Overview of nucleon form factor measurements

Focus on spin observables in electron-nucleon scattering

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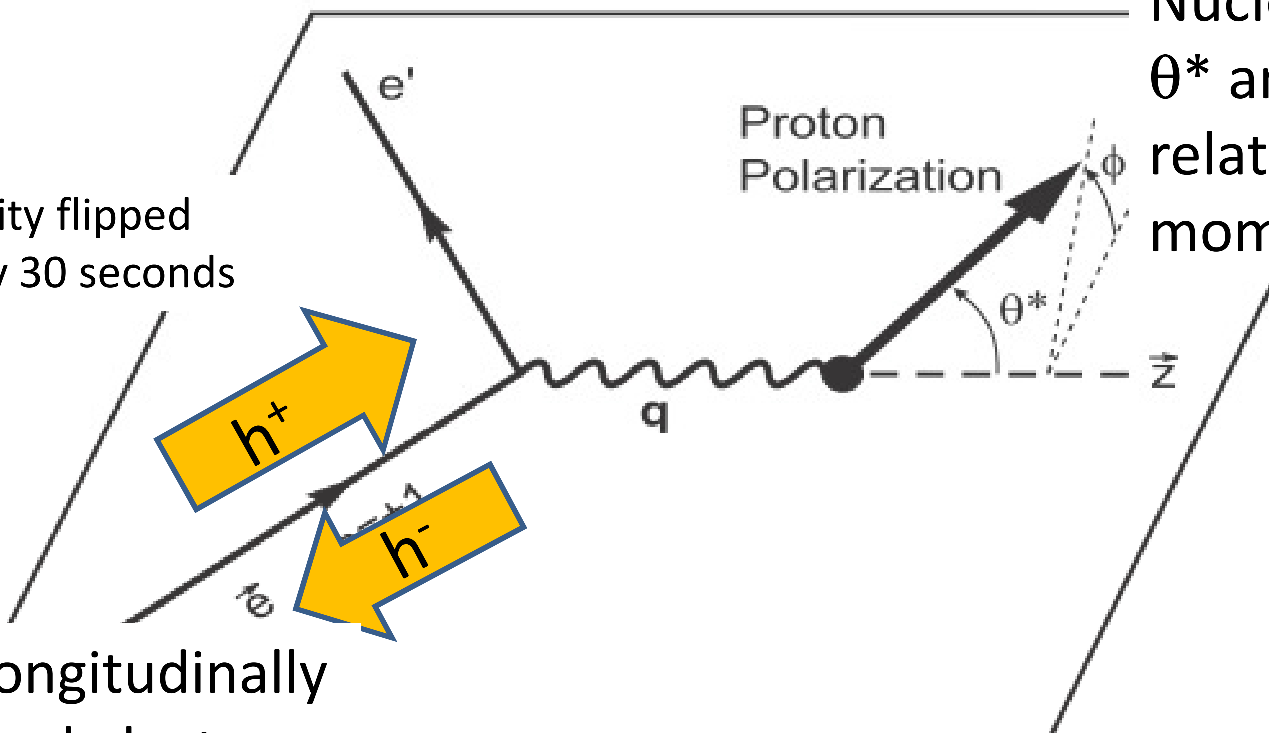
Overview of experiment

- Polarized beam on polarized nucleon (Beam-Target Asymmetries)
  - Polarized proton target
  - Polarized neutron target using polarized ^3He and deuterium
  - Electron storage rings use internal gas target (windowless). Target polarized by atomic beam source method or spin exchange optical pumping.
  - Linear electron accelerators use external gas target (window)
    - 3He gas targets by spin exchange or metastability optical pumping
    - Solid polarized deuterium or hydrogen

- Polarized beam on unpolarized target
  - Spin of scattered nucleon measured by secondary scattering
  - Linear electrons accelerators on high density hydrogen and deuterium targets

Beam-Target Spin Asymmetry

Helicity flipped every 30 seconds



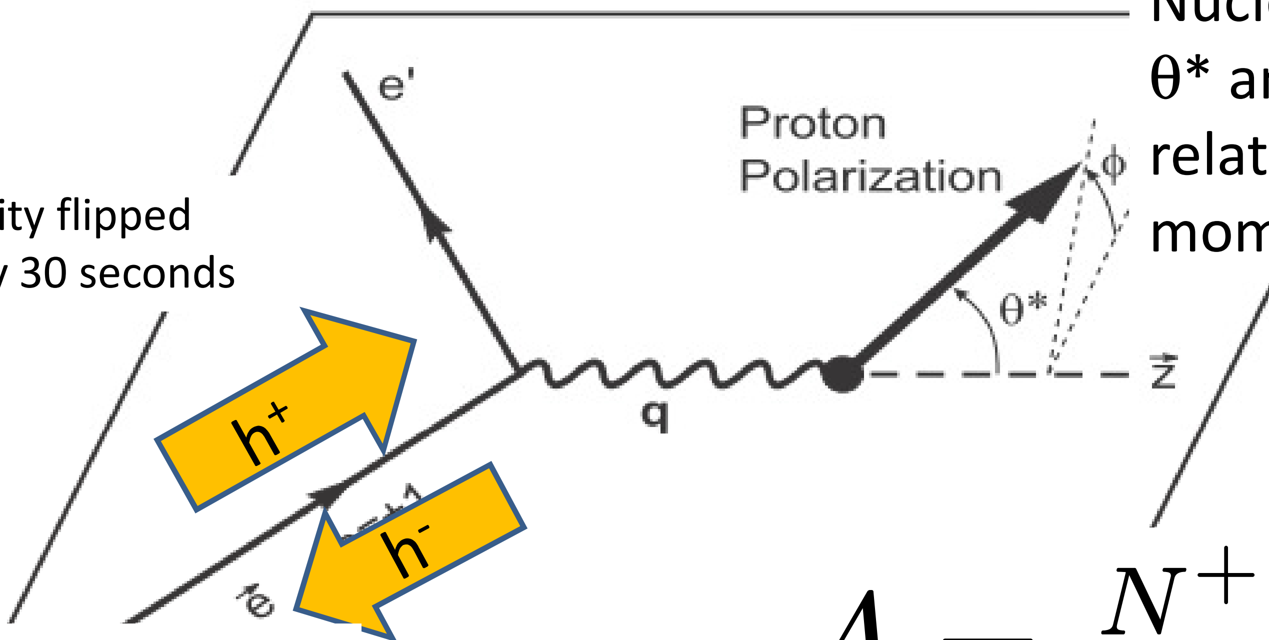
Nucleon polarized at θ* and ϕ* relative to the momentum transfer

85% longitudinally polarized electron beam

Beam-Target Spin Asymmetry

Nucleon polarized at θ^* and ϕ^* relative to the momentum transfer

Helicity flipped every 30 seconds



85% longitudinally polarized electron beam

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

Beam-Target Spin Asymmetry

Nucleon polarized at θ^* and ϕ^* relative to the momentum transfer

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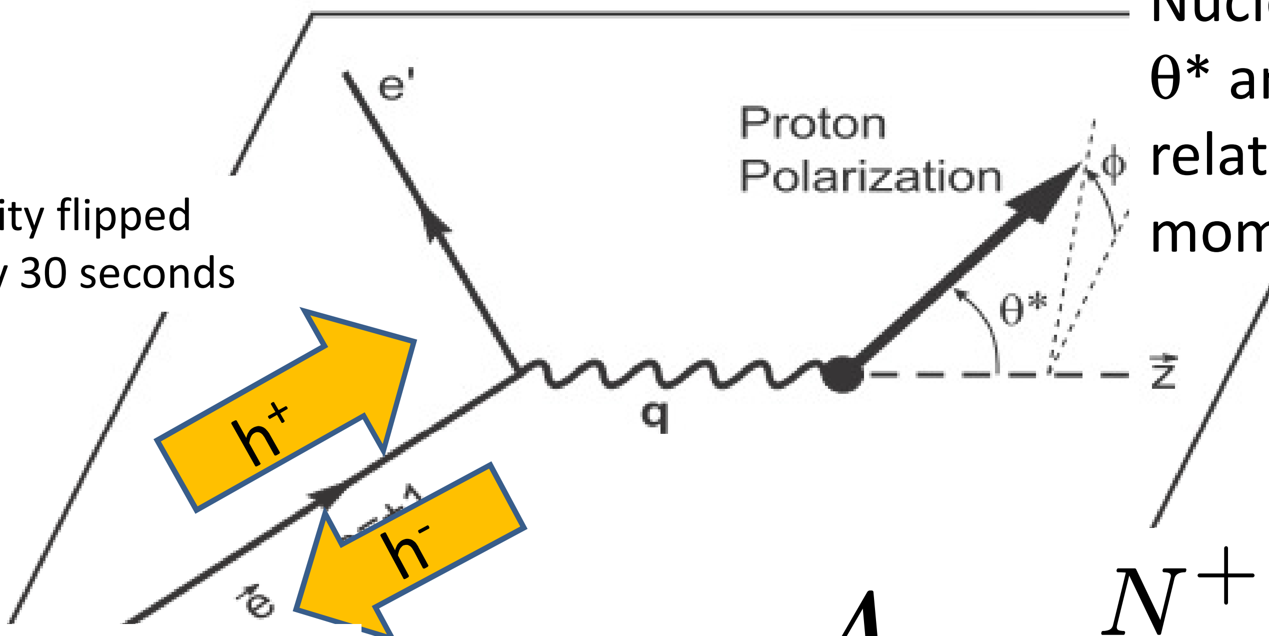
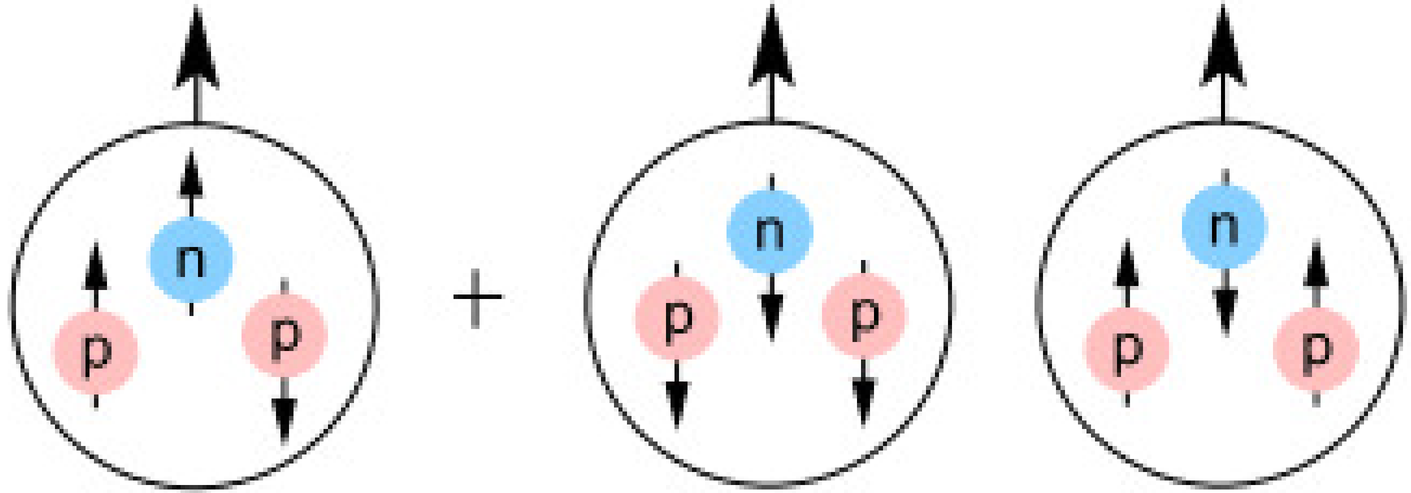


85% longitudinally polarized electron beam

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

$$\boxed{A = P_B P_T \frac{K_1 G_M^2 \cos\theta^\star + K_2 G_E G_M \sin\theta^\star \cos\phi^\star}{G_E^2 + \frac{\tau}{\epsilon} G_M^2}}$$

