University of Glasgow

Jefferson Lab

GEN-II Analysis Status

16th Jan 2024
Hall A Collaboration Winter Meeting

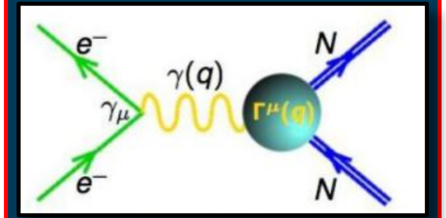
Gary Penman

WORLD CHANGING GLASGOW

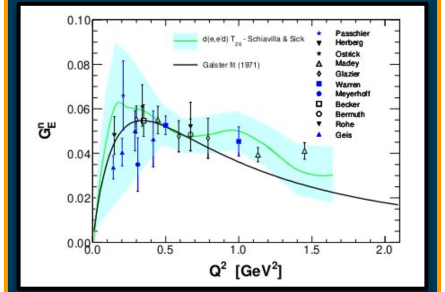
A WORLD TOP 100 UNIVERSITY

GEN-II: Neutron Electric Form Factor at High Q^2

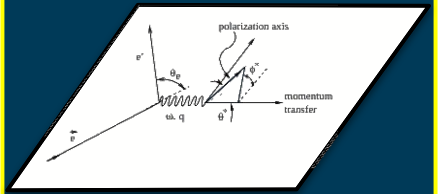
Double polarized semi-exclusive 3He(e,e'n)pp quasi-elastic scattering



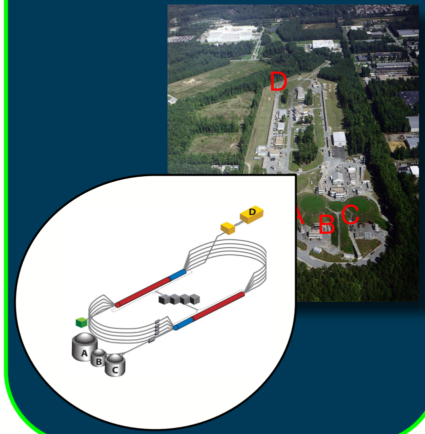
Extract Sachs Form Factor GEn with precise high Q2 GMn data.



Measure transverse asymmetry $A_\perp$ of cross section



Hall A - Thomas Jefferson National Accelerator Facility



Nucleon Electromagnetic Form Factors

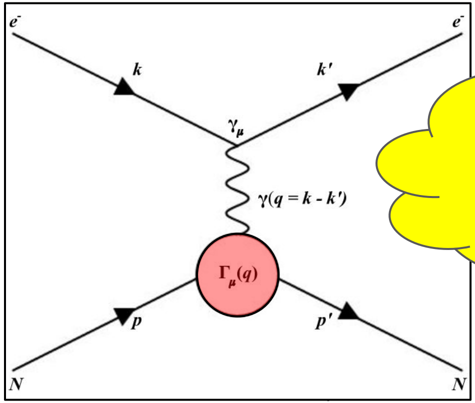
Pauli, Dirac FFs

$$F_{1p}(0) = 1$$
$$F_{2p}(0) = \mu_p - 1$$
$$F_{1n}(0) = 0$$
$$F_{2n}(0) = \mu_n$$

Sach's EMFFs

$$G_E^{p(n)} = F_1^{p(n)} - \tau F_2^{p(n)}$$
$$G_M^{p(n)} = F_1^{p(n)} + F_2^{p(n)}$$

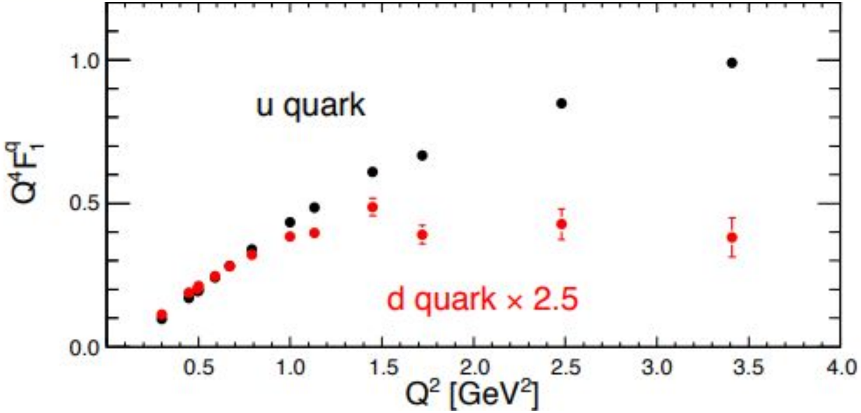
$$\tau \equiv \frac{Q^2}{4M^2}$$



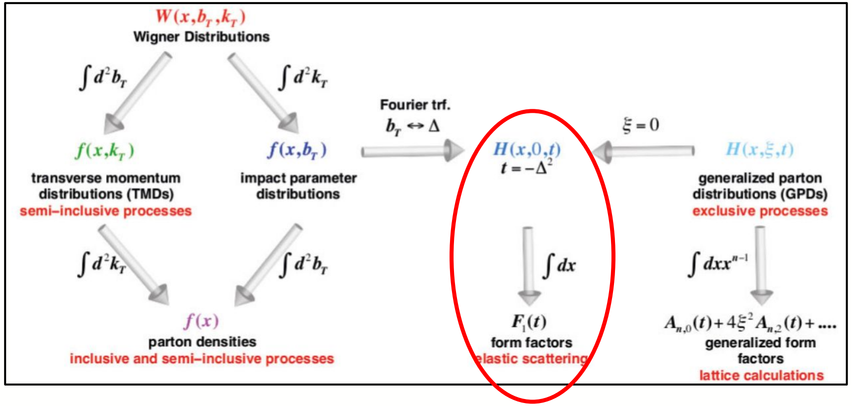
$$\Gamma_\mu(p, p') = \gamma_\mu F_1(Q^2) + \frac{i\sigma_{\nu\mu}}{2M} F_2(Q^2)$$

See G. Cates Talk From 09:00 Today

Nucleon structure is revealed in the Q^2 evolution of the form factors



Flavour decomposition of the nucleon form factors, indicating potential diquark degrees of freedom. G. D. Cates, et. al, PRL. 106, 252003 (2011)



SBS Form Factor Program

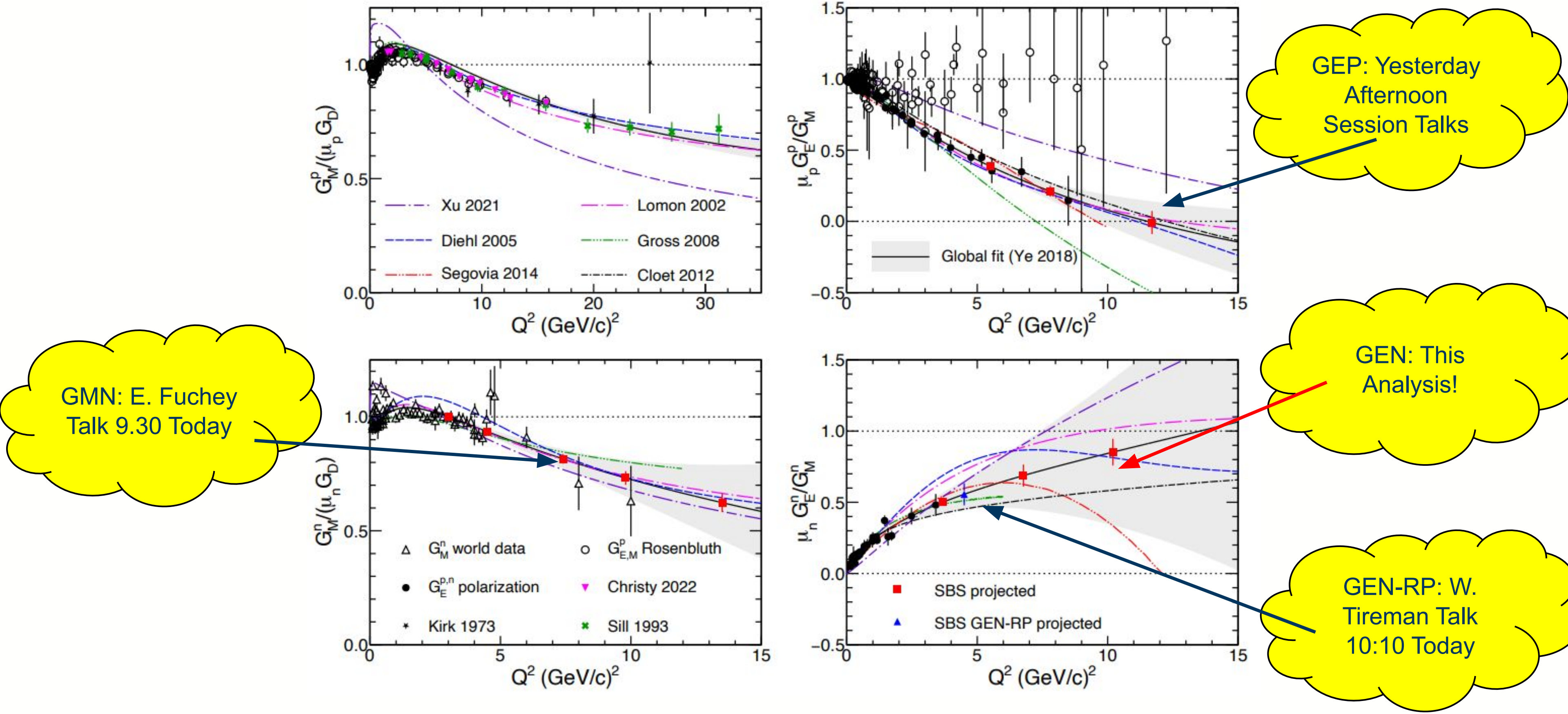
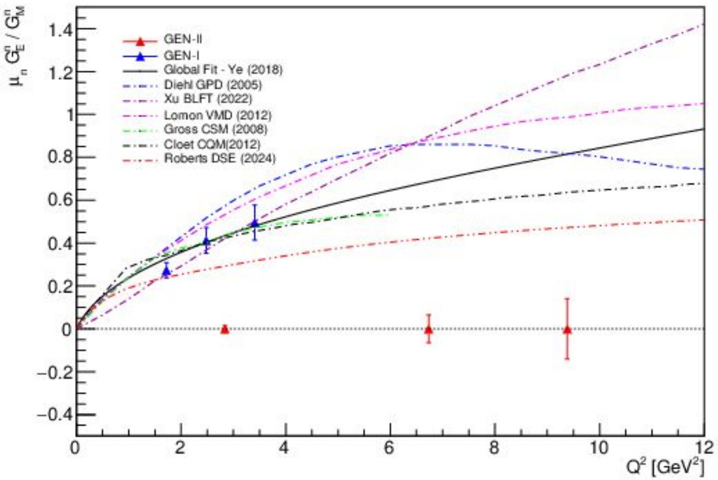


Figure from A. Puckett, *50 Years of QCD*, EPJ C 83, 1125 (2023)

GEN-II: Electric Form Factor of the Neutron

Table 1: Kinematic settings of GEN-II experiment.

