Spin Physics in Jefferson Lab's Hall C

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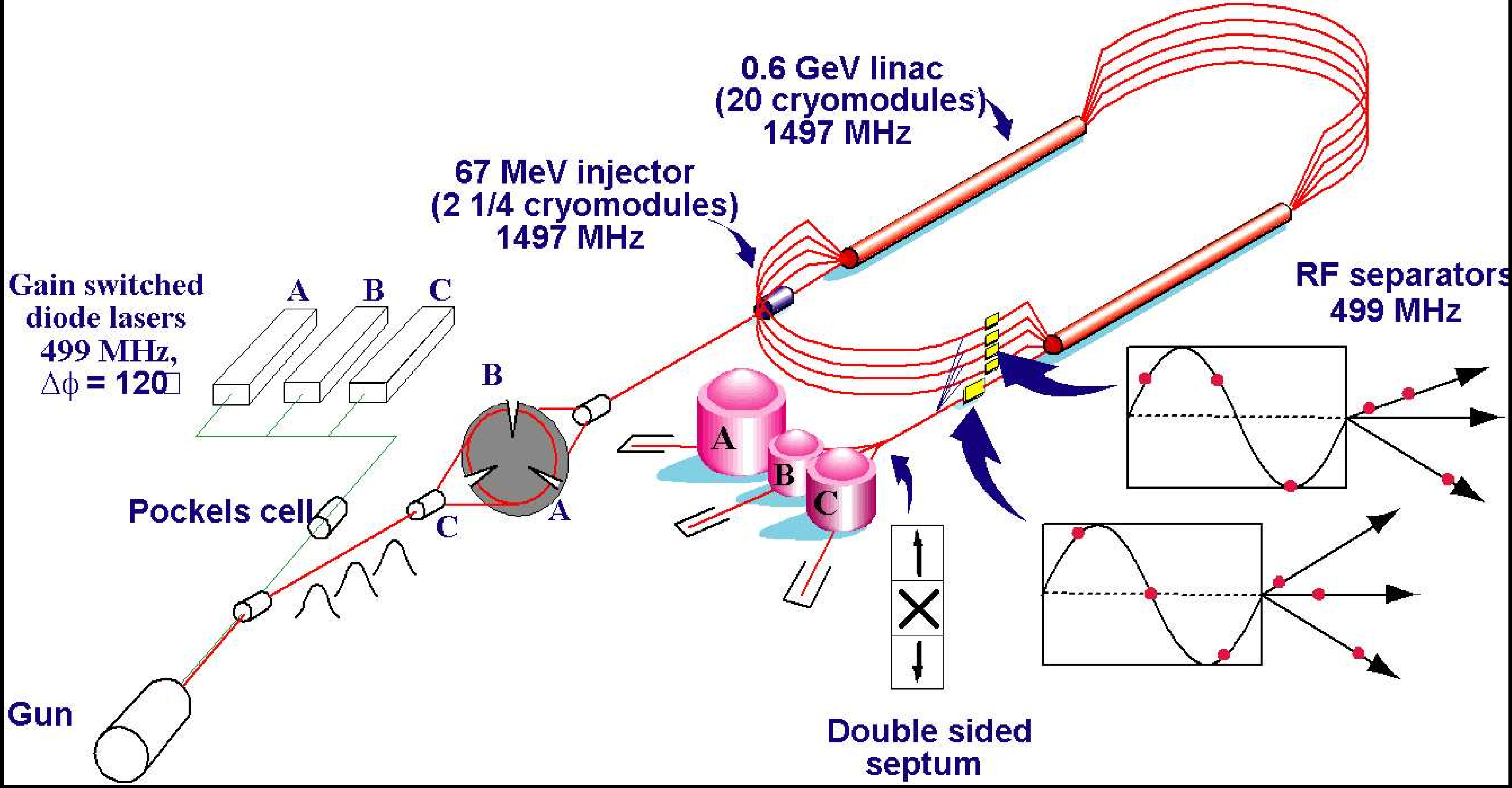
Outline

- Introduction
  - *Jefferson Lab, Hall C*
  - *Concepts & Definitions*
- Experiments & Measurements
  - *Spin as Goal*
  - *Spin as Tool*
- Summary & Outlook



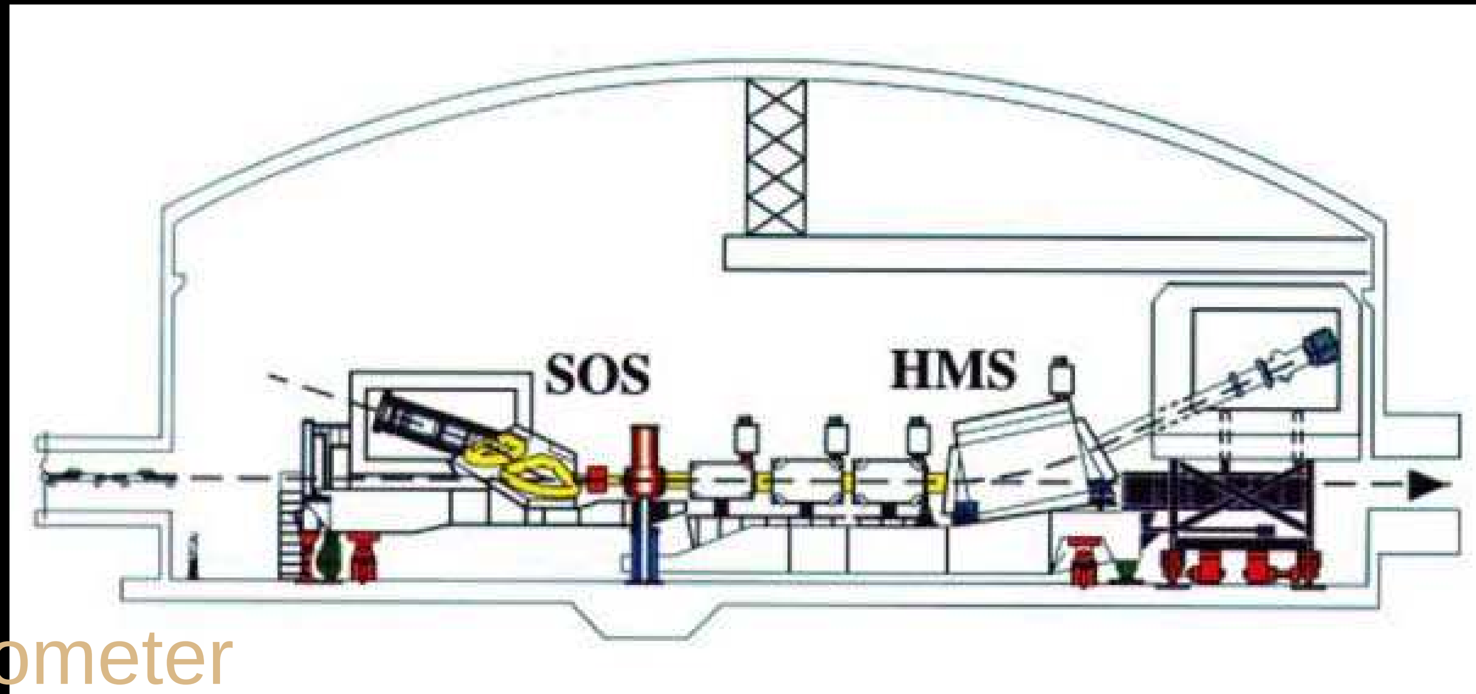
CEBAF: Continuous Electron Beam Accelerator Facility

at the

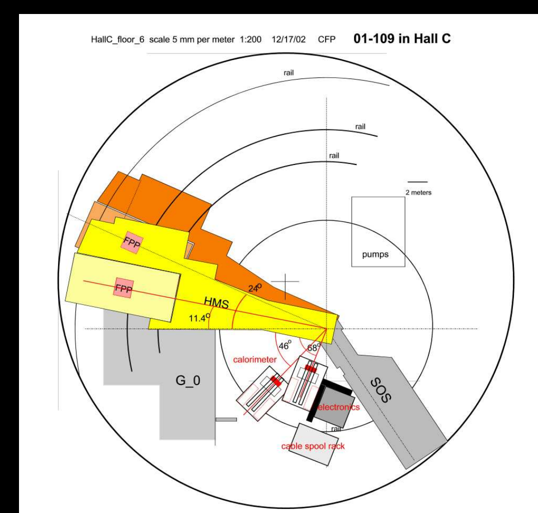
Thomas Jefferson National Accelerator Facility

Newport News, Virginia, USA

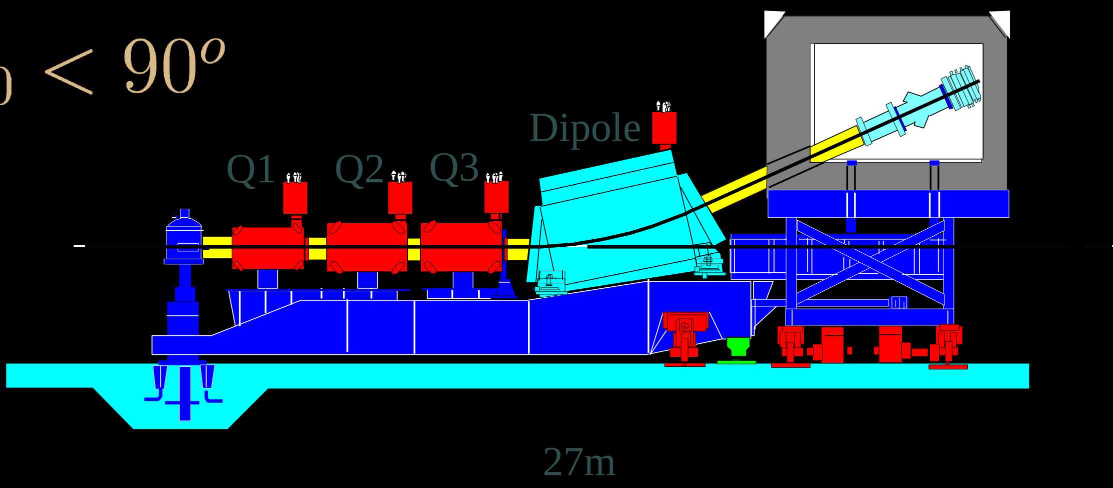
Introduction – Hall C



- 2 Spectrometer
  - *High Momentum Spectrometer, Short Orbit Spectrometer*
- Cryogenic Target: ℓH_2, ℓD_2, solids
  - *or: UVa Polarized Target, other options*
- Møller Polarimeter for Beam
  - *Compton Polarimeter being added*
- G^0 target & detectors



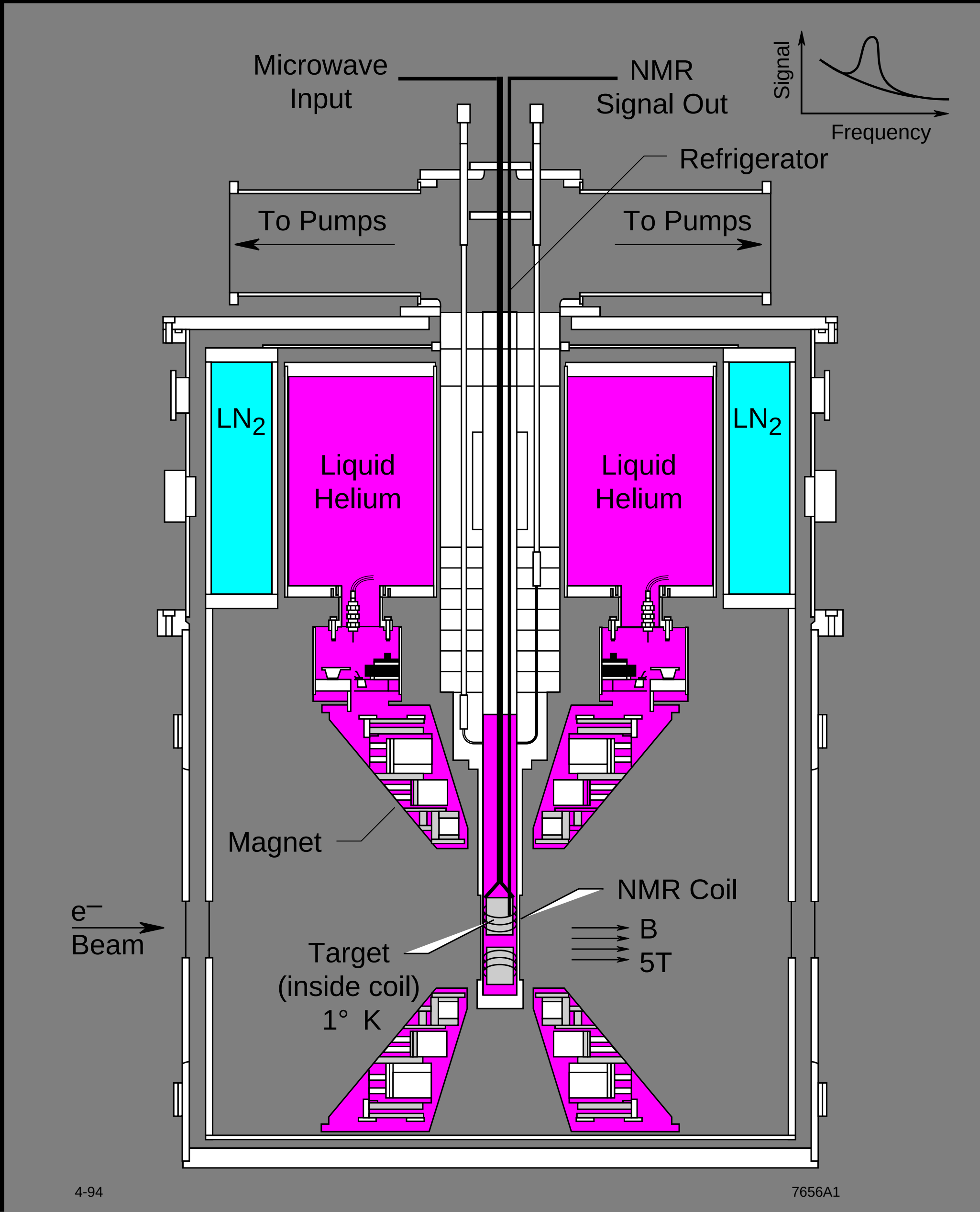
High Momentum Spectrometer



- movable: $12.5^o < \theta_0 < 90^o$
- 1 dipole magnet,
  3 quadrupoles
  - $\pm 9\%$ *acceptance*
  - $0.5 < p_0 < 7.5\ GeV/c$
- shielded detector package
  - *scintillator hodoscopes, wire drift chambers*
  - *gas Cerenkov, segmented Pb glass calorimeter*
- well-studied tracking, reconstruction
  - *provides electron ID, event time, momentum & energy*
  - *determines track position & direction at target*

UVa Polarized Target

- frozen NH_3, ND_3, LiD
- ^{4}He evaporation refrigerator
- $5T$ polarizing field
- remotely movable insert
- dynamic nuclear polarization driven by microwaves
- NMR system for polarization measurement



Spin Experiments in Hall C

Two Basic Categories of Experiments:

- Spin is the *Goal*
  - *Polarization Measurements (T_{20})*
  - *Spin Structure Functions (RSS, SANE)*
- Spin is a *Tool*
  - *Form Factor Measurements (G_E^n, G_E^p/G_M^p)*
  - *Parity Experiments (G^0, Q_{weak})*

omitting some subjects, e.g. spin-dependent transitions in hyperon nuclear spectroscopy (E-89-009, E-01-011)

Experiments – Spin as Goal

- T_{20} (E-94-018):
  Deuteron Tensor Polarization
  - *published*
- RSS (E-01-006):
  Resonance Region Spin Structure Functions
  - *ongoing analysis*
- SANE (E-03-109):
  Spin Asymmetries of the Nucleon Experiment
  - *planned, 2007?*

E-94-018: T_{20}

Measurement of the Deuteron Tensor Polarization at Large Momentum Transfers in $D(e, e'd)$ Scattering

- Ran in 1997 – published
- Coincidence Measurement of Deuteron Tensor Polarization Observables t_{20}, t_{21} and t_{22}
- Used $\ell\,{}^2H_2$ Target, HMS & Custom Polarimeter
- Via Analyzing Interaction ${}^1H(\vec{d}, 2p)n$ in Secondary $\ell\,{}^1H_2$ Target
- Relate to Deuteron Form Factors G_C (monopole), G_M (magnetic dipole) and G_Q (quadrupole)

E-94-018: T_{20}

Measurement via Efficiency ϵ

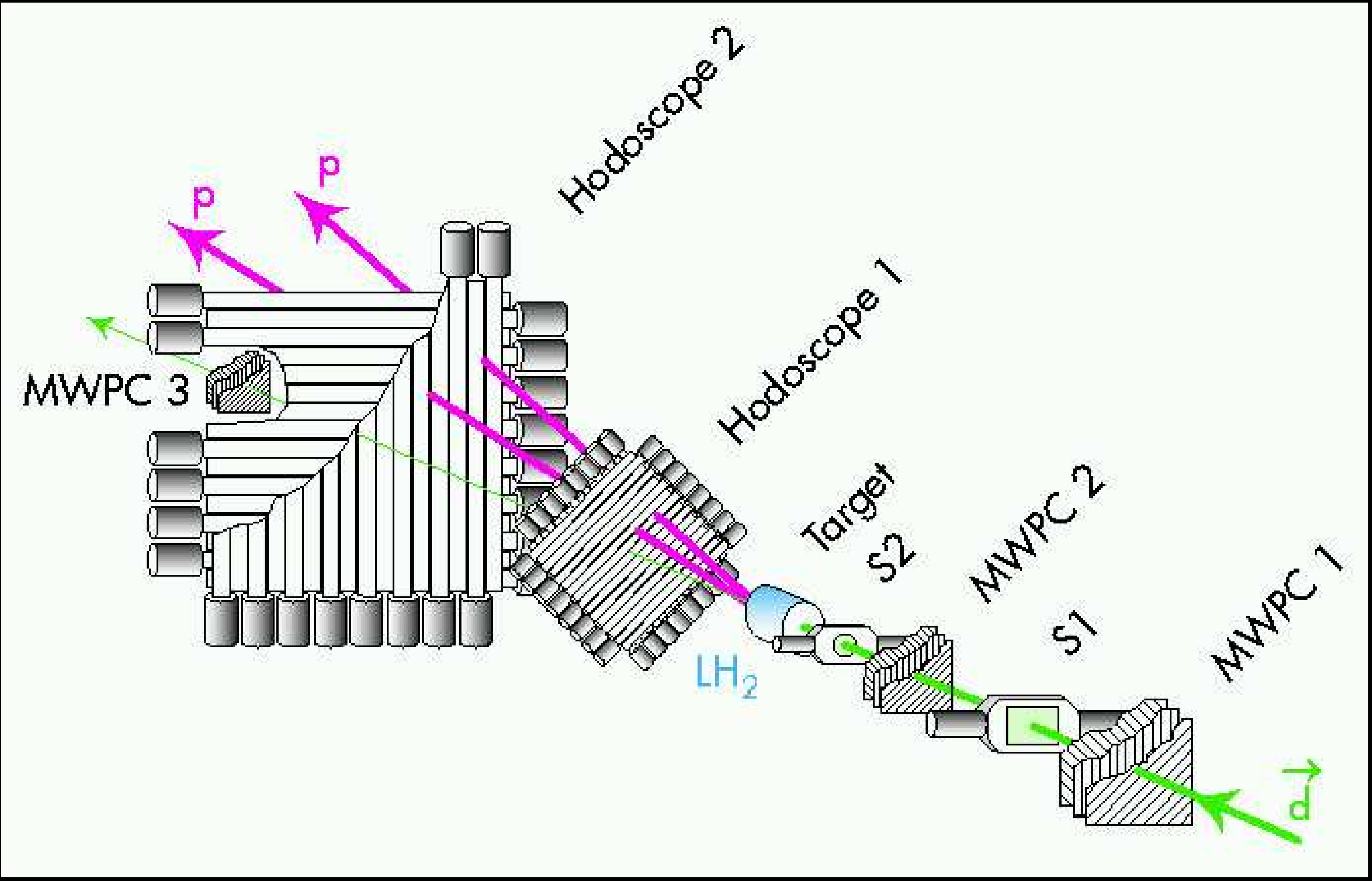
of Analyzing Interaction ${}^1H(\vec{d}, 2p)n$:

$$\frac{\epsilon_{\text{pol}}(\theta,\phi)}{\epsilon_{\text{unpol}}(\theta)} = 1 + t_{20}\mathcal{T}_{20}(\theta) + 2\cos(\phi)\; t_{21}\mathcal{T}_{21}(\theta) + 2\cos(2\phi)\, t_{22}\mathcal{T}_{22}(\theta)$$

