Hadron Form Factors: Experimental Overview

Mark Pitt, Virginia Tech
Lightcone 2002

- Nucleon electromagnetic form factors
  - spacelike, including strange form factors
  - timelike
  - transition form factors, with focus on $N \rightarrow \Delta$
- Meson form factors
  - spacelike π^+ form factor
  - spacelike K^+ form factor
- Other form factors
- Outlook

Nucleon Spacelike ($q^2 < 0$) Electromagnetic Form Factors

$$J^{\gamma}_{\mu} = F_1^{\gamma}\gamma_{\mu} + F_2^{\gamma}\frac{i\sigma_{\mu\nu}q^{\nu}}{2M_N}$$

↑ Dirac ↑ Pauli

Sachs: $G_E = F_1 - \tau F_2 \quad G_M = F_1 + F_2$

- 1960's – early 1990's : G^p_E, G^p_M, G^n_E, G^n_M measured using Rosenbluth separation in e + p (elastic) and e + d (quasielastic):

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

- early 1990's – present: Polarization observables and ratio techniques used

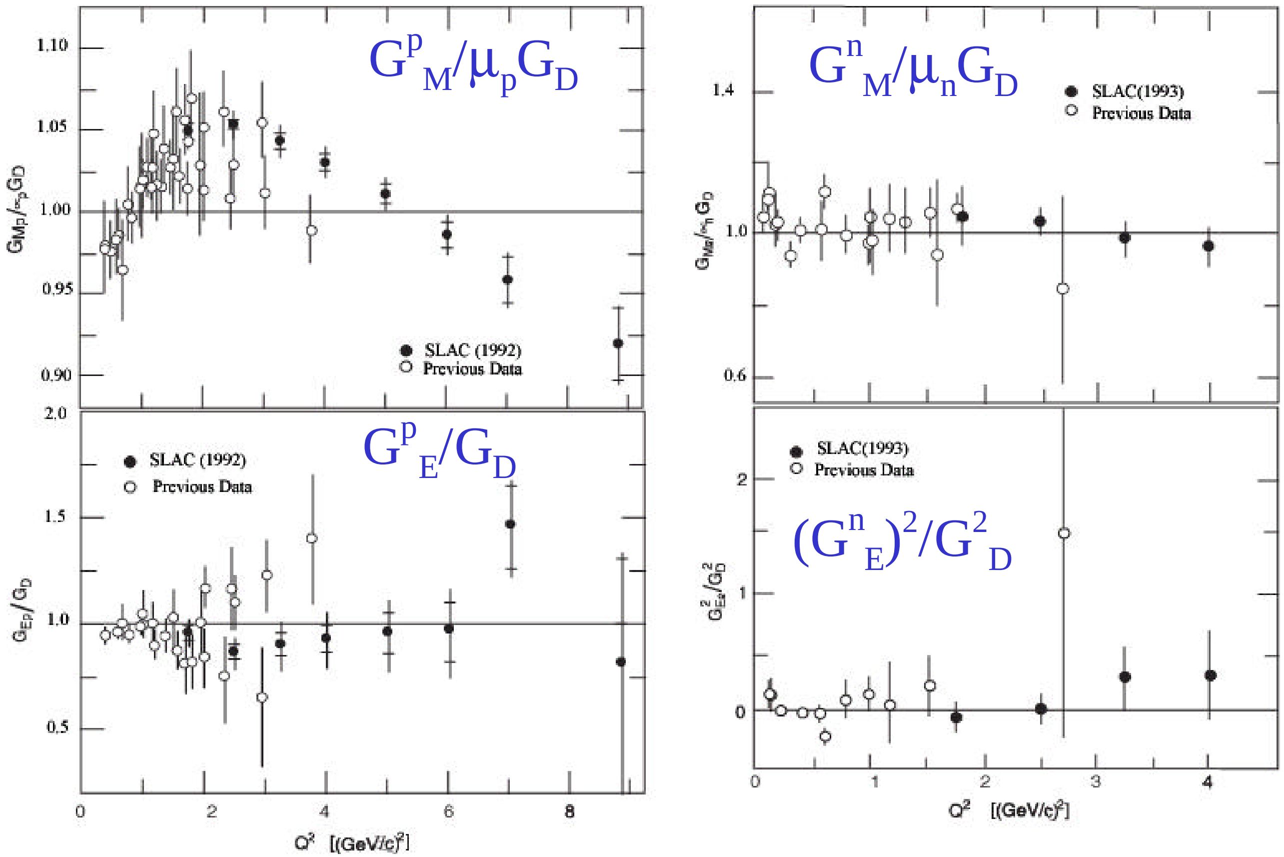
$$\vec{e} + \vec{N} \rightarrow e' + N' \qquad \vec{e} + N \rightarrow e' + \vec{N}'$$

$$\frac{d\sigma}{d\Omega} = \underbrace{\ldots(G_E^2 + \ldots G_M^2)}_{(d\sigma/d\Omega)_{unpol}} + \underbrace{\ldots P_e P_N^{\perp} G_E G_M}_{A_{\perp}} + \underbrace{\ldots P_e P_N^{\parallel} G_M^2}_{A_{\parallel}}$$

Nucleon Spacelike EM Form Factors, World Data - 1993

Relative error ~ 2%

~ 10-20%



~ 5-10%

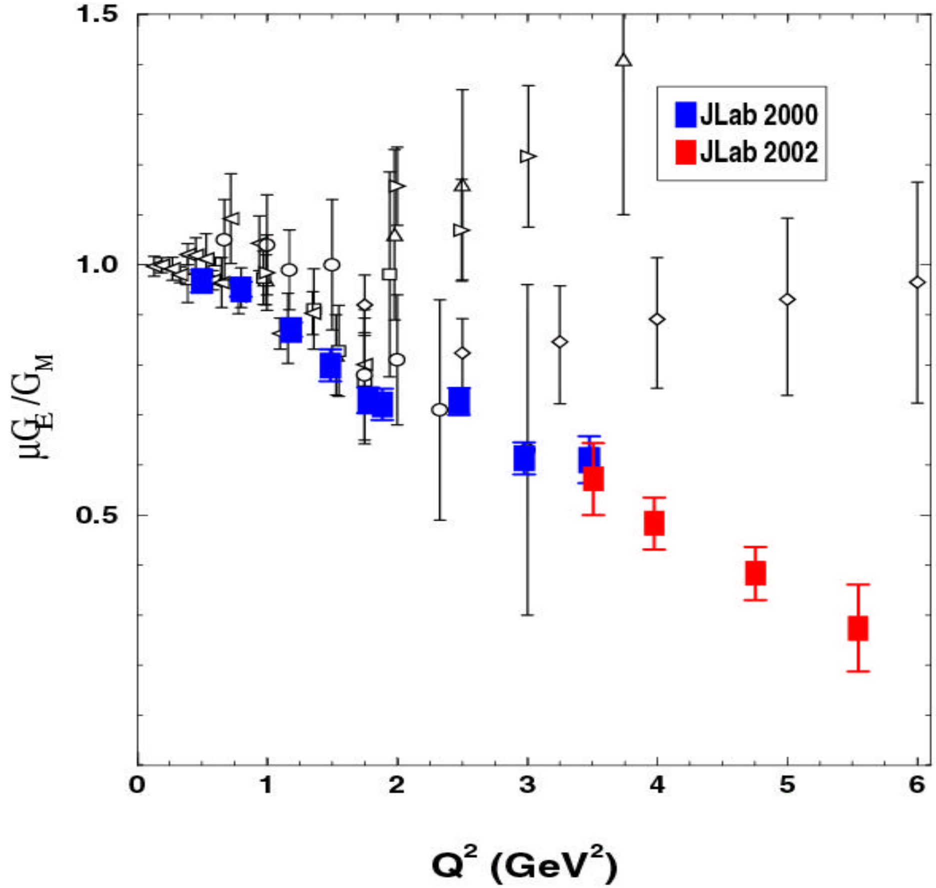
~ 50-100%

Knowledge of nucleon spacelike EM form factors in 1993:

→ G^p_E, G^p_M, G^n_M follow dipole form $G_D = (1 + Q^2/0.71)^{-2}$ at ~20% level

→ $G^n_E \sim 0$ (from quasielastic e-d data)

