SBS Hadron Calorimeter GMn Performance

Timing/Energy Resolution and Elastic Proton Detection Efficiency

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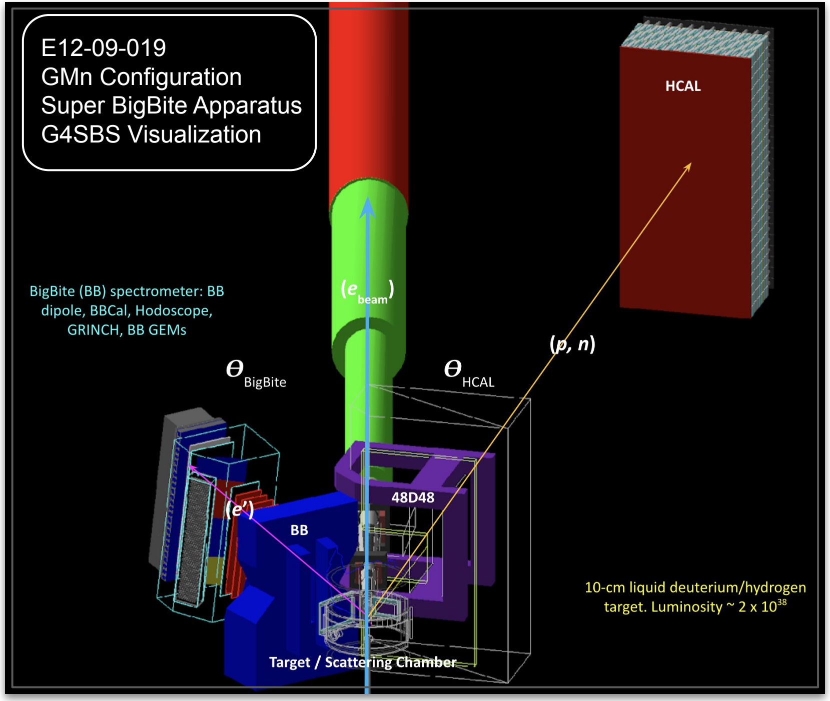
Topics

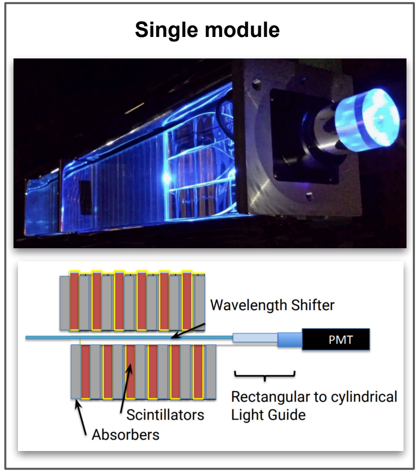
- HCal design
  - Overview
  - Performance
- GMn performance
  - Energy
  - Position
  - Timing
- Physics deliverables
- Preliminary proton detection efficiency



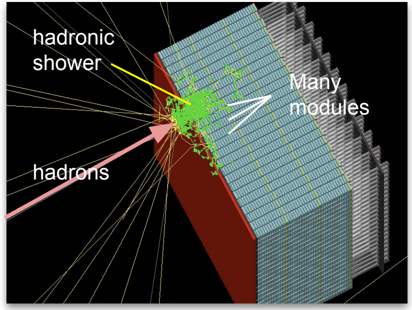
Design - Function Overview

- HCal is a sampling, segmented hadron calorimeter developed for SBS experiments
  - *12 cols x 24 rows (288 channels/modules)*
  - Each module: *15 cm x 15 cm x 1 m*
  - Full acceptance: *180 cm x 360 cm*
  - *4 craneable assemblies, 40 tons*
- HCal measures hadron energy, position, and timing
- Energy: Hadrons interact with iron absorbers to create showers of many particles ➡ shower energy is converted to light via scintillator ➡ light is converted to analog signal via PMT.
  - A portion of the initial hadron energy is sampled: the *sampling fraction*
- Position: Shower deposits energy in localized set of modules (a *cluster*). Signal source determines location by channel.
- Timing: Difference in time between signal in HCal and trigger
  - Both ADC and TDC provide timing for HCal relative to BigBite trigger reference