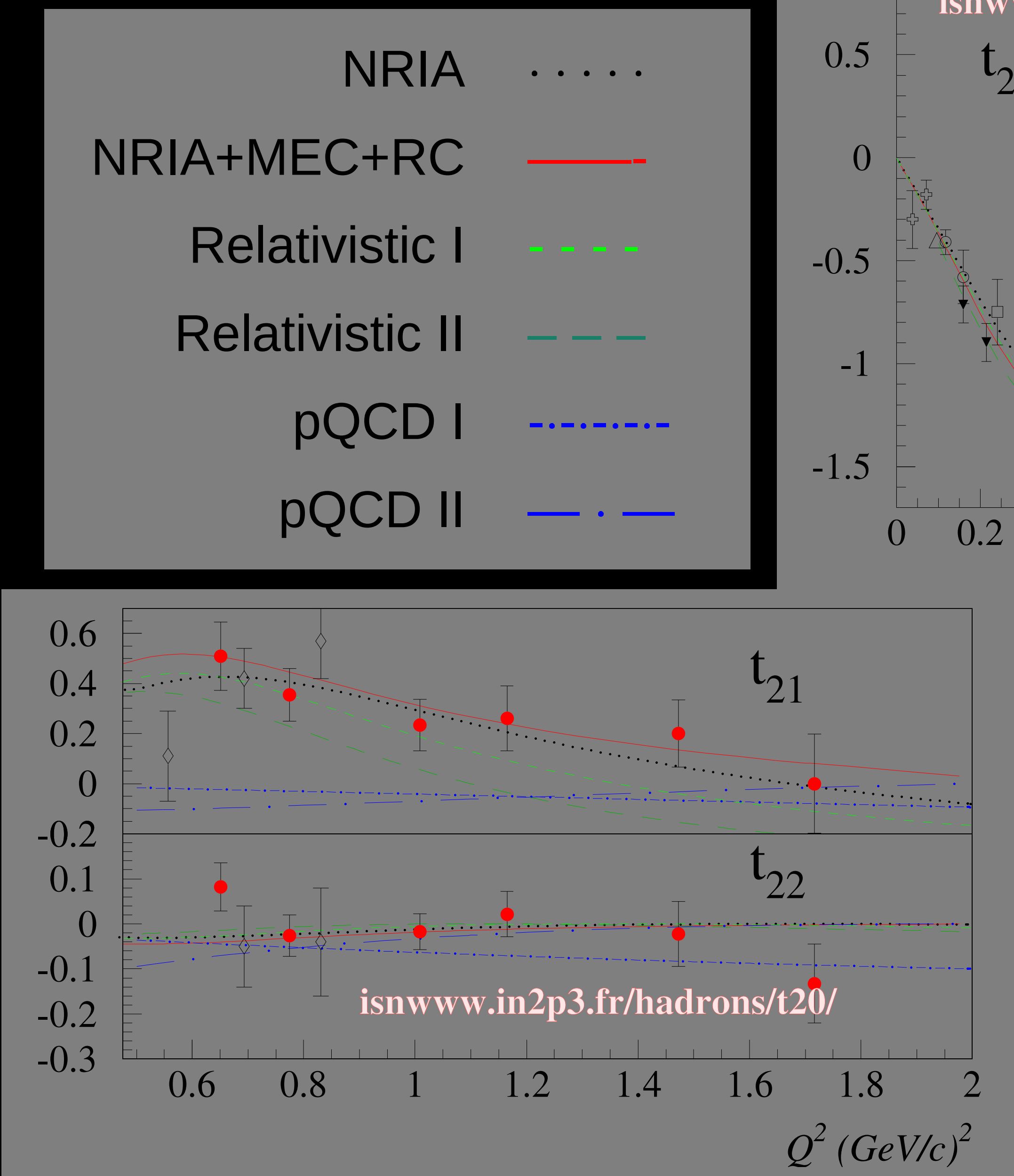
$\mathcal{T}_{2x}$ and ϵ_{unpol} independently from **SATURNE**

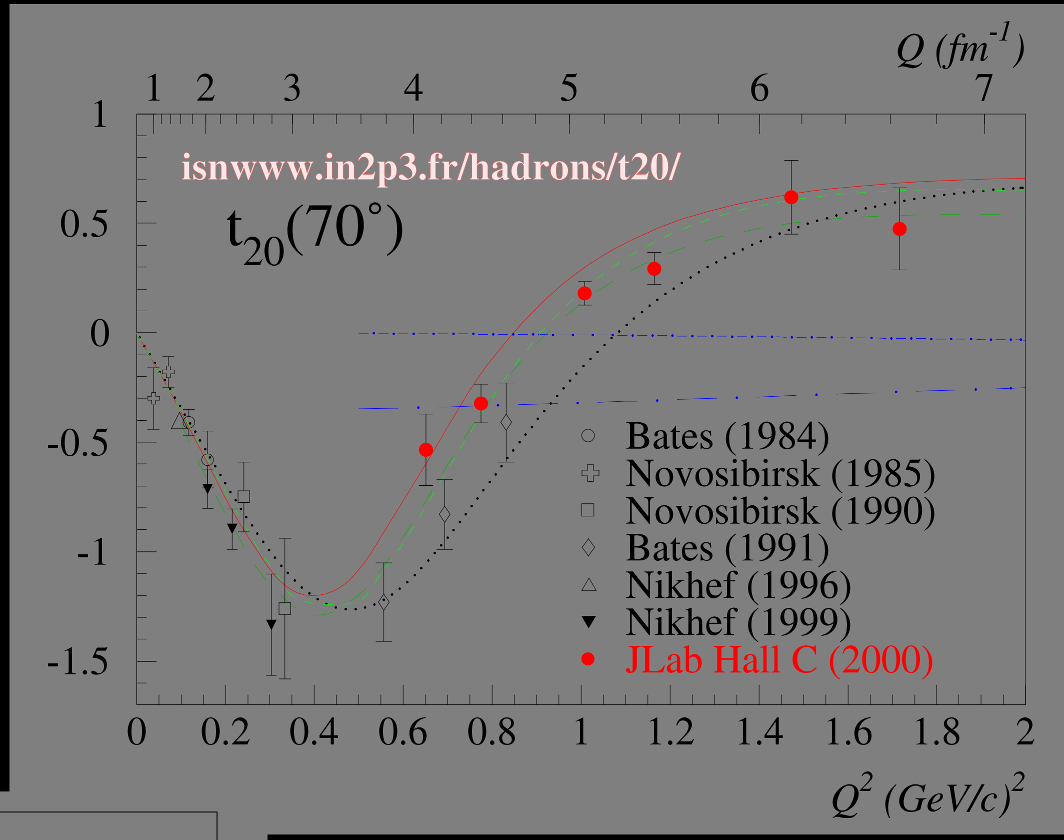
$\mathcal{T}_{2x} =$ Analyzing Power $\quad \theta = \angle(\vec{d}, 2p) \quad \phi =$ polarization direction of $\vec{d}$

T_{20} – Setup: POLDER

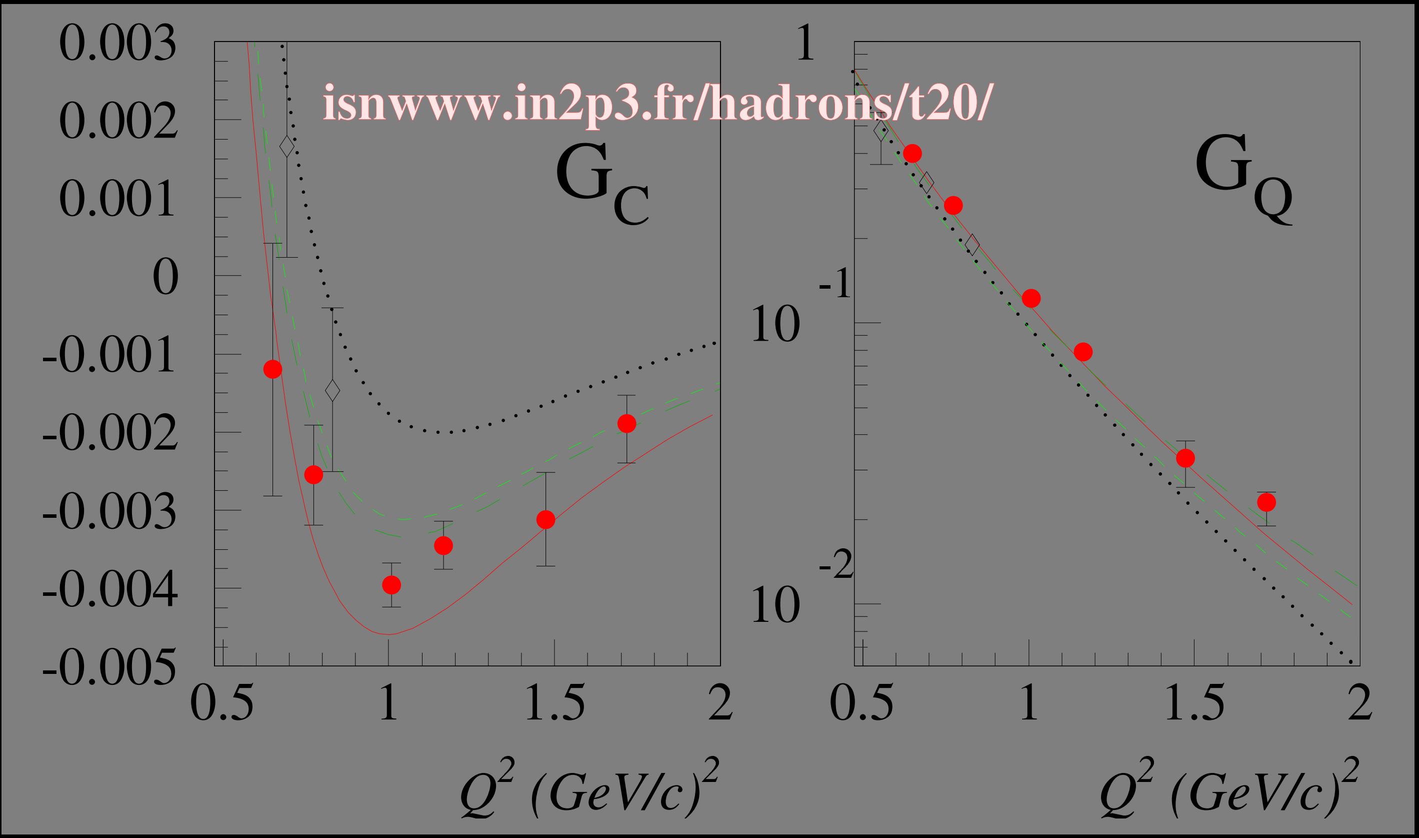


T_{20} – Results

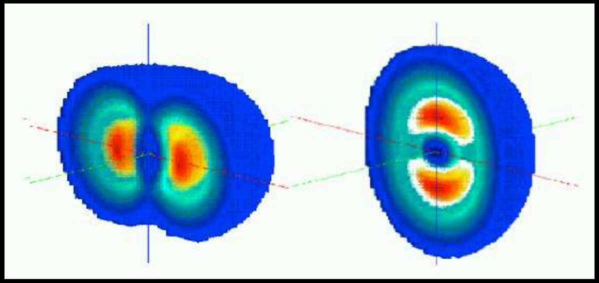

NRIA
NRIA+MEC+RC
Relativistic I
Relativistic II
pQCD I
pQCD II
t21
t22
isnwww.in2p3.fr/hadrons/t20/
Q2 (GeV/c)2


Q (fm-1)
isnwww.in2p3.fr/hadrons/t20/
t20(70°)
Bates (1984)
Novosibirsk (1985)
Novosibirsk (1990)
Bates (1991)
Nikhef (1996)
Nikhef (1999)
JLab Hall C (2000)
Q2 (GeV/c)2

T_{20} – *Results*



isnwww.in2p3.fr/hadrons/t20/
G_C
G_Q
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005
1
10^{-1}
10^{-2}
0.5
1
1.5
2
Q^2 $(GeV/c)^2$
Q^2 $(GeV/c)^2$



E-01-006: RSS

Nucleon Spin Structure in the Resonance Region

- Inclusive Scattering, Polarized Beam & Target
- Proton & Deuteron,
  g_1 & g_2 or $A_{\|}$ & $A_{\perp}$ or A_1 & A_2
  - *consistent setup, minimal model input*
- ran January – March 2002

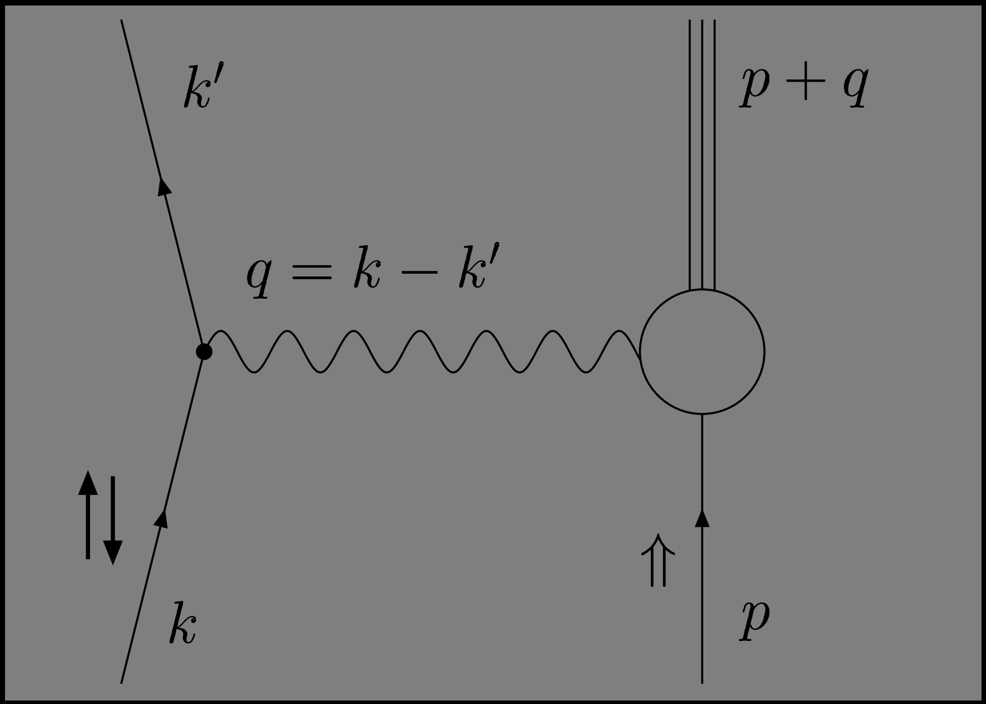
$\Rightarrow$ W Dependence

$\Rightarrow$ Polarized Local Duality

$\Rightarrow$ GDH Sum Rule

$\Rightarrow$ Higher Twist Effects

Asymmetries and Spin Structure



$$A_{\parallel} = \frac{\sigma^{\downarrow\Uparrow} - \sigma^{\uparrow\Uparrow}}{\sigma^{\downarrow\Uparrow} + \sigma^{\uparrow\Uparrow}}$$

$$A_{\perp} = \frac{\sigma^{\uparrow\Leftarrow} - \sigma^{\downarrow\Leftarrow}}{\sigma^{\uparrow\Leftarrow} + \sigma^{\downarrow\Leftarrow}}$$

$$A_1 = \frac{\sigma^T_{1/2} - \sigma^T_{3/2}}{\sigma^T_{1/2} + \sigma^T_{3/2}}$$