Proton Electromagnetic Form Factor Ratio: G^p_E / G^p_M



Older data: Rosenbluth separation

JLab 2000: M. K. Jones, *et al.*

JLab 2002: O. Gayou, *et al.*

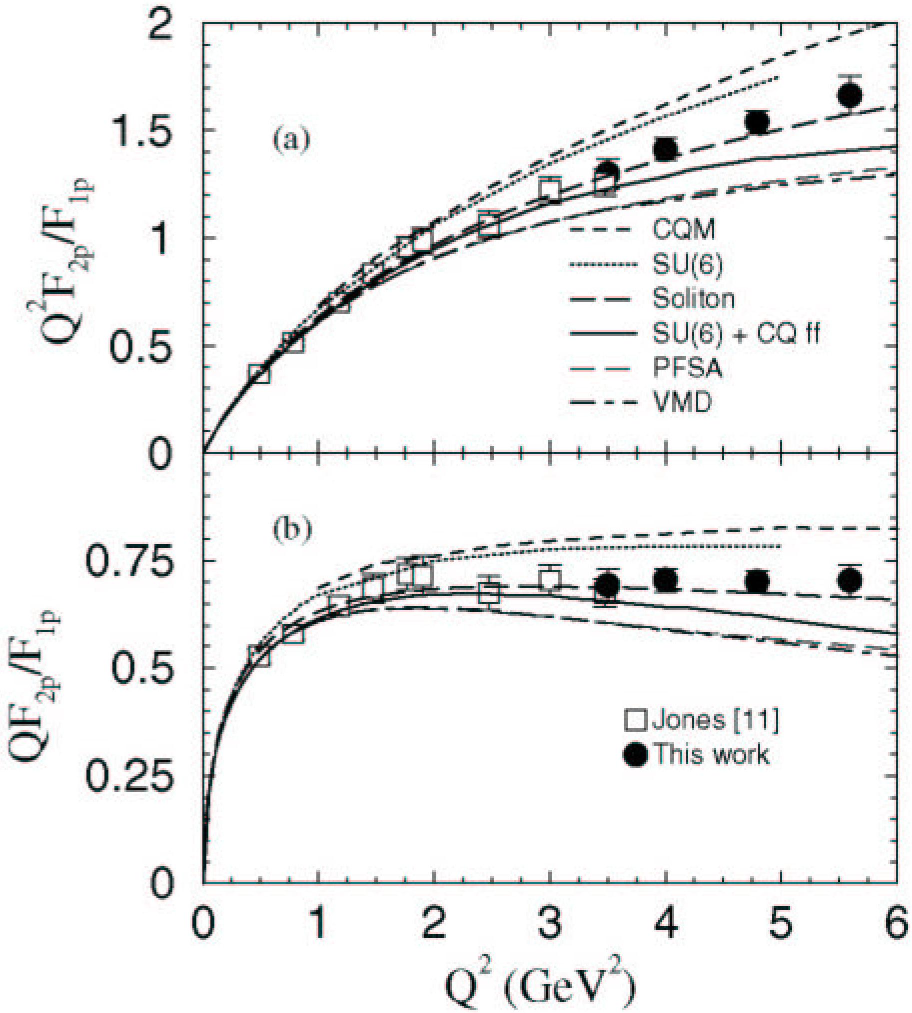
using measurements of recoil proton polarization in Hall A with

$$\vec{e} + p \rightarrow e + \vec{p}$$

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

→ Difference in the spatial distribution of charge and magnetization currents in the proton

Proton EM Form Factor Ratio F^p_2 / F^p_1: pQCD predictions



pQCD prediction: As $Q^2 \to \infty$

$F^p_1 \propto 1/Q^4$ $F^p_2 \propto 1/Q^6$

$Q^2 F^p_2 / F^p_1 \to$ constant

→ not being reached yet

Ralston, *et al.* suggested different scaling behavior:

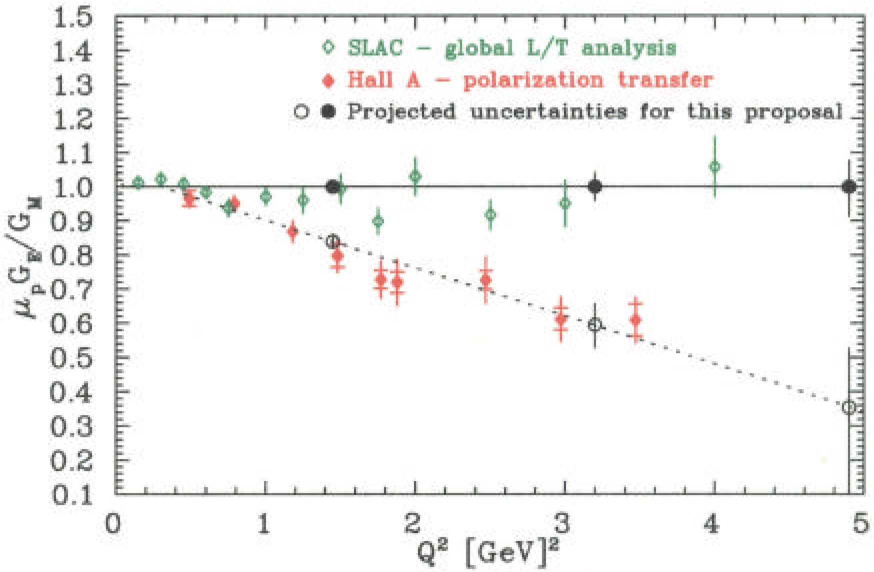
$F^p_2 / F^p_1 \propto 1/Q$

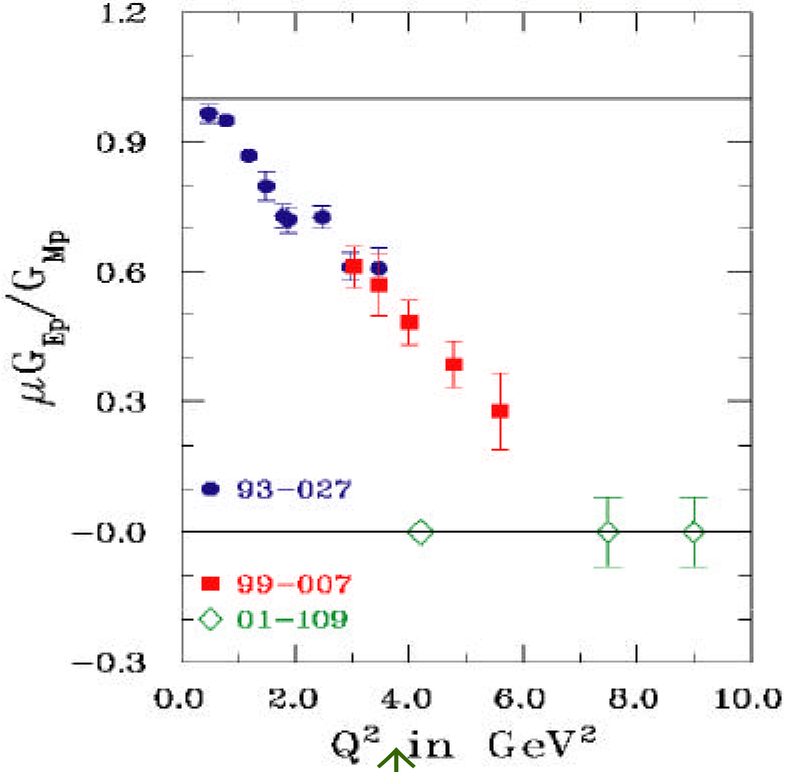
when quark orbital angular momentum included

G^p_E / G^p_M : Upcoming measurements

JLab experiment E01-001:
J. Arrington, R. Segel, *et al.*

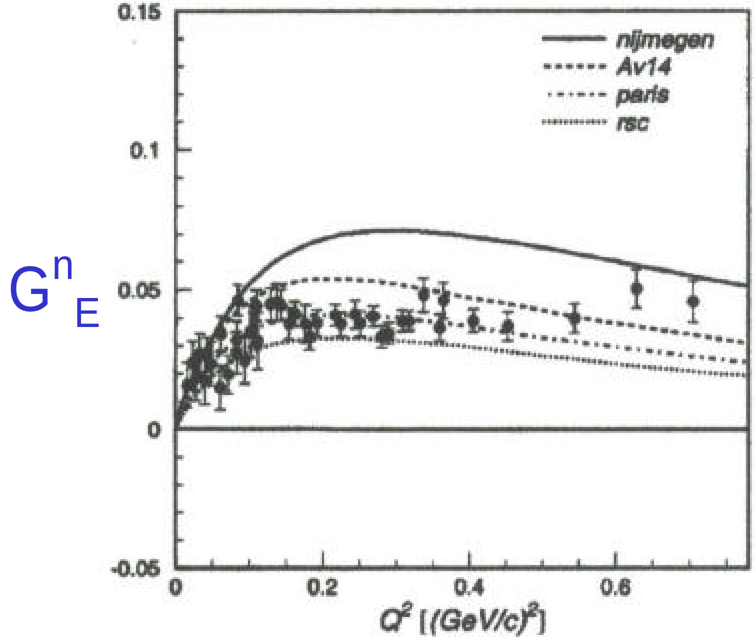
"Super-Rosenbluth" separation in Hall A
→ recently completed data-taking





JLab experiment E01-109:
C.F. Pedrisat, *et al.*
Recoil proton polarimetry in Hall C
→Extend Q^2 up to 9.0 GeV^2
→ At 12 GeV go to Q^2~14.0 GeV^2

Neutron Electric Form Factor G^n_E: Status in Early 1990's



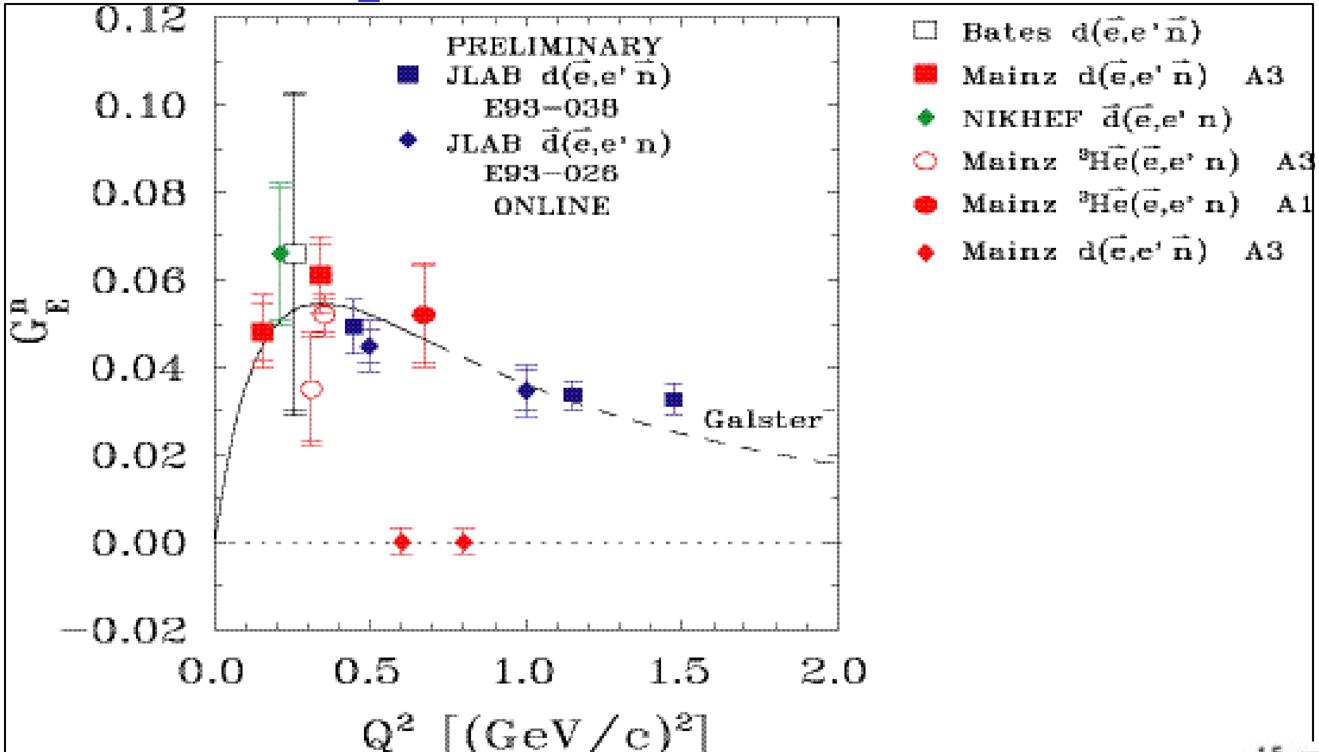
- Slope at Q^2=0: well known from slow neutron-atom scattering:

$$\langle r_n^2 \rangle = -6 \frac{dG_E^n(Q^2)}{dQ^2}\bigg|_{Q^2=0} = -0.113 \pm 0.003 \pm 0.004 \text{ fm}^2 \qquad \text{(Kopecky, } et\ al. \text{1995)}$$

- Platchkov, et al. (1990) deuteron elastic form factor measurements

$\longrightarrow$ ~50% systematic uncertainty from choice of nucleon-nucleon potential used in deuteron wavefunction calculation

G^n_E: Current Status and Future Prospects



Data from:
beam-target asymmetries
recoil polarization
in:

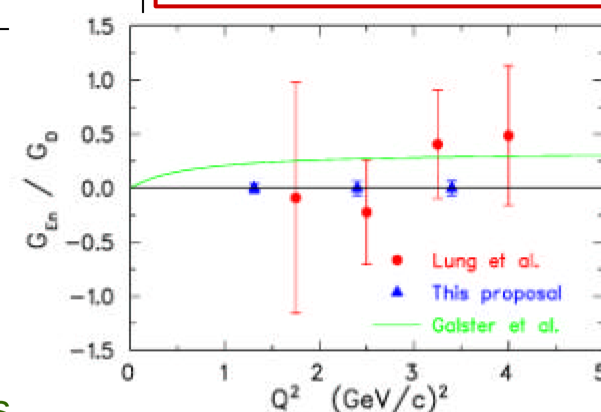
d (e, e' n)

d (e, e' n)

^{3}He (e, e' n)

at:

Mainz MAMI
Jefferson Lab
NIKHEF
MIT-Bates

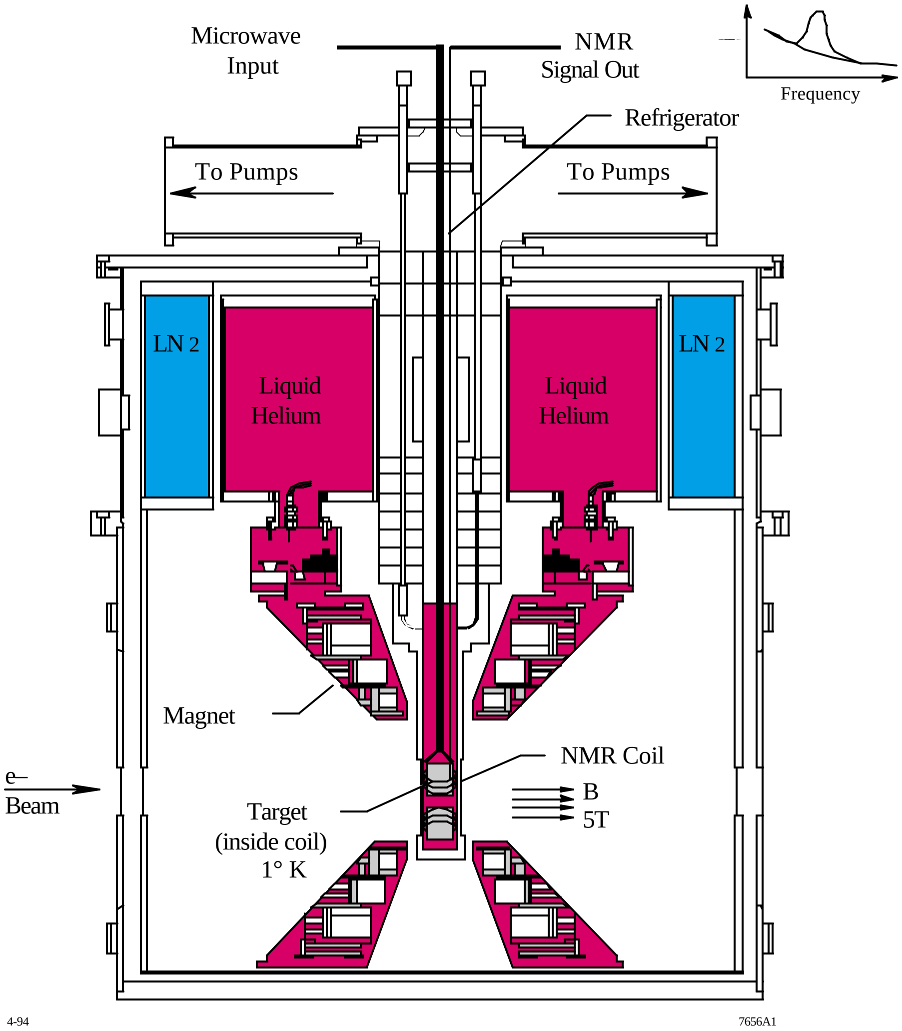


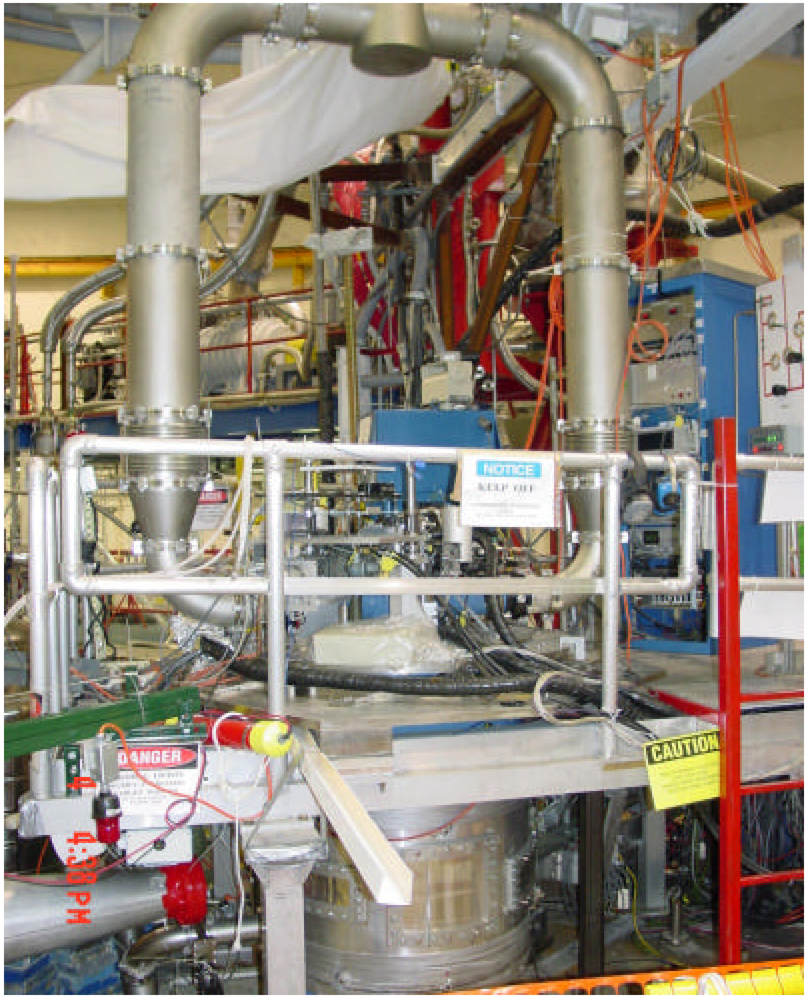
Upcoming experiments:

- E02-013 (Hall A) at JLab ^{3}He (e, e' n) at Q^2 = 1.3, 2.4, 3.4 (GeV/c)^2
- BLAST at MIT-Bates (Q^2 = 0.1 – 0.8 (GeV/c)^2)

