Nucleon Form Factors

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Introduction

- Form Factor

  response of system to momentum transfer Q, often normalized to that of point-like system

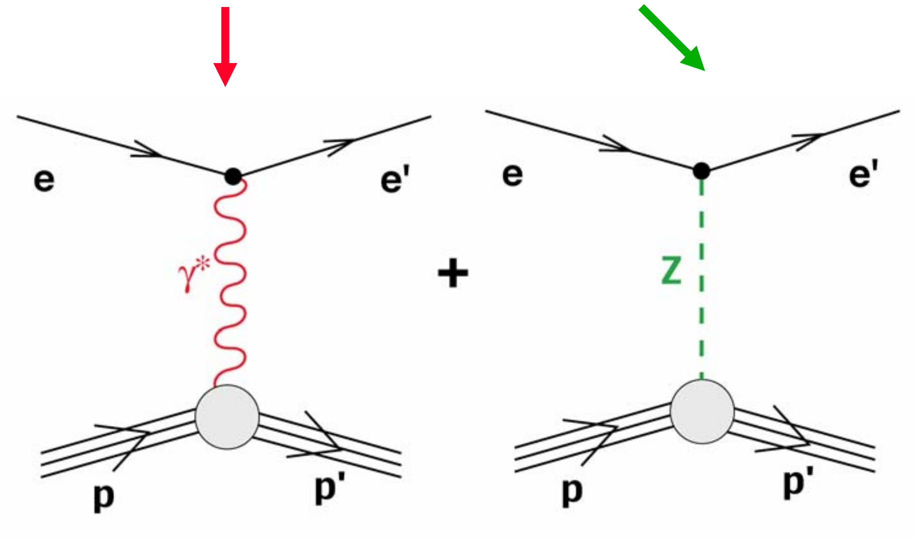
  Examples:

  ← Scattering of photons by bound atoms

  ← Nuclear beta decay

  ← X-ray scattering from crystal

  ← Electromagnetic and weak probing of nucleon



parity conserving

parity violating

Nucleon Electro-Magnetic Form Factors

- Fundamental ingredients in "Classical" nuclear theory
  - A testing ground for theories constructing nucleons from quarks and gluons
  - Provides insight in spatial distribution of charge and magnetization
  - Wavelength of probe can be tuned by selecting momentum transfer Q:

< 0.1 GeV^2	integral quantities (charge radius,…)
0.1-10 GeV^2	internal structure of nucleon
> 20 GeV^2	pQCD scaling

Caveat: If Q is several times the nucleon mass (~Compton wavelength), dynamical effects due to relativistic boosts are introduced, making physical interpretation more difficult

Formalism

Dirac (non-spin-flip) F_1 and Pauli (spin-flip) F_2 Form Factors

$$\frac{d\sigma}{d\Omega}(E,\theta) = \frac{\alpha^2 E'\cos^2(\frac{\theta}{2})}{4E^3\sin^4(\frac{\theta}{2})}[(F_1^2 + \kappa^2\tau F_2^2) + 2\tau(F_1 + \kappa F_2)^2\tan^2(\frac{\theta}{2})]$$

with E (E') incoming (outgoing) energy, θ scattering angle, κ anomalous magnetic moment and $\tau = Q^2/4M^2$

Alternatively, Sachs Form Factors G_E and G_M can be used

$$F_1 = G_E + \tau G_M \qquad F_2 = \frac{G_M - G_E}{\kappa(1+\tau)} \qquad \tau = \frac{Q^2}{4M^2}$$

$$\frac{d\sigma}{d\Omega}(E,\theta) = \sigma_M[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2\tan^2(\frac{\theta}{2})]$$

$$\sigma_M = \frac{\alpha^2 E'\cos^2(\frac{\theta}{2})}{4E^3\sin^4(\frac{\theta}{2})}$$

In the Breit (centre-of mass) frame the Sachs FF can be written as the Fourier transforms of the charge and magnetization radial density distributions

The Pre-JLab Era

- Stern (1932) measured the proton magnetic moment $\mu_p \sim 2.5\ \mu_{Dirac}$ indicating that the proton was not a point-like particle
- Hofstadter (1950's) provided the first measurement of the proton's radius through elastic electron scattering
- Subsequent data (≤ 1993) were based on:
  Rosenbluth separation for proton,
  severely limiting the accuracy for G_E^p at $Q^2 > 1\ GeV^2$

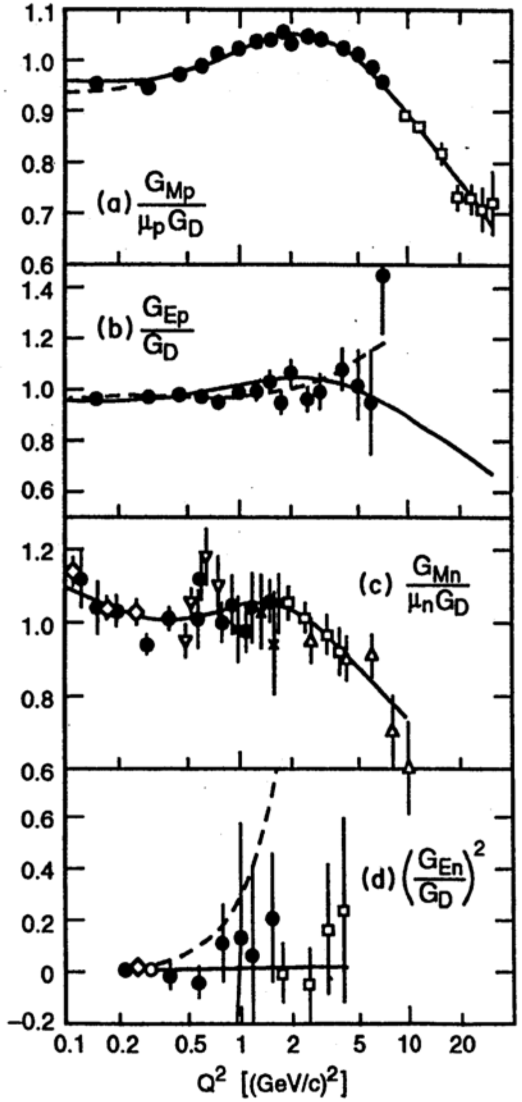
- Early interpretation based on Vector-Meson Dominance

- Good description with phenomenological dipole form factor:

$$\boxed{G_D = \left\{\frac{\Lambda^2}{\Lambda^2 + Q^2}\right\}^2 \quad \textbf{with} \ \ \Lambda = 0.84\,GeV}$$

corresponding to ρ (770 MeV) and ω (782 MeV) meson resonances in timelike region and to exponential distribution in coordinate space

Global Analysis



P. Bosted *et al.*
PRC 51, 409 (1995)

$$G_E^p / G_D = G_M^p / G_D = \left(1 + \sum_{i=1}^{5} a_i Q^i\right);$$

$$G_M^n / G_D = \left(1 + \sum_{i=1}^{4} b_i Q^i\right); \quad G_E^n = 0$$

Three form factors very similar

G_E^n zero within errors -> accurate data on G_E^n early goal of JLab

Modern Era

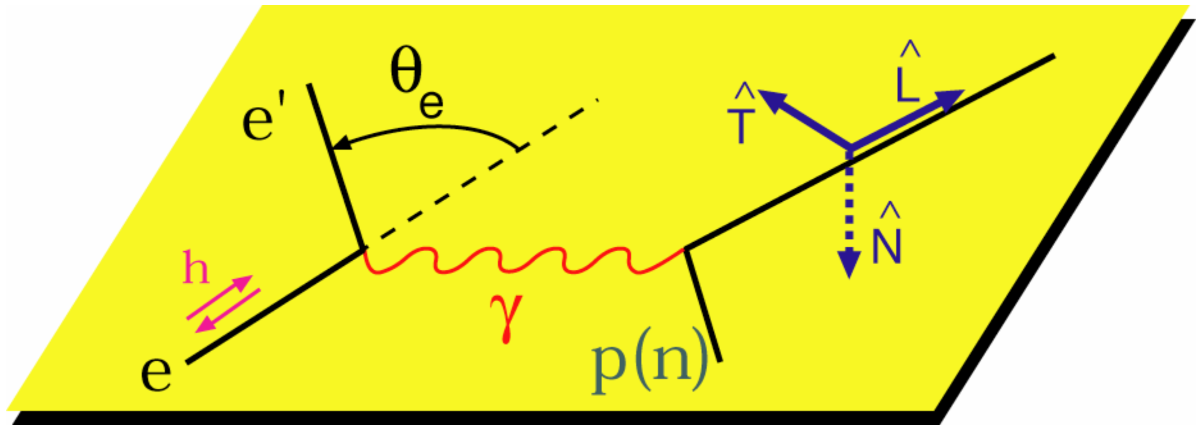
Akhiezer et al., Sov. Phys. JETP 6, 588 (1958) and
Arnold, Carlson and Gross, PR C 23, 363 (1981)
showed that:

accuracy of form-factor measurements can be significantly improved by measuring an interference term $G_E G_M$ through the beam helicity asymmetry with a polarized target or with recoil polarimetry

Had to wait over 30 years for development of

- Polarized beam with
  high intensity (~100 μA) and high polarization (>70 %)
  (strained GaAs, high-power diode/Ti-Sapphire lasers)
- Beam polarimeters with 1-3 % absolute accuracy
- Polarized targets with a high polarization or
- Ejectile polarimeters with large analyzing powers

Spin Transfer Reaction



$$\boxed{J \propto G_E + \sigma \times Q * G_M}$$

Polarized electron transfers longitudinal polarization to G_E, but transverse polarization to G_M

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

No error contributions from

- analyzing power
- beam polarimetry

Polarimeter only sensitive to transverse polarization components

Use dipole magnet to precess longitudinal component to normal

Double Polarization Experiments to Measure G^n_E

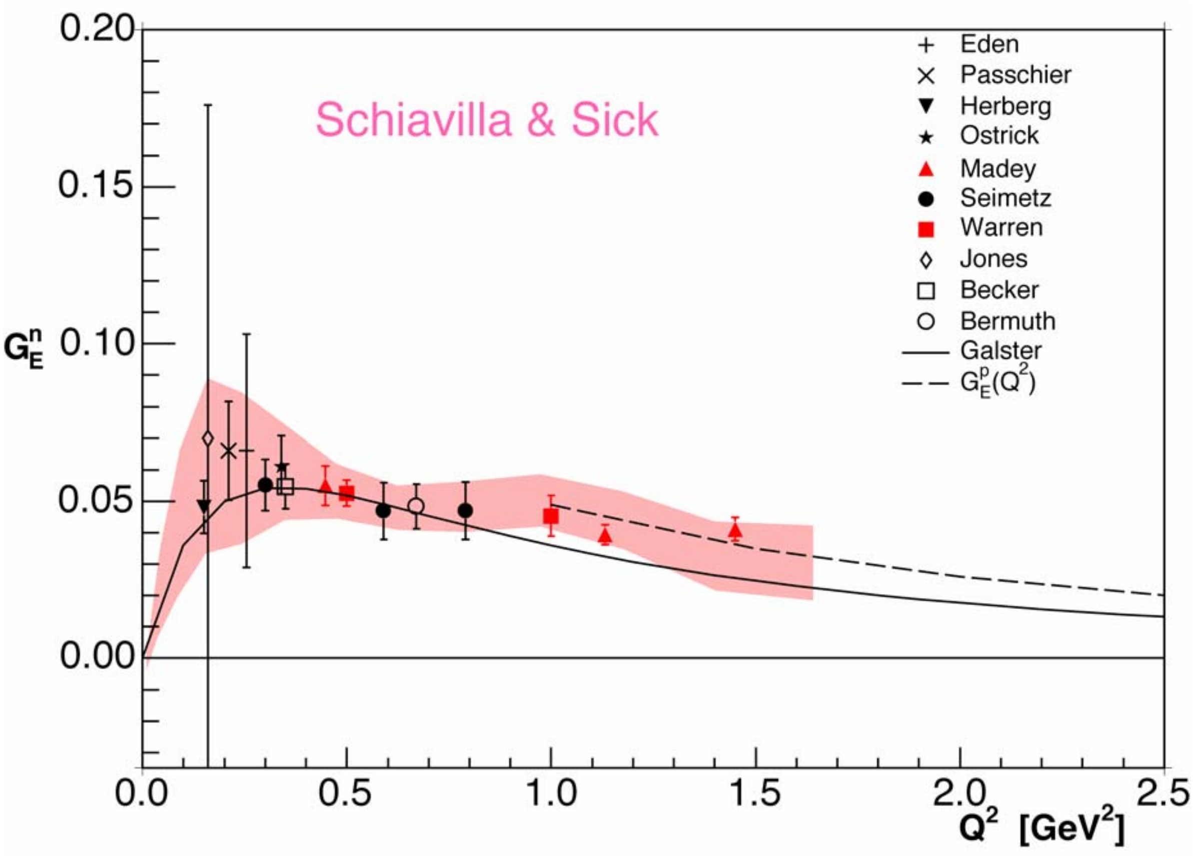
- Study the (e,e'n) reaction from a polarized ND_3 target
  limitations: low current (~80 nA) on target
  deuteron polarization (~25 %)

- Study the (e,e'n) reaction from a LD_2 target and measure the neutron polarization with a polarimeter
  limitations: Figure of Merit of polarimeter

- Study the (e,e'n) reaction from a polarized ^{3}He target
  limitations: current on target (12 μA)
  target polarization (40 %)
  nuclear medium corrections

$$\boxed{\frac{G_E^n}{G_M^n} = \frac{A_\perp}{A_\parallel}\sqrt{\tau + \tau(1+\tau)\tan^2(\frac{\theta}{2})}}$$

Neutron Electric Form Factor G_E^n



Galster:
a parametrization fitted to old (<1971) data set of very limited quality

For $Q^2 > 1$ GeV^2 data hint that G_E^n has similar Q^2-behaviour as G_E^p

Most recent results (Mainz, JLab) are in excellent agreement, even though all three different techniques were used

Measuring G^n_M

Old method: quasi-elastic scattering from ^{2}H
large systematic errors due to subtraction of proton contribution

$$R_D = \frac{\dfrac{d^3\sigma(eD \Rightarrow e'n(p))}{dE'\,d\Omega_{e'}d\Omega_n}}{\dfrac{d^3\sigma(eD \Rightarrow e'p(n))}{dE'\,d\Omega_{e'}d\Omega_p}}$$

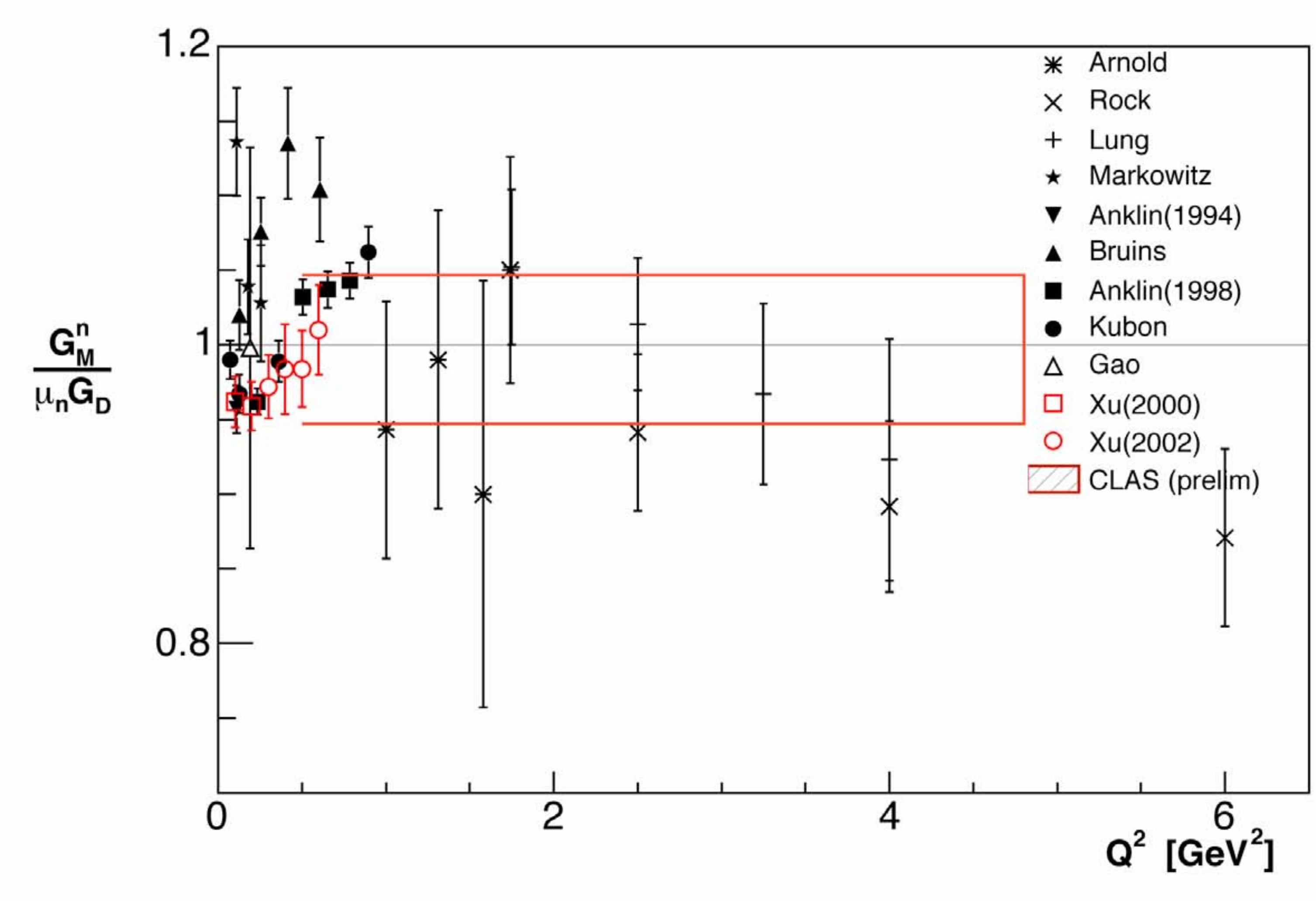
- Measure (en)/(ep) ratio
  Luminosities cancel
  Determine neutron detector efficiency
    - On-line through e+p->e'+π^+(+n) reaction (CLAS)
    - Off-line with neutron beam (Mainz)

- Measure inclusive quasi-elastic scattering off polarized ^{3}He

$$A = \frac{-\left(\cos\theta^* v_{T'}R_{T'} + 2\sin\theta^*\cos\varphi^* v_{TL'}R_{TL'}\right)}{v_L R_L + v_T R_T}$$

$R_{T'}$ directly sensitive to $(G_M{}^n)^2$

Preliminary G^n_M Results from CLAS



$G_M{}^n$ closely follows G_D behaviour up to 5 GeV^2

Early Measurements of G_E^p

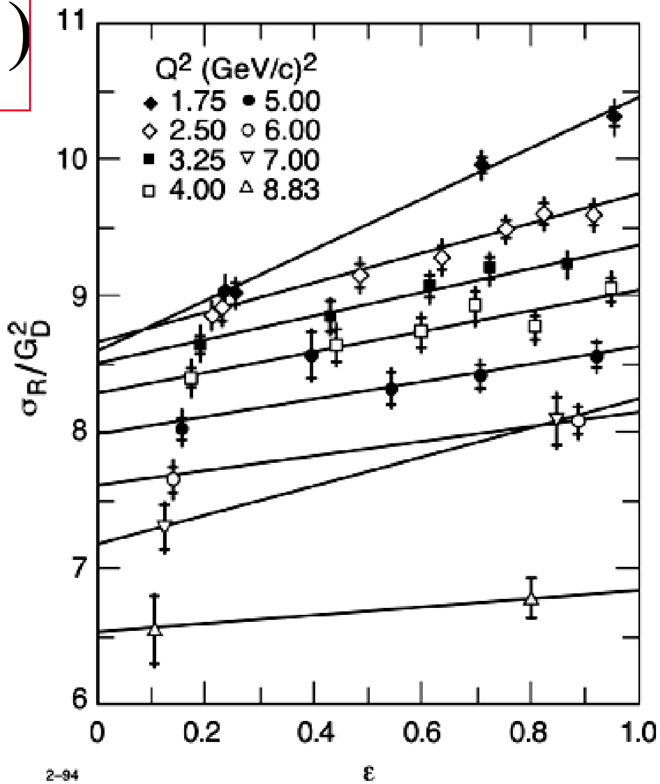
- relied on Rosenbluth separation
- measure $d\sigma/d\Omega$ at constant Q^2
- G_E^p inversely weighted with Q^2, increasing the systematic error above $Q^2 \sim 1$ GeV^2

$$\sigma_R\left(Q^2,\varepsilon\right)=\varepsilon\left(1+\frac{1}{\tau}\right)\frac{E}{E'}\frac{\sigma(E,\theta)}{\sigma_{Mott}}=(G_M^p)^2\left(Q^2\right)+\frac{\varepsilon}{\tau}(G_E^p)^2\left(Q^2\right)$$

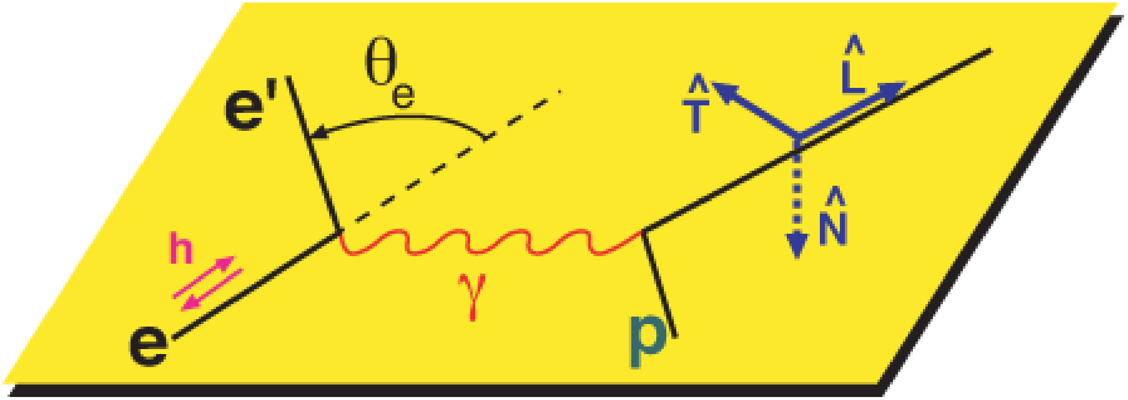
$$Q^2=4EE'\sin^2\left(\frac{\theta}{2}\right)$$

$$\varepsilon=\frac{1}{1+2(1+\tau)\tan^2(\theta/2)}$$

At 6 GeV^2 σ_R changes by only 8% from ε=0 to ε=1 if $G_E^p=G_M^p/\mu_p$
Hence, measurement of G_e^p with 10% accuracy requires 1.6% cross-section measurement



Spin Transfer Reaction $^1H(\vec{e},e'\vec{p})$



$$P_n = 0$$

$$\pm hP_t = \mp h 2\sqrt{\tau(1+\tau)} G_E^p G_M^p \tan\left(\frac{\theta_e}{2}\right) / I_0$$

$$\pm hP_l = \pm h\left(E_e + E_{e'}\right)\left(G_M^p\right)^2 \sqrt{\tau(1+\tau)} \tan^2\left(\frac{\theta_e}{2}\right) / M / I_0$$

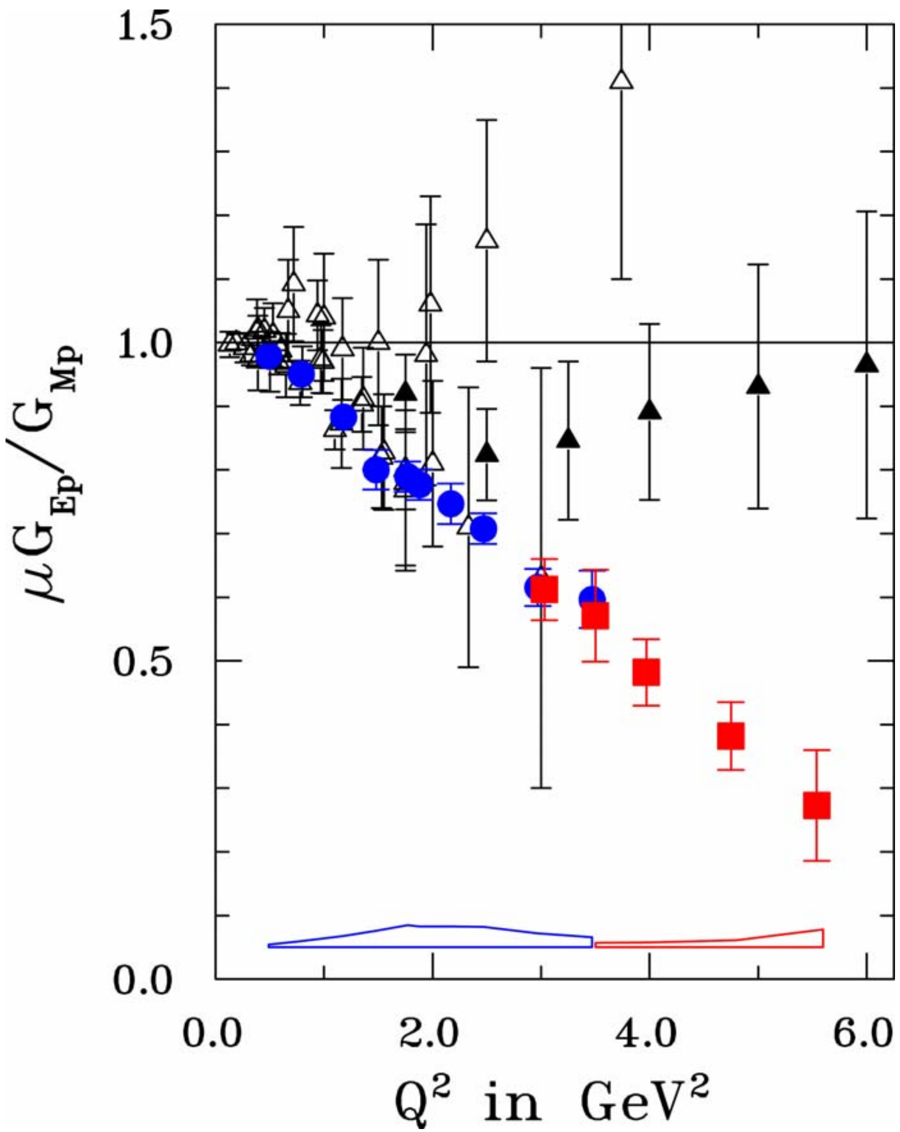
$$I_0 = \left\{G_E^p\left(Q^2\right)\right\}^2 + \tau\left\{G_M^p\left(Q^2\right)\right\}^2\left[1 + 2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)\right]$$