KIN	Q^2 [GeV^2]	E_{beam} [GeV]	θ_{BB} [deg]	d_{BB} [m]	θ_{SBS} [deg]	d_{SBS} [m]	θ_{HCAL} [deg]	d_{HCAL} [m]	$p_{e'}$ [GeV]	p_p [GeV]
GEN2	3.0	4.291	29.5	1.63	34.7	2.8	34.7	17	2.69	2.37
GEN3	6.83	6.373	36.5	1.63	22.1	2.8	21.6	17	2.73	4.51
GEN4	9.82	8.448	35.0	1.63	18.0	2.8	18.0	17	3.21	6.11



Statistical projections based on A. Puckett calculations August 2023

- GEN-II ran from Oct 2022 - Mar 2023 (GEN2,3,4a) and Sept - Oct 2023 (GEN4b).
- Approximate statistics in “good” runs collected at each kinematic are given below.
- A re-evaluation of the “good” run list will be performed for all kinematics.
- This talk will attempt to summarise the latest work in calibrations and analysis by students in the collaboration, towards realising physics results.

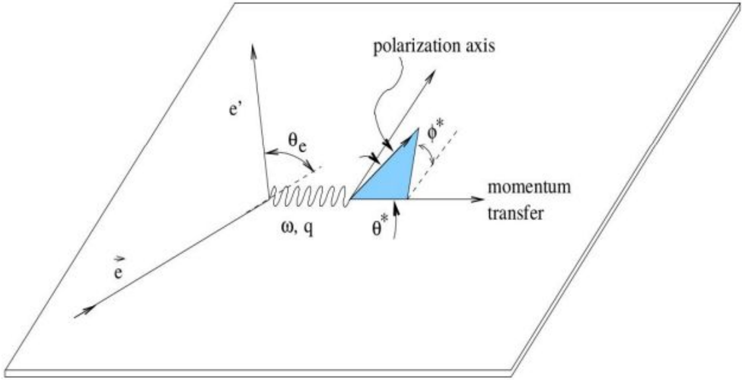
KIN	N_{event} [M]
GEN2	183
GEN3	520
GEN4a	171
GEN4b	390

Double Polarization Method

Longitudinally polarised electron on a transversely polarised neutron target:

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

Σ corresponds to the unpolarized cross section.
Δ corresponds to the polarized cross section.
h is helicity (± 1)



$$A_N = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{\Delta}{\Sigma}$$

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

The sum of background modifications to the raw asymmetry:

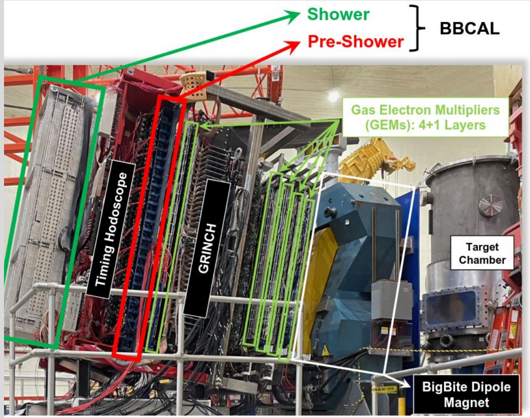
- Timing Accidentals
- Inclusive DIS background
- Pions mis-ID as electrons in Bigbite
- QE protons under neutron peak
- QE scattering from N2 in target cell
- Nuclear effects

$$A_{\text{phys}} = \frac{A_{\text{raw}} - \Sigma_\chi f_\chi A_\chi}{P_{\text{He}^3} P_{\text{n}} P_{\text{beam}} (1 - \Sigma_\chi f_\chi)}$$

GEN-II Experimental Setup: SBS

Electron Arm: Bigbite

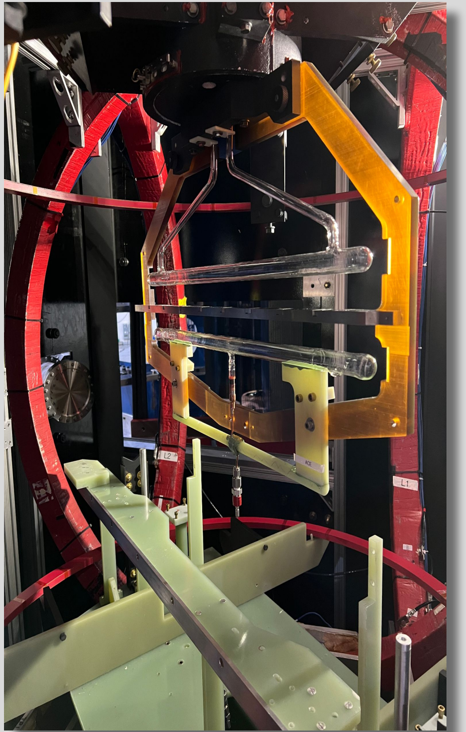
- 750A Dipole Magnet
- Full Detector Stack
  - Calo Trigger
  - GEM Tracking
  - Cherenkov
  - Timing Hodoscope



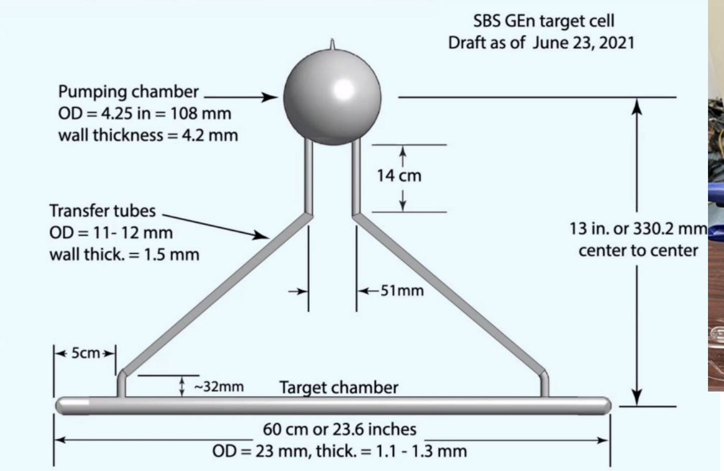
Nucleon Arm: SBS

- 2100A Dipole Magnet
- Hadron Calorimeter
- GEMS (Some Runs)

