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

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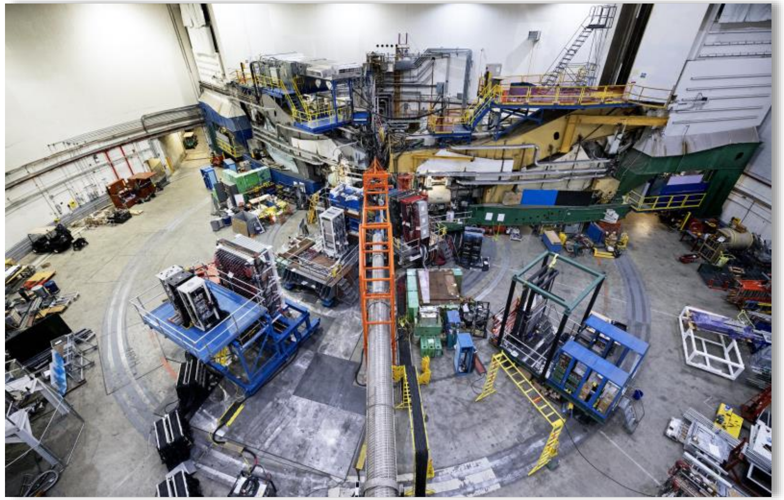
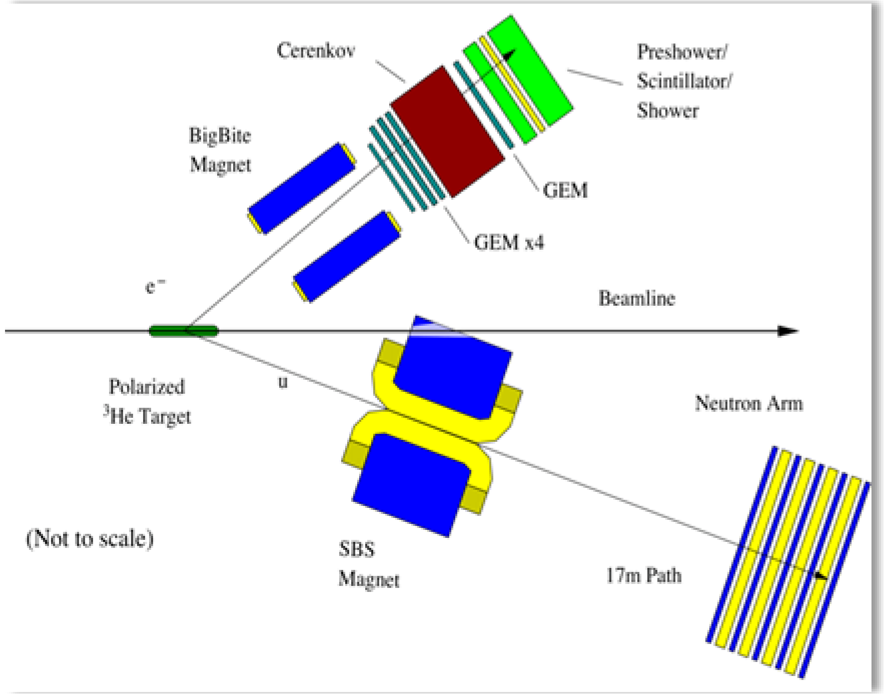
GEn-II Experiment

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

Kin	$Q^2(GeV^2)$	$E_{beam}(GeV)$	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



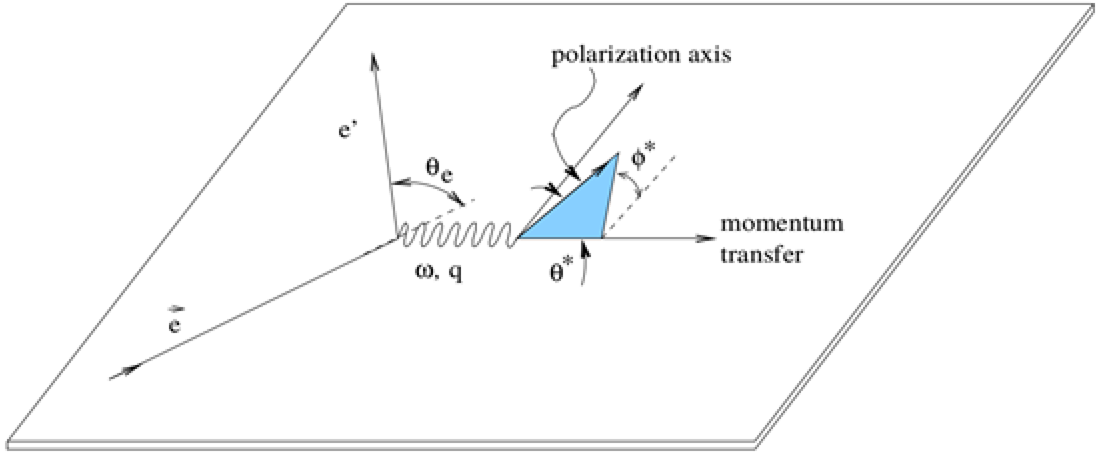
Hall A during SBS Programme



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 $A_{raw} \rightarrow A_{phys} \rightarrow \Lambda$

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

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

Double Polarization Method

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

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

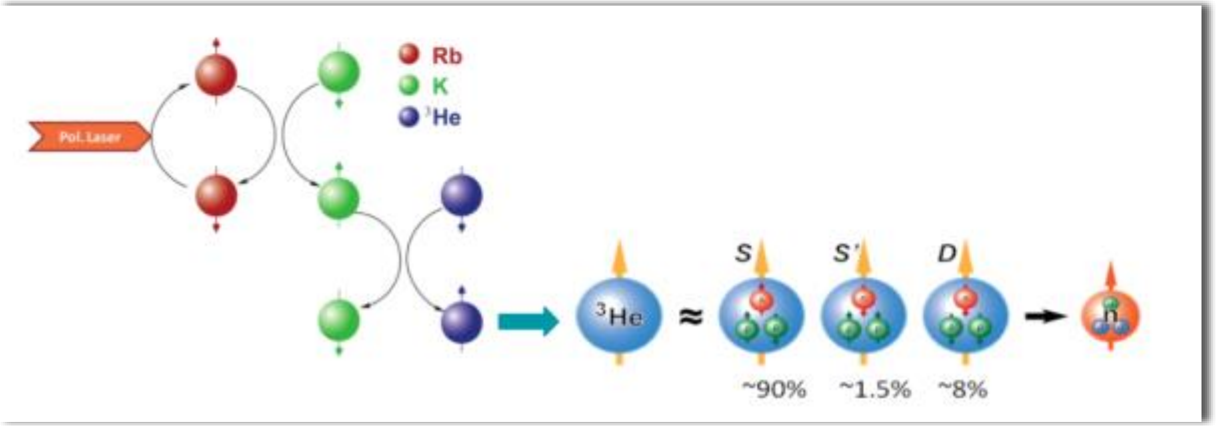
P_x polarization perpendicular to the q vector and P_z polarization parallel to the q vector

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

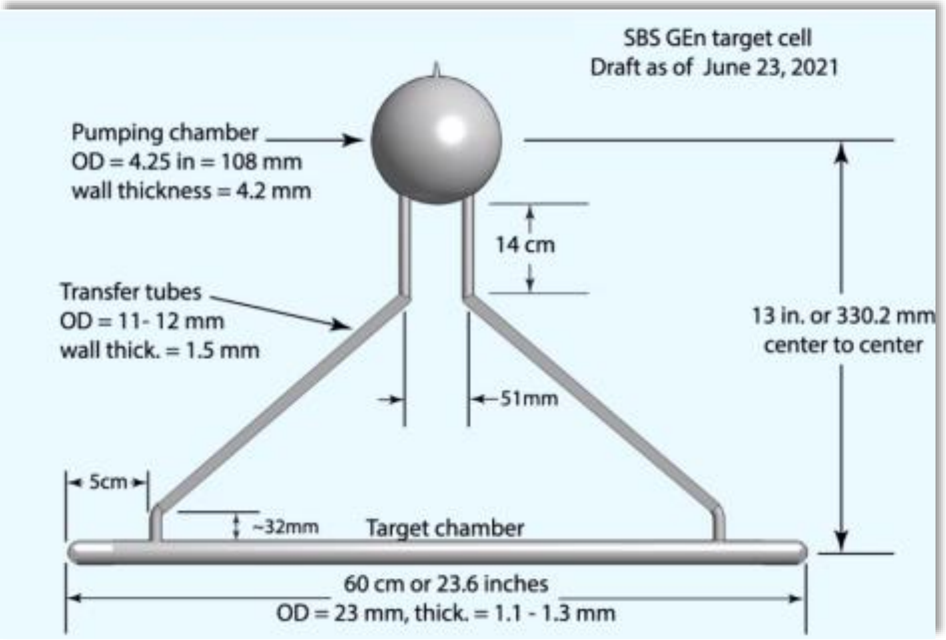
- By taking $\epsilon = \frac{1}{1+2(1+\tau)tan^2(\theta/2)}$, $P_x = sin\theta^* \, cos\phi^*$, $P_z = cos\theta^*$ and $\Lambda = \frac{G_E^n}{G_M^n}$ asymmetry can be further simplified;

