Measurement of the Neutron Electric Form Factor (G_E^n) in $\overrightarrow{D}(\overrightarrow{e}, e'n)p$ Quasi-elastic Scattering at $Q^2 = 0.5(GeV/c)^2$

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Sep 8, 2000

Introduction

-Concept
-Interpretation
-Models
-Measurements
-$\overrightarrow{D}(\overrightarrow{e}, e'n)p$ technique

Experiment

-Overview
-Moller Polarimeter
-Polarized Target
-Neutron Detector

Analysis

Results

G_e^N Concept

$e - N$ cross section (one photon exchange):

$$\sigma = \sigma_m \frac{E'}{E_0} \left\{ (F_1)^2 + \tau \left[2 (F_1 + F_2)^2 \tan^2 (\Theta_e) + (F_2)^2 \right] \right\}$$

$$\sigma_m = \frac{\alpha^2 \cos^2 (\Theta/2)}{4E^2 \sin^4 (\Theta/2)}$$

$$Q^2 = \overrightarrow{q}^2 - \nu^2 = 4EE' \sin^2 (\Theta_e/2) \;;\; \tau = Q^2/4M^2$$

Sachs Form Factors:

$$G_E \left(Q^2\right) = F_1(Q^2) - \tau F_2 \left(Q^2\right)$$

$$G_M \left(Q^2\right) = F_1 \left(Q^2\right) + F_2 \left(Q^2\right)$$

$Q^2 = 0$ limit

$$G_E^p = 1 \;\; G_E^n = 0 \quad G_M^p = 2.79 \;\; G_M^n = -1.91$$

$e - n$ cross section

$$\sigma = \sigma_m \frac{E'}{E_0} \left(\frac{(G_E^n)^2 + \tau (G_M^n)^2}{1 + \tau} + 2\tau (G_M^n)^2 \tan^2 \left(\frac{\Theta_e}{2} \right) \right)$$

G_E^n Interpretation

In the nonrelativistic limit (Breit Frame):
G_E is F.T. of the charge distribution $\rho(r)$:

$$
\begin{aligned}
G_E^n\left(\overrightarrow{q}^{\,2}\right) &= \frac{1}{(2\pi)^3}\int d^3r\,\rho(\overrightarrow{r})\exp(-i\overrightarrow{q}\cdot\overrightarrow{r}) \\
&= \int d^3\overrightarrow{r}\,\rho\left(\overrightarrow{r}\right) - \frac{\overrightarrow{q}^{\,2}}{6}\int d^3\overrightarrow{r}\,\rho\left(\overrightarrow{r}\right)\overrightarrow{r}^{\,2} + \ldots \\
&= 0 - \frac{\overrightarrow{q}^{\,2}}{6}\left\langle r^2\right\rangle_E + \ldots
\end{aligned}
$$

General interpretation under discussion:
N. Isgur Phys. Rev. Lett. 83, 272 (1999)
"Interpreting *the Neutron's Electric Form Factor. Rest Frame Charge Distribution or Foldy Term?"*

G_E^n **Models**

- Low Q^2: *Vector Meson Dominance Models (VMD)*
  The virtual photon couples to the nucleon through a vector meson
  G. Höhler et al, Nucl. Phys. B114 (1976) 505

- High Q^2: *Perturbative QCD (PQCD)*
  Photon couples directly to nucleon or its quark constituents
  PQCD predicts scaling behaviour for large Q^2 :
  $G_{E,M} \propto 1/Q^4$

- Intermediate Q^2: *Phenomenological Model*
  incorporates constraints from VMD and asymptotic predictions of PQCD
  M. Gari and W.Kruempelmann, Z. Phys. A322 (1985) 689

- Intermediate Q^2: *Quark Models*
  - MIT Bag Modell
    D. Lu et al, ADP-97-16T253 (1997)
  - Constituent Quark Model
    M. Ivanov et al, Few Body Systems 21, 131 (1996)
  - Diquark Model
    P. Kroll et al, Z. Phys. 338,339 (1991)

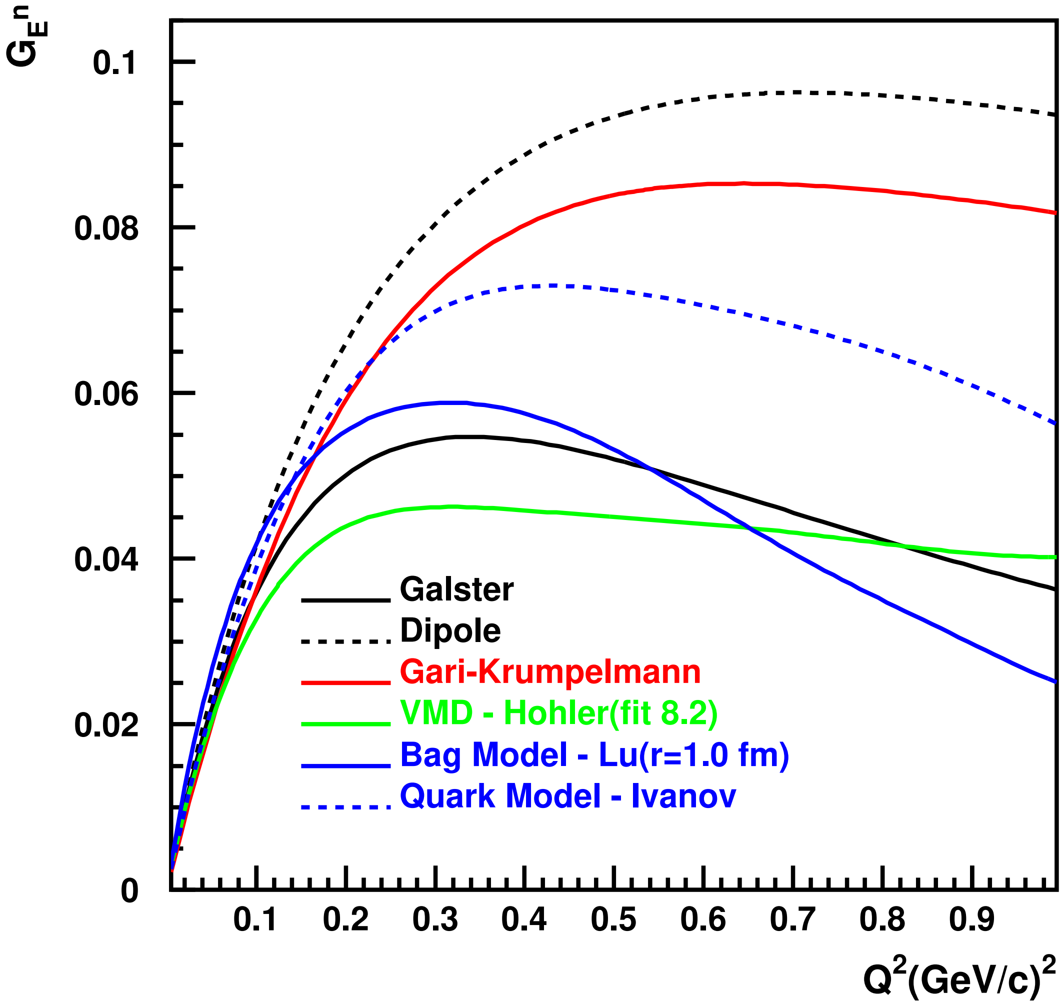
Parametrizations:

- **Dipole Model**
  good description of early $G^p_{E,M}$ measurements

$$
\begin{aligned}
G_D &= \left(1 + \frac{Q^2}{0.71(GeV/c)^2}\right)^{-2} \\
G_E^p &= G_D = \frac{G_M^p}{\mu_p} = \frac{G_M^n}{\mu_n} \\
G_E^n &= -\tau \mu_n G_D\,; \;\; \tau = \frac{Q^2}{4M^2}
\end{aligned}
$$

- **Galster Parametrization**
  from $e - D$ elastic scattering

$$G_E^n = -\frac{\tau \mu_n}{1 + 5.6\tau} G_D$$



G_E^n
0.1
0.08
0.06
0.04
0.02
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
$Q^2(GeV/c)^2$
Galster
Dipole
Gari-Krumpelmann
VMD - Hohler(fit 8.2)
Bag Model - Lu(r=1.0 fm)
Quark Model - Ivanov

G_E^n Measurements

- Basic problem: No free neutron target
- Inclusive cross section measurements on Deuterium:
  - Elastic $e - D$ scattering at small angles:
    $\rightarrow$ dependence on nucleon nucleon potential
    $\rightarrow$ subtraction of dominant proton contribution
  - Quasielastic $e - D$ scattering
    $\rightarrow$ Rosenbluth separation
    $\rightarrow$ Sensitive to deuteron structure
- Double Polarization measurements
  asymmetry measurement
  detection of neutron in coincidence
  $\rightarrow$ less sensitive to deutron structure
  $\rightarrow$ avoid Rosenbluth separation
  $\rightarrow$ avoid subtraction of proton contribution
  - $D(\overrightarrow{e}, e'\overrightarrow{n})p$
  - $\overrightarrow{D}(\overrightarrow{e}, e'n)p$, $\overrightarrow{^3He}(\overrightarrow{e}, e'n)pp$