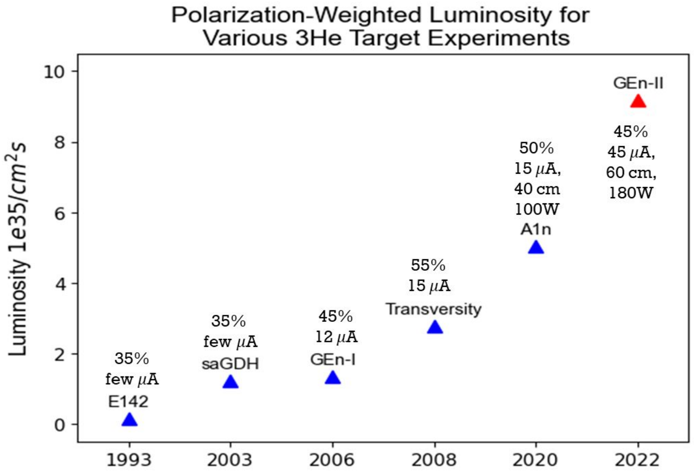
Polarised ^{3}He Target

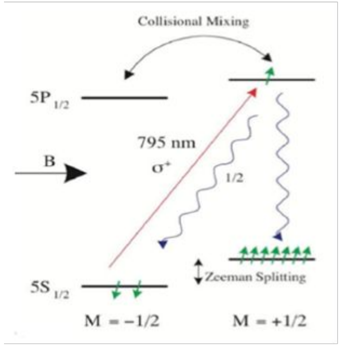


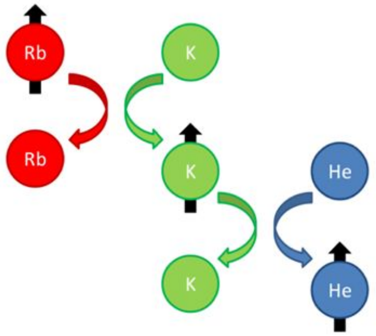
Polarised ^{3}He Target

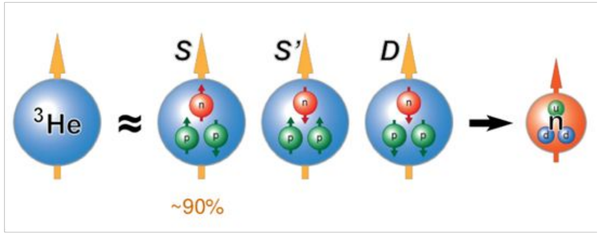


Target Cell Under Preparation in the Lab



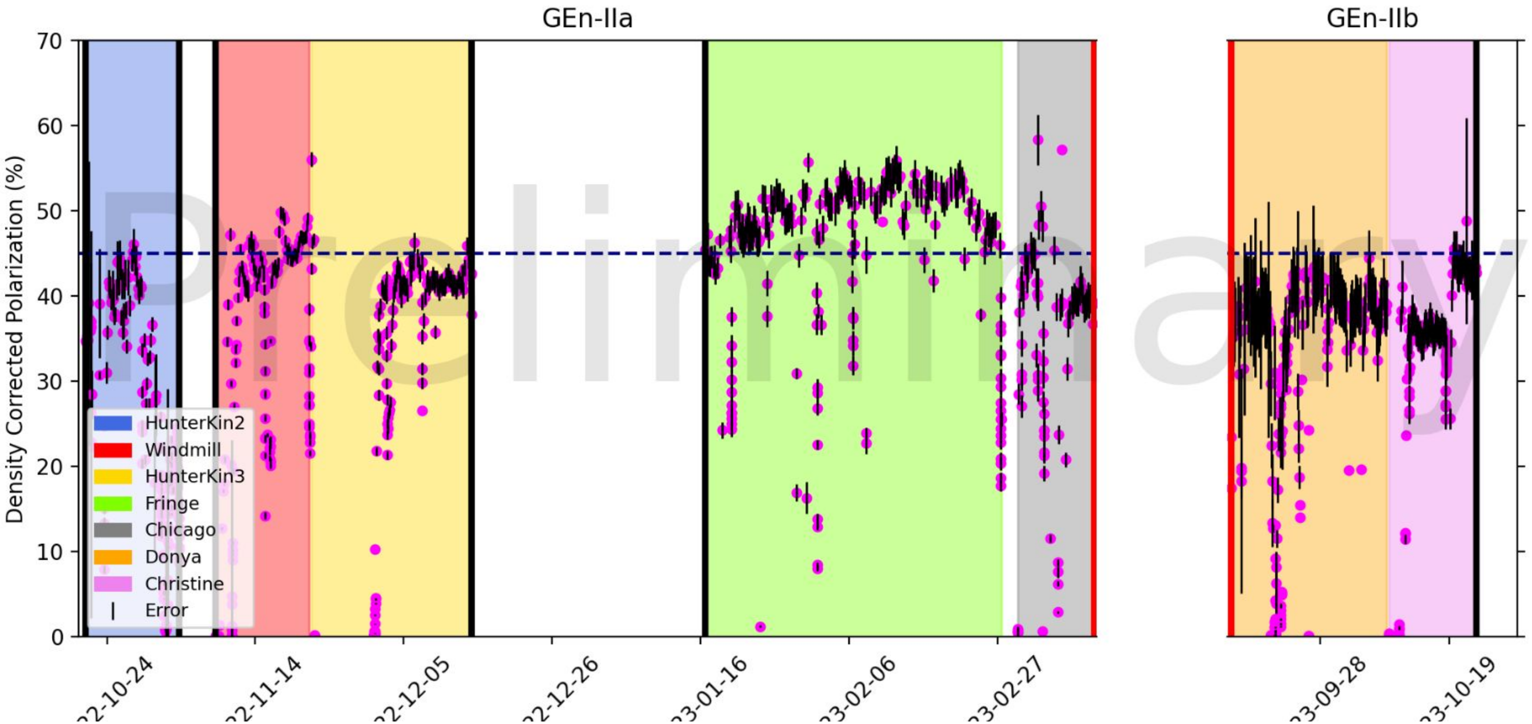






Images from A. Tadepalli, *A high luminosity polarized He3 target*, QNP 2024

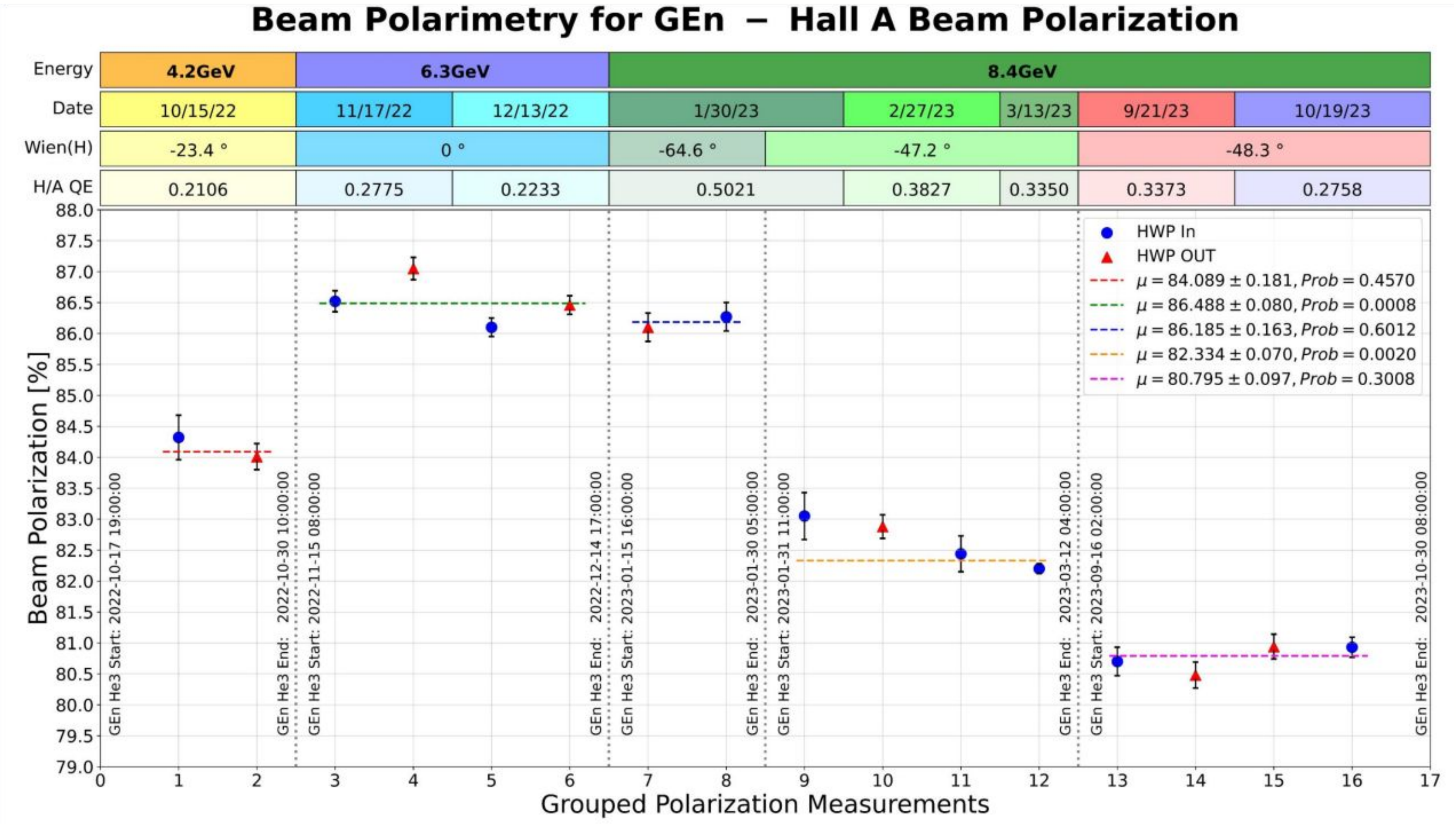
Calibration: Target Polarisation



- Most of the data taken at 45 uA (than previously done at 30 uA for A1n/d2n experiments)
- Offline polarimetry is almost complete
- Hunter is working on calculating our achieved average weighted luminosity.

Credit: Hunter Presley

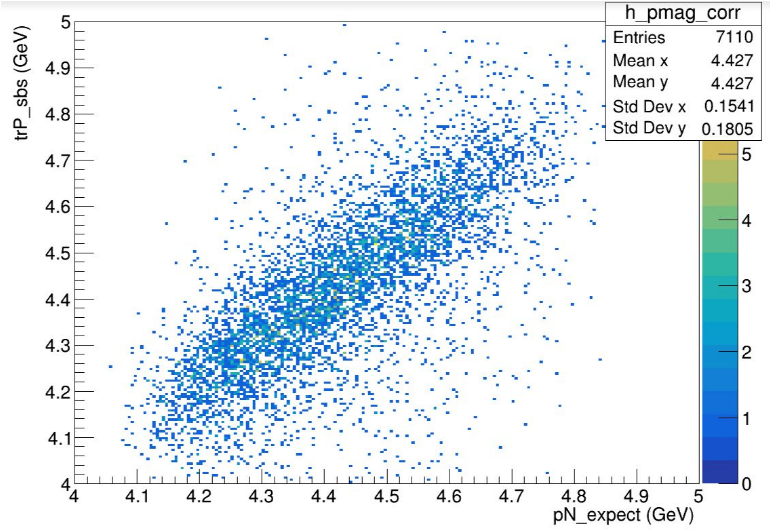
Calibration: Beam Polarisation



Credit: Faraz Chahili

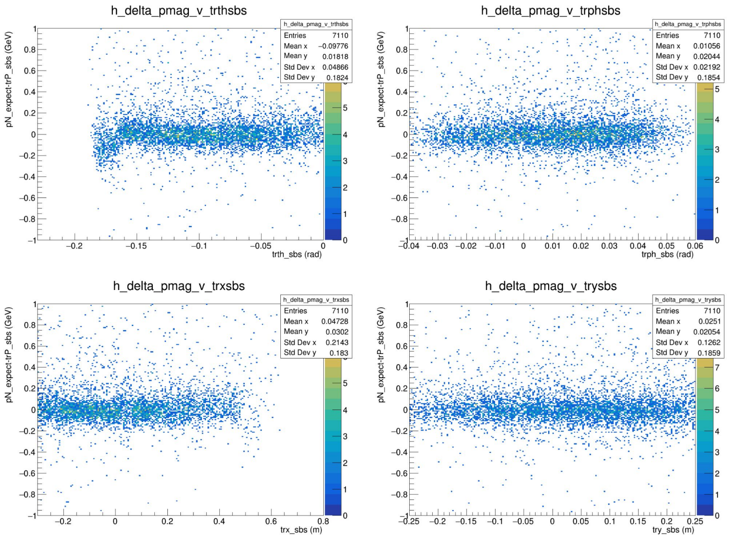
Calibration: GEMS

The BBGEMS and optics were calibrated for pass1. Vimukthi is now investigating the extent to which the SBS GEMS might be used, since they were "on" for a subset of runs in each kinematic.



Momentum reconstructed in SBS GEM tracking vs projected from QE kinematics. GEN3 He3 data.

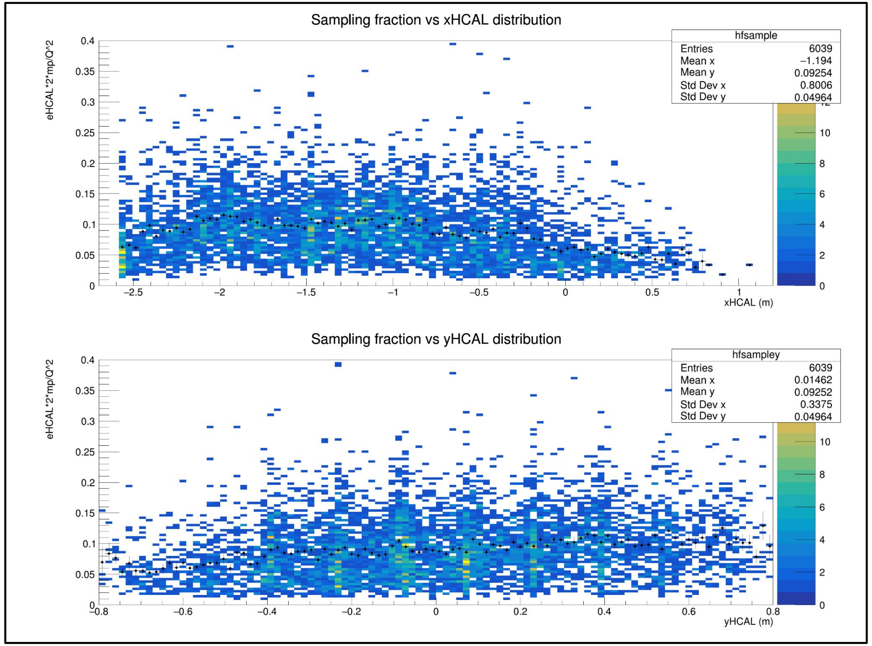
- $|t_{coin} - 95| < 8$ ns
- $|dy+0.008| < 0.5$ m
- $|dx+1.53| < 0.5$ m
- $|W^2-0.88| < 0.5$ GeV^2