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

Polarized He3 Target

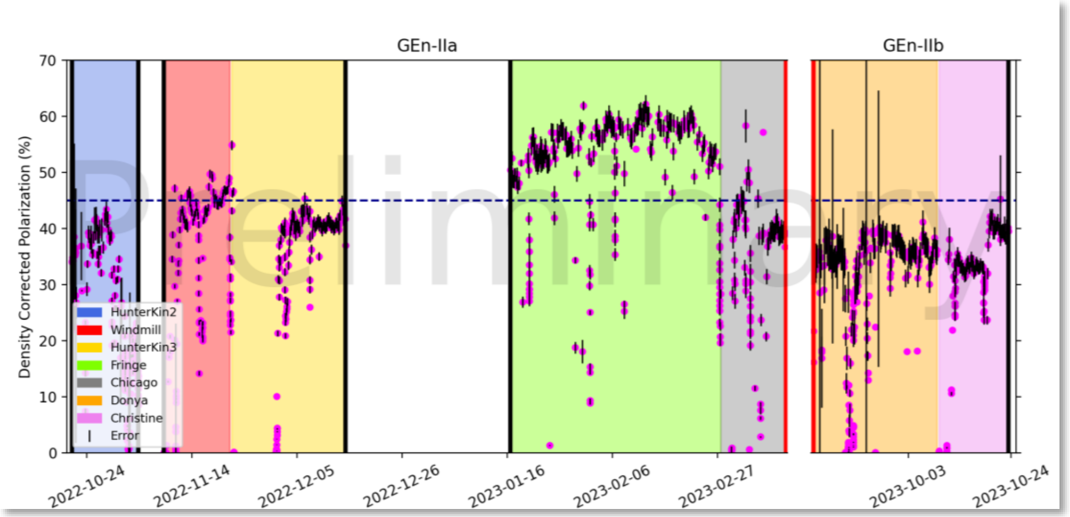


Spin-exchange optical pumping to polarize neutrons



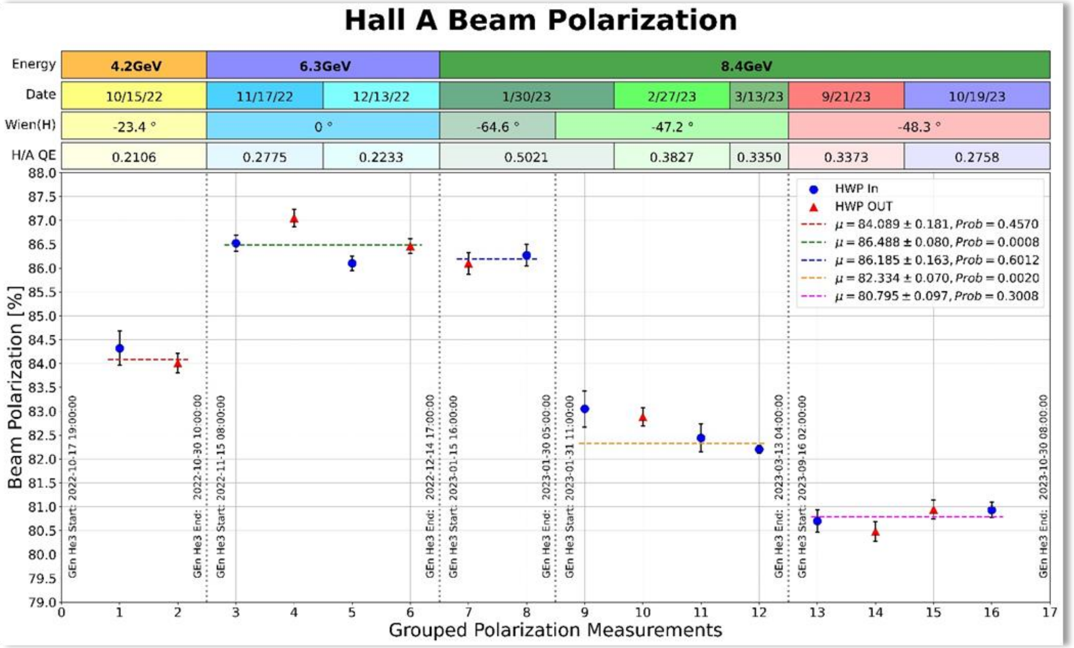
Schematic of the ^3He target

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

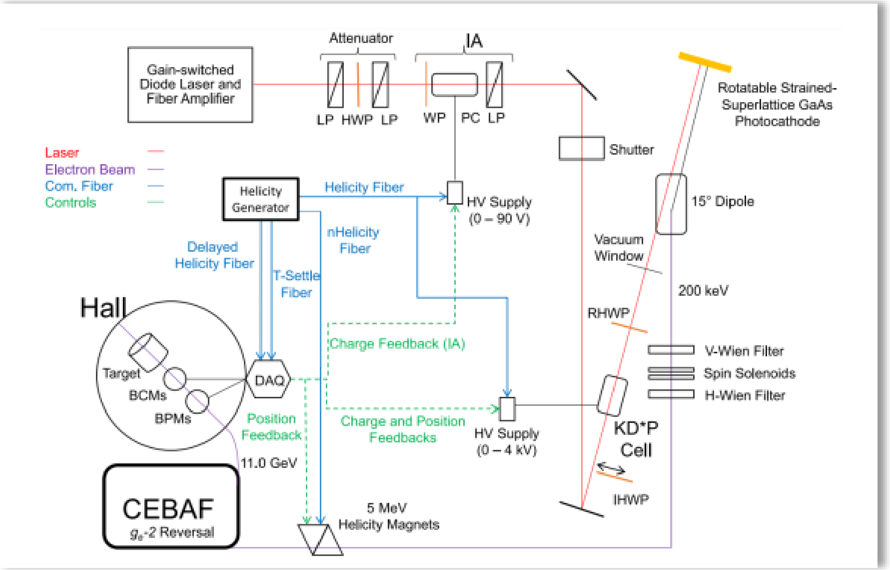


Results of all NMR Measurements during GEn-II * **Hunter Presley**

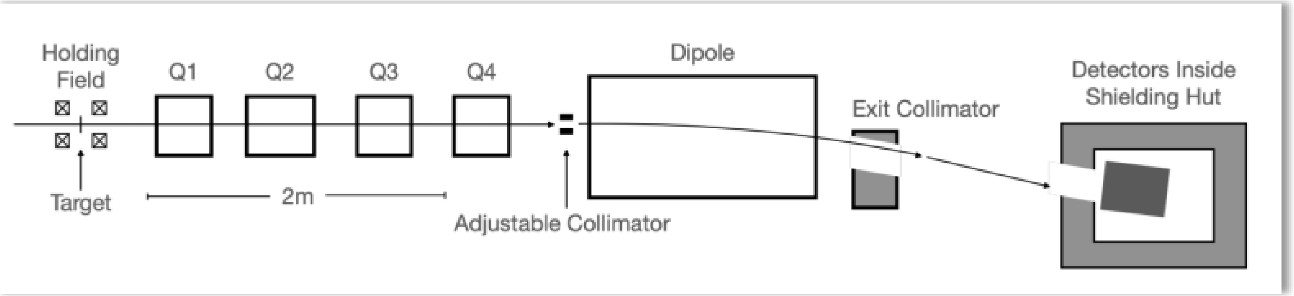
Beam Polarization



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

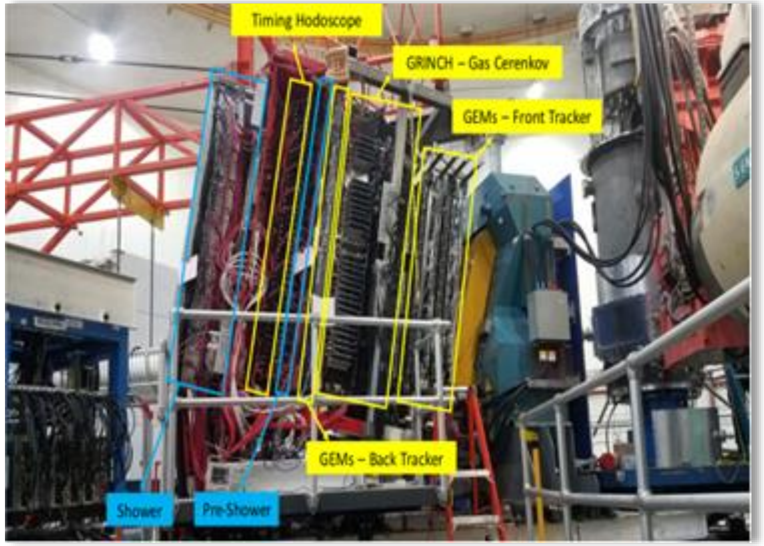
Electron and Hadron Arms

Electron Arm

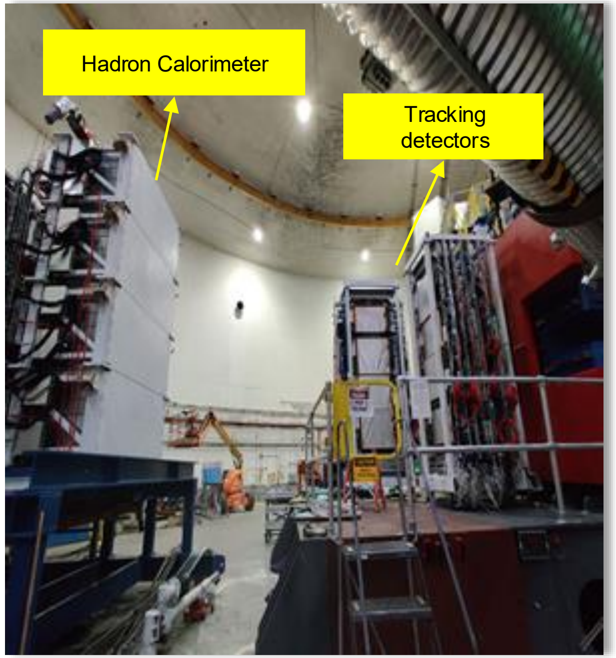
- BigBite magnet : dipole magnet for momentum reconstruction of scattered electrons
- GEM detectors : reconstruct charged particle tracks and momentum using Bigbite magnet optics
- GRINCH : Gas Ring Cherenkov detector for PID
- Timing hodoscope : high-precision timing information
- Pre-shower and shower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