Elastic $e - D$ Scattering

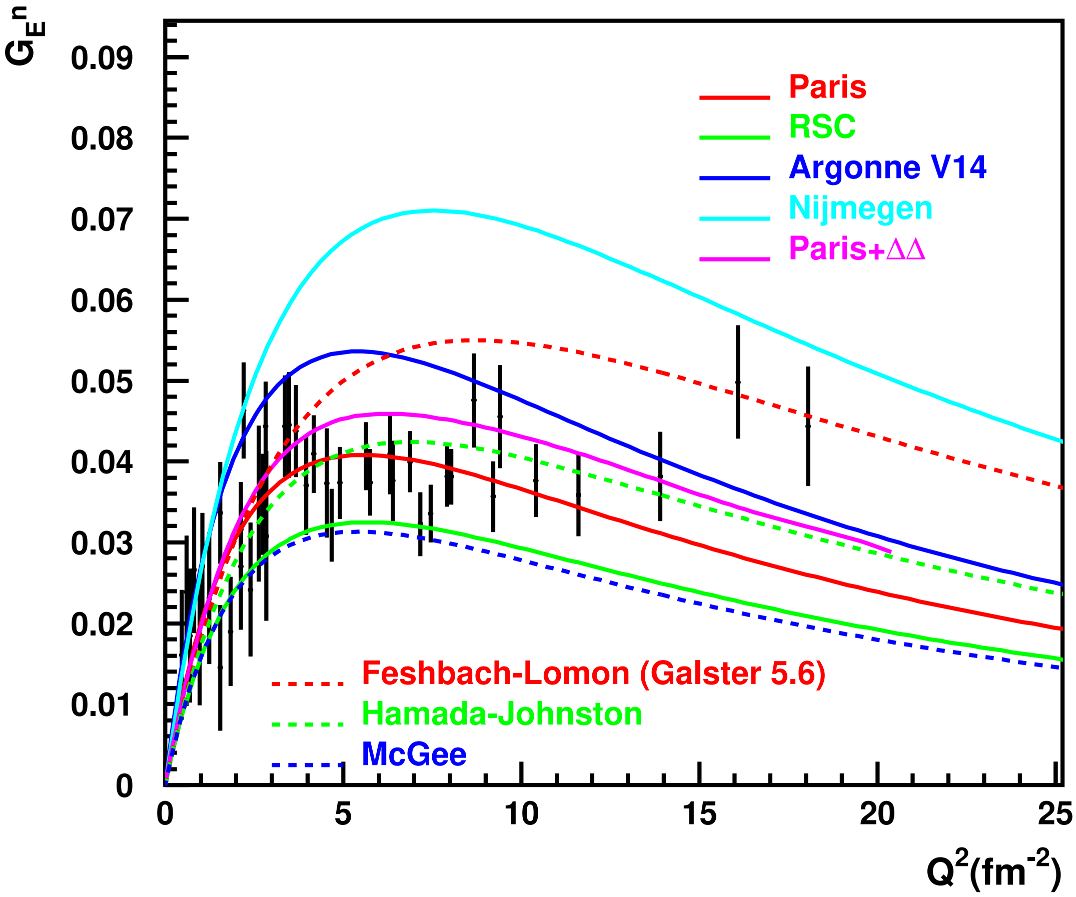
Born approximation

$$\sigma \propto A\left(Q^2\right) + B\left(Q^2\right)\tan^2\left(\frac{\Theta_e}{2}\right)$$

small θ_e approximation

$$\sigma \propto A\left(Q^2\right) \simeq \left(G_E^p + G_E^n\right)^2 f\left[u\left(k\right), w\left(k\right)\right]$$

- Extraction of G_E^n requires
  $\rightarrow$deuteron wave function $f\left[u\left(k\right), w\left(k\right)\right]$
  $\rightarrow$subtraction of proton contribution G_E^p



DESY: *S. Galster et al, Nucl. Phys. B32, 221 (1971)*
Saclay: *S. Platchkov et al, Nucl. Phys A510, 740 (1990)*

Quasielastic $e - D$ Scattering

PWIA model (Durand and McGee): Cross section is incoherent sum of p and n cross section folded with deuteron structure.

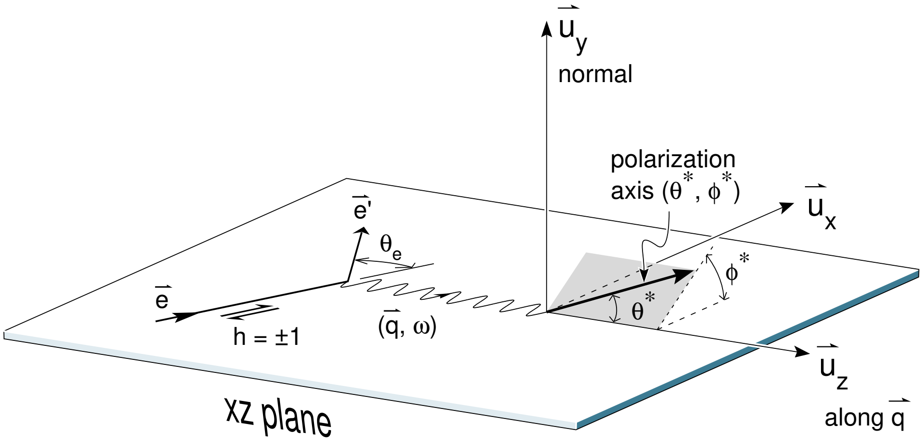
$$
\begin{aligned}
\sigma &= \left(\sigma_p + \sigma_n\right) I\left(u, w\right) \\
&= \left\{ \varepsilon \left[\left(G_E^p\right)^2 + \left(G_E^n\right)^2 \right] + \frac{\nu^2}{Q^2} \left[\left(G_M^p\right)^2 + \left(G_M^n\right)^2 \right] \right\} I\left(u, w\right) \\
&= \varepsilon R_L + R_T \\
& \varepsilon = \left[1 + 2\left(1+\tau\right) \tan^2\left(\theta_e/2\right) \right]
\end{aligned}
$$

- Extraction of G_E^n:
  Rosenbluth Separation $\Rightarrow R_L$
  Subtraction of proton contribution.

- Problems:
  Unfavorable error propagation
  Sensitivity to deuteron structure

SLAC: *A. Lung et al, Phys. Rev. Lett. 70, 718 (1993)*
$\rightarrow$No indication of non-zero G_E^n

Experimental technique for $\vec{D}(\vec{e}, e'n)p$



Cross section:

$$\sigma = \Sigma + h\Delta \; ; \;\; h = \pm 1$$

Asymmetry

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

Σ is the elastic unpolarized $e - n$ cross section

$$\Sigma = \sigma_m \frac{E'}{E_0} \left(\frac{\left(G_E^n\right)^2 + \tau \left(G_M^n\right)}{(1+\tau)} + 2\tau \left(G_M^n\right)^2 \tan^2\left(\frac{\Theta_e}{2}\right) \right)$$

Δ depends on direction of target polarization: $\Theta^\star$, $\Phi^\star$

$$\Delta = -2\sigma_m \frac{E'}{E_0} \sqrt{\frac{\tau}{1+\tau}} \tan\left(\frac{\Theta_e}{2}\right) \left\{ \sqrt{\tau \left(1 + (1+\tau)\tan^2\left(\frac{\Theta_e}{2}\right)\right)} \cos\Theta^\star \left(G_M^n\right)^2 + \sin\Theta^\star \cos\Phi^\star G_E^n G_M^n \right\}$$

Neutron Asymmetry for $\Theta^\star = \pi/2$ and $\phi^\star = 0$

$$A_n = \frac{-2\sqrt{\tau(1+\tau)}\,\tan\left(\Theta_e/2\right) G_E^n G_M^n}{\left(G_E^n\right)^2 + \tau\left(1 + 2\left(1+\tau\right)\tan^2\left(\Theta_e/2\right)\right)\left(G_M^n\right)^2}$$

Deuteron asymmetry $A_{ed}^V = \gamma A_n$

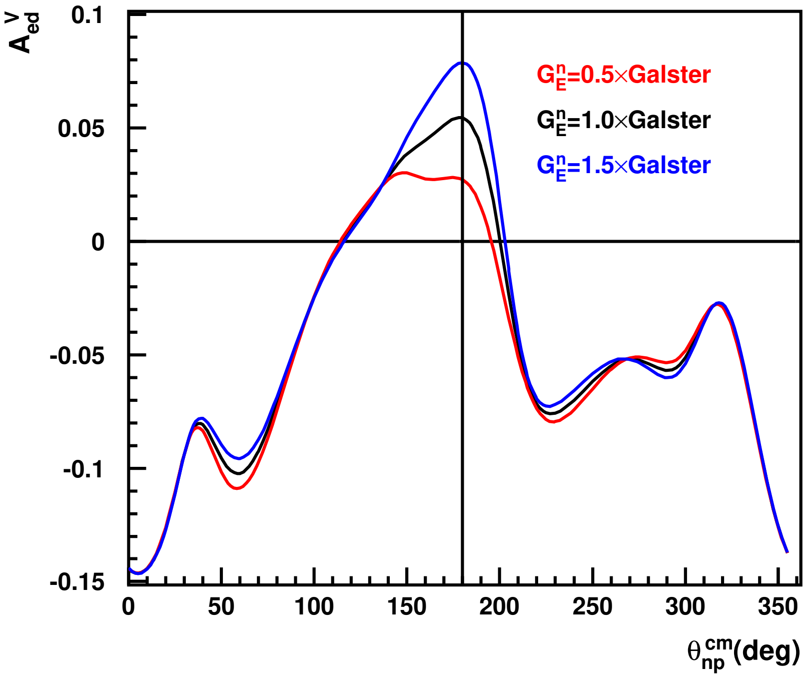
$\gamma = 0.92$: correction factor for the D-state of the deuteron