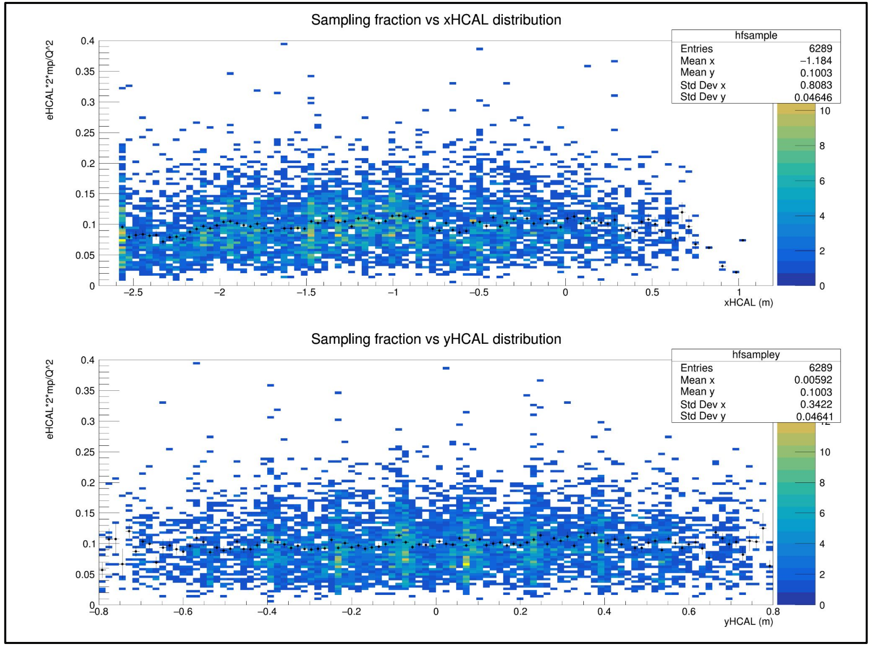


Credit: Vimukthi H. Gamage

Calibration: Calorimeter Energy Reconstruction

Pass 1 vs improved hcal calibration comparison for GEN3. Vimukthi is currently working on improving all the kinematic points in preparation for the pass 2 replay. Kate is also looking at the BBCal energy reconstruction and simulation mismatch.





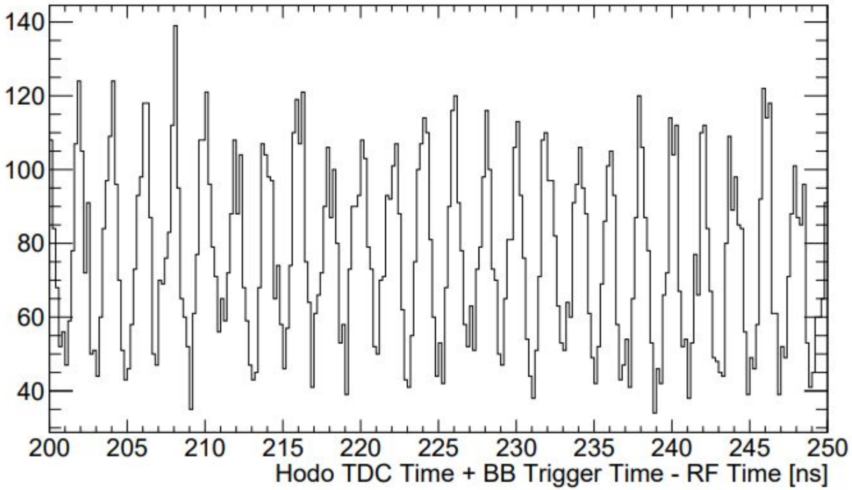
Pass 1 replay

New GEN3 calibration

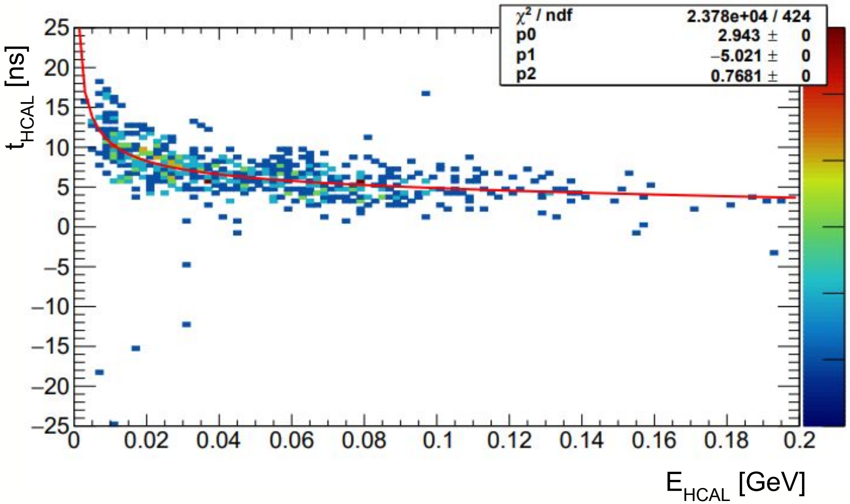
Credit: Vimukthi H. Gamage

Calibration: Timing

Significant efforts have been made the last year to develop a new global timing calibration to achieve the best possible coincidence time between spectrometer arms. These are ongoing with weekly progress.



Resolving the beam RF structure in GEN2 H2 data after a global fit to all timing parameters and then aligning the hodoscope paddles with relative RF offsets.

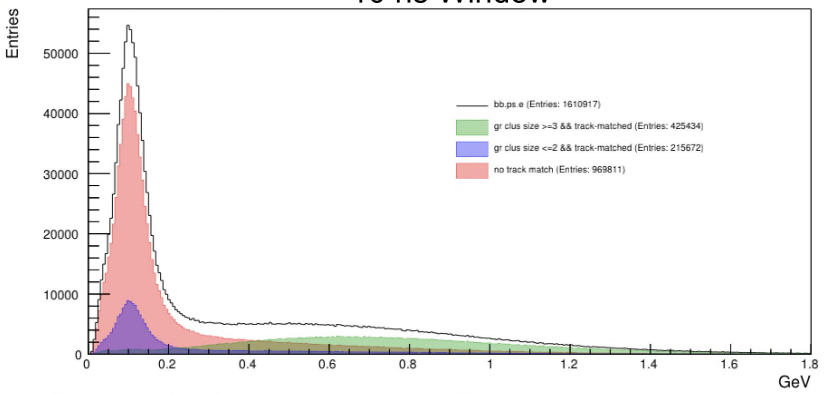


Example of a timewalk fit to HCAL (block 3) in GEN2 H2 data.

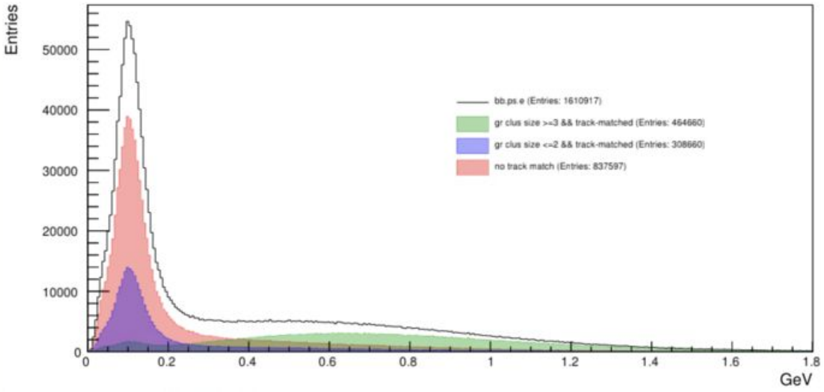
The current goal is to now investigate / develop a single fit for the complete coincidence time between HODO TDC and HCAL TDC.

Calibration: GRINCH

10 ns Window



20 ns Window

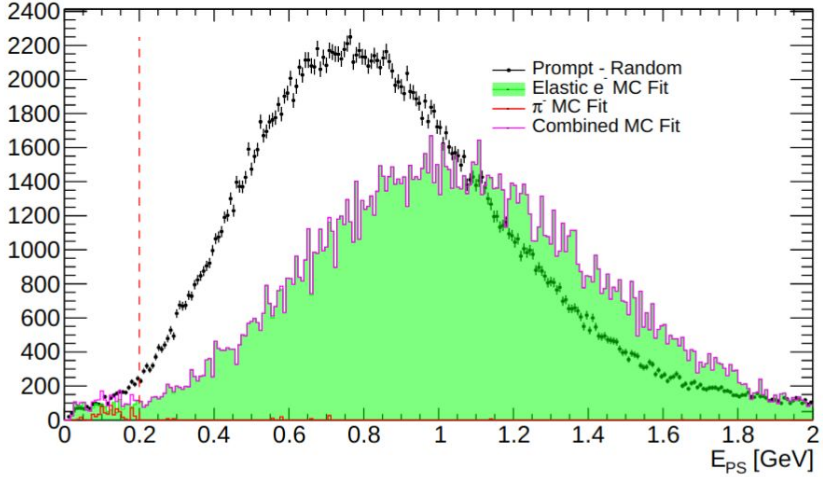


Credit: Jack Jackson

Jack generated new timing offsets which corrected the track matching, and is now investigating how the timing window cut in the GRINCH clustering affects the track matching of the cluster, and working with the simulation to look at the comparison.

There is a known mis-match between the preshower energy in sim and data which is also under study.