$$A_2 = \frac{\sigma^{TL}_{1/2}}{\sigma^T_{1/2} + \sigma^T_{3/2}}$$

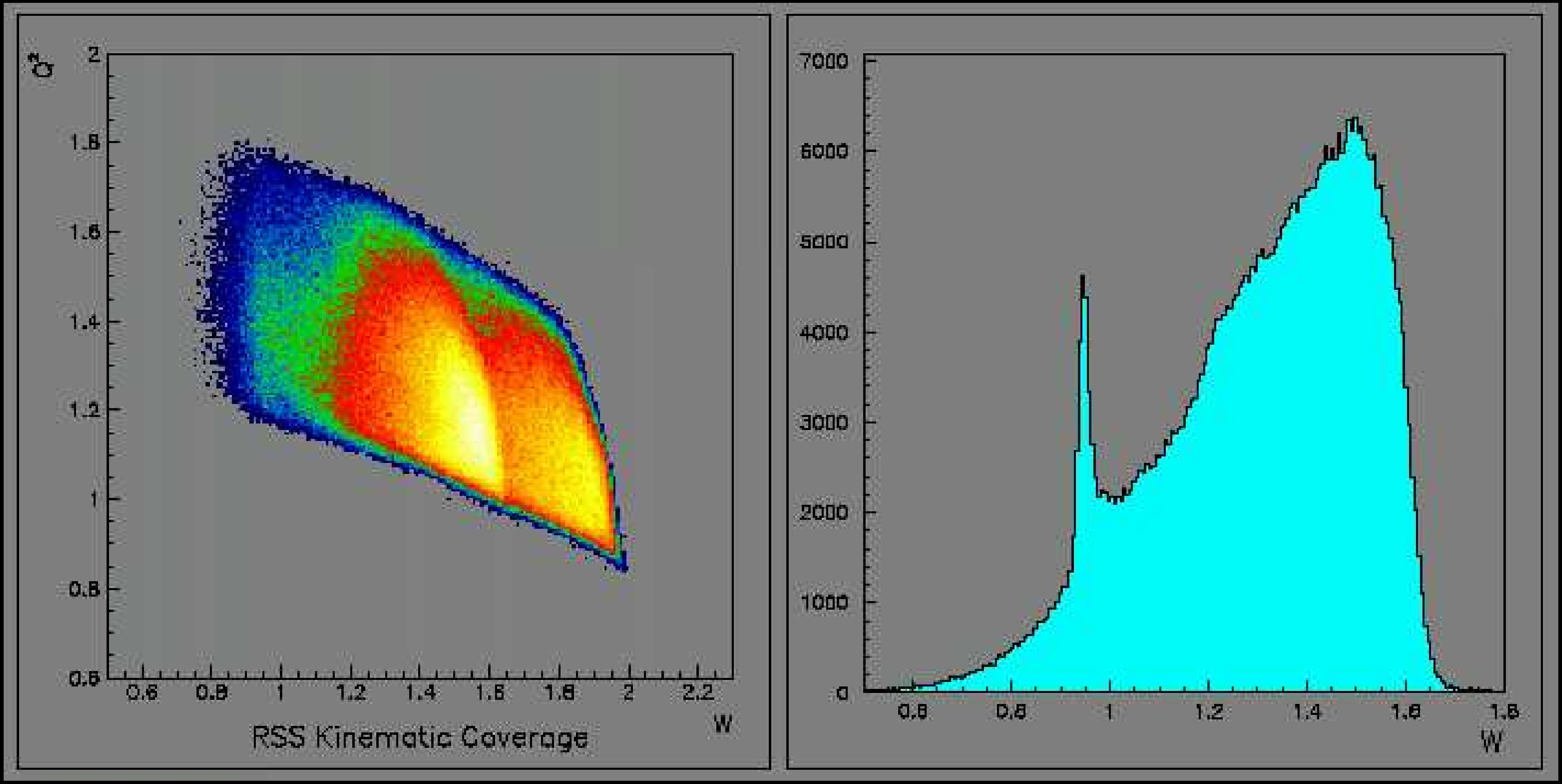
$$A_{\parallel} = D\,(A_1 + \eta A_2) \qquad A_{\perp} = d\,(A_2 - \zeta A_1)$$

$$g_1 = \frac{F_1}{1+\gamma^2}\,(A_1 + \gamma A_2) \qquad g_2 = \frac{F_1}{1+\gamma^2}\,(A_2/\gamma - A_1)$$

$$D = \frac{1 - E'\epsilon/E}{1+\epsilon R} \qquad d = D\sqrt{\frac{2\epsilon}{1+\epsilon}} \qquad \eta = \frac{\epsilon\sqrt{Q^2}}{E - E'\epsilon} \qquad \zeta = \frac{\eta\,(1+\epsilon)}{2\epsilon}$$

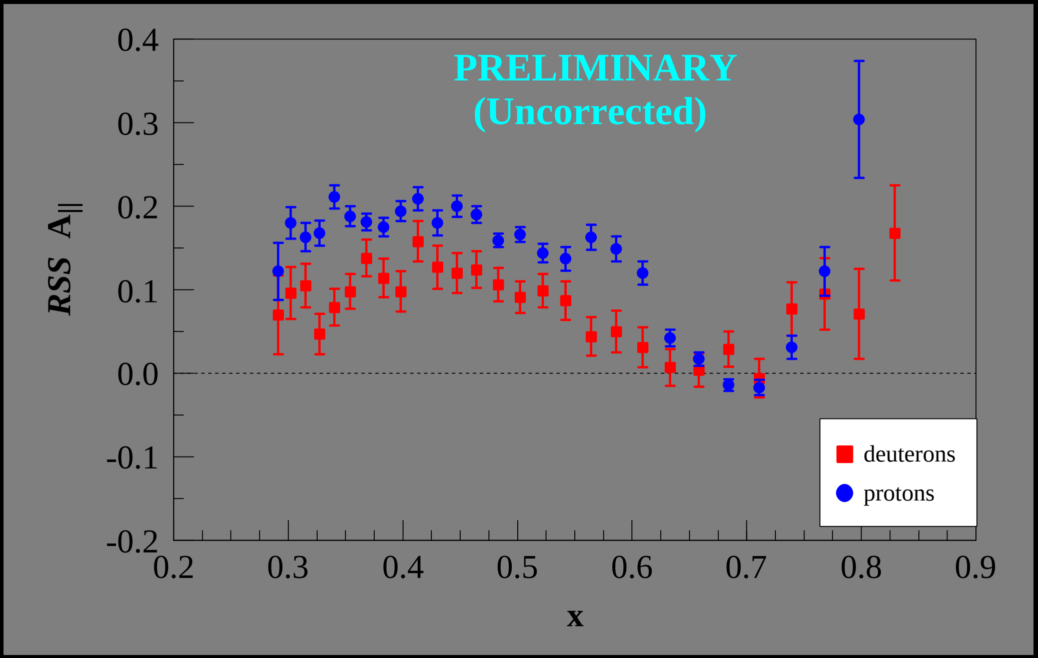
$$Q^2 = -q^2 \qquad \gamma^2 = \frac{Q^2}{\nu^2} \qquad \epsilon^{-1} = 1 + 2(1 + \frac{\nu^2}{Q^2})\tan^2(\frac{\theta}{2})$$

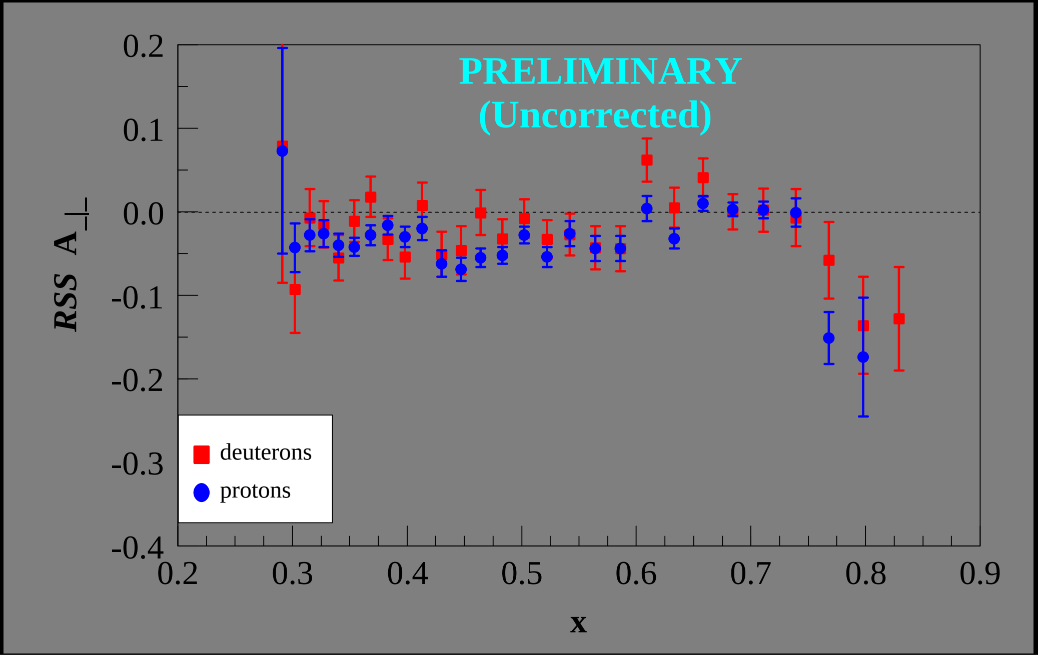
RSS – Kinematics



Example: longitudinal NH_3

RSS – Results





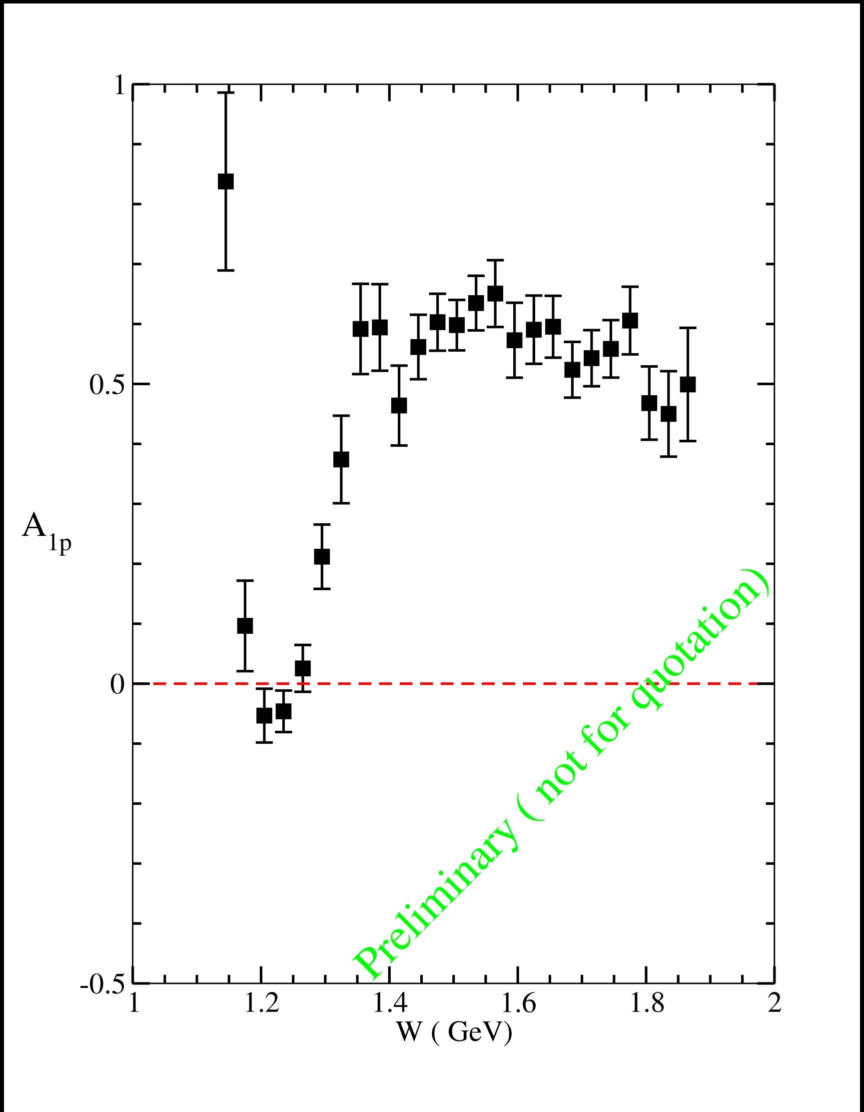
$$A^{raw} = \frac{N^{\downarrow\Uparrow} - N^{\uparrow\Uparrow}}{N^{\downarrow\Uparrow} + N^{\uparrow\Uparrow}}$$

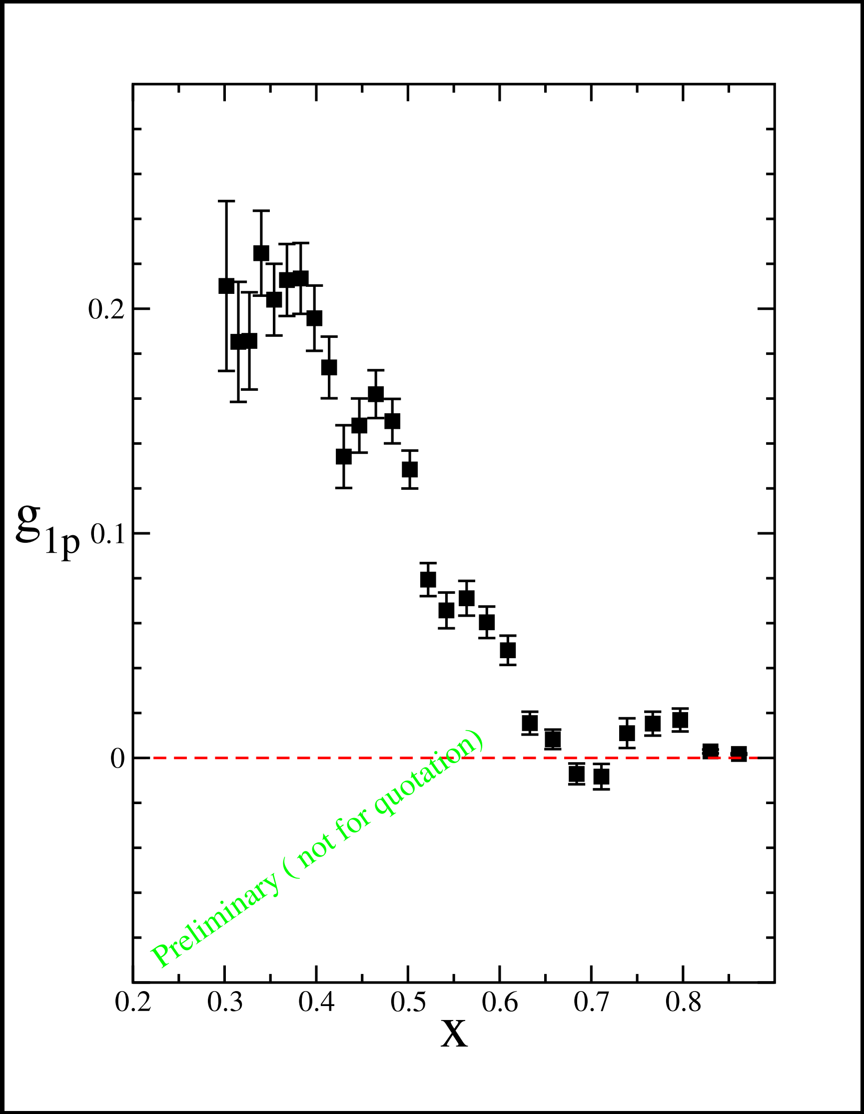
charge normalized: $N^i \rightarrow N^i/Q_i$

$$A = \frac{A^{raw}}{f\,\mathcal{P}_{beam}\,\mathcal{P}_{target}} + A_{RC}$$

$\mathcal{P}_{beam}$	Beam Polarization
$\mathcal{P}_{target}$	Target Polarization
f	Dilution Factor
A_{RC}	Radiative Corrections

RSS – Results

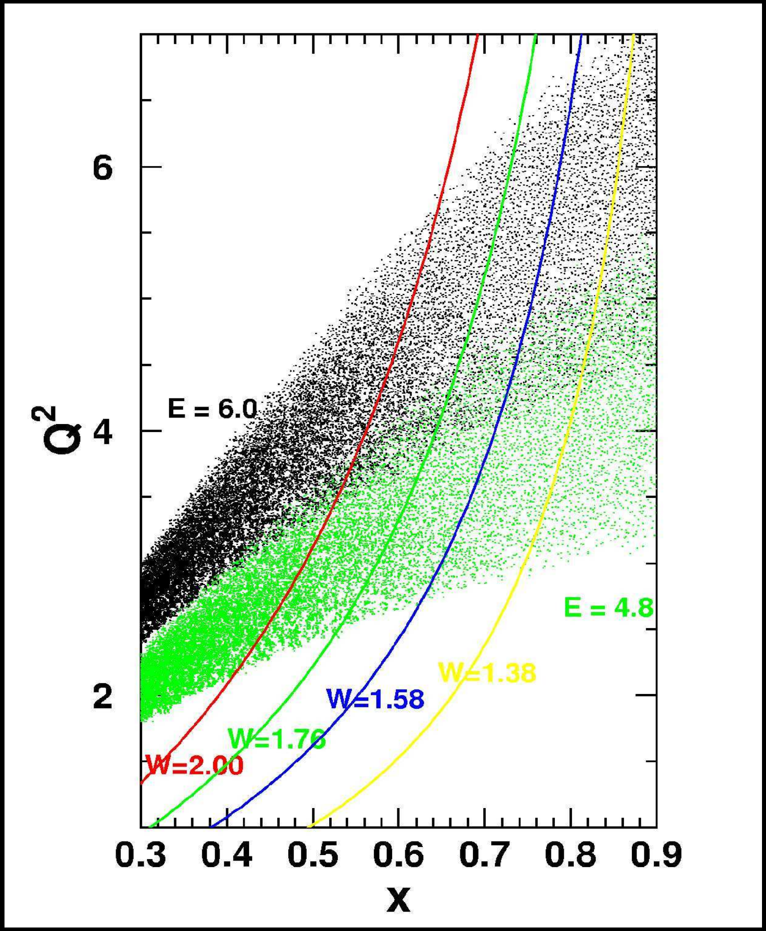




based on Hall C fits for R and F_2

E-03-109: SANE

Spin Asymmetries of the Nucleon Experiment



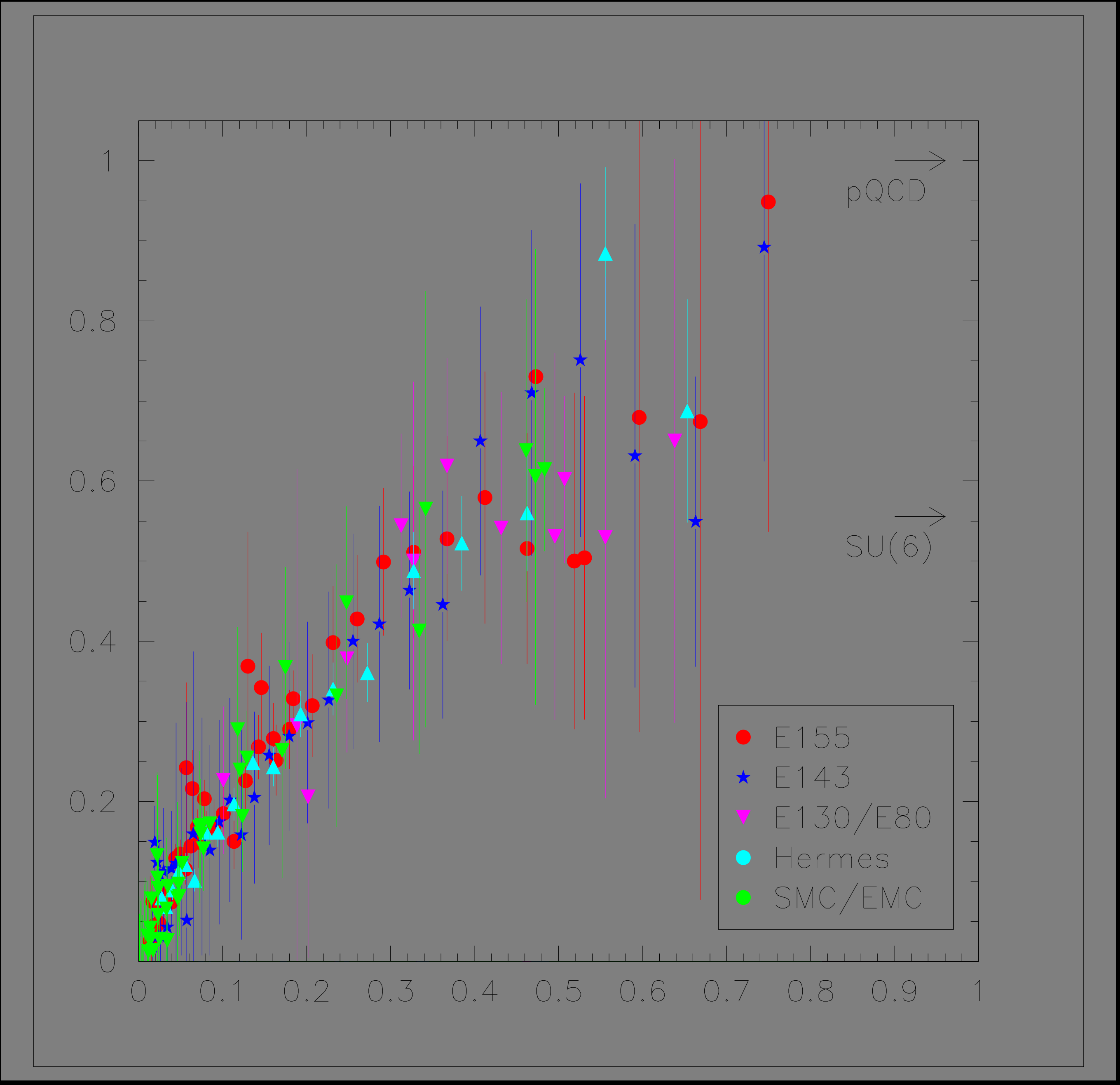
- Proton SSF at Large x_{Bj}
- A_1 for $x_{Bj} \to 1$
- 1^{st} Resonance Region A_2
- Systematically Related $\longrightarrow g_1,\ g_2$