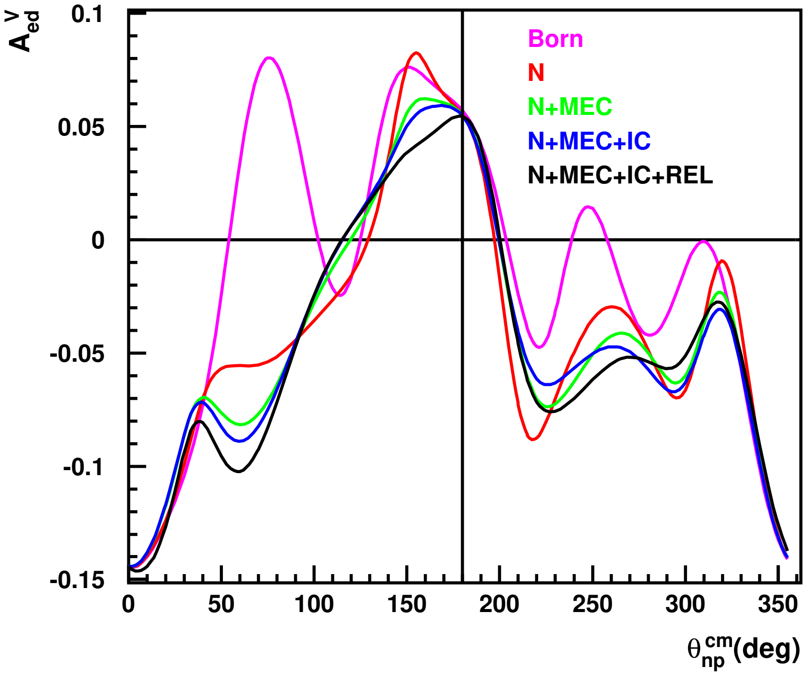
Theoretical Calculations of electrodisintegration of the deuteron:

H. Arenhövel et al, Z. Phys. A 331, 123 (1988)

A_{ed}^V has low sensitivity to potential models and subnuclear degrees of freedom (MEC, IC) in the quasi-elastic region

Arenhövel Calculations



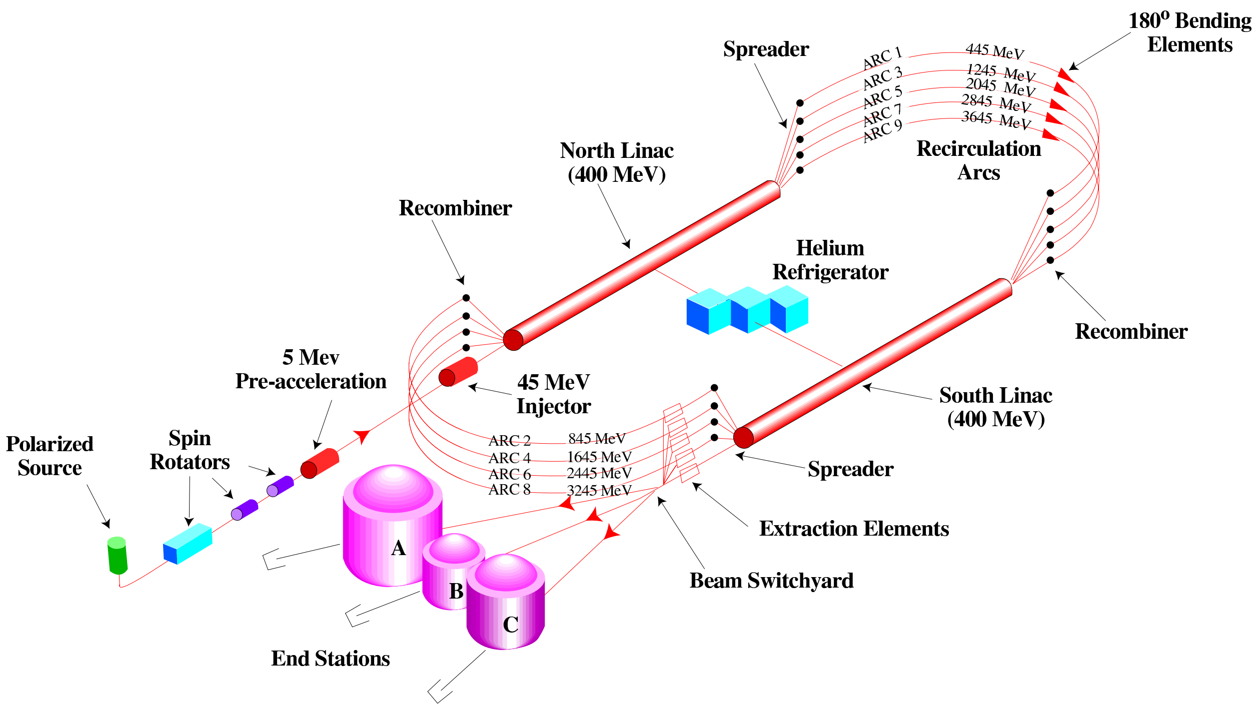


E=2.721 GeV; E′=2.460 GeV; Θ_e=15.8 deg

Θ_{np}^{cm}: Angle between $\vec{q}$ and relative n-p momentum in cm system. 180 deg corresponds to neutron in direction of $\vec{q}$.

EXPERIMENT E-93026

- Measured in Hall C at Thomas Jefferson National Accelerator Facility (Jlab) in Newport News, Virginia, USA
- Measuring period: Aug 1998 - Oct 1998 (Continuation in 2001)
- Kinematics:
  $Q^2 = 0.5(GeV/c)^2$ and $Q^2 = 1.0(GeV/c)^2$



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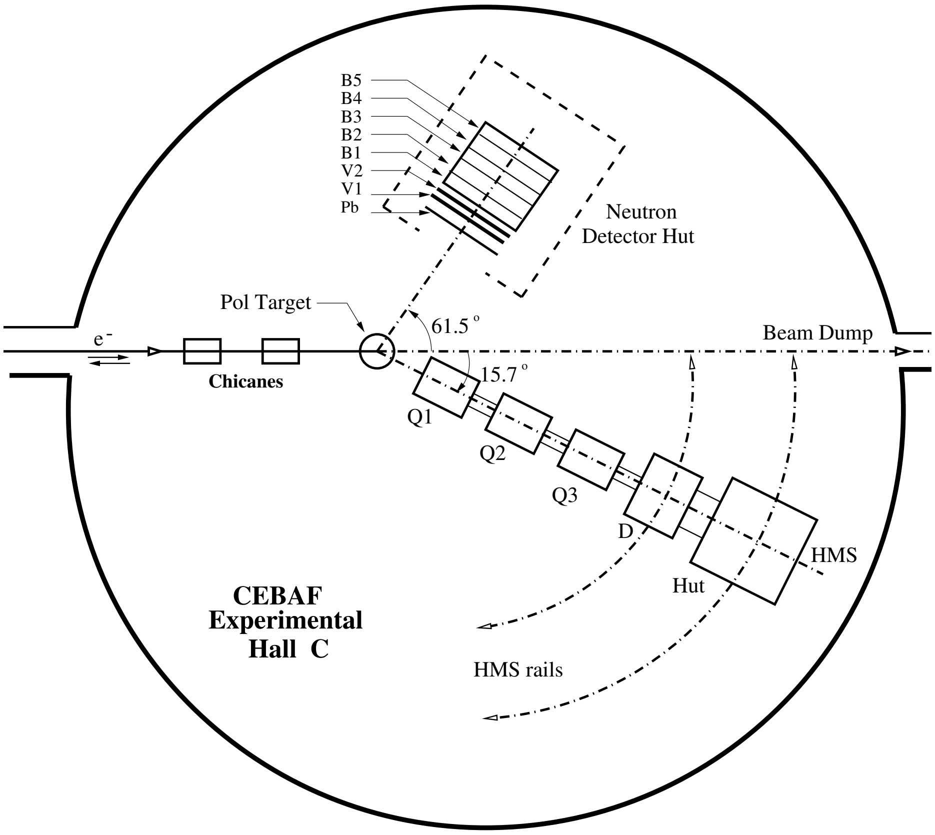
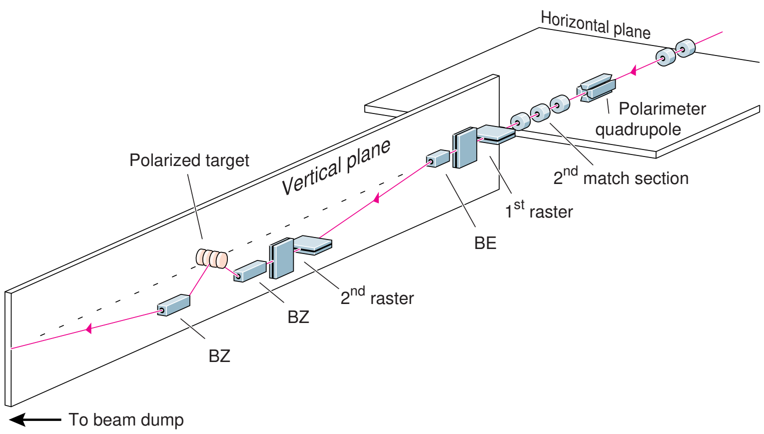
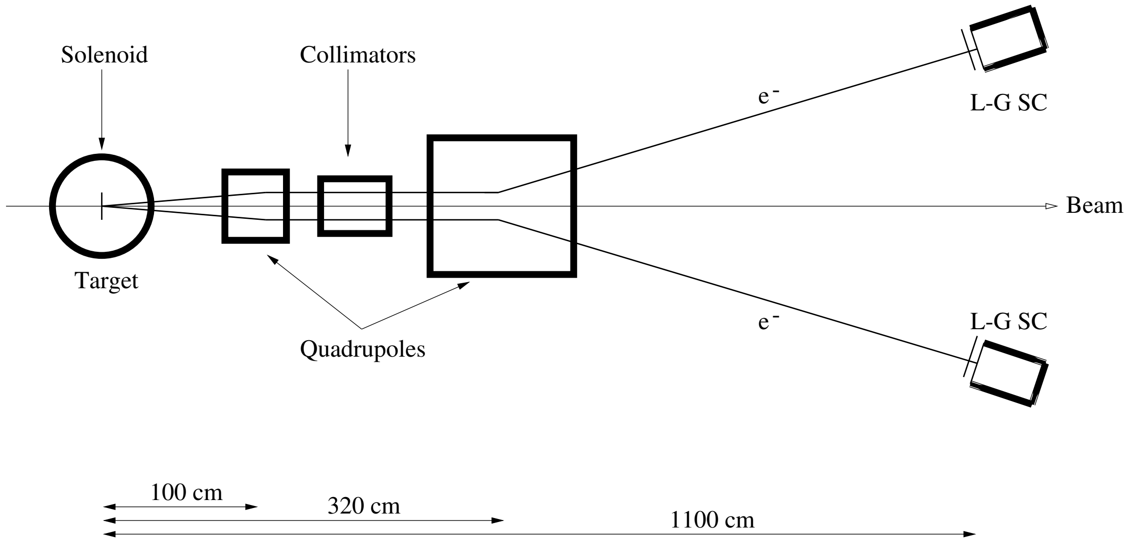
Setup in Hall C





