Measurement of the Neutron Electric Form Factor (G_E^n) in $\overrightarrow{D}(\overrightarrow{e}, e'n)p$ Quasi-elastic Scattering at Jefferson Lab

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June 6, 2002

Outline

Does the Nucleon have Structure?

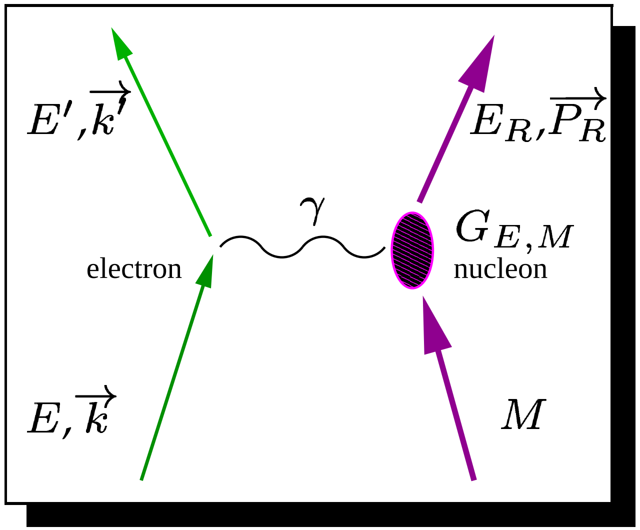
Early Indications

- Anomalous magnetic moments of p and n
  O. Stern, Nature 132 (1933) 169
- Non-zero neutron charge radius from scattering of thermal neutrons on atoms
- Elastic electron scattering on proton and deuteron
  Mc Allister, R. Hofstadter Phys Rev 102 (1956) 851

Nucleon Form Factors

Elastic electron-nucleon cross section (one photon exchange):

$$\sigma = \frac{\sigma_{mott} E'}{(1+\tau)E} \left\{ {G_E}^2 + \tau \left[1 + 2\,(1+\tau)\tan^2\left(\frac{\Theta_e}{2}\right) {G_M}^2 \right] \right\}$$



e scatt. angle: Θ_e

pointlike target: $\sigma_{mott} = \frac{\alpha^2 \cos^2(\Theta_e/2)}{4E^2 \sin^4(\Theta_e/2)}$

Kin. factor: $\tau = Q^2/4M^2$

4-momentum transfer:

$$\begin{aligned} Q^2 &= \left(\vec{k} - \vec{k'}\right)^2 - (E - E')^2 \\ &= 4EE' \sin^2(\Theta_e/2) \end{aligned}$$

$Q^2 = 0$ limit:

proton: $G_E^p = 1$ $G_M^p = 2.79$ neutron: $G_E^n = 0$ $G_M^n = -1.91$

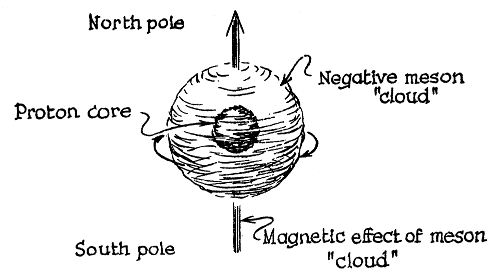
G_E^n Interpretation

In the nonrelativistic limit $Q^2 = \vec{q}^{\,2}$ (Breit Frame) G_E is Fourier Transform of the charge distribution $\rho(r)$:

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

Experimental: Mean square charge radius $\left\langle r^2\right\rangle_E$ is negative.

Theory has intuitive explanation:



pion-nucleon theory: n = p + π^- cloud

valence quark model: n = ddu & spin-spin force $\Rightarrow d \rightarrow$ periphery

G_E^n Models

- Low Q^2 *Vector Meson Dominance Models (VMD)*
  The virtual photon couples to the nucleon through a vector meson
- 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 Models*
    VMD constraints and PQCD asymptotics
  - *QuarkModels*
    MIT Bag Modell
    Constituent Quark Model

G_E^n Parametrizations

Dipole Parametrization: Good description of early $G_{E,M}^p$ data

$$G_D = \left(1 + \frac{Q^2}{0.71(GeV/c)^2}\right)^{-2}$$

$$G_E^p = G_D = \frac{G_M^p}{\mu_p} = \frac{G_M^n}{\mu_n}$$

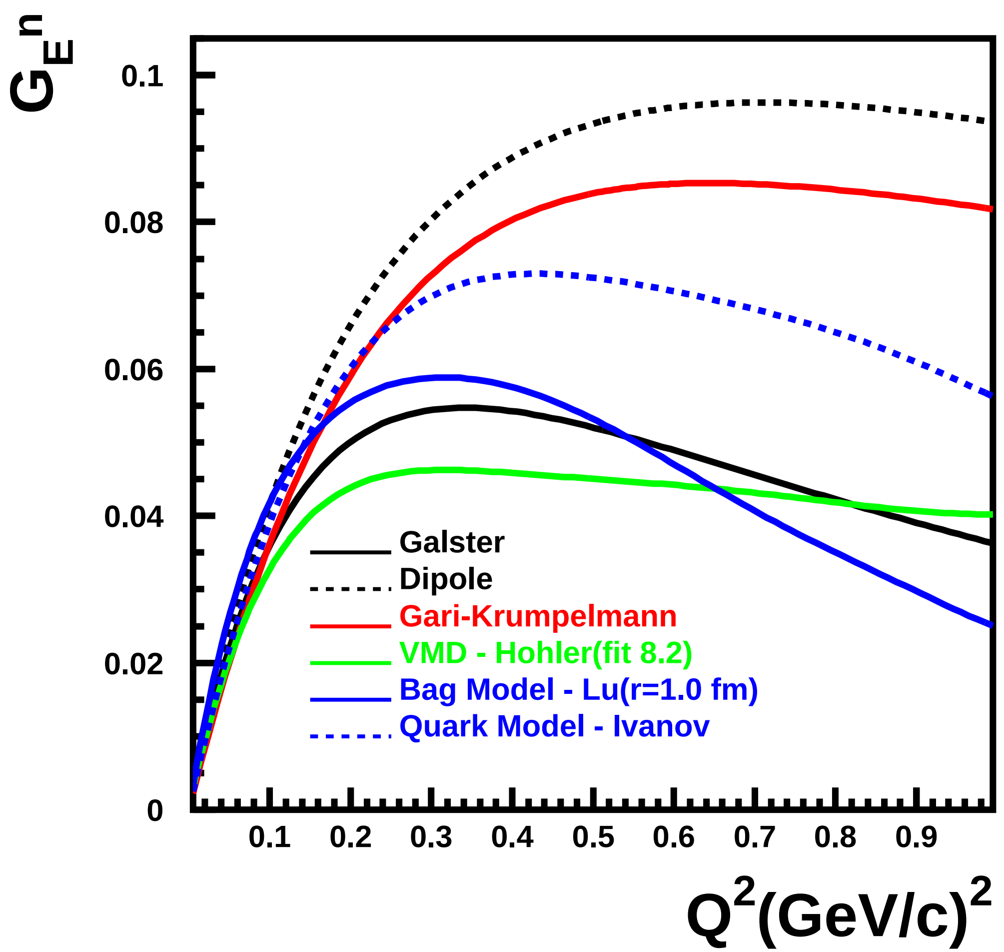
$$G_E^n = -\tau \mu_n G_D \; ; \; \tau = \frac{Q^2}{4M^2}$$

$G_D = \left(1 + \frac{Q^2}{k^2}\right)^{-2}$
implies an exponential
charge distribution:
$\rho(r) \propto e^{-kr}$

Galster Parametrization: From $e - D$ elastic scattering

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

G_E^n Models and Parametrizations



G_E^n Measurements

No free neutron target $\Longrightarrow$ Use deuteron

- Inclusive cross section measurements on Deuterium:
  - Elastic $e-D$ scattering at small angles:
    depends on N-N potential, subtraction of proton contribution
  - Quasielastic $e-D$ scattering
    Rosenbluth separation, 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
  $D(\vec{e}, e'\vec{n})p$, $\vec{D}(\vec{e}, e'n)p$, $\overrightarrow{^3He}(\vec{e}, e'n)pp$

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

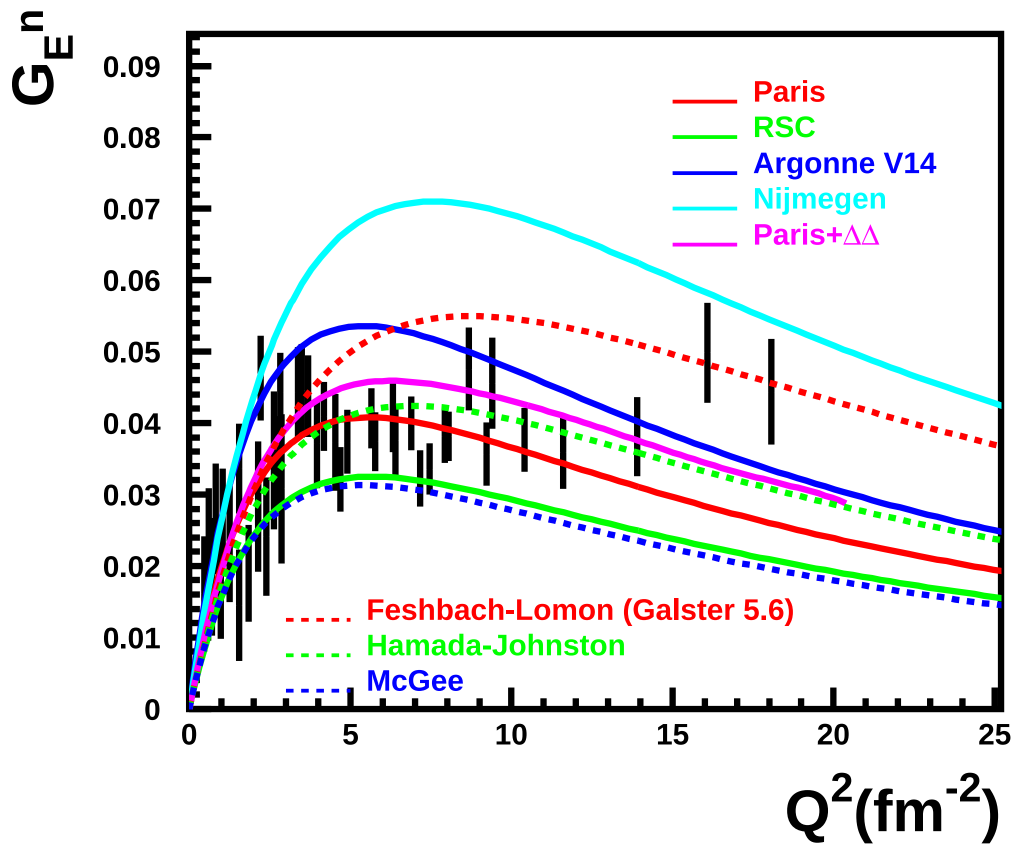
$$\sigma \propto A\left(Q^2\right) \simeq \left(G_E^p + G_E^n\right)^2 f\left[u\left(k\right), w\left(k\right)\right]$$

Extraction of G_E^n requires

→deuteron wave function $f\left[u\left(k\right), w\left(k\right)\right]$

→subtraction of proton contribution G_E^p

G_E^n from $e - D$ elastic



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.