$\Rightarrow$ Kinematic Dependence

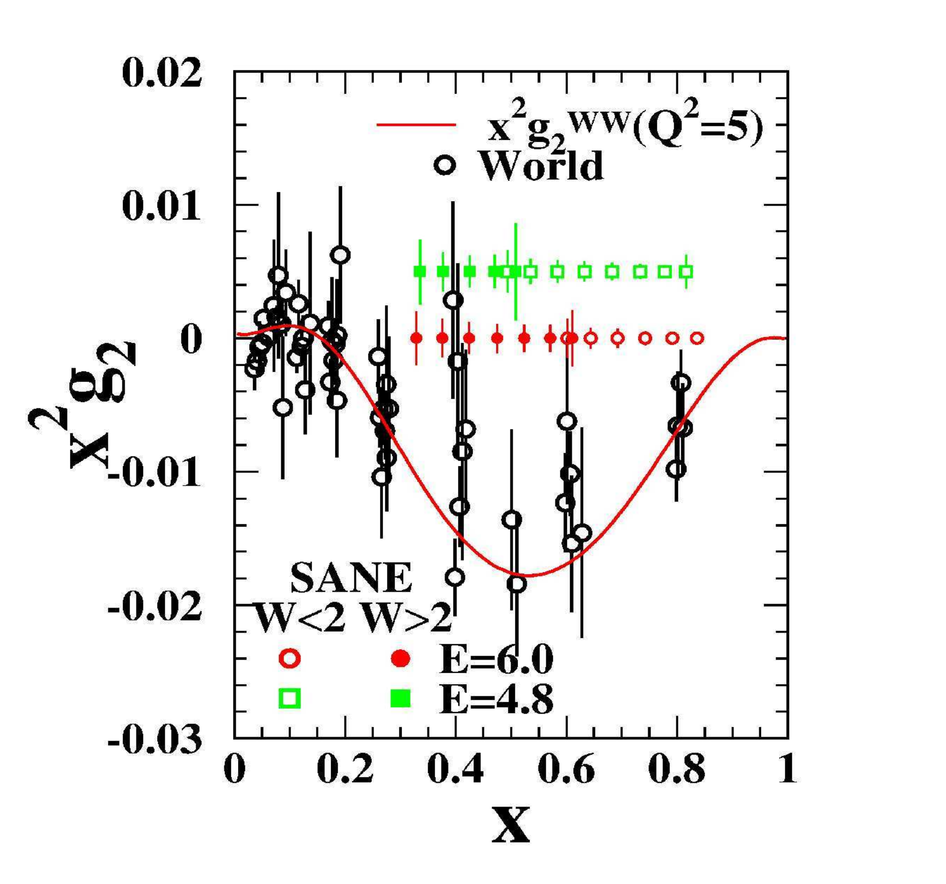
$\Rightarrow$ Polarized Local Duality

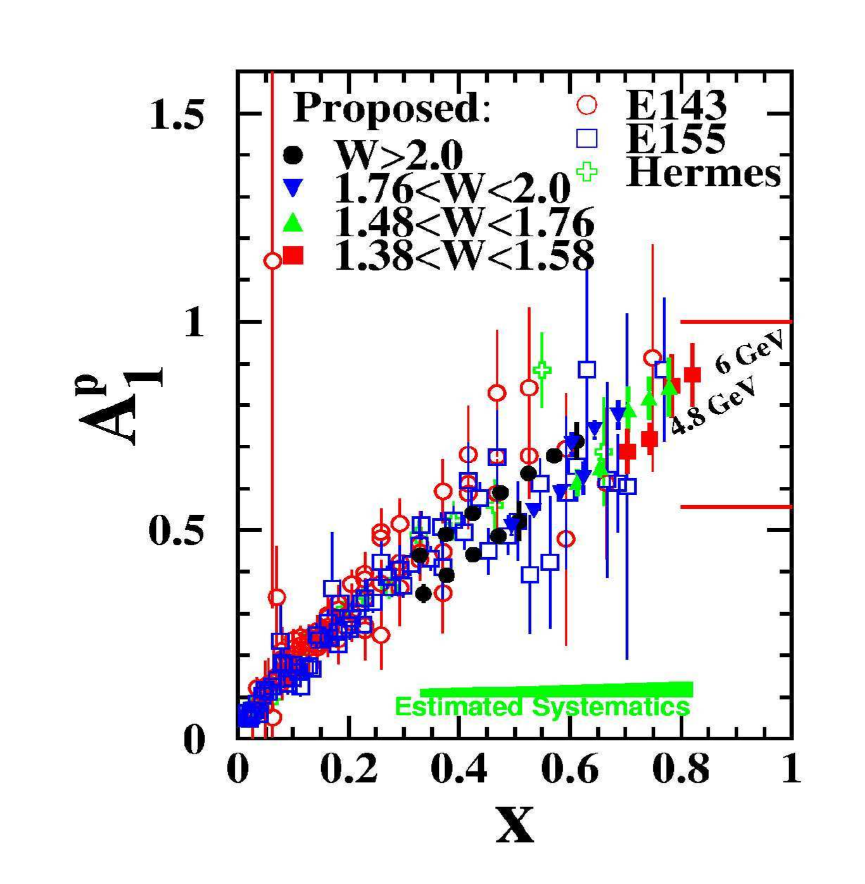
$\Rightarrow$ Twist-3 Contributions

SANE – Proton A_1 vs. x_{Bj}

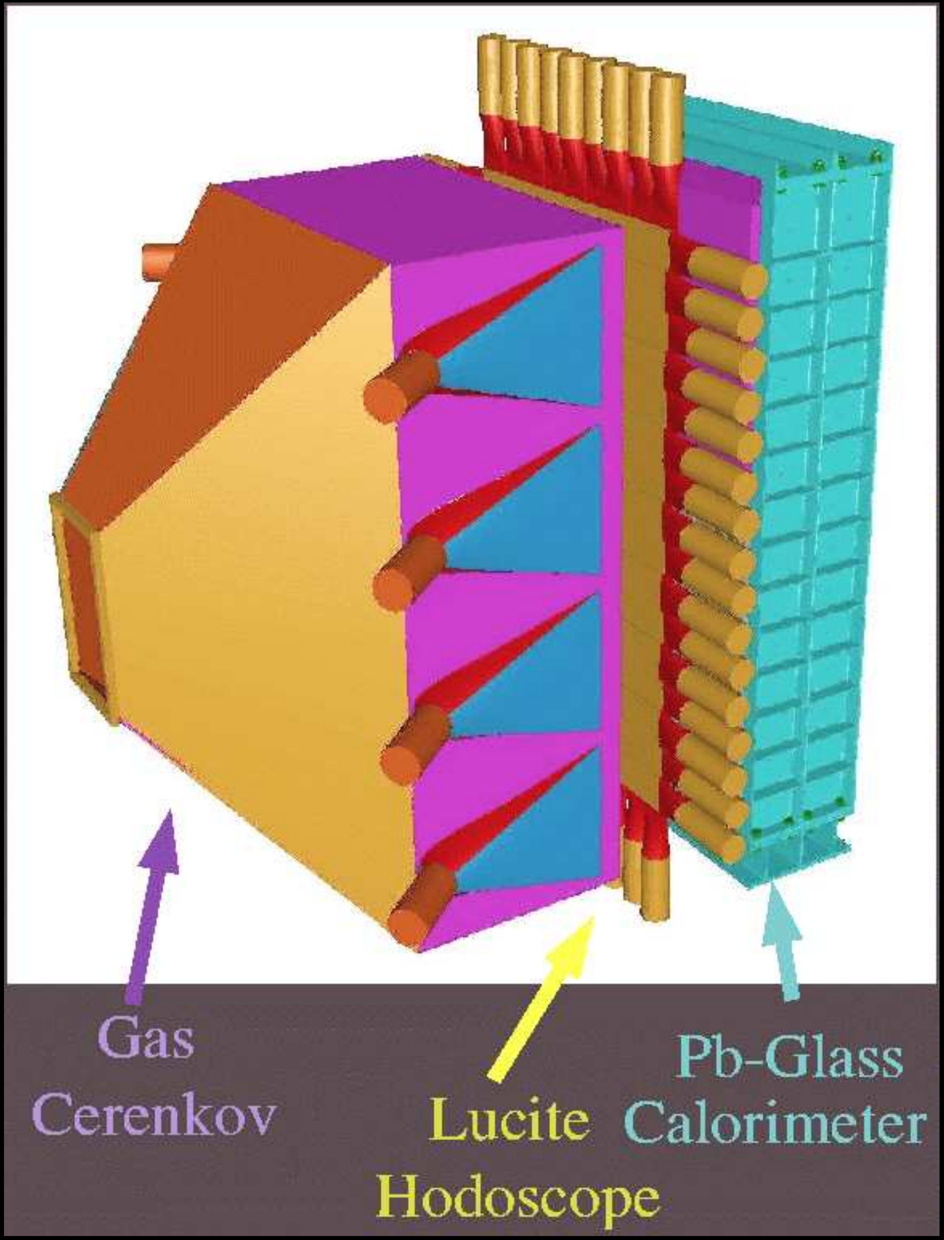


SANE – Expectations



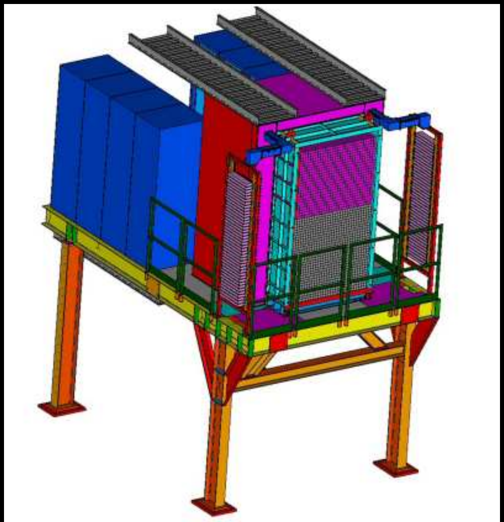


SANE – Setup



- UVa Polarized Target
- ← Big Electron Telescope Array
- HMS only for Background Studies

BigCal



- 1744 Pb Glass Blks
  $\sim 4\,cm \times 4\,cm \times 40\,cm$
- $120\,cm \times 220\,cm$,
  56 Rows
- $140\,msr$ @ $4.35\,m$
- Event Time,
  Energy & Position

Experiments: Spin as Tool

- Form Factor Measurements
  - Neutron
    E-93-026 (Gen98, Gen01), E-93-038
    - *published*
  - Proton
    E-01-109 (GEp-III), E-04-019 (2γ)
    - *planned*
- Parity Experiments
  - E-00-006 (G^0)
    - *ongoing analysis, more planned*
  - E-02-020 (Q_{weak})
    - *planned*

Form Factors

Spacial Extent of Charge & Current (Sub-Structure)

$\rightarrow$ Anomalous Magnetic Moment

- Fundamental Quantities
- Test of QCD
- Required for Study of Other Physics
  e.g. Few-Body Structure Functions

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

Spin-Based Methods:

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

Formalism

Sachs Form Factors for Elastic Scattering

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

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

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

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

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

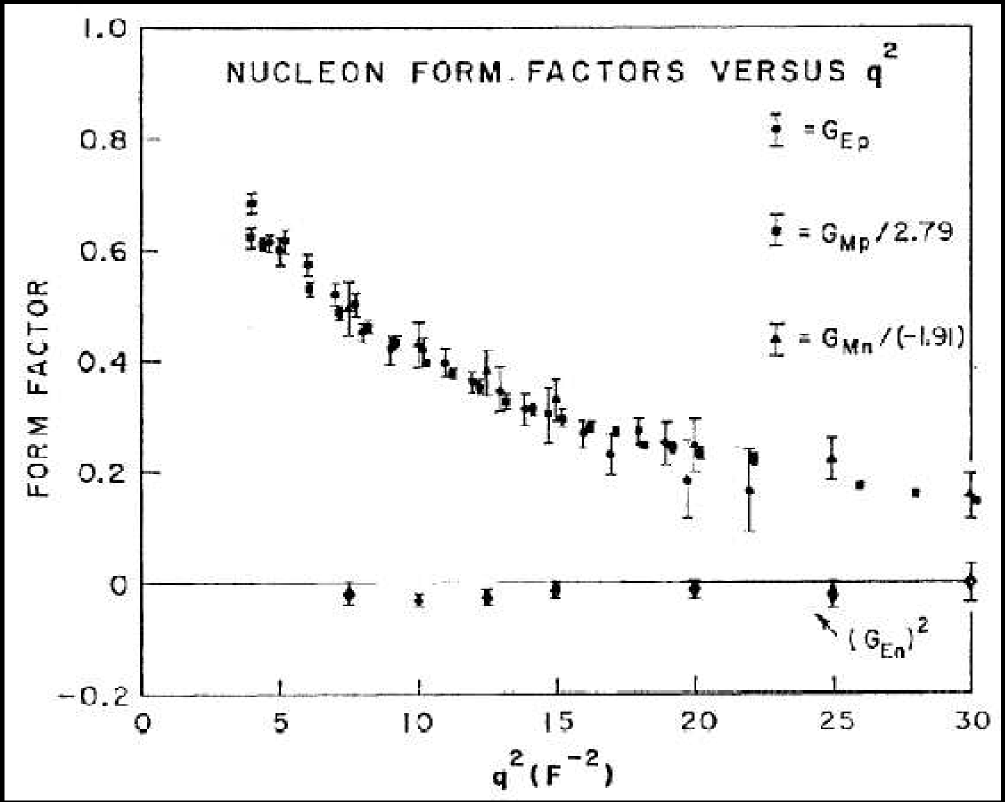
Phys. Rev. 139, B458 (1965)

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

FT fi tted to Data:

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

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



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 ($x \to 1$):

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

G_E^n: *Neutron Charge Form Factor*

E-93-026

- ran in 1998 (Gen98) and in 2001 (Gen01)
- doubly polarized quasi-elastic scattering:
  polarized e^- off polarized d in ND_3
- measured G_E^n at $Q^2 = 0.5$ and $Q^2 = 1\ GeV^2$

E-93-038

- ran in 2000
- recoil polarization:
  polarized e^- scattering off ℓD_2
- measured G_E^n at $Q^2 = 0.5$, 1.0 and $1.5\ GeV^2$