Moller Polarimeter



Based on polarized electron-electron scattering (moller scattering)

Beam and Target longitudinally polarized:

$$A = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} = A_{zz}(\Theta)\, P_z^B P_z^T$$

A_{zz}: longitudinal analyzing power from calculation and MC

P_z^T: Target Polarization

Target (4μm Fe foil) polarized to saturation normal to foil plane by 3 Tesla field

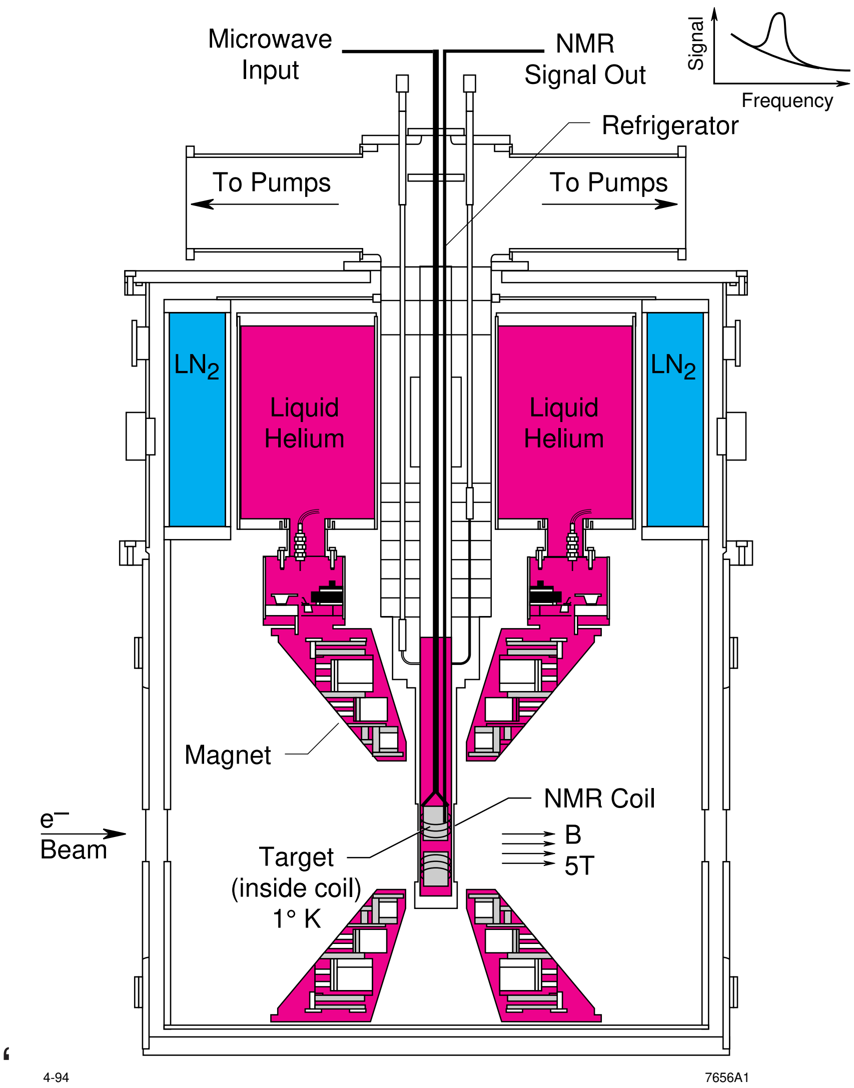
Coincidence Measurement to suppress Mott background

2 Quadrupoles to bend electrons away from beam line

Detector: hodoscope array | collimator | lead glass block

$\Delta P_z^B / P_z^B = 1\%$ in 20 minutes

Polarized Target



Target material: $^{15}ND_3$ (doped by irradiation)

Polarization:

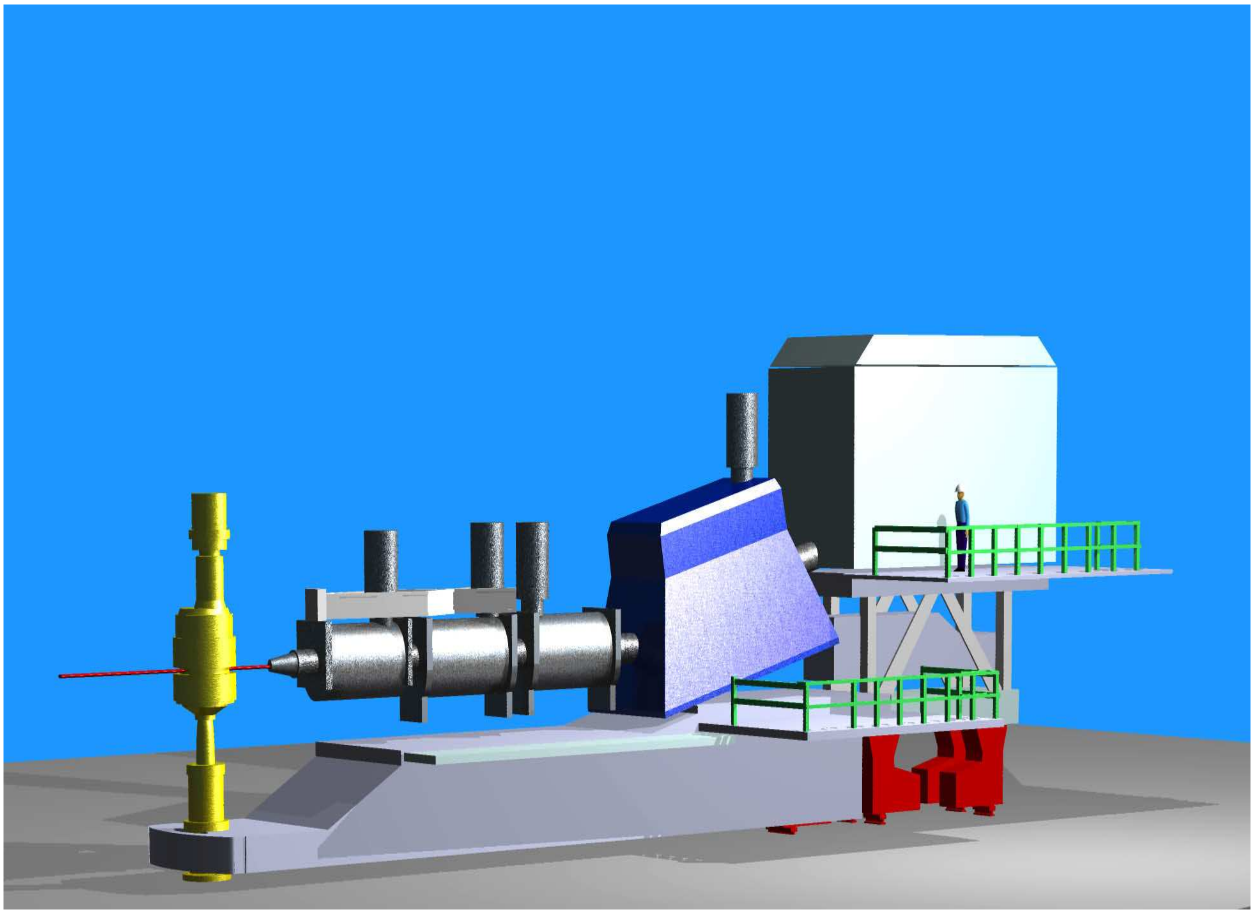
Dynamic Nuclear Polarization with Microwaves (140 GHz)

