E12-17-004 GEN-RP Experiment

Bhasitha Dharmasena Purijjala
on behalf of the E12-17-004 collaboration

Jan 22 2025

SBS Experiment Series

Talks in this session

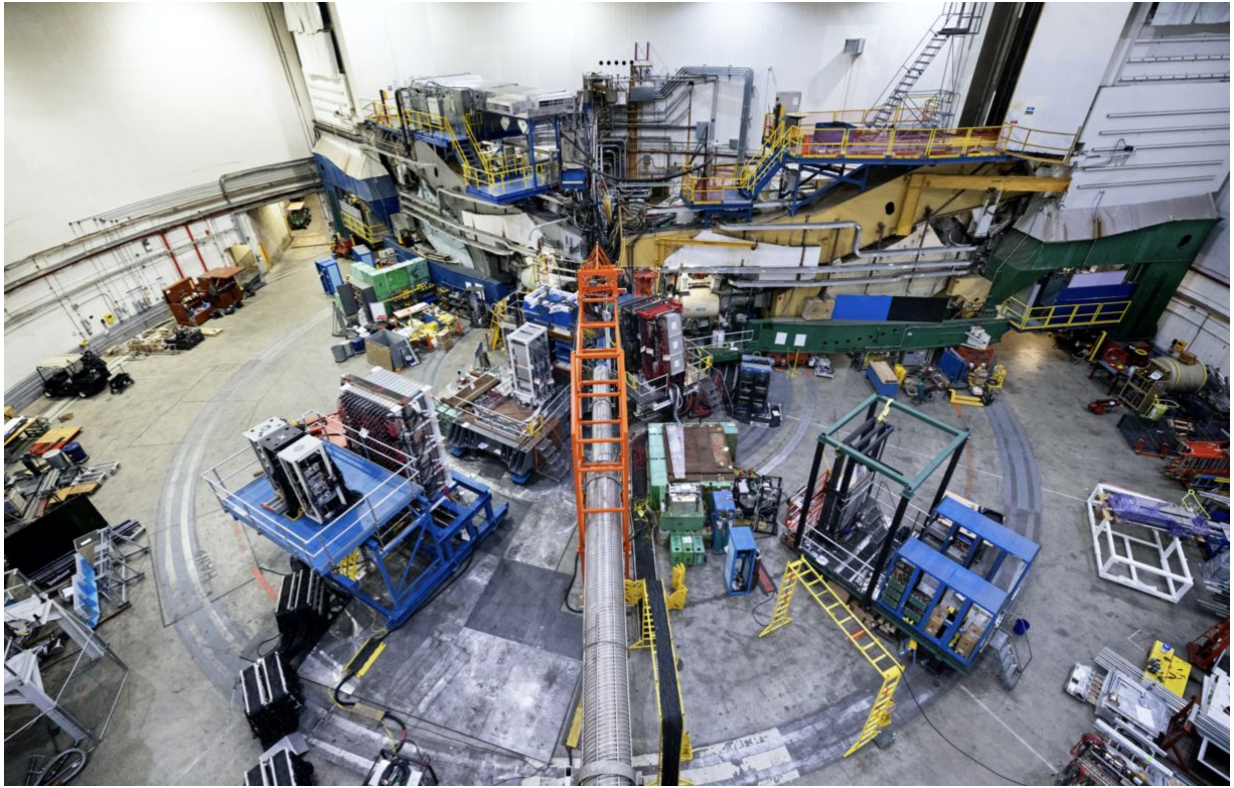
- GEP -V Overview
- GEP-V ECal
- GEP-V Tracking

- GMN
- nTPE

- GEN-II

- **GEN-RP - this talk**

- Future SBS Experiments



e-N scattering

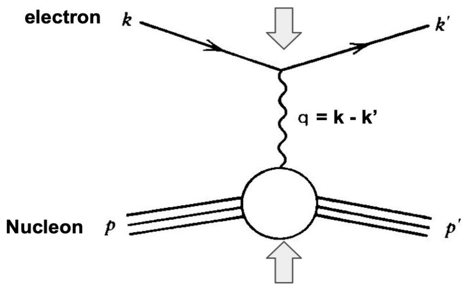
and

Nucleon Form Factors

e-N Scattering and Form Factors

Scattering Amplitude : $i\mathcal{M} = \frac{-ig_{\mu\nu}}{q_\mu^2}[ie\bar{u}(k')\gamma^\nu u(k)][-ie\bar{v}(p')\Gamma^\mu(p',p)v(p)]$

$$j^\mu = -e\bar{u}_e(k')\gamma^\mu u_e(k)$$



$$J^\mu = e\,\bar{u}_p(p')\left[F_1(Q^2)\gamma^\mu + \frac{i\kappa}{2M}F_2(Q^2)\sigma^{\mu\nu}q_\nu\right]u_p(p')$$

- $F_1(Q^2)$ and $F_2(Q^2)$ are the Pauli and Dirac Form Factors
- G_M and G_E are the Sachs Form Factors defined from F_1 and F_2, they describe the electric and magnetic distributions

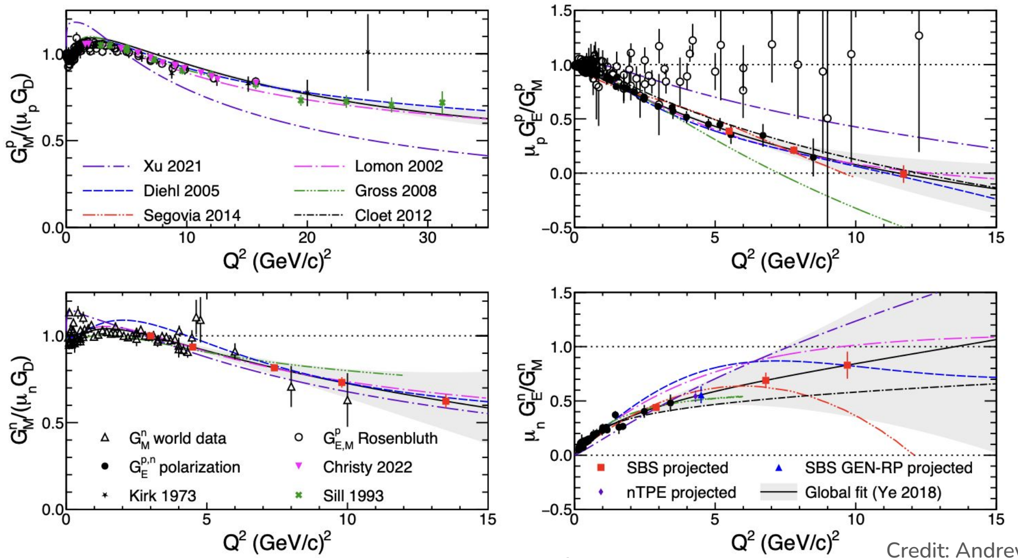
$G_M = F_1 + \kappa F_2$	$G_E = F_1 - k\tau F_2$

$\tau = \frac{Q^2}{4M^2}$

Super BigBite Spectrometer(SBS) Program at Jefferson Lab

Measuring elastic electromagnetic form factors of the nucleons at the highest 4-momentum transfer (Q^2) and precision achieved so far

- **GMn & nTPE** - Measurement of G^n_M up to Q^2 = 13.5 $(GeV/c)^2$
- **GEn-II** - Measurement of G^n_E/G^n_M up to Q^2 = 10 $(GeV/c)^2$ using a polarized target
- **GEn-RP** - Measurement of G^n_E/G^n_M at Q^2 = 4.4 $(GeV/c)^2$ using a double polarized methods
- **GEp-V** - Measurement of G^p_E/G^p_M up to Q^2 = 12 $(GeV/c)^2$



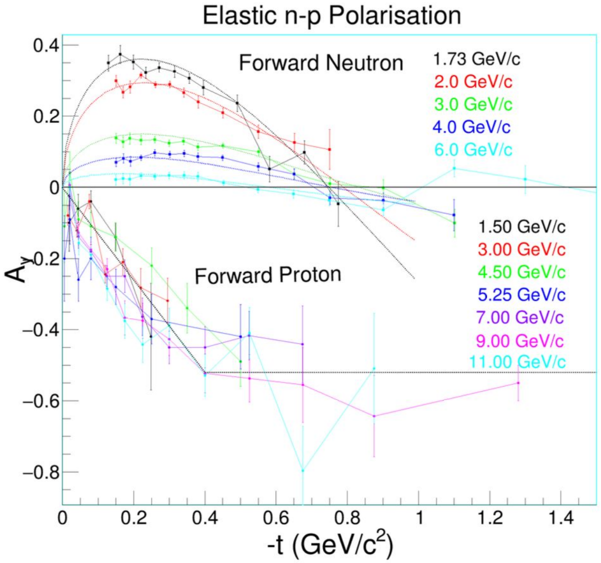
projection of SBS high Q^2 form factor data

