GEN-II Experiment

Measuring the Neutron Electric Form Factor at High Q^2

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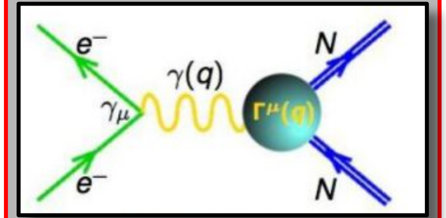
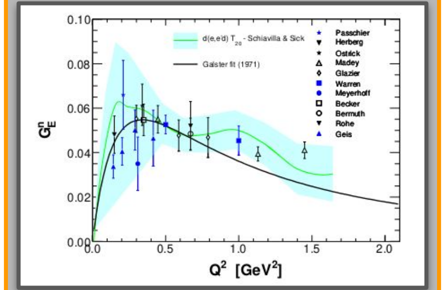
10.04.24

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

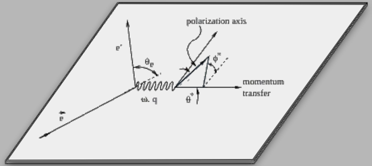
Double polarized semi-exclusive **3He(e,e'n)pp** quasi-elastic scattering



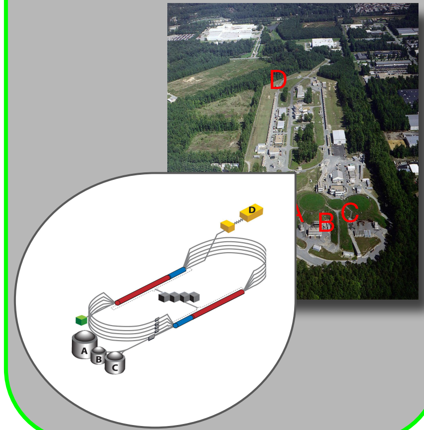
Extract Sachs Form Factor **GEn** with precise high Q2 GMn data.



Measure transverse asymmetry $A_\perp$ of cross section



Hall A - Thomas Jefferson National Accelerator Facility



Elastic eN Scattering and Form Factors

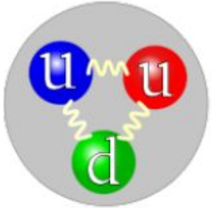
R. Hofstadter et al. (1950s)

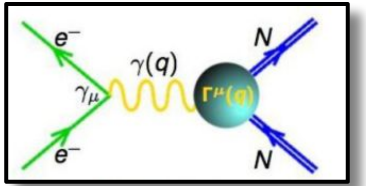
$$\sigma(\theta_e) = \sigma_M \left| \int \rho(r) e^{iq\cdot r} d^3 r \right|^2 = \sigma_M \, |F(q)|^2$$

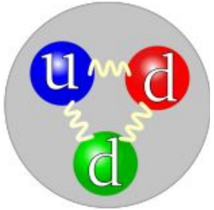
$$\begin{aligned} F_{1p}(0) &= 1 \\ F_{2p}(0) &= \kappa_p \\ F_{1n}(0) &= 0 \\ F_{2n}(0) &= \kappa_n \end{aligned} \qquad \begin{aligned} \kappa_p &= \mu_p - 1 \\ \kappa_n &= \mu_n \end{aligned}$$

$Q^2 = 0$

$Q^2 = (\bar{q} - q)^2$

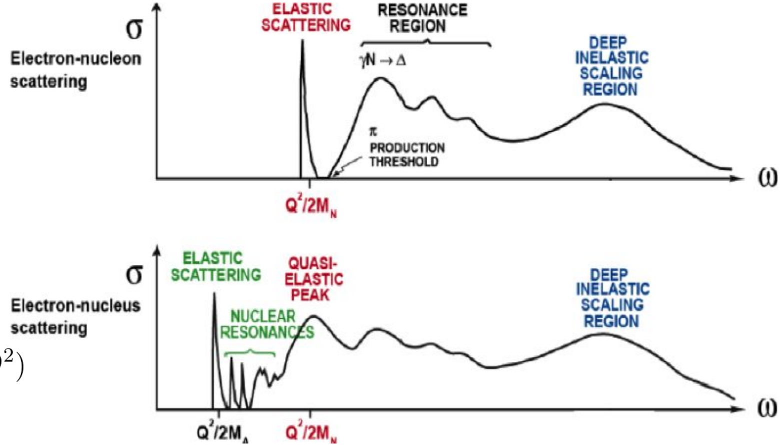






Born Term:

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



F_1: helicity non-conserving, Pauli FF
F_2: helicity conserving, Dirac FF

F.J. Ernst et al (1960s)

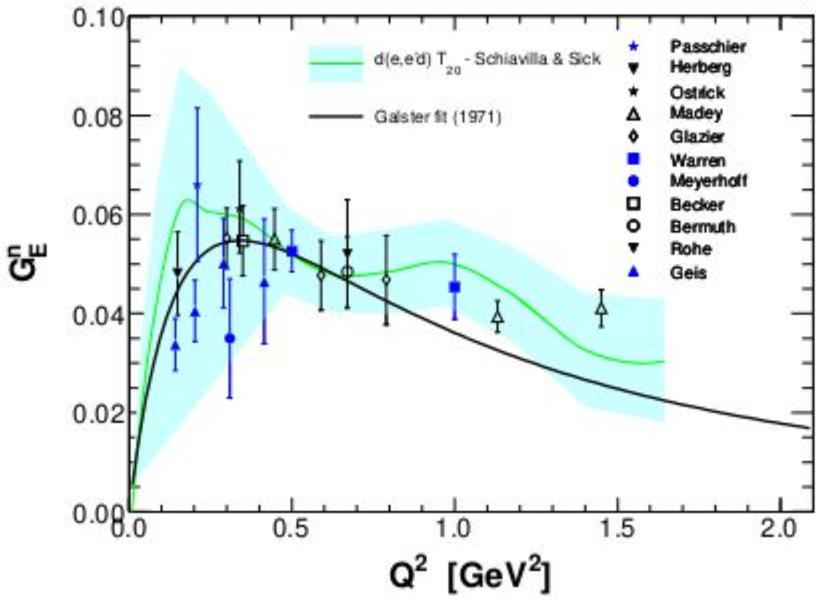
$$G_E = F_1 - \frac{Q^2}{M^2} F_2 \qquad G_M = F_1 + F_2$$

$$\frac{d\sigma}{d\Omega} = \underbrace{\frac{\alpha^2}{4E^2 \sin^4\theta/2} \frac{E}{E'}}_{\text{point-like target}} \left[\frac{\overbrace{G_E^2}^{\text{Electric form-factor}} + \tau G_M^2}{1+\tau} \cos^2\theta/2 + 2\tau \underbrace{G_M^2}_{\text{Magnetic form-factor}} \sin^2\theta/2 \right]$$

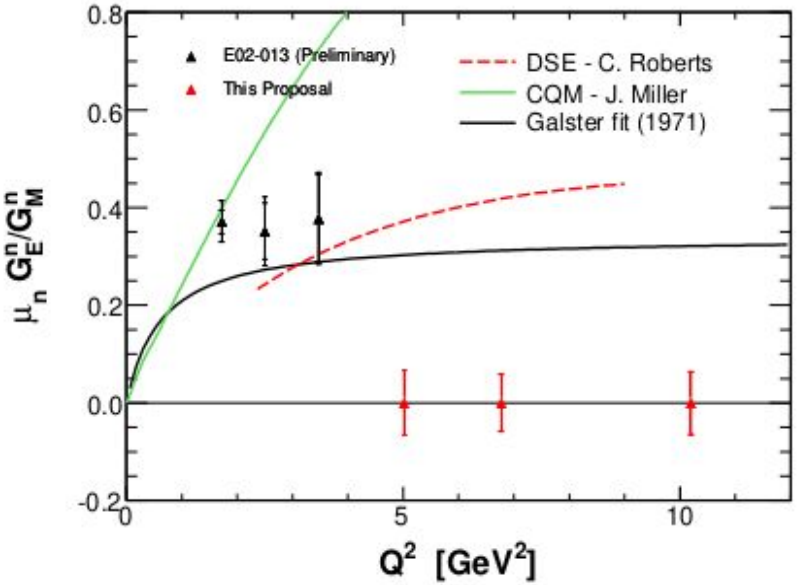
$$\tau \equiv \frac{Q^2}{4M^2}$$

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

Electric Form Factor of the Neutron (GEn)



World data for GEn from polarized measurements

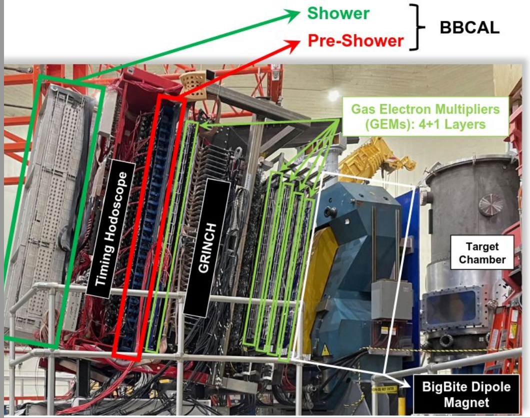


Projected points for GEn-II experiment and preliminary GEn-I points.