5 Tesla field

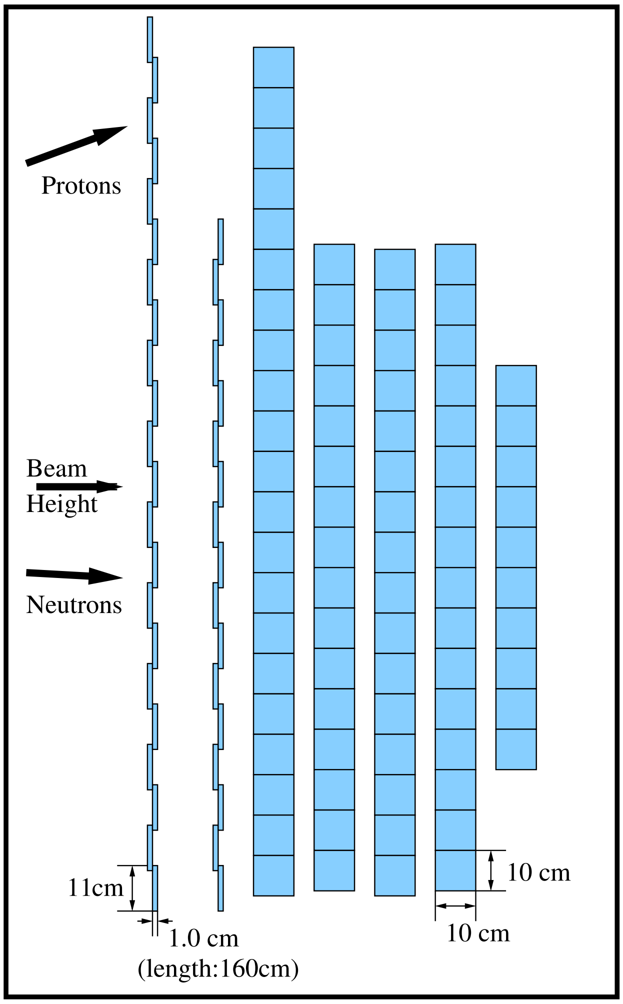
^4He evaporation system $\rightarrow$ 1 K

Polarization Measurement: NMR readout

High Momentum Spectrometer (HMS)



Neutron Detector



Detector material: Plastic Scintillator

79 Bars & 39 Paddles: PM’s on each side

Shielding: Concrete house, lead curtain

ANALYSIS

- Event Reconstruction
  - HMS standard reconstruction + target magnet + raster
  - NDET tracking: Particle Identification

$\Rightarrow$variables: w, $Ypos$, $cointime$, θ_{nq}

- Event Selection and Normalization
  $\rightarrow$ Normalized yields: $N^{\uparrow}$, $N^{\downarrow}$

- Experimental asymmetries:
  $\varepsilon = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} = P_B \cdot P_T \cdot f \cdot A^V_{ed}$
  - Beam Polarization P_B from moller polarimetry, $\simeq 77\%$
  - Target polarization P_T: average: 22%
  - Dilution factor $f = \frac{N_{polarized}}{N}$ from ^{12}C data and MC

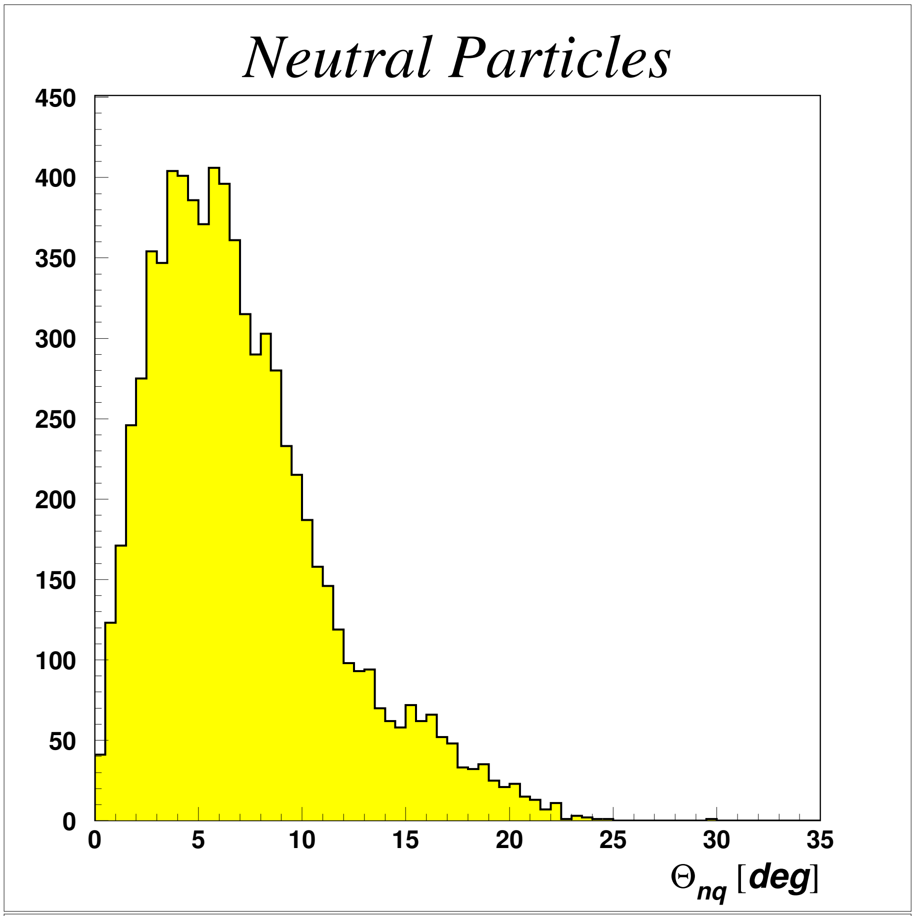
- Radiative corrections, Accidental background subtraction

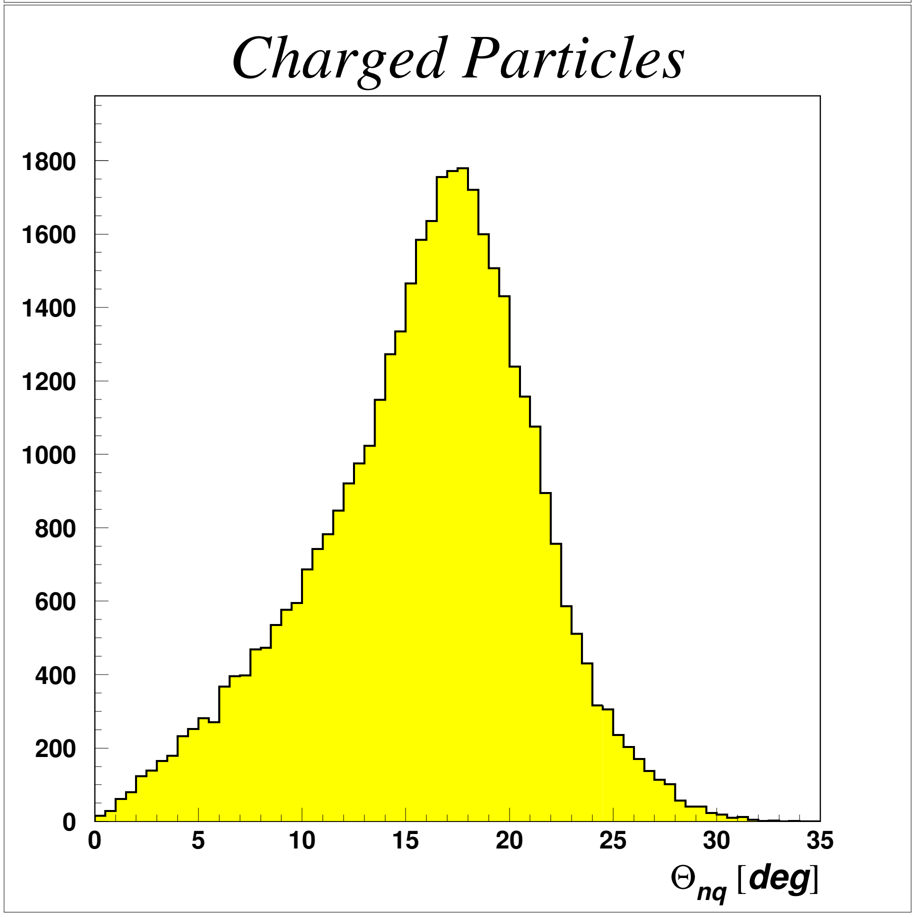
$\Rightarrow$ measured deuteron asymmetry A^V_{ed}

- Theoretical calculations of A^V_{ed} (for different G^n_E models) from Arenhövel for a kinematical grid

- Average theoretical A^V_{ed} over experimental acceptance using MC and compare with measured A^V_{ed}

$\Rightarrow$ G^n_E

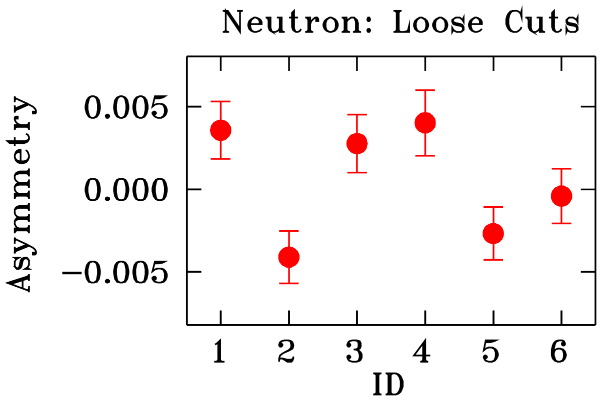

Neutral Particles
450
400
350
300
250
200
150
100
50
0
0
5
10
15
20
25
30
35
Θ_{nq} [deg]

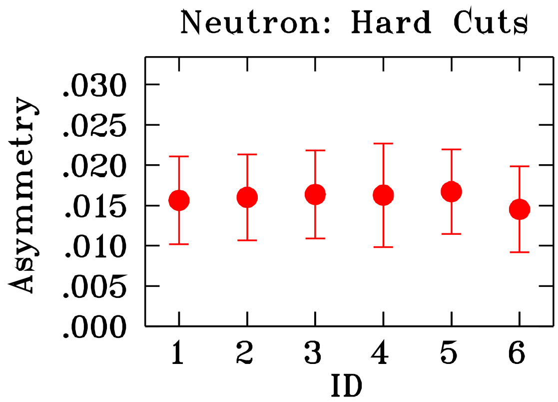

Charged Particles
1800
1600
1400
1200
1000
800
600
400
200
0
0
5
10
15
20
25
30
35
Θ_{nq} [deg]

