Precision measurements of nucleon form factors with medium energy electron probes at Jefferson Lab

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LANL Seminar

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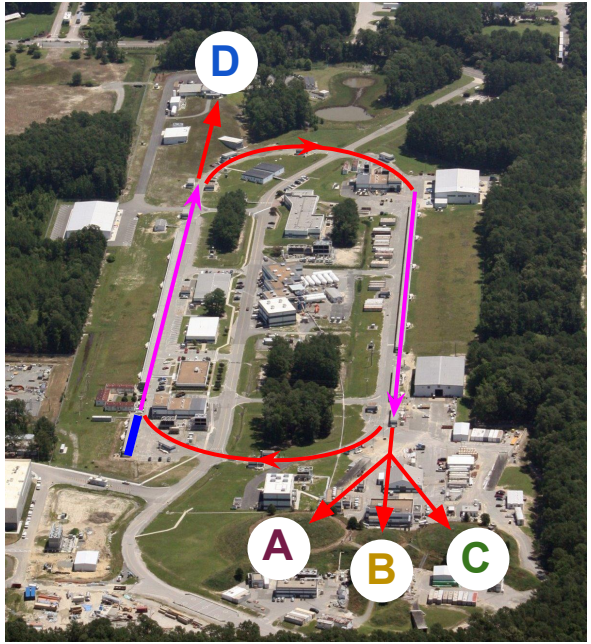
Topics to Cover Today

- Jefferson Lab and Hall A
  - Lab and Hall overview
  - Electron scattering
- Physics Goals
  - Elastic form factors
  - Two Photon Exchange
- Super BigBite Spectrometer
  - Magnets and Layout
  - Detector Subsystems
  - The Hadron Calorimeter (HCal)
- Elastic Selection
  - Tracking and reconstruction
  - Hadron detection and “delta” plots
- Simulations
  - Monte Carlo and Geant4
- Analysis
  - HCal calibrations/performance
  - HCal detection efficiency
  - GMn extraction and world data

Jefferson Lab (JLab) - CEBAF

- CEBAF: Continuous Electron Beam Accelerator Facility
- Four experimental halls: **A**, **B**, **C**, and **D**
- Injector: photocathode gun system injects continuous wave (CW) electrons into the “racetrack” accelerator
- 2x Linear Accelerators (Linacs)
  - Superconducting Radio Frequency (SRF) Linac
  - Novel Niobium SRF cavity technology
  - CW: beam bunches configurable *250 MHz* or *500 MHz*
- Arc magnets allow for CW recirculation
  - Capable of 5.5 recirculations (*passes*)
  - Beam energy: up to 11 GeV in Hall A

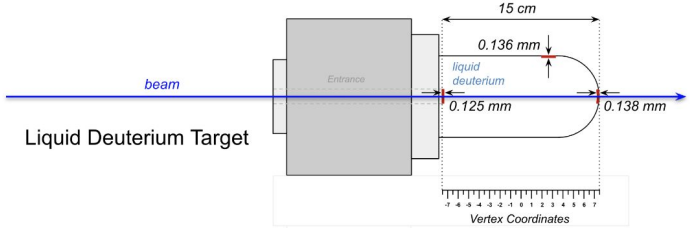
Jefferson Lab Aerial View



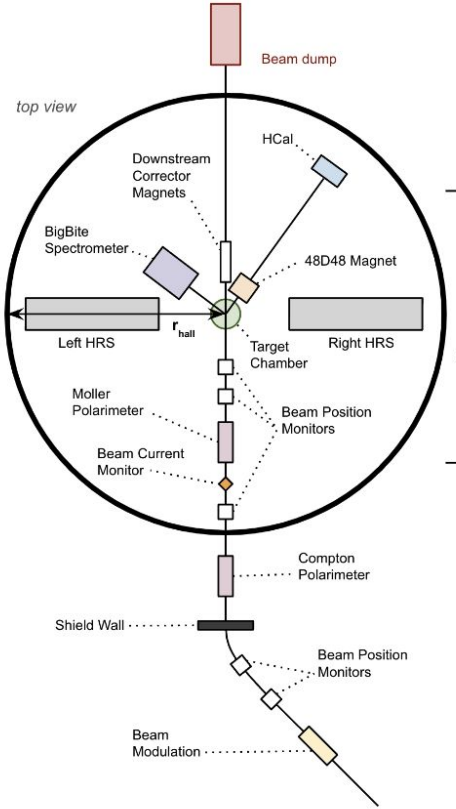
One seven-cell SRF Niobium Cavity

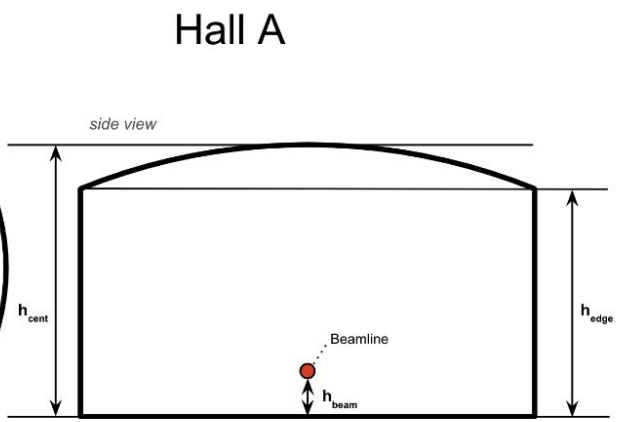
Jefferson Lab (JLab) - Hall A

- "Fixed" stationary target cell
- Largest of the four halls
  - May host large temporary installations
- High electron beam current
  - Up to 100 uA
  - High statistics over time relative to other accelerators and JLab experimental halls



For example: With a 15cm liquid deuterium target and 15 uA, luminosity ~10^{37} nucleons/cm^2/s

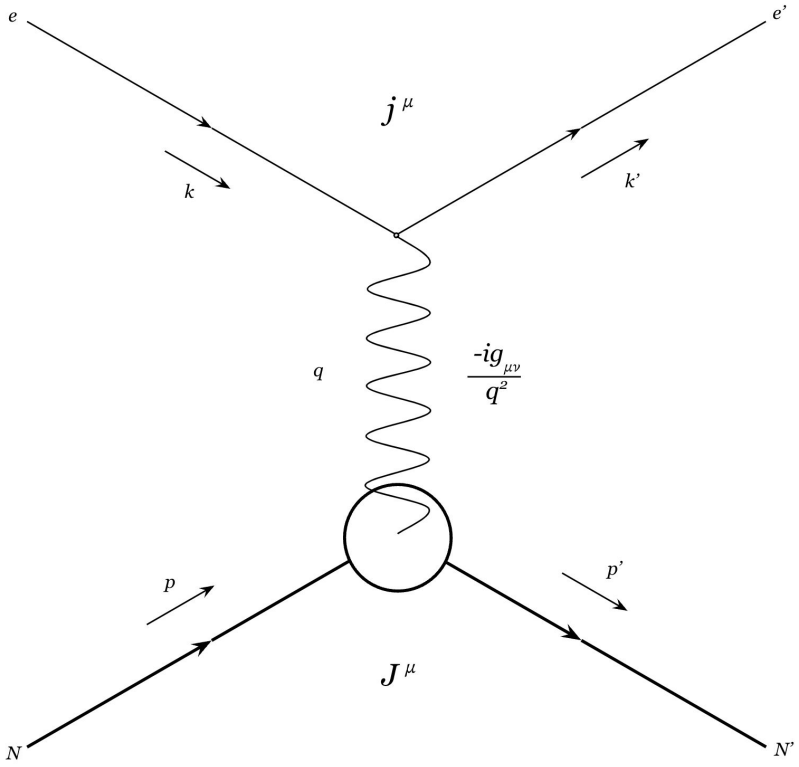




$r_{hall} \cong 26.8$ m
$h_{cent} \cong 24$ m
$h_{edge} \cong 16$ m
$h_{beam} \cong 3.05$ m

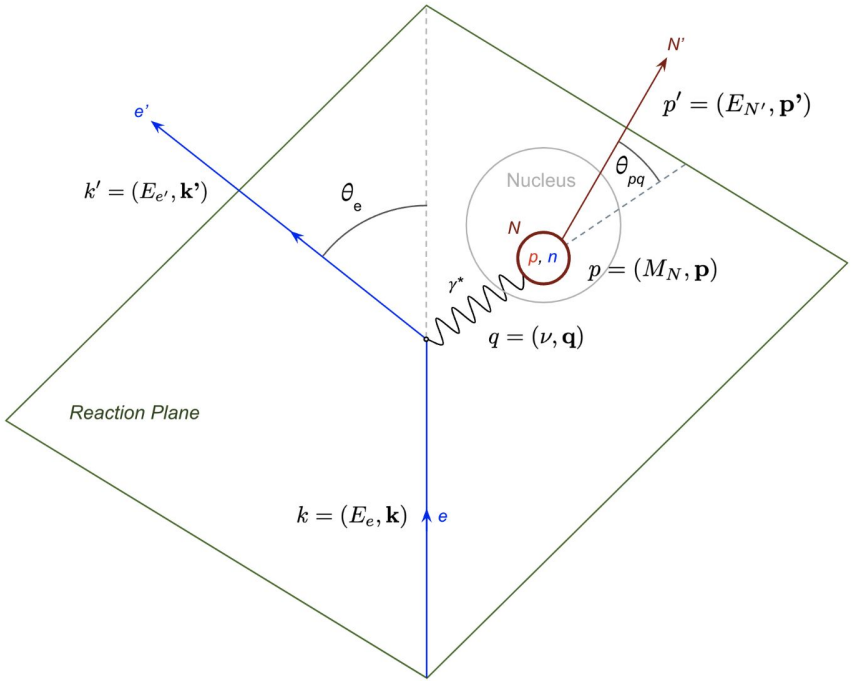
**figure not precisely to scale*

Physics Goals



JLab - Quasielastic *eN* Scattering

- Incoming electron *e* exchanges a virtual photon γ^* with nucleon *N* approximately at rest, resulting in a scattered electron e' and intact final state nucleon *N'*.



- Elastic kinematics *mostly* determine the final state electron and final state nucleon properties $(\mathbf{p} \approx 0 \text{ and } \theta_{pq} \approx 0)$:

$$q = k - k'$$

$$-q^2 \equiv Q^2 = 2EE'(1 - \cos(\theta_e))$$

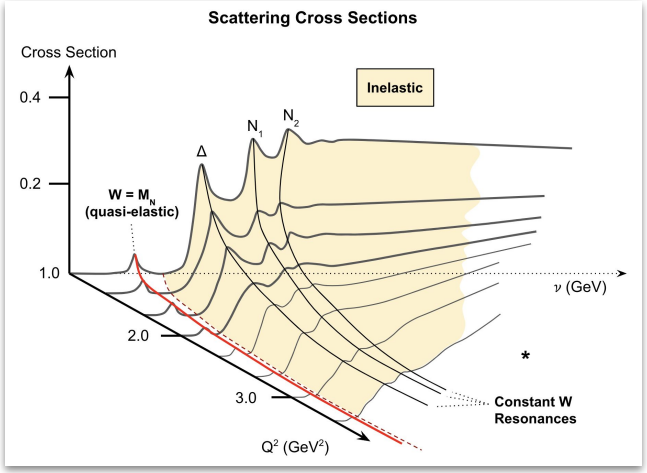
- The invariant mass *W* is approximately the nucleon mass:

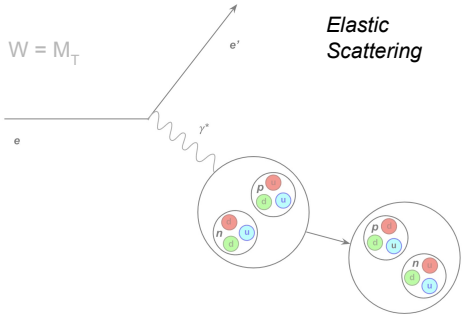
$$\nu = E_e - E_{e'}$$

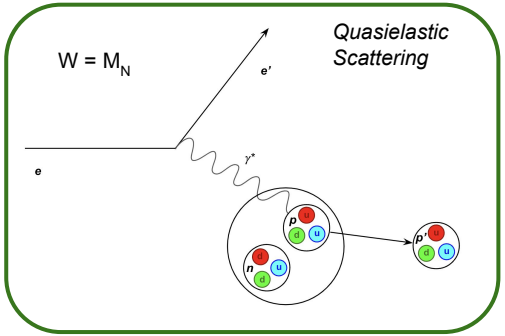
$$W = \sqrt{M_N^2 + 2M_N\nu - Q^2} \approx M_N$$

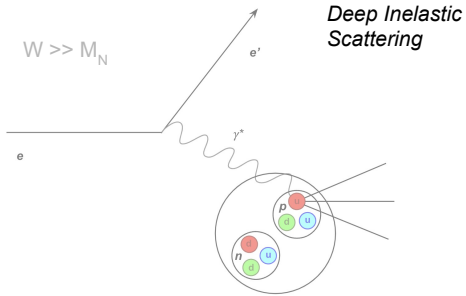
JLab - Electron Scattering

- What we know:
  - Beam energy and position (*k*)
  - Final state particle position, energy, and timing information from detector subsystems (*k'* and *p'*)
- We can reconstruct the probability of interaction for quasielastic scattering - or cross section
- The quasielastic cross section is very low at high Q^2 - need high luminosity and strong *quasielastic selection*
- Hall A at JLab is ideal for this research









*plot concept credit, Xiaochao Zheng

Electromagnetic Form Factors

- Nucleons are not point-like fermions!
- The differential cross section of the nucleon can be represented by a point-like part and a structure part that describes the internal structure of the nucleon

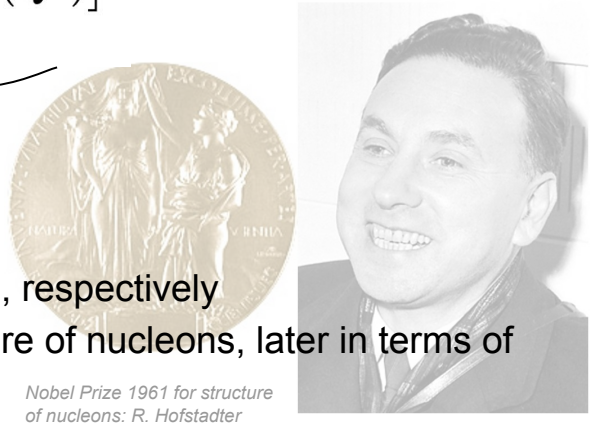
- To describe elastic form factors we need a a couple more definitions..

$$\epsilon = 1/\left(1 + 2(1+\tau)\tan^2(\theta_e/2)\right)$$

$$\tau = Q^2/4M_N^2$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} = \underbrace{\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}}}_{\textit{point-like part}} \underbrace{\frac{1}{\epsilon(1+\tau)}\left[\epsilon G_E^2(Q^2) + \tau G_M^2(Q^2)\right]}_{\textit{structure part}}$$

- This is the Rosenbluth Formula
- G_E and G_M are the *Sachs Electric* and *Sachs Magnetic* Form Factors, respectively
- For his pioneering work using electron probes to describe the structure of nucleons, later in terms of form factors, Robert Hofstadter won the nobel prize



Nobel Prize 1961 for structure of nucleons: R. Hofstadter

Interpreting Form Factors

- Form factors are different between isospin states of the nucleon (proton and neutron) and are functions of Q^2
  - Extrapolation to $Q^2 = 0$ yields the charge and magnetic moments of each nucleon:

$$\text{proton},\ Q^2 = 0 \quad \rightarrow \quad G_E^p(0) = 1, \quad G_M^p(0) = \mu_p$$
$$\text{neutron},\ Q^2 = 0 \quad \rightarrow \quad G_E^n(0) = 0, \quad G_M^n(0) = \mu_n$$

- At low Q^2 ($Q^2 << M_N^2$), form factors are the fourier transforms of the charge and magnetic distributions in the nucleon
  - The charge and magnetization radius of a spherically symmetric nucleon can be approximated via Taylor expansion and integration:

$$G_E(Q^2) = \int \rho(\mathbf{x}) e^{-i\mathbf{q}\cdot\mathbf{x}} d^3\mathbf{x}$$
$$G_M(Q^2) = \int M(\mathbf{x}) e^{-i\mathbf{q}\cdot\mathbf{x}} d^3\mathbf{x}$$

$$\longrightarrow \quad \langle r^2 \rangle = -6 \frac{dG_{E,M}}{dQ^2}\bigg|_{Q^2 \to 0}$$

The Born Approximation and TPE

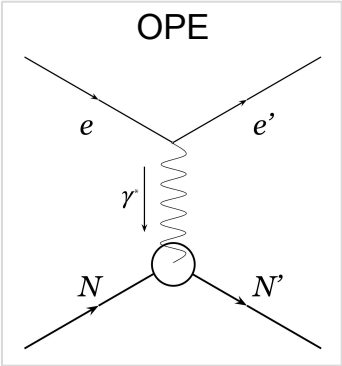
- The Rosenbluth formula assumes one virtual photon exchange (OPE)
  - This is the *Born Approximation*

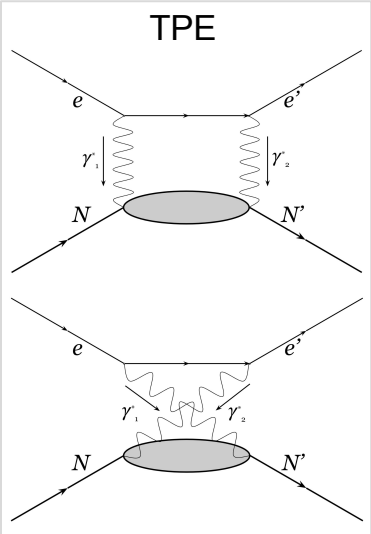
- *However* - corrections to the scattering cross section exist for additional virtual photons exchanged
  - Each additional photon is suppressed by α^2 per photon exchange
  - Can still contribute meaningfully to cross sections at higher Q^2!

- The next to leading order correction to the cross section is “hard” two photon exchange (TPE):

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{NLO corrected}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Rosenbluth}} + \Delta_{\text{TPE}}$$

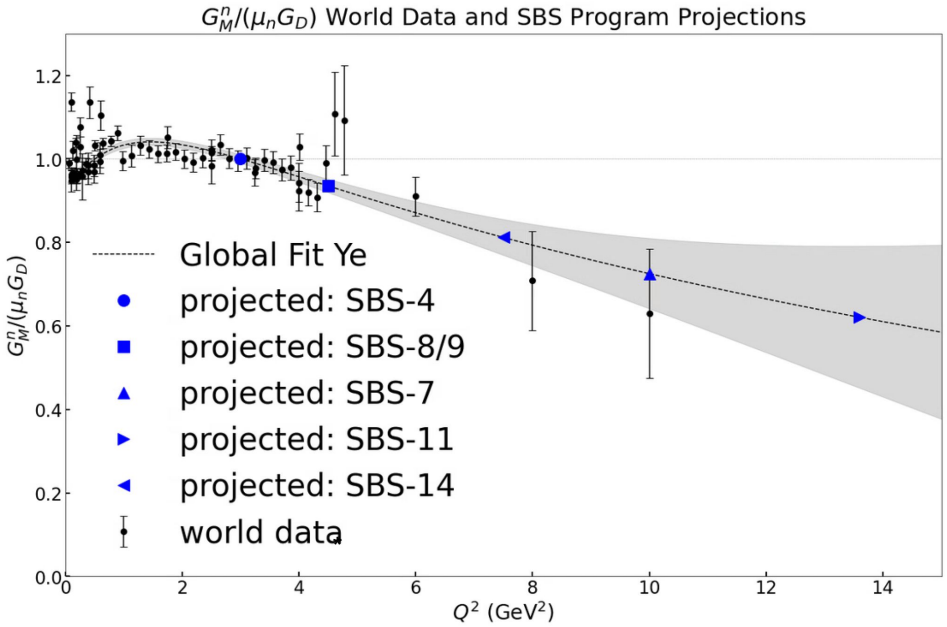
Tree-level and first loop order Feynman diagrams





GMn with Born Approximation

- The full experimental SBS program will measure the form factors: G_E^p, G_E^n, and G_M^n with relatively high precision at unprecedented Q^2
- We measure the neutron to proton cross section *ratio* to cancel shared systematic error (*Durand technique*)
- After corrections to this ratio, we can extract the model-dependent form factor G_M^n
- *G_M^n is the first experiment to use the Super Bigbite Spectrometer and is the commissioning experiment for the SBS program!*



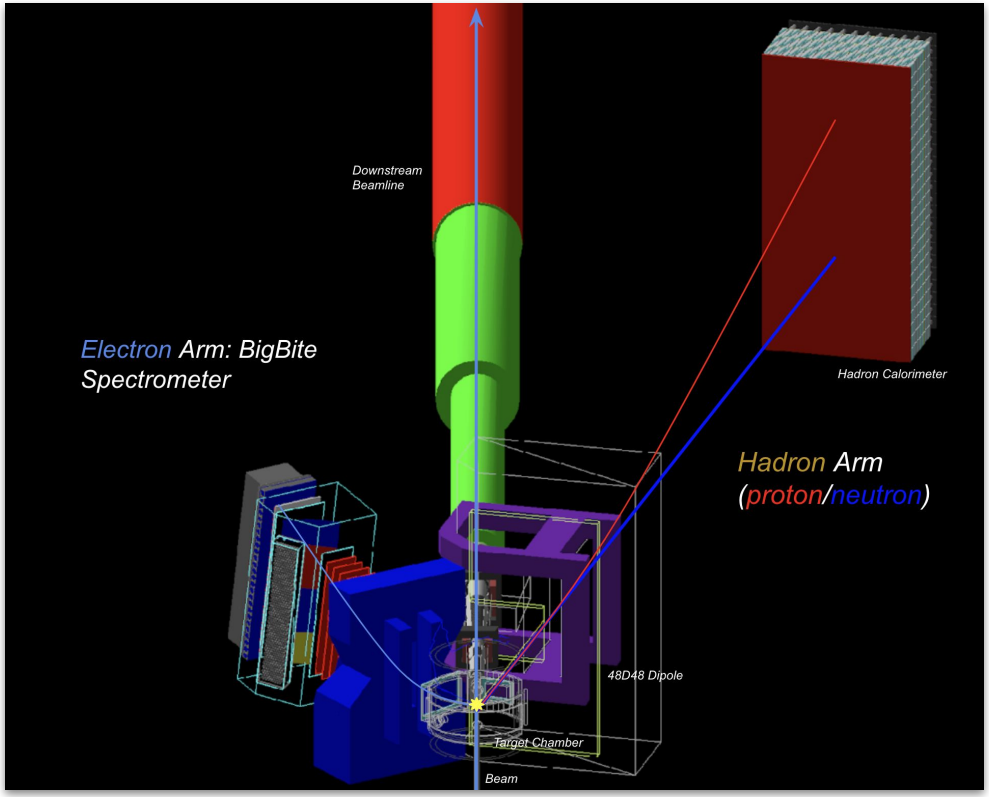
Projected points located arbitrarily on global fit.
No error included.