Hall A Experimental Setup: Super Bigbite Spectrometer

Electron Arm: Bigbite

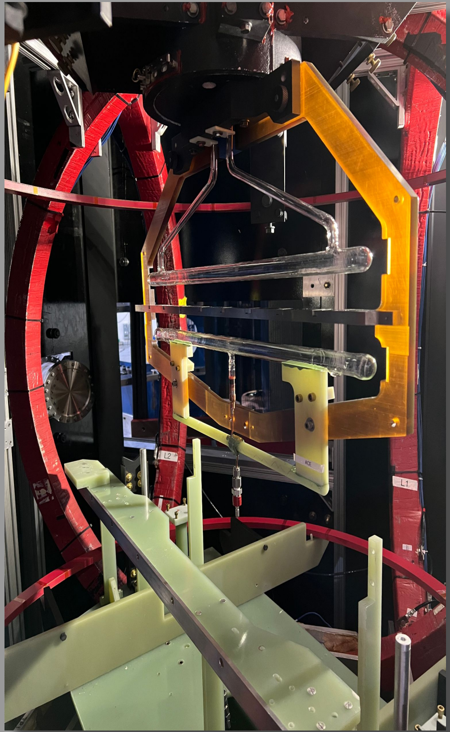
- 750A Dipole Magnet
- Full Detector Stack
  - Calo Trigger
  - GEM Tracking
  - Cherenkov
  - Timing Hodoscope



Nucleon Arm: SBS

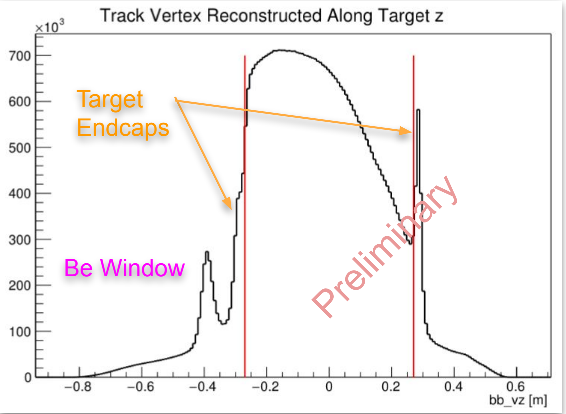
- 2100A Dipole Magnet
- Hadron Calorimeter

Polarised ^{3}He Target

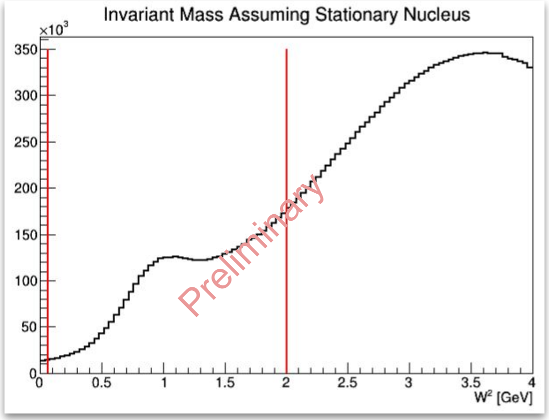


Analysis: e^- Track Selection

Tracking Performed by Gas Electron Multipliers (GEMs)
Calorimeter trigger provides a track search region.
Track algorithm finds all possible tracks with at least 3 hits within the 5 GEM layers
Track Algorithm produces a “best track” per event with 99%+ efficiency



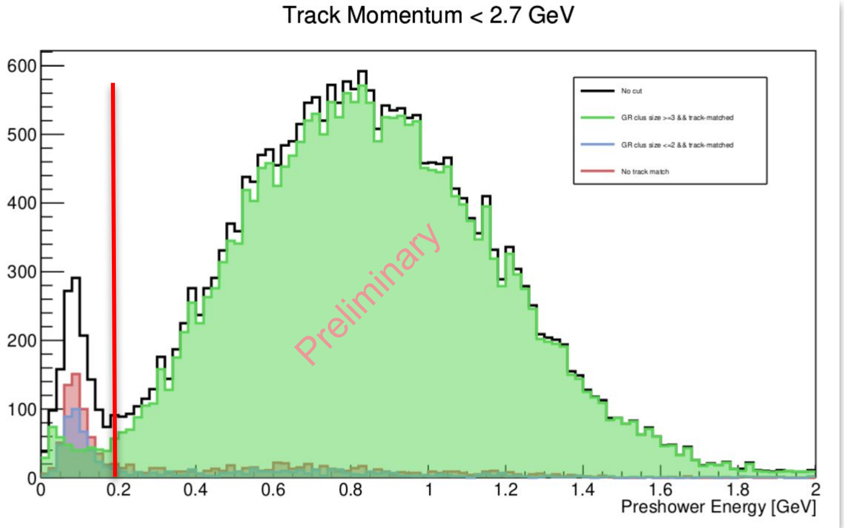
Remove scattering associated with target and beryllium beam-pipe window.



A wide starting cut around the nucleon mass squared, 0.88 GeV^2 removes superelastic & most inelastic events

<u>π^- rejection</u>

π^- and e^- exhibit clear and different behaviors in the preshower calorimeter and GRINCH cherenkov detector in energy deposition and cluster size respectively