HCal, Target-facing-side, Hall A



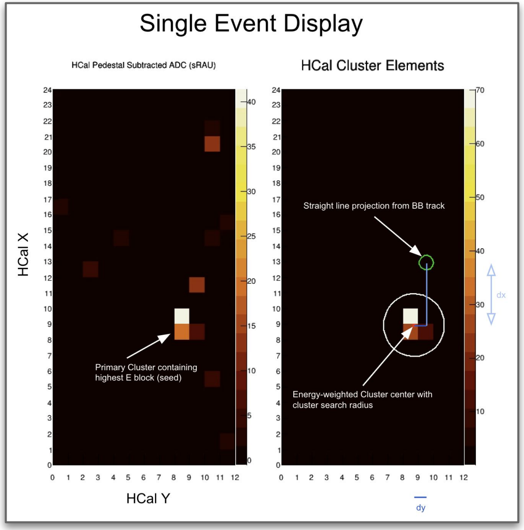
1/288 Single Modules in HCal

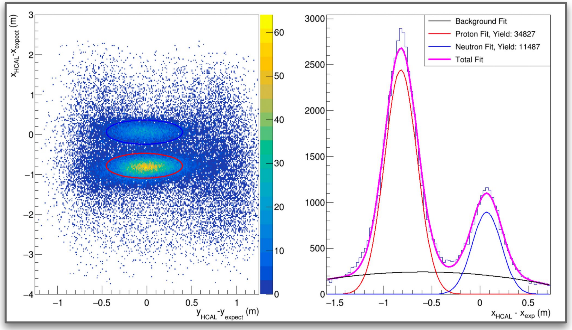


Visualization from G4SBS: HCal, top view

Design - Performance Expectations

- GMn and nTPE must detect and separate protons and neutrons to evaluate cross-section ratio
  - 1 T field provided by SBS magnet bends recoil protons to the top of HCal acceptance
  - Primary proton-neutron particle ID
- Position
  - High segmentation (*288 channels*) separates hadronic showers from different events
  - Resolution limited by block acceptance (*15cm x 15 cm*)
- Energy
  - Energy sampled per event uniform across full acceptance and read out by flash analog-to-digital converter (fADC250) by channel
  - Recoil nucleon position reconstruction improved via calculation of energy-weighted cluster centroid per event
  - Expected energy resolution: *30% - 50%*
- Timing
  - Parallel analog path to time-to-digital converter (F1TDC) by channel
  - F1TDC resolution: 0.5ns
  - Timing also available from fADC (*4ns bins*)





GMn Performance - Energy

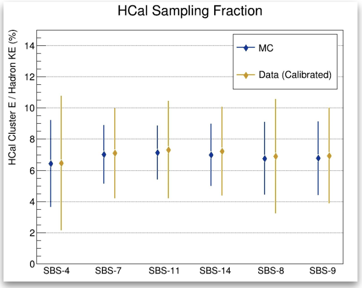
- Calibrations (complete for current pass)
  - Integrated ADC (pC) ➡ E (GeV) via χ^2 minimization on linear system
  - Relate total hadron E (from BB) to cluster elements with sampling fraction (MC)

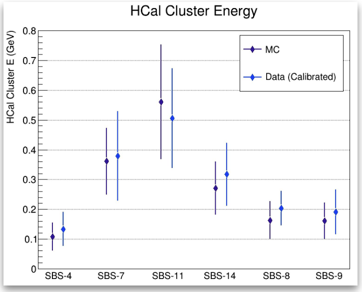
$$\chi^2 = \sum_{i=1}^{n} \left(E_i - \sum_j c_j A_j^i \right)^2 / \sigma_E^2$$

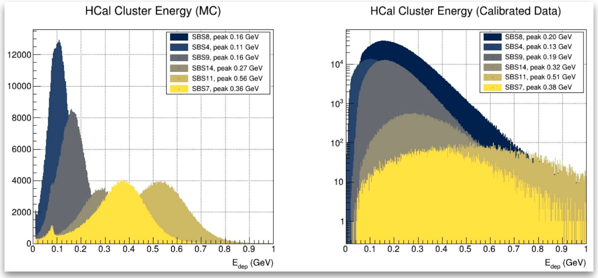
$$\sigma_E^2 \approx E_i$$

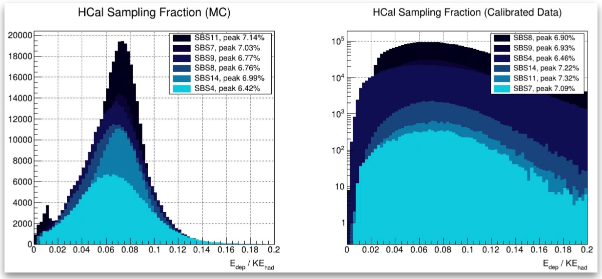
$$\frac{d\chi^2}{dc_k} = 2 \sum_{i=1}^{n} \frac{1}{E_i} \left(E_i - \sum_j c_j A_j \right) A_k = 0$$

Minimize









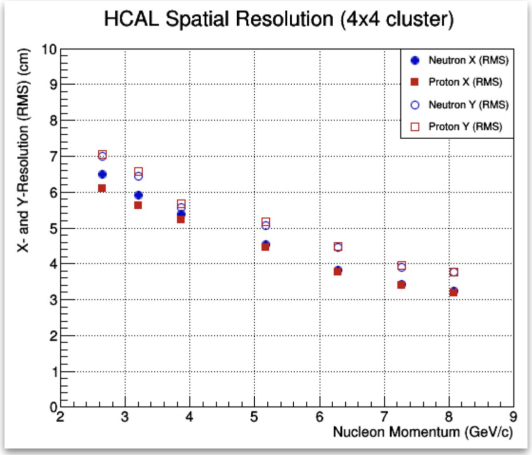
- Post-calibration
  - MC and data agree well over all kinematics
  - Energy resolution trends towards better resolution at higher Q^2