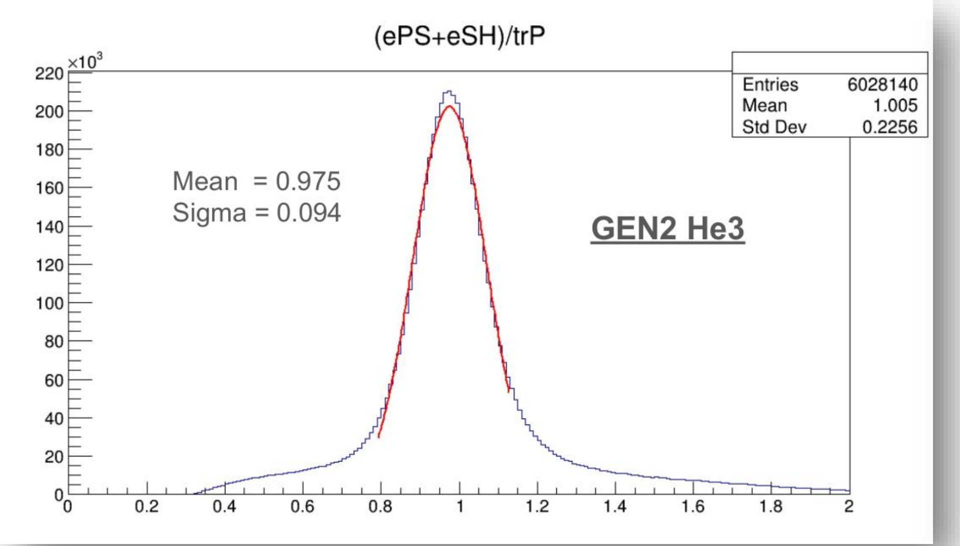
BigBite Spectrometer



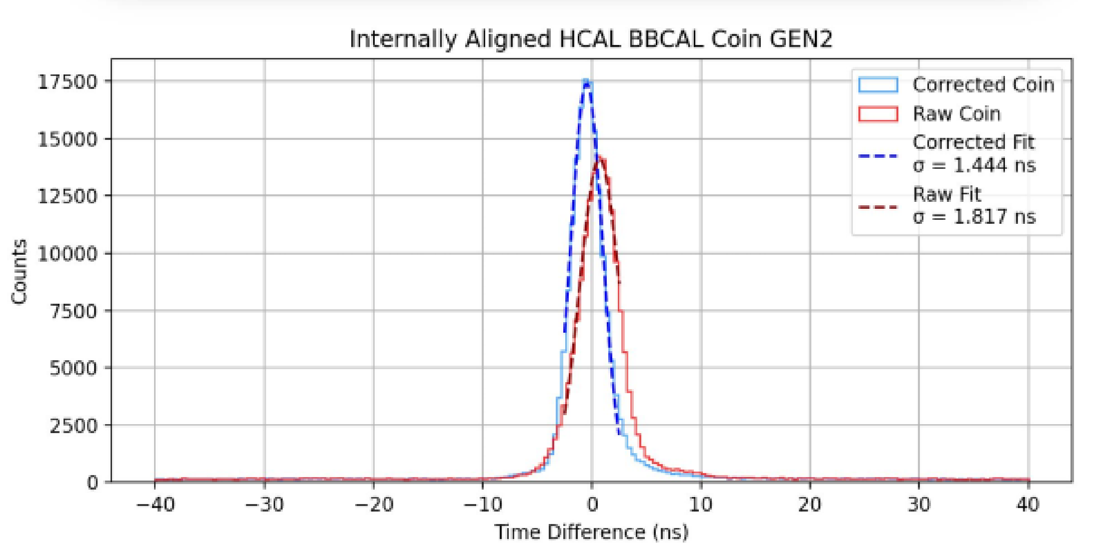
Super BigBite Spectrometer

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

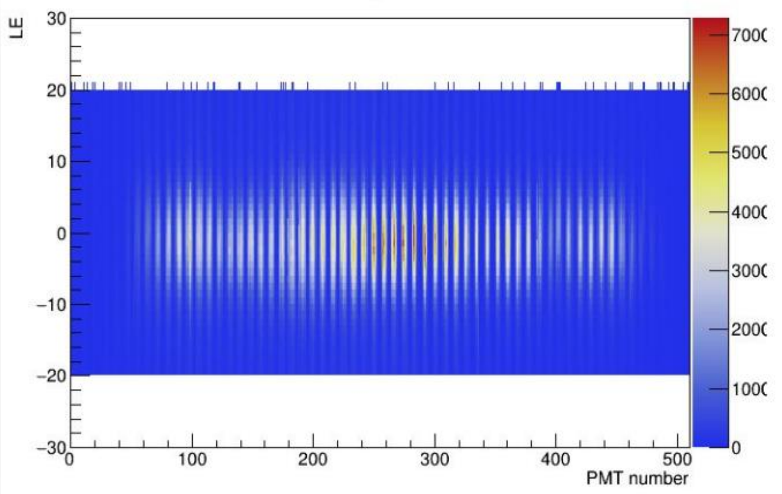


E/p distribution of BBCal for GEN2 He3 data ***Kate Evans**

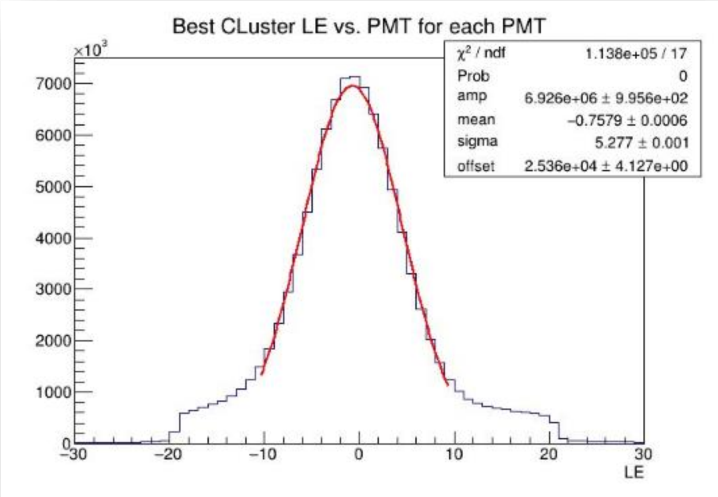


Coincidence time improvement for GEN2 He3 data ***Hunter Presley**

Overall pass2 calibration highlights

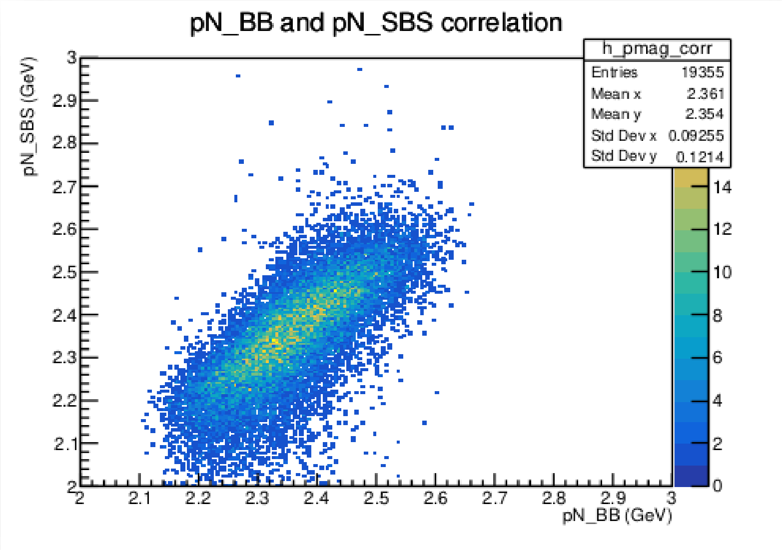


GRINCH leading edge time (ns) vs PMT number for GEN2 He3 data *Jack Jackson

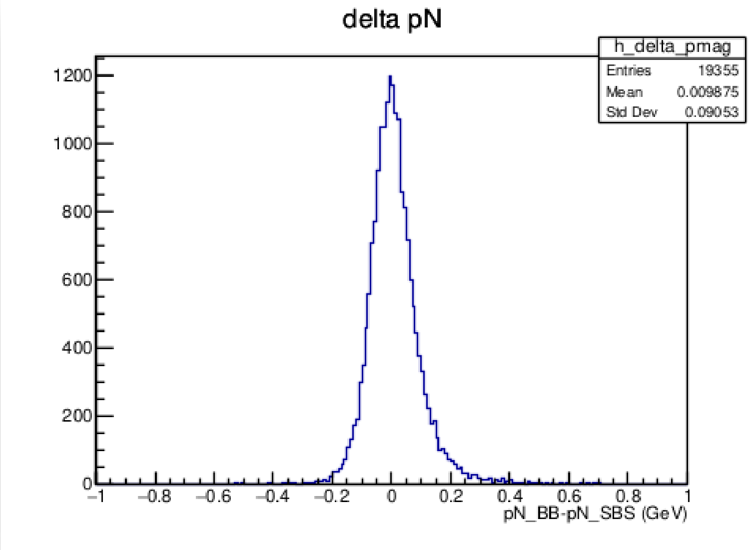


GRINCH leading edge time (ns) distribution for GEN2 He3 data *Jack Jackson

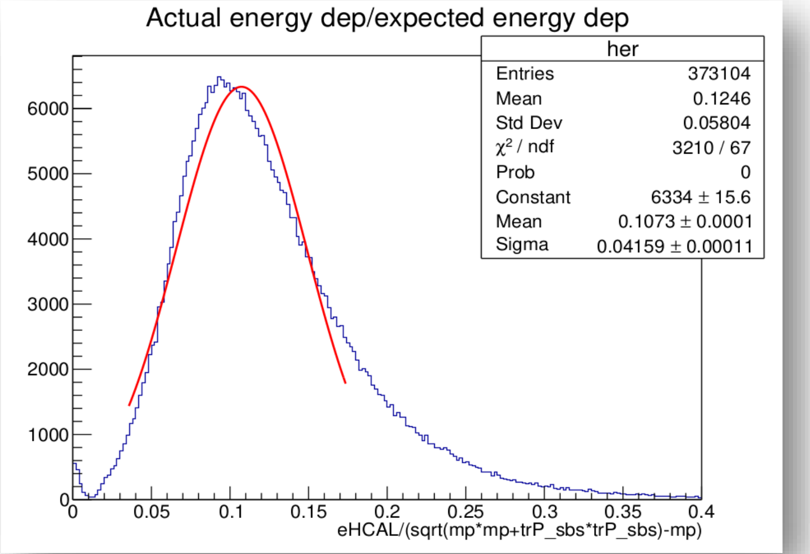
All kinematics : https://sbs.jlab.org/cgi-bin/DocDB/private/ShowDocument?docid=694



