Measurement of the Contribution of Two Photon Exchange to the Electron-Neutron Elastic Scattering Cross Section (nTPE) Using the Super Bigbite Spectrometer

Sebastian Seeds for the SBS Collaboration - 6.17.22

Abstract

In the Born approximation, one photon exchange (OPE) is expected to dominate e-p and e-n scattering. Using the Rosenbluth technique to separate Sachs form factors, we can extract nucleon cross sections at different values of the virtual photon polarization. With these data, the relative contribution of two photon exchange (TPE) to e-n scattering can be obtained.

The discrepancy between elastic scattering measurements which determine form factors using nucleon polarization transfer and the Rosenbluth method seem to show a large contribution of two photon exchange to e-n scattering. At Jefferson National Laboratory during the Fall and Winter of 2021/2022 we collected precision data on the magnetic form factor of the neutron (GMn) at two kinematic points with the same Q^2 (4.5 GeV^2), but different virtual photon polarizations, to extract nTPE with good precision. Here, we give a description of the setup, experimental technique, and projected results for experiment **E12-20-010** nTPE.

Theory and Background

Rosenbluth Slope (RS) and the Rosenbluth Technique

The principle measurement of nTPE is the elastic electron-neutron cross section. Generally, the nucleon cross section can be parameterized in terms of a point-like Mott term and a second term that encodes electric and magnetic distributions of the nucleon containing the Sachs form factors (FF) G_E and G_M.

$$\left(\frac{d\sigma}{d\Omega}\right)_{eN\to eN} = \frac{\sigma_{Mott}}{\epsilon(1+\tau)}\left[\tau G_M^2(Q^2) + \epsilon G_E^2(Q^2)\right]$$

$$\sigma_r = \frac{d\sigma}{d\Omega}\frac{\epsilon(1+\tau)}{\sigma_{Mott}} = \tau G_M^2(Q^2) + \epsilon G_E^2(Q^2)$$

$$\sigma_r = \sigma_T + \epsilon\,\sigma_L$$

Where

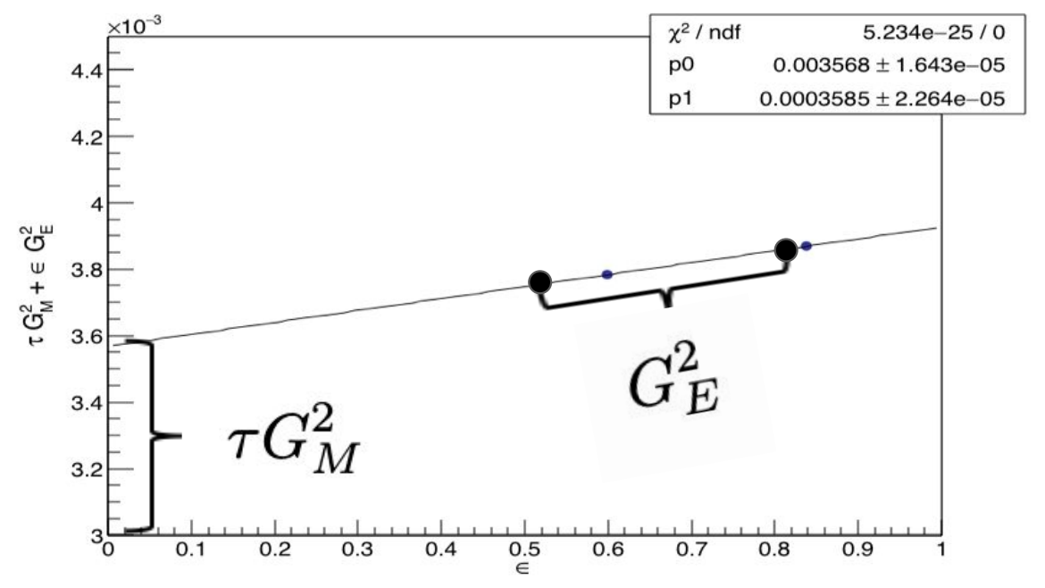
$$\epsilon = 1/\left(1 + 2\left(1 + \frac{Q^2}{4M_n}\right)\tan^2(\theta/2)\right)$$

$$\tau \equiv -q^2/4M^2$$

And RS or S^n is:

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

- In the Born approximation (assuming one virtual photon exchange, **OPE**) the Sachs form factors G_M and G_E can be separated.
- With some further reparameterization in terms of the reduced cross section σ_r, the equation can be written with experimental observables.
- The FF can be extracted from y-intercept and slope of the reduced cross section at different virtual photon polarizations (ε) where the measured reduced cross section ($\tau G_M^2 + \epsilon G_E^2$) is *linear in ε*
- Obtain neutron RS (**S^n**) for neutron at our kinematics with measurements at different ε
  - Note that by holding Q^2 fixed, we vary ε by changing the electron-arm deflection angle θ
- Discrepancy between recoil polarimetry result and Rosenbluth technique result can be explained by two-photon-exchange (**TPE)**



Measurement Technique and Theoretical Impact

- SBS8 and SBS9 provide the two measurements of ε
- Will measure ε via ratio method for simultaneous measurement of *d(e,e'n)* and *d(e,e'p)* (Durand technique) reducing systematic uncertainties.
  - Systematics canceled: nucleon momentum/binding
  - Systematics partially canceled: inelastic e-n contamination and nucleon charge exchange on final state interactions
  - *A* is the experimental observable
  - *B* is known from world data
- At Q^2 = 4.5 GeV^2, RS for proton is known from world data:
  - S^p = 0.087 ± 0.01

