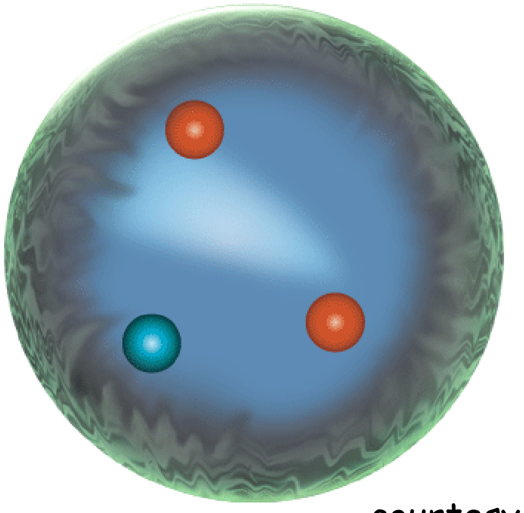
What's new in Parity-Violating e-p scattering?

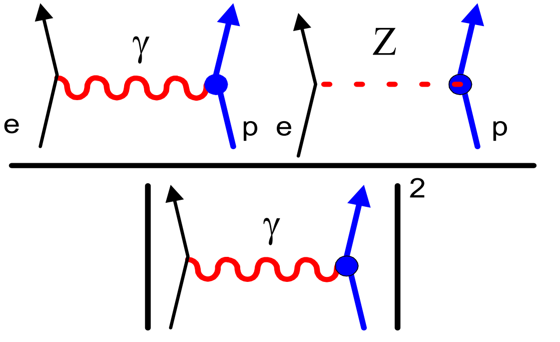
E. Beise
University of Maryland
on leave at National Science Foundation



courtesy of JLab

New results on strangeness

Future opportunities
- precision tests of Standard Model
- new possibilities in hadron structure



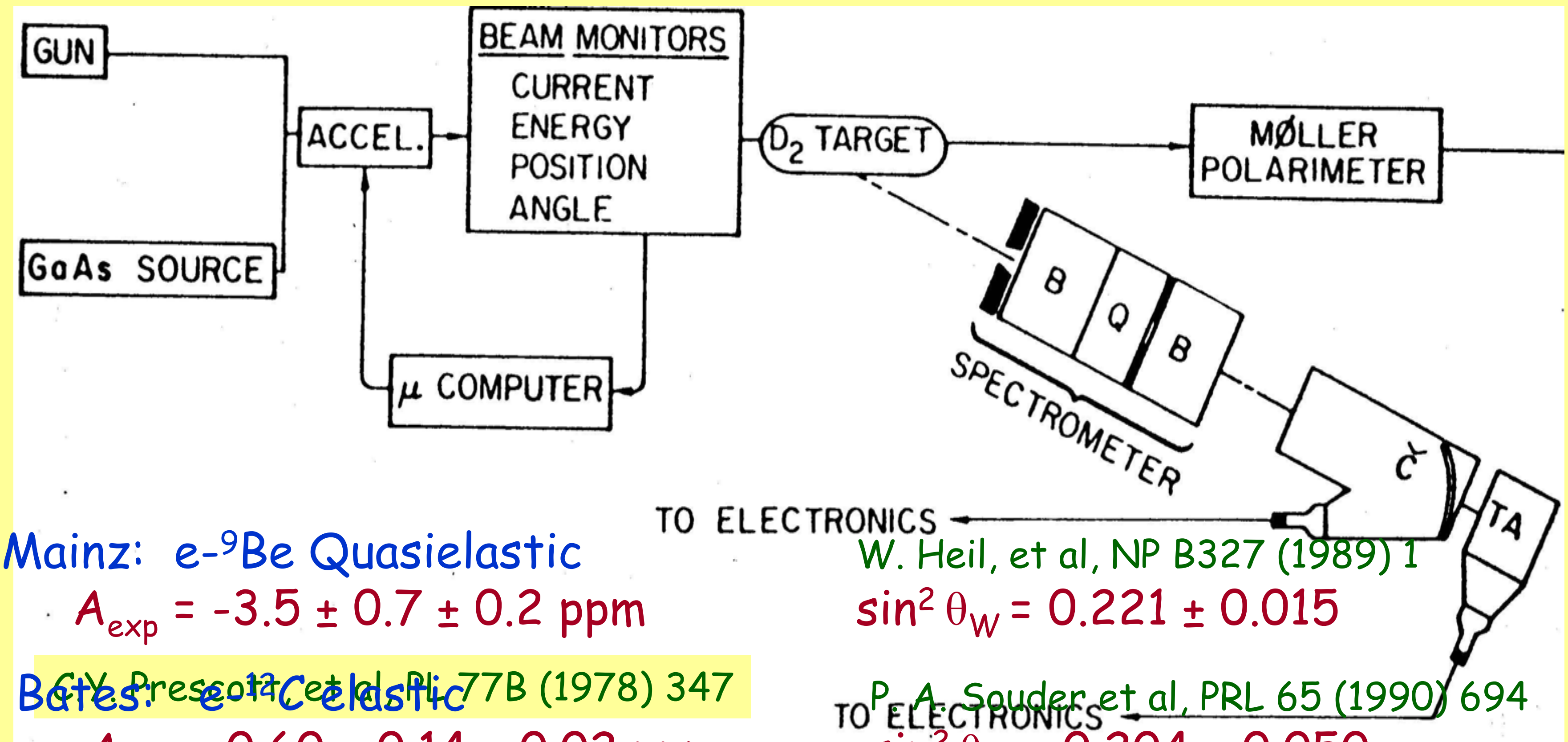
Support from U.S. NSF and DOE gratefully acknowledged

Parity Violating Electron-Nucleon Scattering

SLAC: e + d (DIS) E=16-22 GeV, Q^2 1.6 GeV^2

$A/Q^2 \sim -95 \pm 16$ ppm $\sin^2\theta_W = 0.20 \pm 0.03$

C.Y. Prescott, et al, PL 77B (1978) 347



Mainz: e-^{9}Be Quasielastic

$A_{exp} = -3.5 \pm 0.7 \pm 0.2$ ppm

W. Heil, et al, NP B327 (1989) 1

$\sin^2\theta_W = 0.221 \pm 0.015$

Bates: e-^{12}C elastic

$A_{exp} = 0.60 \pm 0.14 \pm 0.02$ ppm

P. A. Souder et al, PRL 65 (1990) 694

$\sin^2\theta_W = 0.204 \pm 0.050$

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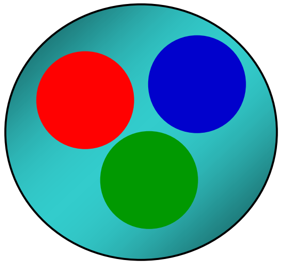
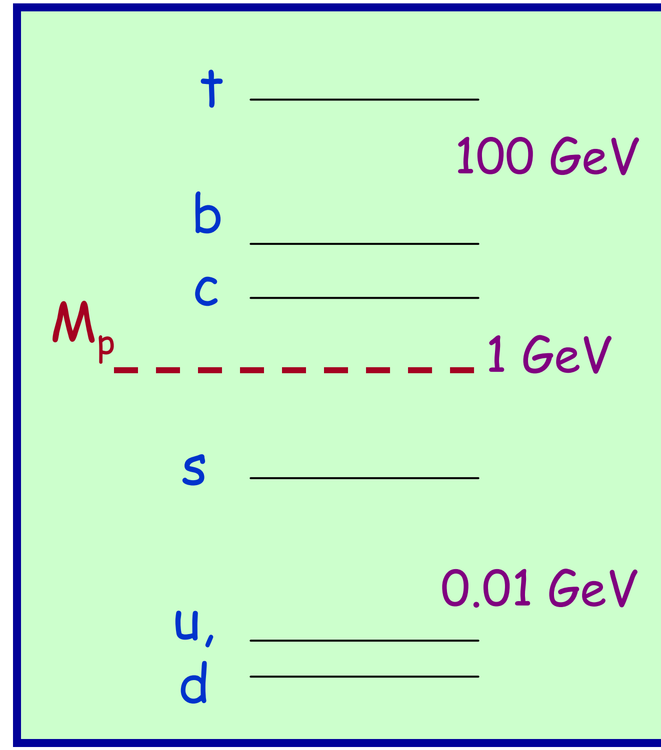
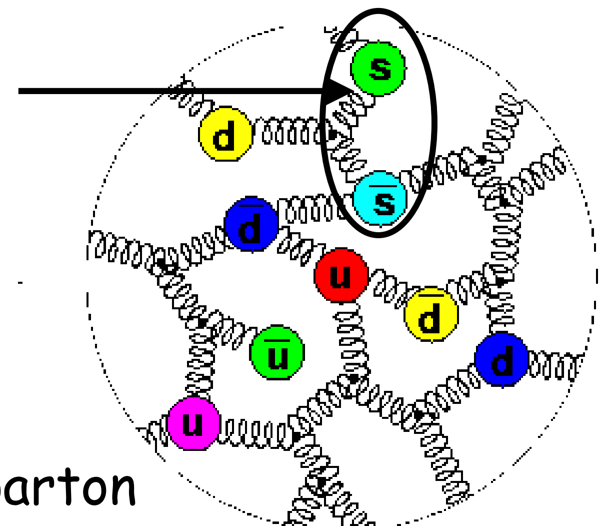
Views of the Nucleon



quark model

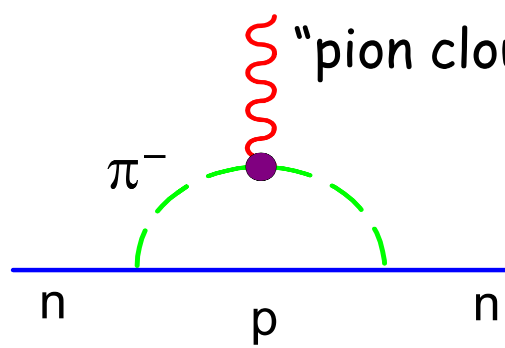


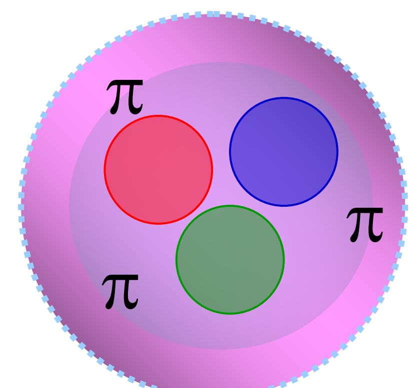
look explicitly at strange quarks



QCD/parton description

"pion cloud"





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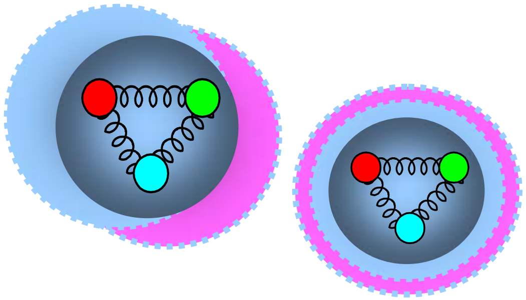
Spatial distribution of s-quarks in the nucleon



Access via form factors: contribution to nucleon charge and magnetism

Electromagnetic:

$$G \rightarrow \langle N | \sum e_q \bar{q} \Gamma_\mu q | N \rangle$$

$$G^{\gamma,p} = \frac{2}{3} G^{u,p} - \frac{1}{3}\left(G^{d,p} + G^{s,p}\right)$$

and use

$$G^{u,p} = G^{d,n}$$
$$G^{d,p} = G^{u,n}$$
$$G^{s,p} = G^{s,n}$$

} charge symmetry

e.g. G. Miller, PRC 57 (98) 1492

	EM charge	Weak charge
e	-1	$-1 + 4\sin^2\theta_W$
u	$+2/3$	$1 - 8/3\sin^2\theta_W$
d	$-1/3$	$-1 + 4/3\sin^2\theta_W$
s	$-1/3$	$-1 + 4/3\sin^2\theta_W$

$$G^{u,p}_{E,M} = \left(3 - 4\sin^2\theta_W\right) G^{\gamma,p}_{E,M} - G^{Z,p}_{E,M}$$
$$G^{d,p}_{E,M} = \left(2 - 4\sin^2\theta_W\right) G^{\gamma,p}_{E,M} - G^{\gamma,n}_{E,M} - G^{Z,p}_{E,M}$$
$$G^{s,p}_{E,M} = \left(1 - 4\sin^2\theta_W\right) G^{\gamma,p}_{E,M} - G^{\gamma,n}_{E,M} - G^{Z,p}_{E,M}$$

$$\sin^2\theta_W = 0.2312 \pm 0.00015$$

what might be expected?