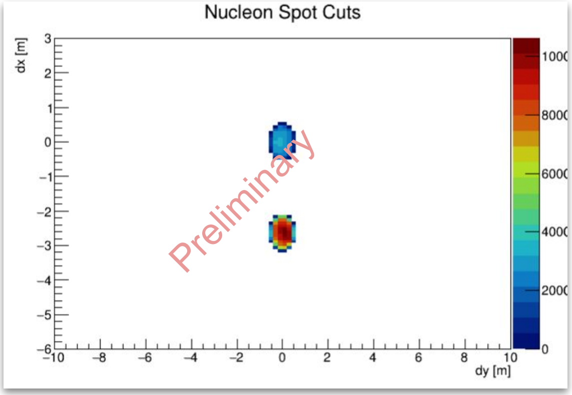


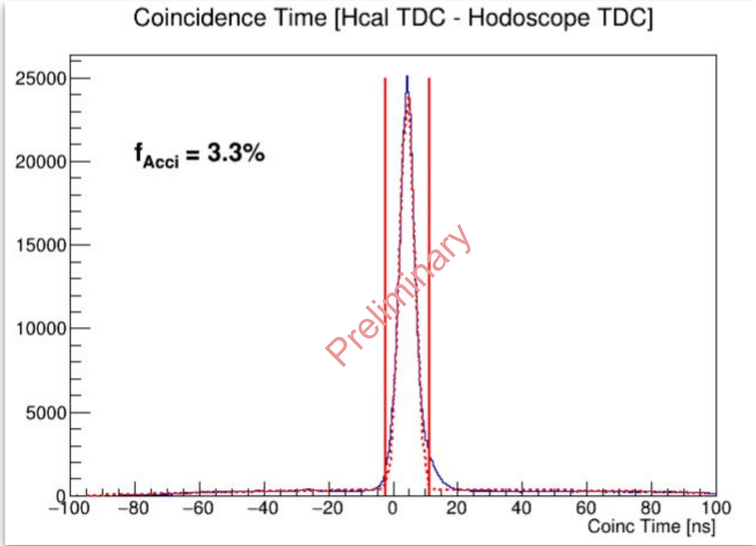
Exclusive Nucleon Selection

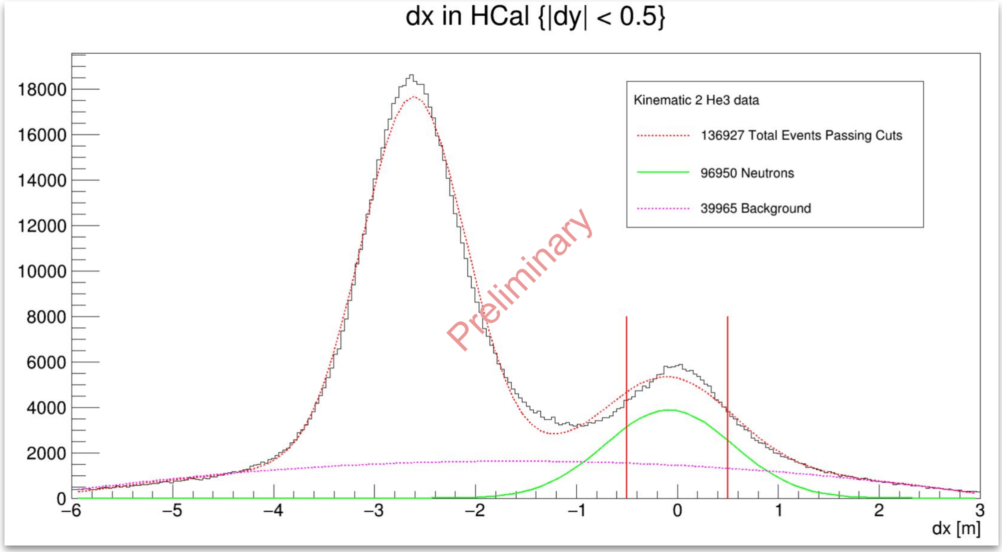
Demand coincidence trigger between Bigbite and SBS.

Project q-vector towards HCal.

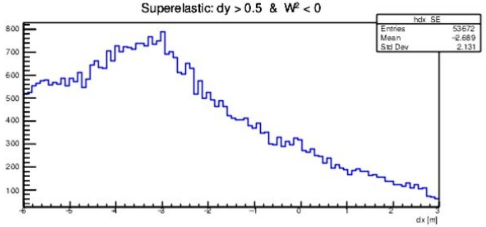
Quasi-elastic position projected-detected cuts (dx, dy) select on QE spots

