Strangeness in the Proportion:
Strangeness in the Nucleon probed via Parity-Violating Electron Scattering

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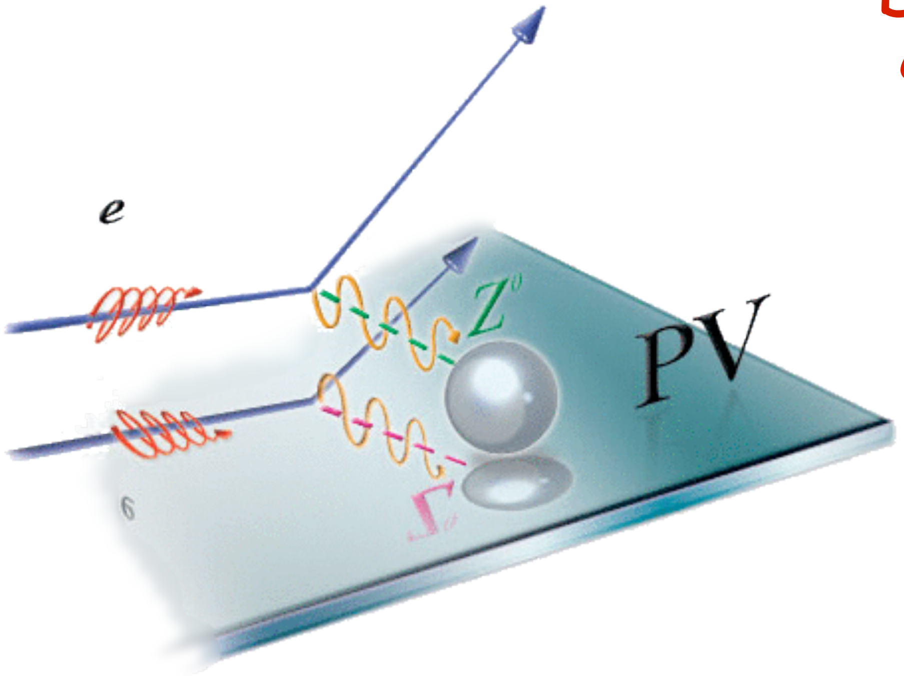
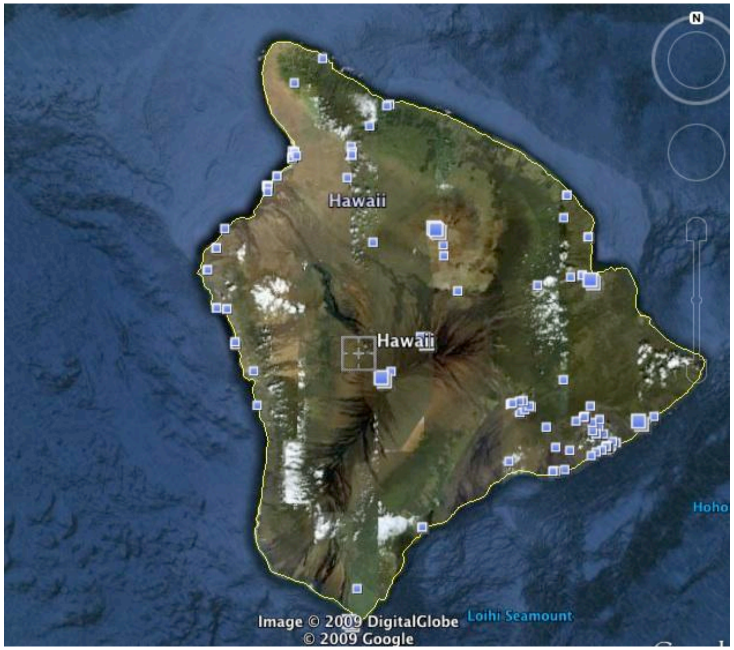
College of William & Mary

G0 and HAPPEx Collaborations



Joint Meeting of the DNP & JPS
Waikoloa Hawaii, October 13-17, 2009



The College of WILLIAM & MARY

Jefferson Lab

Outline

- Parity violation in electron scattering
- Vector Strange Form Factors: $\boxed{G_E^s \text{ and } G_M^s}$
- World Experimental Effort

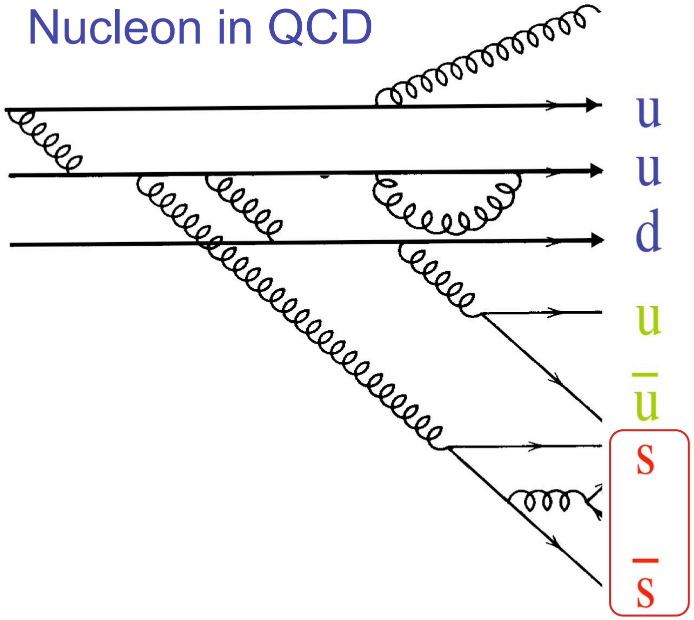
- Recent Results from PV-A4, G0 at backward angles:
  - Separated form factors at $Q^2 = 0.23, 0.63\ (\text{GeV}/c)^2$