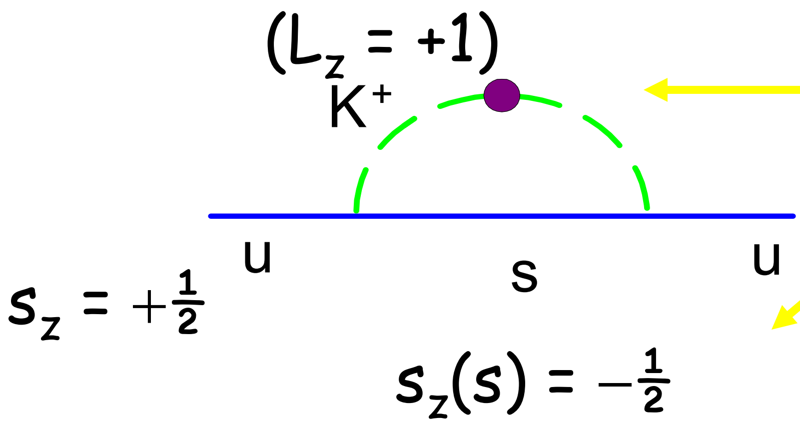
$$\mu_s = G_M^s(0)$$

$$\rho_s = \left.\frac{dG_E^s(\tau)}{d\tau}\right|_{\tau=0} = 4M_N^2 \left.\frac{dG_E^s(Q^2)}{dQ^2}\right|_{Q^2=0}$$

and

$$\mu_p = \tfrac{2}{3}\mu_u - \tfrac{1}{3}\mu_d - \tfrac{1}{3}\mu_s = 2.79$$

If μ_s is negative, then s and sbar would make (+) overall contribution to μ_p.



Hannelius, Riska + Glozman, Nucl. Phys. A 665 (2000) 353

(Jaffe convention): positive charge radius $\rightarrow$ negative ρ_s

$\rightarrow$ $G_E^s < 0$ $\rightarrow$ s-quark on the outside (on average)

see R. Jaffe, PLB 229 (1989) 275
or Geiger & Isgur, PRD 55 (1997) 299

Lattice QCD "inspired" prediction

Leinweber etal, PRL 94, 212001 (2005)

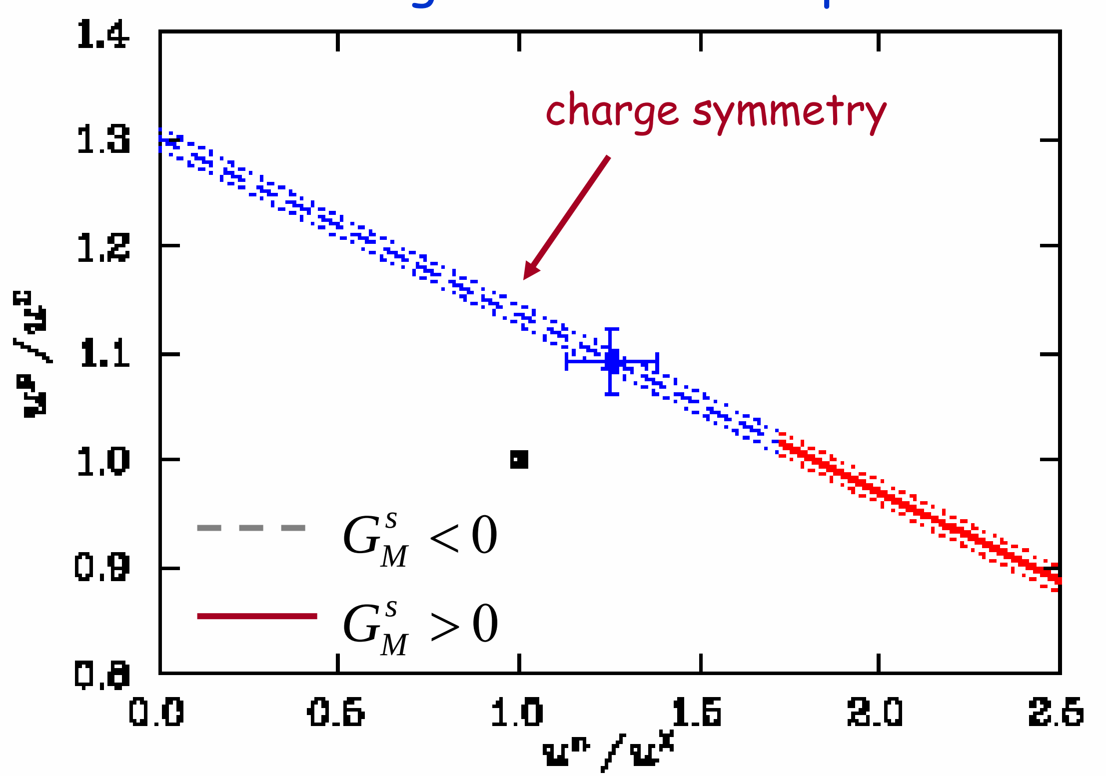
"...challenge for future experiments"

Combine (quenched) lattice calcs. + chiral extrapolation

Compute valence quark contributions to baryon magnetic moments: environment sensitivity

result: s-quarks in μ_p must be small and (–)

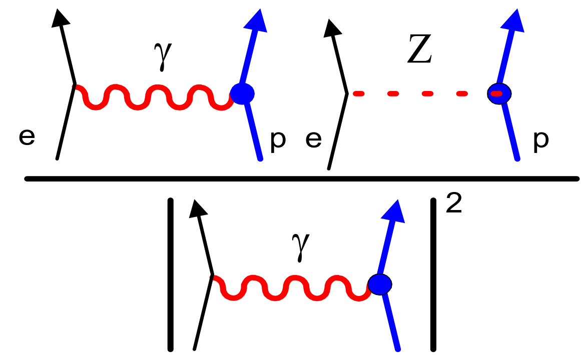
$$G_M^s(0) = -0.046 \pm 0.019$$



assumes "disconnected loops" are purely isoscalar...

Parity Violating elastic e-N scattering

polarized electrons, unpolarized target



$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right] \frac{A_E + A_M + A_A}{2\sigma_{unpol}}$$

forward →

backward →

$$A_E = \varepsilon(\theta) G_E^Z G_E^\gamma$$

$$A_M = \tau G_M^Z G_M^\gamma$$

$$A_A = -(1 - 4\sin^2\theta_W)\varepsilon' G_A^e G_M^\gamma$$

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

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

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

Neutral Weak ffs contain explicit contributions from strange sea

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

$$G_A^e(Q^2) = -G_A^Z + (\eta F_A^\gamma + R^e) + \Delta s$$

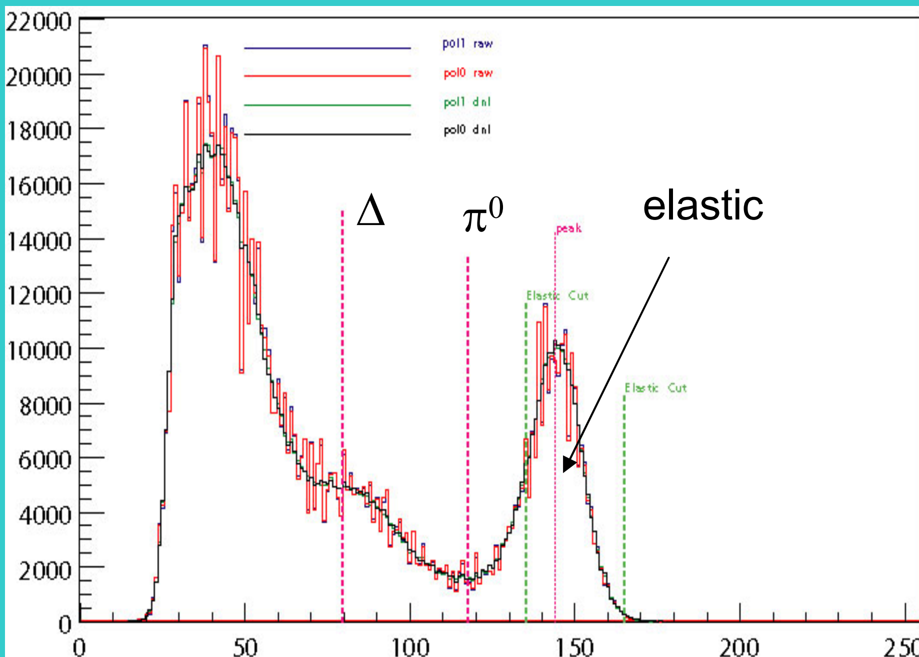
$$\eta = \frac{8\pi\alpha\sqrt{2}}{1 - 4\sin^2\theta_W} = 3.45$$

$G^Z_A(0) = 1.2695 \pm 0.0035$ (from β decay)

E. Beise, U Maryland/NSF

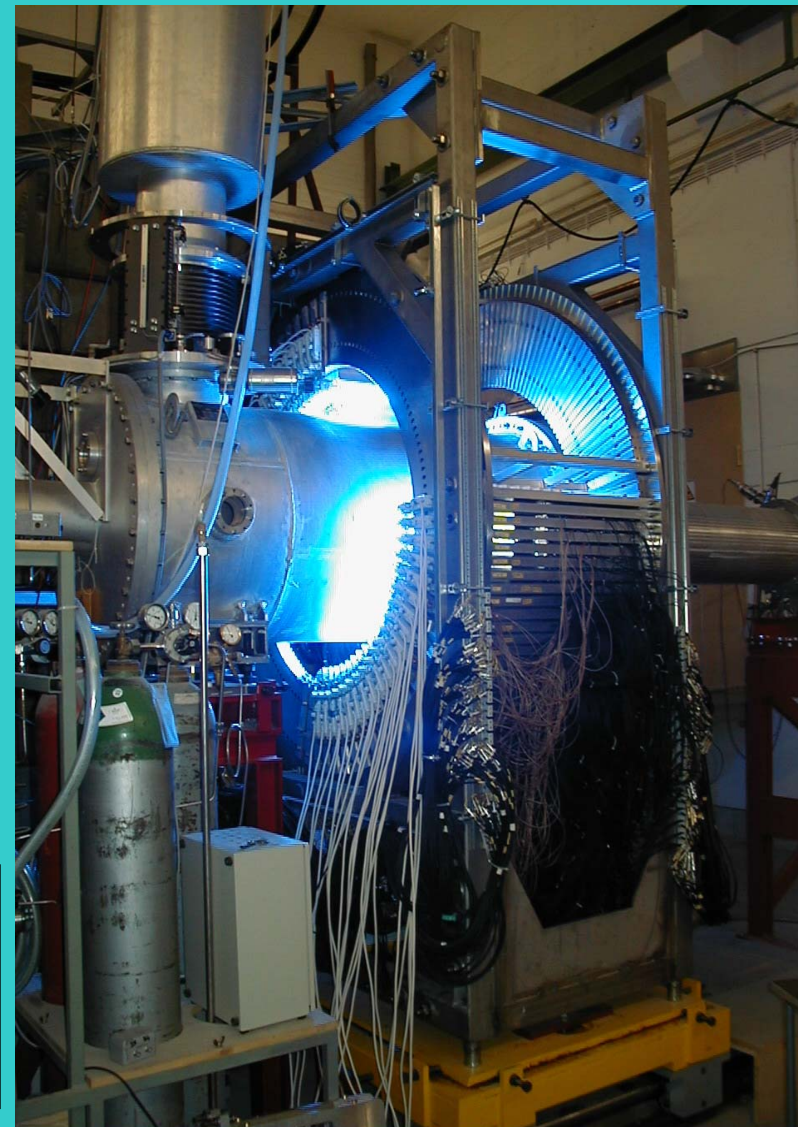
Experiments before 2005

PV-A4 at Mainz



$$\mathrm{I:}\ A_{\mathrm{exp}} = -5.6 \pm 0.6 \pm 0.2\,\mathrm{ppm}$$

$$\mathrm{II:}\ A_{\mathrm{exp}} = -1.36 \pm 0.29 \pm 0.13\,\mathrm{ppm}$$



2004 Summary of experiments

SAMPLE: $Q^2 = 0.1\ GeV^2$

$$G_M^s = 0.37 \pm 0.20 \pm 0.26 \pm 0.07$$

HAPPEX I: $Q^2 = 0.48$

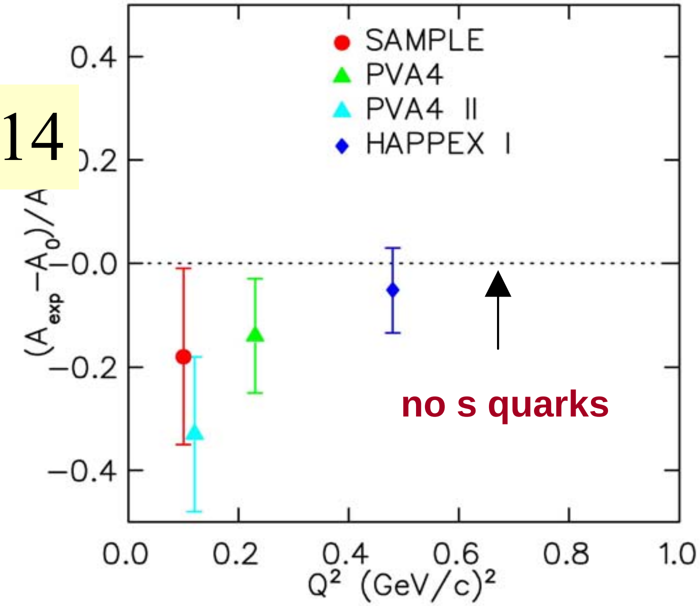
$$G_E^s + 0.39\, G_M^s = 0.025 \pm 0.020 \pm 0.014$$

