The Neutron Electric Form Factor at Q^2 up to 7 $(GeV/c)^2$ from the Reaction $^2H(\vec{e},e'\vec{n})^1H$ via Recoil Polarimetry

PR-09-006 Jefferson Lab PAC 34

Spokespersons

B.D. Anderson (Kent State University)

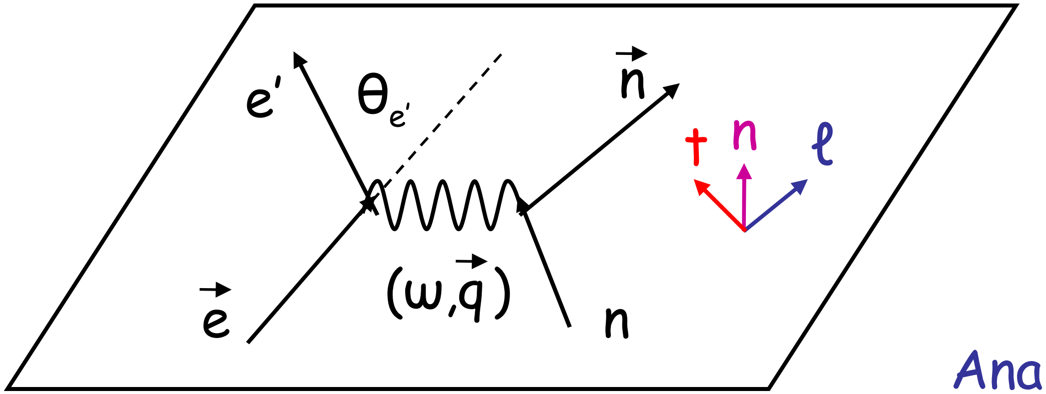
J. Arrington (Argonne National Lab)
S. Kowalski (MIT)
R. Madey (Kent State University)
B. Plaster (University of Kentucky)
A. Semenov (University of Regina)

History & Overview

- ✘ E04-110 approved by PAC 26 to measure the neutron electric form factor G_{EN} at Q^2 = 4.3 (GeV/c)^2 via recoil polarimetry from the quasielastic $^2H(\vec{e},e'\vec{n})^1H$ reaction
- ✘ Jeopardy resubmission of E04-110 to PAC 33 was deferred with regret because it could not be fit into the schedule with the 6 GeV beam
- ✘ Here we propose G_{EN} measurements at Q^2 = 3.95, 5.22, and 6.88 (GeV/c)^2 ; with 10, 15, and 30 days of the beam time (accordingly), the projected uncertainties are about $\Delta G_{EN} = 0.002$
  - ✔ Provide continuity with E93-038 results (recoil polarimetry from deuteron up to Q^2 = 1.45 (GeV/c)^2; ~2.5% systematics [achieved])
  - ✔ Cross-check with recent (unpublished) E02-013 results (polarized ^{3}He target asymmetries at Q^2 = 1.3, 2.4, and 3.4 (GeV/c)^2; ~10% systematics [declared in E02-013 proposal])

Recoil polarimetry technique

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



electron scattering plane

Recoil polarization

$$P_t = -P_e K_t G_{En} G_{Mn}$$

$$P_\ell = P_e K_\ell G_{Mn}^2$$

Analyzed by second scattering in polarimeter with analyzing power A_y

Ratio Technique: Measure both P_t and P_ℓ

$$\frac{P_t}{P_\ell} = -\frac{K_t}{K_\ell}\frac{G_{En}}{G_{Mn}} \longrightarrow$$

small systematics

A_y and P_e cancel

→

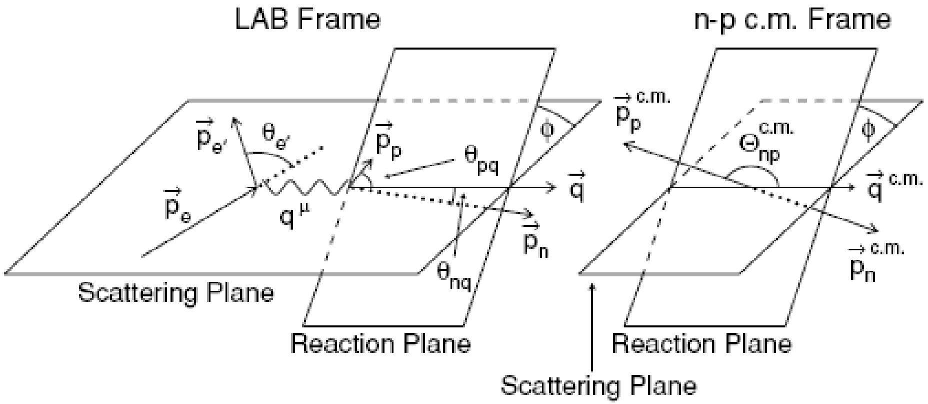
determines sign of G_{En}/G_{Mn}

Quasielastic $^2H(\vec{e},e'\vec{n})^1H$ reaction

Arenhövel (1987): For quasifree emission in $^2H(\vec{e},e'\vec{n})^1H$

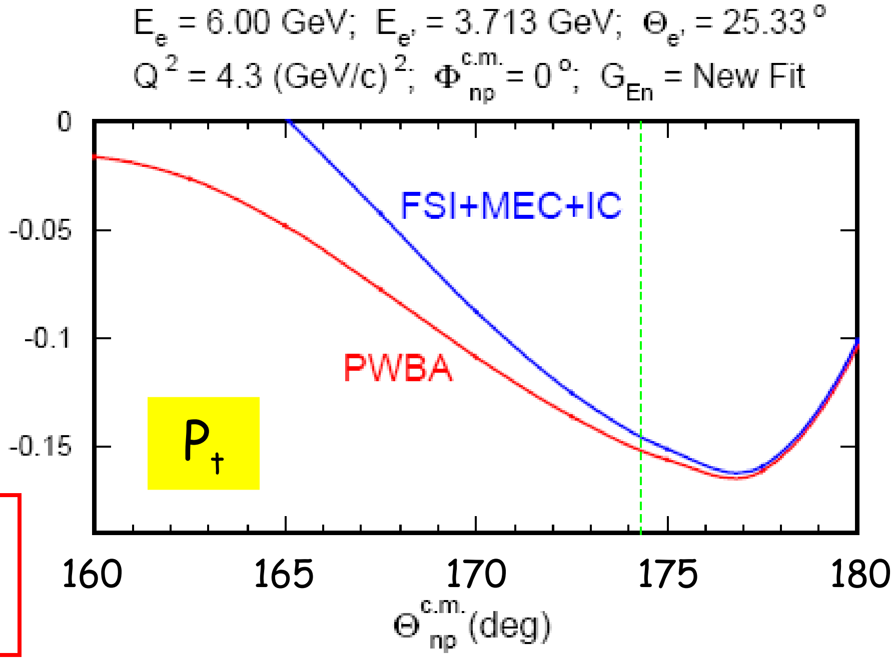
P_t proportional to G_{En} [as in $n(\vec{e},e'\vec{n})$]

Insensitive to FSI, MEC, IC, and choice of NN potential for deuteron wavefunction

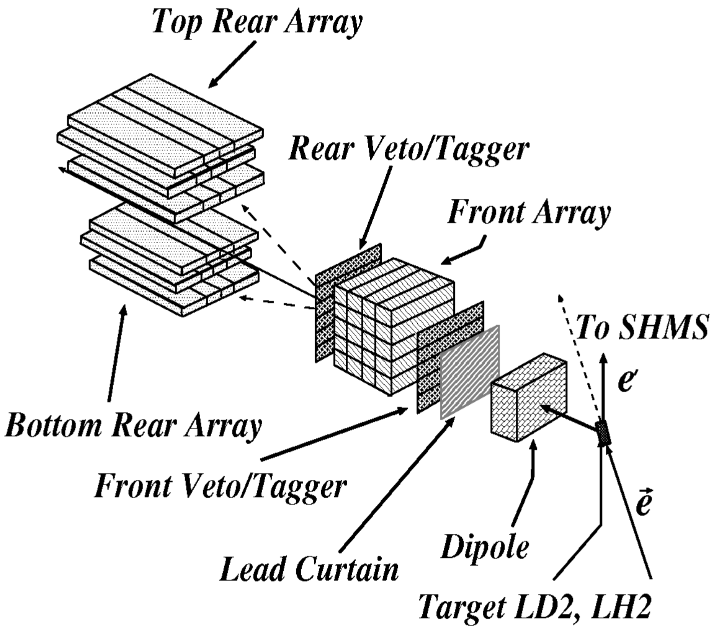


$(\Theta_{np})^{c.m.} = 180°$

perfect quasifree neutron emission



Overview of experiment: NPOL



Primary NPOL components

Front Array: analyzer via spin-dependent n-p scattering

Top/Bottom Rear Array: up-down scattering asymmetry ξ via cross-ratio technique (beam charge asymmetry and NPOL geometrical asymmetry cancel in the ratio)

Pb curtain: attenuates EM radiation

Dipole Magnet: spin precession; deflects charged particles from polarimeter

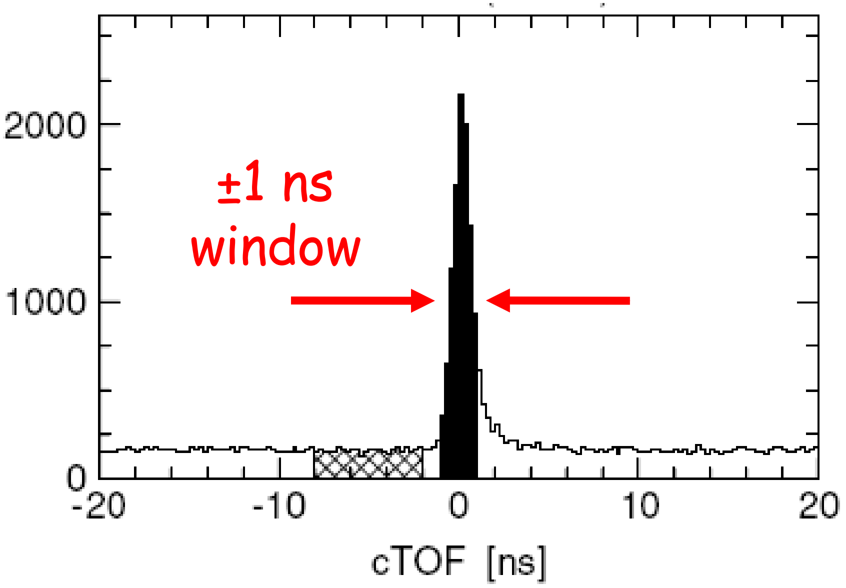
Dipole field permits access to both P_t and P_ℓ →

$$\xi(\chi) = A_y\left[P_t \cos\chi + P_\ell \sin\chi\right]$$

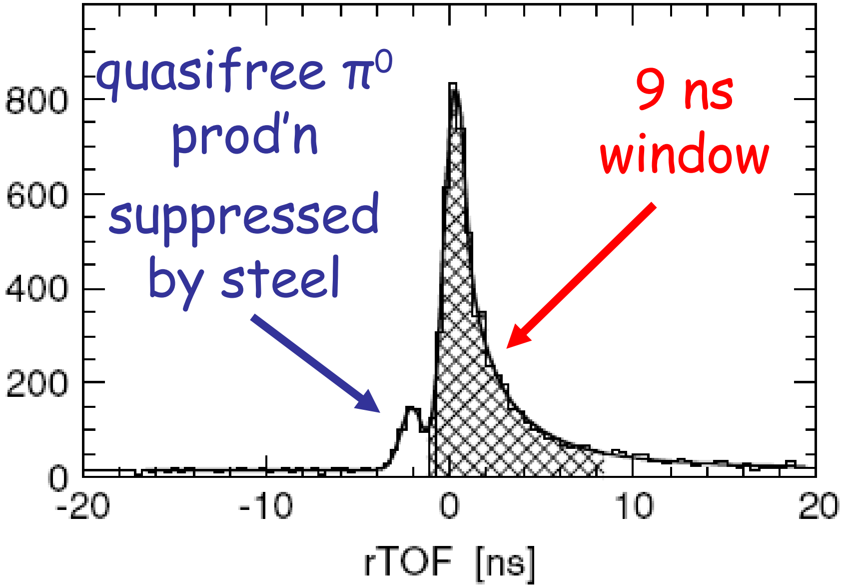
χ = spin precession angle

E93-038 TOF spectra

HMS-NPOL Coincidence



NPOL Front-to-Rear



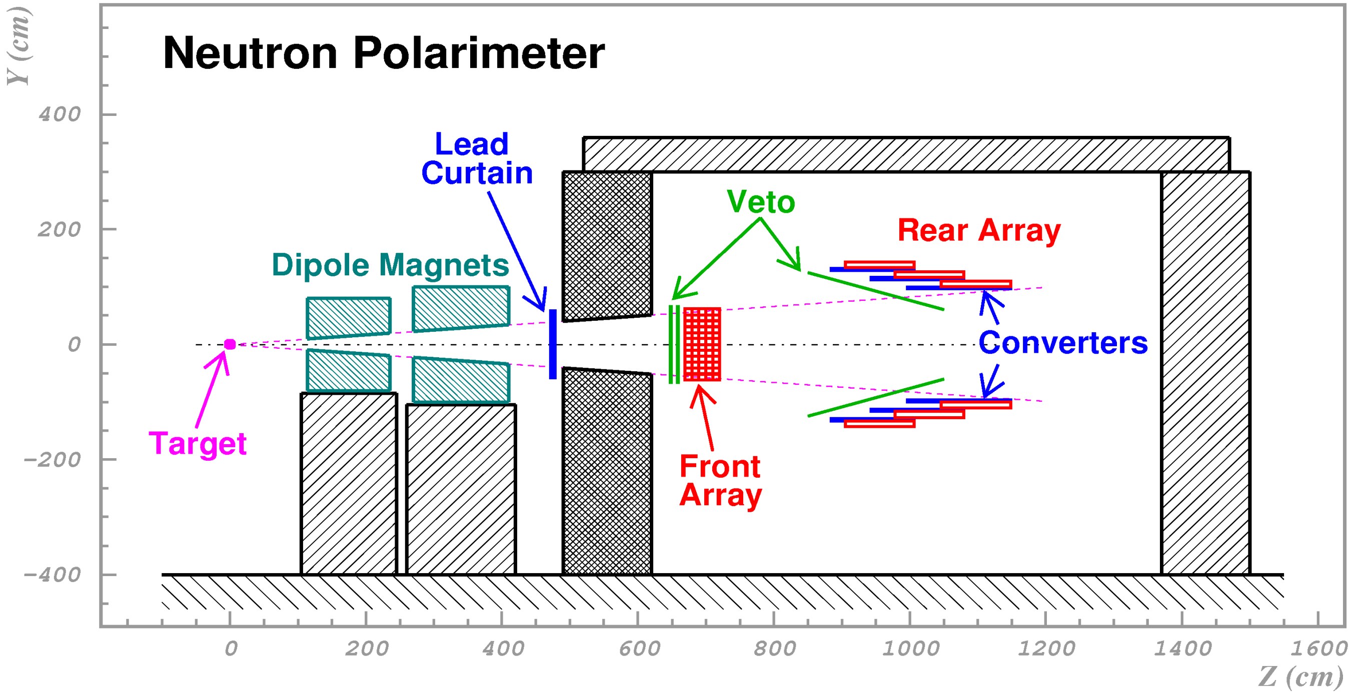
Extraction of asymmetry

Cross-Ratio
(or "Super-Ratio")

$$r=\sqrt{\frac{N_U^+ N_D^-}{N_D^+ N_U^-}} \longrightarrow \xi=\frac{r-1}{r+1}$$

Note big ratio of real events to accidental background!

