minimize systematic errors, neutron magnetic form factor will be extracted from deuterium quasielastic cross sections d(e,en)p / d(e,ep)n
  - (nTPE) With simultaneous e-n / e-p measurements at two virtual photon polarizations, the contribution of two-photon-exchange to the elastic e-n cross section will be extracted
- BigBite spectrometer detects scattered electrons and HCal detects protons and neutrons separated by SBS Dipole



G_M^n Program and Kinematics

- G_M^n completed in winter with five Q^2 points and six kinematics
  - Q^2 = 3,4.5,7.5,10,13.6 GeV^2 completed, extending global data significantly
  - One extra kinematic at Q^2 = 4.5 GeV^2 at a different virtual photon polarization for nTPE
- G_M^n will constrain global parton distributions (GPDs) for broader physics applications and increased understanding of hadronic structure
- As first measurement of electron-neutron Rosenbluth slope for 50 years, nTPE will help to resolve the Form Factor Ratio Puzzle (FFRP)





Plots: Andrew Puckett

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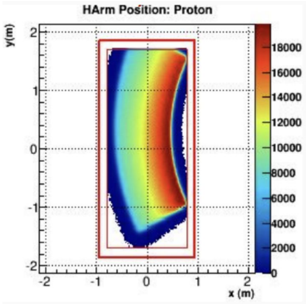
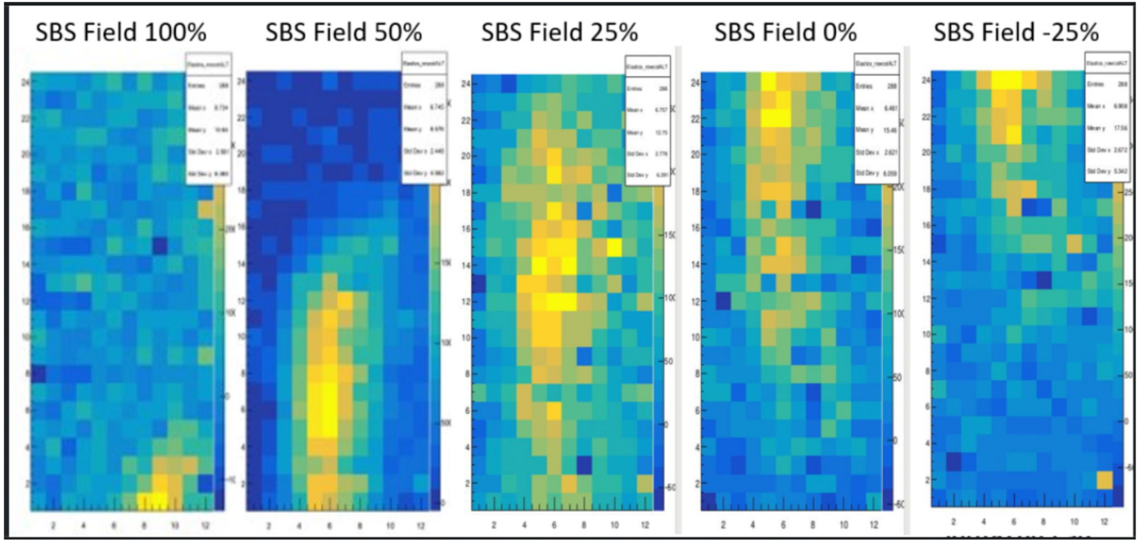
G_M^n Performance - Elastic Protons

- Commissioning of HCal with elastic protons
  - Liquid hydrogen target at Q^2 = 1 GeV^2 for protons high elastic yield
  - Verification of proton detection with SBS Dipole sweep over several field strengths