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



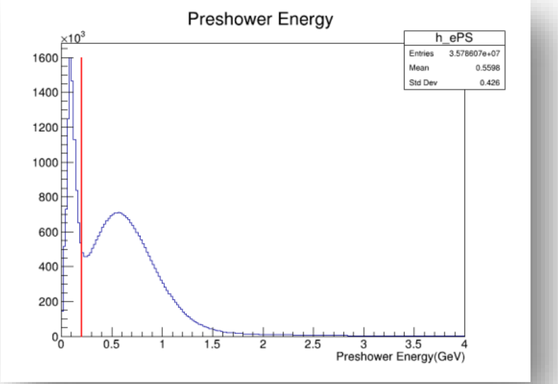
Distribution of difference between the electron arm and hadron arm reconstructed |pN| for GEN2 He3 data



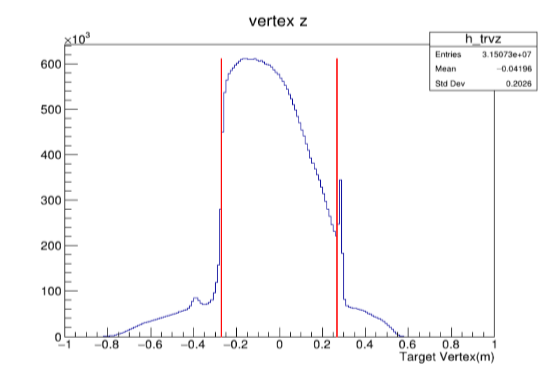
HCal energy sampling fraction distribution for GEN2 He3 data

Event Selection

- Track cuts: number of hits on track, track *chi²/ndf* , track vertex (|vz|<0.27m) -> track originates from the target
- Particle identification: Pre-shower energy (ePS> 0.2 GeV) or Grinch cuts -> reject pions in electron arm
- E/p cut -> quasi-elastic events
- Invariant Mass (W^2)-> quasi-elastic events
- Coincidence time (coin) -> reduce accidental contamination
- Hcal energy (eHCAL) -> reduce background contamination

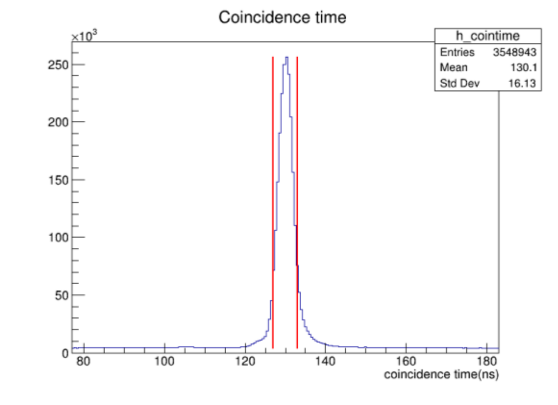


Pre-shower energy distribution for Gen2 ^{3}He data (with vz, and eHCAL cuts)

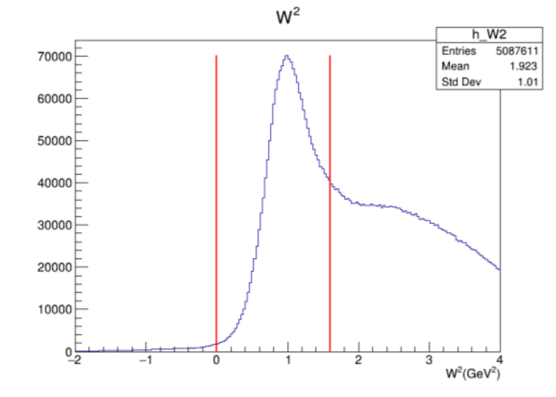


Vertex z distribution for Gen2 ^{3}He data (with ePS, and eHCAL cuts)

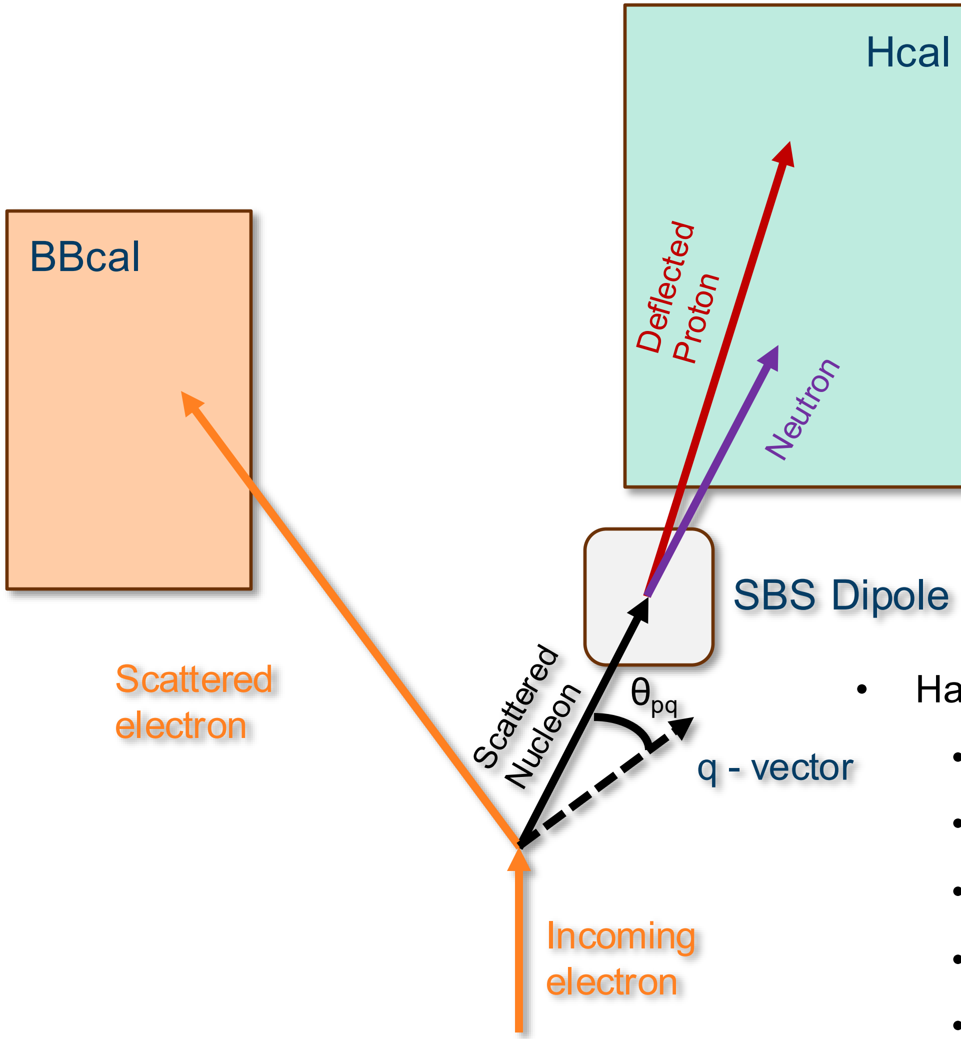
Coincidence time distribution for Gen2 ^{3}He data (with vz, eHCAL, ePS, E/p and W2 cuts)

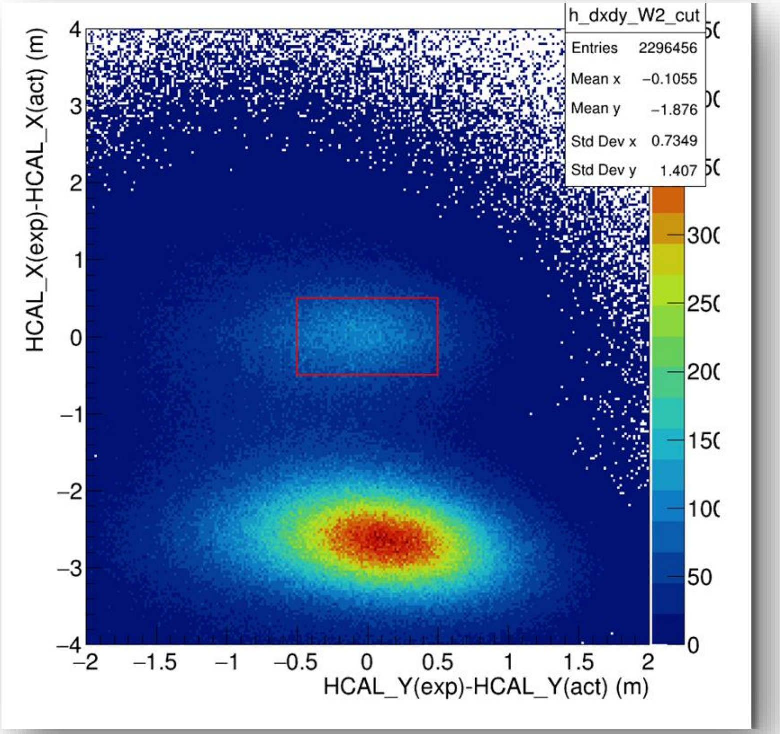


W^2 distribution for Gen2 ^{3}He data (with vz, eHCAL, ePS, E/p and coin cuts)