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

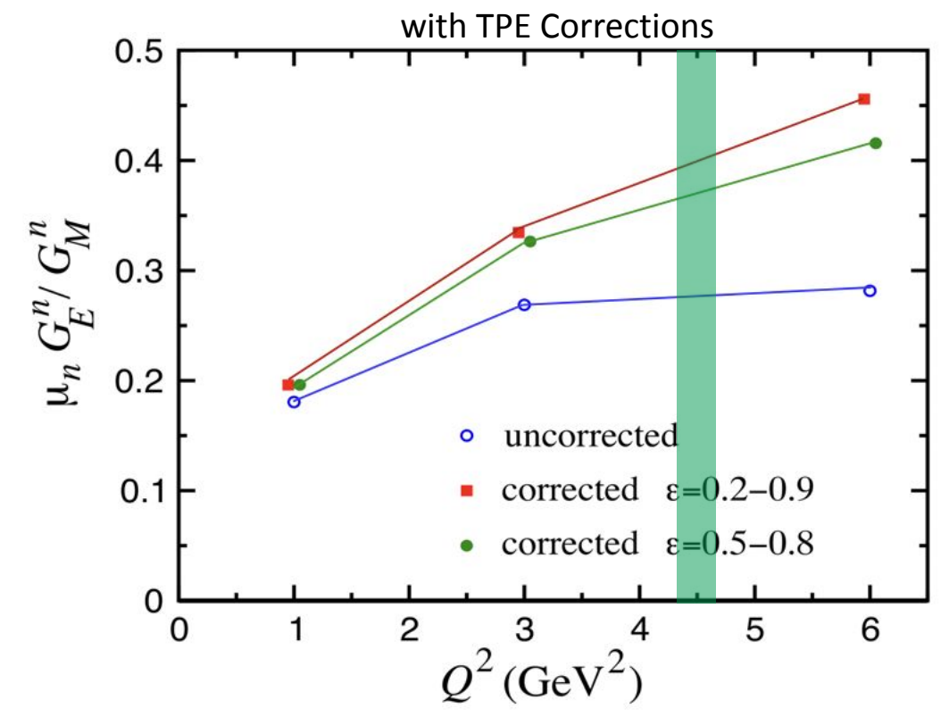
$$B = \frac{1+\epsilon_2 S^p}{1+\epsilon_1 S^p};\quad S^p \quad known$$

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

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

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

S^n Theoretical Projections with TPE Corrections



With **this work**, we will be able to distinguish between TPE corrections from theoretical models which include radiative corrections which will have broader implications on global parton distributions (GPDs), where the Sachs FF are parameterizations of the Dirac (F_1) and Pauli (F_2) FF which are in turn the first moments of GPDs. (κ is the magnetic moment of the nucleon)

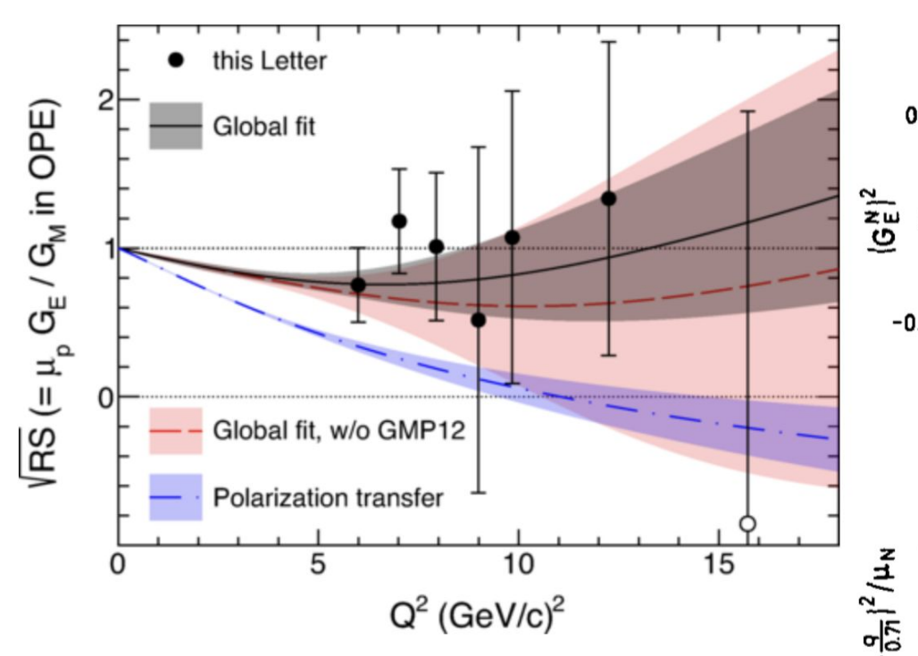
$$F_1 = \frac{G_E + \tau G_M}{1+\tau} \quad ; \quad F_2 = \frac{G_M - G_E}{\kappa(1+\tau)}$$

$$\boxed{\begin{aligned} F_1(t) &= \sum_q \int_0^1 H^q(x,\xi,t,\mu)dx \\ F_2(t) &= \sum_q \int_0^1 E^q(x,\xi,t,\mu)dx \end{aligned}}$$

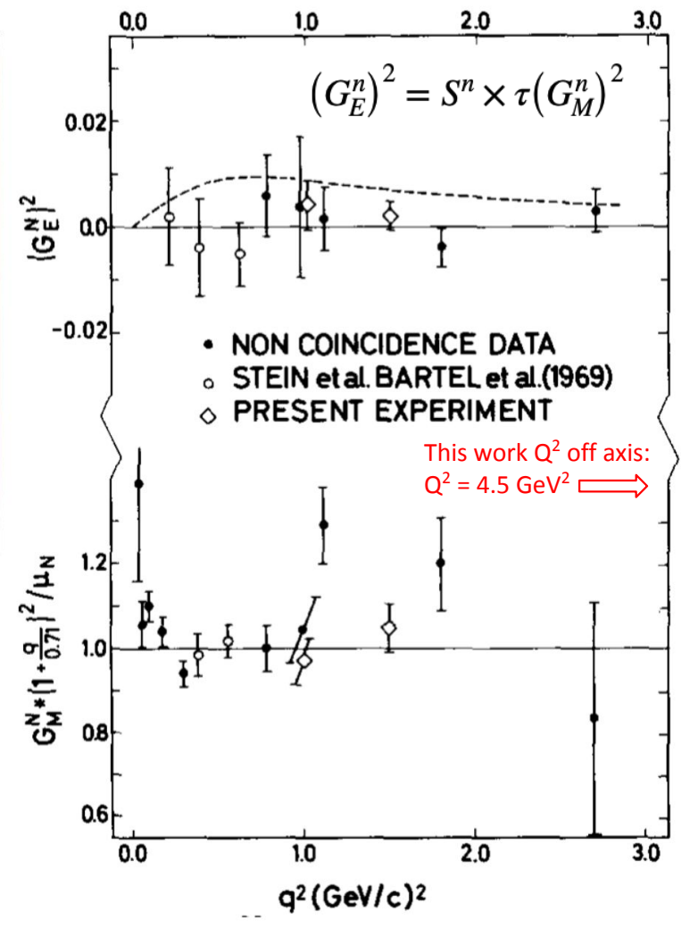
The Form Factor Ratio Puzzle (FFRP)