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

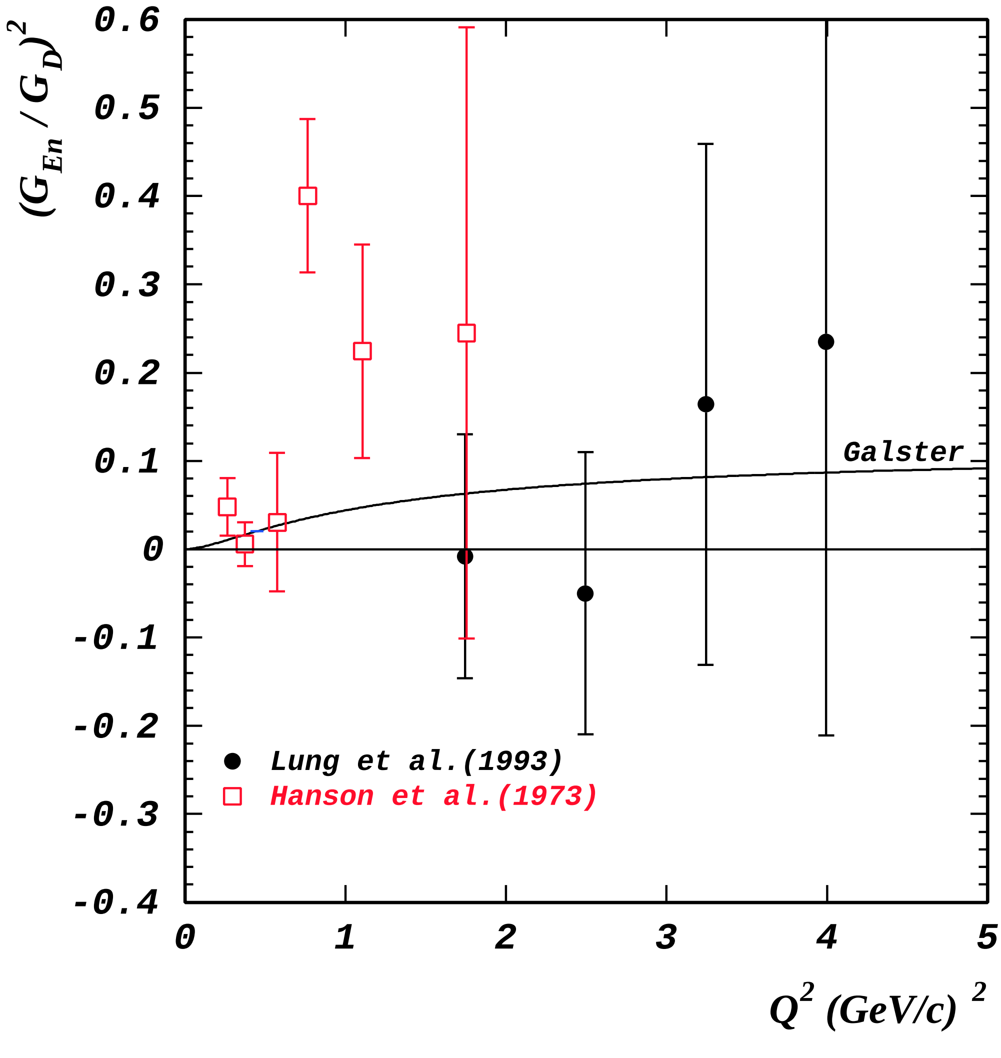
Extraction of G_E^n: Rosenbluth Separation $\Rightarrow R_L$

Subtraction of proton contribution.

Problems: Unfavorable error propagation

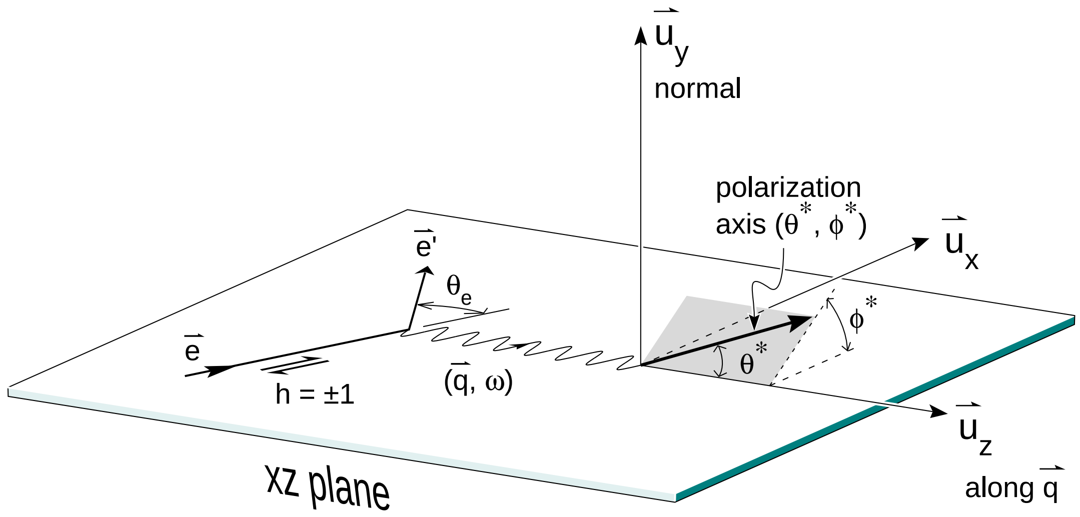
Sensitivity to deuteron structure

G_E^n from quasielastic $e - D$



SLAC: *A. Lung et al, Phys. Rev. Lett. 70, 718 (1993)*

Polarized Electron on Polarized Free Neutron



Neutron Polarization P

Beam Helicity h

Polarized Cross Section:

$\sigma = \sigma_0 \, (1 + hPA)$

$$A = \frac{a \cos \Theta^\star \, (G_M^n)^2 + b \sin \Theta^\star \cos \Phi^\star G_E^n G_M^n}{c \, (G_M^n)^2 + d \, (G_E^n)^2}$$

$$\Theta^\star = 90^\circ \quad \Phi^\star = 0^\circ \quad \Longrightarrow \quad A = \frac{b G_E^n G_M^n}{c \, (G_M^n)^2 + d \, (G_E^n)^2}$$

Polarized Electron on Polarized Deuteron Target

Polarized Cross Section for quasielastic $\vec{D}(\vec{e}, e'n)p$:

$$\sigma(h, P) = \sigma_0 \left(1 + hA + PA_d^V + TA_d^T + hPA_{ed}^V + hTA_{ed}^T\right)$$

h: Beam Helicity

P: Vector Target Polarization

T: Tensor Target Polarization $T = 2 - \sqrt{4 - 3P^2}$

Theoretical Calculations of electrodisintegration of the deuteron:

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

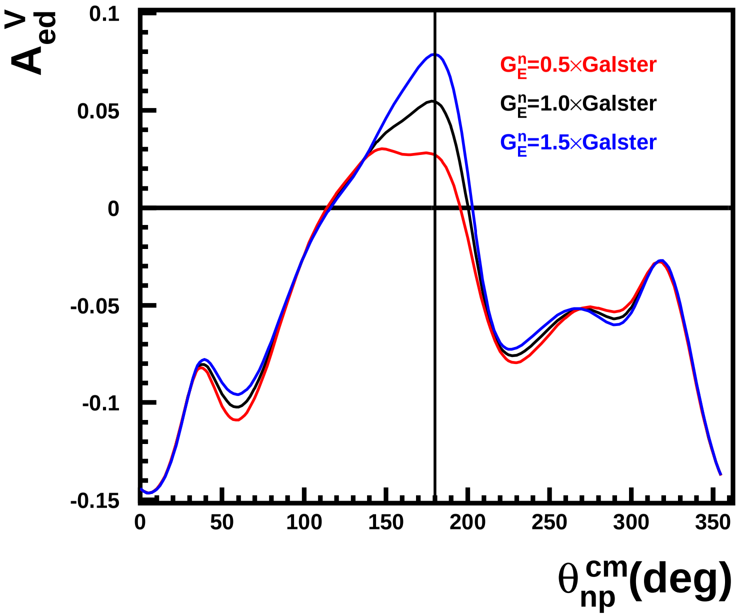
A_{ed}^V is sensitive to G_E^n

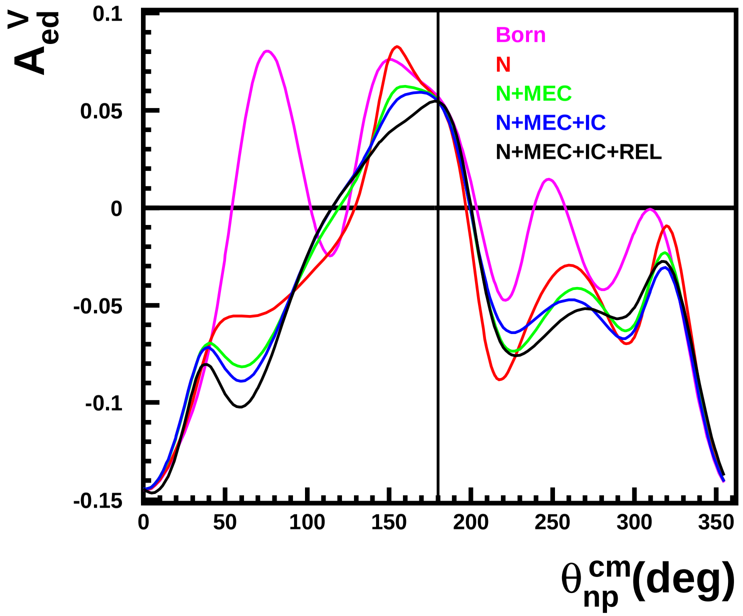
has low sensitivity to potential models

has low sensitivity to subnuclear degrees of freedom (MEC, IC)

under certain kinematical conditions

Arenhövel Calculations





$$E = 2.721 GeV \quad E' = 2.460 GeV \quad \Theta_e = 15.8^\circ \quad \Theta^\star = 90^\circ \quad \Phi^\star = 0^\circ$$

Θ_{np}^{cm}: Angle between $\overrightarrow{q}$ and relative n-p momentum in cm system

180 deg corresponds to neutron in direction of $\overrightarrow{q}$

Experimental Technique for $\overrightarrow{D}(\overrightarrow{e}, e'n)p$

How to access A_{ed}^{V}?

Experiment measures counts for different orientations of h and P:

$$N^{hP} \propto \sigma\,(h, P)$$

Beam-target Asymmetry:

$$\begin{aligned} A_{BT} &= \frac{N^{++} - N^{-+} + N^{--} - N^{+-}}{N^{++} + N^{-+} + N^{++} + N^{++}} \\ &= \frac{hPA_{ed}^{V}}{1 + TA_{d}^{T}} \\ &\simeq hPA_{ed}^{V} \end{aligned}$$