** World data from F. Gross et al. 50 Years of quantum chromodynamics: Introduction and Review*

The Super BigBite Spectrometer

Super BigBite Spectrometer: Composition

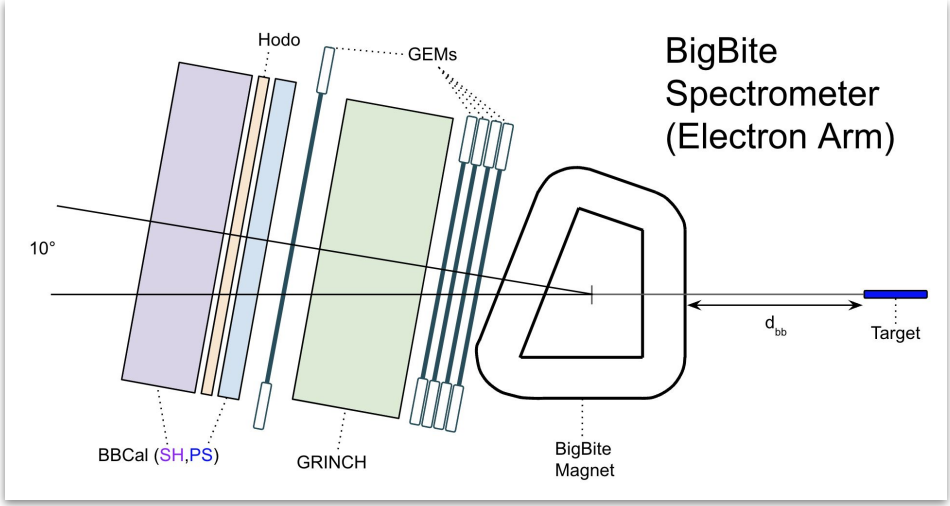
- Two arms: electron and hadron
- Semi-inclusive: measure final state electron (*e'*) and one final state hadron (*N'*) from *d(e,e'n)p* and *d(e,e'p)n* channels
- Electron arm uses **0.9 T*m** capable (max 750 A) BigBite dipole for electron spectrometer
- Hadron arm uses **1.7 T*m** capable (max current 2100 A) 48D48 dipole for proton and neutron separation in Hadron Calorimeter



- *So we trigger on quasielastic electrons in the electron arm, then measure protons and neutrons in the hadron arm*

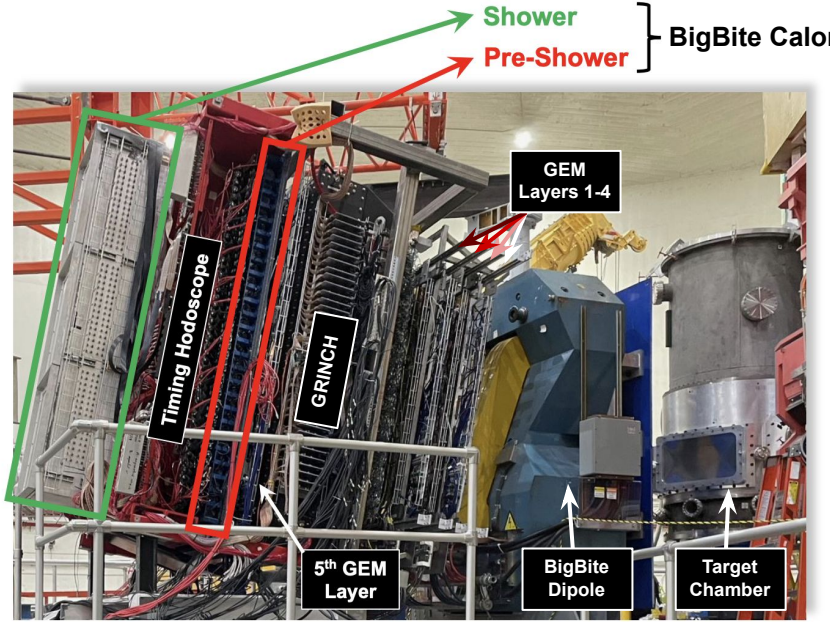
BigBite Spectrometer Subsystems

- Five Gas Electron Multiplier (GEM) planes for **tracking**.
  - High segmentation: ~7000 channels / layer
  - Position resolution ~ 70μm
  - Capable at 25 kHz/mm^2
- Heavy Gas Ring Imaging Cherenkov (GRINCH)
  - Functional threshold cherenkov for particle identification (**PID**, pion rejection)
- Scintillator bar timing Hodoscope
  - Precise **timing** corrections for electron arm

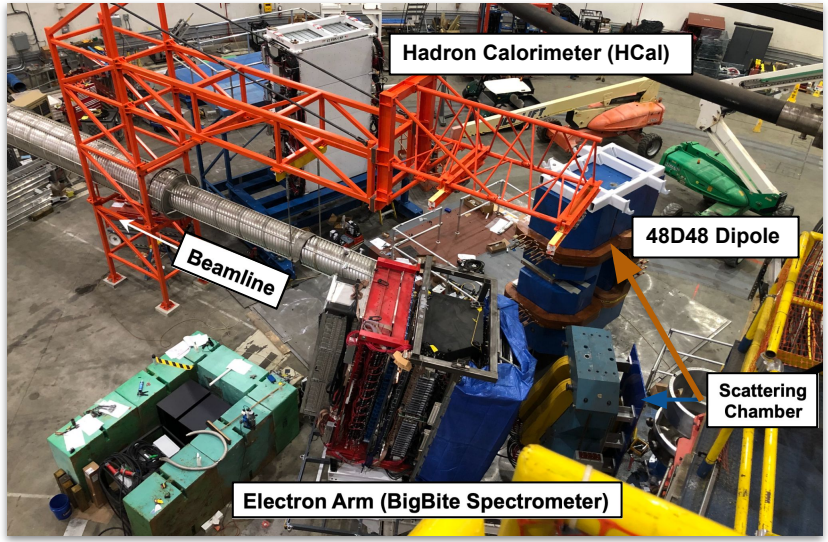


- BigBite lead glass Calorimeter (BBCal)
  - 52 channel preshower section provides **PID** (pion rejection) with a threshold energy cut ~ 200 MeV
  - 189 channel shower section stops quasielastically scattered electrons
  - Sum-over-threshold preshower and shower fADC single-arm electron **trigger**
  - Segmentation provides **tracking** constraint

BigBite Spectrometer and Hadron Arm Layout



Electron Arm



Hadron Arm (right of beamline)

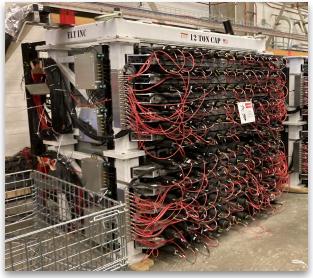
Hadron Calorimeter (HCal) Overview

- HCal is a highly segmented hadron calorimeter
  - Composed of 288 modules (*24 x 12 channels*)
  - Each module: *15 cm x 15 cm x 1 m*
  - Full acceptance: *180 cm x 360 cm*
  - *4 craneable assemblies, 40 tons*
- HCal measures energy, position, and timing of scattered hadrons
- HCal samples part of the energy deposited within it
  - Observed energy sampling fraction: *~10%*
  - Observed energy resolution: *~40%*

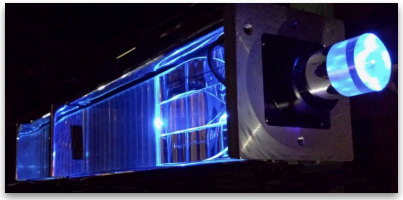
- Position information is used to identify scattered nucleons
- Measured energy provides weighting for cluster position reconstruction
- Timing is used for subtraction of randoms

HCal provides the only means to detect protons and neutrons!

HCal, Target-facing-side, Hall A



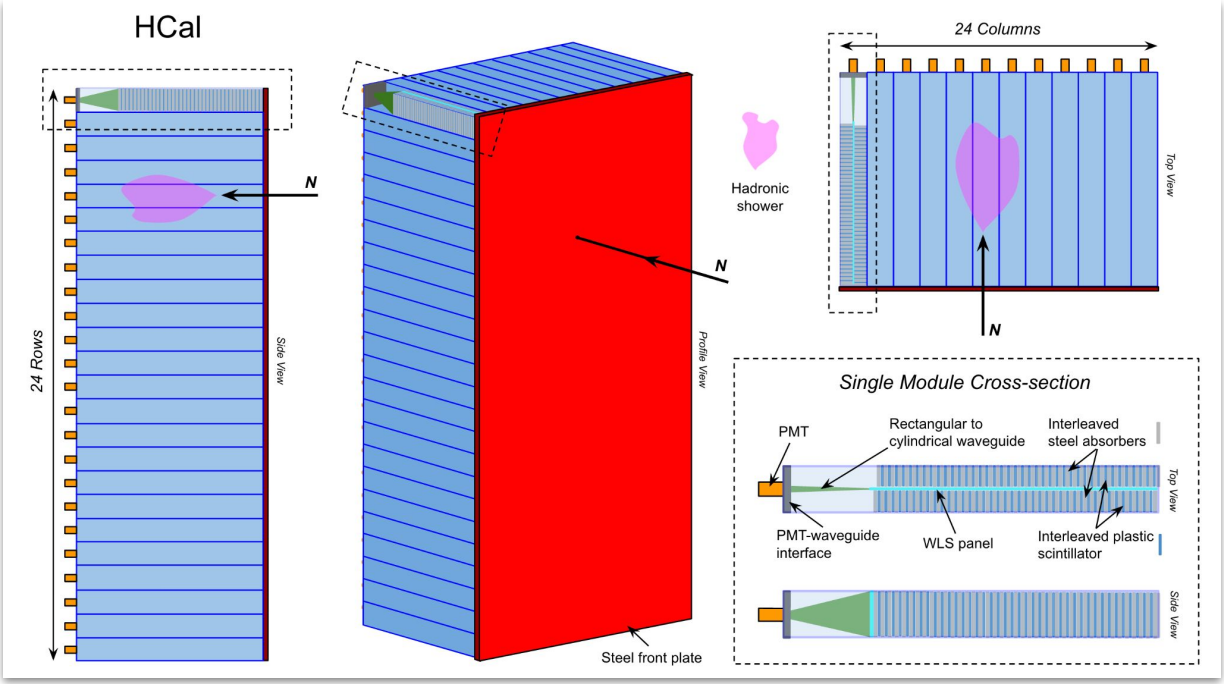
HCal bottom half, rear view



Single module, opened

HCal: Hadron Calorimetry

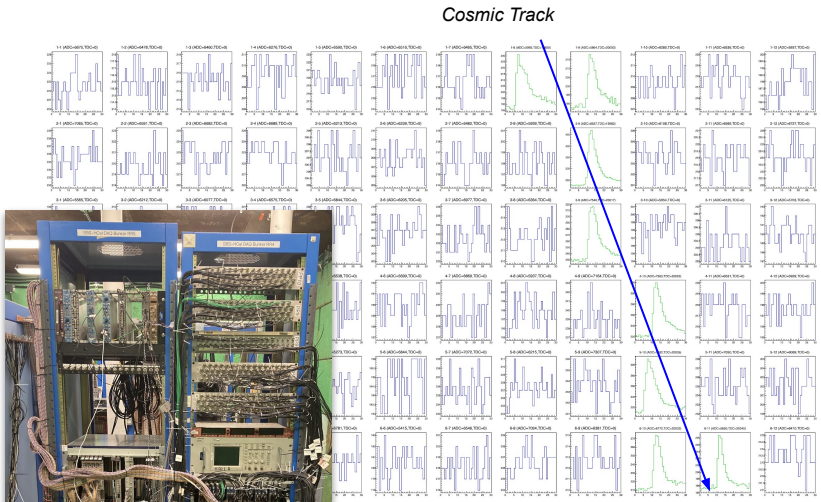
1. Nucleons interact with absorbers producing hadronic showers
2. Part of the electromagnetic radiation is sampled by many plastic scintillators per module
3. A wavelength shifter panel channels light and converts its wavelength to improve PMT efficiency
4. Light is concentrated into a rectangular to cylindrical waveguide
5. Waveguide is coupled to a PMT



Potentially many modules are involved in a single detection event, constituting a *cluster.*

HCal: Data Acquisition

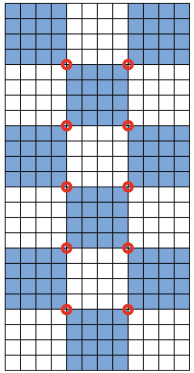
- Crates
  - 2x VXS crates
  - 18x fADC250 flash ADCs with 16 channels each
  - 5x f1TDC with 64 channels each
  - VTP read out controllers enable FPGA trigger formation on HCal ADC/TDC information
- Triggers
  - Coincidence top and bottom of HCal scintillator paddles (cosmics)
  - LED pulser
  - Summing module
    - Sum ADC overlapping regions over threshold
    - Remote threshold controller with DC low-pass filter
    - May be combined with BBCal trigger to form electron arm, hadron arm coincidence trigger.



Single event display, single HCal quadrant

HCal cabling in DAQ bunker

HCal overlapping regions trigger map



Blue and white: fADC sum regions

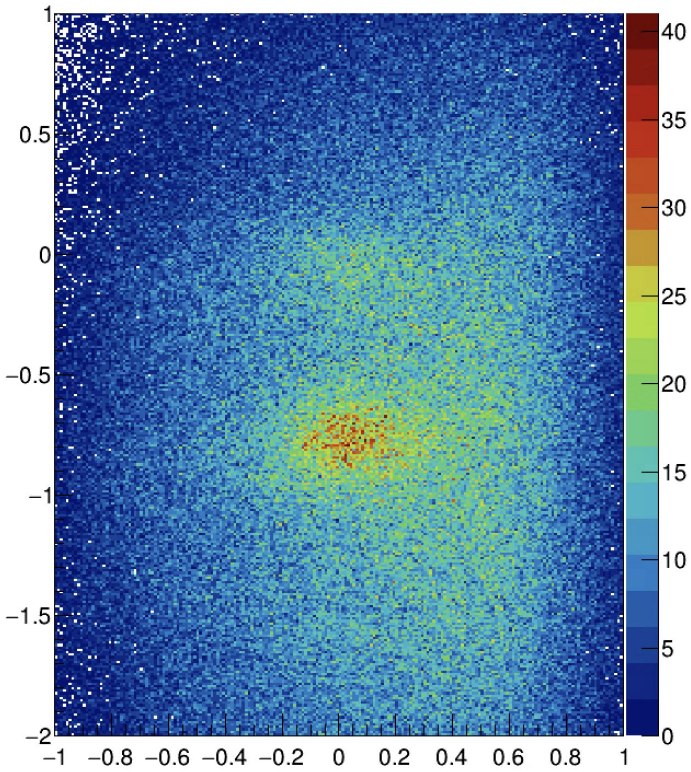
Red circles: summed regions - trigger over threshold

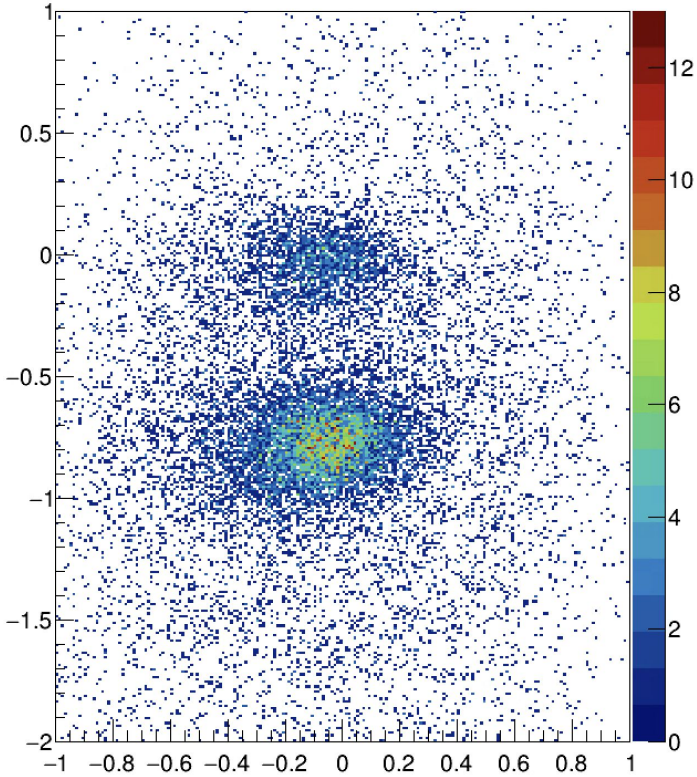
HCal: Design Breakdown

- WLS
  - Chosen to optimize lower decay time, needed for timing, detection, and high-rate performance
  - Centered in modules to shorten absorption length
- Scintillator
  - PPO only (no doping) to match WLS absorption peak more closely
- Light Guide
  - Custom design to match WLS (rectangular) to PMT window (circular)
- ADC
  - Sample width 4 ns, matched to CEBAF electron bunch crossing time
  - Linear interpolation methods available to extract timing. Resolution ~1.2 ns
- TDC
  - Multi-hit functionality at high timing resolution

Hardware	Purpose	Specification
Module	Facilitate hadron showers, provide segmentation for position	40 layers alternating steel/scintillator, 1 WLS, 1 custom light guide, 1 PMT (15cm x 15cm x 1m)
Scintillator	Transduce hadron KE to gamma	PPO 2,5-Diphenyloxazole: fluor, peak 385nm
Wavelength Shifter (WLS)	Shift gamma to PMT peak detection efficiency	St. Gobain BC-484: 3ns decay; peak abs. 375nm; peak emi. 484nm
PMT	Transduce gamma to signal	192 12-stage "CMU" Photonis XP2262, 96 8-stage "JLAB" Photonis XP2282 (center third columns)
ADC	Analog-to-digital conversion (per module)	fADC250: 2V dynamic range; 250 MHz (4 ns bins)
TDC	Time-to-digital conversion (per module)	F1TDC: Multi-hit; 800 ns dynamic range

Elastic Selection

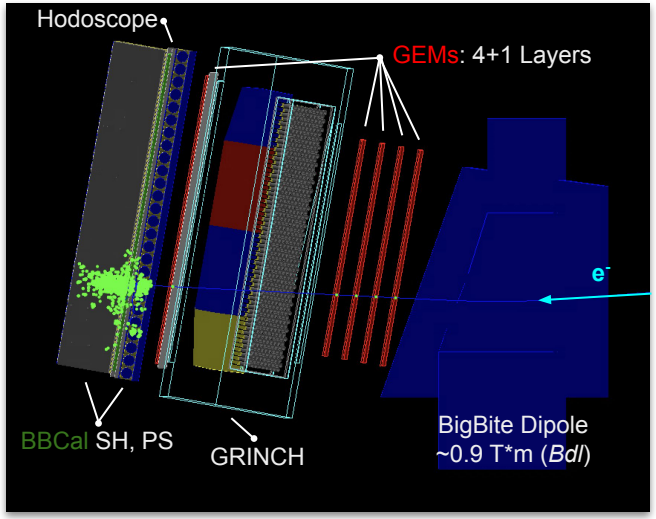




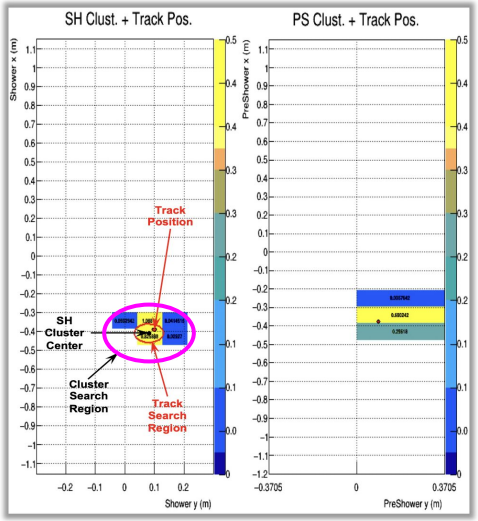
Electron Arm Analysis

- Energy deposited over threshold in BBCal triggers an event
- **Reconstruct** e' track
  - Constrain potential tracks with BBCal and Hodoscope position information
  - Minimize chi-squared per event for potential tracks reconstructed to vertex location in target

Electron Arm - Geant4 Single Event



BBCal Single Event Display



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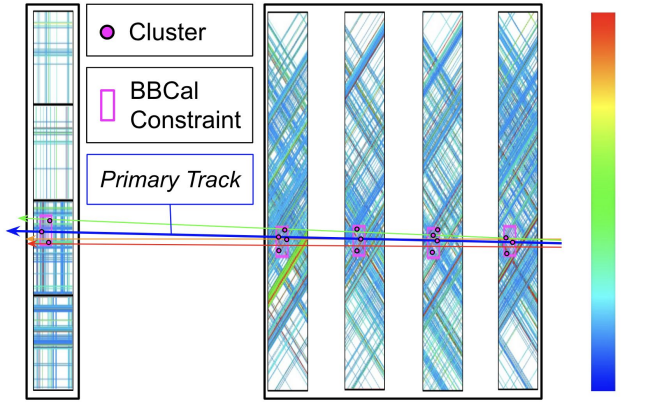
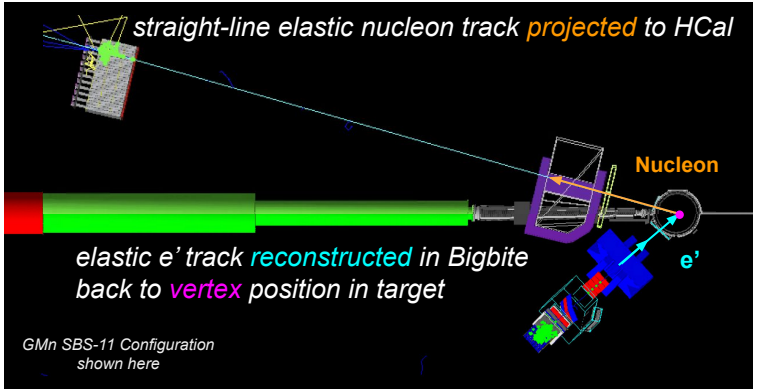


- Constraint reduces search region to **2-3%** of active GEM area
- *Due to high luminosity, without constraints, combinatorics can regularly reach to **> 1M** competing tracks per event!*

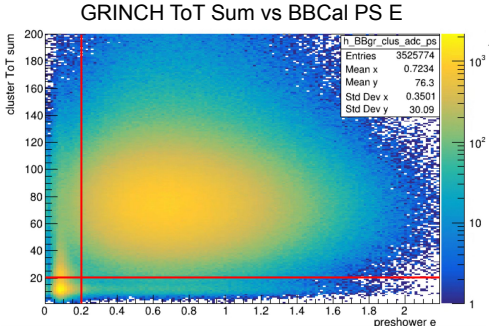
(1) BBCal display Provakar Datta, University of Connecticut

Electron Arm Analysis - Elastic Selection

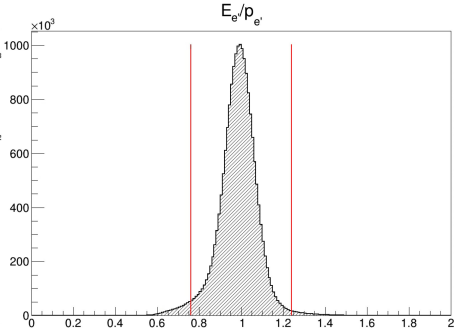
- With electron track we can make judicious cuts to select on quasi-elastic events
- For elastic electrons in BigBite, $E_{e'}/p_{e'}$ should be nearly *unity*
- Track vertex position should originate within the 15 cm cell
- Preshower energy provides pion rejection
- GRINCH time-over-threshold (ToT) sum provides pion rejection
- For elastics, $W = M_N$
- Two arm coincidence time cut further selects elastics
- Using elastic kinematics, project a straight line with *q-vector* out to HCal (this is the *neutron hypothesis*)



Simulated elastic event in SBS

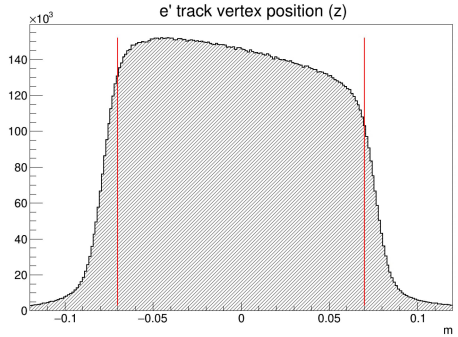


Large electron "spot" with pion bands eliminated with both BBCal preshower and GRINCH PID

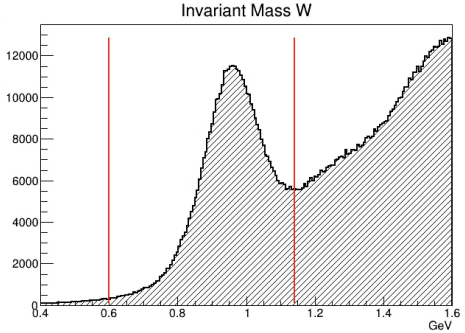


e' p (typical): $p_e \approx 2.5\ GeV/c^2$

e' mass (negligible): $M_e = 0.511\ MeV/c^2$



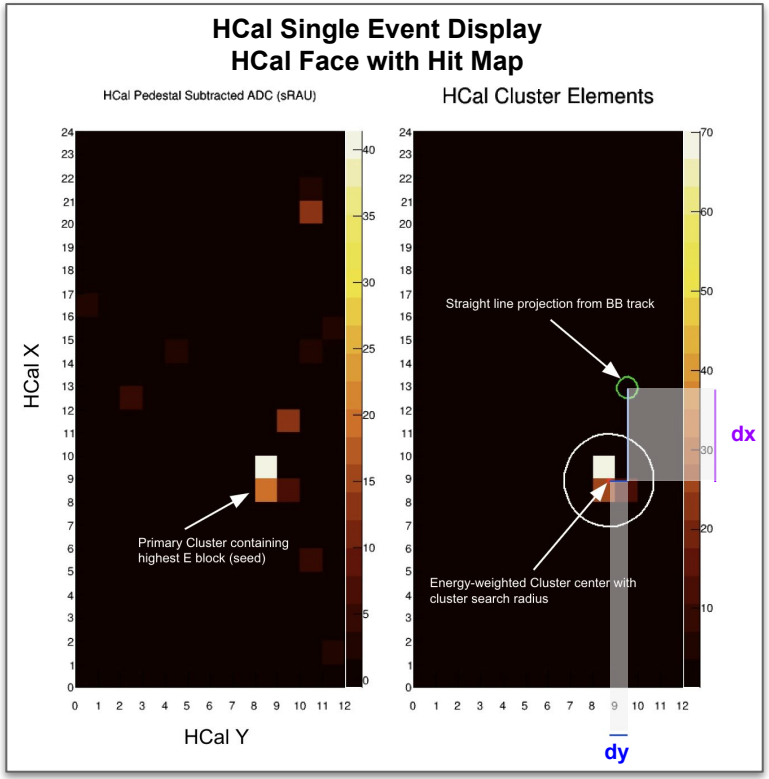
Target endcap scattering events can be cut with precision vertex reconstruction