Enhanced PR-09-006 NPOL



Increased vertical acceptance

Larger front array (60 vs 20 bars): Better matched to SHMS acceptance

Increased NPOL efficiency + suppression of γ's

3-cm-thick steel converters ahead of each layer in rear array

Increased dipole magnetic field

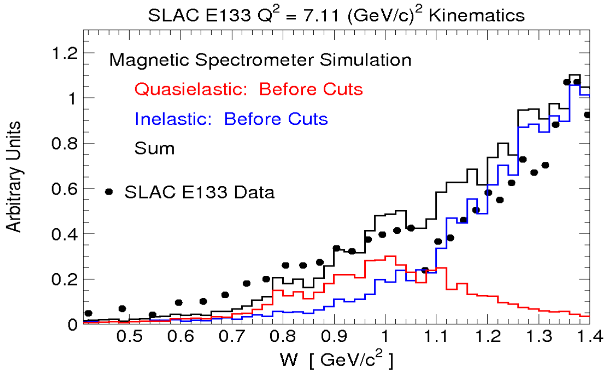
deflects charged particles from the polarimeter

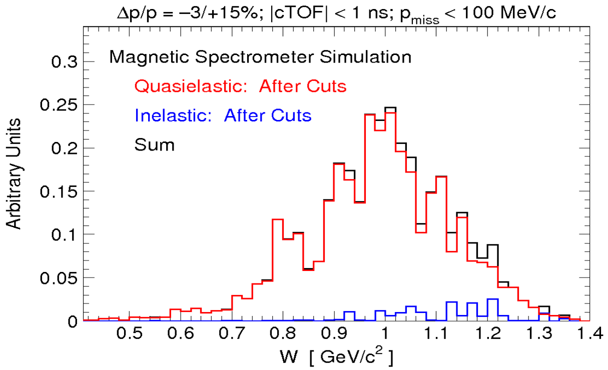
Kinematics

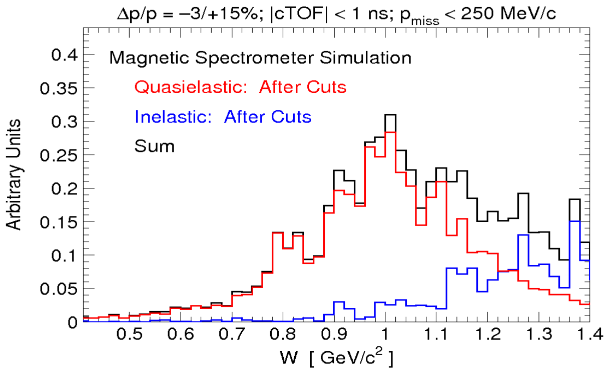
Four-Momentum Transfer, Q^2 $(\mathrm{GeV}/c)^2$	3.95	5.22	6.88
Beam Energy, E_0 (GeV)	4.4	6.6	11.0
Electron Scattering Angle, θ_e (deg)	36.53	26.31	16.79
Scattered Electron Momentum, P_e' (GeV/c)	2.288	3.815	7.330
Neutron Scattering Angle, θ_n (deg)	28.0	28.0	28.0
Neutron Momentum, P_n (GeV/c)	2.901	3.602	4.511

We gave up the point of the original proposal at $Q^2 = 2.18$ $(\mathrm{GeV}/c)^2$ because the required electron scattering angle of 58.6 deg is unavailable with SHMS, and the upgraded HMS can not be used because NPOL shielding hut can not be fit on Hall C floor plan in that case; the beam time request was decreased by 6 days accordingly.

Quasielastic events selection







Simulations with GENGEN

✔ Quasielastic and inelastic invariant mass spectra normalized to SLAC NE-11 [similar kinematics at Q^2=4 $(GeV/c)^2$] and SLAC E133 [Q^2=7 $(GeV/c)^2$]

✔ Cuts on: Missing momentum
Scattered electron momentum bite
NPOL-SHMS coincidence TOF

✔ At Q^2 = 7 $(GeV/c)^2$, inelastic contamination is only 3% (8%) with 100 MeV/c (250 MeV/c) p_{miss} cut

Note: $\vec{p}_{miss}$ calculated solely from $(\omega,\vec{q})$ and θ_{nq} [no TOF]

Estimation of Analyzing Power

No direct data exist

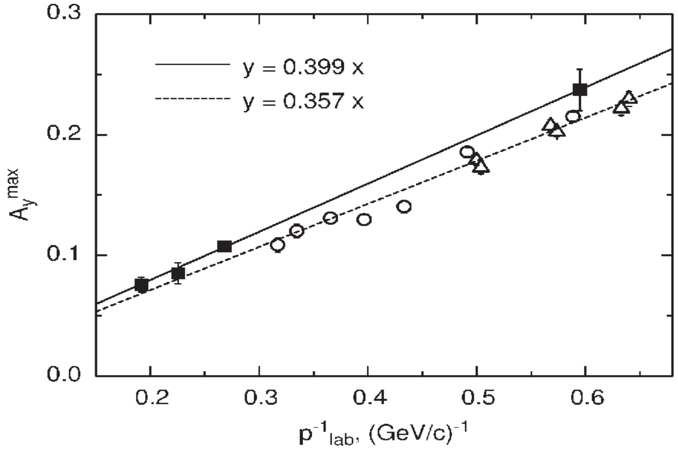


Fig. 5. Momentum dependence of CH_2- and C-data. Solid squares—current data, open circles— Ref. [4], open triangles—Ref. [5]. Solid line—fit of CH_2-data, dashed line—fit of C-data.

From Jlab E93-038:

A_y = 14.4% for P_n (lab)= 1.45 GeV/c

Scale according to

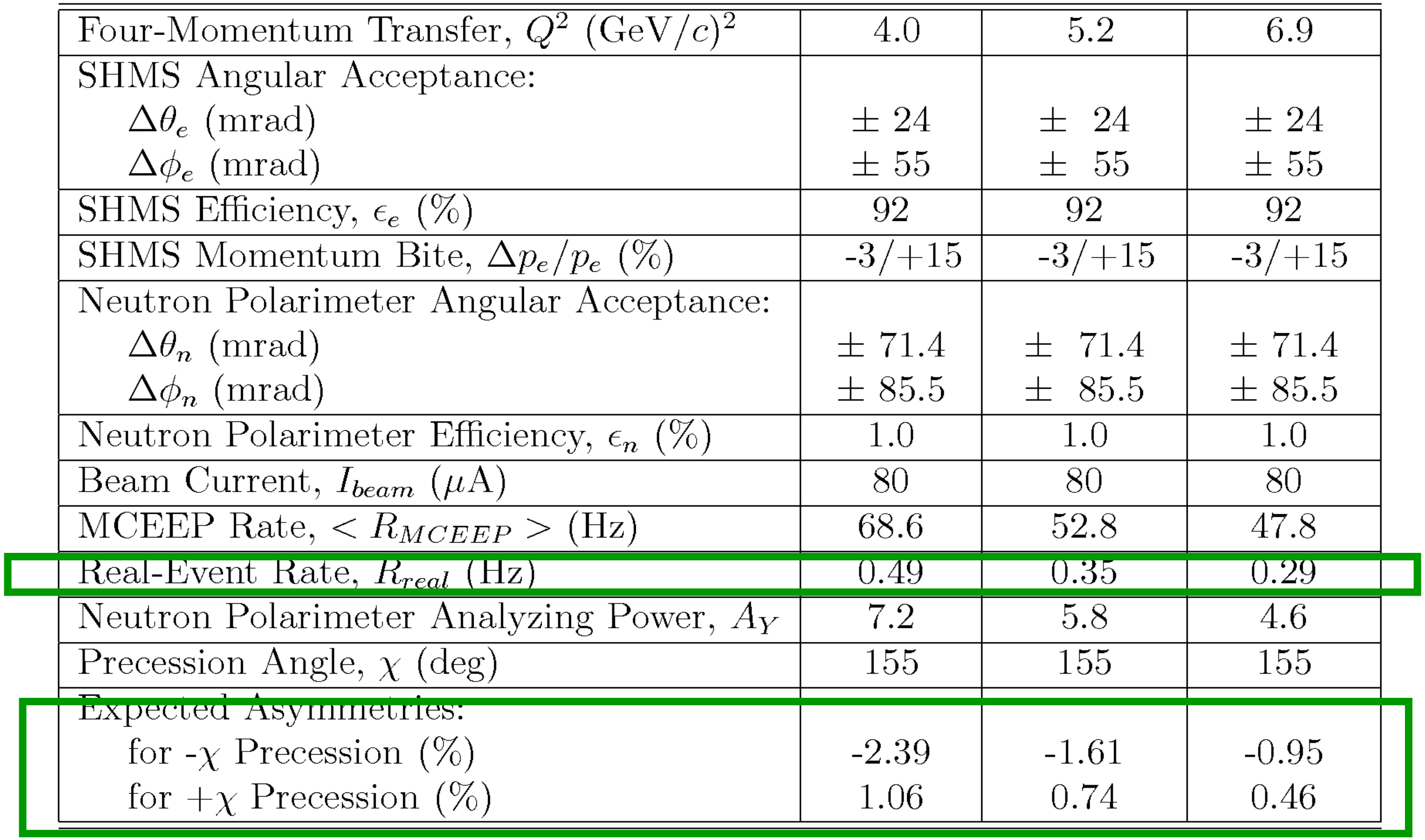
NIM A538 (2005) 431 (for proton scattering on CH_2):

$A_y \sim 1 / P_p$(lab) or $A_y \cdot P_p$(lab) = const

Assuming the analyzing power for neutrons scales the same way as the analyzing power for protons, our best estimation for P_n = 4.51 GeV/c:

A_y = 4.6 %

Projected count rates & asymmetries

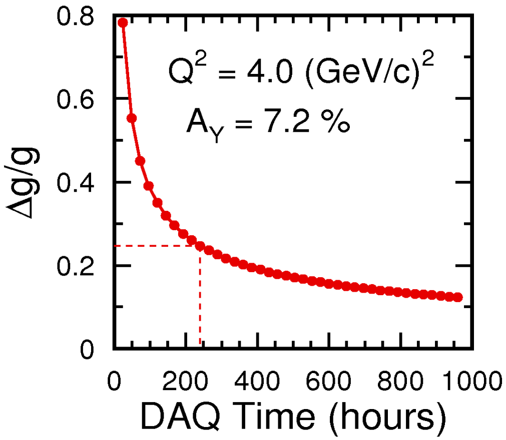


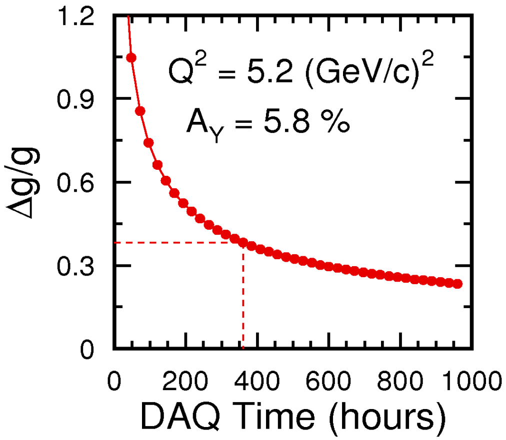
Four-Momentum Transfer, Q^2 (GeV/c)^2	4.0	5.2	6.9
SHMS Angular Acceptance:			
$\Delta\theta_e$ (mrad)	± 24	± 24	± 24
$\Delta\phi_e$ (mrad)	± 55	± 55	± 55
SHMS Efficiency, ϵ_e (%)	92	92	92
SHMS Momentum Bite, $\Delta p_e/p_e$ (%)	-3/+15	-3/+15	-3/+15
Neutron Polarimeter Angular Acceptance:			
$\Delta\theta_n$ (mrad)	± 71.4	± 71.4	± 71.4
$\Delta\phi_n$ (mrad)	± 85.5	± 85.5	± 85.5
Neutron Polarimeter Efficiency, ϵ_n (%)	1.0	1.0	1.0
Beam Current, I_{beam} (μA)	80	80	80
MCEEP Rate, $< R_{MCEEP} >$ (Hz)	68.6	52.8	47.8
Real-Event Rate, R_{real} (Hz)	0.49	0.35	0.29
Neutron Polarimeter Analyzing Power, A_Y	7.2	5.8	4.6
Precession Angle, χ (deg)	155	155	155
Expected Asymmetries:			
for $-\chi$ Precession (%)	-2.39	-1.61	-0.95
for $+\chi$ Precession (%)	1.06	0.74	0.46

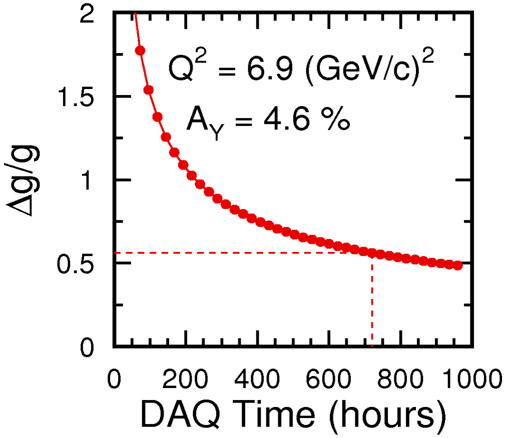
80 μA beam on 40-cm liquid deuterium target

Estimation of real-event rate includes analysis cuts

Projected statistical uncertainties







Asymmetry ratio for ±χ

$$\eta \equiv \frac{\xi_-}{\xi_+} = \frac{P_t \cos\chi - P_\ell \sin\chi}{P_t \cos\chi + P_\ell \sin\chi}$$

Extraction of G_{En}/G_{Mn}

$$g_n \equiv \frac{G_{En}}{G_{Mn}} = K(\theta_{e'}, Q^2) \tan\chi \frac{\eta + 1}{\eta - 1}$$

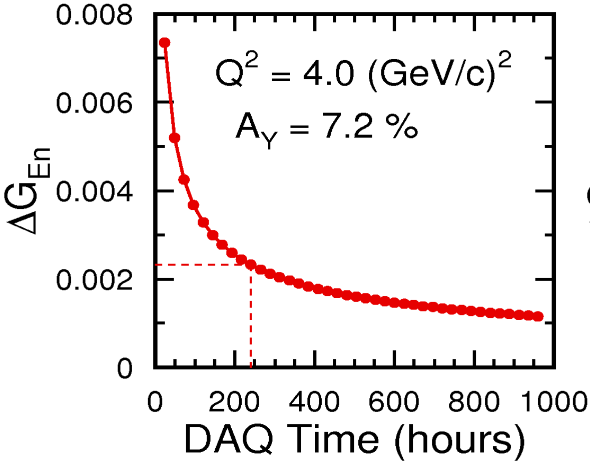
$\chi = \pm 155°$

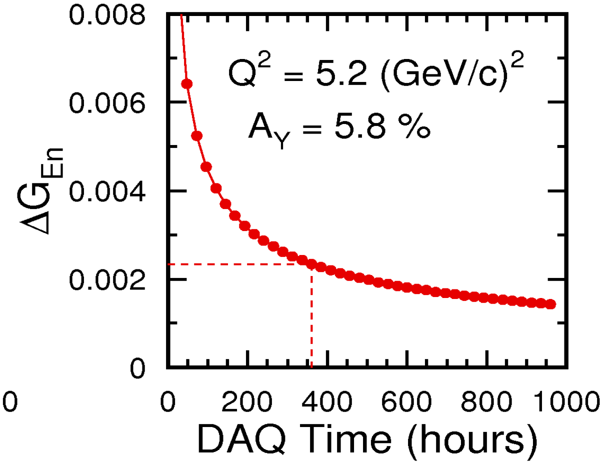
Projected statistical uncertainties

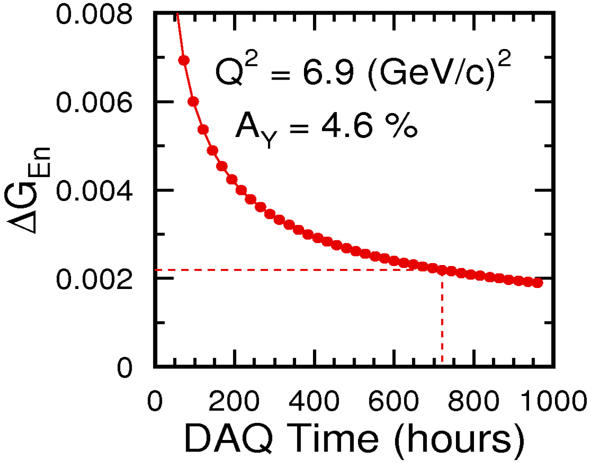
$$\left(\frac{\delta\xi_\pm}{\xi_\pm}\right)^2 = \frac{1}{\xi_\pm^2}\left(\frac{1+2/r}{N_\pm}\right) = \frac{1}{(A_y P_\pm)^2}\left(\frac{1+2/r}{N_\pm}\right)$$

r is a reals-to-accidentals ratio [= **13.3**, **8.1**, and **4.5** at Q^2=4.0, 5.2, and 6.9 $(\mathrm{GeV}/c)^2$]