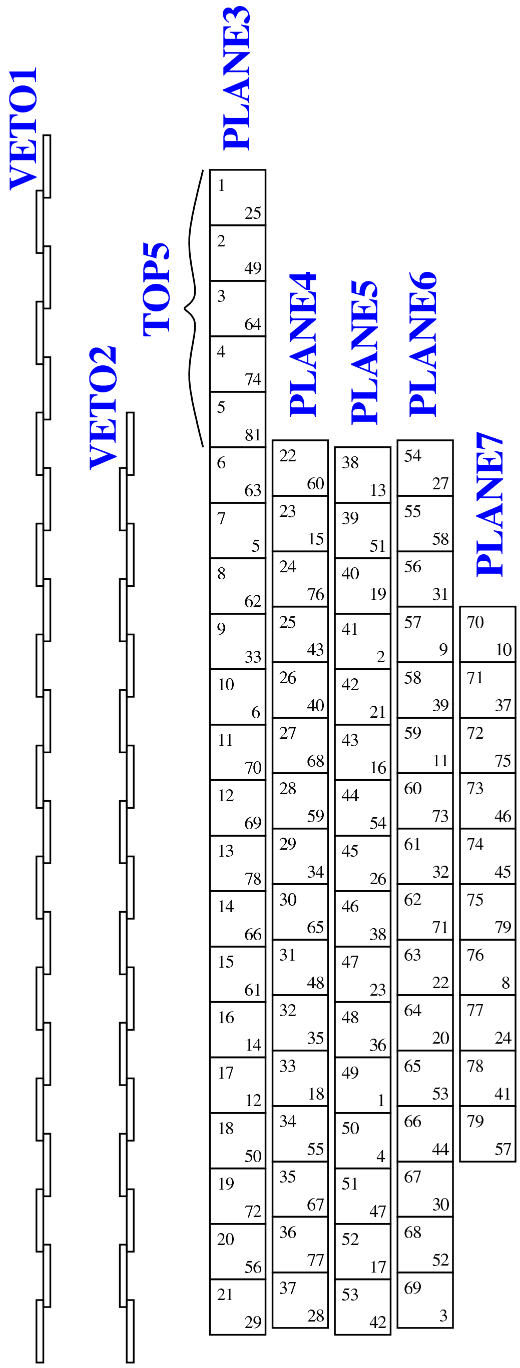
NEUTRON IDENTIFICATION

Definitions:

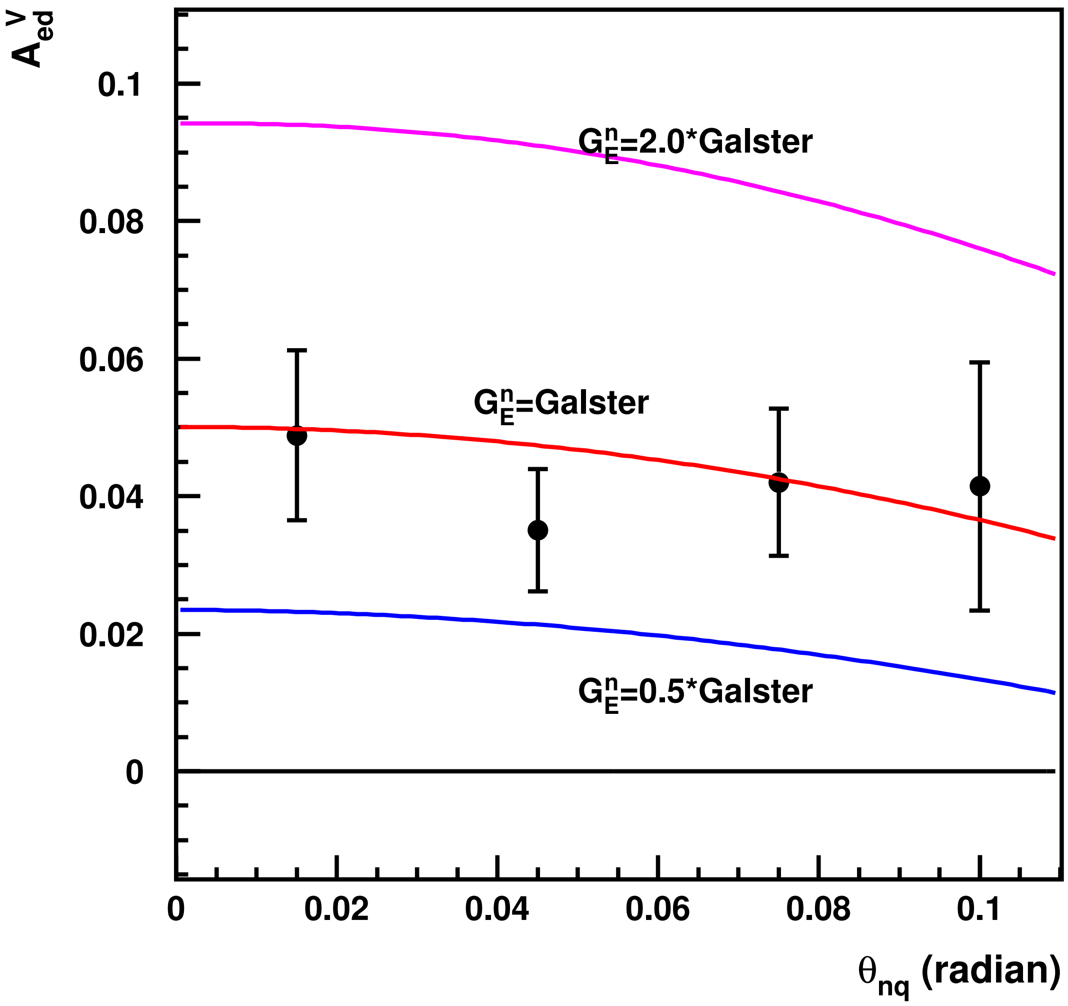
ID1 = Analyzer Neutron
ID2 = (!VETO1) && (!VETO2)
ID3 = ID2 && (!TOP5)
ID4 = ID2 && (!PLANE3)
ID5 = (!VETO1) && (!TOP5)
ID6 = (!VETO2) && (!TOP5)