EXPERIMENT E93026

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

E93026 Collaboration

112 collaborators from 18 institutions

University of Virginia, USA:
Hongguo Zhu, Chris Harris
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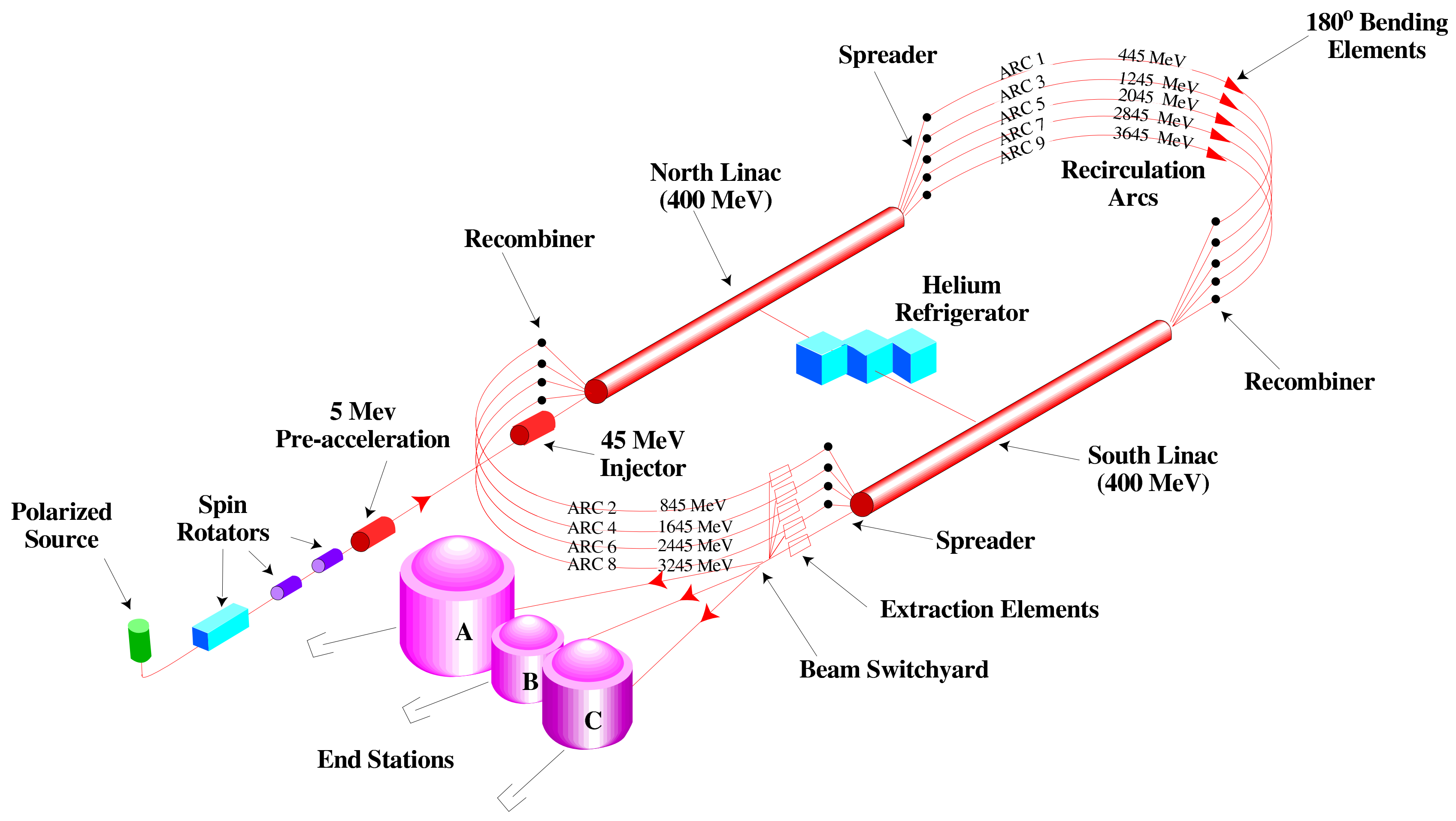
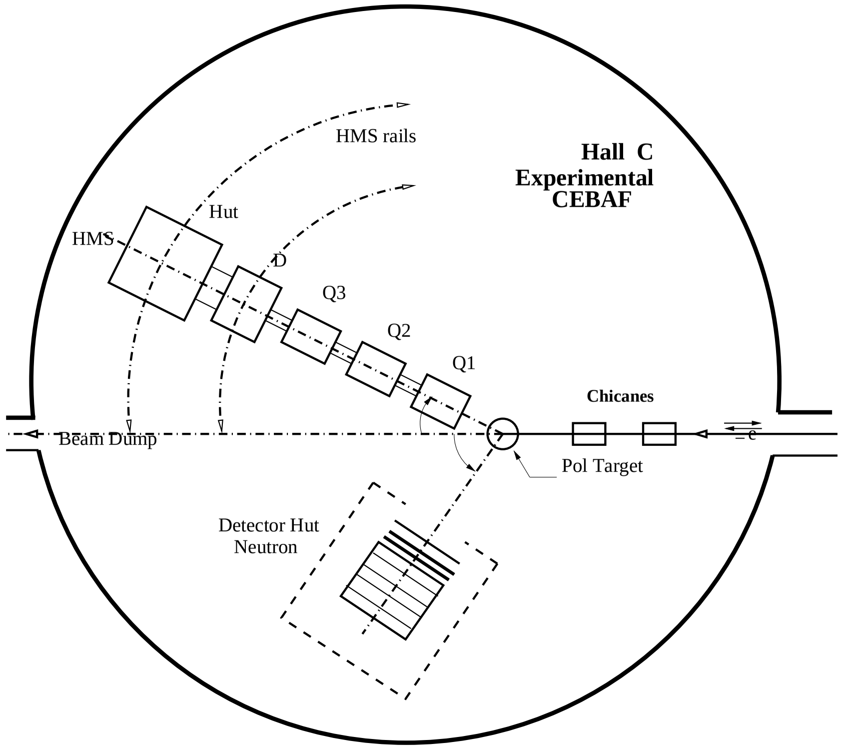
Florida International University, USA
Luminita Coman
University of Maryland, USA
Nikolai Savvinov
Duke University, USA
Hampton University, USA
Jefferson Laboratory, USA
Louisiana Tech University, USA

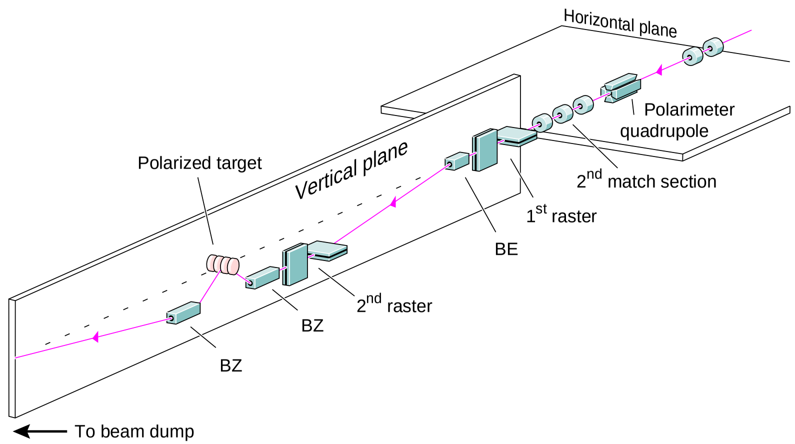
Mississippi State University, USA
North Carolina A&T St. Univ., USA
Vrije Universiteit, Netherlands
Norfolk State University, USA
Old Dominion University, USA
Ohio University, USA
South. Univ. at New Orleans, USA
Tel Aviv University, Israel
Virginia Polytechnic Institute, USA
Yerevan Physics Institute, Armenia

Accelerator

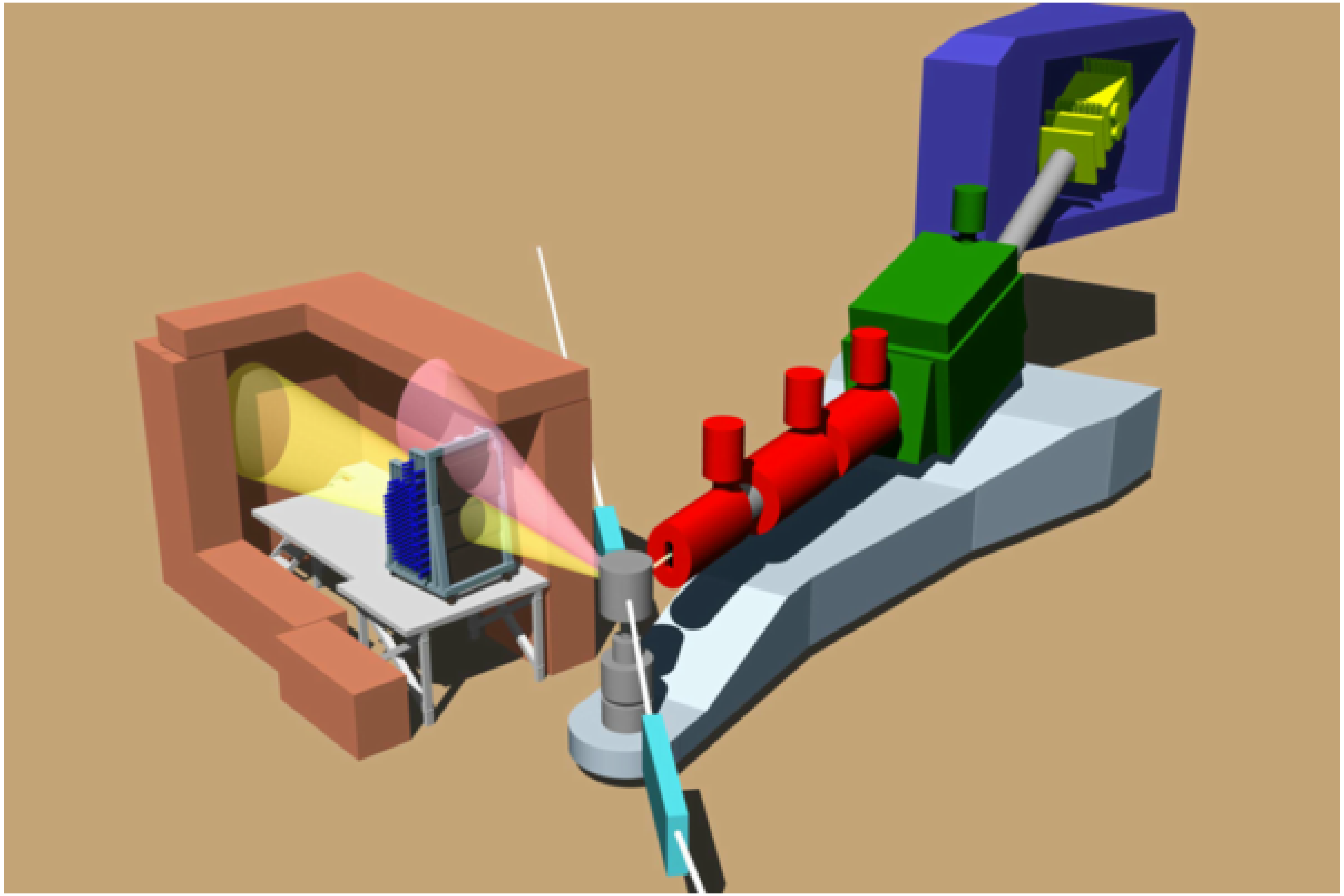


Setup in Hall C



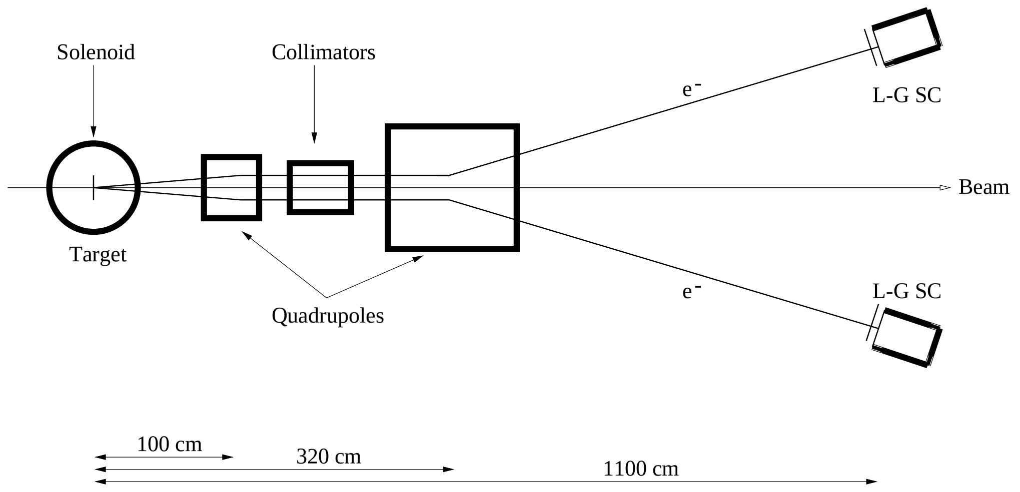


Setup in Hall C



Moller Polarimeter

Polarized electron-electron scattering (moller scattering)