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**

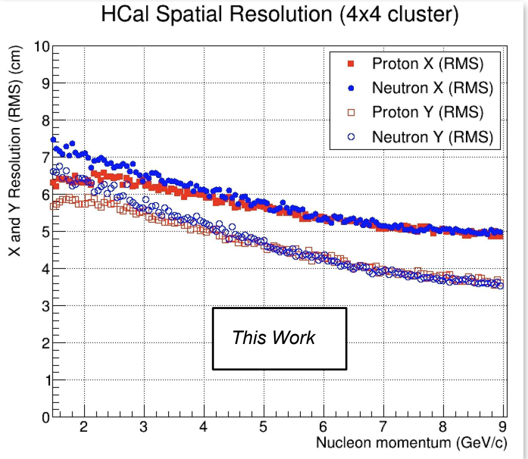
GMn Performance - Position

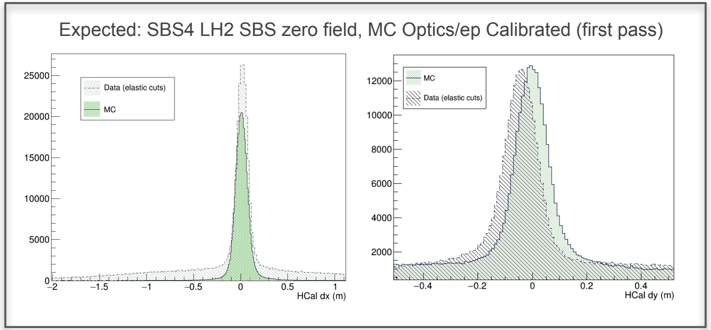
- Delta plots
  - Difference between cluster centroid and expected nucleon location in dispersive (vertical, X) and non-dispersive (horizontal, Y)
  - dx/dy RMS: HCal spatial resolution
- Simulated (no target)
  - PAC expected: proton / neutron generator with 4x4 clusters
  - This work: proton / neutron 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



