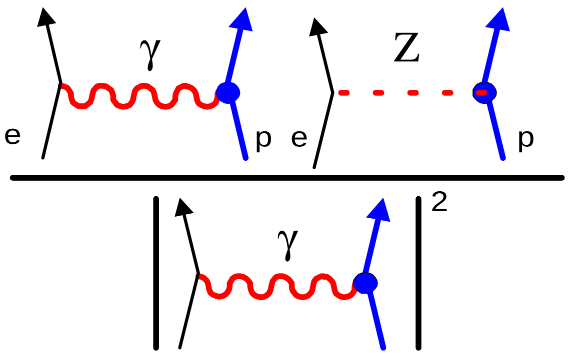
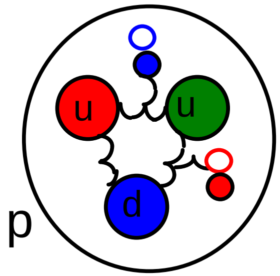
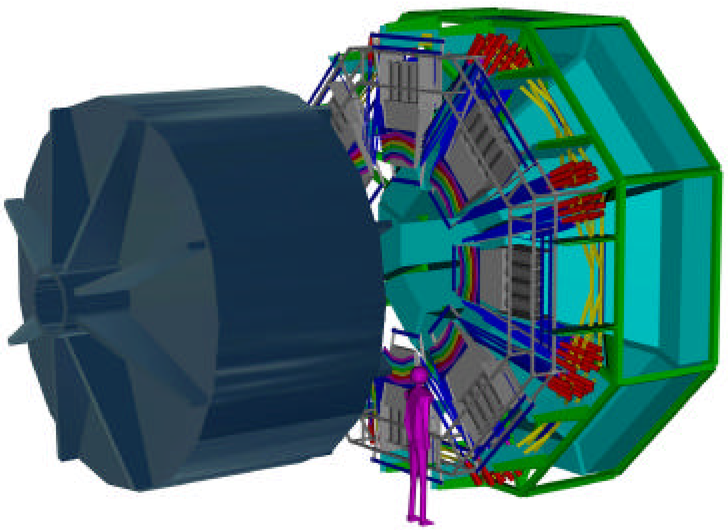
# The Axial Form Factor of the Nucleon
## (as viewed from an electron scatterer)




Nucleon EM and weak form factors
$Q^2$ dependence of $G_A$
$G_A$ as seen by an electron &
electroweak radiative corrections



E. Beise, University of Maryland

# Resources

Talks from NuInt02, NuInt04

(H. Budd, K. McFarland, A. Bodek, S. Wood)

H. Budd, A. Bodek, and J. Arrington, hep-ex/0308005

V. Bernard, L. Elouadrhiri, and U-G. Meissner, J. Phys. G (02) 28

A. Deur (JLab LOI for PAC 25)

G0/SAMPLE programs

S.-L. Zhu, S.J. Puglia, B.R. Holstein and M.J. Ramsey-Musolf,

PRD 62 (2000) 033008

# Electroweak nucleon form factors

pointlike fermions:

$$ieQ_f\gamma_\mu$$

$$i\frac{gM_Z}{4M_W}\gamma_\mu\left(g_V^f+g_A^f\gamma_5\right)$$

| | $Q_f$ | $g_V{}^f$ | $g_A{}^f$ |
|---|---|---|---|
| ν | 0 | 1 | –1 |
| e,μ⁻ | –1 | $-1+4\sin^2\theta_W$ | +1 |
| u,c,t | +2/3 | $1-8/3\sin^2\theta_W$ | –1 |
| d,s,b | –1/3 | $-1+4/3\sin^2\theta_W$ | +1 |

nucleons:

$$\langle N'|J_\mu^\gamma|N\rangle=\bar{u}_N\left[F_1^\gamma(q^2)\gamma_\mu+\frac{i\sigma_{\mu\nu}q^\nu}{2M_N}F_2^\gamma(q^2)+\boxed{\frac{G_F}{M_N^2}F_A^\gamma(q^2)\left(q^2\gamma_\mu-q^\nu\gamma_\nu q_\mu\right)\gamma_5}-\cancel{\frac{i\sigma_{\mu\nu}q^\nu\gamma_5}{2M_N}F_E(q^2)}\right]u_N$$

time reversal violating

$$\langle N'|J_\mu^Z|N\rangle=\bar{u}_N\left[F_1^Z(q^2)\gamma_\mu+\frac{i}{2M_N}F_2^Z\sigma_{\mu\nu}q^\nu\right]u_N$$

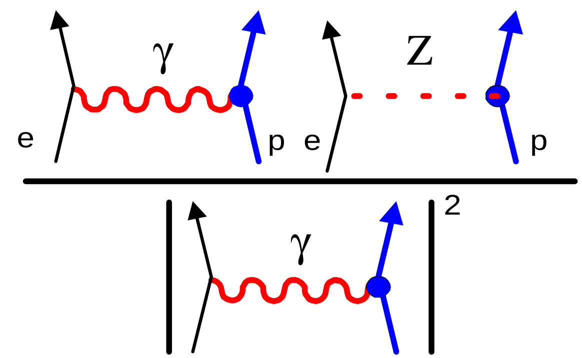
$$\langle N'|J_{\mu5}^Z|N\rangle=\bar{u}_N\left[\boxed{G_A^Z(q^2)\gamma_\mu}+\frac{1}{M_N}\cancel{G_P(q^2)q_\mu}\right]\gamma_5u_N$$

ignore in this talk

# Parity Violating elastic e-N scattering

polarized electrons, unpolarized target

$$A = \frac{s_R - s_L}{s_R + s_L} = \left[\frac{-G_F Q^2}{4pa\sqrt{2}}\right] \frac{A_E + A_M + A_A}{2s_{unpol}}$$




$$A_E = e(q) G_E^Z G_E^g$$

$$A_M = t\, G_M^Z G_M^g$$

$$A_A = -(1 - 4\sin^2 q_W) e' G_A^e G_M^g$$

$\tau = Q^2/4M^2$

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

$\varepsilon' = [\tau(\tau+1)(1-\varepsilon^2)]^{1/2}$

Neutral Weak ffs contain explicit contributions from strange sea

$$G_{E,M}^Z(Q^2) = (1 - 4\sin^2 q_W)(1 + R_A^p) G_{E,M}^p - (1 + R_A^n) G_{E,M}^n - G_{E,M}^s$$

$$G_A^e(Q^2) = -G_A^Z + (hF_A^g + R^e) + \Delta s$$

$$h = \frac{8pa\sqrt{2}}{1 - 4\sin^2 q_W} = 3.45$$

$G^Z_A(0) = 1.2673 \pm 0.0035$ (from β decay)

# neutrino-nucleon (CC) Quasielastic scattering

$\nu_\mu + n \rightarrow \mu^- + p$

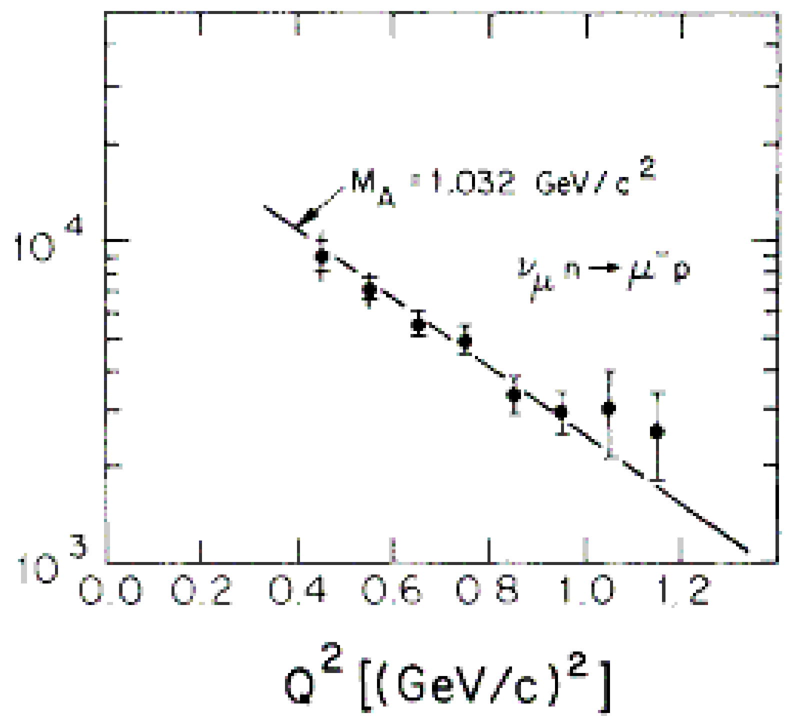
$$\frac{ds}{dQ^2} = \frac{G_F^2 M^2}{8\pi E_n^2}\left( A \pm \frac{(s-u)}{M^2} B + \frac{(s-u)^2}{M^4} C \right) \qquad (+,-) \rightarrow (n, \bar{n})$$

$$A = \frac{(m^2 + Q^2)}{M^2}\left[ \begin{array}{l} (G_A^Z)^2 (1+t) - \left( (F_1^Z)^2 - t\,(F_2^Z)^2 \right)(1-t) + 4t F_1^Z F_2^Z \\ - \dfrac{m^2}{4M^2}\left( (G_A^Z + 2G_P)^2 - 4(1+t) G_P^2 \right) \end{array} \right]$$

$$B = -\frac{Q^2}{M^2} G_A^Z \left( F_1^Z + F_2^Z \right)$$

$$C = \frac{1}{4}\left[ (G_A^Z)^2 + (F_1^Z)^2 + t\,(F_2^Z)^2 \right]$$

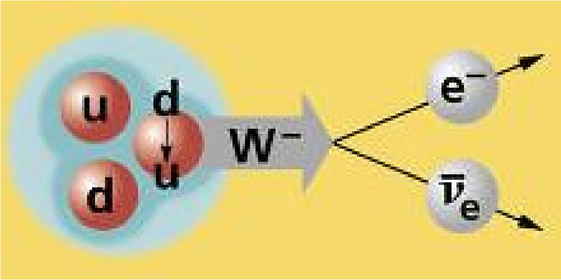
$$(s-u) = 4ME_n - Q^2 - m^2, \quad t = \frac{Q^2}{4M^2}$$