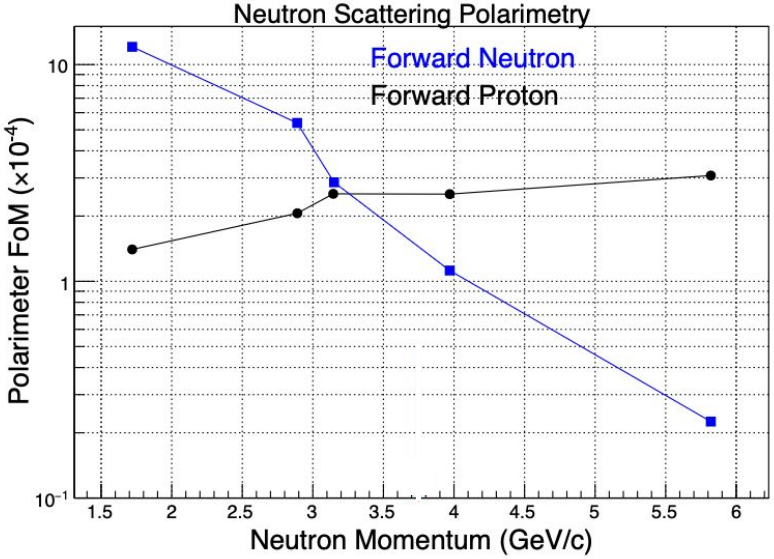
Credit: Andrew Puckett
"50 Years of QCD"(EPJ C, in press) https://arxiv.org/abs/2212.11107

GEnRP Experiment

Polarimetry

- When approaching higher neutron momentum's, the Analyzing power(Ay) drops fast for the conventional method but has no significant effect on the Charge-Exchange(ChEx) reaction Ay
- Higher Figure of Merit(FoM) when approaching higher Momentum transfer for ChEx
- Results from JINR experiment shown below

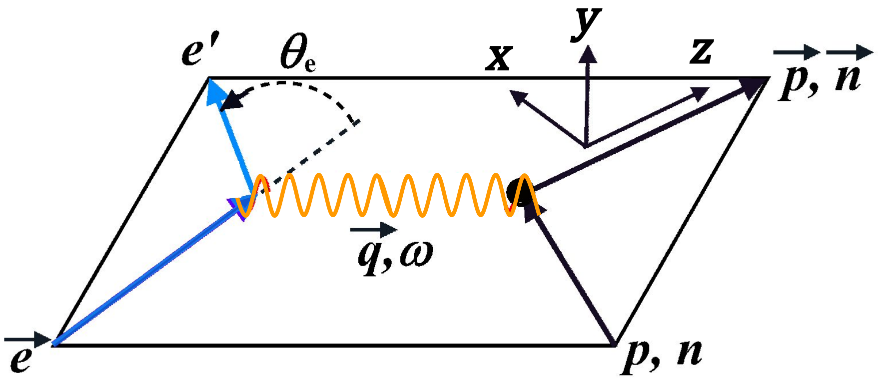




S.N. Basilev et al., Eur. Phys. J. A 56, 26 (2020)

Recoil Polarization Method

- The unpolarized target is struck with the polarized electron beam
- The transferred polarization to the recoiling neutron can be parameterized using the Sachs FFs as follows
- The x component below denotes the transverse polarization and the z component denotes the longitudinal polarization of the recoiling neutron



$$P_x = -hP_e \frac{2\sqrt{\tau(1+\tau)}\tan\frac{\theta_e}{2} G_E G_M}{G_E^2 + \tau G_M^2(1+2(1+\tau)\tan^2\frac{\theta_e}{2}}$$

$$P_y = 0$$

$$P_z = hP_e \frac{2\tau\sqrt{1+\tau+(1+\tau)^2\tan^2\frac{\theta_e}{2}}\tan\frac{\theta_e}{2} G_M^2}{G_E^2 + \tau G_M^2(1+2(1+\tau)\tan^2\frac{\theta_e}{2})}$$

- The ratio of the transferred polarization will be a direct measurement of the neutron FF ratio (while cancelling many of the systematic errors)

$$\frac{P_x}{P_z} = \frac{1}{\sqrt{\tau+\tau(1+\tau)\tan^2\frac{\theta_e}{2}}} \cdot \frac{G_E}{G_M}$$

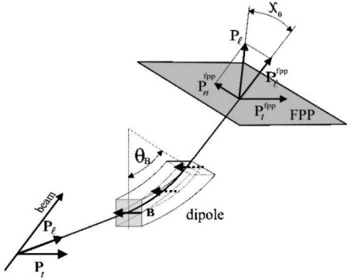
FF Ratio Measurement

- The SBS magnet precesses the polarizations making the longitudinal component of the transferred polarization measurable.

$$\frac{P_x}{P_z} = \frac{1}{\sqrt{\tau + \tau(1+\tau)\tan^2\frac{\theta_e}{2}}} \cdot \frac{G_E}{G_M}$$

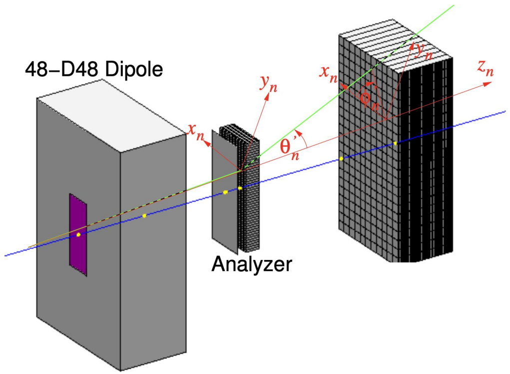
$$P_x^* = A_y^{eff} P_e P_x$$

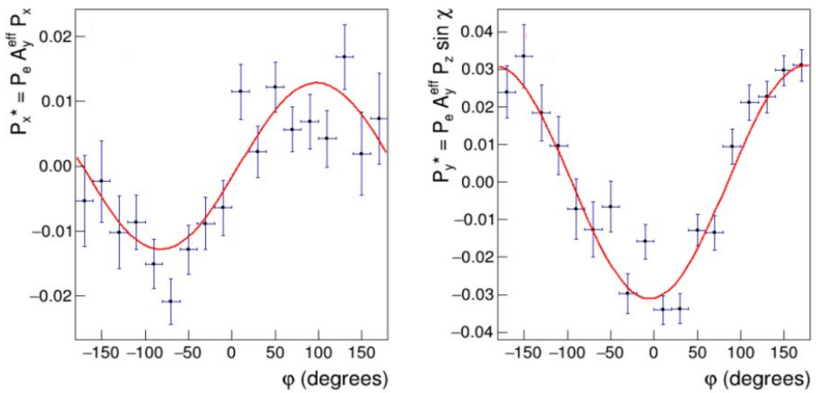
$$P_y^* = A_y^{eff} P_e P_z \sin\chi$$



- N-N scattering depends on the spin-orbit interaction – produces an azimuthal modulation of the scattering cross-section

$$F(\phi_n^{'}) = C\{1 \pm |P_x^*| \sin\phi_n^{'} \pm |P_y^*| \cos\phi_n^{'}\}$$



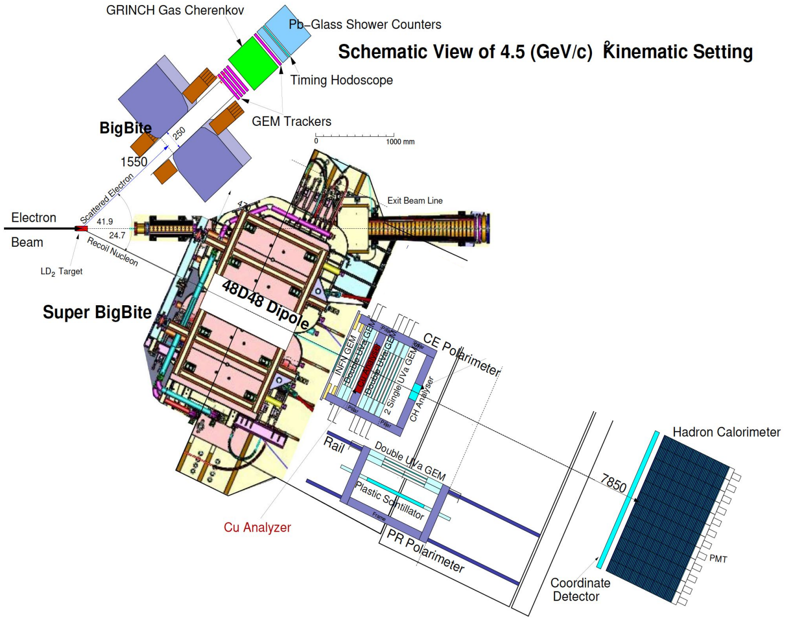


scattering asymmetry from the simulations

GEnRP Experiment Setup

GEn-RP Experiment

- a measurement of the ratio G^n_E/G^n_M
- a proof of principle experiment
- a double polarized measurement at 4.3GeV beam energy
- unpolarized 15cm LD_2 target
- polarized electron beam
- BigBite as the electron arm
- Super-BigBite as the hadron/neutron arm
- 2 polarimetry techniques used
    1. conventional *np* → *np*
    2. charge exchange *np* → *pn*

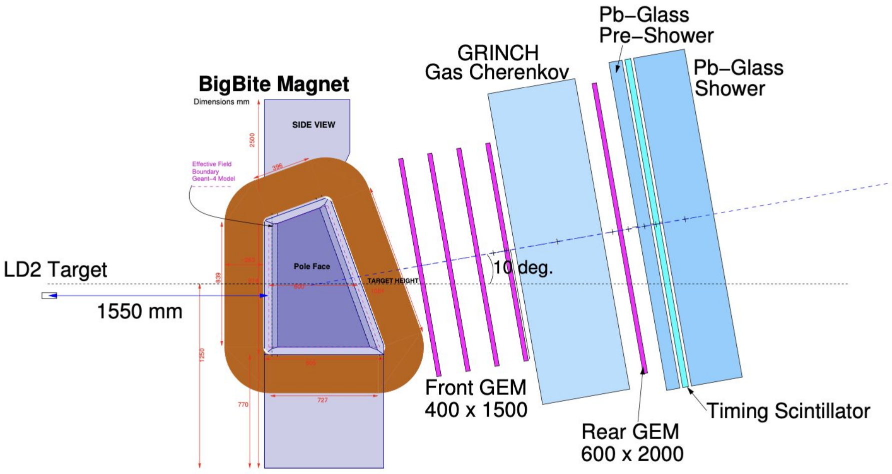


SBS apparatus for GEnRP (plan view)