- From electron-proton (e-p) scattering experiments, there is a large discrepancy between rosenbluth slope as measured with the **Rosenbluth technique** and **polarization transfer** methods.
  - Theoretical models which include radiative corrections reduce the discrepancy, but do not eliminate it.
  - Where TPE explains the discrepancy, a measurement of the discrepancy is a measurement of TPE
- World data for e-n scattering are very sparse and this discrepancy has not been precisely measured beyond Q^2 = 2.0 GeV^2, indeed the TPE contribution has *never* been measured
  - We measured electron-neutron cross sections with different ε at Q^2 = 4.5 GeV^2 for nTPE, sufficient to extract **S^n** and to address the neutron FFRP *for the first time in more than 50 years.*

RS Data - Proton

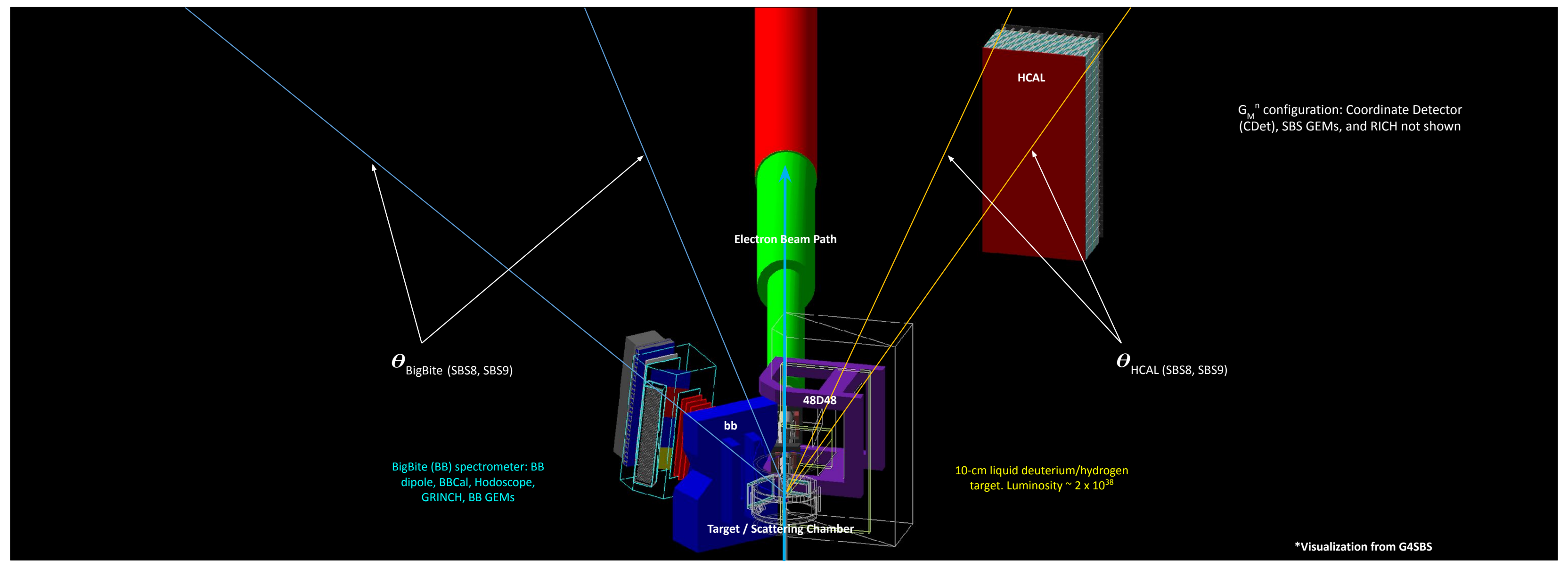


Sachs FF Data - Neutron



Kinematics and Projected Uncertainty

In order to measure nTPE, detailed measurements of the momentum, energy, and position of outgoing electrons and hadrons resulting from quasi-elastic *d(e,e'n)* and *d(e,e'p)* collisions at a single Q^2 (4.5 GeV^2) will be taken. Two main spectrometers are deployed for this task - the hadronic calorimeter (HCAL) to measure scattered protons and neutrons and the BigBite (bb) Spectrometer to measure scattered electrons. With Q^2 fixed, the two positions of the spectrometers allow us to maximize yield at two values of the virtual photon polarization ***ε***.



*Visualization from G4SBS

- The 48D48 dipole $\left(1\,[\mathbf{Tm}] < \int \mathbf{B}_{48D48}\,dl < 2\,[\mathbf{Tm}]\right)$ magnet enables separation of protons and neutrons at **HCAL** so the data can be evaluated for each separately.
- The **bb** magnet enables momentum reconstruction and general particle identification (PID) and is an integral part of the **bb** spectrometer.
- While the main trigger for nTPE is from the BigBite spectrometer, both **bb** and **HCAL** will be used together with a coincidence trigger to select only detection events in the spectrometers which come from collisions originating from the target.

