Nucleon Form Factors

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Outline

- Introduction
- Formalism & Interpretation
  - *Definitions*
  - *Conceptual Interpretation*
  - *Limiting Values & 1$^{\mathrm{st}}$ order approximation*
  - *Modern Models*
- Measurements
  - *Summary of Techniques*
  - *Jlab Experiments*
  - *Hall C Experiments in Detail*
- Summary

Form Factors

spacial extent of charge & current (sub-structure)

$\longrightarrow$ anomalous magnetic moment

- Fundamental Quantities
- Test of QCD
- Required for Study of Other Physics
  - *Few-Body Structure Functions*

Formalism

Sachs Form Factors for Elastic Scattering

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} \times \left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2\frac{\theta_e}{2}\right]$$

$$\tau = \frac{Q^2}{4M^2}$$

Intuitive Interpretation

point-like probe ($Q^2 = 0$)

$$G_E^p = 1 \qquad G_M^p = \quad 2.79\ \mu_N$$

$$G_E^n = 0 \qquad G_M^n = -1.91\ \mu_N$$

Breit frame (NR limit)

Fourier Transform of Charge, Current Distribution

Basic Approximation: Dipole Fit

$$G(Q^2) \approx G(Q^2=0) \times G_D(Q^2)$$

$$G_E^p \approx G_D \quad G_E^n \approx 0 \quad G_M^p \approx 2.79\mu_N G_D \quad G_M^n \approx -1.91\mu_N G_D$$

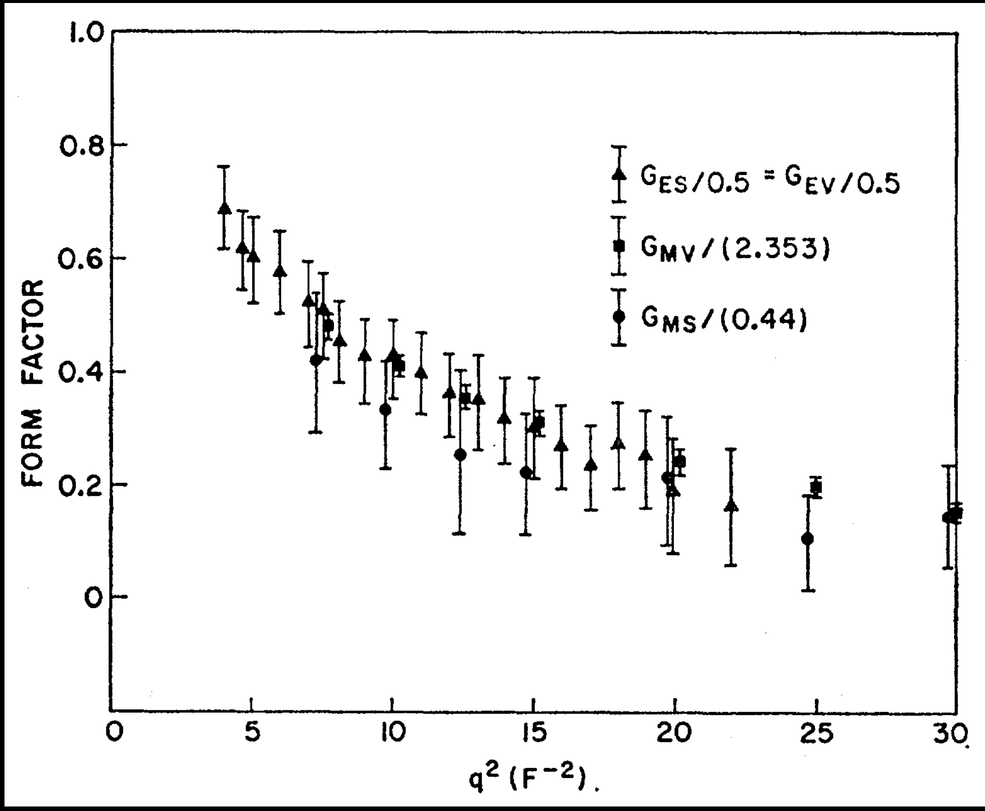
Phys. Rev. 139, B458 (1965)

Based on Exponential Charge Distribution $\sim e^{-\alpha r}$

FT fitted to Data:

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

corresp. to $<r>_{\rm RMS} = 0.81 fm$



Structure Functions

Form Factors for *Elastic* Scattering Only

More General:

Structure Functions $F_1(x, Q^2)$ and $F_2(x, Q^2)$

In the Limit of Elastic Scattering ($x \rightarrow 1$):

$$\begin{aligned} G_E(Q^2) &= F_1(Q^2) - \tau\mu F_2(Q^2) \\ G_M(Q^2) &= F_1(Q^2) + \mu F_2(Q^2) \end{aligned}$$

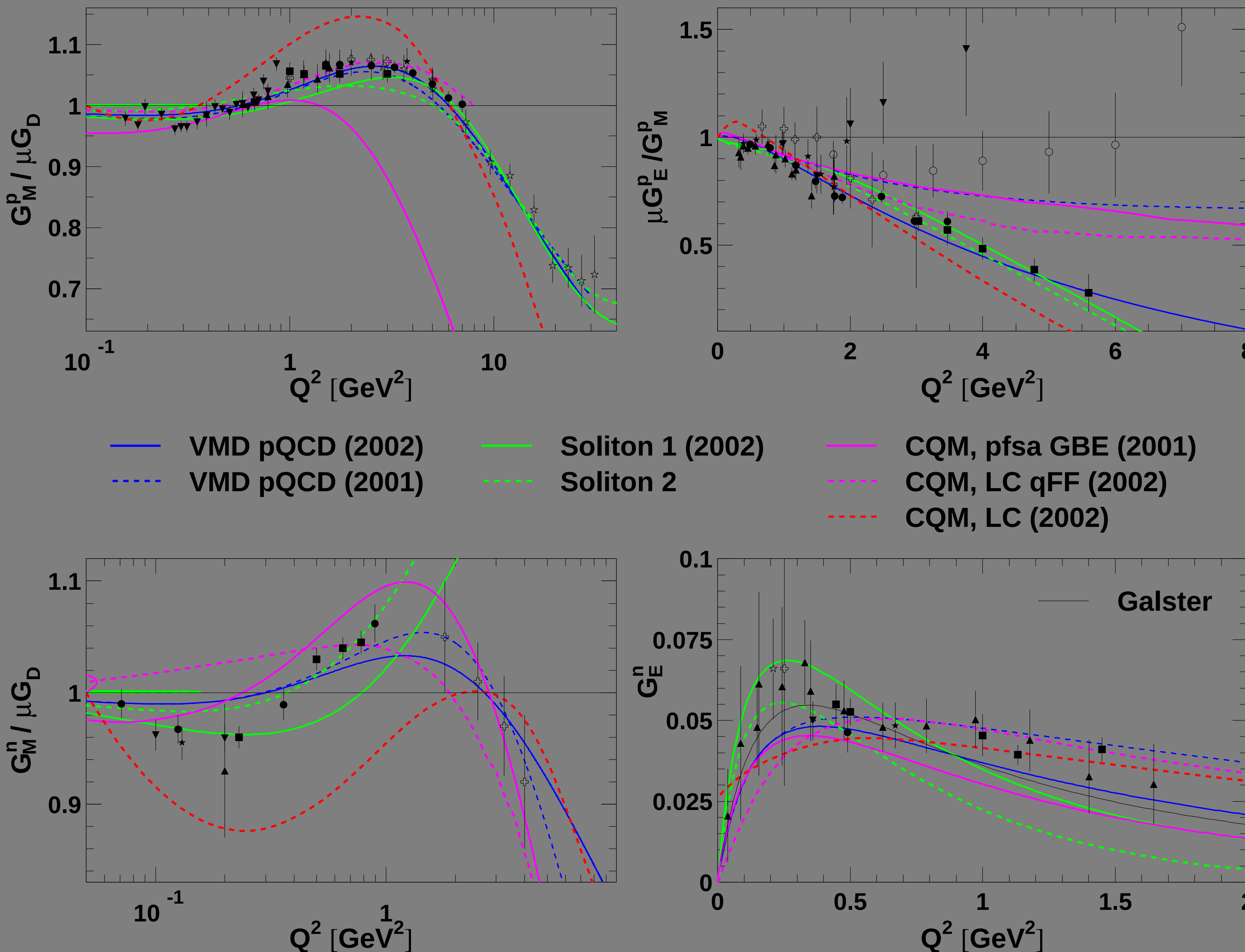
Current Status

Data:

- All Form Factors Measured (G_E^p, G_M^p, G_E^n, G_M^n)
- $0 \leq Q^2 < \sim 10\ GeV^2$

Models:

- Several QCD-based Models
  - *Vector Meson Dominance pQCD*
  - *light front CQM, Goldstone Boson Exchange CQM*
  - *Solitons*
- None Well Describe all Form Factors over *Entire* Measured Range



$G_M^p / \mu G_D$
Q^2 [GeV^2]
$\mu G_E^p / G_M^p$
Q^2 [GeV^2]
VMD pQCD (2002)
VMD pQCD (2001)
Soliton 1 (2002)
Soliton 2
CQM, pfsa GBE (2001)
CQM, LC qFF (2002)
CQM, LC (2002)
$G_M^n / \mu G_D$
Q^2 [GeV^2]
G_E^n
Galster
Q^2 [GeV^2]

Form Factor Measurements

Traditional Methods:

- Cross Section Based
- Rosenbluth Separation

$$\frac{d\sigma}{d\Omega} \sim \frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2 \frac{\theta_e}{2}$$

- Highly Sensitive to Wavefunction Models

Polarization-Based Methods:

- Polarization Observables (asymmetry, LT-ratio)
- Complex Setups
- Asymmetry Measurements Require Absolute Polarization

Form Factors at Jefferson Lab

Proposal, Hall		Form Factor	Technique, Reaction		Year
93-026	C	G_E^n	Asymmetry	$\vec{D}(\vec{e}, e'n)p$	1998,2001
93-027	A	G_E^p/G_M^p	Recoil	$^1\mathrm{H}(\vec{e}, e'\vec{p})$	1998
93-038	C	G_E^n/G_M^n	Recoil	$^2\mathrm{H}(\vec{e}, e'\vec{n})p$	2000/2001
94-017	B	G_M^n	Ratio	$\frac{d(e,e'n)p}{d(e,e'p)n}$	2000
95-001	A	G_M^n	Asymmetry	$^3\overrightarrow{\mathrm{He}}(\vec{e}, e')X$	1999
99-007	A	G_E^p/G_M^p	Recoil	$^1\mathrm{H}(\vec{e}, e'\vec{p})$	2000
01-001	A	G_E^p	Rosenbluth	$^1H(e,p)$	2002
01-109	C	G_E^p/G_M^p	Recoil	$^1\mathrm{H}(\vec{e}, e'\vec{p})$	2005
02-013	A	G_E^n	Asymmetry	$^3\overrightarrow{\mathrm{He}}(\vec{e}, e'n)$	2004

Hall C Form Factor Measurements

Exp. 93-026

- measured G_E^n from polarization asymmetry
- ran 1998 and 2001
- 1998 measurement provided highest Q^2 point at the time

Exp. 93-038

- measured G_E^n from recoil polarization
- ran 2000 and 2001
- currently most accurate measurement at large Q^2

Exp. 01-109

- scheduled to run 2005
- will measure G_E^p/G_M^p through recoil polarization
- extension of spectacular Hall A results

Asymmetry Measurement – Formalism

$$\left(\frac{d\sigma}{d\Omega}\right)^{pol} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \times \left[\Sigma + h\,\mathcal{P}_{\text{target}}\,\Delta\right]$$

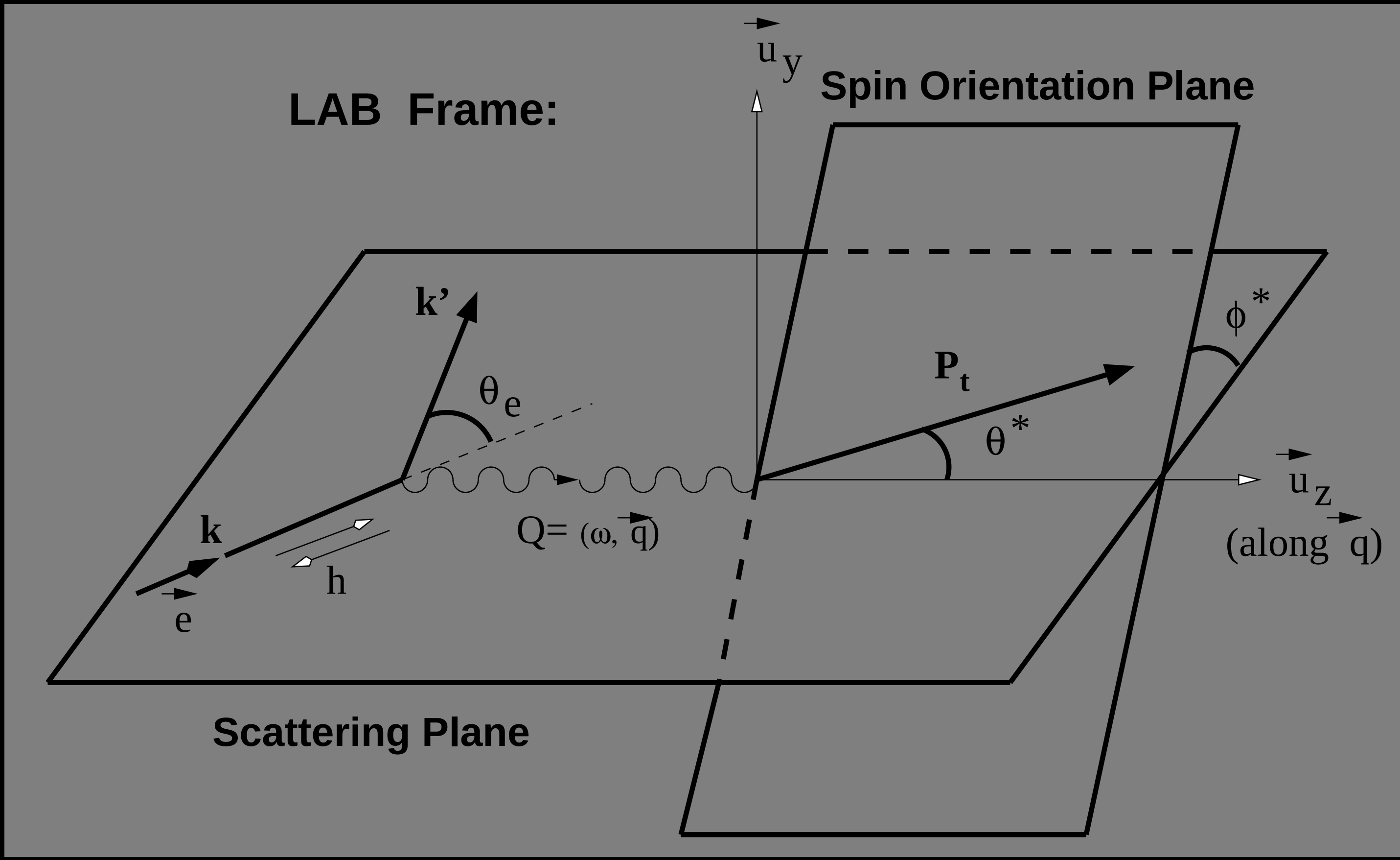
$$\Sigma = \left[\frac{{G_E}^2 + \tau {G_M}^2}{1+\tau} + 2\tau {G_M}^2 \tan^2\frac{\theta_e}{2}\right]$$

$$\Delta = -2\tan\frac{\theta_e}{2}\sqrt{\frac{\tau}{1+\tau}} \times \left[\sqrt{\tau\left(1+(1+\tau)\tan^2\frac{\theta_e}{2}\right)}\cos\theta^*\,{G_M}^2 + G_E\,G_M\sin\theta^*\cos\phi^*\right]$$