Asymmetry Measurement – Formalism

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

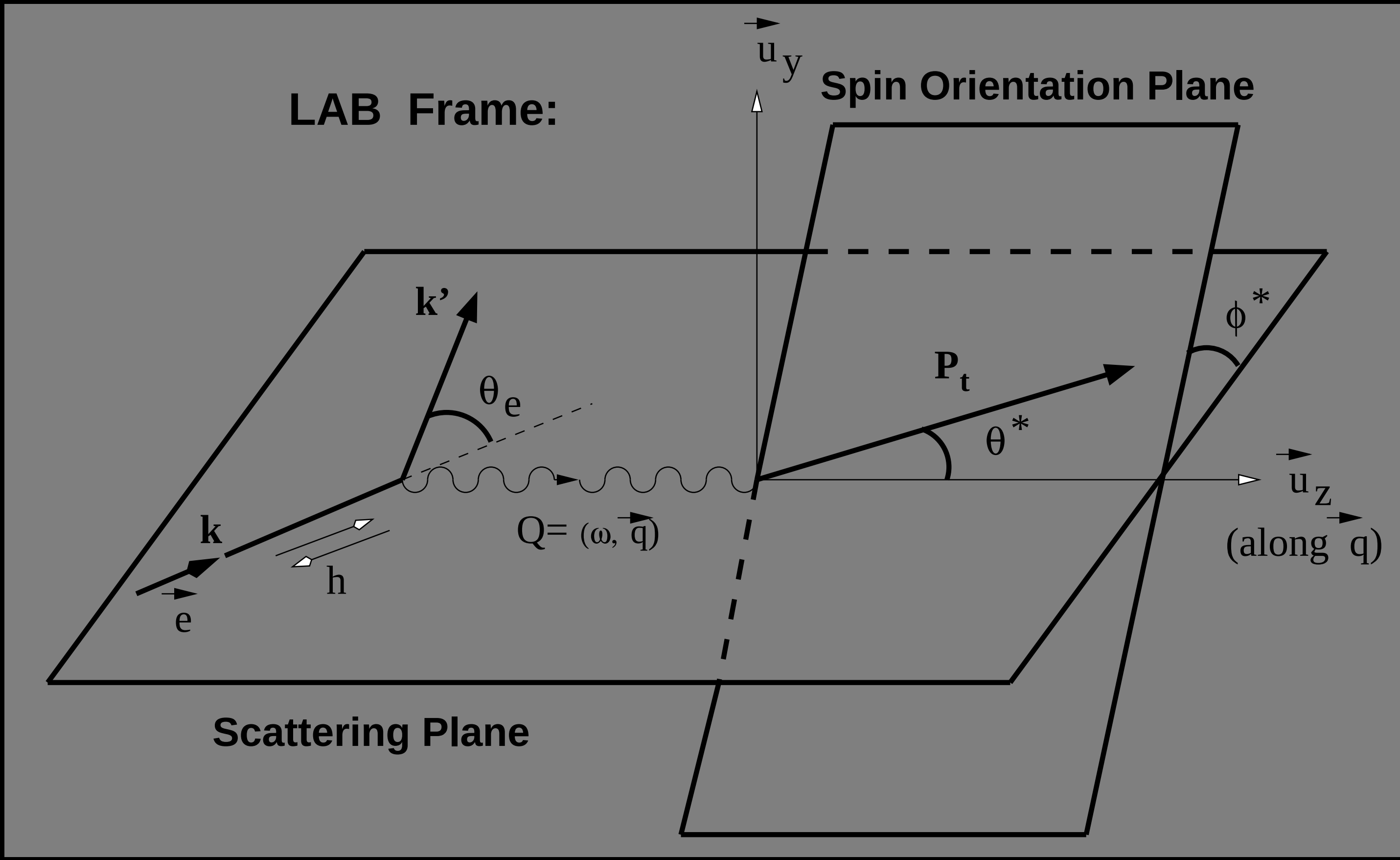
$$\Sigma = \left[\frac{G_E{}^2 + \tau G_M{}^2}{1+\tau} + 2\tau G_M{}^2 \tan^2\frac{\theta_e}{2}\right]$$

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

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

Asymmetry Measurement – Formalism

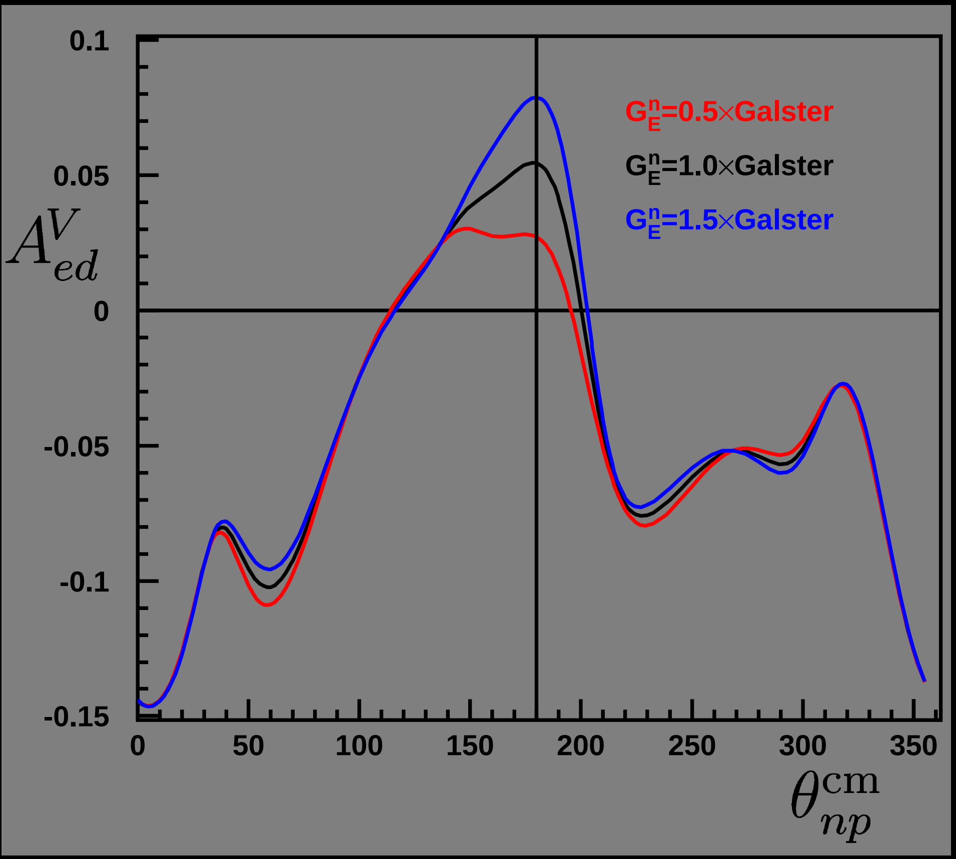
for quasi-free,
$\mathcal{P}_{\text{target}} \perp \vec{q}$
$(\theta^* = 90^o)$
and
$\mathcal{P}_{\text{target}}$ in
scattering plane
$(\phi^* = 0)$,

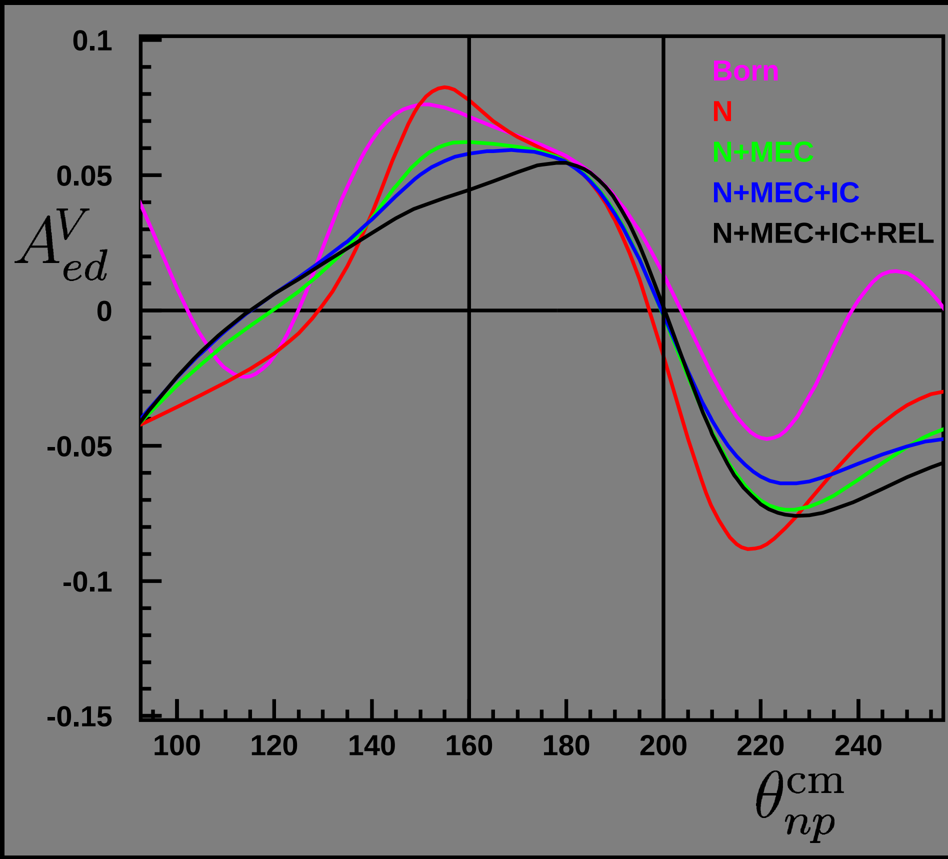


$$A^V = \frac{-2\sqrt{\tau(1+\tau)}\,\tan\frac{\theta_e}{2}\,G_E\,G_M}{{G_E}^2 + \tau[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}]\,{G_M}^2}$$

G_E^n at QE Kinematics

For e^- Scattering Quasi-Elastically off Deuterium:

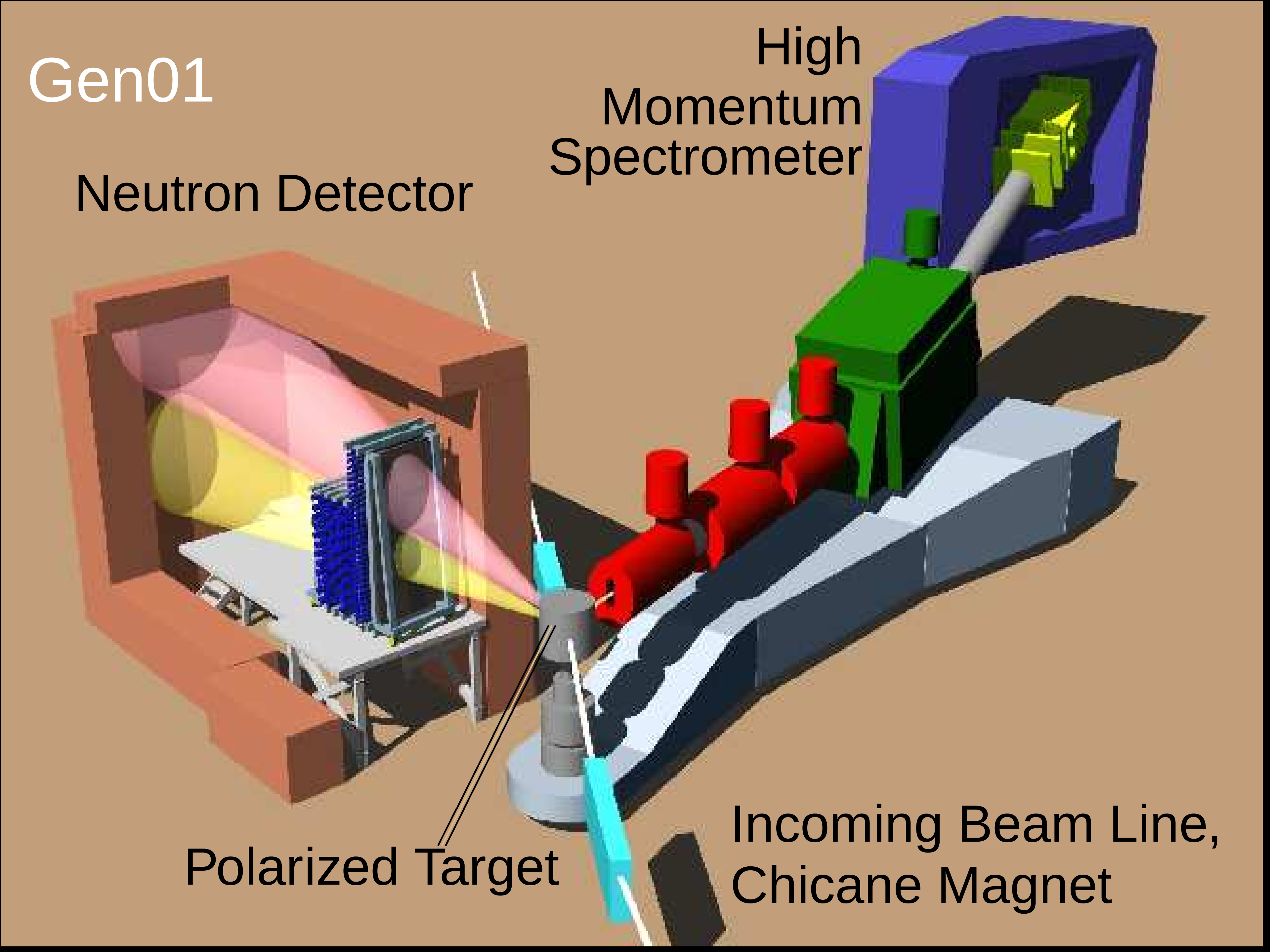




Large Sensitivity to G_E^n

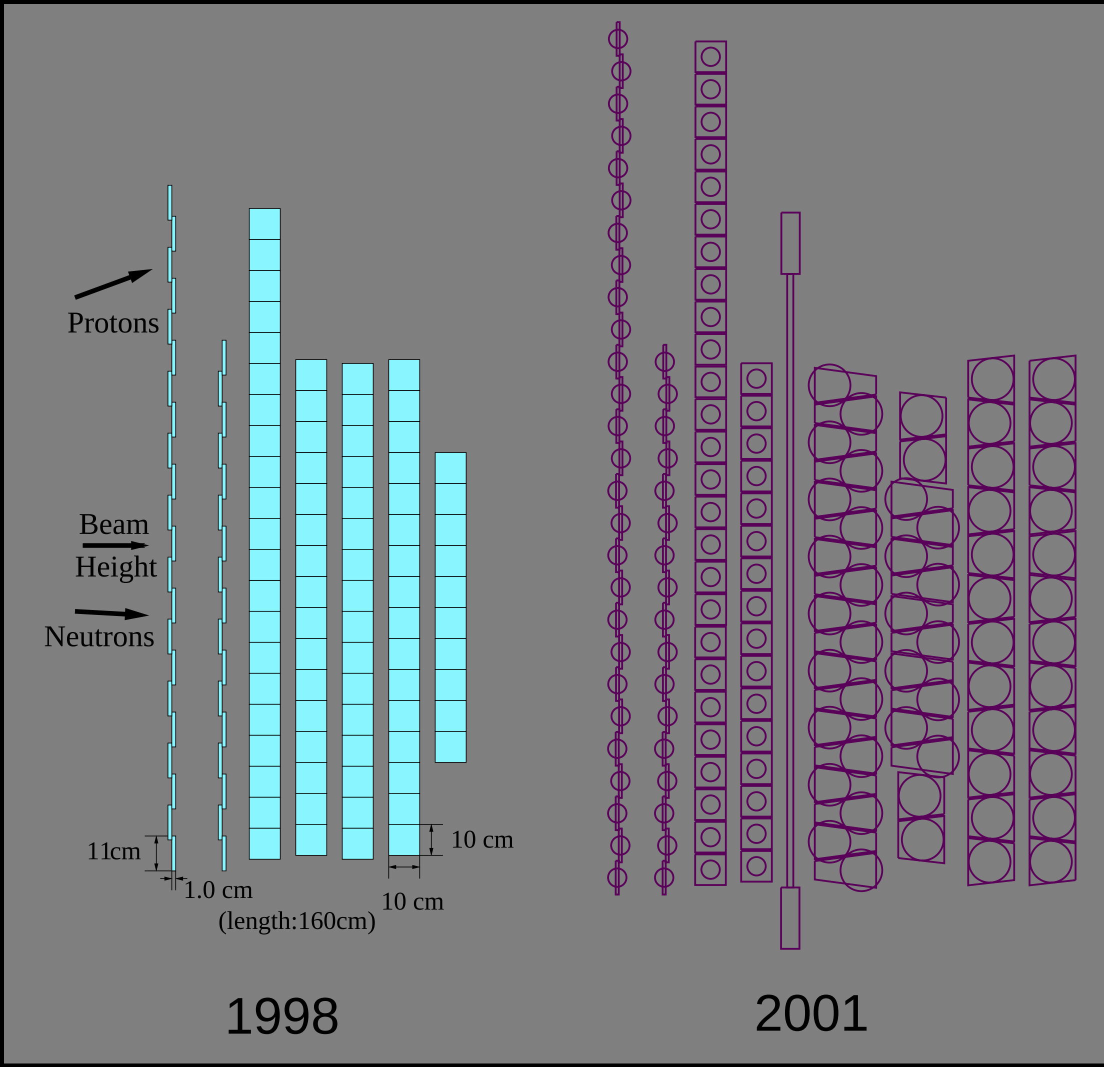
Small Model Dependence

Based on Calculations by H. Arenhövel

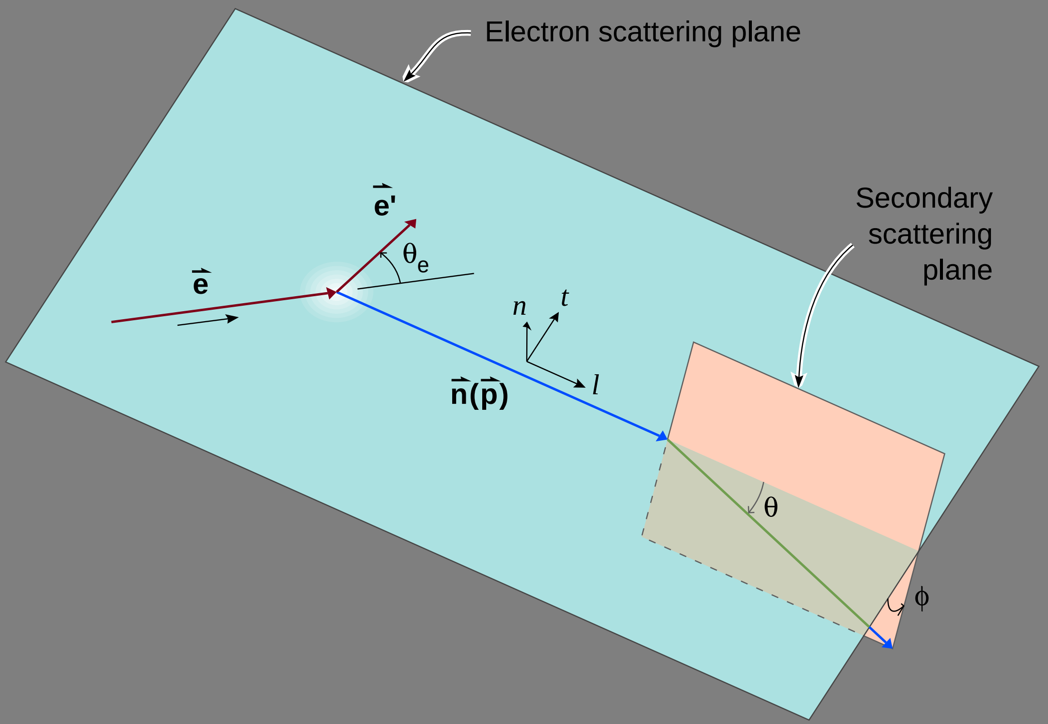

Gen01
High
Momentum
Spectrometer
Neutron Detector
Polarized Target
Incoming Beam Line,
Chicane Magnet

Gen98, Gen01 – Neutron Detector

- segmented scintillator
  - 2 p^+ VETO layers
  - 6 conversion layers
  - high rate: $\sim 100\, kHz$
- vertically extended for symmetric proton acceptance (2001)
- provides 3 space coords, time & energy