We expect **S^n = 0.063 ± 0.010 (stat) ± 0.012 (syst)**

Kin	Q^2 (GeV/c)^2	E (GeV)	E' (GeV)	θ_{BB} (deg)	θ_{SBS} (deg)	**ε**
SBS9	4.5	4.03	1.63	49	22	0.523
SBS8	4.5	5.97	3.59	26.5	29.4	0.804

Systematic Uncertainty

ε	0.599	0.838
Acceptance	0.5%	0.4%
Inelastic contamination	0.9%	0.6%
Nucleon misidentification	0.6%	
Syst. uncertainty on (quadratic sum of the above)	1.3%	1.0%

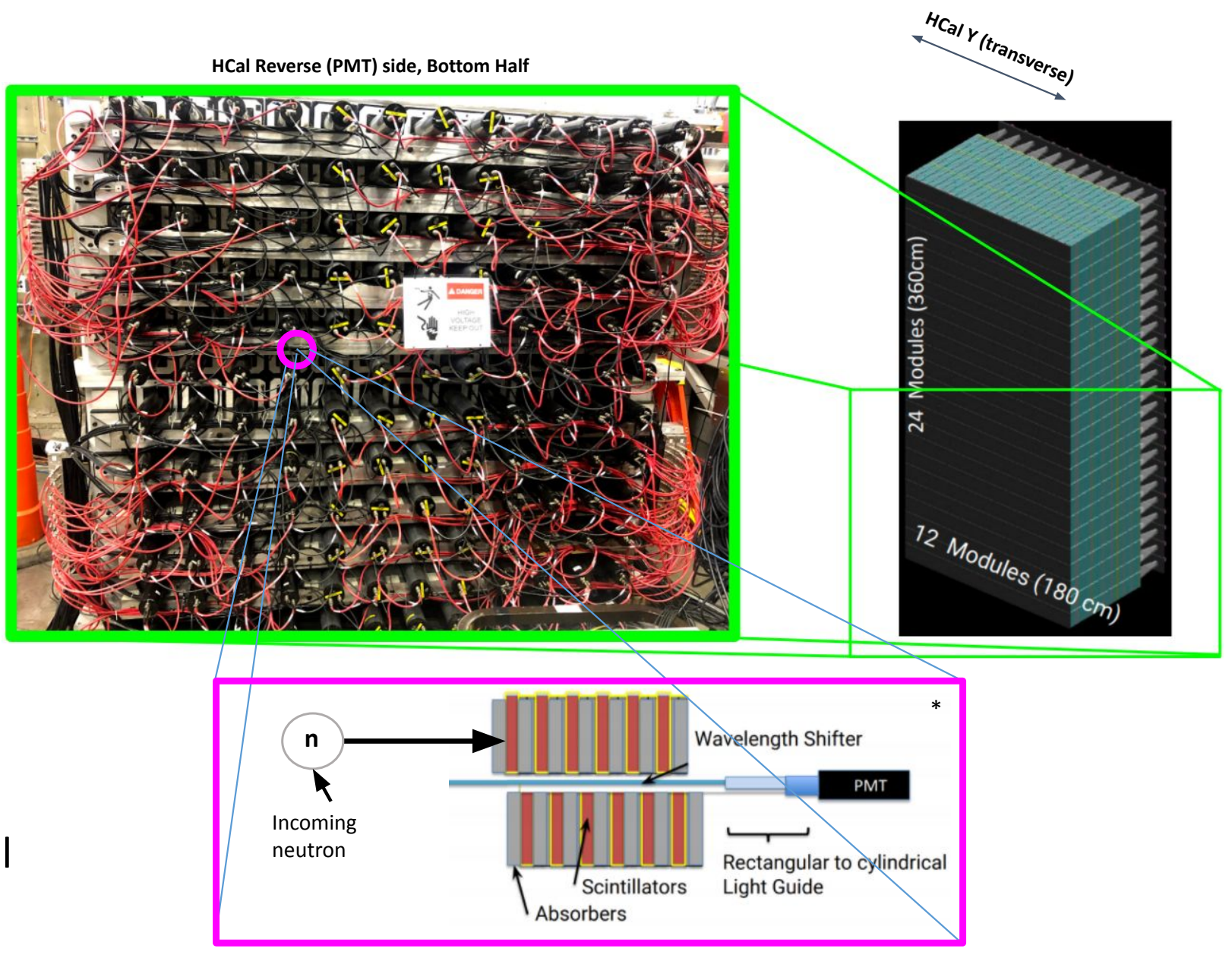
Syst. uncertainty on slope	±0.01
Projected systematic uncertainty	±0.01
$\mu_n G_E^n/G_M^n = 0.55$, Eur. Phys. J. A51, 19 (2015)	±0.05
Combined uncertainty on TPE contribution to S^n	**± 0.012**

Hadron arm - HCal

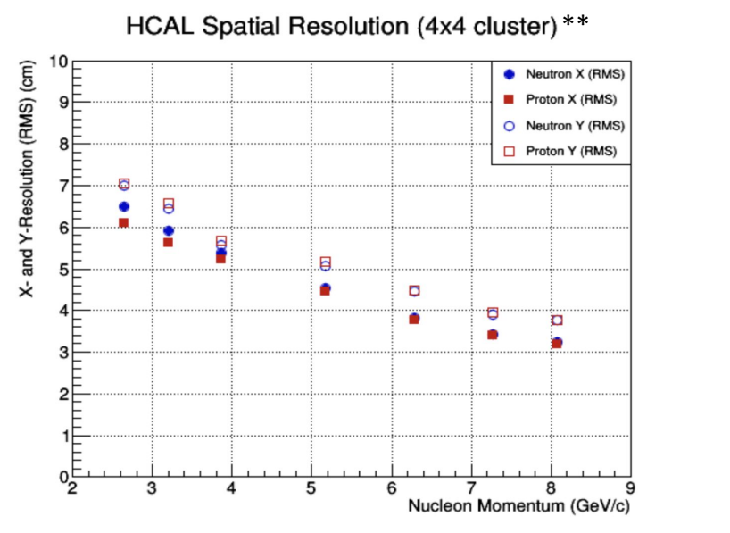
The **40-ton** hadronic calorimeter is located on beam reight and will measure energies, position, and timing of scattered hadrons (protons and neutrons) for nTPE and all SBS experiments. Along with the 48D48 dipole (to bend protons in the dispersive direction), HCal is the hadron arm.