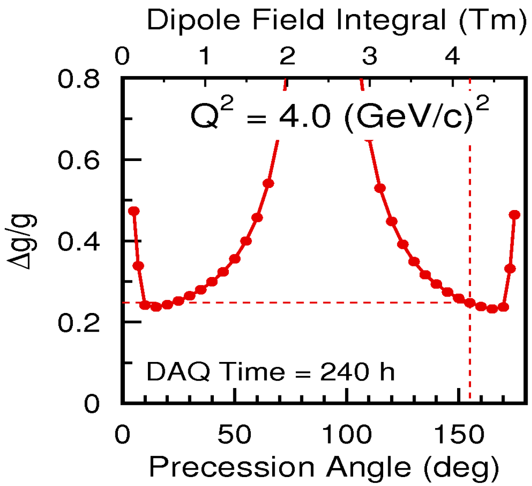
Projected statistical uncertainties

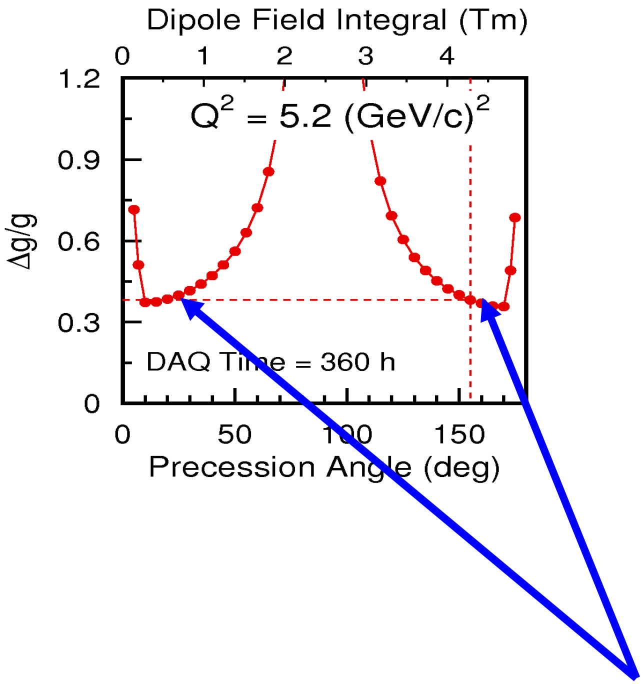


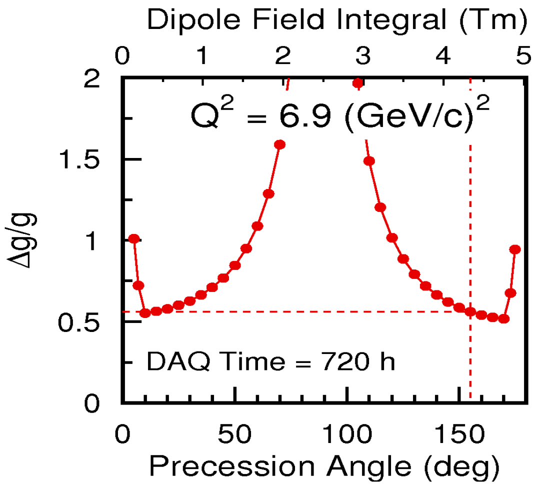




Projected statistical uncertainties

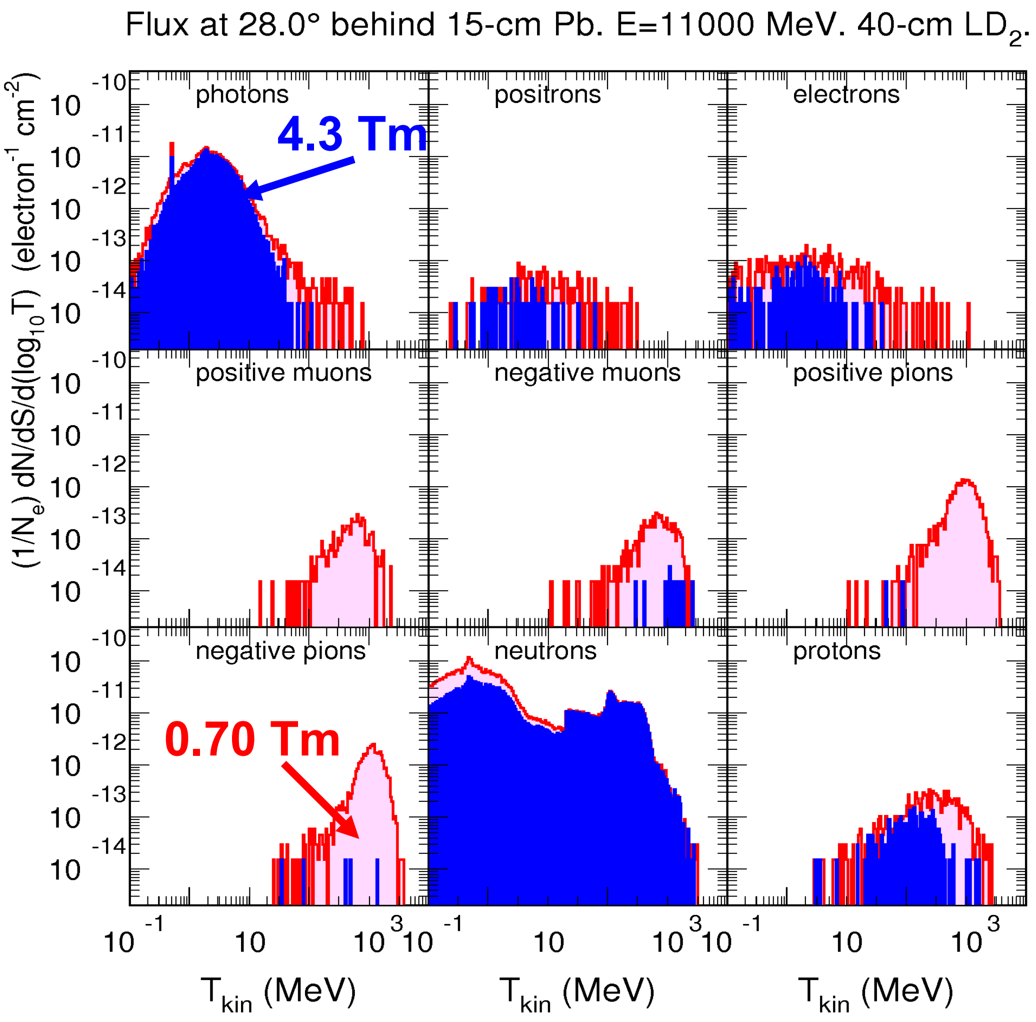






Two “optimal” regions for minimal uncertainties

Impact of magnetic field on backgrounds



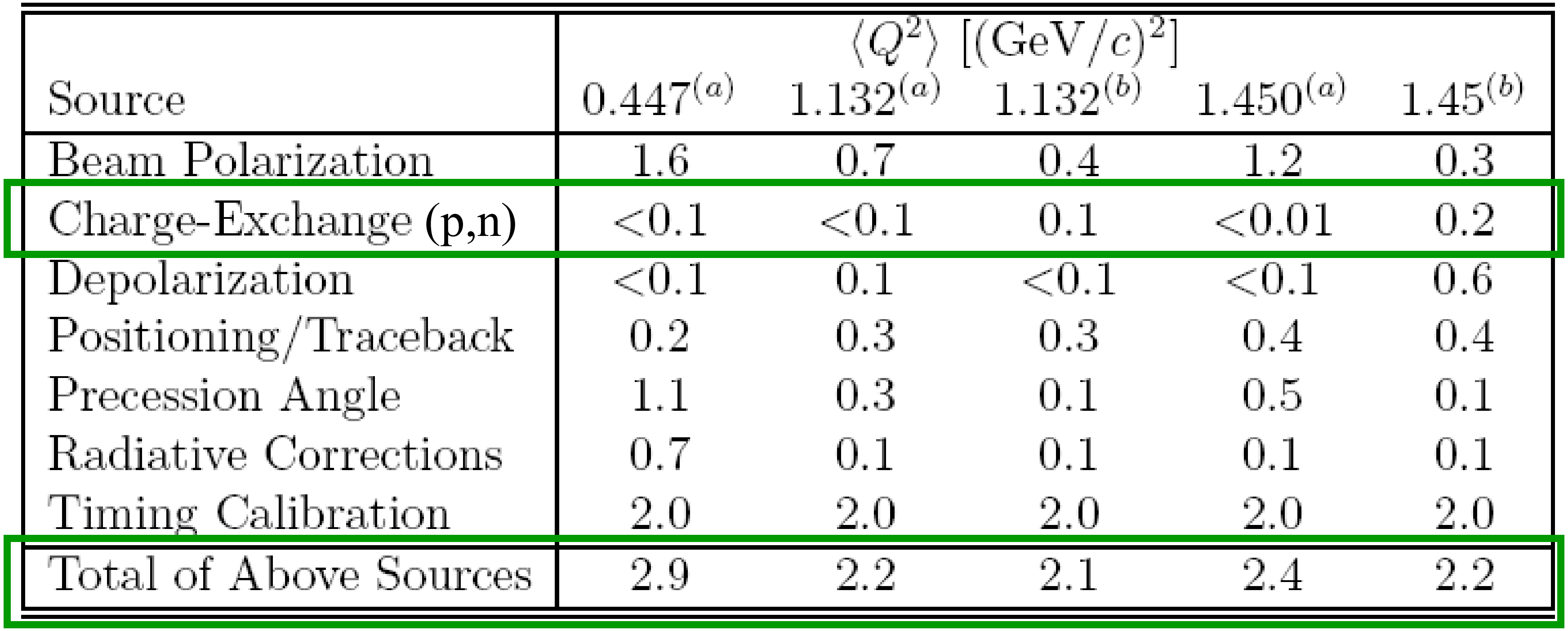
Background Simulation: GEANT3
+ DINREG + GCALOR

✔ High field sweeps charged particles away of the polarimeter; **Veto detector load is estimated to be 38 kHz with high magnetic field**

✔ High field completely sweeps away QE protons

Systematic uncertainties

E93-038 Systematic Uncertainties



	$\langle Q^2 \rangle$ [(GeV/c)^2]				
Source	$0.447^{(a)}$	$1.132^{(a)}$	$1.132^{(b)}$	$1.450^{(a)}$	$1.45^{(b)}$
Beam Polarization	1.6	0.7	0.4	1.2	0.3
Charge-Exchange (p,n)	<0.1	<0.1	0.1	<0.01	0.2
Depolarization	<0.1	0.1	<0.1	<0.1	0.6
Positioning/Traceback	0.2	0.3	0.3	0.4	0.4
Precession Angle	1.1	0.3	0.1	0.5	0.1
Radiative Corrections	0.7	0.1	0.1	0.1	0.1
Timing Calibration	2.0	2.0	2.0	2.0	2.0
Total of Above Sources	2.9	2.2	2.1	2.4	2.2

(a) χ = ±40° precession (b) χ = 0°, ±90° precession

Systematic uncertainties estimated to be small

Total error completely statistics dominated

Scientific motivation

Neutron is a basic building block of matter

Knowledge of G_{En} at high Q^2 is essential for:

✓ Understanding of nucleon structure & effects of relativistic quarks

At high Q^2, pion cloud effects are small compared to the quark core contribution; comparisons of models must consider all four form factors G_{Ep}, G_{Mp}, G_{En}, and G_{Mn}

✓ Understanding of electron scattering data from nuclei

The ratio of isoscalar and isovector cross-sections peaks at $G_{Ep}=G_{En}$

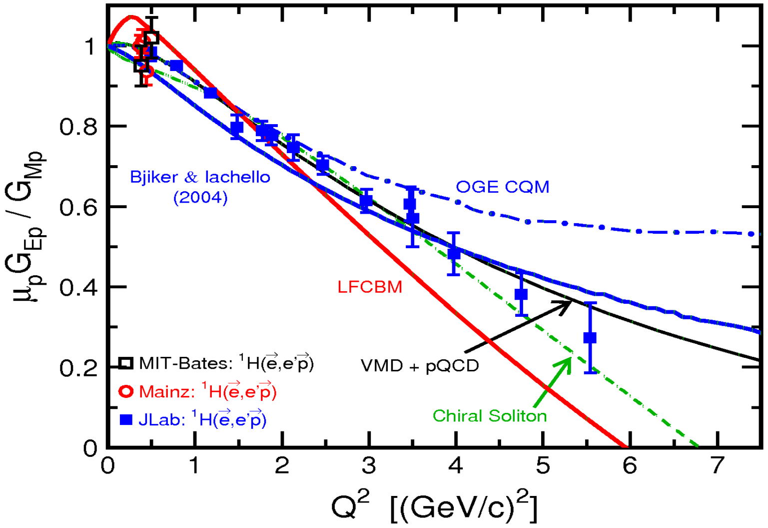
✓ Comparisons to Lattice QCD

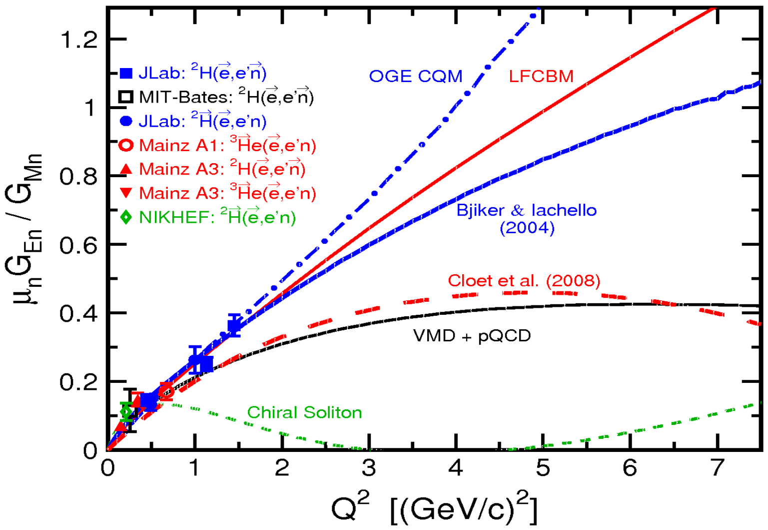
Largest deviation of calculations from experiment for the electric isovector form factor

Theory Review Report

"The proposed measurements ... will result in a comprehensive picture of the neutron electric form factor."