For elastics, the invariant mass transfer should equal the nucleon mass

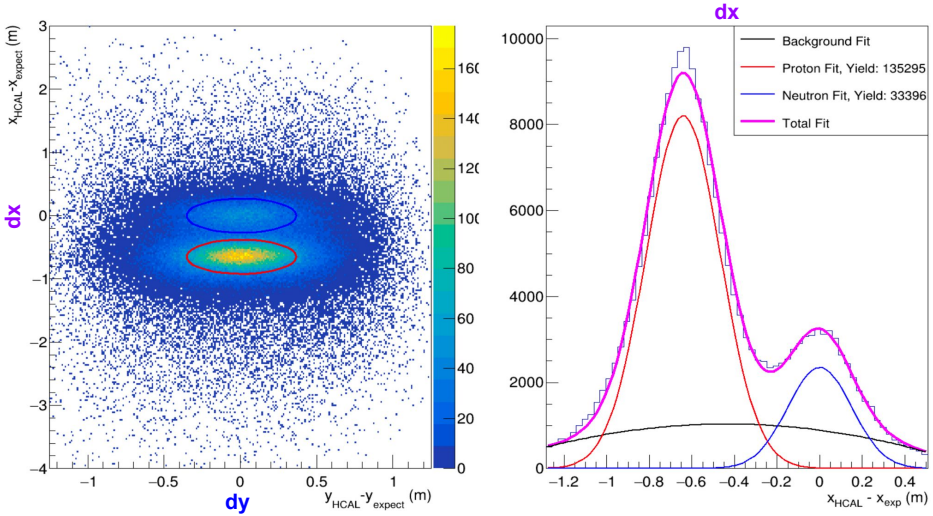
$M_N \approx 0.94\,\mathrm{GeV/c^2}$

Hadron Arm Analysis - Delta Plots

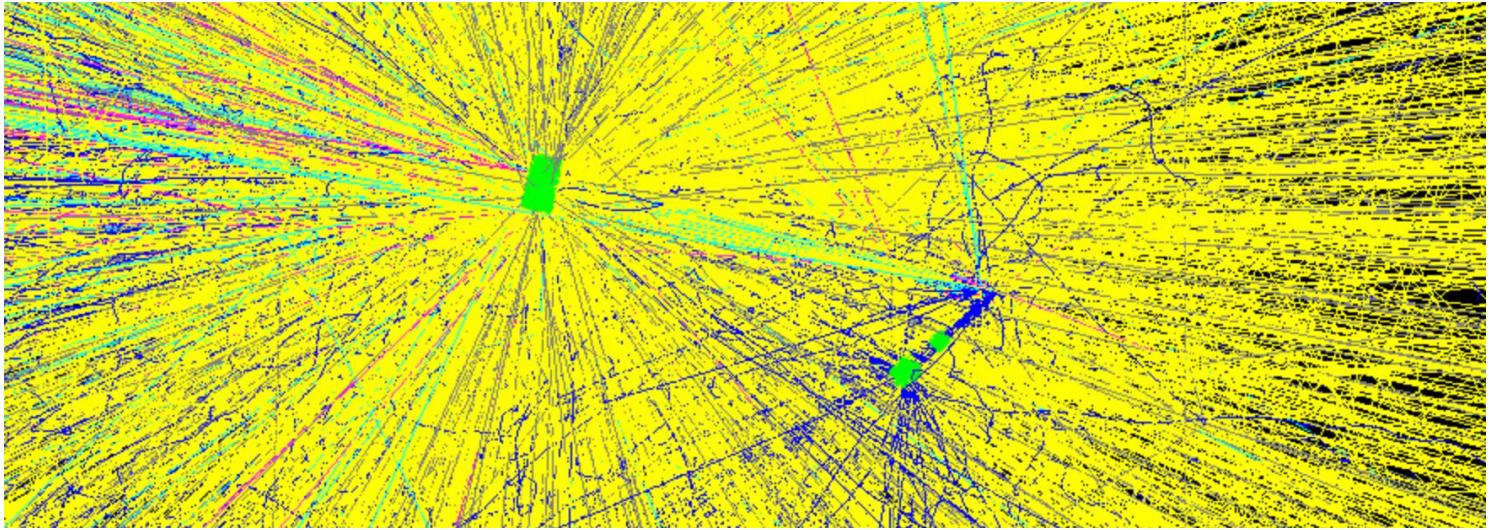


- To extract proton and neutron yields, build distributions of ***dx*** and ***dy***
  - ***dx*** is the vertical (dispersive) difference between the elastic kinematic *neutron hypothesis projection* to HCal from the e' track and the *detected* position measurement of the scattered hadron.
  - ***dy*** is the same as *dx*, but horizontal (transverse) direction.
- From these, assemble proton and neutron "spot" plots and projections
- Can integrate fits to these distributions to extract rough yields, *but there's plenty to do before we extract quasielastic cross sections*

Delta Plots



Simulations

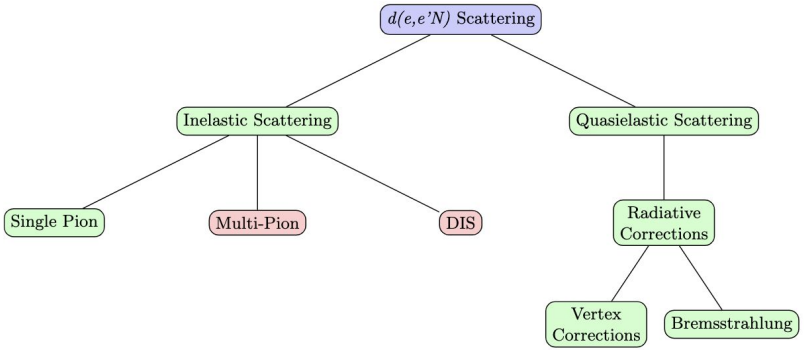


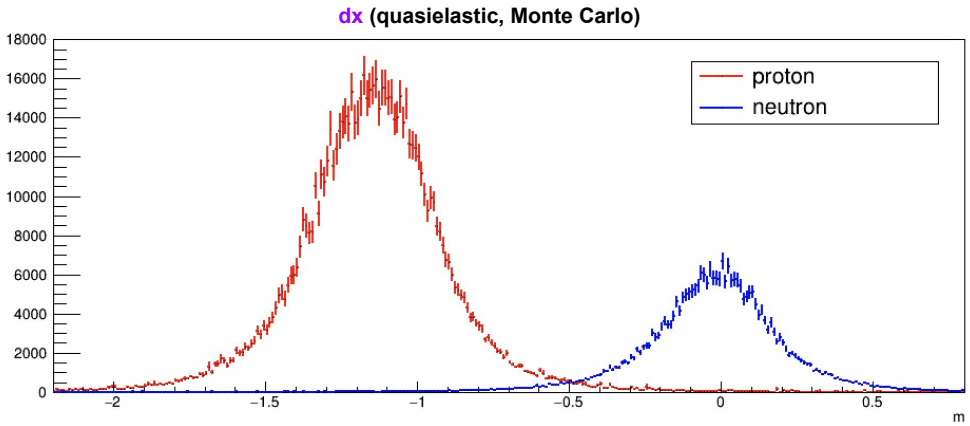
*not Jackson Pollock

Simulations: Motivation

- Precision quasielastic nucleon scattering must account for mechanisms that elastic kinematics alone cannot predict
  - Nuclear binding
  - Nuclear resonance and pion production
  - Fermi motion
  - Radiative corrections
  - Final state interactions
  - And others with lower probability
- SBS uses a *G4SBS*, a simulation framework based on the Geant4 toolkit
  - Geant4 tracks scattered particles through our detectors
  - Custom event generators accurately account for nuclear effects and *some* additional scattering processes (in green)
- Produce *corrected* quasielastic Monte Carlo distributions for comparison to data

Electron-nucleon Scattering Processes

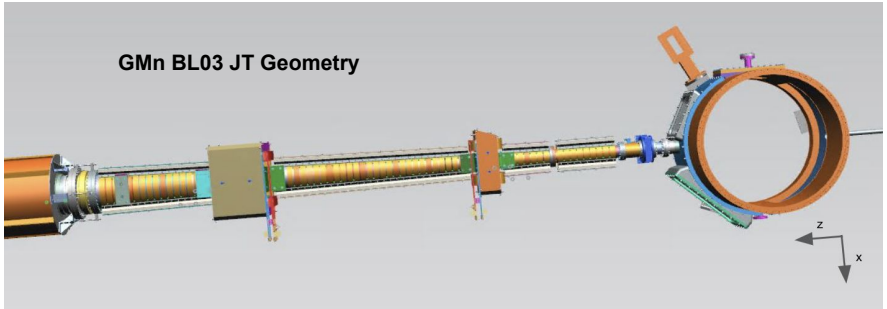




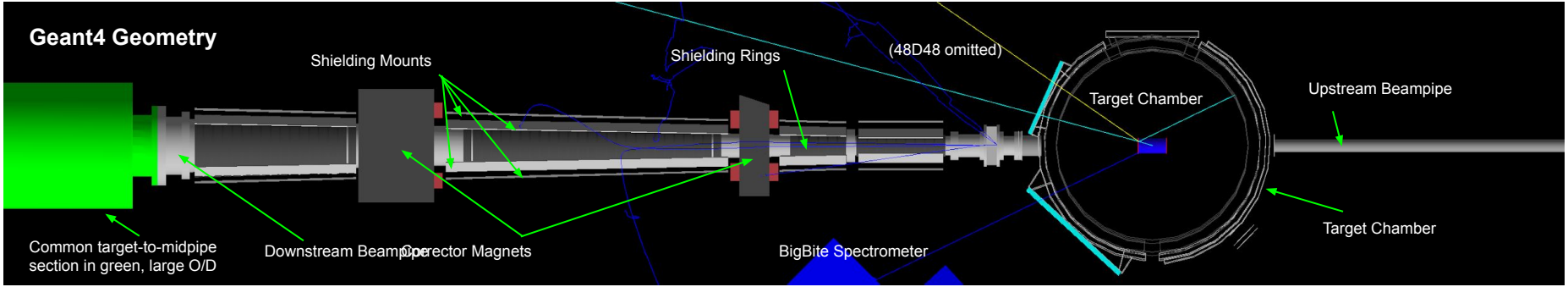
Simulations: Geant4 Geometry

- Geant4 requires sparse models to track particles
  - Inclusion of all CAD/JT parts in geometry results in significant efficiency losses
  - Parts are chosen based on volume, position, and material properties, then manually encoded
- Background and data processing rates assessed and used to improve quality assurance
- Sensitive detector volumes created in detector geometry and physics process flags configure simulations for efficient running
- *Order 10000 computing hours needed to produce sufficient data for extractions*

For example: GMn Beamline Geometry



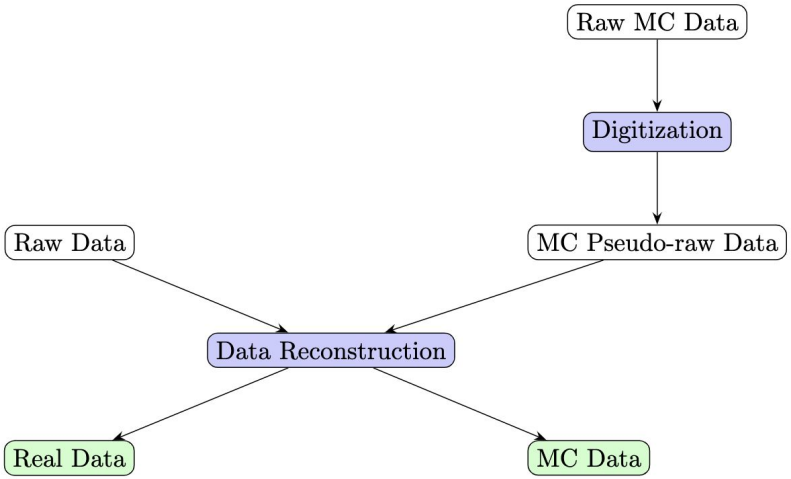
One of several configurations filtered and translated into Geant4



A Note on Data Reconstruction

- Raw analog data is encoded by data acquisition into an efficient binary format (an array of 32 bit words - *EVIO*)
- Data reconstruction software (SBS-offline) processes this data with crate maps, kinematic setting parameters, and physics variables into .root trees for analysis
- Raw Monte Carlo output is interpretable, but must be digitized into pseudo-raw data for reconstruction with the same methods as data

Data Reconstruction Process Tree



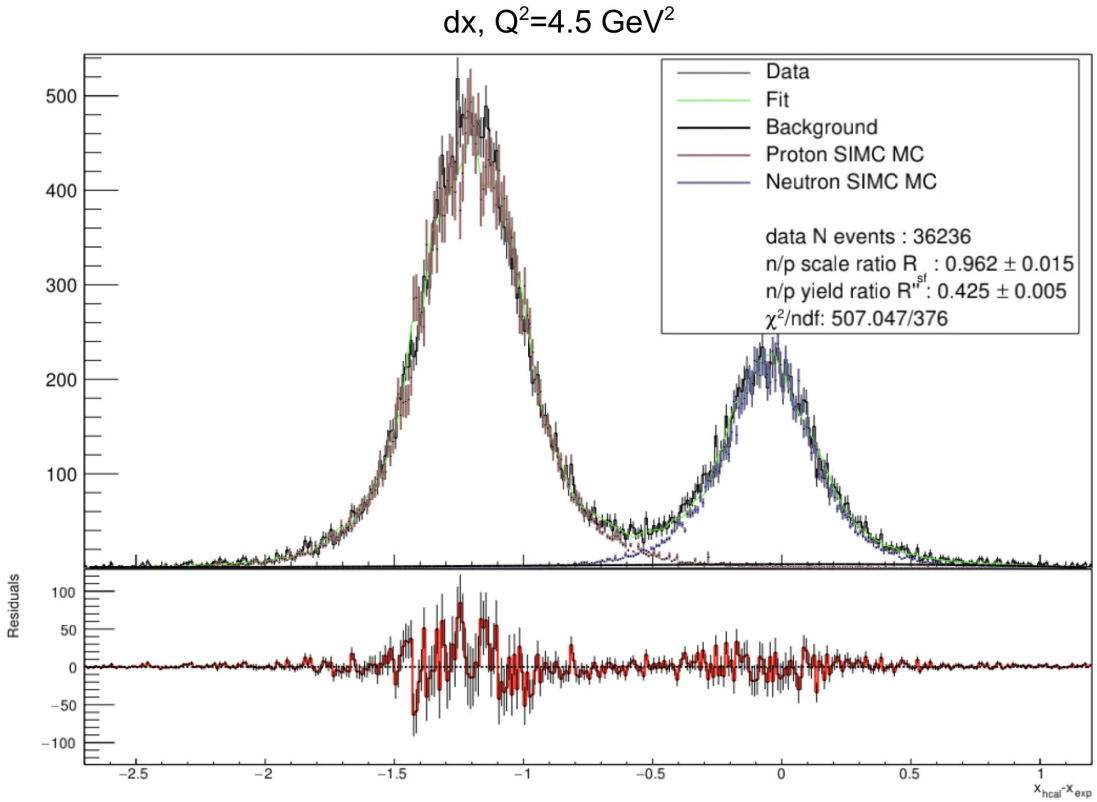
- After reconstruction, an apples-to-apples comparison may be achieved between data and MC

Data Monte Carlo Comparisons

- Match peak positions with accurate 48D48 field maps
- MC is does not have absolute normalization, but relative neutron to proton weights are consistent
- Proton and neutron scale parameters are free to fit the data with various backgrounds
- Extract the ratio of MC neutron scale to MC proton scale parameter:

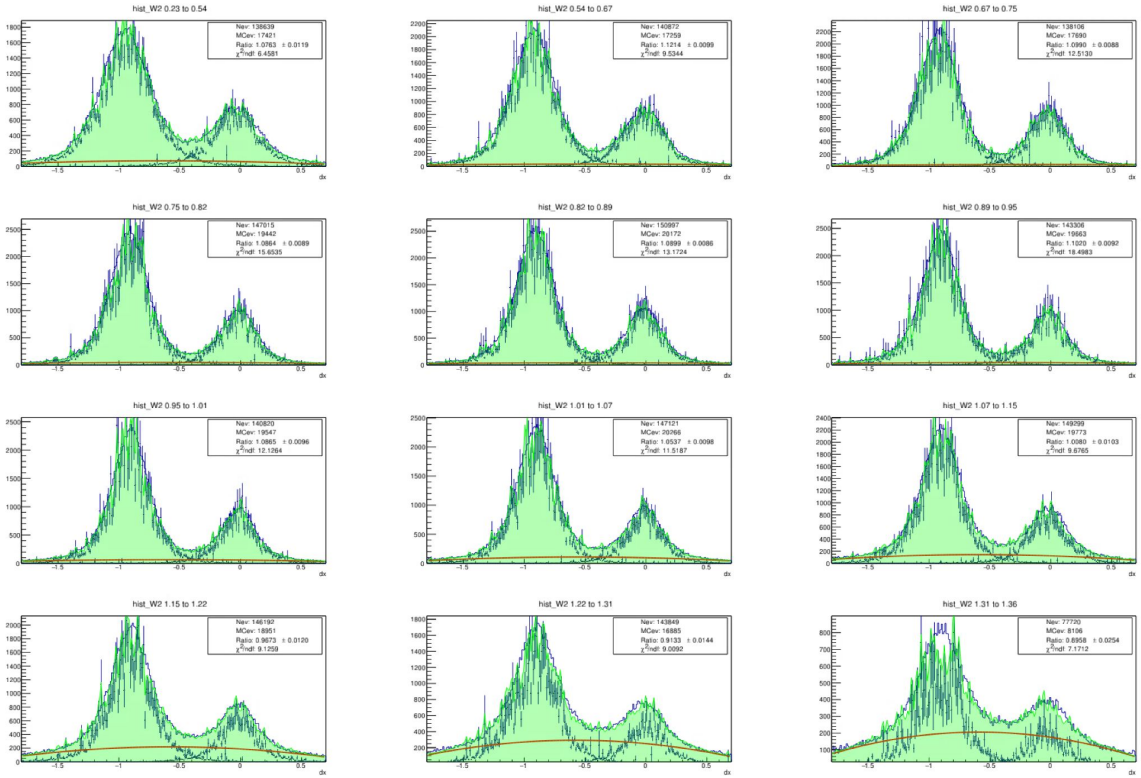
$$R_{sf} = \frac{\text{scale}_n}{\text{scale}_p}$$

- This is the main analysis deliverable from data. *We will extract G_M^n with this!*



Quasielastic eN data from deuterium fit with second-order polynomial and scaled quasielastic Monte Carlo neutron and proton distributions. Monte Carlo statistics are limited.

Systematics, Calibrations, and Extraction



Ratio Method and GMn extraction

- Simultaneous measurements of d(e,e'n) and d(e,e'p) cancels many sources of systematic error on the uncorrected yield ratio *R''* including:
  - Target thickness, beam intensity, DAQ deadtime, *e'* trigger efficiency, *e'* acceptance, target endcap contamination, target boiling effects, BigBite PID efficiency
  - Those that survive are related to *inelastic background, HCal uniformity, and HCal efficiency*
    - **HCal calibrations and analysis are especially important**

$$R'' = \frac{\frac{d\sigma}{d\Omega}\Big|_{\mathrm{d(e,e'n)}}}{\frac{d\sigma}{d\Omega}\Big|_{\mathrm{d(e,e'p)}}} \quad \text{(uncorrected)}$$

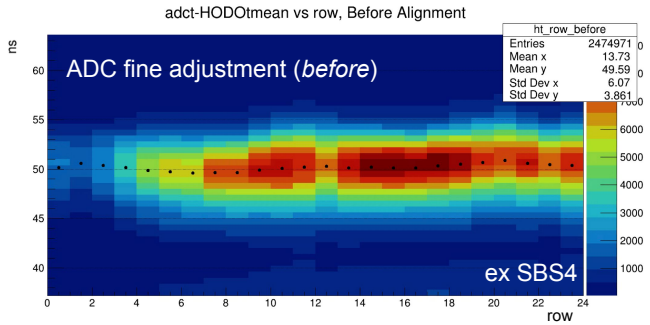
- The corrected ratio R' is derived from the scale factor ratio R_{sf} and form factor parametrizations in *MC*
- *R'* is the *model-independent cross section ratio*, related to the form factors with the Rosenbluth formula:

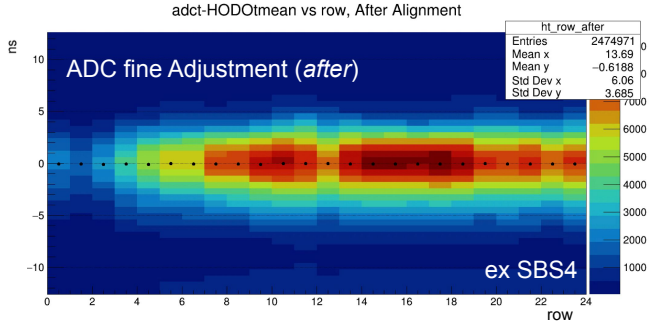
$$R' = R_{sf} \cdot \left[\frac{\frac{d\sigma}{d\Omega}\Big|_{\mathrm{n(e,e')}}}{\frac{d\sigma}{d\Omega}\Big|_{\mathrm{p(e,e')}}}\right]_{MC} \equiv \frac{\frac{\sigma_{\mathrm{Mott}}}{\epsilon_n(1+\tau_n)}\left(\epsilon_n G_E^{n^2}\Big|_{WD} + \tau_n G_M^{n^2}\right)}{\frac{\sigma_{\mathrm{Mott}}}{\epsilon_p(1+\tau_p)}\left(\epsilon_p G_E^{p^2}\Big|_{WD} + \tau_p G_M^{p^2}\Big|_{WD}\right)} \quad \text{(corrected)}$$

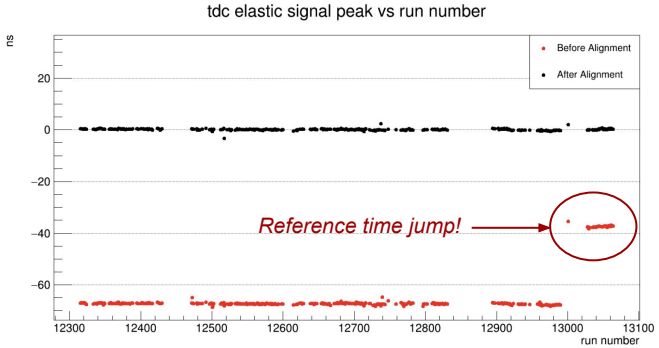
- World data (*WD*) is more abundant for the proton and the SBS program will measure GEn at similar Q^2
- All variables in R' are either known or modeled (*WD*), except for GMn!