Beam & 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

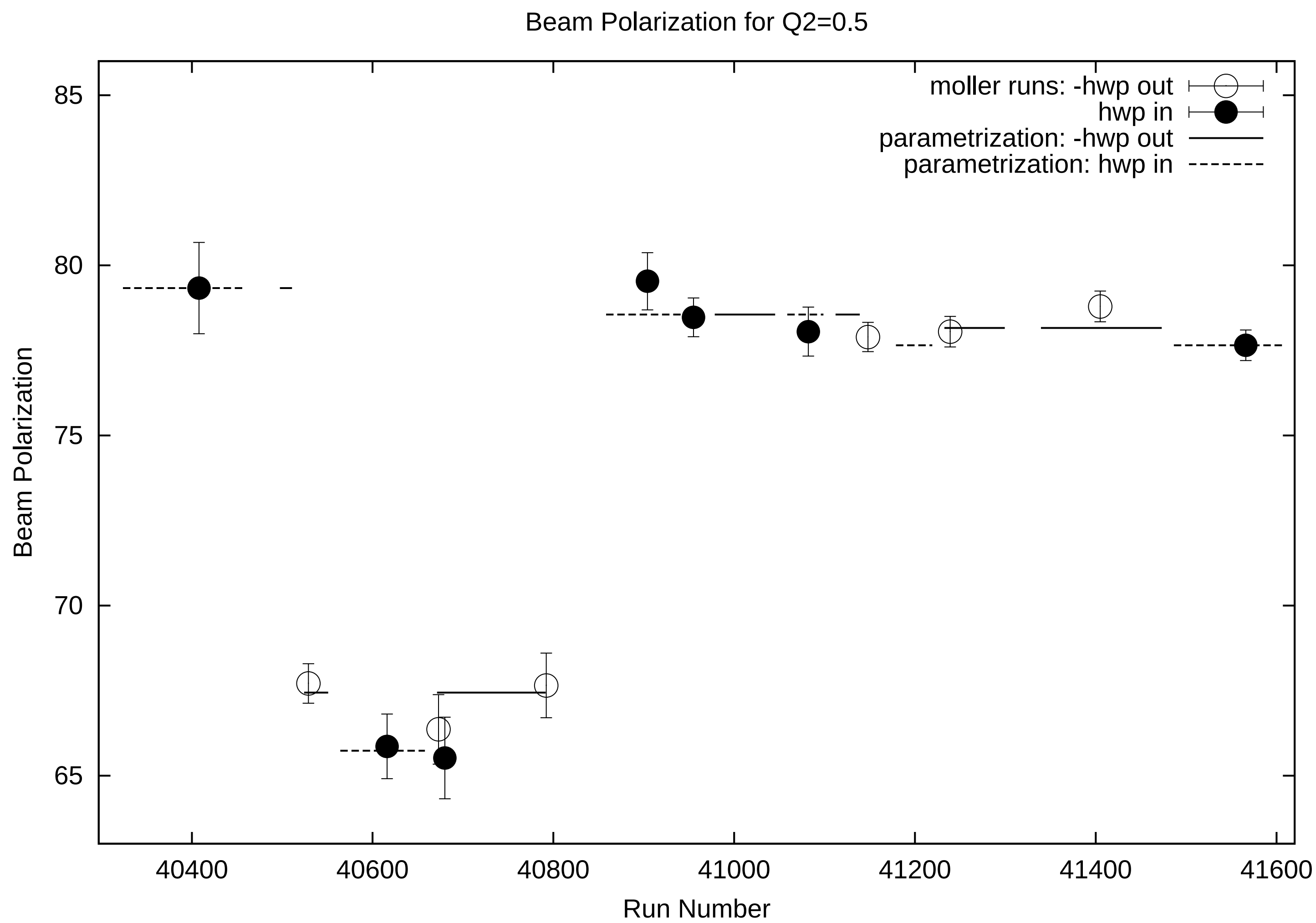
P_z^T: Target Polarization

Target (Fe foil) polarized to saturation normal to foil plane

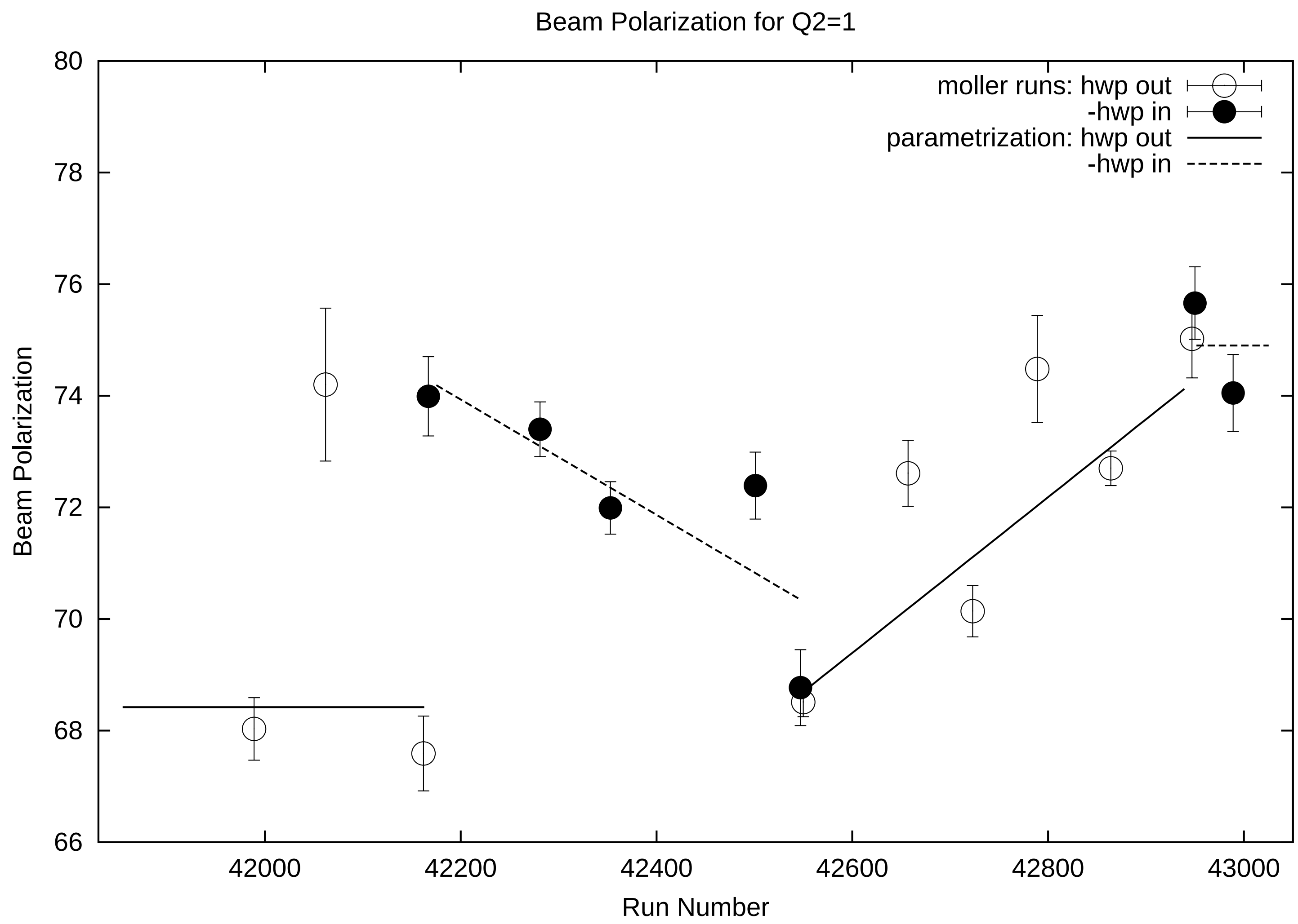
Coincidence Measurement to suppress Mott background

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

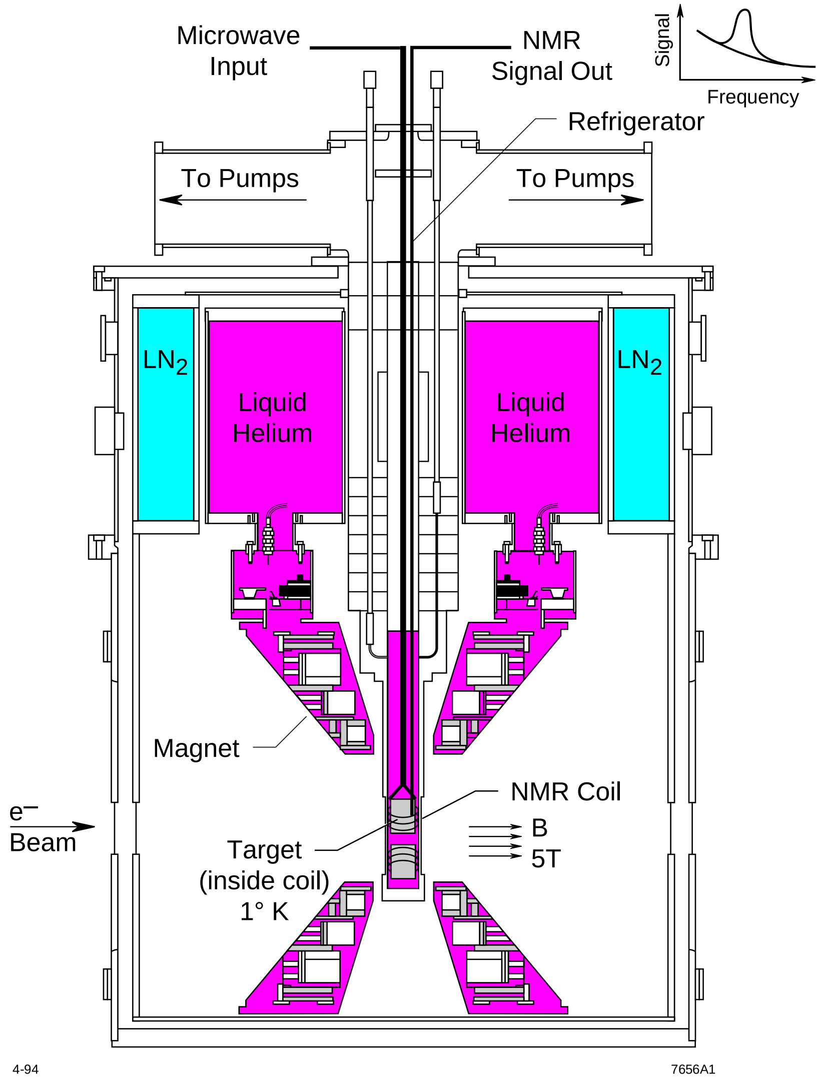
2001 Beam polarization for $Q^2 = 0.5(GeV/c)^2$



2001 Beam polarization for $Q^2 = 1(GeV/c)^2$



Polarized Target



Target material:

$^{15}ND_3$ (doped by irradiation)

Polarization: 25% average

Dynamic Nuclear Polarization

5 Tesla field

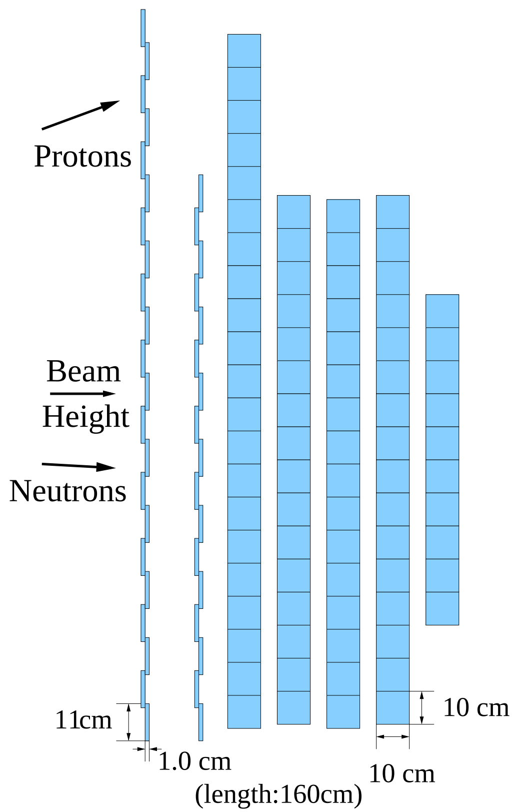
^{4}He evaporation system $\rightarrow$ 1 K

Polarization Measurement:

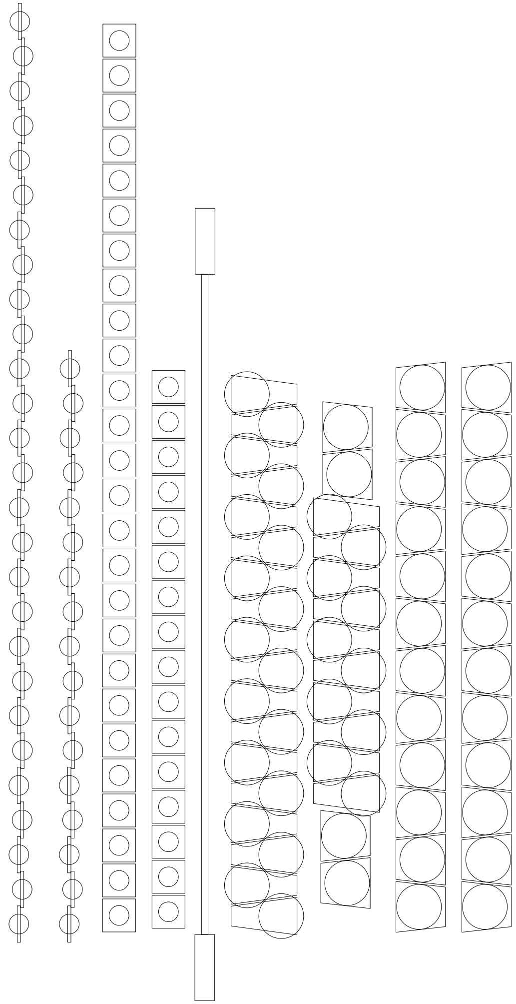
NMR readout

Neutron Detector

1998



2001



Neutron Detector

Offline Analysis Overview

Detector Calibrations: for HMS and NDET

Event Reconstruction: Standard HMS reconstruction + target magnet
NDET tracking: Particle Identification

