Nucleon 05

Workshop on Nucleon Form Factors

Frascati, October 12-14, 2005

Experimental Studies on the Electric Form Factor of the Neutron

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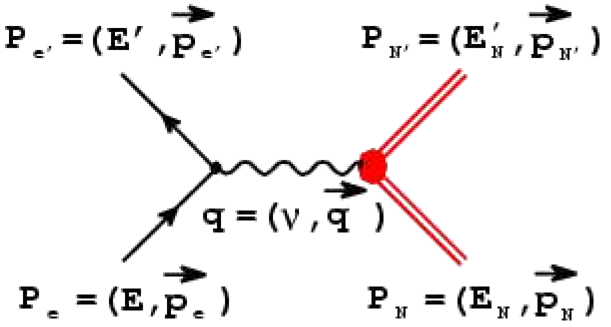
Outline

- Introduction
- History: Neutron Electric Form Factor from Cross Sections
- Double Polarization Experiments
  - Polarized Deuterium: e.g. JLab Hall C - E93-026
  - Recoil Polarization: e.g. JLab Hall C - E93-038
  - Polarized Helium-3: e.g. JLab Hall A - E02-013
- Summary/Outlook

EMFFs : Fundamental Property of the Nucleon

- EMFFs: functions of the hadron current operator
- Fundamental part of a "classical" nucleon theory
  - A testing ground for models constructing nucleons from quarks and gluons (e.g. Lattice QCD or GPDs)
  - Provides insight in spatial distribution of charge and magnetization
  - Wavelength of probe can be tuned by changing the momentum transfer Q:
    - $< 0.1\ (GeV/c)^2$ integral quantities (charge radius, ...)
    - $0.1 - 10\ (GeV/c)^2$ internal structure of the nucleon
      hadronic structure of the photon (VMD) and nucleon structure (pion cloud
      constituent quarks / valence quarks
    - $> 20\ (GeV/c)^2$ pQCD scaling
  - Connection to DIS and Compton scattering via framework of GPDs
- Caution:
  - at large Q (several times the nucleon mass, Compton wavelength) dynamical effects due to relativistic boosts are introduced, making the physical interpretation of EMFF more difficult (no simple Fourier transformation any more)
- Not to forget:
  - EMFF are also essential for understanding form factors of few-body systems, or for extraction of the strange form factors of the nucleons

Form Factors in Elastic Electron - Nucleon Scattering



Nucleon vertex:

$$\Gamma^{\mu}_{EM}(p_N, p_{N'}) = \underbrace{F_1(Q^2)}_{Dirac}\gamma^{\mu} + \frac{i\kappa}{2m}\underbrace{F_2(Q^2)}_{Pauli}\sigma^{\mu\nu}q_{\nu}$$

Sachs form factors:

$$G_E(Q^2) = F_1(Q^2) - \kappa\frac{Q^2}{4m^2}F_2(Q^2)$$
$$G_M(Q^2) = F_1(Q^2) - \kappa F_2(Q^2)$$

Cross Section:

$$\frac{d\sigma}{d\Omega} = \sigma_{NS}\left[\frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}\right]$$

with $\tau = Q^2/4M^2$, κ the anomalous magnetic moment and θ the scattering angle

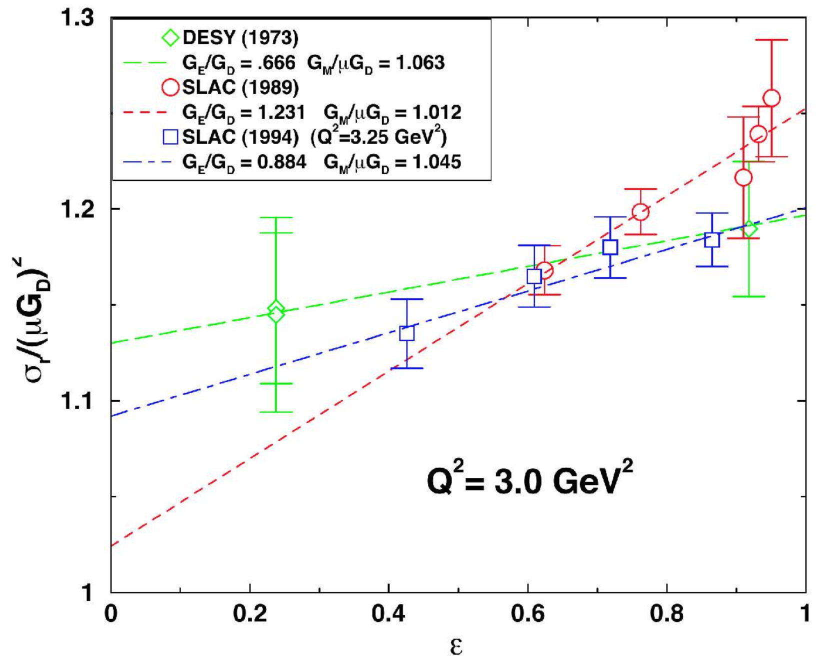
Rosenbluth Separation

$$\frac{\epsilon(1+\tau)}{\sigma_{NS}} \frac{d\sigma}{d\Omega} = \tau \, (G_M)^2 + \epsilon (G_E)^2$$

$$Q^2 = 4EE' \sin^2(\theta/2)$$

$$\tau = Q^2 / 4m_N^2$$

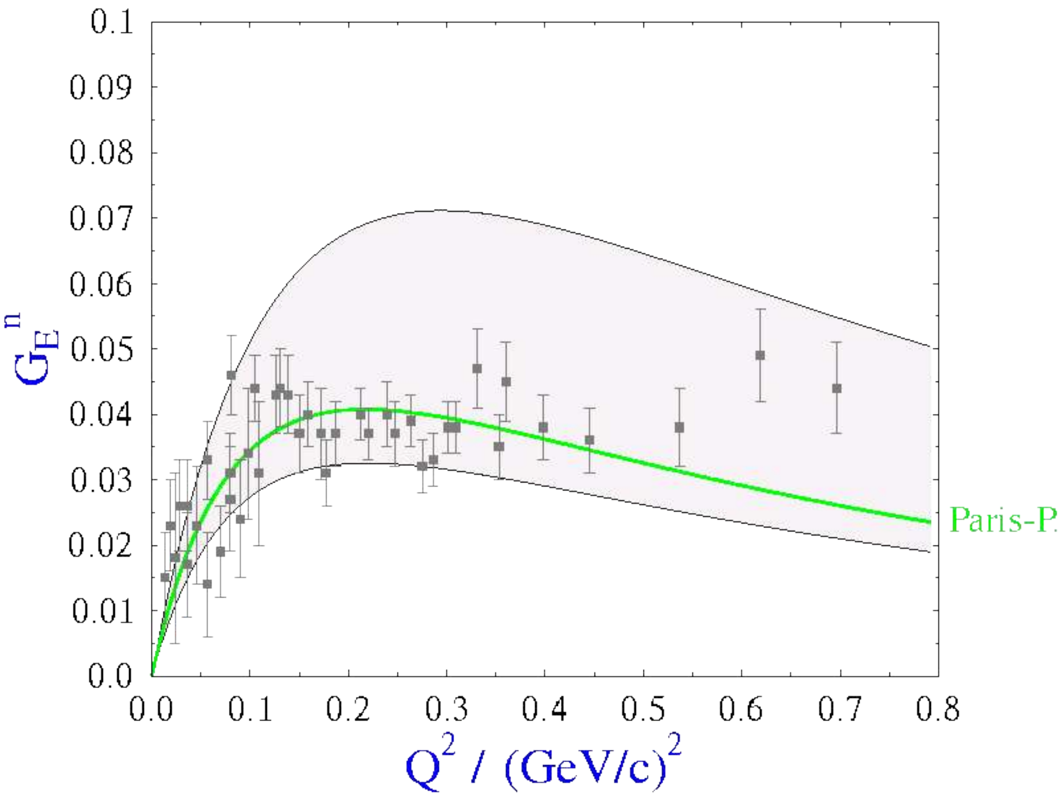
$$\epsilon = \left[1 + 2(1+\tau)\tan^2(\theta/2)\right]^{-1}$$



- Measures $d\sigma/d\Omega$ at constant Q^2; intercept gives G_M, slope gives G_E
- G_E inversely weighted with Q^2, increasing the systematic error above $Q^2 \sim 1\ (\mathrm{GeV}/c)^2$
- Very sensitive to kinematics, acceptances, and radiative corrections

Electric Form Factor of the Neutron

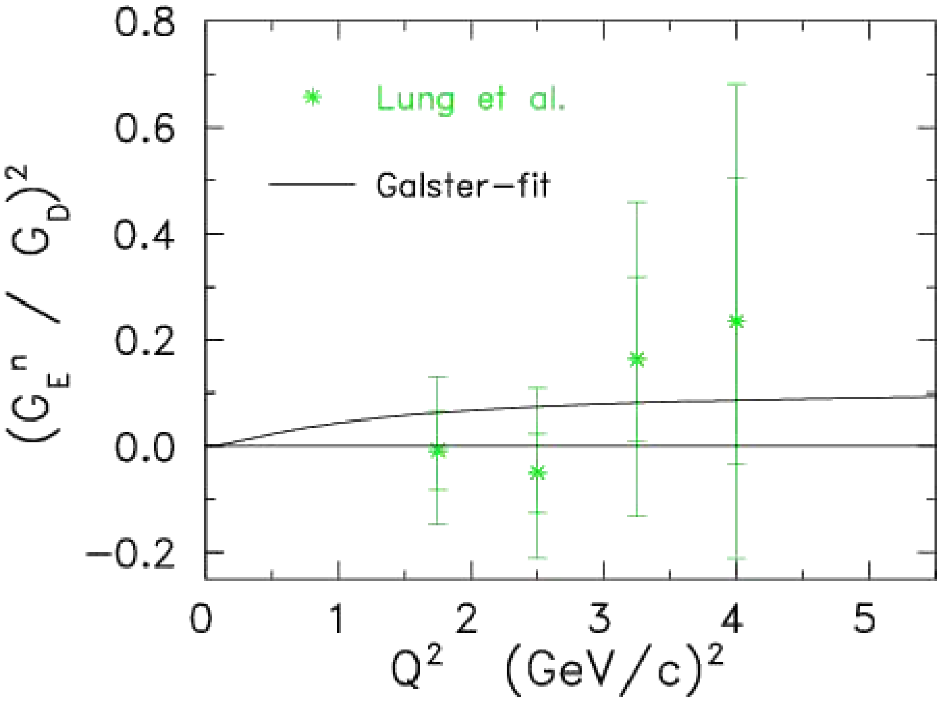
Platchkov et al.: elastic scattering off deuterons