PVA4 I: $Q^2 = 0.24$

$$G_E^s + 0.225\, G_M^s = 0.039 \pm 0.034$$

PVA4 II: $Q^2 = 0.1$

$$G_E^s + 0.106\, G_M^s = 0.071 \pm 0.036$$



new:

HAPPEX II/He: $Q^2 = 0.1$, $\theta = 6^\circ$

G0 FORWARD MODE: $0.1 < Q^2 < 1.0\ GeV^2$

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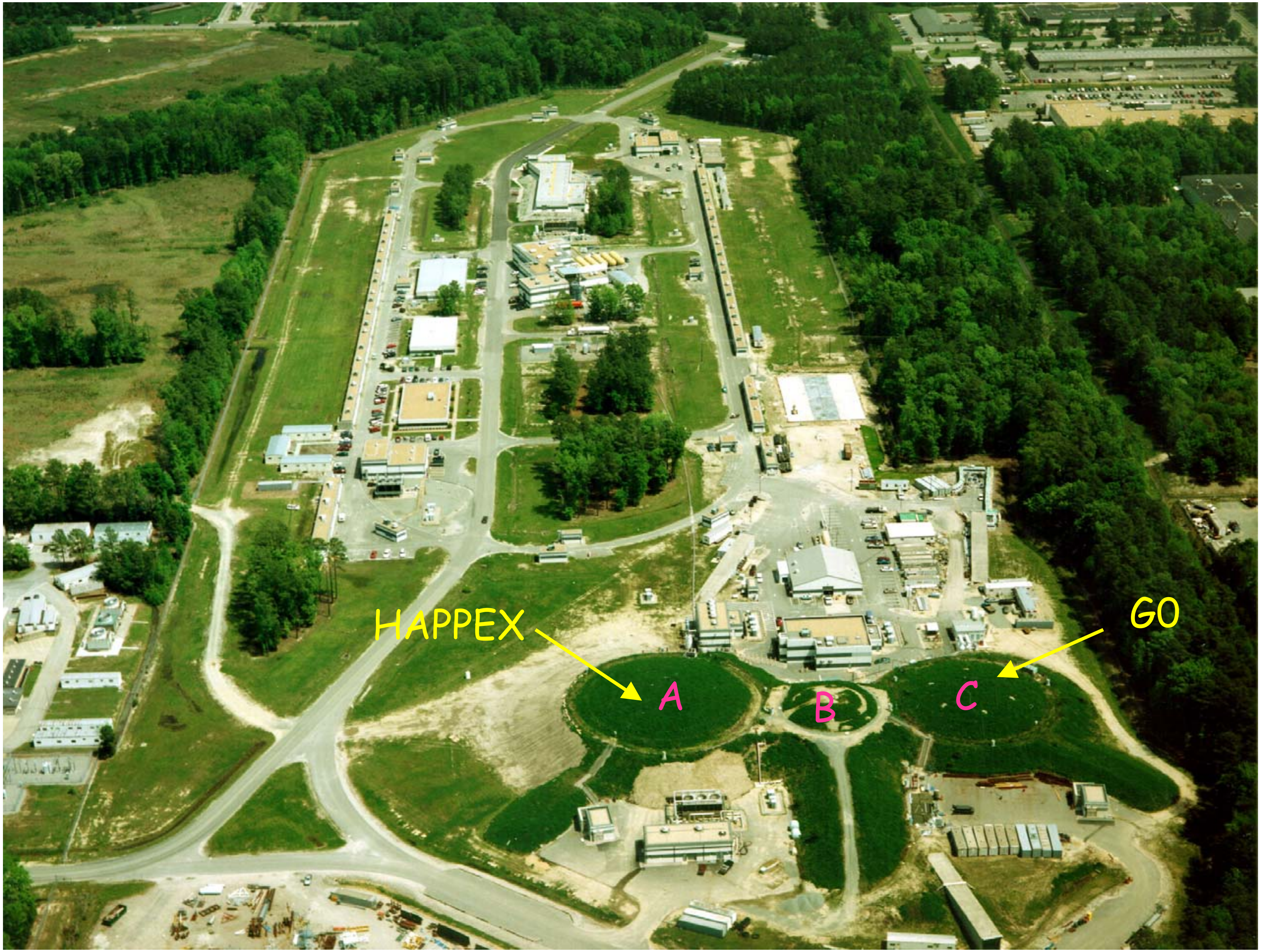
The Jefferson Laboratory experiments, 2005



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JLab "Parity-Quality" beam

G0 beam:
- strained GaAs (P_B ~ 73%)
- 32 ns pulse spacing
- 40 μA beam current

HAPPEX-II beam:
- superlattice (P_B > 85%)
- 2 ns pulse spacing
- 35 μA beam current

Beam Parameter	G0 beam	HAPPEX beam
Charge asymmetry	**-0.14 ± 0.32 ppm**	**-2.6 ± 0.15 ppm**
Position diff	**4 ± 4 nm**	**-8 ± 3 nm**
angle diff	**1.5 ± 1 nrad**	**4 ± 2 nrad**
Energy diff	**29 ± 4 eV**	**66 ± 3 eV**
Total correction to Asymmetry	**-0.02 ± 0.01 ppm**	**0.08 ± 0.03 ppm**

HAPPEX II: H & He targets

3

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	$\delta(G^s_E) = 0.015$

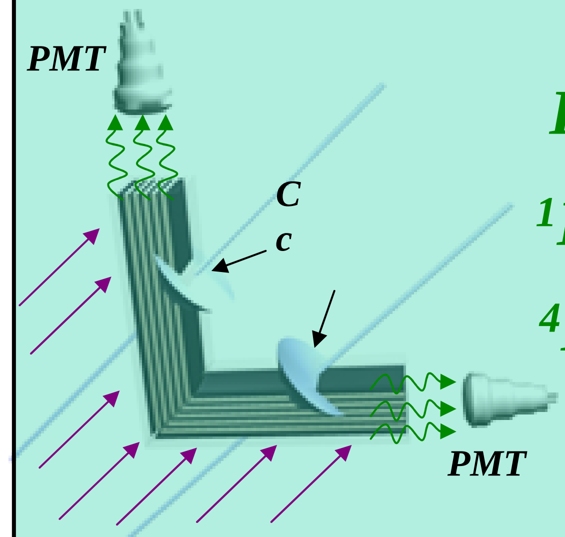
Uses Hall A spectrometers

- new septum magnets (6°)
- new superlattice crystals (P_B = 85-89%)
- Compton polarimetry

+ other improvements

First run data summer 2004,
To be completed starting Jul 05

Brass-Quartz integrating detector



Elastic Rate:

^1H: 120 MHz

^4He: 12 MHz

Background ≤ 3%

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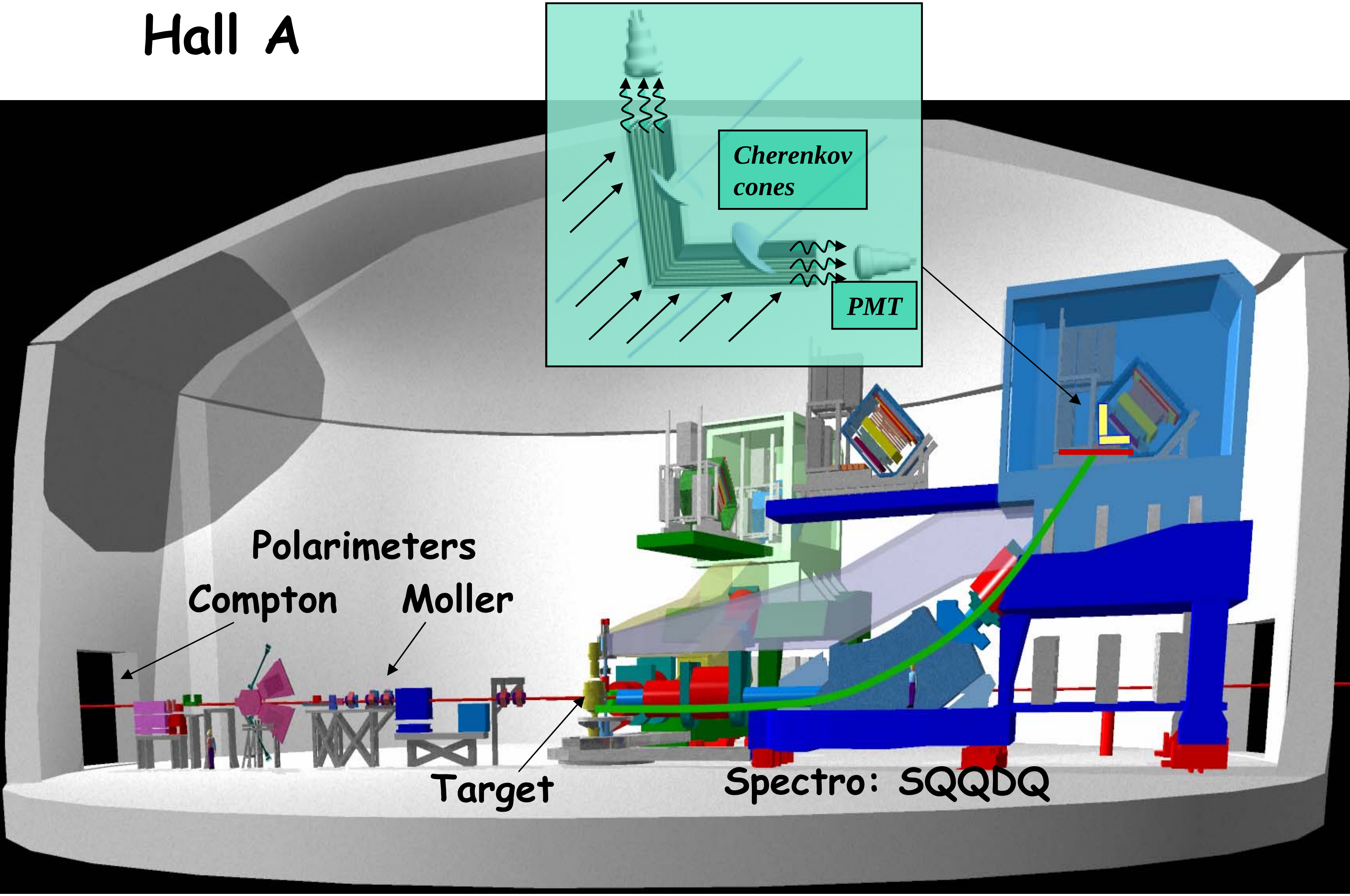
Hall A