Event Selection and Normalization: $\longrightarrow$ Normalized yields

Radiative corrections, Accidental background subtraction

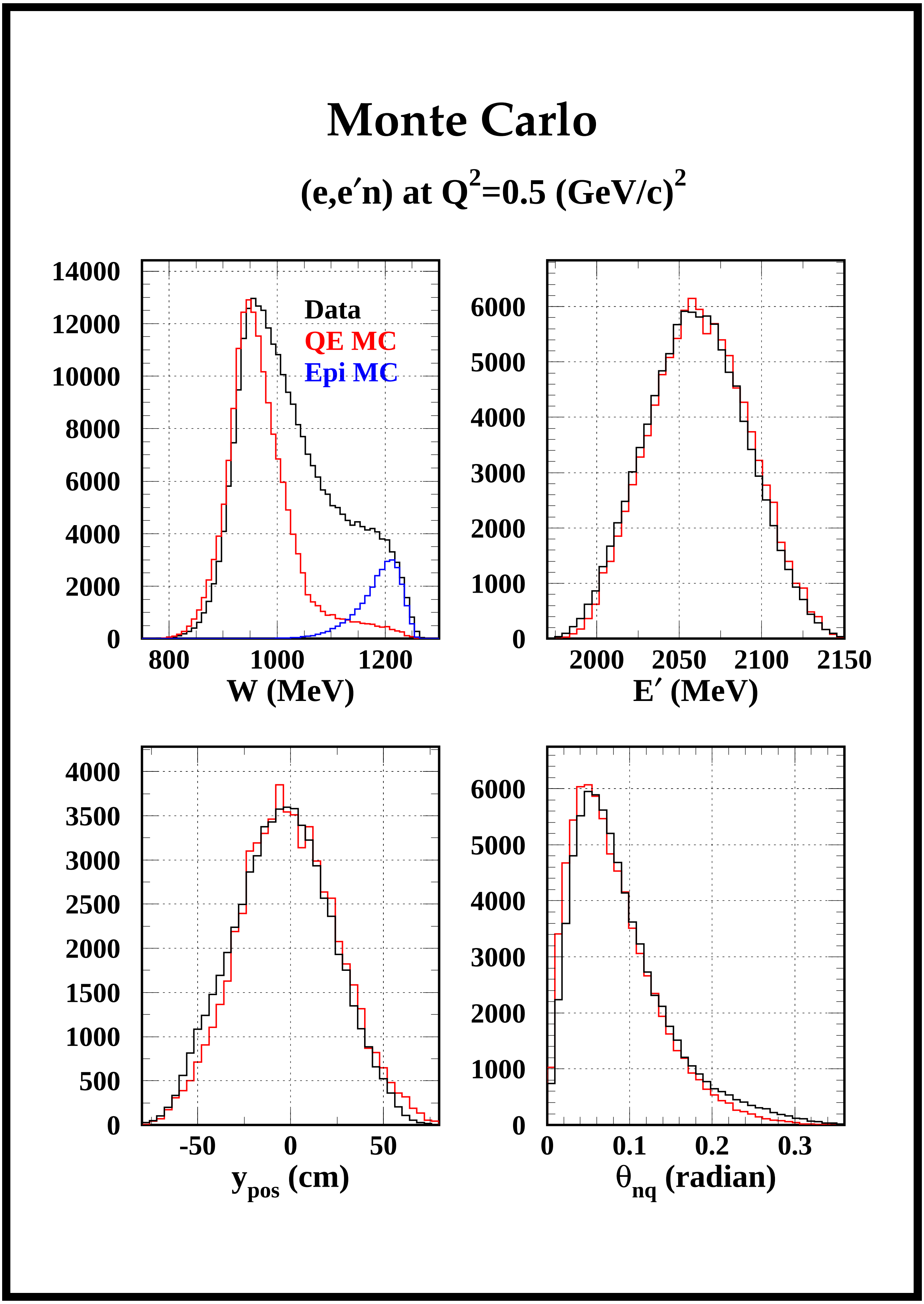
$\Rightarrow$ Experimental asymmetries: $A_{BT} = P_B \cdot P_T \cdot f \cdot A_{ed}^V \Rightarrow \left(A_{ed}^V\right)_{meas}$

Dilution factor $f = \frac{N_{polarized}}{N}$ from ^{12}C data and simulation

Order $\left(A_{ed}^V\right)_{theo}$ from Arenhövel for a kinematical grid

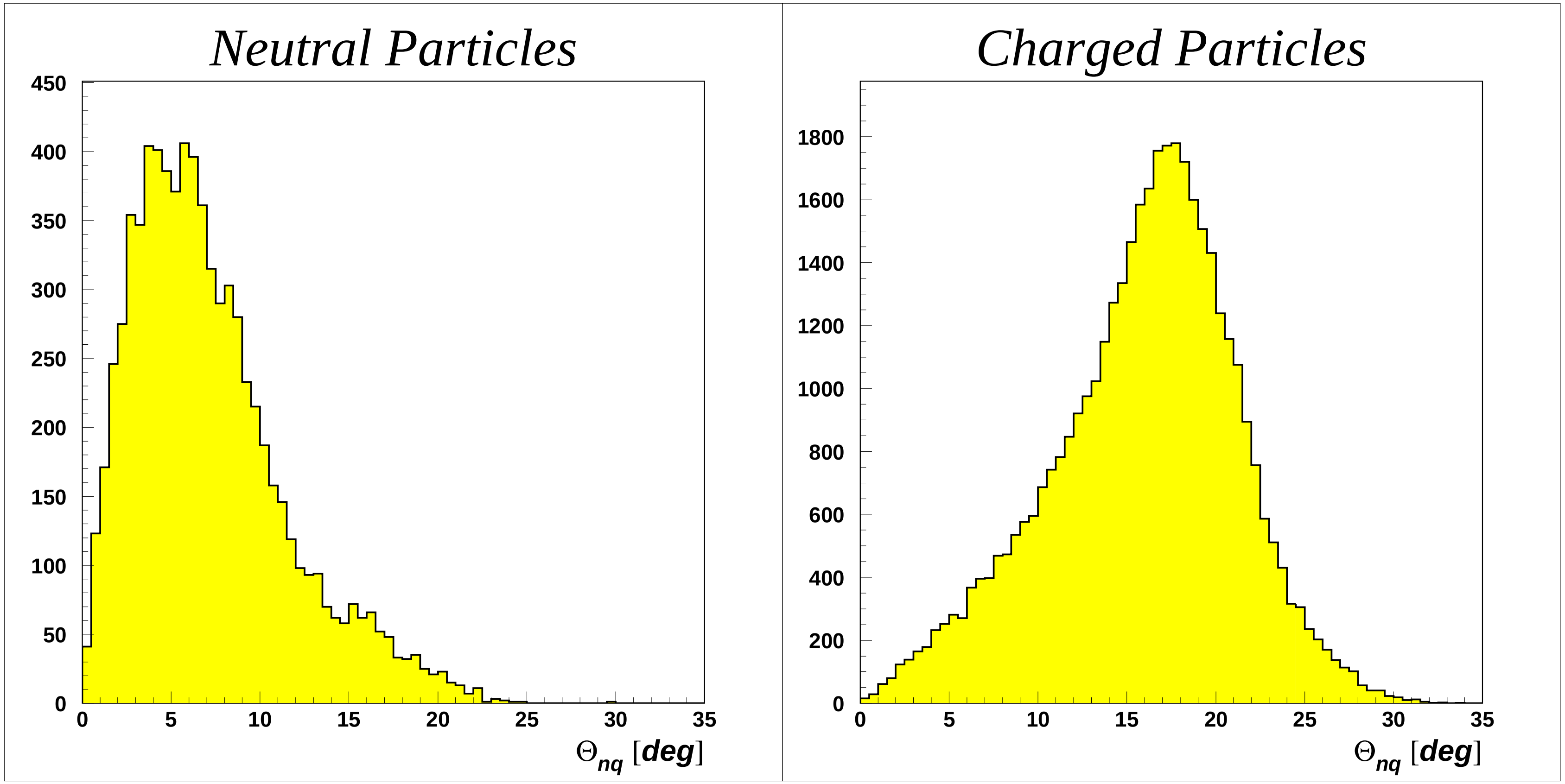
Average $\left(A_{ed}^V\right)_{theo}$ over exp. acceptance and compare with $\left(A_{ed}^V\right)_{meas}$

$\Rightarrow G_E^n$



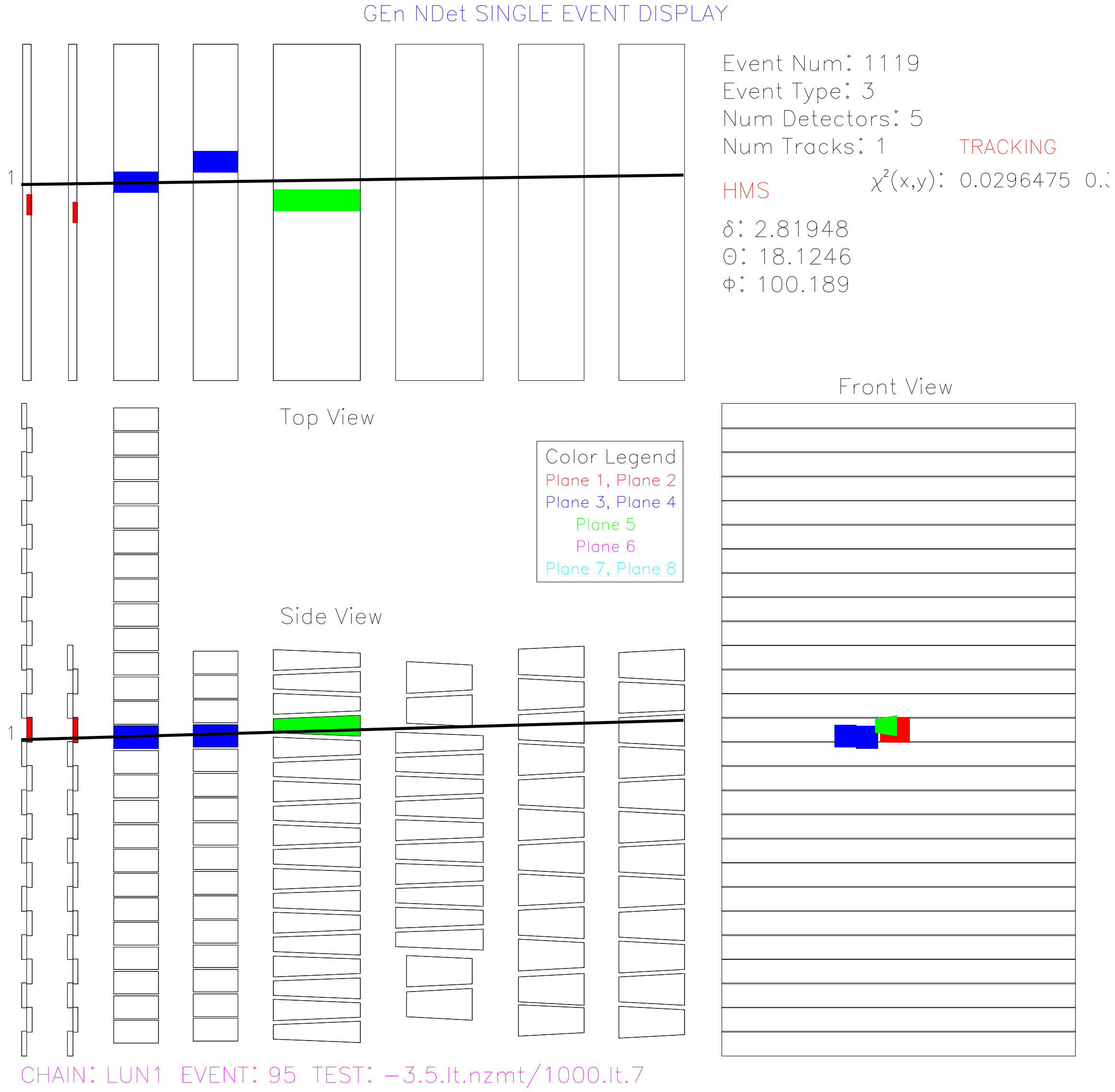
Monte Carlo
(e,e′n) at Q2=0.5 (GeV/c)2
Data
QE MC
Epi MC
W (MeV)
E′ (MeV)
ypos (cm)
θnq (radian)