Measurement via Vector Asymmetry $A^V = \frac{\Delta}{\Sigma} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$

Asymmetry Measurement – Formalism

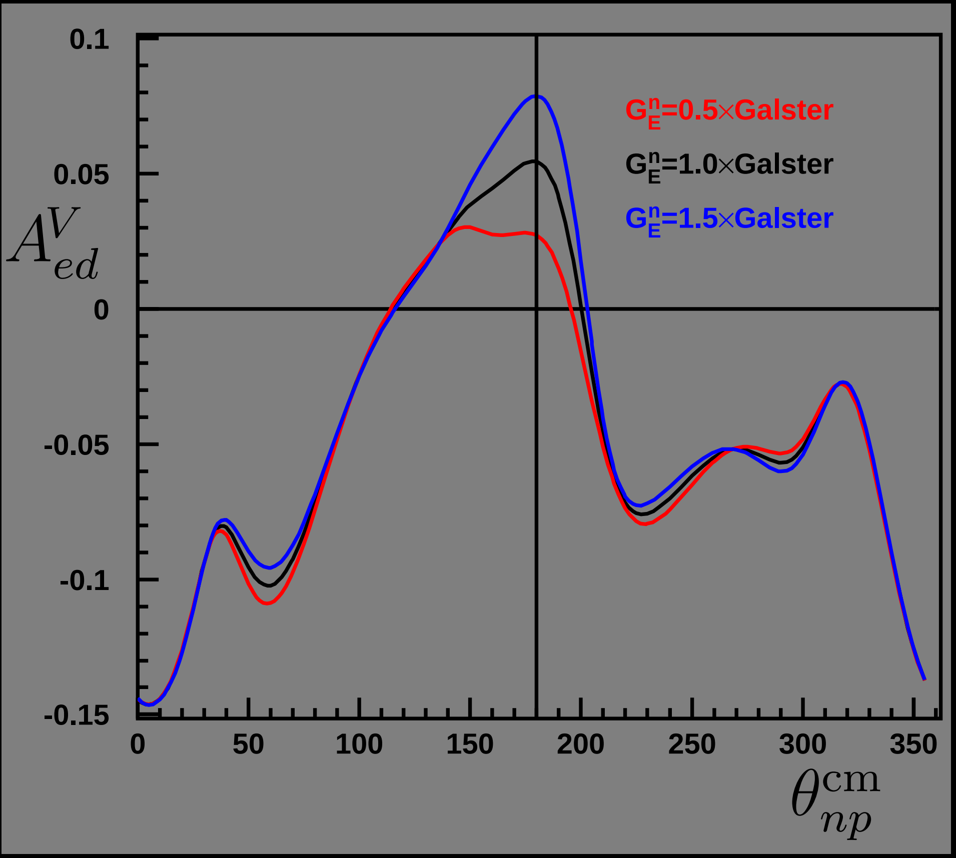
for quasi-free,
$\mathcal{P}_{\mathrm{target}} \perp \vec{q}$
$(\theta^* = 90^o)$
and
$\mathcal{P}_{\mathrm{target}}$ in
scattering plane
$(\phi^* = 0)$,

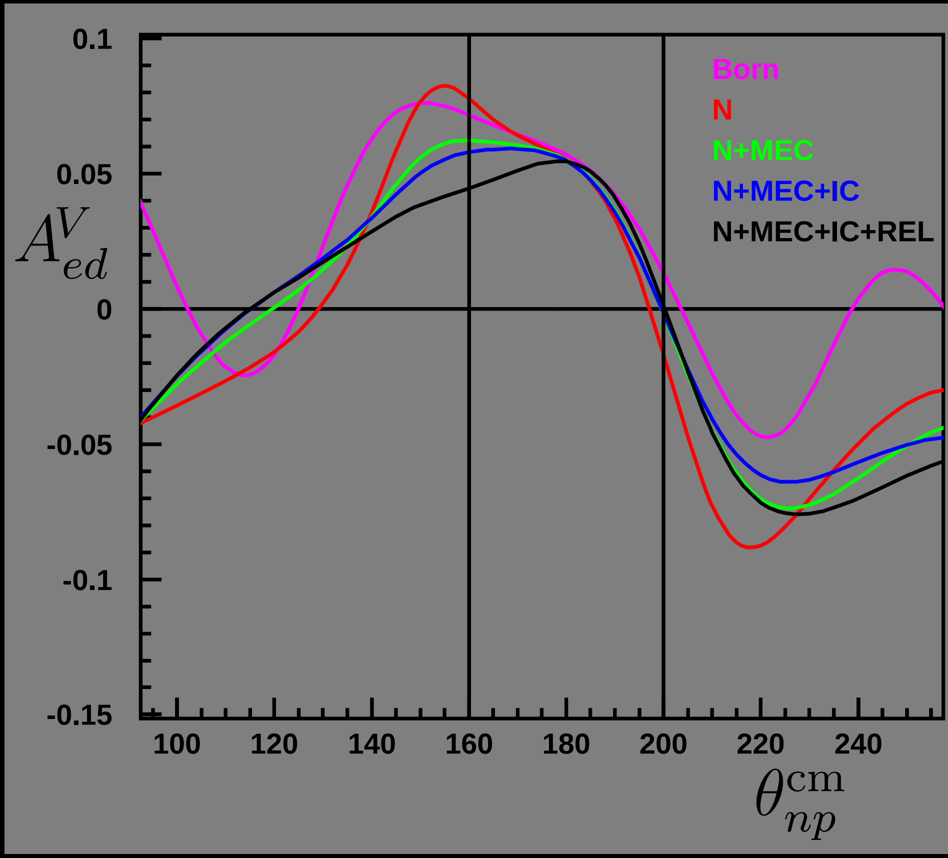


$$A^V = \frac{-2\sqrt{\tau(1+\tau)}\ \tan\frac{\theta_e}{2}\ G_E\ G_M}{{G_E}^2 + \tau[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}]\ {G_M}^2}$$