HCal Calibrations: Timing

- Precise timing in HCal is used to establish accurate coincidence time with electron arm
  - Improved elastic selection
- Goal is to align ADC time and TDC with offsets
  - Wide elastic selection for channels with sparse statistics
  - Tight elastic selection for channels with abundant statistics
  - Use hodoscope for trigger correction
  - Fit each signal with skewed gaussian, extract MPV
  - Pass offset to align by channel
  - Assess SNR for quality checks
- DAQ reference time jumps require calibration on subranges
- Supplemental timing adjustments account for
  - Timewalk
  - Time of flight (ToF)







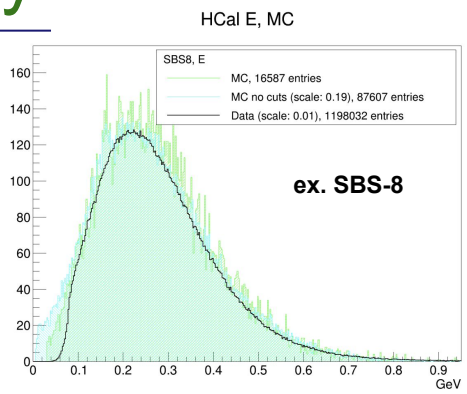
HCal Calibrations: Energy

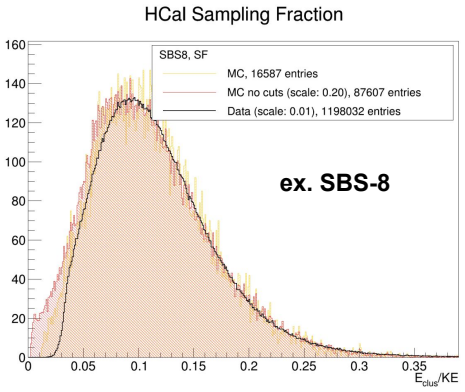
- Goal is to provide ADC gain coefficients
  - Integrated ADC (pC) ➡ E (GeV) via χ^2 minimization on linear system
  - Relate total expected elastic hadron E (from BB) to cluster elements with sampling fraction (MC)

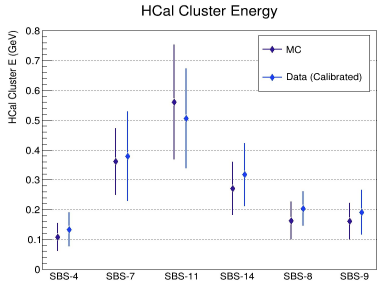
$$\chi^2 = \sum_{i=1}^{n} \left(E_i - \sum_j c_j A_j^i \right)^2 / \sigma_E^2 \qquad \sigma_E^2 \approx E_i$$

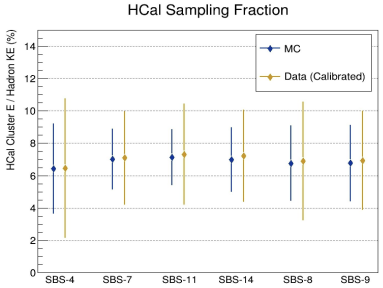
$$\frac{\mathrm{d}\chi^2}{\mathrm{d}c_k} = 2 \sum_{i=1}^{n} \frac{1}{E_i} \left(E_i - \sum_j c_j A_j \right) A_k = 0$$

Minimize







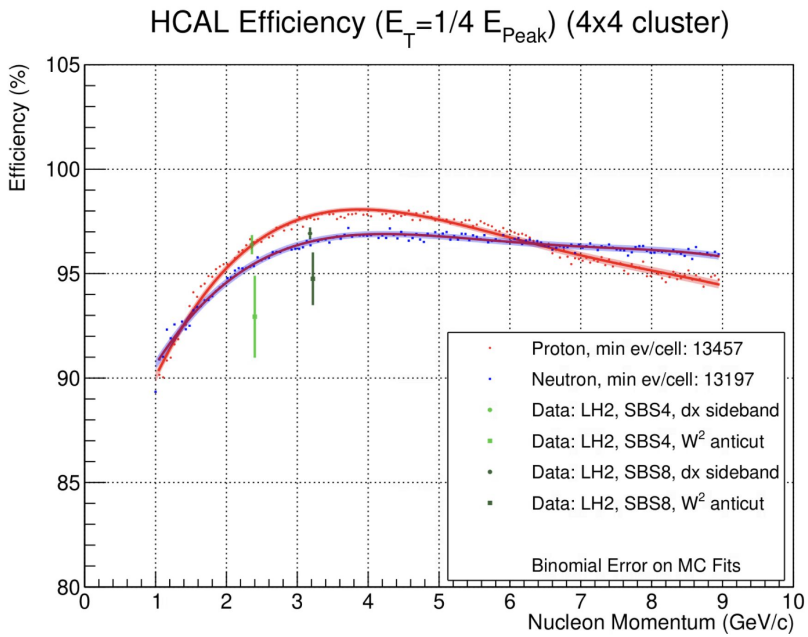


- Quality Checks
  - Calibrated data reproduce MC very well
  - σ_E/E trends towards better resolution at higher nucleon kinetic energy

KINEMATIC	4	7	11	14	8	9
Beam Energy (GeV)	3.739	7.931	9.889	5.983	5.983	4.027
HCal Angle (deg)	31.9	16.1	13.3	17.3	29.4	22.0
Recoil Nucleon Central KE (GeV)	1.62	5.26	7.22	3.98	2.40	2.40
HCal Energy Resolution (%)	**67**	**42**	**41**	**41**	**55**	**45**

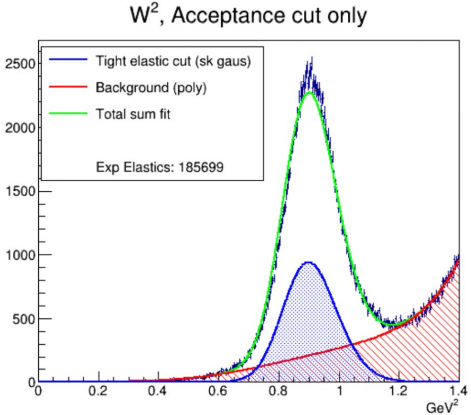
HCal Detection Efficiency

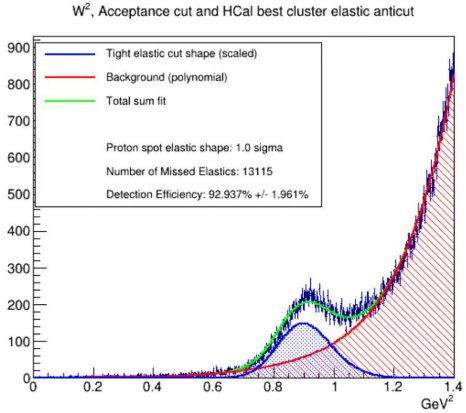
- *The analysis turns on accuracy of the Monte Carlo*
- Assess the detection efficiency with MC for both neutrons and protons
- Verify detection efficiency with data using available methods:
  - dx sideband (proton, liquid hydrogen target)
  - Inclusive W^2 anticut (proton, liquid hydrogen target)
  - Exploit $\gamma(p,\pi^+n)$ channel for tagged neutrons



Data vs MC pictured above. E_T is the threshold energy for MC detections. E_{peak} is evaluated per slice in nucleon momentum p_N

dy Anticut Method Results

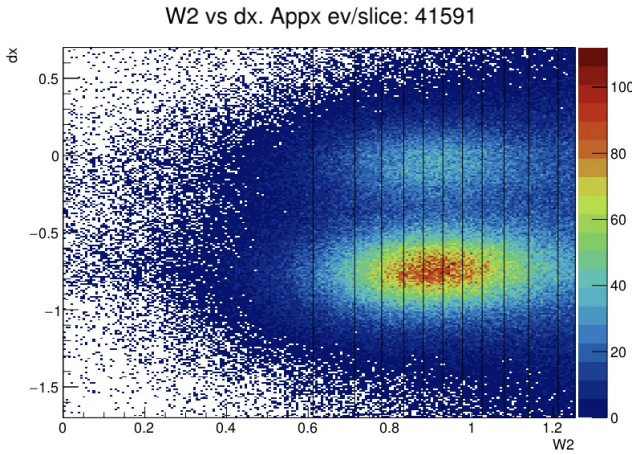


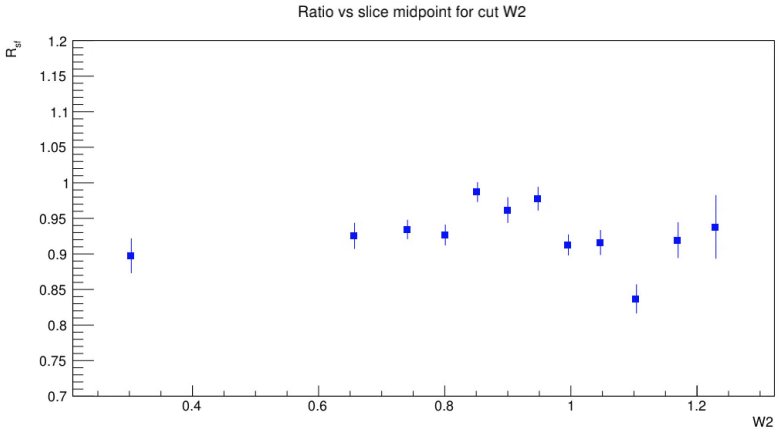


- Data proton detection efficiency will be improved with better MC inelastic BG
- Neutron detection efficiency may become available with forthcoming data

Cut Stability and Systematic Error

- For each cut used to perform elastic selection
  - Populate dx vs cut variable
  - Take approximately equal statistics, independent “slices” on the cut variable
  - Extract the scale factor ratio R_{sf} from each slice using matched cut regions
  - Address non-uniformities with tighter cuts and calibrations
- For each cut which does not cancel on the ratio
  - Use independent cut slices to assess systematic variation
  - Add components in quadrature for total systematic contribution





Wrapping Up

- Electromagnetic form factor measurements using the SBS will greatly improve our understanding of fundamental nucleon structure at much larger Q^2 than before
- The SBS is a new and fully functional detector installation used to extract G_M^n, G_E^n, and G_E^p
  - Successful HCal hardware commissioning, continued support, and online data monitoring has proven itself over several experiments
  - HCal is producing data which meets or exceeds the needs of current experiments
- GMn analysis is not yet mature, but independent analyses are converging and encouraging
- High Q^2 data are difficult to analyze due to the high relative inelastic contamination and analysis will continue into the coming years

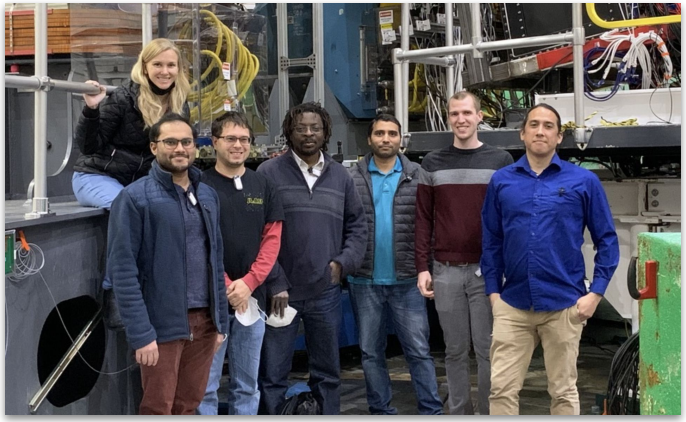
*This work was funded by US Department of Energy Office of Science, Office of Nuclear Physics (Award ID DE-SC0021200)

Thanks

- I am grateful to have had the support of many, but the following have my special thanks for their insight, patience, and mentoring:
  - Andrew Puckett, Mark Jones, Scott Barcus, Brad Sawatzky, Holly Szumila-Vance, Eric Fuchey, Bill Henry, and Arun Tadepalli
- Special thanks to Alex Camsonne for the opportunity to mentor Isaac Smyth and Victoria White whose projects I'm very proud of
- Special thanks to Scott Barcus for his dedication to bringing me up to speed on nuclear instrumentation, and for his patience with me during commissioning
- And I'm indebted to all of the G_M^n and G_E^n graduate students as well!

*This work was funded by US Department of Energy Office of Science, Office of Nuclear Physics (Award ID DE-SC0021200)

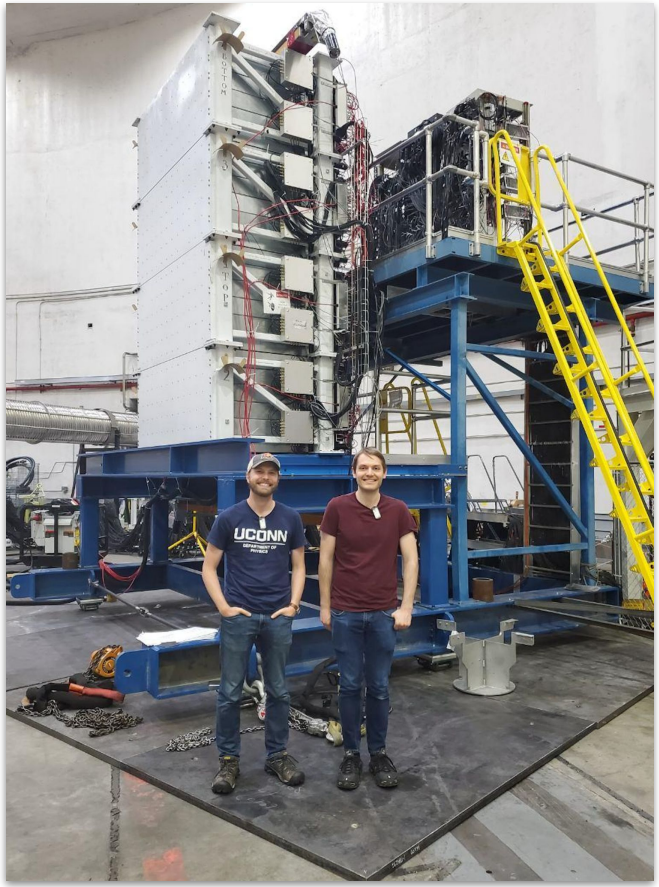
Thank you for the invitation!



Questions?

Pictured (left to right): Dr. Holly Szumila-Vance (JLab), Anuruddha Rathnayake (UVA), Zeke Wertz (W&M), Kondo Gnanvo (JLab), Thir Guitam, Sean Jeffas (UVA), John Boyd (UVA), Provakar Datta (UConn), Dr. Eric Fuchey (W&M), Sebastian Seeds (UConn), Prof. Andrew Puckett (UConn)

Thank you for the invitation!



Questions?

Pictured (left to right): Ralph Marinaro (University of Glasgow), Maria Satnik (W&M), Sebastian Seeds (UConn), Scott Barcus (Los Alamos National Laboratory)

SBS: Active Collaborators

- **UVA**: Prof. Gordon Cates, Prof. Nilanga Liyanage *(polarized target, software, GEMs)*
- **William & Mary (W&M)**: Prof. Todd Averett, Prof. David Armstrong *(polarized target, GRINCH)*
- **University of Glasgow**: Prof. Rachel Montgomery, Prof. David Hamilton *(software, hodoscope)*
- **University of Connecticut (UConn)**: Prof. Andrew Puckett *(software, BigBite calorimeter, hadron calorimeter)*
- **Christopher Newport University (CNU)**: Prof. Peter Monahan *(CDET)*
- **JLab Staff**: Dr. Mark Jones, Dr. Bogdan Wojtsekhowski, Dr. Arun Tadepalli, Dr. Bill Henry, Dr. Ole Hansen, Dr. Bob Michaels, Dr. Alex Camsonne, Dr. Don Jones, Dr. Holly Szumila-Vance, Dr. Mark Dalton
- *Many, many more…*

Backup: Rosenbluth Technique (LT)

- By exploiting the *linearity of* σ_r *in* ϵ on the Born approximation and allowing only ϵ to vary, the form factors can be extracted
  - G_E^2 is the slope
  - τG_M^2 is the y-axis intercept

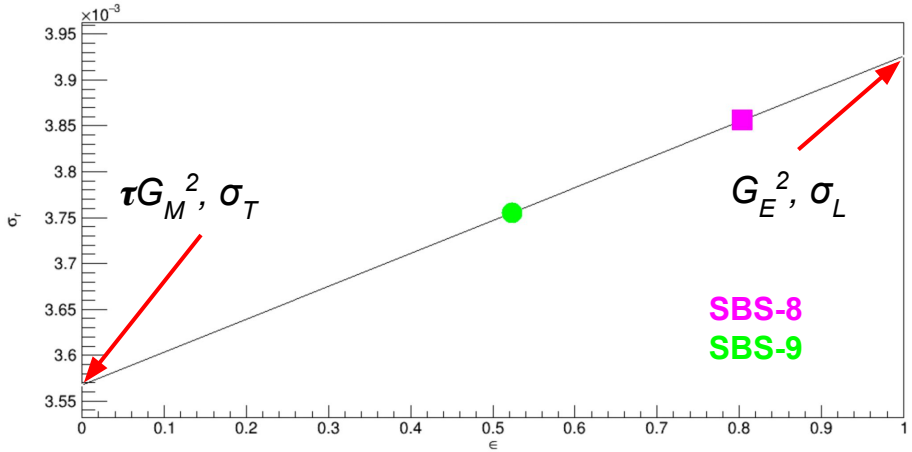
$$\sigma_r = \tau G_M^2 + \epsilon G_E^2$$

- The modified Rosenbluth Slope (RS) is the related directly to the ratio of the Sachs form factors (FFR)

$$\sqrt{\tau \cdot RS} = \sqrt{\frac{\tau|\sigma_L|}{\sigma_T}} = \frac{G_E}{G_M}$$

- By choosing the beam energy and θ, Q^2 can be fixed between two different ϵ points

Example Reduced Cross Section with SBS Points



Measurement

- With proton-neutron separation with the SBS magnet, measure quasi-elastic yields in HCal simultaneously
  - *D(e,e'n)p*
  - *D(e,e'p)n*
- Apply correction factor accounting for variation in hadron efficiencies with simulated data
- Obtain experimental observable A from SBS8 (ϵ_1) and SBS9 (ϵ_2)
- Use experimental observable B from world data from the proton
- Evaluate RS and nTPE via comparison with PT data

$$R_{observed} = \frac{N_n}{N_p}$$

$$R_{corrected} = f_{corr} \cdot R_{observed}$$

$$A = \frac{R_{corrected,\epsilon_1}}{R_{corrected,\epsilon_2}}$$

$$A = \frac{(\sigma_{e-n}/\sigma_{e-p})_{\epsilon_1}}{(\sigma_{e-n}/\sigma_{e-p})_{\epsilon_2}}$$

$$B = \frac{1+\epsilon_2 RS^p}{1+\epsilon_1 RS^p}; \quad RS^p \approx 0.087 \pm 0.010$$

$$A = B \times \frac{1+\epsilon_1 RS^n}{1+\epsilon_2 RS^n} \approx B \times (1+\Delta\epsilon RS^n)$$

$$and \quad with \quad \Delta\epsilon = \epsilon_1 - \epsilon_2 \approx 0.281$$

$$\boxed{RS^n = \frac{A-B}{B\Delta\epsilon}}$$

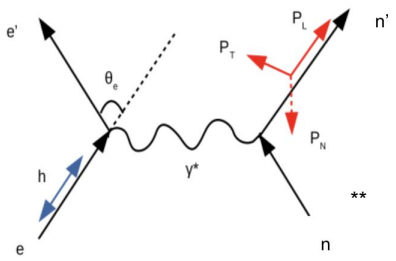
- Durand technique employed to reduce error on measurement where correlated sources of systematic error cancel on the ratio G_E/G_M
  - Nucleon momentum and binding cancelled
  - Inelastic e-n contamination and nucleon charge exchange partially cancelled

Polarization Transfer (PT)

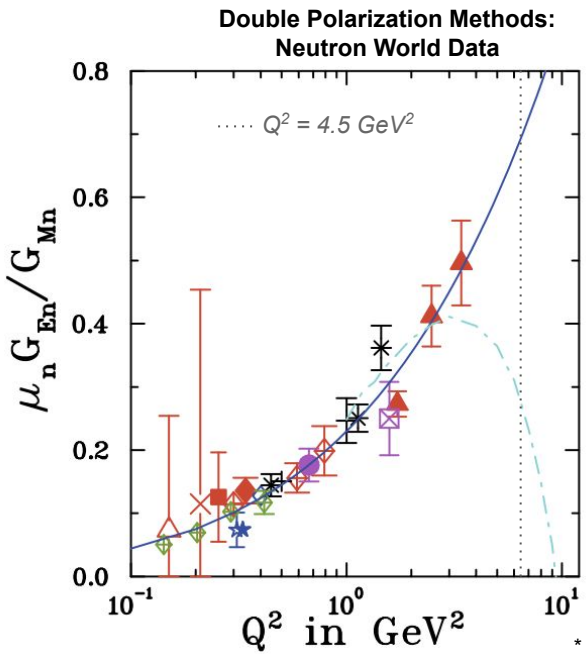
- The FFR is measurable also with polarization transfer methods employing polarized quasi-elastic electron-nucleon scattering
- Can relate the form factors without OPE from polarization observables
  - the transverse polarization (P_T)
  - longitudinal polarization (P_L)

$$I_0 P_T = -2\sqrt{\tau(1+\tau)}G_M^n G_E^n \tan(\theta/2)$$

$$I_0 P_L = \frac{E+E'}{M_n}\sqrt{\tau(1+\tau)}G_M^{n\,2}\tan^2(\theta/2)$$



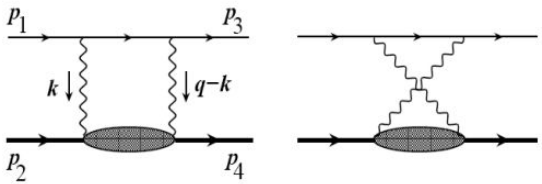
$$\frac{G_E}{G_M} = -\frac{P_T}{P_L}\left(\frac{E+E'}{2M}\right)\tan(\theta/2)$$



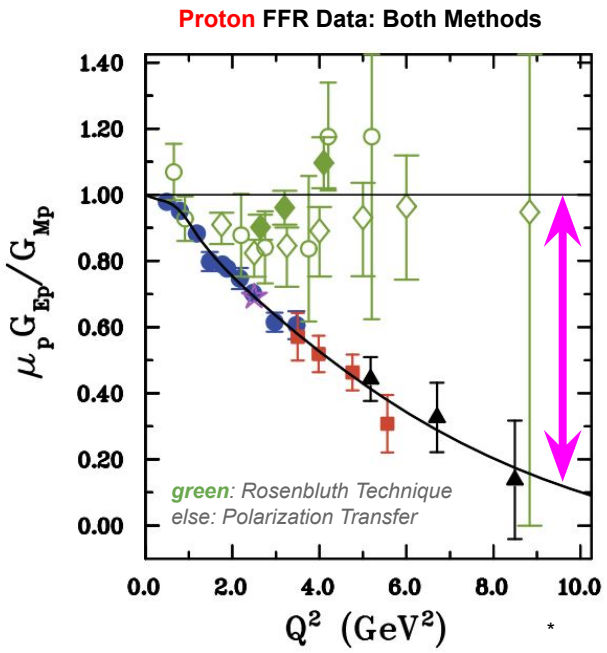
*credit: V. Punjabi, C. F. Perdrisat, M. K. Jones, E. J. Brash, and C. E. Carlson, Eur. Phys. J. A51, 510 79 (2015), arXiv:1503.01452 [nucl-ex].
**credit: E. Christy, 2019 Hall A/C Summer Workshop Slides

The Form Factor Ratio Puzzle

- Proton data show a discrepancy between FFR via LT and PT, and is well documented
  - PT methods are *insensitive to hard TPE*
  - Standard radiative corrections (Mo-Tsai, etc.) applied to data contain only soft TPE components
  - Difference expected to be from this hard TPE contribution!



- No adequate neutron measurement of RS exists to date
  - Most recent FFR measurement *50 years ago* by Bartel et al. up to Q^2 = 2.7 GeV^2

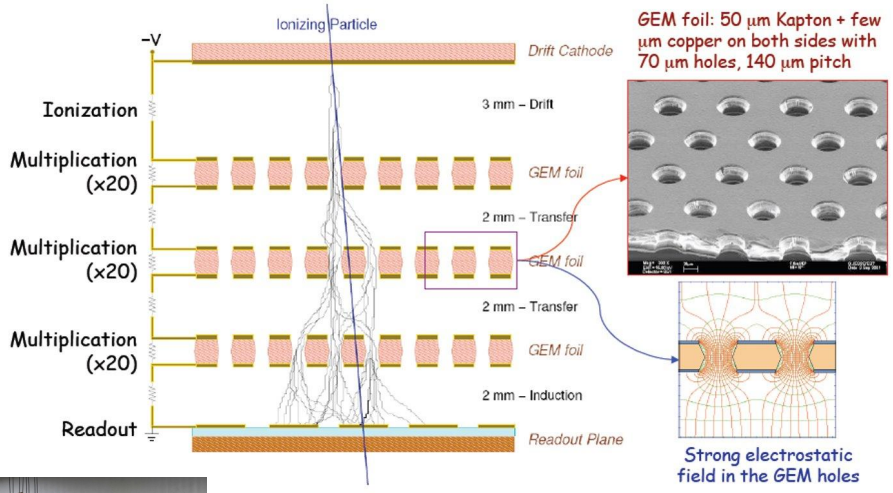


*credit: V. Punjabi, C. F. Perdrisat, M. K. Jones, E. J. Brash, and C. E. Carlson, Eur. Phys. J. A51, 510 79 (2015), arXiv:1503.01452 [nucl-ex].