Simulated Expectation G4SBS

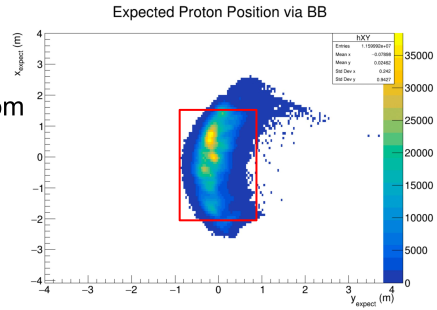
SBS Field 0%



Data in HCal with rough elastic timing cut during commissioning

Expectation from BigBite Arm electron track

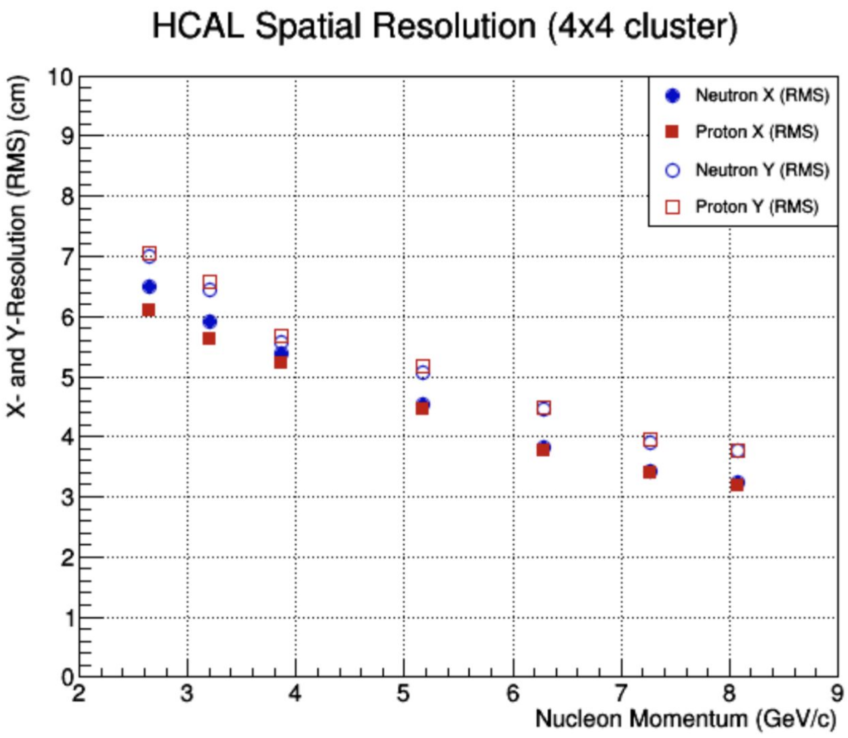
SBS Field 0%



Simulated Expectation Plot: Scott Barcus

G_M^n Performance - Position Resolution Simulations

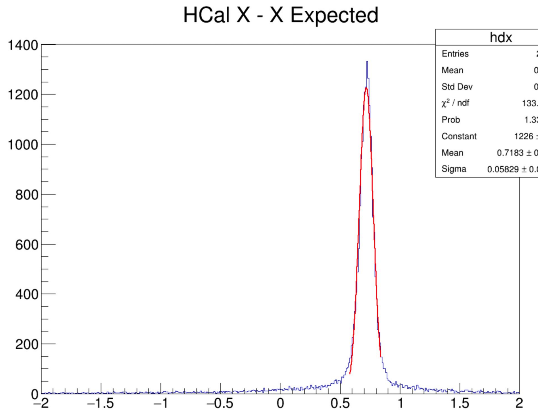
- SBS experiments require HCal to have high position resolution, especially for high Q^2 measurements
  - 2.5 GeV nucleons are expected to have 6-7 cm resolution in dispersive direction.
  - 8 GeV nucleons are expected to have 3-4 cm resolution in dispersive direction.

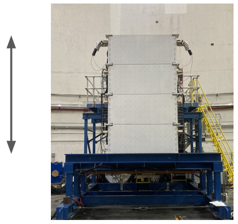


Plot: Juan Carlos Cornejo

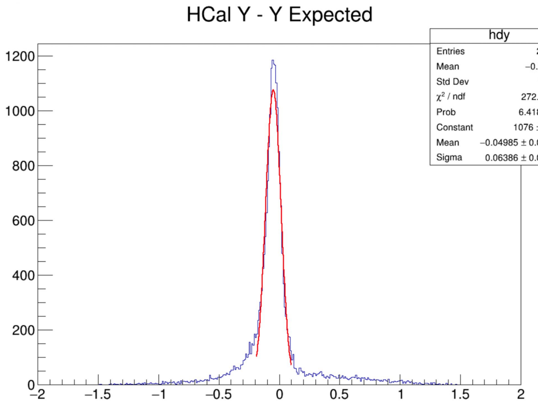
G_M^n Performance - Position Resolution Preliminary

- Hydrogen target (scattered protons)
- SBS field 0% (no proton displacement)
- Expected position of scattered nucleons calculated from reconstructed quasielastic electron tracks in BigBite
- Take the difference between energy-weighted center of cluster in HCal and expected position
  - Nucleon momentum for these data ~ 2.9 GeV (SBS-8)
  - Dispersive Direction (X) Resolution ~ 5.8 cm
  - Transverse Direction (Y) Resolution ~ 6.3 cm
- **Preliminary position resolution meets simulated expectations!**





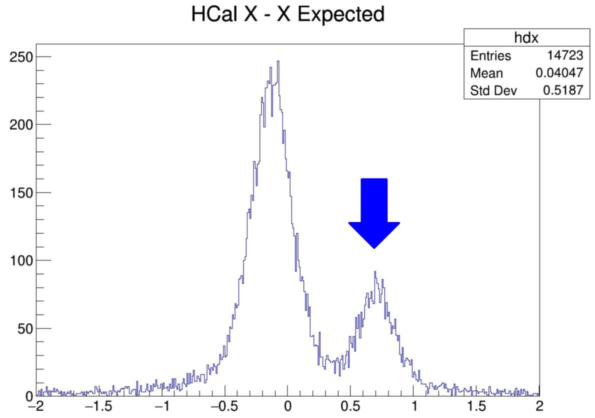
Dispersive Direction

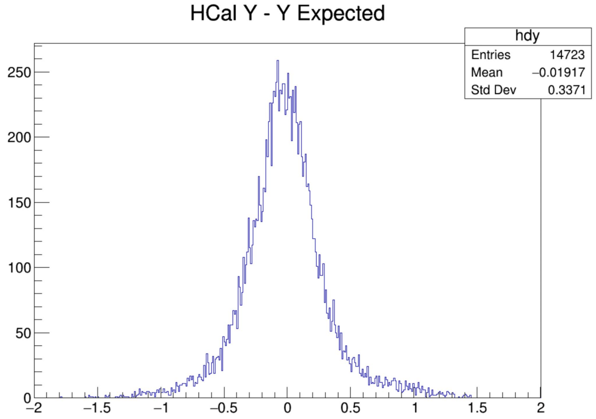


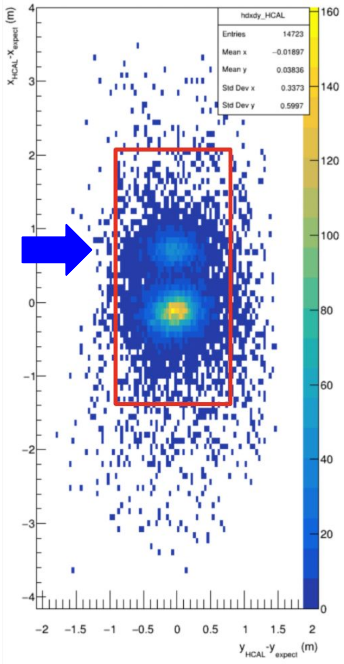
Transverse Direction

G_M^n Performance - Nucleon Position, Deuterium

- Deuterium target (scattered protons and neutrons)
- SBS field 30% (protons displaced ~90 cm)
- Once again, take the difference between energy-weighted center of cluster in HCal and expected position
  - Nucleon momentum for these data ~ 3.0 GeV (SBS-8)
- Distributions broadened due to fermi smearing and other effects
- **Neutron peak in clear view**