Gen01 at QE Kinematics

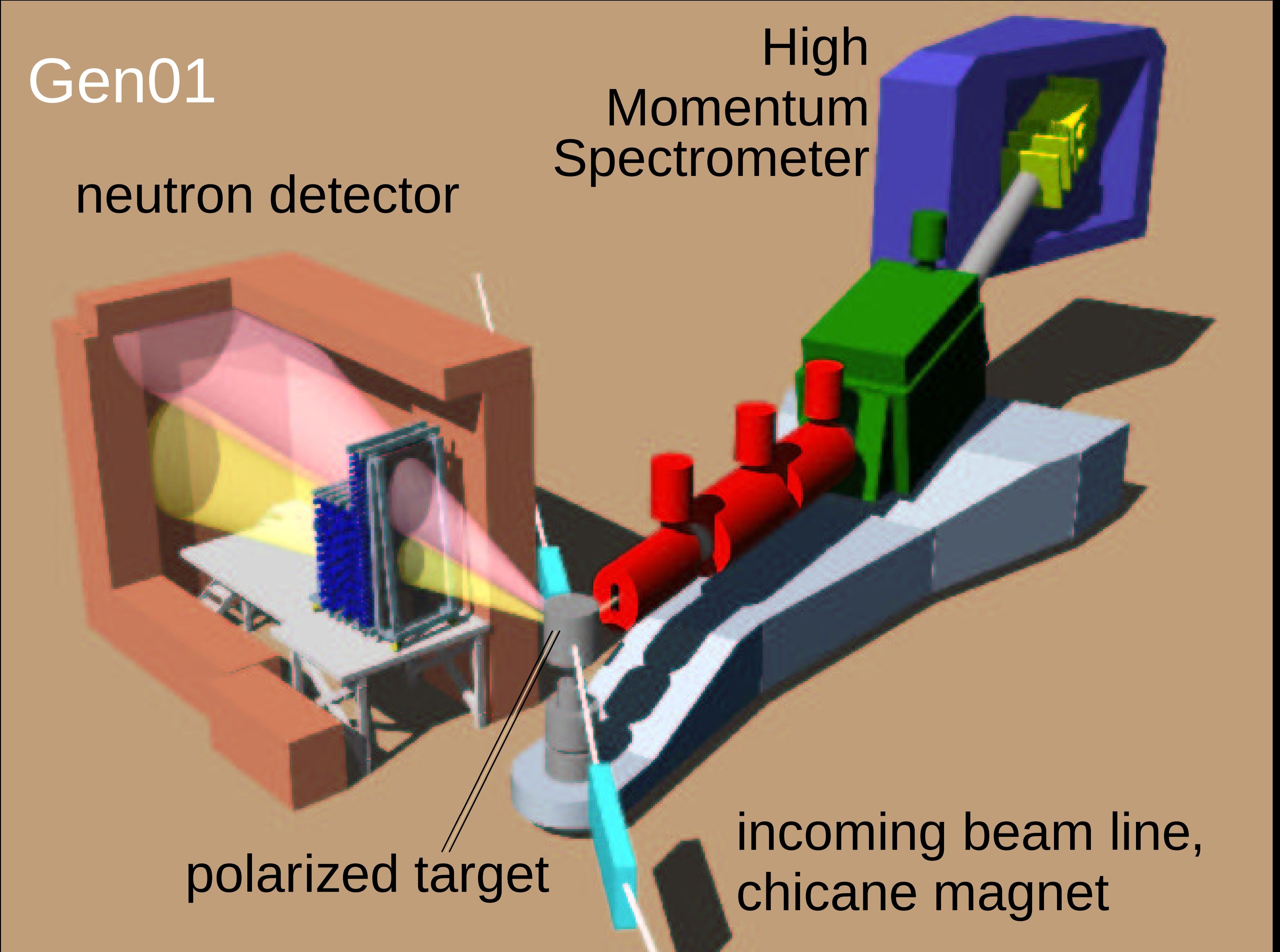
E93-026 Measured G_E^n via Polarization Asymmetry in QE Scattering off Deuterium





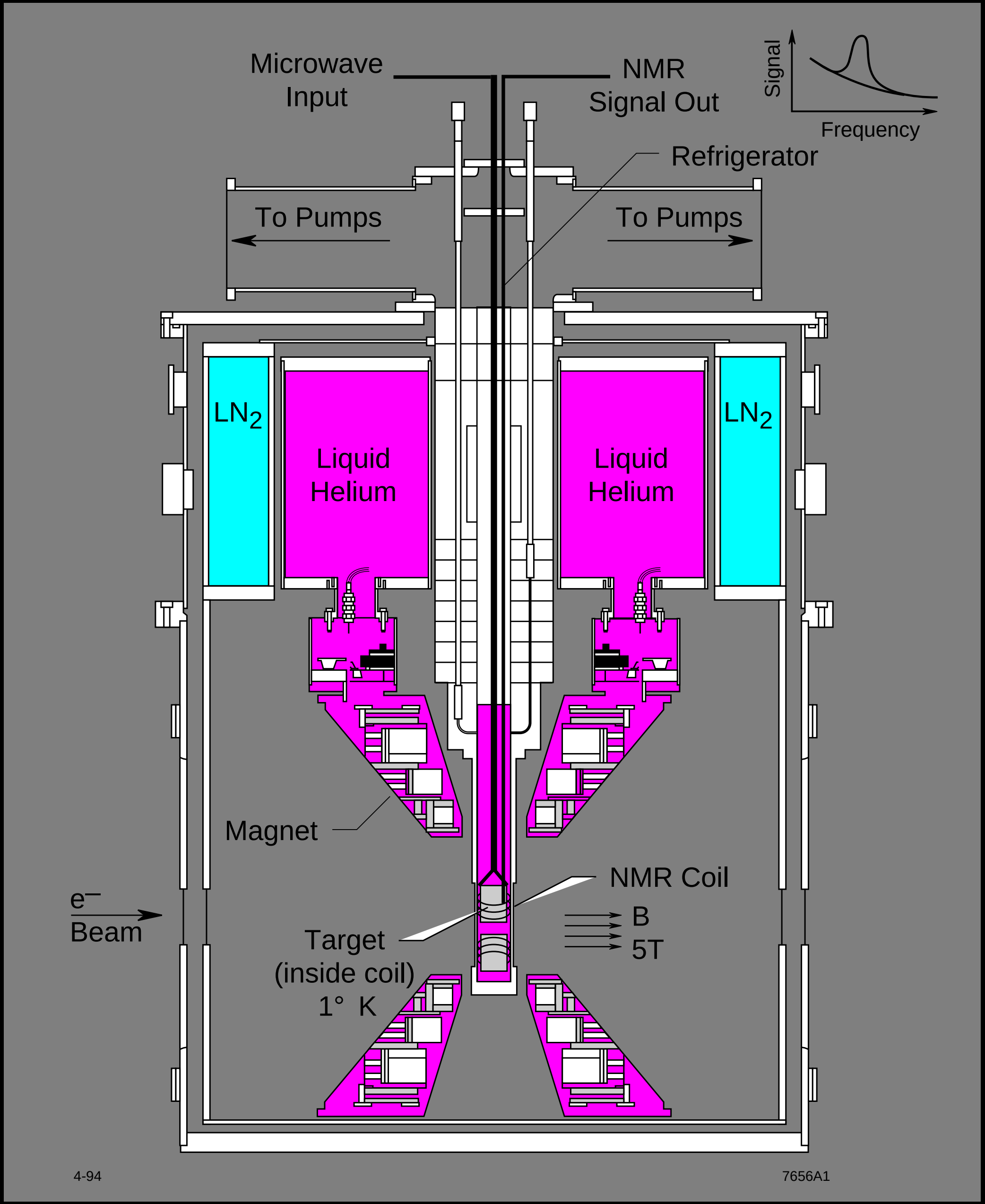
Large Sensitivity to G_E^n

Small Model Dependence


Gen01
High
Momentum
Spectrometer
neutron detector
polarized target
incoming beam line,
chicane magnet