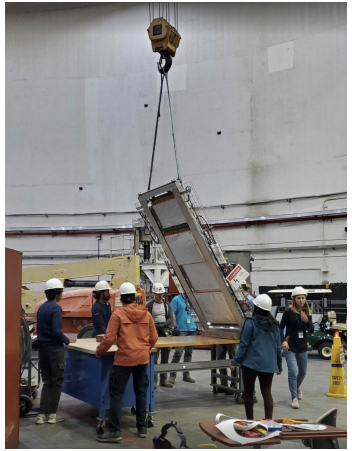
Detectors: GEMs

- *e'* causes ionization of gas within cells with potential, accelerating them to segmented readout planes for tracking
- Very high segmentation enables excellent position resolution (~*7000* channels per layer!)
  - *5* layers in electron arm
- Measures position and timing
  - Position resolution: ***~70 μm***
  - Timing resolution: ***~10 ns***

- Position resolution enables precision tracking in the electron arm.
- *Primary detector subsystem responsible for tracking!*

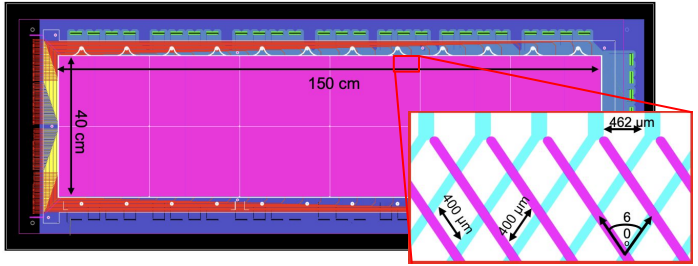


(1)



Students and staff reposition one GEM layer in the hall

GEMs Single Layer Schematic



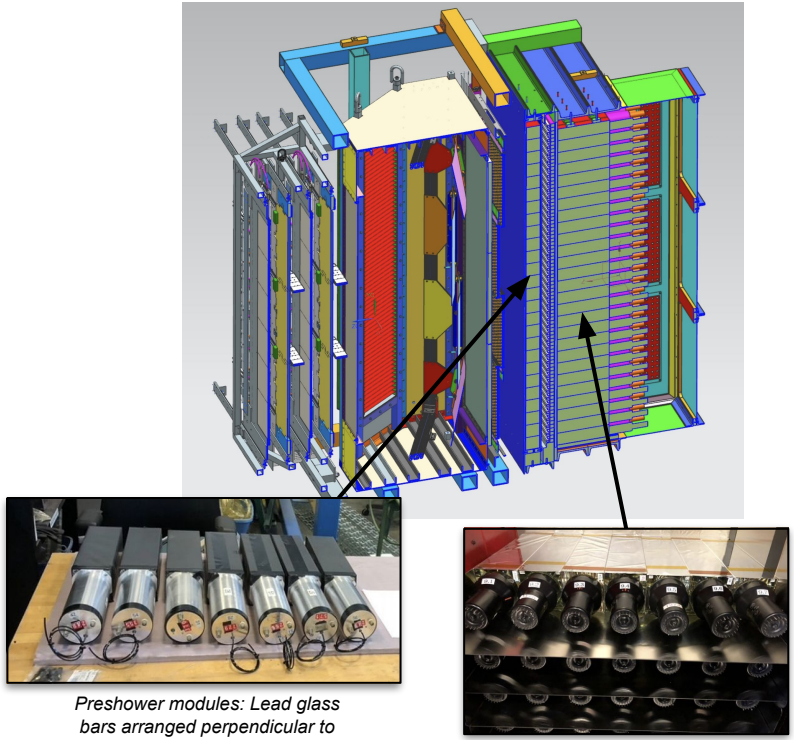
Active area of the UVA GEM with "U-V" strip layout (2)

(1) F. Sauli, NIM A 386, 531 (1997) (2) K. Gnanvo, Commissioning of GEM Trackers for SBS at Jefferson Lab (2019)

Detectors: BigBite Calorimeter

- Lead-glass blocks connected to photomultiplier tubes (PMT) designed and configured primarily to measure energy and position of charged electrons
- Each PMT is read out by a single fADC250 analog to digital channel (ADC)
- Made of two sections: Preshower (PS) and shower (SH)
  - PS 52 channels: pions deposit lower energy in PS enabling PID with pion peak at ***~200 MeV***
  - SH 189 channels: Blocks are longitudinally oriented, designed to stop electrons
  - Total sampling fraction nearly 100%
- Energy resolution: ***~6%***
- *Provides single-arm trigger* for electron arm with sum over energy threshold in PS and SH
  - Mu metal and in-situ cosmic PMT calibrations mitigate effects of strong 48D48 fringe fields
  - Requires excellent electron E/p calibration to prevent bias in the trigger!
- *Also provides tracking constraint for e' reconstruction*

BigBite Cross-section Schematic

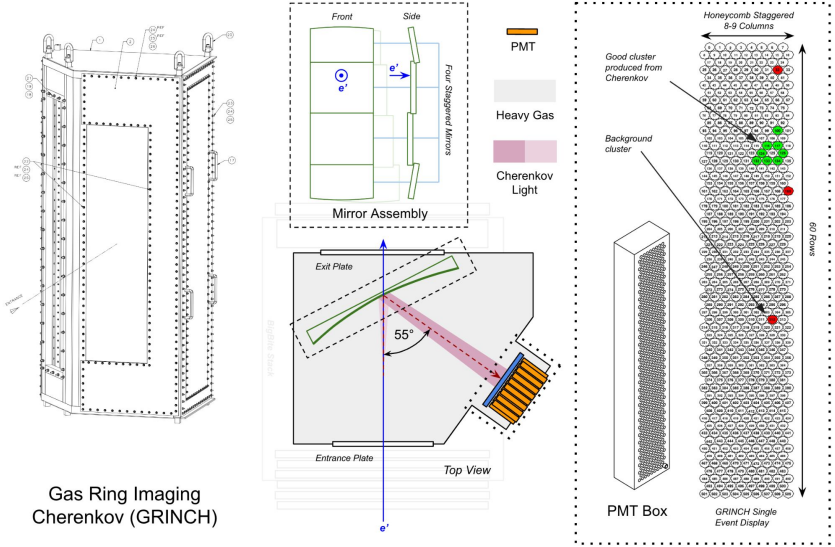


Preshower modules: Lead glass bars arranged perpendicular to e', PMTs on end

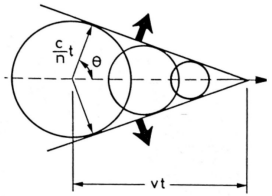
Shower modules: Lead glass bars arranged parallel to e', PMTs on end

Detectors: GRINCH

- The **G**as **R**ing **I**maging **CH**erenkov, **GRINCH**
  - Heavy gas (C_4F_8) filled light-tight “coffin” box promotes cherenkov reactions with charged electrons and pions
  - 510 PMTs in a honeycomb array designed produce clusters with electron signals
- Measures timing with unique properties
  - Each PMT is read out by a single time to digital converter (TDC) channel
  - Timing resolution ***~4.5 ns***
- Designed to mitigate pion contamination for better quasi-elastic e’ selection
  - Much heavier pions with similar momentum as e’ move more slowly and produce smaller rings
  - Pion threshold ***~2.7 GeV/c***
- *Provides efficient pion rejection over all kinematics.*

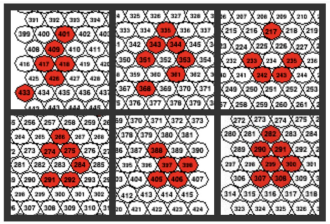


Gas Ring Imaging Cherenkov (GRINCH)



A Cherenkov ring from a charged particle with velocity v propagates through a medium with index n where $\cos(\theta) = c/(nv)$

GRINCH: Single Event Display



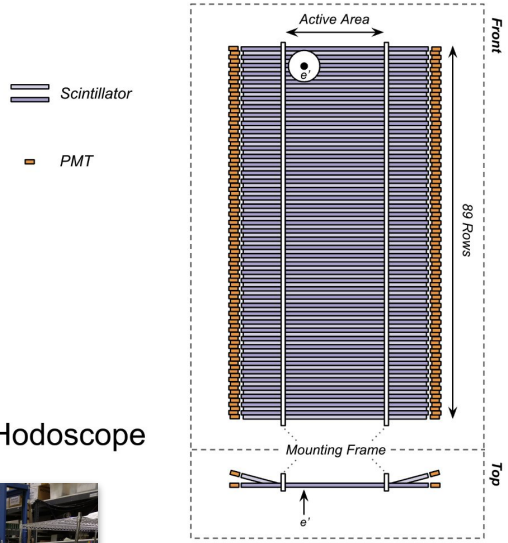
Several good electron event clusters

Detectors: Hodoscope

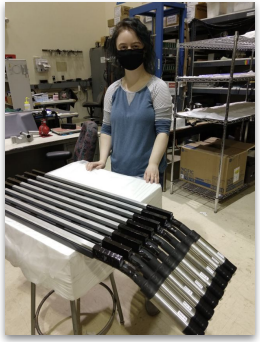
- Consists of 89 plastic scintillator paddles with a PMT on each side (178 channels)
- Each PMT read out by dedicated 1190 TDC channel for precision timing
- Designed to measure precision timing and position
- Timing resolution: ***~600 ps***
  - Can resolve *e'* time-of-flight differences
- Position resolution: ***~5 cm***
  - Segmentation provides dispersive (vertical) resolution
  - $\Delta t = t_{left} - t_{right}$ and e' track matching provides transverse (horizontal) resolution

- Dual-purpose
  - *Sets precision timing for electron arm for better elastic selection with hadron-arm coincidence-time comparison*
  - *Provides e' tracking constraint*

Hodoscope Face-on Schematic



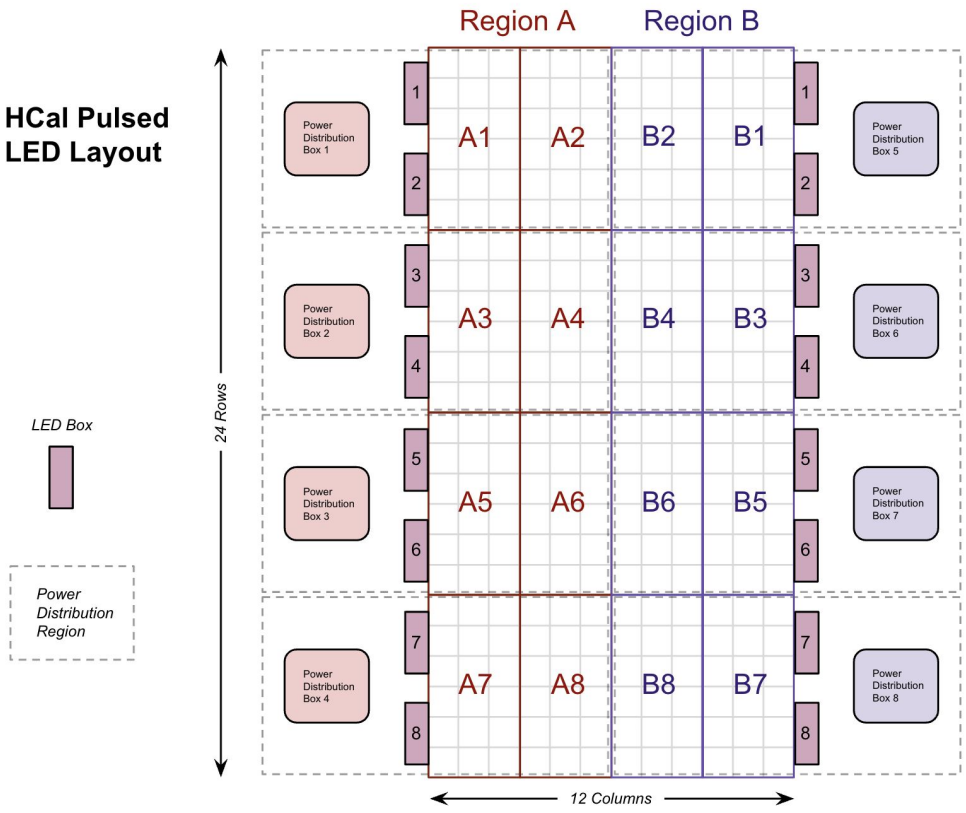
Hodoscope



M. Satnik stands with several scintillator paddles in Jlab Test Lab

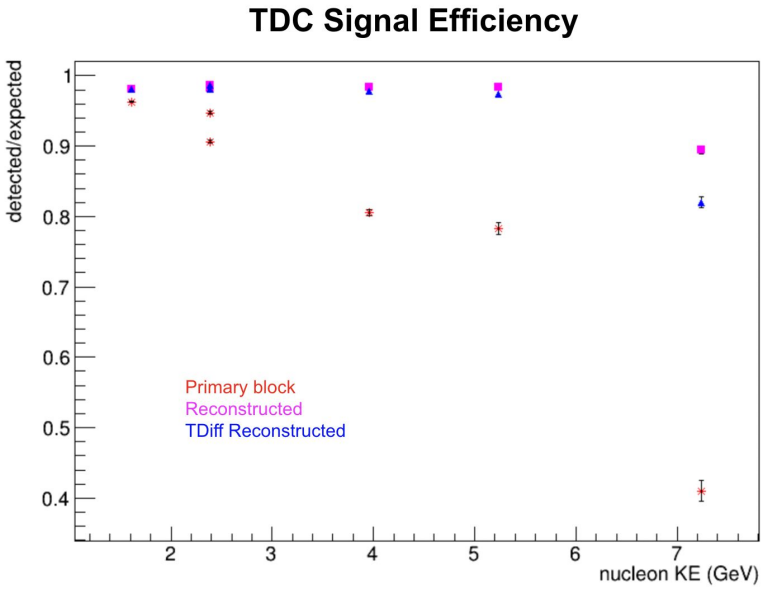
HCal: Pulsed LED Array

- Composed of 6 LEDs of incrementally increasing brightness directed into PMTs per channel
- Frequency and total LEDs per flash configurable
- Pulsed LED array is used to obtain gain curve and alpha parameters for PMTs
- Can also be used to monitor gain stability over experimental lifetime
- Capable of 1-64 times the brightness of a single LED
- Pulse square with ~20 ns duration
- Set to 10 Hz (parasitic) during SBS operations



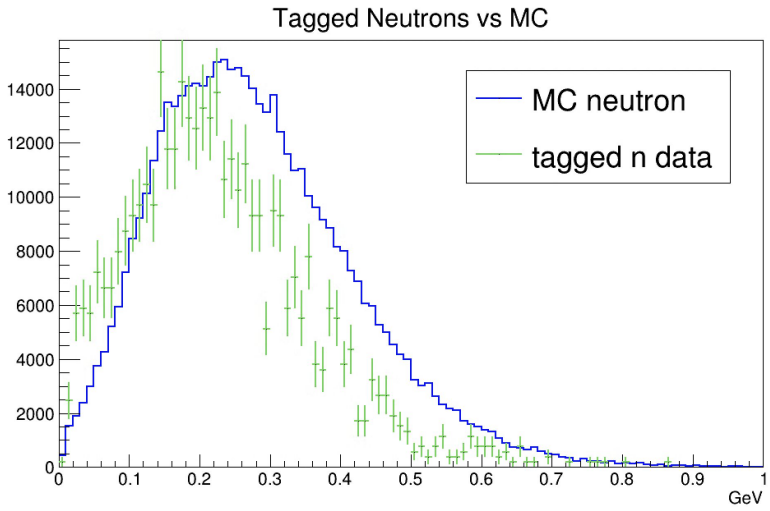
HCal: TDC Efficiency

- Loss of TDC events on many channels was observed
- Investigations led to two concurrent failure modes
  - Unintended bit conversion during data reconstruction led to TDC jitter and the loss of events near the detection threshold
  - f1TDC register unable to handle sustained high rates, return random data at memory address
- Rewrote data reconstruction code to match cast type between coarse and fine processes
- Increased TDC threshold
  - Accepted loss of low energy events
  - Timing is most accurate for high energy events and primary cluster timing comes from highest energy block - drastic improvement of TDC efficiency
    - *Very nearly 100% efficient at all nucleon KE*



Tagged Neutrons Using $\gamma(p,\pi^+n)$ Channel

- Neutron detection efficiency is not accessible with precision due to the lack of a tagged neutron source
- The $\gamma(p,\pi^+n)$ channel produces down-bending π^+ tracks in BigBite, which may be selected on to tag neutrons in HCal
- Optimization of kinematic settings
  - Invert the BigBite magnet polarity to sweep electrons out of acceptance and keep π^+
  - Add copper radiator to increase photon electroproduction cross section
  - Remove CH2 analyzer and polarimeter from hadron arm to clear the path for tagged neutrons to HCal
  - Move electron and hadron arms to optimize single pion and two pion momentum for clean π^+ selection
- These data may be used for precise HCal calibrations and for precise measurement of **HCal neutron detection efficiency**
- Sufficient data could be obtained from current run period in 48 hours. Proposal has been submitted to the coordinating committee for review

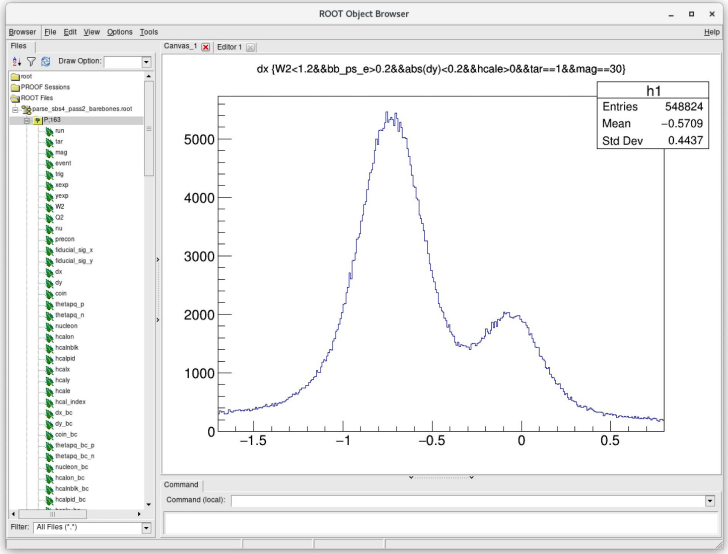


*Analysis using current data without radiator, inverted BigBite magnet, or optimized kinematic settings. Low statistics make analysis of these data difficult ******

**Credit to Andrew Puckett for development of downbending track optics necessary for this analysis*

Augments to Data Reconstruction and Blinding

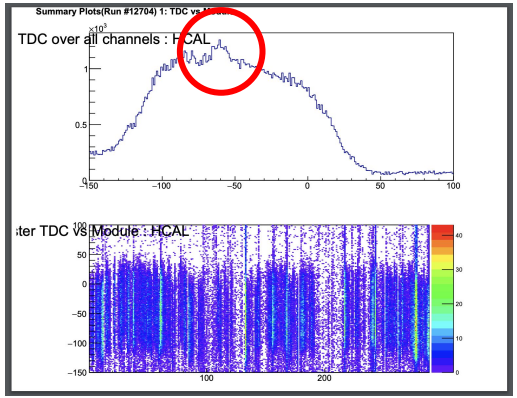
- Calorimeter clustering “island algorithm”
  - Array of energy descending blocks over threshold populated
  - Loop over blocks, associate blocks within 15 cm of primary
  - Add cluster to list, remove used blocks
  - Continue loop until all blocks used
- Primary cluster information includes all block information, but additional clusters do not
- SBS-offline (reconstruction) augments
  - Added maximum time cut to cluster formation (tmax)
  - Added cluster block index to good hits to retain all block information with proper indexing

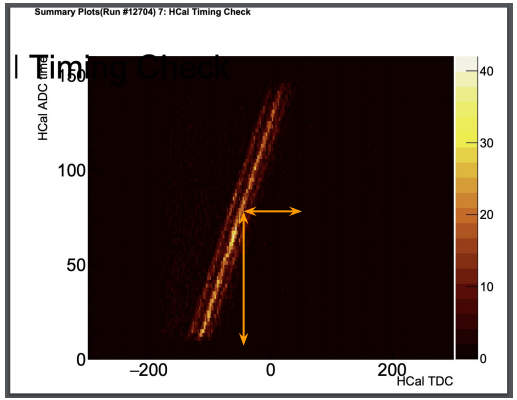


- Parsing scripts (for reconstructed MC and data)
  - Creates new analysis tree output which removes unnecessary branches and noise (with wide elastic cuts)
  - Adds all necessary physics variables for ratio extraction
  - **Blinding**: Adds random number to MC weight for uniform shift - writes this number to secure file

Online Monitoring and DAQ Instability

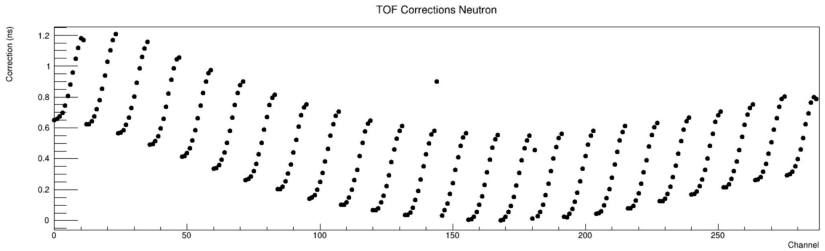
- Online data quality plots (PANGUIN) developed for HCal to enable shift crew to perform data quality analysis.
- PANGUIN revealed that ADC signal at -50ns was lost after configuration change, affecting 3 consecutive runs
- After investigation, the latency (configured at the ROC) had shifted by up to 150ns without apparent cause
  - This occurred repeatedly throughout the run for both ADC and TDC signals
- Corrected latency each time, but signal peak is too easy to miss by shift crew
- Determined that timing shift could easily be determined by plotting both timing signatures against one another (TDC and ADC-time) where the latency is configured in separate ROCs
- DAQ latency root cause and correction addressed in trigger supervisor (TS) after GMn run

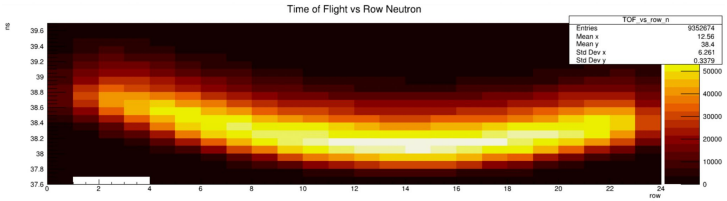


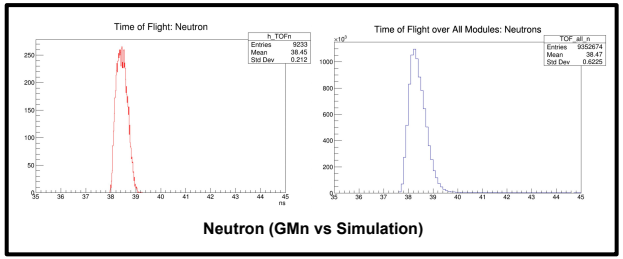


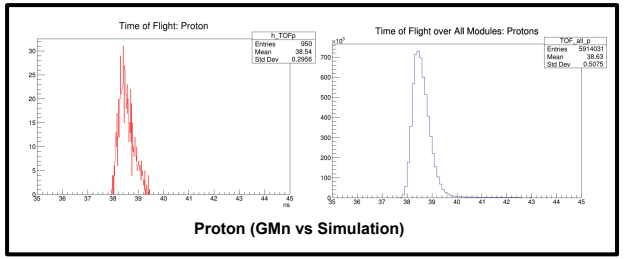
Mentoring: Isaac Smyth and HCal ToF

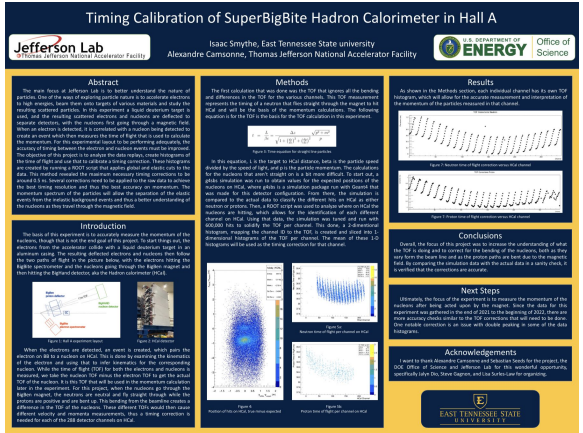
1. Calculate expected time of flight using e' tracks and beta for SBS8
   a. Find corresponding cluster TDC times in HCal (Red)
   b. Build TDC distributions per channel, fit, and get mean TOF
2. Run simulations of SBS8 with magnetic field tuned to 30% field
   a. Write script to take boundary crossing (BC) time from sensitive detectors (SD), the modules/channels in HCal (Blue)
   b. Get simulated difference between event time and BC time
3. Use these times to improve timing cuts on elastics and to improve elastic cluster finding
   a. Current clustering assumes highest energy cluster corresponds to elastic nucleon, which is not always the case
   b. Judicious cuts on timing can eliminate high energy clusters which do not correspond to elastic nucleons, improving efficiency











Ratio Extractions, BG, and Methods

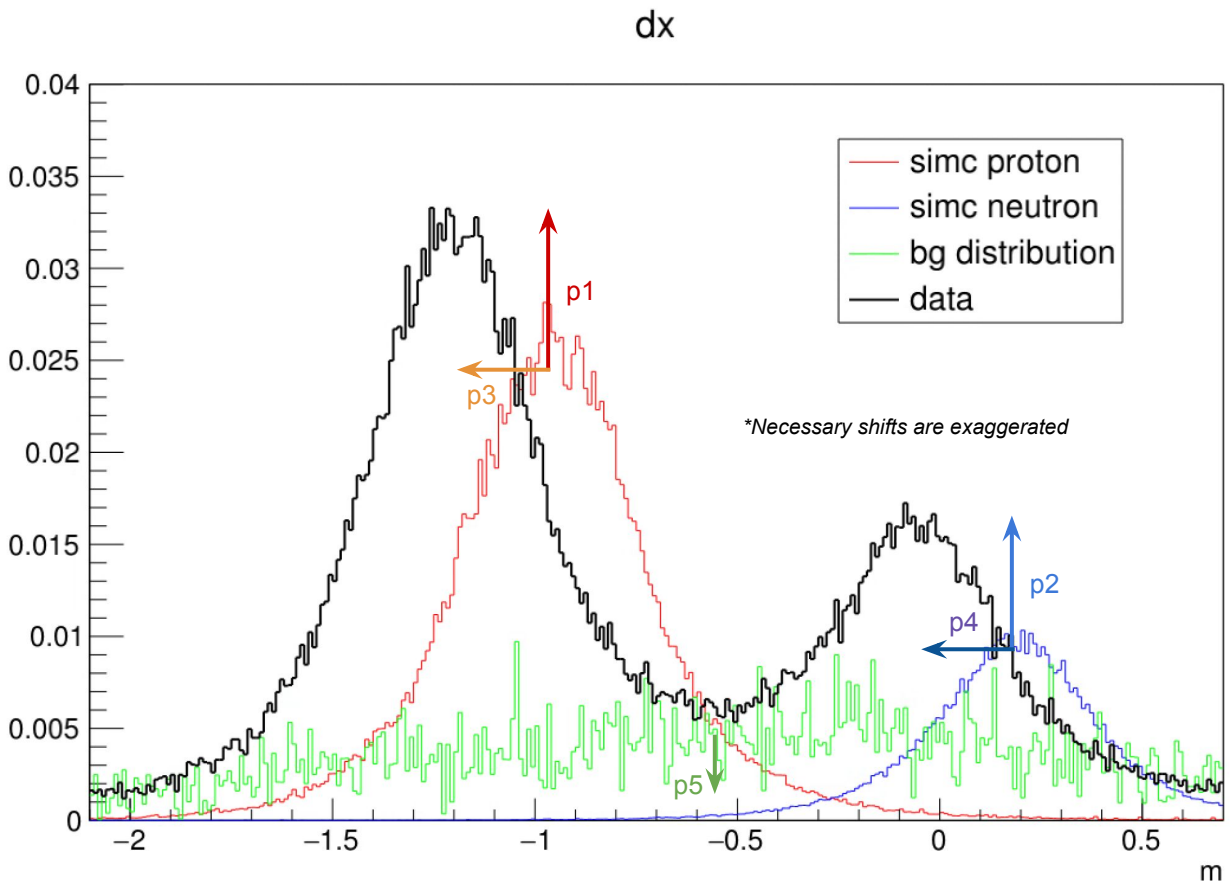
Short description of scale factor ratio R_{sf} extraction:

- Proton signal
  - SIMC elastic distribution
- Neutron signal
  - SIMC elastic distribution
- Background
  - Data anticuts
  - MC inelastic
  - Polynomial fits
- Fits
  - Interpolate with distributions (both signal and background)
  - Free parameter polynomial fits to background
  - Course/fine fitting techniques applied

Example pictured on right:
Total fit to data with dy anticut background, SIMC proton, and SIMC neutron. The free parameters are represented on the example plot.