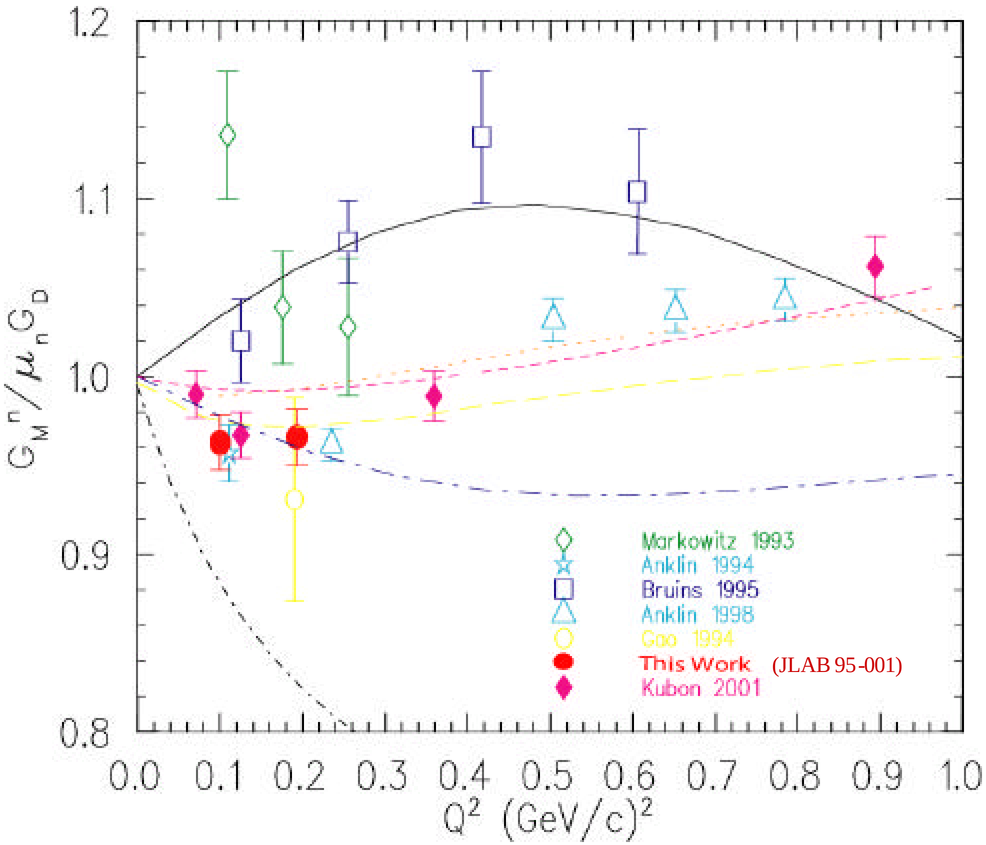
Generally expect ~<10% accuracy up to 3.4 GeV from the complete program of existing and proposed measurements

ND_3 DNP Polarized Target Apparatus of JLAB E93-026





Neutron's Magnetic Form Factor G^n_M: Current Status



The most precise recent data comes from ratio measurements:

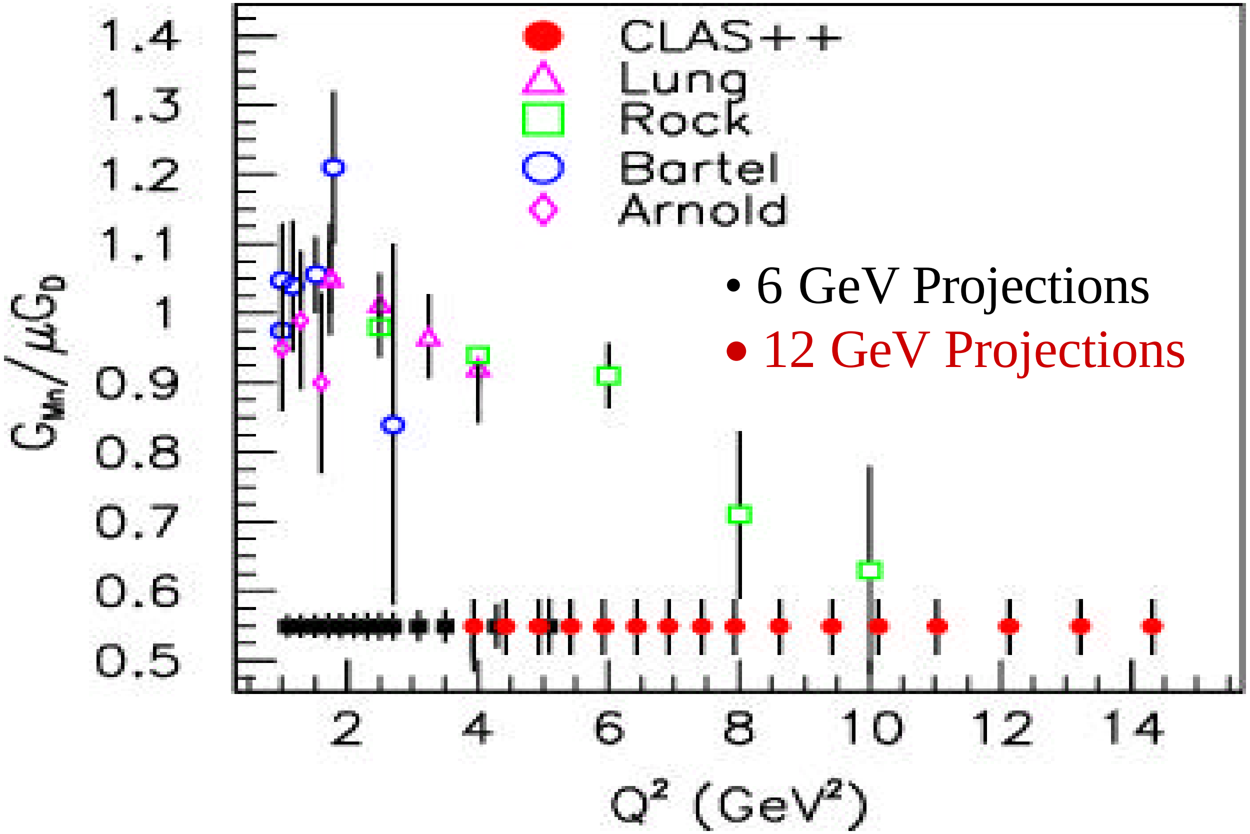
$$\frac{\sigma(d(e,e'n))}{\sigma(d(e,e'p))}$$

at NIKHEF/Mainz (Anklin, Kubon, et al.)
and ELSA at Bonn (Bruins, et al.)

Large (8-10%) systematic discrepancy between the two data sets : likely due to error in neutron detection efficiency

Newest data: JLAB 95-001 (Xu, et al. 2000) $^3\vec{He}(\vec{e}, e')$ in Hall A agrees with NIKHEF/Mainz data at Q^2 = 0.1, 0.2 GeV^2
$\rightarrow$ more data exists (Q^2 = 0.3 - 0.6 GeV^2) but requires improved nuclear corrections (relativistic effects need to be included)

Neutron's Magnetic Form Factor G^n_M : Future Prospects



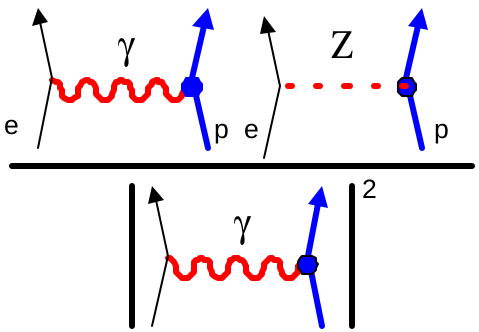
CLAS detector in JLAB Hall B: Will measure σ(d(e,e'n))/σ(d(e,e'p))

- E94-017 (Brooks, et al.): $Q^2 = 0.3 - 5.1$ GeV^2 , data taking completed
- 12 GeV upgrade: will allow for $Q^2 = 4.0 - 14.4$ GeV^2

Nucleon's Neutral Weak Form Factors

Parity-violating electron scattering: elastic $\vec{e} + p$ and quasielastic $\vec{e} + d$

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim$$



extract neutral weak FF: G_E^Z and G_M^Z

Flavor separation of form factors:

$$< p \,|\, J_m^g \,|\, p >: \quad G_{E,M}^{g,p} = \frac{2}{3} G_{E,M}^{u,p} - \frac{1}{3} G_{E,M}^{d,p} - \frac{1}{3} G_{E,M}^{s,p}$$

$$< n \,|\, J_m^g \,|\, n >: \quad G_{E,M}^{g,n} = \frac{2}{3} G_{E,M}^{u,n} - \frac{1}{3} G_{E,M}^{d,n} - \frac{1}{3} G_{E,M}^{s,n}$$

$$< p \,|\, J_m^Z \,|\, p >: \quad G_{E,M}^{Z,p} = \left(1 - \frac{8}{3}\sin^2\theta_W\right) G_{E,M}^{u,p} + \left(-1 + \frac{4}{3}\sin^2\theta_W\right) G_{E,M}^{d,p} + \left(-1 + \frac{4}{3}\sin^2\theta_W\right) G_{E,M}^{s,p}$$

Invoke proton/neutron isospin symmetry → 3 equations, 3 unknowns

$$\left(G_{E,M}^{g,p}, G_{E,M}^{g,n}, G_{E,M}^{Z,p}\right) \Leftrightarrow \left(G_{E,M}^{u}, G_{E,M}^{d}, G_{E,M}^{s}\right)$$

$G^s_E, G^s_M \equiv$ nucleon's vector strange form factors

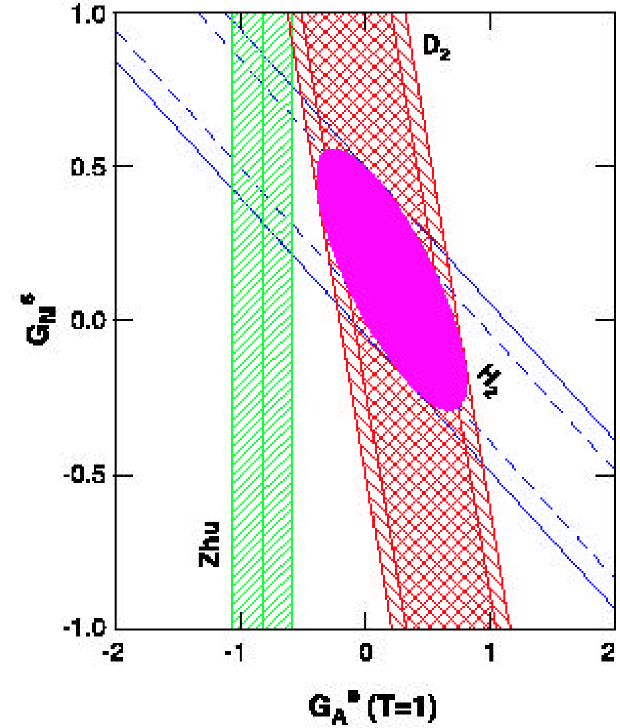
Nucleon's Vector Strange Form Factors – Published Results

