

Measurement of the Neutron Elastic Electromagnetic form factor ratio G_E^n/G_M^n at Large Momentum Transfer (GEn-II Experiment)

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ON BEHALF OF SBS AND GEN-II COLLABORATION
JUNE 18TH , 2025



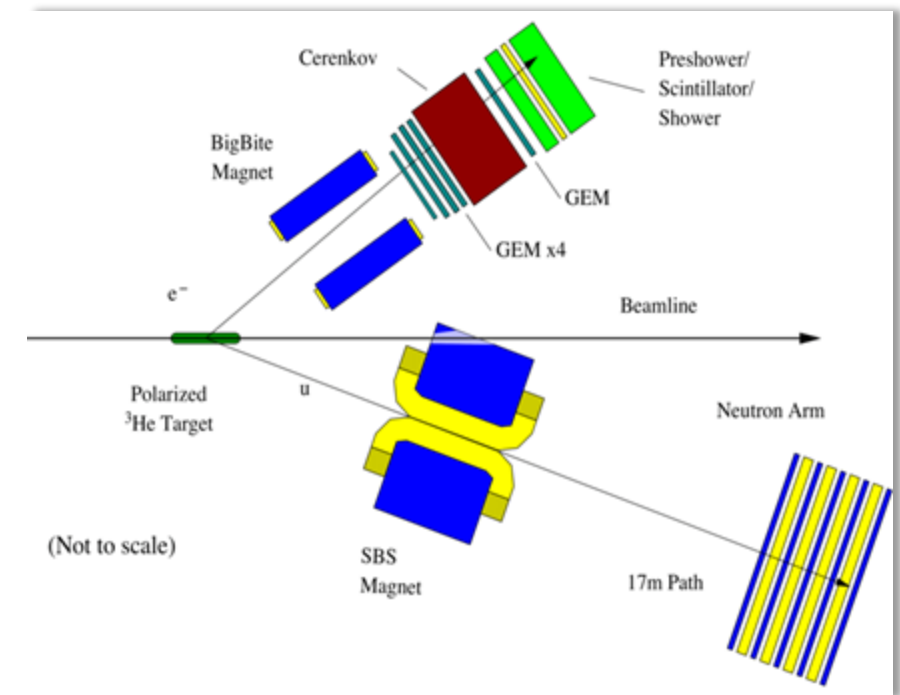
GEn-II Experiment

- Polarized $45\mu A$ electron beam incident on a $60cm$ polarized ^3He target
- $Q^2 = 3.0, 6.8, \text{ and } 9.8 \text{ GeV}^2$
- Run time : Sep 2022 - Nov 2023 (two run periods)
- Polarized ^3He target achieved $\sim 50\%$ polarization

Kin	$Q^2(\text{GeV}^2)$	$E_{\text{beam}}(\text{GeV})$	E arm angle (deg)	H arm angle (deg)	Run time (days)
1	1.79	2.206	29.5	34.7	1
2	3.00	4.291	29.5	34.7	13
3	6.83	6.373	36.5	22.1	33
4	9.82	8.448	35.0	18.0	86



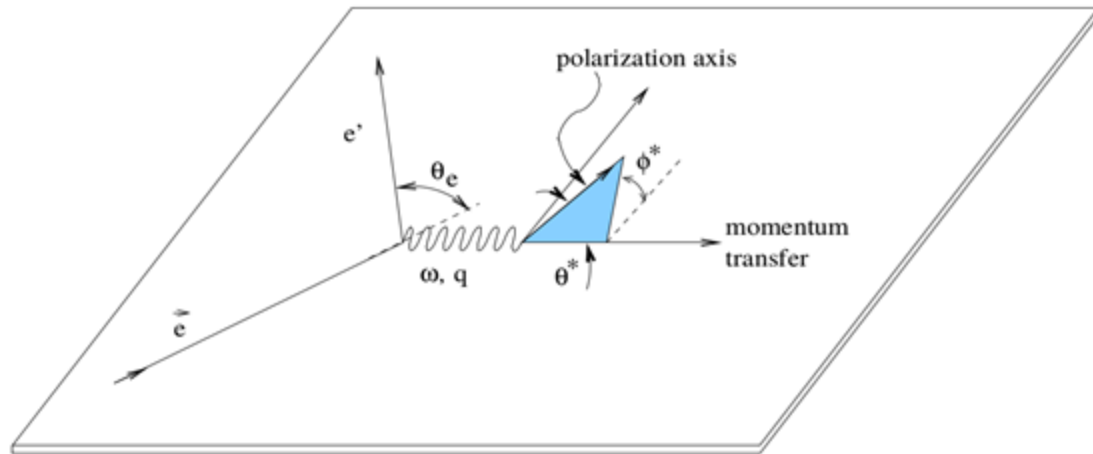
Hall A during SBS Programme



Schematic of the Experiment setup *GEn-II proposal PAC 34

Double Polarization Method

The effective “magnetic moment” of the nucleon for a given Q^2 depends on the electromagnetic form factors. The response of the nucleon to the virtual photon depends on the spin orientation relative to that of the incoming electron which gives rise to a helicity dependent asymmetry related to electromagnetic form factors. By polarizing the nucleon, we can access these helicity dependent observables.



- Elastic scattering cross section of polarized electron beam on a polarized neutron target

$$\sigma = \Sigma + h\Delta$$

- Σ : unpolarized cross section
- Δ : polarized cross section
- h : helicity (± 1)

- Spin Asymmetry : $A_{phys} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{\Delta}{\Sigma}$

- In the experimental analysis we start with $A_{raw} \rightarrow A_{phys} \rightarrow \Lambda$

$$A_{raw} = \frac{N^+ - N^-}{N^+ + N^-} \rightarrow A_{phys} = \frac{A_{raw} - \sum_{x \neq n} f_x A_x}{P_{beam} P_{^3He} P_n f_n} \rightarrow A_{phys} = -\frac{1}{1 + \frac{\epsilon}{\tau} \Lambda^2} \left[\Lambda \sqrt{\frac{2\epsilon(1-\epsilon)}{\tau}} P_x + \sqrt{1 - \epsilon^2} P_z \right]$$

here $\Lambda = \frac{G_E^n}{G_M^n}$

Double Polarization Method

$$A_{phys} = -\frac{G_E^n}{G_M^n} \frac{2\sqrt{\tau(1+\tau)}\tan(\theta/2)\sin\theta^* \cos\phi^*}{(G_E^n/G_M^n)^2 + (\tau + 2\tau(1+\tau)\tan^2(\theta/2))} - \frac{2\tau\sqrt{1+\tau + (1+\tau)^2\tan^2(\theta/2)}\tan(\theta/2)\cos\theta^*}{(G_E^n/G_M^n)^2 + (\tau + 2\tau(1+\tau)\tan^2(\theta/2))}$$

$$A_{phys} = A_{\perp}P_x + A_{\parallel}P_z$$

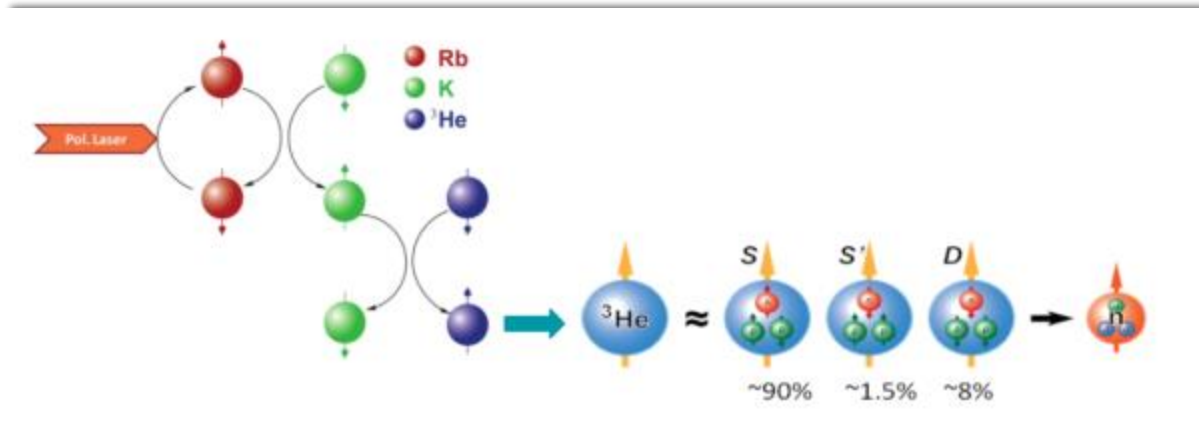
P_x is the polarization component in the scattering plane perpendicular to the q vector and P_z parallel to the q vector

Perpendicular component is more sensitive to the FF ratio, therefore we set the target polarization in that direction

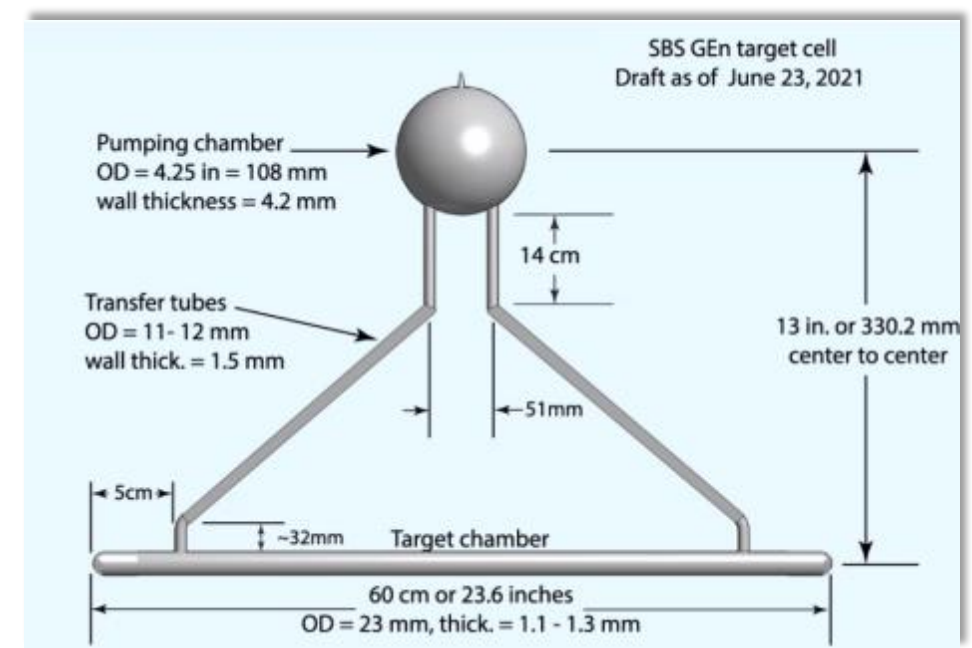
- By taking $\epsilon = \frac{1}{1+2(1+\tau)\tan^2(\theta/2)}$, $P_x = \sin\theta^* \cos\phi^*$, $P_z = \cos\theta^*$ and $\Lambda = \frac{G_E^n}{G_M^n}$ asymmetry can be further simplified;

$$A_{phys} = -\frac{1}{1 + \frac{\epsilon}{\tau} \Lambda^2} \left[\Lambda \sqrt{\frac{2\epsilon(1-\epsilon)}{\tau}} P_x + \sqrt{1-\epsilon^2} P_z \right]$$