- HCal consists of **288 modules** whose signals are read out via flash analog to digital converters (fADCs) and multi-hit time to digital converters (F1TDCs)
- A single module consists of stacked scintillator and iron coupled to a wavelength shifter which is then coupled to Photonis XP2262 and XP2282 photomultiplier tubes (PMTs)
- Each module reads out to a single fADC and F1TDC channel for analysis
- **Precise position resolution is necessary for proton and neutron cross section calculations**
- Simulated position resolution (**these data**):
  - p_n = 2.5 GeV ⟹ 6 - 7 cm
  - p_n = 8 GeV ⟹ 3 - 4 cm
  - **p_n = 2.9 GeV ⟹ 5.5 - 6.5 cm**
- **Precise detection uniformity over HCal also necessary**
  - p_n = 8 GeV ⟹ N/P eff ≈ 0.985
  - **p_n = 2.9 GeV ⟹ N/P eff ≈ 0.966**
- Simulated timing resolution: **0.5 ns**

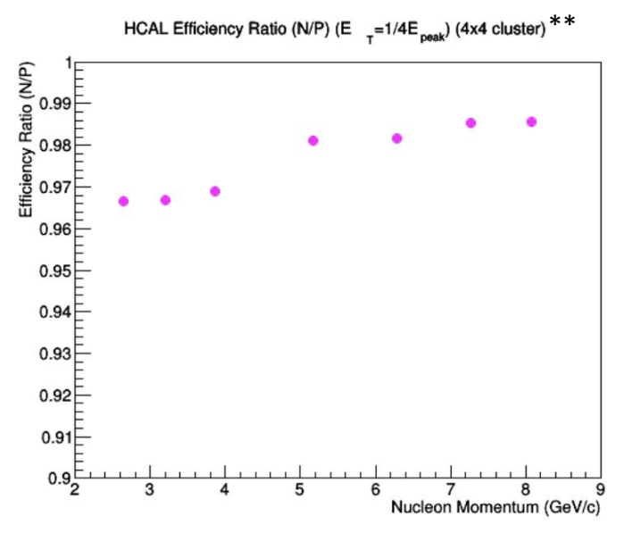
HCal Reverse (PMT) side, Bottom Half



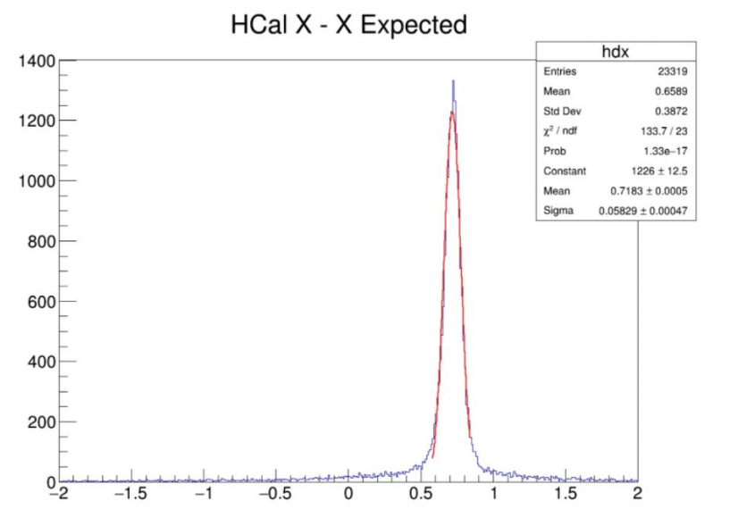
HCAL Spatial Resolution (4x4 cluster)**



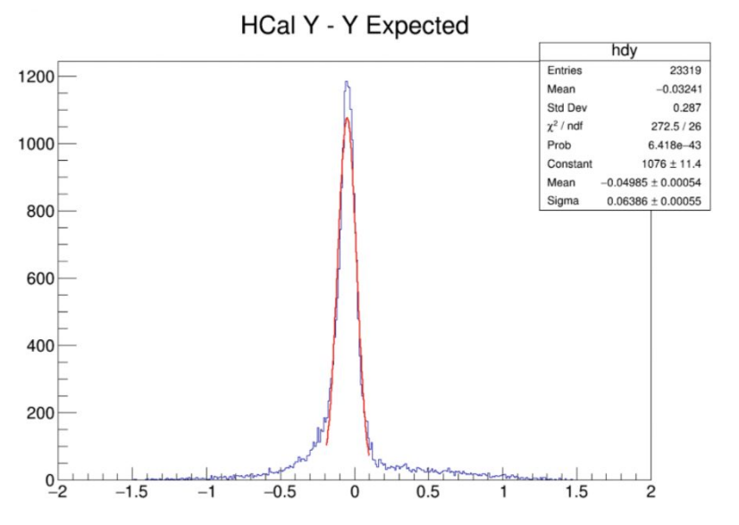
HCAL Efficiency Ratio (N/P) (E_T=1/4E_{peak}) (4x4 cluster)**