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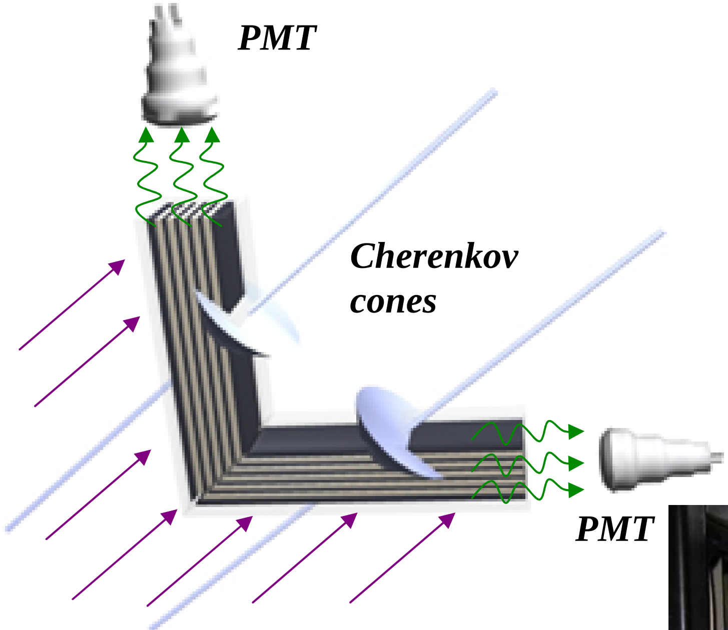
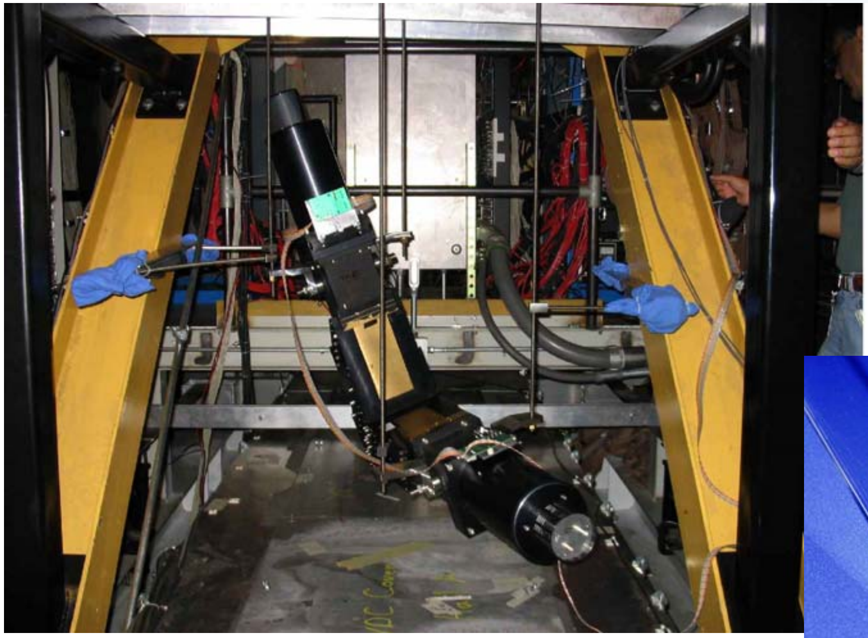
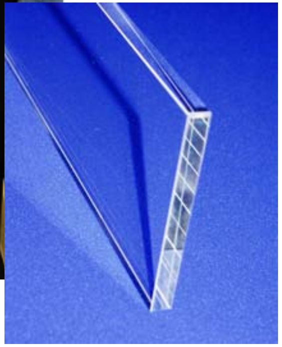
Focal Plane Detectors



Brass-Quartz Integrating Cerenkov Shower Calorimeter

- Insensitive to background
- Directional sensitivity
- High-resolution
- Rad hard





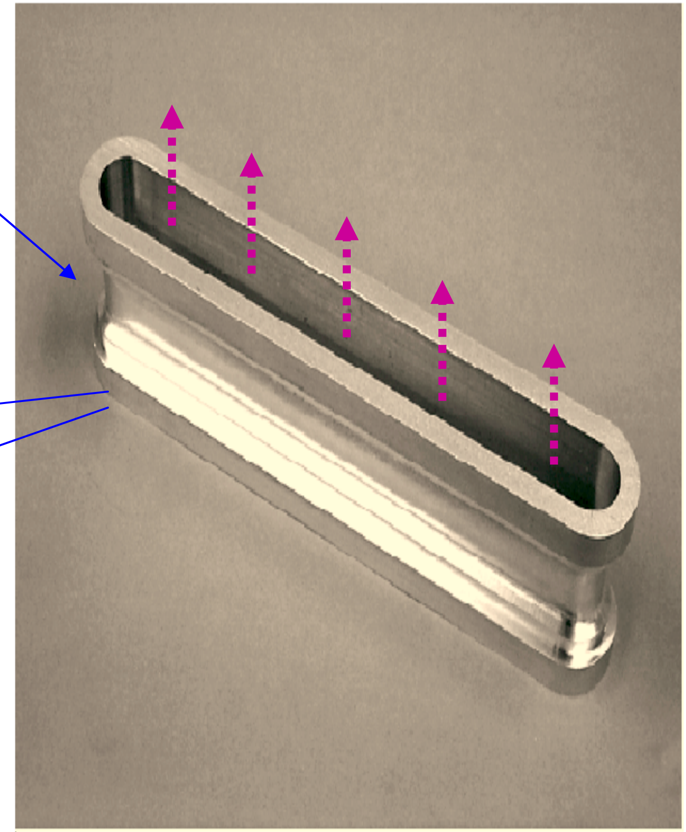
Two segment "L"-shape covers hydrogen elastic peak

Smaller 4He elastic peak requires only ½ single-segment detector

from K. Paschke

Hall A Target

New "race track" design – 20 cm
(transverse cryogen flow)



20 cm LH_2
20 cm ^4He gas cell
Cold (6.6K), dense (230 psi)
Al walls 3-7 mils thick

from K. Paschke

from K. Paschke

2004 HAPPEX-II Results

HAPPEX-^{4}He:

$Q^2 = 0.091\ (\text{GeV/c})^2$

$A_{PV} = +6.72 \pm 0.84\ (\text{stat}) \pm 0.21\ (\text{syst})\ \text{ppm}$

$A(G^s=0) = +7.507\ \text{ppm} \pm 0.075\ \text{ppm}$

$G^s_E = -0.039 \pm 0.041_{(\text{stat})} \pm 0.010_{(\text{syst})} \pm 0.004_{(\text{FF})}$

HAPPEX-H:

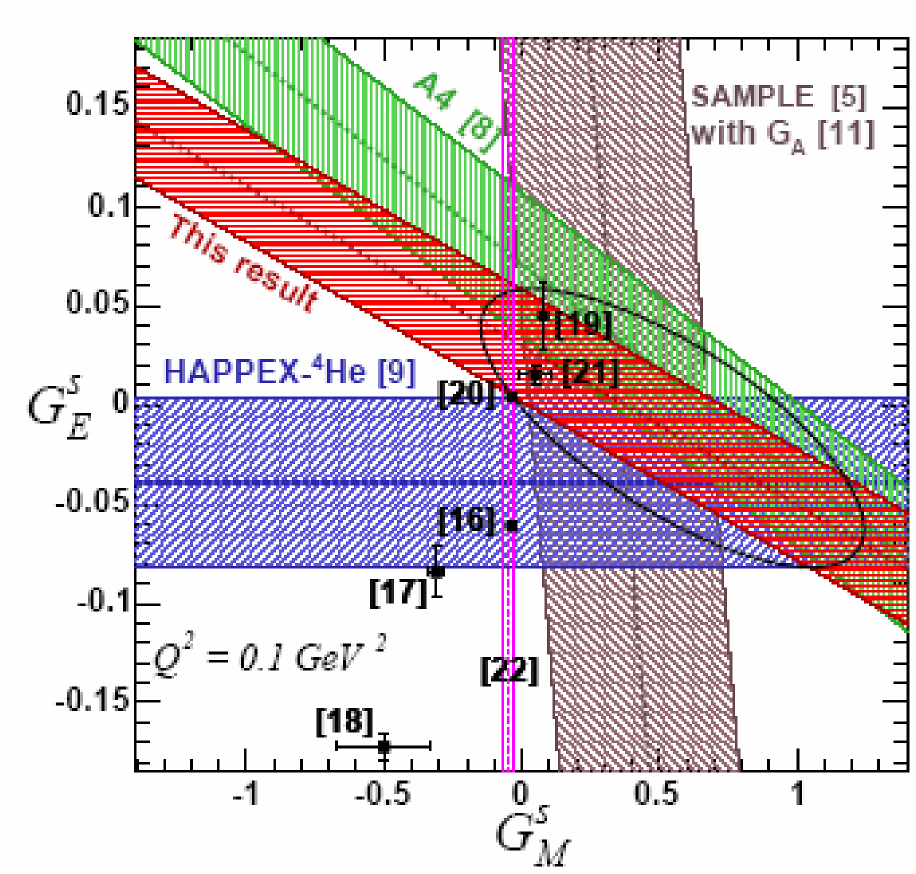
$Q^2 = 0.099\ (\text{GeV/c})^2$

$A_{PV} = -1.14 \pm 0.24\ (\text{stat}) \pm 0.06\ (\text{syst})\ \text{ppm}$

$A(G^s=0) = -1.440\ \text{ppm} \pm 0.105\ \text{ppm}$

$G^s_E + 0.08\ G^s_M = 0.032 \pm 0.026_{(\text{stat})} \pm 0.007_{(\text{syst})} \pm 0.011_{(\text{FF})}$

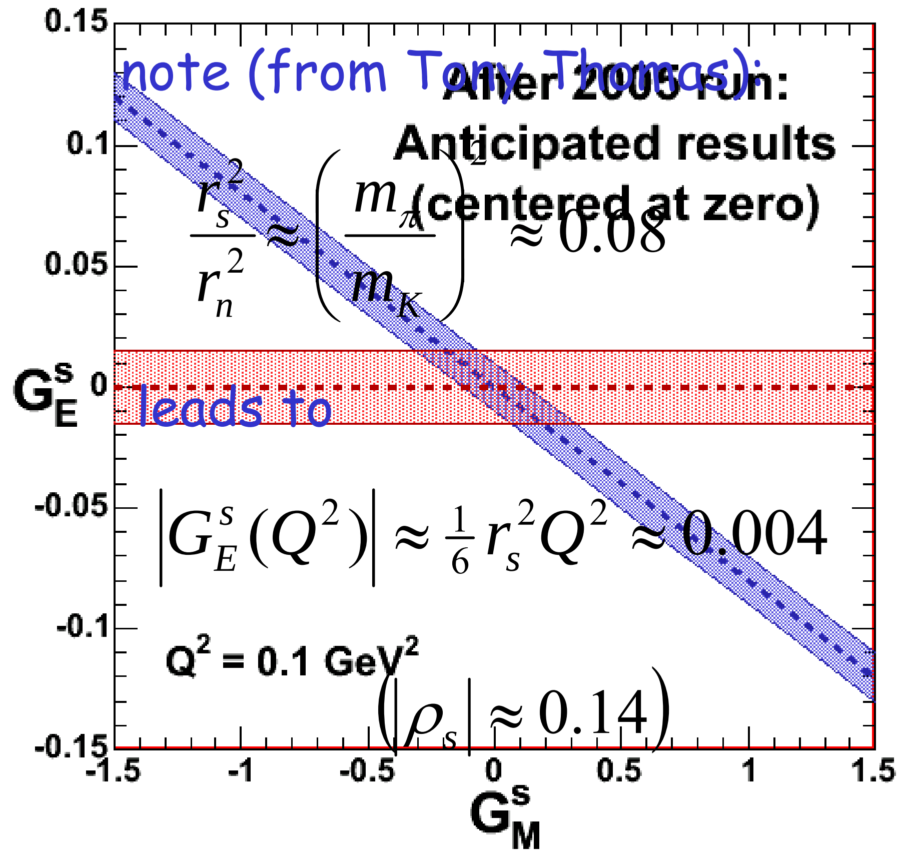
All Q^2=0.1 GeV^2 data combined (except G0)



$$G_M^s(Q^2=0.1) \approx +0.55 \pm 0.28$$

$$\rho_s = \left.\frac{dG_E^s}{d\tau}\right|_{Q^2=0} \approx -0.36 \pm 1.1$$

HAPPEX '05 Run Expected Uncertainties



note (from Tony Thomas):

$$\frac{r_s^2}{r_n^2} \approx \left(\frac{m_\pi}{m_K}\right)^2 \approx 0.08$$

leads to

$$\left|G_E^s(Q^2)\right| \approx \tfrac{1}{6} r_s^2 Q^2 \approx 0.004$$

$$\left(\left|\rho_s\right| \approx 0.14\right)$$

K.Aniol etal nucl-ex/0506010, 0506011
and from K. Paschke

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 $Q^2 \sim 0.1 - 1.0\ (\mathrm{GeV/c})^2$