Polarized He3 Target

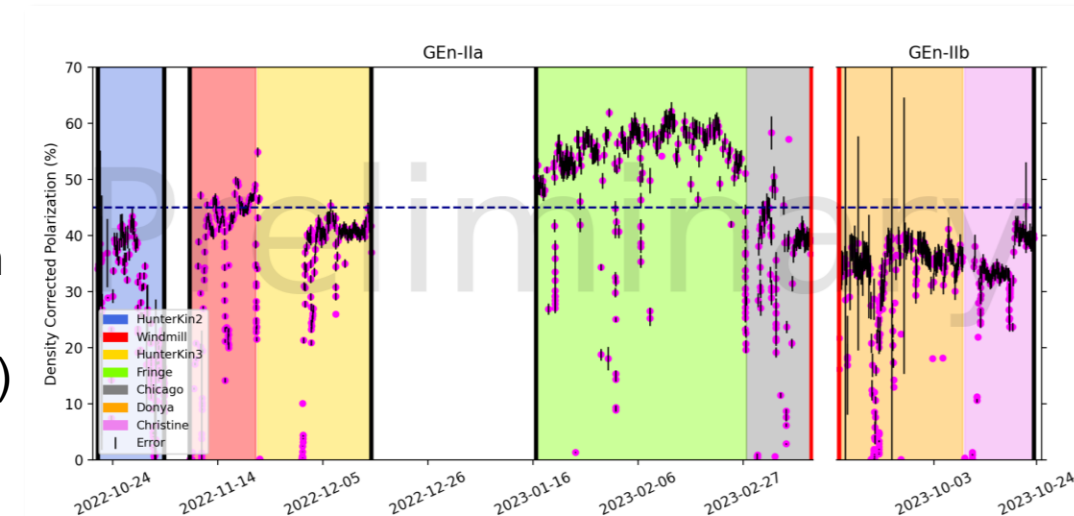


Spin-exchange optical pumping to polarize neutrons



Schematic of the ^3He target

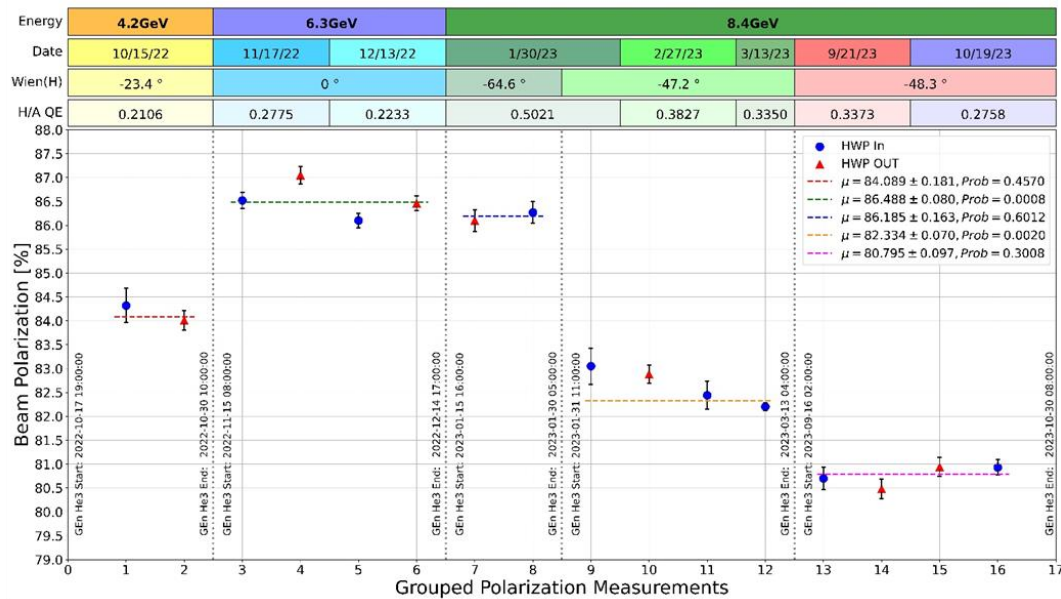
- New target design
 - Increased length (60 cm)
 - Increased polarization
- Pumping chamber contains a mixture of Rb and K plus ^3He
- Up to 200W lasers are used for optical pumping
- Polarized gas is transferred to the target chamber via convection
- Polarized ^3He acts as an effective polarized neutron target
 - effective polarization of Neutron ~87% , and proton ~(-2.8%)
- Target cells achieved a world record polarization-weighted luminosity at 45 μA of beam current – **thanks to Cates' Group**



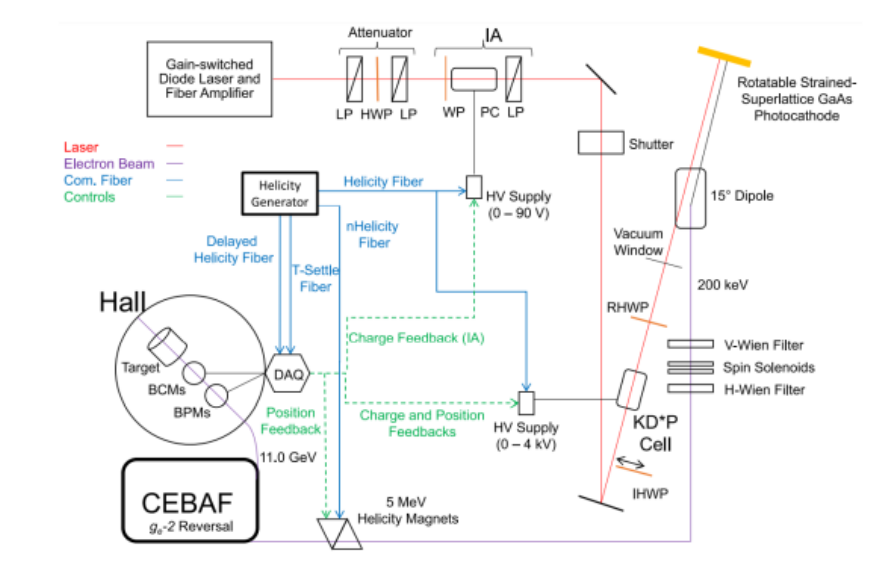
Results of all NMR Measurements during GEN-II * Hunter Presley

Beam Polarization

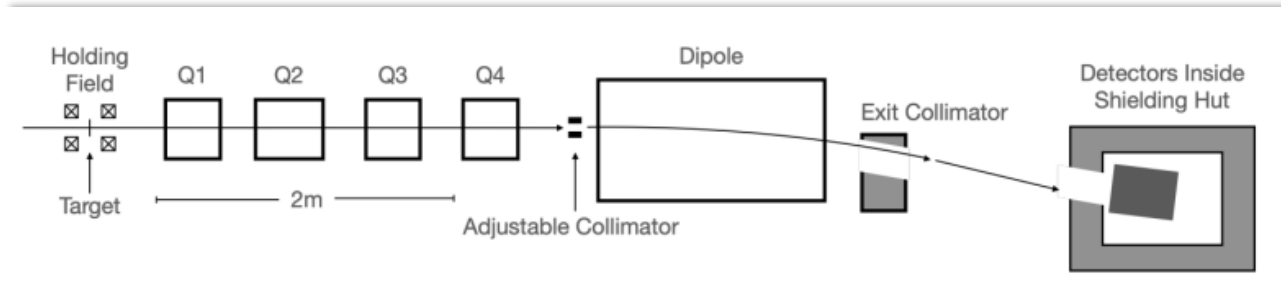
Hall A Beam Polarization



Results of all Moller measurements during GEN-II * **Faraz Chahili**



Injector setup which produces polarized electrons



Schematic of Møller measurement setup in hall A

- The physics asymmetry in GEN-II experiment directly depends on the beam polarization
- Møller scattering is a precise method for measuring beam polarization has been used in hall A for years
- Møller target is a pure iron foil, polarized perpendicular to the beam
- Measures the beam polarization with sub 1% precision in hall A

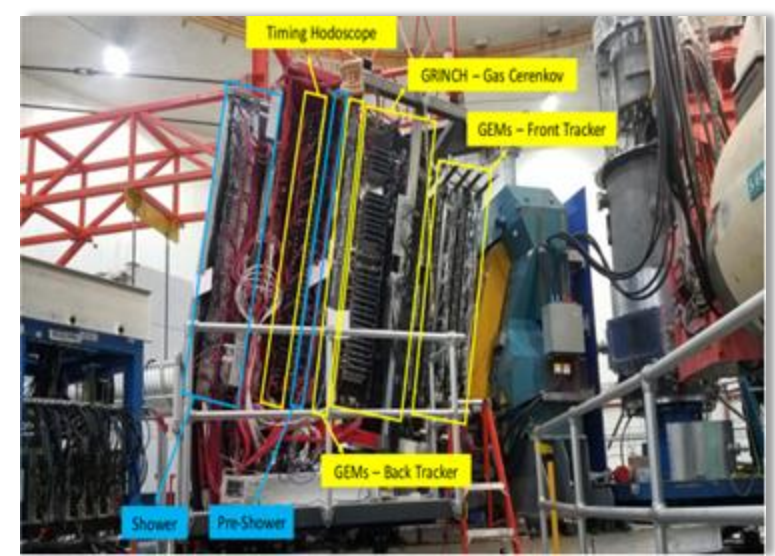
Electron and Hadron Arms

Electron Arm

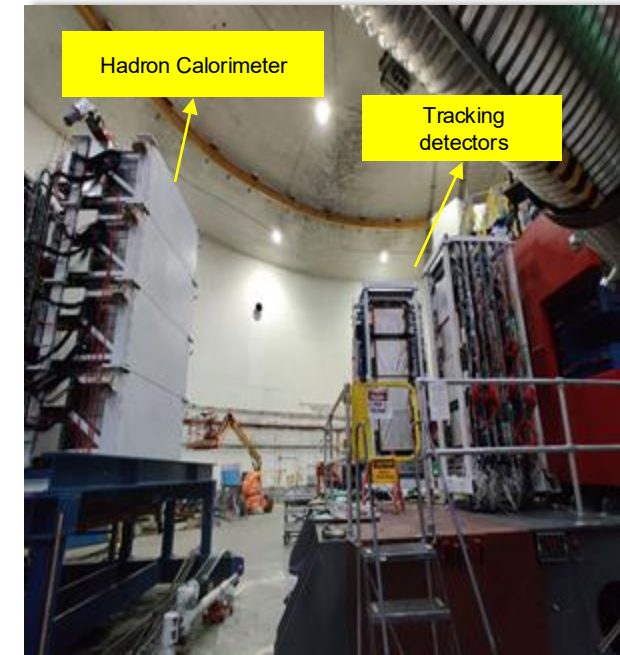
- BigBite magnet : dipole magnet for momentum reconstruction of scattered electrons
- GEM detectors : reconstruct charged particle tracks and momentum using BigBite magnet optics
- GRINCH : Gas Ring Cherenkov detector for PID
- Timing hodoscope : high-precision timing information
- Pre-shower and shower : electron energy and PID