Models

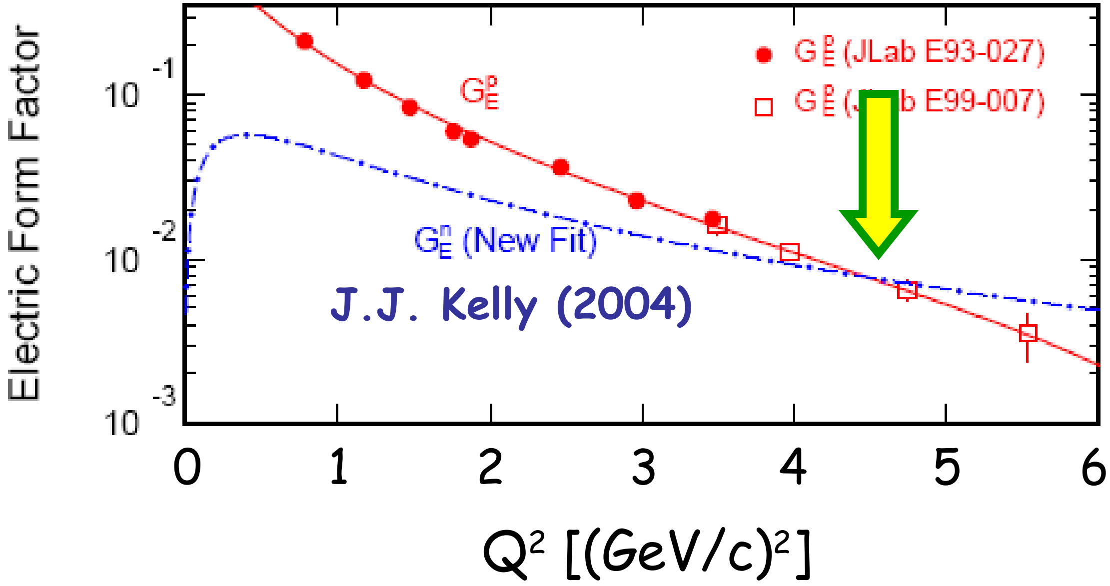




At $Q^2 = 7$ (GeV/c)^2, the uncertainty of $\Delta G_{EN} = 0.002$ corresponds to $\Delta(\mu_n G_{EN}/G_{MN}) \approx 0.25$

G_{EN} measurement **must** provide this level of accuracy **reliably** to be able efficiently test the models

G_{Ep} vs. G_{En}

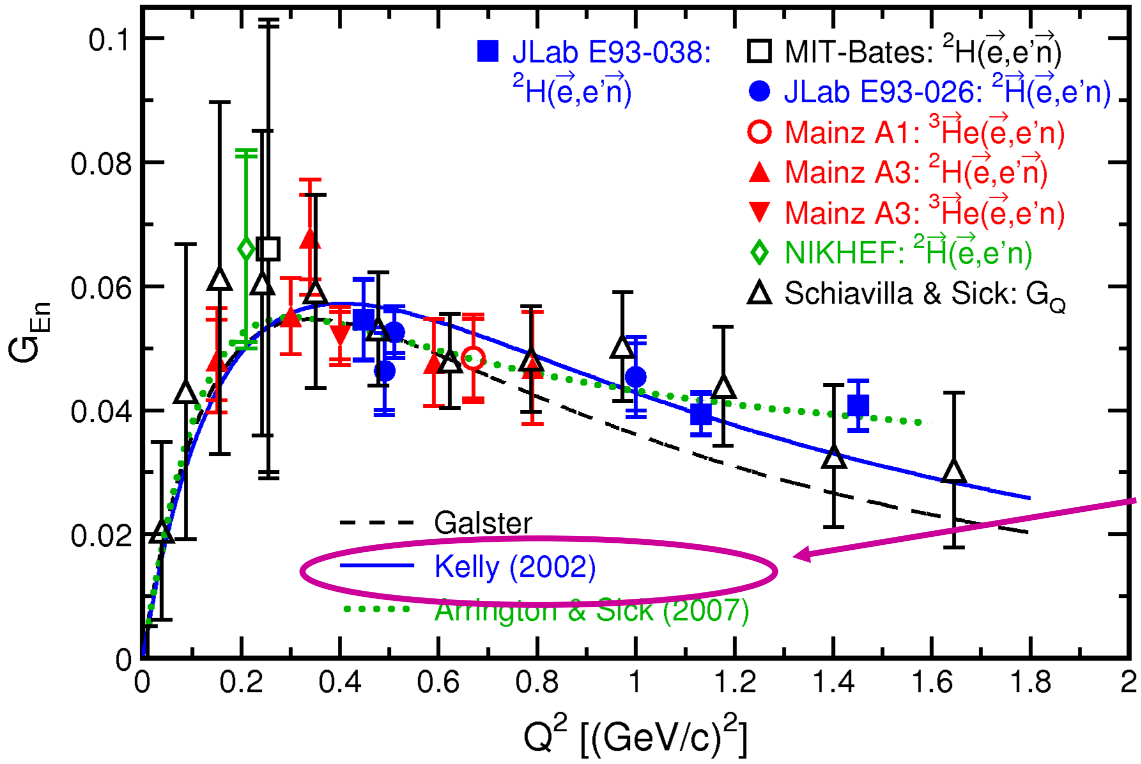


J.J. Kelly (2004)

Possible zero crossing in isovector electric form factor G_E^V at Q^2 ~ 4.5 (GeV/c)^2

Powerful test for lattice QCD calculations

Current published G_{En} data



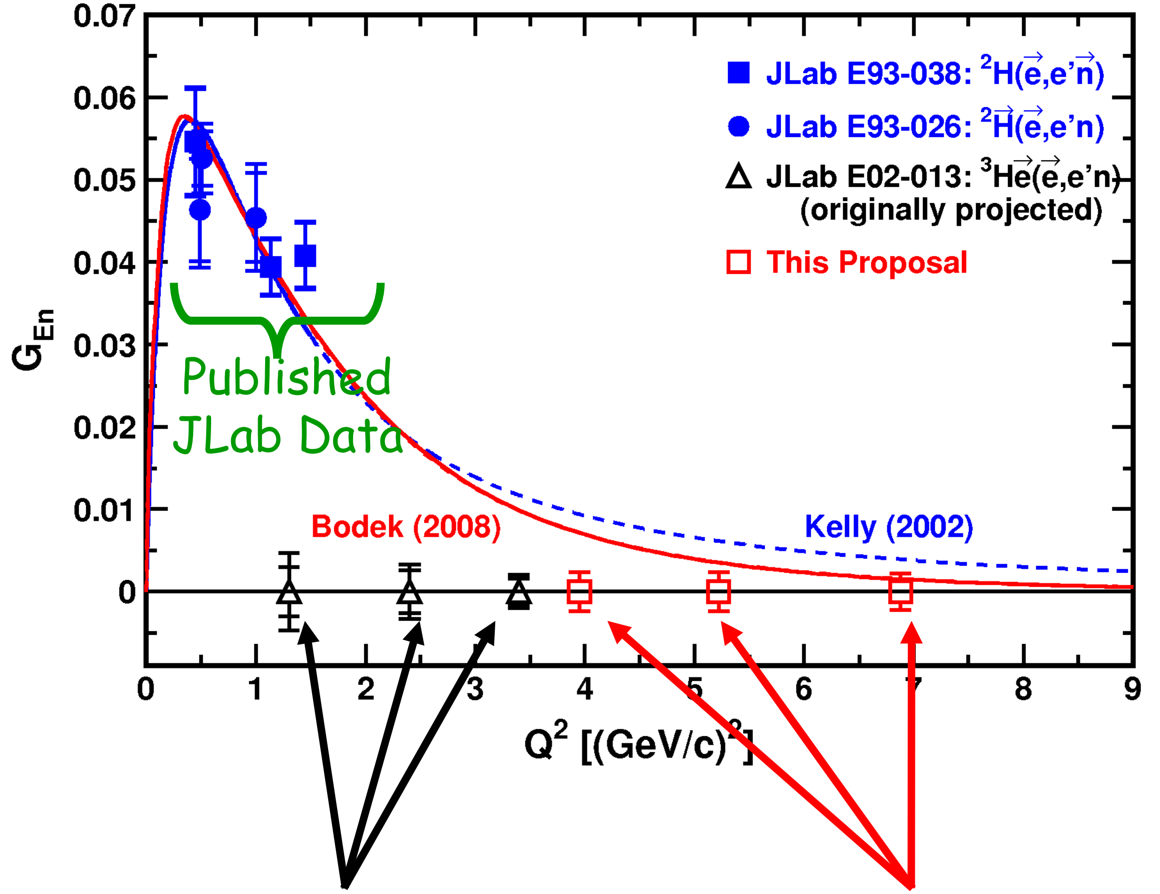
Modified Galster fit

J.J. Kelly, PRC 70, 068202 (2004)

E93-038 { R. Madey et al., PRL 91, 122002 (2003)
B. Plaster et al., PRC 73, 025205 (2006)

→ **Q^2 = 1.13 and 1.45 (GeV/c)^2 most precise values for G_{En} published to date**

Future G_{En} data



E02-013 error bars[proposal]

PR-09-006 error bars [proposal]

Beamtime request (days)

80 μA beam, 80% polarization, 40-cm LD_2 target

G_E^n physics measurements Q^2 [(GeV/c)^2]	4.0	5.2	6.9	Total
LD_2 target	10	15	30	55
LH_2 target	0.5	0.5	0.5	1.5
Dummy target	0.1	0.1	0.2	0.4
Beam polarization	0.3	0.5	1	1.8
Time calibrations [LD_2 target]	0.1	0.1	0.2	0.4
Overhead	0.1	0.3	$0.5^{(a)}$	0.9
Total physics measurements	11.1	16.5	32.4	60

LH_2 target for assessment of false asymmetry/dilution from contamination from two-step process $^2H(\vec{e},e'\vec{p}) + Pb(\vec{p},\vec{n})$

Commissioning time with beam: 7 days [HMS/NPOL/Möller check-out]

(a) Overhead: Charybdis dipole polarity changes; target changes; DAQ operation

Collaboration

R. Madey, B.D. Anderson, A.R. Baldwin,
D.M. Manley, J.W. Watson, W.-M. Zhang
Kent State University

R. Carlini, R. Ent, H. Fenker, D. Gaskell,
M.K. Jones, D. Higinbotham, A. Lung,
D. Mack, G. Smith, S. Taylor, W. Vulcan,
S. Wood, C. Yan
Jefferson Laboratory

S. Kowalski, W. Deconinck
Massachusetts Institute of Technology

A. Yu. Semenov, G. Huber, G.J. Lolos,
Z. Papandreou, I.A. Semenova
University of Regina

B. Plaster, W. Korsch
University of Kentucky

C. Howell
Duke University

J.M. Finn, C. Perdrisat
The College of William and Mary

C. Keppel, L. Tang, I. Albayrak, O. Ates,
C. Chen, M.E. Christy, M. Kohl, Y. Li,
A. Liyanage, Z. Ye, T. Walton, L. Yuan, L. Zhu
Hampton University

A. Ahmidouch, S. Danagoulian,
A. Gasparian
North Carolina A&T University

M. Elaasar
Southern University at New Orleans

H. Arenhövel
University of Mainz

H.G. Mkrtchyan, R. Asaturyan,
A. Mkrtchyan, V. Tadevosyan
Yerevan Physics Institute

A. Opper
George Washington University

S. Wells, N. Simicevic
Louisiana Tech

P. Markowitz, B. Raue,
J. Reinhold
Florida International University

D. Day, P. McKee
University of Virginia

W. Tireman
Northern Michigan University

J. Arrington, K. Hafidi, R.
Holt, P. Reimer, P. Solvignon
Argonne National Laboratory

M. Khandaker, V. Punjabi,
F. Wesselmann
Norfolk State Uniersity

R.E. Segel
Northwestern University

R. Wilson
Harvard University

S. Tajima
Los Alamos National Laboratory

A.I. Malakhov, A.K. Kurilkin,
P.K. Kurilkin, V.P. Ladygin,
S.M. Piyadin
Joint Institute for Nuclear Research

J. Martin
University of Winnipeg

S. Jin, W.-Y. Kim,
S. Stepanyan, S. Yang
Kyungpook National University

H. Breuer
University of Maryland

Collaboration

T. Reichelt
University of Bonn

L. Gan
University of North Carolina – Wilmington

I. Sick
University of Basel

F. Wesselmann
Xavier University of Louisiana

K. McCormick
Pacific Northwest National Laboratory

Major responsibilities

NPOL: Kent State

Dipole magnet: MIT

SHMS: JLab Hall C

Analysis/Simulations: Kentucky, Regina

Vetos: Kentucky, Southern University (New Orleans)

Large/Experienced Collaboration

31 Institutions from USA, Canada, Germany, Armenia, Russia, Korea, Switzerland

TAC Review Comments

✔ "The collaboration probably needs to find a longer dipole, or add another dipole to compliment Charybdis."

Most probably, we will use a second dipole magnet to complement Charybdis.
Magnets at FermiLab:

E831/FOCUS (2): 30"gap + about 2.8 Tm
"Rosie" (unapproved E907): 36"(+) gap + 2.7 Tm
KTeV magnet: 80" gap + about 2.0 Tm
"SM3" magnet (BTeV?): 66" gap + 3.0 Tm (but 126" field length!)

✔ "The largest proposed electron scattering angle (56.8 deg) is not mechanically accessible with SHMS."

We gave up the lowest Q2 point and reduces the beam request by 6 days.

✔ "In the early years of 12 GeV operation, the practical limit on beam current for 11 GeV running will be 75 μA."

Very small increase of the statistical uncertainty by factor SQRT(80/75)=1.03

✔ "The power deposited in the 40cm … targets is more than 500W…"

Qweak heat exchanger will make targets up to 2 kW not impossible.

TAC Review Comment

"The collaboration has considerable experience in using this technique ... A particularly noteworthy strength has always been through Monte Carlo simulations, repeatedly bench-marked with their previous test and production data taken in Hall C."

Theory Review Comment

"We do not see any issues affecting the proposed analysis procedure or interpretation of the data."