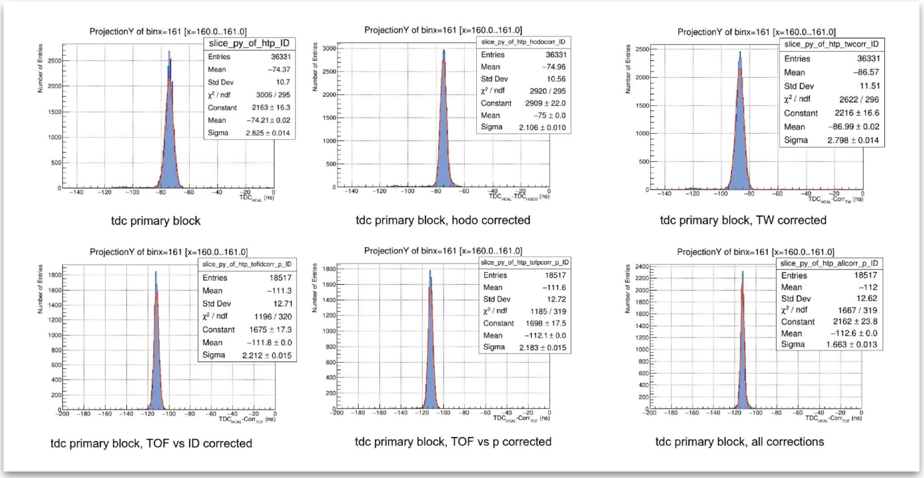
*PAC35, Juan-Carlos Cornejo

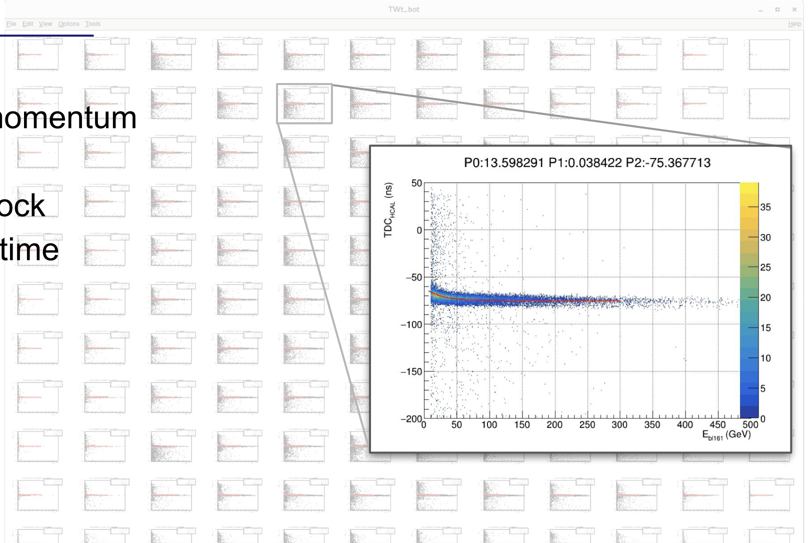


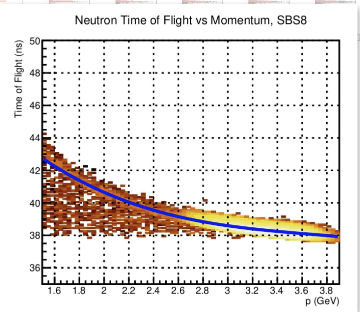


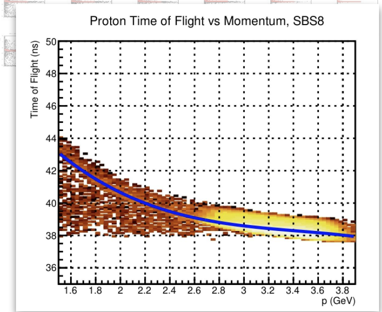
GMn Performance - Timing

- 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
  - Single block TDC RMS (HCal active area): *1.7 ns*







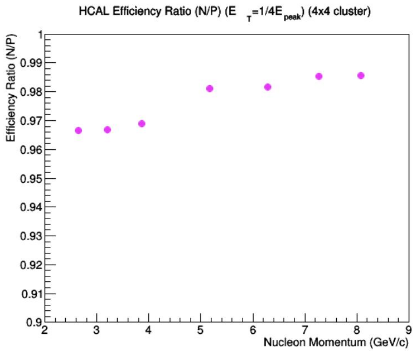


GMn/nTPE Physics Deliverables

- *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!

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

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



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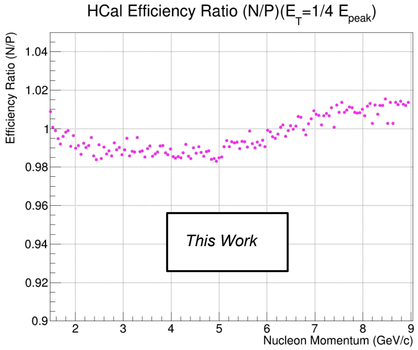
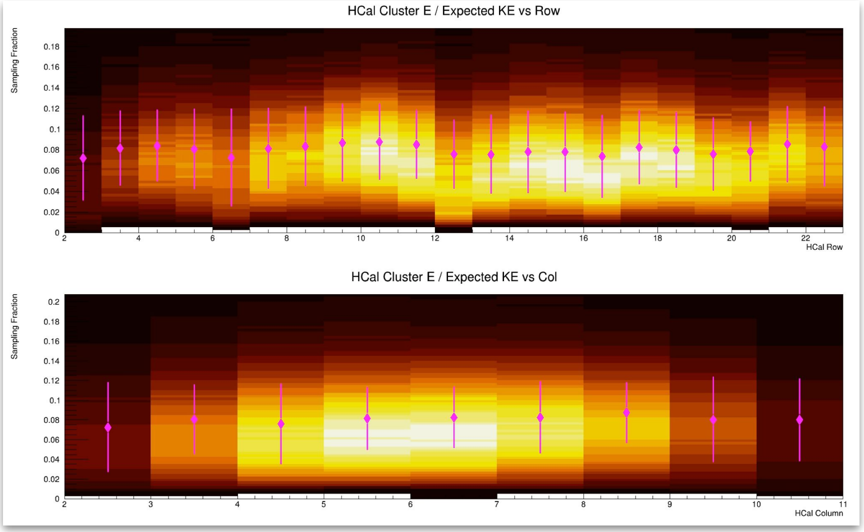
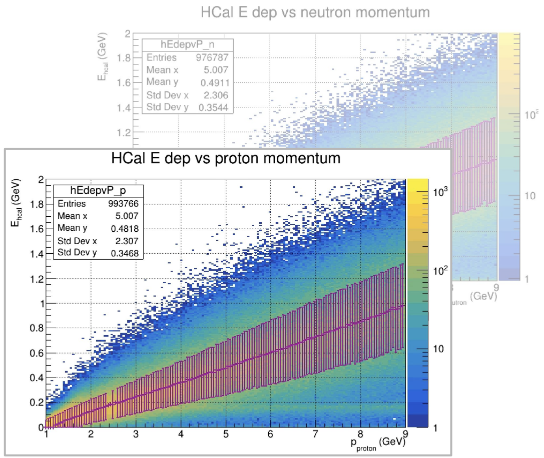