L.A. Ahrens etal, PRD 35 (1987)785

# $g_A$: why is it interesting?

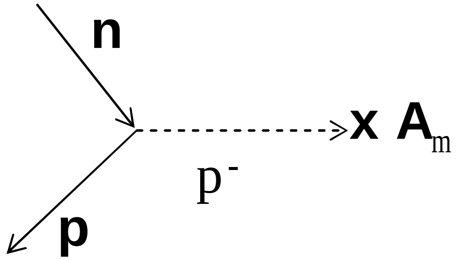
$g_A$ via neutron β decay




quarks:

$V_{ud}$

$g_A = \Delta u - \Delta d$




nucleons/pions:

$$\langle p | A_m(0) | n \rangle = \bar{u}_p \left( g_A g_m g_5 - g_P \frac{1}{2M} q_m g_5 \right) u_n \qquad \langle 0 | A_m | p \rangle = 2 F_p q_m$$

$$\boxed{\frac{g_A}{F_p} = \frac{g_{pnp}}{\sqrt{2} M_N}}$$

Goldberger +Trieman
Phys. Rev. 111 (1958) 354

links strong and weak interactions

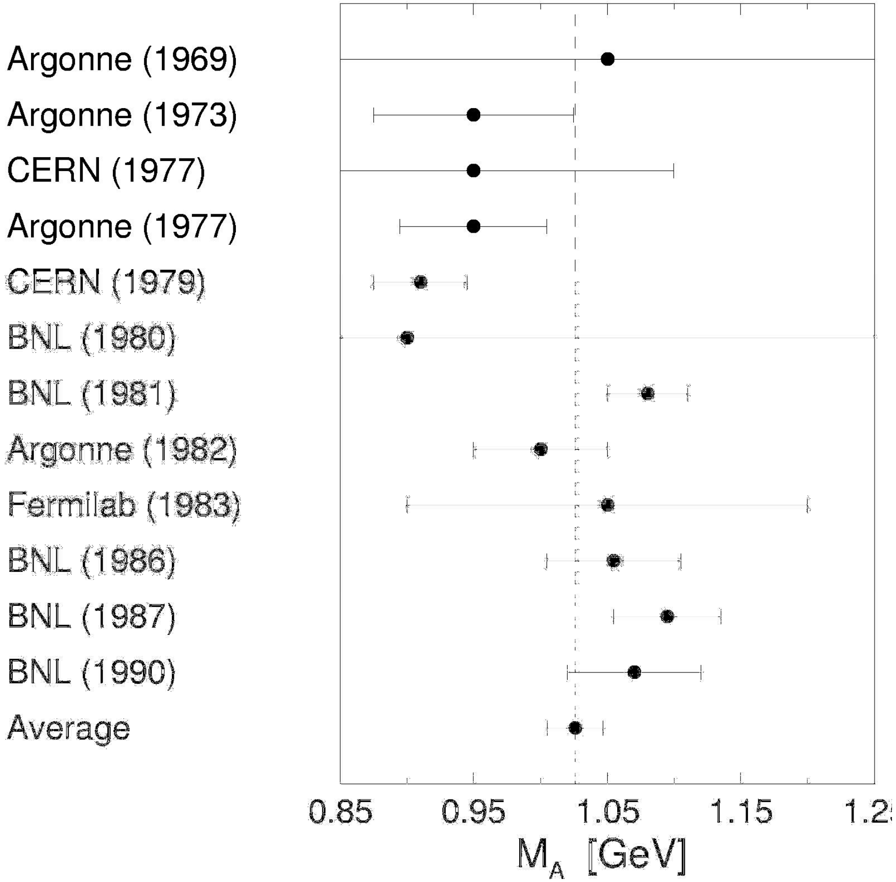
# $Q^2$ dependence of $G_A$

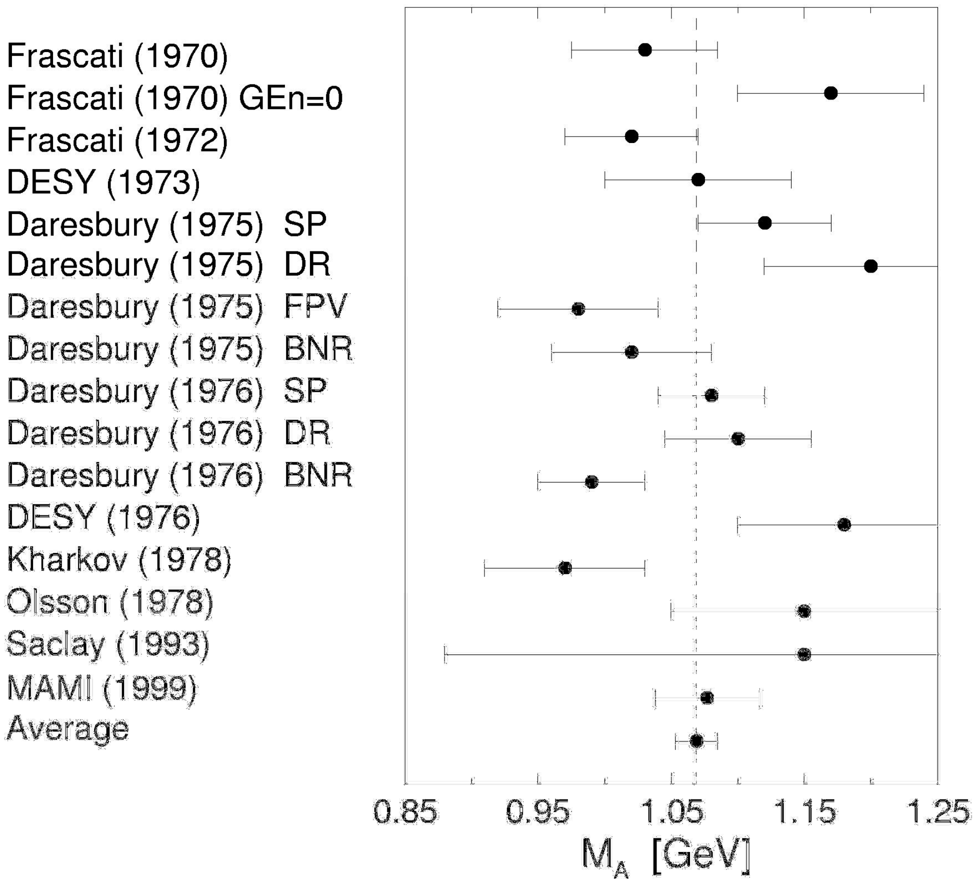
assume
$$G_A(Q^2) = g_A \times \left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$

Liesenfeld etal, PLB (99) 468,
B., E., M., J. Phys. G (02) 28

QE $\nu$-N
$M_A$ = 1.026±0.017 GeV

$p(ee'\pi^+)n$
$M_A$ = 1.068±0.015 GeV



# $M_A$ from $\gamma^* + p \to \pi^+ + n$

$$\frac{ds}{d\Omega_p^*} = \frac{ds_T}{d\Omega_p^*} + e_L^* \frac{ds_L}{d\Omega_p^*}$$

$$E_{0+}^{(-)}(m_p = 0, Q^2) = \frac{eg_A}{8p\, f_p}\left\{1 - \frac{Q^2}{6}\left\langle r_A^2 \right\rangle - \frac{Q^2}{4M_N^2}\left[k_V + \tfrac{1}{2}\right] + O(Q^3)\right\}$$

$$\left\langle r_A^2 \right\rangle = -\frac{6}{g_A}\frac{dG_A}{dQ^2}\bigg|_{Q^2=0} = \frac{12}{M_A^2}$$

$\chi$pt gives correction for finite $m_\pi$ :

$$\left\langle r_A^2 \right\rangle \to \left\langle r_A^2 \right\rangle + \frac{3}{64 f_p^2}\left(1 - \frac{12}{p^2}\right) \quad \Longrightarrow \quad \Delta M_A = 0.055$$

Bernard, Kaiser + Meissner,
PRL 69 (92)1877, PRL 72 (94) 2810.