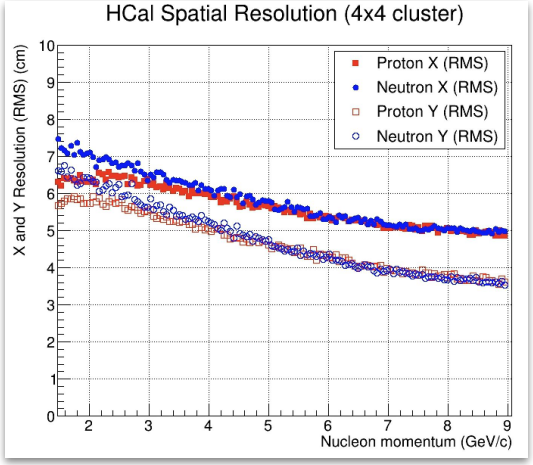
- p1: proton scale
- p2: neutron scale
- p3: proton shift
- p4: neutron shift
- p5: background scale

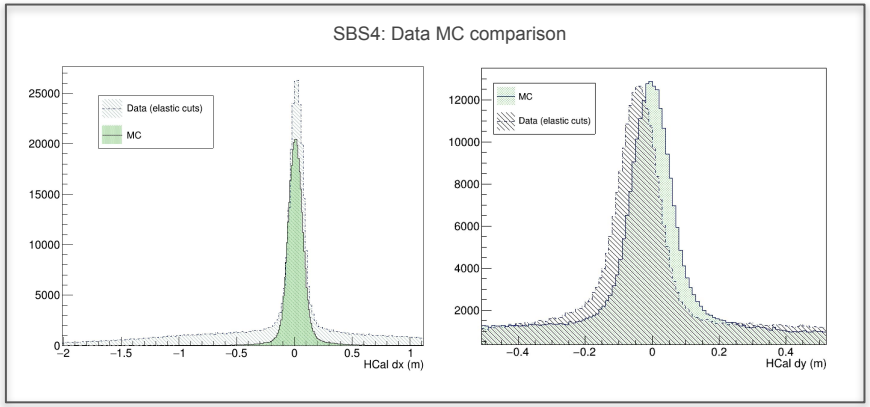
$$R_{sf} = p2/p1$$



HCal Performance - Position

- Delta plots
  - Difference between cluster centroid and expected nucleon location in dispersive (vertical, X) and non-dispersive (horizontal, Y)
  - dx/dy RMS: HCal spatial resolution
- Simulated (no target)
  - PAC expected: proton / neutron generator with 4x4 clusters
  - This work: proton / neutron generator with 4x4 clusters, data digitization, and replay
- Expected / Data (preliminary)
  - Position will be impacted by nucleon momentum and SBS field

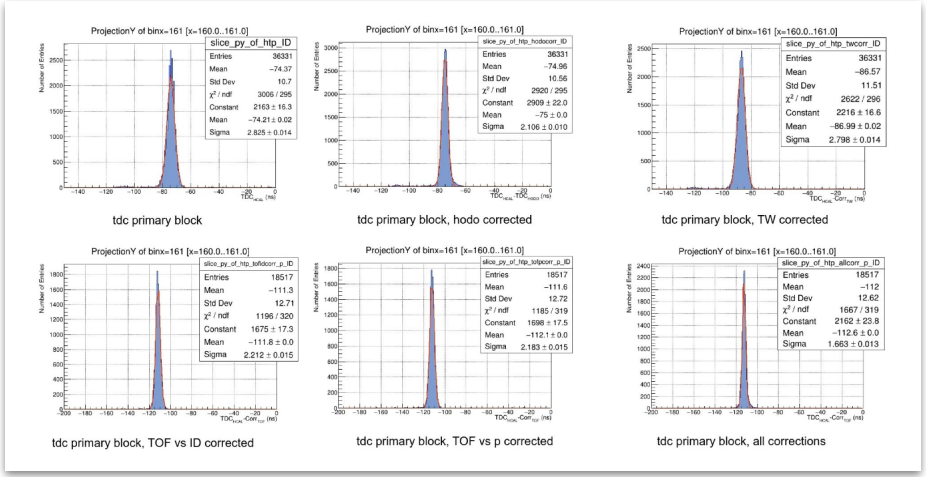


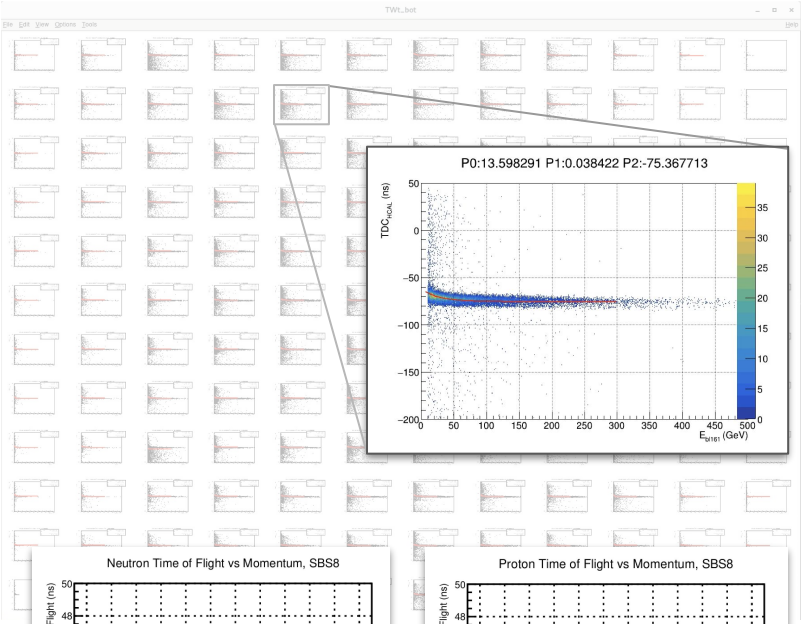


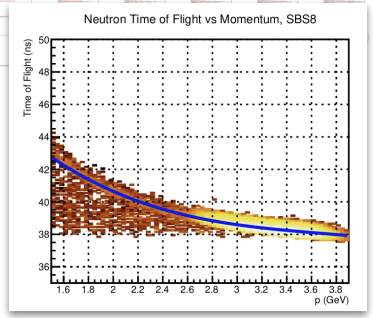
Kinematic	X Res	Y Res	MC X Res	MC Y Res
SBS 4	5.94	6.46	6.10	6.27
SBS 8	5.34	6.12	5.93	7.50

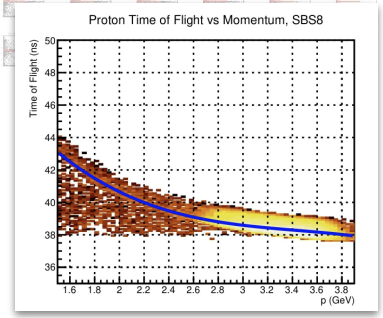
HCal Performance - Timing

- Corrections passed per event (*channel 161 shown*)
  - Time-of-flight (TOF): order-3 polynomial fit to nucleon momentum from MC
  - Timewalk (TW): exponential fit to integrated ADC per block
  - Trigger: difference with e-arm hodoscope cluster mean time



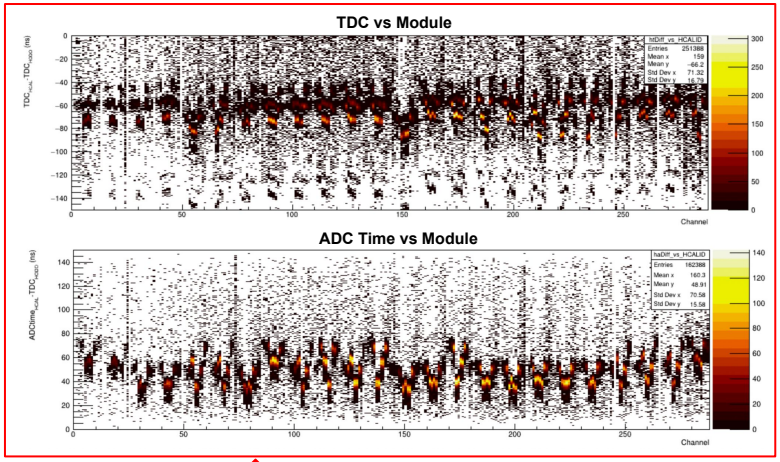






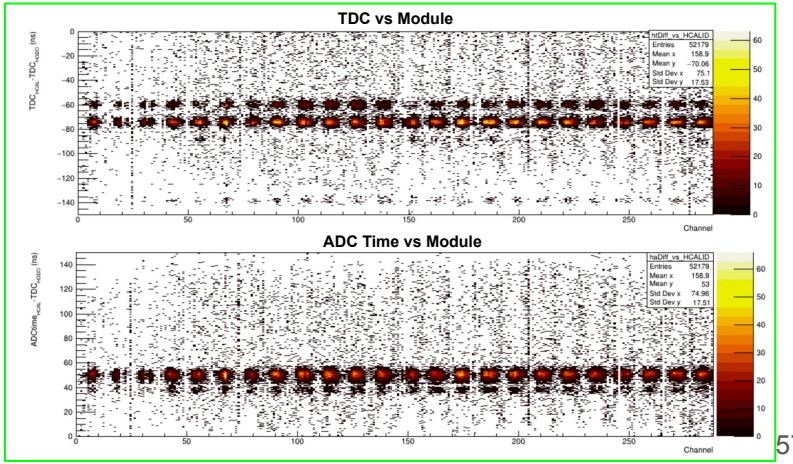
Calibrations - Timing

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

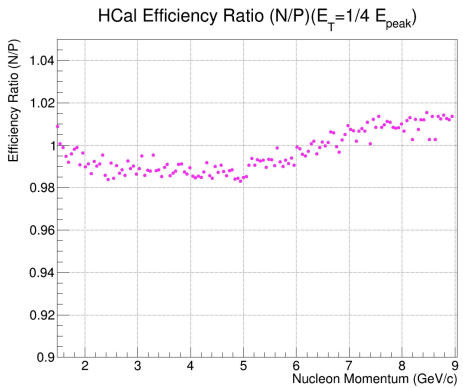


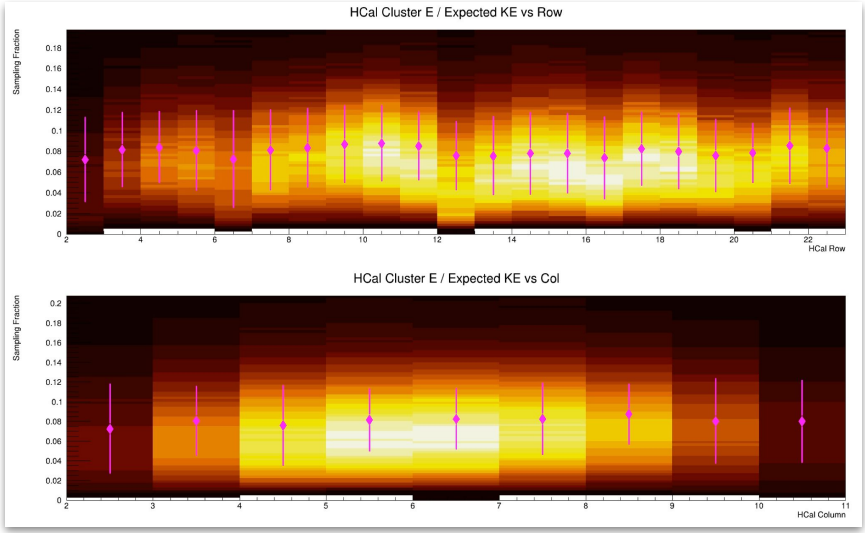
GMn/nTPE Physics Deliverables

- *R”* is the experimental observable and the form factor ratio (FFR) on deuterium
  - Requires simultaneous measurement of protons and neutrons with known detection efficiency
  - Durand technique or “ratio” technique cancels systematic error, but in HCal we need:
    - *Uniformity in detection efficiency*
    - *Proton / neutron efficiency ratio near unity*
- With nuclear corrections, get *R’*, then extract GMn!

$$R'' = \frac{\frac{d\sigma}{d\Omega}\Big|_{d(e,e'n)}}{\frac{d\sigma}{d\Omega}\Big|_{d(e,e'p)}} \Rightarrow R' = \frac{\frac{d\sigma}{d\Omega}\Big|_{n(e,e')}}{\frac{d\sigma}{d\Omega}\Big|_{p(e,e')}} \equiv \frac{\frac{\sigma_{Mott}}{1+\tau}\left(G_E^{n\,2} + \frac{\tau}{\epsilon}G_M^{n\,2}\right)}{\frac{d\sigma}{d\Omega}\Big|_{p(e,e')}}$$

$$\Rightarrow G_M^n = -\sqrt{\frac{1}{\tau}\frac{d\sigma}{d\Omega}\Big|_{p(e,e')}R' - \frac{\epsilon}{\tau}G_E^{n\,2}}$$

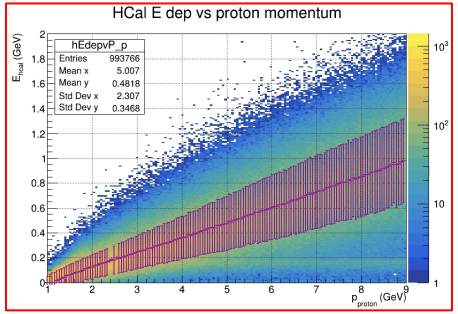


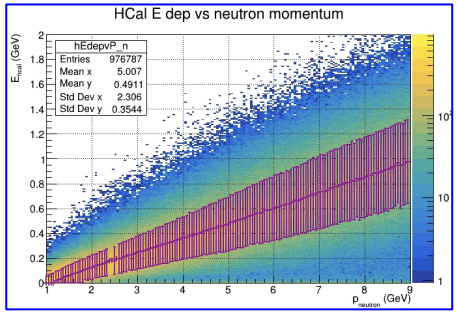


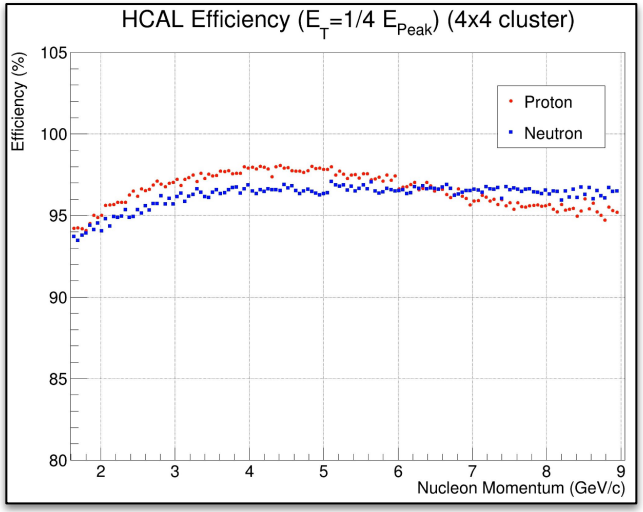
**SBS4 Data, all*

Detection Efficiency (MC)

- Extraction of expected detection efficiency from MC
  - Simulate protons and neutrons with momentum 1-9 GeV, throw flat, populate 1000 ev/ch
  - Get energy spectra v nucleon momentum, fit peaks to extract mean E per bin p
  - Sum events per bin passing E_{mean} / 4 threshold (*pass*)
  - Sum all events per bin (*total*)
  - Efficiency: (*pass*) / (*total*) *100

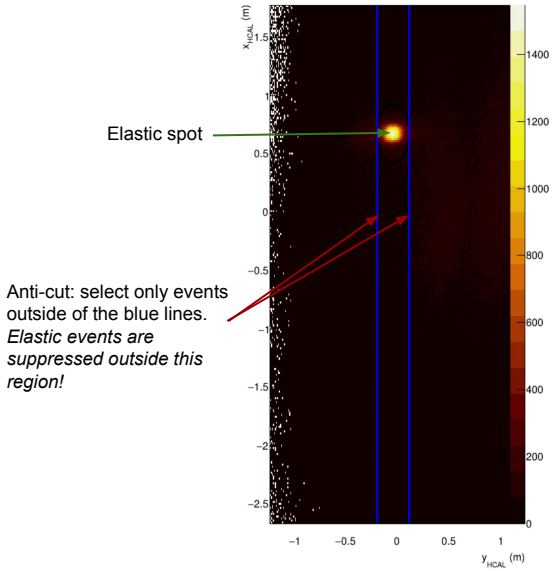






Detection Efficiency: dy Anti-cut Method

- Methodology
  - Focus on protons from liquid hydrogen (*LH2*) with high signal to noise (*SBS 4, high elastic yield / C, relatively low Q^2*)
  - Account for best clusters
    - Per event, select hcal cluster with centroid closest to expected location of elastic hadron with loose coin cut
  - Expected number of elastics from W^2
    - Populate *"full"* histogram with acceptance matching cut only
    - Get *"pure"* elastic sample from cuts on both arms (shape only, elastic cuts)
    - Fit *"total"* histogram to scaled elastic sample and polynomial for background
    - Subtract background from *"full"* histogram to obtain *expected* elastics
  - Detected elastics from W^2 with harm anticut
    - Populate *"anticut"* histogram with acceptance matching cut and HCal dx/dy anticuts
    - Follow steps 2-4 above to extract *missed* elastics
    - Detected elastics: *expected* - *missed*
  - **HCal Detection Efficiency: Detected / Expected**



Elastic Cuts

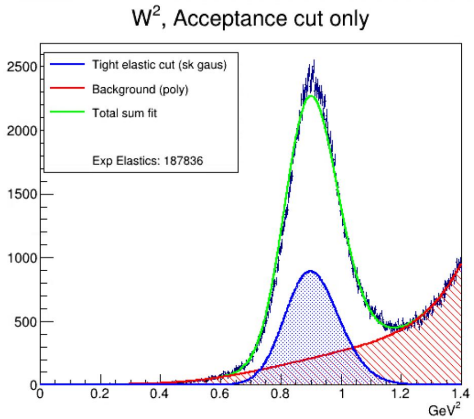
Subsystem	Type	Cut
BigBite	Acceptance	x/y expected HCal active area
BBCal	Preshower Energy	>200 MeV
Tracking	Number Tracks	1
GEMs	Hits	>3 planes
BBCal	Total E	>1.7 GeV
HCal	Coin Time	$<3\sigma$
Physics	θ_{pq}	<0.4 rad
HCal	dy	$<3\sigma$

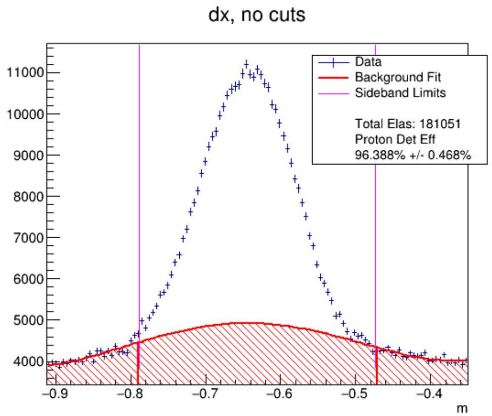
Detection Efficiency: dx Sideband Method

- Methodology
  - Focus on protons from liquid hydrogen (*LH2*) with high SNR (Q^2 = *3.0 GeV*^{2})
  - Account for best clusters
    - Same as dy Anticut
  - Expected number of elastics from W^2
    - Same as dy Anticut
  - Detected elastics from dx distribution with same cuts
    - Perform sideband fit to background with range set by MC statistics < 1%
    - Detected elastics: *data - background*
  - **HCal Detection Efficiency: Detected / Expected**

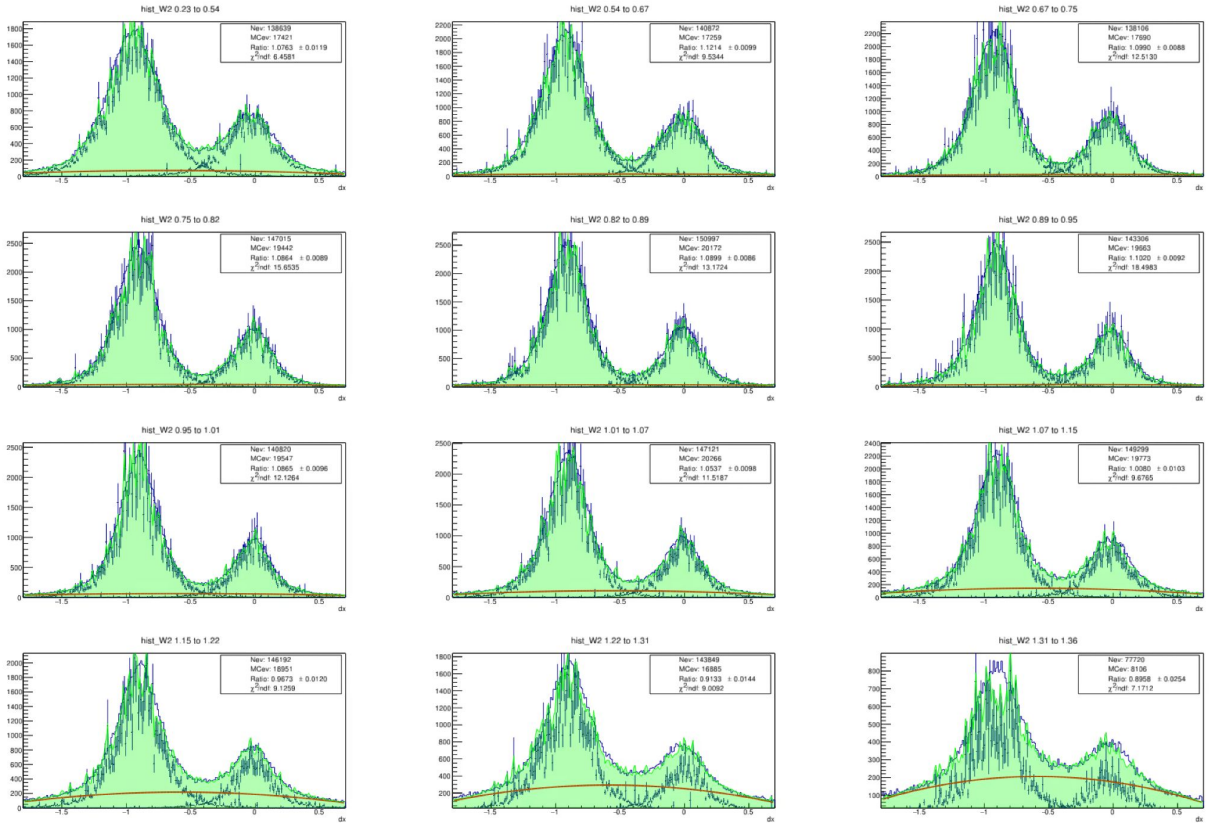
Subsystem	Type	Cut
BigBite	Acceptance	x/y expected HCal active area
BBCal	Preshower Energy	>200 MeV
Tracking	Number Tracks	1
GEMs	Hits	>3 planes
BBCal	Total E	>1.7 GeV
HCal	Coin Time	$<3\sigma$
Physics	θ_{pq}	<0.4 rad
HCal	dy	$<3\sigma$