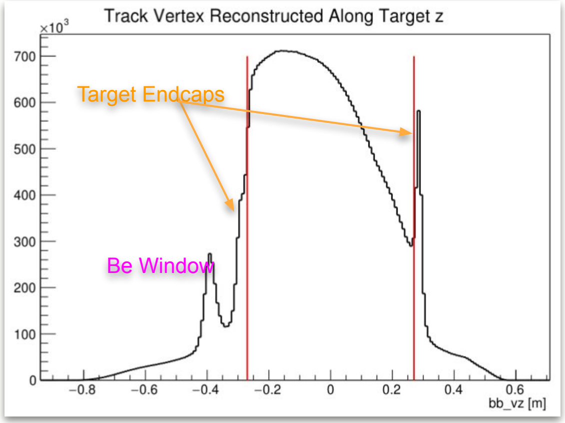
GEN2

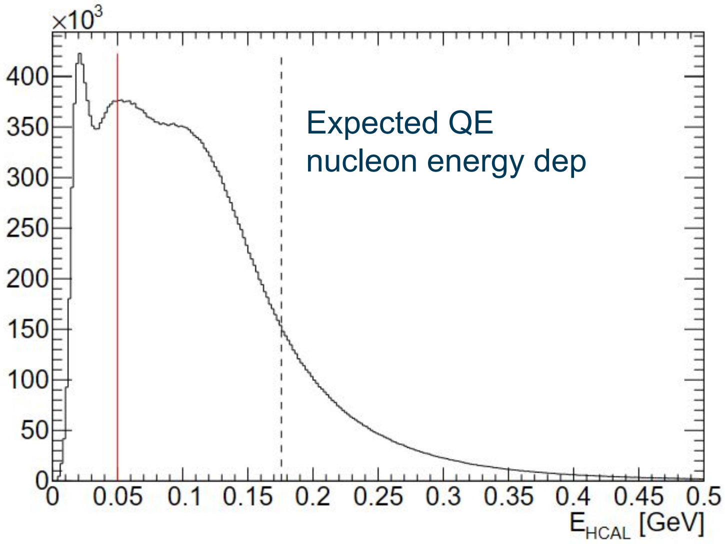


Analysis: Data Reduction Cuts (GEN2)

The GEMS provide information on the electron track via magnetic optics and tracking algorithms.

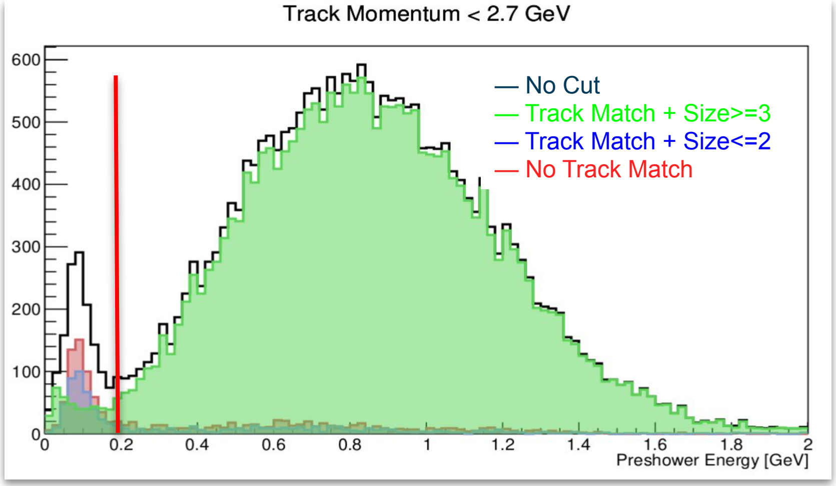
The track can be projected backwards to the target to find the vertex position.





PID performed by selecting on cherenkov clusters and preshower energy deposition

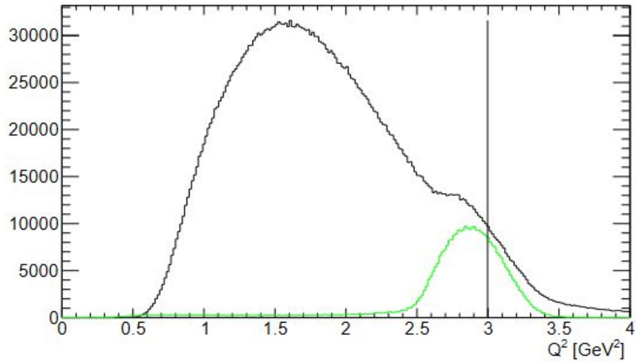
Energy sampled in HCAL has too crude a resolution to reconstruct particle momenta, but we can remove low energy noise.



Analysis: Kinematic Reconstruction (GEN2)

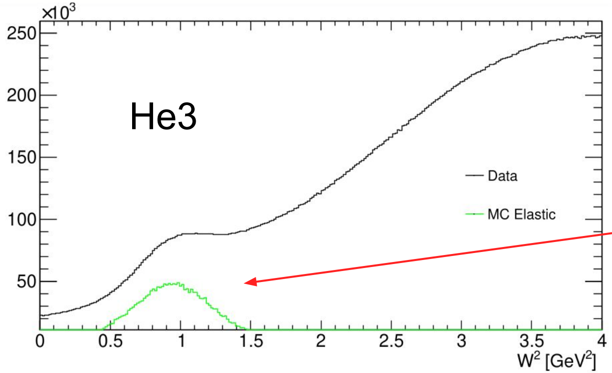
Scattered electron track and beam can be used to calculate q vector and four-momentum transfer squared

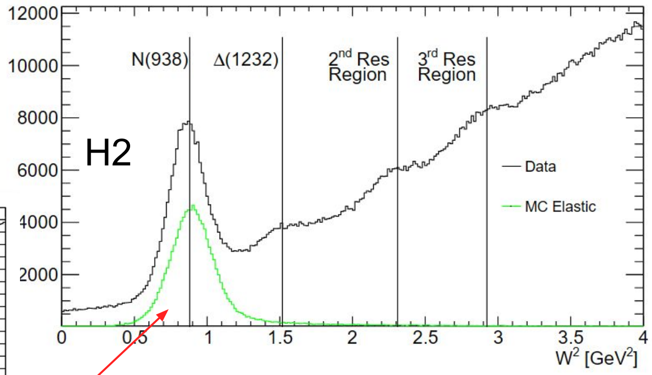
$$Q^2 = -q^2 = -(k - k')^2 = 2E_i E_f(1 - \cos\theta_e)$$



Assuming a stationary target (i.e. ignoring fermi motion) we can calculate the quasi-invariant mass squared

$$W^2 = P^\mu P_\mu = (q + T)^2$$





H2 vs He3 data demonstrates effect of fermi motion on kinematic distributions

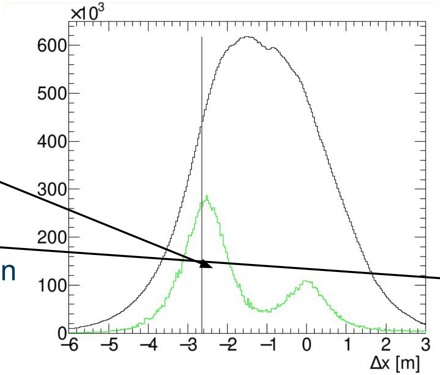
The calculated nucleon four-vector can be used to predict its trajectory and momentum.
High resolution TOF *might* be able to provide a measure of missing momentum in the future.
The position of the tagged nucleon in HCal can be used to construct delta variables

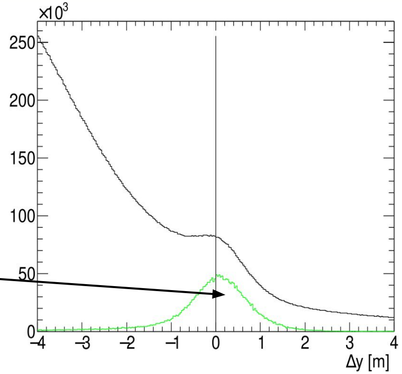
Dispersive direction (p n separation)

$$\Delta x = x_{\mathrm{HCAL}} - x_{\mathrm{expect}}$$

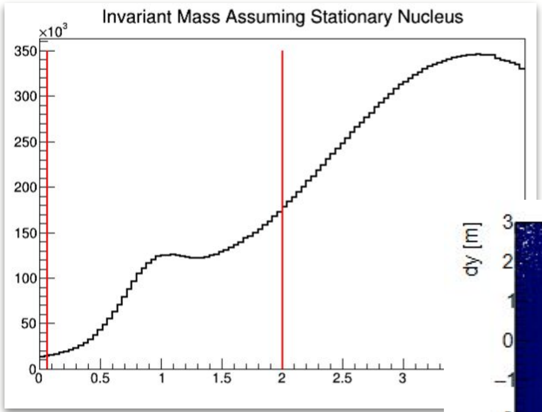
$$\Delta y = y_{\mathrm{HCAL}} - y_{\mathrm{expect}}.$$

Non-dispersive direction (no separation)

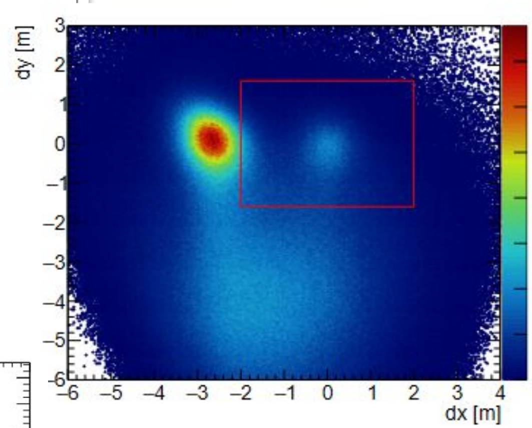




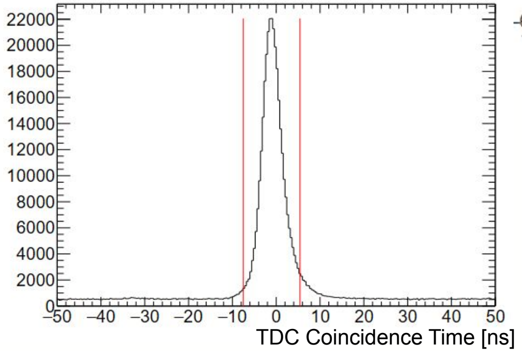
Quasi-elastic Event Selection (GEN2)



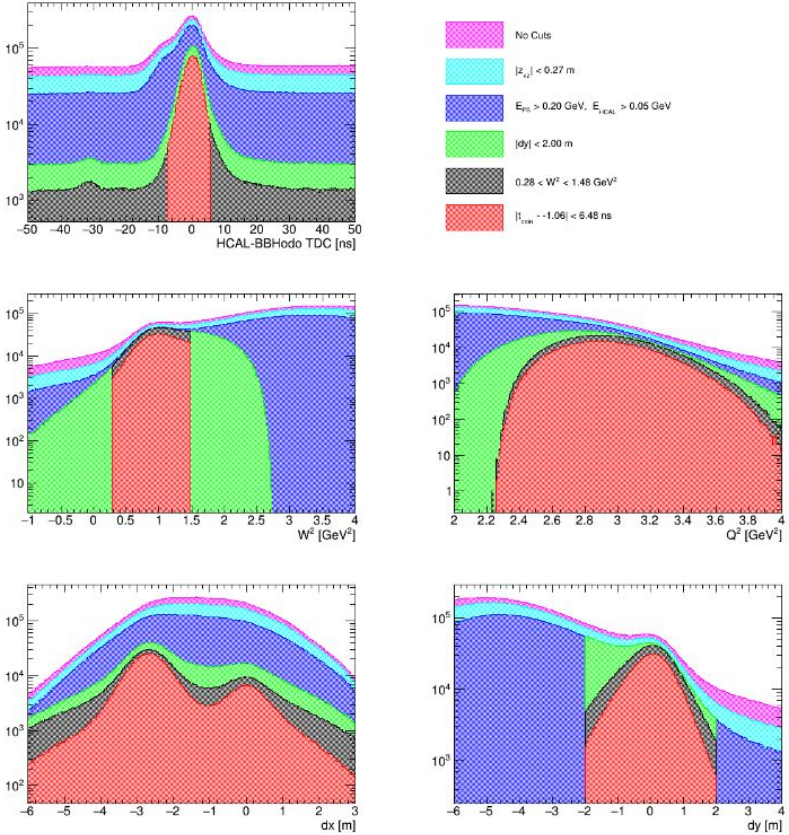
A fairly wide initial W^2 cut removes the large exponential backgrounds while preserving most of the signal peak