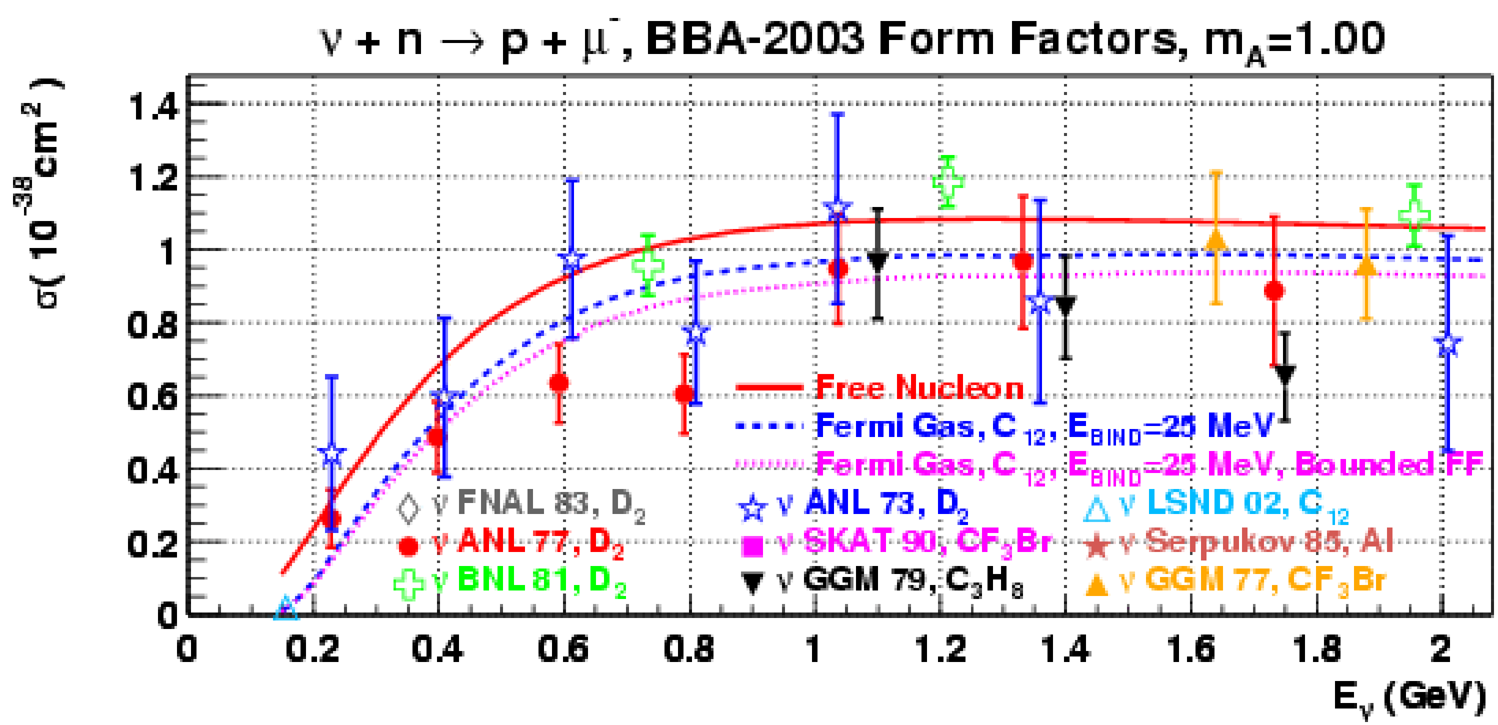
$M_A$ = 1.013 ± 0.015 GeV
agrees well w/ $\nu$ data

# Refit of ν data with updated EM form factors

H. Budd, NuInt02, ‘04 (Budd, Bodek, Arrington, hep-ex/0308005)

| “old”: | “new”: |
| --- | --- |
| $g_A = -1.25$ | $g_A = -1.267$ |
| dipole EM ffs ($G_E^n = 0$) | fitted EM ffs |
| $M_A = 1.026 + 0.020$ | $M_A = 1.001 + 0.020$ |

can change overall normalization of cross sections by several %



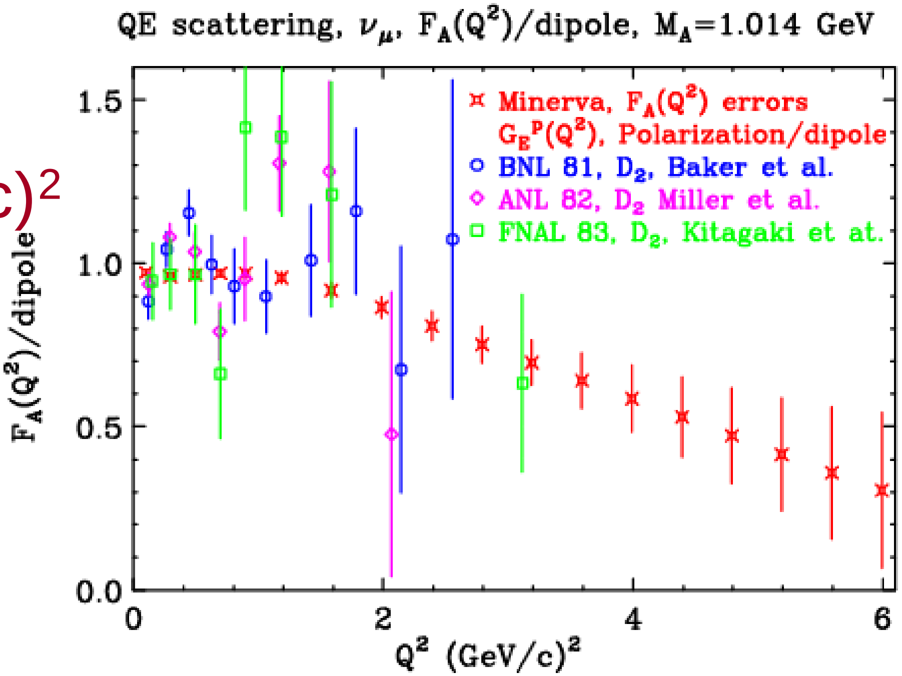
# MINER$\nu$A proposal to measure $G_A(Q^2)$

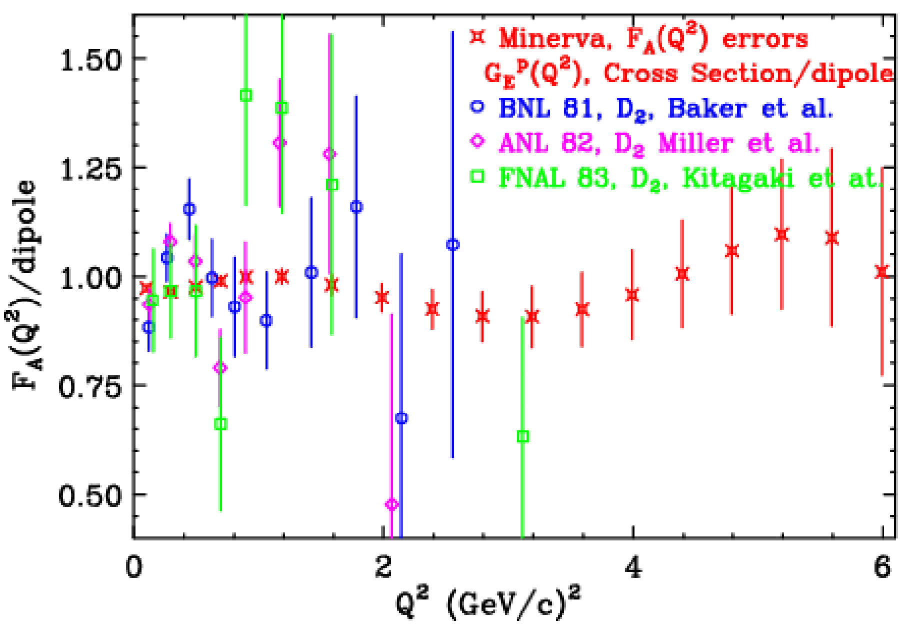
K. McFarland,spokesperson

- high precision at $Q^2 < 2$ (GeV/c)$^2$ (needed for next generation $\nu$-oscillation exps)

- extend determination of $G_A$ to significantly higher $Q^2$ (needed for exps at NUMI)