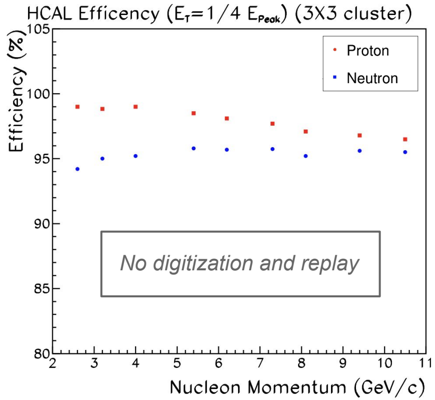


*SBS4 Data, all

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
- *Digitized and replayed simulations are consistent with proposal*





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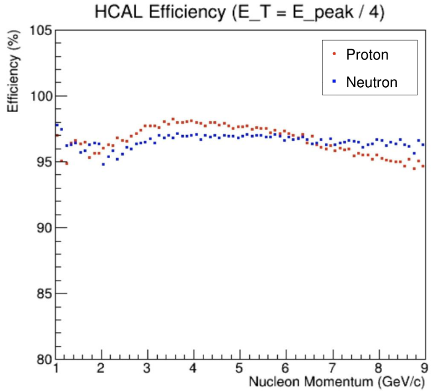
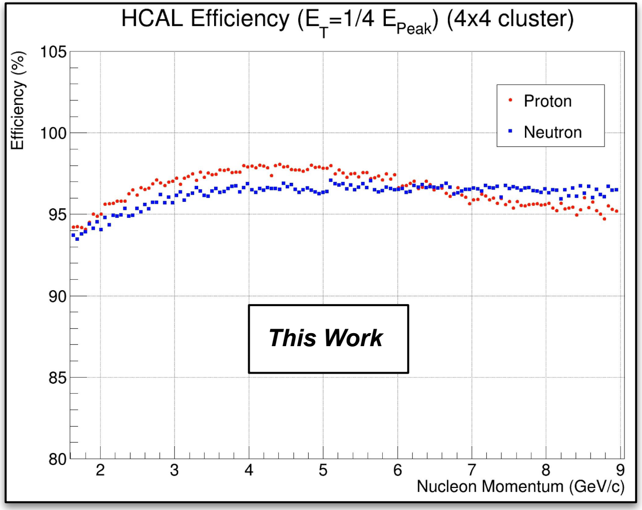
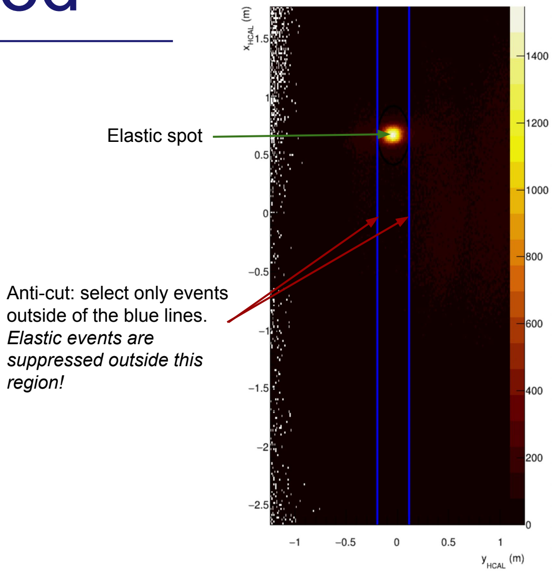