Polarized ^{3}He as a polarized neutron target



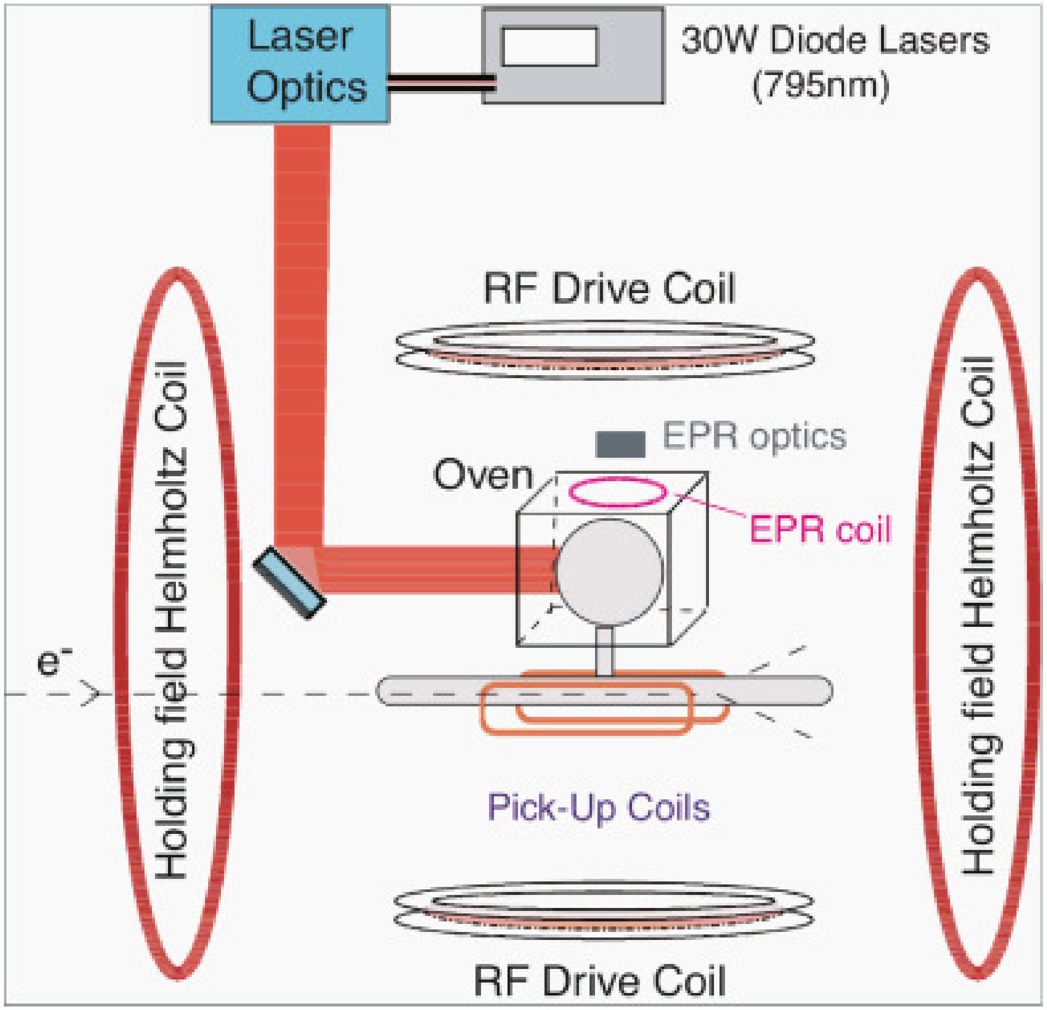
S state ($\sim$88.2%) D state ($\sim$9.8%) S' state ($\sim$1.4%)

P_{n} = 86% and P_{p} = -2.8%

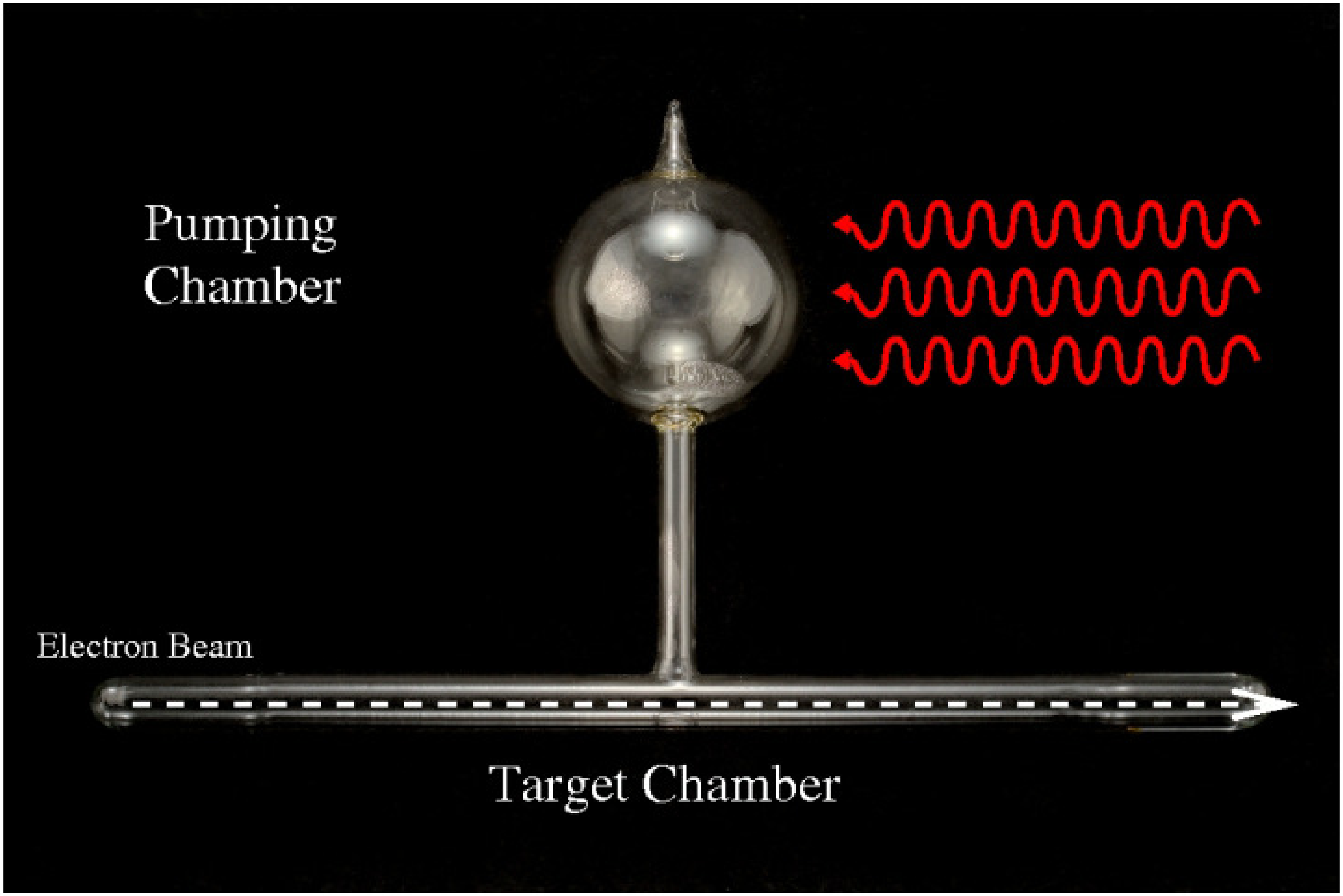
J.L. Friar *et al.*, PRC **42**, (1990) 2310

Polarized ^{3}He target

❑Glass cell holds ^{3}He at 10atm
❑Alkali atoms are polarized by the laser light.
❑^{3}He is polarized by spin exchange with alkali atoms.
❑Helmholtz coils produce 25G holding field to orient the 3He spin
❑Polarization measured by either Nuclear Magnetic Resonance or Electron Para-magnetic Resonance
❑Targets can take 15uA beam currents with 60 -70% polarization



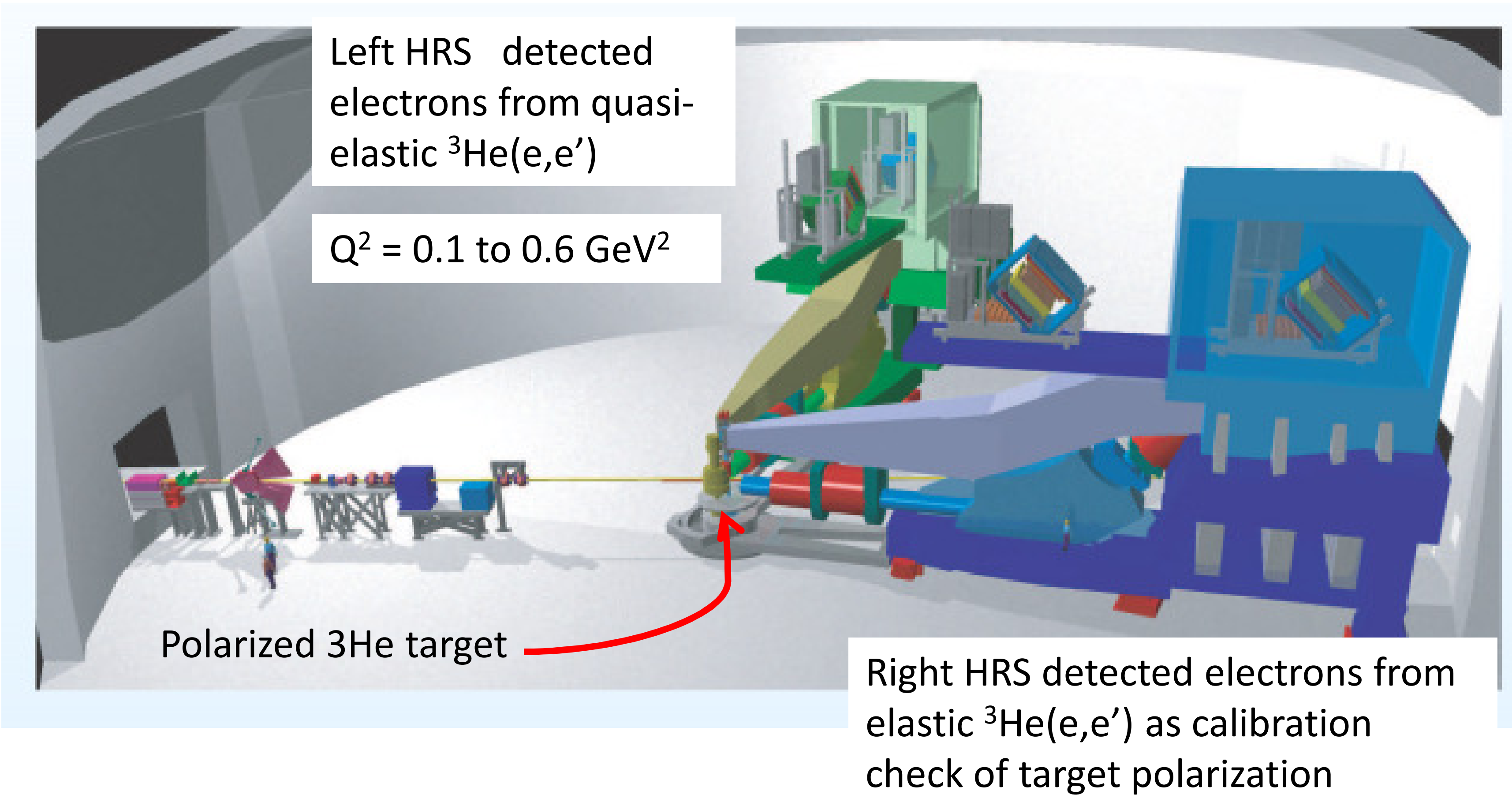
Polarized ^{3}He target



Jlab Hall A quasi-elastic ^{3}He(e,e')

Two Identical **H**igh **R**esolution **S**pectrometers

$\Delta p/p = 10^{-4}$ and $\Delta\Omega$ = 4msr



A_T in quasi-elastic $^3He(e,e')$

$$A = -\frac{\cos\theta^* \nu_{T'} R_{T'} + 2\sin\theta^* \cos\phi^* \nu_{TL'} R_{TL'}}{\nu_L R_L + \nu_T R_T}$$

$$\text{Set } \theta^\star = 0^\circ \text{ then } A_{T'} = -\nu_T R_{T'}/(\nu_T R_T + \nu_L R_L)$$

In PWIA

$$\begin{aligned} R_{T'} &\propto P_n (G_M^n)^2 + P_p (G_M^p)^2 \\ R_{TL'} &\propto P_n G_M^n G_E^n + P_p G_M^p G_E^p \end{aligned}$$