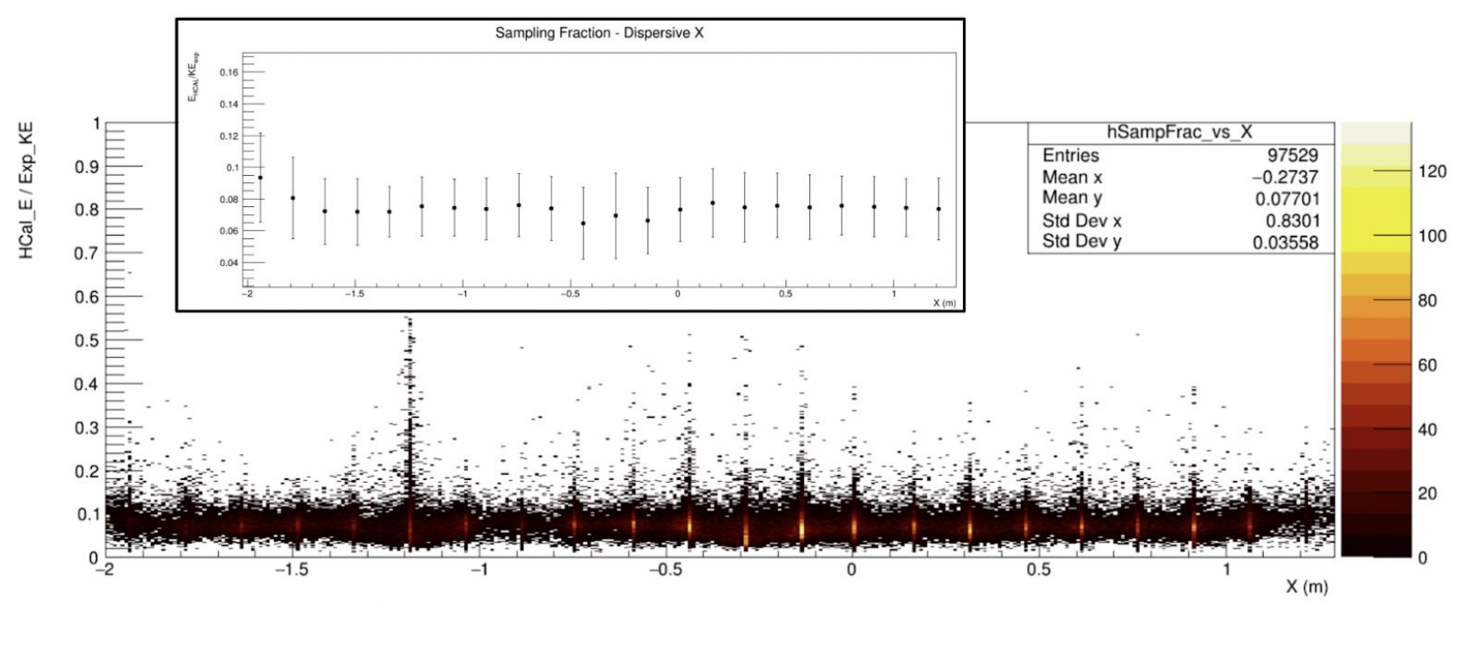


HCal X - X Expected



HCal Y - Y Expected





From the BigBite spectrometer, reconstructed electron tracks provide a q vector for reconstructed projection of scattered hadrons to the face of HCal. By comparing these projections to the energy-weighted center of hadronic shower clusters for each triggered event, HCal position resolution is obtained.

- Preliminary position resolution:
  - **p_n = 2.9 GeV**
    - **HCal X (dispersive direction)** ⟹ **5.8 cm**
    - **HCal Y (transverse direction)** ⟹ **6.3 cm**
- **Sufficient position resolution achieved for nTPE**

Detection uniformity can be estimated with a measurement of the *sampling fraction* for HCal. During hadronic showers in each module, only a fraction of the energy is transduced to signal (we expect from simulation **6.6%**). Protons and neutrons are biased to different ends of HCal in the dispersive direction, so uniformity of this measure is an indicator of detection uniformity.

- Sampling Fraction:
  - (HCal Cluster Energy) / (Expected Hadron Kinetic Energy reconstructed from BigBite)
- Preliminary detection uniformity:
  - **Within 2-3% (consistent with simulations)**

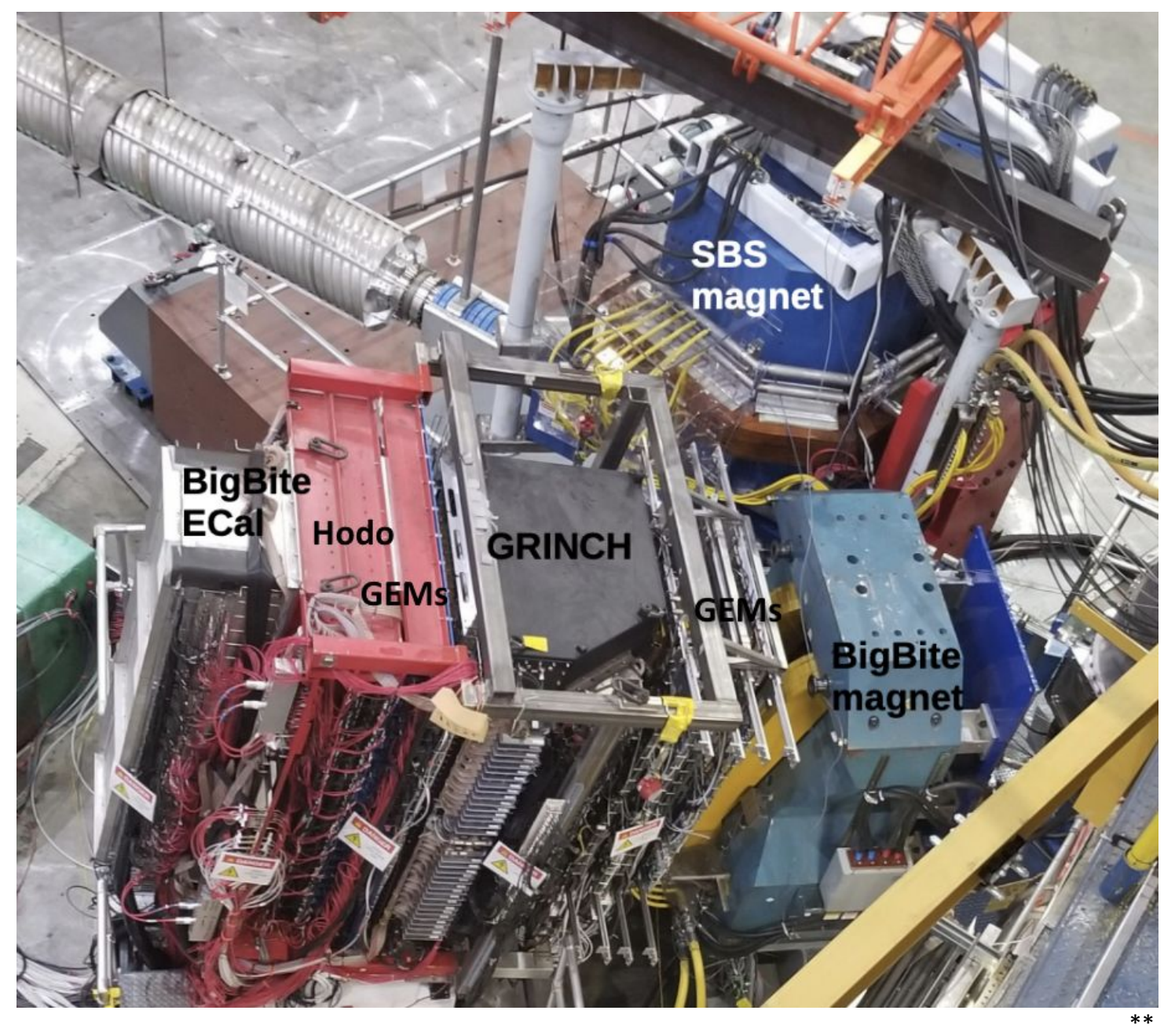
Updated figures will be available following first pass cooking of the GMn data set.