SAMPLE at MIT-Bates:

$\vec{e} + p$ elastic: $A_p = -4.92 \pm 0.61 \pm 0.73$ ppm

$\vec{e} + d$ quasielastic: $A_d = -6.79 \pm 0.64 \pm 0.55$ ppm

$G_M^s(Q^2 = 0.1\,\text{GeV}^2) = 0.14 \pm 0.29 \pm 0.31$



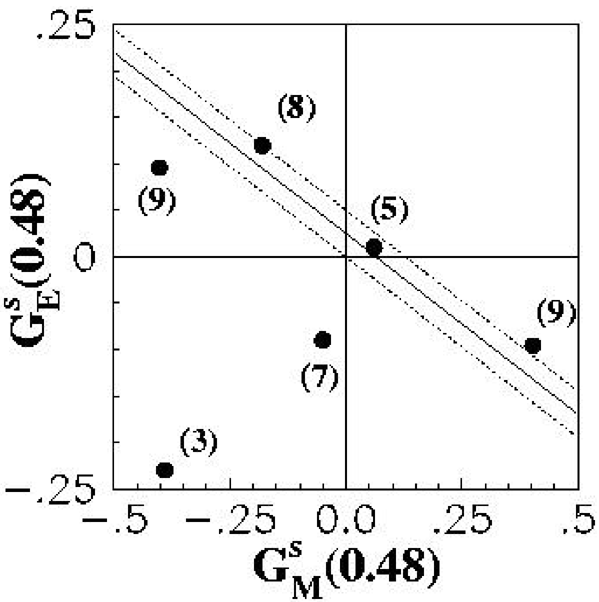
→ < 5% of proton magnetic moment due to strange quark sea

HAPPEX at Jefferson Lab:

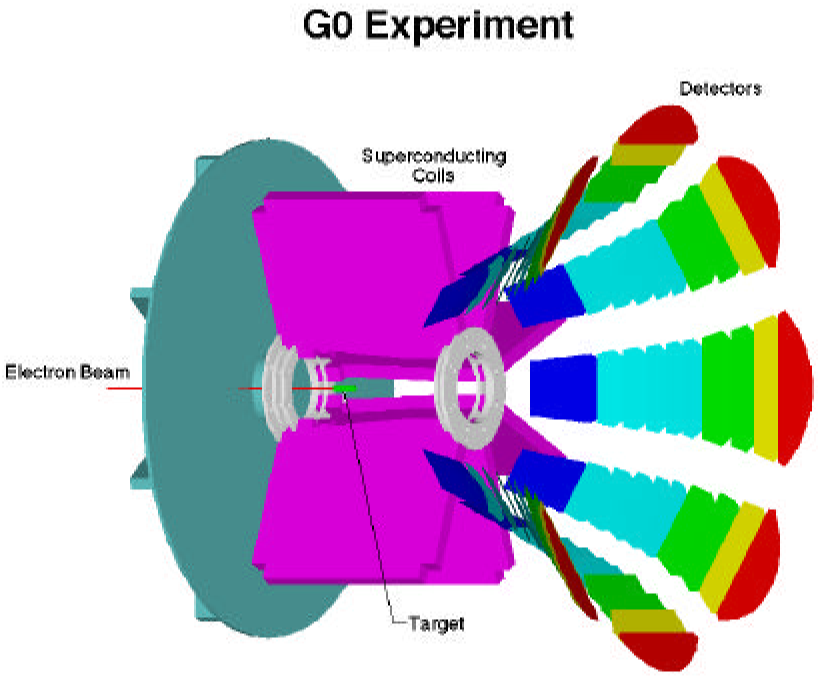
$\vec{e} + p$ elastic: $A_p = -15.05 \pm 0.98 \pm 0.56$ ppm

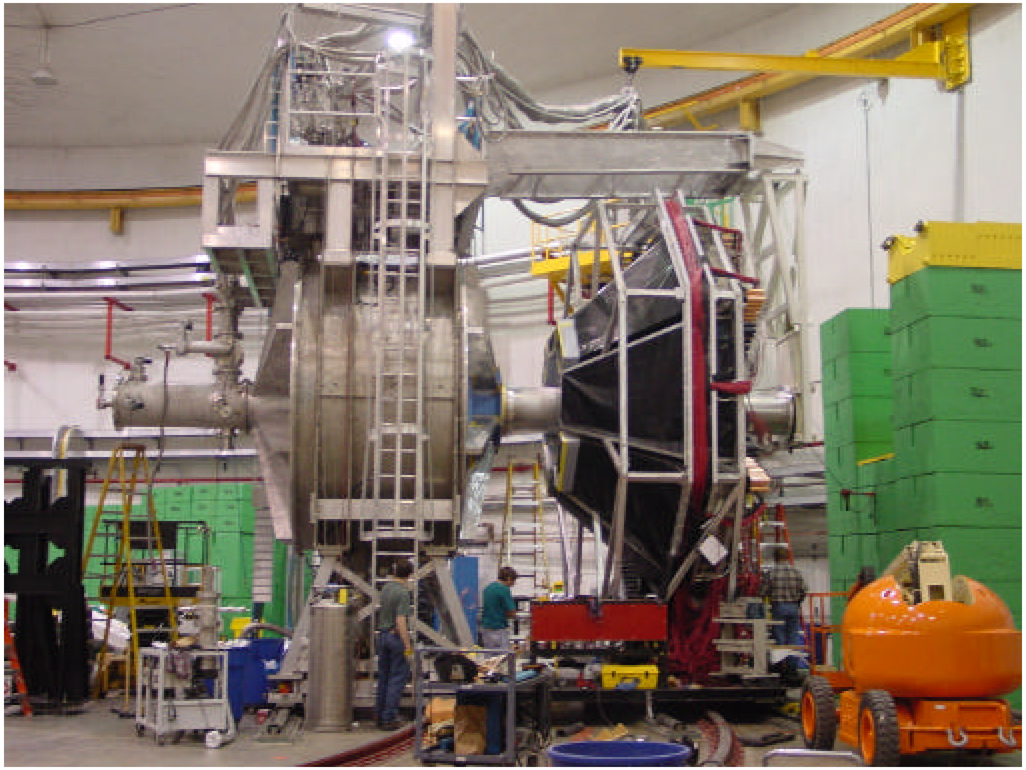
$G_E^s + 0.39 G_M^s = 0.025 \pm 0.020 \pm 0.014$