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

No error contributions from
- analyzing power
- beam polarimetry

JLab Polarization Transfer Data

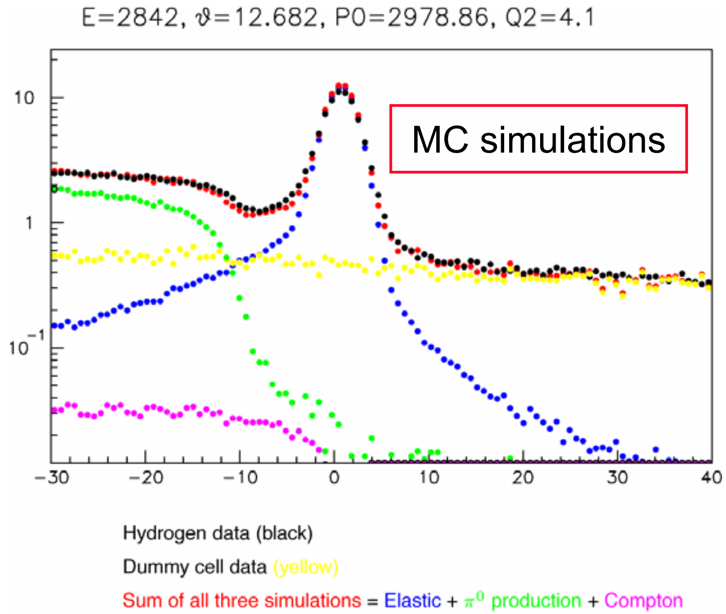
- E93-027 PRL 84, 1398 (2000)
  Used both HRS in Hall A with FPP
- E99-007 PRL 88, 092301 (2002)
  used Pb-glass calorimeter for electron detection to match proton HRS acceptance
- Reanalysis of E93-027 (Pentchev)
  Using corrected HRS properties
- No dependence of polarization transfer on any of the kinematic variables

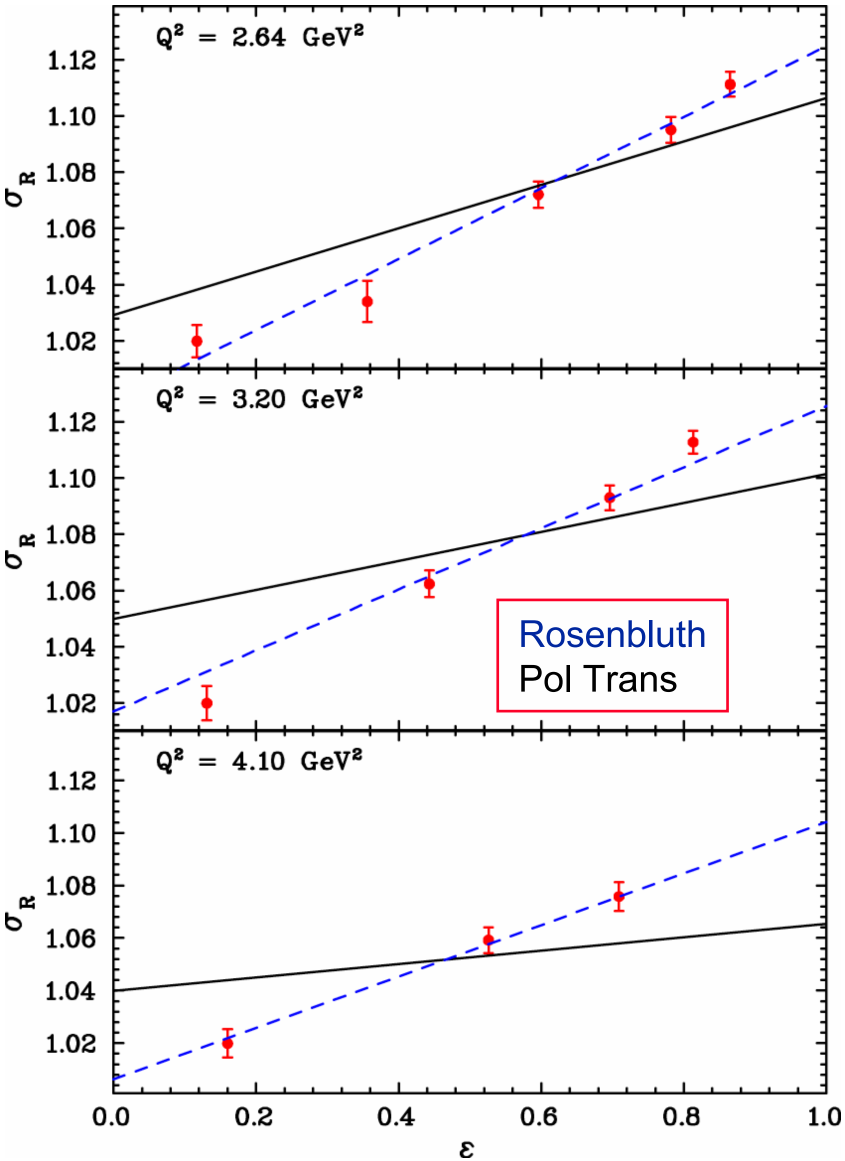


Super-Rosenbluth (E01-001)

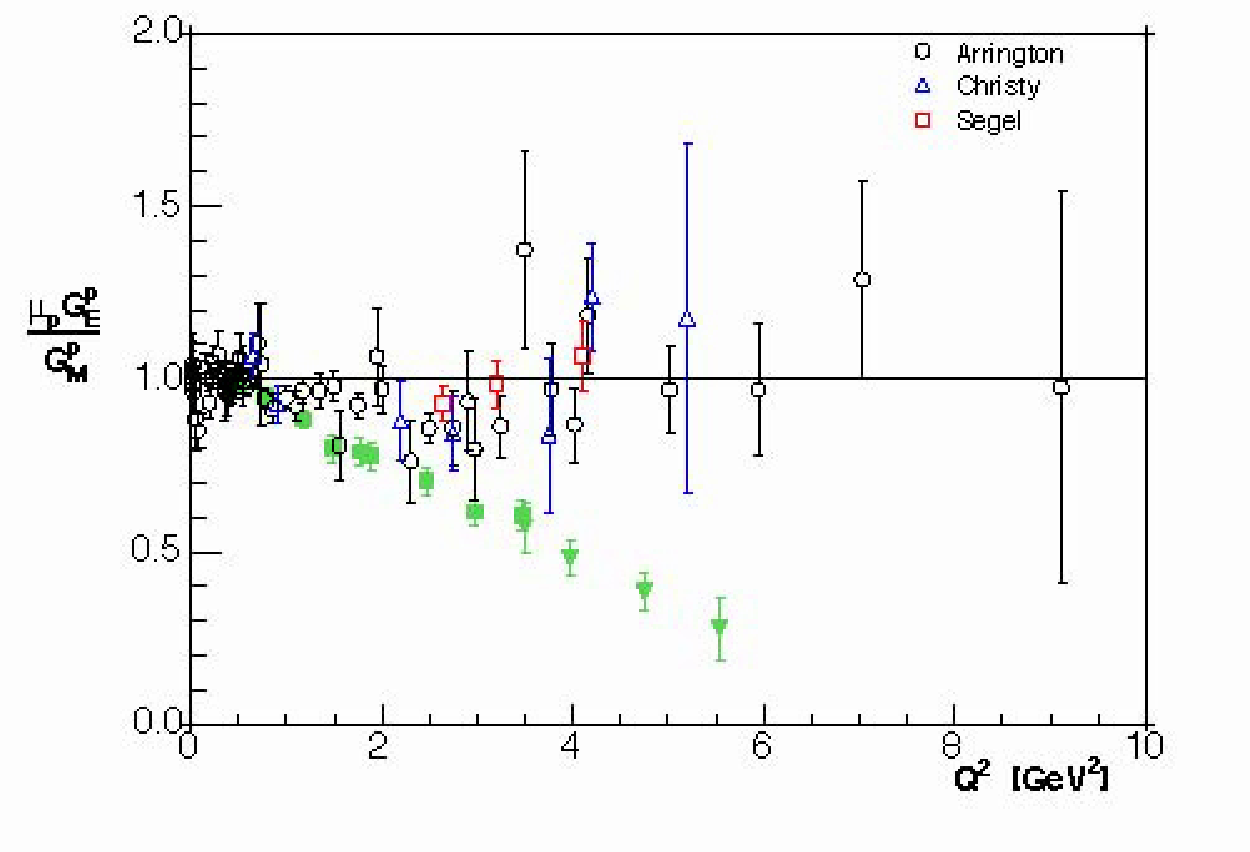
J. Arrington and R. Segel (nucl-ex/0410010)

- Detect recoil protons in HRS-L to diminish sensitivity to:
  - Particle momentum
  - Particle angle
  - Rate
- Use HRS-R as luminosity monitor
- Very careful survey



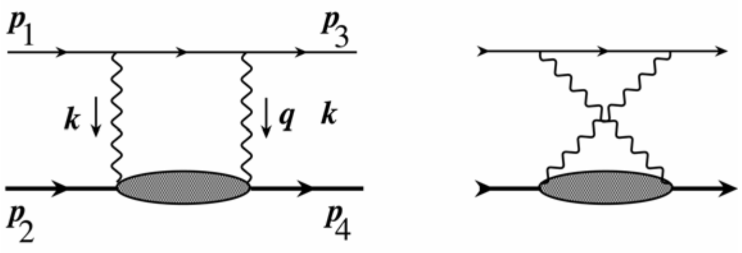


Rosenbluth Compared to Polarization Transfer



- John Arrington performed detailed reanalysis of SLAC data
- Hall C Rosenbluth data (E94-110, Christy) in agreement with SLAC data
- No reason to doubt quality of either Rosenbluth or polarization transfer data
- Investigate possible theoretical sources for discrepancy

Two-photon Contributions

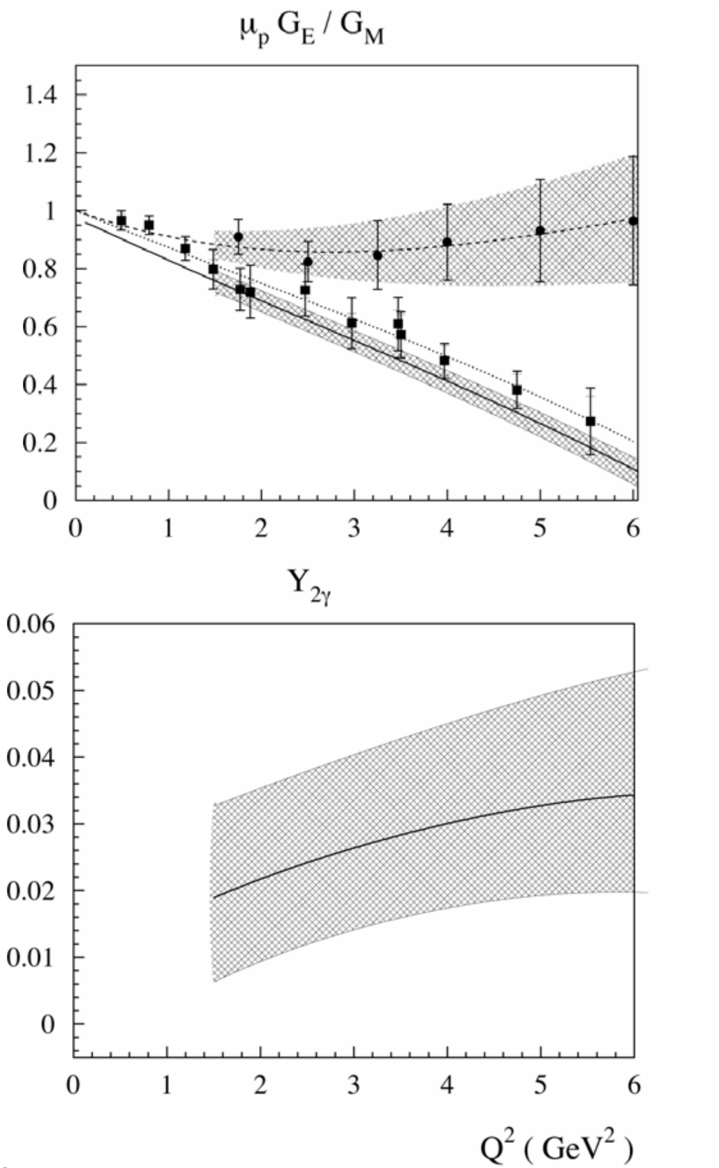


Guichon and Vanderhaeghen (PRL 91, 142303 (2003)) estimated the size of two-photon corrections (TPE) necessary to reconcile the Rosenbluth and polarization transfer data

$$\frac{d\sigma}{d\Omega} \propto \frac{\left|\tilde{G}_M\right|^2}{\tau}\left\{\tau + \varepsilon\frac{\left|\tilde{G}_E\right|^2}{\left|\tilde{G}_M\right|^2} + 2\varepsilon\left(\tau + \frac{\left|\tilde{G}_E\right|}{\left|\tilde{G}_M\right|}\right)Y_{2\gamma}(\nu,Q^2)\right\}$$

$$\frac{P_t}{P_l} \approx -\sqrt{\frac{2\varepsilon}{\tau(1+\varepsilon)}}\left\{\frac{\left|\tilde{G}_E\right|}{\left|\tilde{G}_M\right|} + \left(1 - \frac{2\varepsilon}{1+\varepsilon}\frac{\left|\tilde{G}_E\right|}{\left|\tilde{G}_M\right|}\right)Y_{2\gamma}(\nu,Q^2)\right\}$$

Need ~3% value for $Y_{2\gamma}$ (6% correction to ε-slope), independent of Q^2, which yields minor correction to polarization transfer

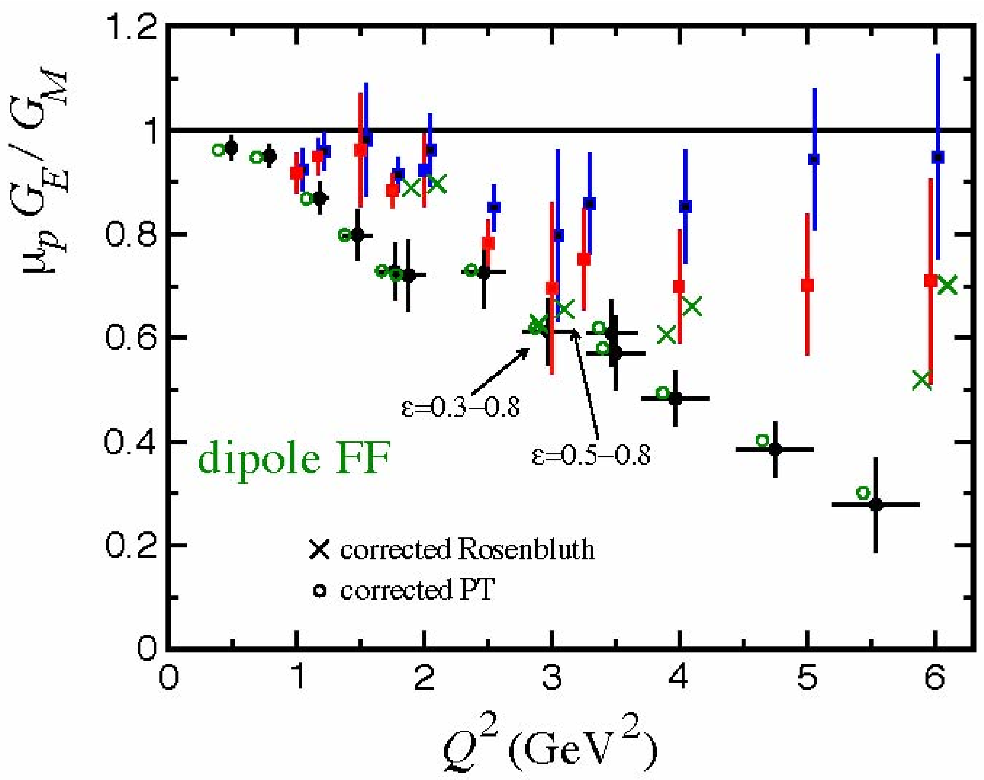


Two-Photon Contributions (cont.)

Blunden, Melnitchouk and Tjon (PRL 91, 142304 (2003)) investigated the box (and cross) diagram in the radiative correction, but only the elastic contribution. The γp form factor was assumed to follow a monopole dependence.

Need estimate of inelastic (resonance) contributions!

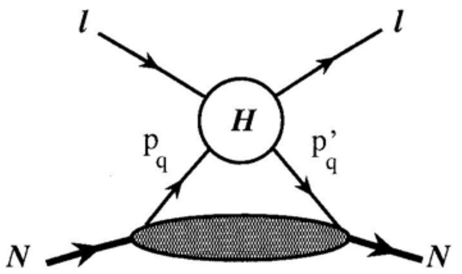
Recent calculations use a more realistic dipole form factor, decreases the discrepancy even more

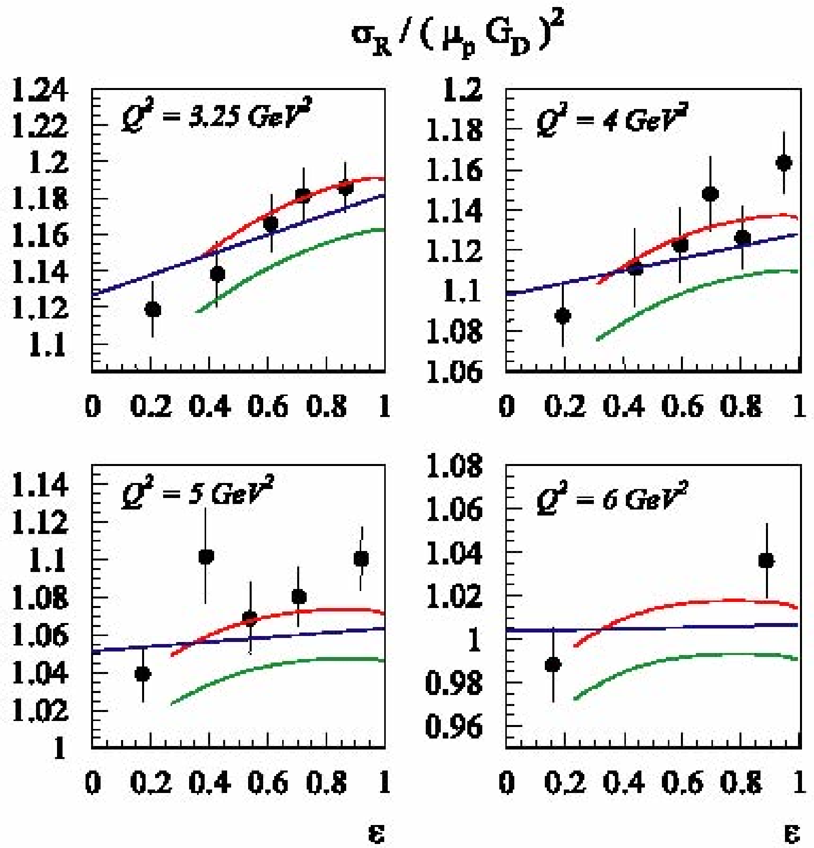


Two-Photon Contributions (cont.)

Chen et al. (PRL 93, 122301 (2004))
Model schematics:

- Hard eq-interaction
- GPDs describe quark emission/absorption
- Soft/hard separation
- Assume factorization

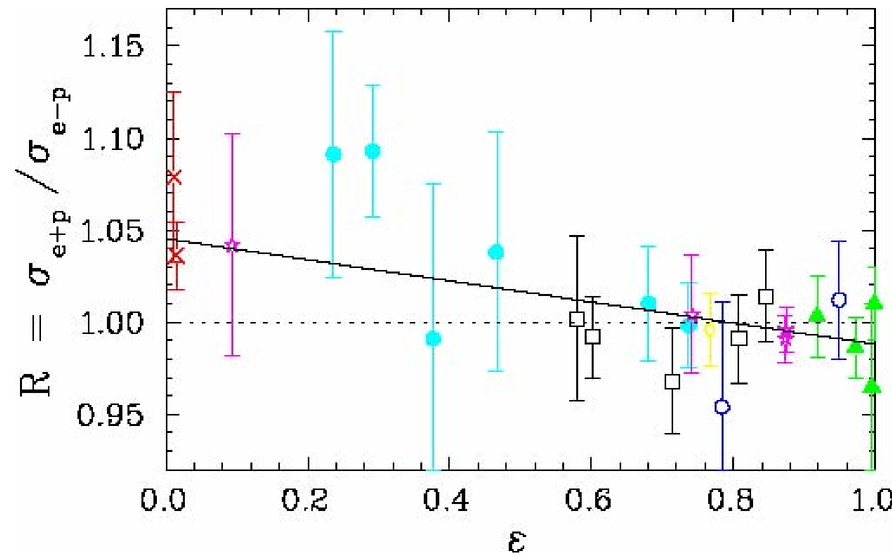




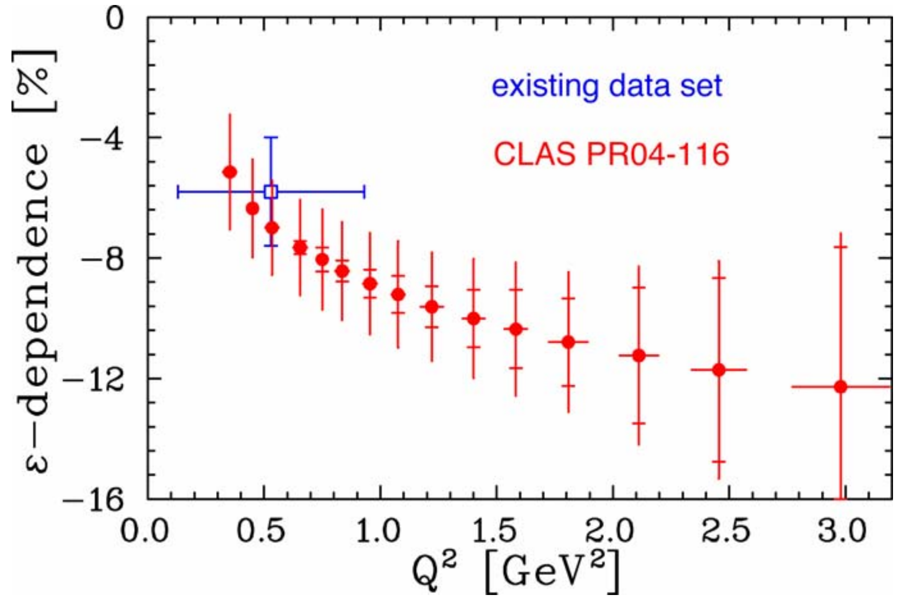
Polarization transfer
$1\gamma+2\gamma$(hard)
$1\gamma+2\gamma$(hard+soft)

Experimental Verification of TPE contributions

Experimental verification
- non-linearity in ε-dependence
  (test of model calculations)
- transverse single-spin asymmetry (imaginary part of two-photon amplitude)
- ratio of e^+p and e^-p cross section (direct measurement of two-photon contributions)