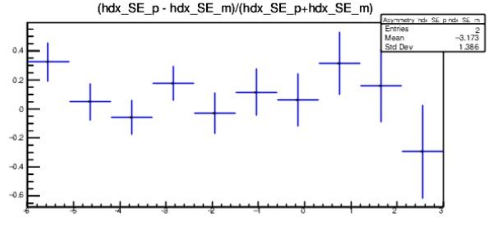


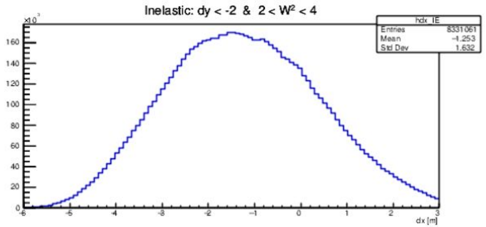


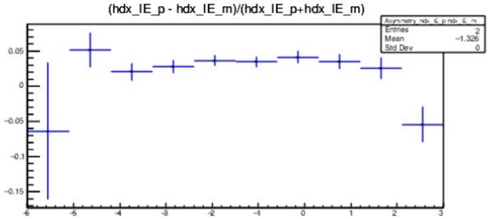


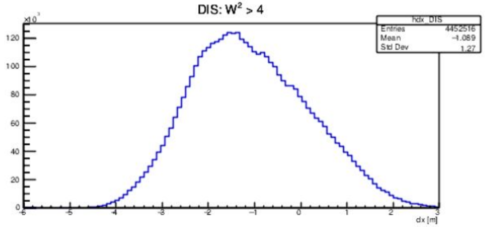
Preliminary Asymmetries and Backgrounds

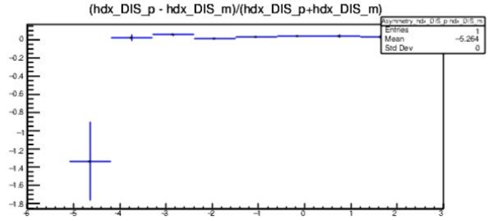


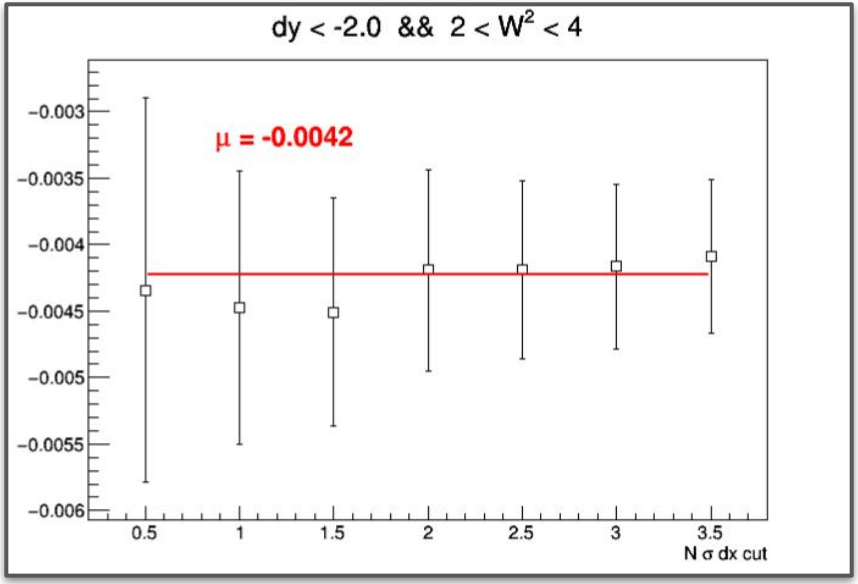






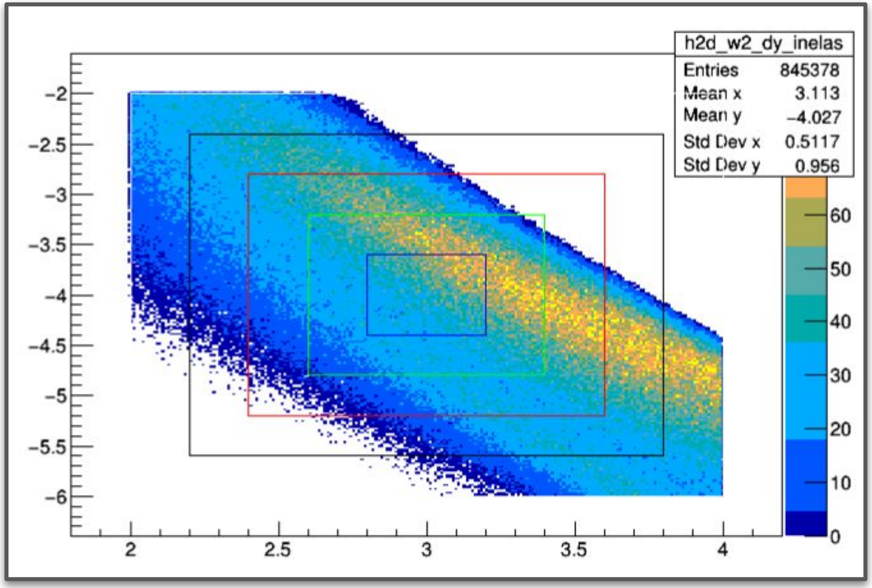


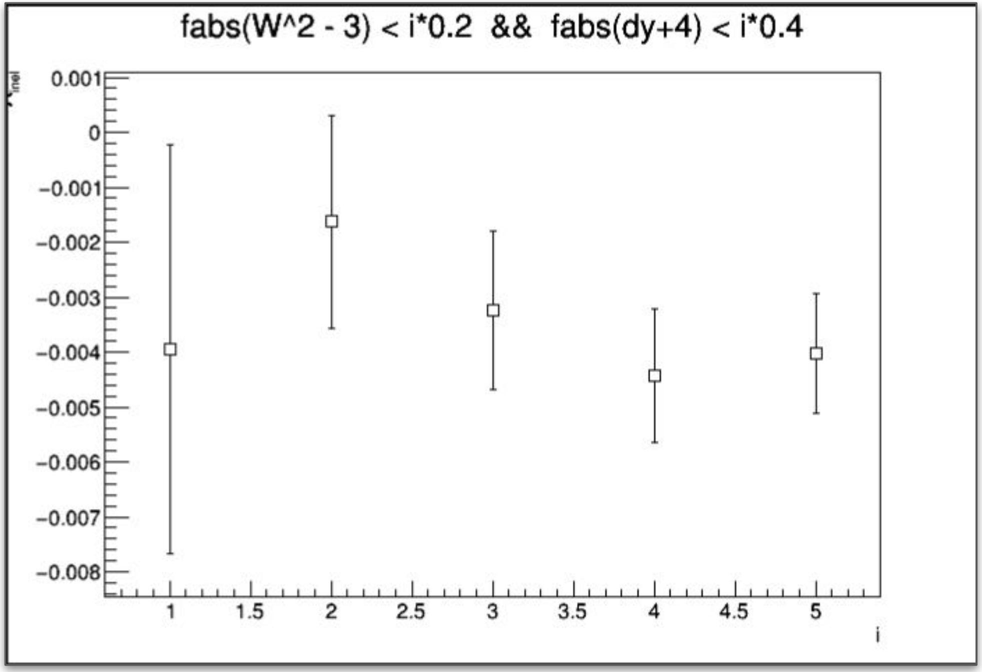




In Progress analysis of background fractions and associated dilution asymmetries

Preliminary Asymmetries and Backgrounds





In Progress analysis of background fractions and associated dilution asymmetries

Conclusion & Next Steps

- Pass 2 data requirements
  - Calorimeter re-calibration on neutron data
  - Inclusion of Cherenkov calibrated database
  - Recalibration of all detectors timing relative to timing hodoscope, due to recent progress in understanding this detector
- Finalise Thesis Analysis
  - Quantify dilution factors and backgrounds using final full simulation data
  - FInish cut optimisation using full uncertainty in every iteration and bin
  - Final event selection cuts
- Publication
  - Full analysis likely a few years more progress. Pass 3 not ruled out.

THANKS!

Backup

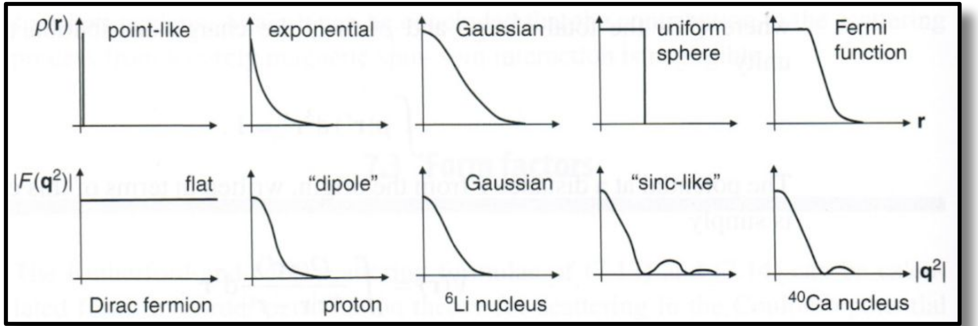
What Is A Form Factor?

Generally, a form factor is just a fourier transform of a charge distribution:

$$F(\vec{q}) = \int d^3r \rho(r) e^{i\vec{q}\cdot\vec{r}}$$

Elastic Form Factors G_E, G_M Describe internal structure of nucleons.

Related to charge and magnetization distributions within the nucleon.

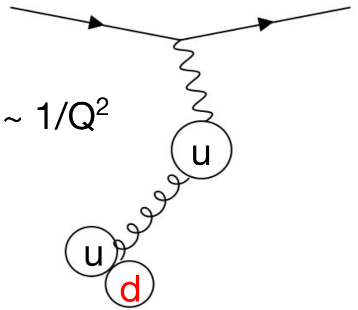


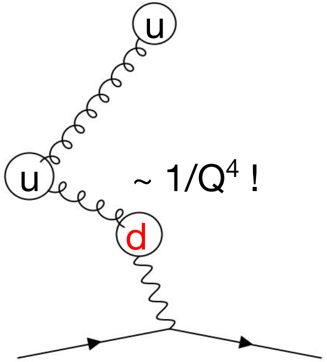
Flavour Separation

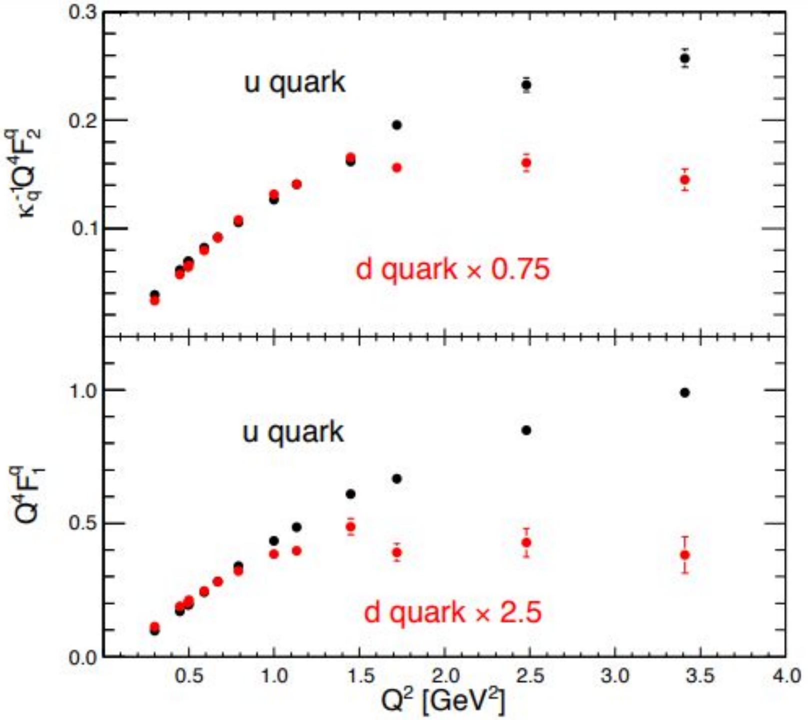
Extracted G_E and G_M can be decomposed

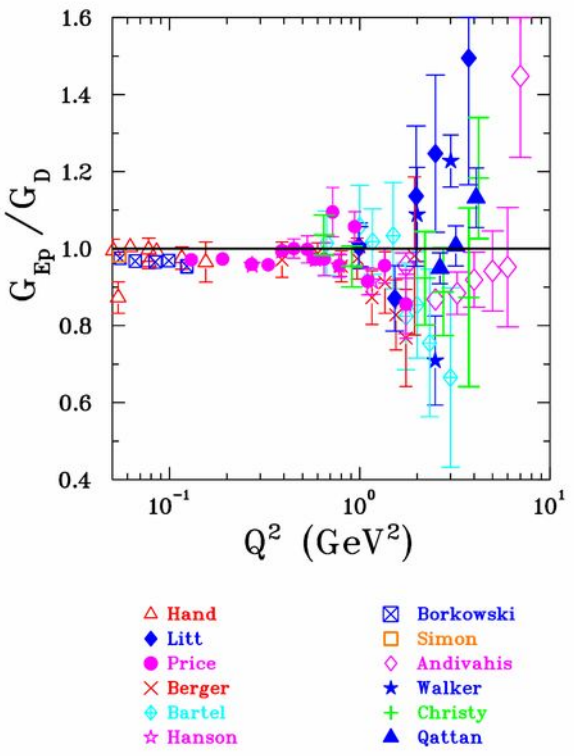
$$F_1 = \frac{G_E + \tau G_M}{1+\tau} \qquad F_2 = -\frac{G_E - G_M}{1+\tau}$$