Spectrometers

BigBite electron arm

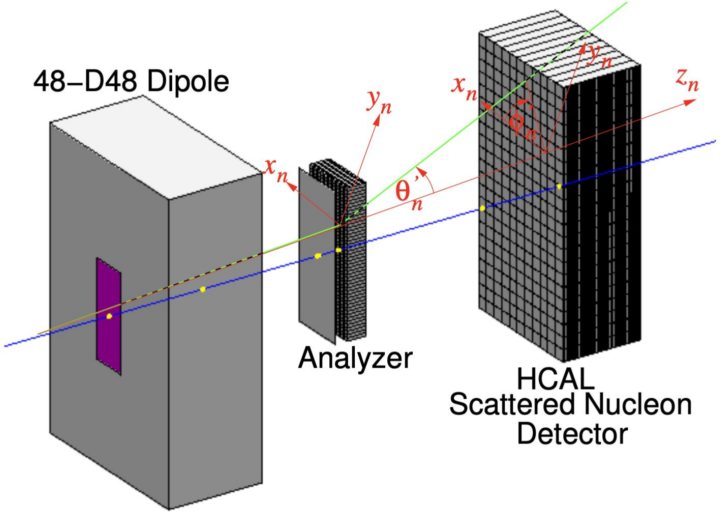
- Dipole magnet - 750A
- BB GEM Tracker
- Timing Hodoscope
- BB Calorimeter
- GRINCH Cherenkov



* This was the final run-period with the BB detector setup

Super BigBite hadron arm

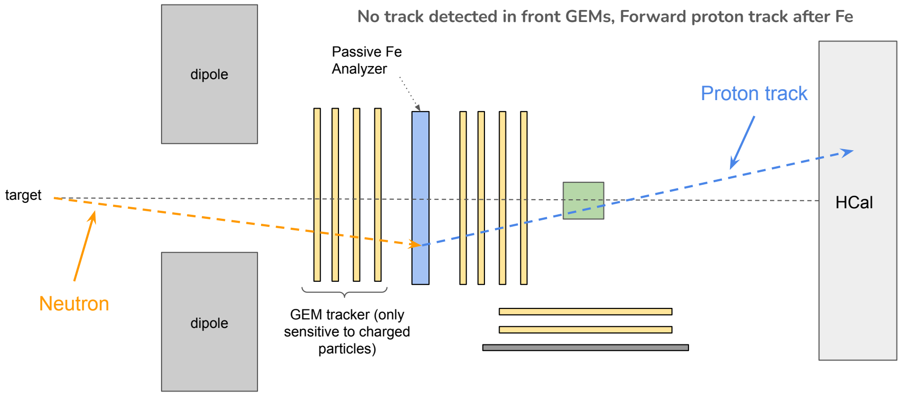
- Dipole Magnet - 2100A
- Hadron calorimeter
- 2 in-line GEM stacks
- 1 side GEM stack
- Passive Analyzer
- Active Analyzer
- Side hodoscope layer



Processes

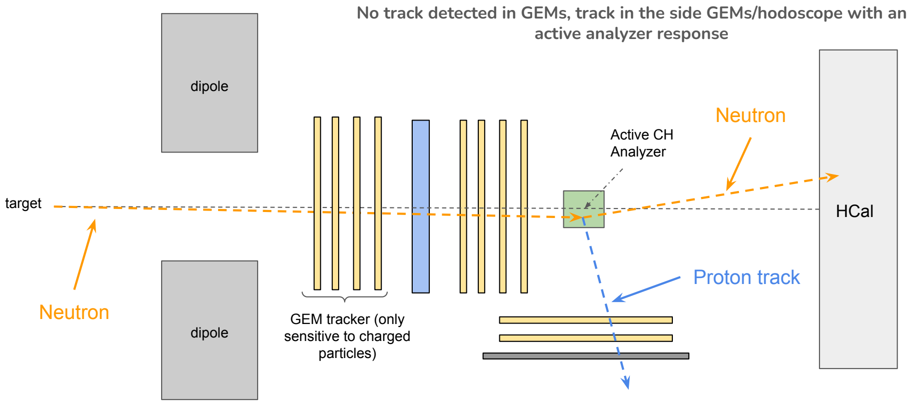
Charge-Exchange

(TOP VIEW)



Conventional Scattering

(TOP VIEW)



Data Analysis

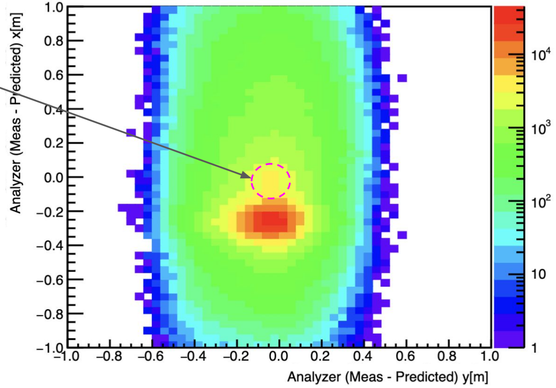
Run Summary

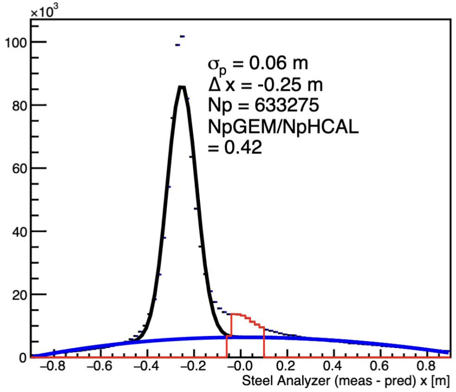
- Completed data taking during April 16 - May 14 2024
- 10-12uA beam current on LD2 target
- 82% polarized beam
- BB(750A), SBS(2100A) magnets at 100%
- BB, SBS Spectrometer angels at 42.5° and 24.7°
- 3 hours of LH2 data per day
- 11.8 C total LD2 data collected
- 3-4 kHz data acquisition rate (~1.2GB/s)

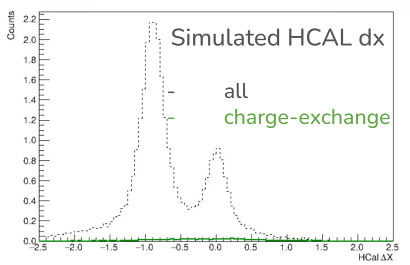
Charge-Exchange Event Separation

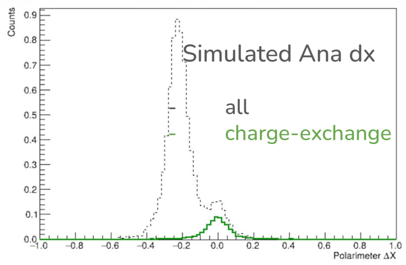
- The hadrons coming from the target goes through the SBS magnet
- Using the precise q-vector generated using BB information we can calculate the expected position of the hadron(if not deflected from the SBS magnet) on the analyzer plate(or the HCAL)
- With the deflection from the SBS magnet we can see two separate peaks for Neutrons and Protons
- We can not use the HCAL as a reliable method of distinguishing the particles like it’s done in other SBS experiments (GEn-II or GMn) because of the possible deflections analyzer in the middle, specially for the charge-exchange events
- Neutron events can be further isolated from Protons using the condition of not having a track before analyzer