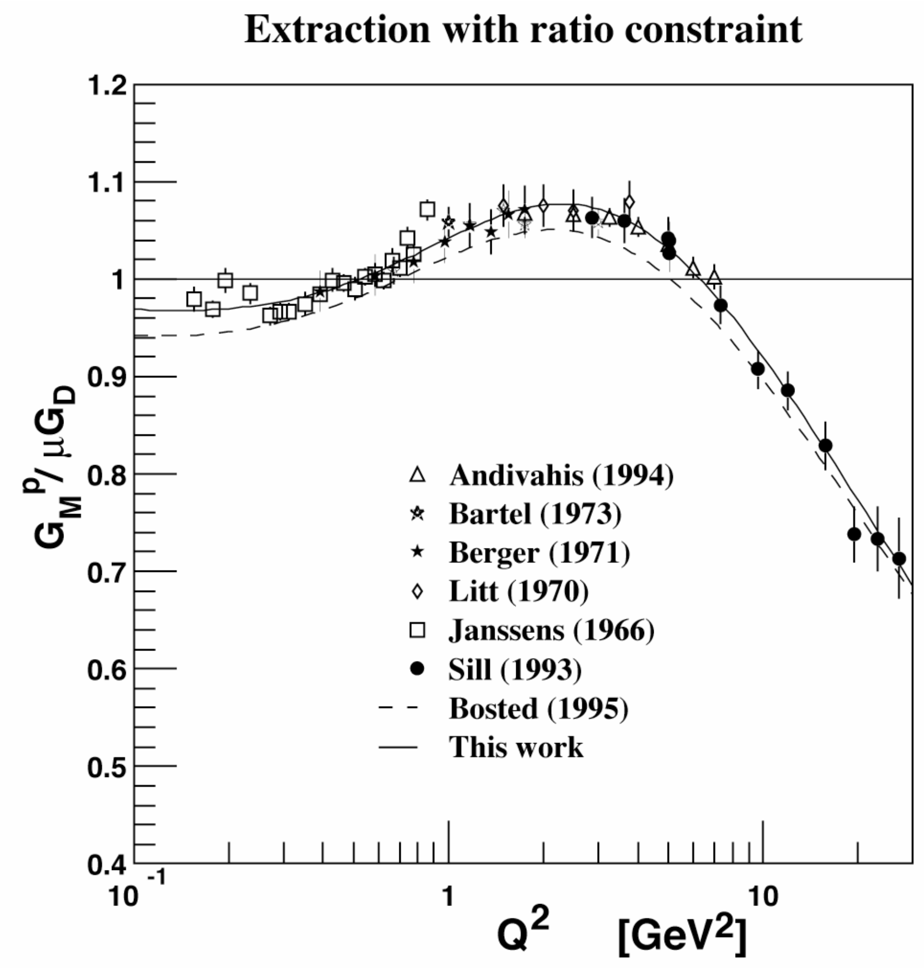


- CLAS experiment E04-116 aims at a measurement of the ε-dependence of the e+/e- ratio for Q^2-values up to 2.0 GeV^2
- At the VEPP-3 ring that ratio will be measured at two ε– and Q^2-values



Reanalysis of SLAC data on G_M^p

E. Brash *et al.* (PRC 65, 051001 (2002)) have reanalyzed SLAC data with JLab G_E^p/G_M^p results as constraint, using a similar fit function as Bosted Reanalysis results in 1.5-3% increase of G_M^p data



Theory

$$F_{1,2}^{is,iv} = \sum g_X \frac{m_X^2}{m_X^2 + Q^2} F_{1,2}(Q^2)$$

- Vector Meson Dominance
  Photon couples to nucleon exchanging vector meson (ρ,ω,ϕ)
  Adjust high-Q^2 behaviour to pQCD scaling
  Include 2π-continuum in finite width of ρ
- Lomon 3 isoscalar, isovector poles, intrinsic core FF
- Iachello 2 isoscalar, 1 isovector pole, intrinsic core FF
- Hammer 4 isoscalar, 3 isovector poles, no additional FF

- Relativistic chiral soliton model
- Holzwarth one VM in Lagrangian, boost to Breit frame
- Goeke NJL Lagrangian, few parameters

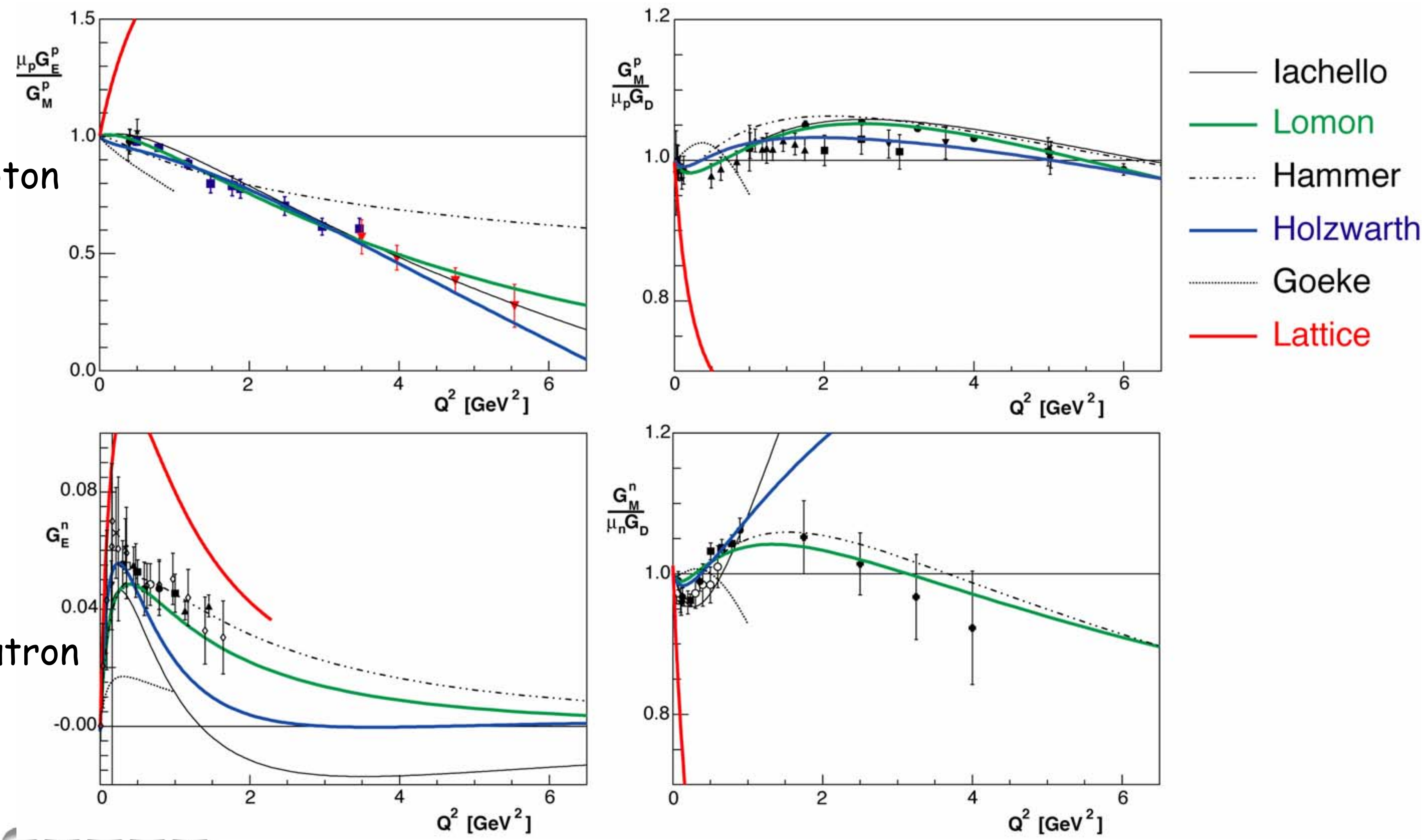
- Lattice QCD (Schierholz, QCDSF)
  quenched approximation, box size of 1.6 fm, m_π = 650 MeV
  chiral "unquenching" and extrapolation to m_π = 140 MeV (Adelaide)

Vector-Meson Dominance

charge magnetization

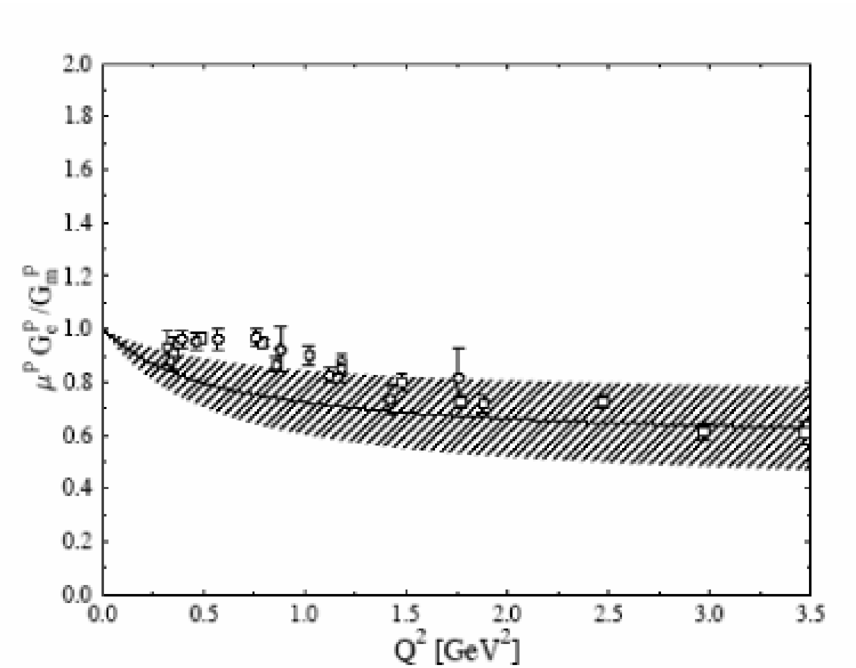
proton

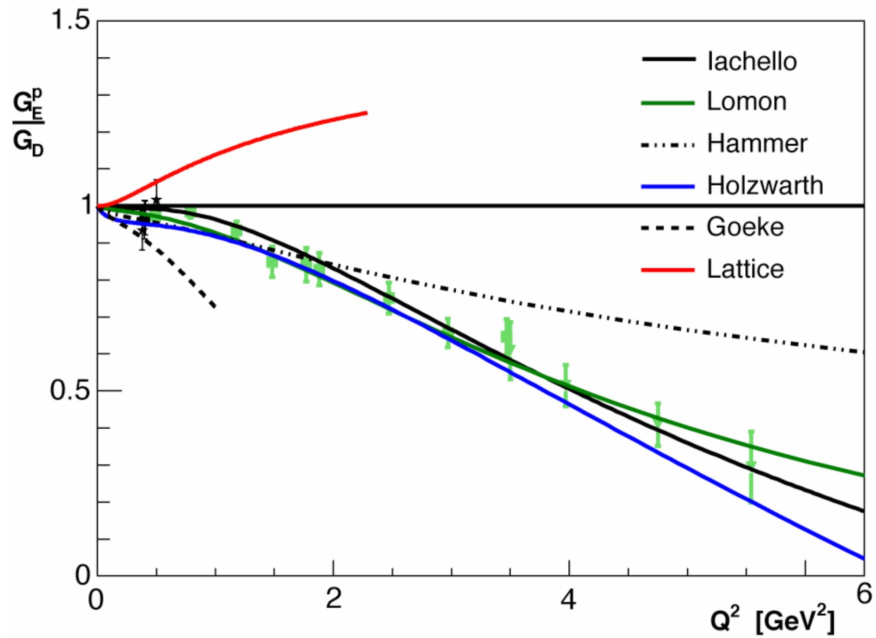
neutron



Chiral Extrapolation of Lattice QCD

- Problem is how to extrapolate LQCD results to the physical pion mass
- QCDSF uses a linear extrapolation in m_π for the dipole mass fitted to the FF
- Adelaide group uses the same for the isoscalar radii, but an $a/m_\pi + b\ln(m_\pi)$ behaviour for the isovector radii
- Additionally, one should question whether a chiral extrapolation is valid at m_π=650 MeV

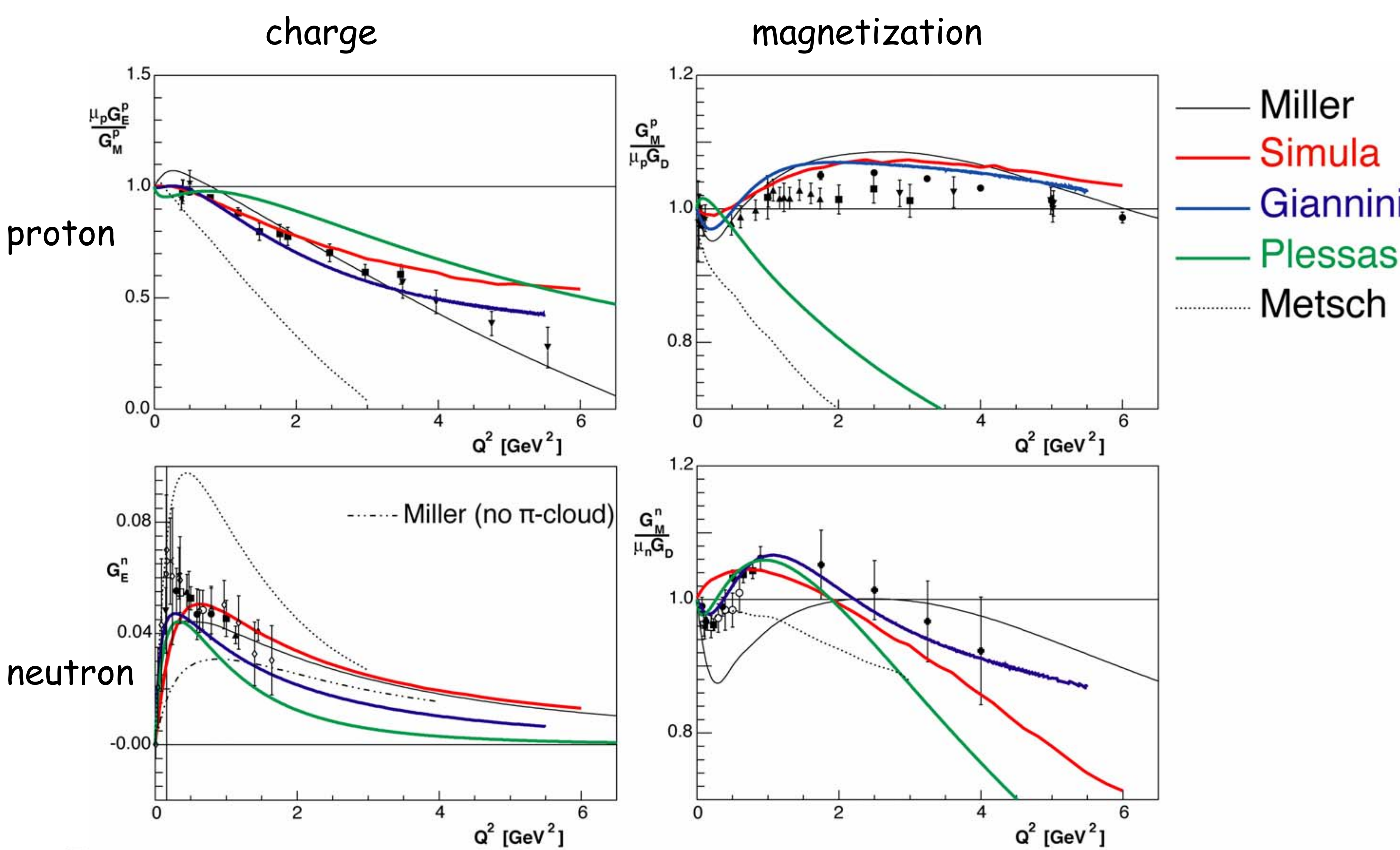




Theory

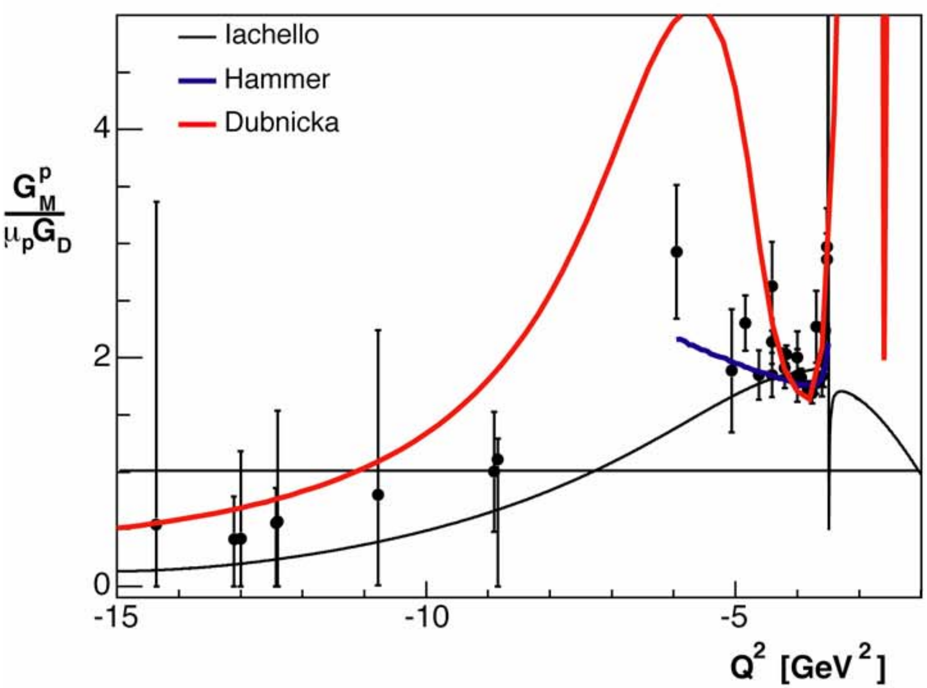
- Relativistic Constituent Quark Models
  Variety of q-q potentials (harmonic oscillator, hypercentral, linear)
  Non-relativistic treatment of quark dynamics, relativistic EM currents
- Miller: extension of cloudy bag model, light-front kinematics
  wave function and pion cloud adjusted to static parameters
- Cardarelli & Simula
  Isgur-Capstick oge potential, light-front kinematics
  constituent quark FF in agreement with DIS data
- Wagenbrunn & Plessas
  point-form spectator approximation
  linear confinement potential, Goldstone-boson exchange
- Giannini et al.
  gluon-gluon interaction in hypercentral model
  boost to Breit frame
- Metsch et al.
  solve Bethe-Salpeter equation, linear confinement potential

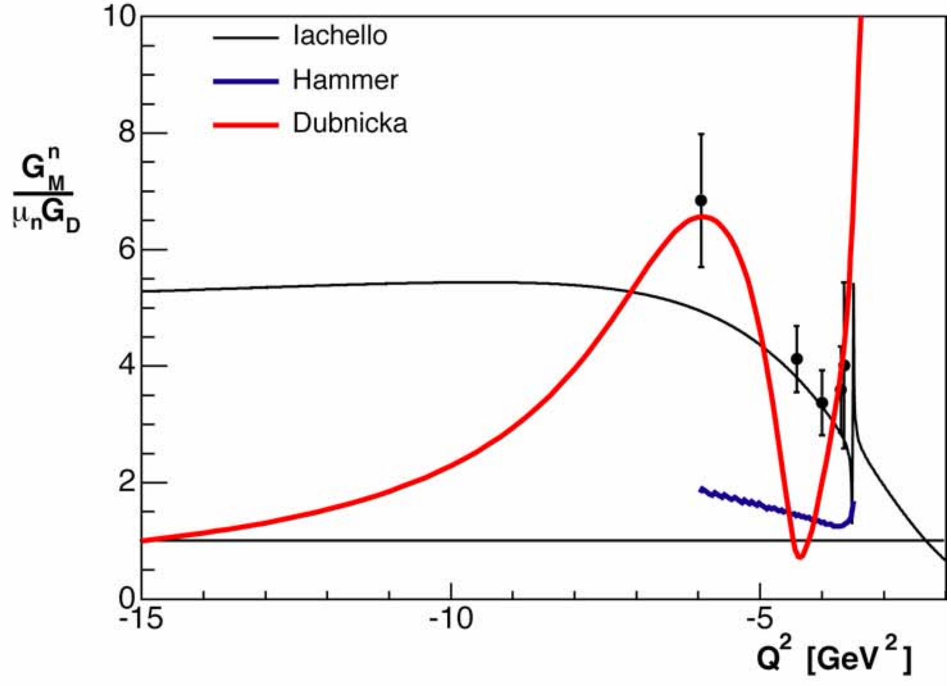
Relativistic Constituent Quark



Time-Like Region

- Can be probed through $e^+e^- \rightarrow N\bar{N}$ or inverse reaction





- Data quality insufficient to separate charge and magnetization contributions
- No scaling observed with dipole form factor
- Iachello only model in reasonable agreement with data

Charge and Magnetization Radii

$$\langle r^2 \rangle \equiv 4\pi \int \rho(r)\, r^4\, dr = -\frac{6}{G(0)} \frac{dG(Q^2)}{dQ^2}$$

Experimental values

$\langle r_E^2 \rangle_p^{1/2} = 0.895+0.018$ fm

$\langle r_M^2 \rangle_p^{1/2} = 0.855+0.035$ fm

$\langle r_E^2 \rangle_n = -0.0119+0.003$ fm^2

$\langle r_M^2 \rangle_n^{1/2} = 0.87+0.01$ fm

Even at low Q2-values Coulomb distortion effects have to be taken into account

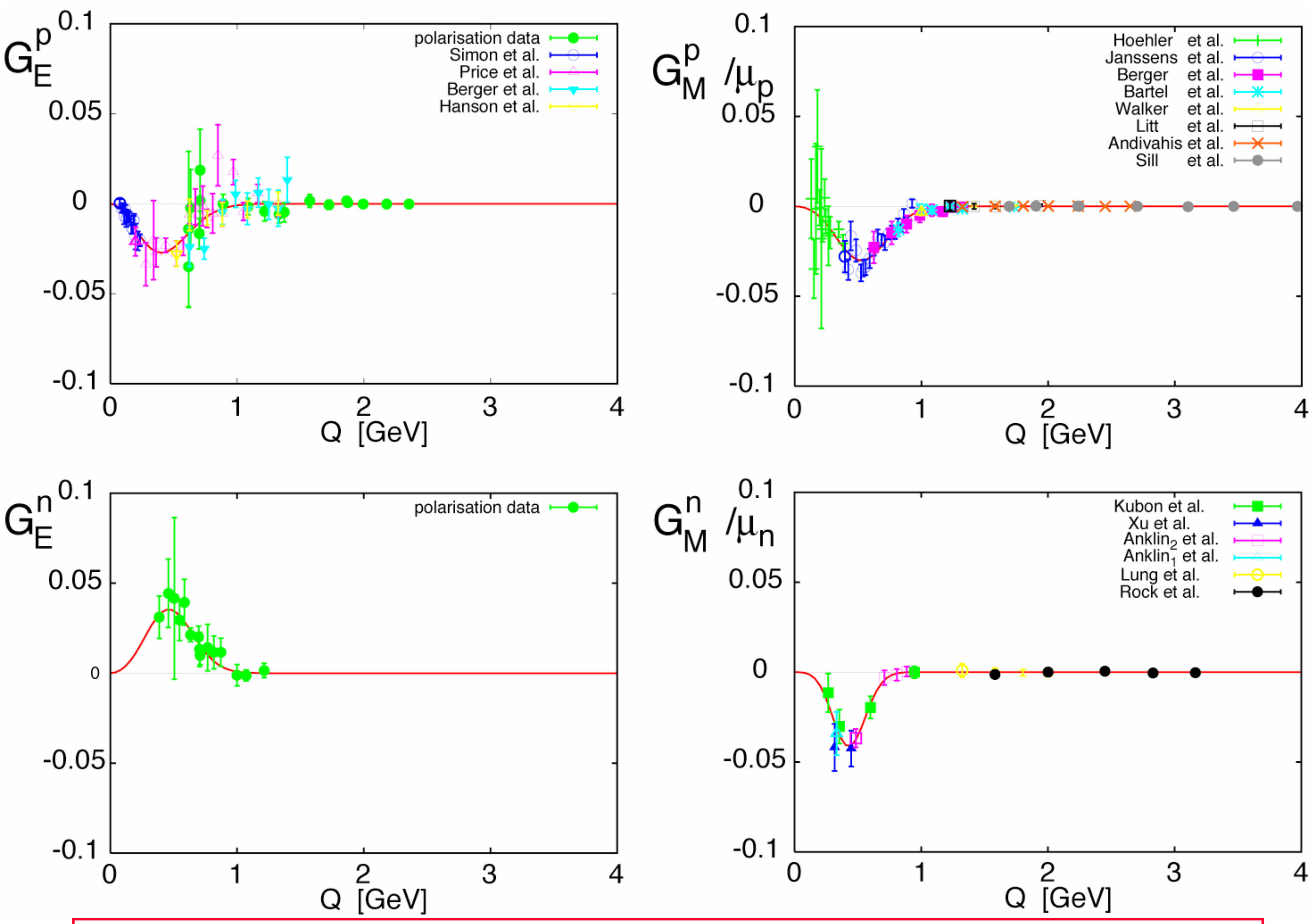
Three non-zero radii are identical within experimental accuracy

$$\frac{dG_E^n(Q^2)}{dQ^2}\bigg|_{Q^2=0} = \frac{dF_1^n(Q^2)}{dQ^2}\bigg|_{Q^2=0} - \frac{F_2^n(0)}{4M^2}$$