$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_M \frac{E'}{E} \left(\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2\frac{\theta}{2}\right)$$

- No target with free neutrons
  - elastic scattering of D or ^{3}He
- Challenges:
  - Contribution from the proton
  - Elastic cross section gets small (limiting method to low Q^2)
  - Nuclear effects, model dependencies, FSI, MEC
- Net charge of neutron is 0,
  - G_E^n is small at low Q^2
- Cross section dominated by G_M^n

Electric Form Factor of the Neutron at Higher Q^2



- No target with free neutrons
  - quasi-elastic scattering of D
- Nuclear effects, model dependencies, FSI, MEC
- Contributions from the proton
- Contributions from magnetic form factors dominate

Constraints on G_E^n from the Inverse Reaction

See e.g.: S. Kopecky et al., Phys. Rev. C56 (1997) 2229

- Scattering of thermal neutrons on atomic electrons
- Kinematically limited to very low momentum transfers
- Gives charge radius of the neutron
  - $\langle r^2_{ch,n} \rangle = -0.1148(23)\ fm^2$
- Charge radius is related to the slope of G_E^n at $Q^2=0$

Modern Era

- Akhiezer et al., Sov. Phys. JETP 6, 588 (1958) and Arnold, Carlson and Gross, PR C 23, 363 (1981) showed that:
  - accuracy of form-factor measurements can be significantly improved by measuring an interference term $G_E G_M$ through the beam helicity asymmetry with a polarized target or with recoil polarimetry
- It took a whille (over 30 years) to develop:
  - Polarized electron beams with high intensity (~100uA) and high polarization (>70%, strained GaAs, high-power diode/TiSa lasers)
  - Beam polarimetry with 1-3% accuracy
  - Polarized targets with high polarization
  - Ejectile polarimeters with large analyzing powers

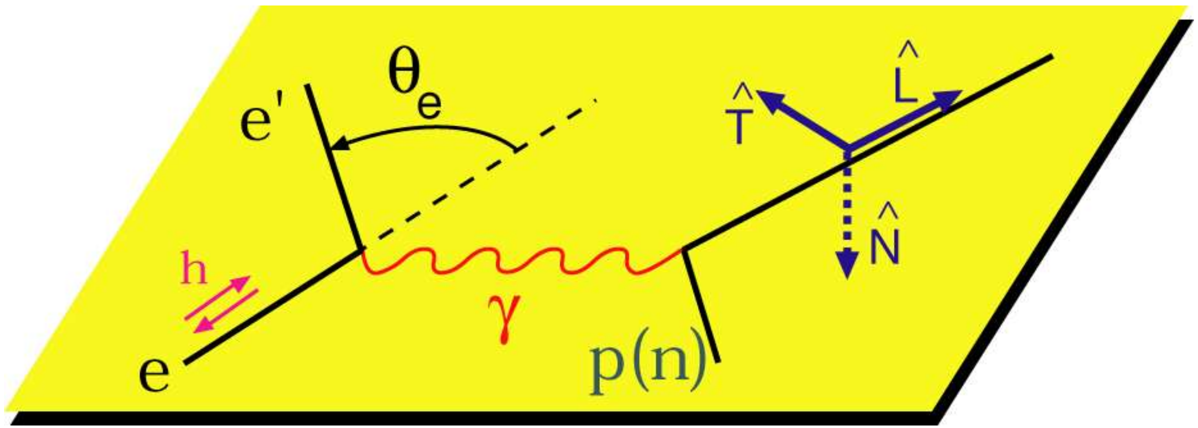
Double Polarization Approaches to Measure G_E^n

- $^2\vec{D}(\vec{e}, e'n)$ with polarized beam and polarized ND_3 target
  (NIKHEF, JLab Hall C)
  limitations: low current (~80 nA)
  deuteron polarization (25%)
- $^2D(\vec{e}, e'\vec{n})$ from LD_2 target and utilizing recoil polarimeter
  (Bates, Mainz, JLab Hall C)
  limitations: Figure of Merit of polarimeter
- $^3\vec{He}(\vec{e}, e'n)$ with polarized beam and polarized ^{3}He target
  (Bates, NIKHEF, Mainz, JLab E02-013)
  limitations: current on target (12 μA), target polarization (40%),
  nuclear medium corrections

For all three types:

- Asymmetry measurement, interference enhances the small amplitude contribution
- Avoids Rosenbluth separation
- Avoids subtraction of large proton contribution

Spin Transfer Reaction



Polarized electrons transfer longitudinal polarization due to G_E,

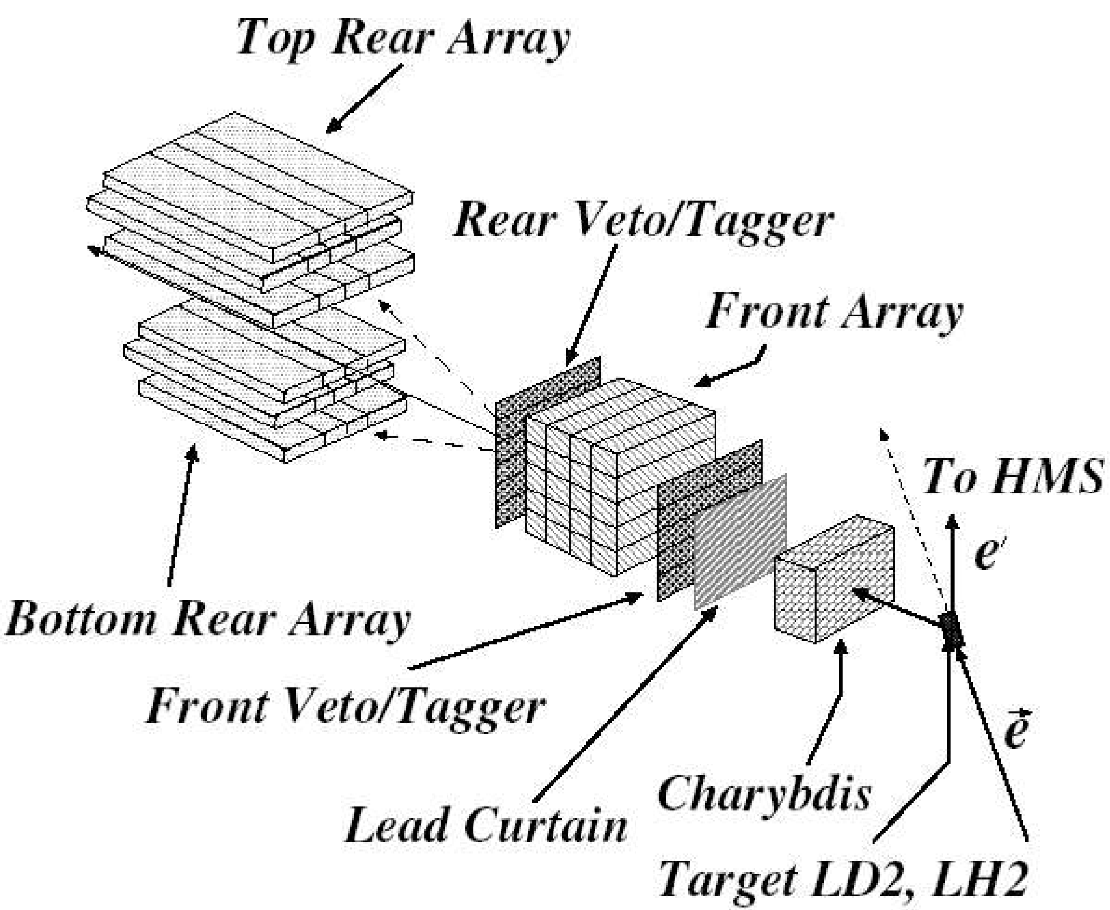
but transverse polarization due to G_M

$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{E_e + E_{e'}}{2M}\tan(\theta_e/2)$$

Polarimeter only sensitive to transverse polarization components, therefore magnet is needed to precess longitudinal component to normal

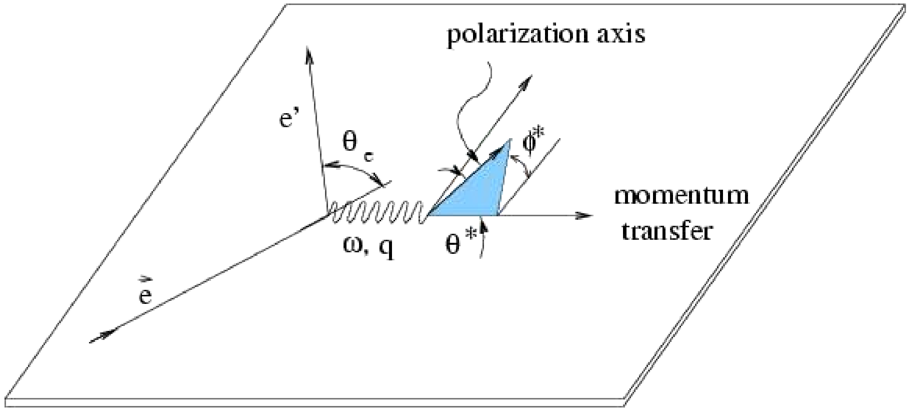
By measuring the ratio, no error contributions from analyzing power or beam polarimetry

E93-038: G_E^n in Hall C via $^2H(\vec{e},e'\vec{n})$



- quasi-elastic kinematics: insensitive to nuclear potential and MEC/IC
- ratio Pt/Pl neither depends on absolute value of analyzing power nor beam polarization
- Charybdis magnet for spin-precession
- Experiment run in 2000/2001
- Q^2=0.45, 1.13 and 1.45 $(GeV/c)^2$
- Similar experiments at MIT Bates and at MAMI A1 and A3 covering Q^2= 0.15 – 0.8 $(GeV/c)^2$

Beam / Target Asymmetry



Asymmetry:

$$A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

$$= A_\perp \ \sin\theta^\star \cos\phi^\star + A_\parallel \ \cos\theta^\star$$

(assuming $P_e = P_n = 1$)

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

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

(with $\tau = Q^2/4m_N^2$)