Charge-Exchange region of interest at (0, 0) in dx, dy



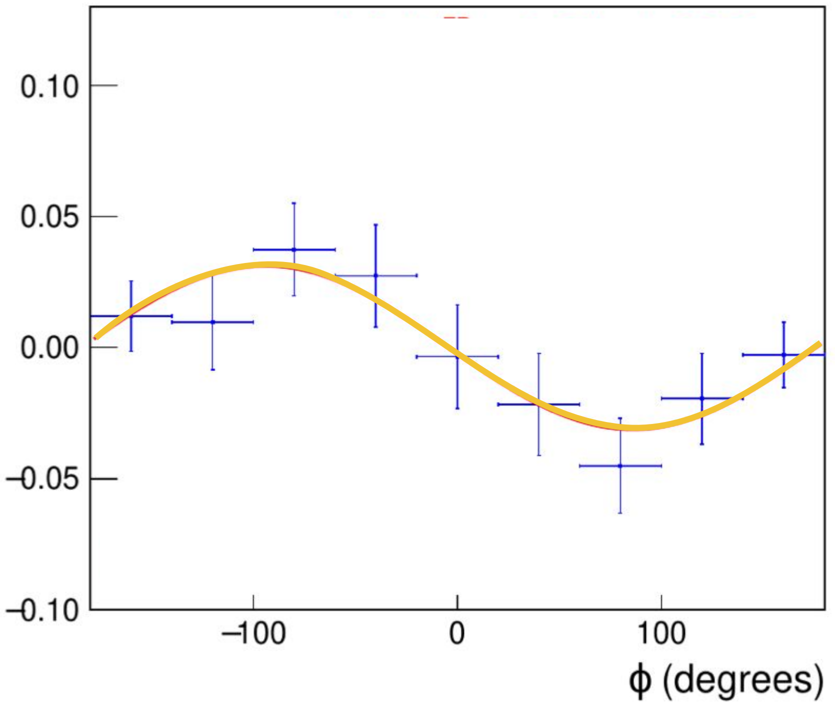






Simulations: Andrew Cheyne

Charge-Exchange channel Asymmetry



More work needs to be done for better isolation of the charge-exchange channel

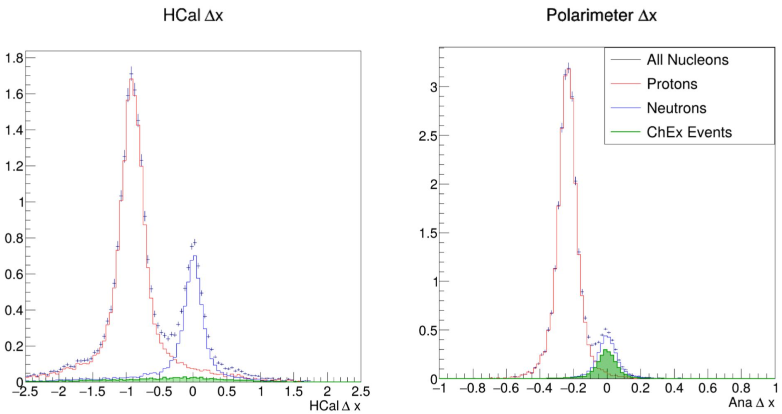
Credits: David Hamilton

Calibrations Status

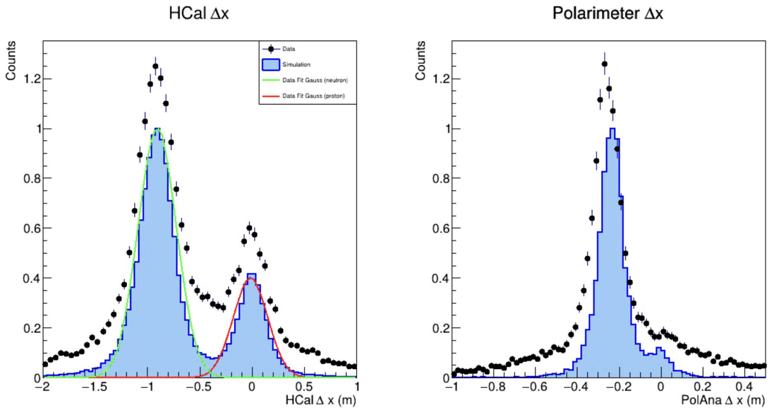
- Detector Calibrations needed for a cooking pass are completed
- Previous calibrations
  - GEMs in BB and SBS - credits Andrew Puckett
  - Magnet Optics- credits Andrew Puckett
  - BB Calorimeter energy calibration - credits Andrew Cheyne
  - HCal energy reconstruction

Data Simulations comparisons

Andrew Cheyne



simulation results of dx distributions on the Analyzer plate and on the HCAL face



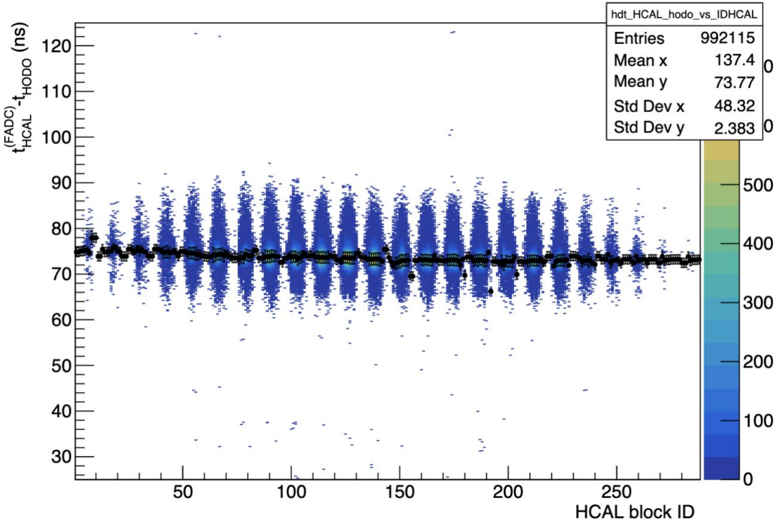
data simulation overlay checking reconstruction

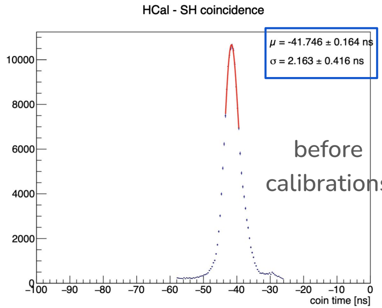
- this is work in progress
- working on adding the backgrounds into the simulations
- once completed can be used to study the effects of cuts and understand experimental dilution, proton contamination etc.
- MC truth info can be used to isolate certain channels (e.g. charge-exchange) and use that to see how our cut choice affects things like Asymmetry and Analysing power
- with this expected event sample percentages we can investigate how tracking efficiencies and proton contamination affects Ay and optimise the data cuts

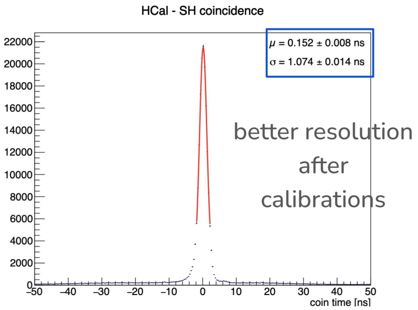
Timing Calibrations

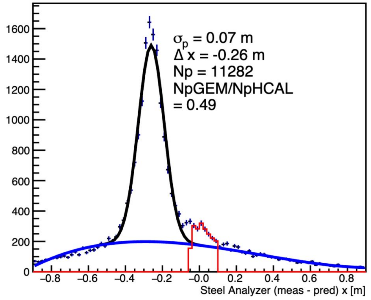
- Accidental timing background can be removed using the a coincidence time cut between the two spectrometer arms. A good timing resolution is important
- Recent developments in timing using the BB Hodoscope by Andrew Puckett and others
- These were implemented in the for GEn-RP
- Improvements in coincidence timing resolution from ~2.1ns to ~1.0ns

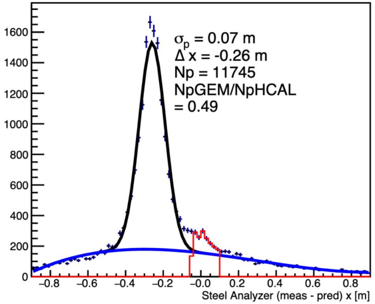
Talk from Anu on GMn contains detailed information of this method





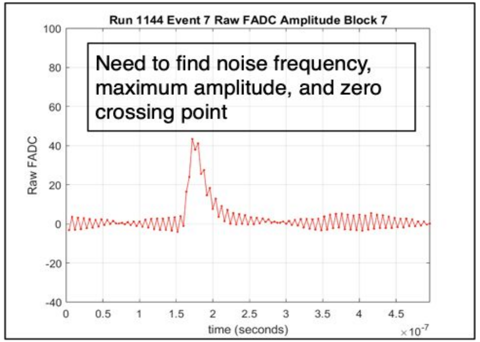


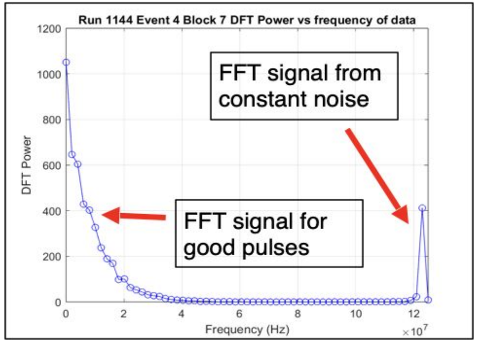




Active Analyzer Raw Signal Analysis

Results of event analysis with Fast Fourier Transform(FFT) - William Tireman





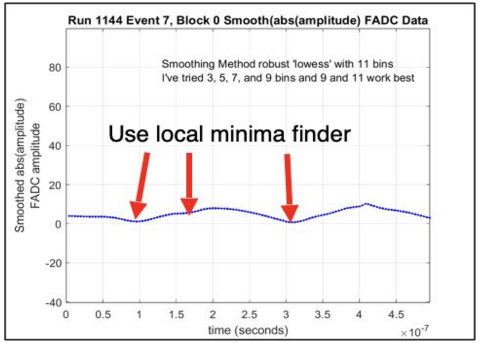
FFT results:

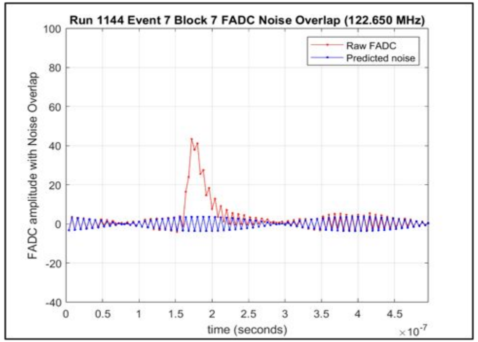
noise frequency 122.650 MHz

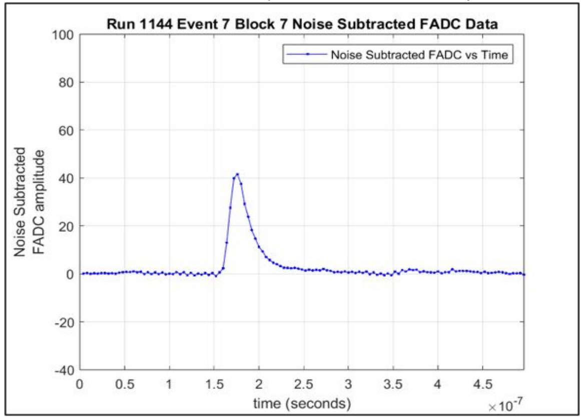
Sine function $A_0 = 0.180 P_{peak}^{0.5}$