at $Q^2 = 0.48\,\text{GeV}^2$

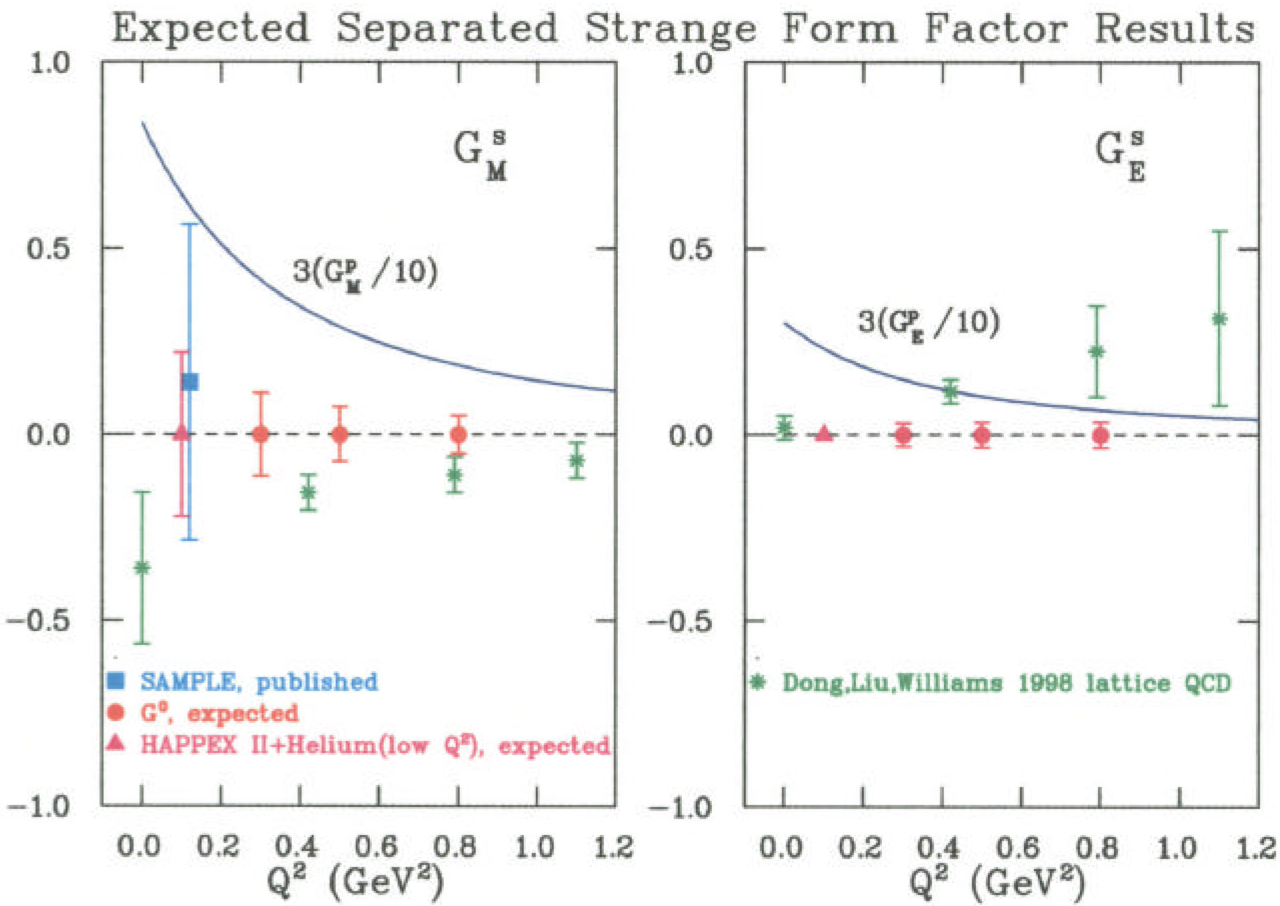


The G^0 Experiment at Jefferson Lab





Nucleon's Vector Strange Form Factors – Anticipated Results



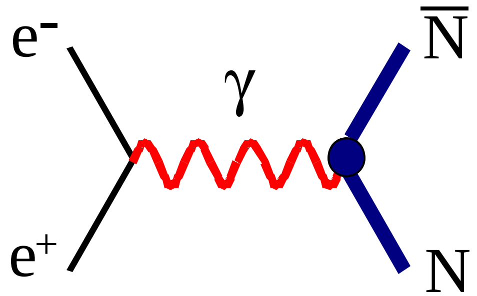
Ongoing experiments at JLAB (G^0 and HAPPEX), Mainz MAMI (A4) will provide:

- separated form factors G^s_E and G^s_M
- ultimate precision ~<3% of G^p_E and G^p_M

in the next few years

Nucleon timelike ($q^2>0$) electromagnetic form factors

Timelike EM Form Factors: $s = q^2 > 0$



Proton: $p\bar{p} \rightarrow e^+ e^-$ (CERN LEAR, Fermilab)

$e^+ e^- \rightarrow p\bar{p}$ (ADONE at Frascati, Orsay)

Neutron: $e^+ e^- \rightarrow n\bar{n}$ (FENICE at ADONE)

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta C}{4s}\left[|G_M|^2 (1+\cos^2\theta) + \frac{4M_N^2}{s} |G_E|^2 \sin^2\theta \right]$$

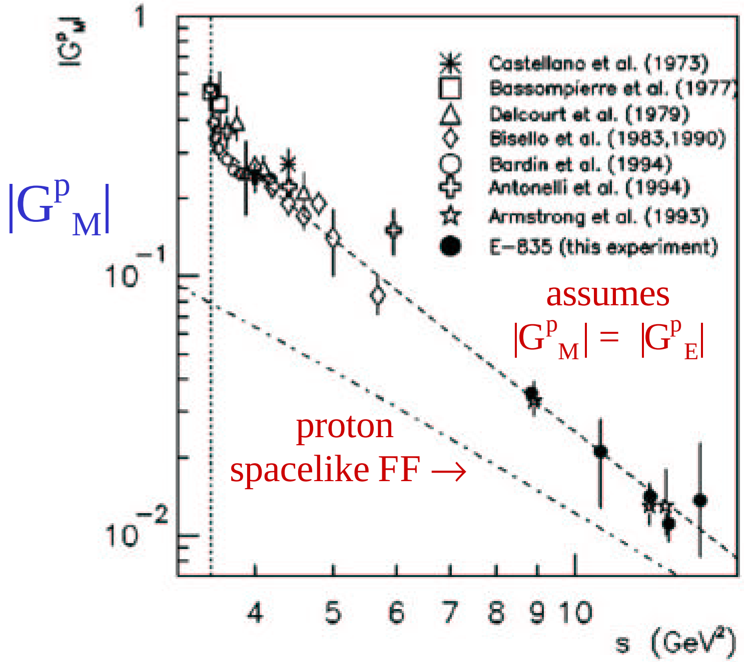
Existing data does not have adequate statistics to separate G_E and G_M

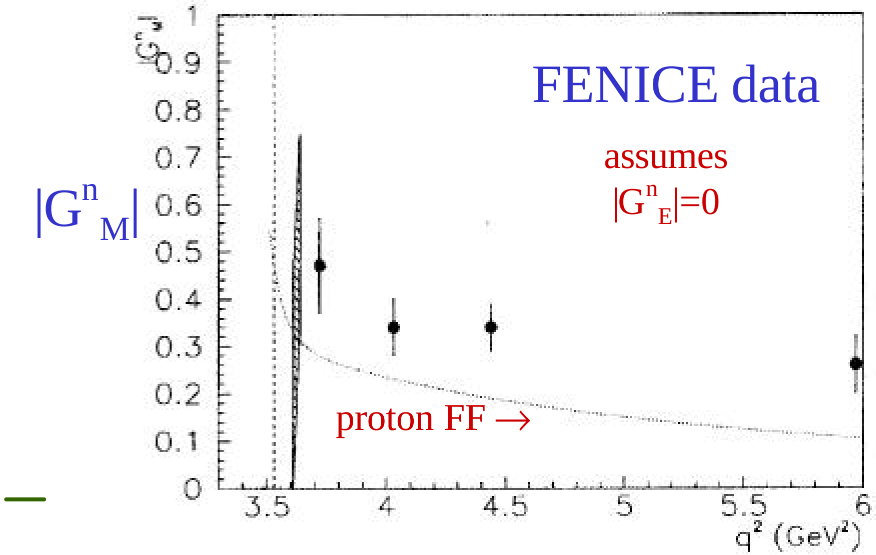
$\rightarrow$ Either a) $|G_E| = |G_M|$ (true at threshold where $s = q^2 = 4 M^2_N$)

or b) $|G_E| = 0$

is assumed to extract G^p_M and G^n_M

Nucleon timelike EM form factors – current status





Notable features of the timelike form factor data:

- Rapid fall of G^p_M just above threshold – sub-threshold $N\bar{N}$ bound state?
- $G^n_M > G^p_M$ far above threshold, contrary to pQCD prediction ~ (q_d/q_u) ~ 0.50
- Timelike G^p_M > spacelike G^p_M for large q^2, contrary to pQCD expectation
- Generally, observation of $\sigma(e^+ e^- \rightarrow n \bar{n}) > \sigma(e^+ e^- \rightarrow p \bar{p})$ near threshold is considered surprising

Nucleon timelike EM form factors – future prospects

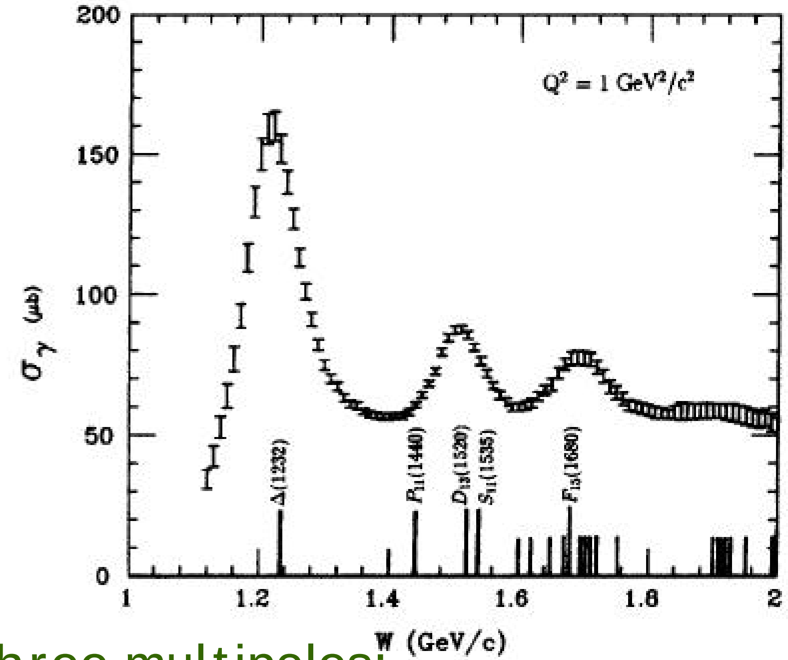
PEP-N initiative at SLAC:

- Asymmetric e^+e^- collider at SLAC at $E_{cm} = 1 – 3.1$ GeV
  - 3.1 GeV PEP-II LER e^+ beam on 100 – 800 MeV e^- beam
  - Asymmetric feature boosts nucleons for easier detection
- Possible measurements
  - Proposed luminosity would allow for separation of $|G_E|$ and $|G_M|$ for both proton and neutron
  - Polarization measurement of outgoing nucleons would allow for the complex phase difference of G_E and G_M to be measured

Nucleon $\rightarrow$ Resonance Transition Form Factors

Electromagnetic FF in the nucleon $\rightarrow$ resonance transitions:

$\gamma^* p \rightarrow \Delta_{33}$ (1232)
P_{11} (1440)
D_{13} (1520)
S_{11} (1535)
F_{15} (1680)



$\gamma^* N \rightarrow \Delta$ transition: Characterized by three multipoles:

M_{1+} magnetic dipole E_{1+} electric quadrupole S_{1+} scalar quadrupole

1. Low Q^2: E_{1+}/M_{1+} and S_{1+}/M_{1+} measure deformation of N or Δ
   $\rightarrow$ sensitive to tensor force between quarks
2. High Q^2: pQCD helicity conservation predicts $E_{1+} = M_{1+}$

$$A_{1/2} = -\frac{1}{2}\left(M_{1+} + 3E_{1+}\right): \text{helicity - conserving}$$

$$A_{3/2} = -\frac{\sqrt{3}}{2}\left(M_{1+} - E_{1+}\right): \text{helicity - nonconserving}$$