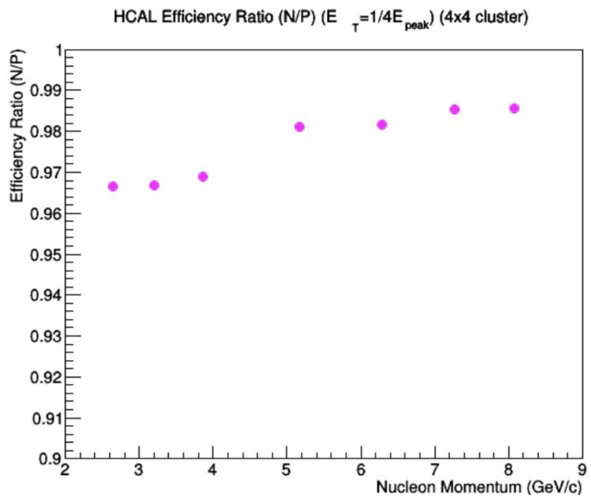


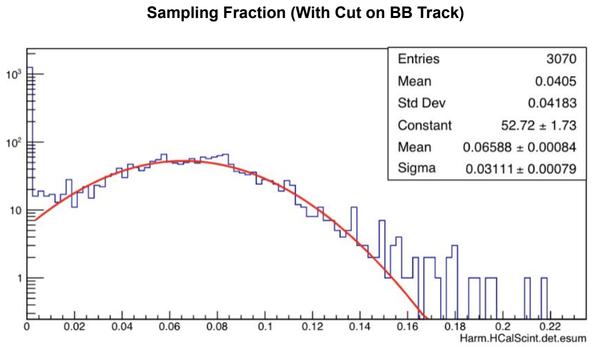




G_M^n Performance - Sampling Fraction

- Ratio measurements require comparable detection efficiencies across HCal
  - n/p cross section ratio becomes inaccurate if detection is biased to one scattered nucleon
  - n/p efficiency ratio expected from simulation
    - eff ≈ 0.985 at 7-8 GeV
    - eff ≈ 0.966 at 2.5-4 GeV.
  - *Detection efficiency must be uniform!*
- SBS Dipole field displaces protons on HCal
  - Calculate expected position of scattered nucleon with reconstructed electron track in BigBite
  - Check uniformity of detected energy / expected energy across HCal - this is the *sampling fraction*
  - Simulations predict sampling fraction of 6.6%

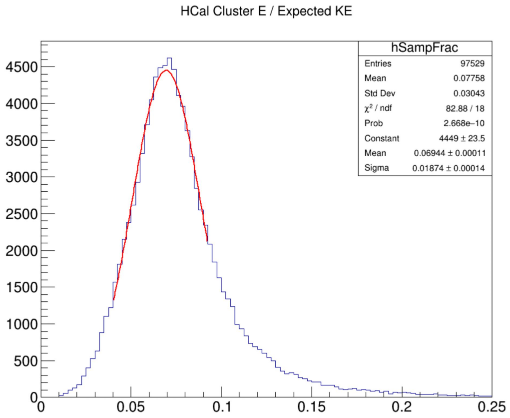


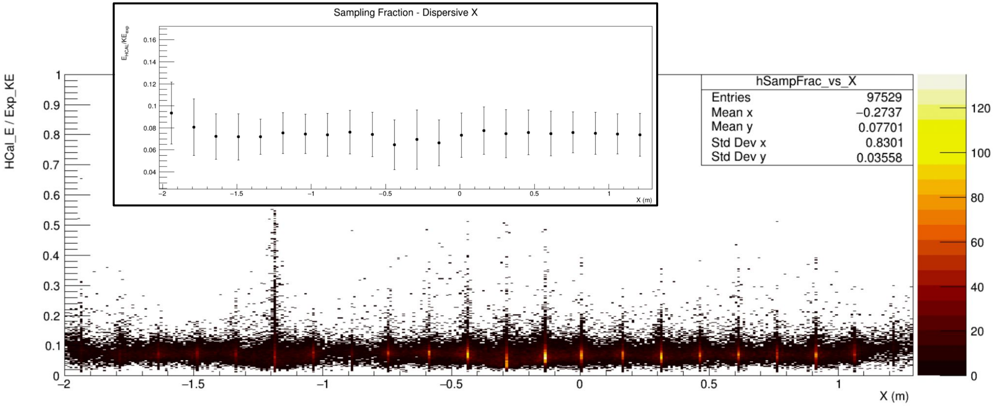


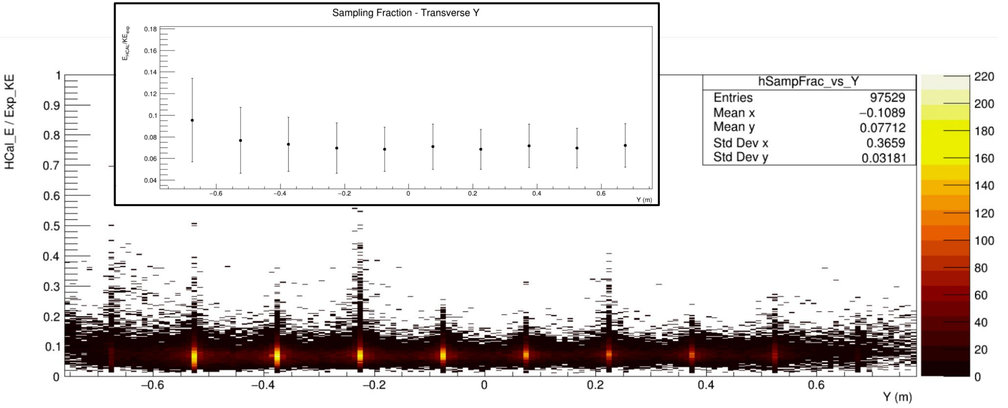
Simulation Plots: Juan Carlos Cornejo (top) and Eric Fuchey (bottom)

G_M^n Performance - Detection Efficiency Preliminary

- $E_{beam} \approx 5.965$ GeV, $Q^2 \approx 4.5$ GeV^2 (SBS8)
  - Mean sampling fraction ≈ 6.9%
  - Uniformity by row (top, dispersive)
  - Uniformity by column (bottom, transverse)
- Better uniformity expected after first pass data cooking and recalibration