*GMn Analysis, Provakar Datta



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**

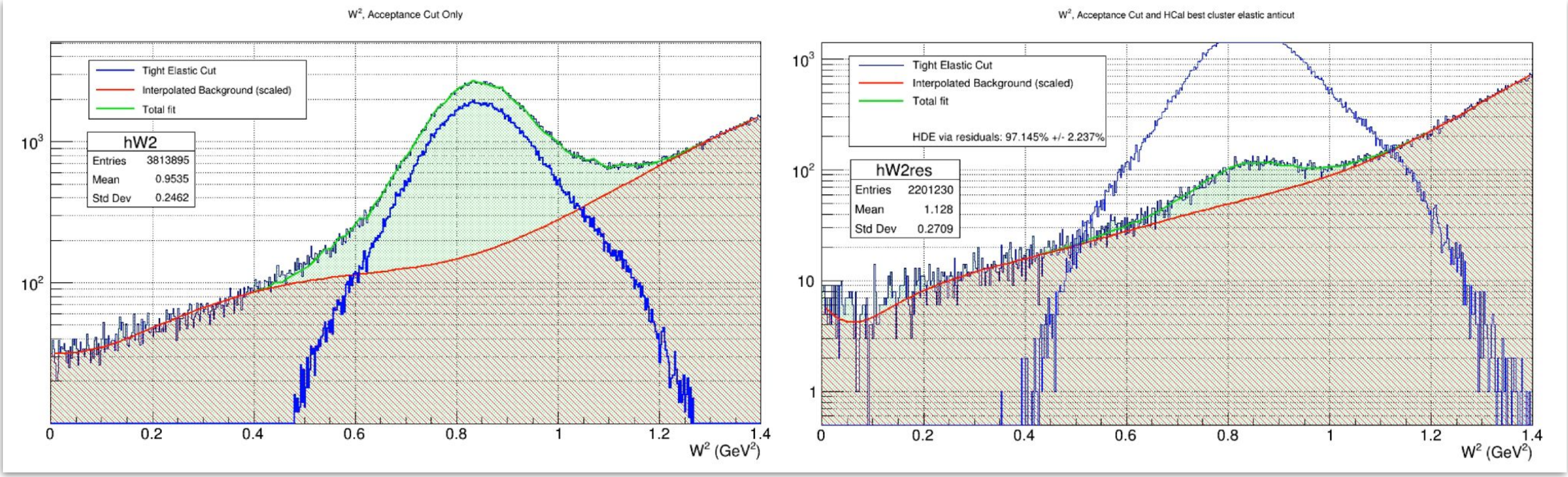


Elastic Cuts

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	$<3\sigma$

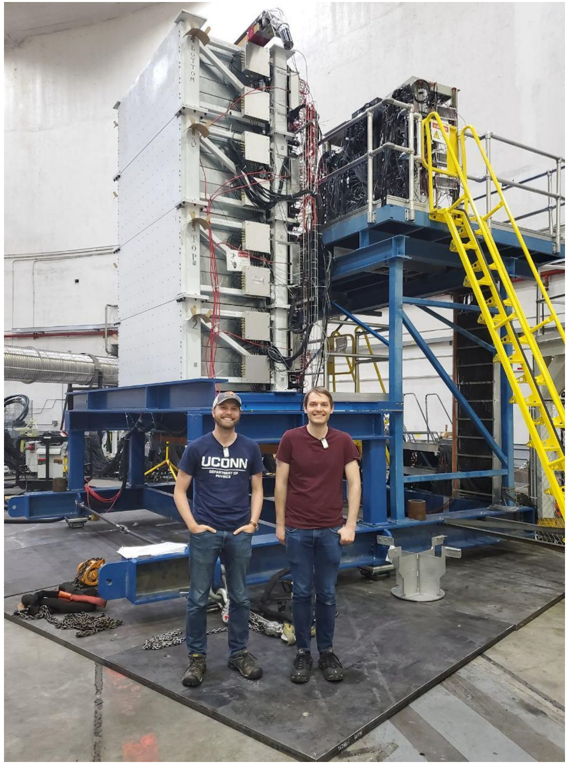
Design - Proton Detection Efficiency

- HCal Detection Efficiency (HDE) with anti-cut method: 97%
- Corroborated with simple exponential/gaussian fit method: 95% (not shown)
- MC expected: 94%
- *Exploring other methods to test robustness of this result*



Acknowledgements

- Many were involved in the design, construction, and commissioning of HCal, but special thanks to Brian Quinn, Scott Barcus, and Juan Carlos Cornejo for their patient mentorship and contributions to HCal leading up to and throughout GMn.



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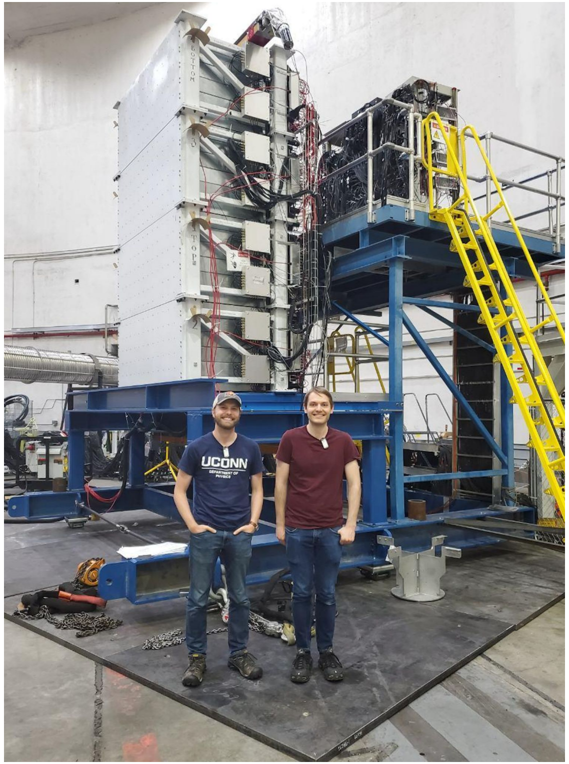


Questions?