Experiments either:

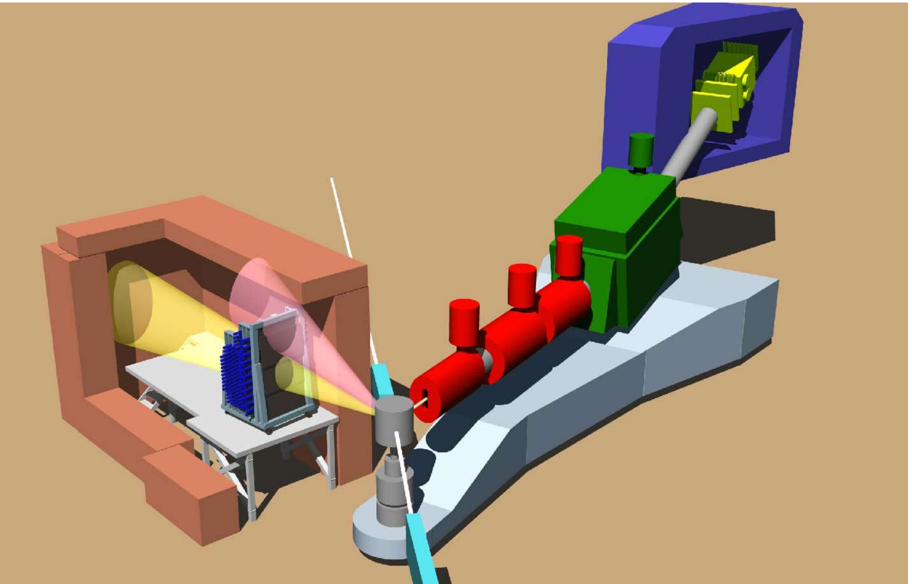
- measure both components (by rotating target spin)

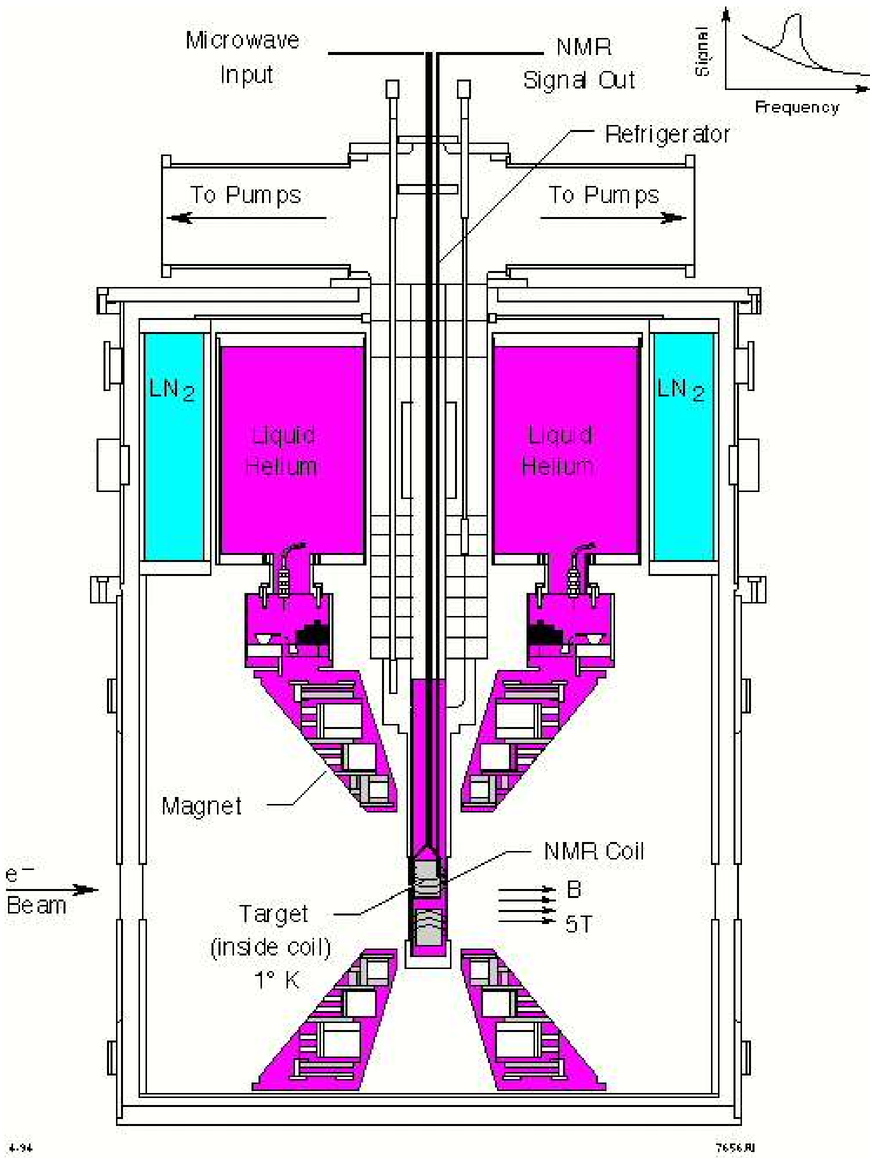
or

- rely on polarimetry

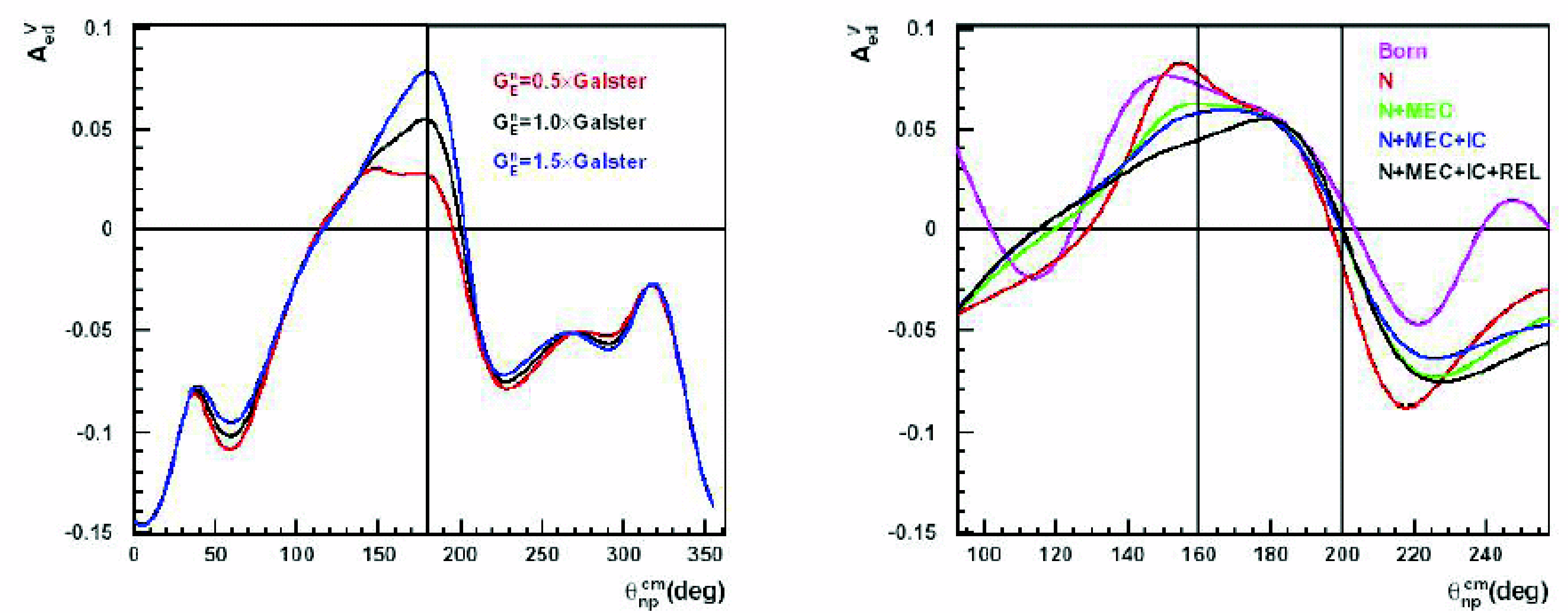
E93-026: G_E^n in Hall C via $^2\vec{H}(\vec{e},e'n)$

- Polarized Deuterium Target
  - frozen $^{15}ND_3$
  - 5T magnetic field
  - dynamic polarization
- HMS spectrometer + neutron array
- Q^2 = 0.5 and 1.0 $(GeV/c)^2$



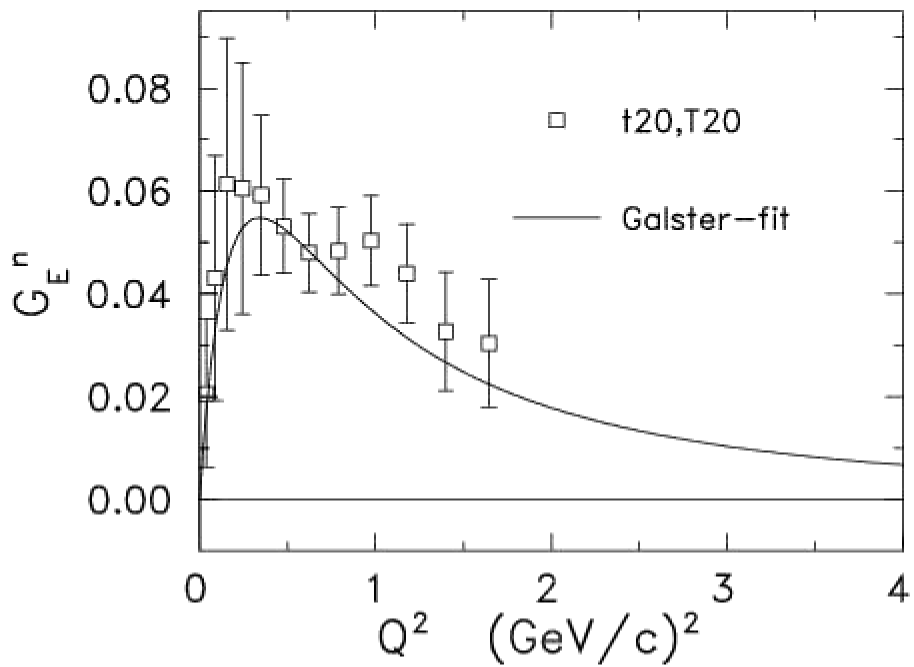


G_E^n from $\vec{D}(\vec{e},e'n)p$



- measuring A^V_{ed}: $\sigma(h,P) = \sigma_0\ (1 + hP\ A^V_{ed})$
- quasielasitc kinematics
  - low sensitivity to potential, and to MEC and IC
  - sensitive to G_E^n