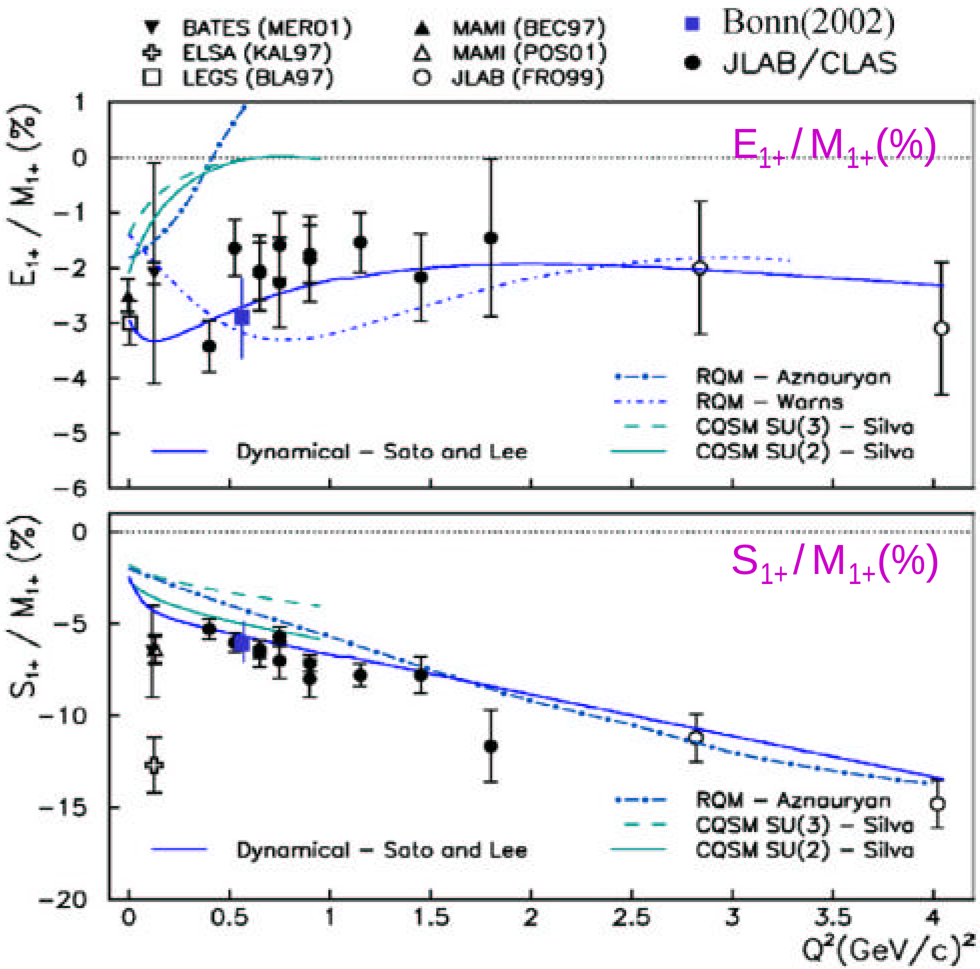
$N \rightarrow \Delta$ transition form factors – current status

Experiments: (photoproduction) $\gamma\, p \rightarrow \Delta \rightarrow p\, \pi^0$ (electroproduction) $p(e,e'p)\pi^0$

$Q^2 = 0 – 0.2\ GeV^2$: Mainz MAMI, Bonn ELSA, LEGS at Brookhaven, MIT-Bates

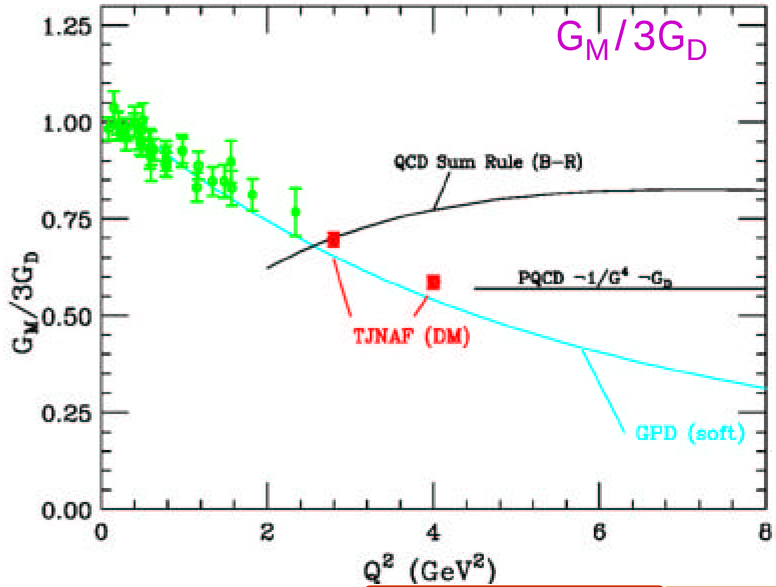
$Q^2 = 0.4 – 1.8\ GeV^2$: JLAB Hall B CLAS (Joo, *et al.,* PRL88, 122001 (2002))

$Q^2 = 2.8 – 4.0\ GeV^2$: JLAB Hall C (Frolov, *et al.,* PRL82, 45 (1999))



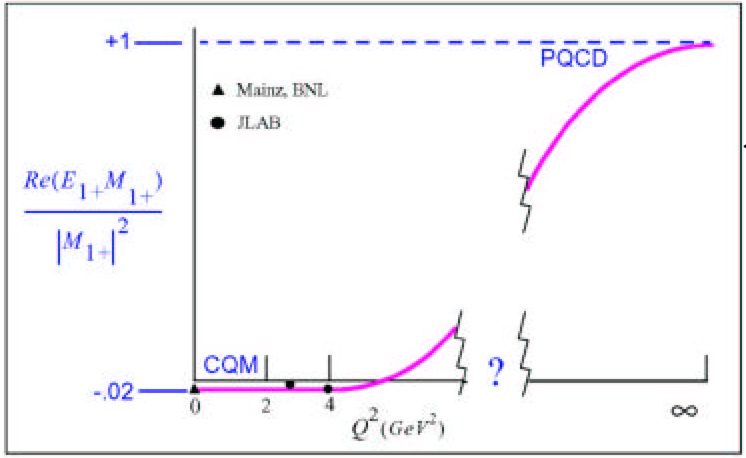
Conclusions to date:

- G_M falls faster with Q^2 than nucleon form factors
- E/M, S/M small, no transition to pQCD observed at this Q^2

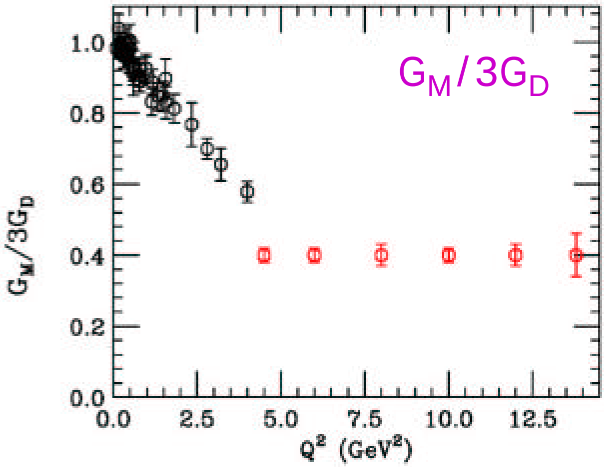


M. Pitt, Virginia Tech
Lightcone 2002,LANL

$N \to \Delta$ transition form factors – future plans



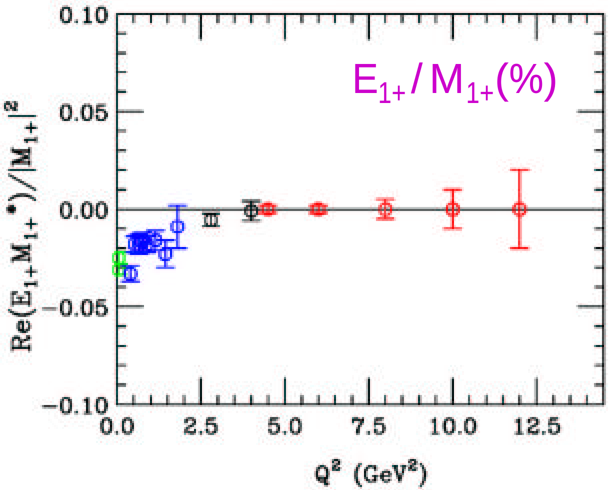
Where is the transition to pQCD?



Future plans:

1. JLAB97-101: extend previous results to $Q^2 \sim 7.5$ GeV^2 (Stoler, et al.)
2. JLAB 12 GeV: possible to extend up to $Q^2 \sim 14$ GeV^2 (Stoler, et al.)