*Figure: Scott Barcus **Plot: Juan Carlos Cornejo

Electron Arm - BigBite Spectrometer

The BigBite spectrometer is capable of precision position and momentum reconstruction of scattered electrons. Many subsystems make it up:

- **The bb dipole magnet:** Creates bend angle dependent on momenta of charged scattered particles. Used for momentum reconstruction and pion rejection. Field strength
- **4 planes of Gas Electron Multipliers (GEM):** Used for high precision electron track reconstruction.
- **Gas Ring Imaging Cherenkov (GRINCH) detector:** Used for particle identification (not fully implemented for nTPE).
- **Fifth GEM plane:** Used with the first four GEM planes for precision track reconstruction.
- **BBCal PreShower Calorimeter:** Used for pion rejection and part of main trigger.
- **Timing Hodoscope:** Used for precision track timing measurements.
- **BBCal Shower Calorimeter:** Used for energy reconstruction and part of main trigger.



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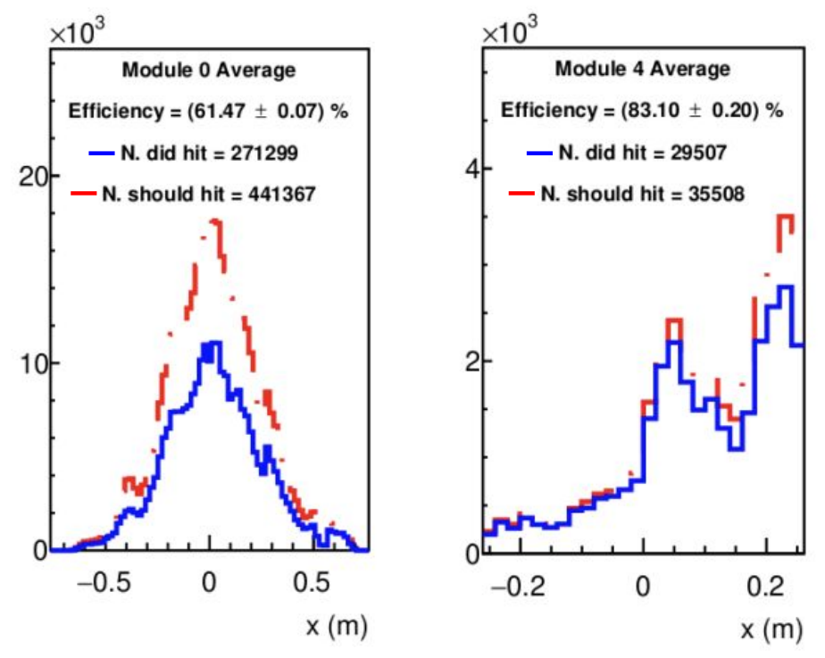
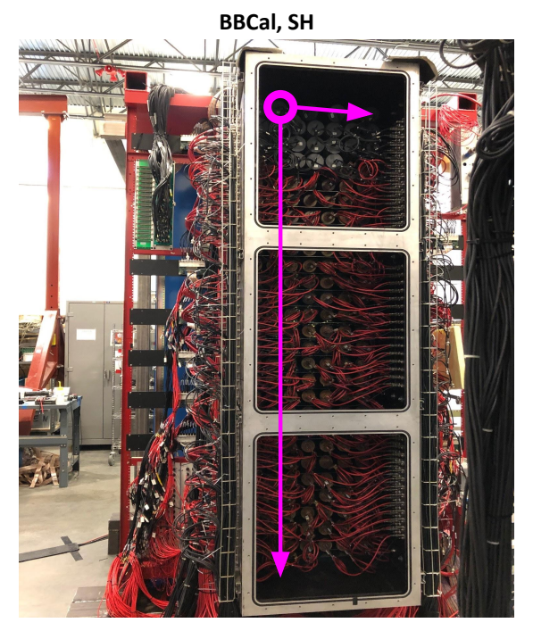
GEMs: nTPE requires quasielastic selection and precision tracking of electrons through the BigBite arm of the detector. This function allows for the precise determination of quasielastic protons and neutrons in HCal and is integral to the calculation of cross sections.

- To meet the high rates expected, traditional wire chambers are replaced with GEMs
  - Via COMPASS results, GEMs are capable at **25 kHz/mm²** (in-beam performance for this work still under investigation)
- Expected position resolution 70 μm.
- With digitized monte-carlo data (via G4SBS) tracking efficiency with current algorithms **60-80%**



BBCal, SH



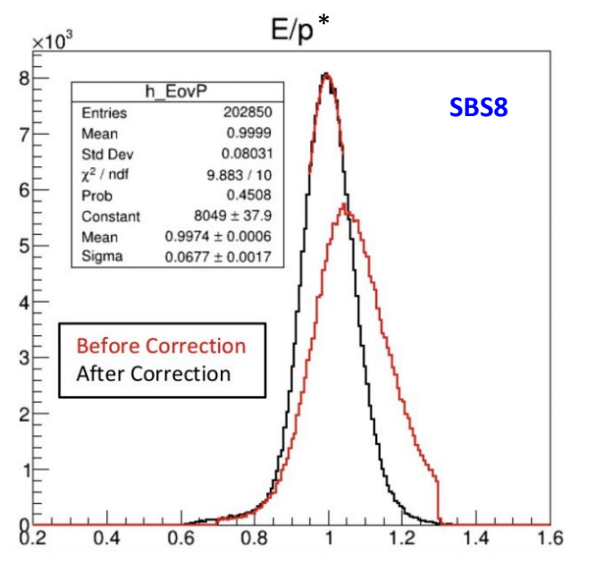
BBCal preShower (PS) and shower (SH) calorimeters: Designed to detect electrons, these are made of lead-glass blocks, each of which is coupled to a photomultiplier tube (PMT). Sums over these blocks past threshold constitutes the main trigger for the experiment.