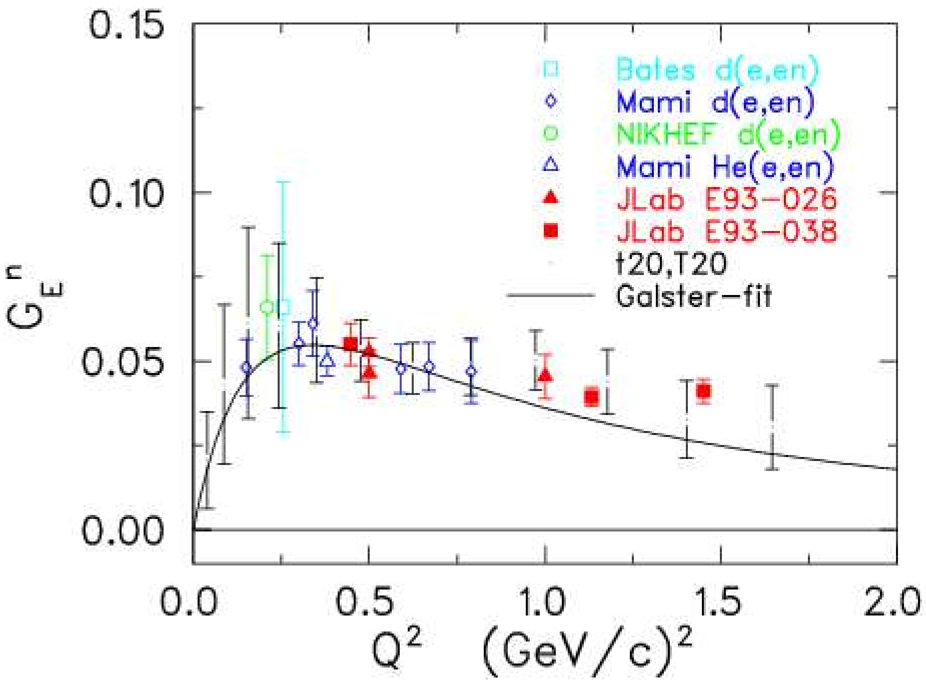
Results on G_E^n from $A(Q^2)$ and T20



R.Schiavilla and I.Sick, Phys.Rev.C64 (2001) 041002

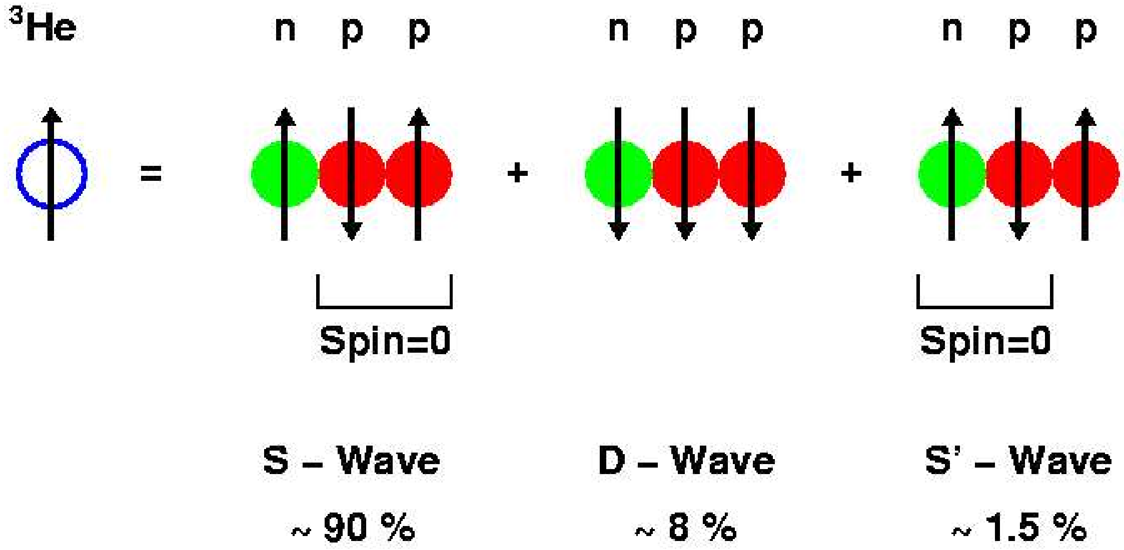
method is also limited to Q^2 below 2 $(GeV/c)^2$

Data on G_E^n from Double Polarization Experiments



- Galster: parametrization fitted to old (<1971) data set
- For $Q^2 > 1\ (GeV/c)^2$: similar Q^2 behaviour as G_E^p
- Most recent results (from Mainz and JLab) using all three approaches are in excellent agreement
- no accurate data available for $Q^2 > 1.5\ (GeV/c)^2$

^{3}He as an Effective Neutron Target

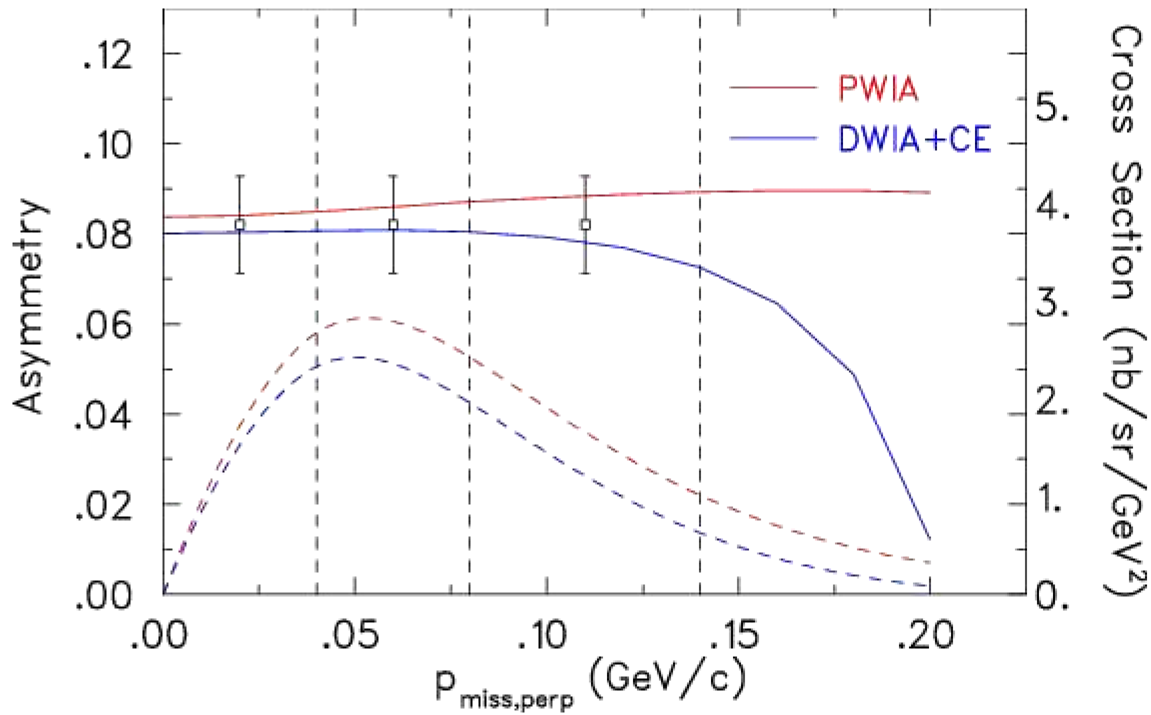


- Naïve picture:
  - neutron carries the spin of ^{3}He, protons are unpolarized
- Actual calculations:
  - neutron polarization ~86%; proton polarization ~-2.8%
  - further medium effects: reduction of cross section (reproduced by Glauber approximation type calculations e.g.)

Generalized Eikonal Approximation (GEA)

Calculations by M. Sargsian

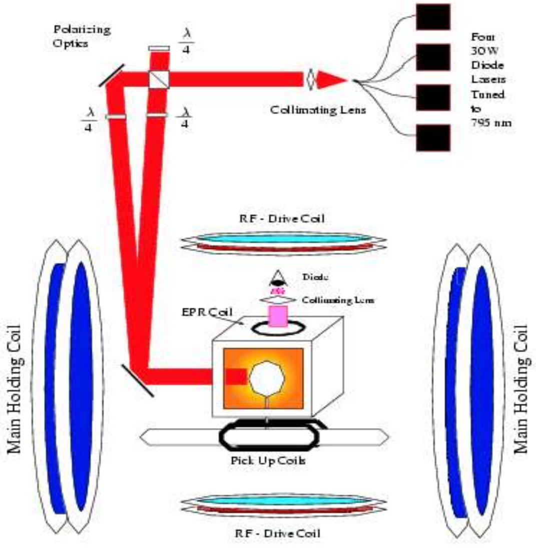
- Calculations in the framework of GEA
- Fully relativistic
- Includes FSI
- Good agreement with JLab A(e,e'p) data for $Q^2 > 1\ (GeV/c)^2$ (Garrow *et al.*)
- FSI accurate for $p_{miss} < 250$ MeV/c

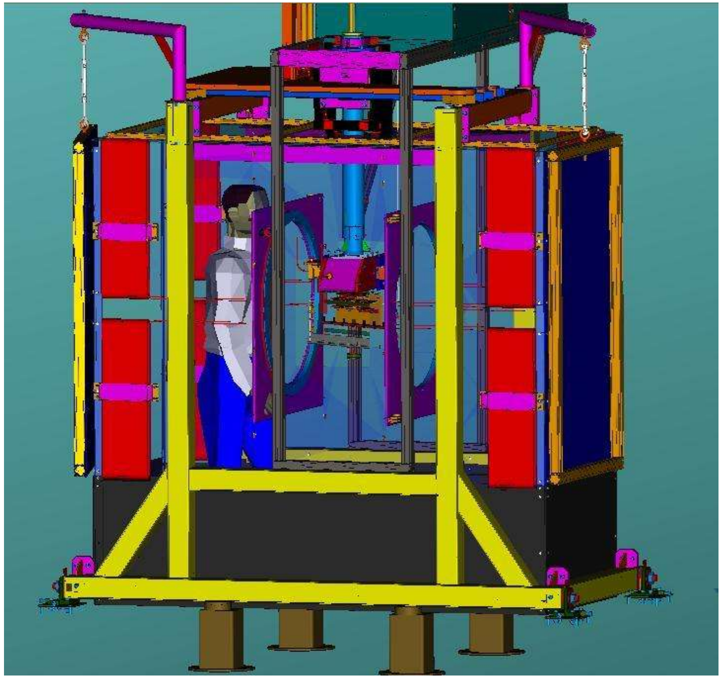


The Hall A Polarized Helium-3 Target

So far: (G_M^n, A1n, g2n, GDH, SAGDH)