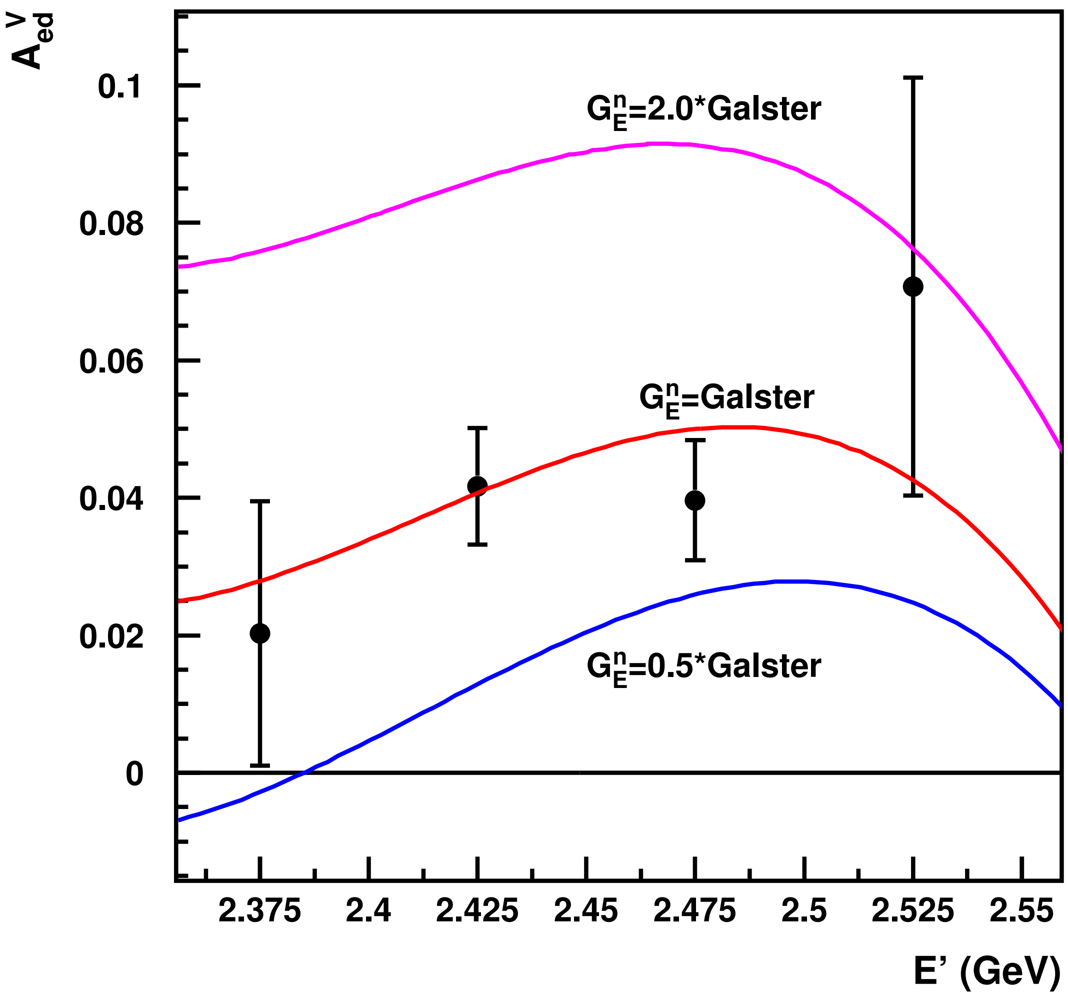


- θ_{nq}: Angle between 3-momentum transfer ($\vec{q}$) and hadron track



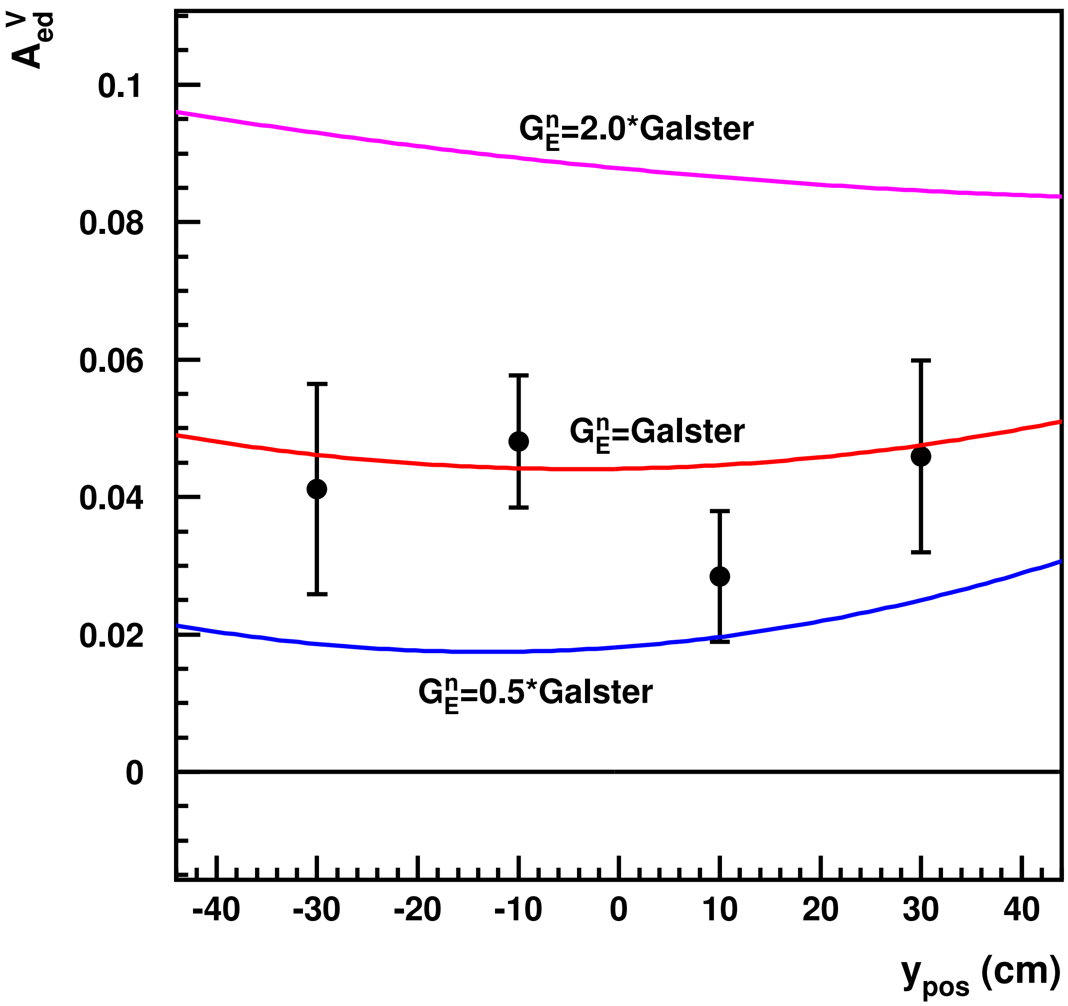
Fit: $G_E^n = (0.90 \pm 0.12) \times (G_E^n)_{Galster}$

E': Energy of the scattered electron



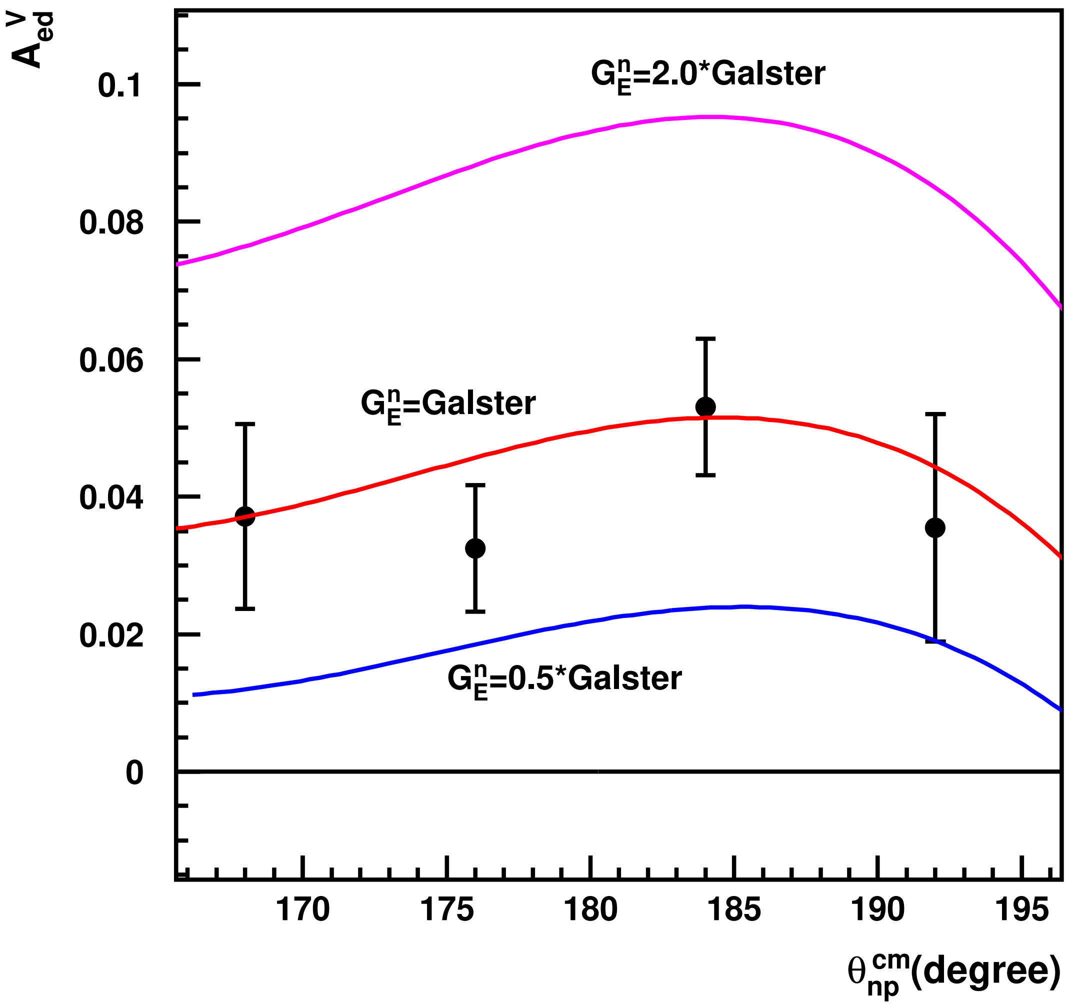
Fit: $G_E^n = (0.91 \pm 0.13) \times (G_E^n)_{Galster}$

Y_{pos}: Horizontal coordinate of the hadron track in the neutron detector



Fit: $G_E^n = (0.89 \pm 0.12) \times (G_E^n)_{Galster}$

θ_{np}^{cm}: A Angle between 3-momentum transfer ($\overrightarrow{q}$) and relative n-p momentum in the cm system (180 deg corresponds to neutron in direction of $\overrightarrow{q}$)