- Implications & Conclusions

" *There is no excellent beauty that hath not some strangeness in the proportion* "

Francis Bacon 1561-1626

Strangeness in the nucleon


Nucleon in QCD

- $P = uud + \underbrace{u\bar{u} + d\bar{d} + s\bar{s} + g \ + ...}_{\text{« sea »}}$

- s quark: clean candidate to study the sea

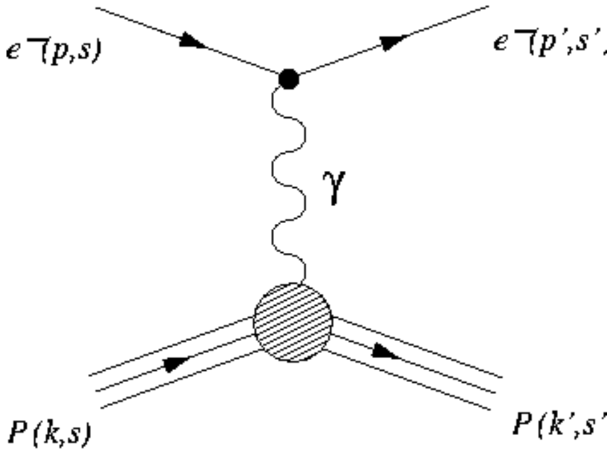
- How much do virtual $s\bar{s}$ pairs contribute to the structure of the nucleon ?
  Momentum : 4% (DIS)
  Spin : 0 to -10% (polarized DIS)
  Mass : 0 to 30% (πN-sigma term)*
  (update: see Tony Thomas' talk...)

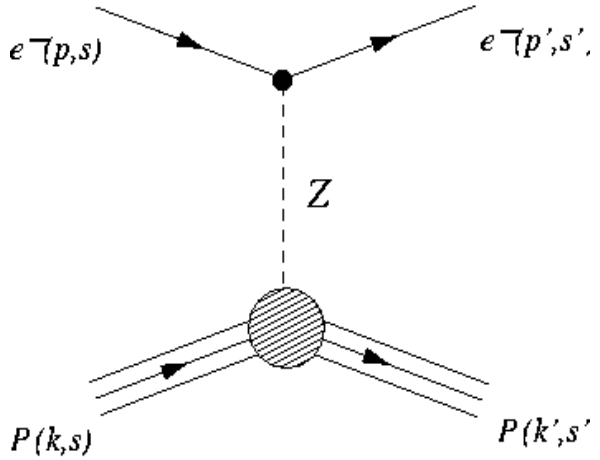
also: OZI violations in $p\bar{p} \rightarrow \frac{\phi\gamma}{\omega\gamma}$

Goal: Determine the contributions of the strange quark sea ($s\bar{s}$) to the charge and magnetization distributions in the nucleon :

Vector "strange form factors": G^s_E and G^s_M

Parity Violating Electron Scattering
→ Weak NC Amplitudes





Interference: $\sigma \sim |M^{EM}|^2 + |M^{NC}|^2 + 2Re(M^{EM*})M^{NC}$

Interference with EM amplitude makes Neutral Current (NC) amplitude accessible →

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{\left|M_{PV}^{NC}\right|}{\left|M^{EM}\right|} \sim \frac{Q^2}{(M_Z)^2}$$

Small ($\sim 10^{-6}$) cross section asymmetry isolates weak interaction

Nucleon Form Factors

Adopt Sachs FF: $G_E^\gamma = F_1^\gamma + \tau F_2^\gamma$ $\quad G_M^\gamma = F_1^\gamma + F_2^\gamma$

(*Roughly*: Fourier transforms of charge and magnetization)

NC and EM probe same hadronic flavor structure, with different couplings:

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

$$G_{E/M}^Z = \left(1 - \frac{8}{3}\sin^2\theta_W\right) G_{E/M}^u - \left(1 - \frac{4}{3}\sin^2\theta_W\right) G_{E/M}^d - \left(1 - \frac{4}{3}\sin^2\theta_W\right) G_{E/M}^s$$