- Spin exchange between optically pumped alkali-metal vapor and ^{3}He
- High pressure cell, 10 atm, 40cm long
- Targetpolarisation ~40%
- Beam currents up to 15μA
- Luminosity 1.0*10^{36} e-neutron/s/cm^2



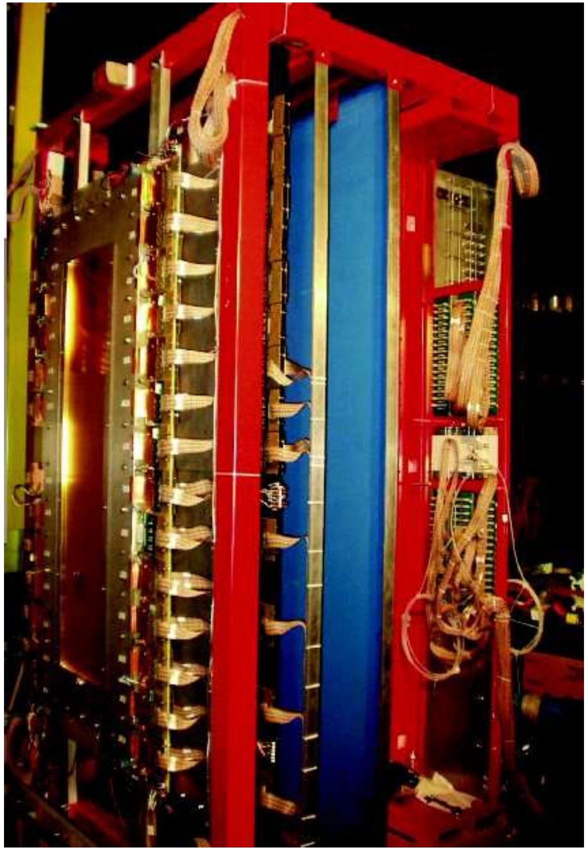


For G_E^n in Hall A

- Improved cell geometry
- Laser-Combiner with fiber optics
- K/Rb mixture instead of pure Rb
- Metal-box: magnet plus shielding

Two New Detector Systems

(Large Acceptance, Open Geometry)



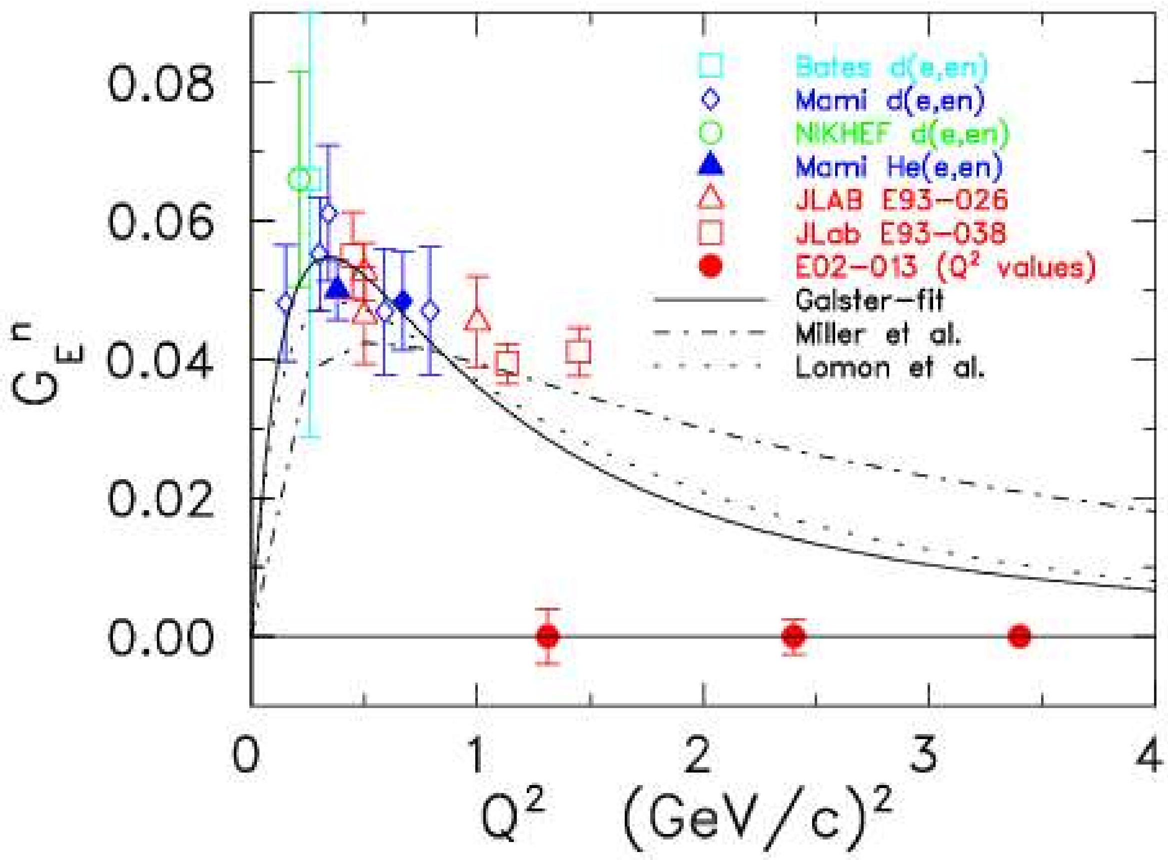
BigBite (electrons)

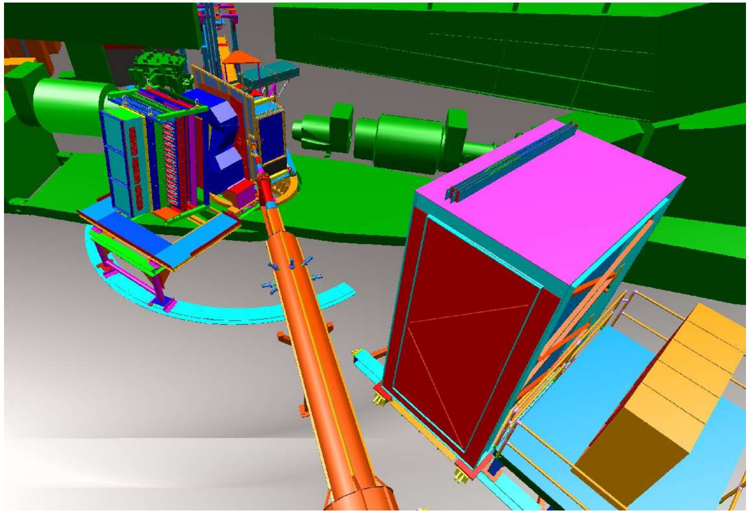
- large drift chamber, 15 planes, 2500 wires
- lead glass calorimeter (pion separation)
- scintillators

BigHAND (neutrons)

- 240 neutron bars
- 180 veto detectors
- 4.7m x 1.6m active area
- good timing resolution (300 ps)
- good efficiencies for neutrons, high thresholds to minimize background

E02-013: G_E^n for large Q^2 in Hall A





- medium luminosity of the Hall A pol. ^3He target allows use of two large acceptance devices with open geometry
- better FOM than with deuterium and recoil polarimetry

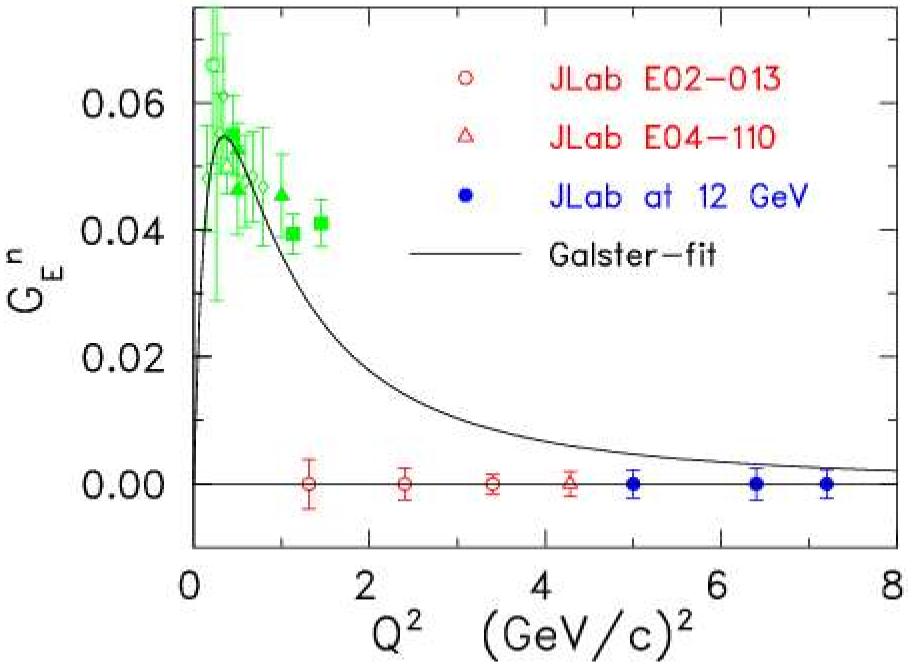
Boosting the Recoil Polarization Method to Measure G_E^n at Higher Q^2

- so far: highest Q^2 = 1.5 $(GeV/c)^2$ with this method (E93-038, Hall C)
- approved Hall C experiment (E04-110) will
  - utilize successful approach of E93-038
  - increase acceptance of polarimeter (larger neutron array, tapering the poles of Charybdis magnet)
  - increase efficiency of the neutron polarimeter (more neutron detectors, steel converters)
  - with JLab at 6 GeV: Q^2 = 4.3 $(GeV/c)^2$ and ∂G_E^n = 0.002 in 25 days
  - with JLab at 12 GeV: Q^2 values up to 8.1 $(GeV/c)^2$ are possible (using HMS in Hall C)