Need zero crossing to find ∅

$$A_{noise} = A_0 \sin\left(2\pi f_{peak} t - \varnothing\right)$$





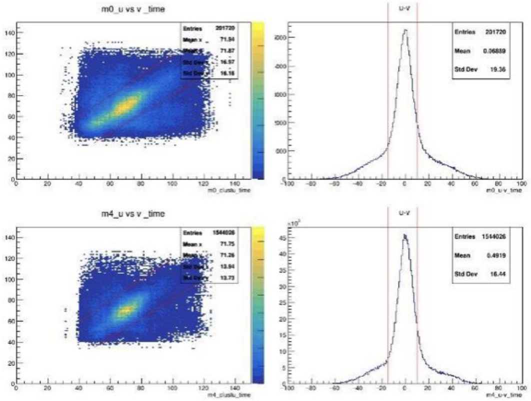


- Then used a local minimum finding algorithm with a minimum prominence cut of 1.8
- Currently use the first minimum that is found to set the zero crossing point: $\varnothing = 2\pi f_{peak} B_{min} dt$
- Results show 85% success rate at generating noise function for subtraction
- Next major step is to incorporate into SBS offline

Side GEMs and Hodoscope

Saru Dhital

- First two(top, bottom plots-Time Correlation plot between PR detector's layers
- 1D plots of U - V coordinate axis



➢ **Delta_t vs Geometrical mean of ADCs(left and right);**

From my plot on (right side first plot)- most event cluster around geometrical mean equal to 50-100 with delta_tnearly equal to zero. I can see here, spreadness of delta_t reduces slightly when geometrical mean increases.Here, it gives time walk slightly appears.

➢ **Delta_t vs Adc_ L plot**

I can see here spread of delta_t is wider when it has lower adc value. It means if we have lower adc-smallersignal ,the delta_t is larger- it is attenuation affect.

Delta_t vs Adc_R plot

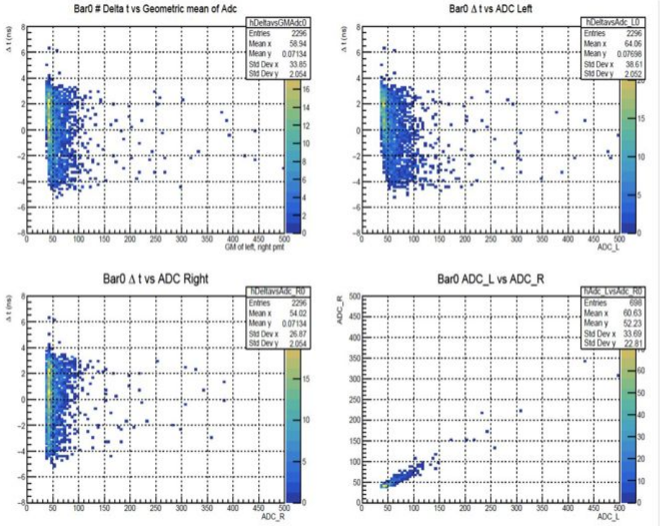
Similarly, delta_t is greater than 0 which is closer to right pmts, it means larger adc_R.it shows attenuation pattern.

Small signals which have large timing spread and large signal gives timing more stable.

Adc_L vs Adc_R

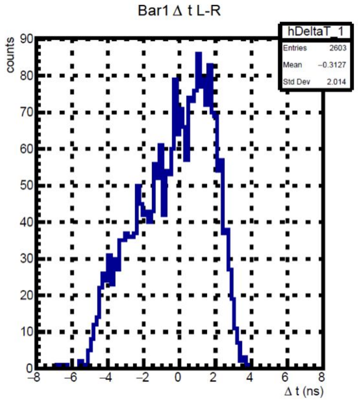
From the plot, I can say that the most points are along the bar where adc_L is nearly equal to adc_R.

Light detected in left and right PMTs is fairly symmetric.

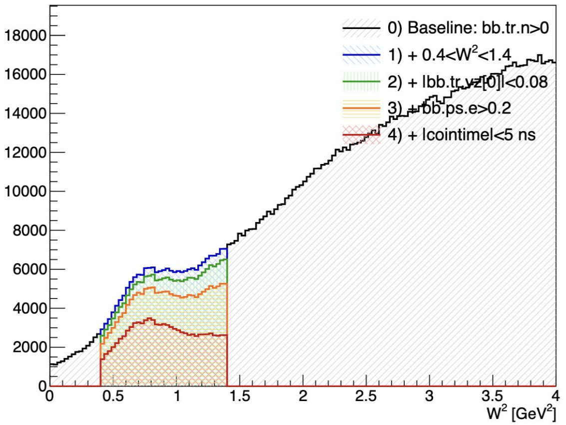


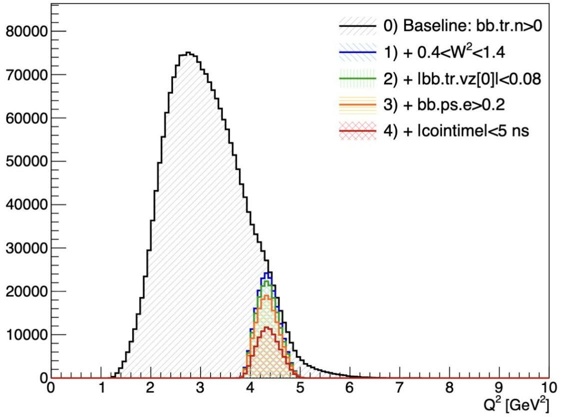
➢ **Delta_t plot:**

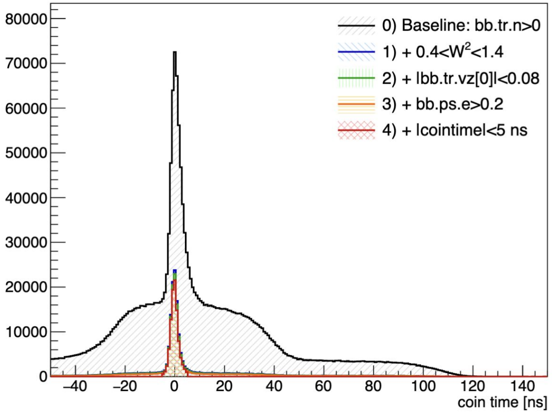
Time difference between two pmts(left and right pmts on a same bar)



Quasi-elastic Event Selection







- Track cuts: track chi^2/ndf, number of hits on a track for all trackers. Need at least one track on the BB side for the event to be useful in the analysis
- Target vertex: |vz|<0.08m for the track to be a physical track originating from the target
- Rejecting pions: ePS>0.2GeV
- Invariant Mass(W^2): select quasi-elastic events
- Coincidance time: reject accidentals
- And other cuts such as dx,dy cuts which are not shown in the plots here

These selection cuts to be to be optimised through systematic analysis

Next Steps

FF Ratio Extraction

Using a single average precession angle

$$F(\phi_n') = C\{1 \pm |P_x^*| \sin\phi_n' \pm |P_y^*| \cos\phi_n'\}$$

extracted from fits

$$P_x^* = A_y^{eff} P_e P_x$$

$$P_y^* = A_y^{eff} P_e P_z \sin\chi$$

$$\frac{P_x}{P_z} = \frac{1}{\sqrt{\tau + \tau(1+\tau)\tan^2\frac{\theta_e}{2}}} \cdot \frac{G_E}{G_M}$$

Using a maximum likelihood estimation method

$$\lambda_0^{(i)} \equiv a_1 \cos\phi_i + b_1 \sin\phi_i + a_2 \cos 2\phi_i + b_2 \sin 2\phi_i + \cdots$$

$$\lambda_x^{(i)} \equiv h\,\epsilon_i A_y^{(i)} S_{yx}^{(i)} \cos\phi_i - S_{xx}^{(i)} \sin\phi_i$$

$$\lambda_y^{(i)} \equiv A_y^{(i)} S_{yy}^{(i)} \cos\phi_i - S_{xy}^{(i)} \sin\phi_i$$

$$\lambda_z^{(i)} \equiv h\,\epsilon_i A_y^{(i)} S_{yz}^{(i)} \cos\phi_i - S_{xz}^{(i)} \sin\phi_i$$

Spin precession calculated for individual events

$$\sum_{i=1}^{N_{\text{event}}} \begin{pmatrix} \lambda_x^{(i)}(1-\lambda_0^{(i)}) \\ \lambda_y^{(i)}(1-\lambda_0^{(i)}) \\ \lambda_z^{(i)}(1-\lambda_0^{(i)}) \end{pmatrix} = \sum_{i=1}^{N_{\text{event}}} \begin{pmatrix} (\lambda_x^{(i)})^2 & \lambda_x^{(i)}\lambda_y^{(i)} & \lambda_x^{(i)}\lambda_z^{(i)} \\ \lambda_y^{(i)}\lambda_x^{(i)} & (\lambda_y^{(i)})^2 & \lambda_y^{(i)}\lambda_z^{(i)} \\ \lambda_z^{(i)}\lambda_x^{(i)} & \lambda_z^{(i)}\lambda_y^{(i)} & (\lambda_z^{(i)})^2 \end{pmatrix} \begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix}$$

Event matrix inversion

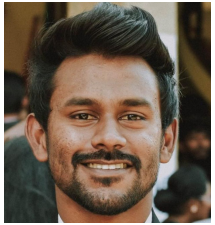
$$\frac{P_x}{P_z} = \frac{1}{\sqrt{\tau + \tau(1+\tau)\tan^2\frac{\theta_e}{2}}} \cdot \frac{G_E}{G_M}$$

More to be done

- Next cooking pass to be started
- More detector calibrations
- Looking at MOLLER measurements
- Beam line studies
- FF ratio extraction & polarization modulation through magnet
- Simulation and comparisons with data
- Corrections
- Proton studies
- etc.