Foldy term = -0.0126 fm^2 canceled by relativistic corrections (Isgur)

implying neutron charge distribution is determined by G_E^n

Low Q^2 Systematics



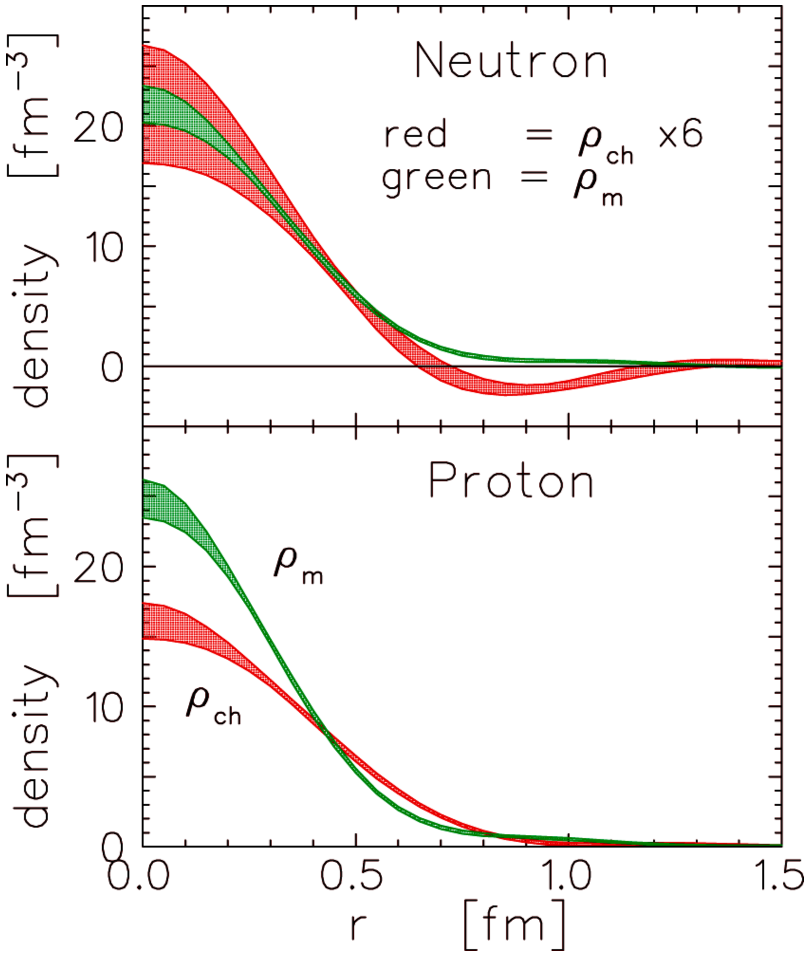
All EMFF show minimum (maximum for G_E^n) at $Q \approx 0.5$ GeV

Pion Cloud

- Kelly has performed simultaneous fit to all four EMFF in coordinate space using Laguerre-Gaussian expansion and first-order approximation for Lorentz contraction of local Breit frame

$$\tilde{G}_{E,M}(k) = G_{E,M}(Q^2)(1+\tau)^2 \quad \textbf{with} \quad k^2 = \frac{Q^2}{1+\tau} \quad \textbf{and} \quad \tau = \left(\frac{Q}{2M}\right)^2$$

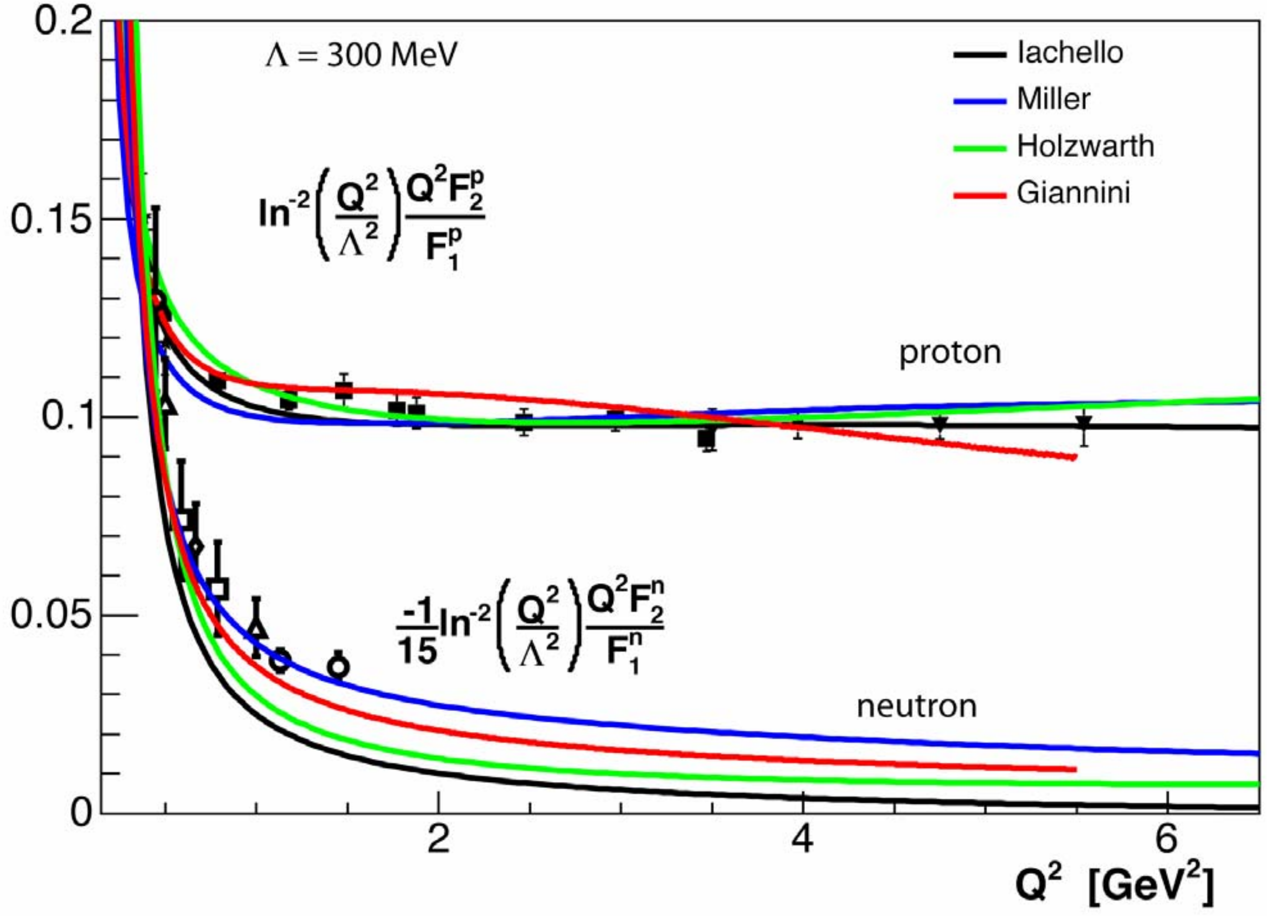
- Friedrich and Walcher have performed a similar analysis using a sum of dipole FF for valence quarks but neglecting the Lorentz contraction
- Both observe a structure in the proton and neutron densities at ~0.9 fm which they assign to a pion cloud



- Hammer et al. have extracted the pion cloud assigned to the $N\bar{N}2\pi$ component which they find to peak at ~ 0.4 fm

High-Q^2 Behaviour

Belitsky et al. have included logarithmic corrections in pQCD limit



They warn that the observed scaling could very well be precocious

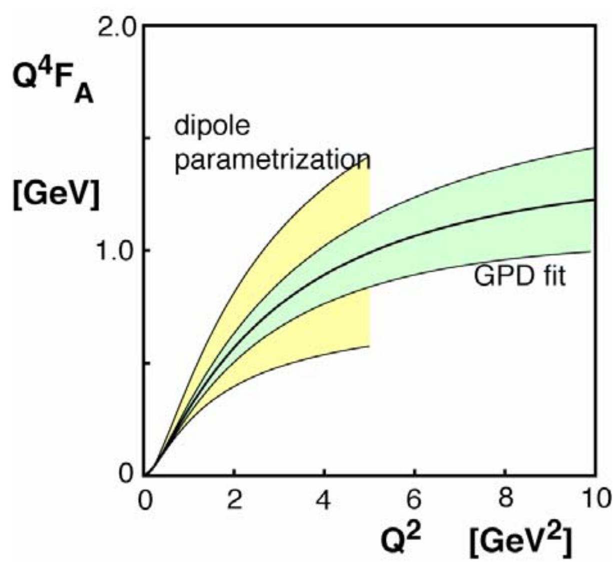
Proton Tomography

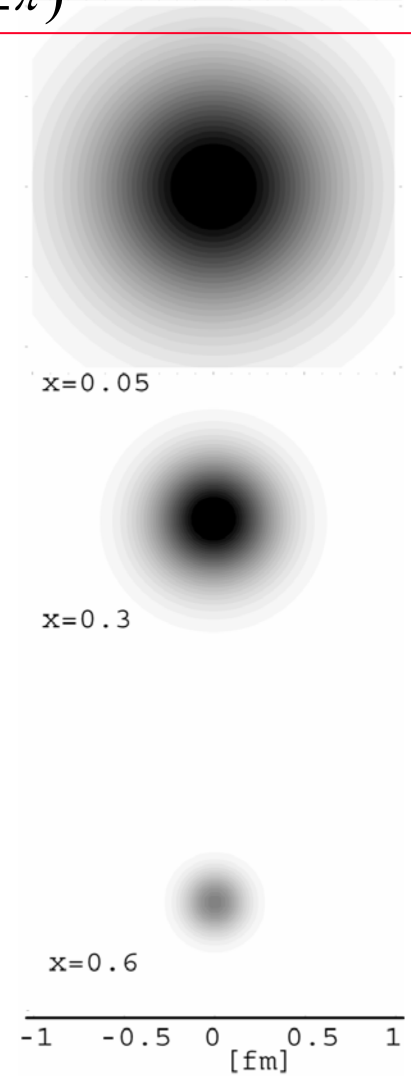
$$u_v(x,b) = \int \frac{d^2\Delta}{(2\pi)^2} e^{-ib\Delta} H_v^u(x,t=-\Delta^2)$$

Generalized Parton Distributions

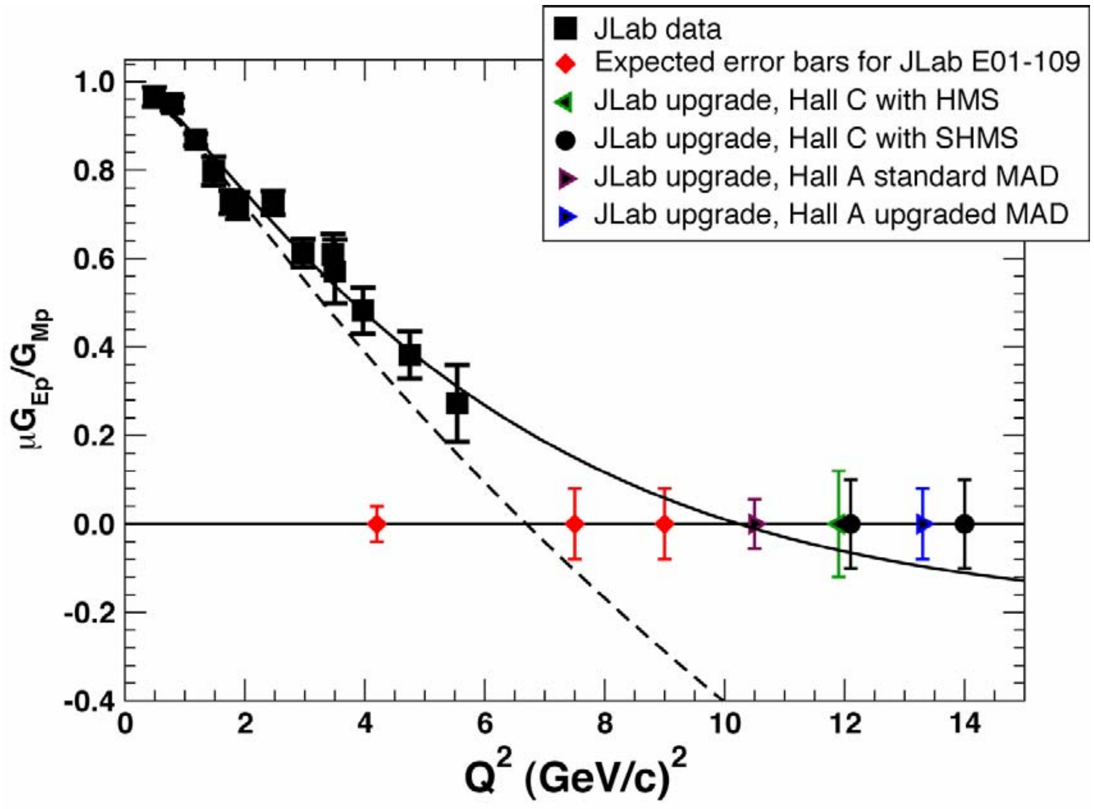
(see presentation by Michel Garcon)

- Diehl et al. (hep-ph/0408173) have fit the GPDs to existing EMFF data set, consistent with Regge phenomenology at low x and simple high-x behaviour
- They obtain good description of $G_A(Q^2)$ and WACS and provide visualization of GPDs



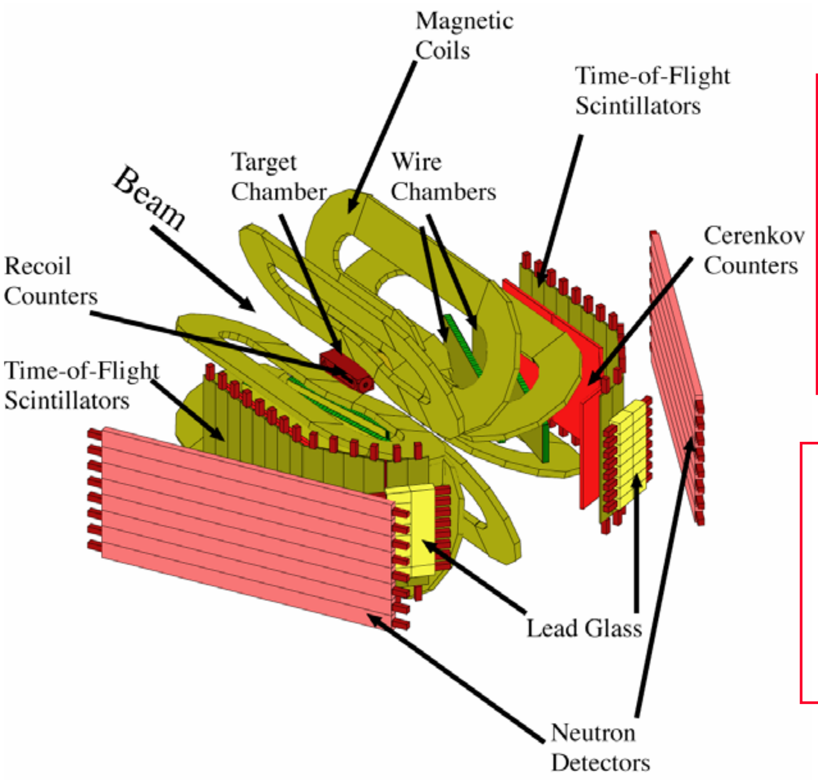


Future extensions for G_E^p



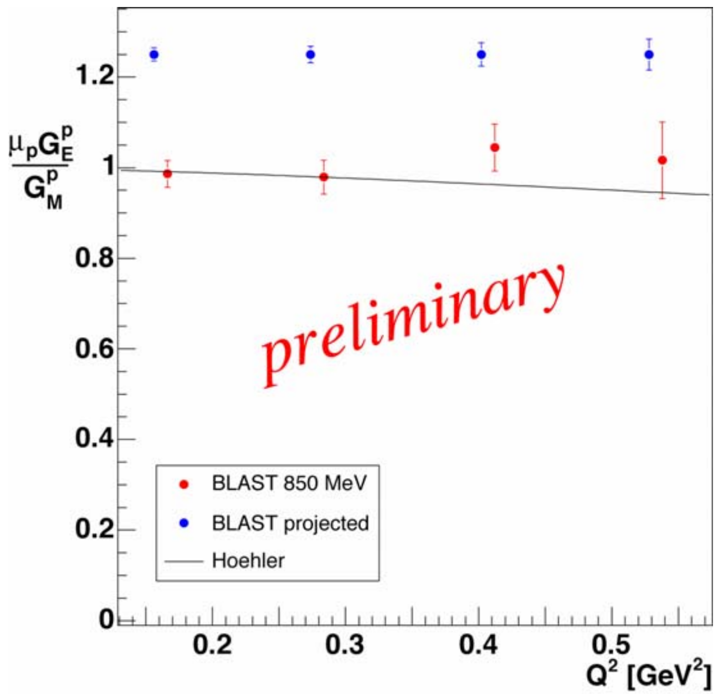
- Perdrisat *et al.* E01-109 (expected to run late 2006)
  Use Hall C HMS (with new FPP) and larger Pb-glass calorimeter
- MAD in Hall A or SHMS in Hall C at 11 GeV

G_E^n and G_E^p measurements from BLAST



Session V
Friday 14:30
Vitaliy Ziskin
Friday 14:50
Chris Crawford

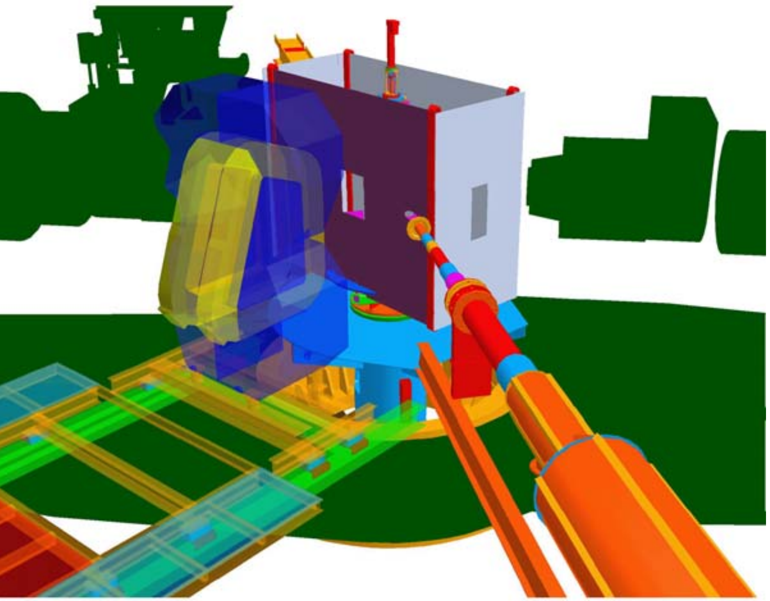
Storage ring
Internal target
$p_e \cdot p_b \approx 0.25$
25% statistics

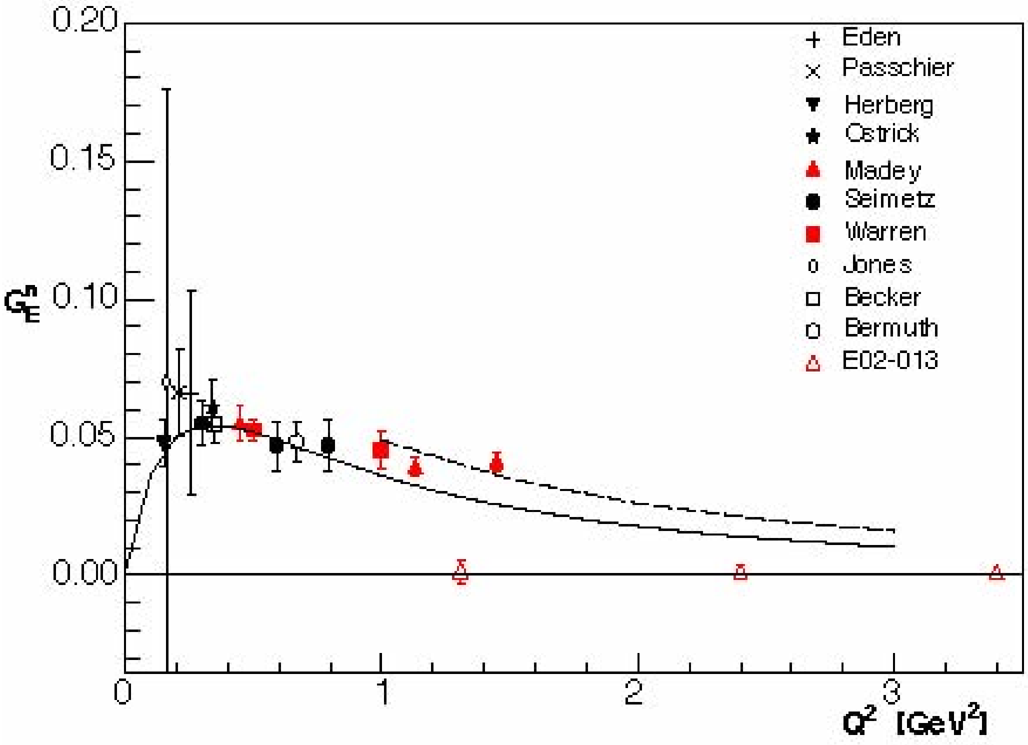


Key features of BLAST measurement:

- Asymmetry ratio from two sectors minimizes systematic uncertainties
- Quick change from polarized hydrogen (G_E^p) to polarized deuterium (G_E^n)

Future Extensions for G_E^n





- E02-013 (Hall A) – polarized beam, polarized ^{3}He target, 100 msr electron detector and neutron detector allow extension to 3.4 GeV^2 (will run early 2006)
- At 11 GeV further improvements of polarized ^{3}He target extension to ~7 GeV^2

Strange Quarks in the Nucleon

Strange quarks ($s\bar{s}$ pairs) can contribute to the mass, momentum, spin, magnetic moment and charge radius of the nucleon

- Mass: Σ term in π-N scattering at $Q^2 = 0$ ~ 45 MeV implies an $s\bar{s}$ contribution to the nucleon mass

$$\langle N \,|\, \bar{s}s \,|\, N \rangle \sim 0 - 300 \text{ MeV}$$

- Momentum: deep-inelastic neutrino scattering indicate $s\bar{s}$ carry significant nucleon momentum at $x_{Bjorken} < 0.1$

$$\int_0^1 x(s+\bar{s})dx \sim 2\%$$

- Spin: spin-dependent deep-inelastic lepton scattering provides estimate for the $s\bar{s}$ contribution to the nucleon spin

$$\langle N \,|\, \bar{s}\gamma^5 s \,|\, N \rangle \sim 0 - -20\%$$

- Parity violating electron scattering can provide estimates of the $s\bar{s}$ contributions to the nucleon's magnetic moment and charge radius

Neutral Weak Nucleon Form Factors G_E^s and G_M^s

Parity-violating asymmetry for elastic electron-proton scattering

$$A_{PV}^{p} \equiv \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \left(-\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\right)\frac{\varepsilon G_E^p G_E^Z + \tau G_M^p G_M^Z - \varepsilon'\left(1-4\sin^2\theta_W\right)G_M^p G_A^e}{\varepsilon\left(G_E^p\right)^2 + \tau\left(G_M^p\right)^2}$$

$$\tau = \frac{Q^2}{4M_p^2};\quad \varepsilon = \frac{1}{1+2(1+\tau)\tan^2(\theta_e/2)};\quad \varepsilon' = \sqrt{\left(1-\varepsilon^2\right)\tau(1+\tau)}$$

Introduce flavor form factors

$$G_{E,M}^{p} = \frac{2}{3}G_{E,M}^{u} - \frac{1}{3}G_{E,M}^{d} - \frac{1}{3}G_{E,M}^{s}$$

$$G_{E,M}^{n} = \frac{2}{3}G_{E,M}^{d} - \frac{1}{3}G_{E,M}^{u} - \frac{1}{3}G_{E,M}^{s}$$

Assume isospin symmetry

$$G_E^u \equiv G_E^{pu} = G_E^{nd};\quad G_E^d \equiv G_E^{pd} = G_E^{nu};\quad G_E^s \equiv G_E^{ps} = G_E^{ns}$$

to extract the strange form factor from the measured A_{PV}

$$G_{E,M}^{s} = \left(1-4\sin^2\theta_W\right)G_{E,M}^{p} - G_{E.M}^{n} - G_{E,M}^{Z,p}$$

Extracting the Strange Form Factors

$$\boxed{A_{PV}^{p} \equiv \frac{\sigma_{+} - \sigma_{-}}{\sigma_{+} + \sigma_{-}} = \left(-\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \right) \frac{\varepsilon G_E^p G_E^Z + \tau G_M^p G_M^Z - \varepsilon'\left(1 - 4\sin^2\theta_W\right) G_M^p G_A^e}{\varepsilon\left(G_E^p\right)^2 + \tau\left(G_M^p\right)^2}}$$

- The measured asymmetry has three Z^0-exchange contributions: G_E^z, G_M^z, G_A^e
- To separate these one needs three measurements:
  - At a forward angle on the proton
  - At a backward angle on the proton
  - At a backward angle on the deuteron

$$\boxed{A_d = \frac{\sigma_p A_p + \sigma_n A_n}{\sigma_d}}$$

G_A^e also has three components
neutral weak axial form factor
anapole moment
(electroweak) radiative corrections

Instrumentation for PVES

$$A_{PV} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \approx 10^{-6}$$

$$\frac{\sigma_A}{A} = \frac{1}{A}\frac{1}{\sqrt{2N}} = 5\%$$

$$N \approx 10^{13} - 10^{14} \text{ !!!}$$

Need
- Highest possible luminosity
- High rate capability
- High beam polarization