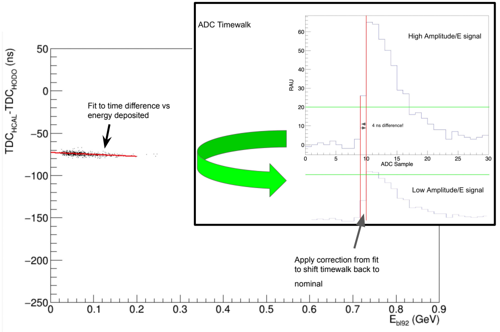


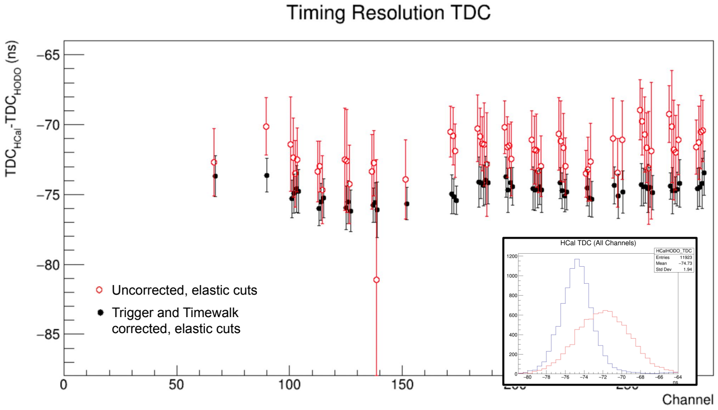




G_M^n Performance - Timing Resolution

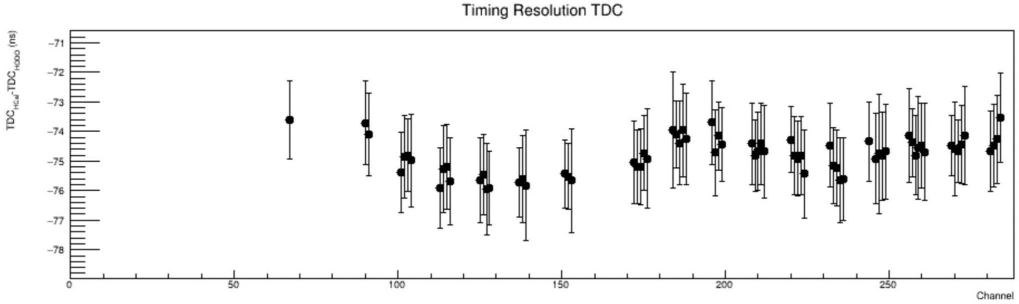
- Expected TDC timing efficiency by design ≈ 0.5 ns
- Both ADC and TDC have timing resolution
    - TDC better, but both are investigated
- Significant jitter exists on HCal TDC signals from several sources
    - Timewalk: Rising edge of raw signal impacted by amplitude
    - Time of flight (TOF): Scattered nucleons have different momenta and take different paths to HCal
    - Trigger: Electronics jitter from BigBite trigger impacts reference time for all signals
- Each can be addressed
    - Timewalk: Apply exponential energy-dependent correction to timing per event
    - TOF: Reconstruct momenta and energy using BigBite electron track and apply corrections to timing per event
    - Trigger: Use RF-corrected hodoscope timing as reference

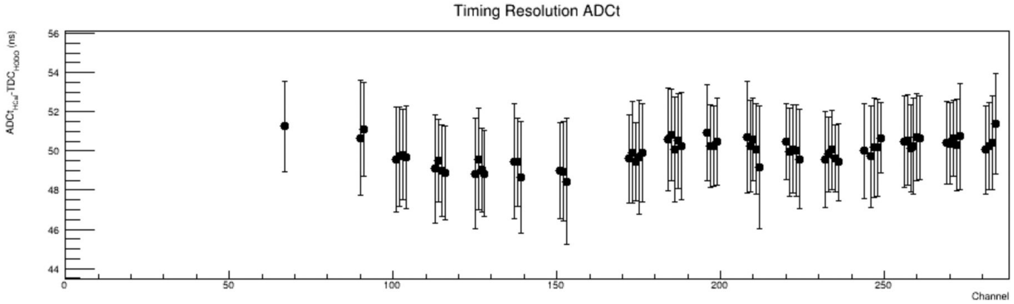




G_M^n Performance - Timing Resolution Preliminary

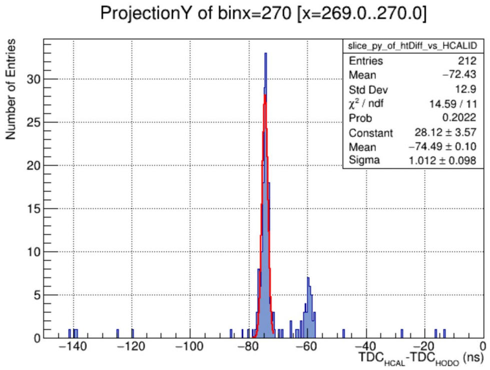
- Strict elastic cuts and expected position cuts on scattered quasielastic protons
- Mean TDC resolution over all channels ≈ 1.4 ns (as good as 1.0 ns)
- Mean ADC time resolution ≈ 2.4 ns (as good as 1.7 ns)
- Improvements expected
  - Prior to first pass, data are sparse
  - TOF, timewalk corrections pending first pass cooking