Hadron Arm

- Super BigBite magnet : deflects protons relative to the undeflected neutrons
- Hadron Calorimeter : sampling calorimeter that provides position, energy and timing information of neutrons and protons



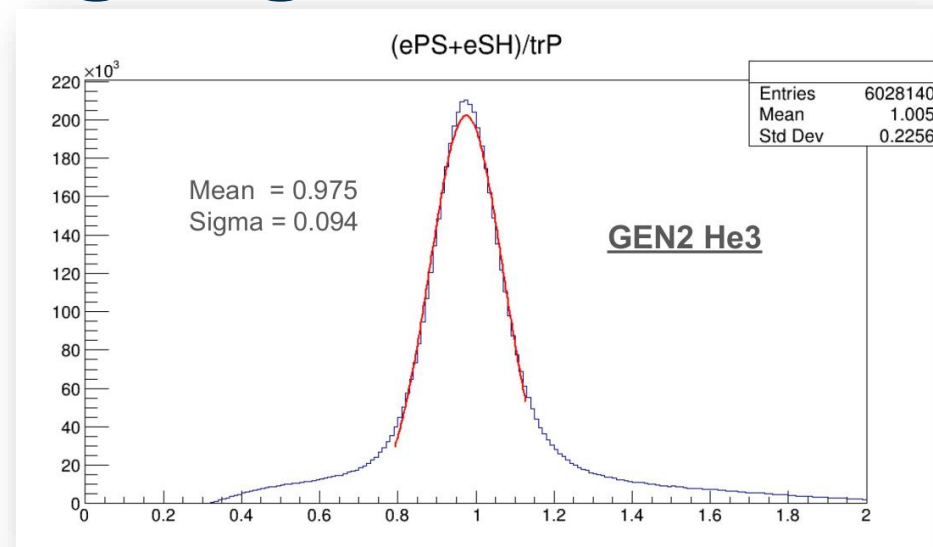
BigBite Spectrometer



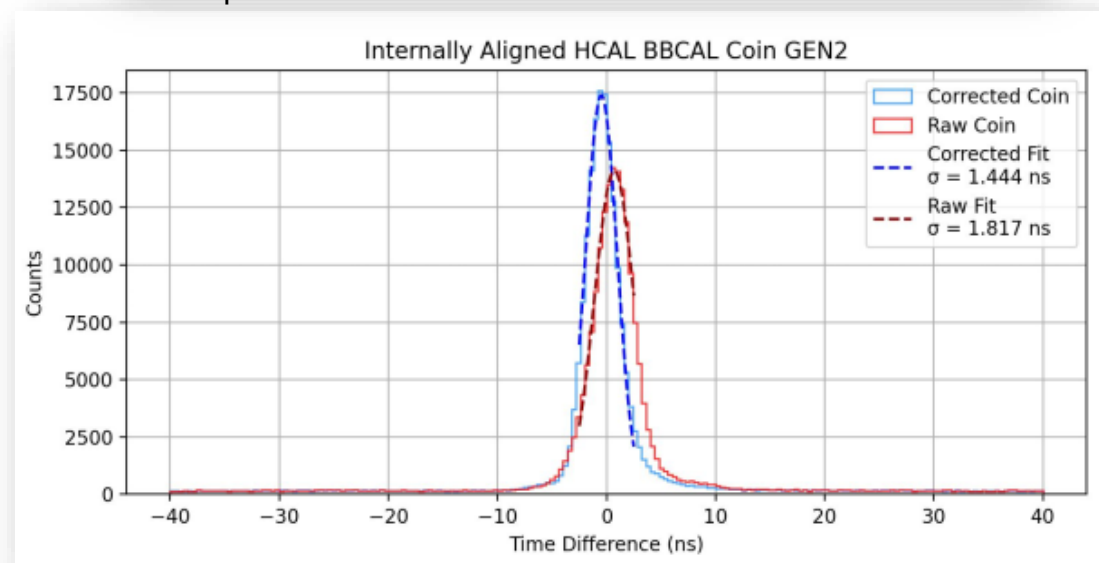
Super BigBite Spectrometer

Overall pass2 calibration highlights

- Bigbite Spectrometer
 - Momentum resolution : 1.5-2%
 - Angular resolution : 1-2 mrad
 - Vertex resolution : 2 – 7 mm
 - BBCAL energy resolution : ~6.5%
- Super Bigbite Spectrometer
 - Position resolution : 5 – 6 cm
 - Energy resolution : 35-40%
 - Angular resolution : 3 mrad
 - Momentum resolution for protons : 1.5%
- Coincidence time resolution : 1.5 - 1.8 ns

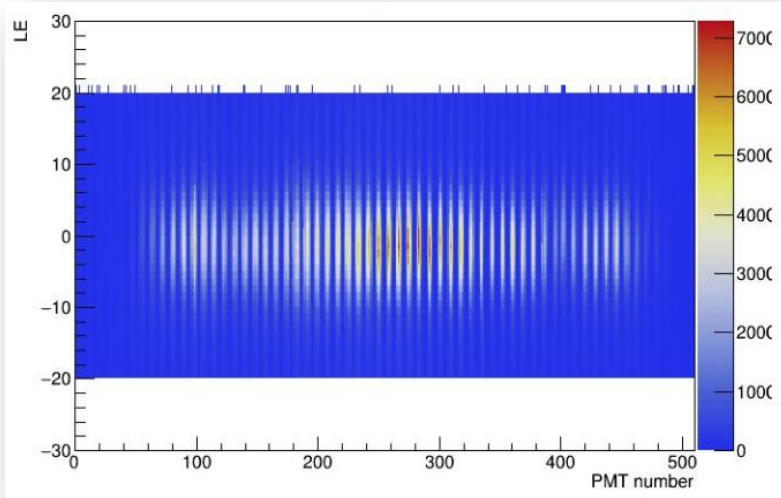


E/p distribution of BBCal for GEN2 He3 data *Kate Evans

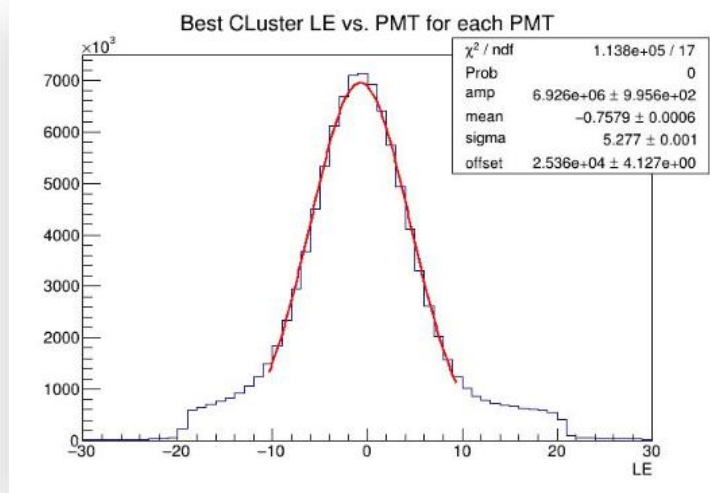


Coincidence time improvement for GEN2 He3 data *Hunter Presley

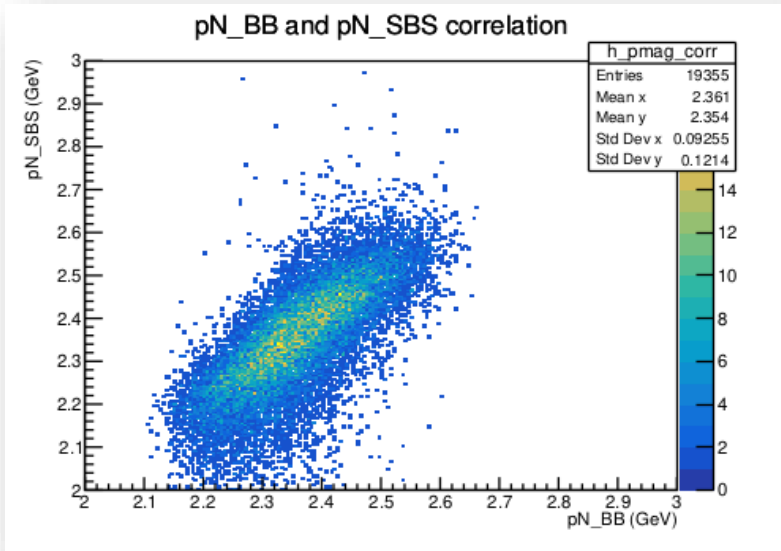
Overall pass2 calibration highlights



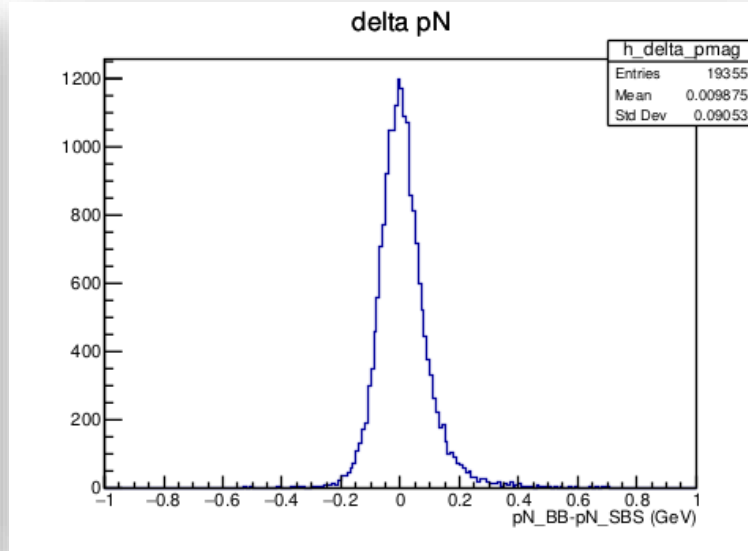
GRINCH leading edge time (ns) vs PMT number for GEN2 He3 data ***Jack Jackson**



GRINCH leading edge time (ns) distribution for GEN2 He3 data ***Jack Jackson**



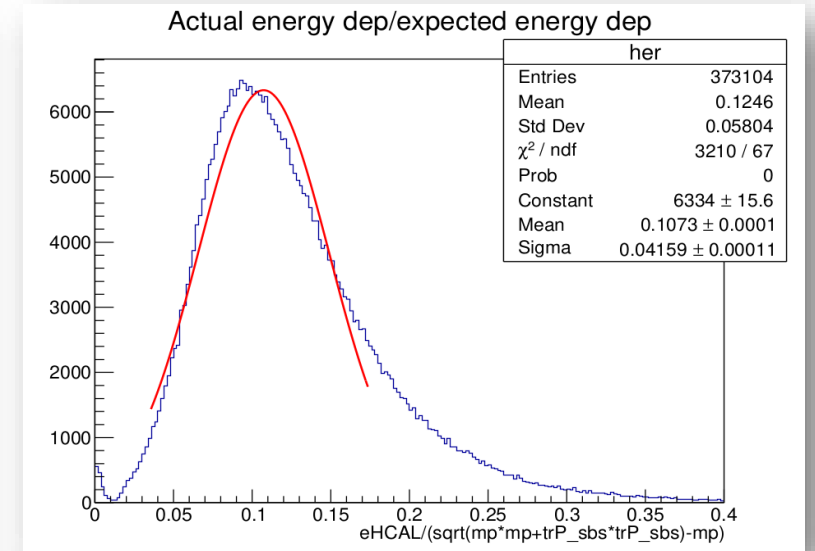
Correlation between the electron arm vs hadron arm reconstructed |pN| for GEN2 He3 data