Detectors
- Integrating:
  noise, radiation hardness
- Counting:
  dead time, background rejection

Spectrometer
- Good background rejection
- Scatter from magnetized iron

Cumulative Beam Asymmetry
- Helicity-correlated asymmetry
  Δx~10 nm, $\Delta I/I$~1 ppm, $\Delta E/E$~100 ppb

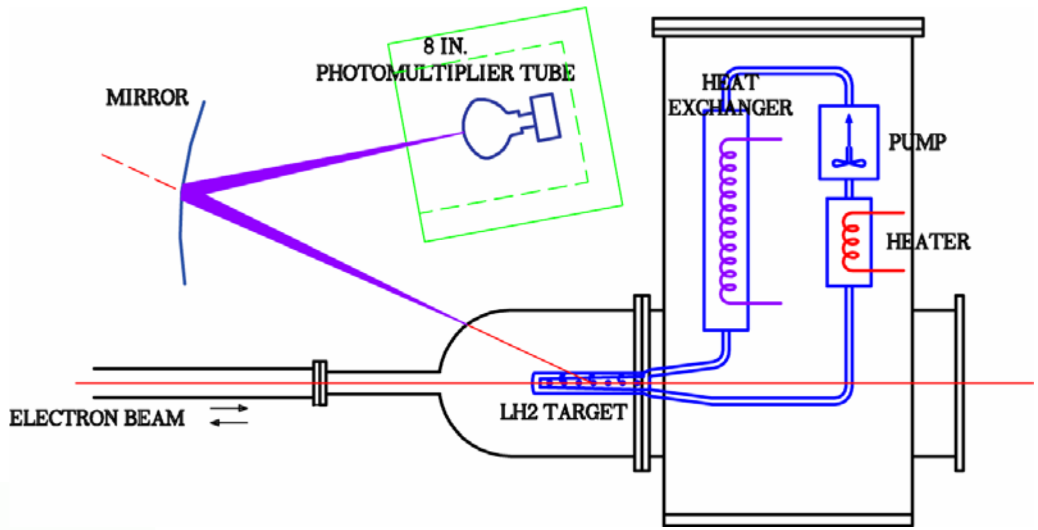
Helicity flips
- Pockels cell
- half-wave plate flips

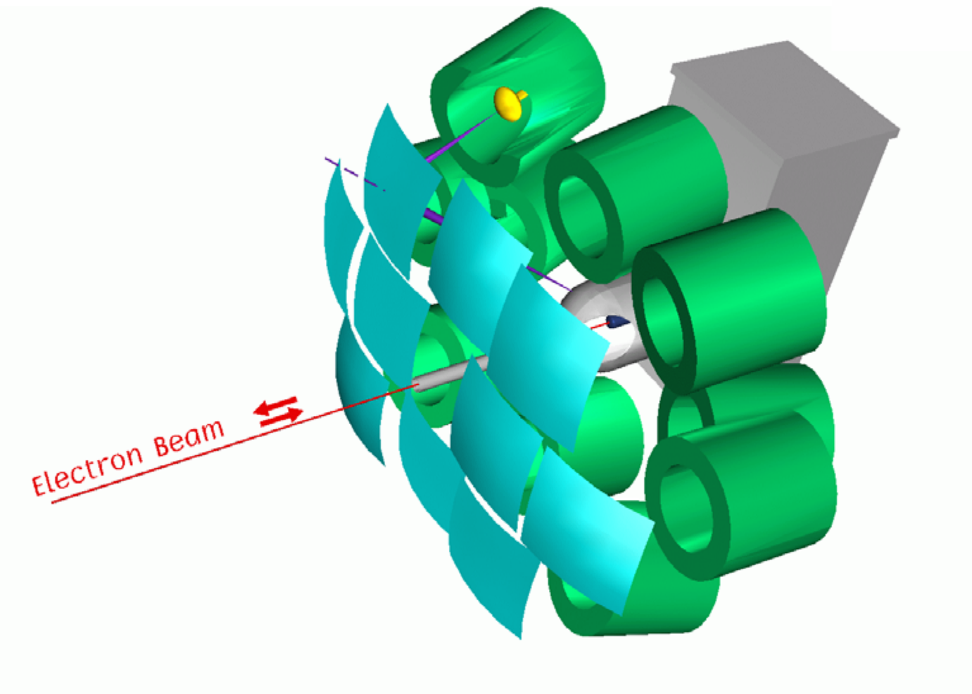
The Experimental Program for G_E^s and G_M^s

Lab Exp	type	target	Q^2 GeV^2	A_{phys} ppm	sensitivity	status
MIT-Bates						
SAMPLE	int	H	0.1	8	$\mu_s+0.4G_A^Z$	published
SAMPLE-II	int	D	0.1	8	$\mu_s+2.0G_A^Z$	published
SAMPLE-III	int	D	0.03	3	$\mu_s+3.0G_A^Z$	published
JLab Hall A						
HAPPEX	int	H	0.48	15	$G_E^s+0.39G_M^s$	published
HAPPEX-II	int	H	0.10	1.5	$G_E^s+0.08G_M^s$	2004/5
HAPPEX-He	int	He	0.10	10	ρ_s	2004/5
Mainz						
A4	count	H,D	0.10, 0.23	1 - 10	G_E^s, G_M^s	running
JLab Hall C						
G0	count	H,D	0.1 - 0.8	1 - 30	G_E^s, G_M^s	2004/6

SAMPLE at MIT-Bates

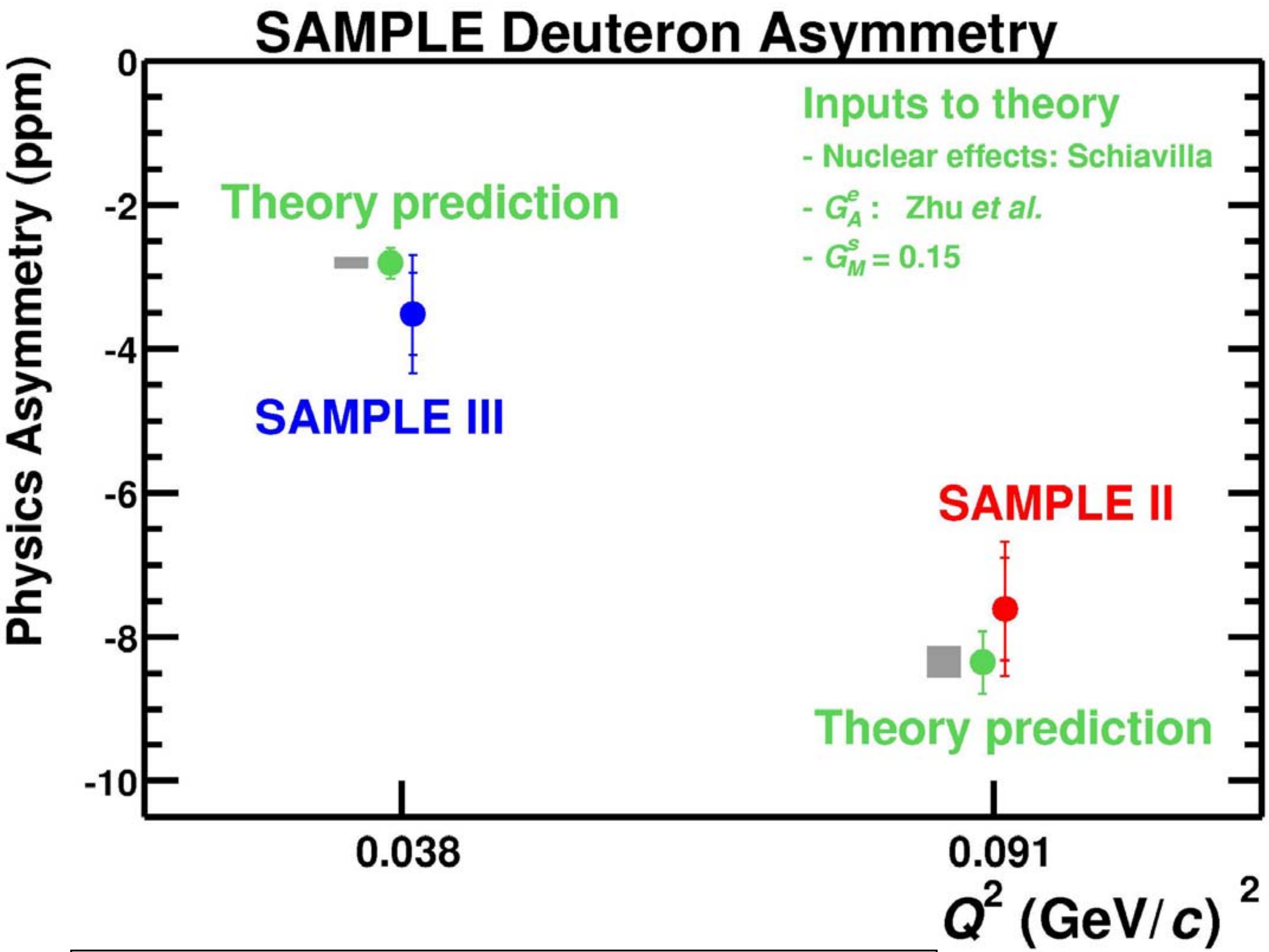
- Measure G_M^s at Q^2 ~0.1 GeV^2
- Air-Cherenkov detector covering 2 sr from 130°-170°
- Integrating electronics for asymmetry measurements
- Pulse-counting mode for background measurements





SAMPLE (1998):	H_2 target
	E_{beam} 200 MeV
SAMPLEII (1999):	D_2 target
	E_{beam} 200 MeV
SAMPLEIII (2001):	D_2 target
	E_{beam} 125 MeV

Results from the Deuterium Measurements



T. Ito *et al.*, PRL 92, 102003 (2004)

SAMPLE at MIT-Bates

SAMPLE
D.T. Spayde et al., PLB 583, 79 (2004)

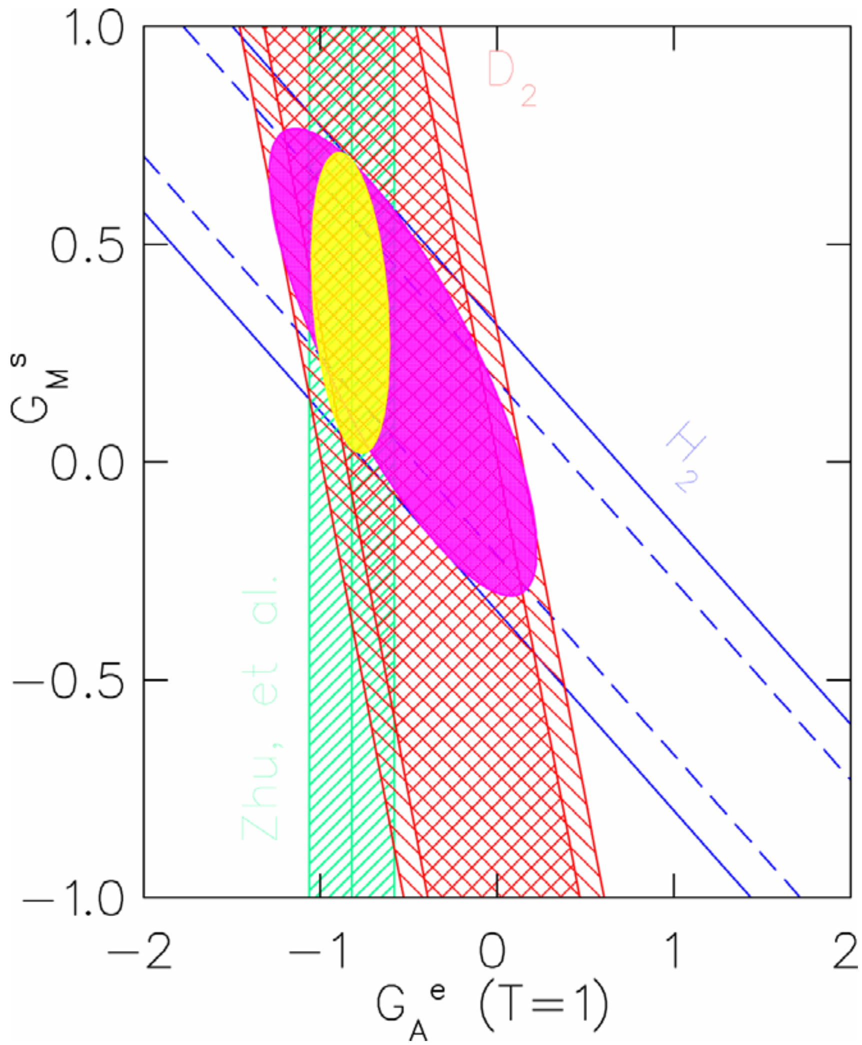
A_p = -5.61 ± 0.67 ± 0.88 ppm

SAMPLEII
T.M. Ito et al., PRL 92, 102003 (2004)

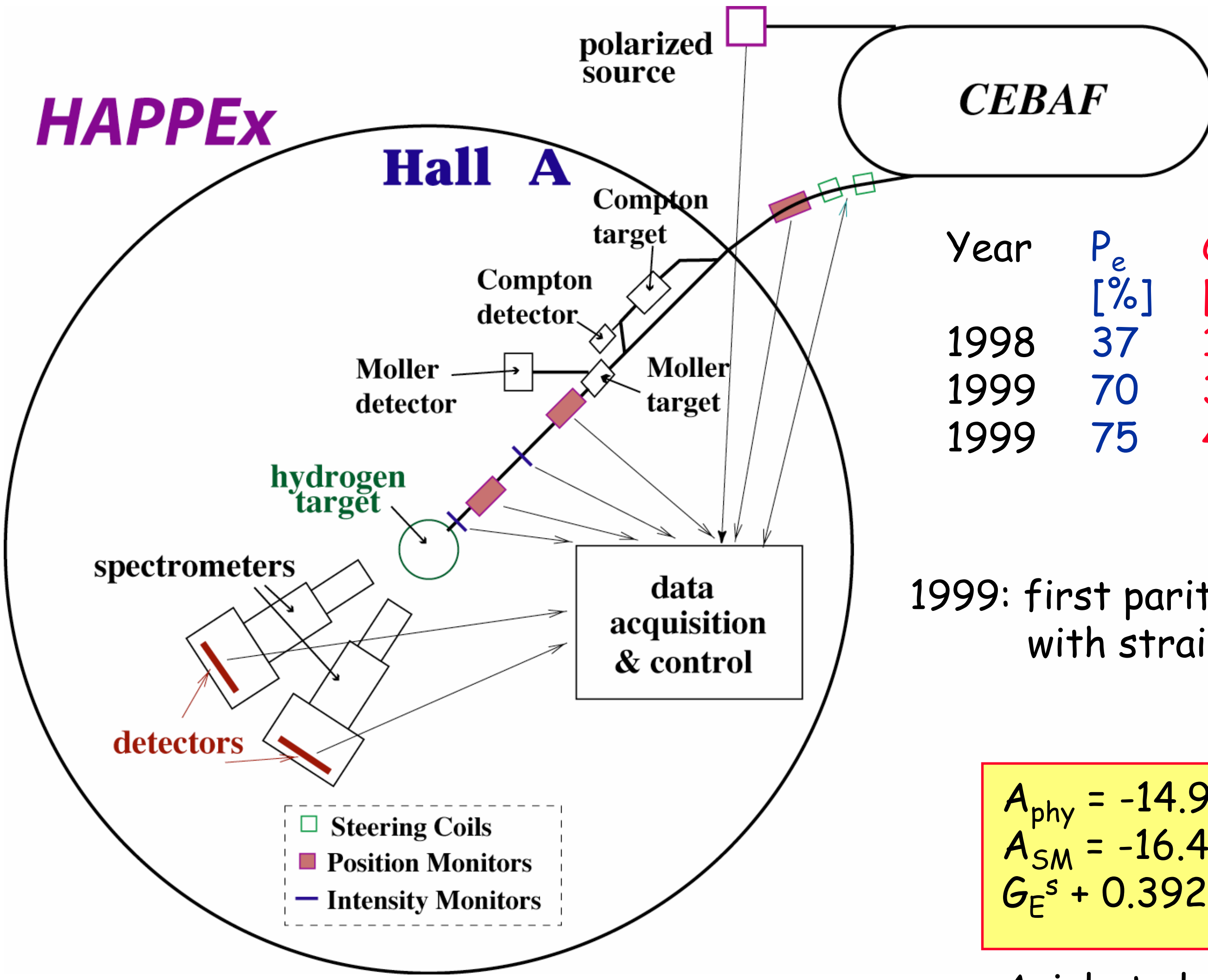
A_d = -7.77 ± 0.73 ± 0.62 ppm

Combine both results at Q^2 = 0.11 GeV^2

$G_M{}^s$ = 0.37 ± 0.20 ± 0.26 ± 0.07
μ_s = 0.37 ± 0.20 ± 0.26 ± 0.15
$G_A{}^e(T = 1)$ = -0.53 ± 0.57 ± 0.50
$G_A{}^e(T = 1)$ = -0.84 ± 0.26 (theory)



HAPPEx-I in Hall A at JLab



$Q^2 = 0.477\ GeV^2$

Year	P_e [%]	Current [μA]	Integrated Charge [C]
1998	37	100	80
1999	70	35	75
1999	75	45	15

1999: first parity violation measurement with strained GaAs photocathode

$A_{phy} = -14.92 \pm 0.98 \pm 0.56$ ppm
$A_{SM} = -16.46 \pm 0.88$ ppm
$G_E^s + 0.392\ G_M^s = 0.014 \pm 0.20 \pm 0.10$

Aniol et al., PRC 69, 065501 (2004)

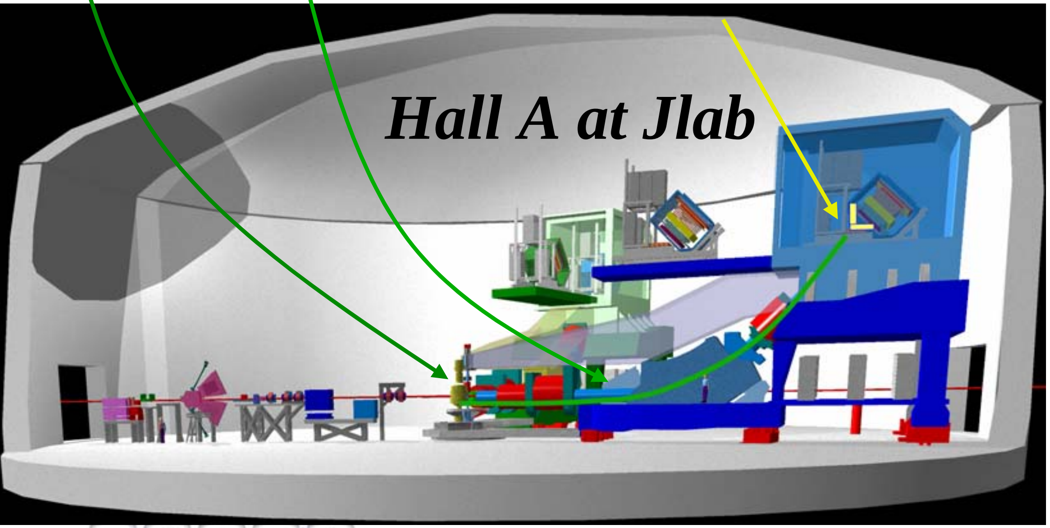
HAPPEx-H and HAPPEx-He

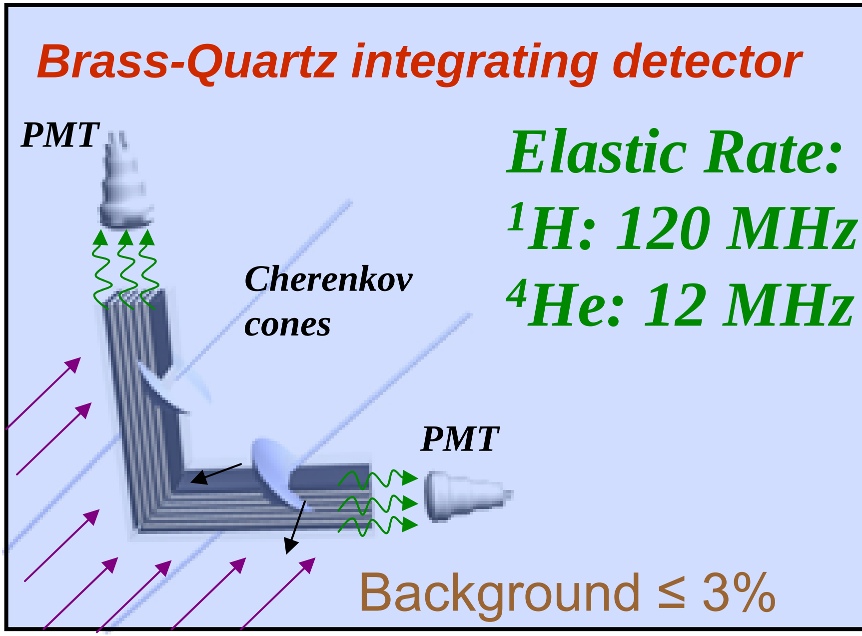
3 GeV beam in Hall A $\theta_{lab} \sim 6°$ $Q^2 \sim 0.1\ GeV^2$

target	A_{PV} $G^s = 0$ [ppm]	Stat. Error [ppm]	Syst. Error [ppm]	sensitivity
^1H	-1.6	0.08	0.04	$\delta(G^s_E+0.08G^s_M) = 0.010$
^4He	+7.8	0.18	0.18	$\delta(G^s_E) = 0.015$

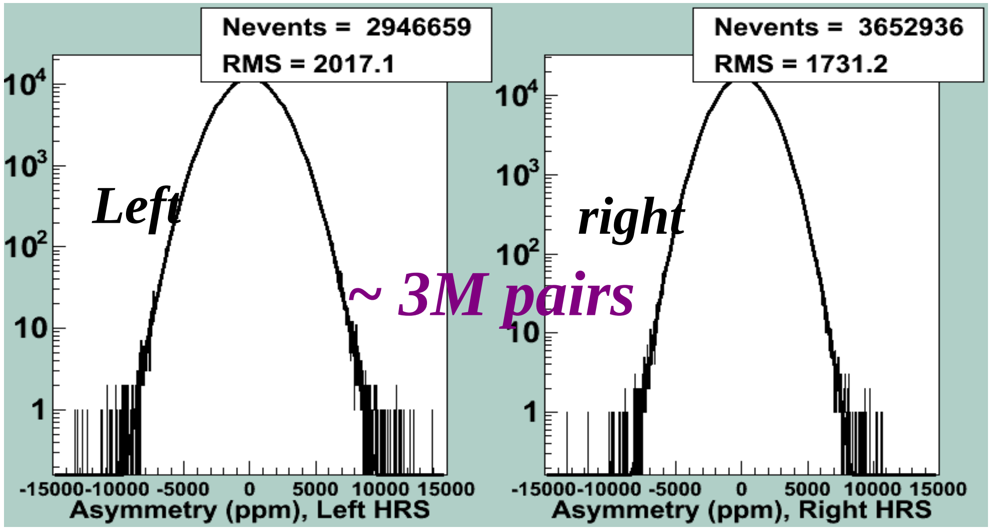
Session V
Friday 15:30
David Lhuillier

Septum magnets (not shown)
High Resolution Spectrometers
detectors





2004 ^{4}He Data: “Unblinded” A_{raw}



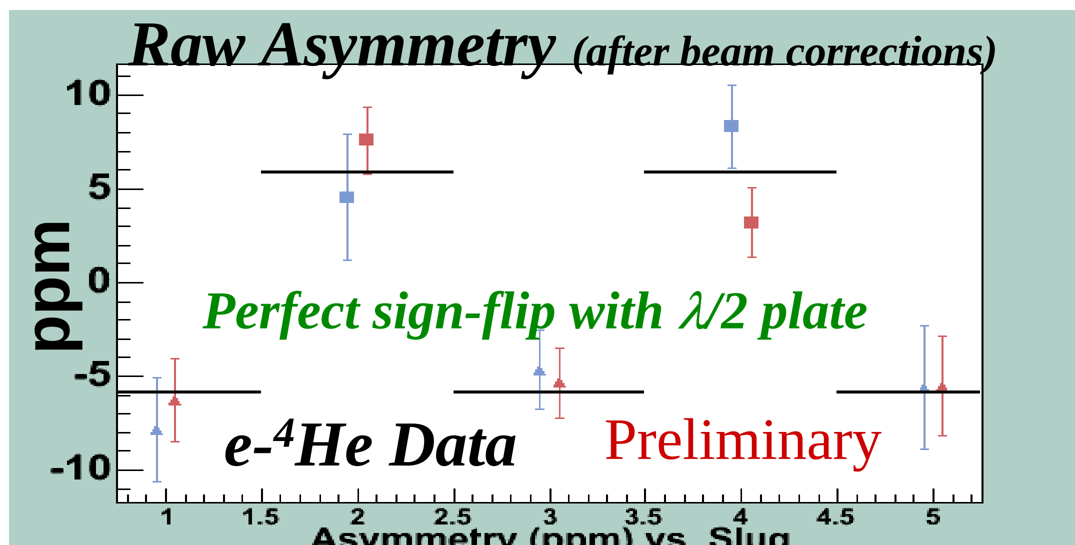
Helicity Window Pair Asymmetry

- ^{4}He run: June 8-22, 2004
- Dense gas target
- Super-lattice photocathode
- Beam Polarization ~ 86%
- Beam asymmetries small
- No active position feedback

A_{raw} = + 5.87 ppm $\pm$ 0.71 ppm (stat)

- Charge asymmetry < 0.4 ppm
- Position difference < 10 nm
- Energy difference < 10 ppb
- Angle difference < 5 nrad

A_{raw} correction < 0.2 ppm



^{4}He Physics Result

A_{PV} (after all corrections):
+7.40 ± 0.89 (stat) ± 0.57 (sys) ppm

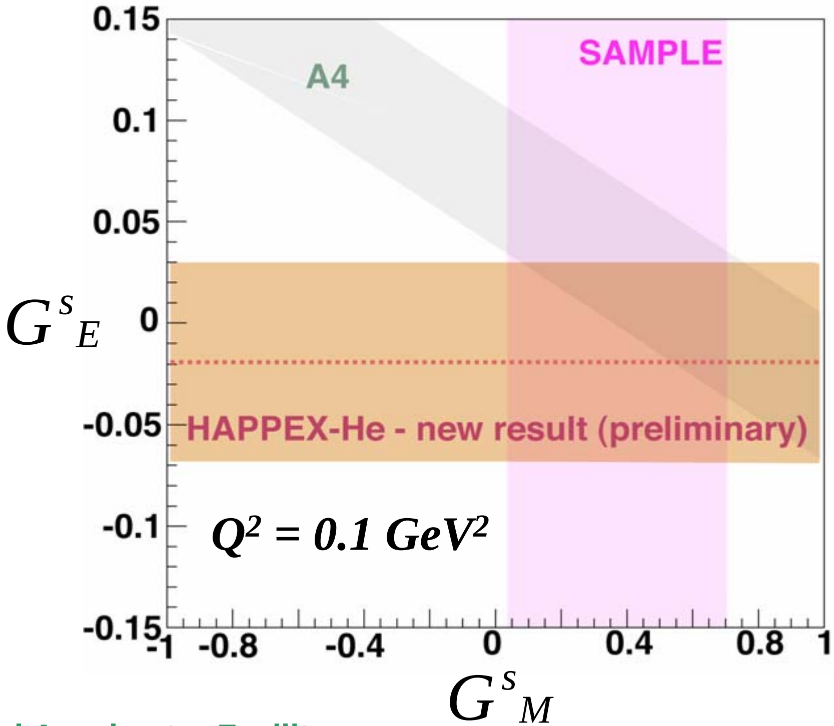
Preliminary!