Proton deflection



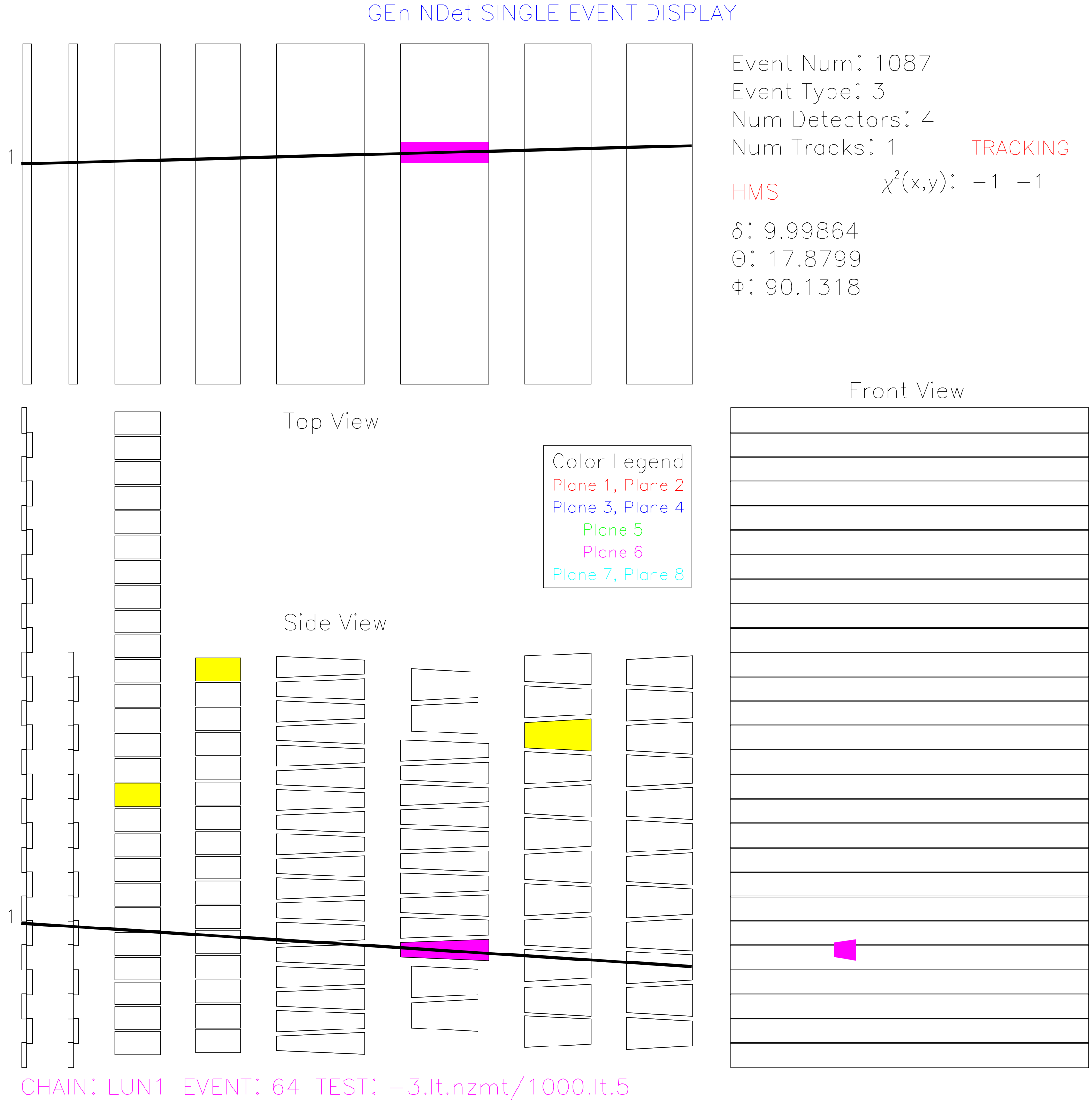
Cut in θ_{nq} allows suppression of protons.

Tracking



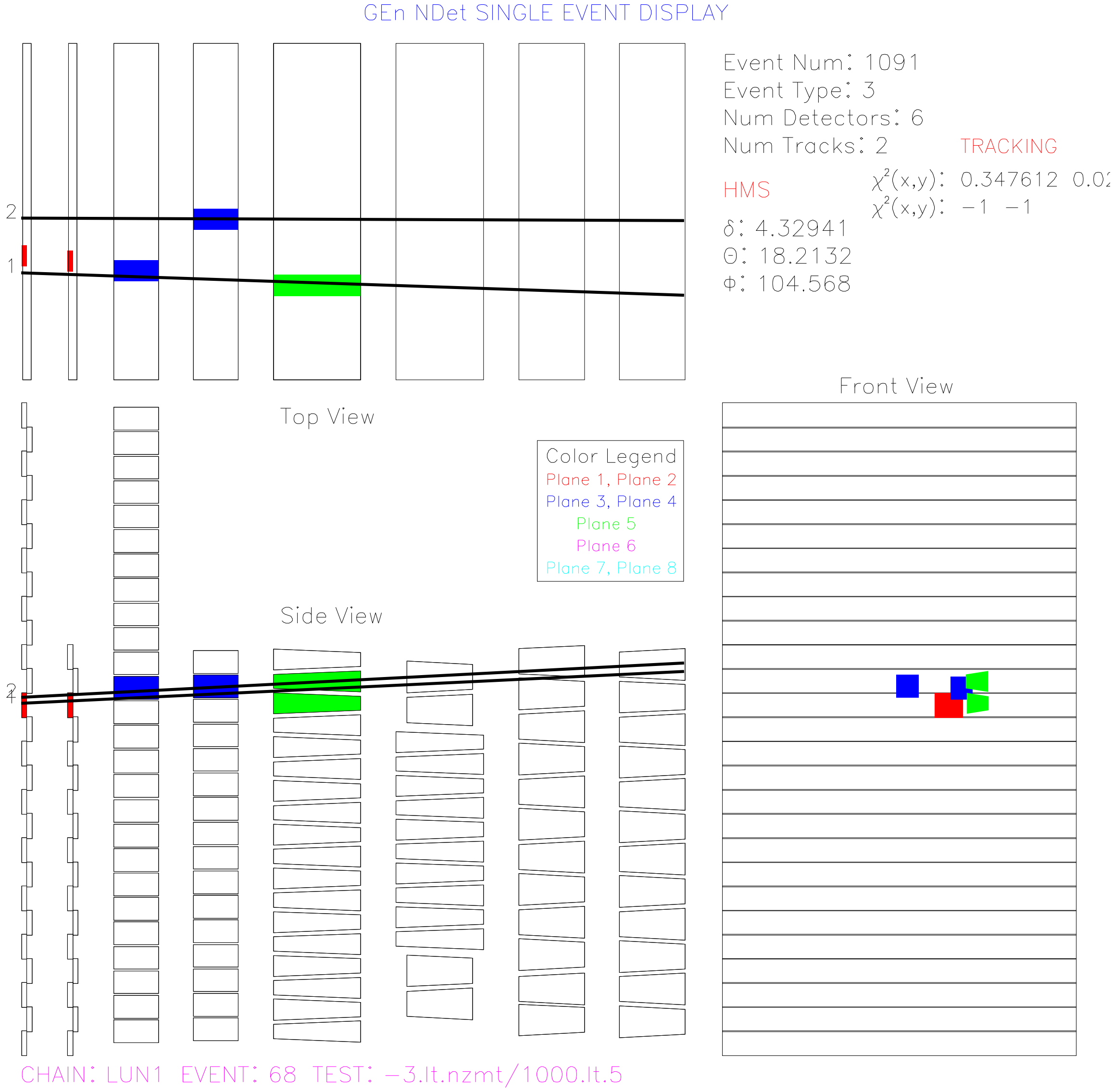
Proton track

Tracking



Neutron track

Tracking

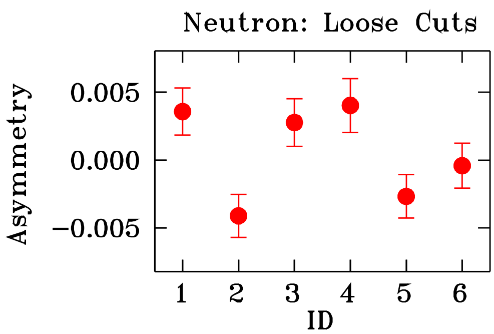


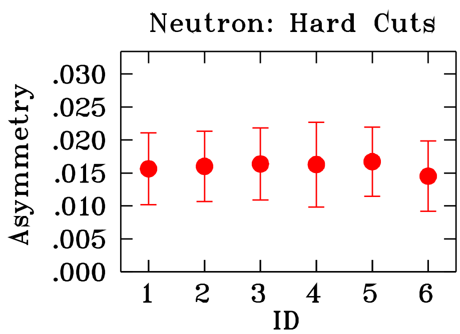
Bad double track

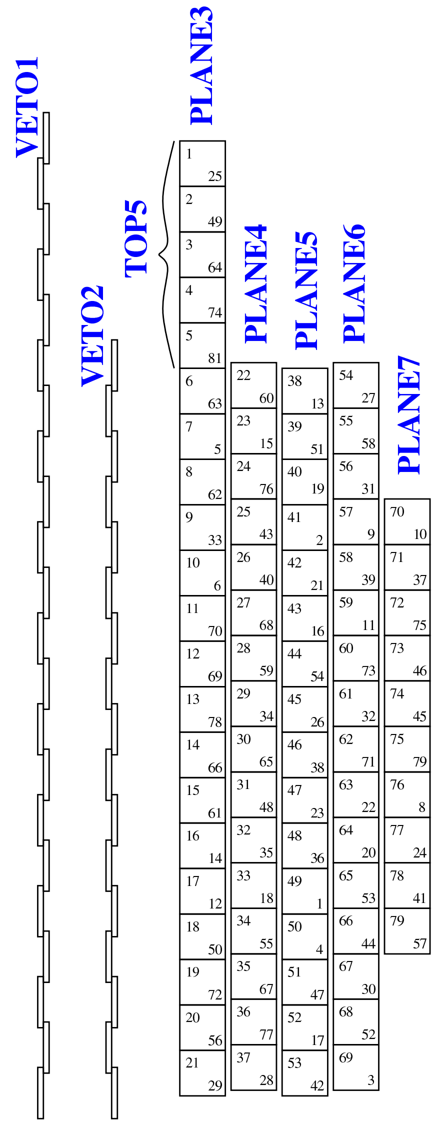
NEUTRON IDENTIFICATION

Definitions:

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

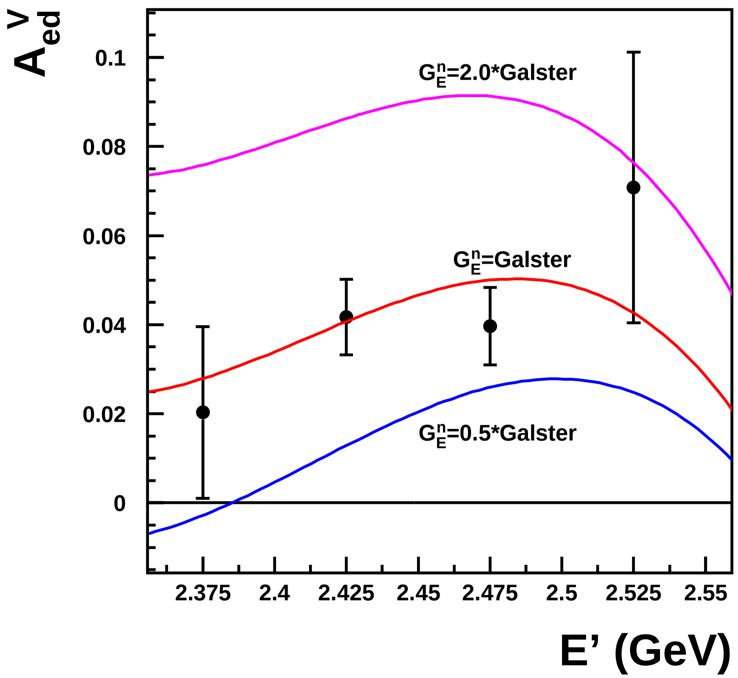






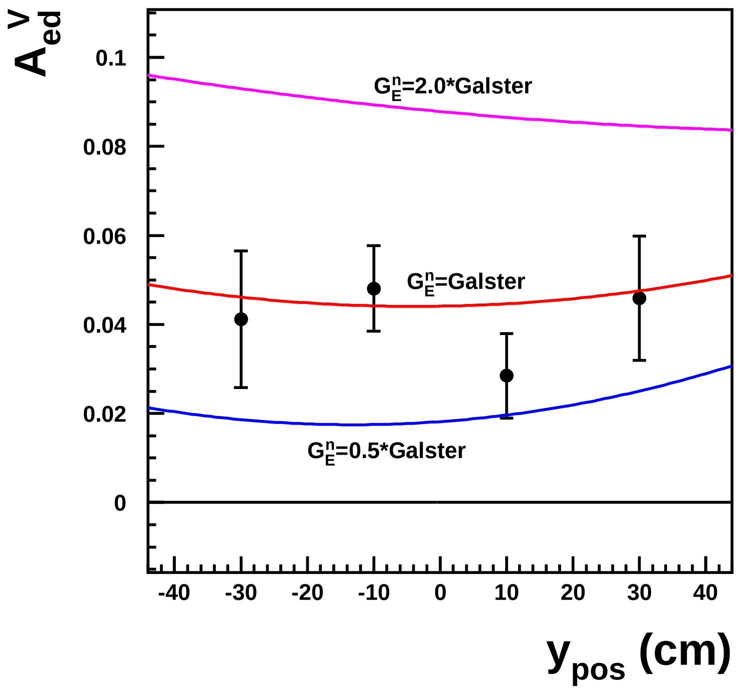
Extracting G_E^n

E': Energy of the scattered electron



Fit: $G_E^n = (0.91 \pm 0.13) \cdot Galster$

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

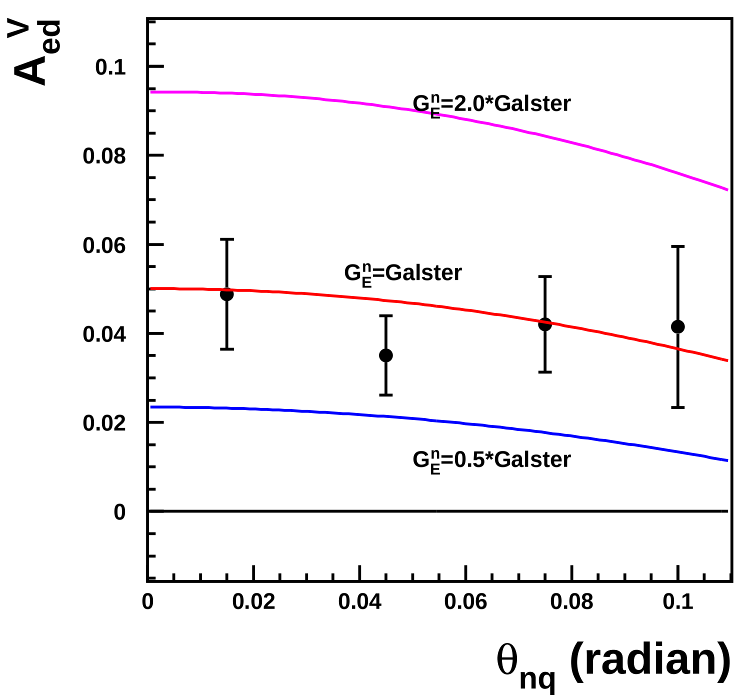


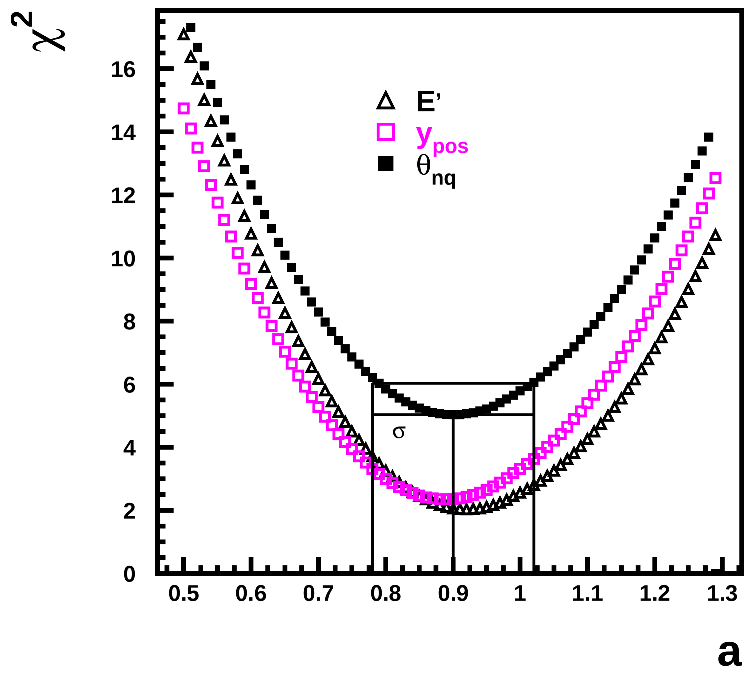
Fit: $G_E^n = (0.89 \pm 0.12) \cdot Galster$

Extracting G_E^n

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

χ^2 minimization





Fit: $G_E^n = (0.90 \pm 0.12) \cdot Galster$

$G_E^n = a \cdot Galster$

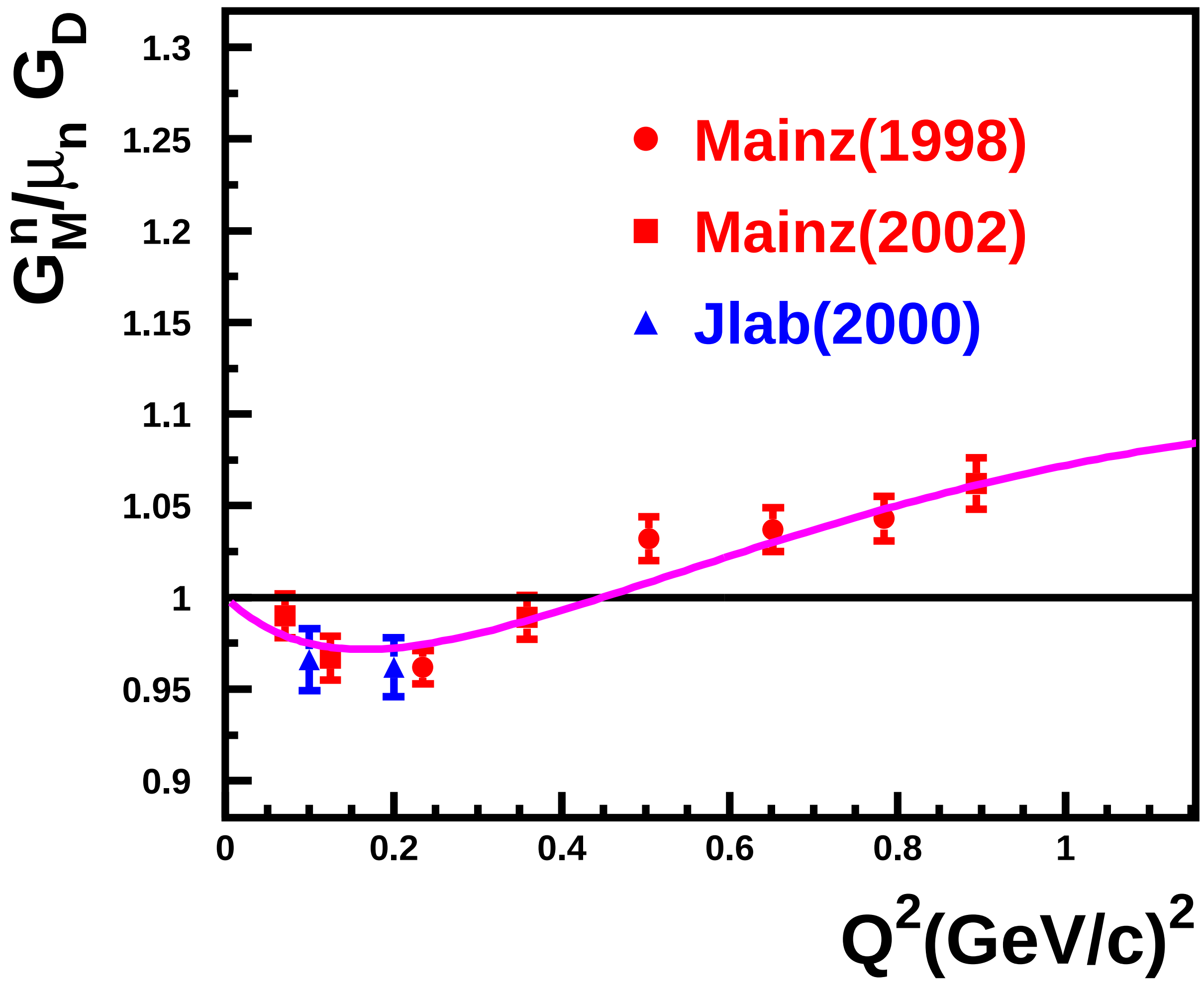
RESULTS

Final (98)*	$Q^2 = 0.5\,(GeV/c)^2$	$G_E^n = 0.04632 \pm 0.0070$
Preliminary (2001)	$Q^2 = 0.5\,(GeV/c)^2$	$G_E^n = xxx \pm xxx$
Preliminary (2001)	$Q^2 = 1.0\,(GeV/c)^2$	$G_E^n = xxx \pm xxx$

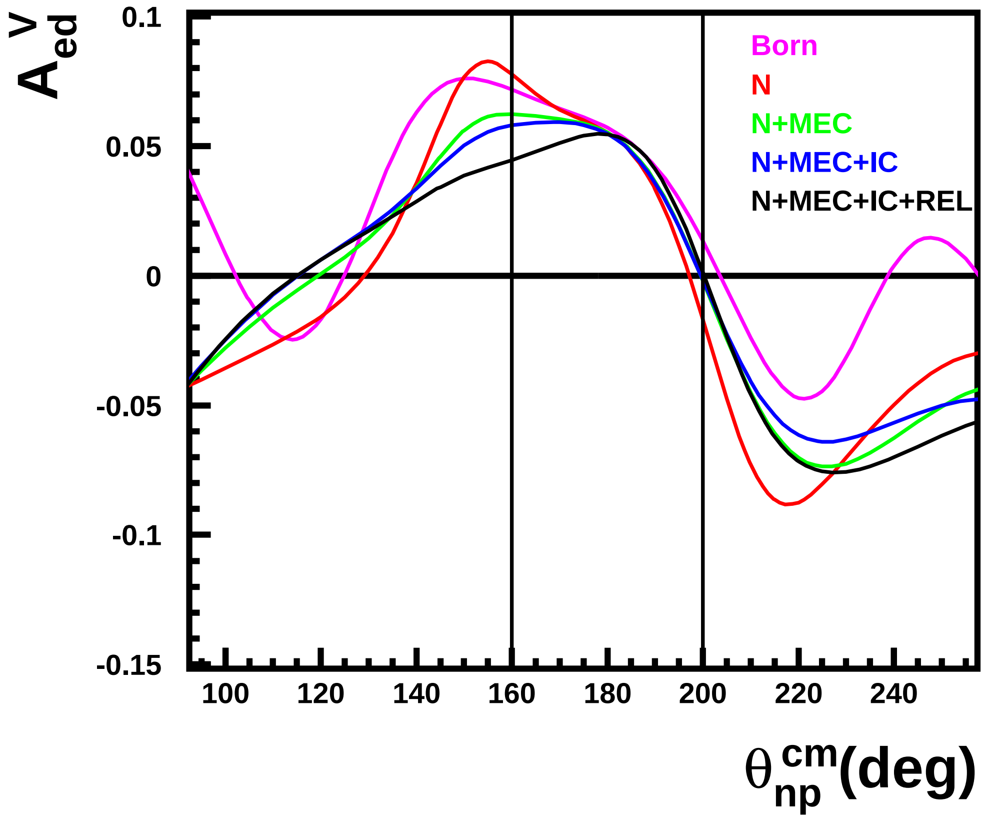
* *PRL 87 (2001) 081801*

Systematics	98	01 (predicted)
Target Polarization	5.8%	3-5%
Dilution Factor	3.9%	3%
Cut Dependence	2.4%	2%
Kinematics	2.2%	2%
G_M^n	1.7%	1.7%
Beam Polarization	1.0%	1-3%
Other	1.0%	1%
Sum	8.0%	6-8%