- can look for deviations from dipole behavior




figures from H. Budd

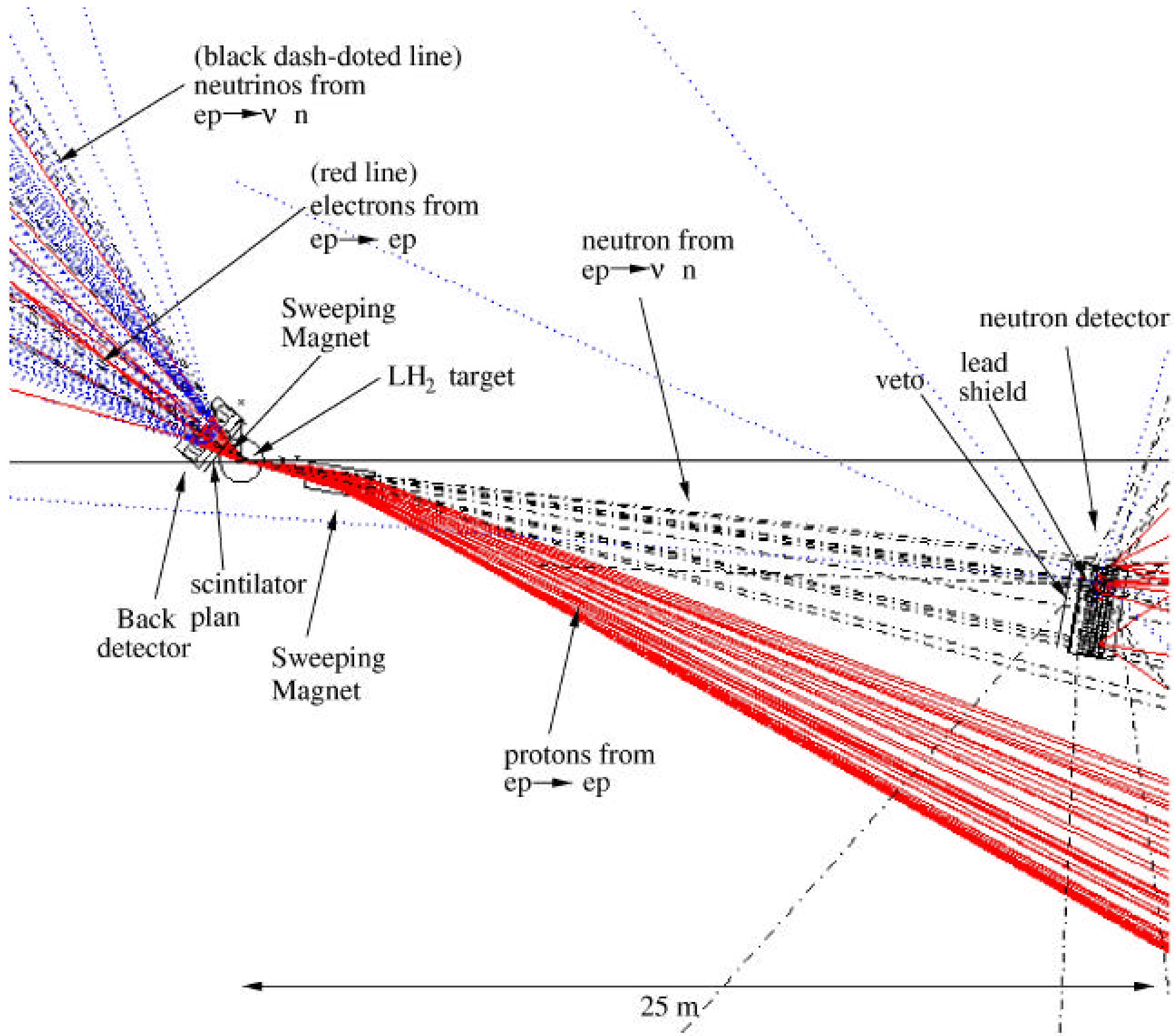
# JLab LOI: $G_A$ using $\vec{e} + p$ ® n + n

get precise (4%) data at $Q^2$ 1-3 $(GeV/c)^2$

detect neutron at forward angles

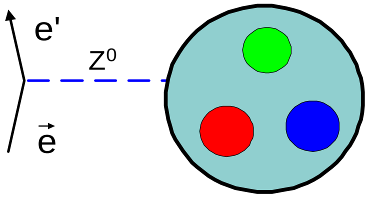
main bckgnd is $\gamma + p \rightarrow n + \pi^+$

measure PV asymmetry to constrain background

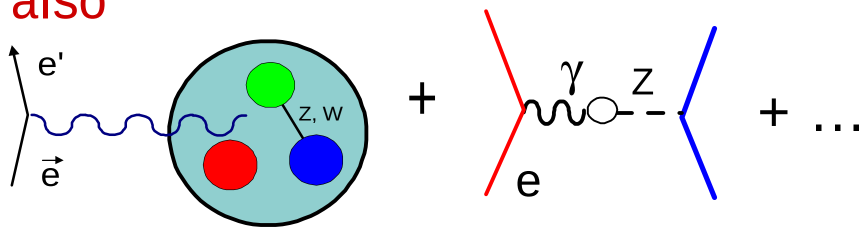


# Axial Coupling and the Anapole Moment

$A_{PV}$ measures



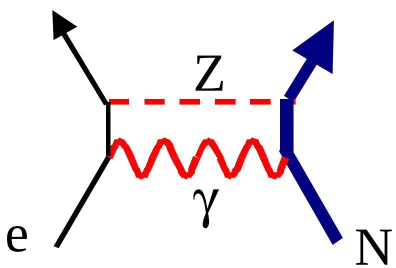

but also




Anapole terms: parity mixing in target wave function

I. Zel'dovich, JETP Lett 33 (1957) 1531

$$G_A^e(Q^2) = -t_3\left(1 + R_A^{T=1}\right)G_A(Q^2) + \sqrt{3}R_A^{T=0}G_A^8(Q^2) + \Delta s$$



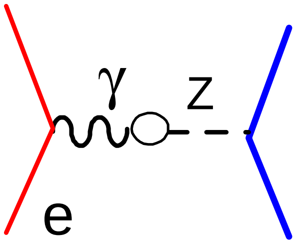

and electroweak radiative corrections

from hyperon decay:

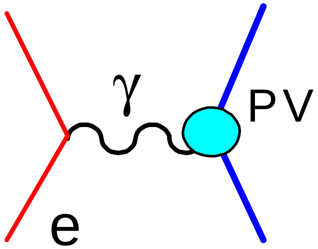
$$G_A^8(0) = 0.217 \pm 0.043$$

best access to $G^e_A$ is quasielastic e-d scattering (T=1 only...)

# “many-quark” corrections to $R_A$



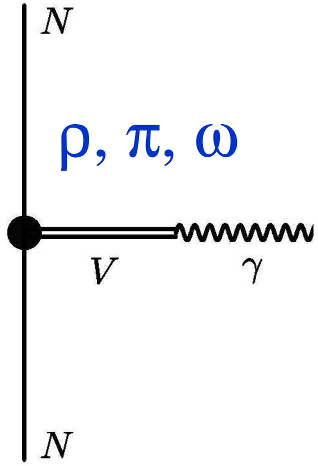

$R_A$ dominated by “1-quark” contributions such as “γ-Z mixing”




Anapole contributions “small” but uncertain.

Zhu etal, PRD 62 (2000) 033008.

HBχPT, cast in terms of hadronic PV couplings.
Also consider K loops (small contribution)




| Source | $R_A^{T=1}$ | $R_A^{T=0}$ |
|---|---|---|
| 1-quark | -0.18 | 0.07 |
| Anapole | -0.06 ± 0.24 | 0.01 ± 0.14 |
| Total | -0.24 ± 0.24 | 0.08 ± 0.14 |

$\overline{\text{MS}}$ scheme ($\sin^2\theta_W = 0.231$)

# $Q^2$ Dependence of $F_A^g$?

See also Riska, NPA 678 (2000) 79

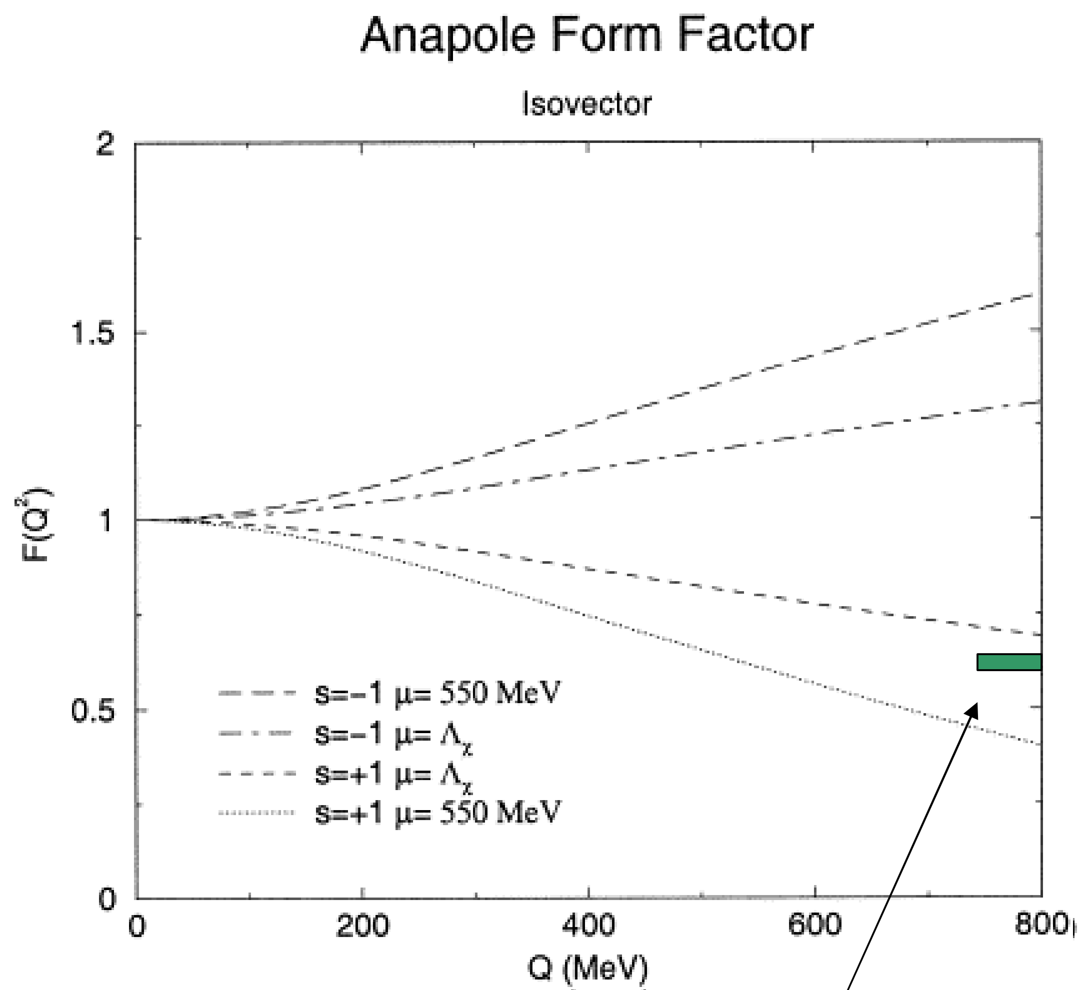
Maekawa, Viega, van Kolck, PLB 488 (2000) 167

$\chi$PT framework

T=0 and T=1 components behave differently

T=0 only at leading order, dominated by pion cloud

T=1 is NLO, mostly "r"-like with some unconstrained constants




"$G_A$" - like

Both are "softer" than $G_A$

# Quasielastic PV (ee') in Deuterium

Use Quasielastic scattering from deuterium as lever arm for $G_A^e$

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

vector s-quark contributions in p and n largely cancel.