Projections for JLAB at 12 GeV



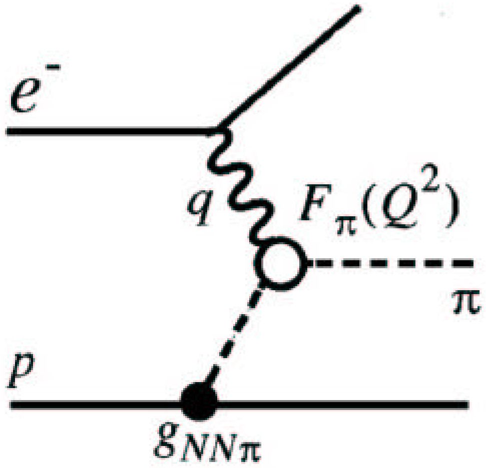
Charged Pion Electromagnetic Spacelike Form Factor

Low Q^2 (up to 0.28 GeV^2): Scattering of π from atomic electrons

High Q^2 (0.28 – 3.5 GeV^2): Extract F_π from pion electroproduction

p (e, e' π^+)n

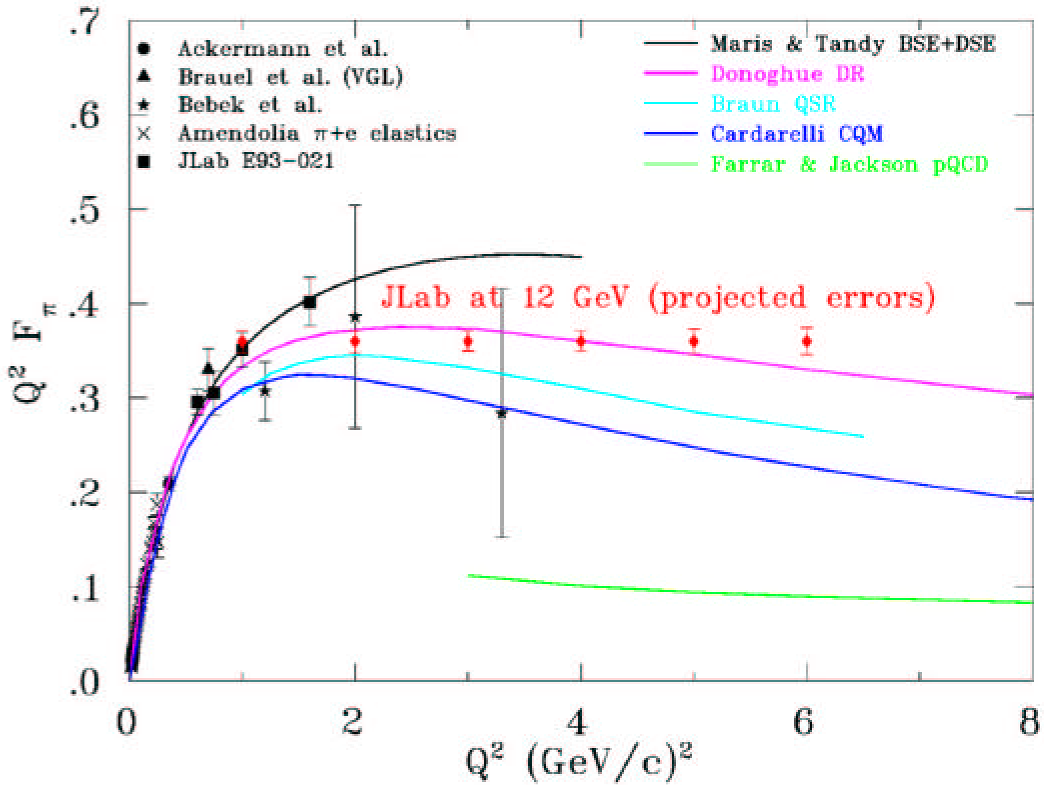
$$\sigma_L \propto -\frac{2tQ^2}{(t-m_\pi^2)^2} F_\pi^2(Q^2)$$



Assumption: Pion-pole diagram dominates the longitudinal cross-section for small t, experimental L/T separation required

$\rightarrow$ model for pion electroproduction required to extract F_π

Charged Pion EM Spacelike Form Factor – Current Status and Future Plans



Due to simpler valence structure, pQCD may become important at lower Q^2 for pion than nucleon

pQCD prediction as $Q^2 \rightarrow \infty$

$$\text{pQCD}: F_\pi(Q^2) = \frac{8\pi\alpha_s f_\pi^2}{Q^2}$$

Recent data: JLAB E93-021, Mack et al. from $Q^2 = 0.6 – 1.6$ GeV^2

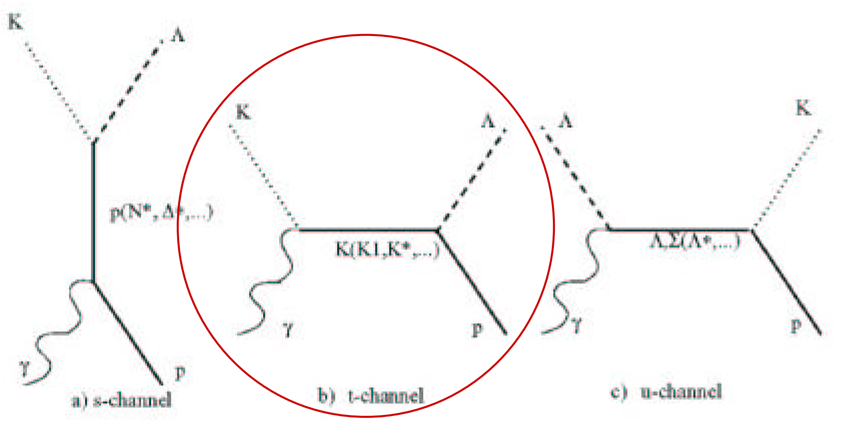
Future data: JLAB E01-004, $Q^2 = 1.6, 2.0, 2.5$ GeV^2, data-taking 2002
JLAB at 12 GeV, Q^2 up to 6.0 GeV^2

Charged Kaon Electromagnetic Spacelike Form Factor

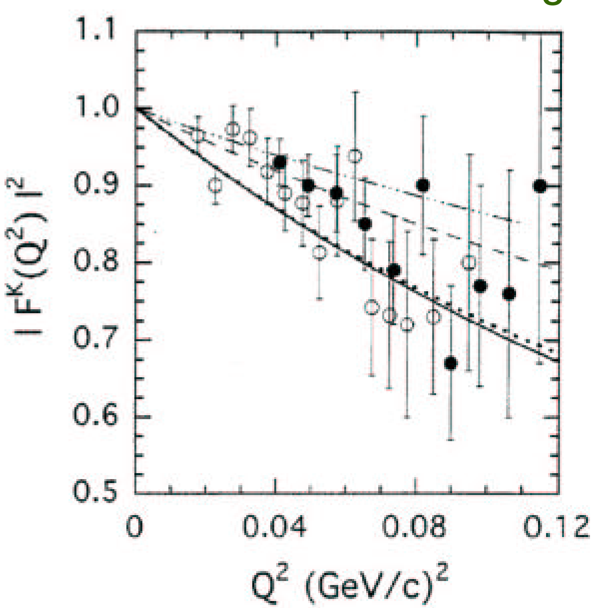
High Q^2 requires kaon electroproduction measurements:

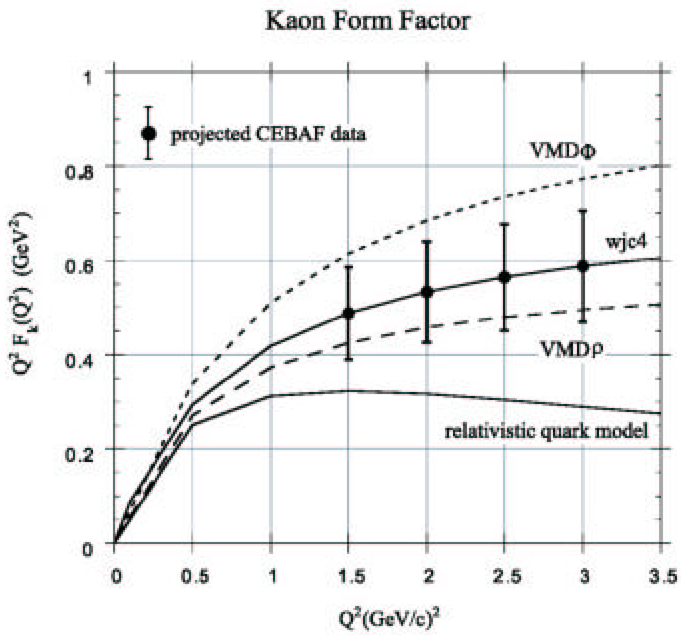
$$p\,(e,e'K^+)\,Y$$

As in pion electroproduction, an L/T separation and a kaon electroproduction model are required to extract F_K



Existing data:
from K-e scattering





Projected results from JLAB E98-108:

- recently completed data-taking
- analysis in progress

Other Form Factors

- Baryon form factors (besides p and n)
  - spacelike: Only Σ^- charge radius measured:

    $\langle r^2 \rangle = .91 \pm .32 \pm .40\ \text{fm}^2$ (WA89)

    $\langle r^2 \rangle = .61 \pm .12 \pm .09\ \text{fm}^2$ (SELEX)

  - timelike: only Λ measured with poor statistics

- Meson form factors
  - Timelike charged pion form factor (measured to $Q^2 \sim 10\ \text{GeV}^2$)
    - statistical accuracy of data above 1 GeV^2 is limited
  - Timelike charged/neutral kaon form factors (to $Q^2 \sim 4.4\ \text{GeV}^2$)
    - statistical accuracy of data above 1 GeV^2 is limited
  - π^0 form factor: meson photon transition form factor
    - $\gamma^*\gamma \rightarrow \pi^0$ measured at CLEO from 1.5 – 9 GeV^2

Outlook

Highlights of 1993 - 2002:

- Unexpected result for G^p_E/G^p_M
- Significantly improved determination of G^n_E
- First measurements of nucleon's strange vector form factors
- Significantly improved measurements on $N \rightarrow \Delta$ transition FF
- First measurements of neutron's timelike form factor
- Accurate determination of π^+ spacelike form factor

Anticipated results in next several years

- Precise determination of nucleon's strange vector form factors
- Extended Q^2 range for G^p_E/G^p_M, G^n_E, $N \rightarrow \Delta$, π^+ spacelike FF

Other future possibilities

- JLAB at 12 GeV – extended Q^2 range for spacelike FF
- PEP-N at SLAC: timelike FF measurements of many baryons and mesons