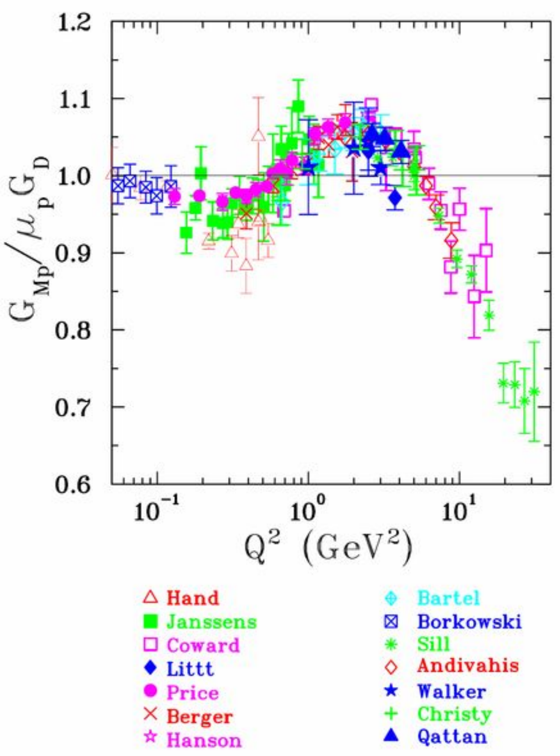
Different behaviour of u and d quarks may indicate **diquark correlations**





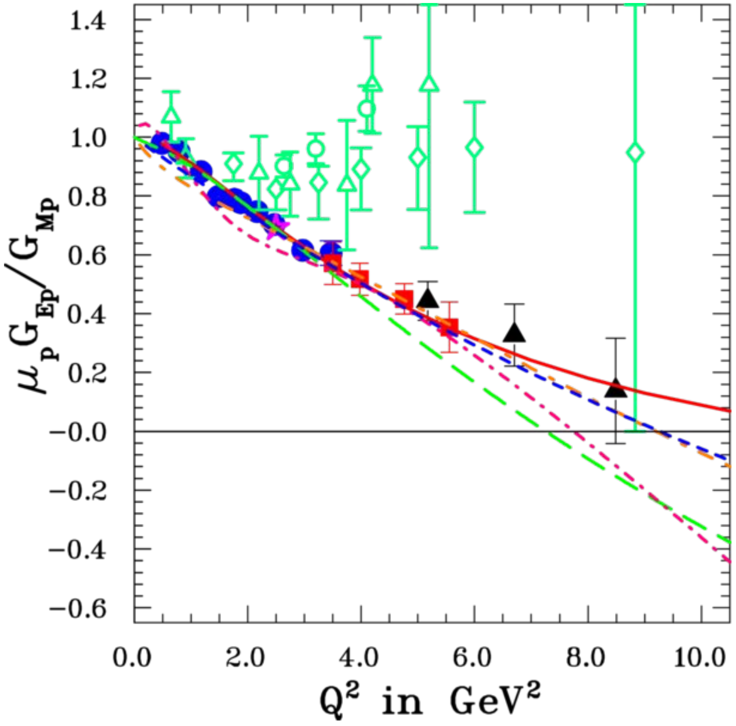






Global Database for proton form factors obtained via Rosenbluth Separation method.
Neutron form factors much less well understood - <u>no free neutron targets!</u>

Proton FFs in Double Polarisation Experiments

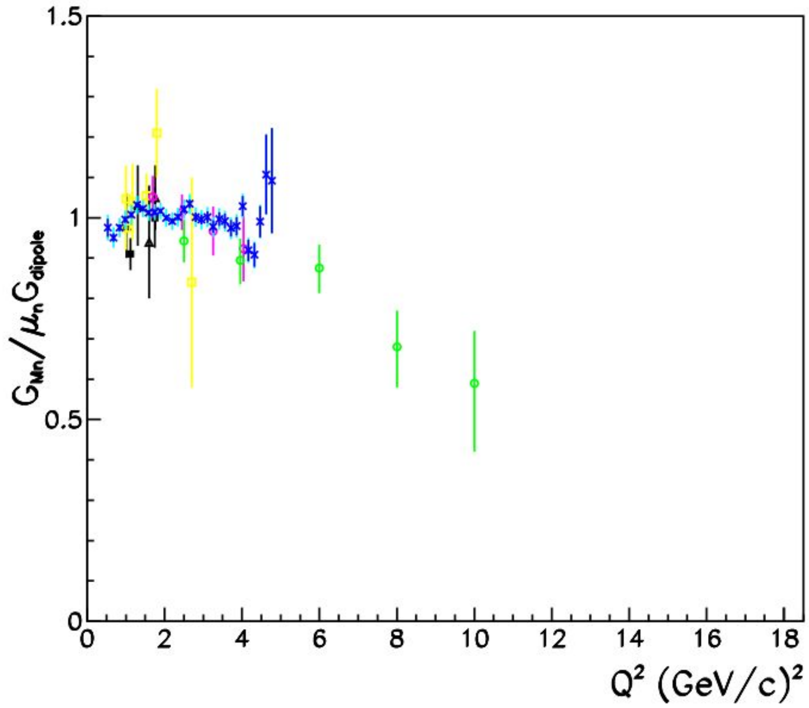


Recoil Polarisation techniques area more sensitive way to measure G^E_p which is multiplied by G^M_p in the transverse component of the polarization, P_T.

Unlike the Rosenbluth Method, the cross section is not increasingly dominated by G^2_M at large Q^2.

World data for μG^E_p / G^M_p is shown on the left.

Magnetic Form Factor of the Neutron (GMn)

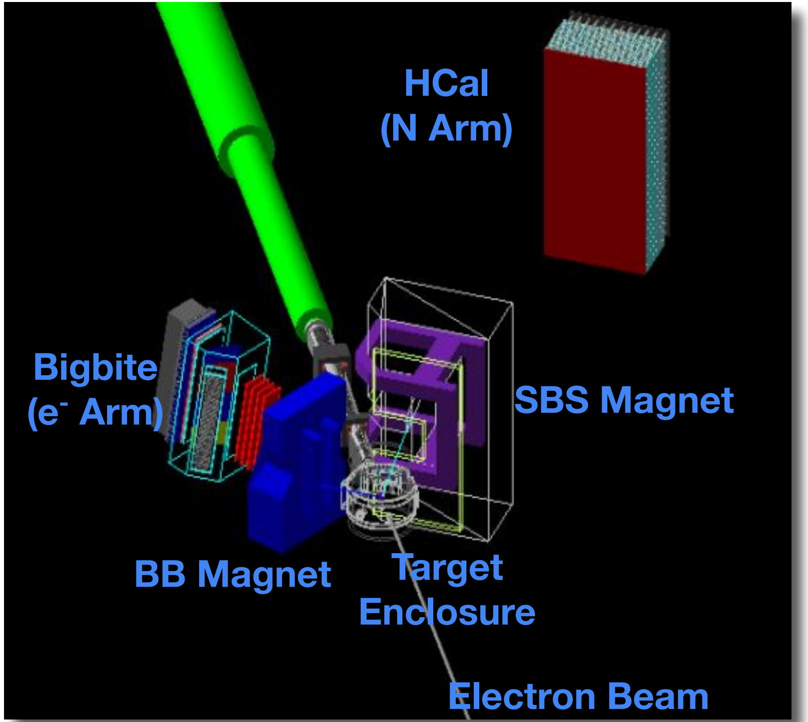


Existing data for GMn (Q^2 > 1 GeV), plotted as ratio to scaled dipole approximation.

Blue - CLAS e5 run, green + magenta - SLAC, yellow - old/legacy

SBS should have reduced systematic uncertainty at high Q^2 in part due to ratio method.

Hall A: Super Bigbite Spectrometer (SBS)



2 arm spectrometer - large $\bar{x},\bar{p}$ acceptance!