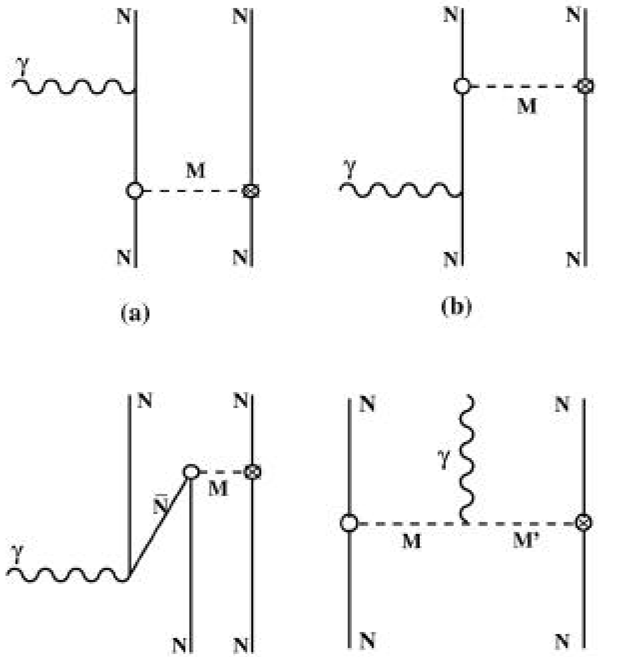
But there is NN physics:

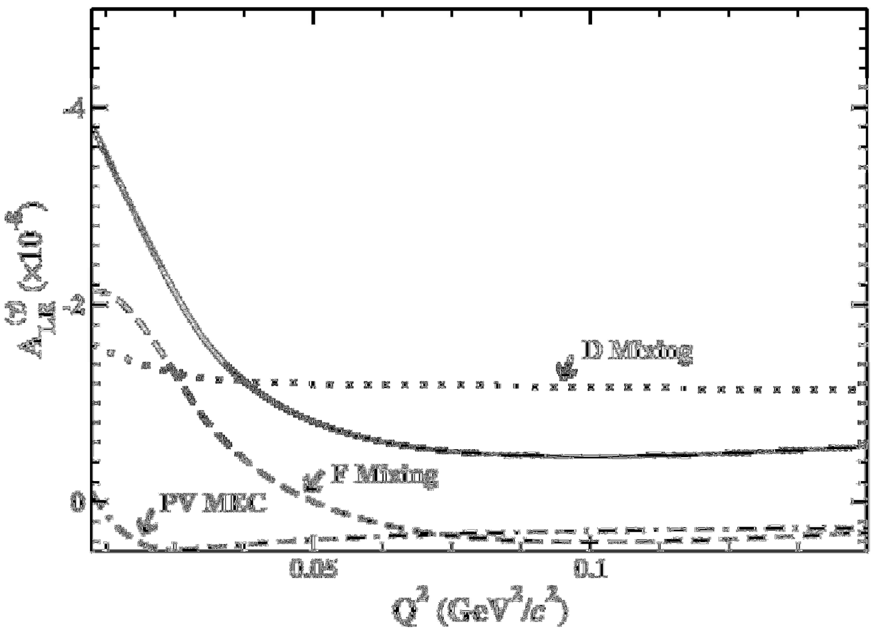
(Parity conserving) nuclear corrections: 1-3% at backward angles
(Diaconescu, Schiavilla + van Kolck, PRC 63 (2001) 044007)

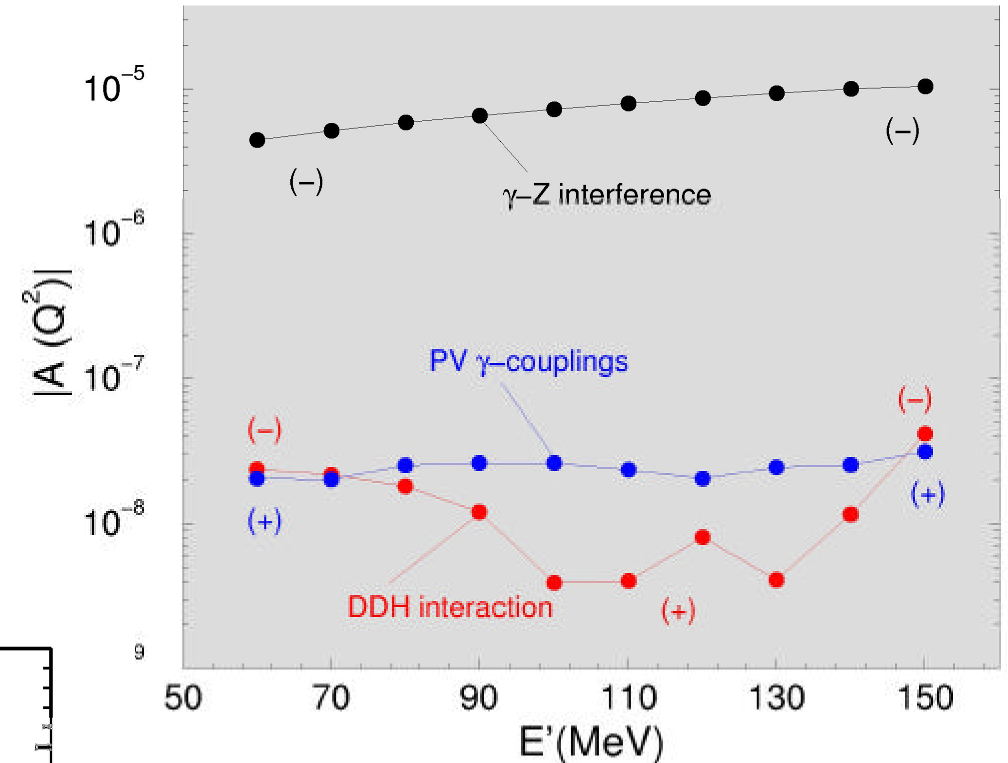
SAMPLE exp: Elastic scattering and threshold breakup:
1-2% correction to $A_{phys}$
elastic very sensitive to $G_M^s$
threshold breakup mildly sensitive to $G_A^e$