People


Andrew Cheyne
(University of Glasgow)


Bhasitha Dharmasena
(University of Virginia)


Saru Dhital
(Hampton University)

Students


David Hamilton
(University of Glasgow)


Michael Kohl
(Hampton University)


Andrew Puckett
(University of Connecticut)


William Tireman
(Northern Michigan University)


Bogdan Wojtsekhowski
(Jefferson Lab)

Spokespeople


Jiwan Poudel
(Jefferson Lab)

Special Thanks

A huge thank to everyone involved and supported in every way!

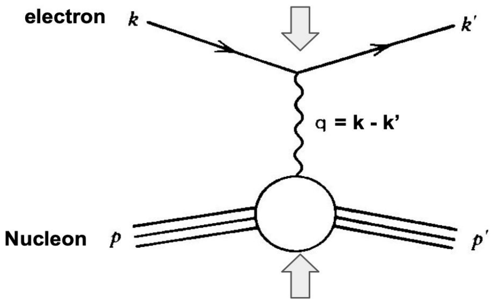
Thank You !

Backups

e-N Scattering and Form Factors

Scattering Amplitude : $i\mathcal{M} = \frac{-ig_{\mu\nu}}{q_\mu^2}[ie\bar{u}(k')\gamma^\nu u(k)][-ie\bar{v}(p')\Gamma^\mu(p',p)v(p)]$

$$j^\mu = -e\bar{u}_e(k')\gamma^\mu u_e(k)$$



$$J^\mu = e\,\bar{u}_p(p')\left[F_1(Q^2)\gamma^\mu + \frac{i\kappa}{2M}F_2(Q^2)\sigma^{\mu\nu}q_\nu\right]u_p(p')$$

- single photon approximation
- electron transition current is well known
- nucleon transition current is complex and unknown
- electron transition current can be parameterized using *Dirac* and *Pauli* Form Factors, $F_1(Q^2)$ and $F_2(Q^2)$

Nucleon Internal Structure Measurements

Magnetic Moment of a point-like spin ½ particle $\mu = \frac{qe'}{2e}\mu_N$

Theory Predicted → for a point-like proton $\rightarrow \mu_N = \frac{q}{m}|\vec{s}|$

for a point-like neutron $\rightarrow$ 0

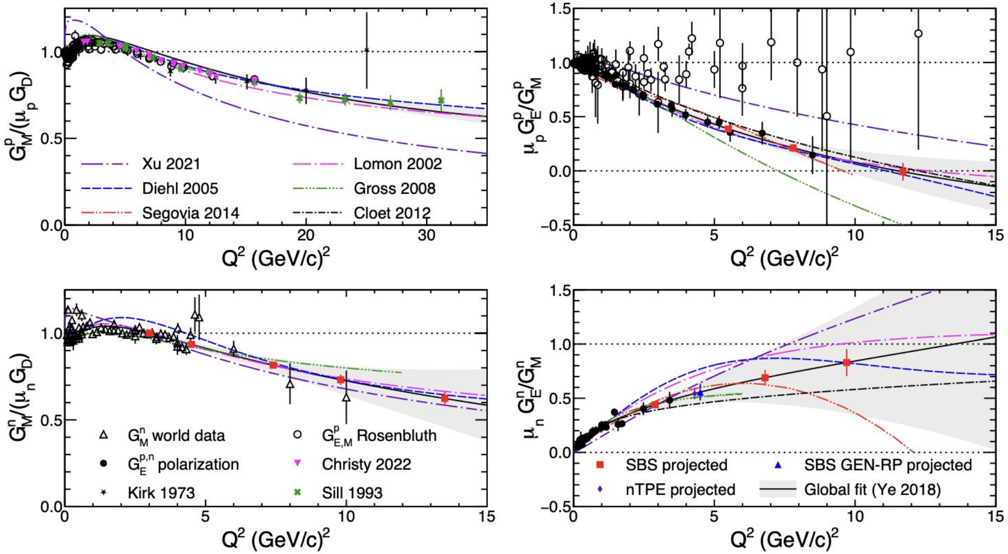
Experimental results suggested otherwise → for the proton $\rightarrow \mu = 2.79\mu_N$

for the neutron $\rightarrow \mu = -1.91\mu_N$

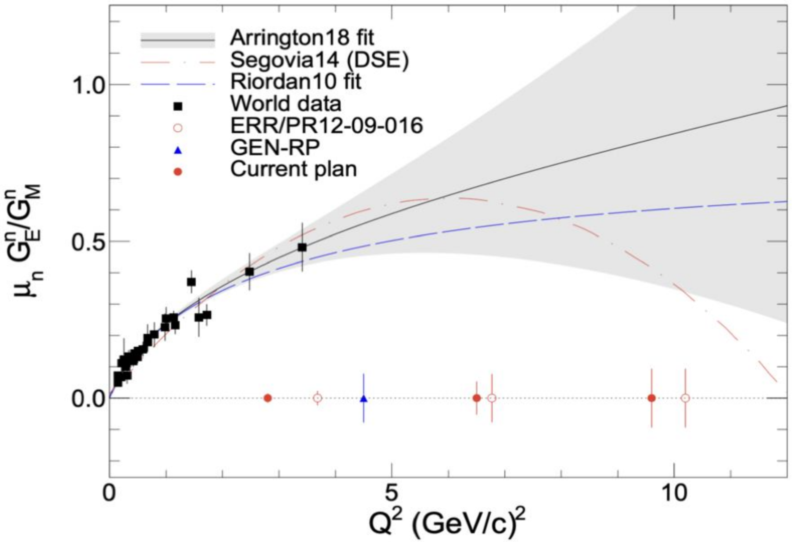
Proton and Neutron magnetic moment was first measure in 1933 and 1940 and provided the first evidence that the Proton and Neutron are not point-like particles

Super BigBite Spectrometer(SBS) Program at Jefferson Lab

Dipole Form Factor $$G_D(Q^2) = \frac{1}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}\ ;\ \Lambda = 0.71\ (GeV/c)^2$$



projection of SBS high Q^2 form factor data



global G^n_E (G^n_E/G^n_M) measurements

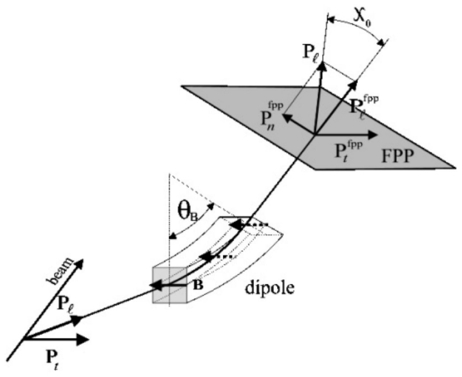
Using G_D we can,

- **Normalize to baseline behavior, making deviations from dipole behavior more visible**
- **Compare different FFs in the same scale**
- **Observe subtle differences as the curve falls sharply**

34

FF Extraction

- The polarization components can be extracted at the analyzers using the azimuthal distributions of the secondary scattering
- The transferred polarizations to the nucleons at the target can be obtained by reverse processing the spin precession using the known magnet optics
- Once the individual transferred polarizations at the target are obtained, the neutron's electromagnetic factor ratio can be obtained
- The already known magnetic G^n_M (from previous SBS experiments) can be used to obtain the G^n_E

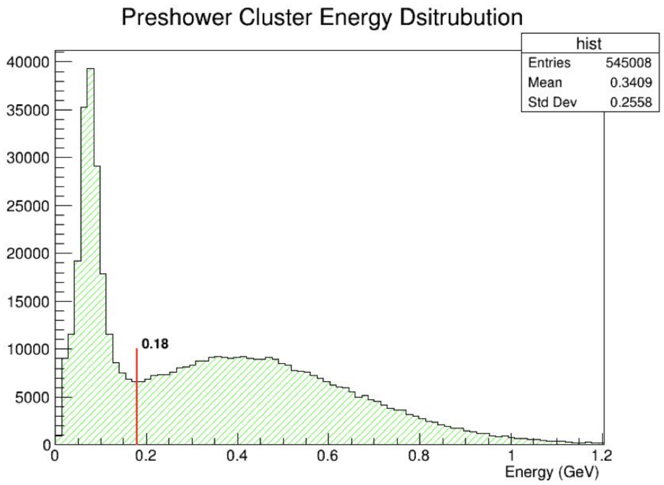


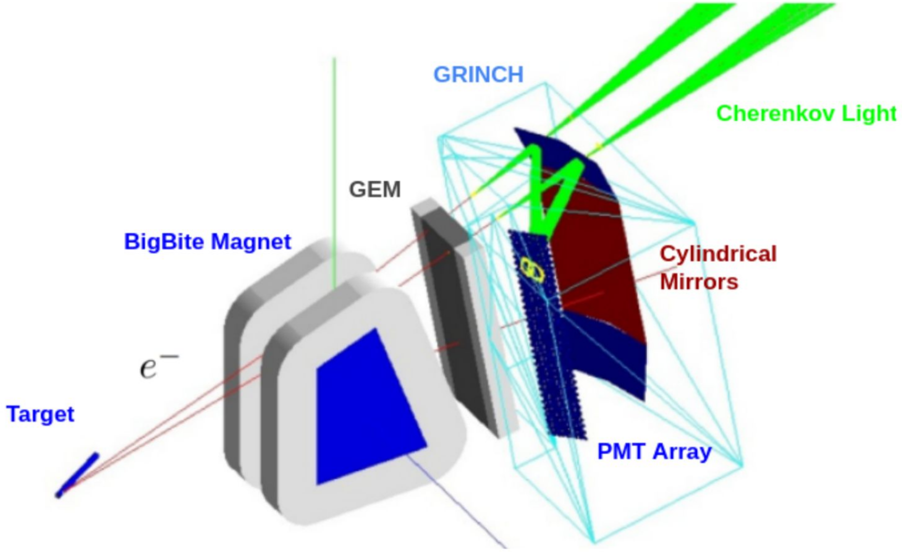
$$\chi = \frac{2\mu_n}{\hbar c}\frac{1}{\beta_n}\int_L \mathbf{B}.dl$$