Distribution of difference between the electron arm and hadron arm reconstructed |pN| for GEN2 He3 data

All kinematics :

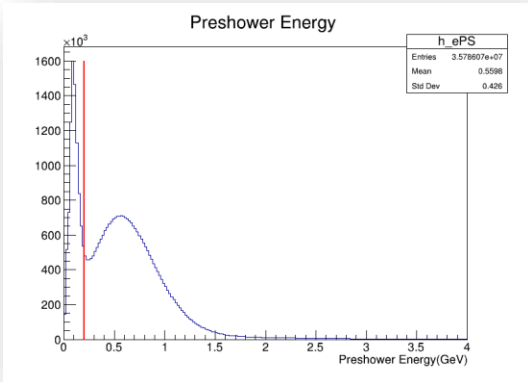
<https://sbs.jlab.org/cgi-bin/DocDB/private/ShowDocument?docid=694>



HCal energy sampling fraction distribution for GEN2 He3 data

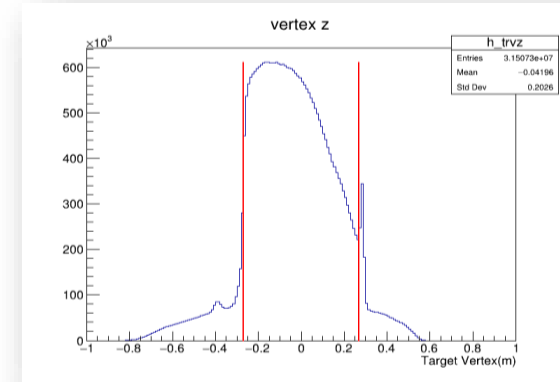
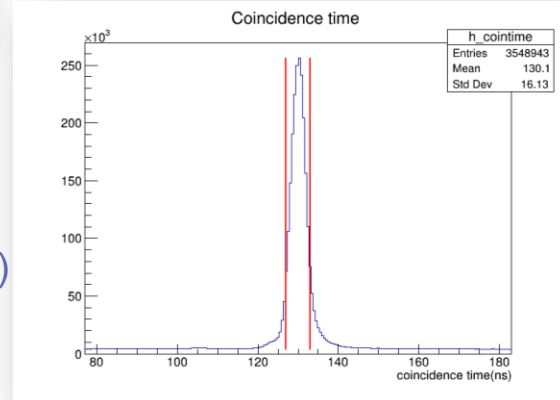
Event Selection

- Track cuts: number of hits on track, track χ^2/ndf , track vertex ($|v_z| < 0.27\text{m}$) \rightarrow track originates from the target
- Particle identification: Pre-shower energy ($ePS > 0.2\text{ GeV}$) or Grinch cuts \rightarrow reject pions in electron arm
- E/p cut \rightarrow quasi-elastic events
- Invariant Mass (W^2) \rightarrow quasi-elastic events
- Coincidence time (coin) \rightarrow reduce accidental contamination
- Hcal energy (eHCAL) \rightarrow reduce background contamination



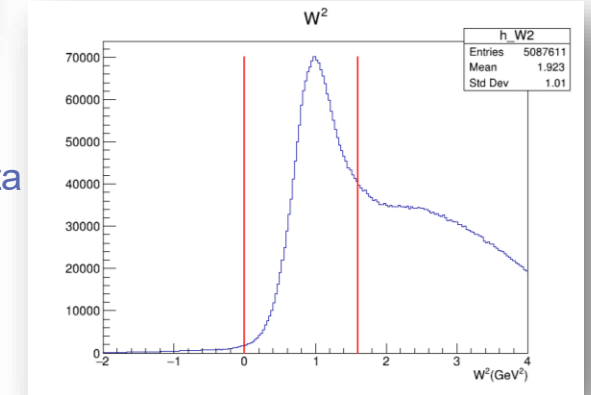
Pre-shower energy distribution for Gen2 ^3He data (with v_z , and eHCAL cuts)

Coincidence time distribution for Gen2 ^3He data (with v_z , eHCAL, ePS, E/p and W^2 cuts)

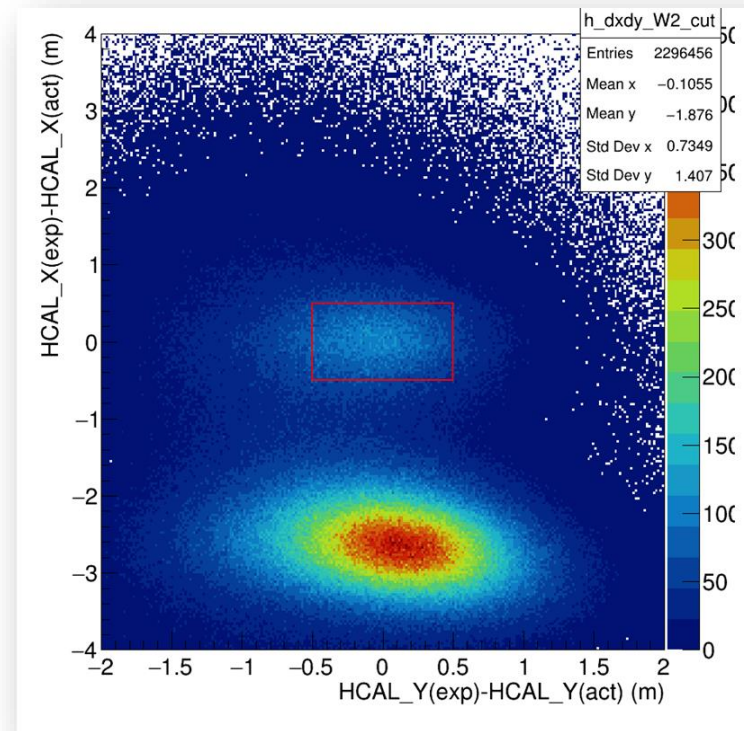
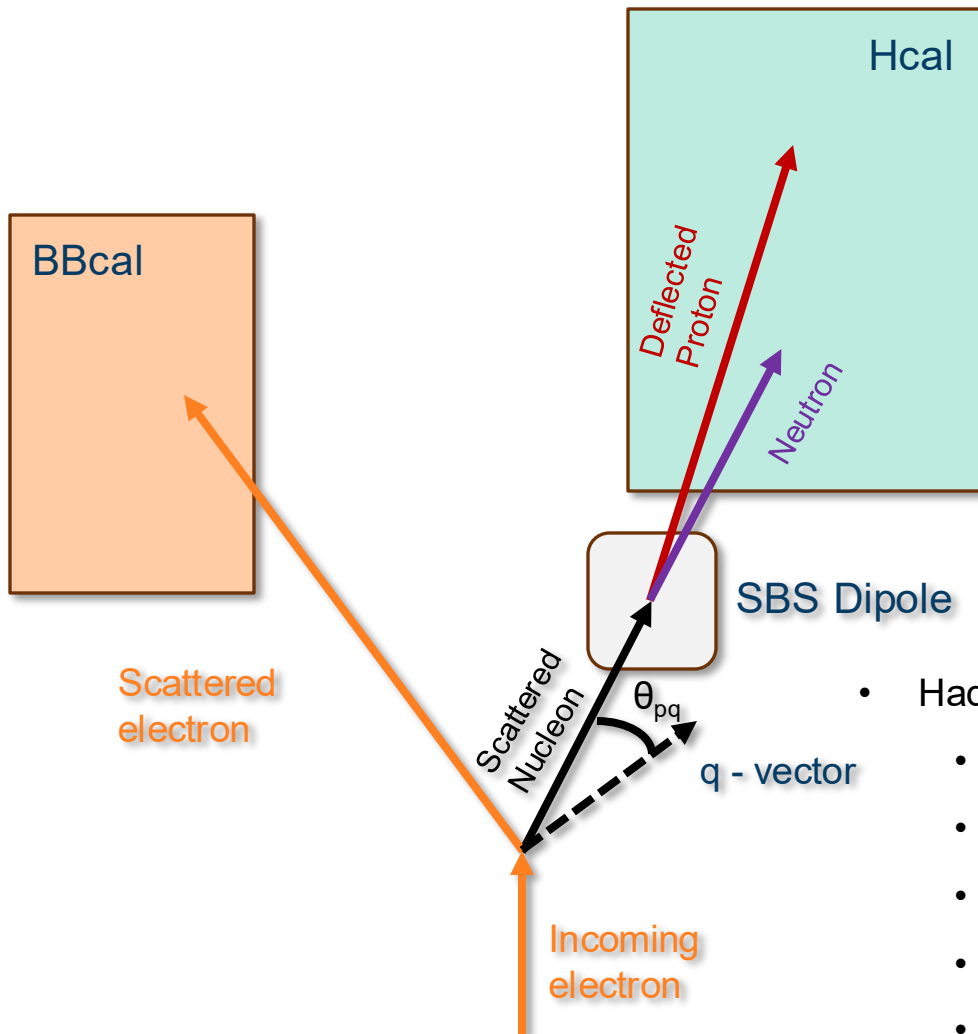


Vertex z distribution for Gen2 ^3He data (with ePS, and eHCAL cuts)

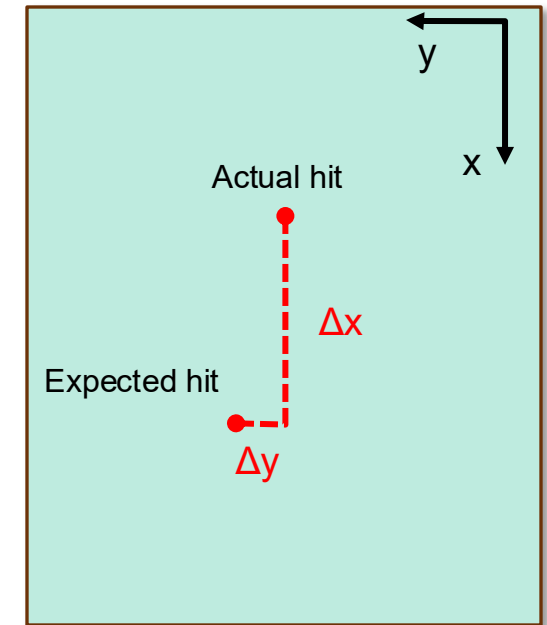
W^2 distribution for Gen2 ^3He data (with v_z , eHCAL, ePS, E/p and coin cuts)