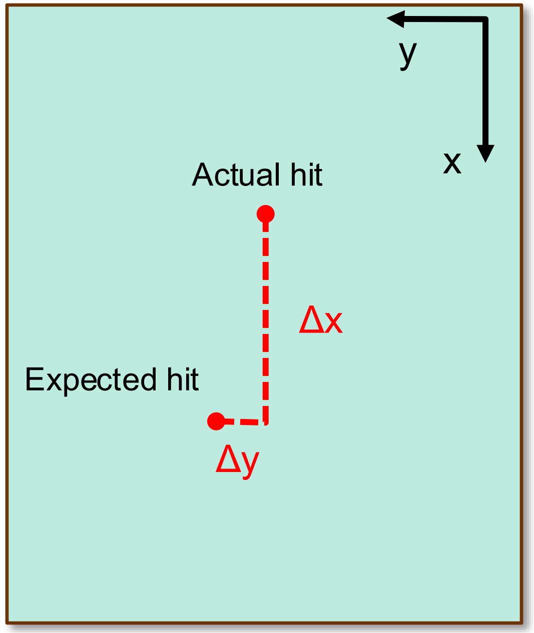


PID in Hadron Arm





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

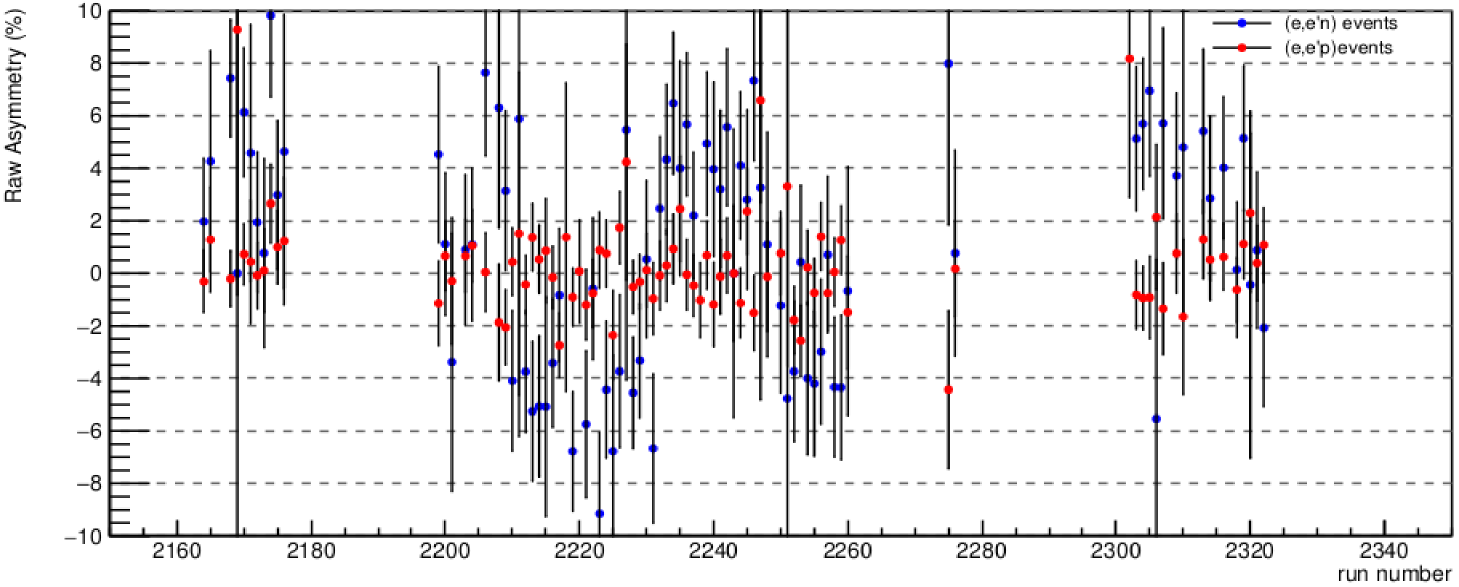


Face of the HCal

- Hadron Particle Identification (Kin2: |dx|<0.5m and |dy|<0.5m)
  - 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

$$h_{raw} = P_{IHWP} P_{kin} h_{meas} \qquad A_{raw} = \frac{N^+ - N^-}{N^+ + N^-} \qquad A_n = \frac{A_{raw} - \sum_{x \neq n} f_x A_x}{f_n}$$



Raw asymmetry across runs for GEN2 ^{3}He 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%

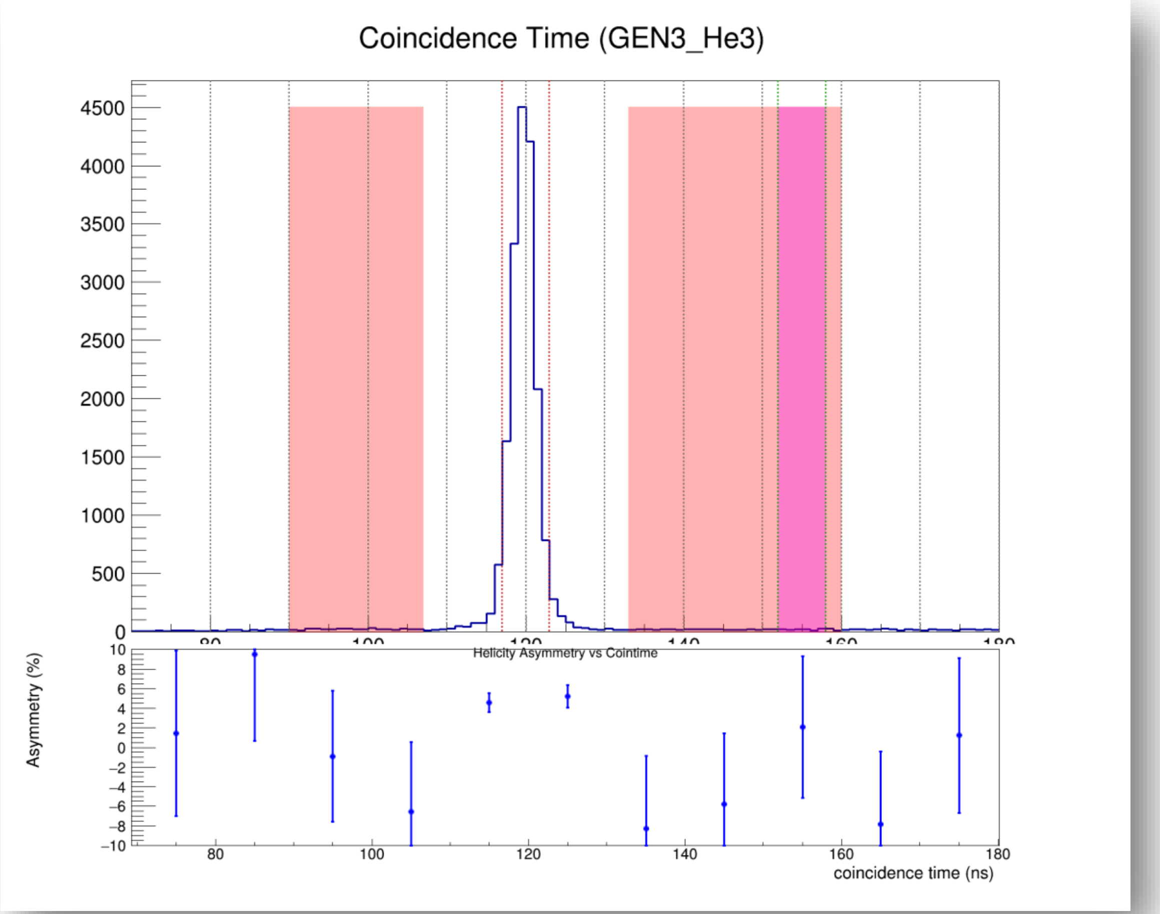
$$A_n = P_{beam} P_{^3He} P_n A_{phys}$$

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

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

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 ^{3}He data

Nitrogen in the target chamber

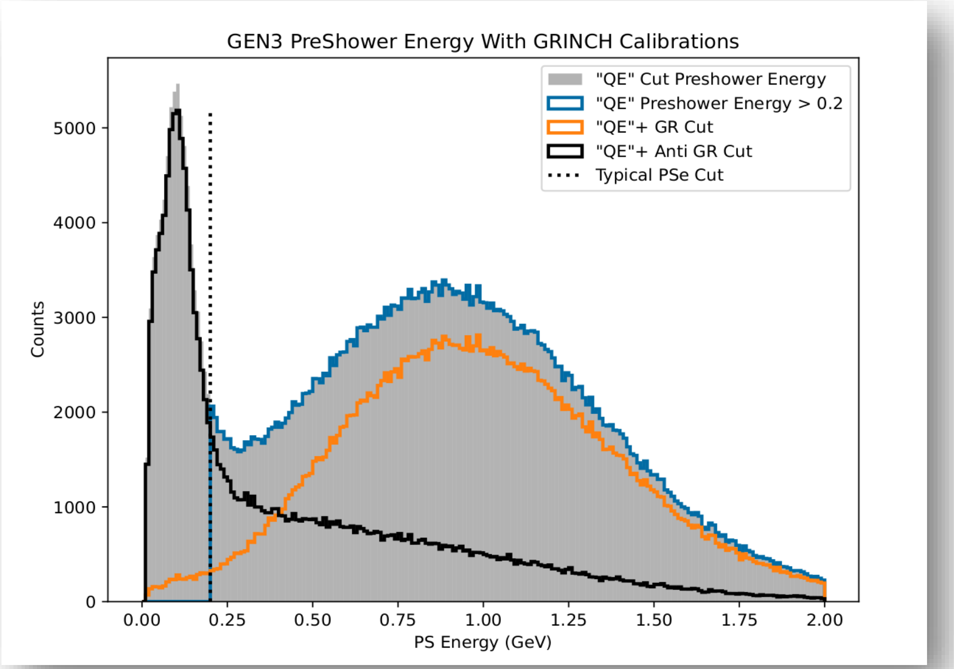
- The polarized 3 He targets are filled with approximately ~1-2% of Nitrogen to reduce depolarization effects from the de-excitation of the alkali atoms in the pumping chamber
- Because of this, however, quasi-elastic neutron events which come from nitrogen are present in the data sample and must be accounted for
- The nitrogen correction must account for
  - difference in cross sections between N_2 and ^{3}He -> geant4 simulations -> *S*
  - fraction of neutrons present from N_2 over the fraction of neutrons present from ^{3}He
- 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

$$\mathrm{f}_{N_2} = \frac{14 \cdot n_{\mathrm{N}_2}}{14 \cdot n_{\mathrm{N}_2} + n_{\mathrm{He}^3}} \cdot S$$