- Beam asymmetry corrections ~ 0.1 ppm
- Normalization errors dominate
- Ongoing analysis to significantly reduce these errors

Theory prediction (no strange quarks):
+7.82 ppm

G^s_E (Q^2 = 0.1 GeV^2) =
-0.019 ± 0.041 (stat) ± 0.026 (sys)

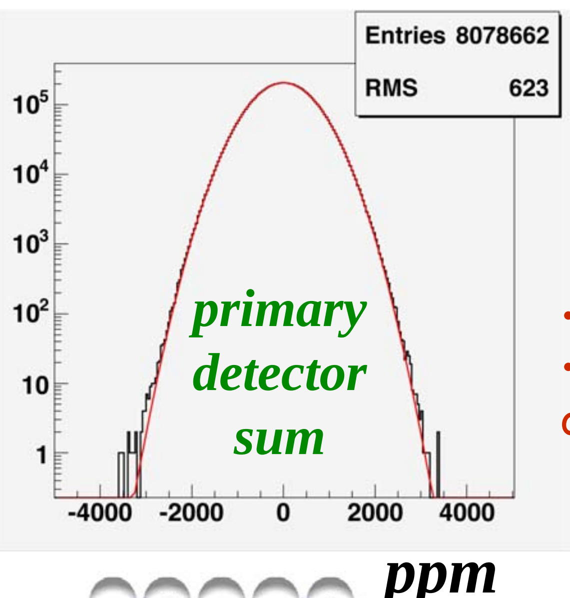
- Statistics to be increased by x10
- Tentatively scheduled for late 2005

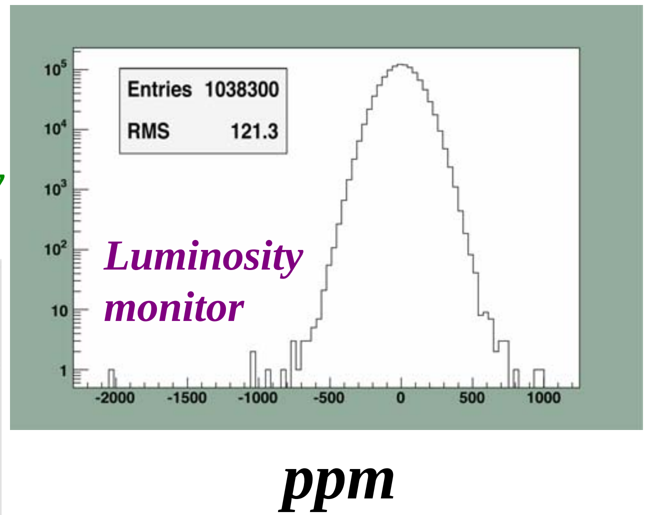


^{1}H Run and Future Prospects

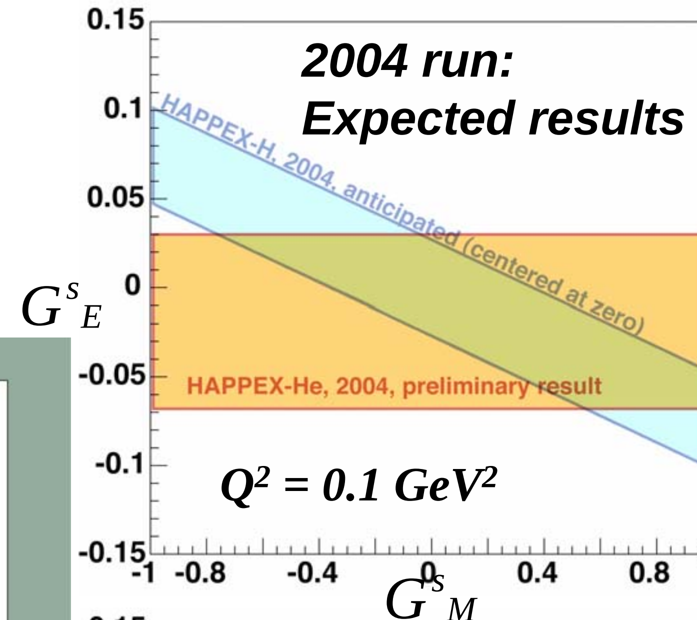
- *Successful ^{1}H run, June 24 - July 26 2004*
- *~8M window pairs in final data sample*
- *Preliminary results by end of October*
- *Statistics to be increased by x5 (late 2005)*

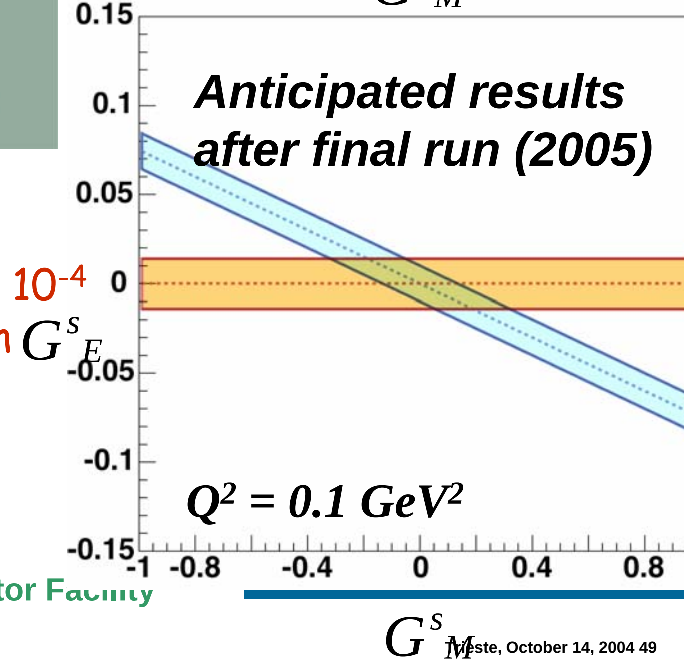
30 Hz Window-Pair Polarization Asymmetry



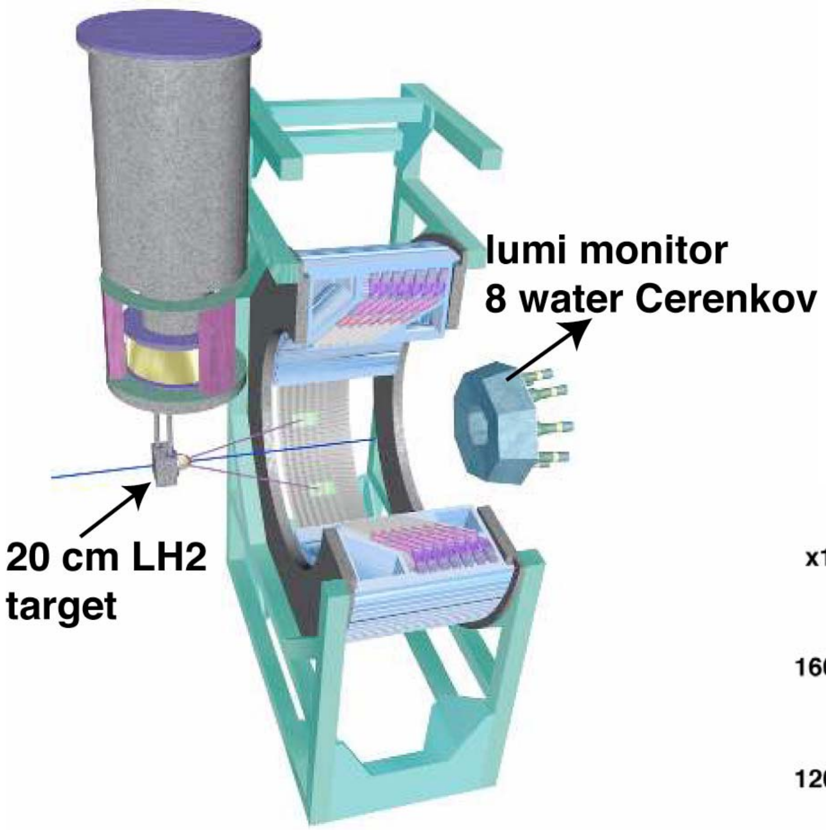


•Target density fluctuations < 10^{-4}
•Detector asymmetry gaussian over 5 orders of magnitude





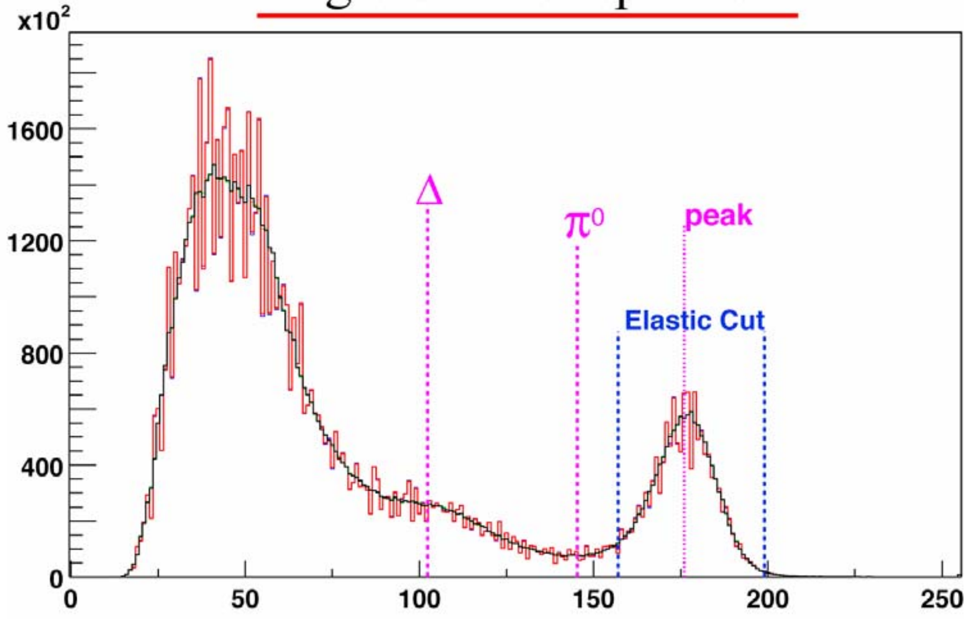
A4 at Mainz



- Detector: 1022 PbF_2 blocks covering 0.8 sr from 30° to 40°
- Counting experiment at 100 kHz per channel, summing over 9 adjacent channels

MAMI
E_{max} 855 MeV
20 μA on 20 cm LH_2

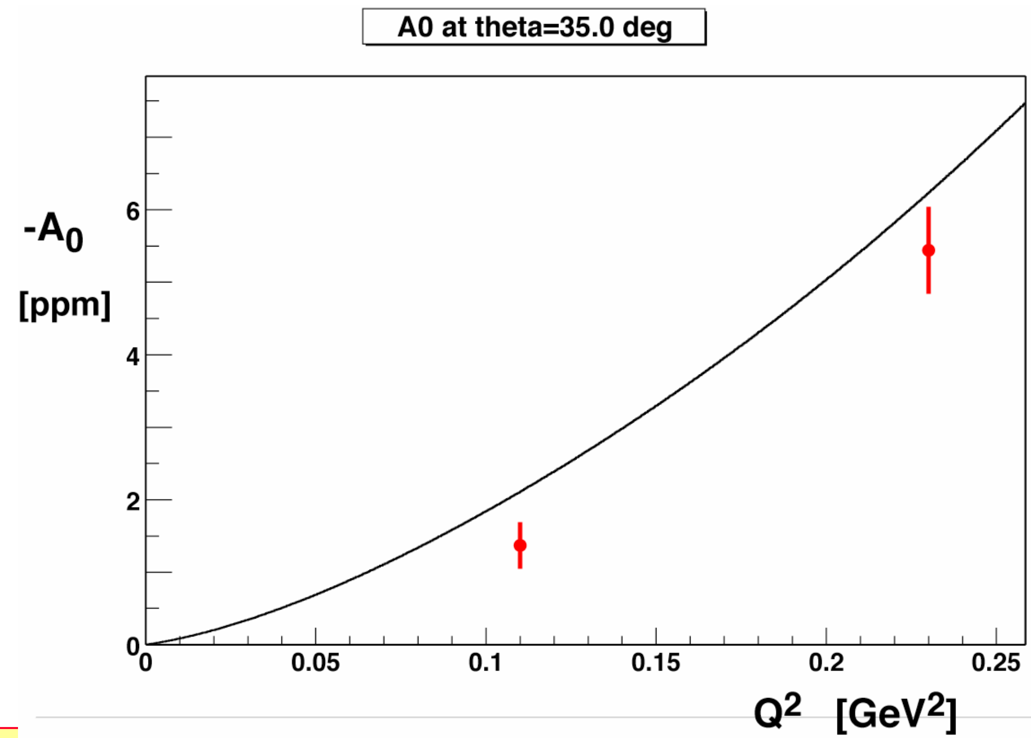
single detector spectrum



A4 at Mainz

Forward measurements
at Q^2 = 0.23 and 0.10 GeV^2

-



Q^2= 0.23 GeV^2

A_{phy}= -5.44 ± 0.54 ± 0.26

G_E^s + 0.225 G_M^s = 0.039 ± 0.034

Q^2= 0.10 GeV^2

A_{phy}= -1.40 ± 0.29 ± 0.11

G_E^s + 0.106 G_M^s = 0.074 ± 0.036

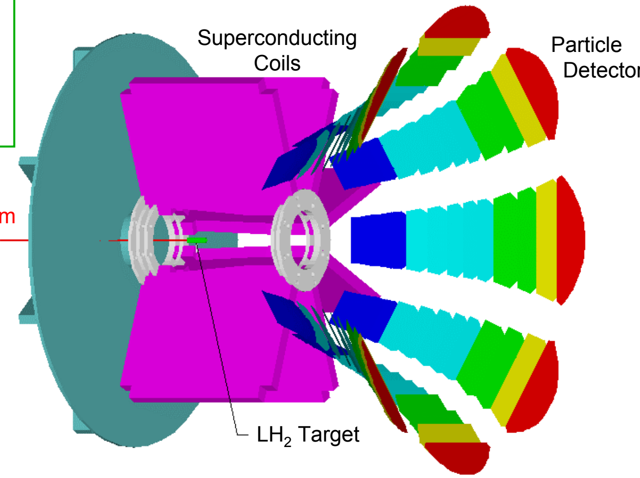
Future Program
- Rotate detector to backward angle
- Measure proton and deuteron at 0.23, 0.47 GeV^2

G0 Experiment

Caltech, Carnegie Mellon, W&M, Hampton, IPN-Orsay, LPSC-Grenoble, Kentucky, La. Tech, NMSU, JLab, TRIUMF, UConn, UIUC, UMan, UMd, UMass, UNBC, VPI, Yerevan

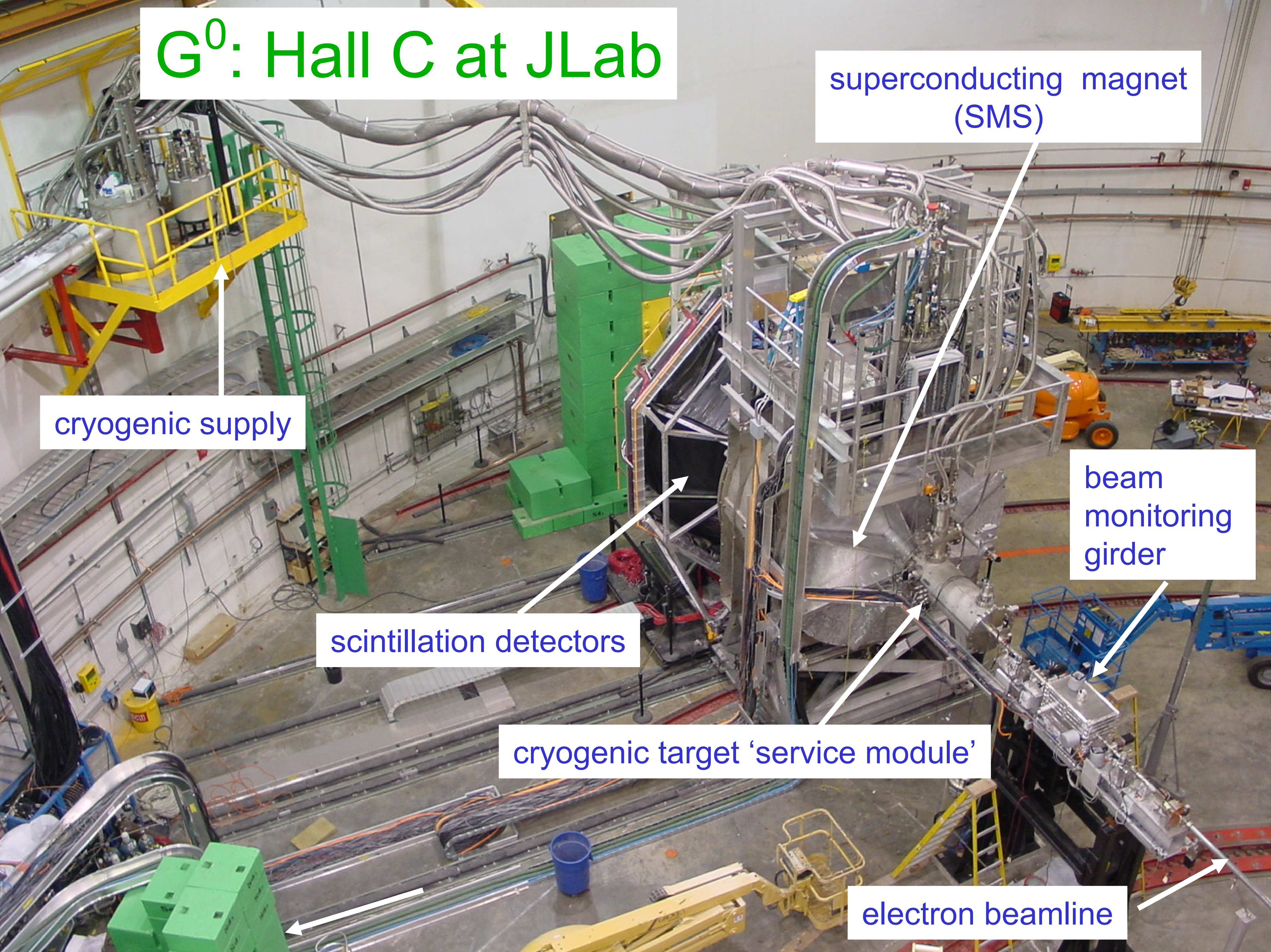
- Use SC toroidal magnet with detector segmented in eight identical sectors
  - 20 cm long LH_2 target
  - Counting mode (TOF spectra)
- Measure forward and backward asymmetries
  - recoil protons for forward measurement
  - electrons for backward measurements
    - elastic/inelastic for ^1H, elastic for ^2H

- Forward angle measurements complete
- First (800 MeV) backward angle run late 2005



E_{beam} = 3 GeV
0.33 - 0.93 GeV
I_{beam} = 40 μA
P_{beam} = 75%
θ = 52 - 76^0 $\Delta\Omega$ = 0.9 sr
104 - 116^0 0.5 sr
l_{target} = 20 cm
$L = 2.1 \times 10^{38}$ cm^{-2} s^{-1}
A ~ -2 to -50 ppm (forward)
-12 to -70 ppm (backward)