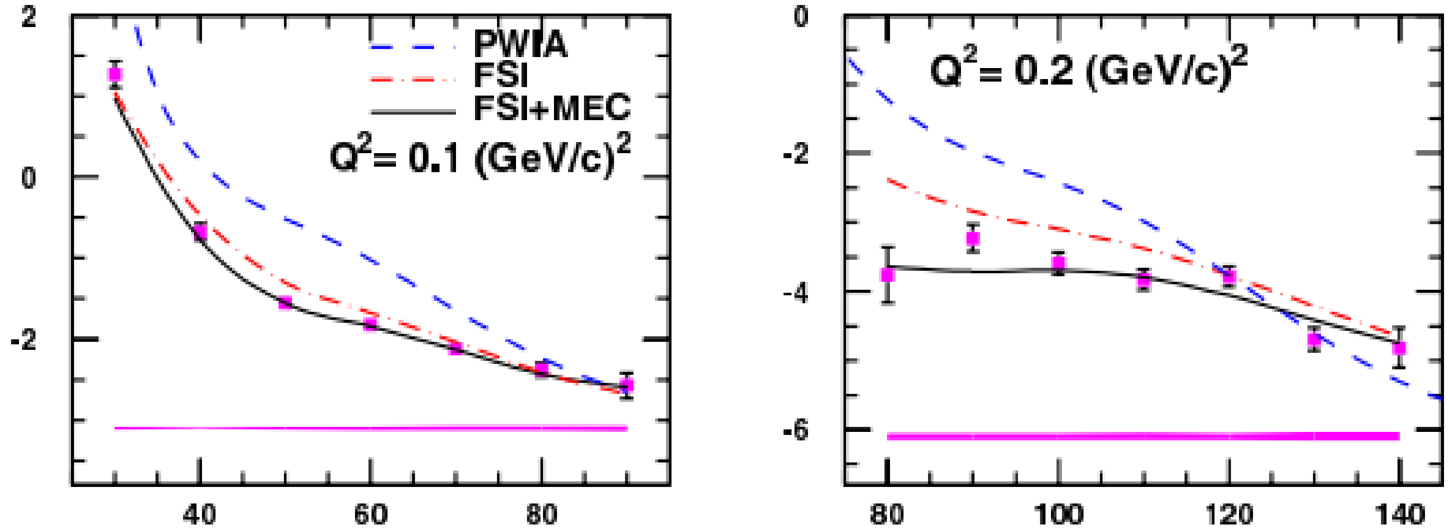
In ^{3}He polarization of the neutron is larger than the proton

$$P_n >> P_p$$

$$A_{T'}({G_M^n}^2) = \frac{1 + a(G_M^n)^2}{b + c(G_M^n)^2}$$

Extracting G_{Mn} from A_T in $^3He(e,e)$

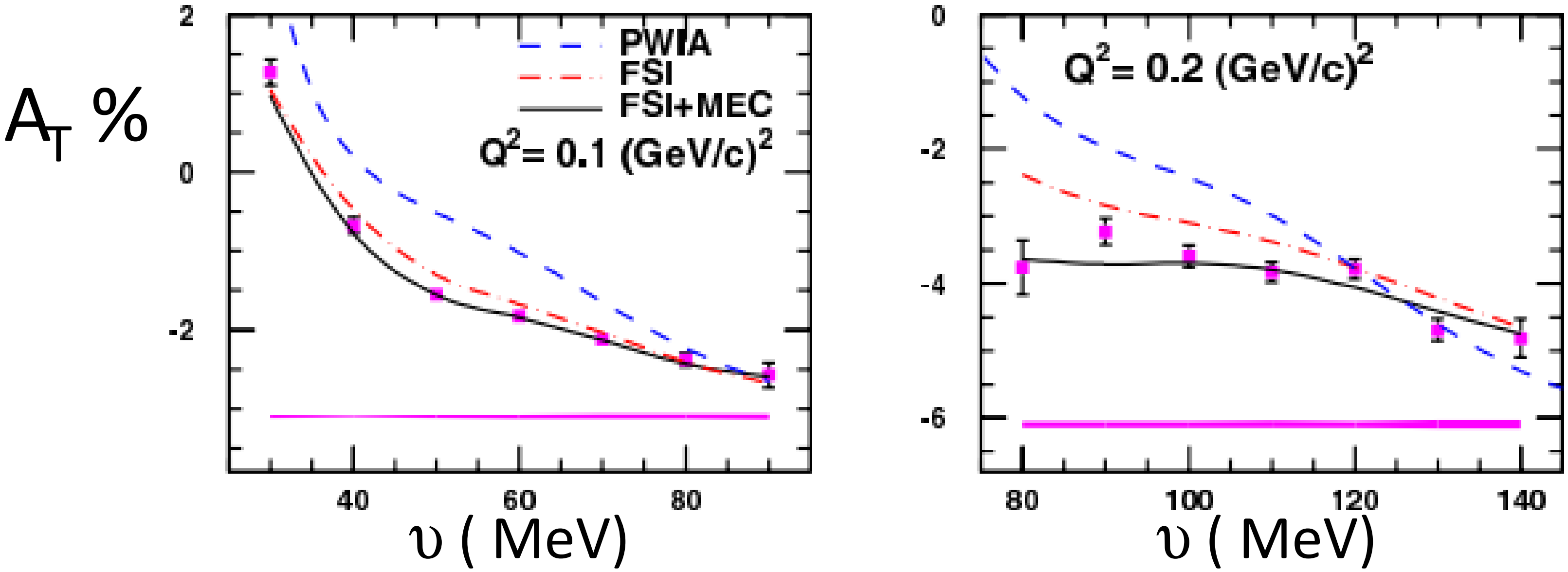
A_T %



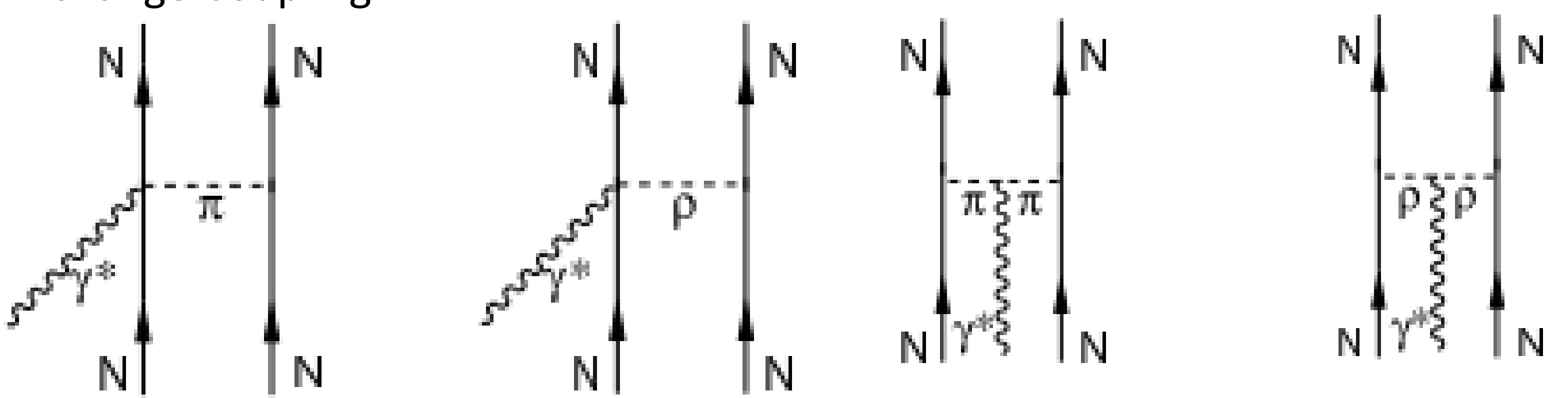
υ (MeV)

υ (MeV)

Extracting G_{Mn} from A_T in ^{3}He(e,e)



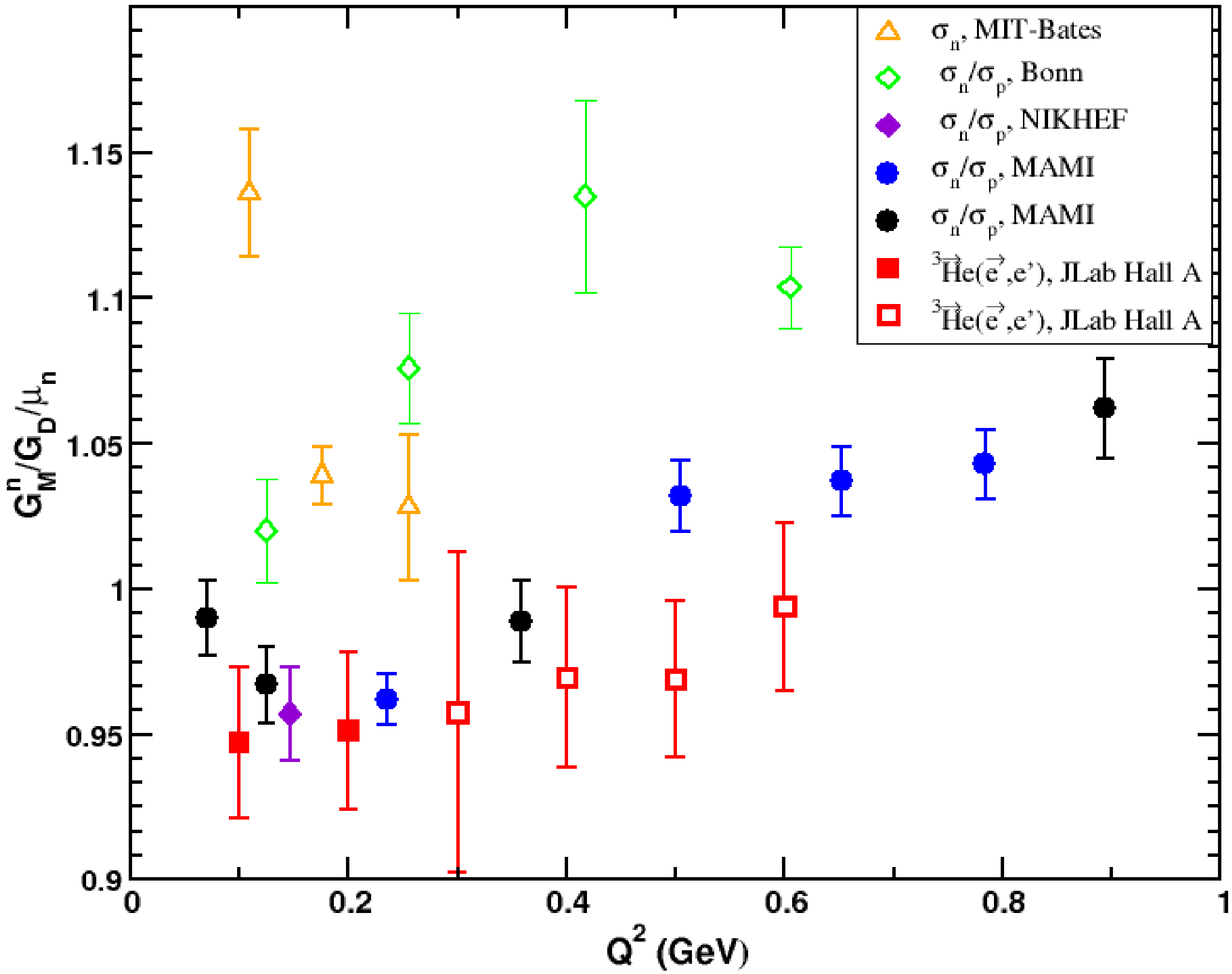
Meson Exchange Coupling



Coupling to correlated nucleon pairs

Coupling to in-flight mesons

Neutron Magnetic Form Factor: G_{Mn}

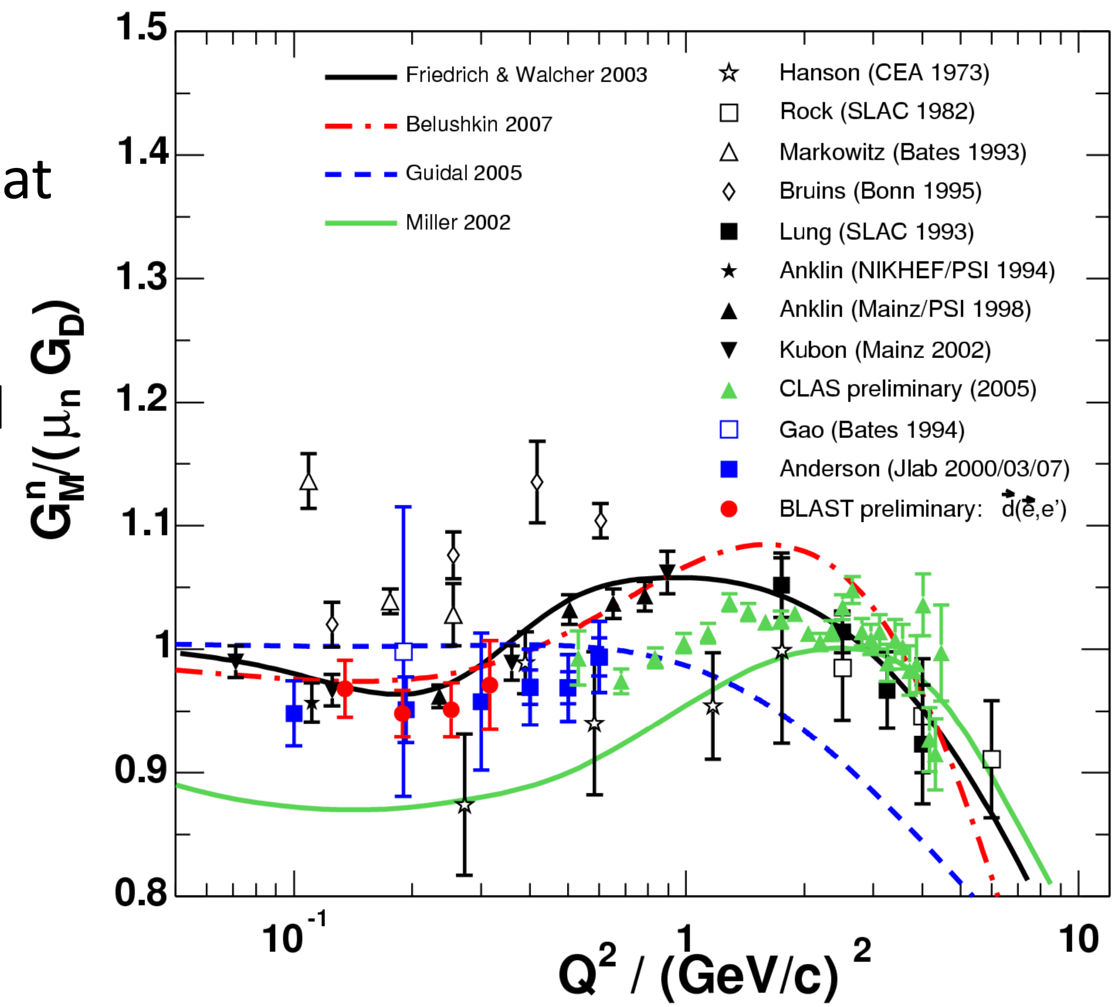


Neutron Magnetic Form Factor: G_{Mn}

- New preliminary results using the BLAST detector at MIT-Bates

- Electron ring and internal gas target

- Use inclusive $^{2}\vec{\mathrm{H}}(\vec{\mathrm{e}},\mathrm{e}')$ which is sensitive to G_{Mn}/G_{Mp}