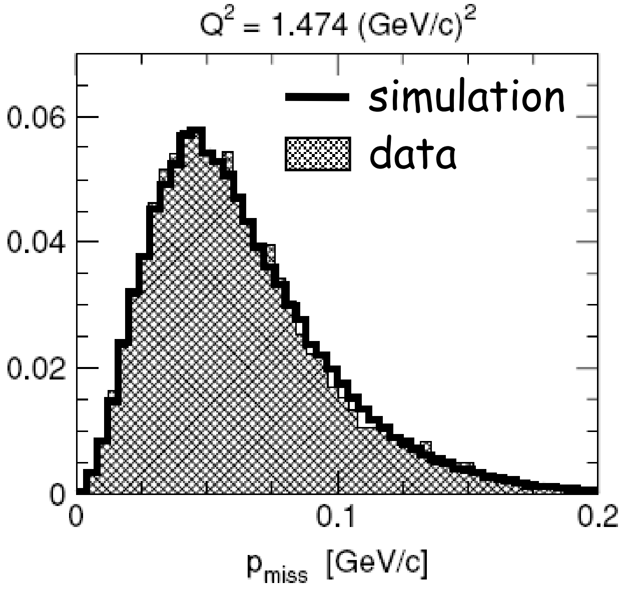
Backup slides

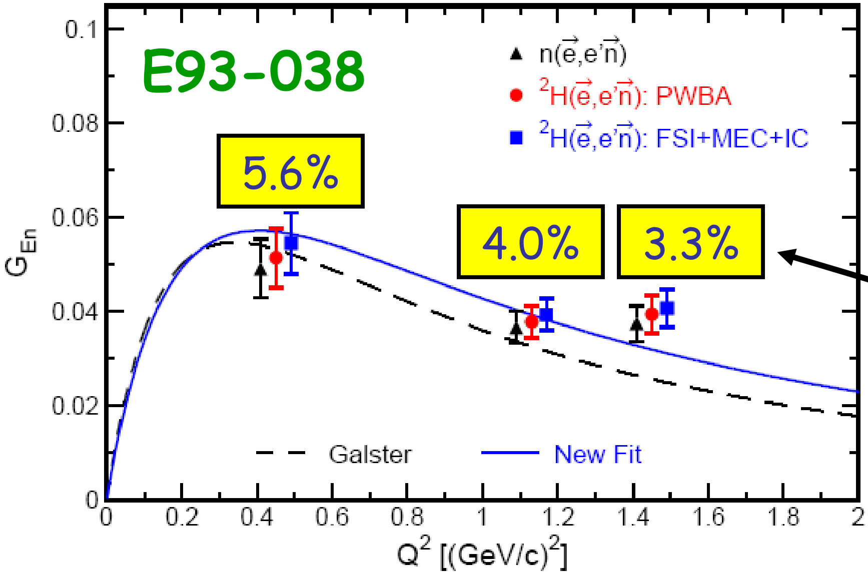
	Cost
1. **Front Array**	
1.1 6 [10 cm × 10 cm × 100 cm] Scintillator & Light Pipes	$8,400
1.2 28 [1 cm × 10 cm × 106 cm] Veto Scintillator & Light Pipes	$27,000
1.3 88 Photomultiplies Tubes (2-in diam)	$88,000
1.4 72 Magnetic Shields (for 2-in diam PMT) [Borrow]	0
1.5 68 Additional Preamplifiers [To be provided by KSU]	0
Subtotal Front Array	**$123,400**
2. **Rear Array**	
2.1 20 [1 cm × 25 cm × 106 cm] Veto Scintillator & Adiabatic Light Pipes	$40,000
2.2 44 Photomultiplier Tubes (5-in diam)	$110,000
2.3 40 Photomultiplier Tubes (2-in diam)	$40,000
2.4 24 Magnetic Shields (for 5-in diam PMT)	$6,000
2.5 40 Magnetic Shields (for 2-in diam PMT) [Borrow]	0
2.6 40 Preamplifiers [to be provided by KSU]	0
Subtotal Rear Array	**$196,000**
3. **Electronic Modules**	
3.1 6 Quad Discriminators [to be provided by JLab]	$18,000
Subtotal Electronic Modules	**$18,000**
Total	**$337,400**

FSI corrections

Arenhövel FSI+MEC+IC model for $^2H(e,e'n)^1H$ averaged over acceptance [2 independent simulations]

1) Relativistic PWBA model for kinematic acceptance
2) FSI+MEC+IC corrections





With similar range of acceptance/cuts in p_{miss}, 3.3% should be robust estimate of upper range for FSI corrections at $Q^2 = 2.8/4.3\ (GeV/c)^2$

Two-photon exchange for G_{En}/G_{Mn}

PHYSICAL REVIEW C **72**, 034612 (2005)

Two-photon exchange in elastic electron-nucleon scattering

P. G. Blunden,[1] W. Melnitchouk,[2] and J. A. Tjon[2,3]

[1]*Department of Physics and Astronomy, University of Manitoba, Winnipeg, Manitoba, Canada R3T 2N2*
[2]*Jefferson Lab, 12000 Jefferson Ave., Newport News, Virginia 23606, USA*
[3]*Department of Physics, University of Maryland, College Park, Maryland 20742-4111, USA*
(Received 13 June 2005; published 30 September 2005)

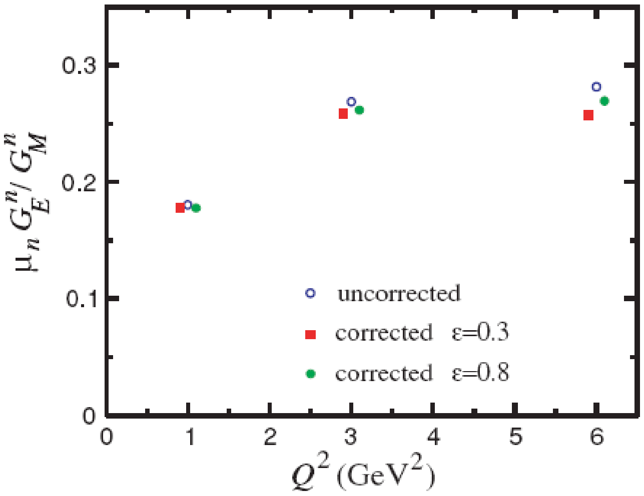
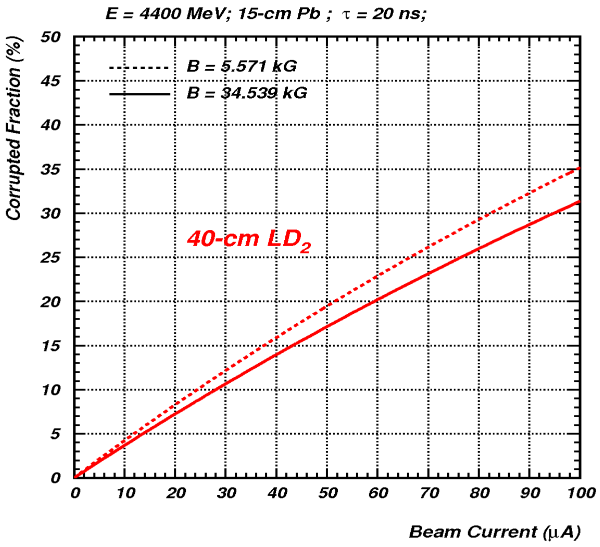


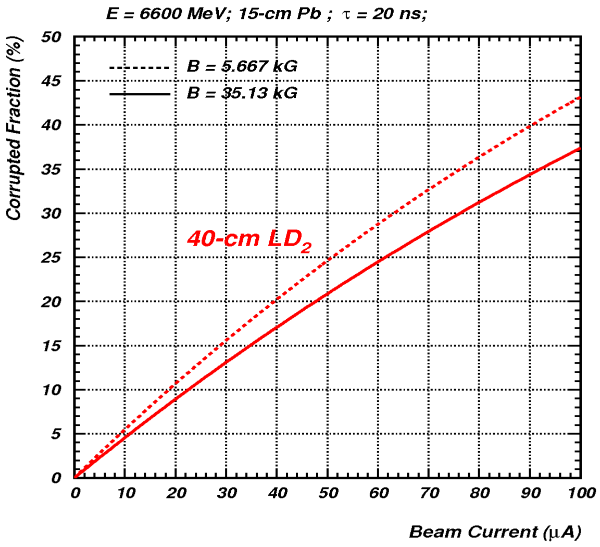
FIG. 14. (Color online) Effect of 2γ exchange on the ratio of neutron form factors $\mu_n G_E^n / G_M^n$ using polarization transfer. The uncorrected points (open circles) are from the parametrization in Ref. [16], and the points corrected for 2γ exchange correspond to $\varepsilon = 0.3$ (filled squares) and $\varepsilon = 0.8$ (filled circles) (offset for clarity).

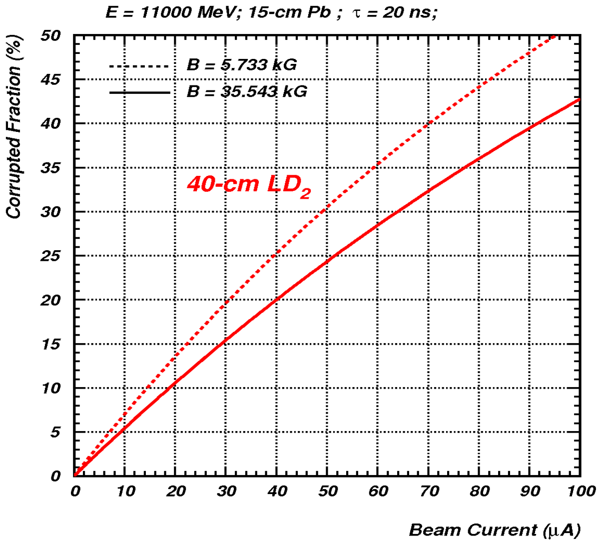
In the Jefferson Lab experiment [42] to measure G_E^n / G_M^n at $Q^2 = 1.45$ GeV^2 the value of ε was around 0.9, at which the 2γ correction was $\approx$2.5%. In the recently approved extension of this measurement to $Q^2 \approx 4.3$ GeV^2 [43], the 2γ correction for $\varepsilon \approx 0.82$ is expected to be around 3%. Although small, these corrections will be important to take into account to achieve precision at the several-percent level. Furthermore, the two-photon exchange effects may also need to be taken into account when extracting the neutron magnetic form factor G_M^n from cross-section data.

2-gamma correction smaller than statistical error

Corrupted events

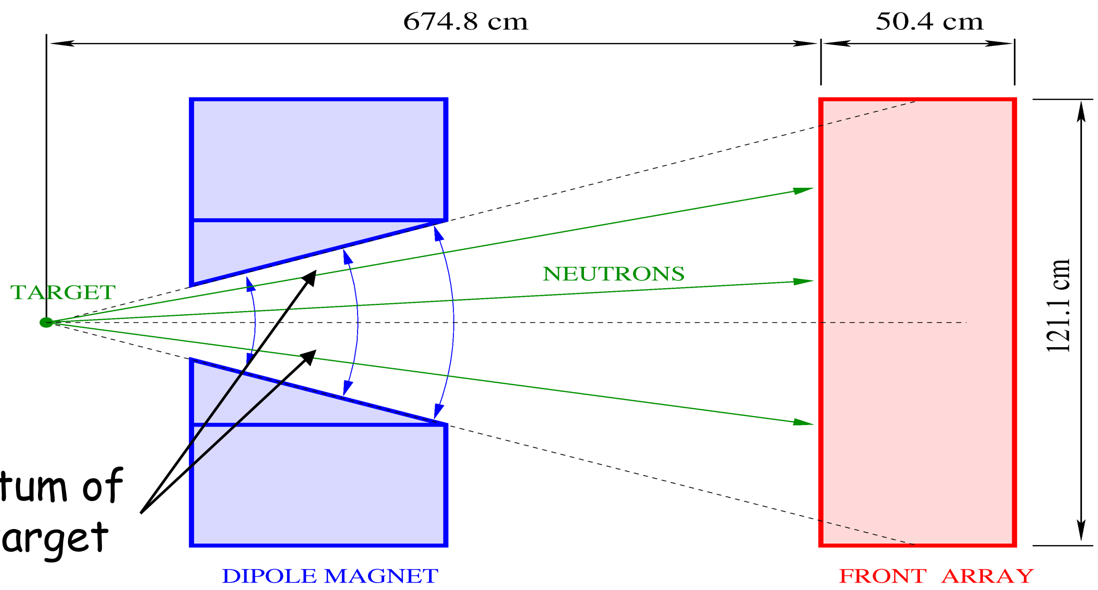






Using singles rates for neutral/charged particles, we estimate the fraction of "corrupted event" as a probability of detected accidental hit "nearby" the QE neutron scattering event in NPOL (viz., in 20 ns time window & 50-cm y-coordinate)

Enhanced NPOL



Schematic:
Not to scale

B-field ⊥ to momentum of
all neutrons from target

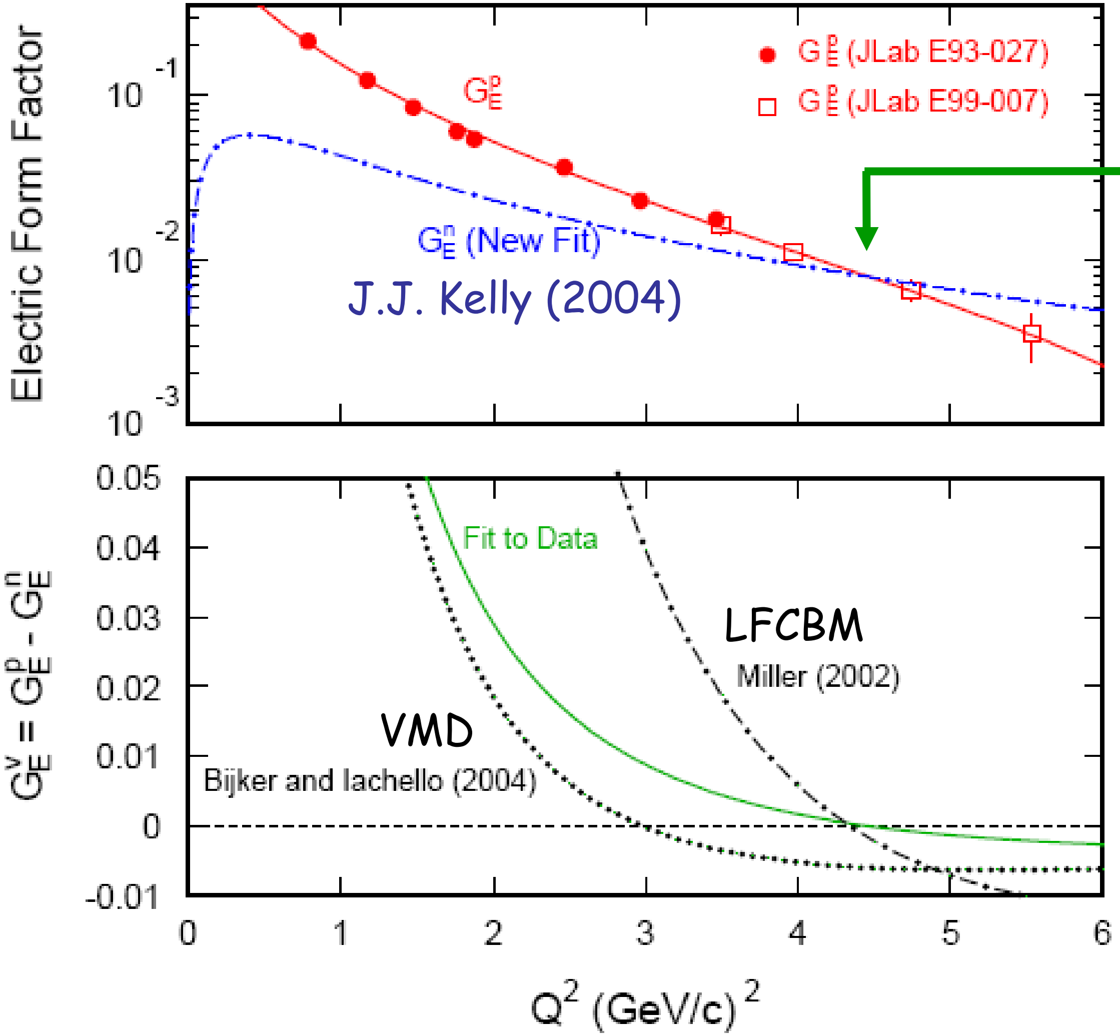
Charybdis modifications to match increased vertical acceptance