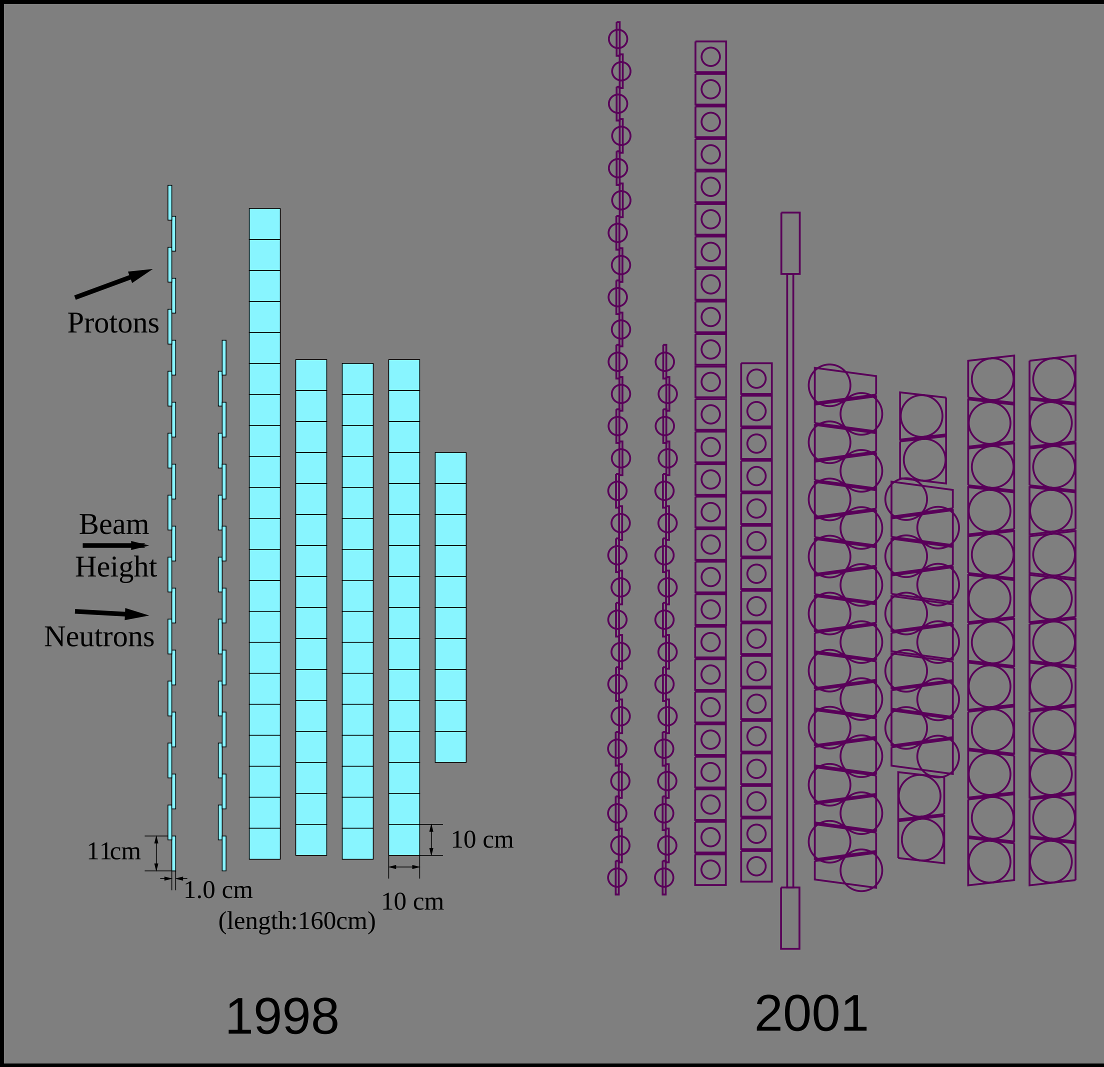
Gen01 – Polarized Target

- frozen ND_3
- ^{4}He evaporation refrigerator
- $5T$ polarizing field
- remotely movable insert
- dynamic nuclear polarization driven by microwaves

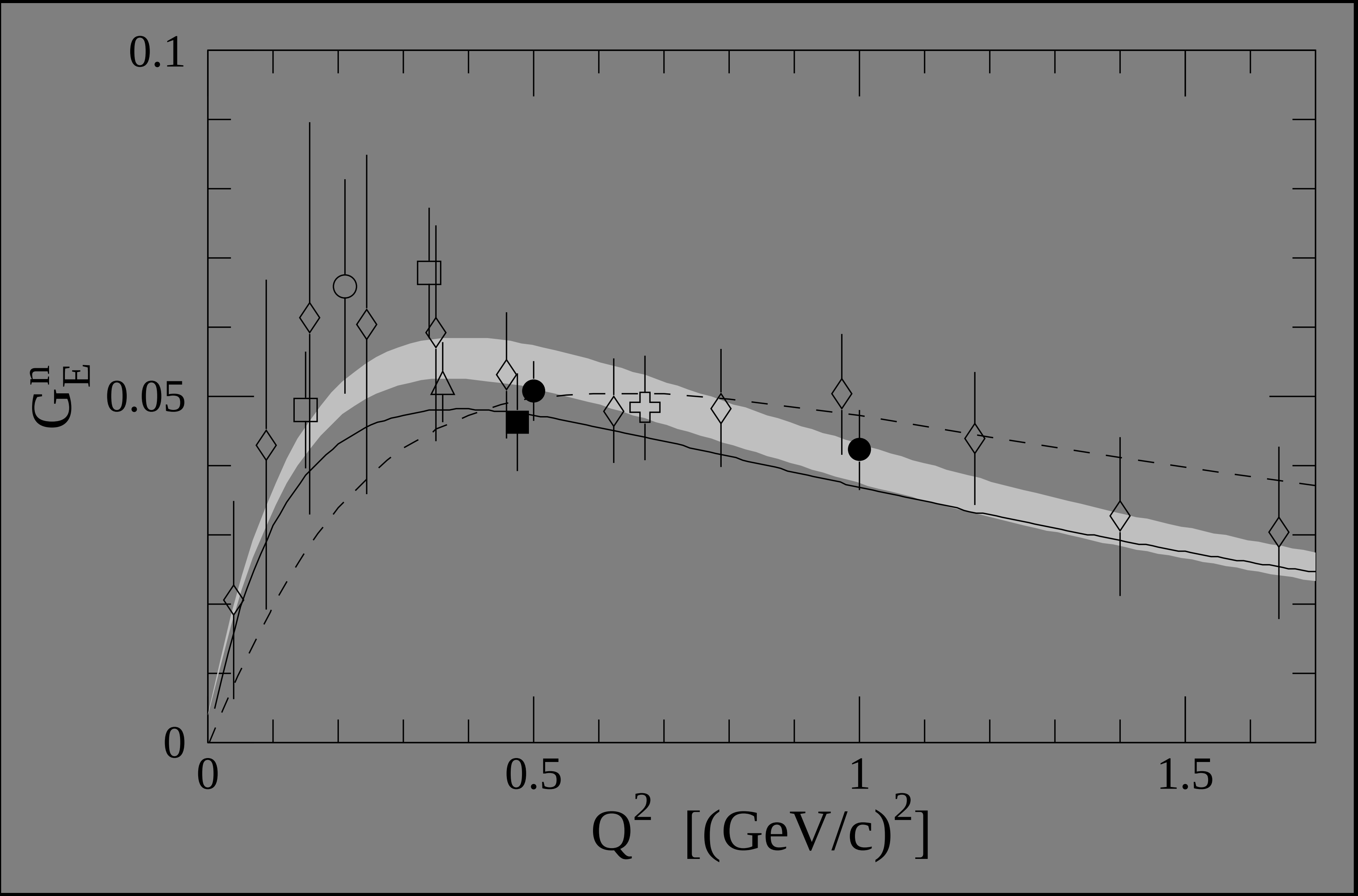


Gen01 – Neutron Detector

- segmented scintillator
  - *2 p^+ VETO layers*
  - *6 conversion layers*
  - *high rate: $\sim 100\,kHz$*
- vertically extended for symmetric proton acceptance
- provides 3 space coords, time & energy