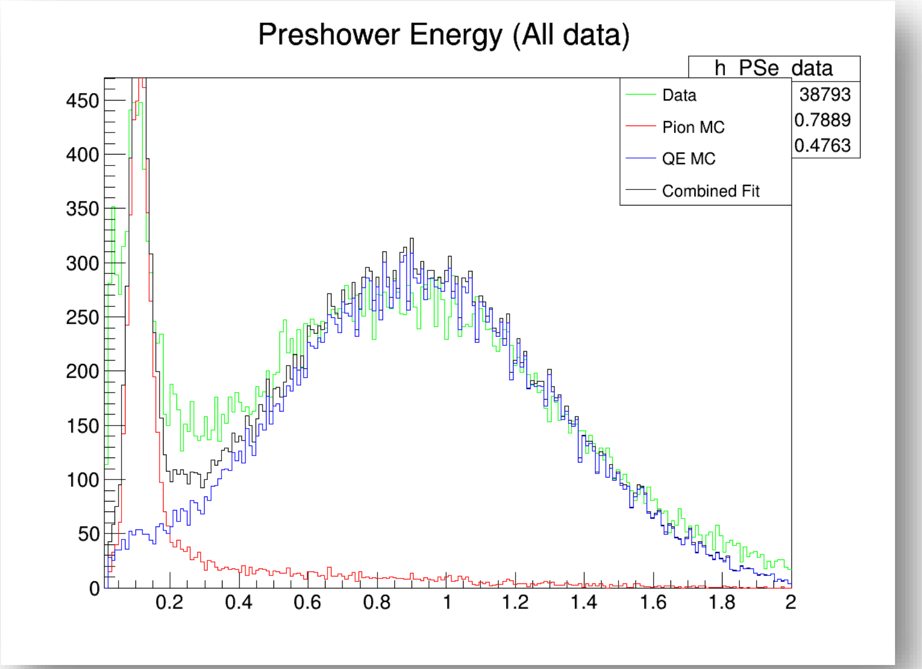
$$S = \frac{n_{\mathrm{N}_2}^{\mathrm{sim}}}{n_{\mathrm{He}^3}^{\mathrm{sim}} \cdot 14}.$$

where n_{N2} 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 ^{3}He with GRINCH cuts ***Jack Jackson**



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

- Pions deposit less energy (MIPs) in the BBCal compared to electrons -> cut on deposited energy (ePS>0.2GeV)
- 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

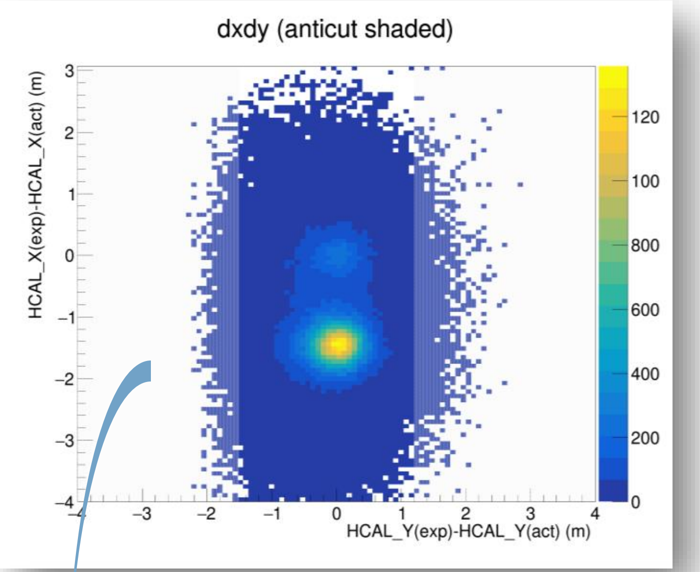
Simulation fitting

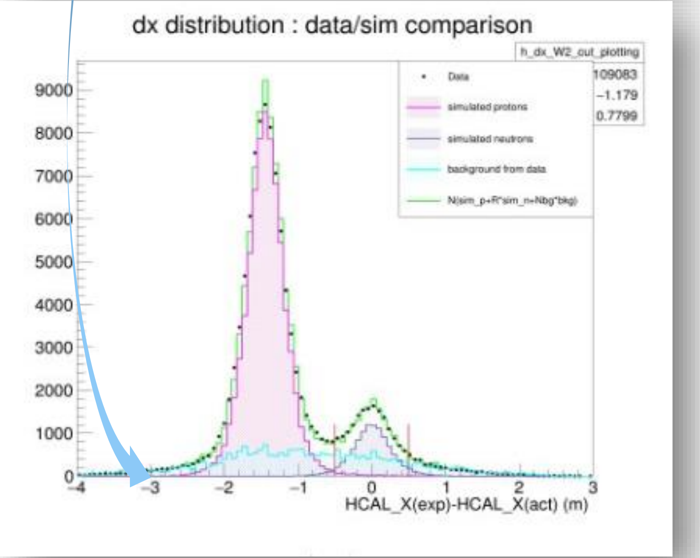
G4SBS
- G4SBS was created using the Geant4 Framework
- Simulation output is digitized and processed exactly like real data
- Simulated and real data are compared to extract the physics

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

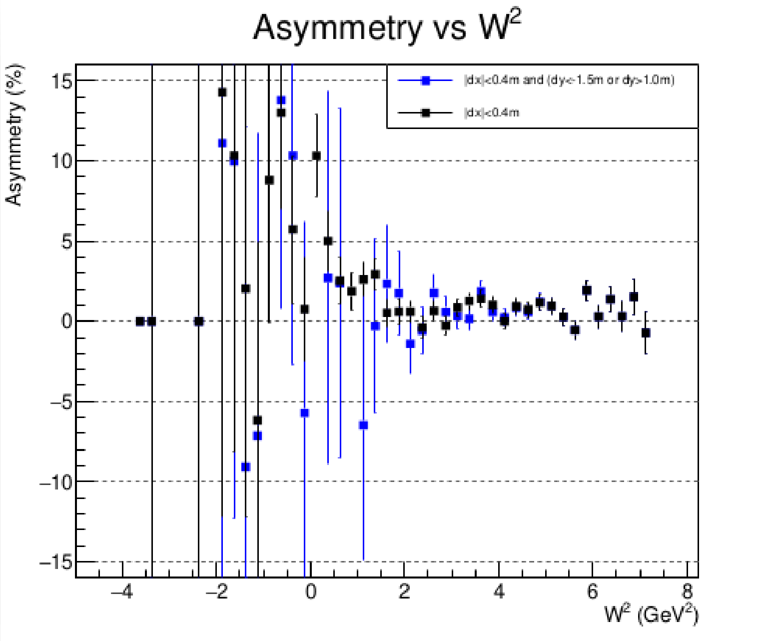




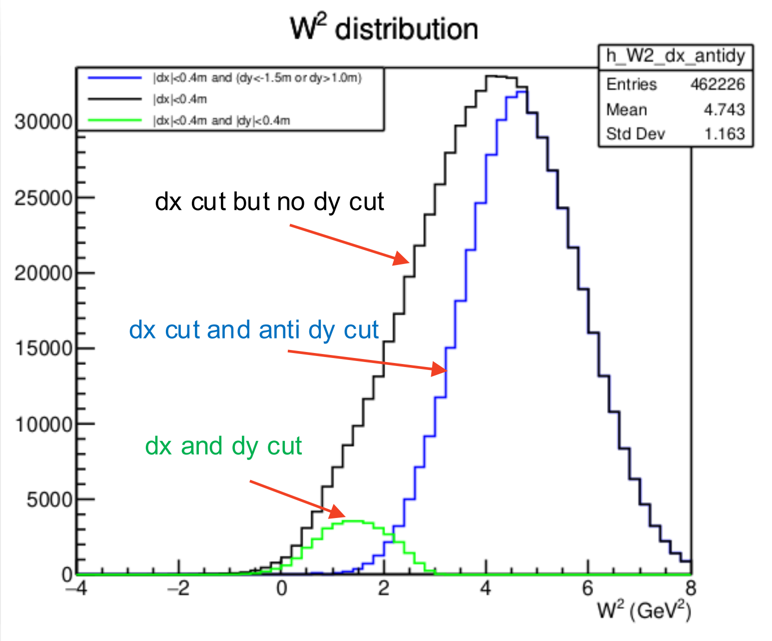
delta-x vs delta-y distribution (top) and
delta-x distribution with anti-cut background distribution for GEN3 ^{3}He data

- Fraction of Inelastic and proton contamination under the neutron peak are obtained by simulationd fitting method