High precision form factor measurements

Installed 2020/21

First experimental run 2021/22 (GMn)

Polarised ^{3}He target installed 2022

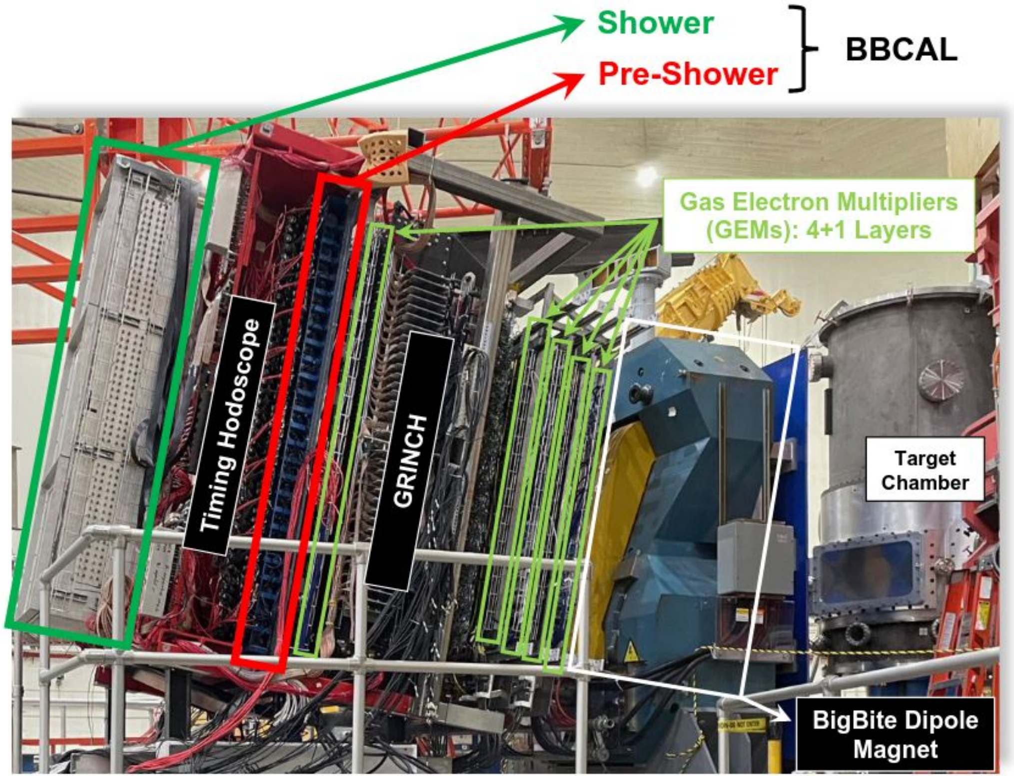
First ^{3}He run 2022/23 (GEn) completed

Future experiments GEn-RP, Pion SDPO, GEp-V - extend in to 2025

Electron Arm: Bigbite

- Bigbite magnet
- (4 Front +1 Rear) XY gas electron multiplier (GEM) tracking layers.
- Gas Cherenkov (GRINCH) detector
- Preshower Calorimeter (2x26 lead-glass blocks)
- Timing Hodoscope (89bars + 178pmts)
- Shower Calorimeter (7x27 lead-glass blocks)

BBCAL forms single arm trigger. Analogue sum of energy deposited in each trigger block.

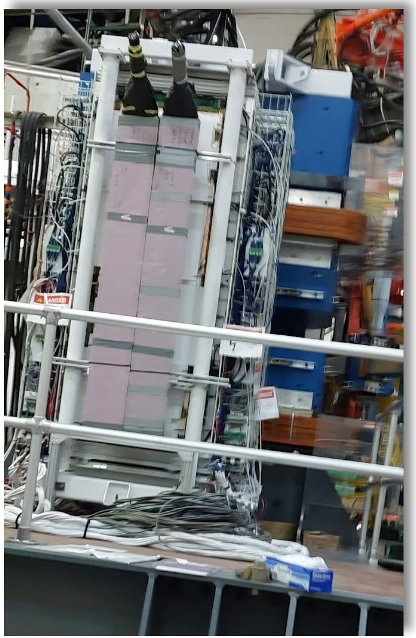


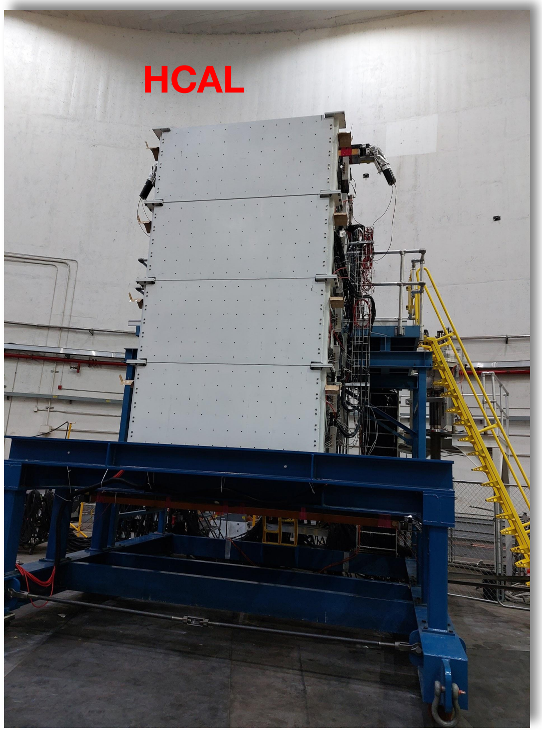
P. Datta (FC NHP 2022)
https://indico.jlab.org/event/529/contributions/10270/attachments/8180/11693/F%26C_MIT_gmn%26bbcal_2022.pdf

Nucleon Arm: Super Bigbite

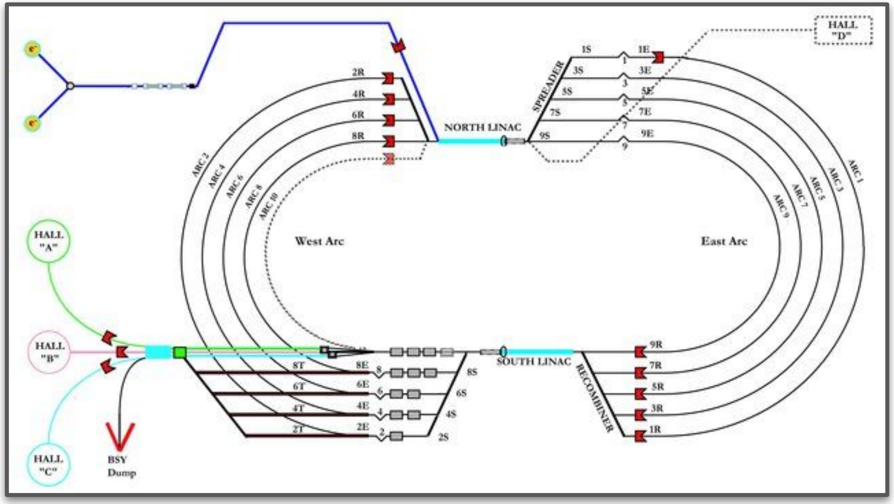
- SBS Magnet
  - 2100A at 100% - p,n separation!
- (2INFN + 6UVa) GEM layers
  - Fully utilised in GEp
- Hadron Calorimeter [HCAL] (242 Fe/Scintillator plate blocks)
  - ~700ps TOF and ~30% energy resolution

HCAL + BBCAL function as coincidence trigger





CEBAF: Continuous Electron Beam Accelerator Facility



Linearly polarised electron beams up to 12 GeV and around 85% polarisation to four experimental halls simultaneously

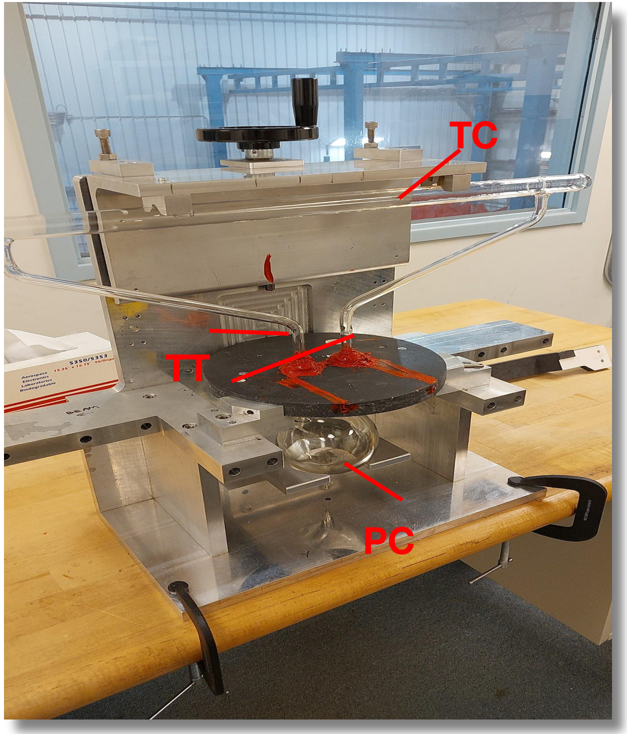
Polarised ^3He Target

10 atm glass ‘cell’ comprised of pumping chamber (PC), transfer tubes (TT) and target chamber (TC).