Recoil Polarimetry – Formalism



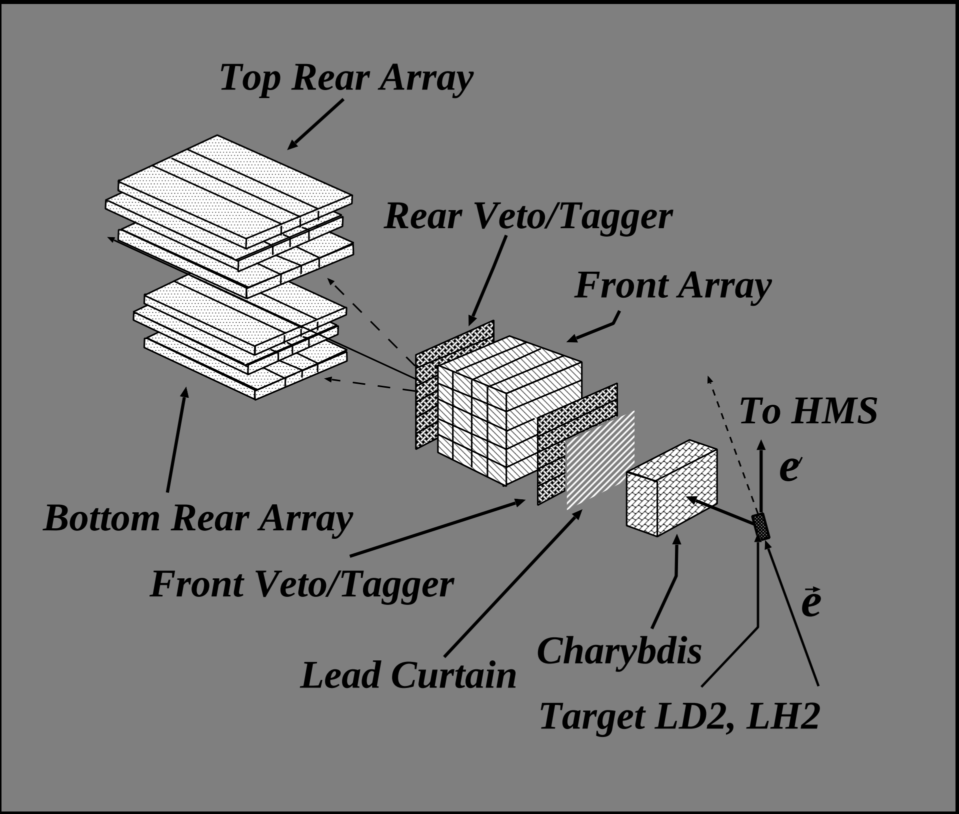
$$I_0 P_t = -2\sqrt{\tau(1+\tau)}\, G_E G_M \tan(\theta_e/2)$$

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

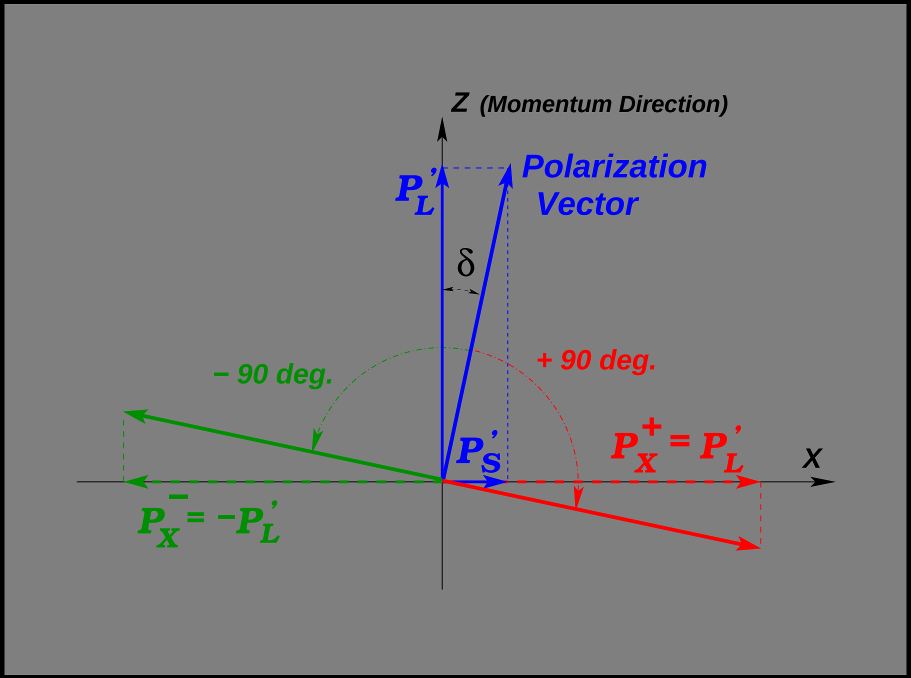
$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{(E_e + E_{e'})}{2M_N}\tan\left(\frac{\theta_e}{2}\right)$$

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

Recoil Polarimetry – E93-038



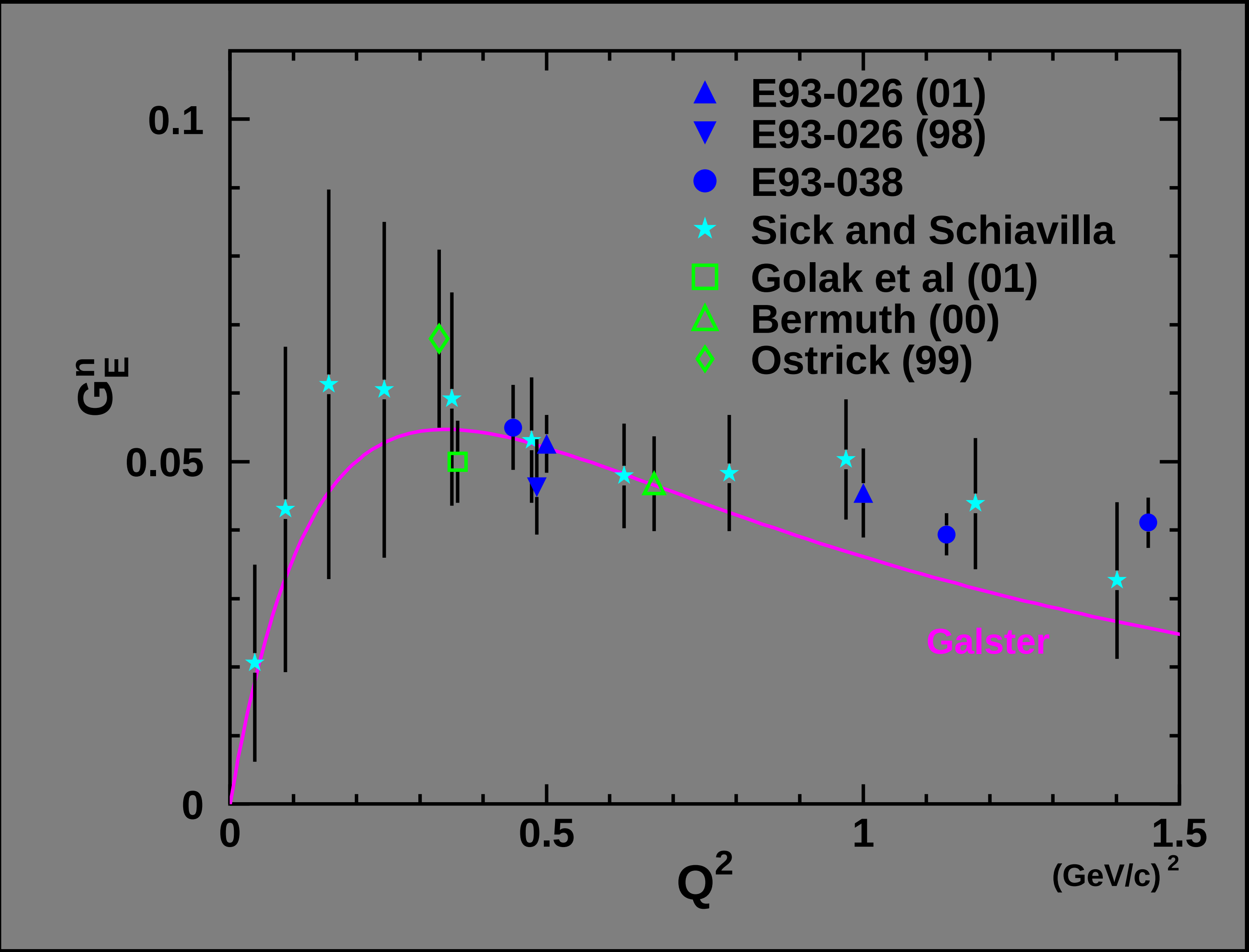
- want to determine P_l and P_t at target
- polarimeter sensitive to transverse pol only



→ rotate longitudinal pol with *Charybdis* magnet

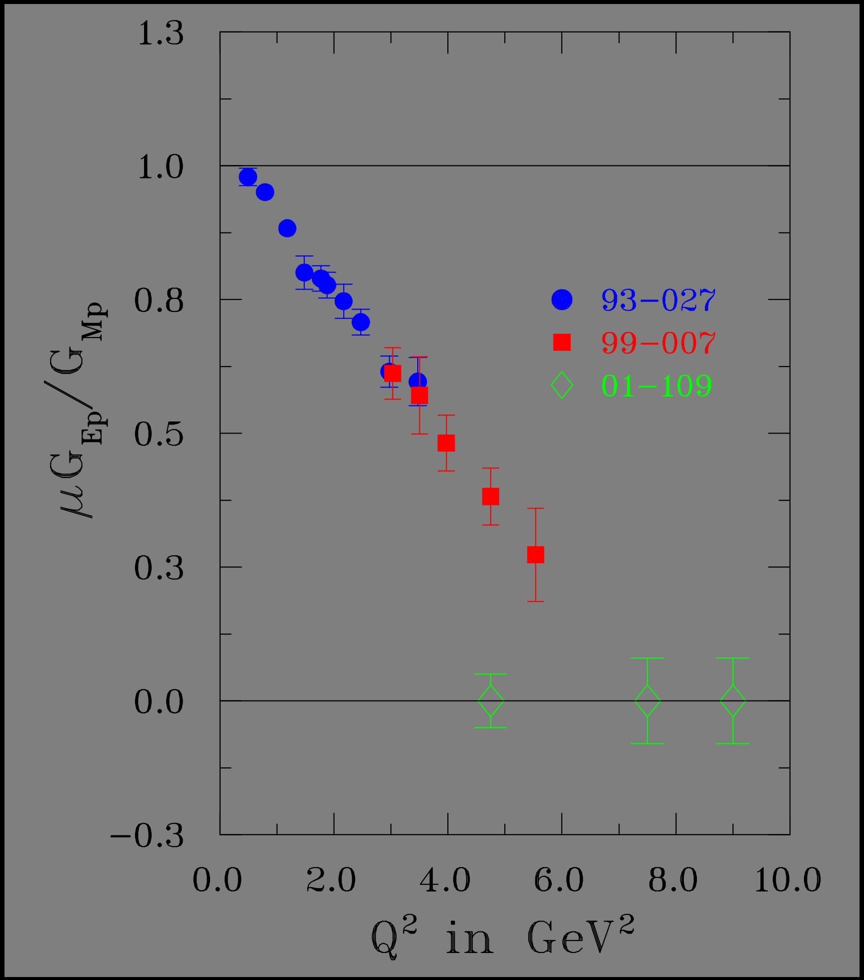
$$P_t^{\text{pol}} = P_l \sin\chi + P_t \cos\chi$$

G_E^n — Results



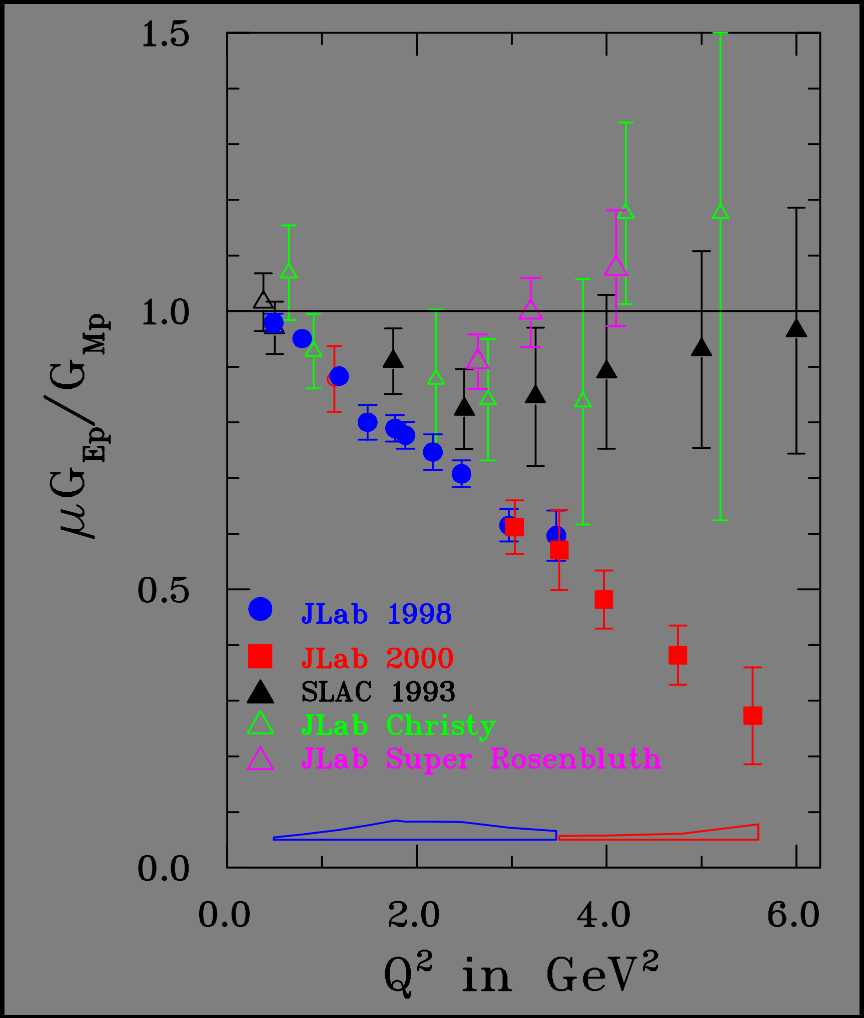
Plans for recoil polarization up to $Q^2 = 5.6\ GeV^2$

E-01-109: GEp-III



- Measurement of G_E^p/G_M^p
- Recoil Polarization
- Expands on Hall A Work:
  - Higher Q^2: $5, 7.5, 9\,GeV^2$
  - Different Systematics
- Planned 2005/2006