Status of G_M^n



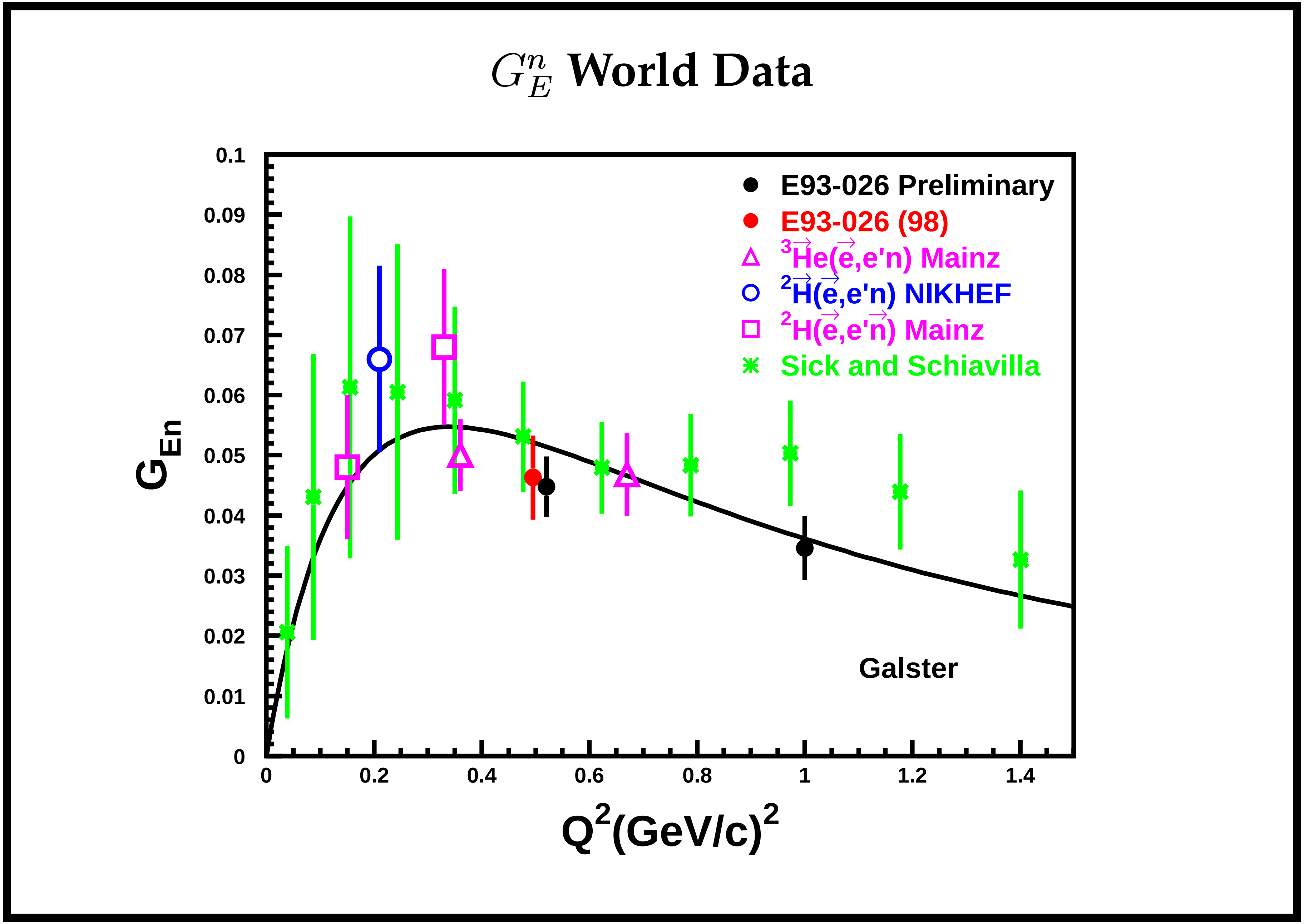
Reaction Mechanism Dependence



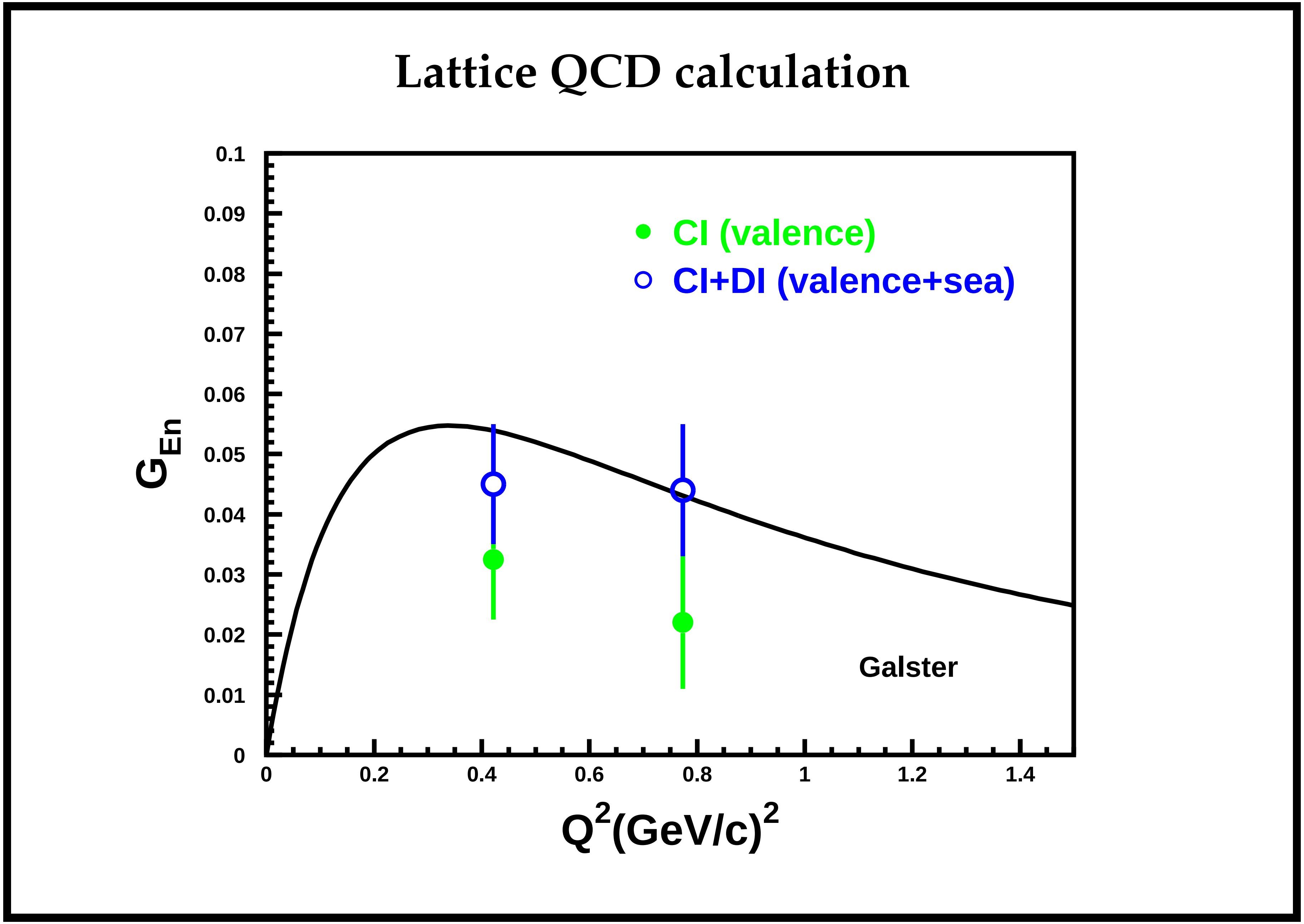
Experimental acceptance:

$160^\circ < \theta_{np}^{cm} < 180^\circ$

14% Difference between full Calculation and Born

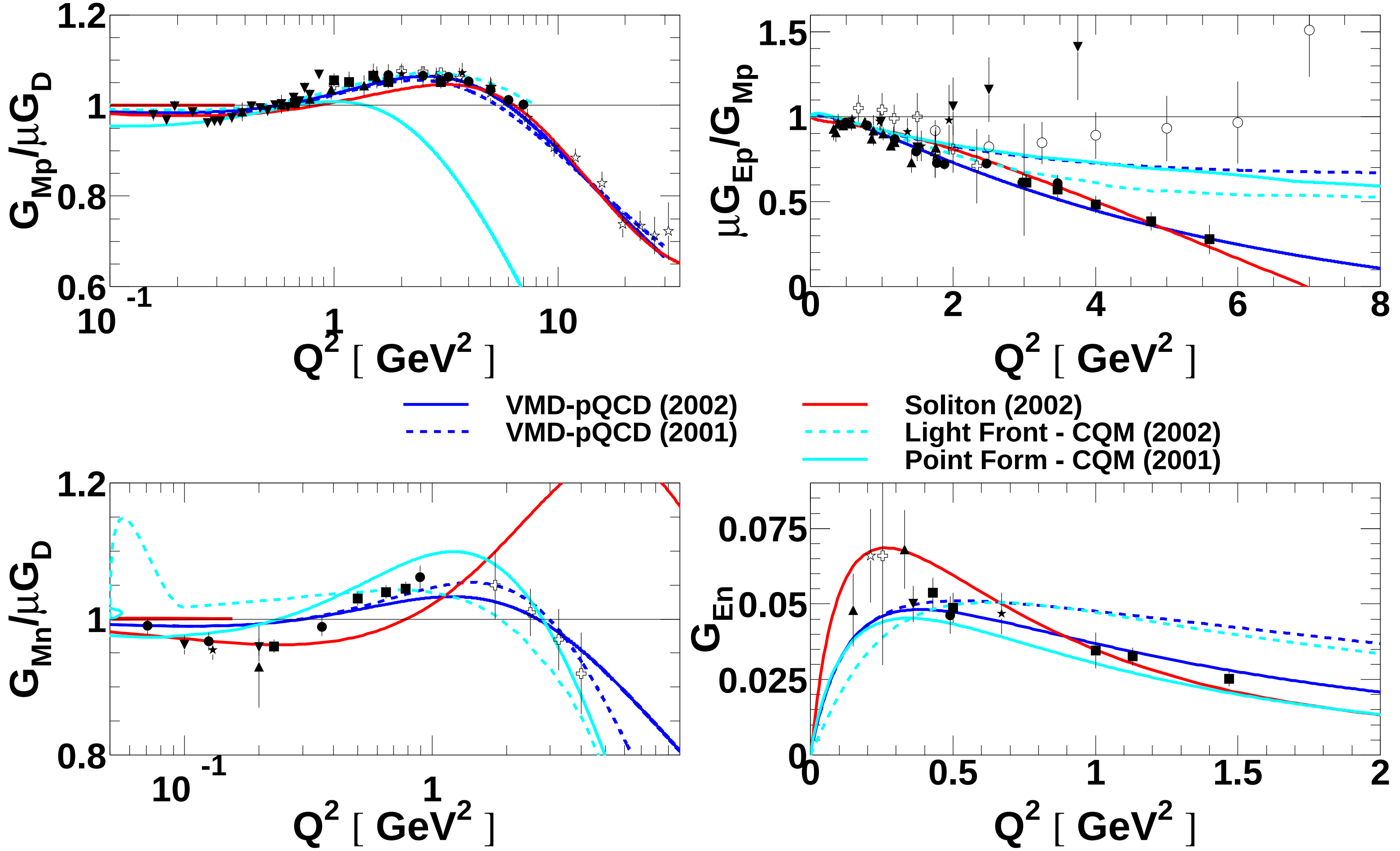


G_E^n World Data
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
G_{En}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
$Q^2 (GeV/c)^2$
E93-026 Preliminary
E93-026 (98)
$^3\vec{He}(\vec{e},e'n)$ Mainz
$^2\vec{H}(\vec{e},e'n)$ NIKHEF
$^2H(\vec{e},e'\vec{n})$ Mainz
Sick and Schiavilla
Galster



Lattice QCD calculation
CI (valence)
CI+DI (valence+sea)
Galster
G_{En}
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
$Q^2(GeV/c)^2$

Nucleon Form Factors and Models



G_E^n Outlook

- Under analysis:
  - Jlab E93026 $\vec{D}(\vec{e}, e'n)p$, $Q^2 = 0.5, 1.0\,(GeV/c)^2$
  - Jlab $D(\vec{e}, e'\vec{n})p$, $Q^2 = 0.45, 1.1, 1.45\,(GeV/c)^2$
- To be completed this summer:
  - Mainz $D(\vec{e}, e'\vec{n})p$, $Q^2 = 0.6, 0.8\,(GeV/c)^2$
- Future measurements:
  - Jlab $\overrightarrow{^3He}(\vec{e}, e'n)pp$, up to $Q^2 = 3.2\,(GeV/c)^2$
  - Bates $\vec{D}(\vec{e}, e'n)p$ and $\overrightarrow{^3He}(\vec{e}, e'n)pp$ up to $Q^2 = 1.0\,(GeV/c)^2$