G_{En} from quasielastic $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{n})$

Experiment done at MAMI

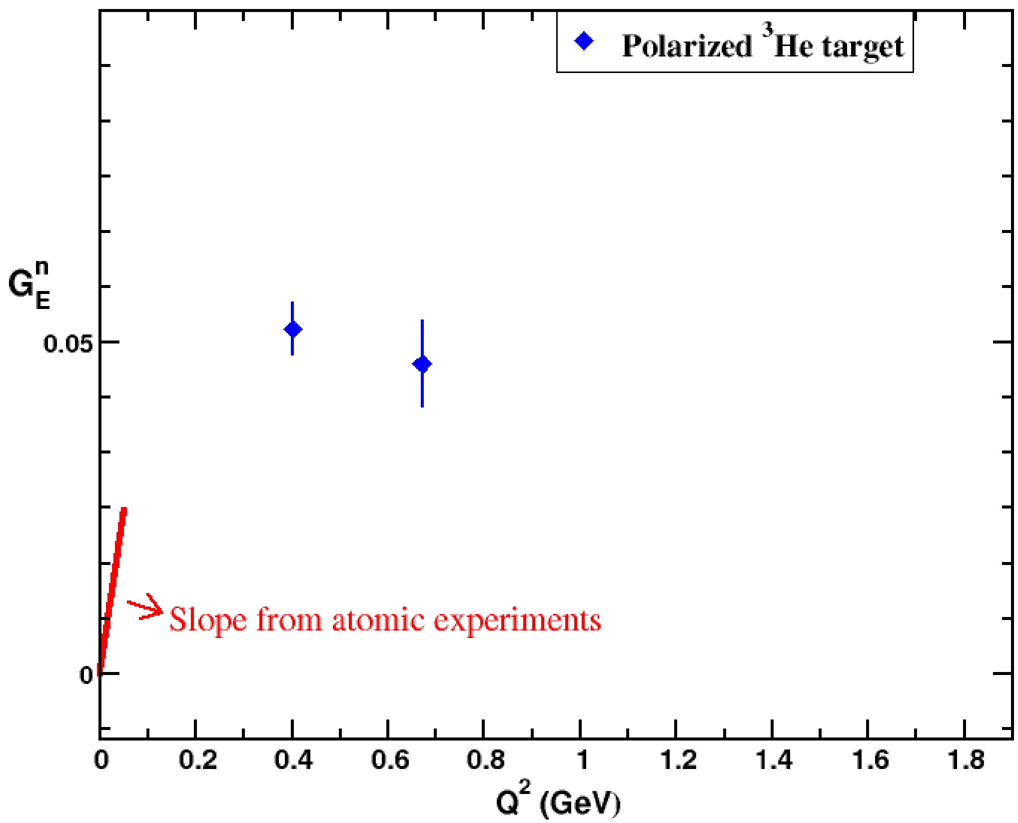
$$\boxed{A = P_B P_T \frac{K_1 G_M^2 \cos\theta^\star + K_2 G_E G_M \sin\theta^\star \cos\phi^\star}{G_E^2 + \frac{\tau}{\epsilon} G_M^2}}$$

$$\theta^* = 90^\circ \qquad A_\perp \propto P_B P_T G_E / G_M$$

$$\theta^* = 0^\circ \qquad A_\parallel \propto P_B P_T$$

$$G_E / G_M \propto A_\perp / A_\parallel$$

Neutron Electric Form Factor: G_{En}



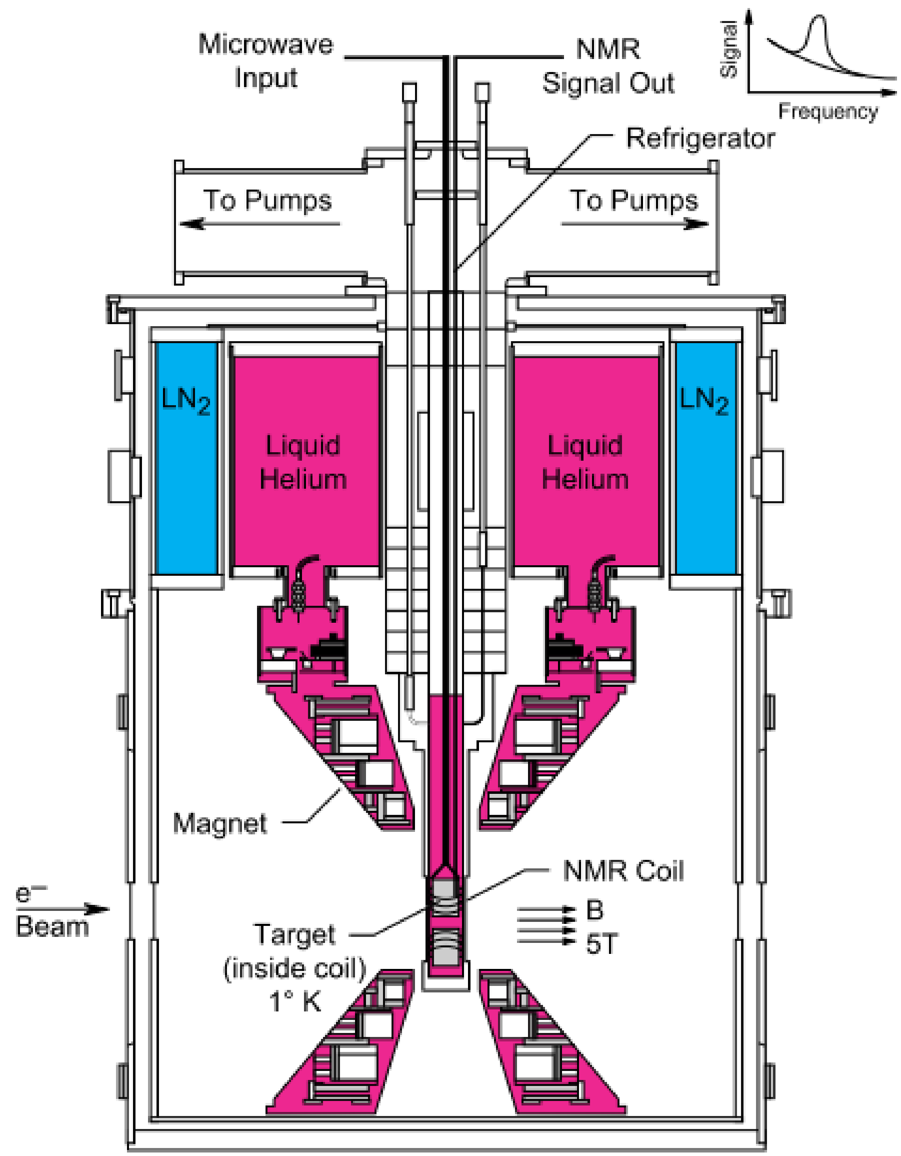
Theory important for reliably extracting G_E/G_M from nuclear effects

At $Q^2 = 0.4$, 25% difference between G_E extracted from PWIA and full calculation (Final State Interactions are the most important)

At $Q^2 = 0.7$, expected FSI to be a 3% effect.

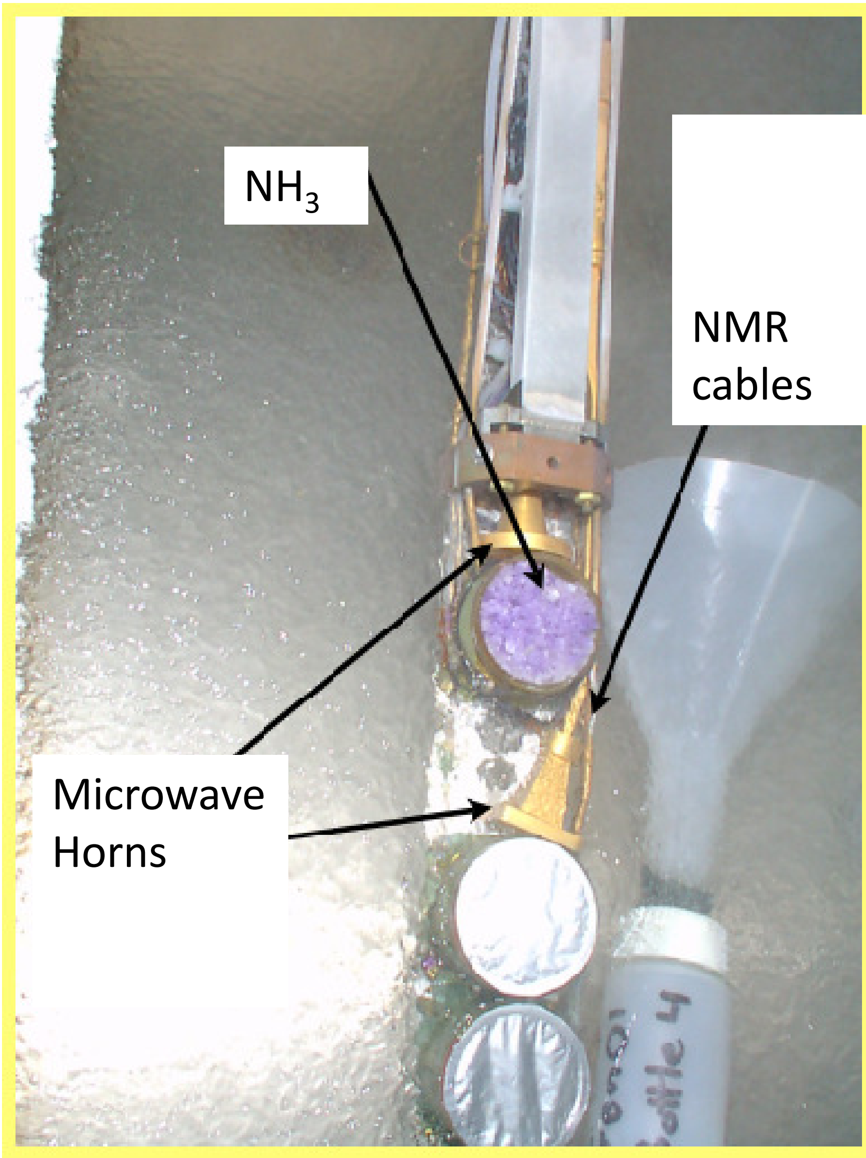
Polarized deuteron or proton target

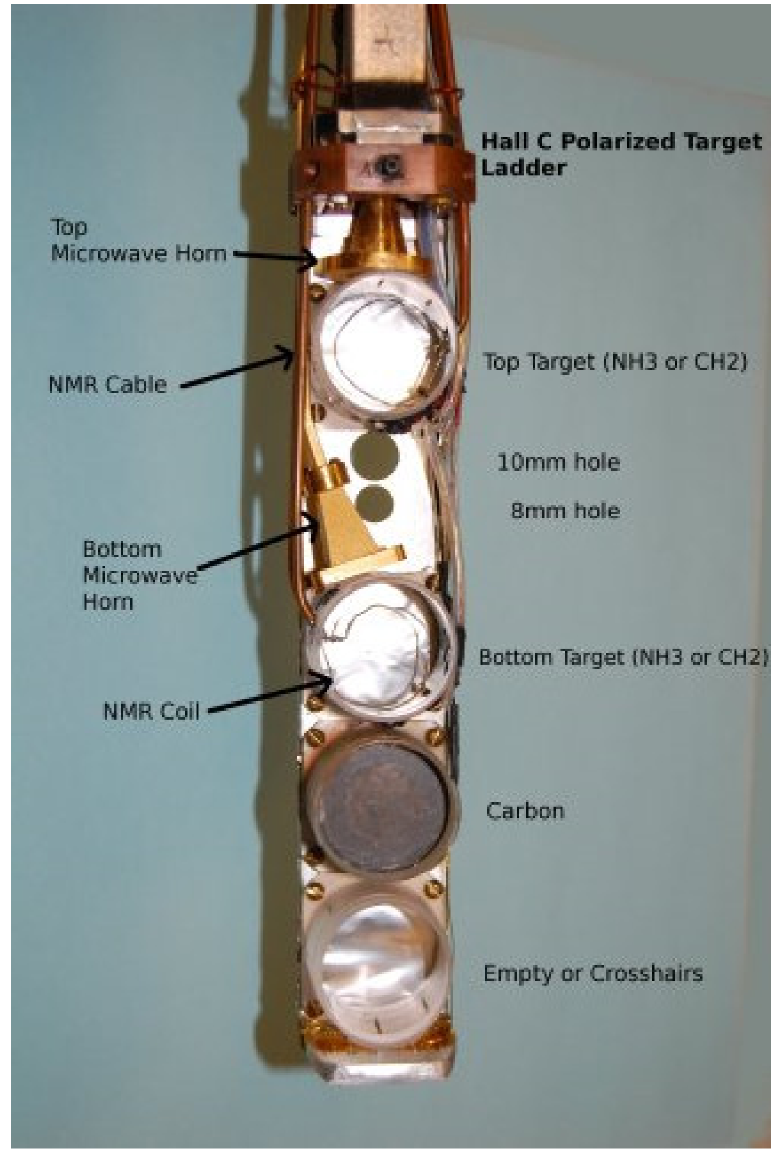
- ❑Helmholtz coils produce field of 5T
- ❑Target material frozen ammonia ($^{14}ND_3$ or $^{14}NH_3$). Needs to be irradiate to produce unpaired electrons.
- ❑Helium refrigerator (helium bath with pumps to produce low pressure) cools target to 1 K
- ❑140 GHz microwaves irradiate target and dynamically polarize the target. The unpaired electrons are 100% polarized which is transferred to the H or D
- ❑Produce proton polarized to 70-90% and deuterons polarized to 20-40%
- ❑Only low 100nA currents possible. Beam heating destroys the polarization of the material