*What about parity-violating nuclear corrections?*

# Hadronic PV contributions to the deuteron



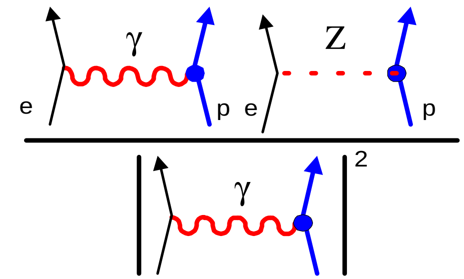



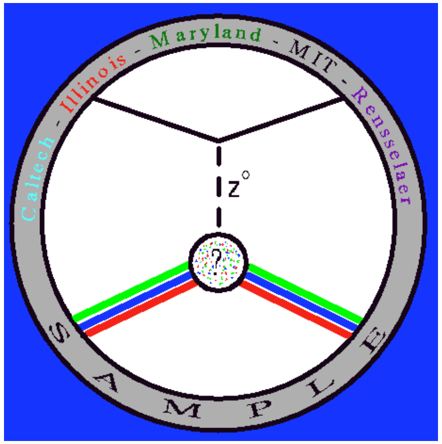




Schiavilla, Carlson + Paris, PRC 67 (2003) 032501

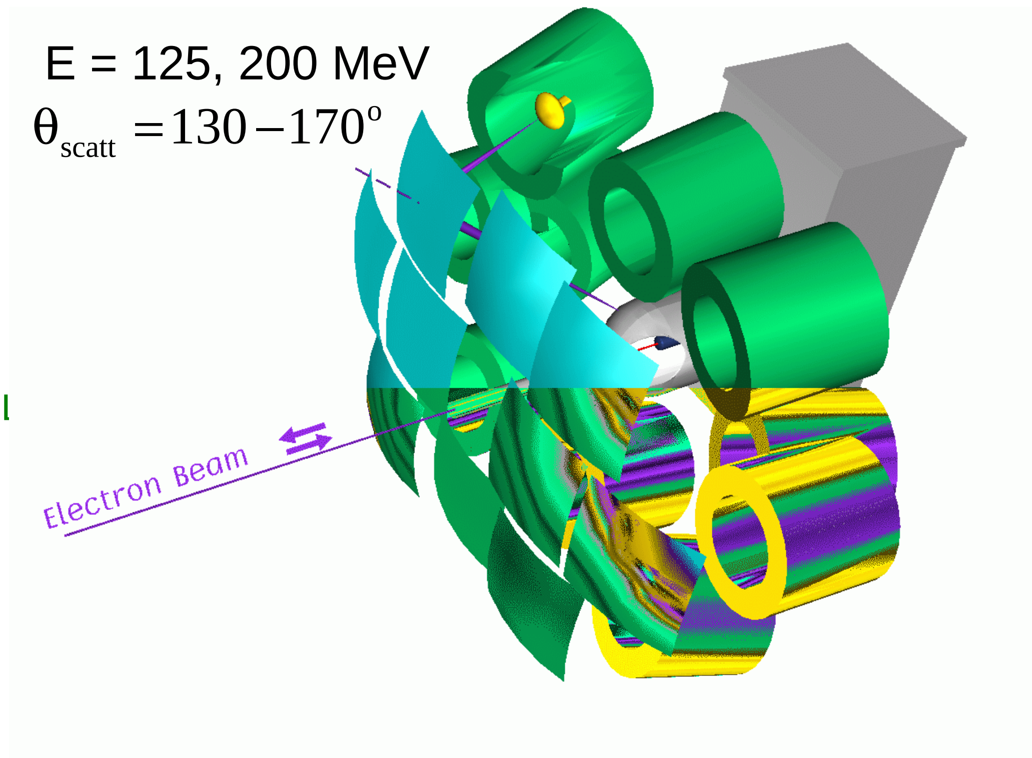
Liu, Prezeau, + Ramsey-Musolf, PRC 67 (2003) 035501

# SAMPLE: Parity Violating Electron Scattering from Hydrogen and Deuterium




Kellogg Radiation Lab, Caltech Pasadena, CA
Nuclear Physics Lab, Univ. of Illinois, Urbana, IL
MIT-Bates Linear Accelerator Center
Univ. of Maryland, College Park, MD
Virginia Polytechnic Institute, Blacksburg, VA
Louisiana Tech, Ralston, LA
University of Kentucky, Lexington, KY
College of William and Mary, Williamsburg, VA
Argonne National Laboratory, Argonne, IL
2001: add MIT, Grenoble




At MIT-Bates linear accelerator
Middleton, MA

$$A = \sum_{i=1}^{10} \frac{Y_i^+ - Y_i^-}{Y_i^+ + Y_i^-}$$

# SAMPLE Experiment Summary

(1998) SAMPLE I: e-p at 200 MeV [$Q^2$ = 0.1 $(GeV/c)^2$]

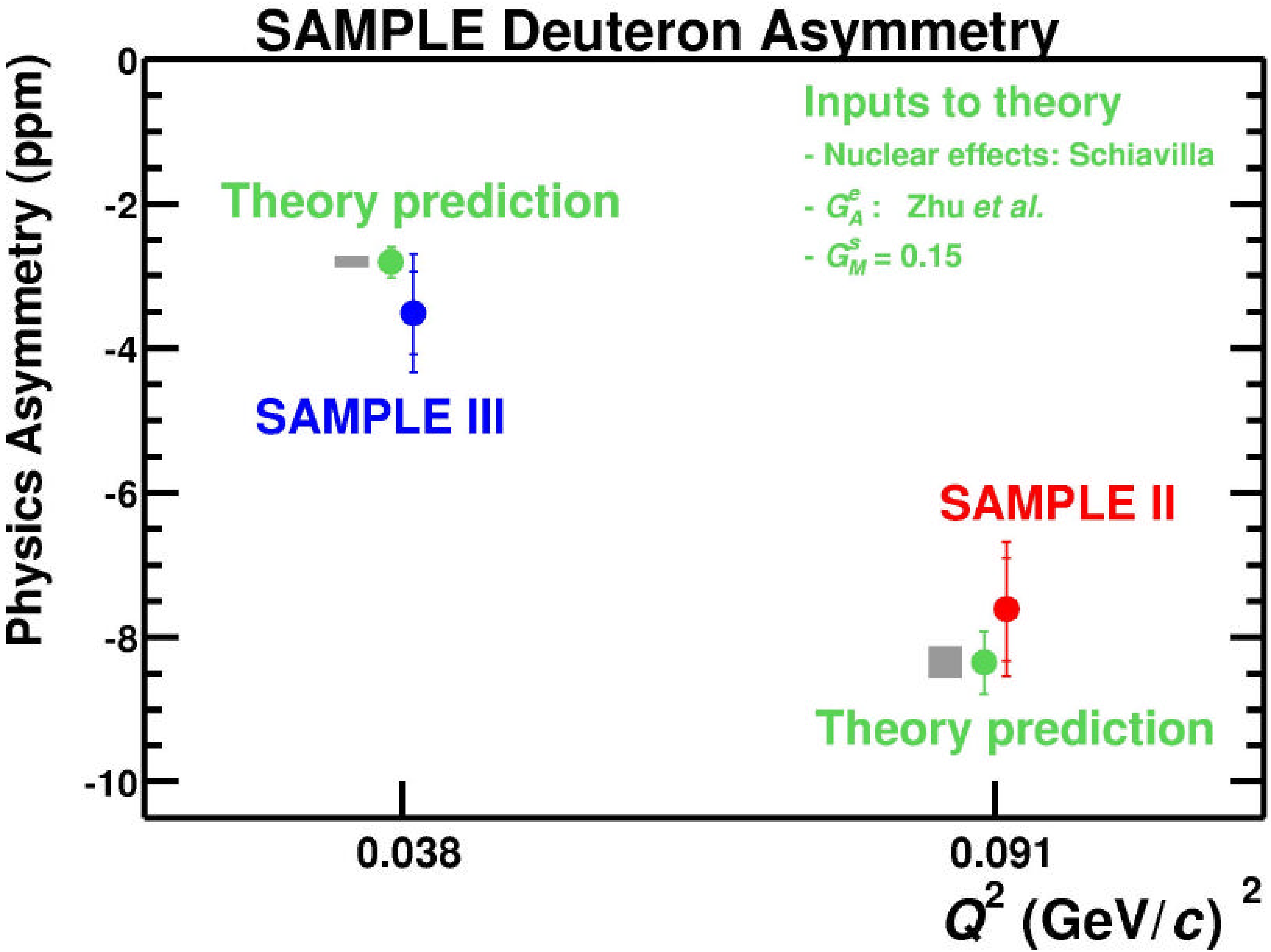
$$A_p = -5.56 + 3.37 G_M^s + 1.54 G_A^{e(T=1)} \ ppm$$

(1999) SAMPLE II: quasielastic e-d at 200 MeV

$$A_d = -7.06 + 0.72 G_M^s + 1.66 G_A^{e(T=1)} \ ppm$$

(2001) SAMPLE III: QE e-d at 120 MeV [$Q^2$ = 0.03 $(GeV/c)^2$]

$$A_d = -2.14 + 0.27 G_M^s + 0.76 G_A^{e(T=1)} \ ppm$$




T. Ito, etal, PRL 92 (2004) 102003

# PV (ee') and e-quark couplings

$$L_{PV}^{e-H} = \frac{G_F}{\sqrt{2}} \times \sum_i \left[ C_{1i}\, \bar{e} g_m g^5 e\, \bar{q} g^m q + C_{2i}\, \bar{e} g_m e\, \bar{q} g^m g^5 q \right]$$

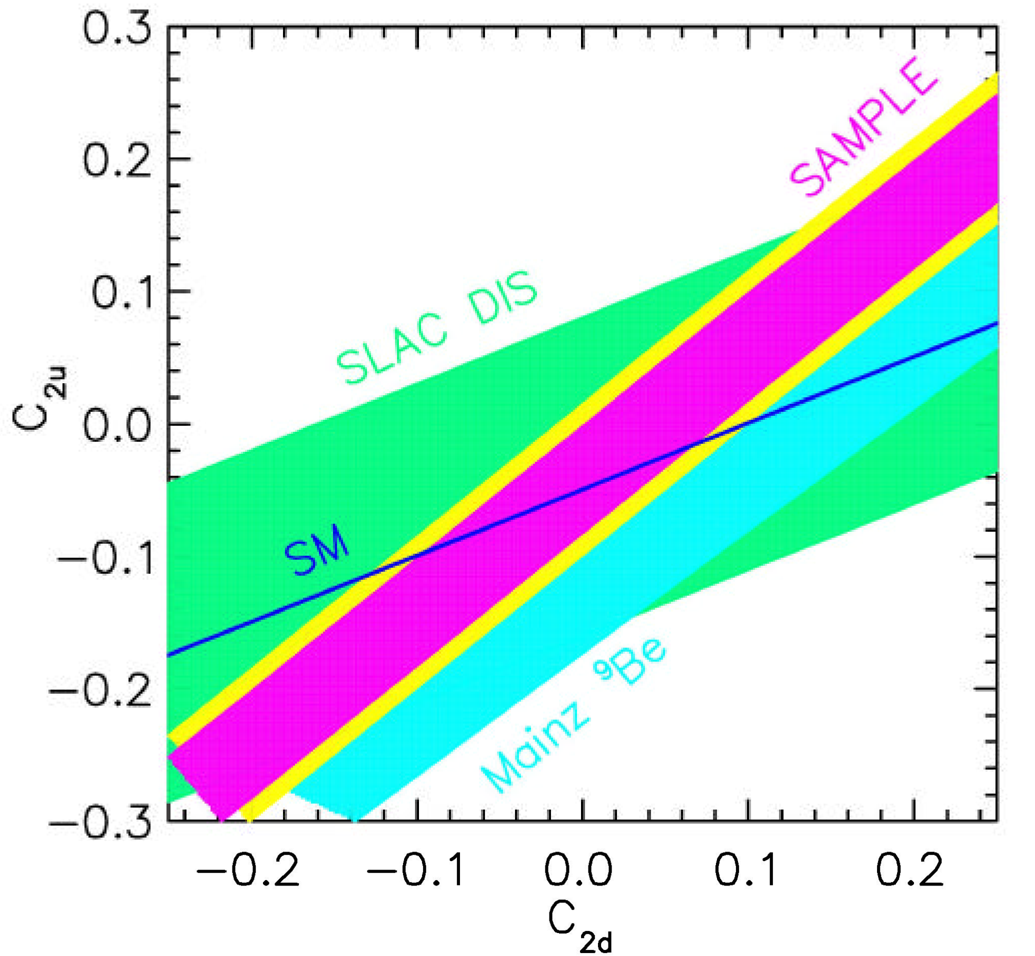
$$C_{2u} = r_{eq}\left(-\tfrac{1}{2} + 2\hat{k}_{eq} \sin^2 q_W\right) + l_{2u}$$
$$C_{2d} = r_{eq}\left(\tfrac{1}{2} - 2\hat{k}_{eq} \sin^2 q_W\right) + l_{2d}$$