Spectrometers and Beams for Measurements at Higher Momentum Transfers

present: BigBite or HRS(HMS)

- maximum beam energy 6 GeV
- BigBite has large solid angle (76 msr) but electron momentum limited to 1.5 GeV/c, therefore it needs to stay at backward angles (smaller cross section)
- HRS/HMS would allow larger electron momenta, but solid angle is significantly smaller (6 msr / 8 msr)
- below ~4 $(GeV/c)^2$ BigBite wins



after 12 GeV upgrade:

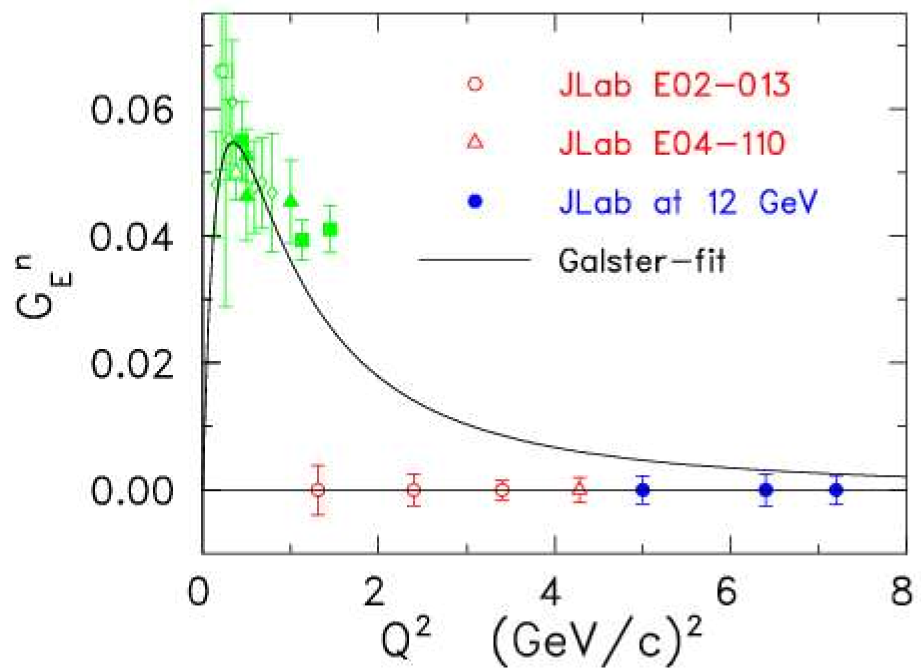
- using 8.8 and 11 GeV beam and existing HMS and neutron detector: Q^2 values of ~6.4 $(GeV/c)^2$ feasible
- using a larger acceptance spectrometer (SuperBigBite, MAD) for electron detection: Q^2 values of up to 8.0 $(GeV/c)^2$ seem feasible

Summary / Outlook

Laboratory	Collaboration	Q^2 (GeV/c^2)	Reaction	Status
MIT-Bates	E85-05	0.26	$D(\vec{e},e'\vec{n})$	1994
	Blast	< 0.8	$\vec{D}(\vec{e},e'n)$	
	Blast	< 0.8	$^3\vec{He}(\vec{e},e'n)$	
Mainz MAMI	A3	0.31	$^3\vec{He}(\vec{e},e'n)$	1994
	A3	0.15, 0.34	$D(\vec{e},e'\vec{n})$	1999
	A3	0.39	$^3\vec{He}(\vec{e},e'n)$	1999
	A1	0.67	$^3\vec{He}(\vec{e},e'n)$	1999/2003
	A1	0.3, 0.6, 0.8	$D(\vec{e},e'\vec{n})$	2004
NIKHEF		0.21	$\vec{D}(\vec{e},e'n)$	1999
JLab	E93-026	0.5, 1.0	$\vec{D}(\vec{e},e'n)$	2001/2004
	E93-038	0.45, 1.15, 1.47	$D(\vec{e},e'\vec{n})$	2003
	E02-013	1.3, 2.4, 3.4	$^3\vec{He}(\vec{e},e'n)$	Approved
	E04-110	4.3	$D(\vec{e},e'\vec{n})$	Approved
JLab @ 12 GeV	Hall A	> 6.0	$^3\vec{He}(\vec{e},e'n)$	Feasible
JLab @ 12 GeV	Hall C	6.0 – 8.0	$D(\vec{e},e'\vec{n})$	Feasible

Summary/Outlook

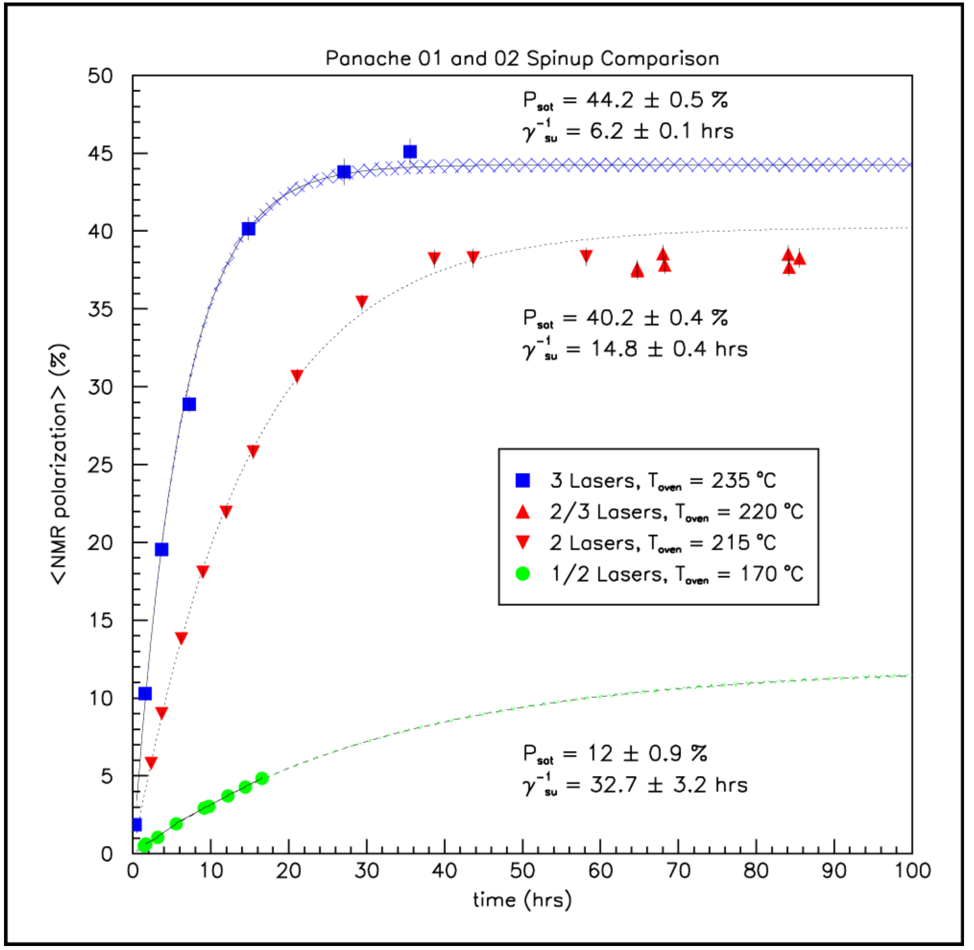
- Very active experimental program on electro-magnetic form factors of the nucleon at JLab and elsewhere
- possible because of the availability of polarized electron beam (>100uA, >75% polarized), polarized targets and polarimeters with high analyzing power
- Exciting new data on G_E^n from JLab (and MAMI), but also on G_E^p and G_M^n
- JLab Experiment E02-013 will significantly increase our knowledge about the electric form factor of the neutron at higher momentum transfers
- Future plans to extend EMFF measurements at JLab



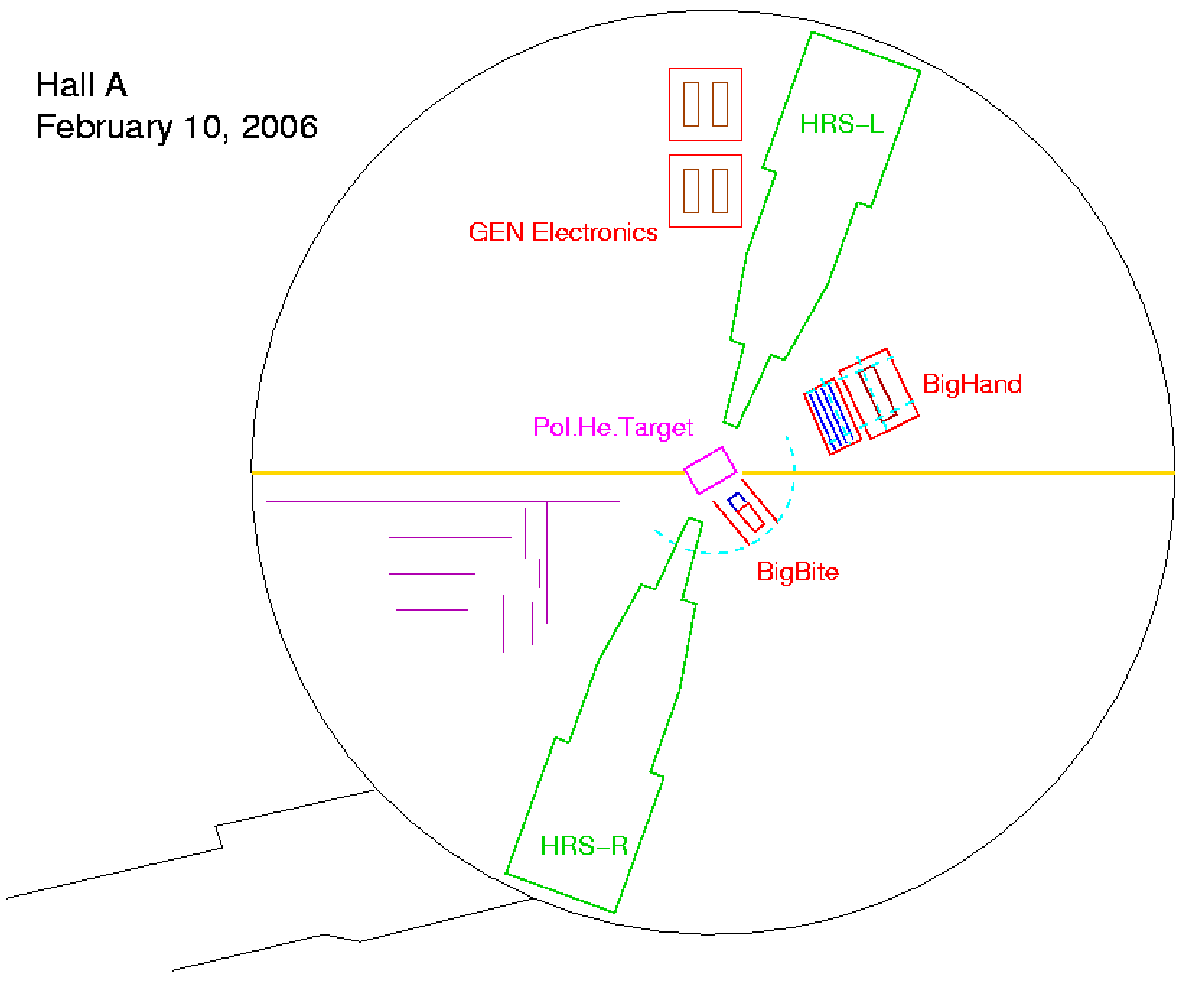
Possible Boosts for G_E^n Experiments:

Polarized ^{3}He-Target Improvements

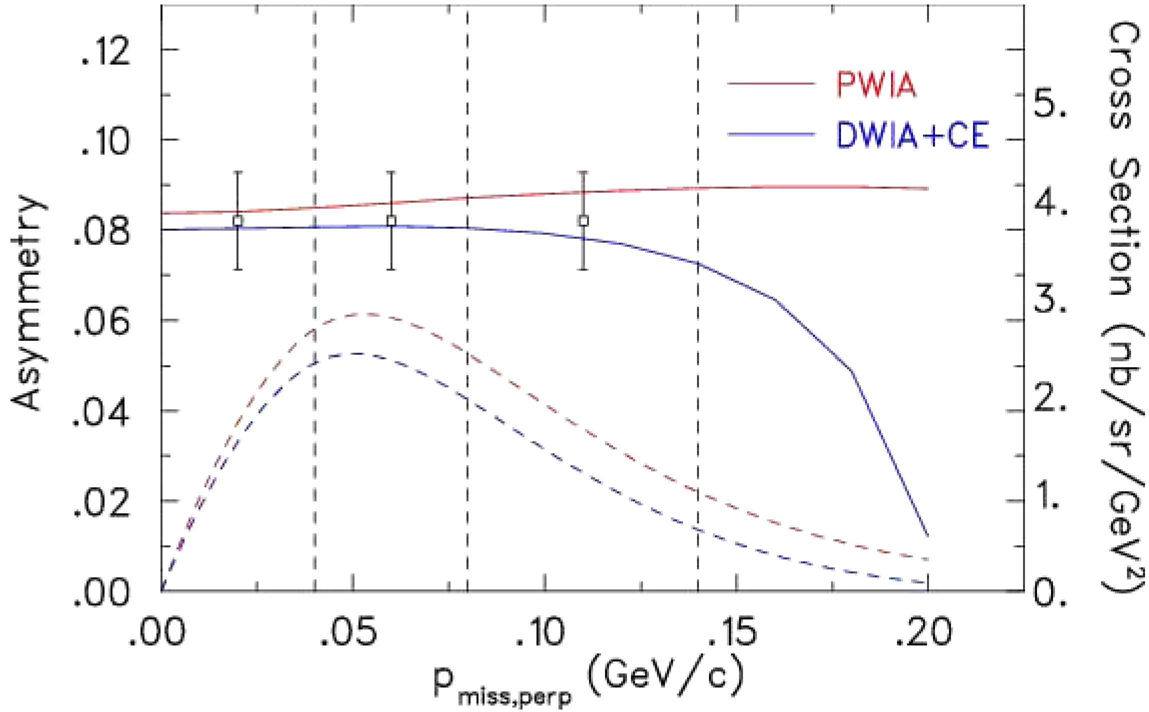
- Increase in usable beam current an polarization very desirable
- New laser technology is becoming available, allowing to combine light of several Lasers in a compact setup (E02-013 will use a 5-1 combiner)
- Modifications of the cell design with larger pumping cells (long term: cylindrical instead of spherical pumping cells) and improved gas flow
- coating of glass, modifications of the end-caps to decrease depolarization and increase durability
- Use of Rb/K mixture instead of pure Rb