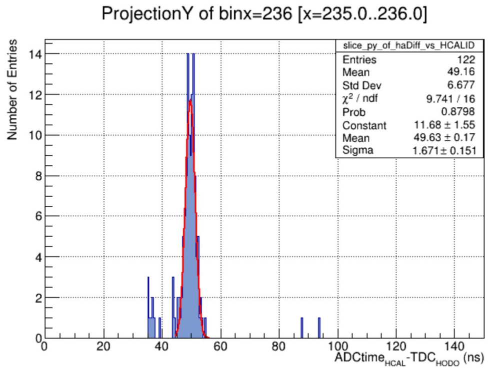


Example Slices

TDC

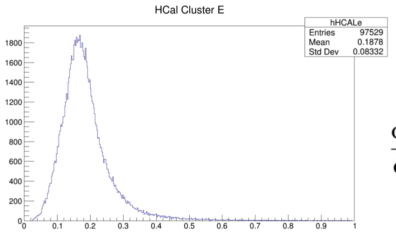


ADC time



Calibrations - Energy

1. Energy Calibrations by channel from scattered protons at $Q^2 = 4.5$ GeV^2
    a. Relate ADC values (pC) to deposited energy (GeV)
        i. c_j in GeV/pC
            1. pC for integrated ADC waveforms
        ii. Indices *i, j* over hits within cluster
        iii. Energy E_i
            1. Kinetic energy of hadron incident to HCal
                a. Calculated assuming elastic scattering from BigBite track momentum and beam
            2. Apply sampling fraction of 7.95% for HCal
                a. Obtained from monte-carlo simulations
    b. Chi squared minimization with linear system of equations relating energy deposited on single channel to total deposited energy of elastically scattered hadron in cluster per event.
        i. Populate matrix with measured integrated ADC values (pC)
        ii. Reject cells with insufficient statistics
            1. Set diag element for cell to 1, all coupled set to 0
        iii. Solve for coefficients via inversion of matrix
    c. Apply coefficients by channel to convert ADC values to energy deposited in HCal!

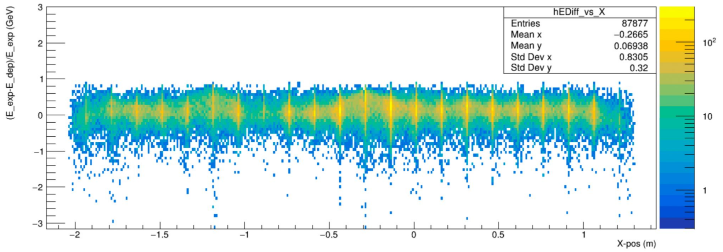


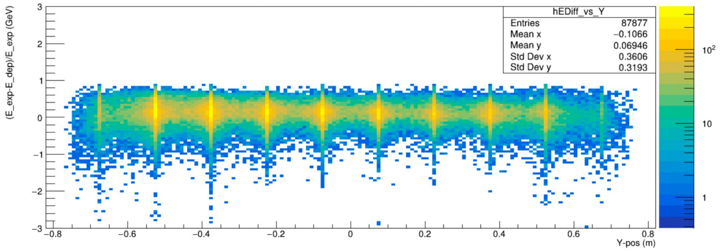
$$\chi^2 = \sum_{i=1}^{n} \left(E_i - \sum_j c_j A_j^i \right)^2 / \sigma_E^2$$

$$\sigma_E^2 \approx E_i$$

$$\frac{d\chi^2}{dc_k} = 2 \sum_{i=1}^{n} \frac{1}{E_i} \left(E_i - \sum_j c_j A_j \right) A_k = 0$$

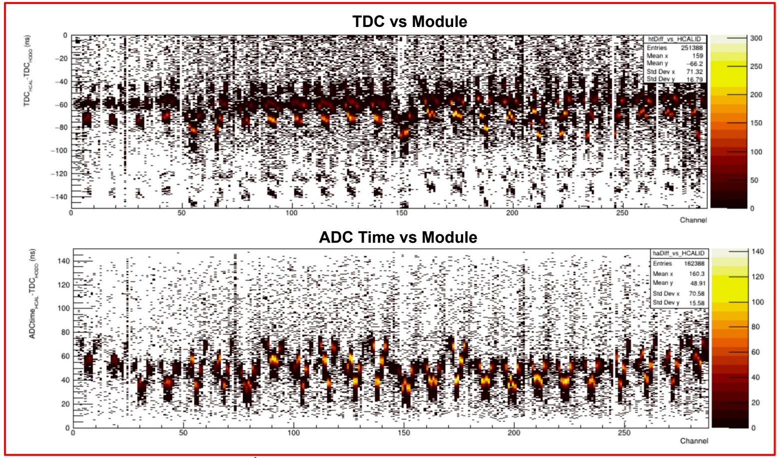
Minimize





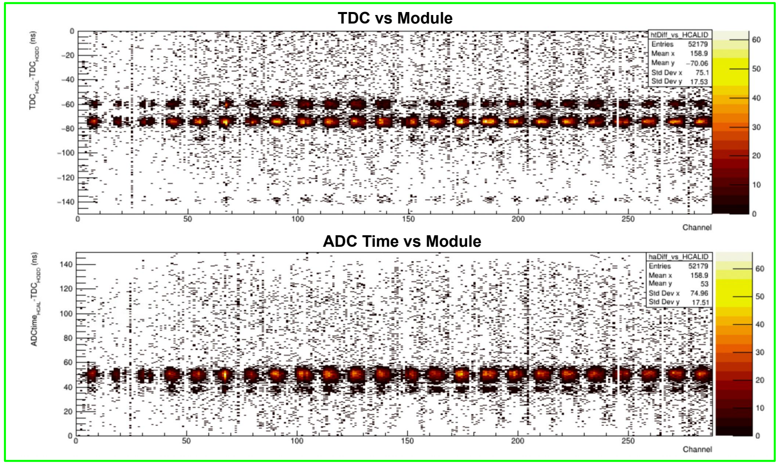
Calibrations - Timing

1. Align ADC time and TDC signals from coincidence target events using elastically scattered protons at Q^2 = 3 GeV^2
    a. Elastic hadrons expected to arrive at HCal in time relative to the BigBite single arm trigger (reference time)
        i. Cut on elastic events using q-vector from BigBite arm and build distributions of ADC time and TDC time by channel
    b. Make by-channel corrections to raw ADC time and TDC
        i. Use hodoscope mean TDC to clean up jitter in reference time
        ii. Address energy-dependent timewalk corrections (not shown)
        iii. Apply time-of-flight corrections exploiting q-vector (not shown)
    c. Select target time within ADC(TDC) window: 55ns(-75ns)
    d. Extract mean ADC time and mean TDC and calculate offset to target times
    e. Pass offsets by channel to achieve relative timing alignment between them!