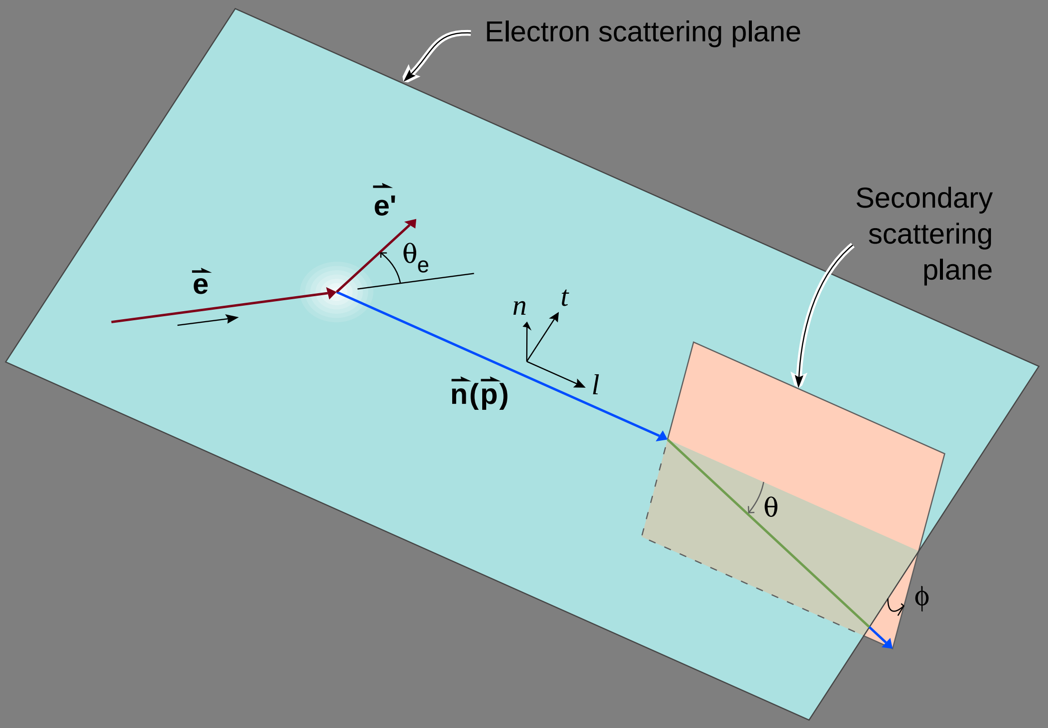


Gen01 – Results



nucl-ex/0308021

Recoil Polarimetry – Formalism



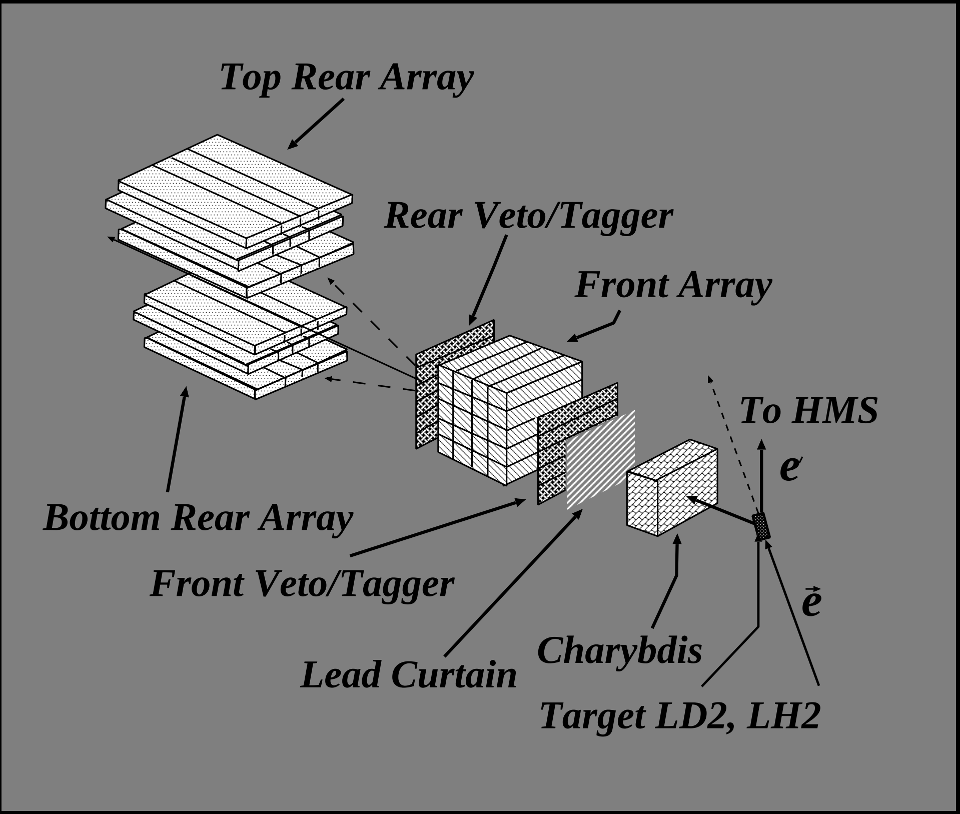
$$I_0 P_t = -2\sqrt{\tau(1+\tau)}\, G_E G_M \tan(\theta_e/2)$$

$$I_0 P_l = \frac{1}{M_N}(E_e + E_{e'})\sqrt{\tau(1+\tau)}\, G_M^2 \tan^2(\theta_e/2)$$

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

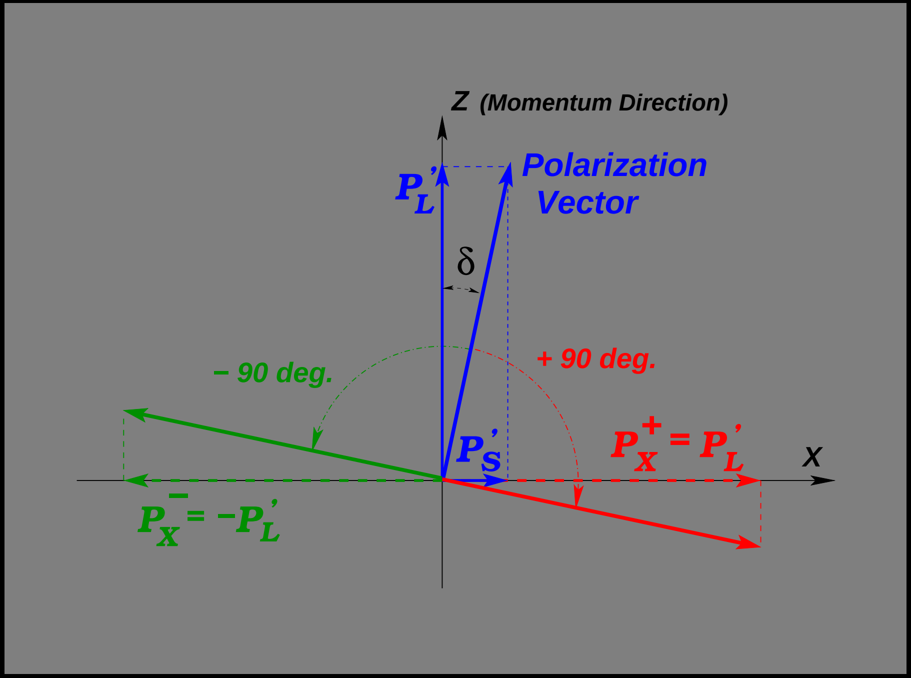
Direct measurement of form factor ratio by measuring the ratio of the transfered polarization P_t and P_l