Next we can select around the neutron spot in dx,dy



Accidental timing background removed by cutting on the coincidence peak



Ultimately these choices of QE cuts are optimised through systematic analysis

Extracting GE/GM and GE

What we measure

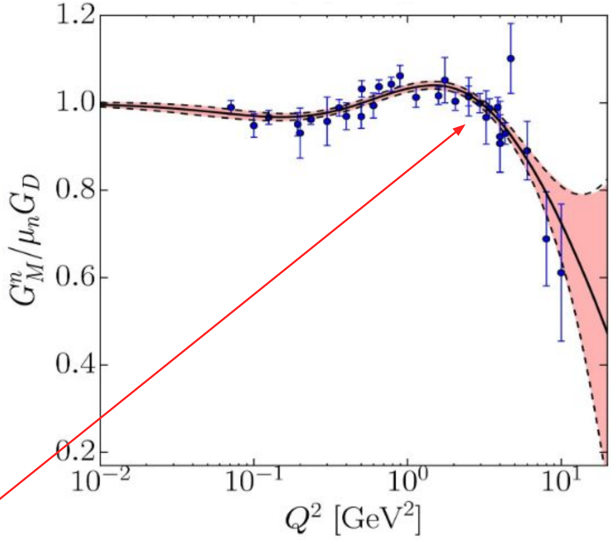
$$A_{\text{phys}} = A_\perp \sin\theta^* \cos\phi^* + A_\parallel \cos\theta^*$$

$$A_\parallel = -\frac{\sqrt{1-\epsilon^2}}{1+\frac{\epsilon}{\tau}r^2}$$

$$A_\perp = -\sqrt{\frac{2\epsilon(1-\epsilon)}{\tau}}\frac{r}{1+\frac{\epsilon}{\tau}r^2}$$

Small contribution from perpendicular component due to large acceptance (and polarisation direction being slightly wrong)

Transverse component of asymmetry maximised by having transversely polarised target - $\theta^* \sim \pi$



$$A = \frac{\epsilon A_{\text{phys}}}{\tau}$$

Measure physics quantities over events and form new quantities

$$B = \sqrt{\frac{2\epsilon(1-\epsilon)}{\tau}}\sin\theta^* \cos\phi^*$$

$$C = A_{\text{phys}} + \sqrt{1-\epsilon^2}\cos\theta^*$$

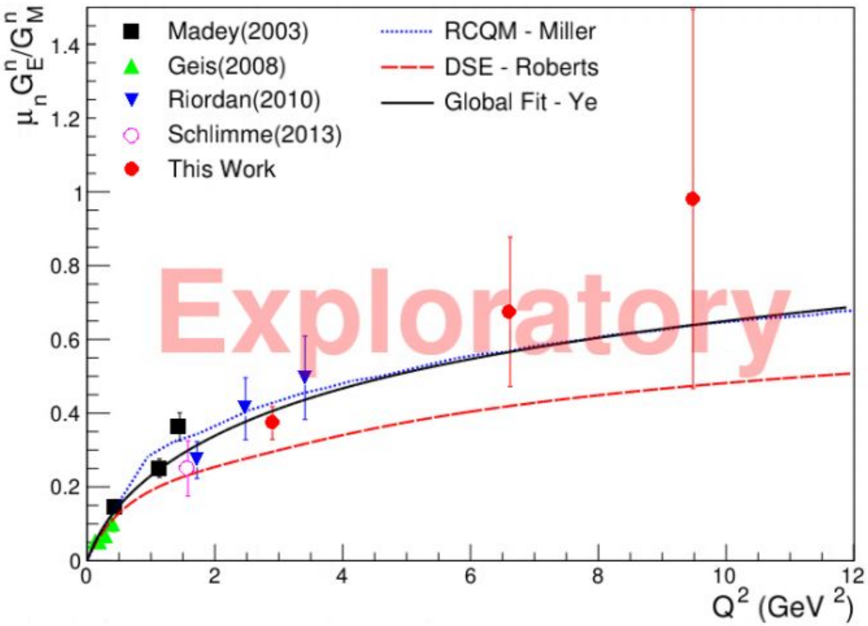
Rearranging provides quadratic!
Solving for r yields form factor ratio

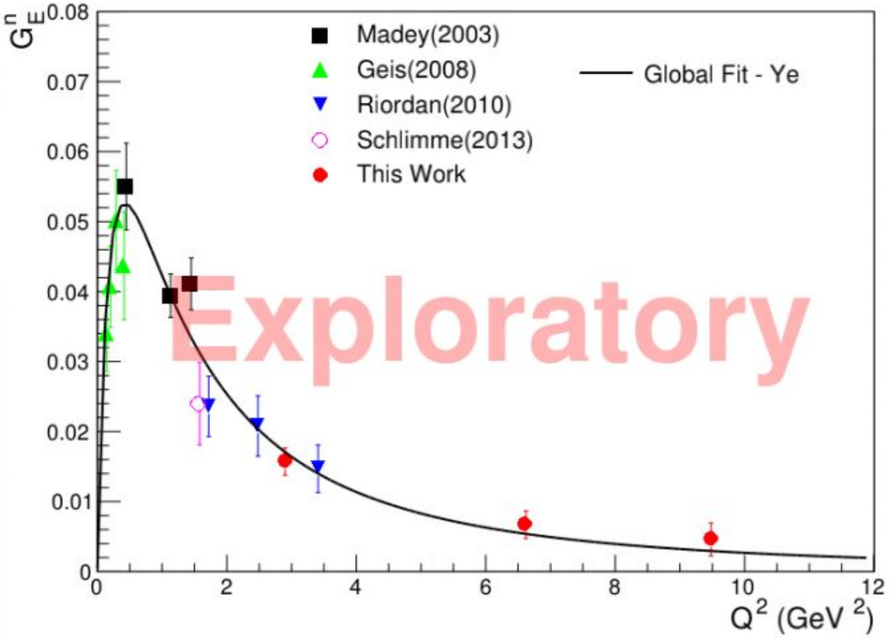
$$Ar^2 + Br + C = 0$$

$$G_E^n = r * G_M^n\big|_{\text{Ye}}$$

Global fit to high precision world data for magnetic form factor does very well to match at this Q^2. Can use this to explicitly extract GEn

Exploratory Results





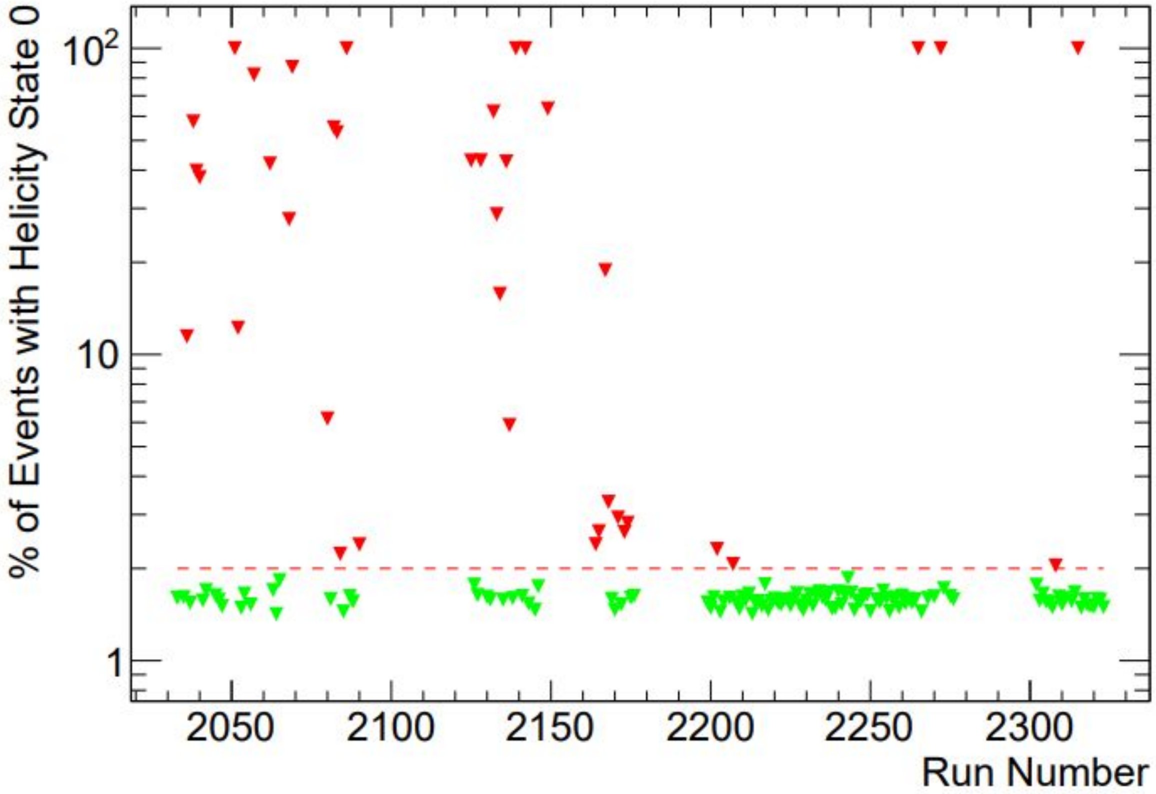
Exploratory results from the thesis of S. Jeffas (Graduated), July 2024.

The extremely preliminary nature of these results should be stressed. Ongoing calibration efforts are expected to improve the precision particularly in the two high Q^2 points.

Thank You!


BACKUP

Data: Beam Helicity and Polarisation



Helicity unknown for first 1000 events of a run while the quad pattern is decoded.

Events with unknown helicity state are discarded.

Asymmetry Formalism

What we measure: Asymmetry between +,- helicity states for events.