E-01-109: GEp-III



- Measurement of G_E^p/G_M^p
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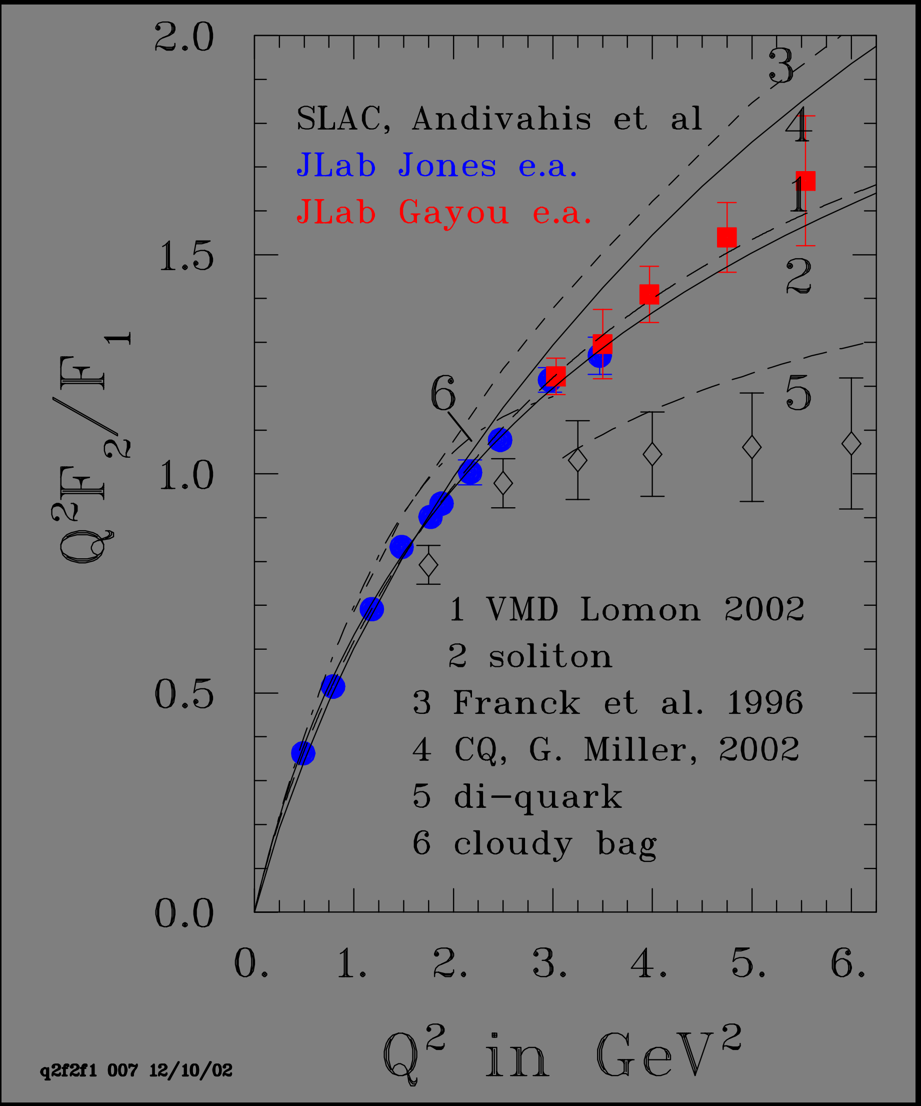
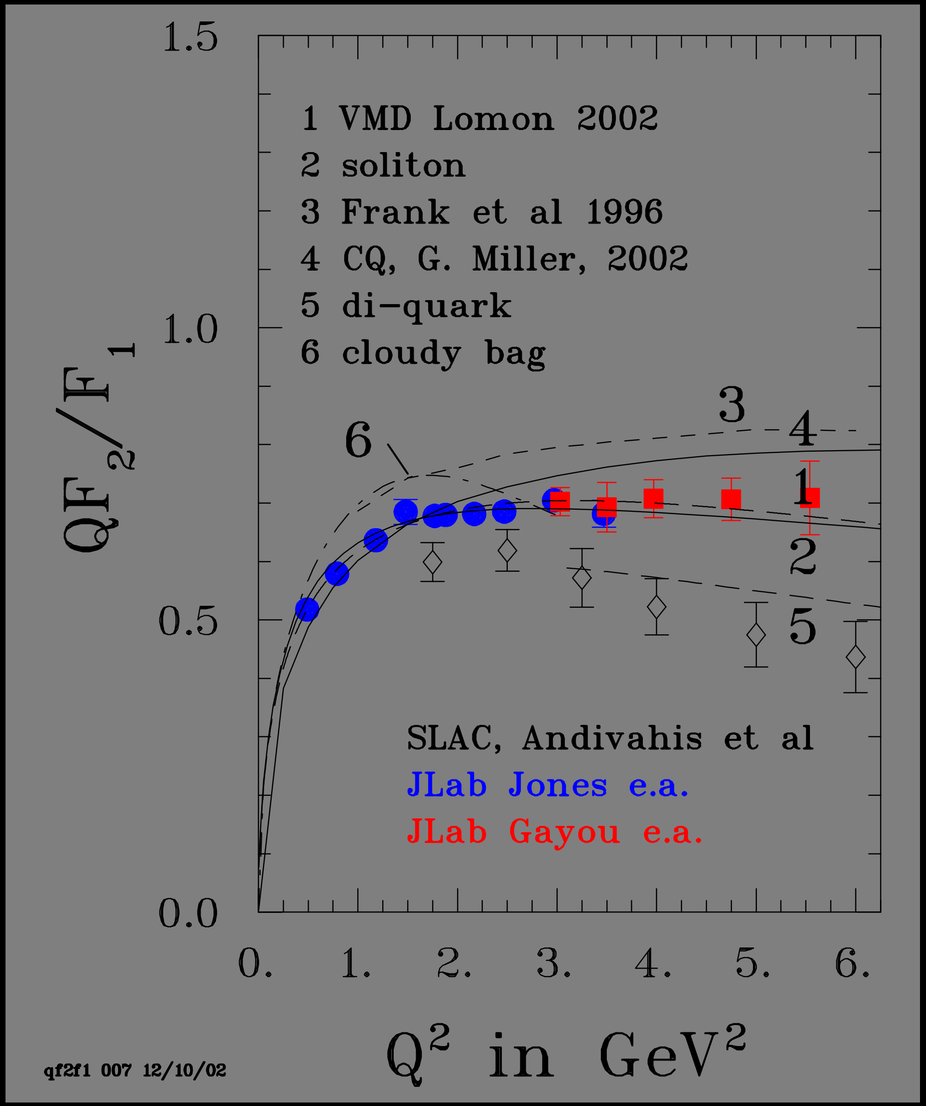
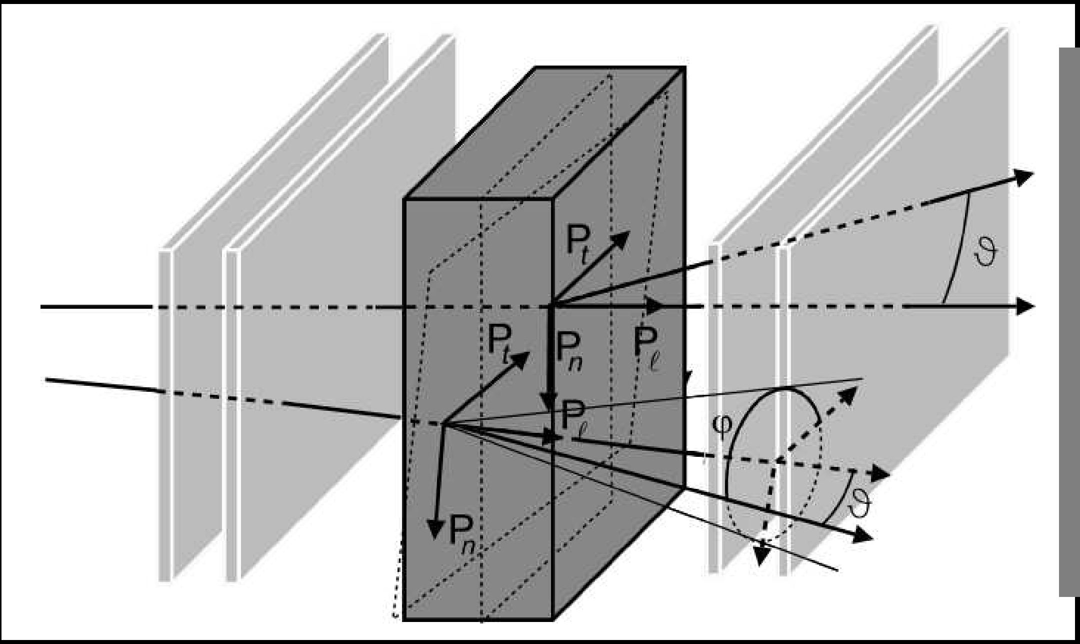
G_E^p in Hall A

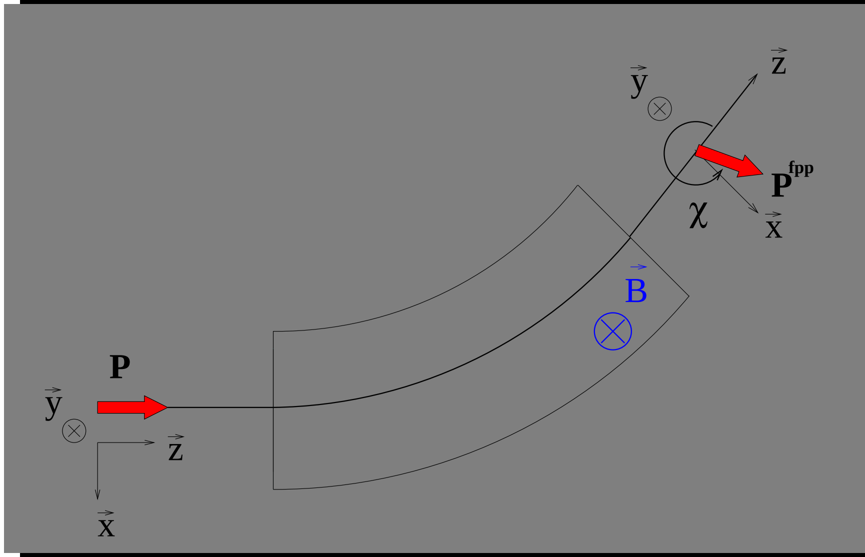

SLAC, Andivahis et al
JLab Jones e.a.
JLab Gayou e.a.
1 VMD Lomon 2002
2 soliton
3 Franck et al. 1996
4 CQ, G. Miller, 2002
5 di−quark
6 cloudy bag
Q^2F_2/F_1
Q^2 in GeV^2
q2f2f1 007 12/10/02


1 VMD Lomon 2002
2 soliton
3 Frank et al 1996
4 CQ, G. Miller, 2002
5 di−quark
6 cloudy bag
SLAC, Andivahis et al
JLab Jones e.a.
JLab Gayou e.a.
QF_2/F_1
Q^2 in GeV^2
qf2f1 007 12/10/02

Recoil Polarimetry – E01-109

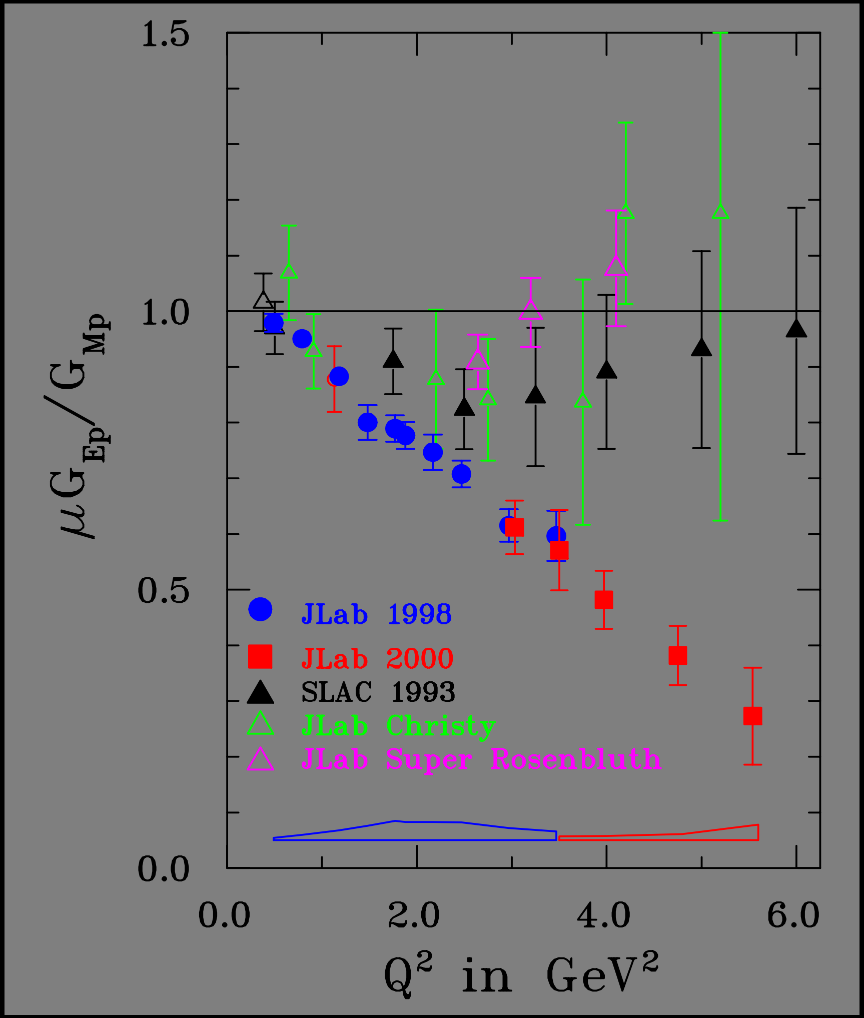
- Detect Scattered e^- in **BigCal**
- Protons in HMS with new Focal Plane Polarimeter
  $\Rightarrow$ HMS Dipole Rotates Polarization Vector





E-04-019: TPEX

Measurement of the Two-Photon Exchange Contribution in $e-p$ Elastic Scattering Using Recoil Polarization



- Resolve pol–unpol Discrepancy
- Generalization of Form Factors
- Examine ϵ-Dependence at Fixed Q^2
- Significant New Theory
- To Run after GEp-III (same setup)

E-04-019: TPEX

Traditional 1γ Recoil Polarization:

$$\frac{P_t}{P_l} = -\sqrt{\frac{\epsilon}{\tau\,(1+\epsilon)}}\,\frac{G_E}{G_M}$$

Extended for TPEX:

$$\frac{P_t}{P_l} = -\sqrt{\frac{\epsilon}{\tau\,(1+\epsilon)}}\,\frac{G_E/G_M + Y_{2\gamma}(\epsilon)}{1 + 2\,\epsilon\,Y_{2\gamma}(\epsilon)/(1+\epsilon)}$$

$$\epsilon^{-1} = 1 + 2(1 + \tfrac{\nu^2}{Q^2})\tan^2(\tfrac{\theta}{2})$$

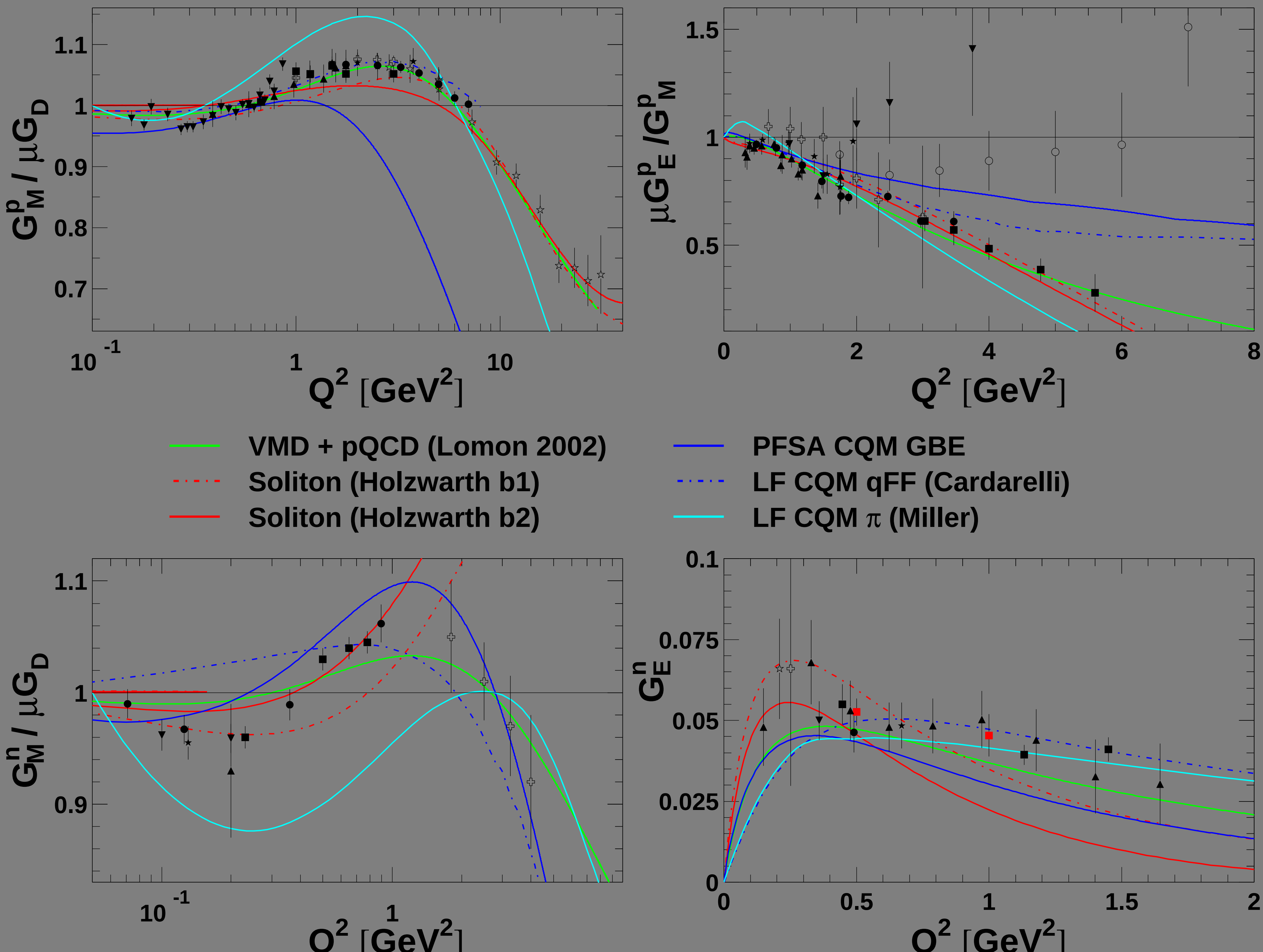
Form Factors – Current Status

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:

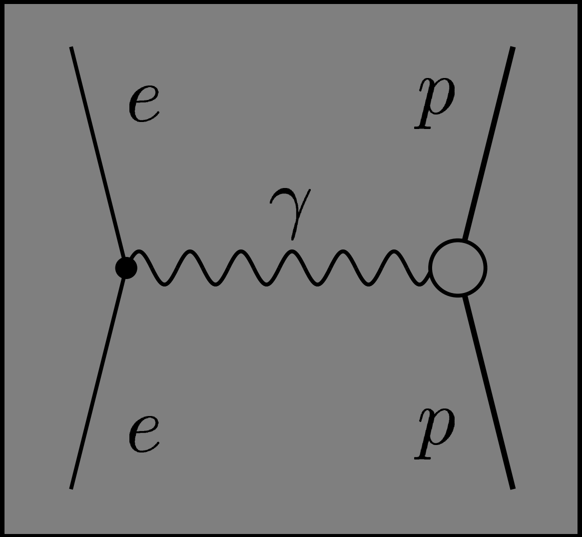
- Several QCD-based Models
  - *Vector Meson Dominance pQCD*
  - *light front CQM, Goldstone Boson Exchange CQM*
  - *Solitons*
- None Well Describe all Form Factors over *Entire* Measured Range



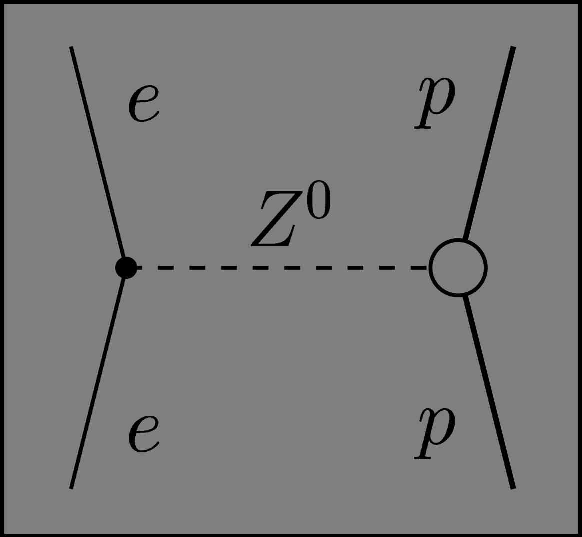
$G_M^p / \mu G_D$
1.1
1
0.9
0.8
0.7
10^{-1}
1
10
Q^2 [GeV^2]
$\mu G_E^p / G_M^p$
1.5
1
0.5
0
2
4
6
8
Q^2 [GeV^2]
VMD + pQCD (Lomon 2002)
Soliton (Holzwarth b1)
Soliton (Holzwarth b2)
PFSA CQM GBE
LF CQM qFF (Cardarelli)
LF CQM π (Miller)
$G_M^n / \mu G_D$
1.1
1
0.9
10^{-1}
1
Q^2 [GeV^2]
G_E^n
0.1
0.075
0.05
0.025
0
0
0.5
1
1.5
2
Q^2 [GeV^2]

Parity Experiments – Theory

Include Weak Interaction in $e - p$ Scattering:



$G_E^{\gamma}, G_M^{\gamma}$



$G_E^{Z^0}, G_M^{Z^0}, G_A^{Z^0}$

Cross Section $\sigma = |M_{\gamma} + M_{Z^0}|^2$

Interference Term $M_{\gamma} \times M_{Z^0}$ Violates Parity

$$\frac{M_{\gamma} \times M_Z}{M_{\gamma}^2} \sim 1/20\,000$$

Parity Experiments – Theory

$$A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = -\frac{G_F Q^2}{\sqrt{2}\,\pi\alpha}\,\frac{A_E + A_M + A_A}{A_D} \propto \frac{M_\gamma \times M_Z}{M_\gamma^2}$$

$$\begin{aligned} A_E &= \epsilon\, G_E^\gamma\, G_E^Z \\ A_M &= \tau\, G_M^\gamma\, G_M^Z \\ A_A &= -\frac{1}{2}(1 - 4\sin^2\theta_W)\sqrt{\tau(1+\tau)(1-\epsilon^2)}\, G_E^\gamma\, G_A^Z \\ A_D &= \epsilon\, {G_E^\gamma}^2 + \tau\, {G_M^\gamma}^2 \end{aligned}$$