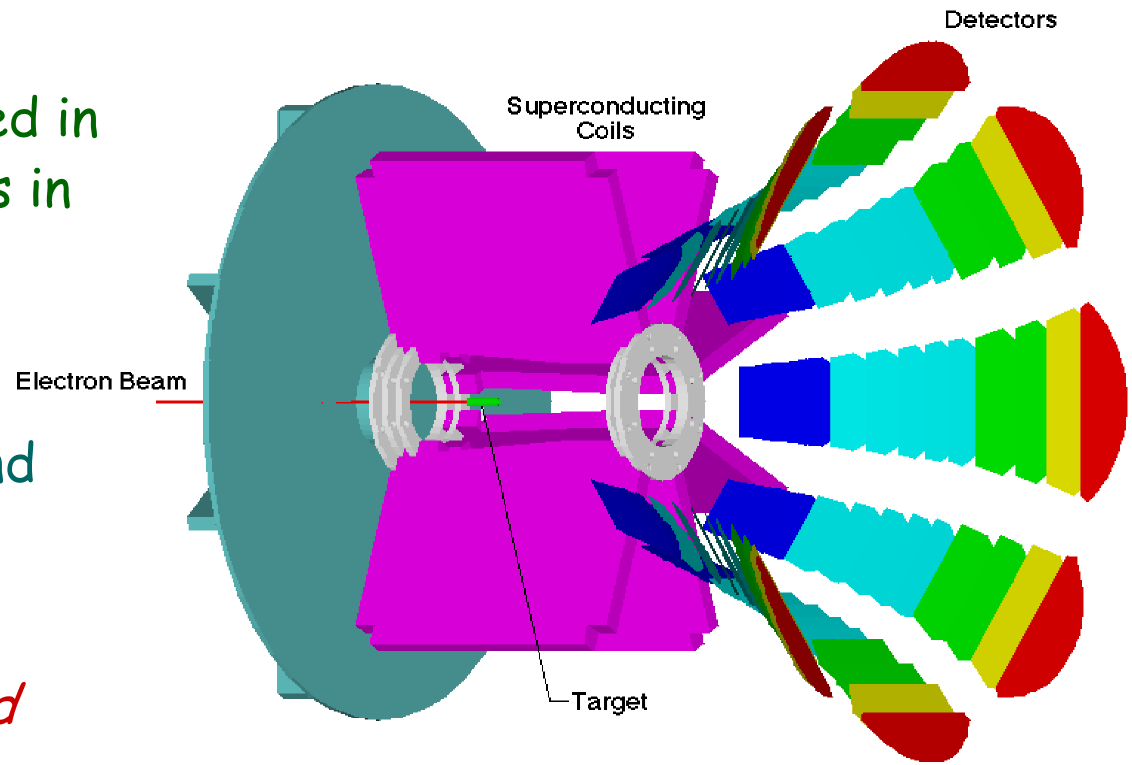
• superconducting toroidal magnet

• scattered particles detected in segmented scintillator arrays in spectrometer focal plane

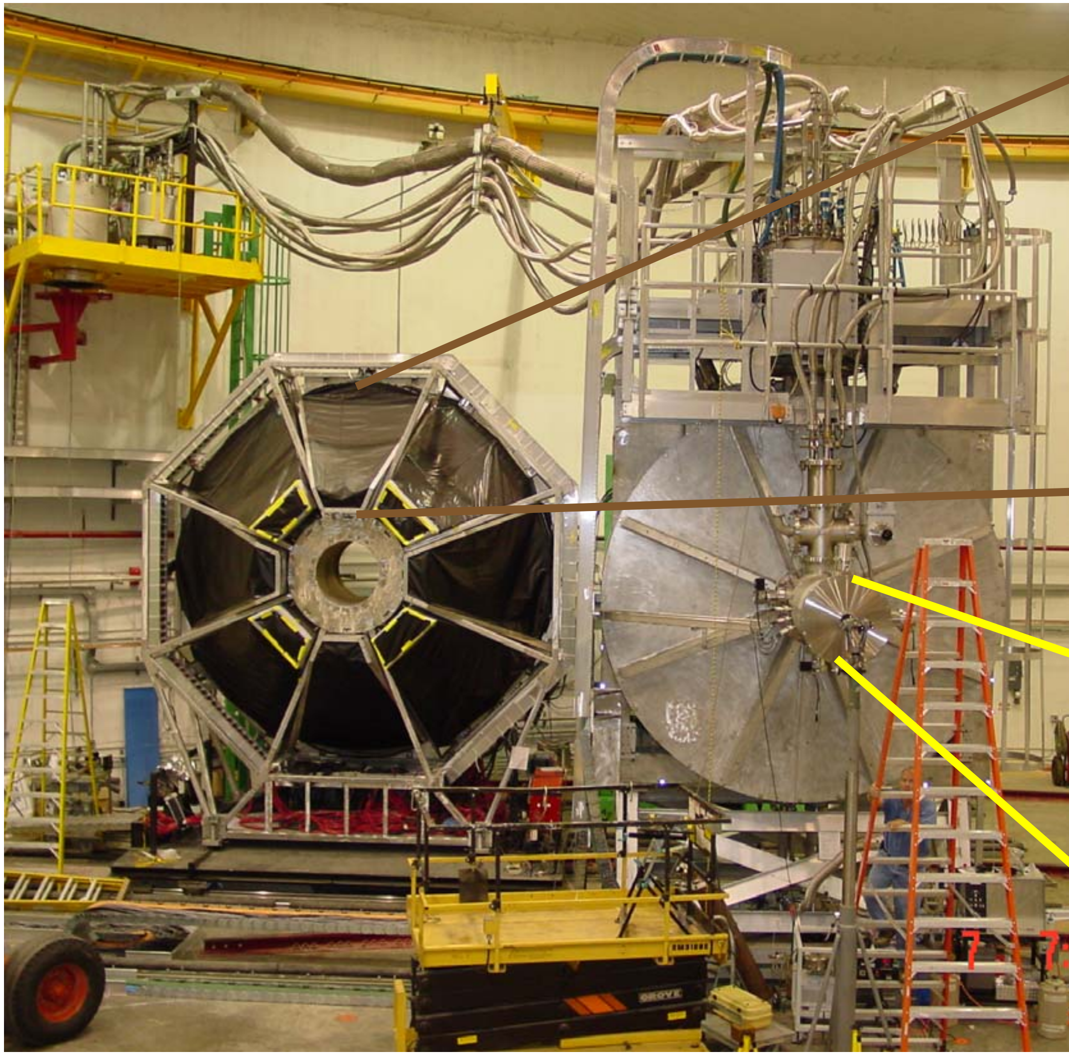
• custom electronics count and process scattered particles at > 1 MHz

• *forward angle run completed*

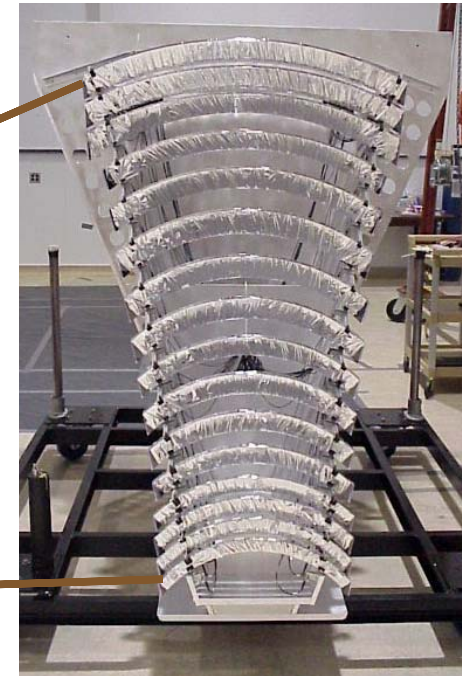
• *start backward angle late 05*



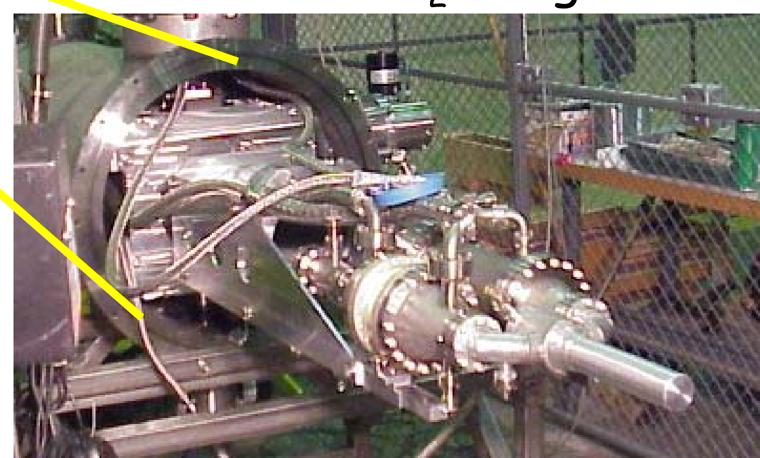
G0 Apparatus



One octant's scintillator array



20 cm LH_2 Target



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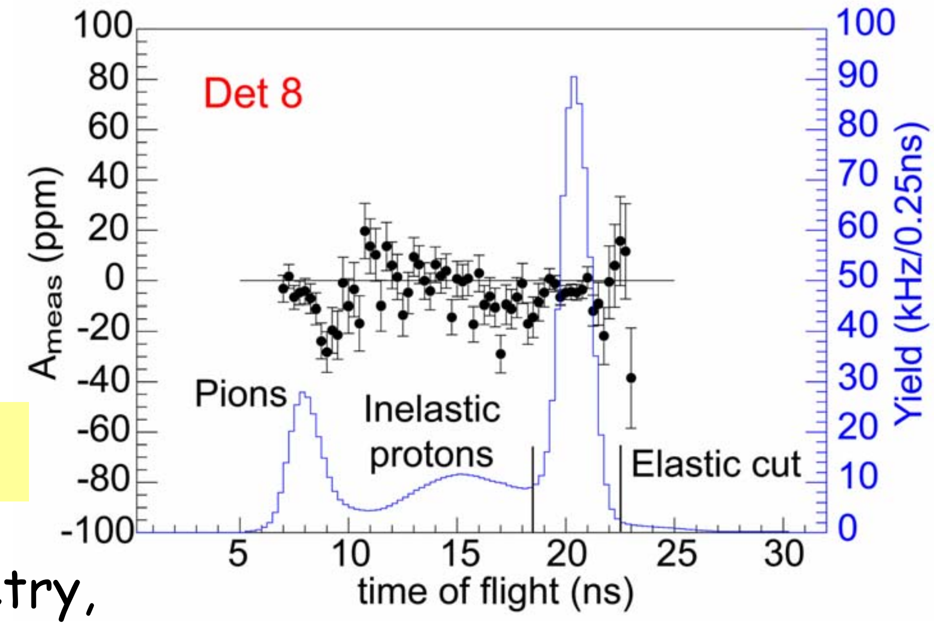
Data analysis/correction for backgrounds

- Measure yield and asymmetry of entire spectrum
- Correct asymmetry according to

$$f = \frac{Y_{back}}{Y_{meas}}$$



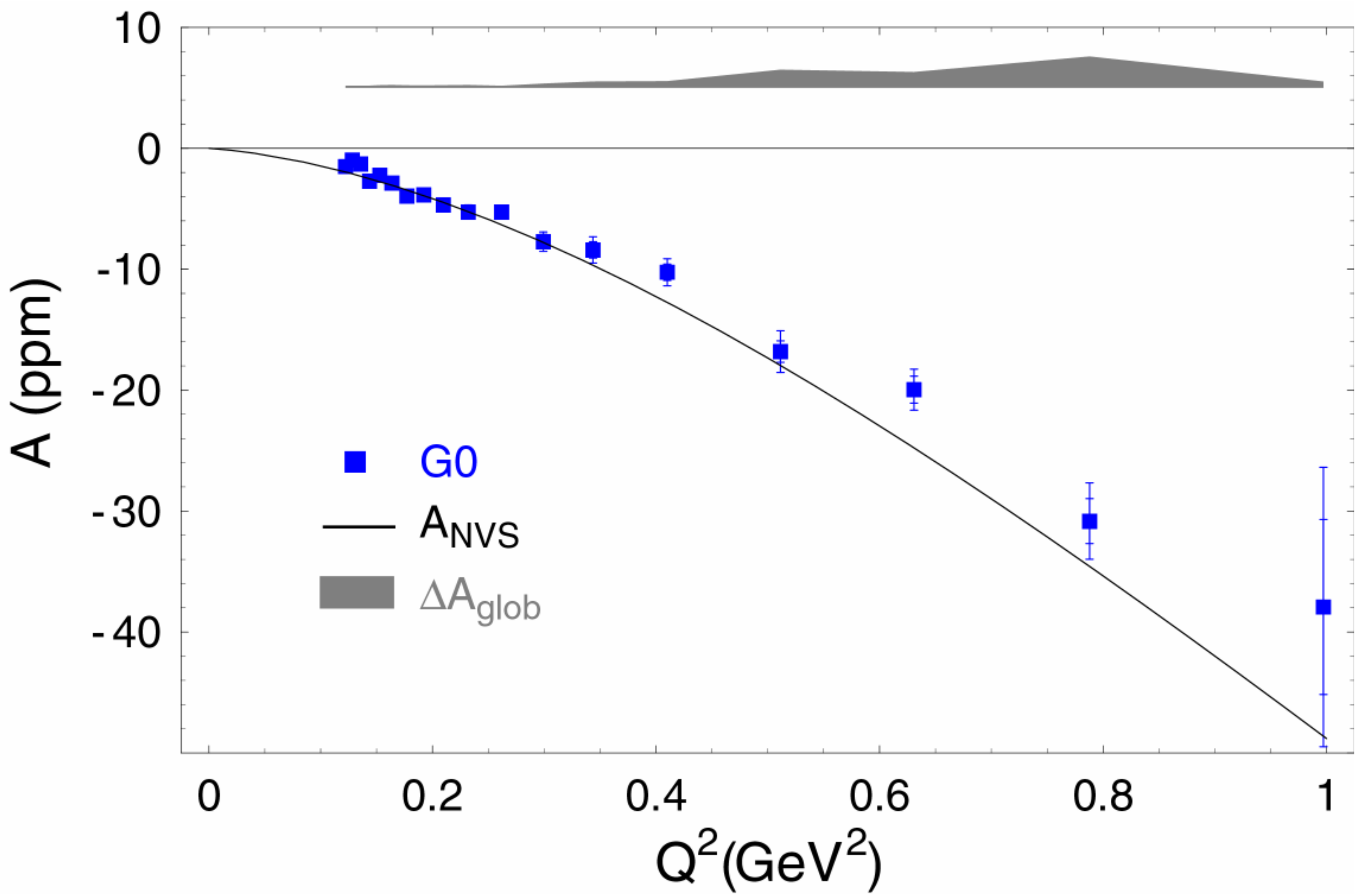
$$A_{meas} = (1 - f)A_{el} + f A_{back}$$