D. Crabb and D. Day, NIM A356, 9 (1995)

Polarized deuteron or proton target





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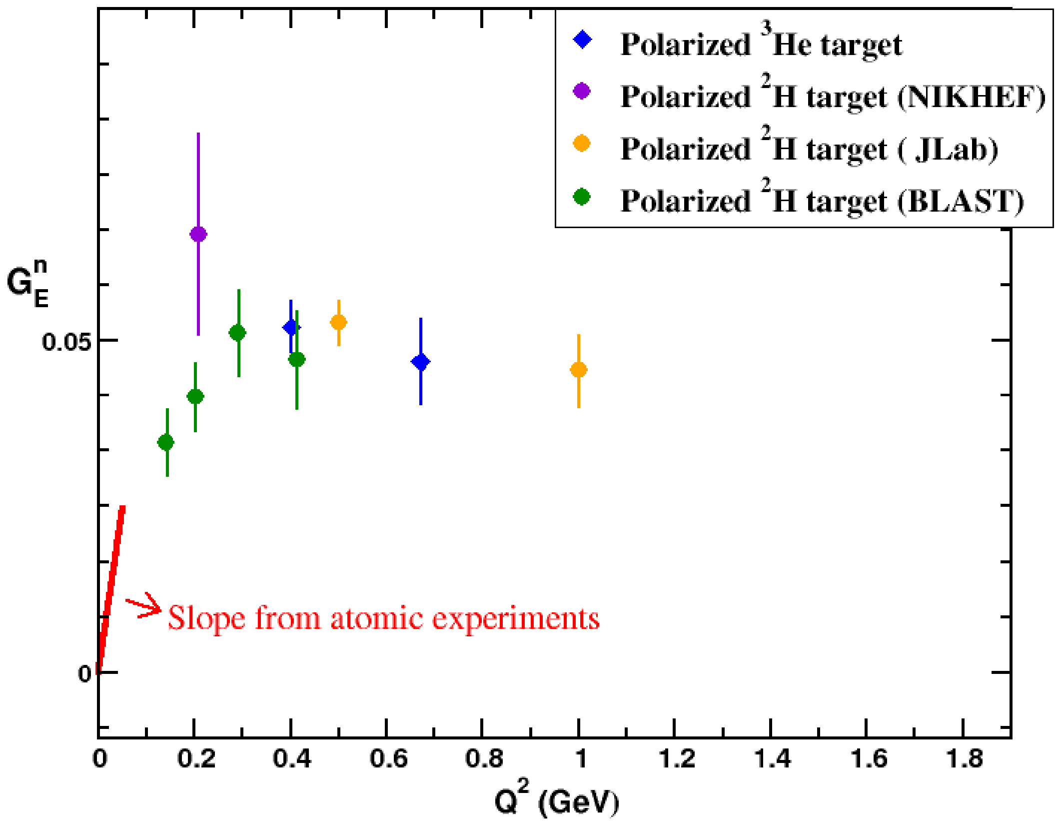


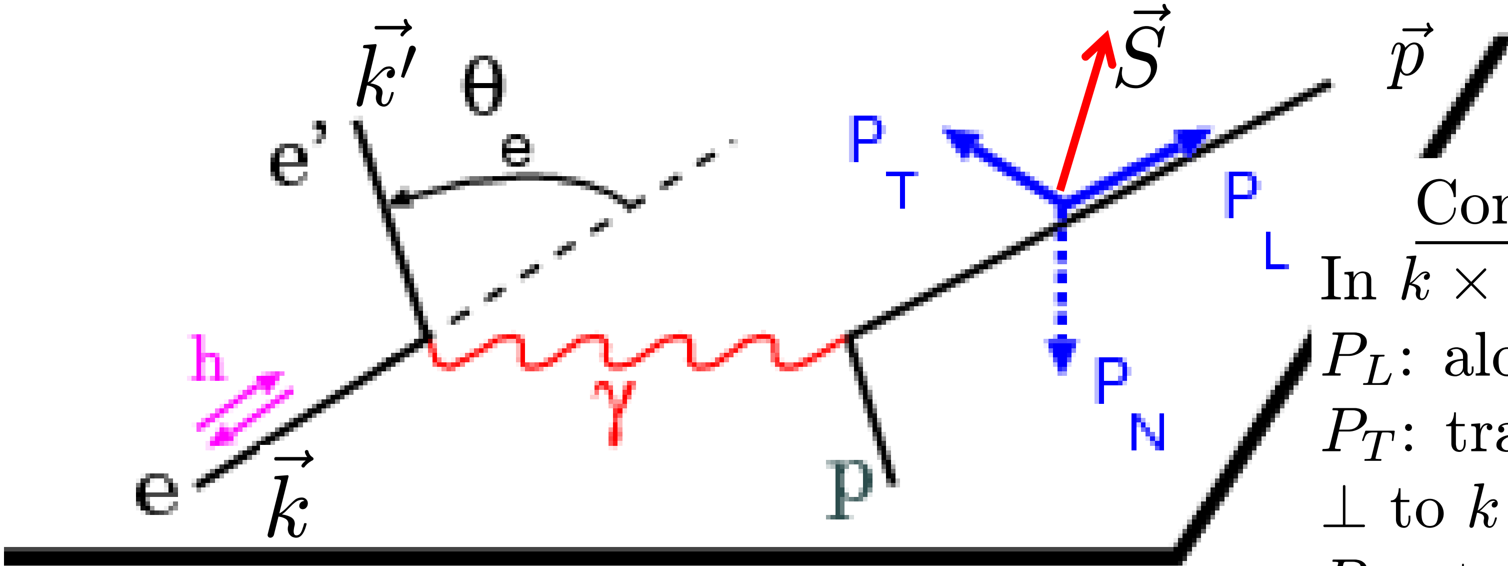
Quasi-free $\vec{\mathrm{d}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{n})$

In PWIA with $\Theta^* = 90^o$

$$A_{ed}^V = P_B P_T V \frac{a G_E G_M}{G_E^2 + \tau/\epsilon G_M^2}$$

- NIKHEF used electron storage ring with internal gas target.
- JLab used solid $^{15}ND_3$ target Measured to $Q^2 = 1$
- MIT-Bates used internal gas target and large acceptance BLAST detector

Recoil Polarization



Components of $\vec{S}$

In $k \times k'$ plane

P_L: along $\vec{p}$

P_T: transverse to $\vec{p}$

$\perp$ to $k \times k'$ plane

P_N: transverse to $\vec{p}$

One-photon exchange (Born) approximation: $P_N = 0$

$$P_T = -2\sqrt{\tau(1+\tau)}G_E G_M \tan\frac{\theta_e}{2} / I_o$$

$$P_L = \frac{E+E'}{M}\sqrt{\tau(1+\tau)}G_M^2 \tan^2\frac{\theta_e}{2} / I_o \qquad I_o = G_E^2 + \frac{\tau}{\epsilon}G_M^2$$

$$\frac{G_E}{G_M} = -\frac{P_T}{P_L}\frac{E+E'}{2M}\tan\frac{\theta_e}{2}$$

Polarimetry basics

- Measure proton spin by secondary scattering on a nucleus (^{12}C, CH_n, H_2 …)
- An asymmetry in the scattering is caused by the spin-orbit part of the nucleon-nucleon potential

$$V(\vec{r}) \propto \vec{L} \cdot \vec{S} \qquad\qquad \vec{L} = \vec{r} \times \vec{p}$$

- Only components of S that perpendicular to the momentum vector produce an asymmetry

$$\Sigma_{UD} = P_T A = \frac{N_{Up} - N_{Down}}{N_{Up} + N_{Down}}$$

$$\Sigma_{LR} = P_N A = \frac{N_{Left} - N_{Right}}{N_{Left} + N_{Right}}$$

- *A* is the analyzer power of the scattering material.

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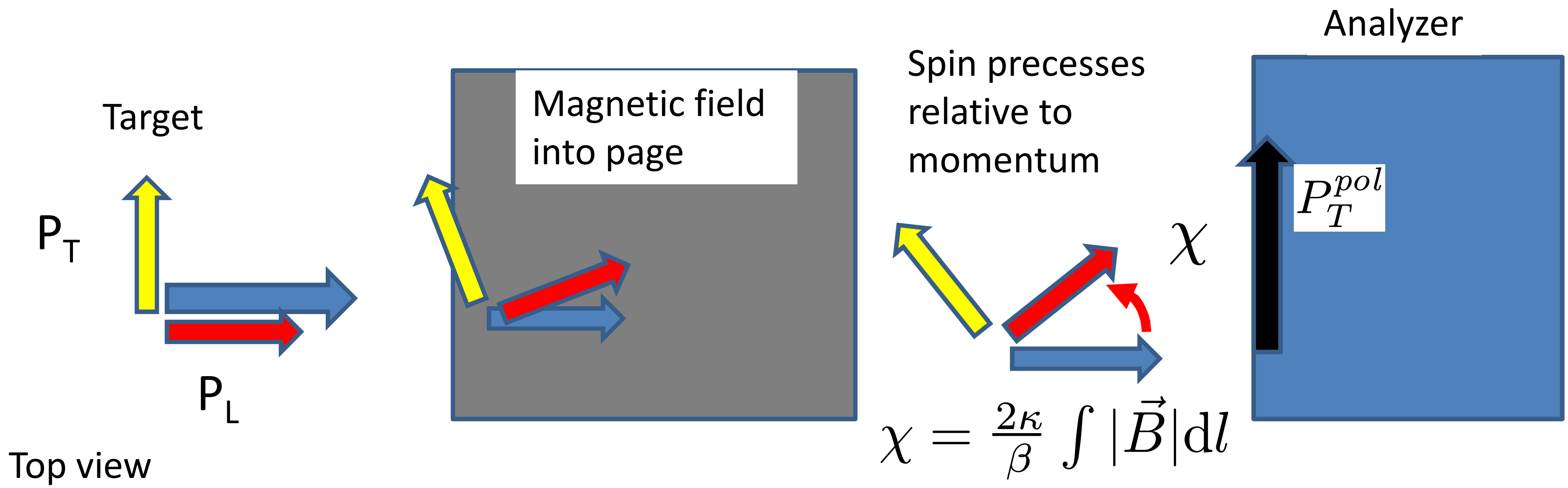
- *A* is the analyzer power of the scattering material.

- How does one measure the P_L of the outgoing proton spin?