JLab Hall A During E02-013

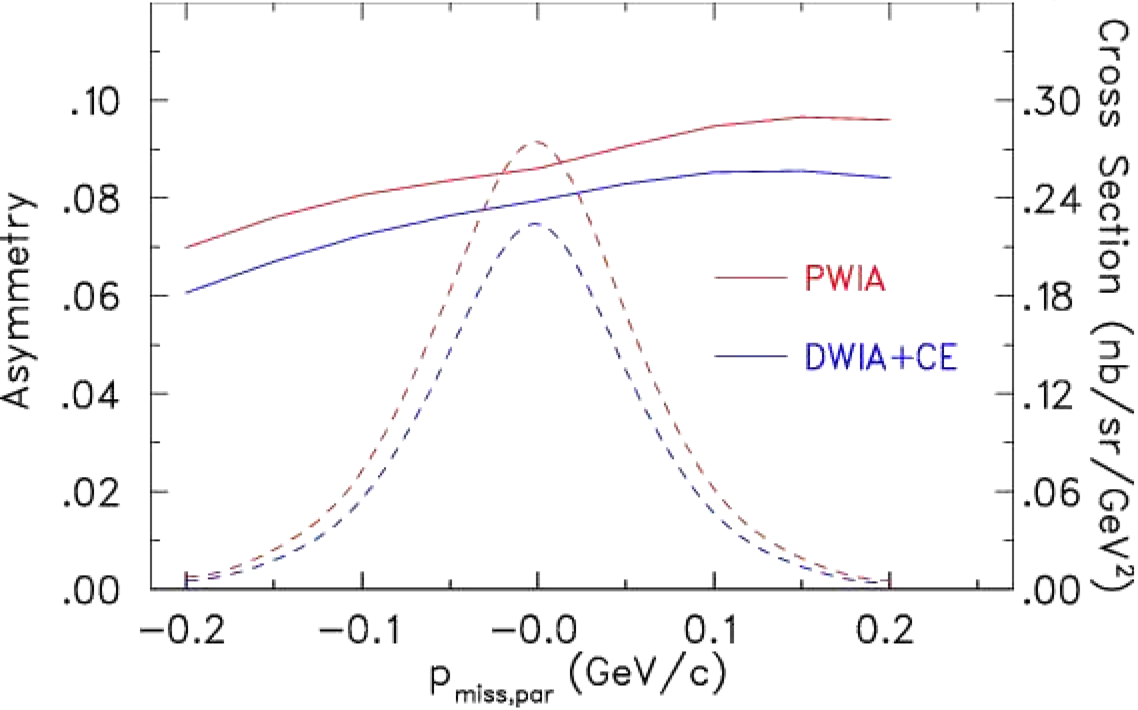


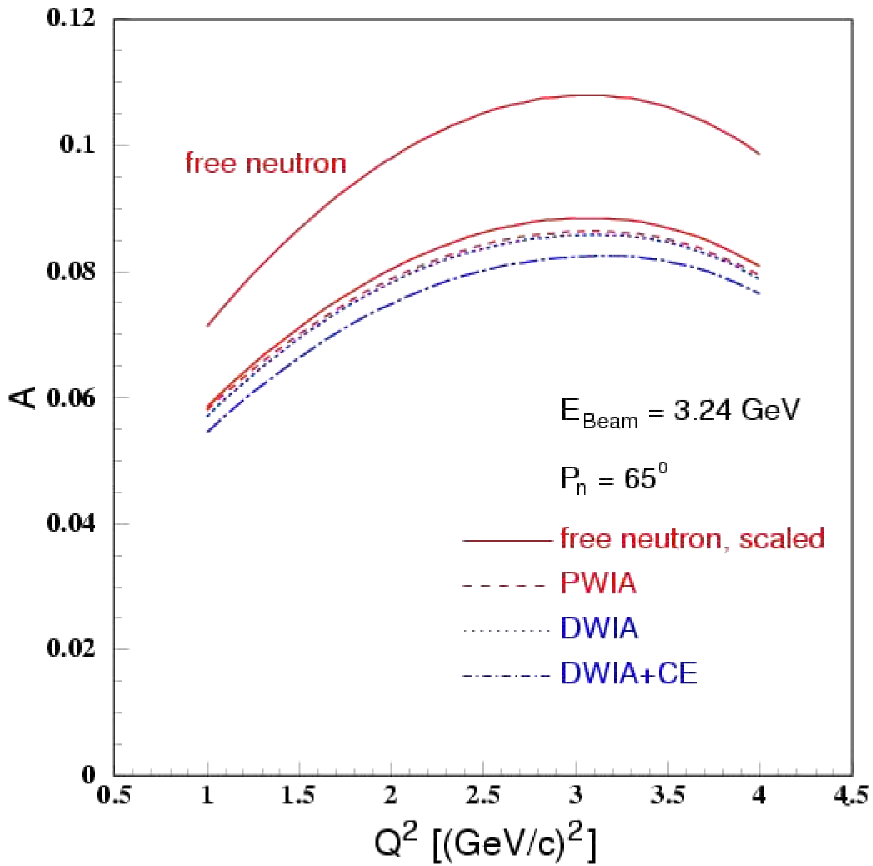
GEA Results II

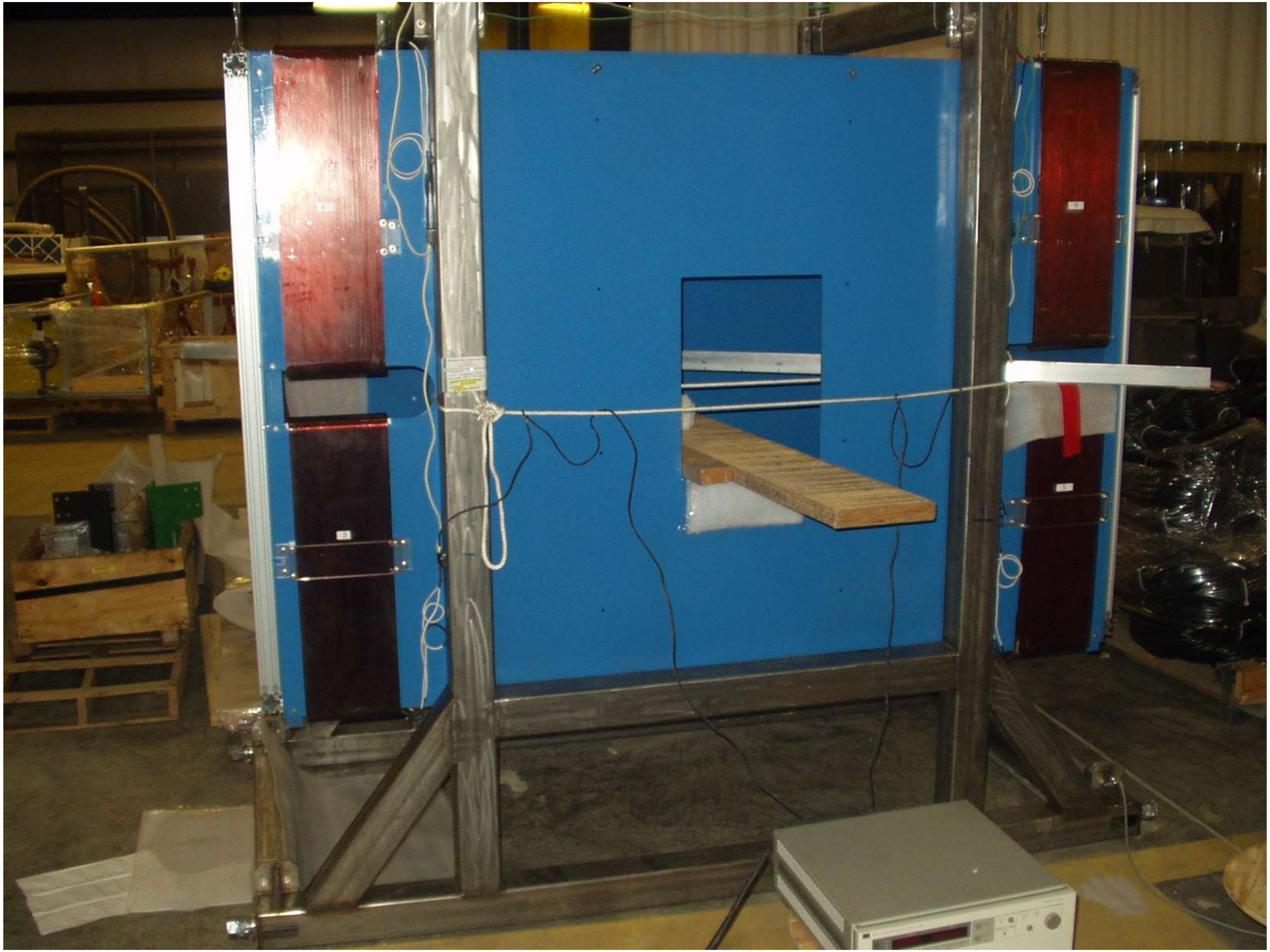


- Asymmetry does not vary strongly within our bins in missing momentum

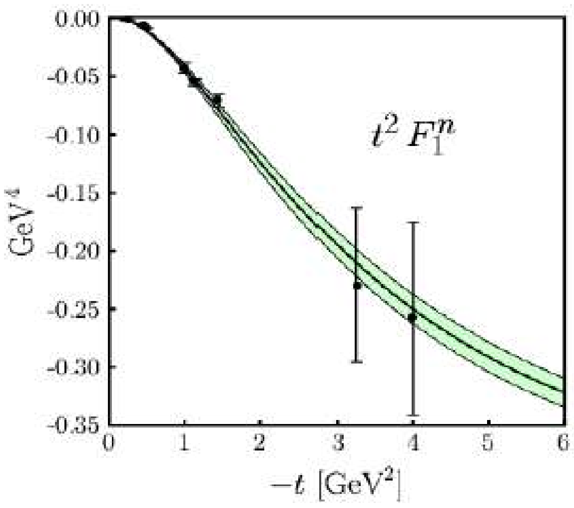
GEA Results (M.Sargsian)

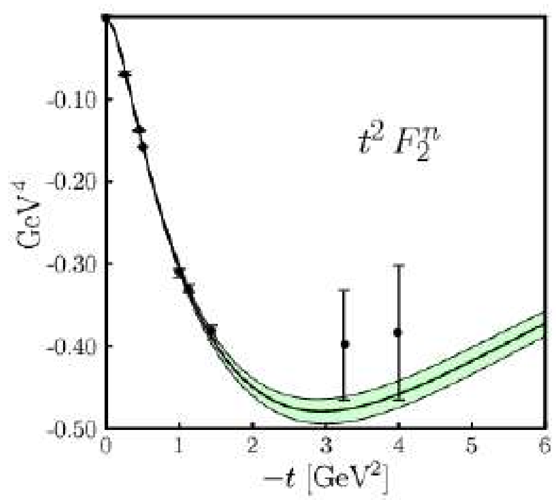






Constructing GPDs (Kroll et al.)

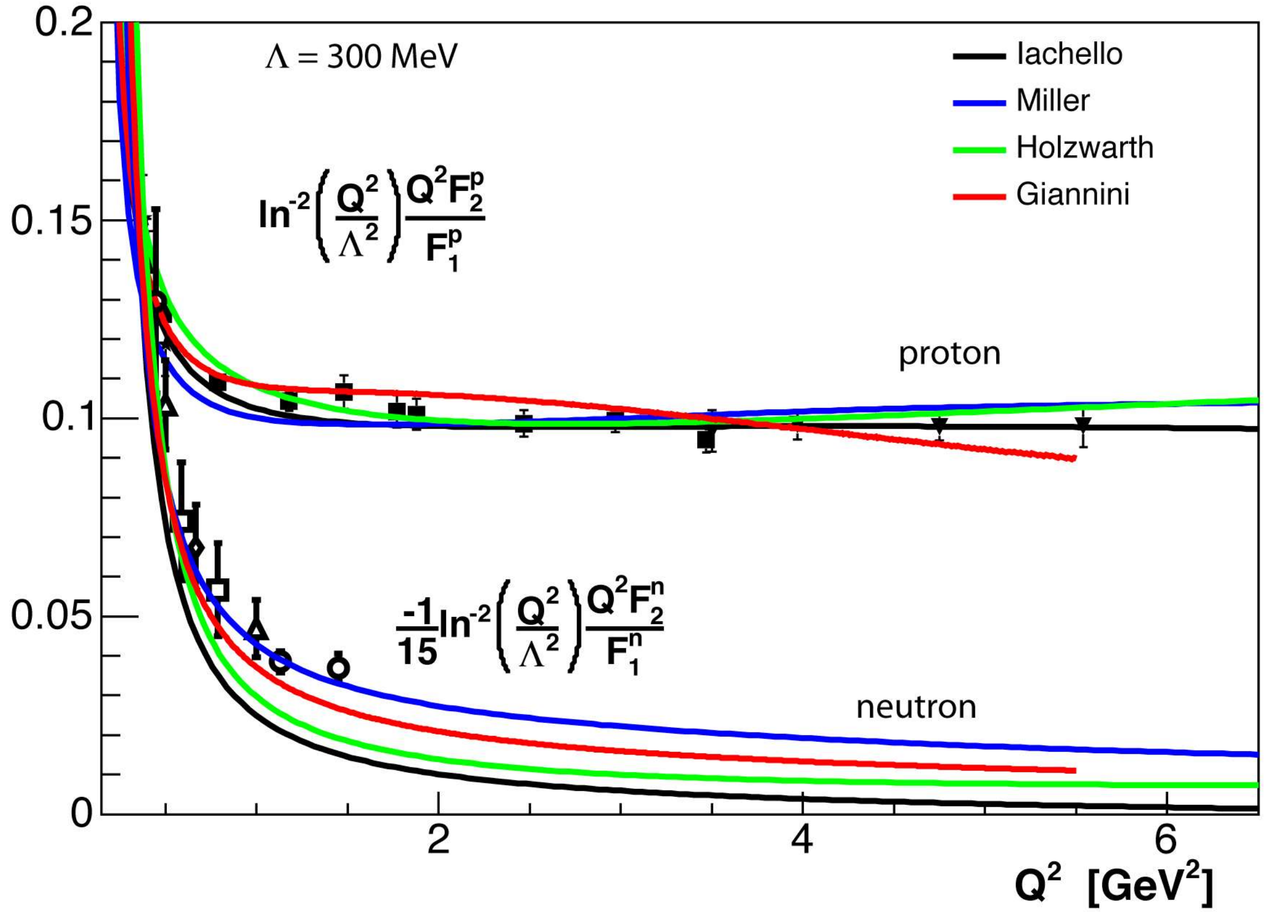




- Phenomenological ansatz, using
  - experimental data on q(x) from DIS (here CTEQ)
  - ansatz consistent with phenom. and theo. constraints (large -t and x: gaussian L.C. w.f., small -t and x Regge behavior)
  - simple ansatz, with only a few fit parameters, determined by fitting against F_1, F_2 and F_A
- Data on Electric Form Factor of Neutron is currently weakest point of the fit

High-Q² Behaviour

Or: Neutron Data Wanted!



Jefferson Lab Experiment E02-013

Cross Section Asymmetry in

$^3\vec{\mathrm{He}}(\vec{e}, e'n)$

To obtain G_E^n at three different Q^2

Q^2 $(\mathrm{GeV/c})^2$	E_i GeV	θ_e deg	p_e GeV/c	θ_n deg	p_n GeV/c	T_n GeV
1.31	1.644	54.6	0.95	35.2	1.34	0.70
2.40	2.444	54.6	1.17	28.3	2.01	1.28
3.40	3.244	50.6	1.43	25.4	2.58	1.81

Approved beam time: 32 days

Expected (statistical) uncertainty: less than 15%

Scheduled for early 2006

E02-013: Layout for $^3\vec{He}(\vec{e},e'n)$