The sum of background modifications to the raw asymmetry:

- Timing Accidentals
- Inclusive DIS background
- Pions mis-ID as electrons in Bigbite
- QE protons under neutron peak
- QE scattering from N2 in target cell
- Nuclear effects

$$A_{\mathrm{phys}} = \frac{A_{\mathrm{raw}} - \Sigma_{\chi} f_{\chi} A_{\chi}}{P_{\mathrm{He}^3} P_{\mathrm{n}} P_{\mathrm{beam}} (1 - \Sigma_{\chi} f_{\chi})}$$

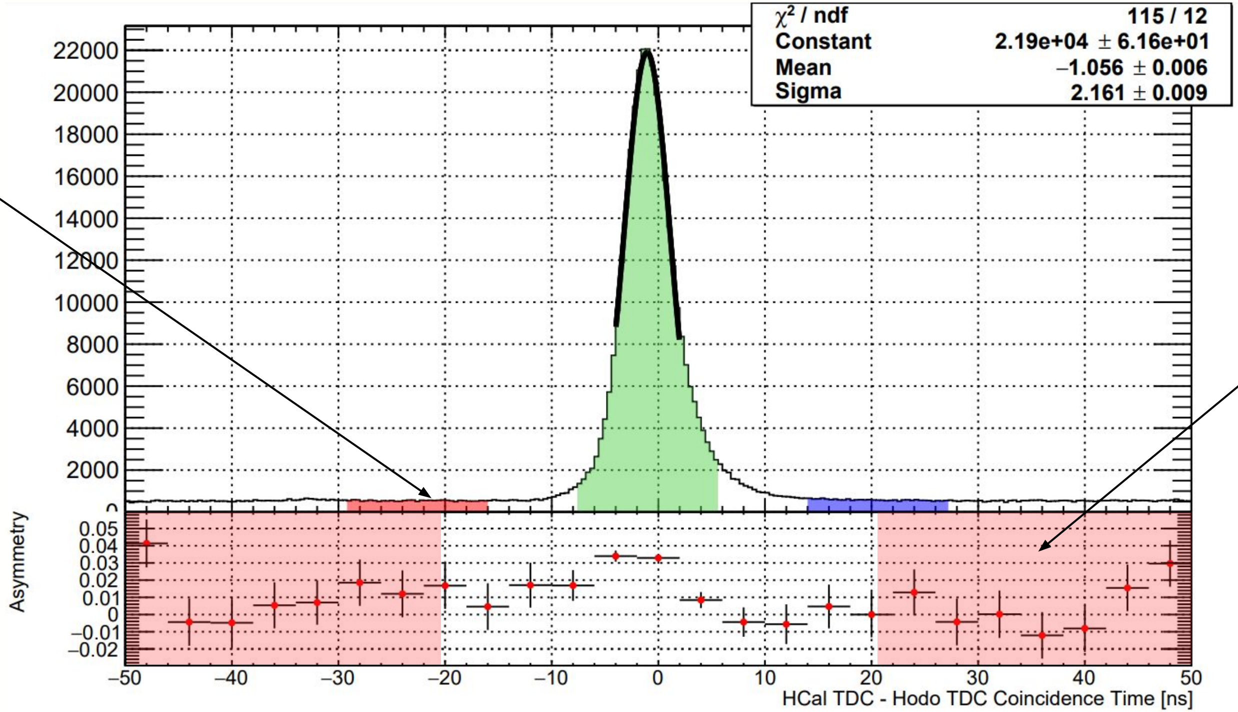
Polarisation of the target, beam and neutron within ^{3}He

Fraction of event sample as a result of purely QE scattered neutrons

Timing Accidentals and Prompt Random Subtraction

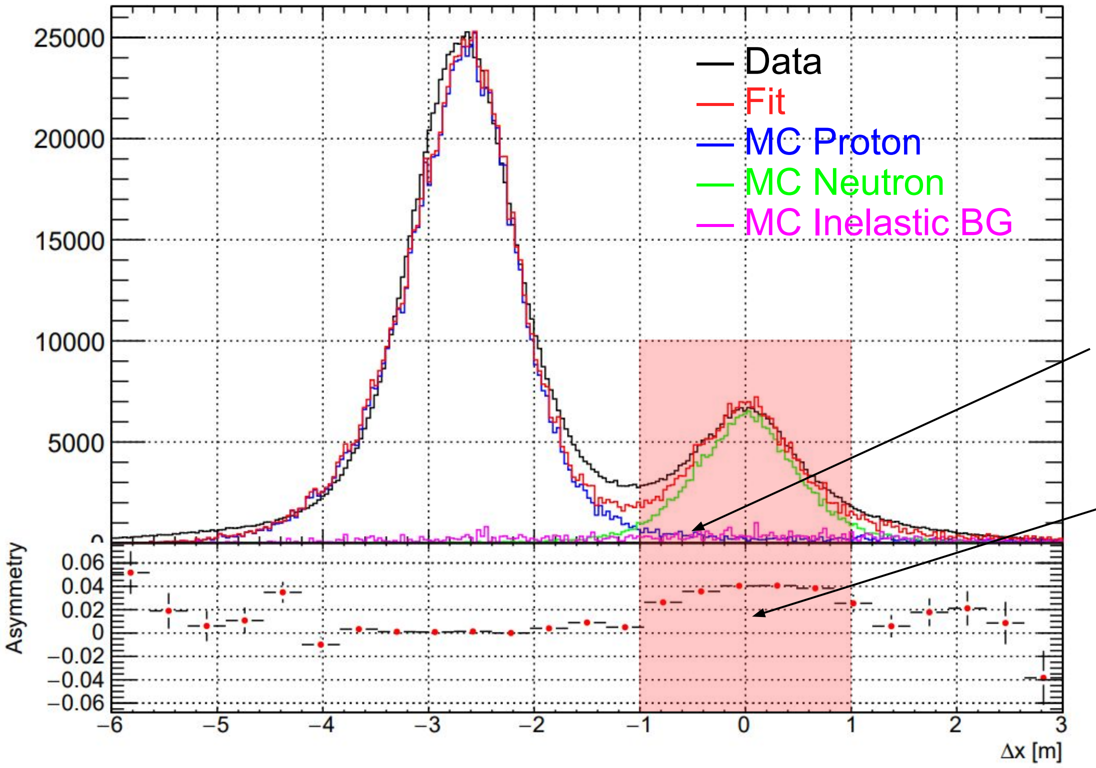
“Flat” background means that accidental background can be subtracted: prompt-random subtraction.

Ratio of sideband integral to peak integral provides accidental contamination fraction f_{Acci} = 5.4 %.



Asymmetry associated with accidentals measured outside of 5σ cut window

Physics Backgrounds and dx Fitting



Recall: dx is the difference in projected and measured position of the particle on the hadron calorimeter, in the *dispersive* direction of the SBS Magnet.

Magnet provides nucleon separation - 2 peaks!

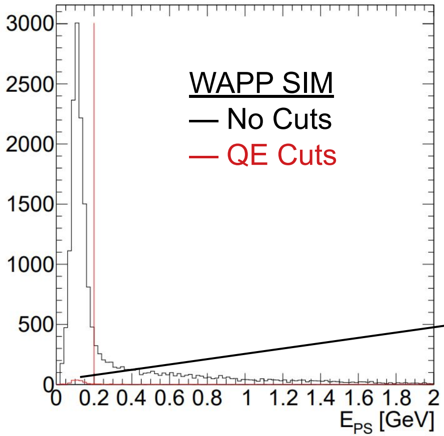
Fit provides the scale for background from QE proton tail, and inclusive electro-production events.

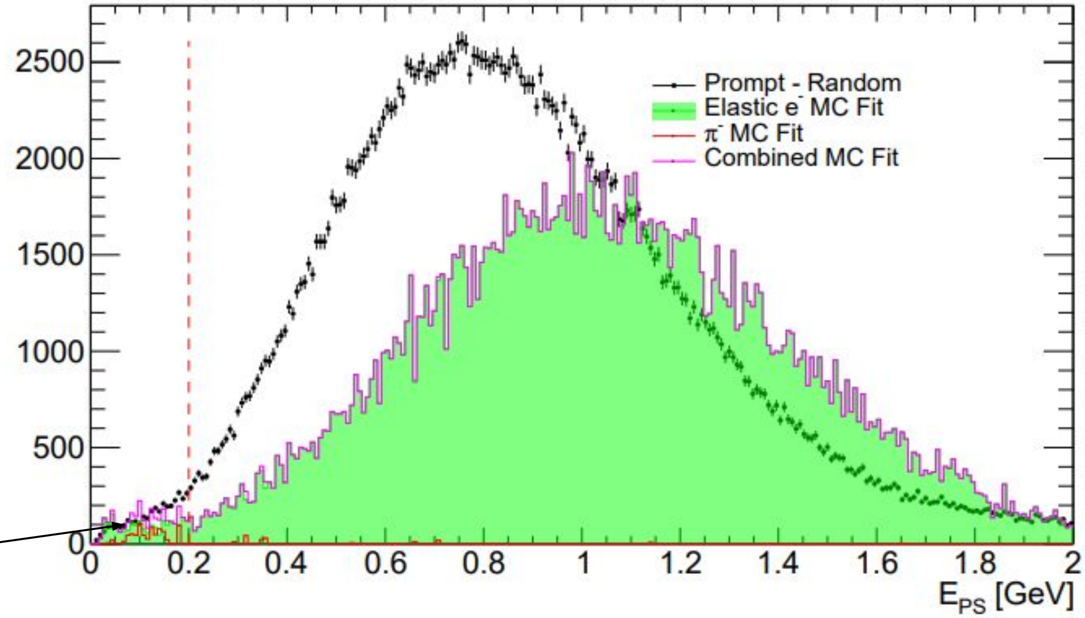
Raw asymmetry measured in chosen dx cut region, +-1m shown here for example.