PC Filled with ^3He, N_2, and 2 alkali metals (K-19 and Rb-85)

PC resides inside ceramic ‘oven’ at around 260 degrees C.

~650nm lasers directed into sides of PC via mirror system, with about 160 W total power.



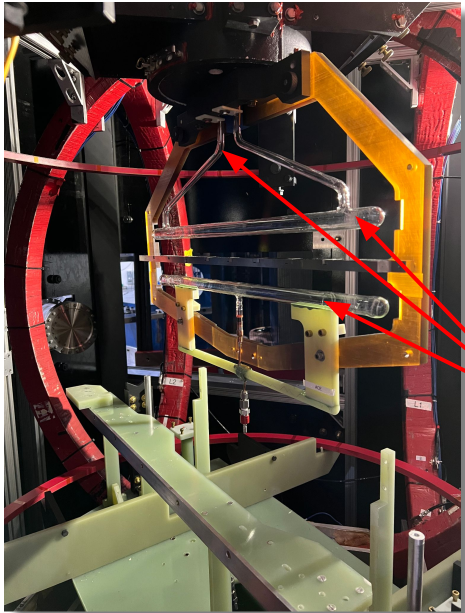
Polarised ^{3}He Target

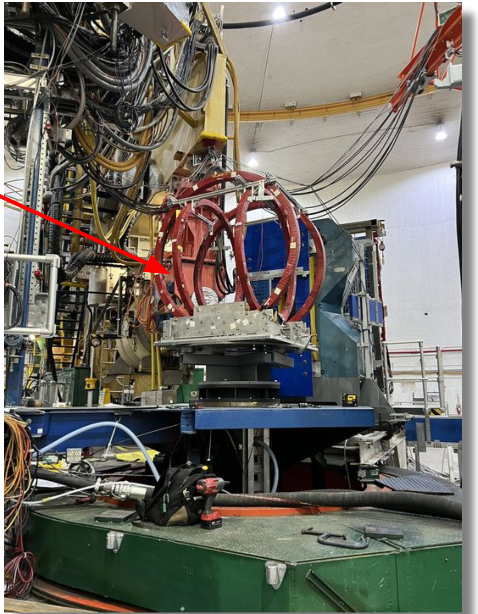
Entire system located within set of Helmholtz (HH) coils.

Downstream transfer tube has heater strip to induce convection around cell.

^{3}He gas polarised via spin exchange optical pumping (SEOP).

Rotate to match magnets





RTDs for Temp monitoring

Spin Exchange Optical Pumping (SEOP)

Alkali vapor polarized by optical pumping from laser radiation.

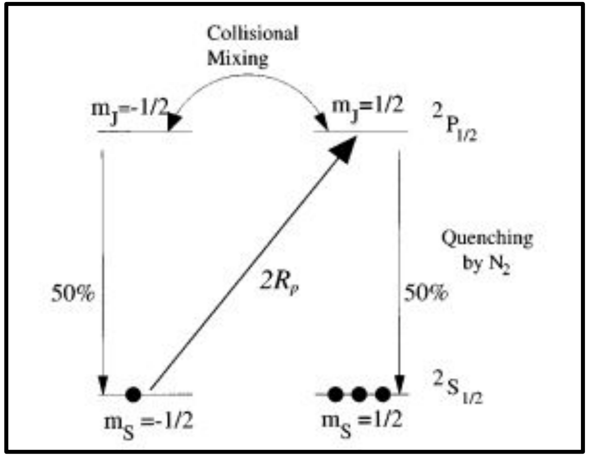
Collide with ^{3}He transferring spin via hyperfine interactions

$$P_{\mathrm{He}}(t) = P_{\mathrm{Alk}} \frac{\gamma_{se}}{\gamma_{se}(1+X)+\Gamma}\left(1-e^{-t(\gamma_{se}+\Gamma)}\right)$$

Nitrogen Suppresses reradiation via quenching of excited atoms

Mix of Kb and K increases ***efficiency*** of polarization of the helium

High power diode lasers allow for larger ***volume*** of helium to be polarized



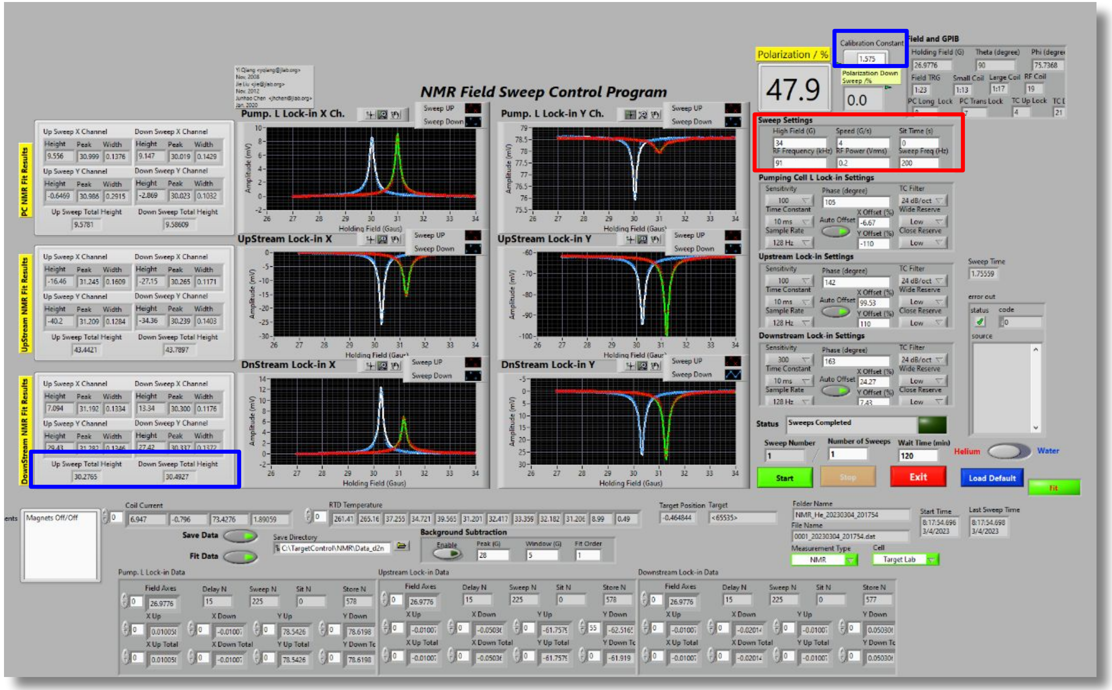
Nuclear Magnetic Resonance (NMR)