E93-038: 21.0-cm pole gap for 0.5-m vertical acceptance

PR-09-006: tapered [19.5-cm to 40.4-cm] pole gap for 1.2-m vertical acceptance

field integral $\chi = -\frac{g_n e}{2 m_p c \beta_n} \int B \, \Delta\ell$

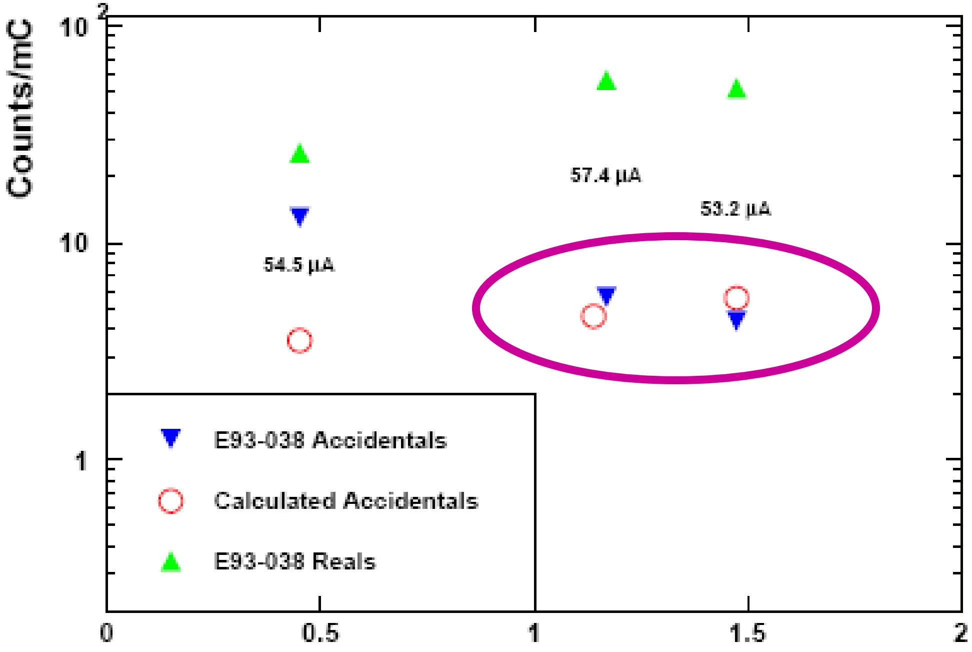
G_{Ep} vs. G_{En}



Possible zero crossing in isovector electric form factor G_E^V at Q^2 ~ 4.5 (GeV/c)^2

Powerful test for models and lattice QCD

Reals/accidentals simulation



Simulation of accidentals

HMS singles [MONQEE]

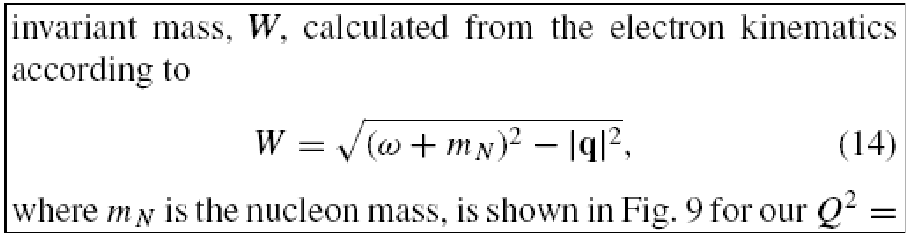
NPOL singles from inclusive neutrons [GEANT]

Projection for PR-09-006

Q^2 = 4.0 (GeV/c)^2 R/A = 13.3
Q^2 = 5.2 (GeV/c)^2 R/A = 8.1
Q^2 = 6.9 (GeV/c)^2 R/A = 4.5

Results reliable with R/A so high

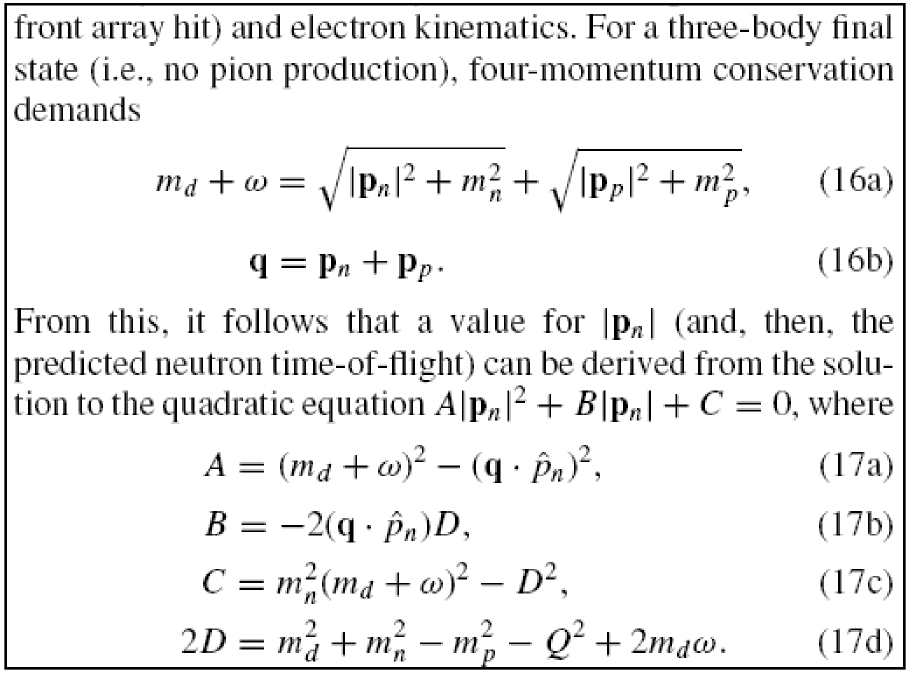
Calculation of kinematic variables



invariant mass, W, calculated from the electron kinematics according to

$$W = \sqrt{(\omega + m_N)^2 - |\mathbf{q}|^2}, \qquad (14)$$

where m_N is the nucleon mass, is shown in Fig. 9 for our $Q^2 =$



front array hit) and electron kinematics. For a three-body final state (i.e., no pion production), four-momentum conservation demands

$$m_d + \omega = \sqrt{|\mathbf{p}_n|^2 + m_n^2} + \sqrt{|\mathbf{p}_p|^2 + m_p^2}, \qquad (16a)$$

$$\mathbf{q} = \mathbf{p}_n + \mathbf{p}_p. \qquad (16b)$$

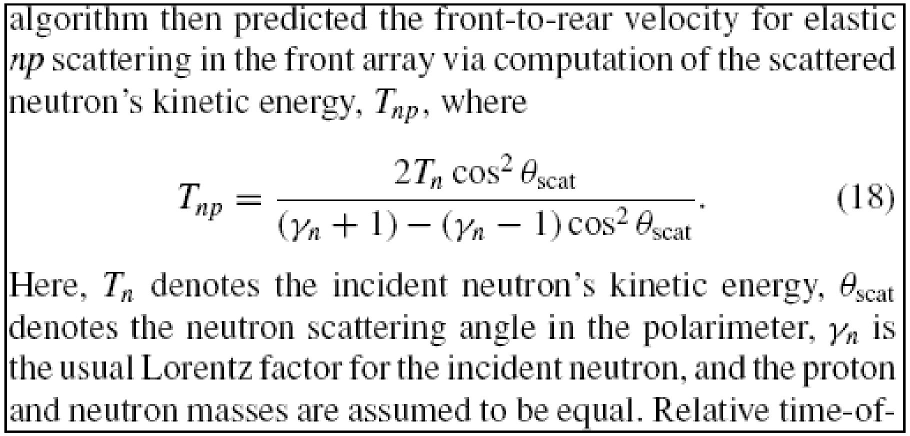
From this, it follows that a value for $|\mathbf{p}_n|$ (and, then, the predicted neutron time-of-flight) can be derived from the solution to the quadratic equation $A|\mathbf{p}_n|^2 + B|\mathbf{p}_n| + C = 0$, where

$$A = (m_d + \omega)^2 - (\mathbf{q} \cdot \hat{p}_n)^2, \qquad (17a)$$

$$B = -2(\mathbf{q} \cdot \hat{p}_n)D, \qquad (17b)$$

$$C = m_n^2(m_d + \omega)^2 - D^2, \qquad (17c)$$

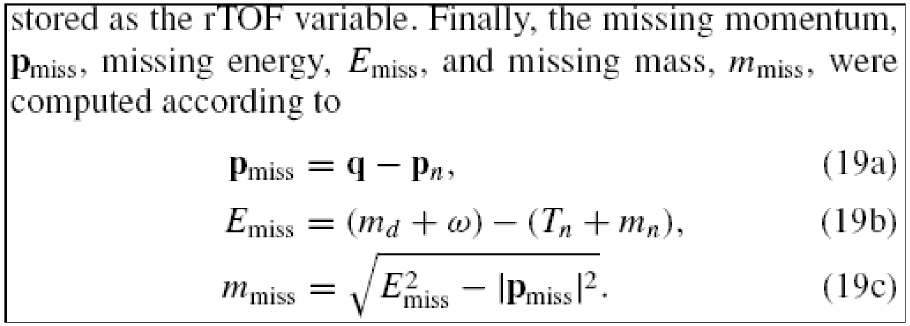
$$2D = m_d^2 + m_n^2 - m_p^2 - Q^2 + 2m_d\omega. \qquad (17d)$$



algorithm then predicted the front-to-rear velocity for elastic np scattering in the front array via computation of the scattered neutron's kinetic energy, T_{np}, where

$$T_{np} = \frac{2T_n \cos^2\theta_{\mathrm{scat}}}{(\gamma_n + 1) - (\gamma_n - 1)\cos^2\theta_{\mathrm{scat}}}. \qquad (18)$$

Here, T_n denotes the incident neutron's kinetic energy, θ_{scat} denotes the neutron scattering angle in the polarimeter, γ_n is the usual Lorentz factor for the incident neutron, and the proton and neutron masses are assumed to be equal. Relative time-of-



stored as the rTOF variable. Finally, the missing momentum, $\mathbf{p}_{\mathrm{miss}}$, missing energy, E_{miss}, and missing mass, m_{miss}, were computed according to

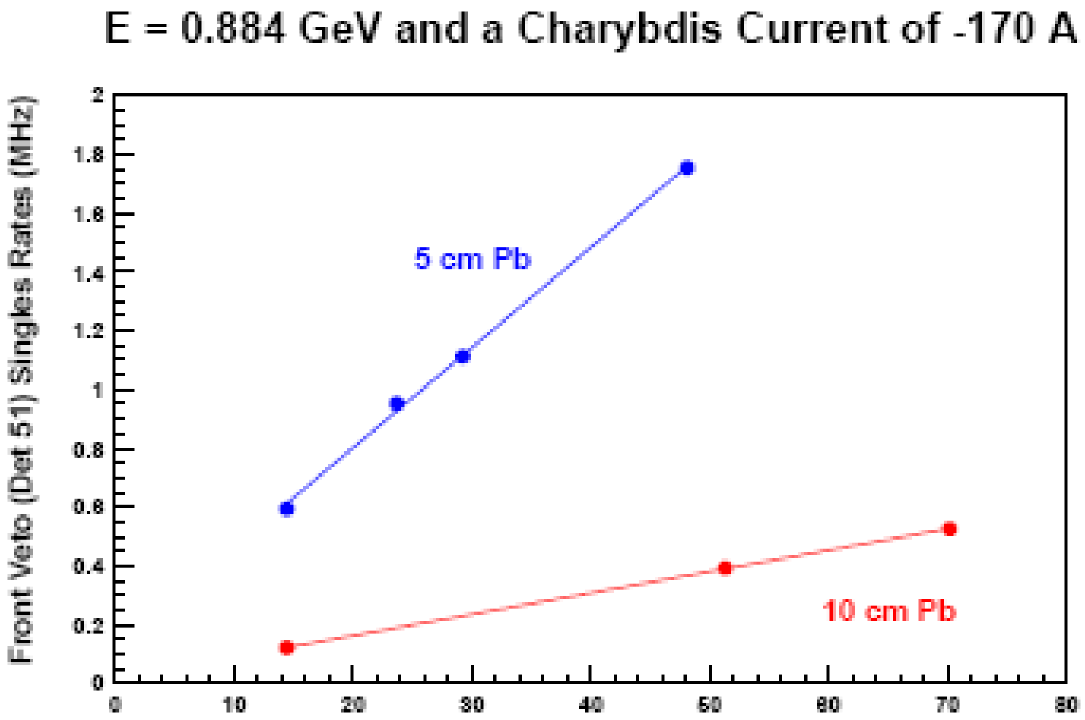
$$\mathbf{p}_{\mathrm{miss}} = \mathbf{q} - \mathbf{p}_n, \qquad (19a)$$

$$E_{\mathrm{miss}} = (m_d + \omega) - (T_n + m_n), \qquad (19b)$$

$$m_{\mathrm{miss}} = \sqrt{E_{\mathrm{miss}}^2 - |\mathbf{p}_{\mathrm{miss}}|^2}. \qquad (19c)$$

Note: $\vec{p}_{\mathrm{miss}}$ calculated solely from $(\omega, \vec{q})$ and θ_{nq} [no TOF]

Pb-curtain thickness



E = 0.884 GeV and a Charybdis Current of -170 A

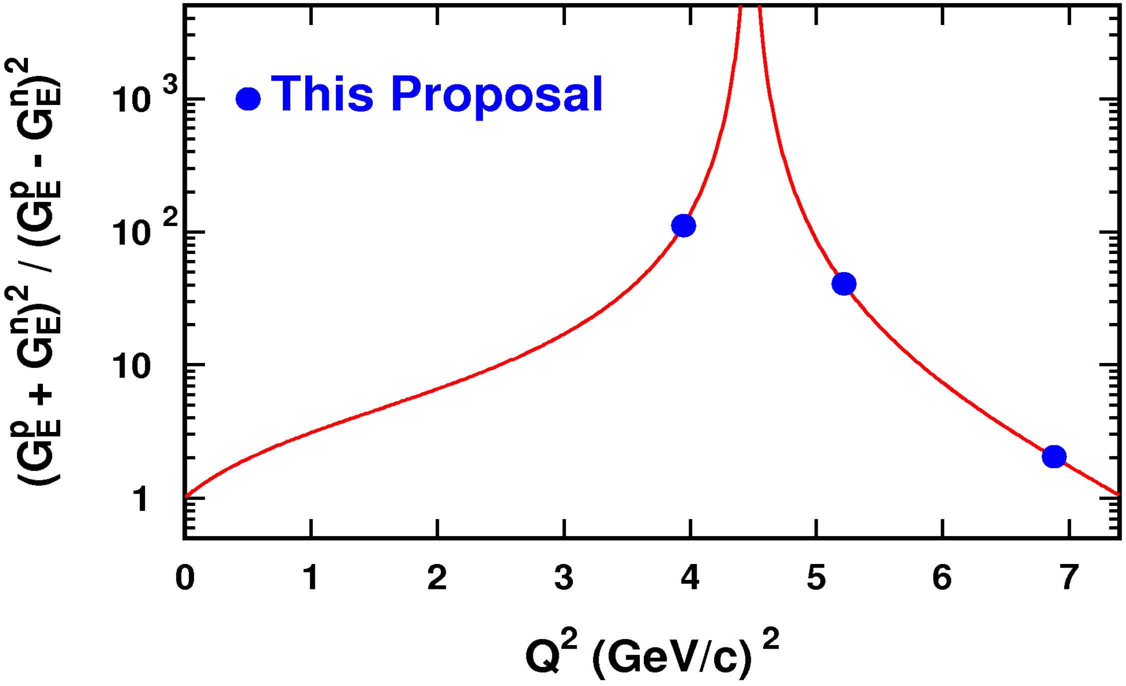
If singles rates unacceptably high, will increase Pb-curtain thickness