where A_{el} is the raw elastic asymmetry,

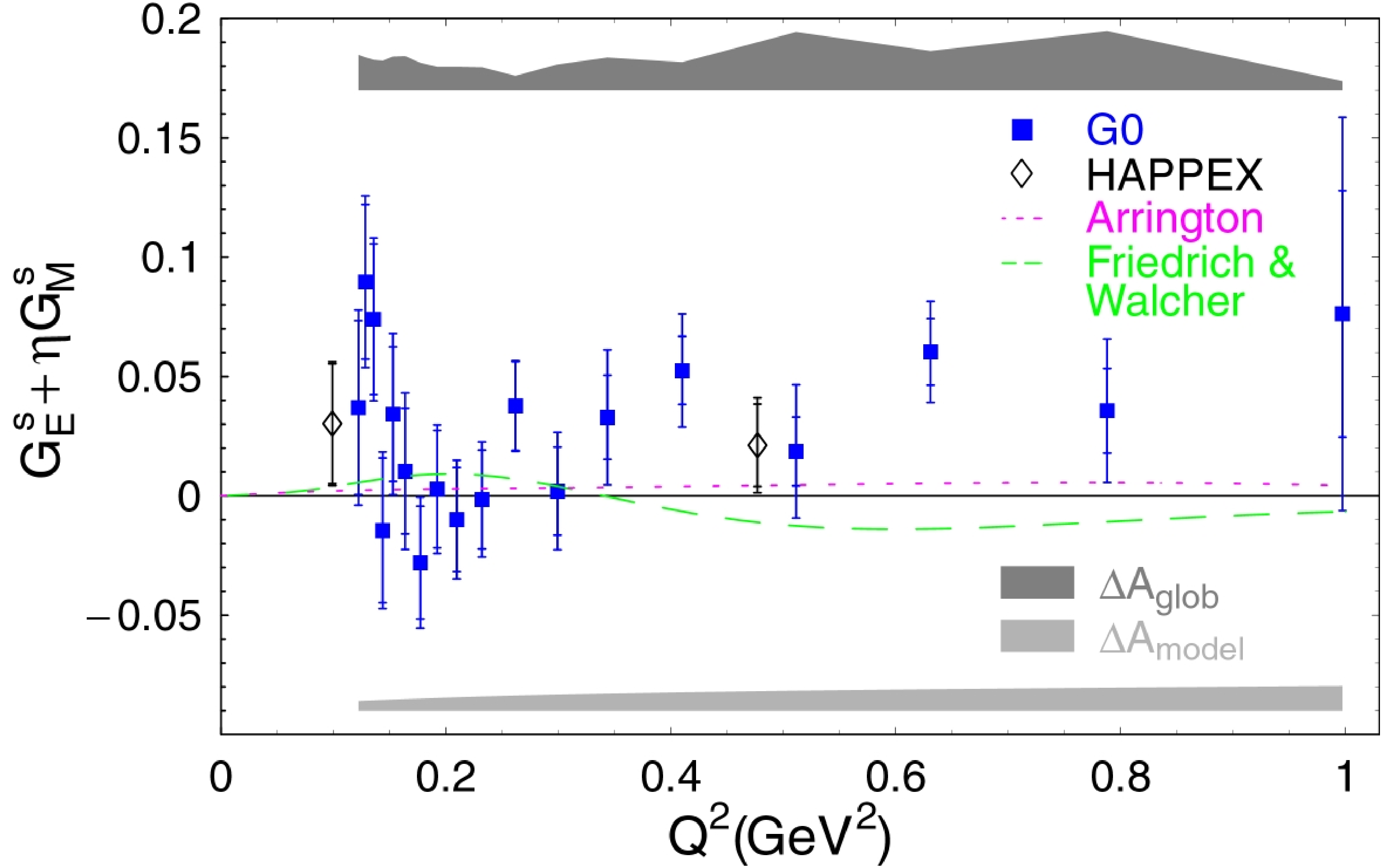
- Actual analysis: f = f(t)
  - det. 1-14
    - fit Y_{back} (poly'l of degree 4), Gaussian for elastic peak
    - then fit A_{back} (poly'l of degree 2), constant A_{el}
  - det. 15
    - interpolate over detectors for Y_{back}, A_{back}
    - fit 3 constants for A_{el}

G0 Experimental Asymmetries

- "no vector strange" asymmetry, A_{NVS}, is $A(G_E^s=0, G_M^s= 0)$
- EM form factors: Kelly PRC **70** (2004) 068202
- inside error bars: stat, outside: stat & pt-pt