BigBite Electron Arm

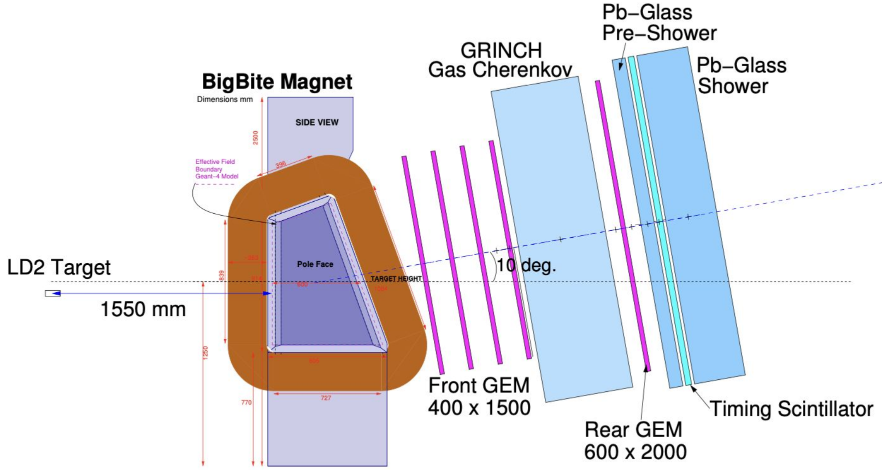
GRINCH gas cherenkov

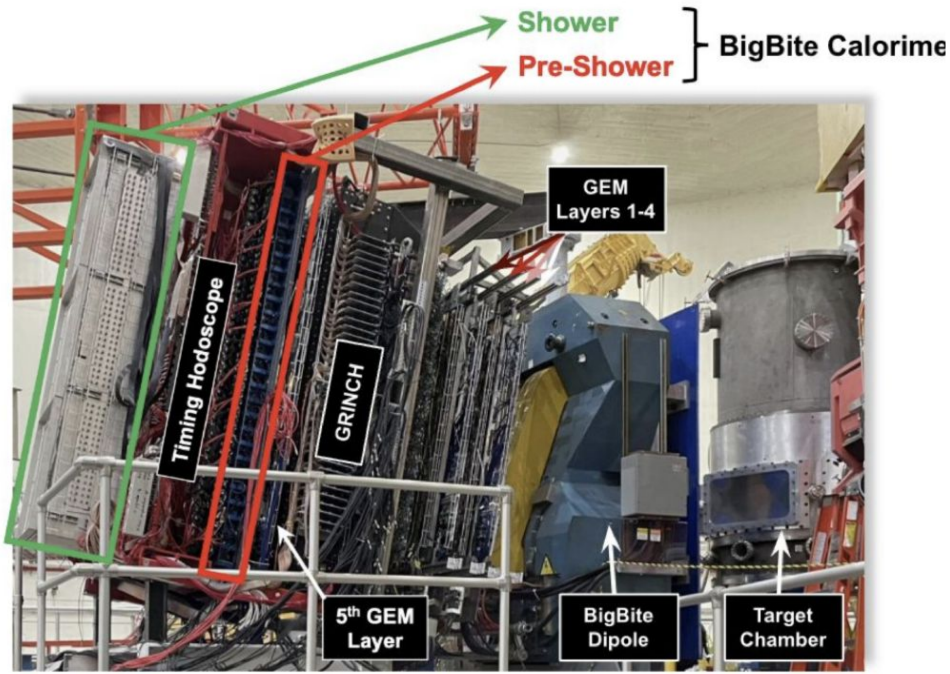
- used for particle identification
- separates electrons from pions
- electrons emit Cherenkov radiation and pions do not
- C_4F_8O heavy gas is used





BigBite Electron Arm

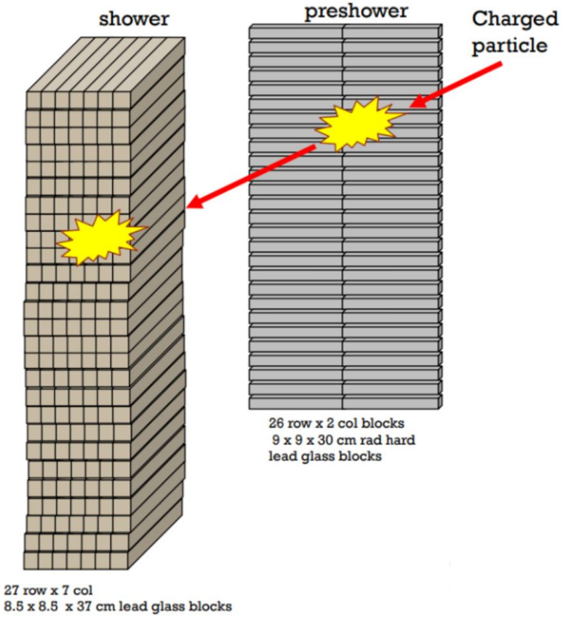




BigBite Electron Arm

Pb-Glass Calorimeter

- provides energy measurements for the electron arm
- tuned for elastically scattered electrons
- additional correlations between shower and pre-shower to distinguish electrons from pions



GEMs config

- resolutions of each of the detectors

  SBS Magnet: 2.0 - 2.5 Tm field strength

  HCAL: a time resolution of 0.5 ns RMS, and an angular resolution of 5 mrad

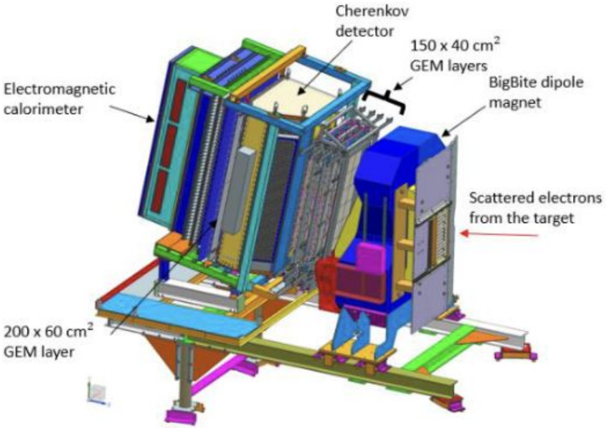
  GEMs: For tracking it achieved 70 µm position resolution and a momentum resolution of $\sigma_p/p \sim 1.5\%$

  BBCAL: energy resolution of~6% and timing resolution of 2.5 ns

  Hodoscope: a position resolution of 4-6 cm in the non-dispersive (horizontal) and 1.5-2 cm in the dispersive (vertical) directions, and time resolution of 500-750 ps have been observed.

Tracking Detectors

GEMs in GEn-RP Experiment



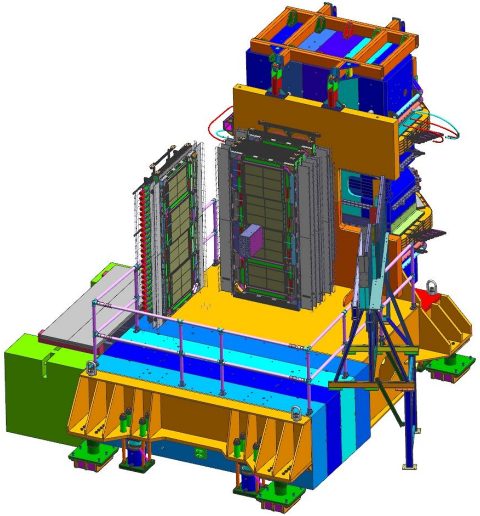
bigbite detector assembly

BigBite Spectrometer (electron arm)

- 4 UV layers (single UV module per layer)
- 1 XY layer (4 XY modules per layer)
- ~ 42,000 total data channels

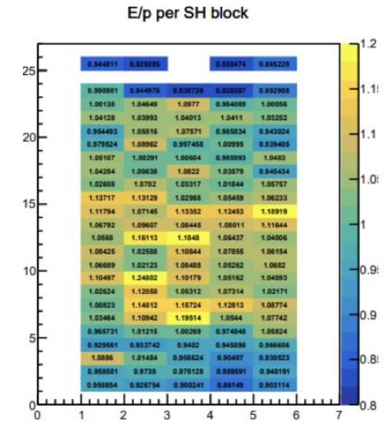
Super BigBite Spectrometer (Hadron arm)