$$C_{2u} - C_{2d} = -\frac{G_A^e(T=1)}{G_A^Z(Q^2)}\left(1 - 4\sin^2 q_W\right)$$

PDG: -0.062

SAMPLE II:
-0.042± 0.040 ± 0.035 ± 0.020

SAMPLE III:
-0.12 ± 0.05 ± 0.05 ± 0.022
(stat) (sys) (hadronic)

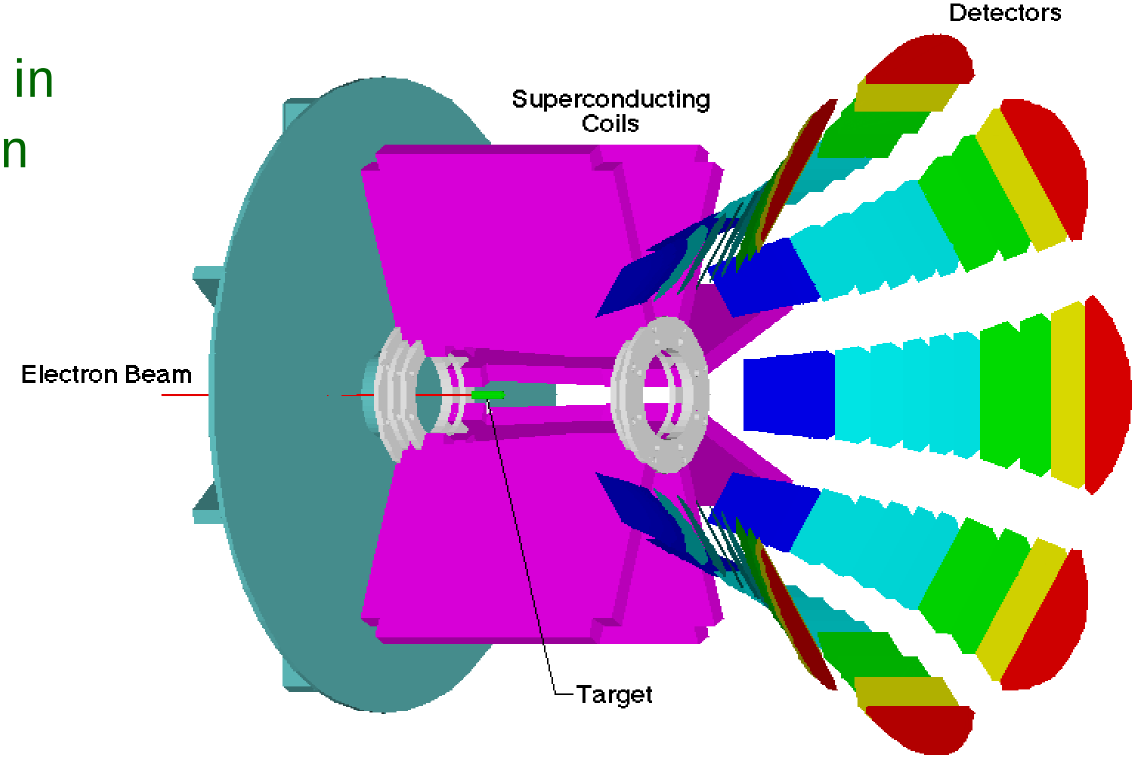


# The G0 experiment at JLAB

- Forward and backward angle PV e-p elastic and e-d (quasielastic) in JLab Hall C

$G_E^s, G_M^s$ and $G_A^e$ separated over range $Q^2 \sim 0.1 - 1.0\ (\mathrm{GeV/c})^2$

- superconducting toroidal magnet
- scattered particles detected in segmented scintillator arrays in spectrometer focal plane
- custom electronics count and process scattered particles at > 1 MHz
- *first engineering run 2002*
- *first data taking early 2004*



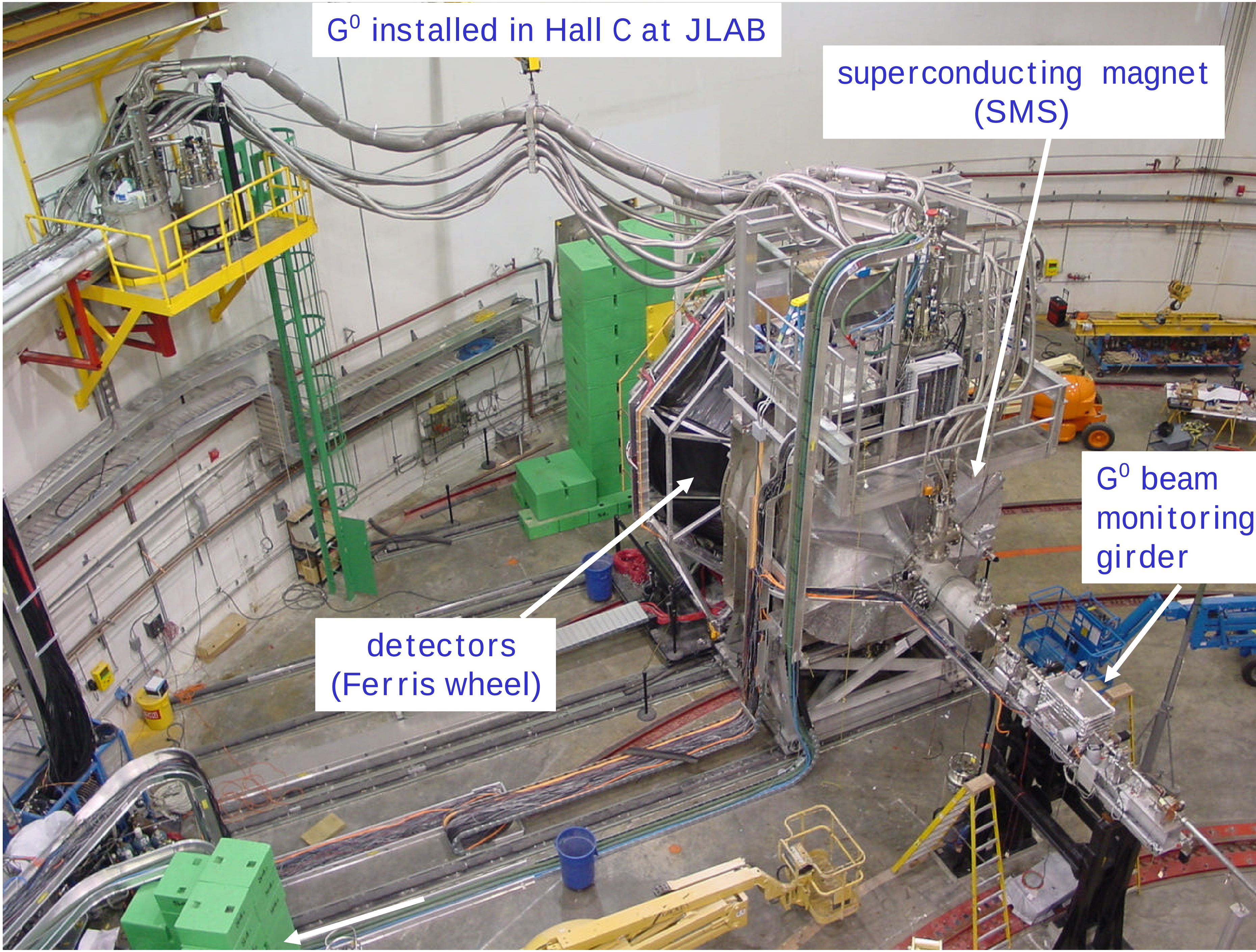
# G0 elastic scattering program

$A_F$ : one measurement for all $Q^2$ $\rightarrow$ detect recoil protons
$A_B$ : three measurements for three $Q^2$ values: $\rightarrow$ detect electrons at 108°
$A_d$ : Quasielastic scattering (x3) from deuterium $\rightarrow$ detect electrons at 108°

$$\begin{pmatrix} A_F \\ A_B \\ A_d \end{pmatrix} = \begin{pmatrix} x_F & c_F & y_F \\ x_B & c_B & y_B \\ x_d & c_d & y_d \end{pmatrix} \begin{pmatrix} G_E^s \\ G_M^s \\ G_A^e \end{pmatrix} + \begin{pmatrix} h_F \\ h_B \\ h_d \end{pmatrix}$$

at $Q^2 = 0.44\ (\mathrm{GeV/c})^2$

| | η (ppm) | ξ (ppm) | χ (ppm) | ψ (ppm) |
|---|---|---|---|---|
| $A_F$ | -13.77 | 51.80 | 18.63 | 1.01 |
| $A_B$ | -25.01 | 16.10 | 31.41 | 6.96 |
| $A_d$ | -34.00 | 13.13 | 7.07 | 8.41 |