Spin rotation in magnetic field

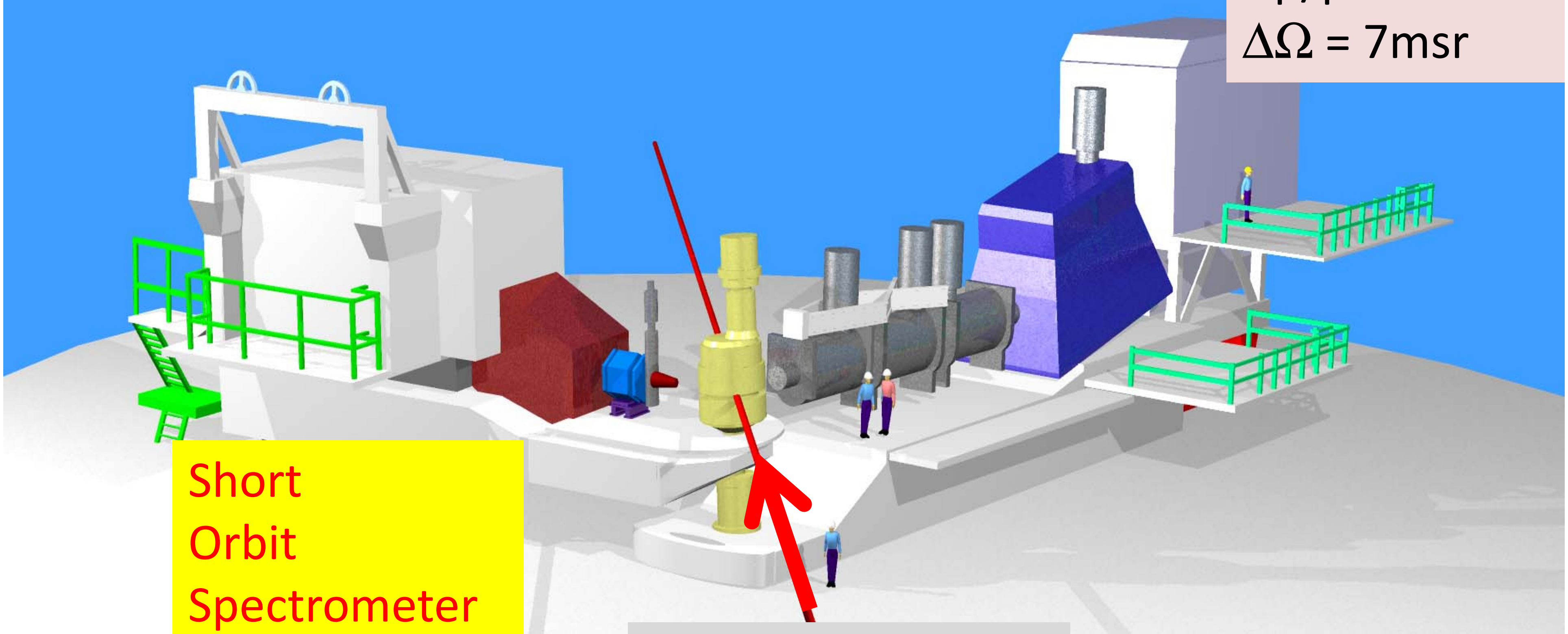
Neutron traveling through a magnet field



$$P_T^{pol} = P_L \sin\chi + P_T \cos\chi$$

$$\Sigma_{UD} = P_T^{pol} A = \frac{N_{Up} - N_{Down}}{N_{Up} + N_{Down}}$$

Jlab Hall C



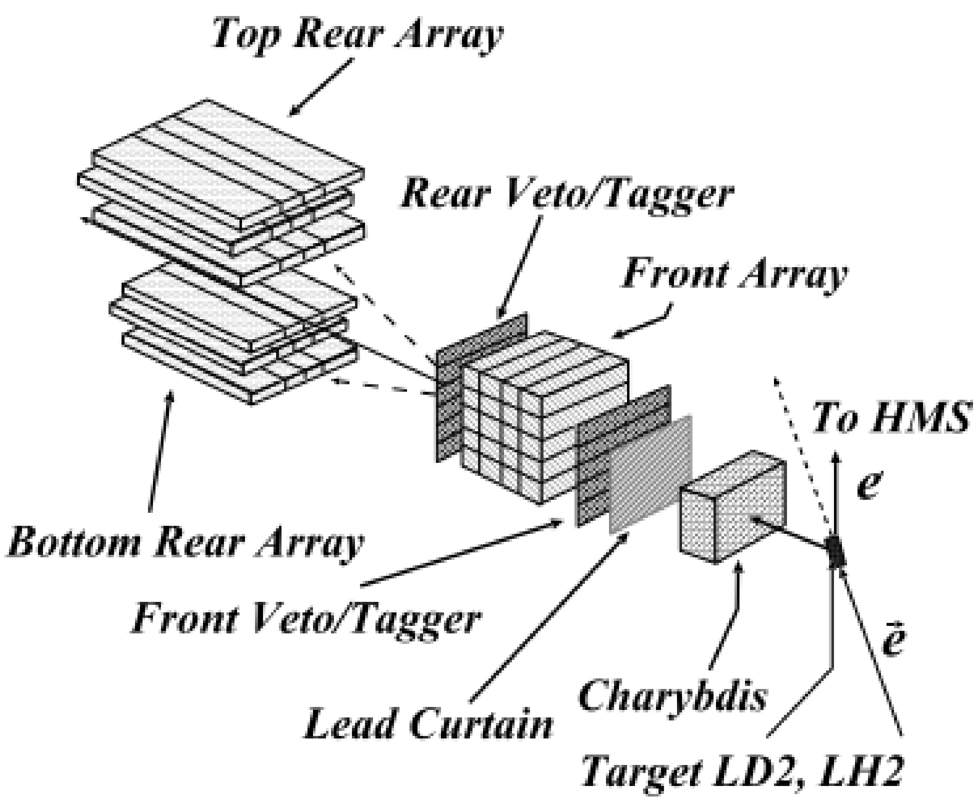
High Momentum Spectrometer
$\Delta p/p = 10^{-3}$
$\Delta\Omega$ = 7msr

Short Orbit Spectrometer

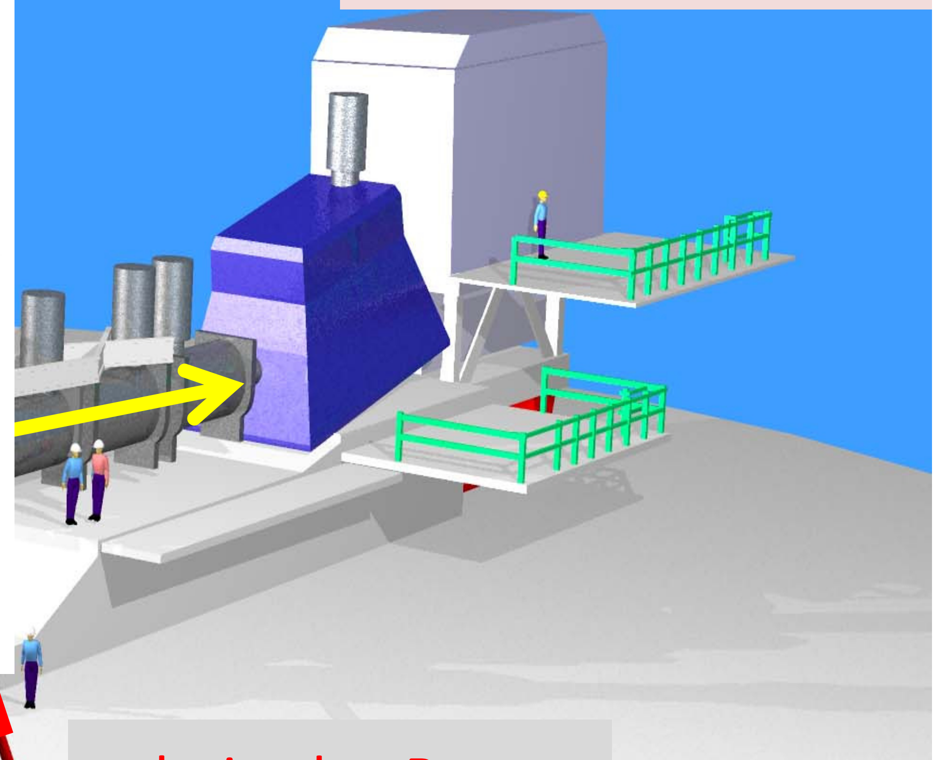
polarized e^- Beam

Measure $d(\vec{e}, e'\vec{n})$

Neutron detector and polarimeter



High Momentum Spectrometer detects electron
$Q^2 = 0.5, 1.2, 1.5\ \mathrm{GeV}^2$



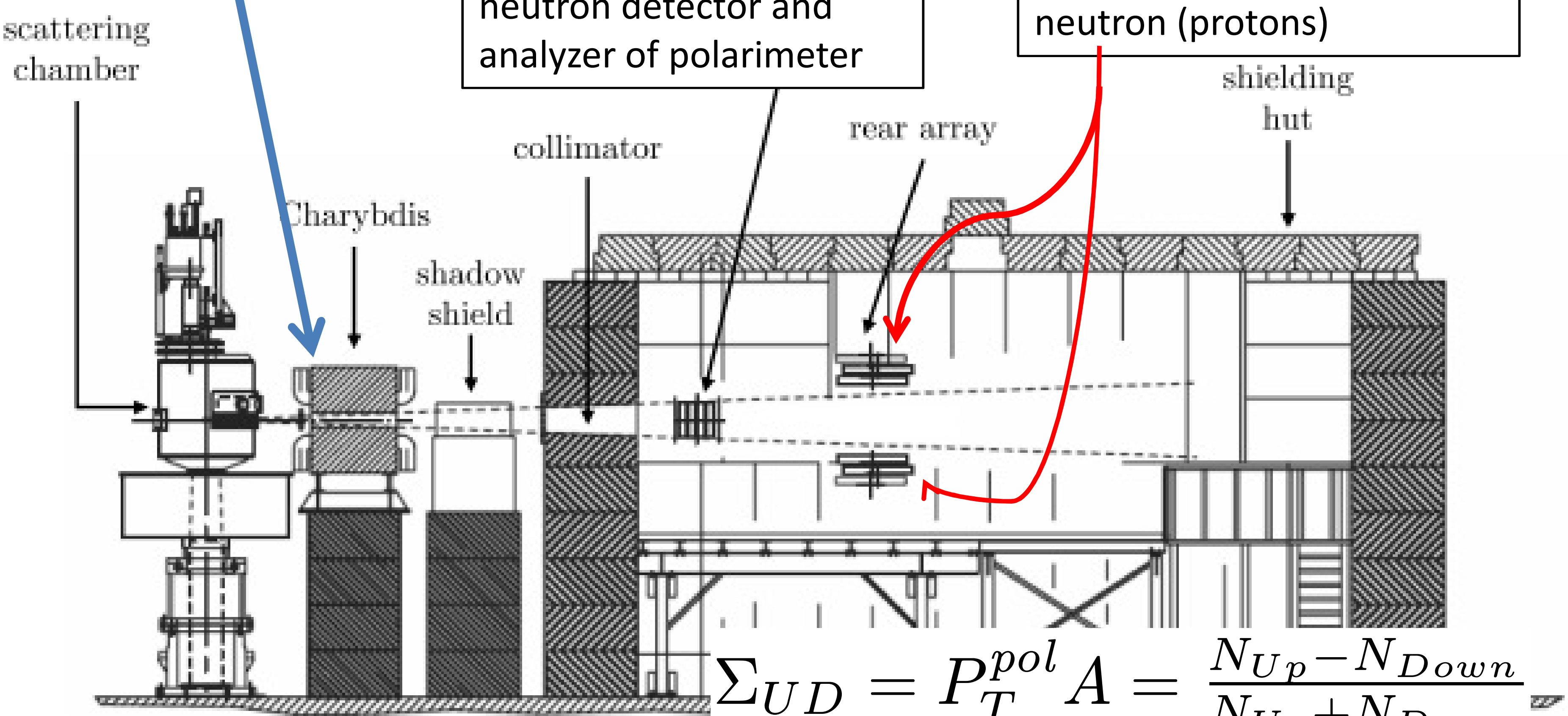
polarized e^- Beam

Side view of neutron polarimeter

Dipole magnet with field in the vertical direction

Scintillator array is neutron detector and analyzer of polarimeter

Scintillator arrays above and below the scattering plane detect secondary scattered neutron (protons)

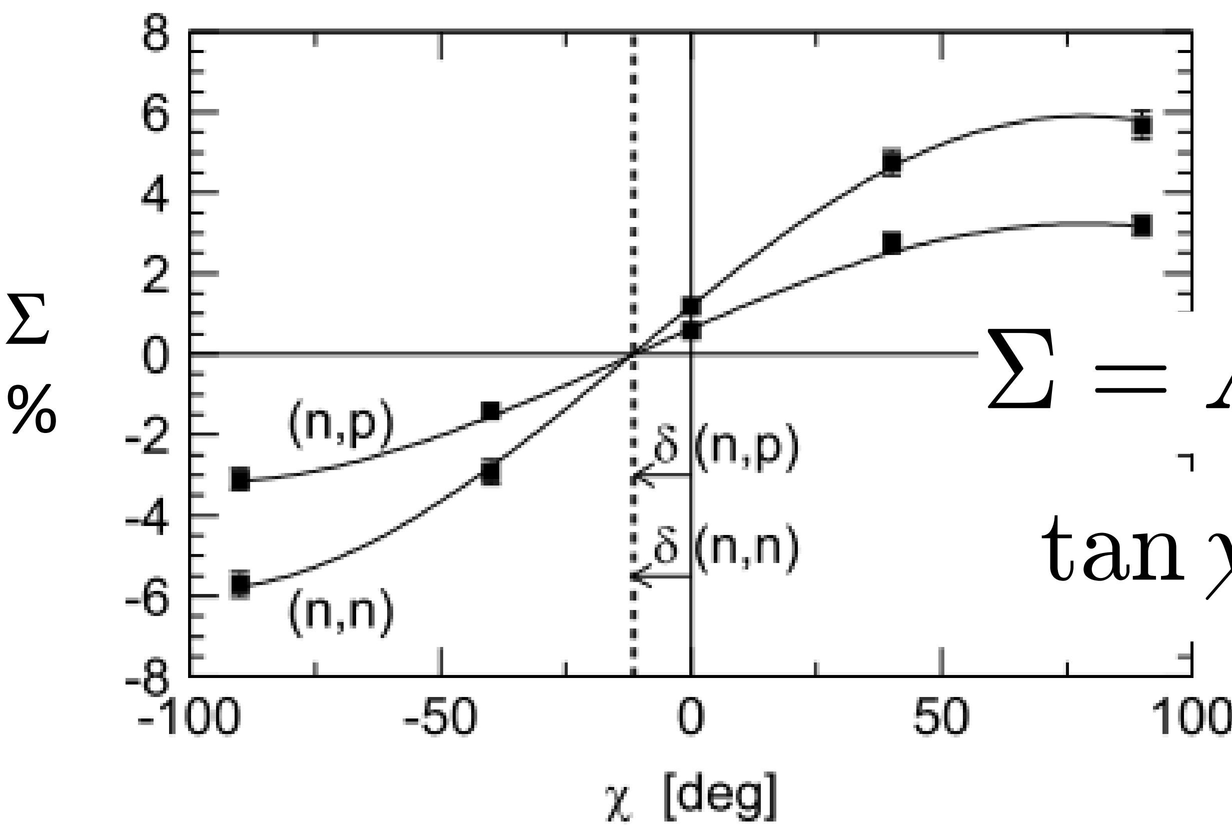


$$\Sigma_{UD} = P_T^{pol} A = \frac{N_{Up} - N_{Down}}{N_{Up} + N_{Down}}$$

Extracting Neutron G_E/G_M

- Measure asymmetry Σ at different precession angles χ by varying magnet field.