- Decrease in neutron rate (partly) compensated by smaller "corrupted event" fraction

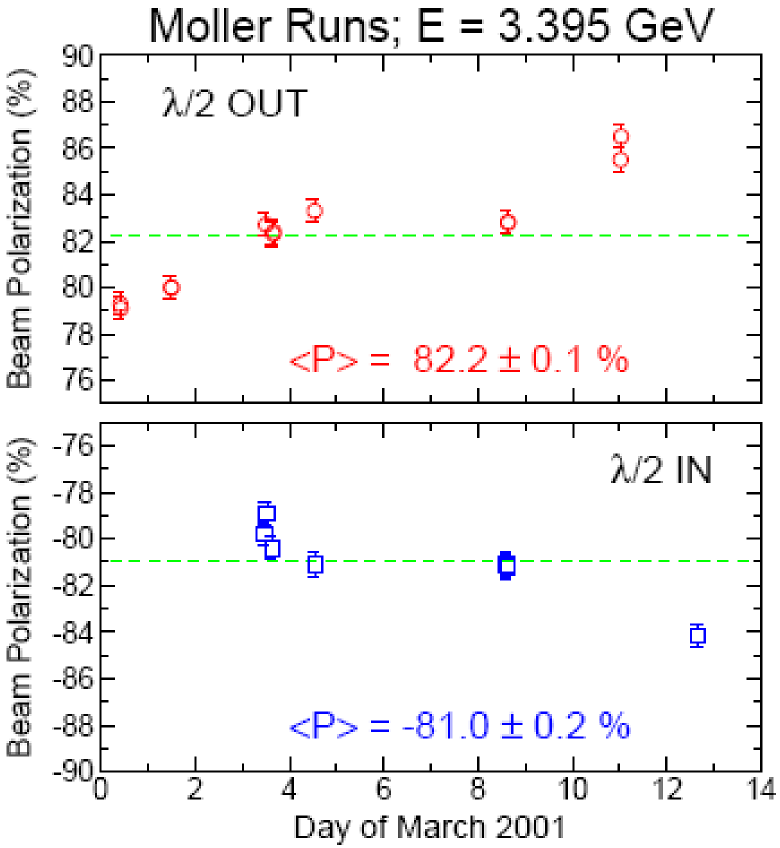
Isoscalar/isovector cross sections

Ratio of isoscalar to isovector cross sections

$$\frac{\sigma_{isoscalar}}{\sigma_{isovector}} = \left(\frac{G_E^p + G_E^n}{G_E^p - G_E^n}\right)^2$$



Beam polarization stability



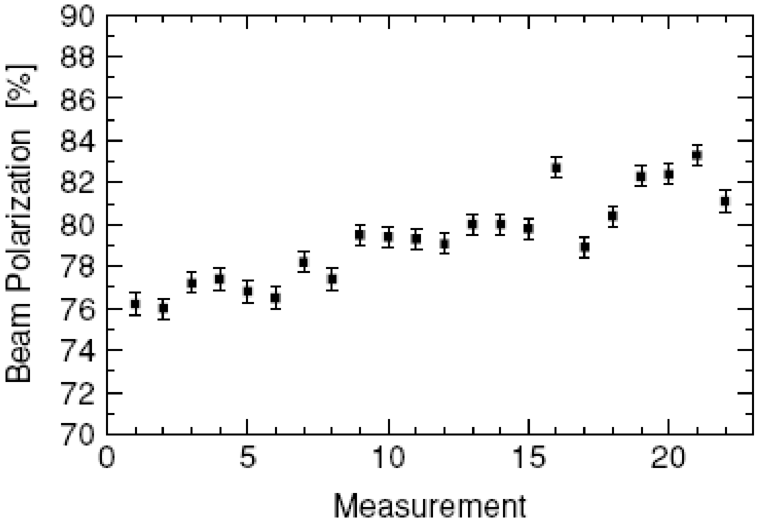
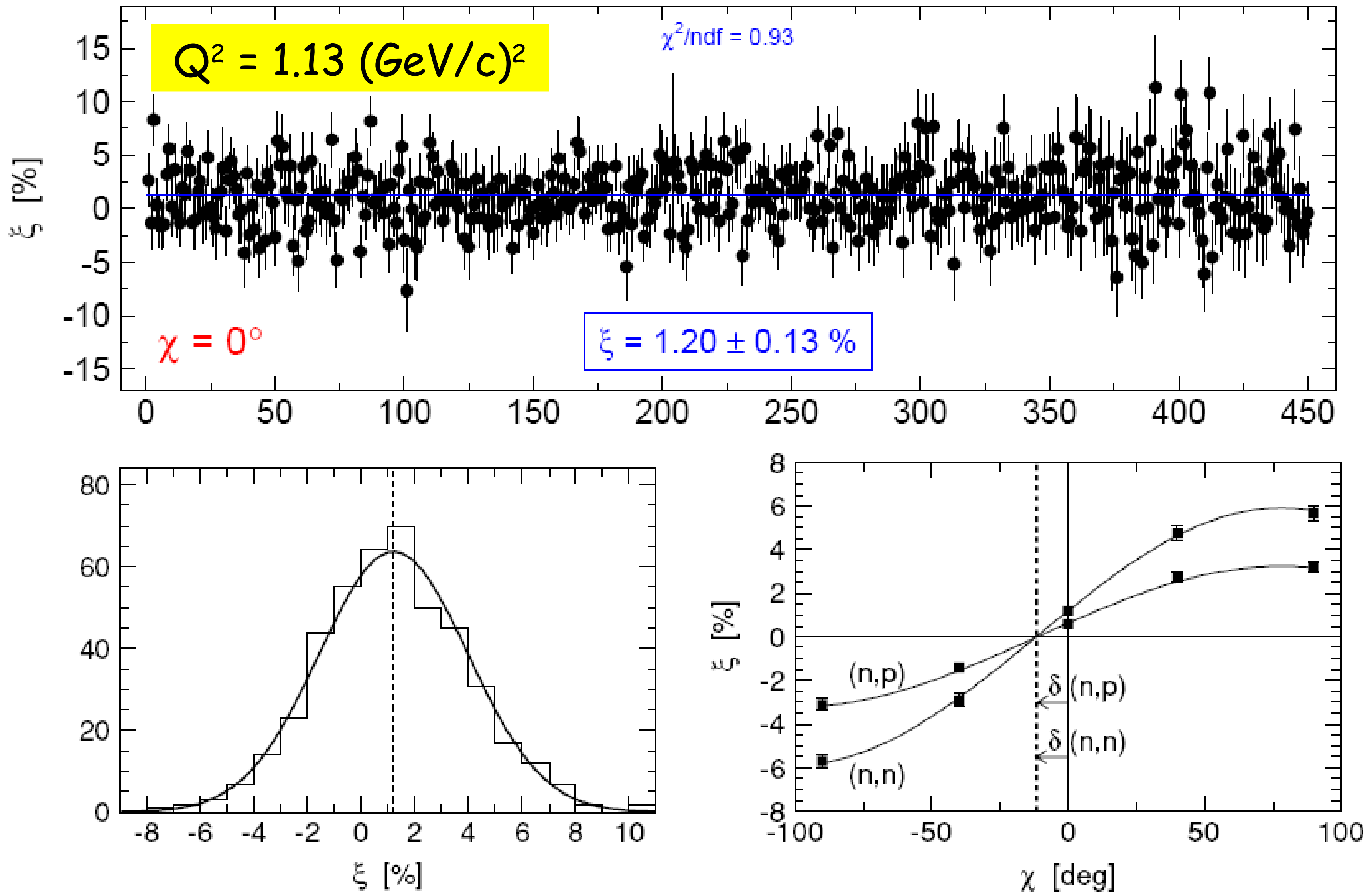


FIG. 17. Results of 23 successive Møller beam-polarization measurements conducted during the $Q^2 = 1.474\,(\mathrm{GeV}/c)^2$ $\chi = \pm 40^\circ$ running period spanning the days of February 20, 2001, through March 5, 2001. The errors shown are statistical.

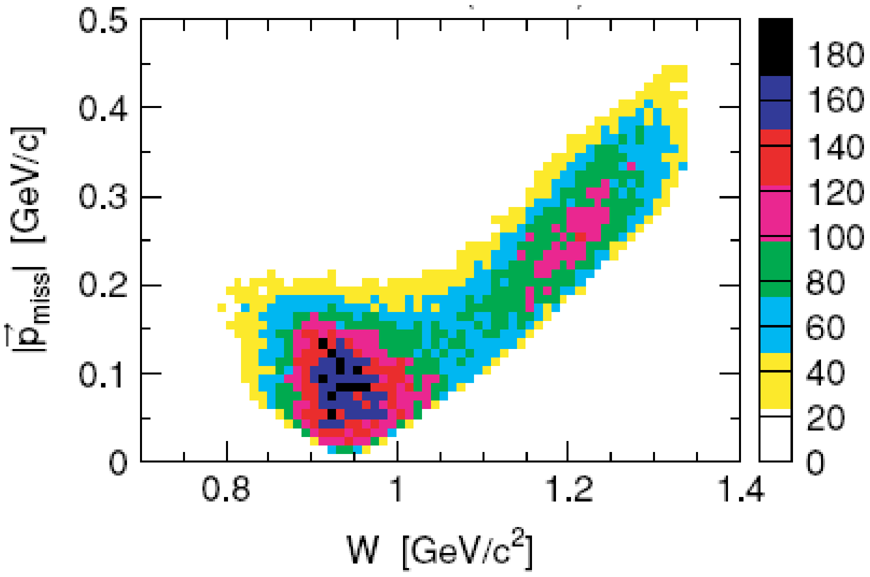
E93-038 asymmetries

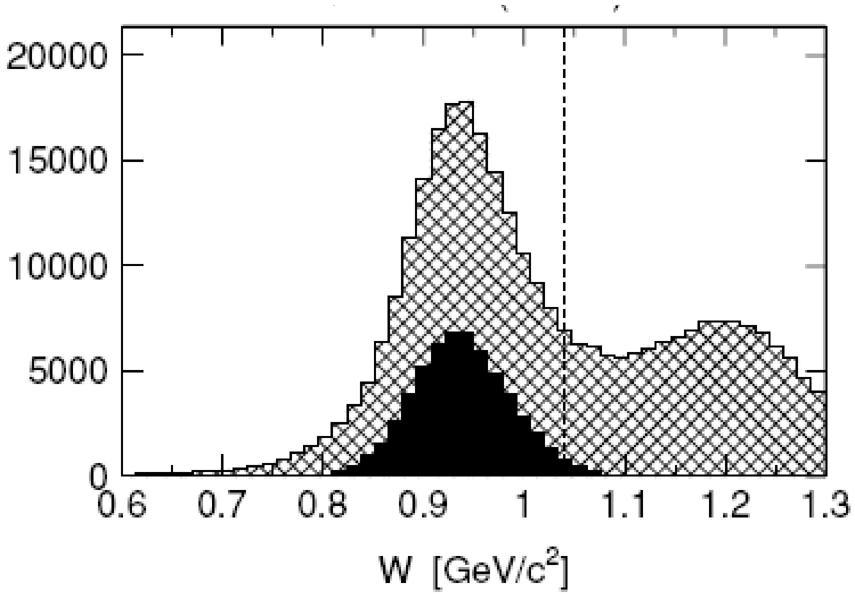


Quasielastic events: E93-038

E93-038: full range of kinematic acceptance at $Q^2 = 1.45\ (\mathrm{GeV}/c)^2$

p_{miss} vs. invariant mass W





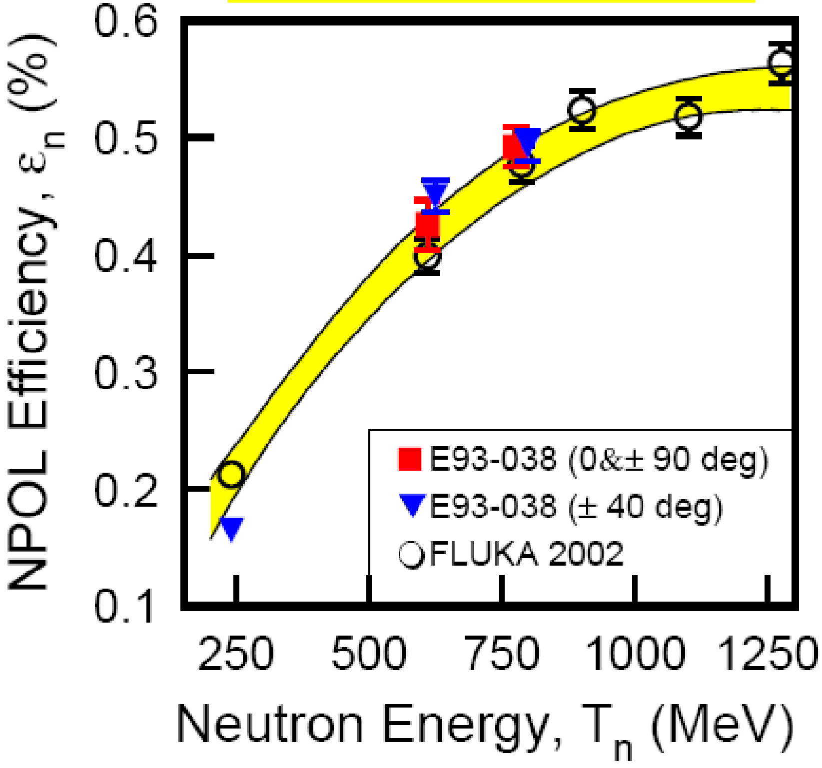
E93-038: tight cuts on

- Missing momentum
- Scattered electron momentum bite
- HMS-NPOL coincidence TOF

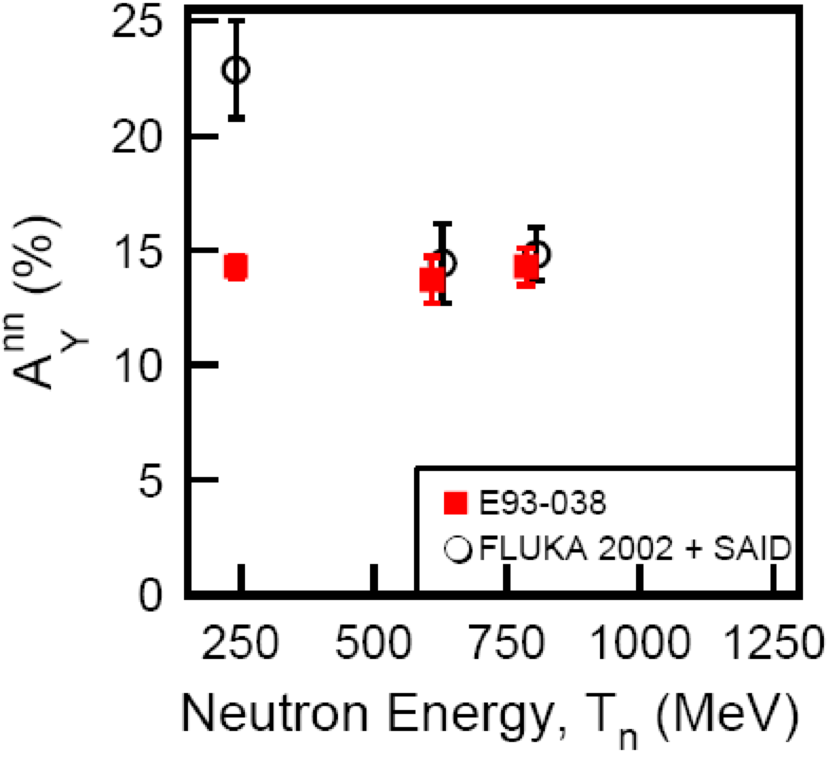
→ **Powerful selection tool for quasielastic neutrons**