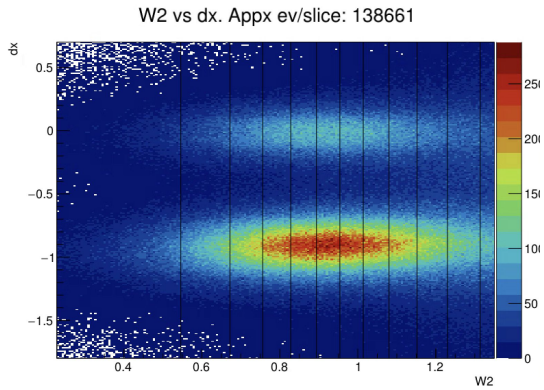
Elastic Cuts, Q^2 = 3.0 GeV^2

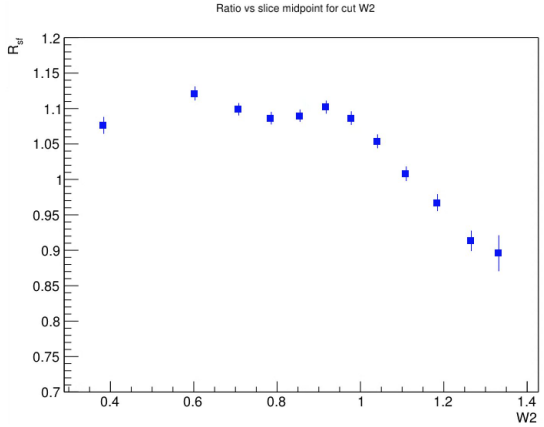




Cut Stability and Systematic Error - W^2 SBS8



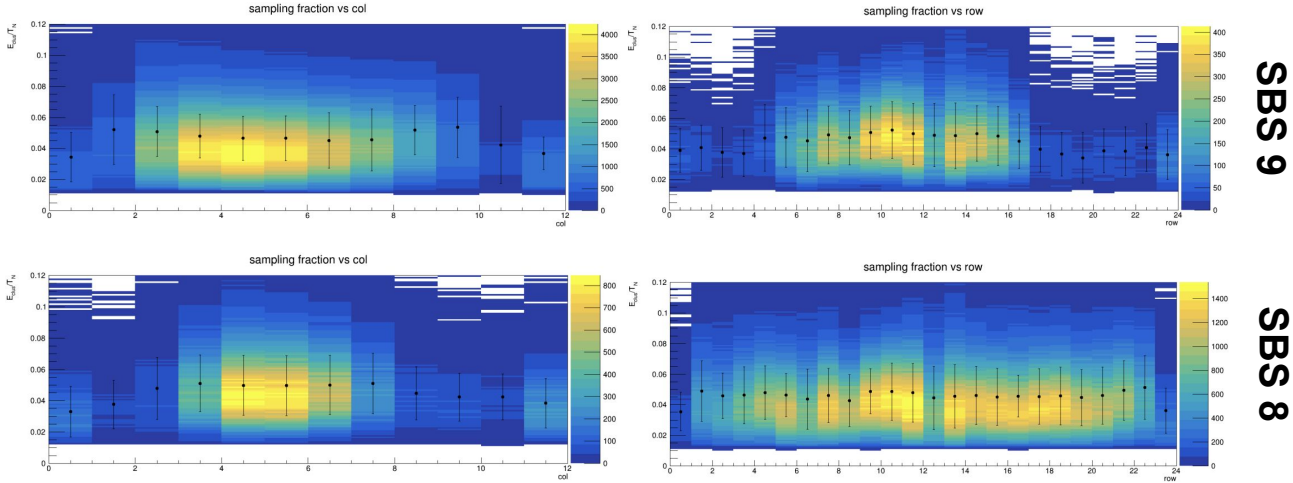




Crucial Systematics

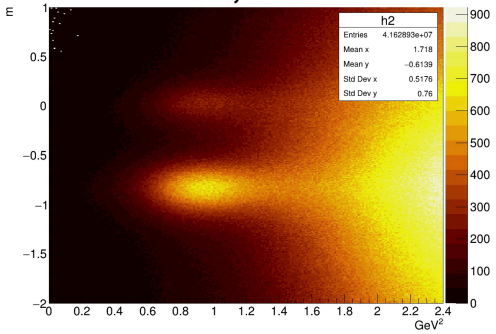
- Inelastic contamination
  - Modeled with Monte Carlo, but verified with data comparisons
- HCal position detection uniformity ensures that Durand technique can be applied to significantly reduce systematic uncertainties
  - Uniformity to within 2% sampling fraction within HCal active area
- For the same reason, HCal detection efficiency must be very similar for protons and neutrons (next slide)

Transverse Uniformity | **Dispersive Uniformity**

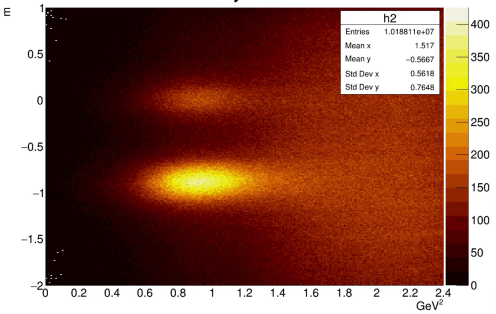


Inelastic Contamination (data)

SBS 8, dx vs W^2



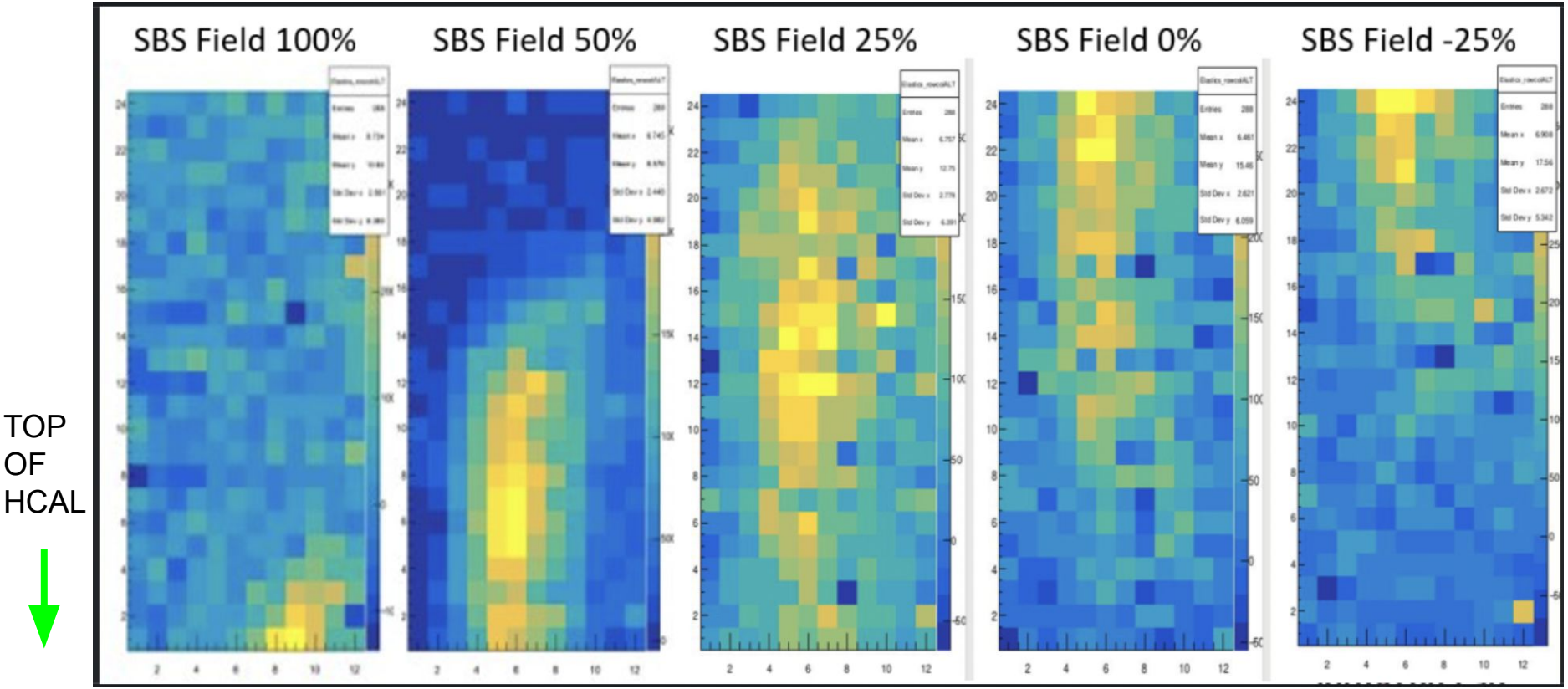
SBS 9, dx vs W^2



**Separation of proton and neutron spots from inelastic background indicates low relative contamination*

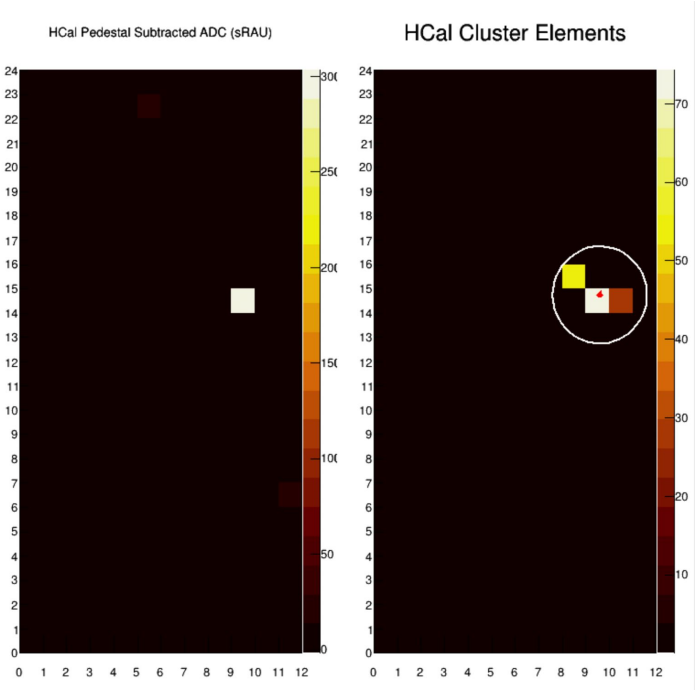
UGLY BACKUP

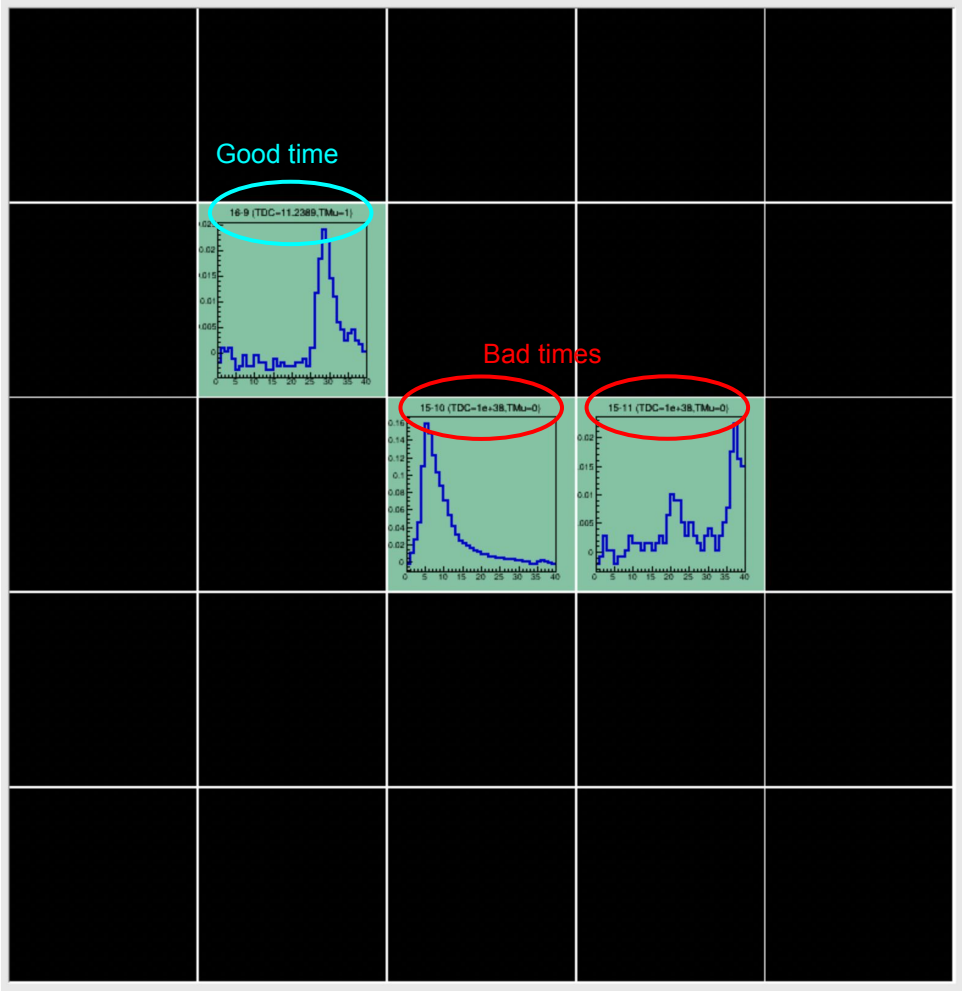
Proton Spot: 1.92 GeV, LH2 (Full SBS field 2100A)



HCal TDC time reconstruction

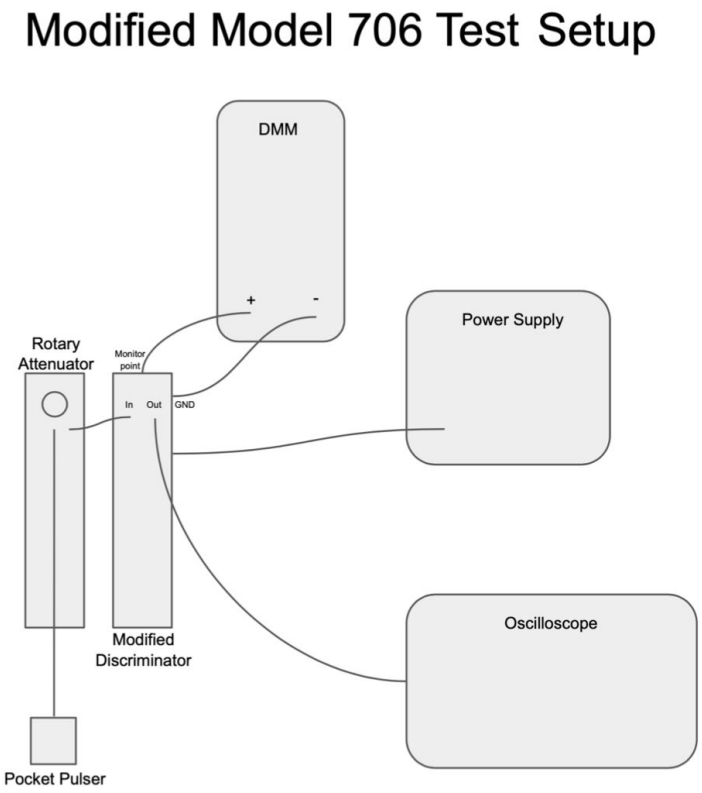
1. Look at additional elements of the cluster for available times
   a. Some percentage of cluster tdc times can be recovered





PS706 Test - Setup

- Power supply attached to PS706 rear LEMO port
- By channel - input signal produced via PS417 pocket pulser attenuated via PS804 Rotary Attenuator
- By channel - input signal monitored via oscope
- By channel - output signal monitored via oscope
- Nominal thresholds monitored with DMM via monitor point on face of PS706 and ground



PS706 Test - Functionality Test

- Measured values from DMM are the point where a pulse from PS417 of known amplitude disappears when tuning threshold with power supply from high to low
- Each channel has 2 output ports
- Pulse 1 = -556 mV
- Pulse 2 = -376 mV
- **All channels functional and thresholds correct within estimated uncertainty**
- **Positive voltage into rear LEMO corresponds to negative shift in threshold**

Table 1: Thresholds by Channel

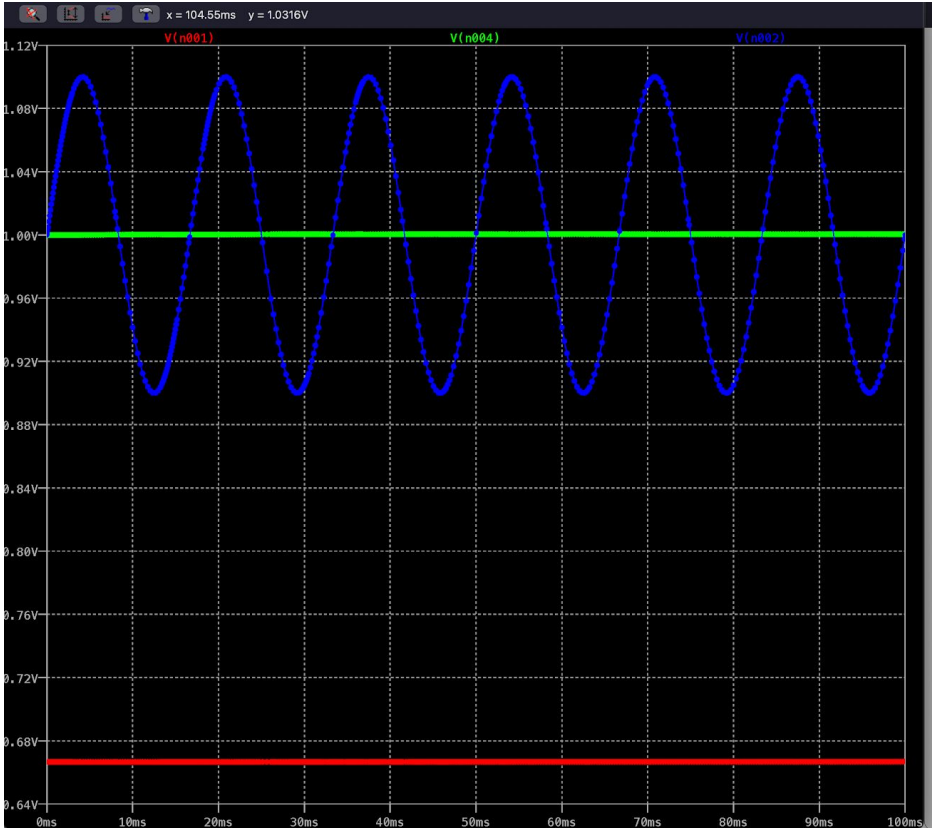
Channel	Port 1, Pulse 1 (-mV)	Port 2, Pulse 1 (-mV)	Port 1, Pulse 2 (-mV)
1	562	562	373
2	563	563	374
3	564	564	374
4	562	562	373
5	560	560	373
6	561	561	374
7	562	562	375
8	562	562	375
9	560	560	373
10	562	563	374
11	563	563	374
12	563	563	374
13	564	564	375
14	563	563	374
15	563	563	374
16	563	563	374

Modified PS706 DC Voltage Filter

Motivation

- Filter out any parasitic oscillations picked up over long cables from DAQ to discriminator
- Preliminary design complete and simulated
- Module cases procured
- Building the module and practical tests next

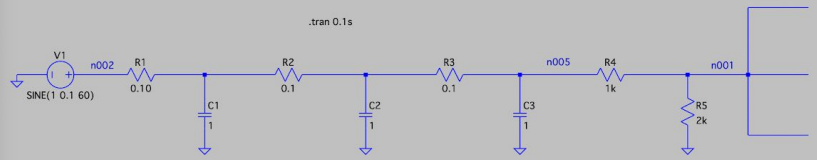
DC Voltage Filter Preliminary Design - 60 Hz Noise



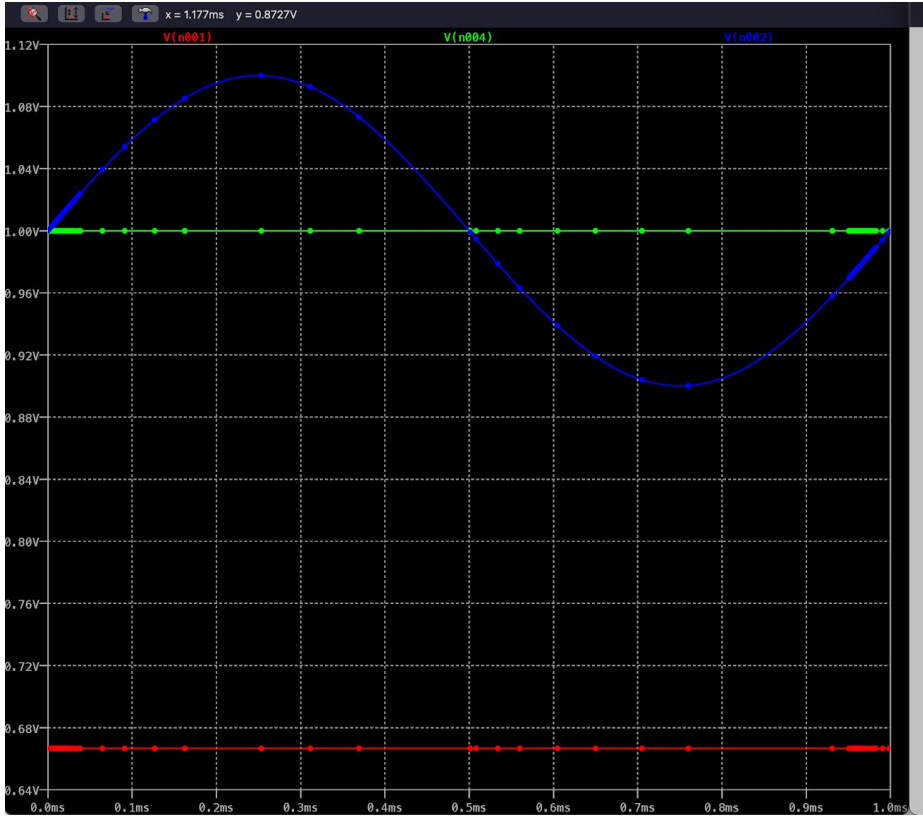
Very simple design: Three low pass filters in series (fc = 1.6 Hz)

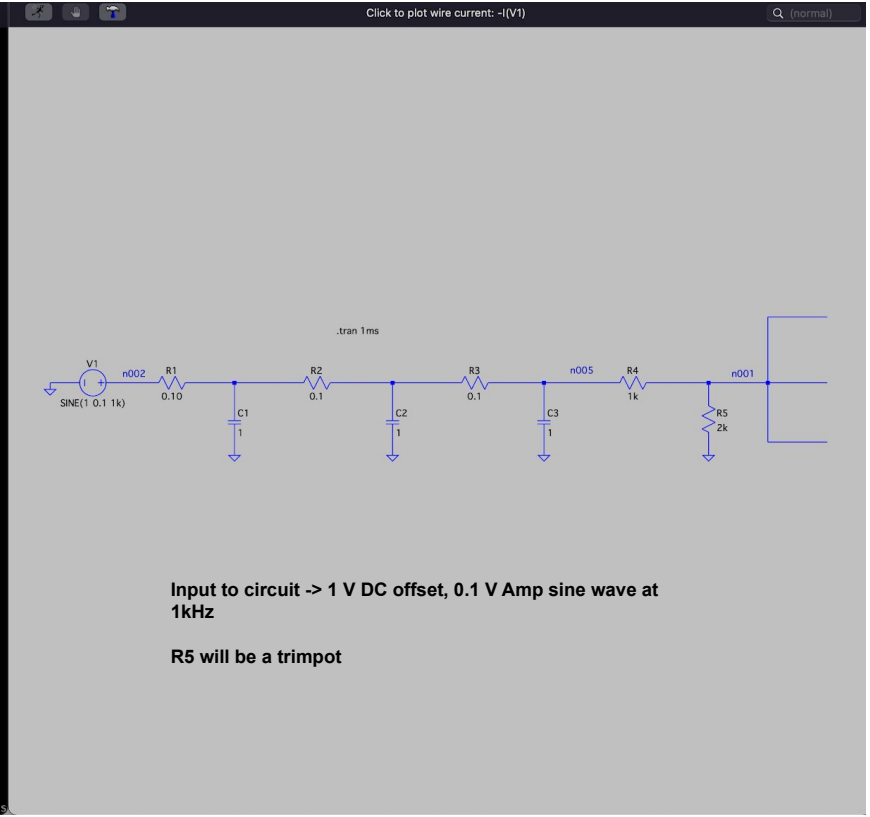
Input to circuit -> 1 V DC offset, 0.1 V Amp sine wave at 60Hz

R5 will be a trimpot



DC Voltage Filter Preliminary Design - 1 kHz Noise





Input to circuit -> 1 V DC offset, 0.1 V Amp sine wave at 1kHz

R5 will be a trimpot

LED Gain Curves - Single Parameter Fits

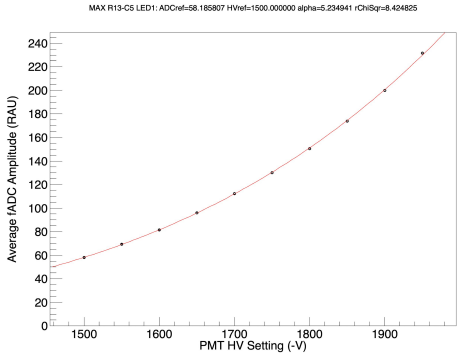
$$ADC_{max} = ADC_{ref}\left[\frac{HV_{set}}{HV_{ref}}\right]^{n_d * \alpha}$$

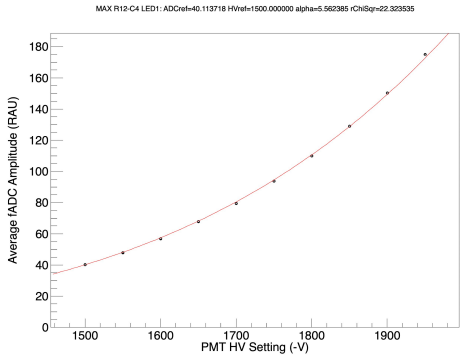
Single fit parameter

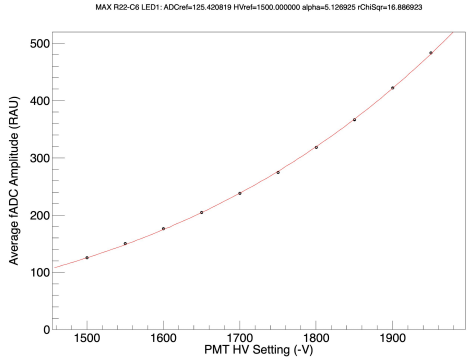
Defining Parameters

- ADC_max -> **Fit function y(x).**
- HV_set -> PMT high voltage setting. X value for fits.
- N_d -> Number of dynodes. 8 for jlab. 12 for cmu. 2 categories across all channels.
- n_d * alpha = alpha'-> Single free fit parameter.
- HV_ref -> Lowest HV setting for pmt across all runs.
- ADC_ref -> ADC value corresponding to lowest HV setting.