Before

After

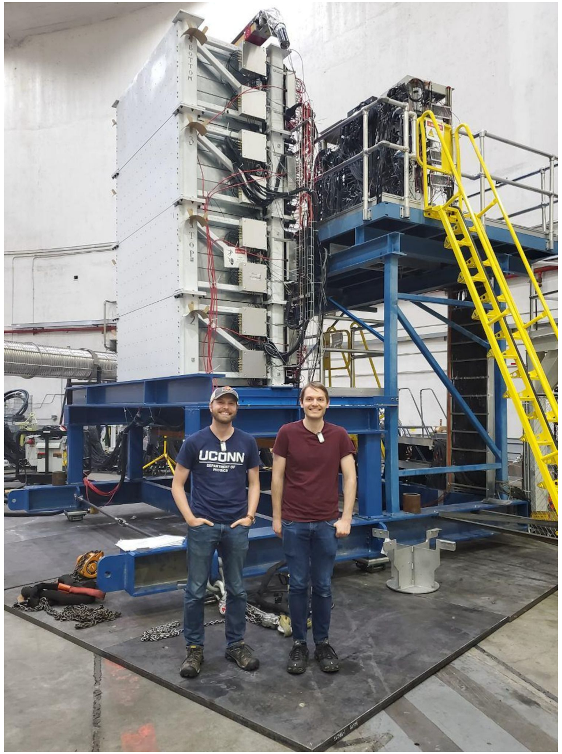


Acknowledgements

The design and construction of HCal was primarily overseen by Gregg Franklin and Brian Quinn, whose efforts primarily made HCal a reality. Many others have been involved the project including, but not limited to:

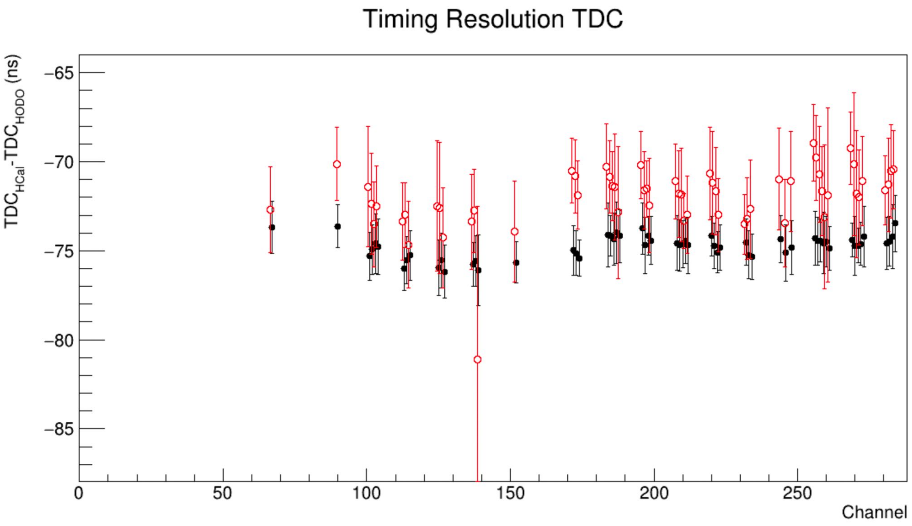
- Chuck Long, Juan Carlos Cornejo, Alex Camsonne, Jessie Butler (and his team), Bryan Moffit, Bogdan Wojtsekhowski, Mark Jones, Andrew Puckett, Eric Fuchey, Arun Tadepalli, Vanessa Brio, and Provakar Datta.

- And thanks to Scott Barcus who has successfully managed preliminary testing, the move, reassembly, and commissioning of HCal for the SBS program!