NPOL performance

Neutron Efficiency



Analyzing Power

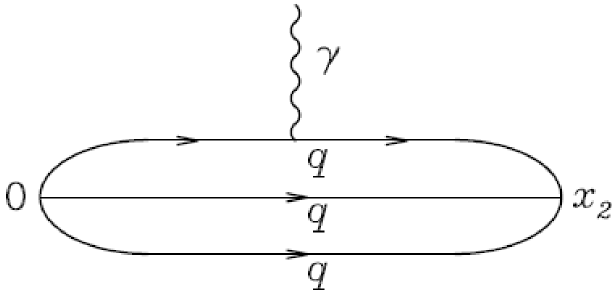


Agreement between simulation/data basis for extrapolation into higher neutron energy range

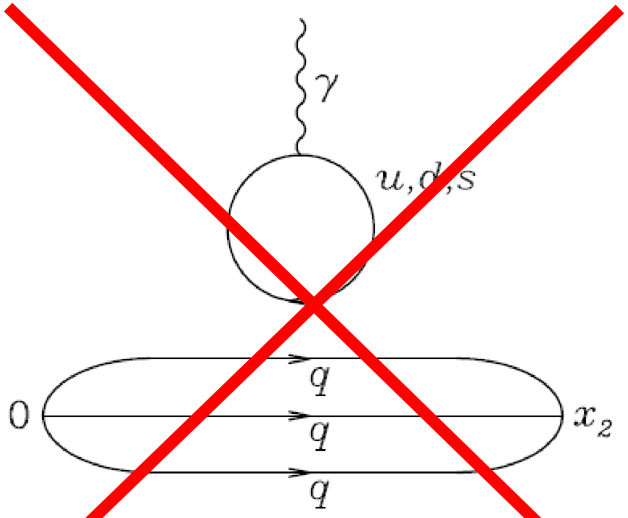
Lattice QCD calculations

Precision experimental data have potential to confront *ab initio* lattice QCD calculations of nucleon form factors

[from S. Boinepalli et al.,
PRD 74, 093005 (2006)]



"Connected" Diagrams



"Disconnected" Diagrams

Isovector
Form Factors

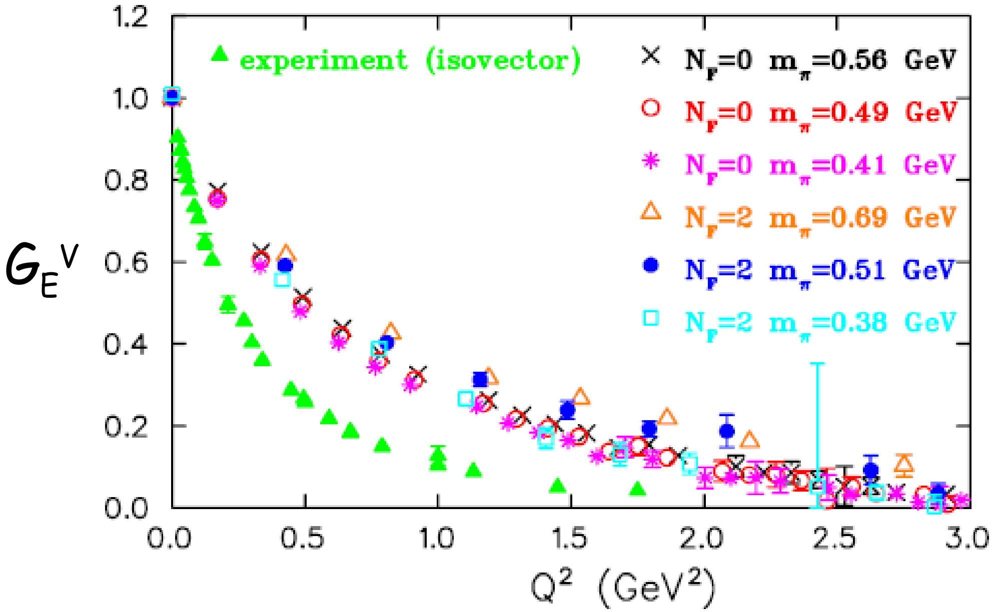
$$G_E^V(Q^2) = G_{Ep}(Q^2) - G_{En}(Q^2)$$

$$G_M^V(Q^2) = G_{Mp}(Q^2) - G_{Mn}(Q^2)$$

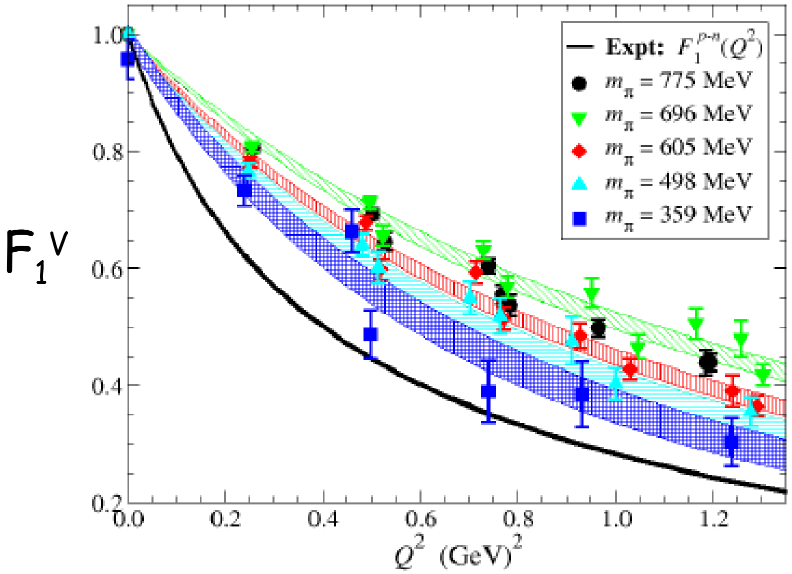
Requires proton
AND neutron
form factors

Lattice QCD calculations

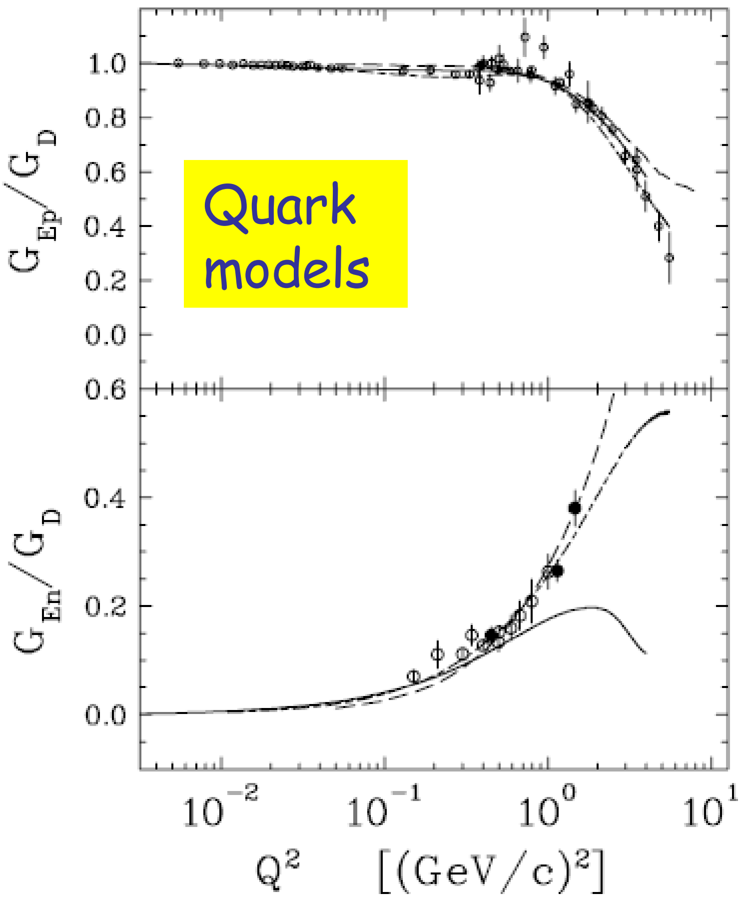
C. Alexandrou, G. Koutsou, J.W. Negele, and A. Tsapalis,
PRD 74, 034508 (2006)



LHPC Collaboration
hep-lat/0610007



Model calculations

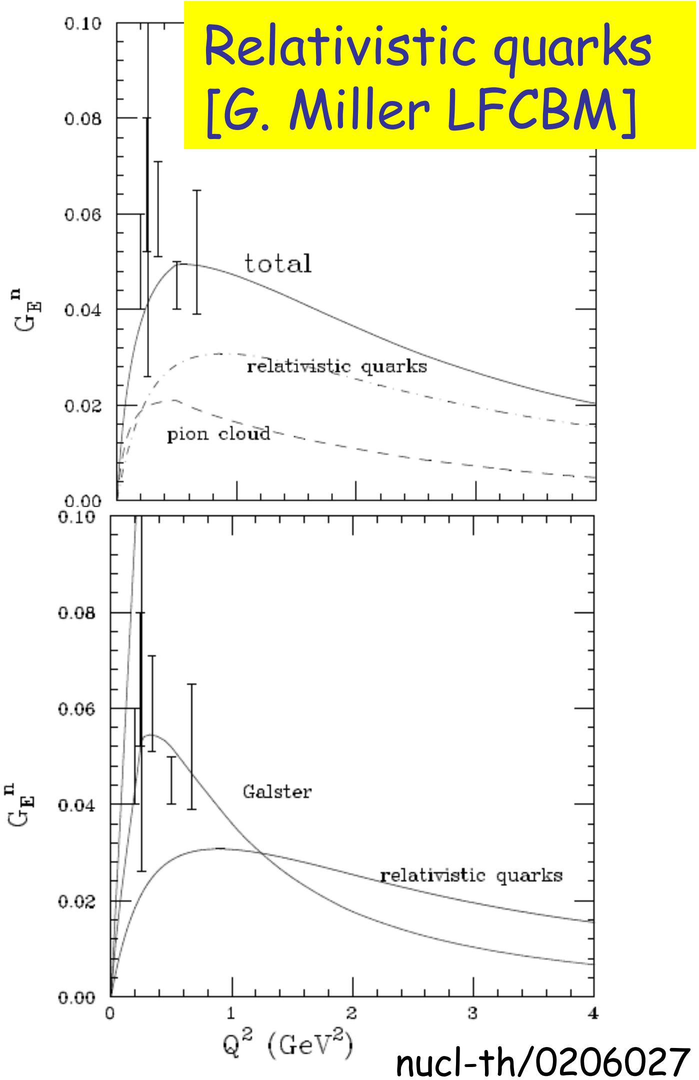


Quark models

———— PFSA

– – – – Light-front OGE + CQ FF

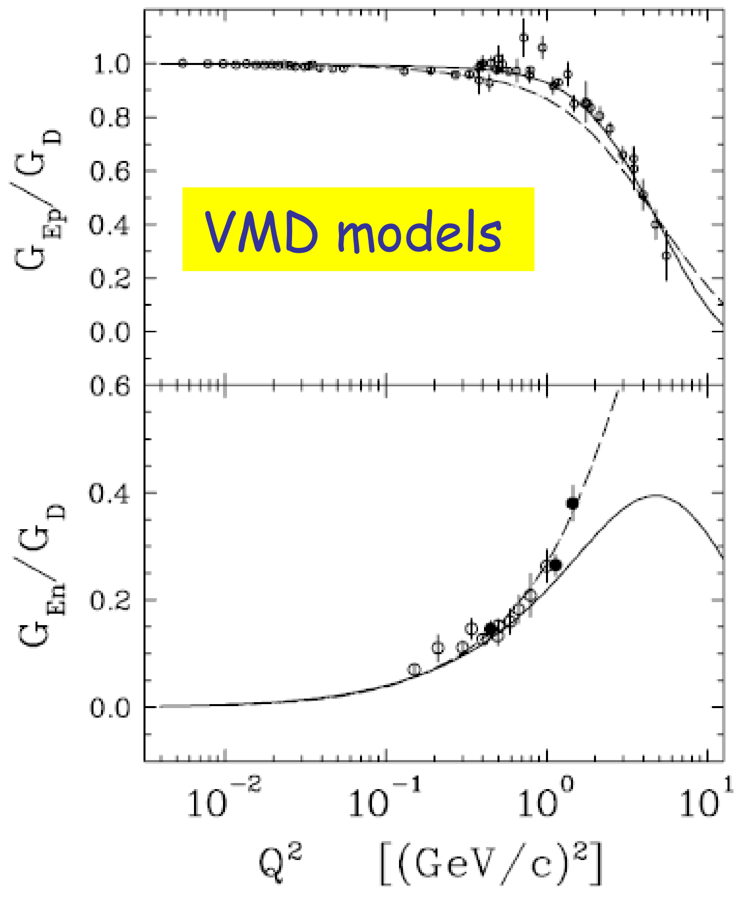
–·–·– hCQM + CQ FF



Relativistic quarks [G. Miller LFCBM]

nucl-th/0206027

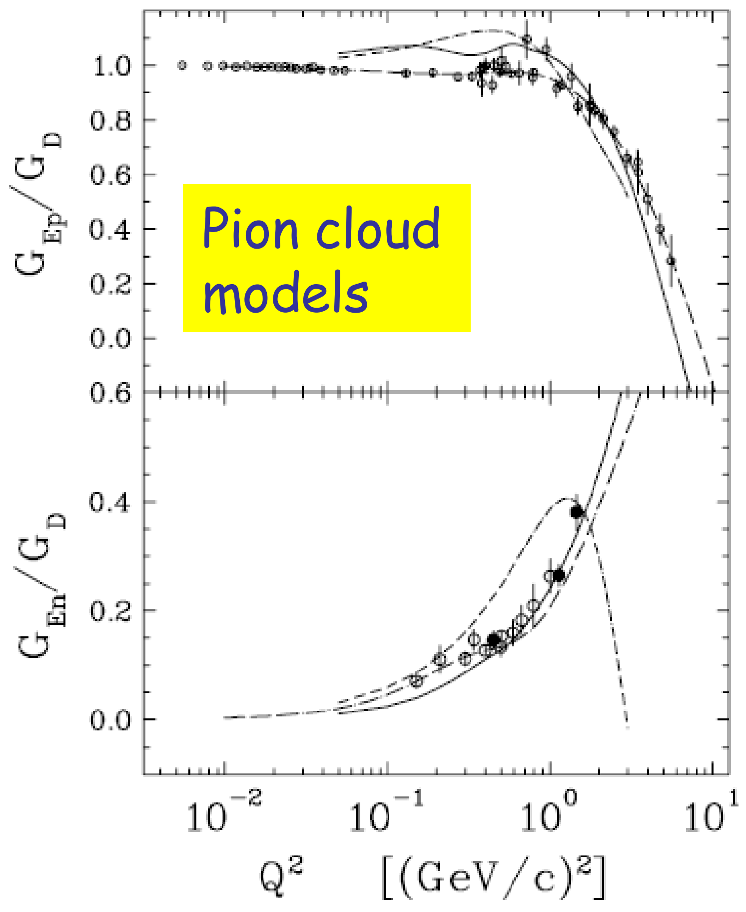
Model calculations



VMD models

—— Lomon

- - - - - Bijker and Iachello



Pion cloud models

—— Miller LFCBM

- - - - - QMC

— — — Friedrich and Walcher