Recoil Polarimetry – E93-038



want to determine P_l and P_t at target

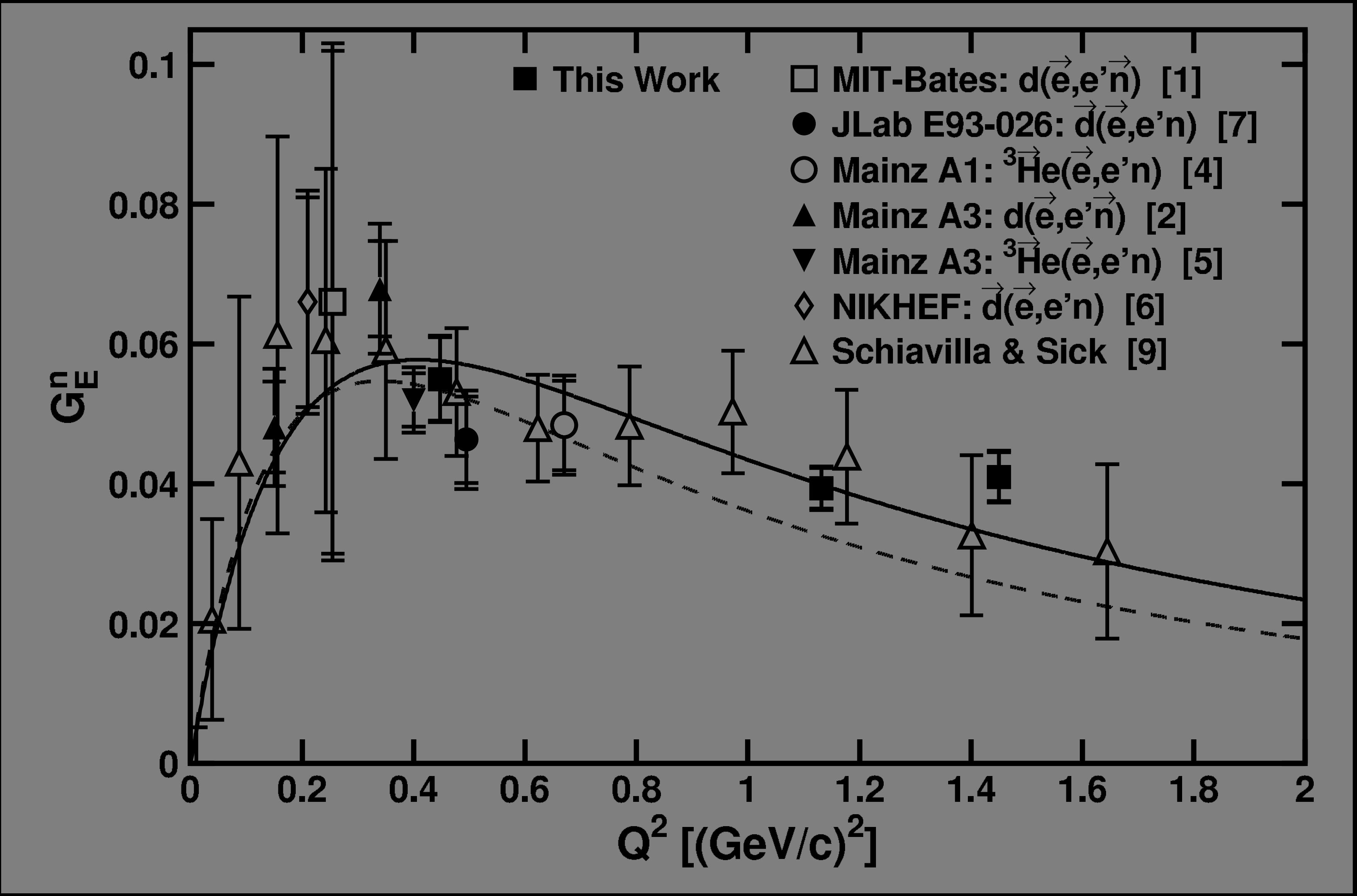
polarimeter sensitive to transverse pol only



→ rotate longitudinal pol with *Charybdis* magnet

$$P_t^{\mathrm{pol}} = P_l \sin\chi + P_t \cos\chi$$

E93-038 – Results



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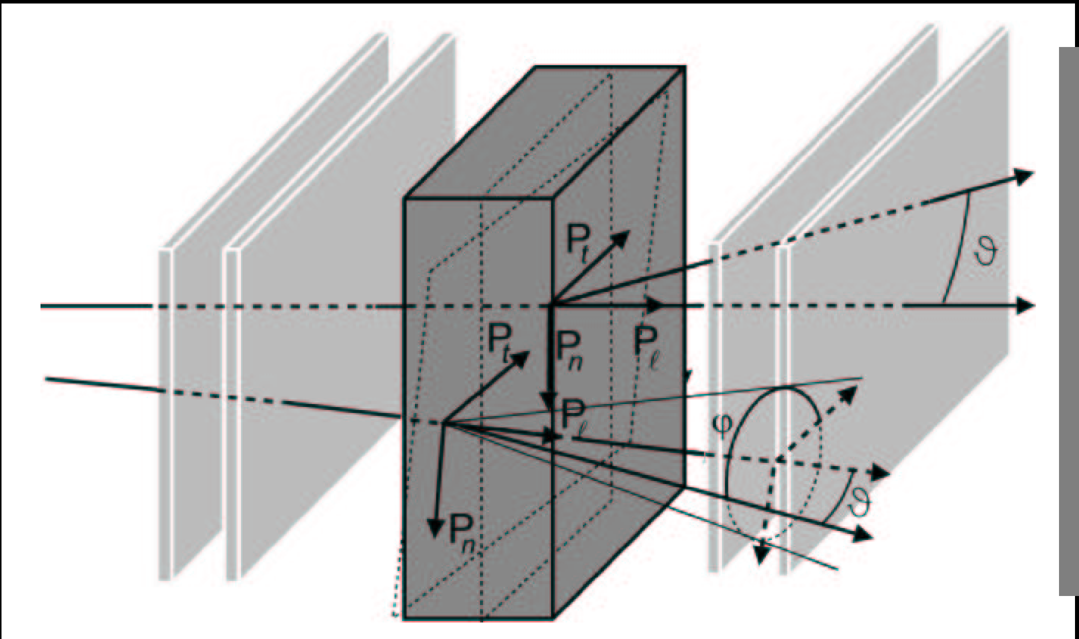
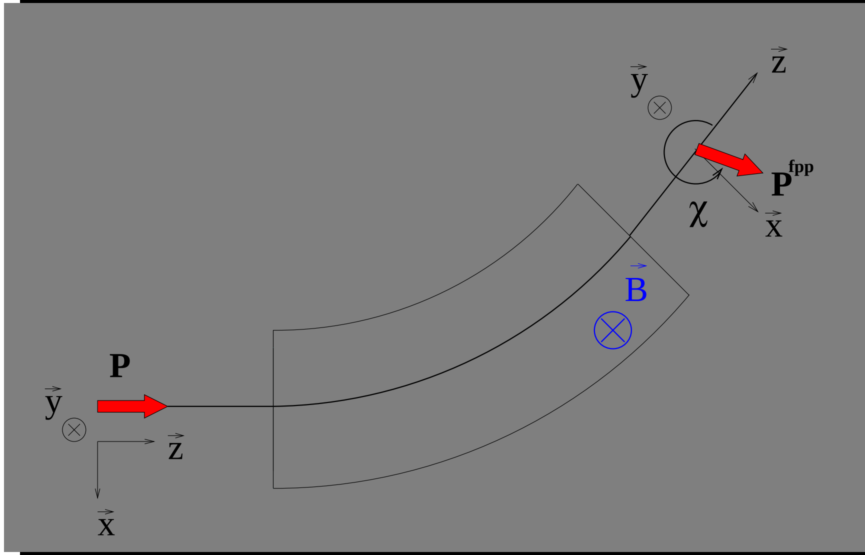
Recoil Polarimetry – E01-109

- Detect proton in HMS,
  Scattered e^- in Custom Calorimeter
- HMS spectrometer rotates polarization vector