PID in Hadron Arm



delta-x vs delta-y (dxdy) plot for Kin2 ^3He data after W^2 and cointime cuts



Face of the HCal

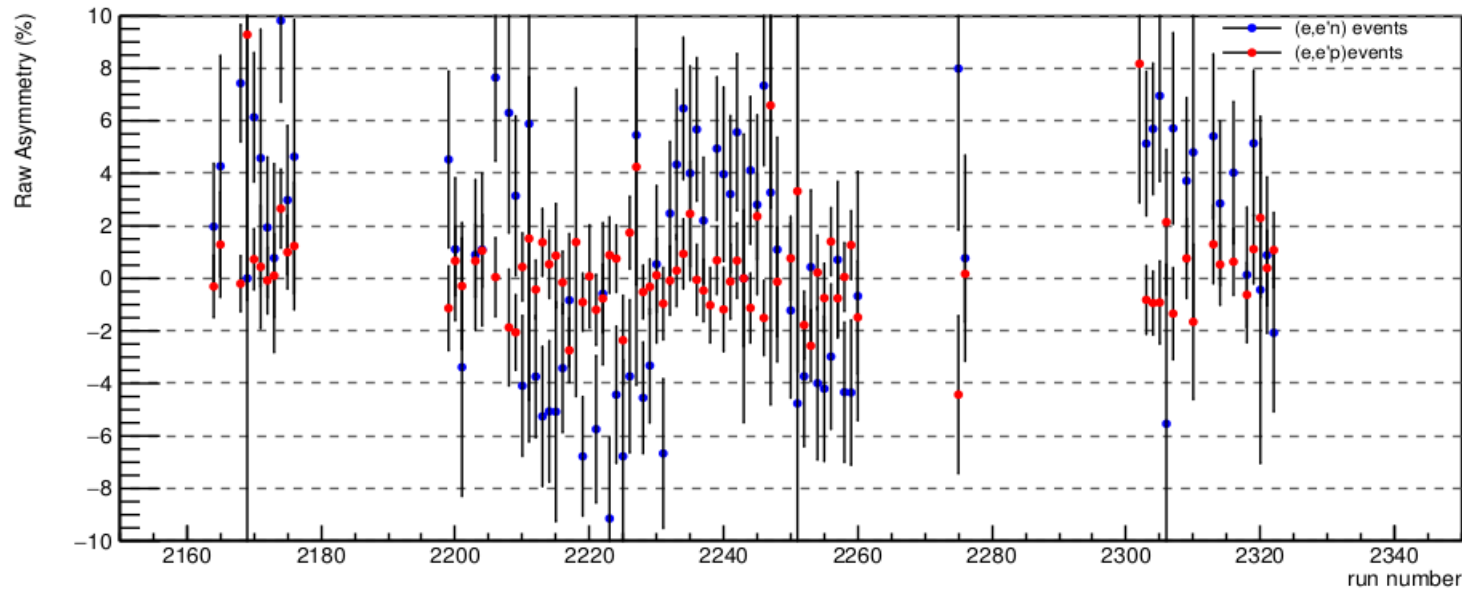
- Hadron Particle Identification (Kin2: $|dx| < 0.5\text{m}$ and $|dy| < 0.5\text{m}$)
 - SBS Dipole deflects the charged particles
 - Expected hit position is derived from the electron arm tracking
 - Delta-x and delta-y are taken as the difference between the expected and actual hit positions
 - Neutrons are centered around the zero of the delta-x vs delta-y distribution
 - SBS magnetic field at 100% throughout the experiment, not interested in the protons

Raw Asymmetry

$$h_{raw} = P_{IHW P} P_{kin} h_{meas}$$

$$A_{raw} = \frac{N^+ - N^-}{N^+ + N^-}$$

$$A_n = \frac{A_{raw} - \sum_{x \neq n} f_x A_x}{f_n}$$



Raw asymmetry across runs for GEN2 ^3He data; blue - neutron events; red - proton events

- Helicity of the events that pass the QE cuts are used to calculate the raw asymmetry
- An insertable half-wave plate flips the beam helicity to reduce electronic noise
- Neutron asymmetry is a non-zero value, and changes sign with half wave plate insertion
- Proton asymmetry is small close to zero, because of the low proton polarization

Corrections and Physics Asymmetry

- Corrections are needed to account for the contaminations that pass through the elastic cuts for neutron events
- List of corrections
 - Timing accidental background
 - Nitrogen in the target chamber
 - Pions passing through the pre-shower cut
 - Inelastic data passing the cuts
 - Elastic protons passing the cuts
 - Nuclear effects
- It is important to do the correction in the above order to avoid double counting
- Effective polarization of the neutron (P_n) is taken as 96%

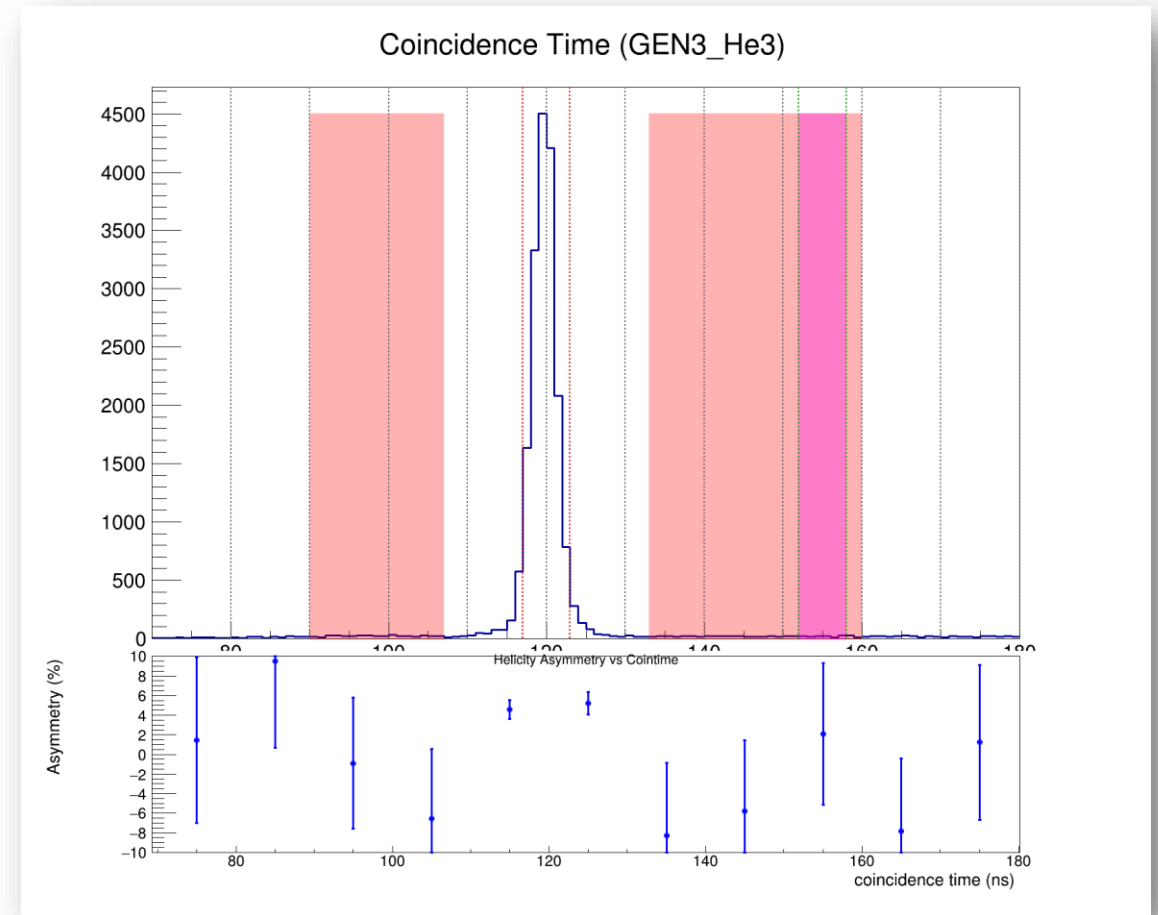
$$A_n = P_{beam} P_{^3He} P_n A_{phys}$$

$$A_{phys} = \frac{A_{raw} - \sum_{x \neq n} f_x A_x}{P_{beam} P_{^3He} P_n f_n}$$

$$A_{phys} = \frac{A_{raw} - f_{acc} A_{acc} - f_{\pi} A_{\pi} - f_{in} A_{in} - f_p A_p - f_{FSI} A_{FSI}}{P_{beam} P_{^3He} P_n (1 - f_{acc} - f_{N_2} - f_{\pi} - f_{in} - f_p - f_{FSI})}$$

Accidentals

- Accidental contamination refers to the events that are out of time yet randomly fall into the QE timing window
- Accident background is mostly flat, as expected because it is random, except near the very edges
- An offset cut (same width as QE - **magenta**) is used to get the accidental fraction (f_{acc})
- An anti-cut (**pink**) is used to get the accidental asymmetry (A_{acc})



Coincidence time distribution for GEN3 ^3He data

Nitrogen in the target chamber

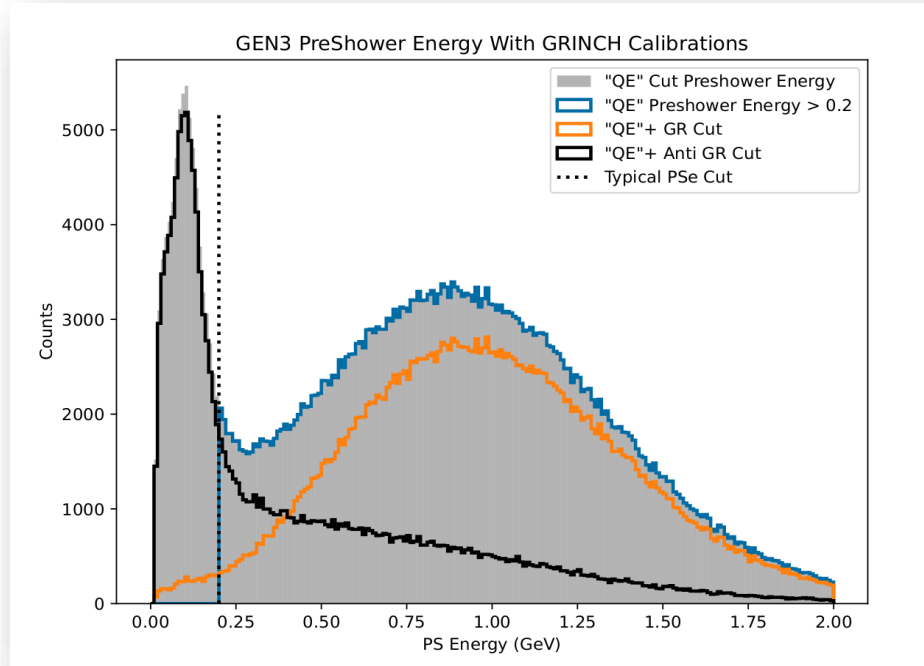
- The polarized ^3He targets are filled with approximately ~1-2% of Nitrogen to reduce depolarization effects from the de-excitation of the alkali atoms in the pumping chamber
- Because of this, however, quasi-elastic neutron events which come from nitrogen are present in the data sample and must be accounted for
- The nitrogen correction must account for
 - difference in cross sections between N_2 and ^3He -> geant4 simulations -> S
 - fraction of neutrons present from N_2 over the fraction of neutrons present from ^3He
- N_2 is unpolarized, therefore the asymmetry is zero
- Alternatively, carbon foil data can be used to approximate the fraction since they have similar number of nucleons

$$f_{\text{N}_2} = \frac{14 \cdot n_{\text{N}_2}}{14 \cdot n_{\text{N}_2} + n_{\text{He}^3}} \cdot S$$