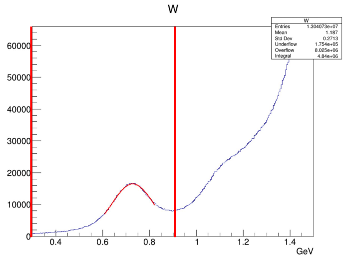


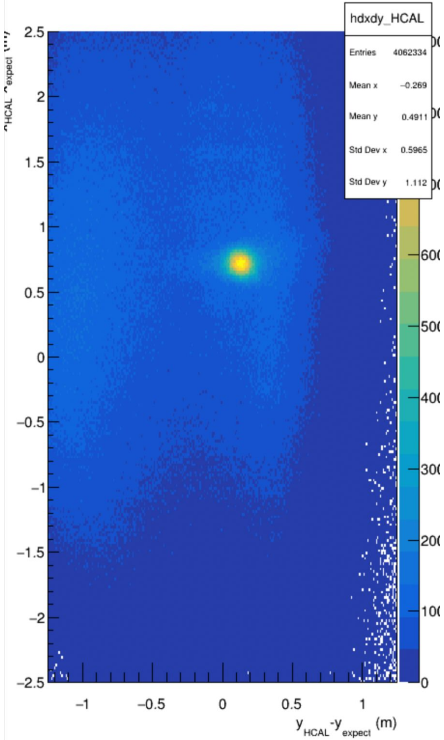
Backup

SBS4, timing comparison



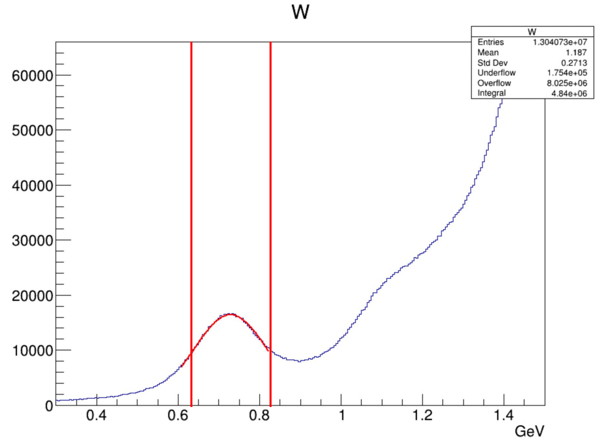
Proton Spot SBS4, LH2

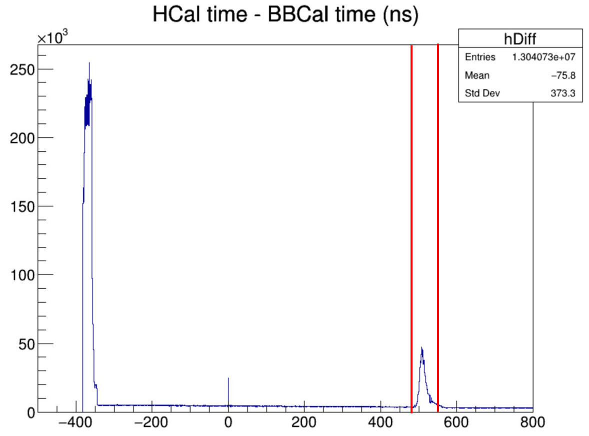


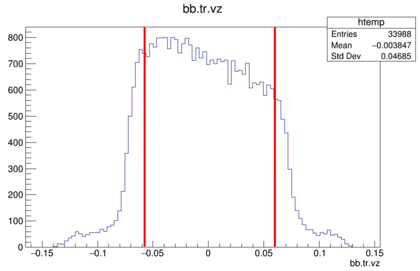


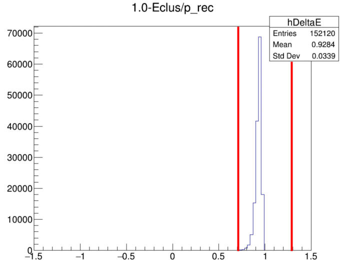
Elastic Cuts

1. Elastics (Can accurately predict hadron energy)
    a. W cut on elastic peak
    b. W calculated from k’, p_{beam}, and p_{targ} (LH2, at rest)
2. BBCal/HCal Trigger Coincidence Time
    a. 510ns +/- 40ns wide cut from TOF calculation
3. E/p electron cut
    a. Unity for electrons, cut 1.0 +/- 0.3
4. BBCal preshower energy deposition (150 MeV, SBS8)
    a. Pion rejection
5. Vertex Position
    a. From BigBite track
    b. Confirms electron originates within bulk of 15 cm target
    c. -8cm < BigBite track vertex position < 8cm









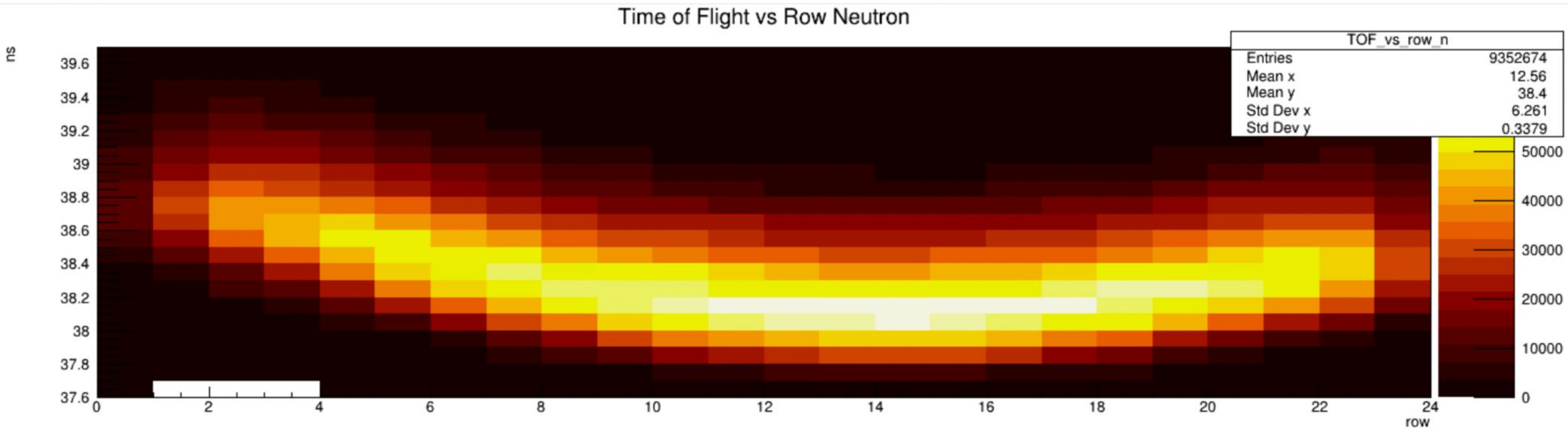
GMn

$$\frac{d\sigma}{d\Omega} = \eta \frac{\sigma_{\mathrm{Mott}}}{1+\tau}\left((G_E)^2 + \frac{\tau}{\epsilon}(G_M)^2\right)$$

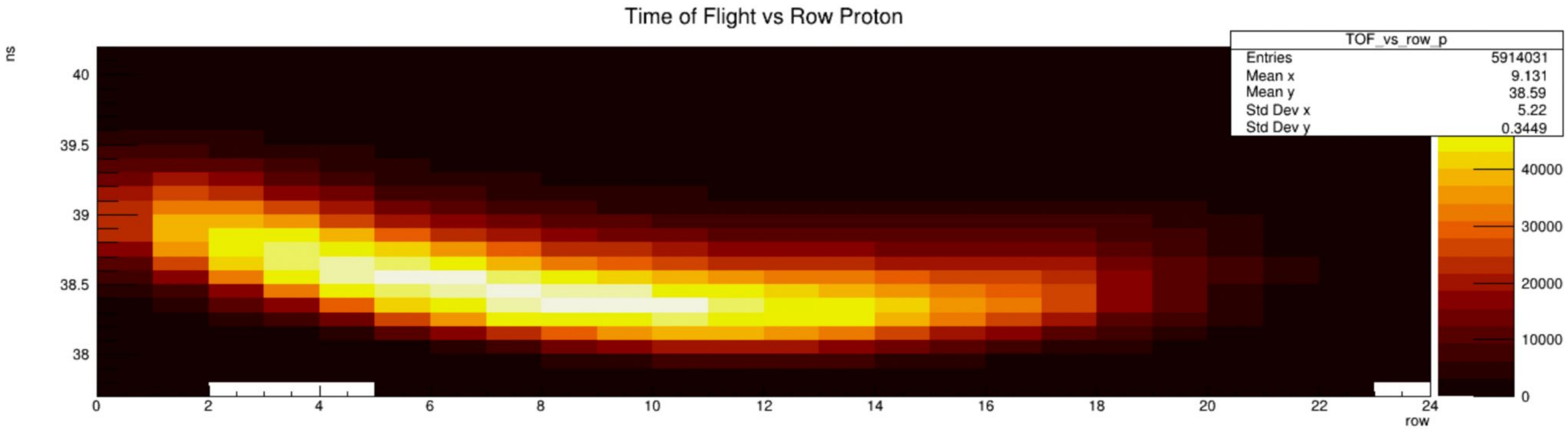
$$R'' = \frac{\left(\frac{d\sigma}{d\Omega}\right)_{d(e,e'n)}}{\left(\frac{d\sigma}{d\Omega}\right)_{d(e,e'p)}} \xrightarrow[\text{corr.}]{\text{nucl.}} \frac{\left(\frac{d\sigma}{d\Omega}\right)_{n(e,e')}}{\left(\frac{d\sigma}{d\Omega}\right)_{p(e,e')}} \xrightarrow[1\gamma]{} \frac{\eta \frac{\sigma_{\mathrm{Mott}}}{1+\tau}\left(\left(G_E^n\right)^2 + \frac{\tau}{\varepsilon}\left(G_M^n\right)^2\right)}{\left(\frac{d\sigma}{d\Omega}\right)_{p(e,e')}}$$