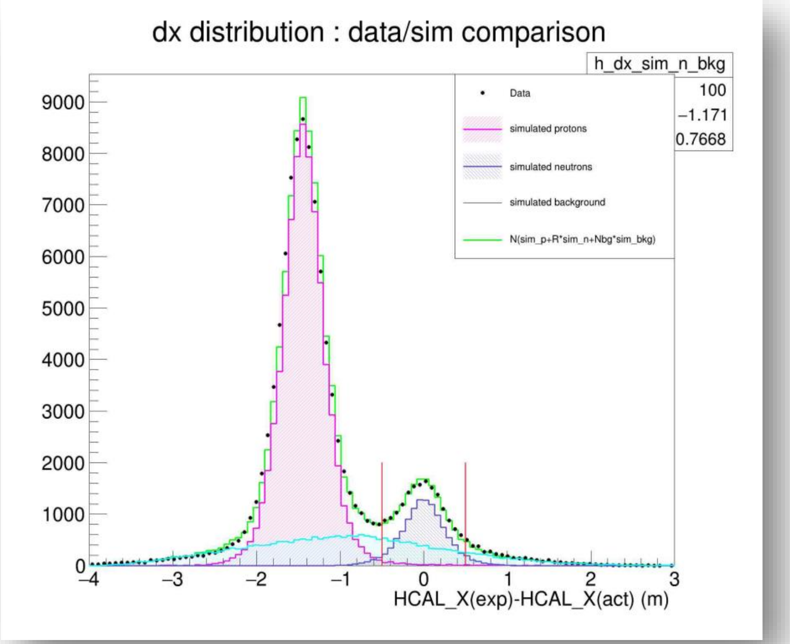
Inelastic background



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



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



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

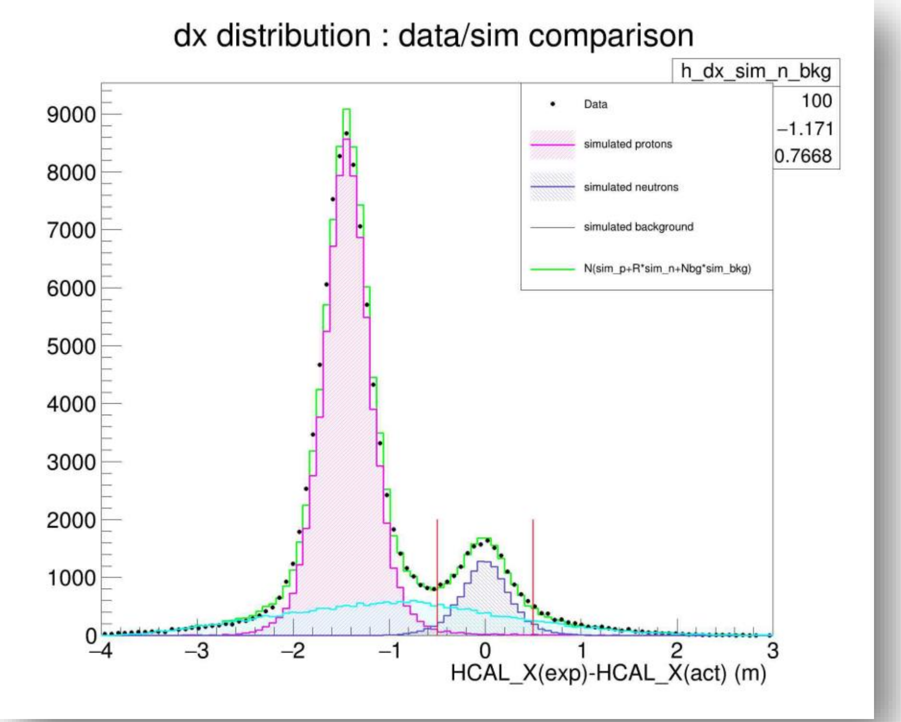
- Understanding the inelastic background is challenging
- Anti dy method is questionable because it assumes a similar shape in the quasi-elastic region
- The main inelastic cross section model for G4SBS is the 2008 and 2010 empirical fit to proton and deuteron data by M.E. Christy and P.E. Bosted – **Jacob 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 ^{3}He 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 ~(-3%)

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

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

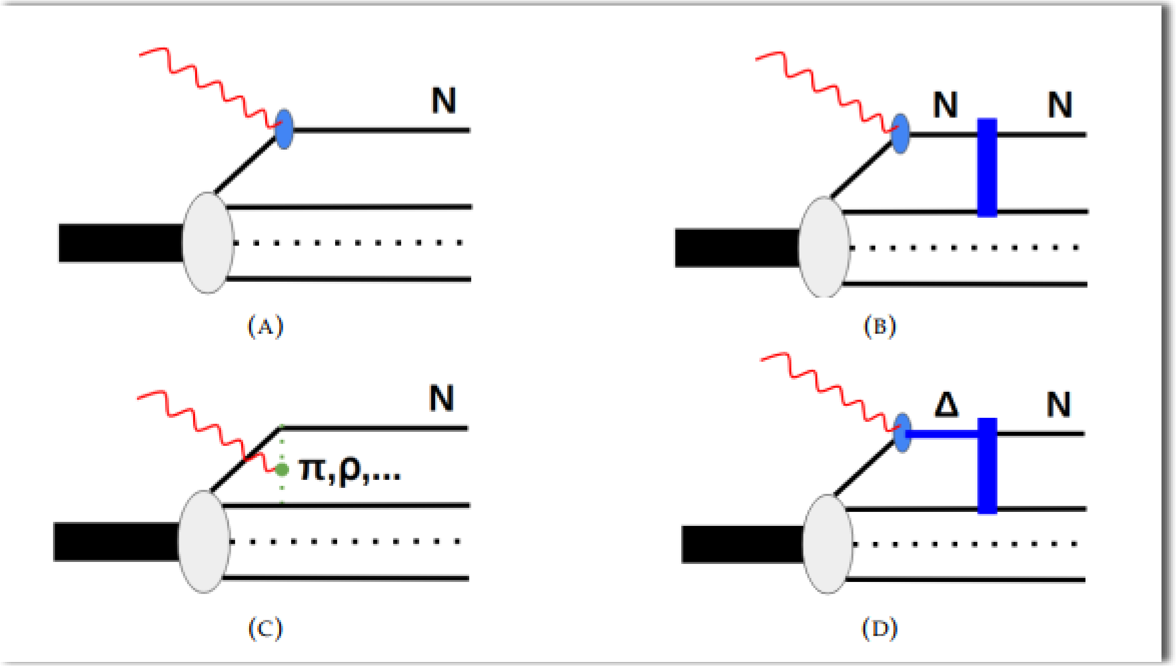


Magenta color protons using g4sbs QE simulation for GEN3 ^{3}He data

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

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

GEn Extraction

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

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

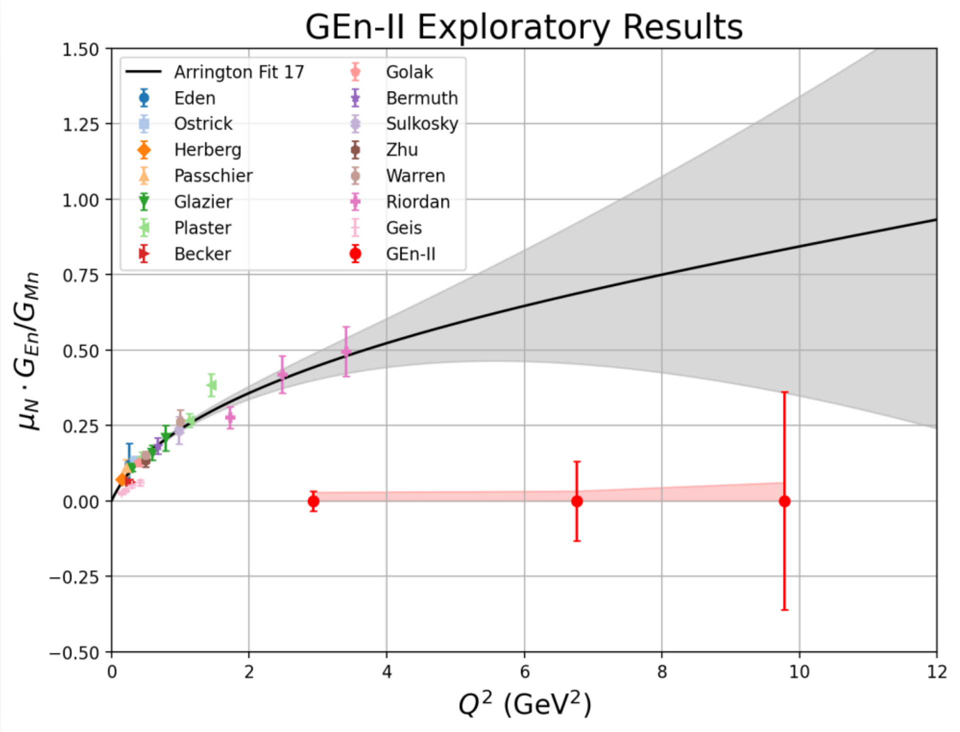
After taking the finite acceptance into account, finally we are ready to extract the ratio. Then using the existing world data for G_M^n, we get G_E^n

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

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 ^{3}He 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



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

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

GEn-II Students and Spokespeople

Kate Evans

Jack Jackson

Faraz Chahili

Hunter Presley

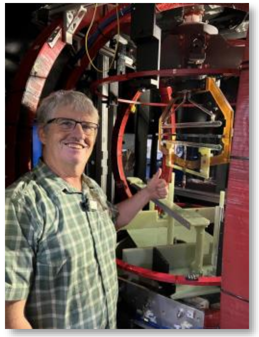
Vimukthi Gamage

Jacob Koenemann

Braiain Mederos

Gordon Cates

Todd Averett



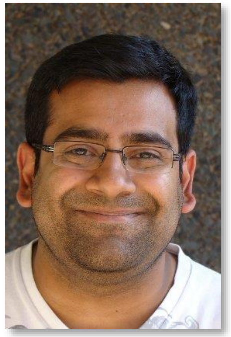
Bogdan Wojtsekhowski

Spokespeople!

Special Thanks!