G$^0$ installed in Hall C at JLAB
superconducting magnet (SMS)
G$^0$ beam monitoring girder
detectors (Ferris wheel)

# G0 Backward Angle

Electron detection: one $Q^2$ per magnet setting: $\theta$ = 108°

E = 424, 576, 799 MeV: $Q^2$ = 0.3, 0.5, 0.8 $(\mathrm{GeV/c})^2$

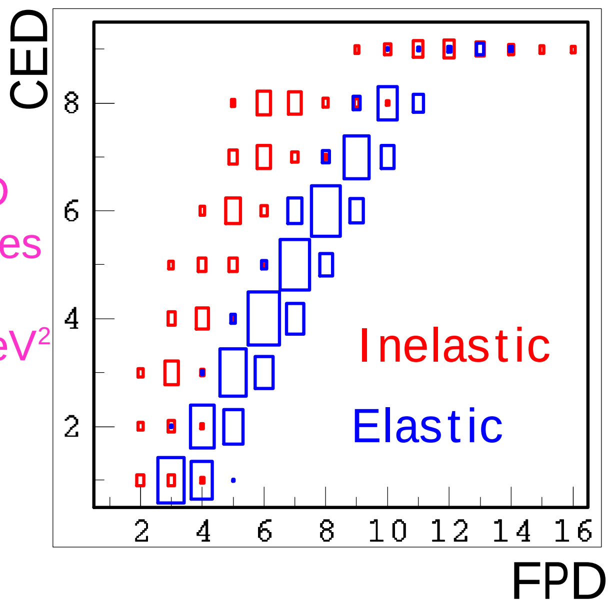
for both $LH_2$ and $LD_2$ targets (total of 6 runs x 700 hours)

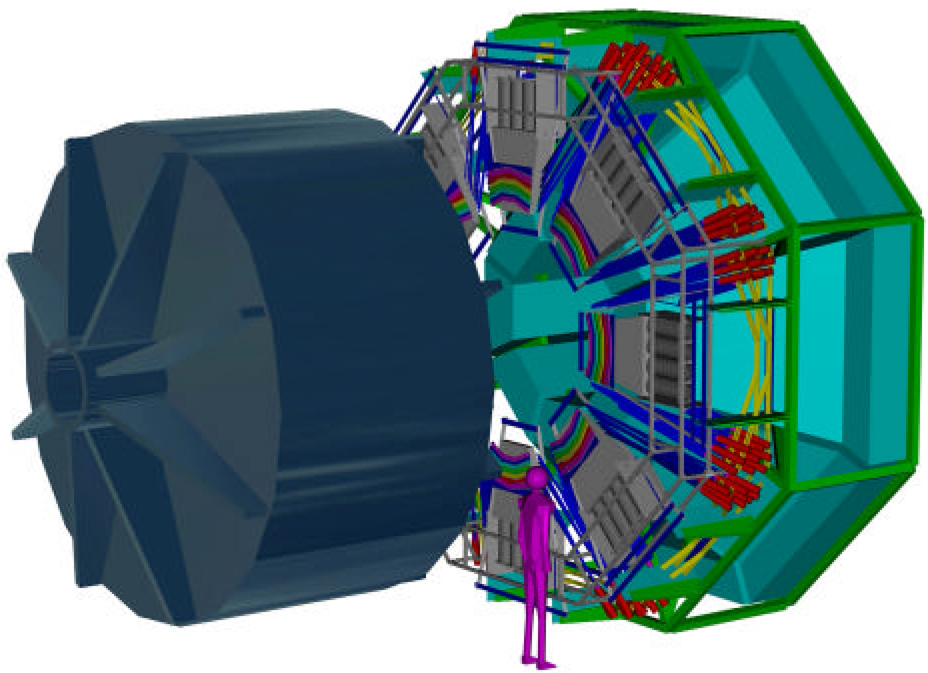
Add Cryostat Exit detectors to define electron trajectory

1 scaler per channel FPD/CED pair

Deuterium: pion rejection required $\rightarrow$ Aerogel Cerenkov detector

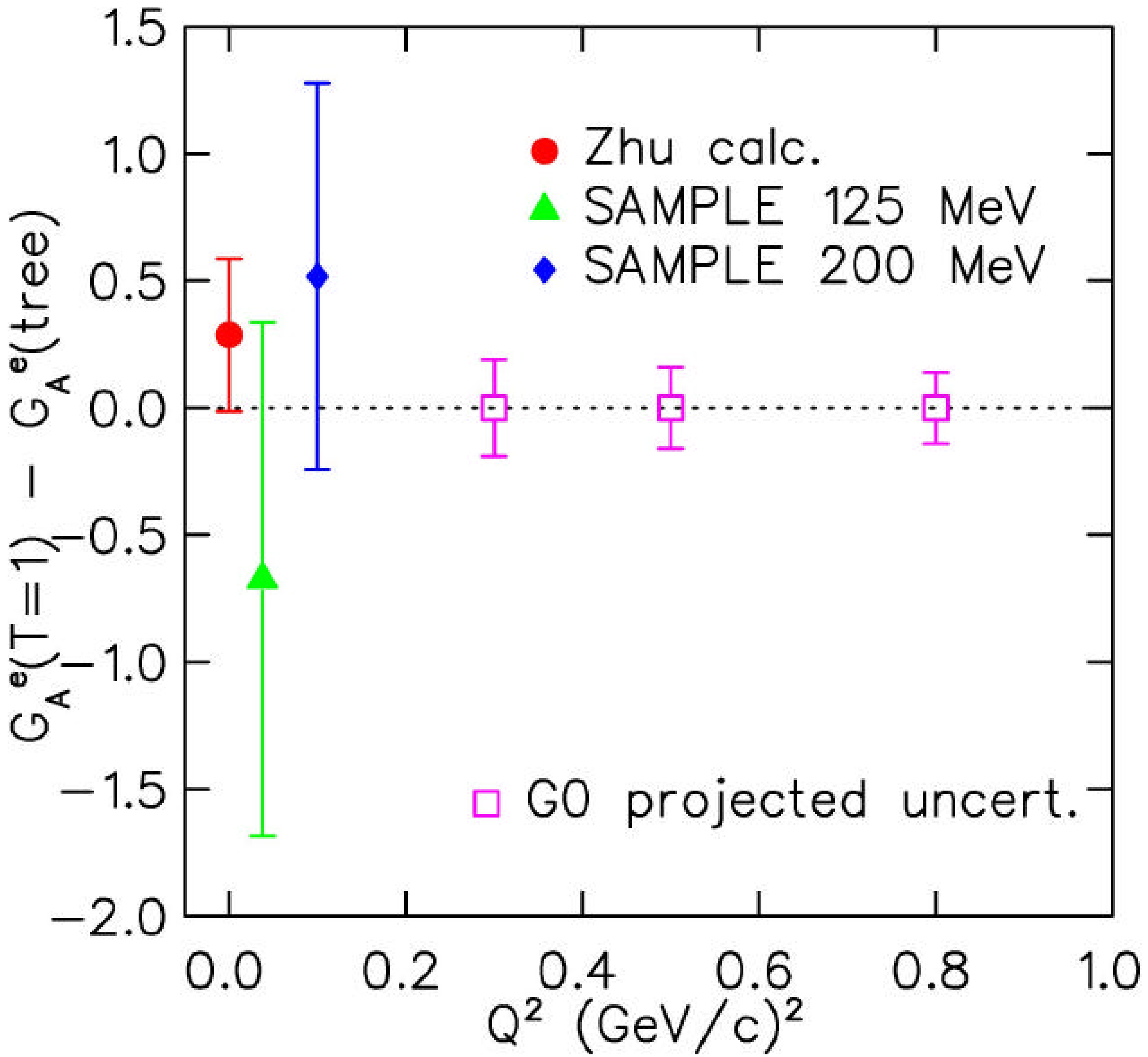
CED/FPD coincidences at $Q^2$ = 0.3 GeV$^2$



# G0 determination of $G_A^e(Q^2)$

$G_A^e$ (tree) is what ν-scattering sees (T=1 only)



# Summary

PV electron scattering experiments are beginning to provide access to spatial distribution of nucleon's strange quark sea.

Information about the axial coupling of an electron to a nucleon is necessary input. $0^{th}$-order contribution has been well-determined from ν-N scattering and p electroproduction (better data key for next gen. neutrino oscillation exps).

Axial ff as seen by electron has additional, uncertain, anapole contributions. First measurements from SAMPLE (low $Q^2$) in good agreement w/ calculation, but not much known yet about $Q^2$ dependence.

G0 program w/ deuterium can put constraints on $Q^2$ dependence.

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