$$\xrightarrow[\text{Electric}]{\text{neutron}} \boxed{R = \frac{\eta\sigma_{\mathrm{Mott}} \frac{\tau/\varepsilon}{1+\tau}\left(G_M^n\right)^2}{\left(\frac{d\sigma}{d\Omega}\right)_{p(e,e')}}}$$

TOF Results Plots - Sim Data - Neutron rows



TOF Results Plots - Sim Data - Proton rows



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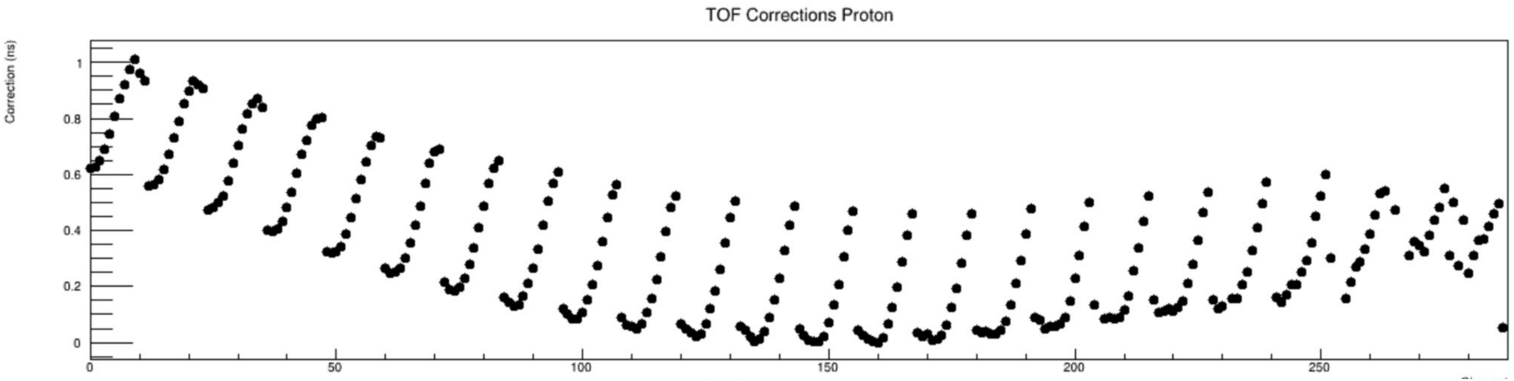
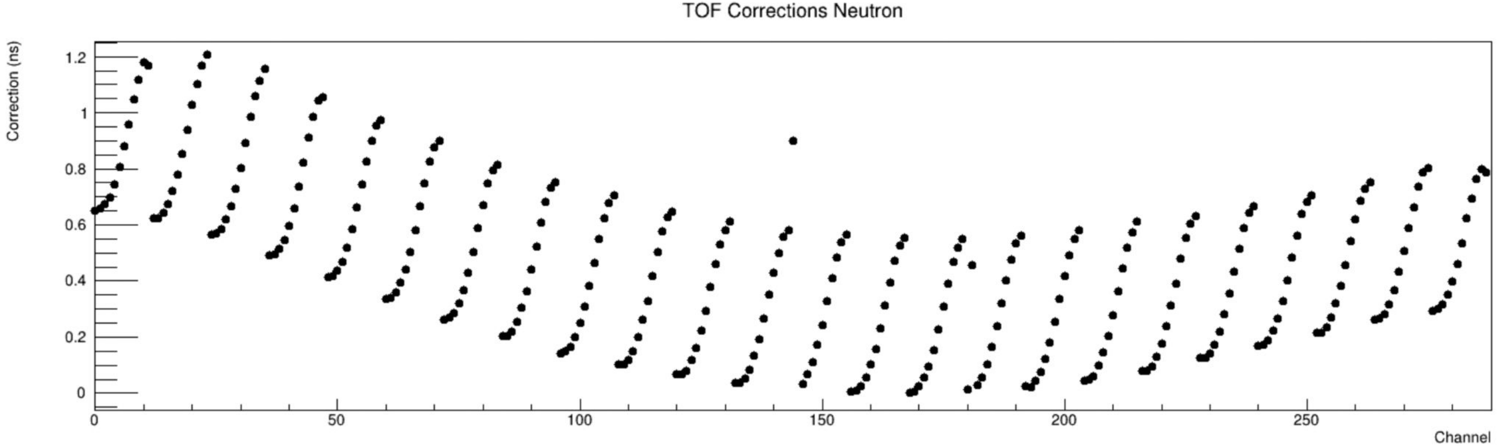
TOF Results Plots - TOF Corrections by Channel (Sim Data)





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GEn Beamline