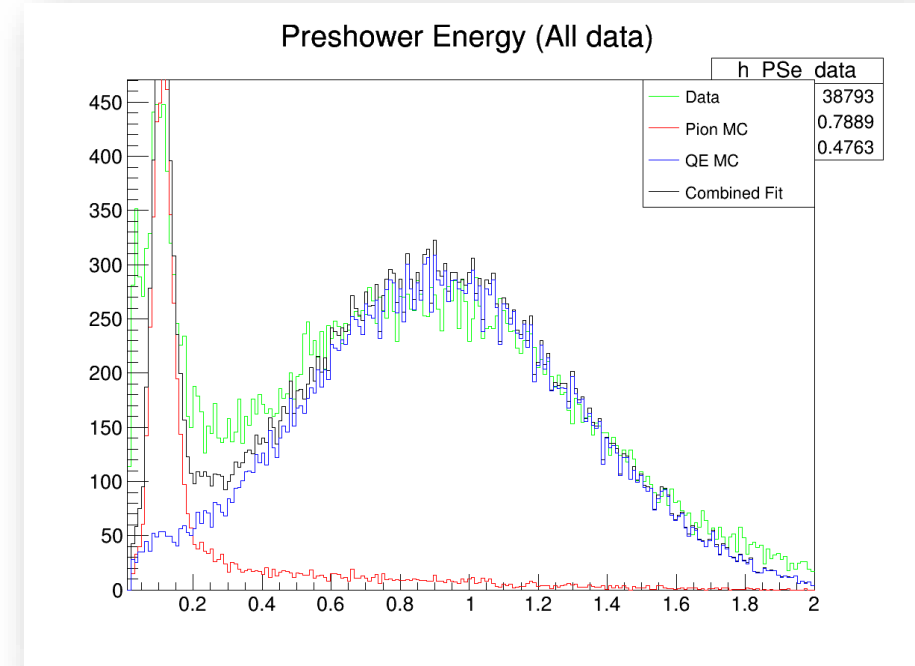
$$S = \frac{n_{\text{N}_2}^{\text{sim}}}{n_{\text{He}^3}^{\text{sim}} \cdot 14}$$

where n_{N_2} is the fraction of Nitrogen gas in the filled target cell, determined at the time of the fill

Pions in Bigbite



Pre-shower energy distribution for GEN3 ^3He
with GRINCH cuts ***Jack Jackson**



Pre-shower energy distribution for GEN3 ^3He
data and simulation comparison

- Pions deposit less energy (MIPs) in the BBCal compared to electrons -> cut on deposited energy ($e\text{PS} > 0.2\text{GeV}$)
- GRINCH detects the Cherenkov light from electrons because they travel faster than the speed of light in the medium (cluster size > 2 and track matching)
- Pion fraction and asymmetry is calculated using the separated-out distribution
- Above distributions have loose QE cuts (loose HCal energy and E/p cuts) to illustrate the split between electron and pion distributions

Simulation fitting

G4SBS

- G4SBS was created using the Geant4 Framework
- Simulation output is digitized and processed exactly like real data
- Simulated and real data are compared to extract the physics

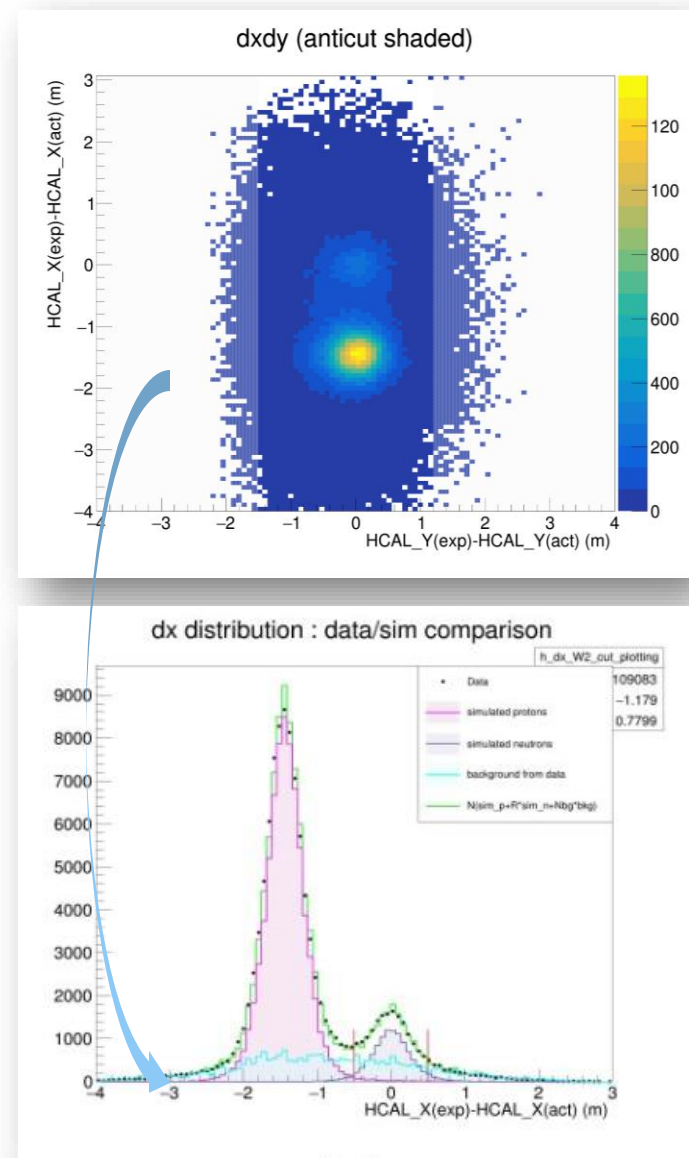
Fitting function

$$sim = N (p_{sim} + R * n_{sim} + N_{bg} * bg_{dist})$$

- p_{sim} – proton shape (simulation)
- n_{sim} – neutron shape (simulation)
- bg_{dist} – background shape
- N, R, N_{bg} – fit parameters (all are normalizations, so the shapes are preserved)

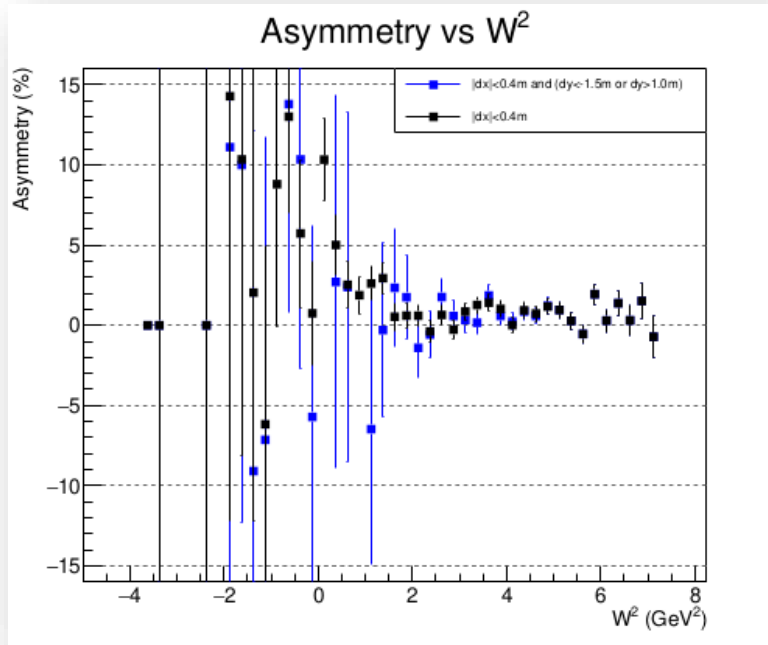
Background distribution

- Anti-dy - dx distribution generated from the same dataset as the signal using good electron events but fail the dy cut
- Inelastic simulation - background shape generated by the simulation of inelastic events using
 - Christy-Bosted model
 - Zheng model
- Fraction of Inelastic and proton contamination under the neutron peak are obtained by simulationd fitting method

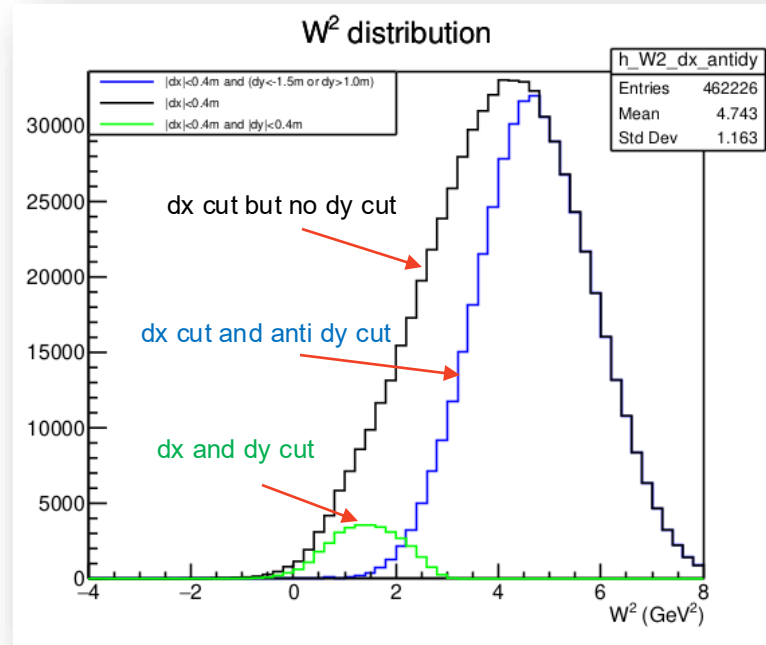


delta-x vs delta-y distribution (top) and
delta-x distribution with anti-cut background distribution for
GEN3 ^3He data