$$\Sigma = P_B A (P_L \sin\chi + P_T \cos\chi)$$



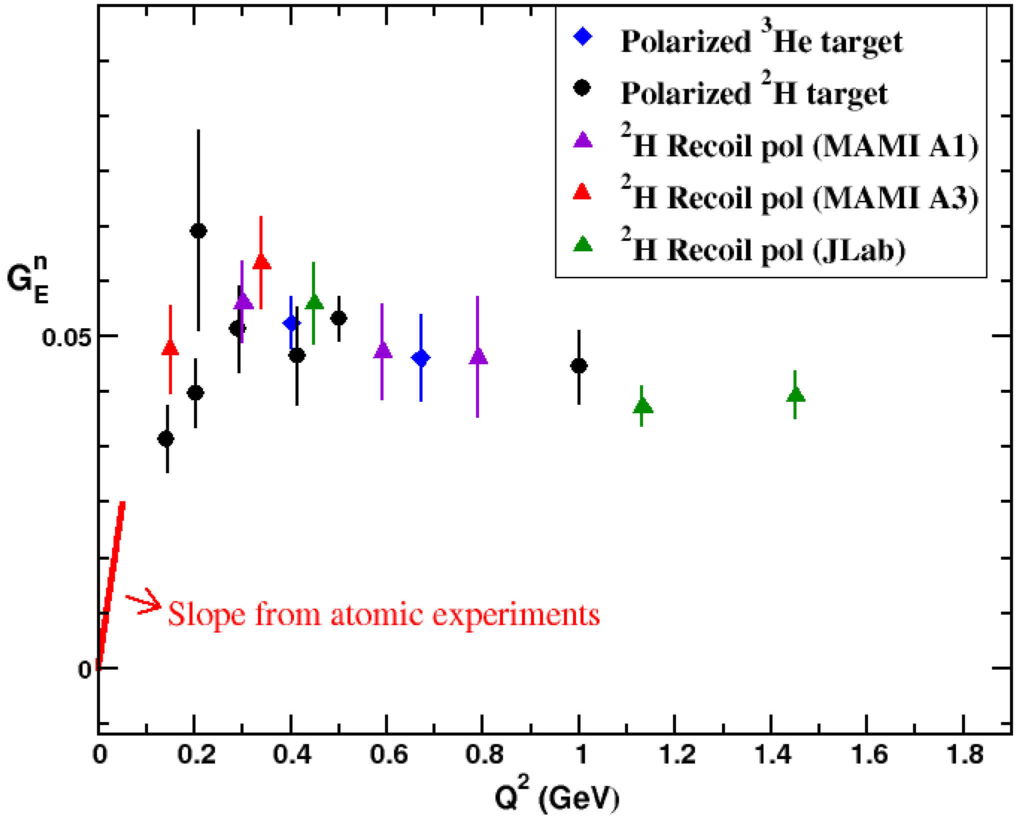
$$\Sigma = A_o \sin(\chi - \chi_o)$$

$$\tan\chi_o = \frac{P_B A P_T}{P_B A P_L}$$

Neutron Electric Form Factor: G_{En}

Recoil Polarization

Quasi-free $\mathrm{d}(\vec{\mathrm{e}},\mathrm{e}'\,\vec{n})$



In PWIA

$$\frac{G_E}{G_M} = -\frac{P_T}{P_L}\frac{(E_e + E_{e'})}{2M}\tan\left(\frac{\theta}{2}\right)$$

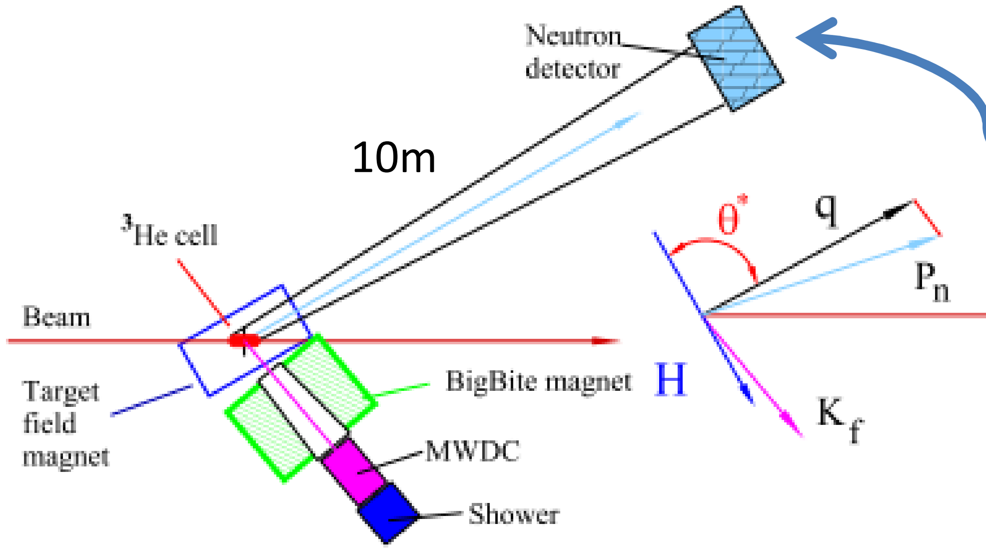
At Mainz,

Q^2 = 0.15 to 0.8

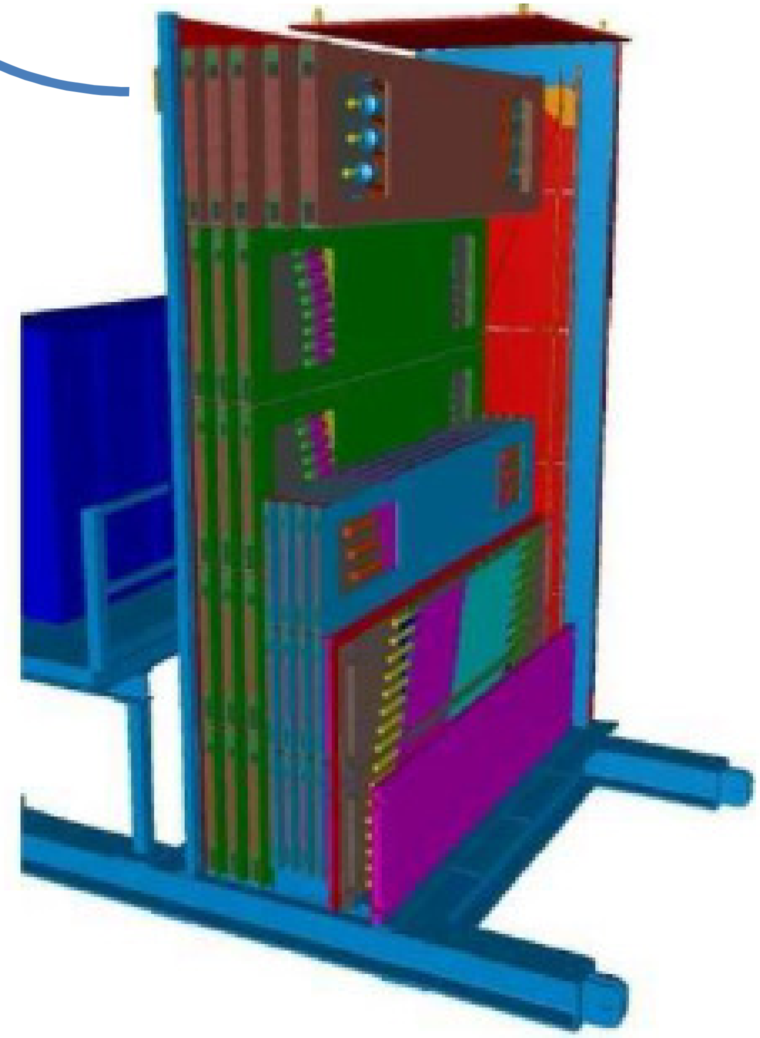
At JLab,

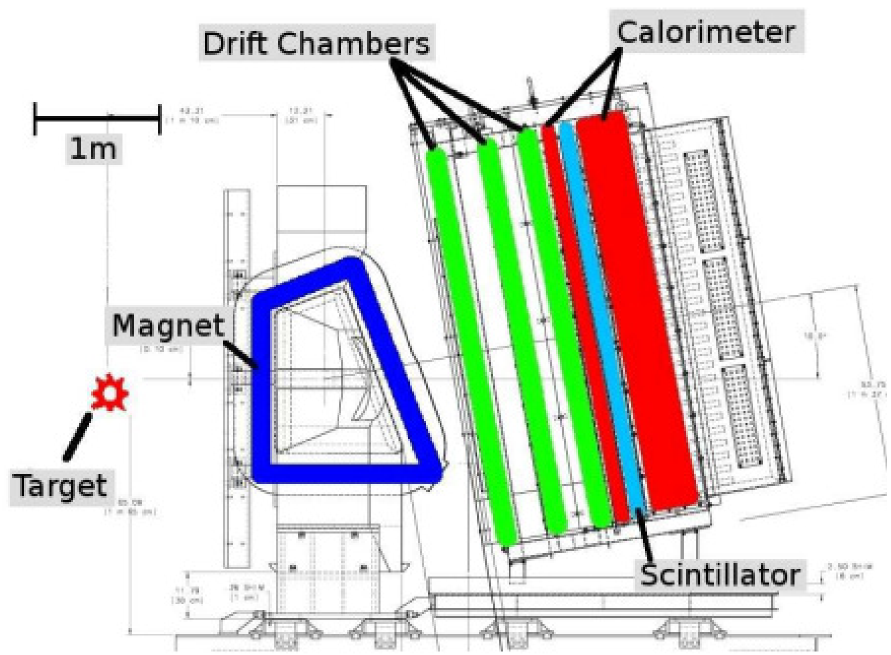
Q^2= 0.45, 1.13, 1.45

Hall A Polarized ^{3}He(e,e'n)