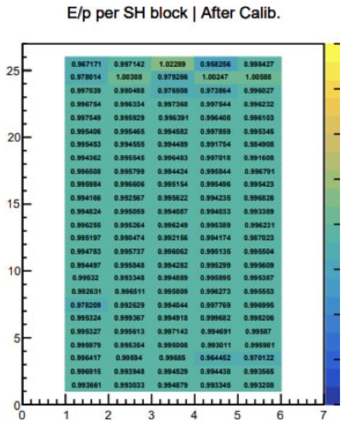
- 2 XW layers (single XW module per layer)
- 8 XY layers (4 XY modules per layer)
- ~ 105,000 total data channels

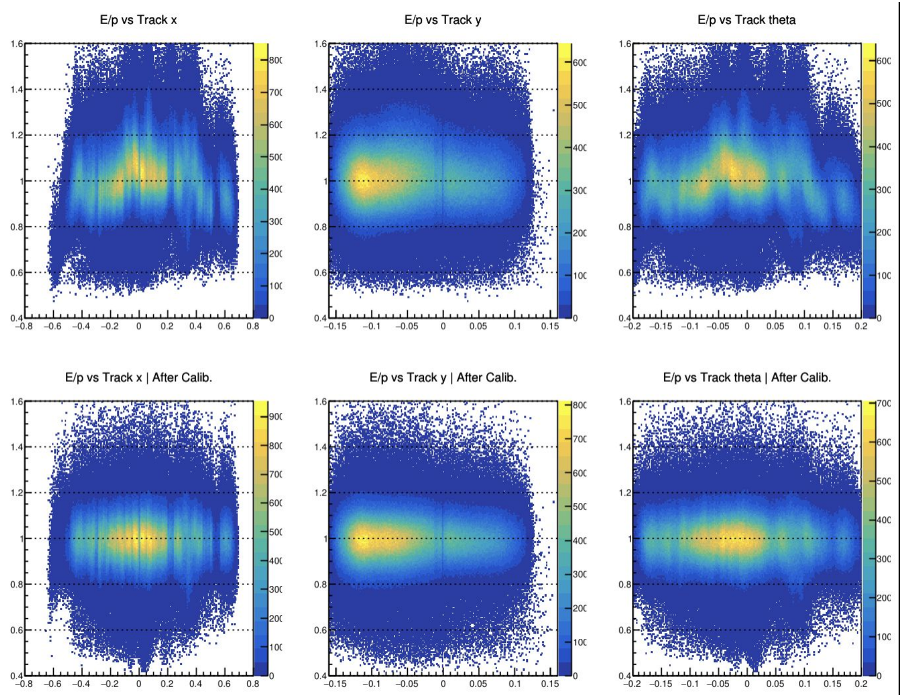


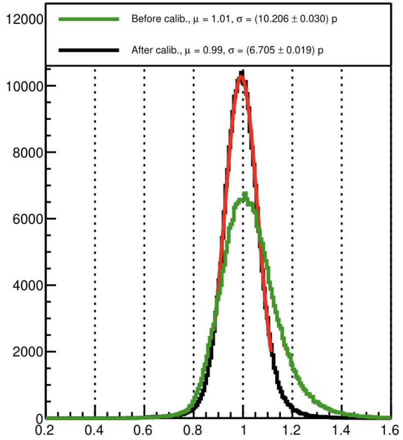
super bigbite detector assembly

BBCal Energy Calibrations









E/p resolution improvement
10.2 → 6.7

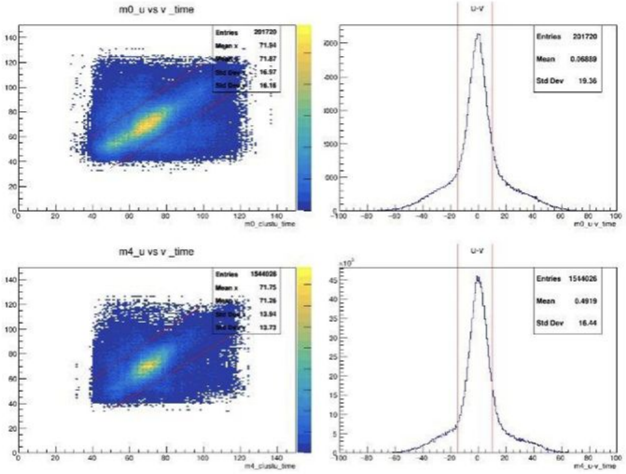
Credits to Provakar and Kate for BBCal calibration scripts and documentation and to Andrew Cheyne for the work on GEnRP data

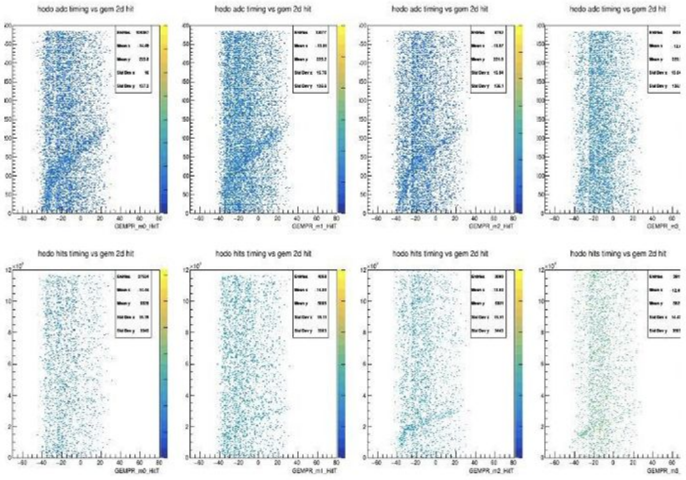
Side GEMs and Hodoscope

Saru Dhital

- First two(top, bottom plots-Time Correlation plot between PR detector's layers
- 1D plots of U - V coordinate axis

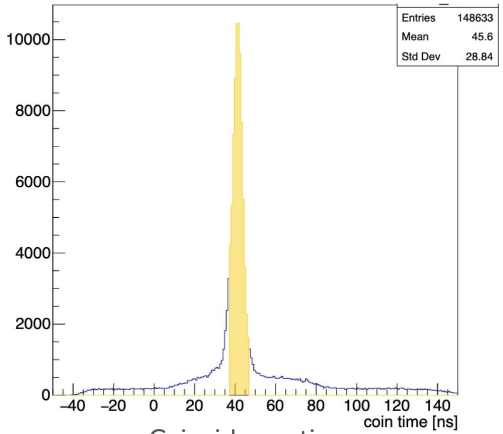
- Top 4 plots-Time Correlation plot between PRdetectors(PRhodscope , PRGEMs) in terms of adc.
- Bottom 4 plots-Time Correlation plot between PRdetectors(PRhodscope , PRGEMs) in terms of adc



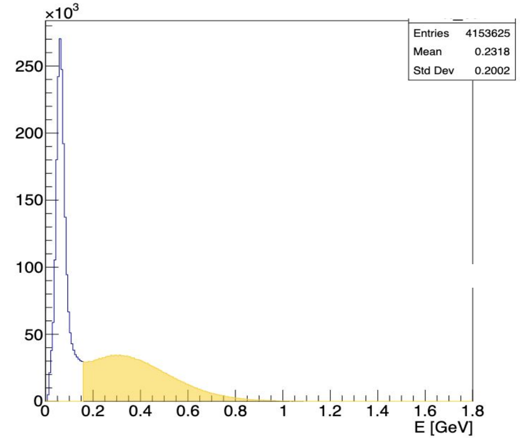


Event Selection

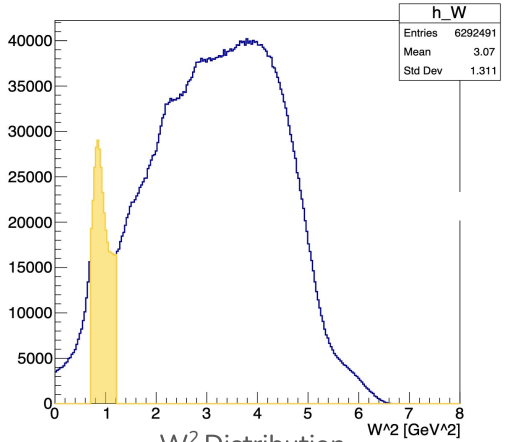
- Preshower Energy: particle identification
  Min: 0.18 to reject pions
- Invariant Mass^2 (W^2): quasi-elastic events
  $\sim 0.76\ \text{GeV}^2 < W^2 < \sim 1.0\ \text{GeV}^2$
- Track vertex:
  $-0.08 <$ Z coordinate < 0.08
- More track quality cuts:
  number of hits on GEMs, track χ^2 etc



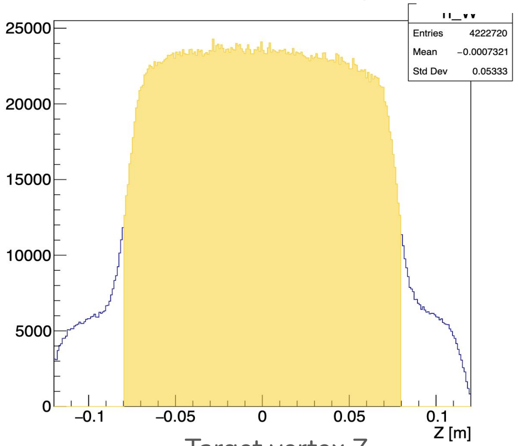
Coincidence time



Preshower energy



W^2 Distribution



Target vertex Z

SBS Collaboration

* Not everyone is in these pictures

Photo credits: Jefferson Lab