- **PS** has **52** blocks (not shown), stacked in 26 rows x 2 columns grid with their long dimension perpendicular to the beam.
- **SH** has **189 blocks**, stacked in 27 rows x 7 columns grid with their long dimension along the beam.
- Via selection of low energy events in the PS, PID and consequent pion rejection is possible in analysis.

Calibration of PS and SH In-Beam with Fringe-Field Effects

- Due to the strong magnetic field produced by the 48D48 dipole magnet, the fringe field affects the performance of BBCal PMTs. As a result, calibration of BBCal before running at each kinematic was necessary
- Precise calibration of BBCal removes position bias from the main trigger

E/p*



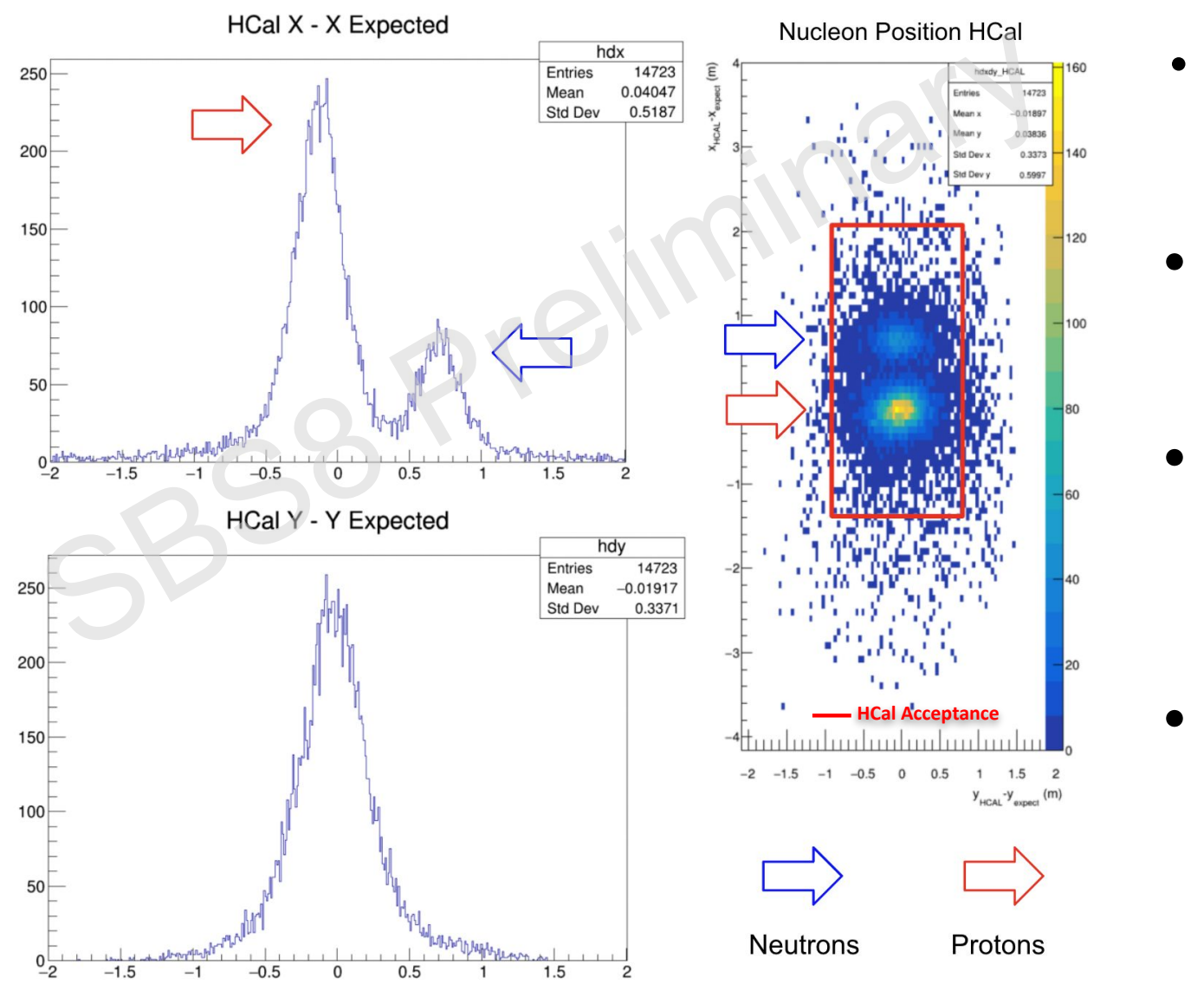
An energy over momentum plot demonstrates the calibration of BBCal where energy is determined from the calorimeter response and momentum is from BigBite tracking. At these Q^2, the mass of the electron is negligible and this distribution should be centered at E/p =1.

Timing Hodoscope: The timing hodoscope is designed to provide precision timing for nucleon time of flight corrections.

- With accelerator RF corrections, **timing resolution of 200 ps** is expected (in-beam performance for this work still under investigation).

*Plot: Provakar Datta **Picture: Eric Fuchey

State of Analysis and Future Work



- Target statistics were met for both Q^2 points during the GMn run period SBS8 and SBS9 January-February 2022.
  - Quasielastic yield: est. **340k (SBS9)**, est. **700k (SBS8)**
- From these data, we see clear separation of proton and neutron peaks and can extract cross sections (cartoon on left - nTPE results forthcoming!).
- First wave of calibrations are complete - we are now waiting for an unprecedented **2 petabytes** of data (five times more data than all previous Hall A experiments combined!) to be cooked.
- GEN-rp, which will run in January of 2023, will provide a measurement of **S^n** using double polarization for direct comparison to nTPE at Q^2 = 4.5 GeV^2. The comparison will further clarify the role of TPE in e-n scattering.

References

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