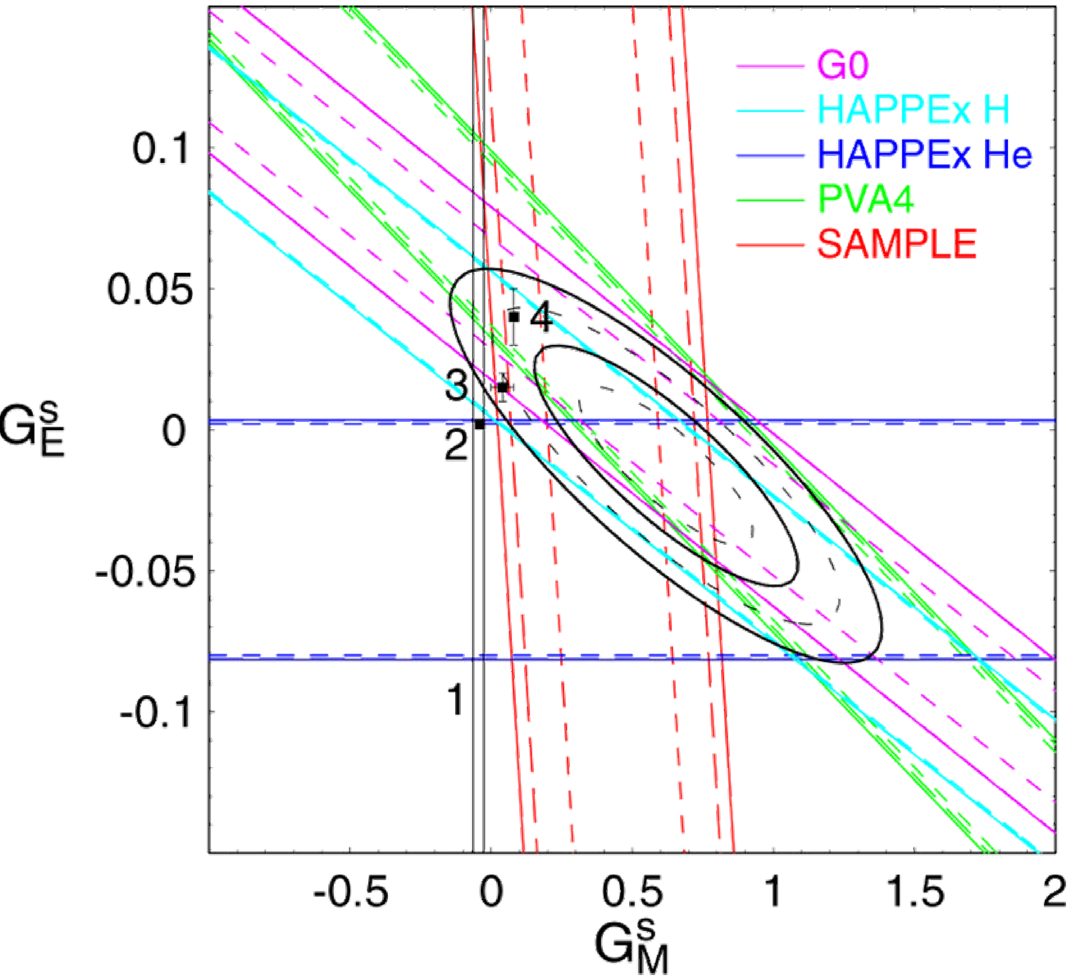


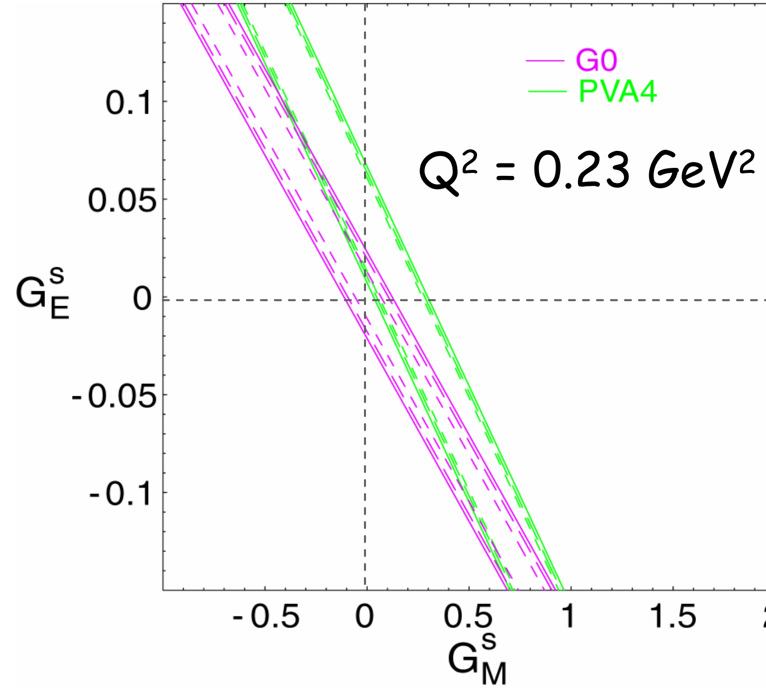
G0 Forward angle Results

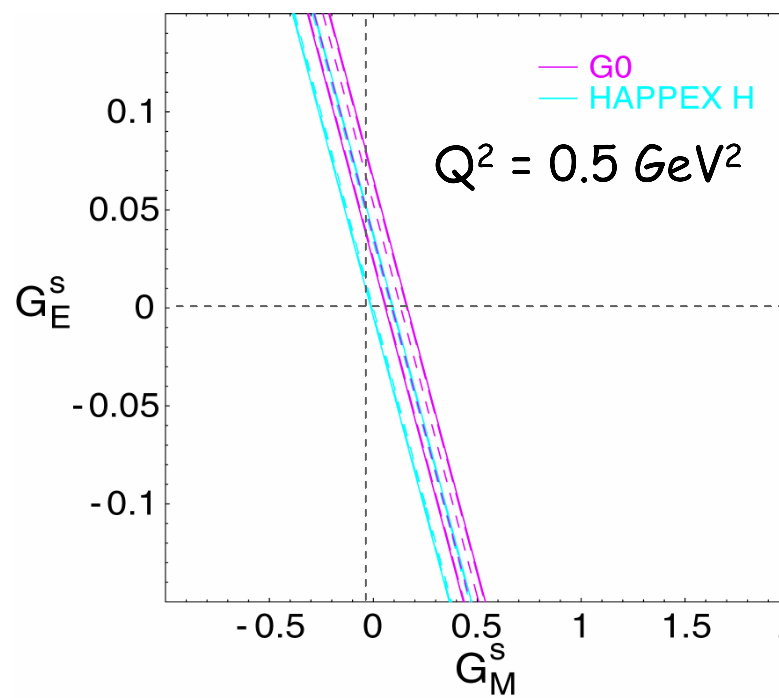


D.S. Armstrong etal, nucl-ex/0506021

$Q^2 = 0.1\ GeV^2$







$G_E^s = -0.013 \pm 0.028$

$G_M^s = +0.62 \pm 0.31$

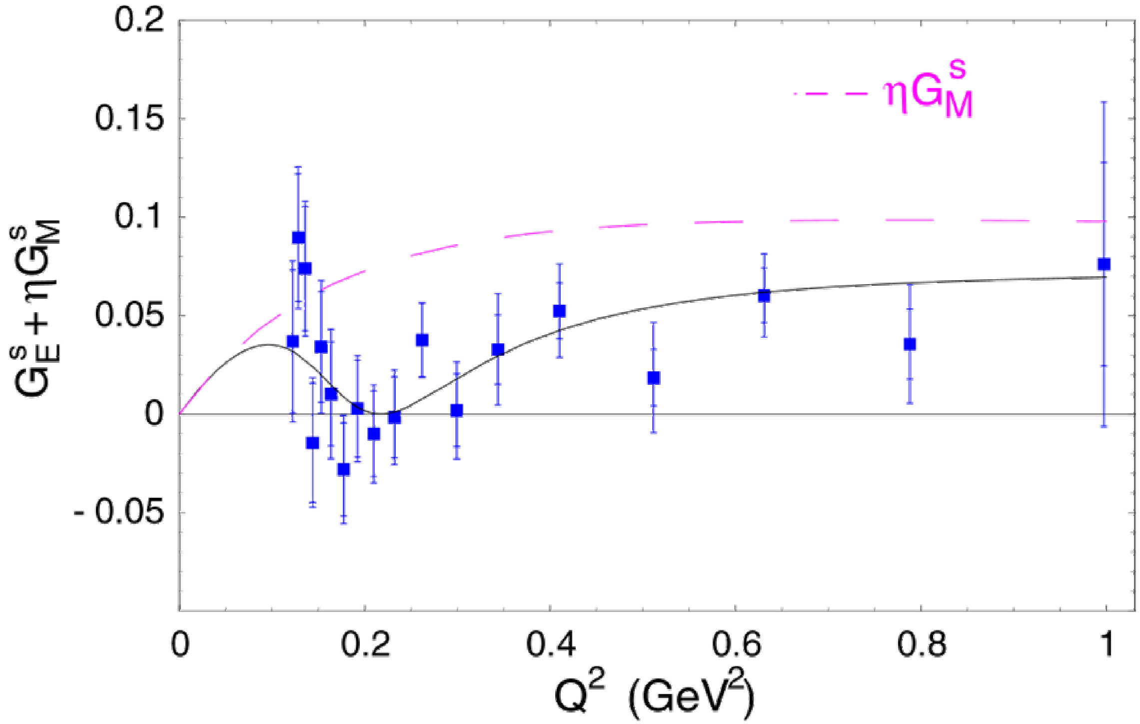
from DHB 17-jun- 05

http://www.npl.uiuc.edu/exp/G0/Forward

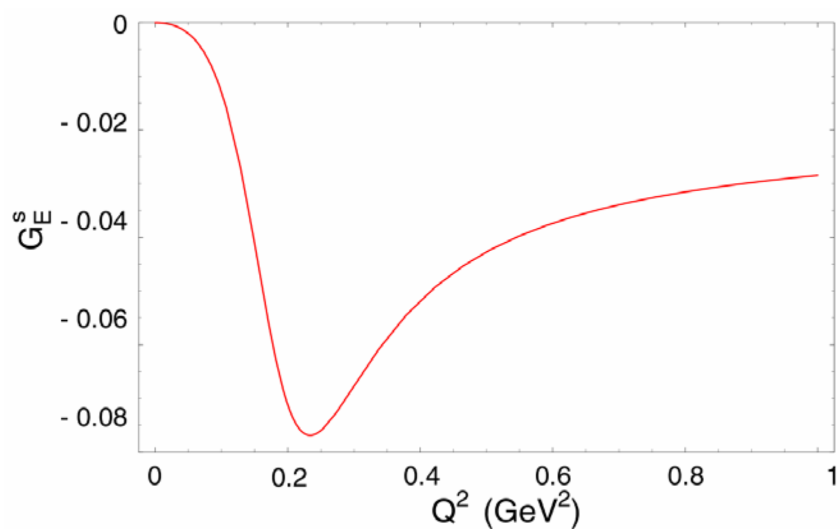
"Fit" to World Hydrogen Data

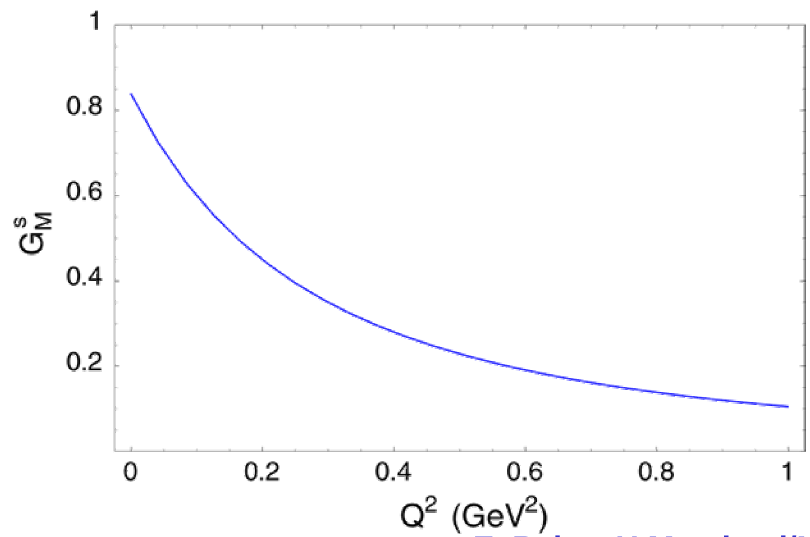
D. Beck, 18-Jun-05

$c_2 = -0.51 \pm 0.25$
$d_1 = -8.5 \pm 0.9$
$d_2 = 24 \pm 6$
$d_3 = 1$
$(\Lambda_M{}^s)^2 = \Lambda^2 / 1.3$



Remember the factor of –1/3





E. Beise, U Maryland/NSF

What's next for strange ffs

G0 backward: detect electrons at $\theta = 108°$

Q^2 = 0.3, 0.5, 0.8 GeV^2

both LH_2 and LD_2 targets

(begin fall 2005)

PV-A4 backward: $\theta = 145°$

Q^2 = 0.23, 0.47 GeV^2

(underway)

HAPPEX (now…)

high precision at Q2 = 0.1 GeV^2

(proposed July 2005)

high precision at Q^2 = 0.6 GeV^2

Future program using Parity Violation

will come with G0 (and PVA4):

- the nucleon's anapole form factor
- N-Δ weak transition from factor
- 2-boson exchange (Parity-conserving transverse asymmetries)

w/ JLab at 6 GeV

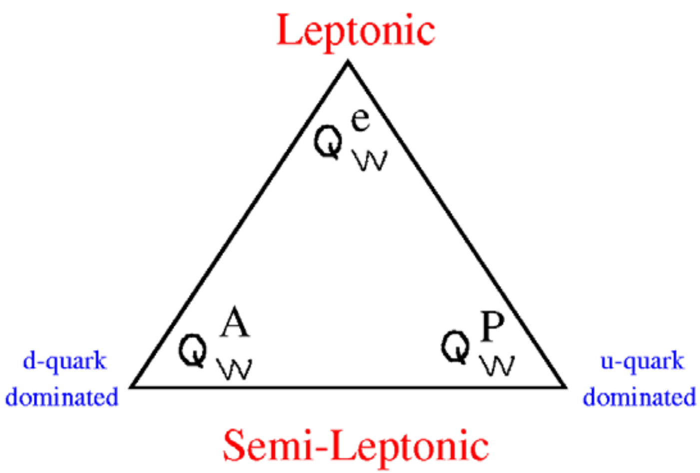
- low energy Standard Model tests
  - QWeak
  - 1st (relook) at Deep Inelastic Scattering
- Hadronic effects and QCD
  - higher twist effects
  - 1st (dedicated) look at the resonance region

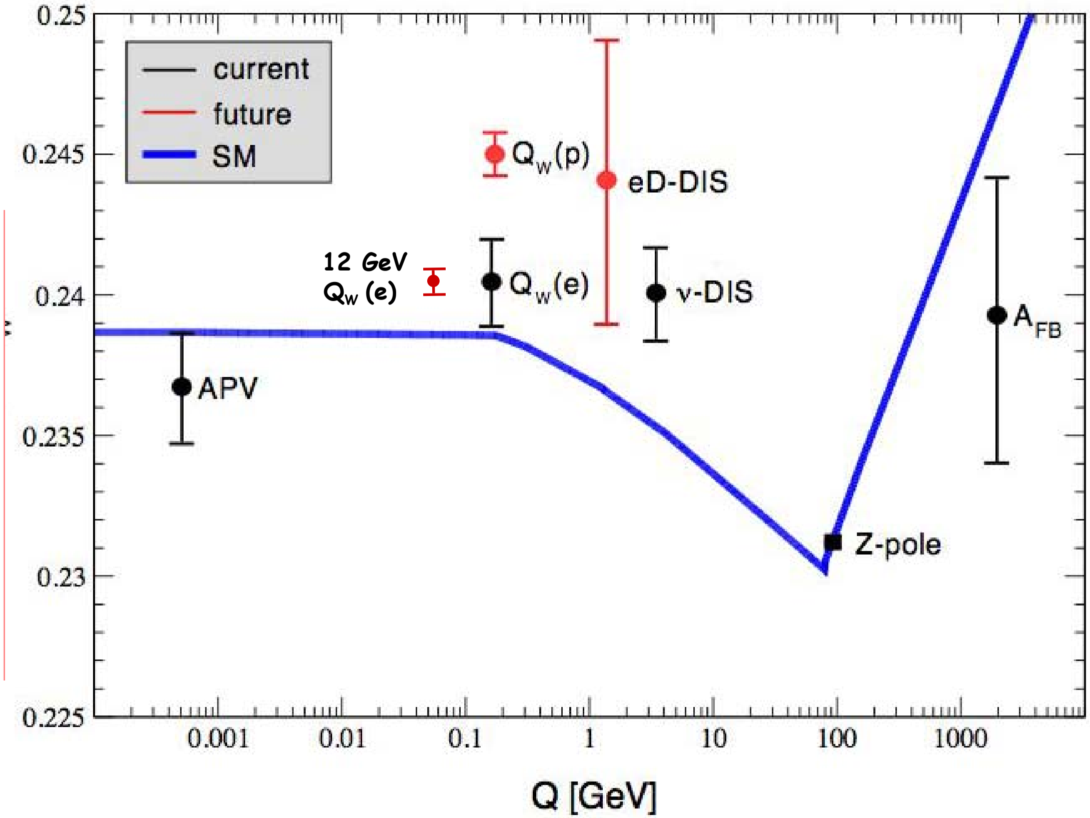
w/ JLab at 11 GeV

- high precision SM tests (e-p, e-d DIS, e-e)
- charge symmetry violation
- EMC effects with a weak probe

"Running of $\sin^2\theta_W$"

Weak "triad"
(M. Ramsey-Musolf)