Fit: $G_E^n = (0.89 \pm 0.12) \times (G_E^n)_{Galster}$

RESULTS

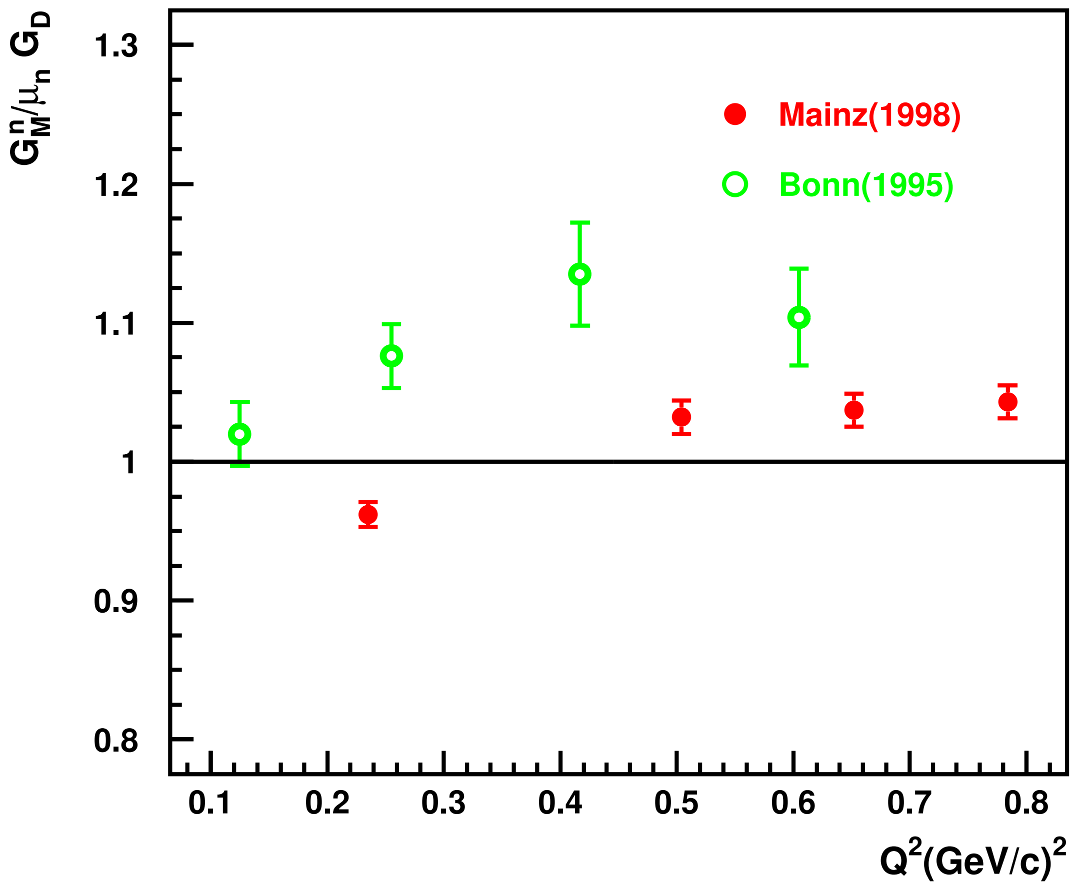
Preliminary result for $Q^2 = 0.5\,(GeV/c)^2$:

$$G_E^n = 0.0468 \pm 0.0063_{stat} \pm 0.0061_{syst}$$

Systematics:

Source	Contribution	status
G_M^n	3.3%	$\surd$
Beam Polarization	1.1%	$\surd$
Target Polarization	5.3%	$\surd$
Dilution factor	10.0%	in progress
Radiative Corrections	1.0%	$\surd$
A_{ed}^V averaging	0.4%	$\surd$
Kinematic Uncertainties	1.9%	$\surd$
NDet position offset	1.4%	$\surd$
Cut dependence	5.0%	in progress
Total $(\Delta G_E^n / G_E^n)_{syst}$	13.1%	in progress

Impact of G_M^n

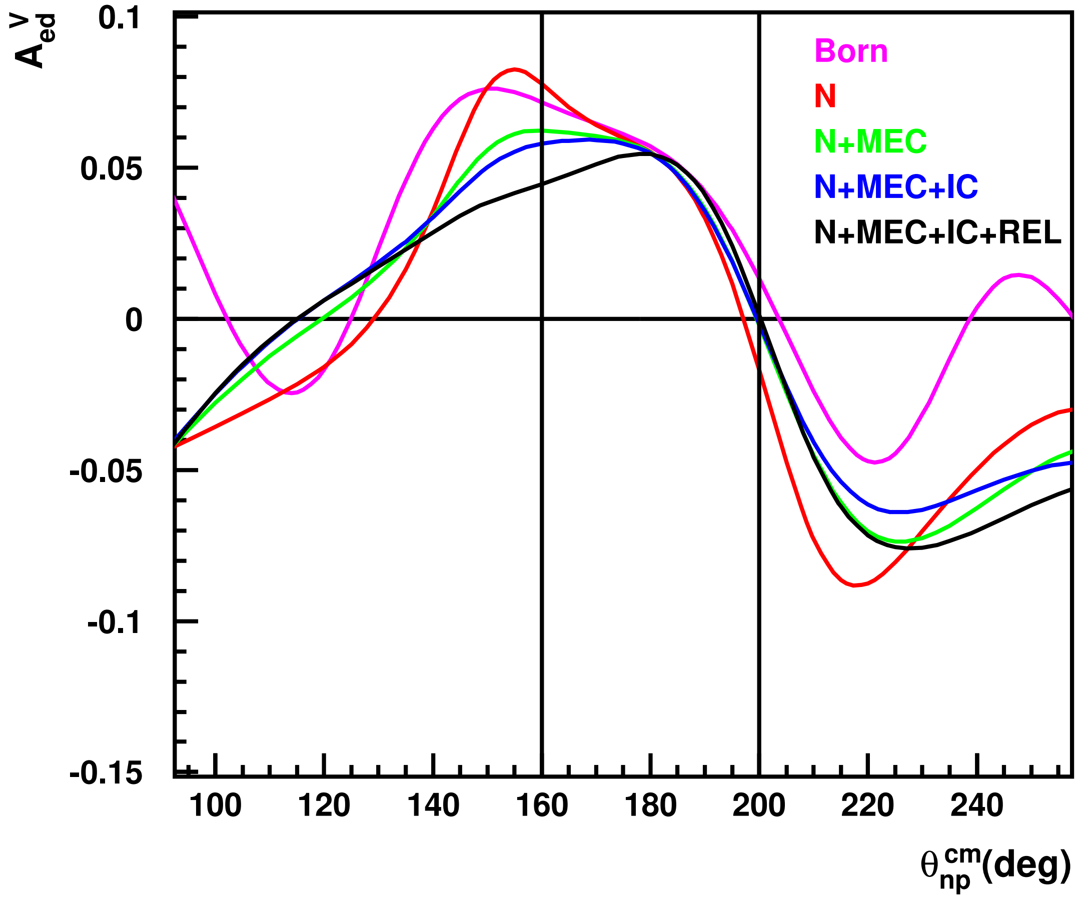


Difference between $G_M^n = \mu_n G_D$ and

G_M^n Mainz: 3%

G_M^n Bonn: 10%

Reaction Mechanism Dependence



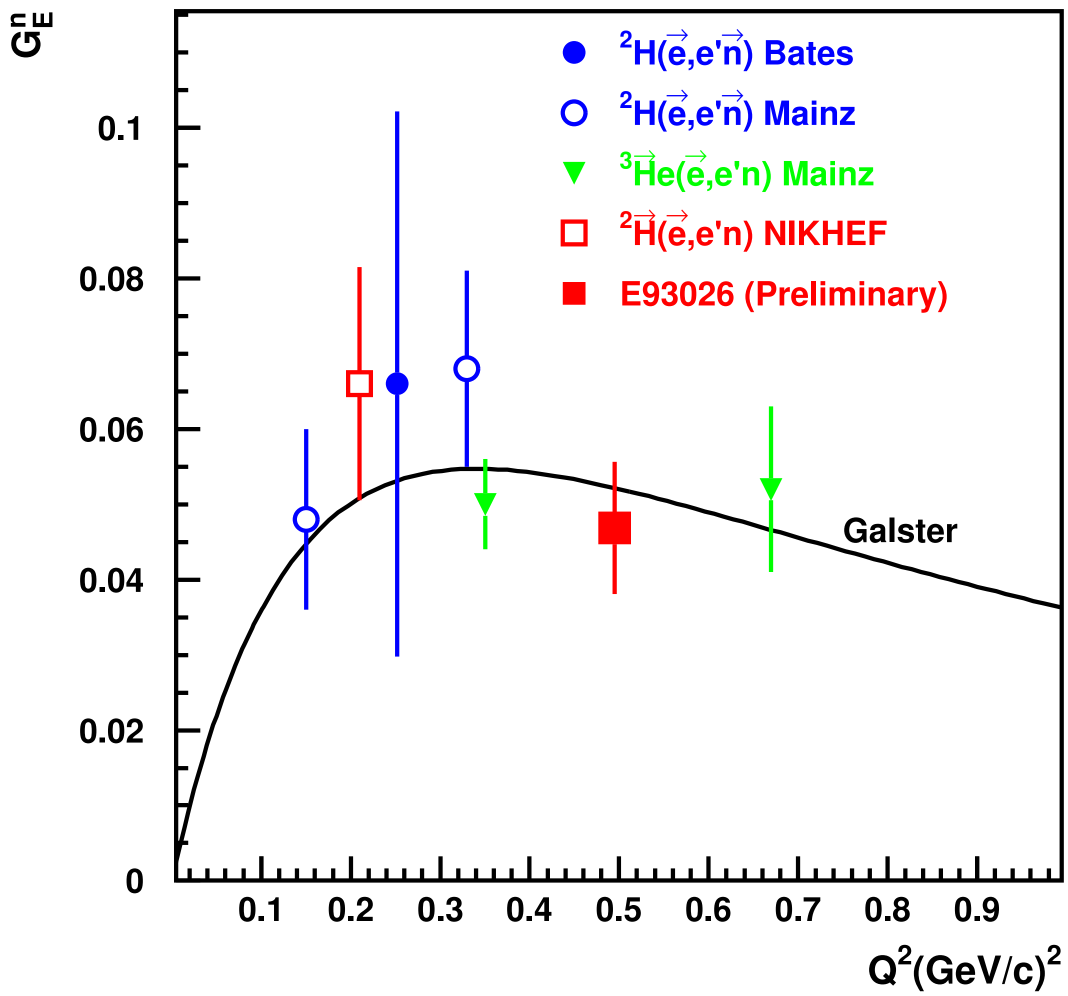
Experimental acceptance: $160deg < \theta^{cm}_{np} < 180deg$

Difference between full Calculation and

Born: 14%

Born + REL: $\simeq$8%

G_E^n World Data (Polarization Experiments)



$\overrightarrow{^3He}$ Mainz at $Q^2 = 0.35 (GeV/c)^2$: with FSI corr

$\overrightarrow{^3He}$ Mainz at $Q^2 = 0.67 (GeV/c)^2$: without FSI corr