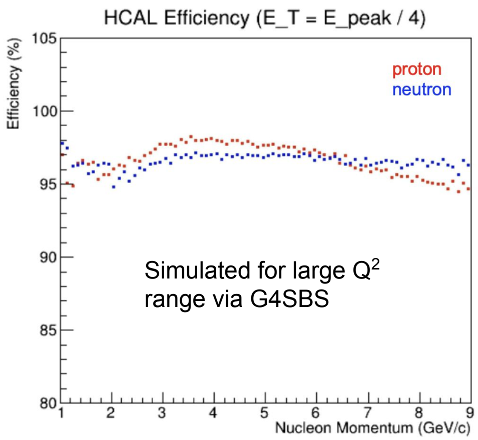
Backup - HCal Specifications

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

Backup - HDE simple fits

- Simulate *expected* efficiencies
  - Threshold: E_peak/4
  - Complete for all kinematics
- Proton (LH2 target)
  - Extract expected elastics using e' track cuts and HCal active area cuts only
  - Extract detected elastics from HCal dispersive delta plot "dx" fits
  - Ratio detected/expected is *observed* eff.
    - 95.3%
- We will check these results against the MC detection efficiencies for $f_{corrected}$

$$eff. = \frac{N_{ev\_over\_threshold}}{N_{ev}}$$



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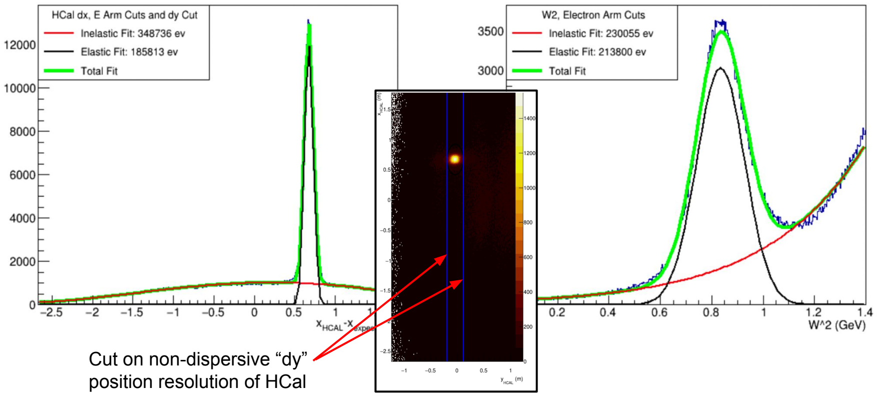
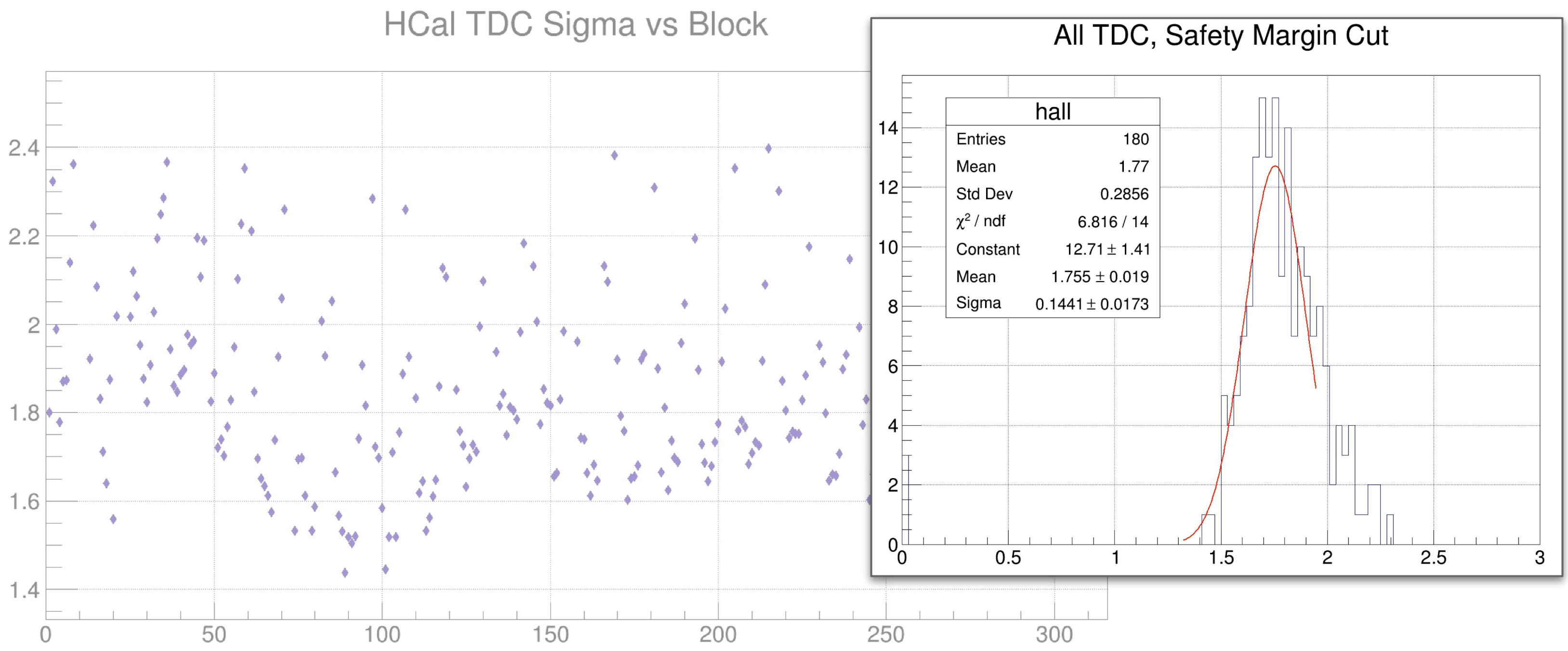