Pion Contamination

PID provided by preshower calorimeter and GRINCH cherenkov

Pion contamination fraction can be calculated by fitting sim pion+electron to data

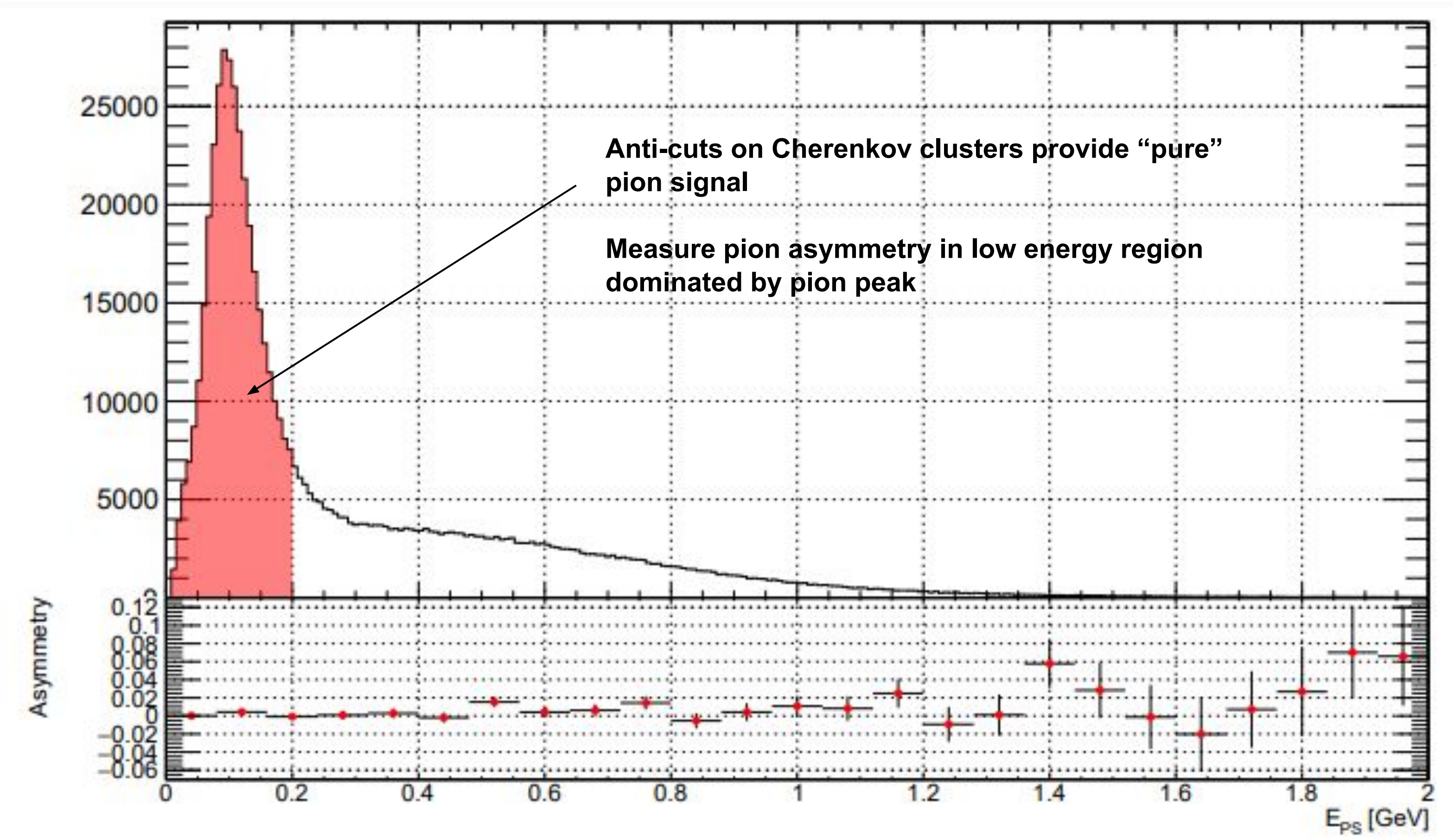




Photopion production monte carlo provides accurate fit to the observed low energy pion peak. After full cuts very little residual pion contamination in Bigbite (electron arm) at this kinematic setting.

SIM elastic electron preshower energy signal matches data poorly due to half understood issues in the MC geometry and reconstruction

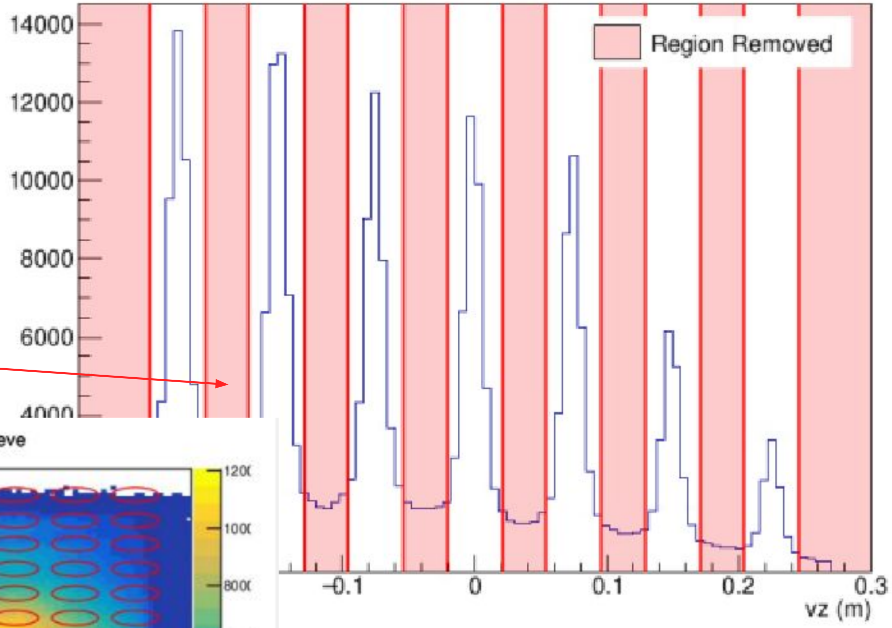
Pion Contamination



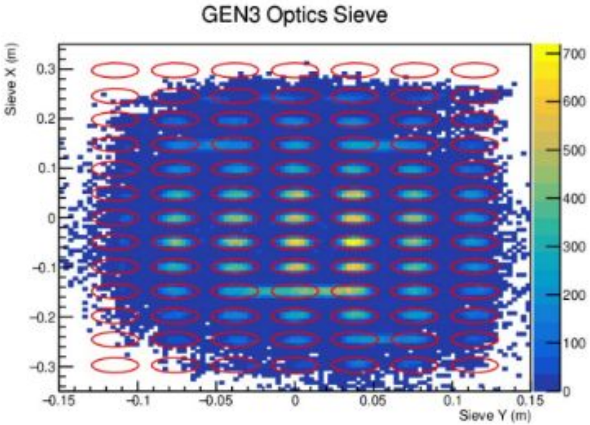
Nitrogen Contamination

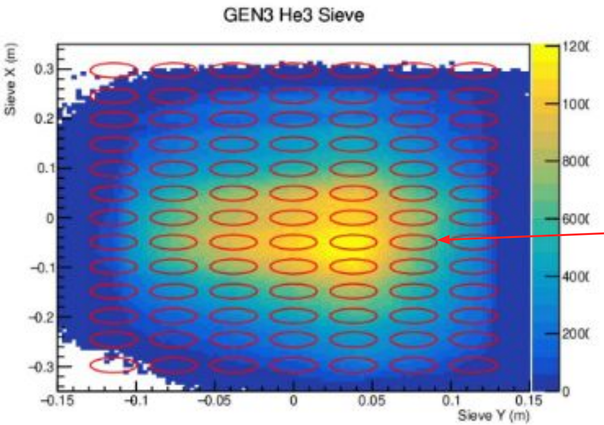
Nitrogen bg fraction estimated using carbon optics data, using ratio of acceptance normalised yields of He3 and C12:

$$f_{N2} = \frac{Q(He3)}{Q(C)} \frac{m_{N2}(He3)}{m_C(C)} \frac{N_C}{N_{He3}}$$



Cuts on the target z of the 7 carbon foils to remove scattering from air





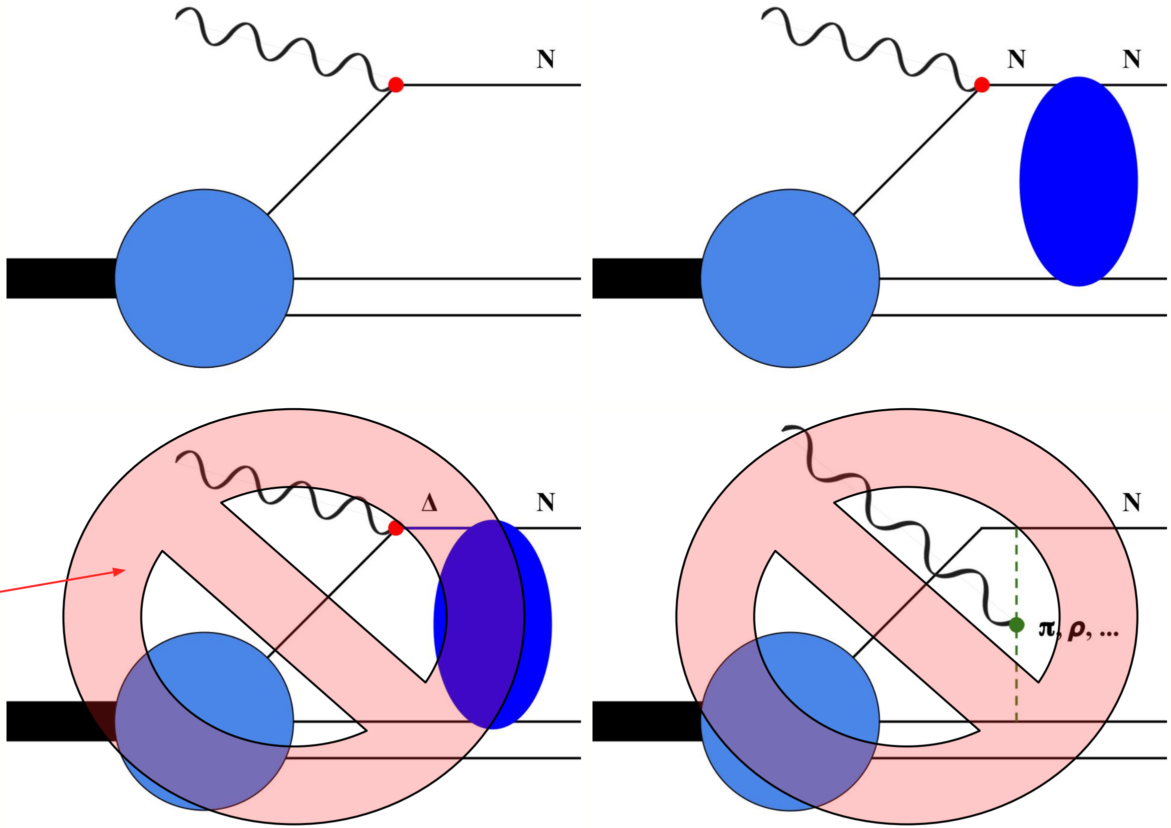
Cut on x,y position at the face of the magnet to match the sieve plate pattern - matches acceptance of C12 and He3 data.

Nuclear Corrections

Different processes can take place in the photon nucleon interaction:

- Plane wave impulse approximation (PWIA)
- Single, Double rescattering etc - Final State Interactions (FSI)
- Excitation into resonance - Isobar Configuration (IC)
- Coupling to virtual meson - Meson Exchange Current (MEC)

Suppressed for ~ $Q^2 > 1\ \mathrm{GeV}^2$



Nuclear Effects expected to manifest as reduction in physical asymmetry through charge exchange effects in FSI