Andrew Puckett

Arun Tadepalli



Gary Penman

Graduated March 2025

Sean Jeffas

Graduated July 2024

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- SBS Collaboration – Bogdan Wojtsekhowski, Andrew Puckett, Gordon Cates, Todd Averett, Arun Tadepalli, Xiaochao Zheng**,** Eric Fuchey, Mark Jones, Alex Camsonne, Holly Szumila-Vance, and all
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- JLab Staff
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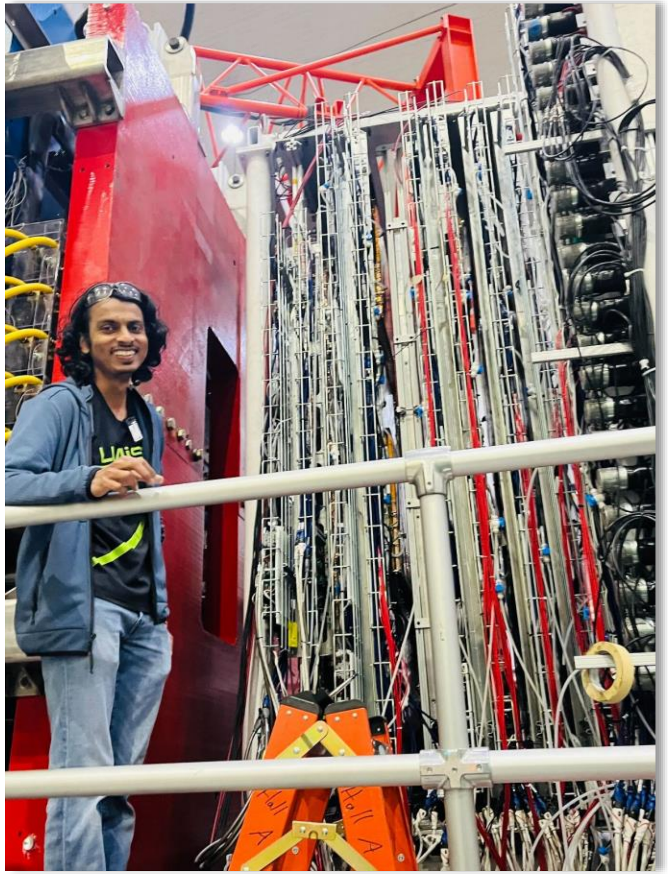
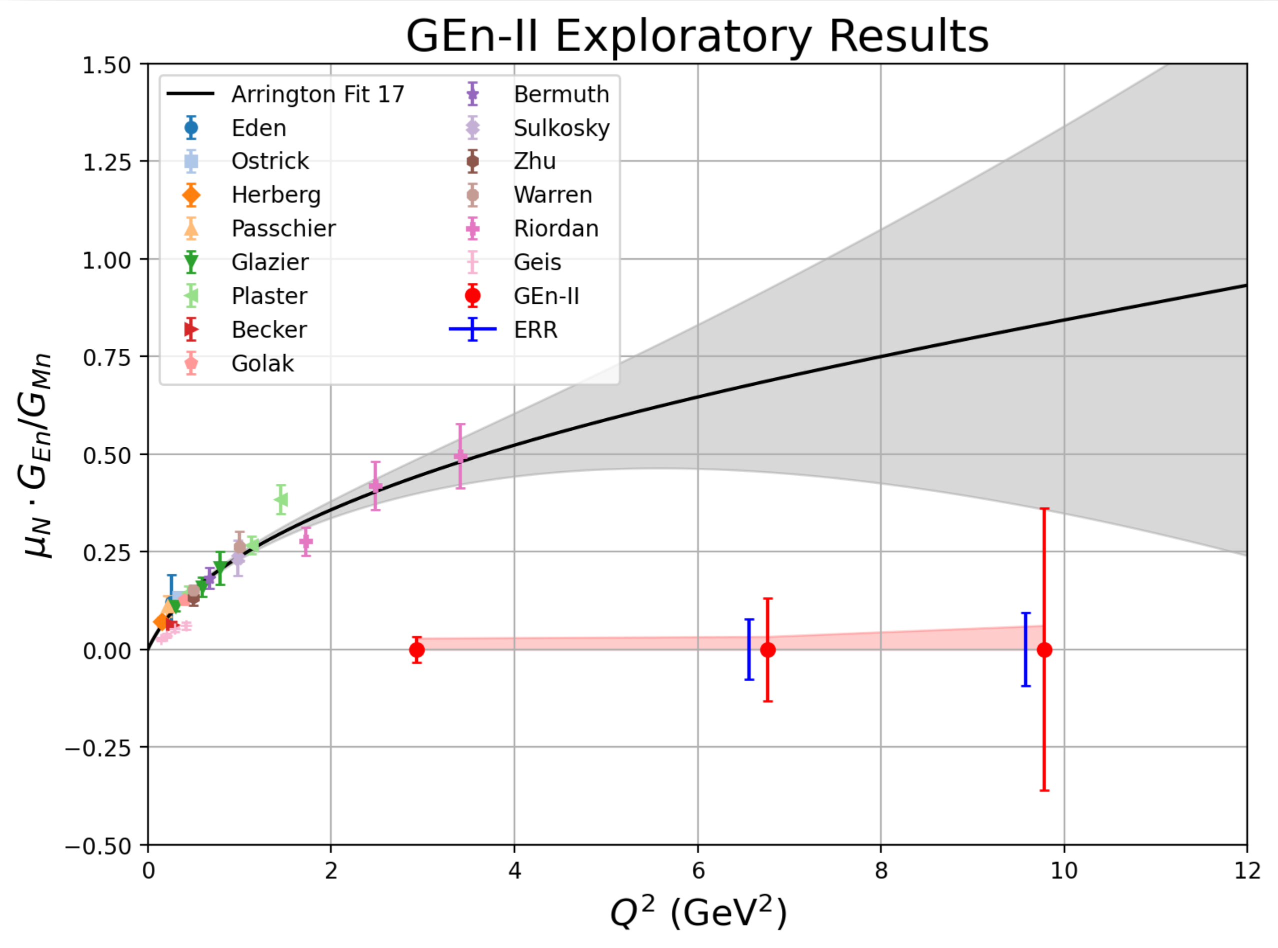


Supplemental

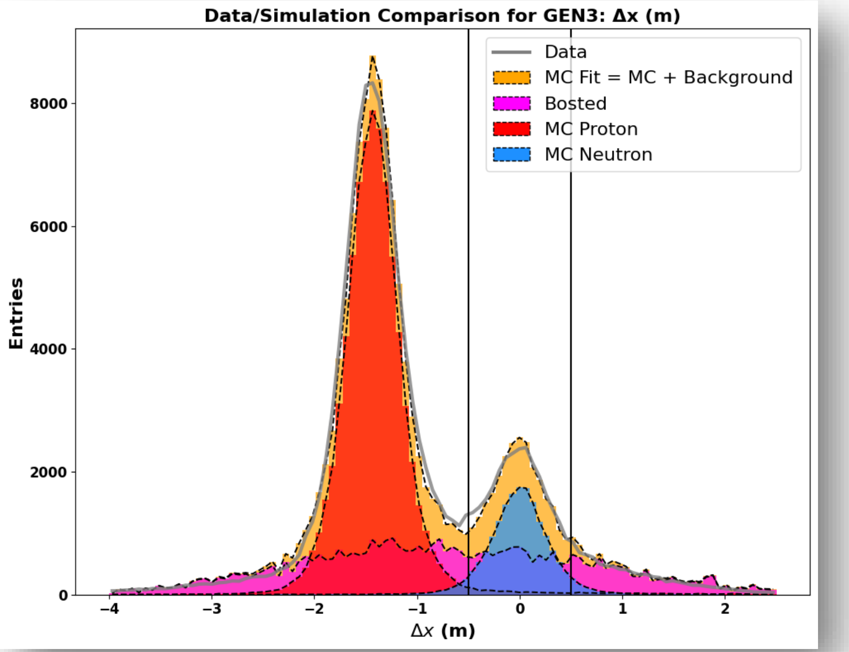
GEn-II Projected error

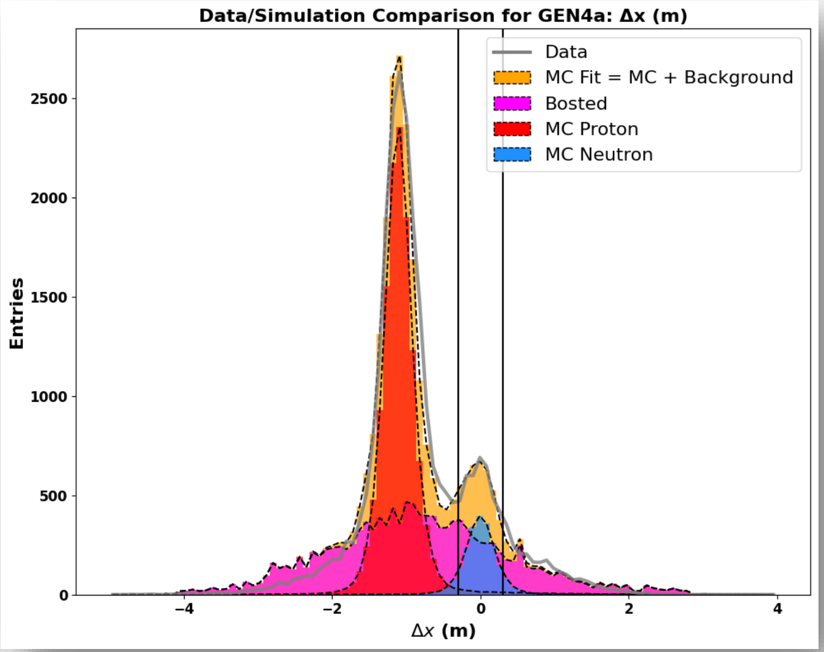


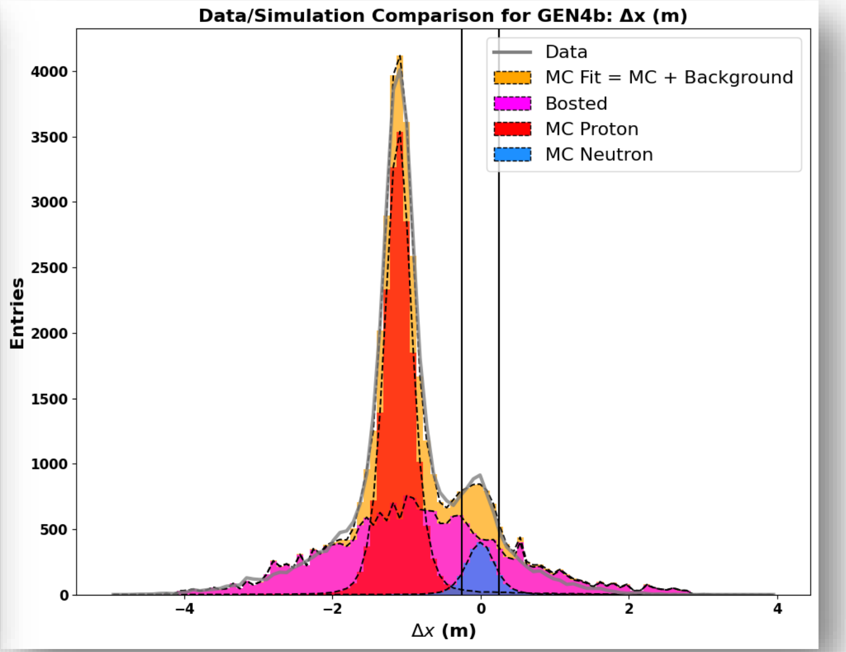
World data with the projected Q^2 points with error bars

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

Simulation Fitting







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

Reference

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