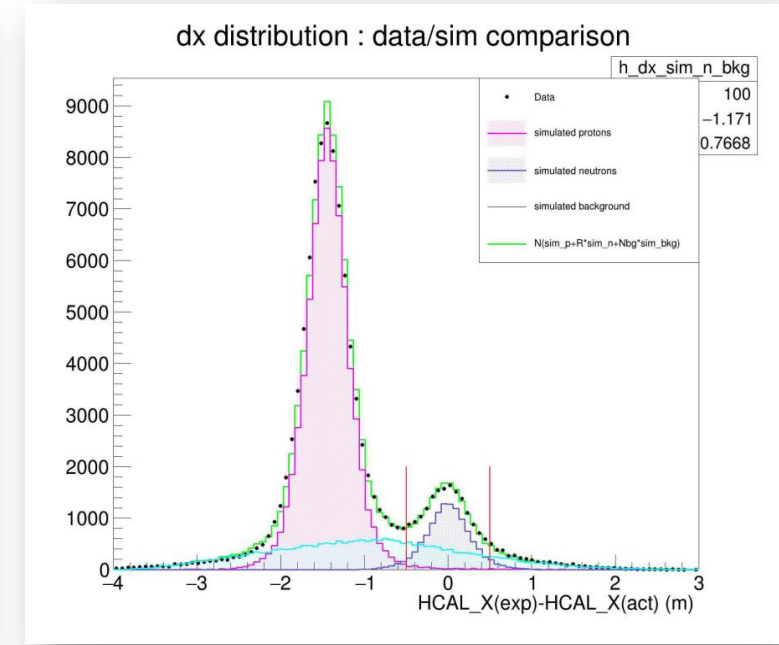
Inelastic background



Asymmetry against W^2 for different cut ranges in dx and dy for GEN3 ³He data



W^2 distributions for different cut ranges in dx and dy for GEN3 ³He data



Cyan color background using **g4sbs inelastic generator** for GEN3 ³He data

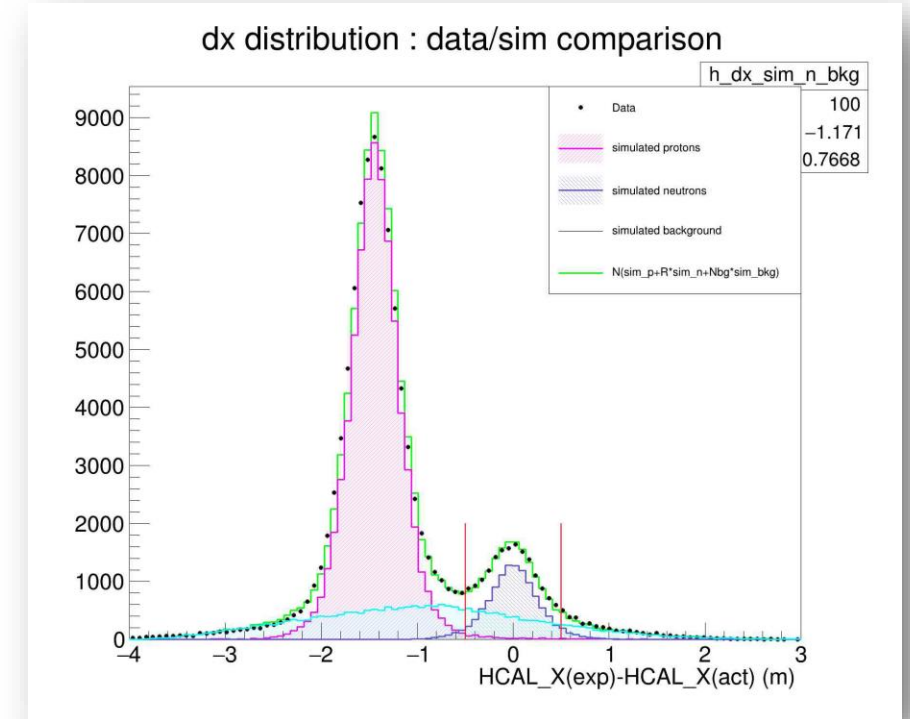
- Understanding the inelastic background is challenging
- Anti dy method is questionable because it assumes a similar shape in the quasi-elastic region
- The main inelastic cross section model for G4SBS is the 2008 and 2010 empirical fit to proton and deuteron data by M.E. Christy and P.E. Bosted – **Jacob Koenemann** is working on improving the simulation for GEN-II
- Similar studies to GMn are going on in which g4sbs inelastic model + timing accidentals are incorporated together
- **Hunter Presley** and **Xiaochao Zheng** are working on implementing ³He structure function model which will also allow us to get an asymmetry for the inelastic background

Protons passing through the cuts

- Similar to inelastic fraction but the proton fraction (f_p) under the neutron peak is obtained using the proton fit
- Asymmetry is calculated using the existing proton parameterization (Λ^p), which is well understood in this Q^2 region
 - Proton polarization $P_p \sim (-3\%)$

$$A_{p,phys} = -\frac{1}{1+\frac{\bar{\epsilon}}{\bar{\tau}}(\Lambda^p)^2} \left[\Lambda^p \sqrt{\frac{2\bar{\epsilon}(1-\bar{\epsilon})}{\bar{\tau}}} \bar{P}_x + \sqrt{1-\bar{\epsilon}^2} \bar{P}_z \right]$$

$$A_p = P_{beam} P_{3He} P_p A_{p,phys}$$

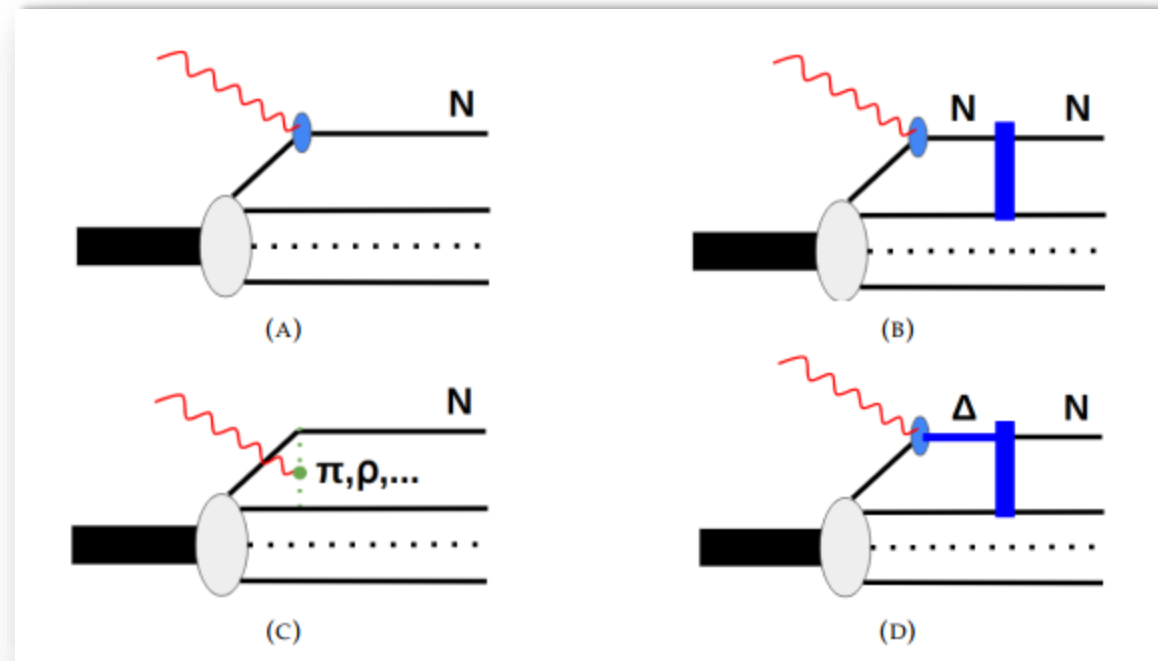


Magenta color protons using g4sbs QE simulation for GEN3 ^3He data

- Alternatively, hadron arm tracking data can be used to calculate the proton/charged -particle background fraction

Nuclear effects and final state interactions

- Some reactions could result in outgoing neutrons which may look like QE neutrons
- Theoretical calculations are required to estimate the contributions from such events
- This work is currently in progress



(A) impulse approximation (B) final state interactions (C) meson exchange currents (D) Isobar currents

*Sargsian, M. M., Abrahamyan, T. V., Strikman, M. I., & Frankfurt, L. L. (2005). Exclusive electrodisintegration of He-3 at high Q^2 . I. Generalized eikonal approximation. *Physical Review C*, 71(4), 044614. <https://doi.org/10.1103/PhysRevC.71.044614>

GEn Extraction

After calculating all the corrections, we must do a run summation to get the A_{phys}

$$A_{phys,i} = \frac{A_{raw,i} - f_{acc}A_{acc} - f_{\pi}A_{\pi} - f_{in}A_{in} - f_pA_p - f_{FSI}A_{FSI}}{P_{beam,i}P_{^3He,i}P_n(1 - f_{acc} - f_{N_2} - f_{\pi} - f_{in} - f_p - f_{FSI})}$$

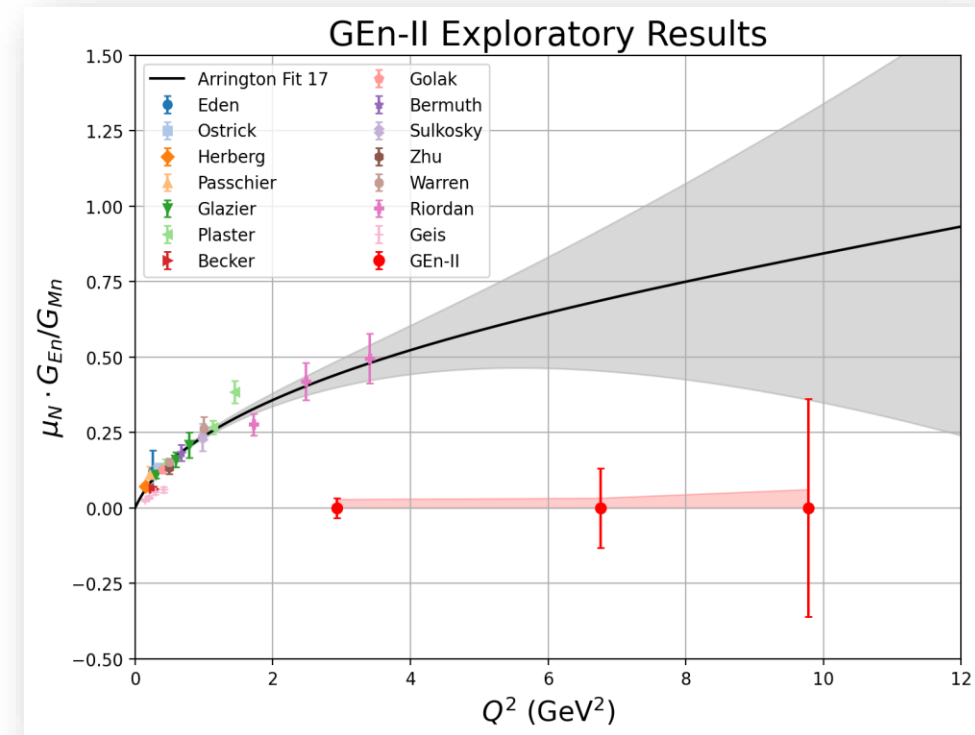
After taking the finite acceptance into account, finally we are ready to extract the ratio. Then using the existing world data for G_M^n , we get G_E^n

$$\left(\frac{\bar{\epsilon}}{\bar{\tau}} A_{phys}\right) \Lambda^2 + \left(\sqrt{\frac{2\bar{\epsilon}(1 - \bar{\epsilon})}{\bar{\tau}}} \bar{P}_x\right) \Lambda + \left(A_{phys} + \sqrt{1 - \bar{\epsilon}^2} \bar{P}_z\right) = 0$$

Where; $\Lambda = \frac{G_E^n}{G_M^n}$ is extracted by solving the quadratic equation

Summary and What's next

- GEn-II completed taking data with a high luminosity polarized ^3He target
- Analysis is well underway
- Calibrations including energy and timing have improved from pass1 to pass2
- Improved calibrations have helped reducing the statistical uncertainty
- Inelastic background needs to be better understood with the help of the simulation



More improvement expected!