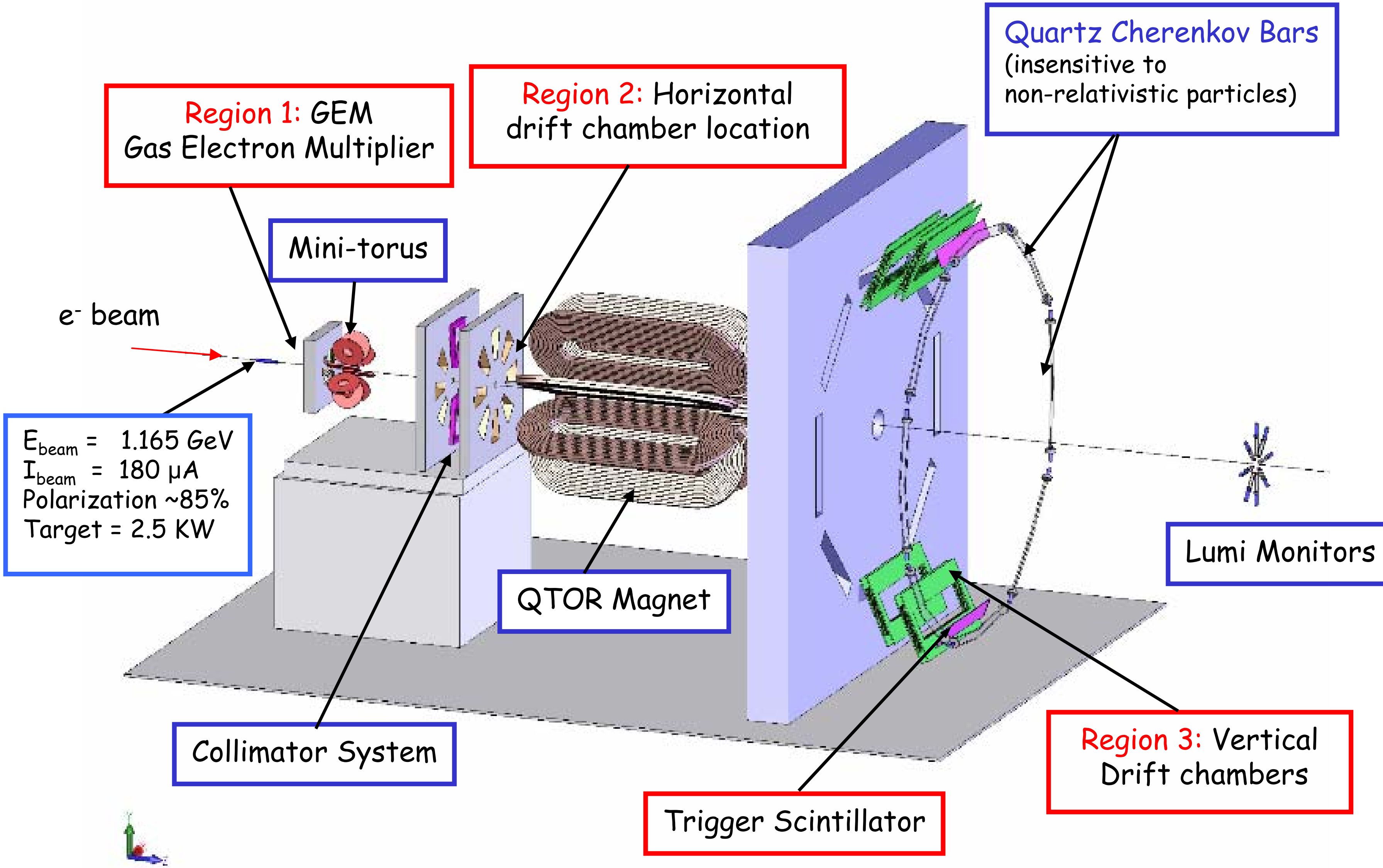
present:
"d-quark dominated" : Cesium APV (Q^A_W)
"pure lepton": SLAC E158 (Q^e_W)

future:
"u-quark dominated" : Q_{weak} (Q^p_W)
"pure lepton":12 GeV e2ePV (Q^e_W)

from M. Pitt

The Qweak Apparatus

(Calibration Mode Only - Production & Calibration Modes)

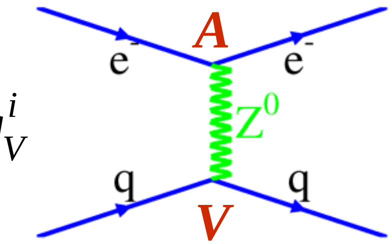


from M. Pitt

PV Deep Inelastic Scattering revisited

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

$$C_{1i} \equiv 2g_A^e g_V^i$$



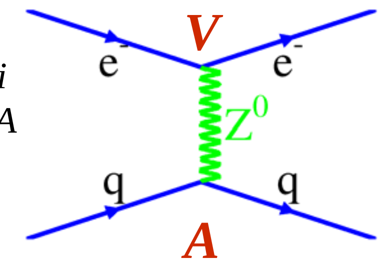
$$y = \frac{E - E'}{E}$$

deuteron:

$$a(x) = \frac{3}{10}\left[(2C_{1u} - C_{1d})\right] + \cdots$$

$$b(x) = \frac{3}{10}\left[(2C_{2u} - C_{2d})\frac{u_v(x) + d_v(x)}{u(x) + d(x)}\right] + \cdots$$

$$C_{2i} \equiv 2g_V^e g_A^i$$



quark structure fns largely cancel → $(2C_{2u} - C_{2d})$

potential sensitivity to higher twist effects

hydrogen:

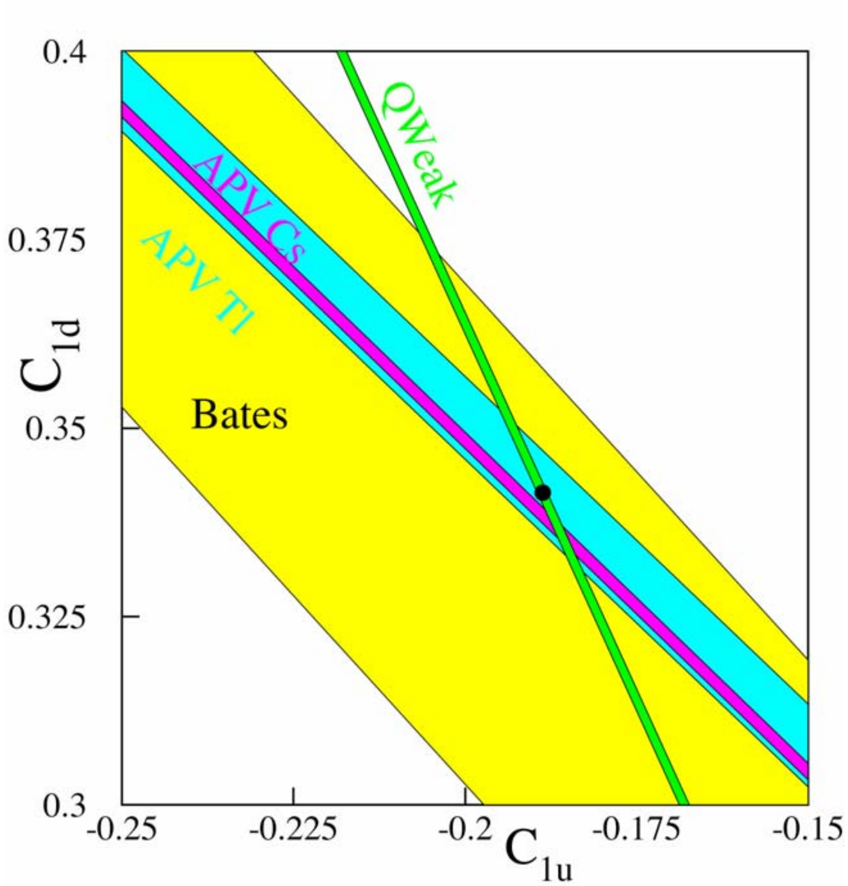
$$a(x) = \frac{u(x) + 0.91\,d(x)}{u(x) + 0.25\,d(x)} \quad + \textit{small corrections}$$

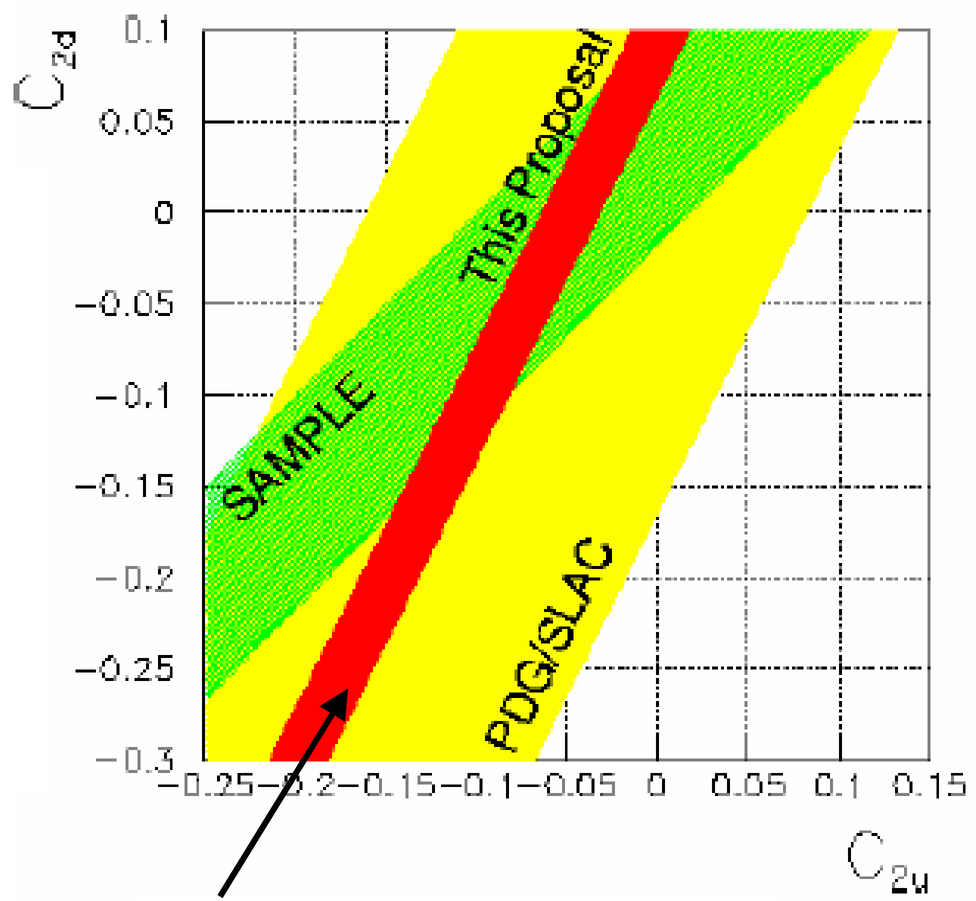
measure d/u directly in proton

potential sensitivity to charge symmetry violation (large x)

from R. Michaels

Parity violating e-quark couplings





e-D DIS (6 GeV), major improvement in axial couplings,
1st look at higher twist effects
(E05-007, Hall A, X. Zheng, P. Reimer)

w/ JLab @ 11 GeV: x20 improvement (likely Hall C)

from R. Michaels, X. Zheng

Summary

PV e-p scattering is evolving!

hadron structure

- new results: s-quarks contribute to proton's charge/ magnetism at <= 5-10% level. How are they distributed (and why)?
- should be known well-enough to proceed with low-energy precision tests of Standard Model

Future program includes wide array of physics

2-γ exchange and transverse asymmetries (S. Phillips poster)

anapole form factors

resonances

higher twist, d/u, CSV

EMC in weak interaction

precision tests of Standard Model

PV in e-Pb scattering – neutron skin

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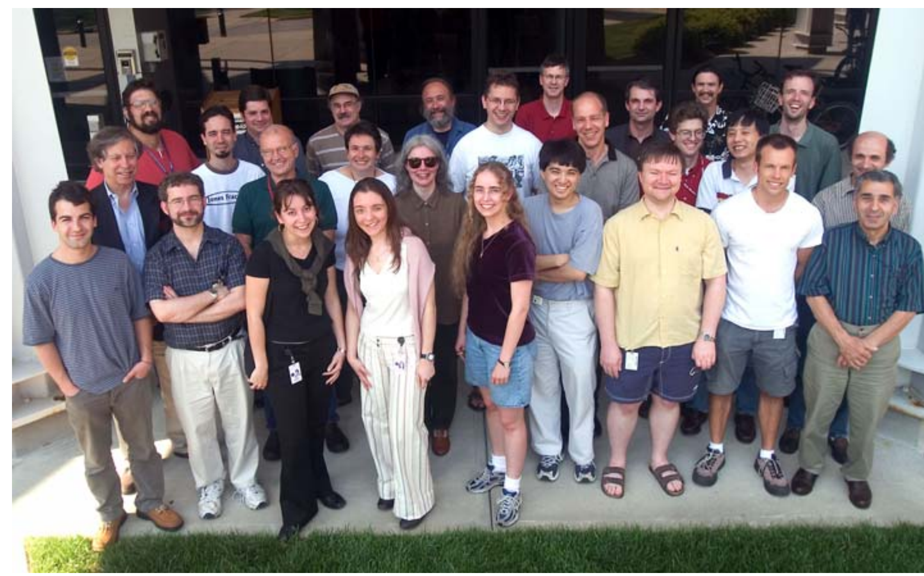

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Exploring Nuclear Matter - Quarks to Stars

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