With Measurements at 2 Different ϵ,
can Extract G_E^Z and G_M^Z Separately

$$\tau = \frac{Q^2}{4M^2} \qquad \epsilon^{-1} = 1 + 2\left(1 + \frac{\nu^2}{Q^2}\right)\tan^2\left(\frac{\theta}{2}\right)$$

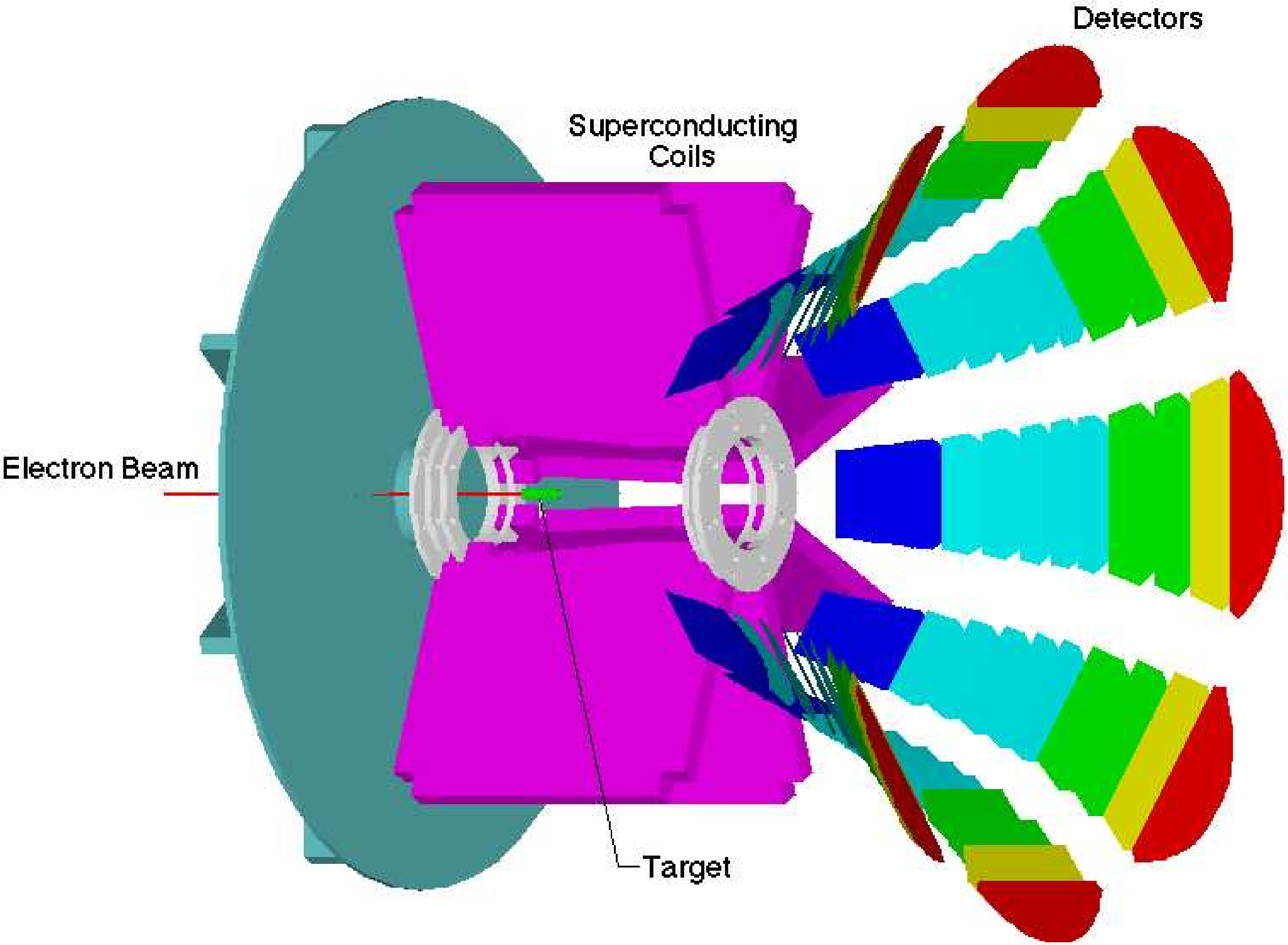
Flavor Singlet G^0

$$
\begin{aligned}
G^0_{E,M} &= \frac{1}{3}\left(G^u_{E,M} + G^d_{E,M} + G^s_{E,M}\right) \\
&= 4\left[\left(\frac{1}{2} - \sin^2\theta_W\right) G^\gamma_{E,M} - G^Z_M\right]
\end{aligned}
$$

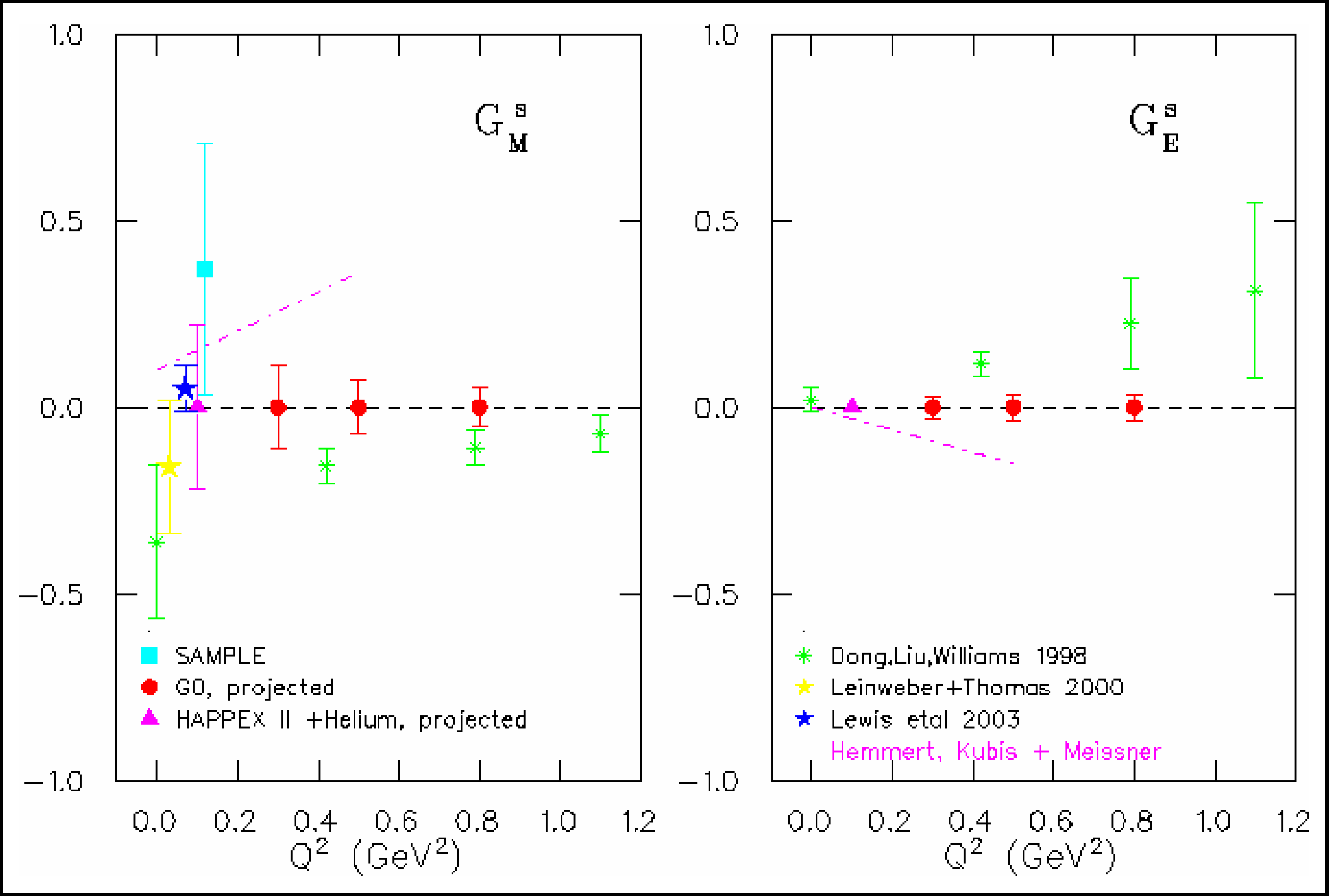
Assuming Isospin Symmetry,
get Weak Part of Quark Form Factors in Proton:

$$
\begin{aligned}
G^{up}_{E,M} &= (3 - 4\sin^2\theta_W)\, G^{\gamma p}_{E,M} - 4\, G^{Zp}_{E,M} \\
G^{dp}_{E,M} &= (2 - 4\sin^2\theta_W)\, G^{\gamma p}_{E,M} + G^{\gamma n}_{E,M} - 4\, G^{Zp}_{E,M} \\
G^{sp}_{E,M} &= (1 - 4\sin^2\theta_W)\, G^{\gamma p}_{E,M} - G^{\gamma n}_{E,M} - 4\, G^{Zp}_{E,M}
\end{aligned}
$$

G0 Experiment



G^0 – Expectations



E-02-020: The Q^p_{weak} Experiment

A Search for Physics at the TeV Scale Via a Measurement of the Proton's Weak Charge

Recall Polarized $e - p$ Scattering Asymmetry:

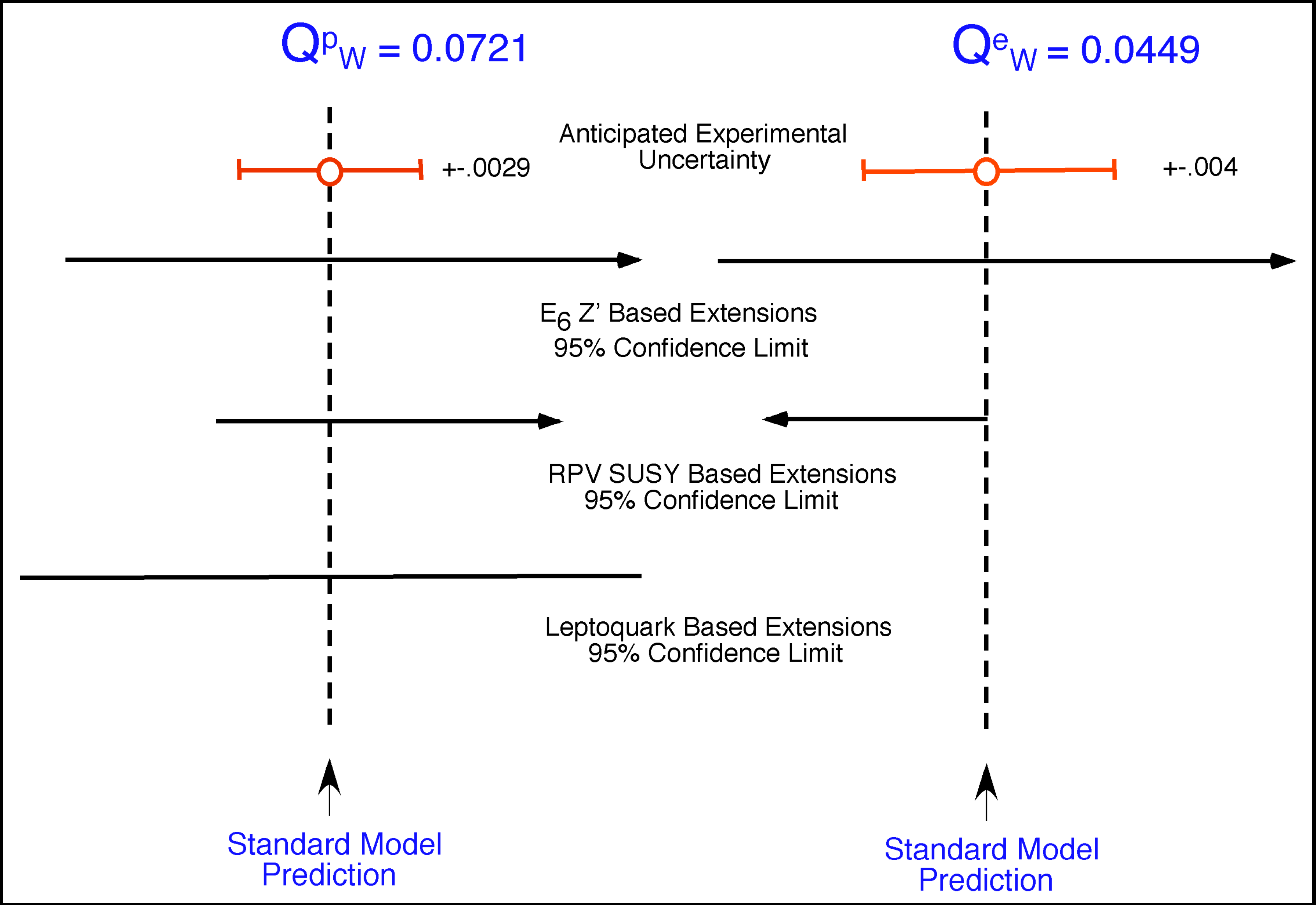
$$A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = -\frac{G_F Q^2}{\sqrt{2}\pi\alpha} \frac{A_E + A_M + A_A}{A_D} \propto \frac{M_\gamma \times M_Z}{M_\gamma^2}$$

For Forward Scattering ($\theta \to 0$, $\epsilon \to 1$, $\tau \ll 1$):

$$A = \frac{-G_F}{4\pi\alpha\sqrt{2}} \left[Q^2 Q^p_{weak} + F^p(Q^2, \theta)\right]$$

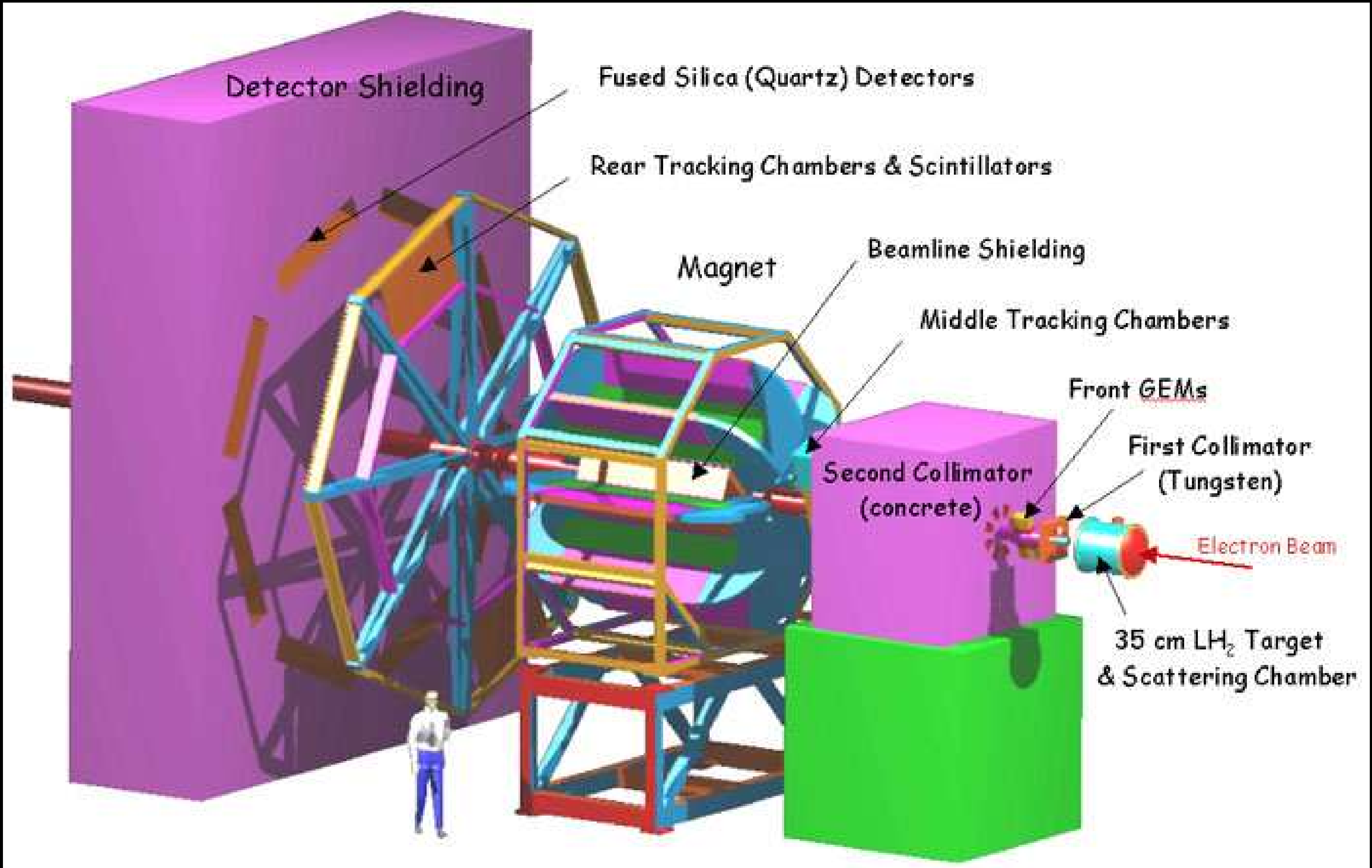
$$\boxed{Q_{weak} = 1 - 4\sin^2\theta_W}$$

Q_{weak}^{p} – Expectations



SLAC E158 Result for $Q_W^e = -0.053 \pm 0.011$

Q_{weak}^p – Setup



Summary & Outlook

- Hall C Well Situated & Equipped to Utilize Jefferson Lab's Polarized CW Beam
- Extensive Experimental Program Measuring & Using Spin:
  - *Deuteron Tensor Polarization*
  - *Spin Structure Functions*
  - *Proton & Neutron Form Factors*
- Ongoing Efforts and Planned Measurements:
  - G_E^n *up to* $Q^2 = 5.6\,GeV^2$, G_E^p *up to* $Q^2 = 9\,GeV^2$
  - *Measure TPEX, Resolve pol – unpol* G_E^p
  - *Ground-Breaking Parity Experiments* G^0 *and* Q^p_{weak}
- Planned $12\,GeV$ Upgrade to Accelerator...