- Apply RF field to spins
  - Resonance → Signal in Coils
- Meet Resonance Criteria Via Adiabatic Fast Passage (AFP)
- Destructive measurement - AFP sweeps cause losses ~1%
- mV:% conversion factor required to get true polarisation value

$$D_x = \frac{US_x + DS_x}{2} \qquad D_y = \frac{US_y + DS_y}{2}$$

$$D = \sqrt{D_x^2 + D_y^2}$$

$$S_{NMR} \approx D$$

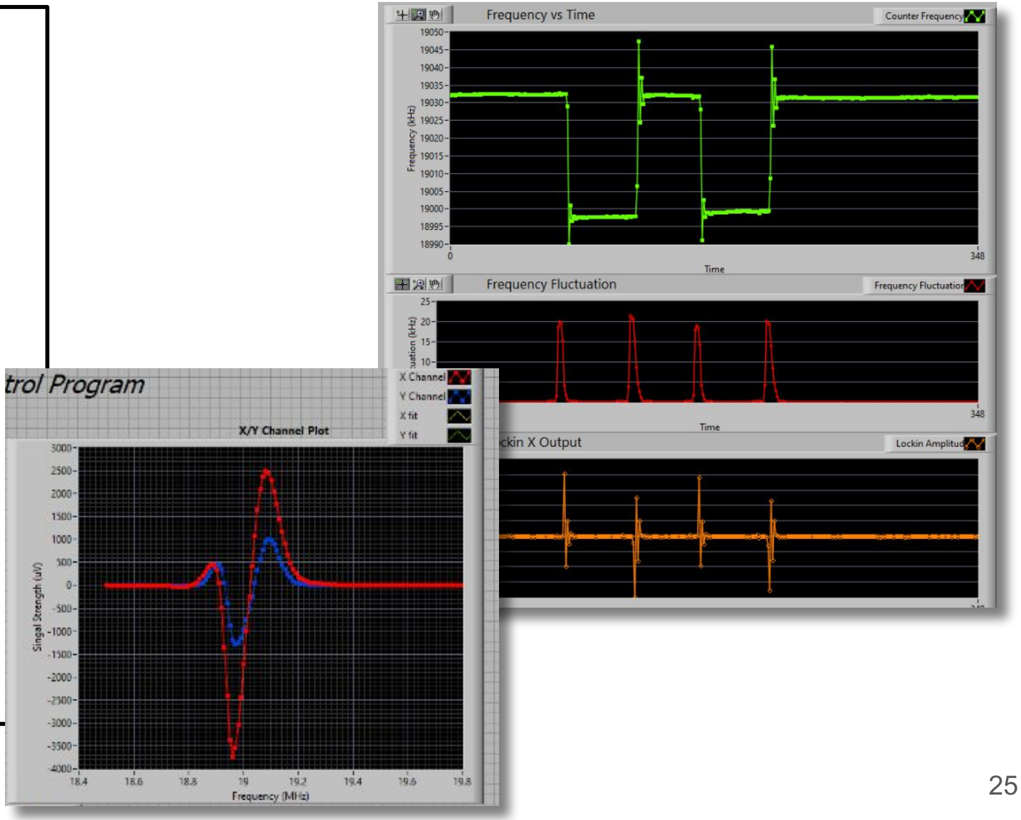


Electron Paramagnetic Resonance (EPR)

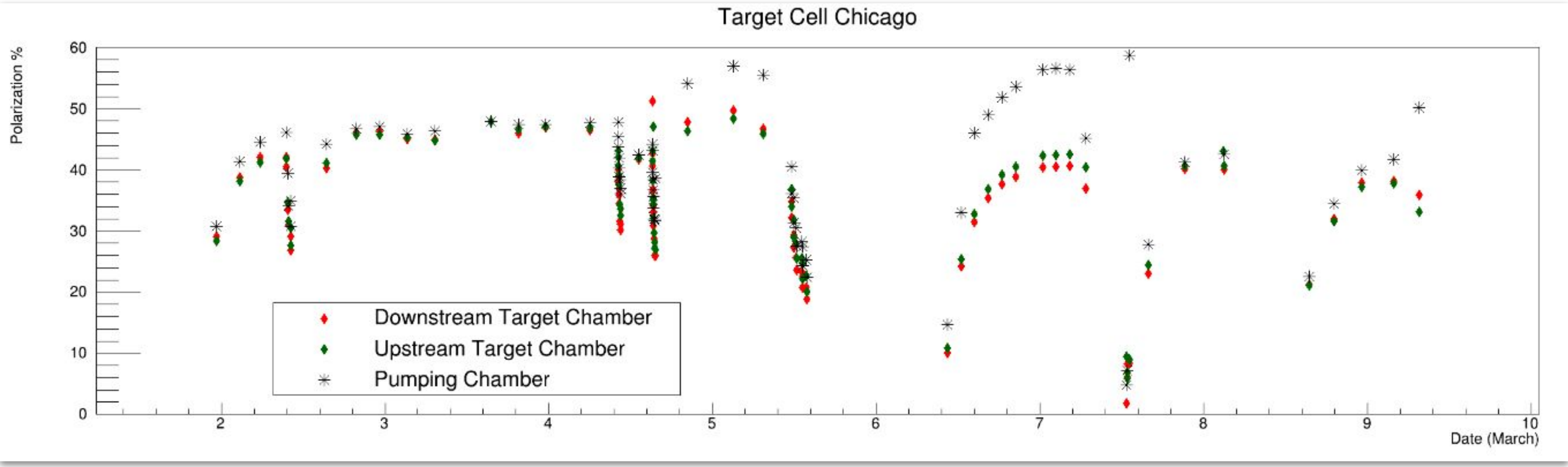
<u>EPR - Measure Zeeman Effect in K electrons</u>

- Frequency sweep over alkali resonance modes
  - Signal when frequency == splitting.
- Signal is first derivative of absorption spectrum
- EPR non destructive - AFP still causes losses.

$$c = \frac{S_{\mathrm{NMR}}}{P_{\mathrm{EPR}}(n_{\mathrm{p}}\Phi_{\mathrm{p}} + n_{\mathrm{t}}\Phi_{\mathrm{t}} + n_{\mathrm{tt}}\Phi_{\mathrm{tt}})}$$



NMR + EPR



Target Cell Chicago
Polarization %
60
50
40
30
20
10
0
2
3
4
5
6
7
8
9
10
Date (March)
Downstream Target Chamber
Upstream Target Chamber
Pumping Chamber

$$\sigma_h = \Sigma + h\Delta$$

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

$$\Sigma = \frac{d\sigma}{d\Omega}\bigg|_{\mathrm{Mott}} \frac{E_f}{E_i}\left(\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2(\theta/2)\right)$$

$$\Delta = -2\frac{d\sigma}{d\Omega}\bigg|_{\mathrm{Mott}} \frac{E_f}{E_i}\sqrt{\frac{\tau}{1+\tau}}\tan(\theta/2)\left[\sqrt{\tau(1+(1+\tau)\tan^2(\theta/2))}\cos\theta^* G_M^2 + \sin\theta^*\cos\phi^* G_M G_E\right]$$

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

$$\boxed{A_\perp = -\frac{G_E^n}{G_M^n}\frac{2\sqrt{\tau(\tau+1)}\tan(\theta/2)}{(G_E^n/G_M^n)^2 + (\tau + 2\tau(1+\tau)\tan^2(\theta/2))}}$$

Statistical Uncertainty Handling

Correlated Asymmetries

$$q = \frac{N^+}{N}$$

$$\sigma_q^2 = \frac{\sigma_{N+}^2}{N^2}$$

$$\sigma_{N+}^2 = Nq(1-q)$$

$$\boxed{\sigma_A^2 = \frac{4q(1-q)}{N} = \frac{4N^+N^-}{N^3}}$$

Asymmetry in Polarisation measurement

$$A = \frac{N^+ - N^-}{N} = PA^{true}$$

$$\begin{aligned}
\sigma_{A^{true}}^2 &= \frac{1}{P^2}\sigma_A^2 + \frac{A^2}{P^4}\sigma_P^2 \\
&= \frac{4N^+N^-}{N^3P^2} + \frac{(N^+ - N^-)^2}{N^2P^4}\sigma_P^2 \\
&= \frac{4q(1-q)}{NP^2} + \frac{(2q-1)^2}{P^4}\sigma_P^2
\end{aligned}$$

$$\begin{aligned}
A^{true} &= \frac{\sum A_i^{true} N_i P_i^2}{\sum N_i P_i^2} \\
&= \frac{\sum (N_i^+ - N_i^-) P_i}{\sum N_i P_i^2} \longrightarrow \boxed{\sigma_{A^{true}}^2 = \frac{4q(1-q)}{\sum N_i P_i^2}}
\end{aligned}$$