World data with the projected
 Q^2 points
with error bars
* **Analysis and Plot Credit :**
Hunter Presley

$$\sigma_{stat} = \frac{\sigma_{Araw}}{P_{beam} P_{^3He} P_n f_n}$$

GEn-II Students and Spokespeople

Kate Evans



Jack Jackson



Faraz Chahili



Hunter Presley



Vimukthi Gamage



Jacob Koenemann



Braian Mederos



Gordon Cates



Todd Averett



Bogdan Wojtsekhowski



← Spokespeople!

Special Thanks! →

Andrew Puckett



Arun Tadepalli



Gary Penman



Graduated
March 2025

Sean Jeffas



Graduated July
2024

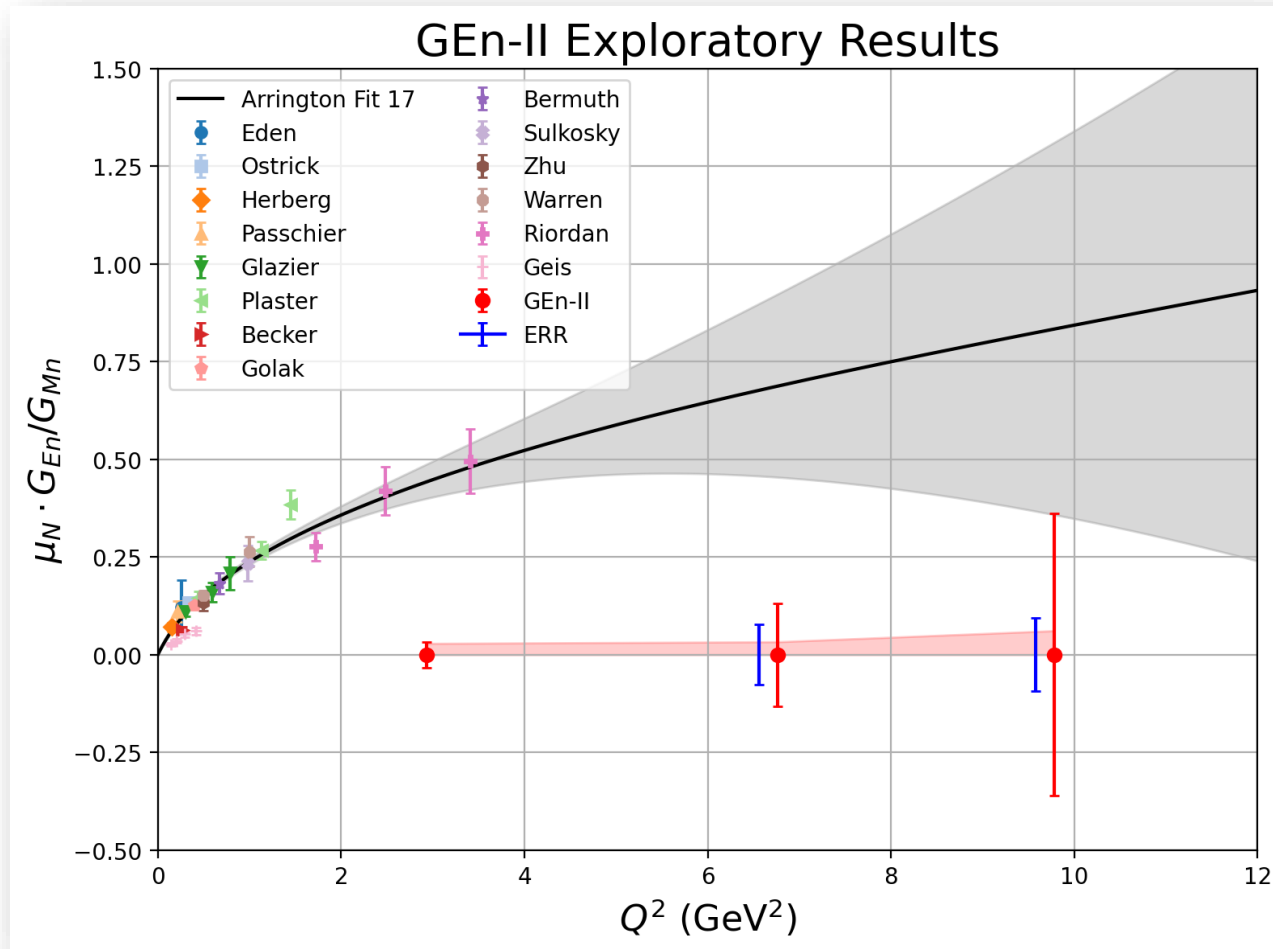
Thank you

- UVA Group – Nilanga Liyanage, Xiaochao Zheng, Kondo Gnanvo, Huong Nguyen, Xinzhan Bai, Asar Ahmed, Anuruddha Rathnayake, John Boyd, Sean Jeffas, Bhashitha Dharmasena, Jacob McMurtry, Mihitha Maithripala, Vidura Vishwanath, Nithya Kularathne, Minh Dao
- Hall A collaboration
- SBS Collaboration – Bogdan Wojtsekhowski, Andrew Puckett, Gordon Cates, Todd Averett, Arun Tadepalli, Eric Fuchey, Mark Jones, Alex Camsonne, Holly Szumila-Vance, and all
- GEn-II and SBS Students
- JLab Staff
- DOE Office of Science for funding (DE-FG02-03ER41240)



Supplemental

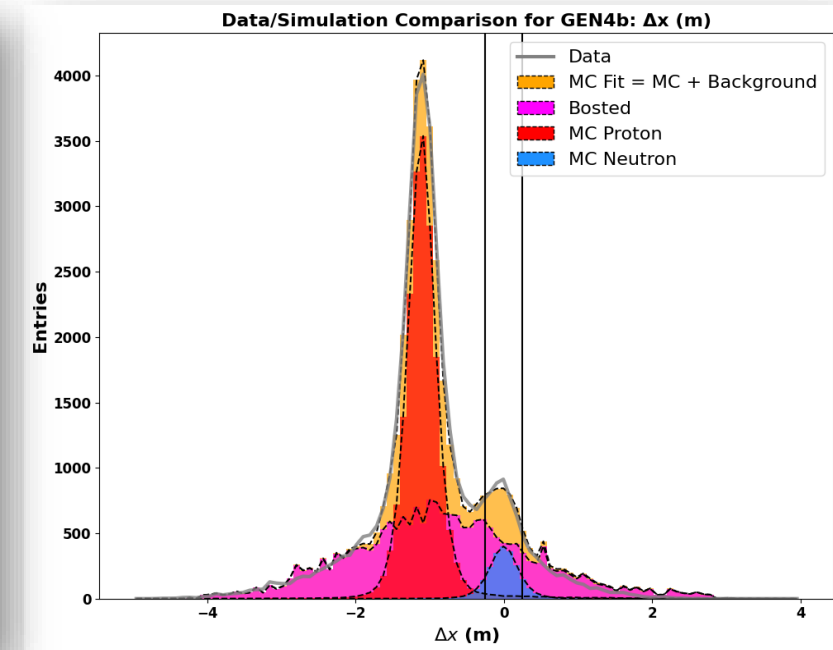
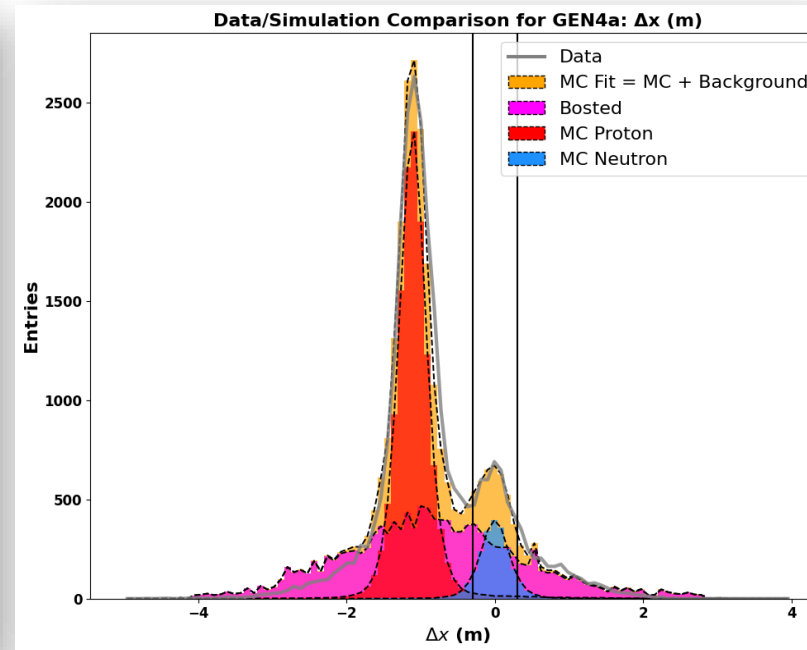
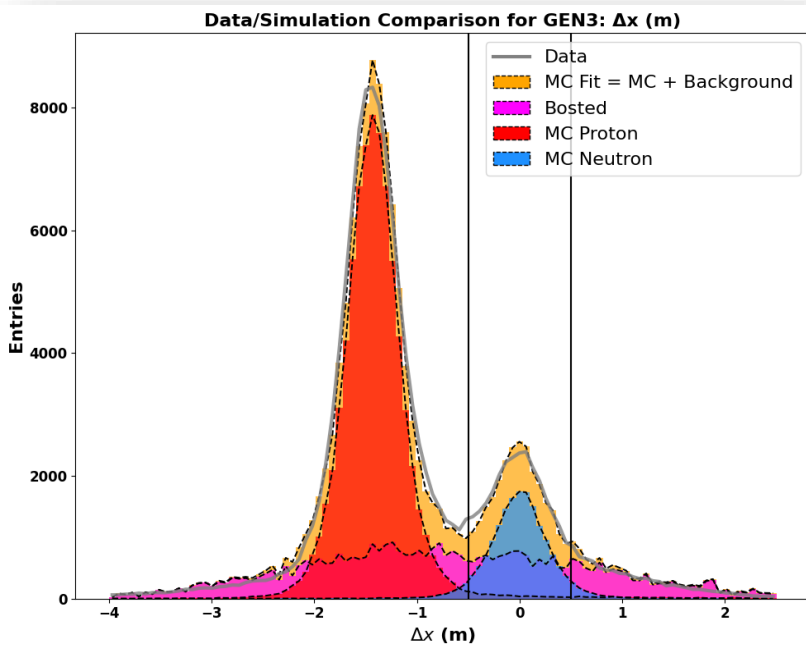
GEn-II Projected error



World data with the projected
 Q^2 points
with error bars

* **Analysis and Plot Credit :**
Hunter Presley

Simulation Fitting



Magenta color background using **g4sbs inelastic generator** for GEN3, 4, and 4b (left to right) ^3He data * **Hunter Presley**

Reference

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