*plot credit: Provakar Datta, GMn Analysis Meeting Slides 11.18.22

Backup - TDC over all blocks

- All data from SBS8, primary block in cluster, block 161 (center of acceptance)

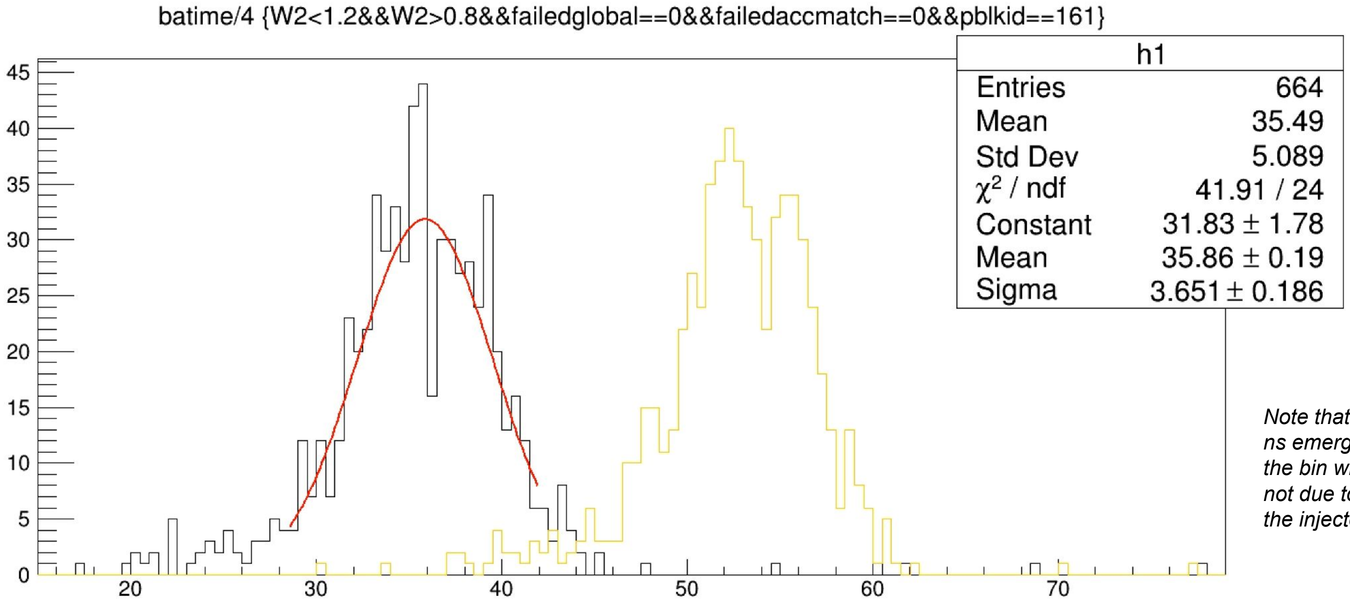


HCal ADC time: Performance of various fits to waveforms (continued)

From these results, the following steps were taken:

- Gaussian Landau convolution fits are removed. After tuning FFT points with SetNofPointsFFT() to attempt to improve processing time, no acceptable limit is possible with sufficient data. Other, more efficient methods to return a convolution fit may exist.
- Threshold methods to obtain rising edge are effective and should be more accurate than methods that rely on the spread in the data and are thus dependent on the amplitude of the signal.
- Where both landau (L) and skewed gaussian (SG) rising edge values exist, alternative atime (AAt) over analyzed data is the rising edge from either L or SG is added to output tree for comparison with current tree atime.
- If neither L or SG rising edge can be obtained, AAt defaults to current tree **atime** (with **batime** in black).

The following plots are over three runs (11589, 11590, 11592) from SBS4 LH2 data (block 161, wide elastic cuts) with no further corrections (hodo, ToF, etc.) applied. The fit is applied to **batime**. No substantial improvement is observed on **batime** (or independent landau and skewed gaussian distributions as compared to **atime**).



Note that the appearance of a 4 ns emergent structure is due to the bin width of ADC waveforms, not due to the RF structure from the injector.

Backup - TOF fits over all kinematics

- Polynomial order 3 fits to MC time-of-flight vs nucleon momentum