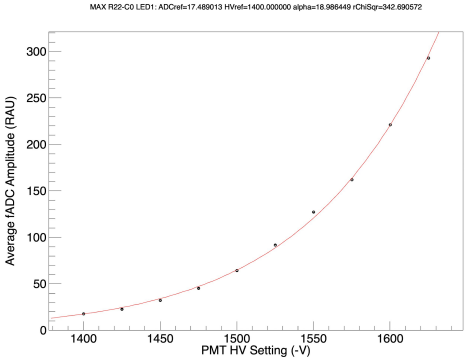
LED Gain Curves

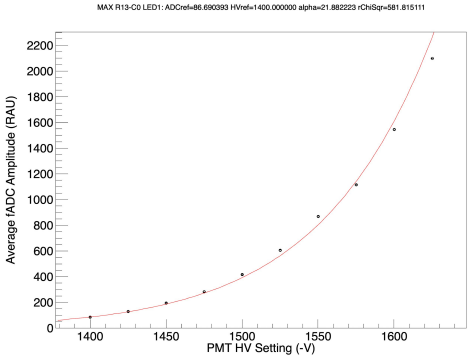


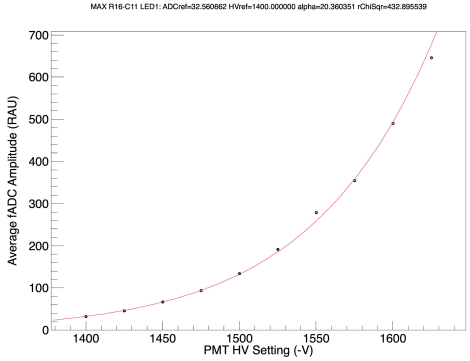




JLab Tubes (N_d = 8)

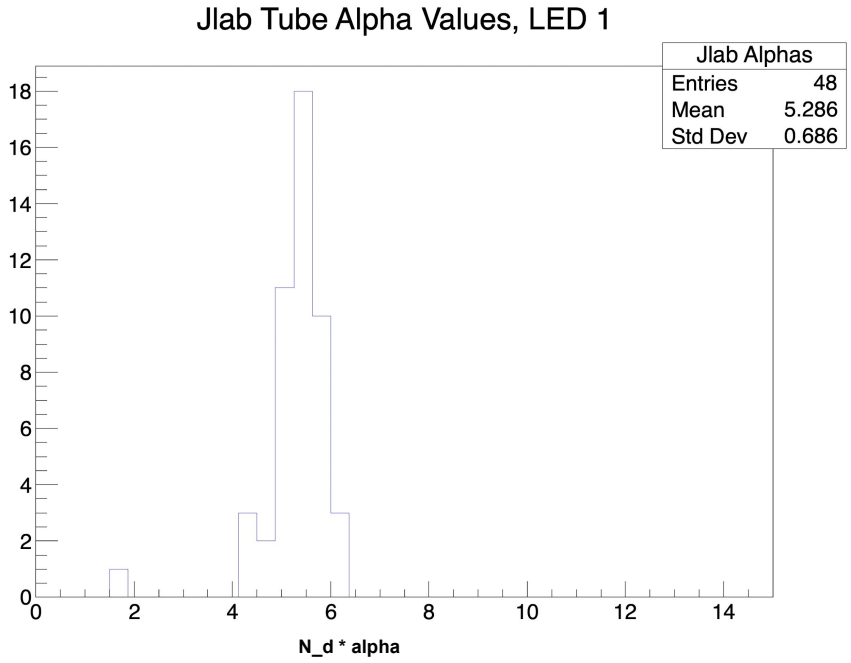


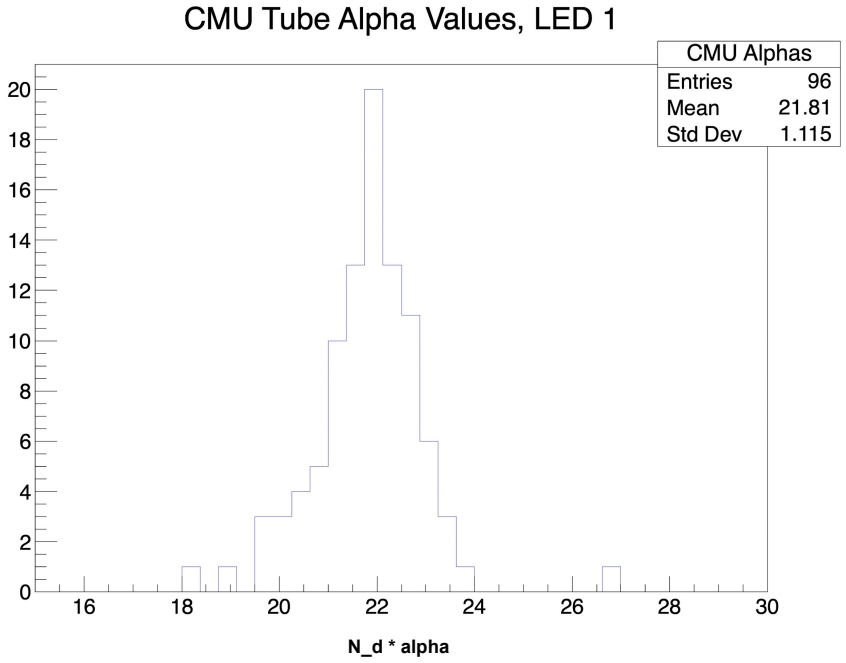




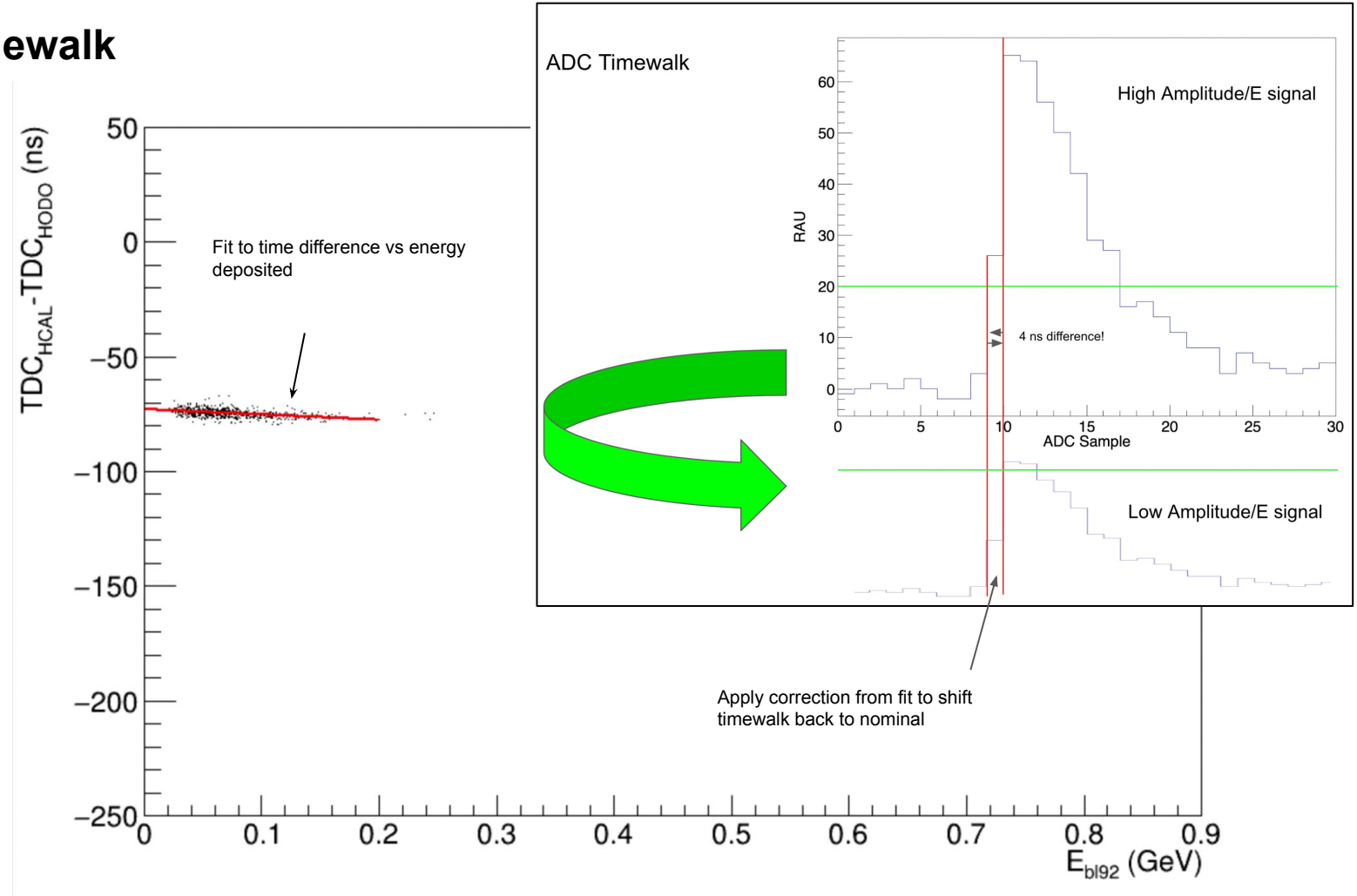
CMU Tubes (N_d = 12)

LED Alpha Parameters (LED 1)



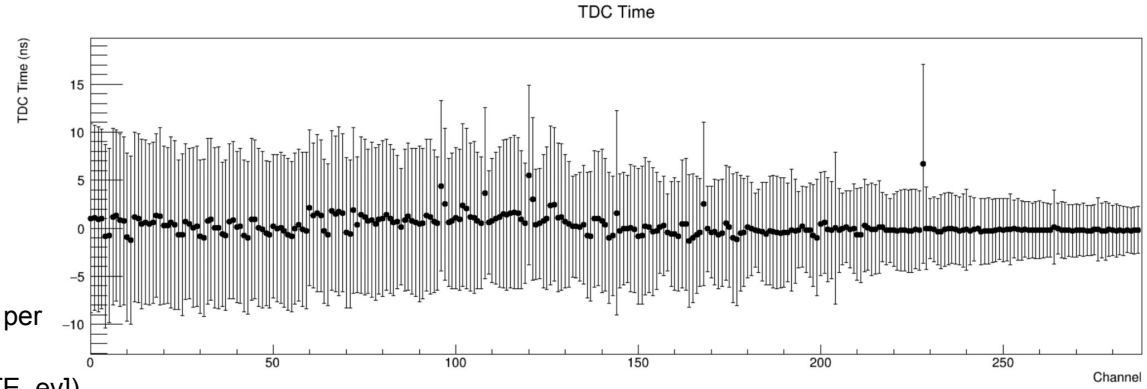


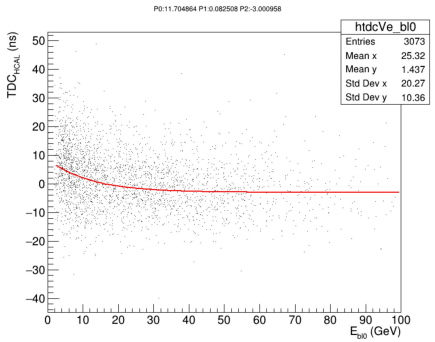
Timewalk

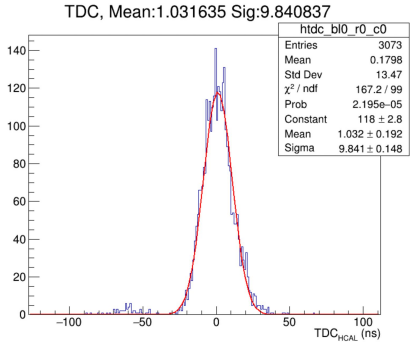

ADC Timewalk
High Amplitude/E signal
RAU
4 ns difference!
ADC Sample
Low Amplitude/E signal
Fit to time difference vs energy deposited
Apply correction from fit to shift timewalk back to nominal
TDC_{HCAL}-TDC_{HODO} (ns)
E_{bl92} (GeV)

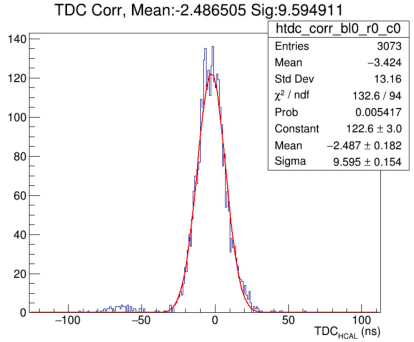
COSMICS: TDC and ADC times after first pass alignment and timewalk corrections (9.7.22)

1. Extract timewalk parameter per channel
   a. Fit f'n: [TDC] = P0*exp(-P1*[E])+P2
   b. Fit TDC vs E per channel
   c. Extract P0, P1
2. Extract TDC offsets per channel
   a. Fit TDC distributions with gaussian
   b. Get TDCmean per channel
   c. TDCmean / TDC calib + old offset
3. Pass offsets to DB, replay data
4. Build corrected TDC distribution with corrections per event
   a. [TDCcorr_ev] = [TDC_ev] - P0*exp(-P1*[E_ev])
5. Get and pass offsets to DB, replay as necessary to improve alignment



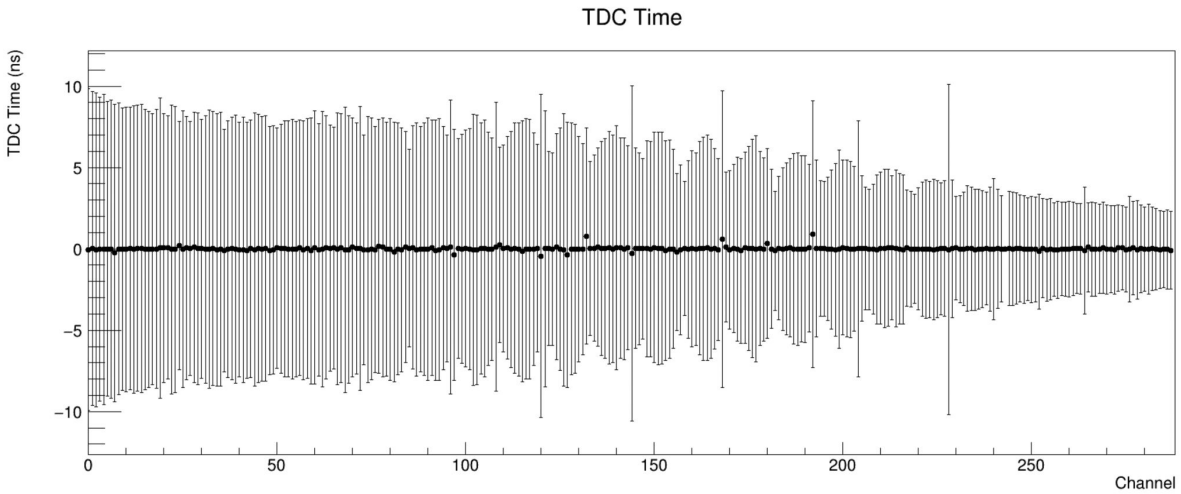


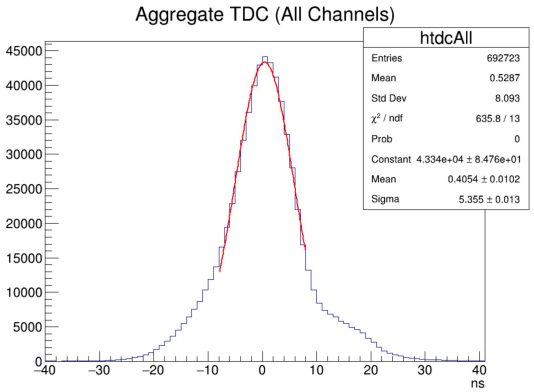


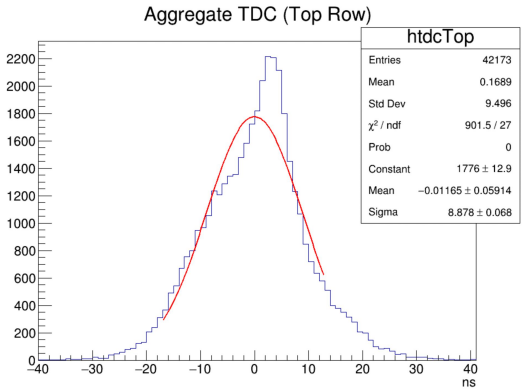


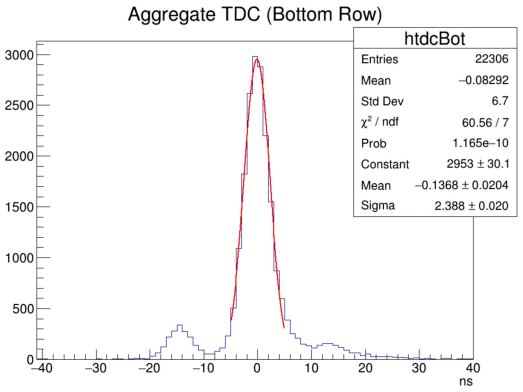
COSMICS: TDC and ADC times after second pass alignment and timewalk corrections

1. Alignment complete
2. Aggregate histograms
   a. TDC all channels
   b. TDC row farthest from trigger paddle
   c. TDC row closest to trigger paddle









BEAM: TDC Alignments

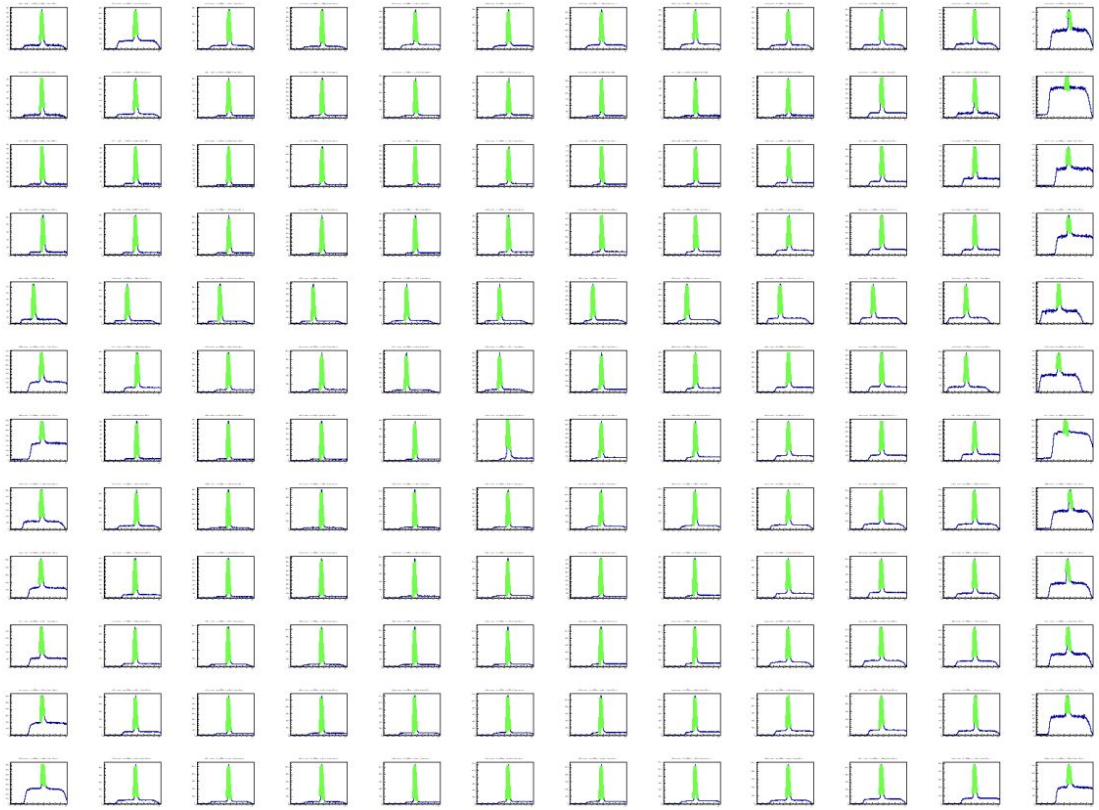


Figure 4: TDC Spectra Fits vs. Channel, Top Half

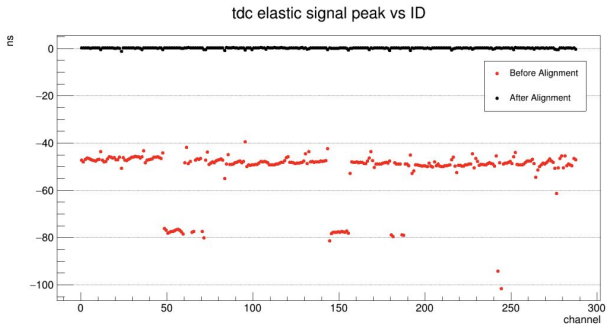


Figure 6: TDC Fit Comparison, Post-Cal in Black

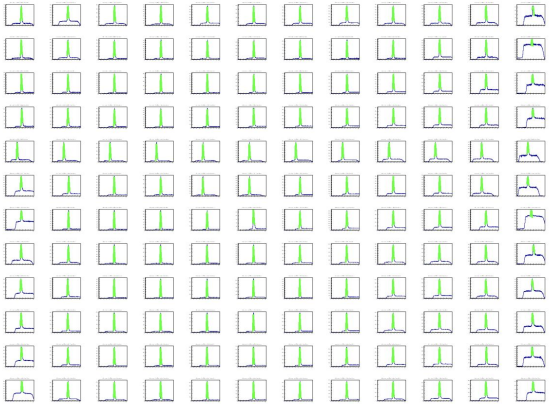


Figure 5: TDC Spectra Fits vs. Channel, Bottom Half

BEAM: TDC Alignments

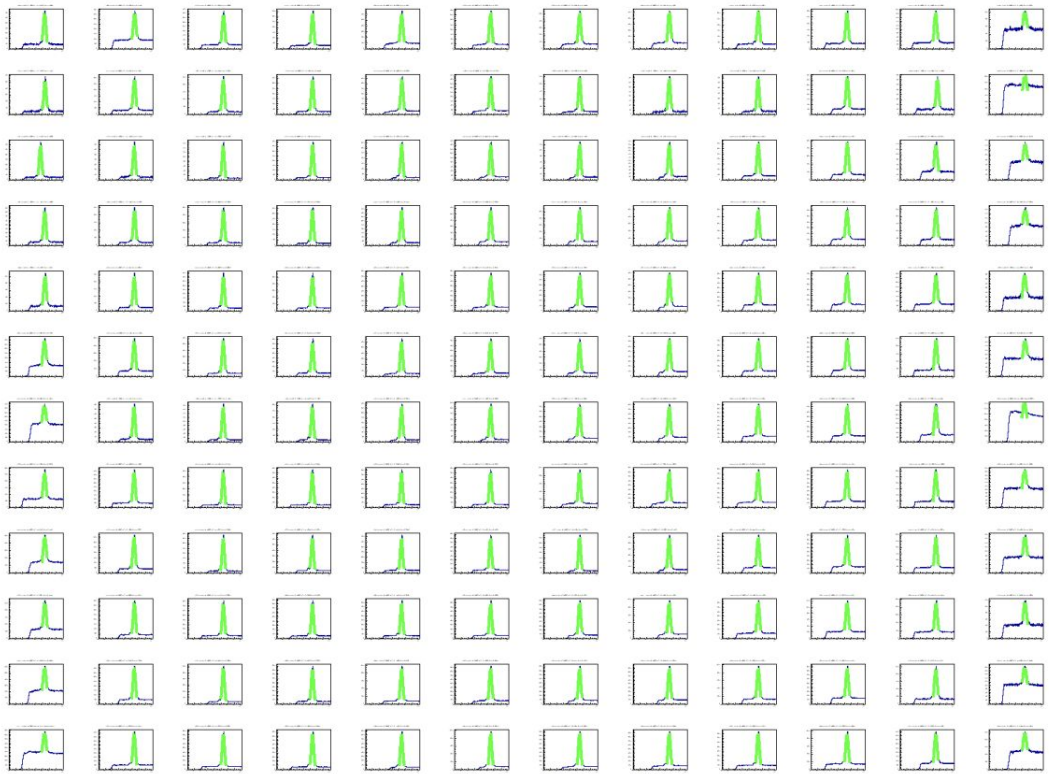


Figure 1: ADCt Spectra Fits vs. Channel, Top Half