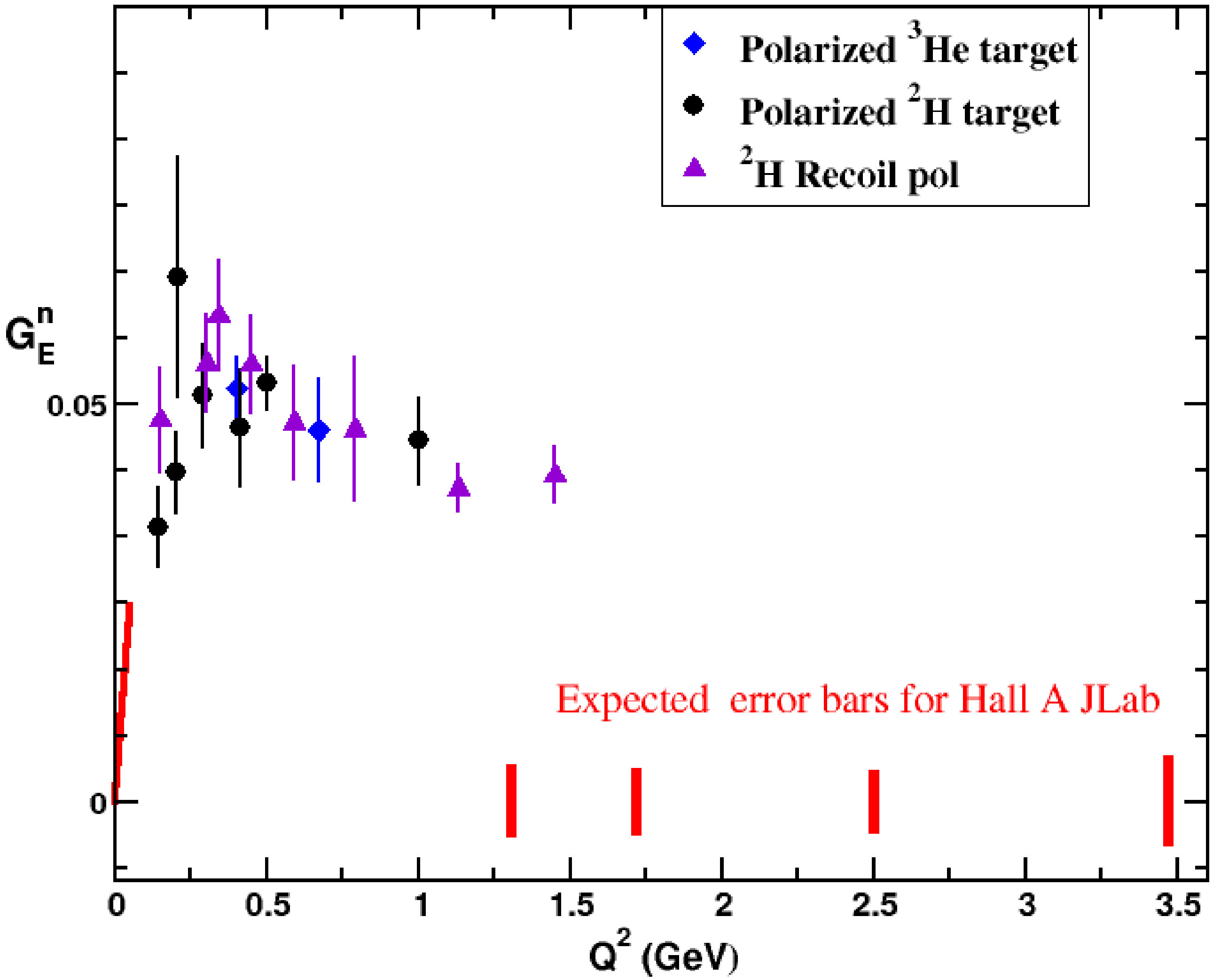


Neutron detector
Covers area of 5 x 1.6 m

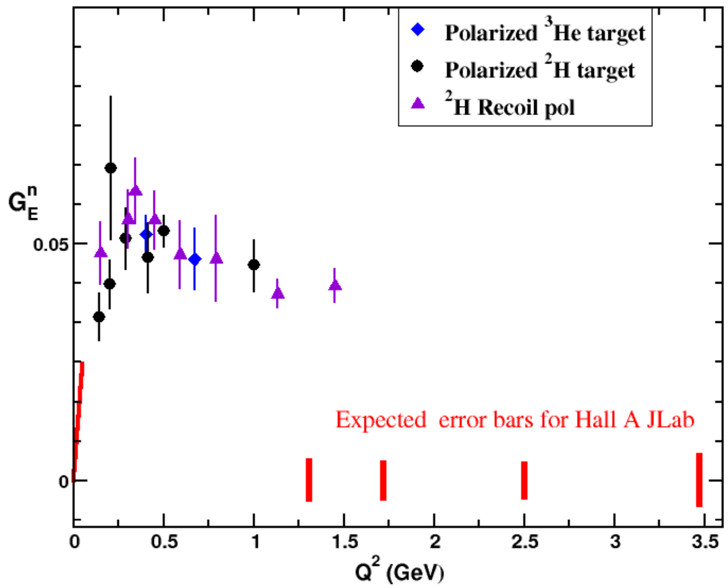


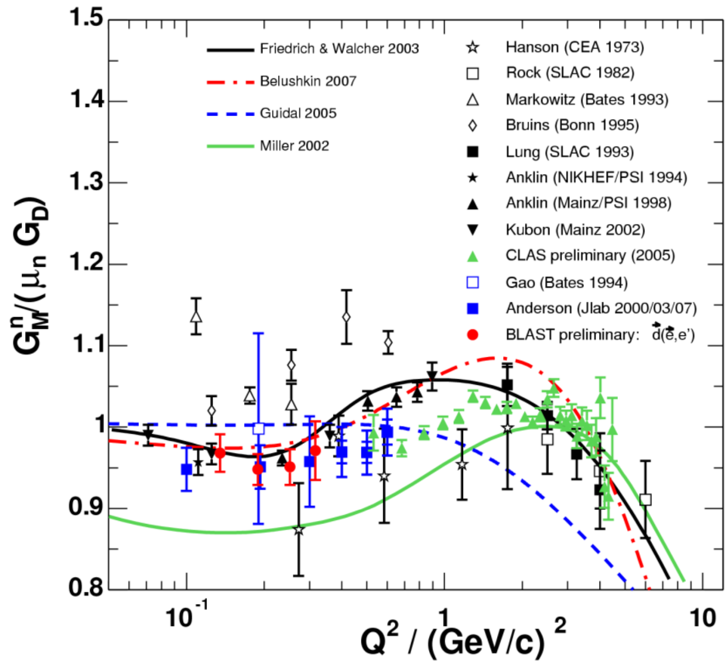


Neutron Electric Form Factor: G_{En}



Summary



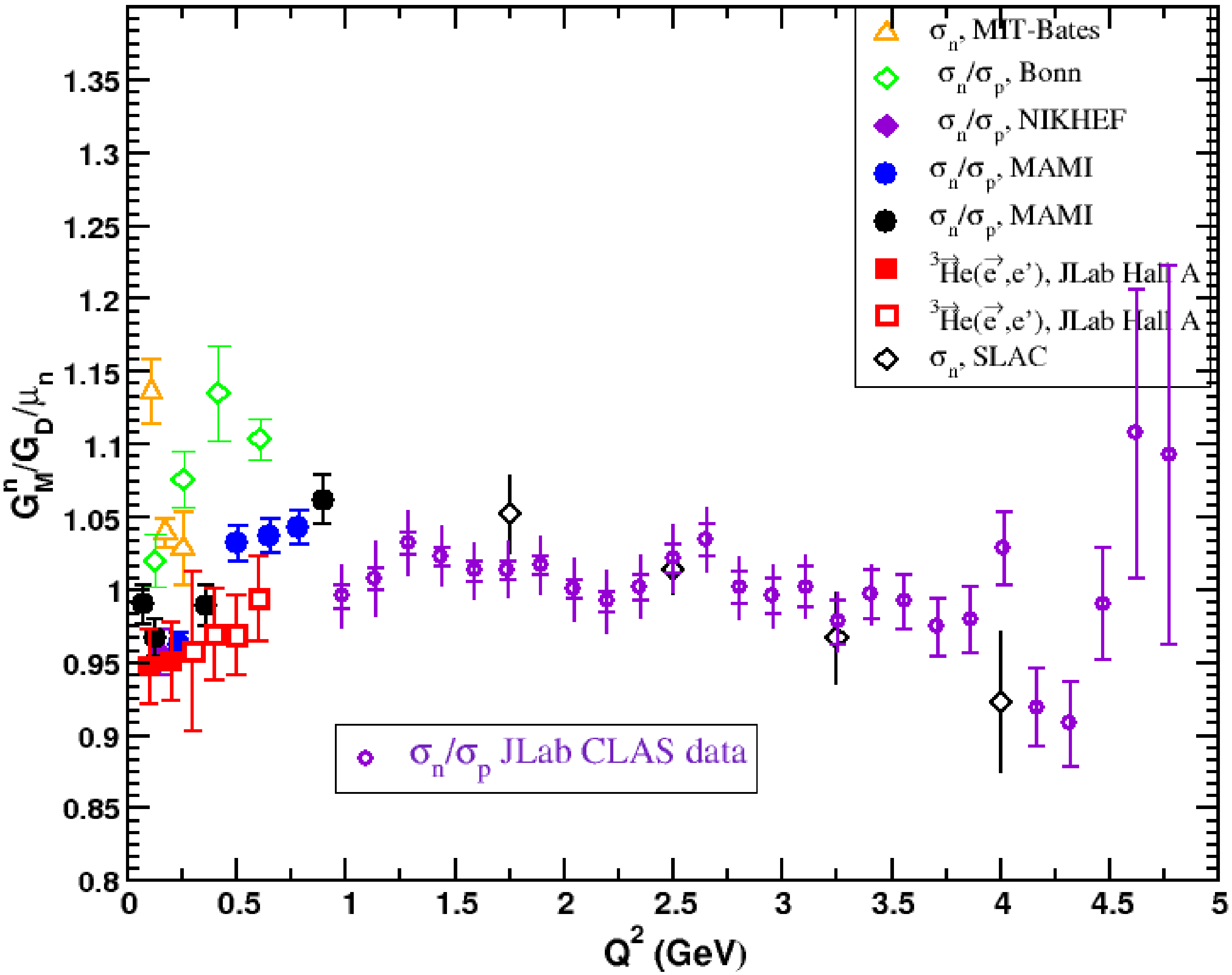


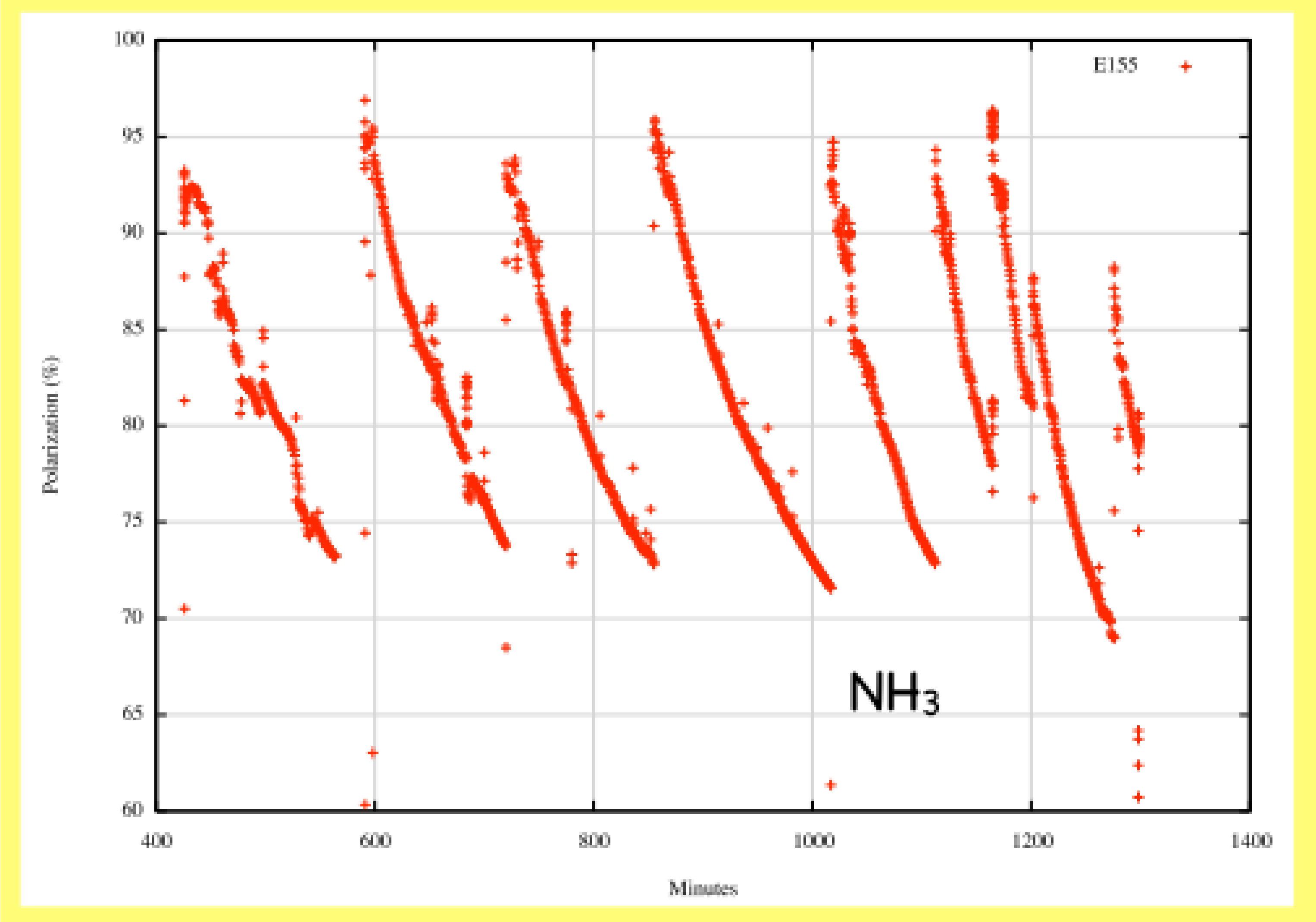
- ➢ Neutron G_E by different techniques agree well. Measured to Q^2 = 3.5 GeV^2
- ➢ Neutron G_M measured to Q^2 = 4.5 GeV^2

Next talk about measuring proton G_E /G_M at Q^2 > 1 GeV^2 using recoil polarization

Backup

Neutron Magnetic Form Factor: G_{Mn}





100
95
90
85
80
75
70
65
60
Polarization (%)
400
600
800
1000
1200
1400
Minutes
E155
NH3