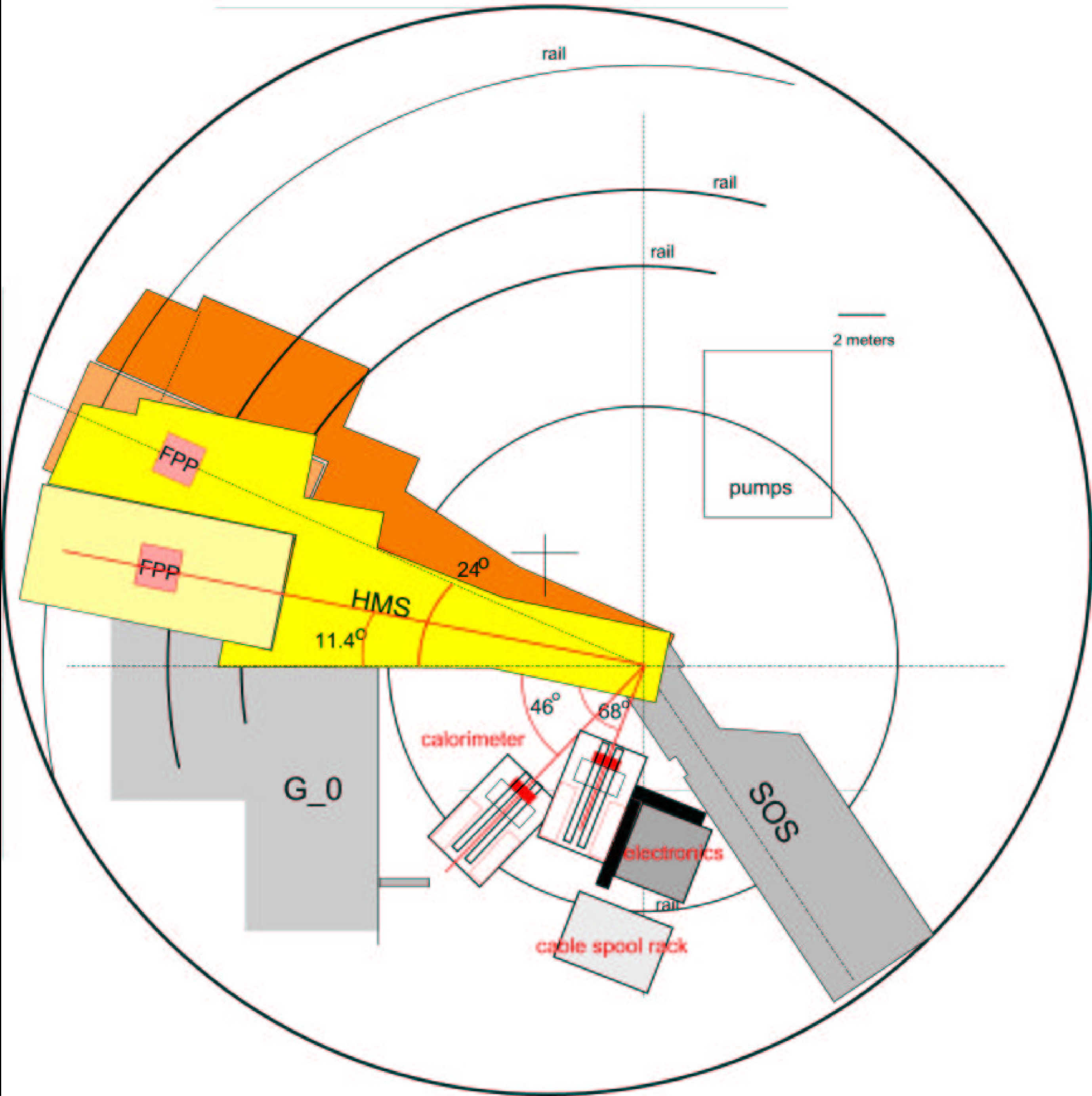




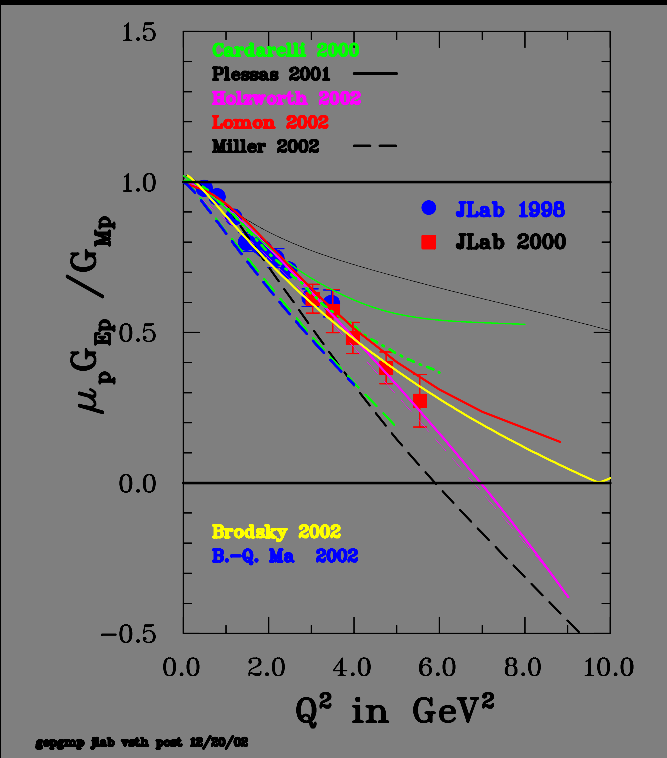
- Transverse Polarization *is* Affected (Quads!)

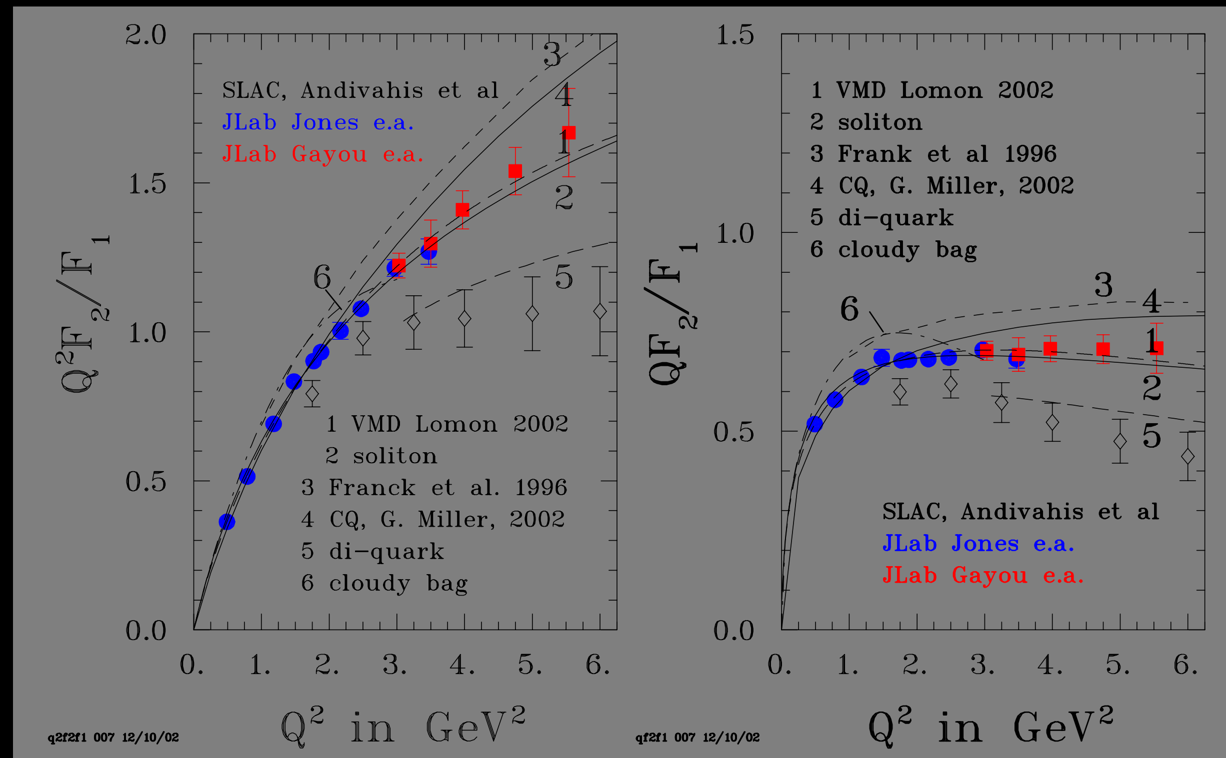
HallC_floor_6 scale 5 mm per meter 1:200 12/17/02 CFP

01-109 in Hall C



G_E^p *in Hall A*





More to come...

Summary

- Form Factors are Vital to Our Understanding of Nature
- Many Experiments have Already been Undertaken
  - *limited kinematic range*
- Significant Contribution from Hall C, other Halls
  - *two recent G_E^n measurements*
  - *upcoming G_E^p/G_M^p*
- Polarization Observables Provide High Accuracy