G^0: Hall C at JLab

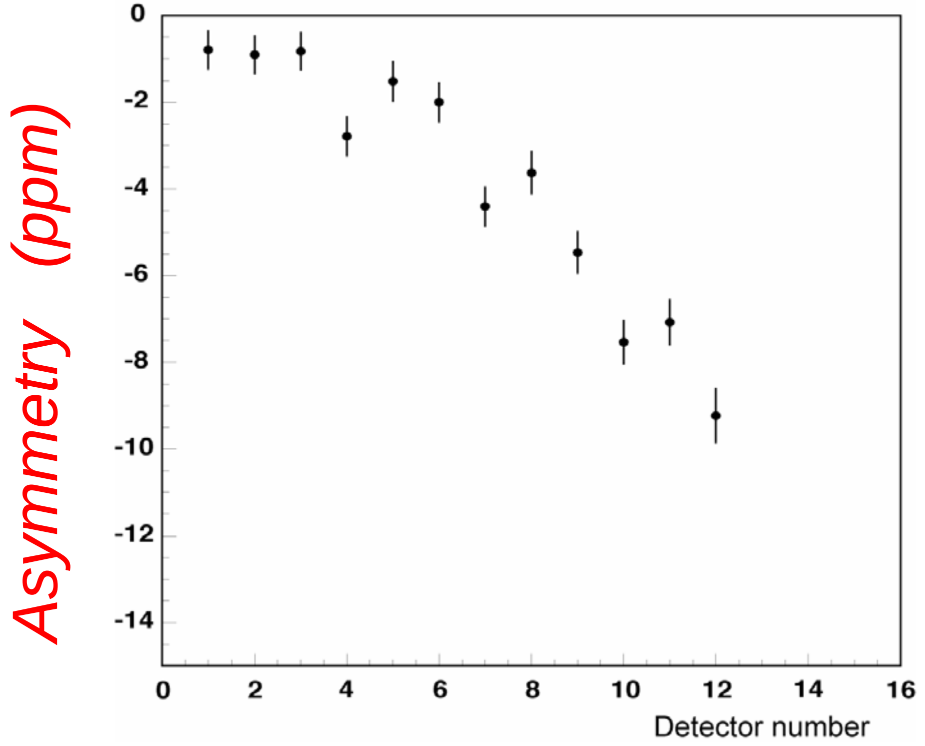


G0 Preliminary Result: Blinding Factor of 25%

- Full statistics – present best background correction

Forward Angle Data

Session V
Friday 15:10
Julie Roche

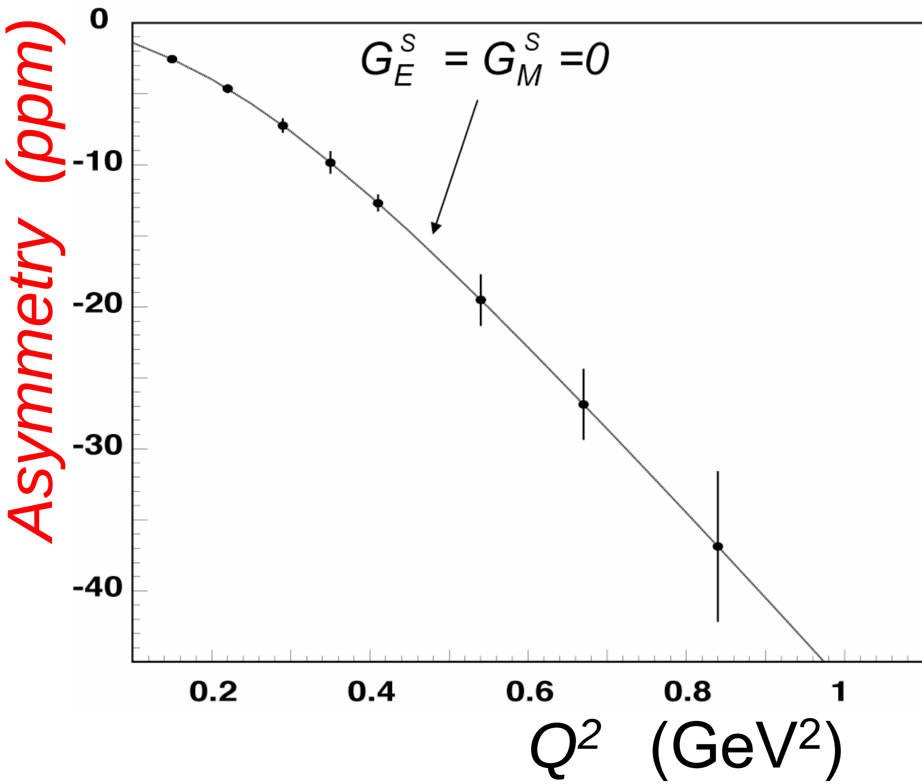


Increasing Q^2

Detectors 13-15: *stay tuned*

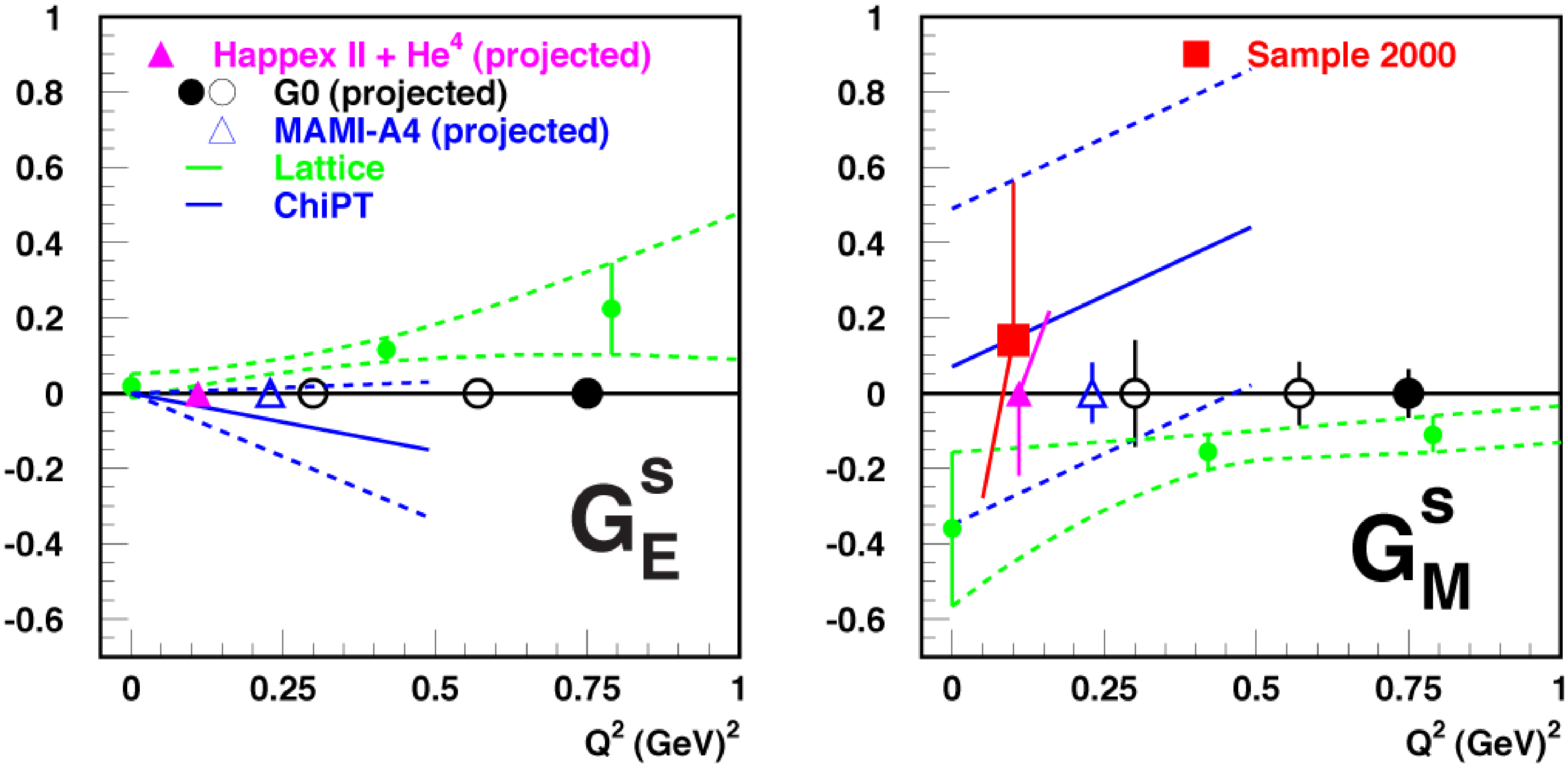
Do Not Quote!

Statistical + Systematic errors



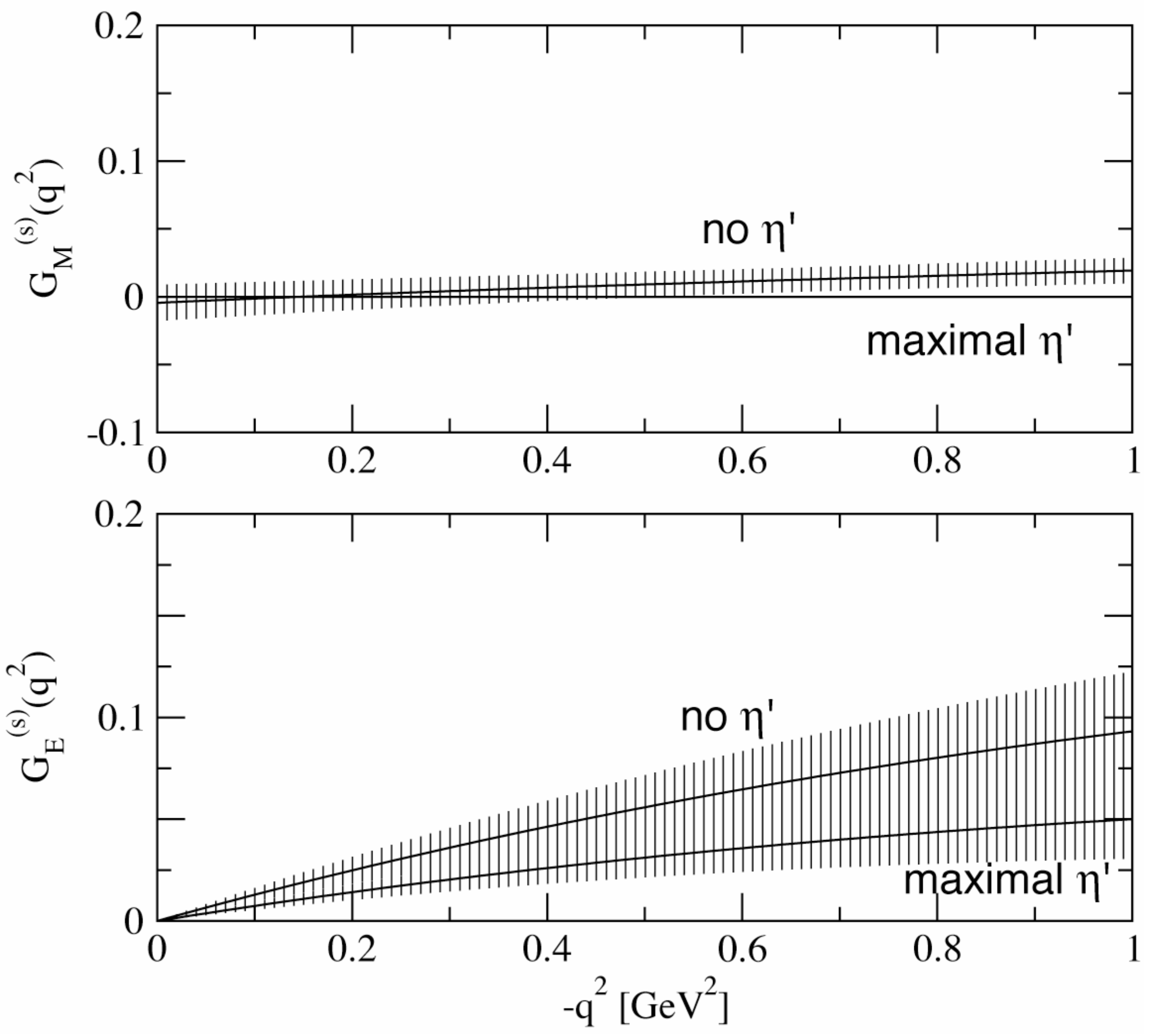
Strange Form Factors G_E^s and G_M^s

Rosenbluth separation of G_E^s and G_M^s



Projected G^0 data indicated by open symbols are not approved yet

Lattice QCD for Strange Form Factors

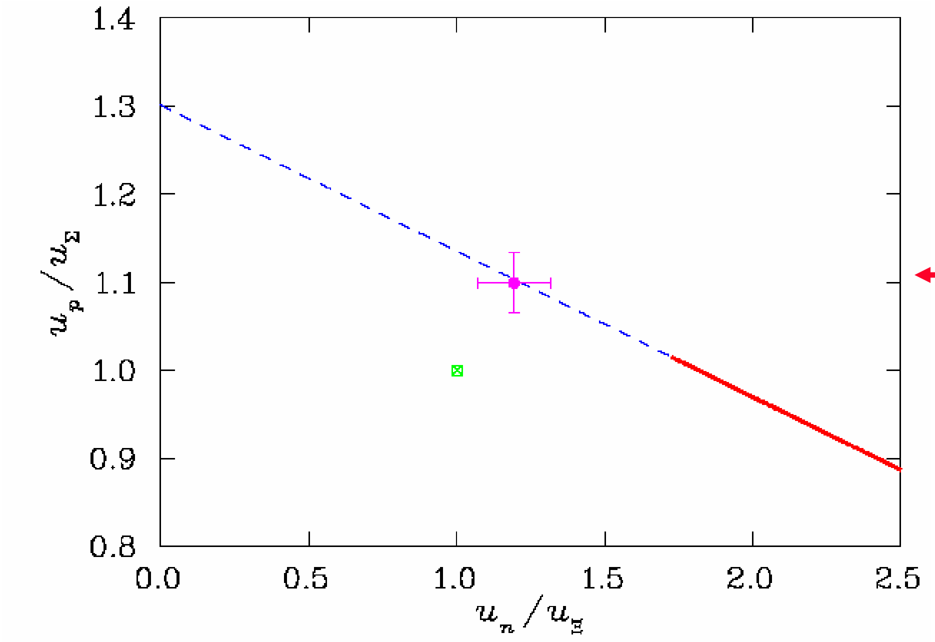


- Quenched QCD
- Wilson fermions
- Chiral PT extrapolation
- $G_M^s(0.1) = 0.05 \pm 0.06$ (SAMPLE)
- $G_E^S + 0.039 G_M^s = 0.07 \pm 0.05$ (HAPPEx)

Lewis, Wilcox & Woloshyn
PRD 67, 013003 (2003)

Combined LQCD/ChPT Prediction for μ_s

Leinweber *et al.*
hep-lat/0406002



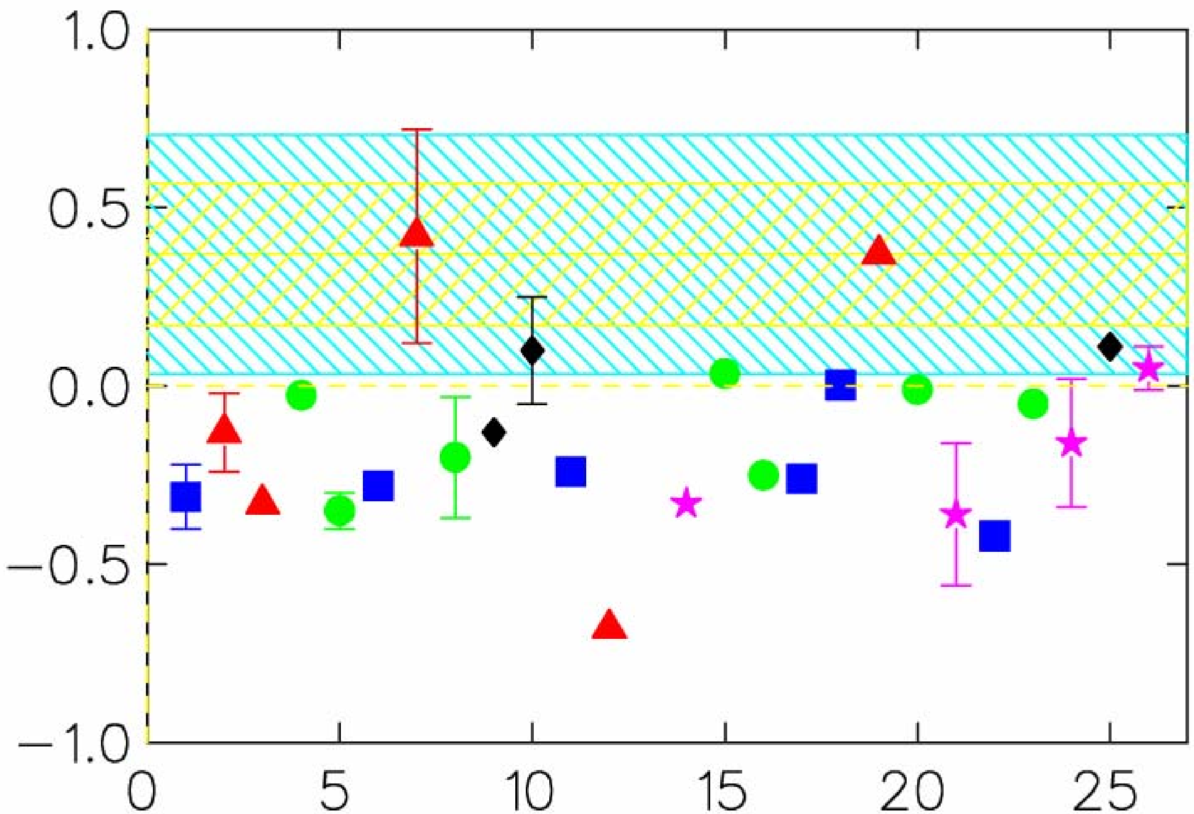
$$\mu_s = F\left(\frac{\mu_p^u}{\mu_\Sigma^u}, \frac{\mu_s}{\mu_d^{loop}}\right)$$

Lattice calculation

- *Charge symmetry*
- *Measured octet magnetic moments*
- *Chiral symmetry*
- *Unquenching*

$\mu_s = -0.051 \pm 0.021\ \mu_N$

Theoretical Predictions for μ_s



SAMPLE result

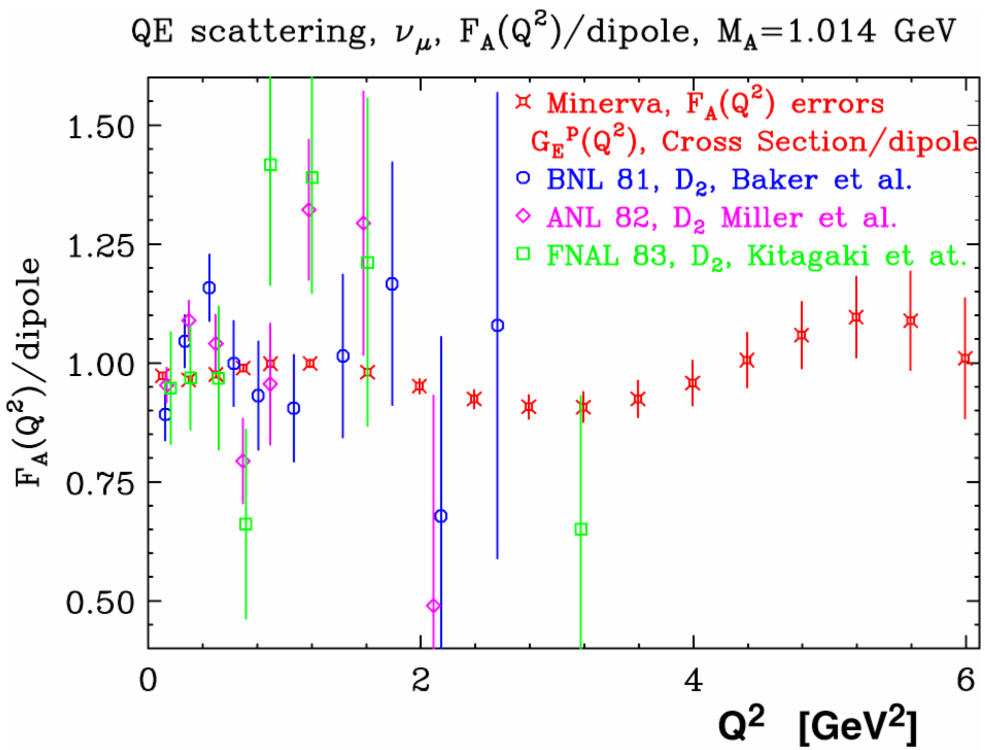
Vector Meson Dominance
Skyrme
Kaon Loops
Lattice QCD

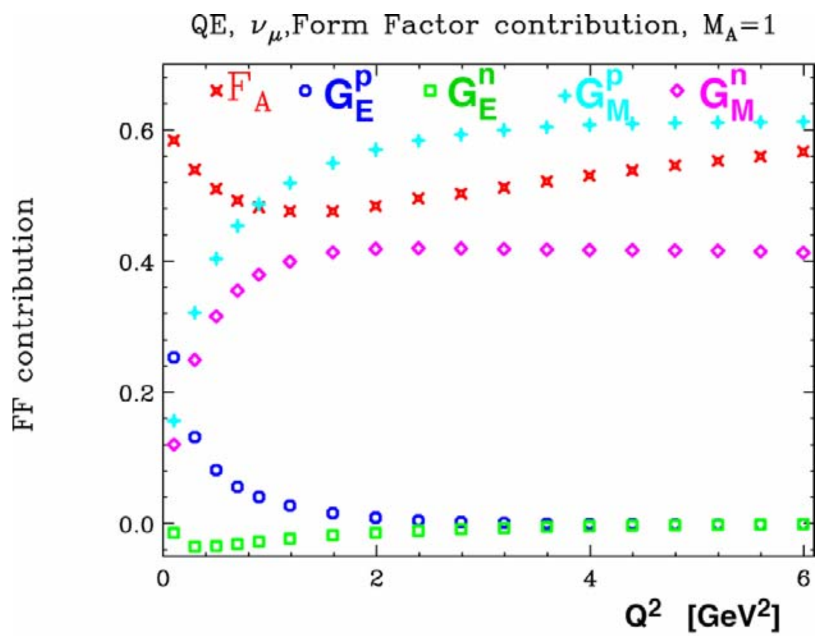
Other:
QCD equalities
quark form factors
……………

Axial Form Factor: MINERνA at FermiLab

- Best dipole fit to existing neutrino data yields M_A = 1.001 ± 0.02 GeV
- Pion electroproduction provides M_A = 1.014 ± 0.016 GeV

$$G_A^{NC}(Q^2) = \frac{g_A}{2\left(1+\frac{Q^2}{M_A^2}\right)}$$



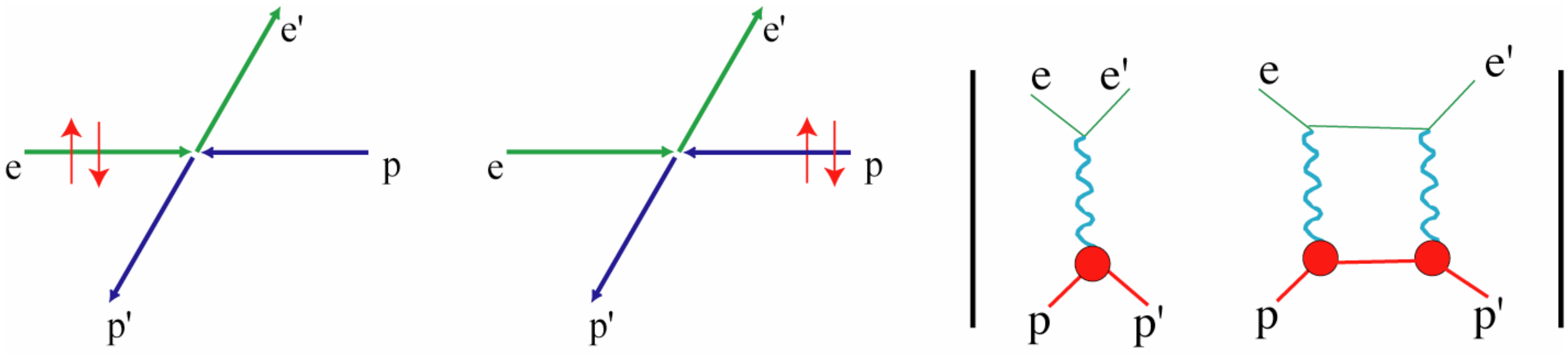


- Neutrino QE scattering
- High-precision measurement of NC axial form factor to Q^2 = 5 GeV^2

Transverse Spin Asymmetry

$$\varepsilon(\theta) = \frac{\sigma_\uparrow(\theta) - \sigma_\downarrow(\theta)}{\sigma_\uparrow(\theta) + \sigma_\downarrow(\theta)} = A(\theta)\langle P \rangle$$

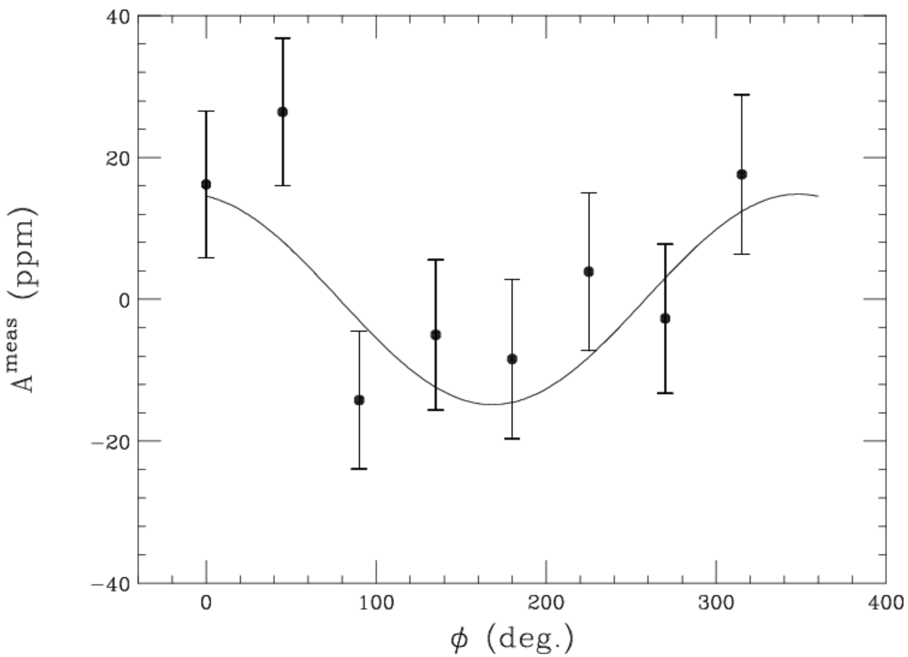
Lowest order contribution is imaginary part of two-photon exchange amplitude



Provides tests of models for two-photon exchange effects
But $A_{beam} \approx 10^{-5}$ while $A_{target} \approx 0.01$

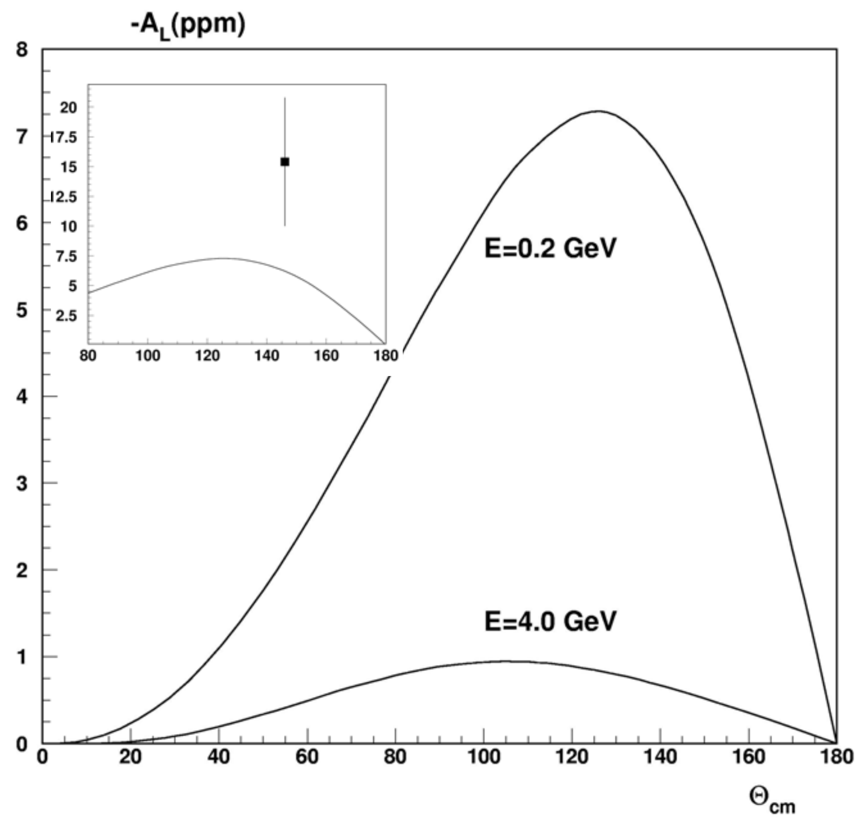
Transverse Spin Asymmetry (SAMPLE)

Measure azimuthal dependence of beam helicity asymmetry with beam polarized transverse to scattering plane



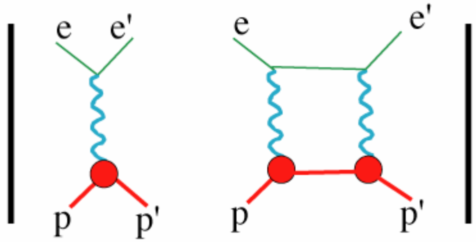
$A = -15.4 \pm 5.4$ ppm

S. P. Wells *et al.*, PRC 63, 064001 (2001)



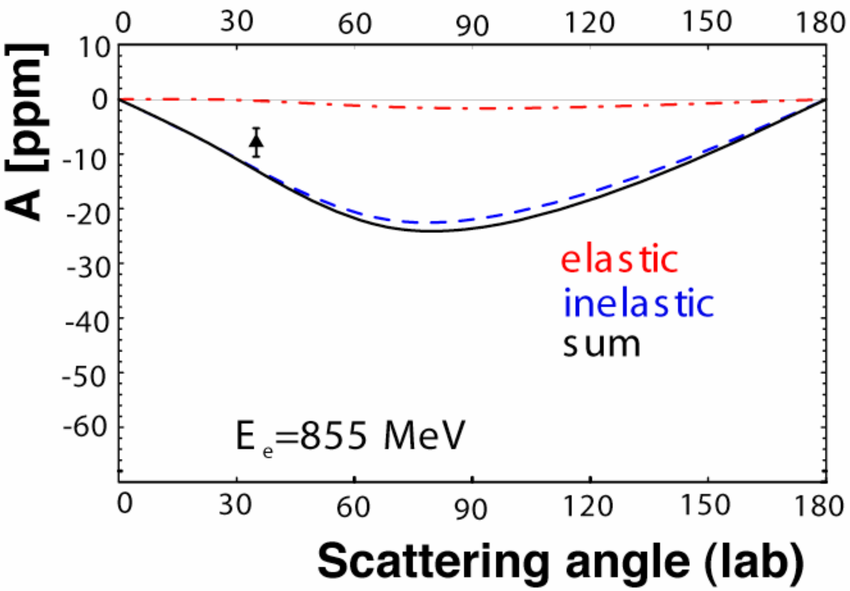
Afanasev *et al.*, hep-ph/0208260

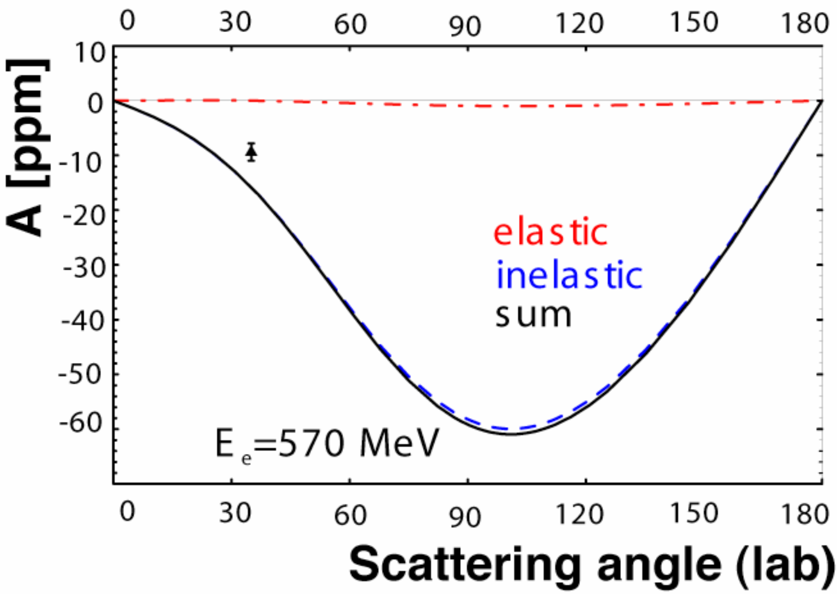
Transverse Spin Asymmetry (A4)



Intermediate state: proton, πN states (MAID)

(B. Pasquini)





Summary

- Very active experimental program on nucleon form factors thanks to development of polarized beam (> 100 μA, > 75 %) with small helicity-correlated properties, polarized targets and polarimeters with large analyzing powers

- Electromagnetic Form Factors
  - G_E^p discrepancy between Rosenbluth and polarization transfer not an experimental problem, but probably caused by TPE effects
  - G_E^n precise data up to Q^2 = 1.5 GeV^2
  - G_M^n precise data up to Q^2 = 5 GeV^2, closely following dipole behaviour
  - Further accurate data will continue to become available as benchmark for Lattice QCD calculations

- Large experimental activity in strange FF studies (SAMPLE, HAPPEx, A4, G^0)
- Thus far, no significant signal for ss contributions, but new accurate data will be accumulated over the next few years
- Significant advances in measurement of transverse SSAs
  - Sensitive test of TPE calculations

SPARES

Introduction

SM Lagrangian

$$L_{\text{int}} = -eJ_{EM}^{\mu}(x)A_{\mu}(x) - \frac{g}{2\cos\theta_W} J_{NC}^{\mu}(x)Z_{\mu}(x) - \frac{g}{2\sqrt{2}} J_{CC}^{\mu}(x)W_{\mu}^{\dagger}(x) + \text{HC}$$

EM current coupled to photon and Z^0-boson field
Elastic electron scattering

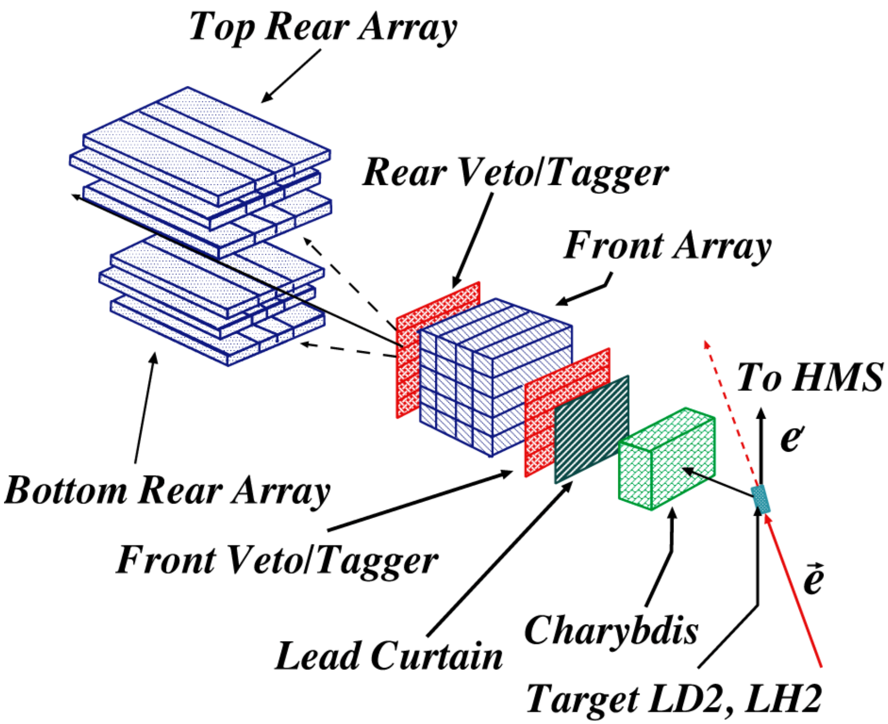
Weak neutral current coupled to neutral Z^0-boson field
Elastic neutrino scattering, parity-violating electron scattering

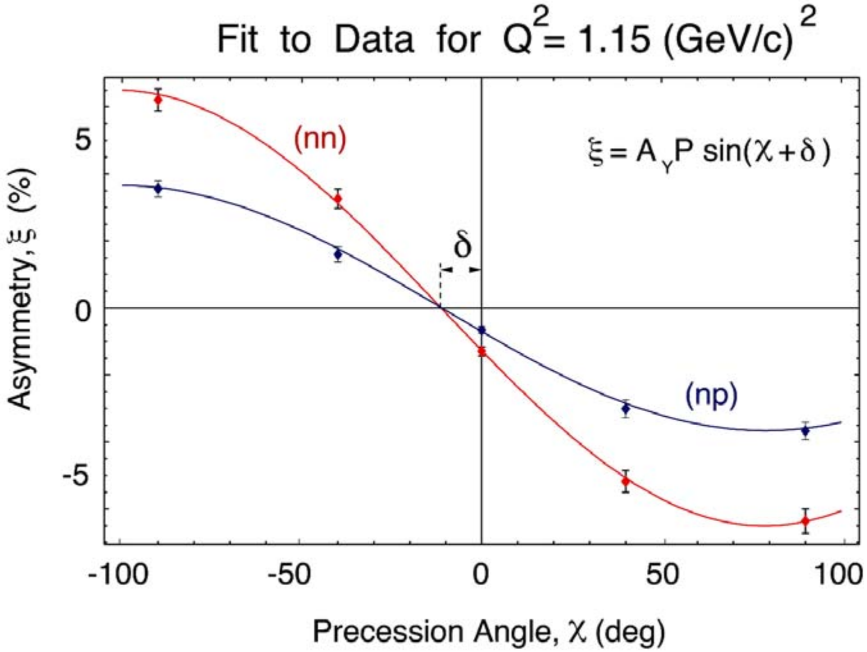
Weak charged current coupled to charged W-boson fields
Beta decay, inelastic neutrino scattering

G^n_E Experiment with Neutron Polarimeter

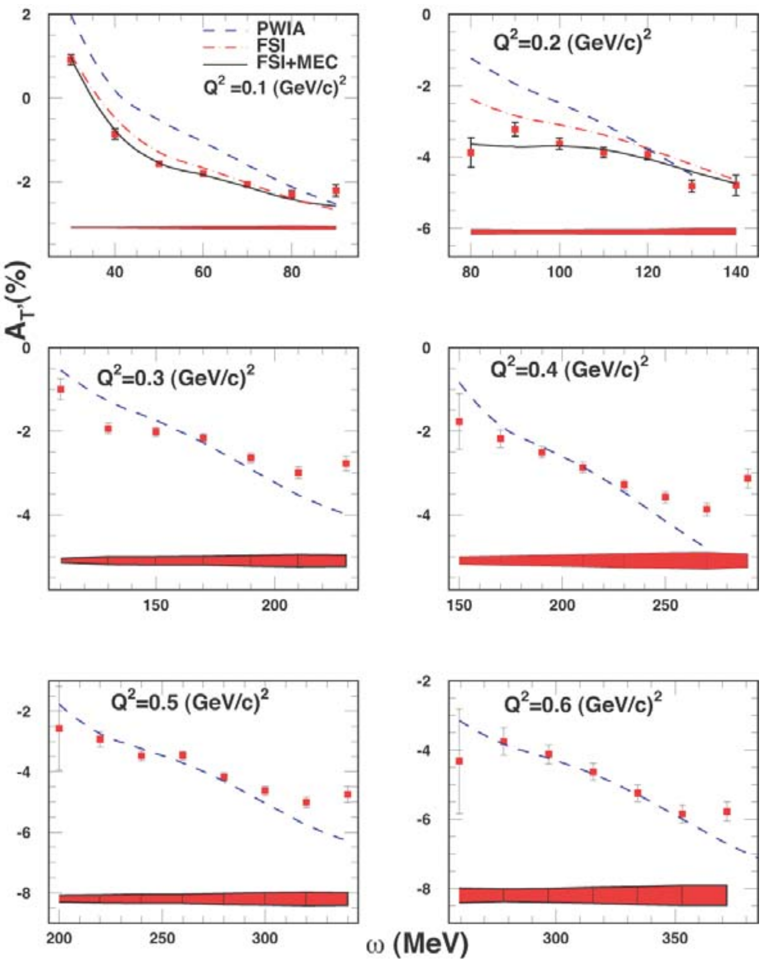
- Use dipole to precess neutron spin
- Up-down asymmetry ξ proportional to neutron sideways polarization
- G_E/G_M depends on phase shift δ w.r.t. precession angle χ

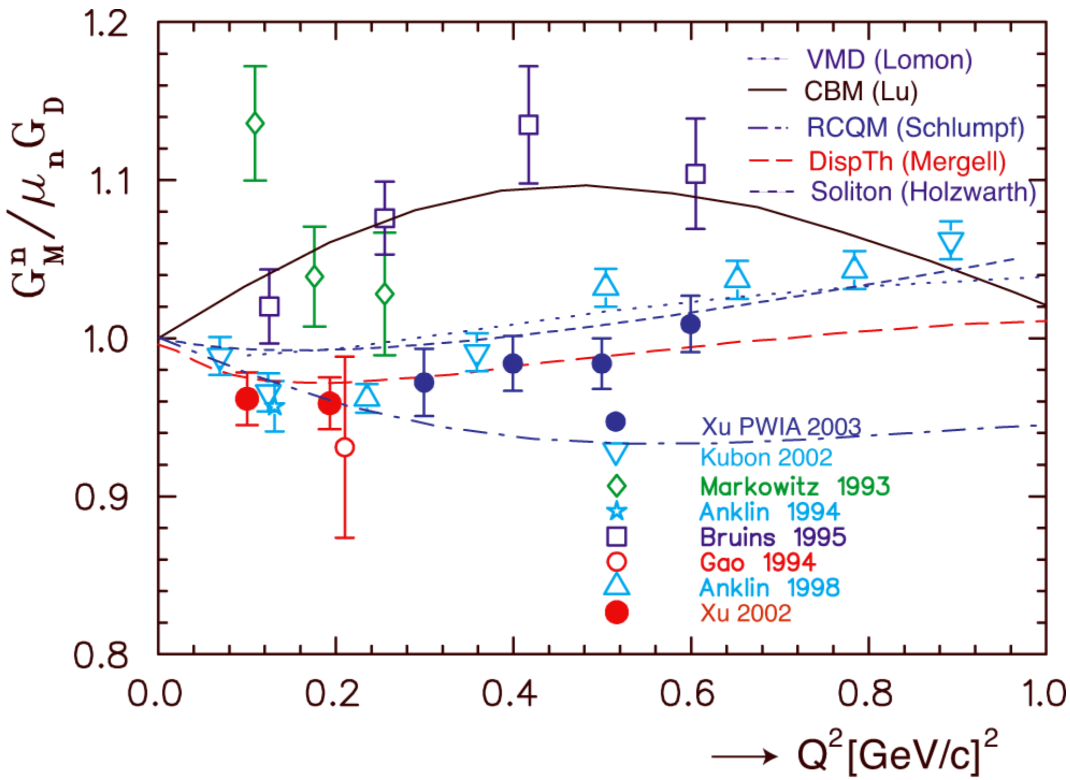
$$\boxed{\xi \propto \sin(\chi+\delta) \Rightarrow \frac{G^n_E}{G^n_M} = -\tan\delta\sqrt{\frac{\tau(1+\varepsilon)}{2\varepsilon}}}$$





Measurement of G^n_M at low Q^2



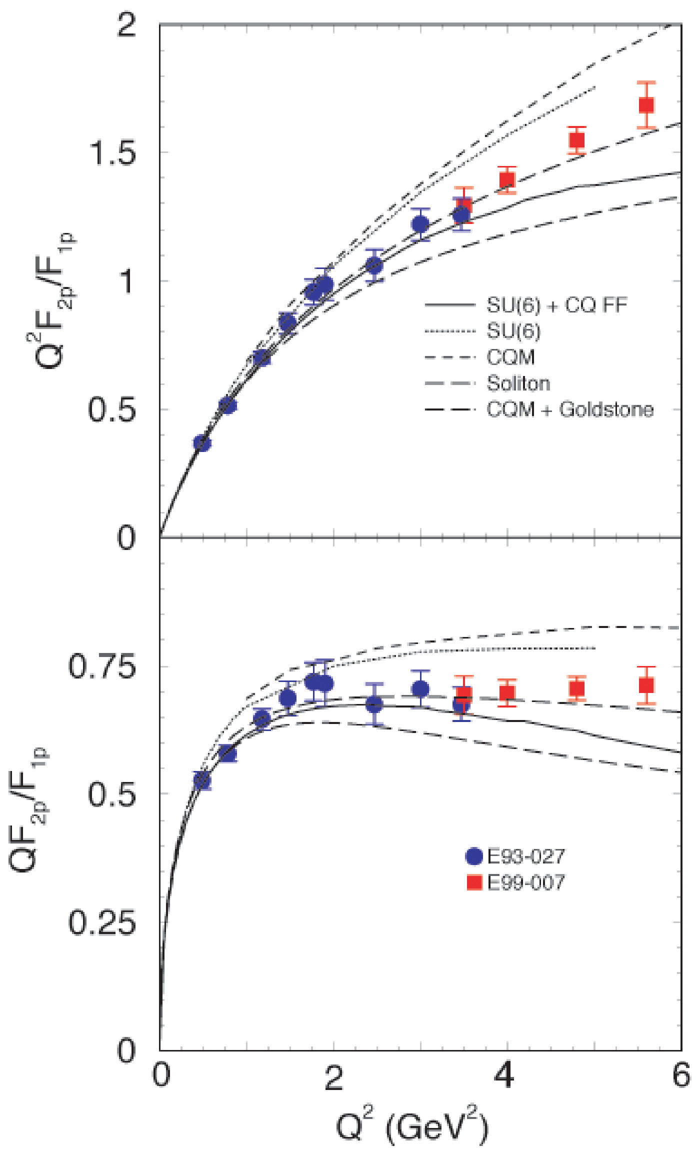


High-Q^2 behaviour

Basic pQCD (Bjørken) scaling predicts
  $F_1 \propto 1/Q^4$; $F_2 \propto 1/Q^6$
    ☒ $F_2/F_1 \propto 1/Q^2$ (Brodsky & Farrar)
Data clearly do not follow this trend

Schlumpf (1994), Miller (1996) and Ralston (2002) agree that by
- freeing the p_T=0 pQCD condition
- applying a (Melosh) transformation to a relativistic (light-front) system
- an orbital angular momentum component is introduced in the proton wf (giving up helicity conservation) and one obtains
    ☒ $F_2/F_1 \propto 1/Q$
- or equivalently a linear drop off of G_E/G_M with Q^2

Brodsky argues that in pQCD limit non-zero OAM contributes to both F_1 and F_2



From Raw to Physics Asymmetries

Form raw asymmetries from measured yields:

$$A_{meas} = \frac{Y_+ - Y_-}{Y_+ + Y_-}$$

- 60 Hz effects
- Long term beam property drifts

Correct raw asymmetries for yield variations:

$$A_{corr} = A_{meas} - \sum_{i=1}^{N} \frac{1}{2Y}\left(\frac{\partial Y}{\partial P_i}\right)\Delta P_i$$

$$\Delta P_i = P_{1+} - P_{1-}$$

- Helicity correlated beam properties

Correct asymmetries for background effects:

$$A_{sig} = \frac{A_{corr} - (1 - f_l)A_C}{f_l f_c}$$

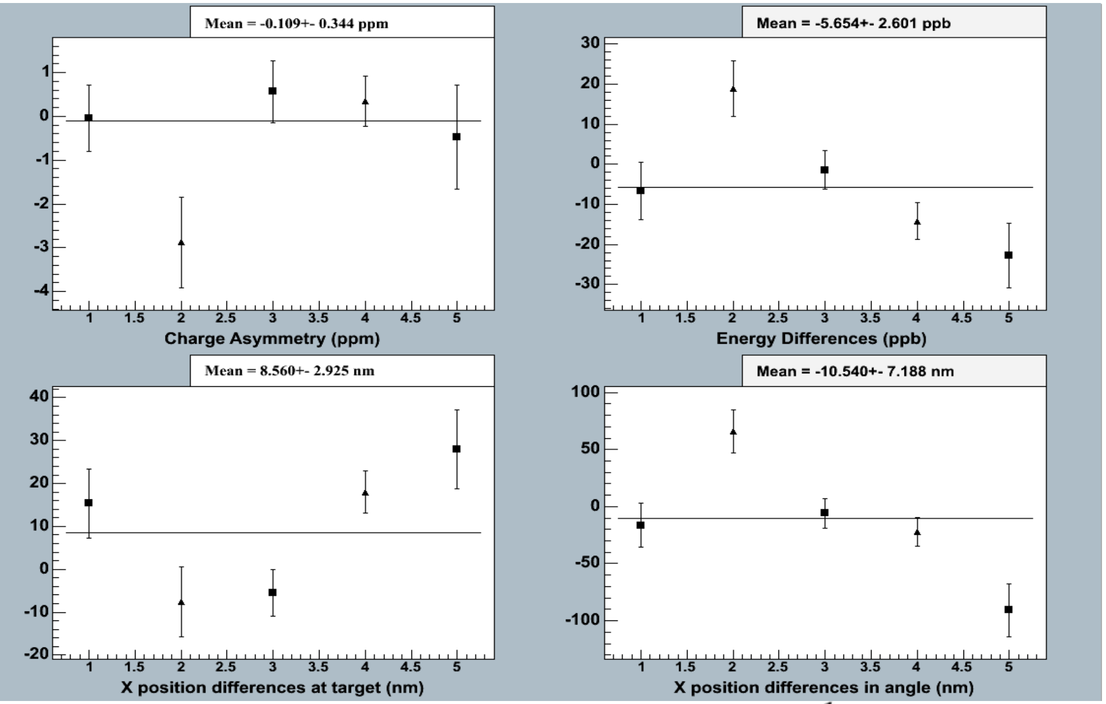
- Background dilution factors
- Background asymmetries

Apply dilution factors:

$$A_{phys} = \frac{R_c}{P_b} A_{sig}$$

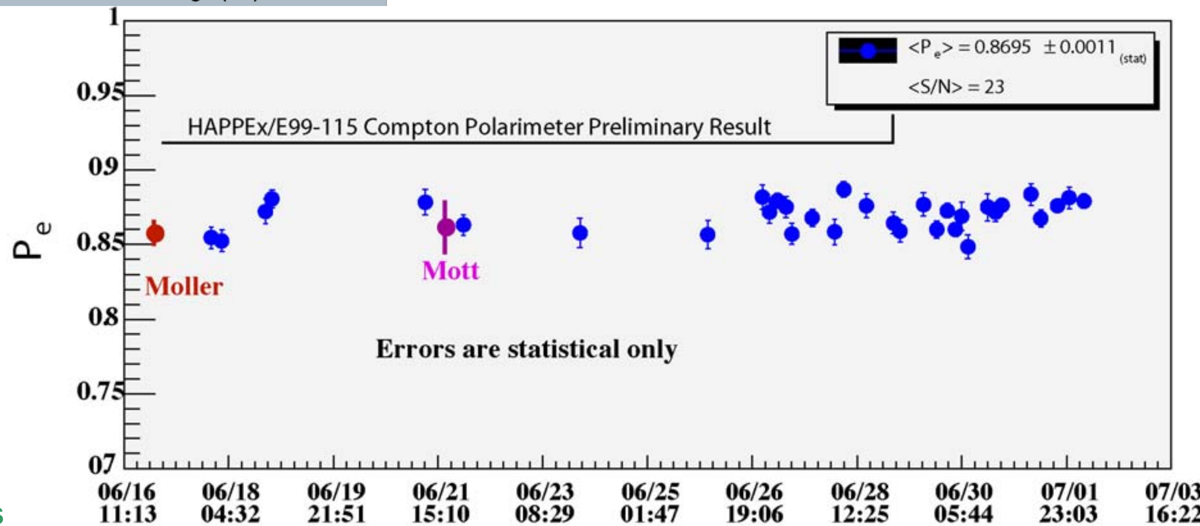
- EM radiative corrections
- Beam polarization

Highly Polarized Beam



- ^{4}He running used superlattice photocathode
- 5 $\lambda/2$ flips during run
- position differences controlled by careful alignment of polarized electron source optical elements
- no active position feedback

Polarization monitored continuously with a Compton polarimeter: Average ~ 86%



G0 Appendix: Leakage Current Correction

- Unanticipated effect: leakage of beam from Hall A, B lasers into C
- Hall A,B beams are 499 MHz, Hall C beam is 32 MHz
- TOF cuts means elastic signal 'sees' 32 MHz beam, but beam current monitors respond to A+B+C beam
  - if large current asymmetry in A, B → false asymmetry in C beam
- Measure effect using signal-free region of TOF spectra
  - verify with studies with other lasers turned off + high-rate luminosity monitors
  - also verify with low-rate runs.
- Typical: 40 nA leakage, 40 μA main beam; leakage asymmetry ~500 ppm
- **Net systematic uncertainty 0.1 ppm**