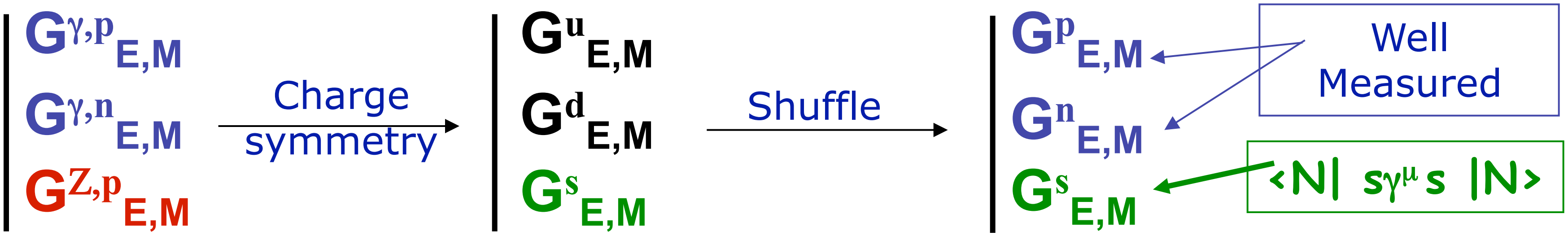
$G^Z_{E/M}$ provide an important benchmark for testing non-perturbative QCD structure of the nucleon

Charge Symmetry

One expects the neutron is ≈ an isospin rotation of the proton*:

$$G^{p,u}_{E/M} = G^{n,d}_{E/M}, \qquad G^{p,d}_{E/M} = G^{n,u}_{E/M}, \qquad G^{p,s}_{E/M} = G^{n,s}_{E/M}$$

$$\boxed{G^{\gamma,p}_{E/M} = \frac{2}{3}G^{u}_{E/M} - \frac{1}{3}G^{d}_{E/M} - \frac{1}{3}G^{s}_{E/M} \longrightarrow G^{\gamma,n}_{E/M} = \frac{2}{3}G^{d}_{E/M} - \frac{1}{3}G^{u}_{E/M} - \frac{1}{3}G^{s}_{E/M}}$$



$G^{\gamma,p}_{E,M}$

$G^{\gamma,n}_{E,M}$

$G^{Z,p}_{E,M}$

Charge symmetry

$G^{u}_{E,M}$

$G^{d}_{E,M}$

$G^{s}_{E,M}$

Shuffle

$G^{p}_{E,M}$

$G^{n}_{E,M}$

$G^{s}_{E,M}$

Well Measured

$\langle N|\, s\gamma^{\mu} s\, |N\rangle$

$$\boxed{A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{M_Z M_\gamma}{|M_\gamma|^2} = -\frac{G_F Q^2}{\sqrt{2}\pi\alpha}\mathrm{F}\left(G^{p}_{E/M}, G^{n}_{E/M}, G^{s}_{E/M}, G_A\right)}$$

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* Effect of charge symmetry violations: B. Kubis & R. Lewis Phys. Rev. C **74** (2006) 015204

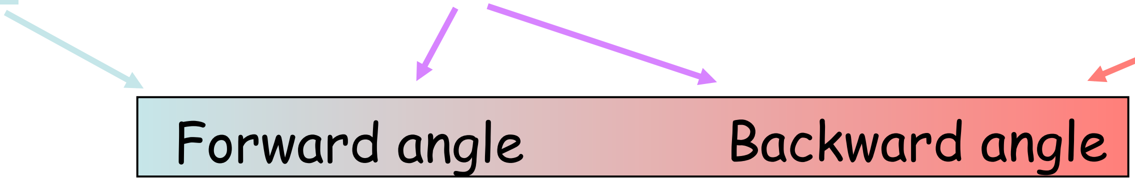
Isolating individual form factors: vary *kinematics* or *target*

For a proton:

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

~ few parts per million

$$A_E = \boxed{\varepsilon}\, G_E^p G_E^Z, \qquad A_M = \boxed{\tau}\, G_M^p G_M^Z, \qquad A_A = -\left(1 - 4\sin^2\theta_W\right)\boxed{\varepsilon'}\, G_M^p G_A^e$$


Forward angle

Backward angle

$$G^Z_{E,M} = (1 - 4\sin^2\theta_W)(1 + R_V^p)G^p_{E,M} - (1_3 + R_V^n)G^n_{E,M} - G^s_{E,M}$$

$$G^e_A = -\tau_3(1 + R_A^{T=1})G_A + \sqrt{3}R_A^{T=0}G^8_A + \Delta s$$

For ^{4}He: G_E^s alone

$$A_{PV} = \frac{G_F Q^2}{\pi\alpha\sqrt{2}}\left[\sin^2\theta_W + \frac{G_E^s}{2(G_E^p + G_E^n)}\right]$$

For deuteron:

enhanced G_A^e sensitivity

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

Theoretical Approaches to Strange Form Factors

Models - a non-exhaustive list:

kaon loops, vector dominance, Skyrme model, chiral quark model, dispersion relations, NJL model, quark-meson coupling model, chiral bag model, HBChPT, chiral hyperbag, QCD equalities, …

- no consensus on magnitudes or even *signs* of G_E^s and G_M^s !

Only model-independent statement: $\boxed{G_E^s(Q^2=0)=0}$

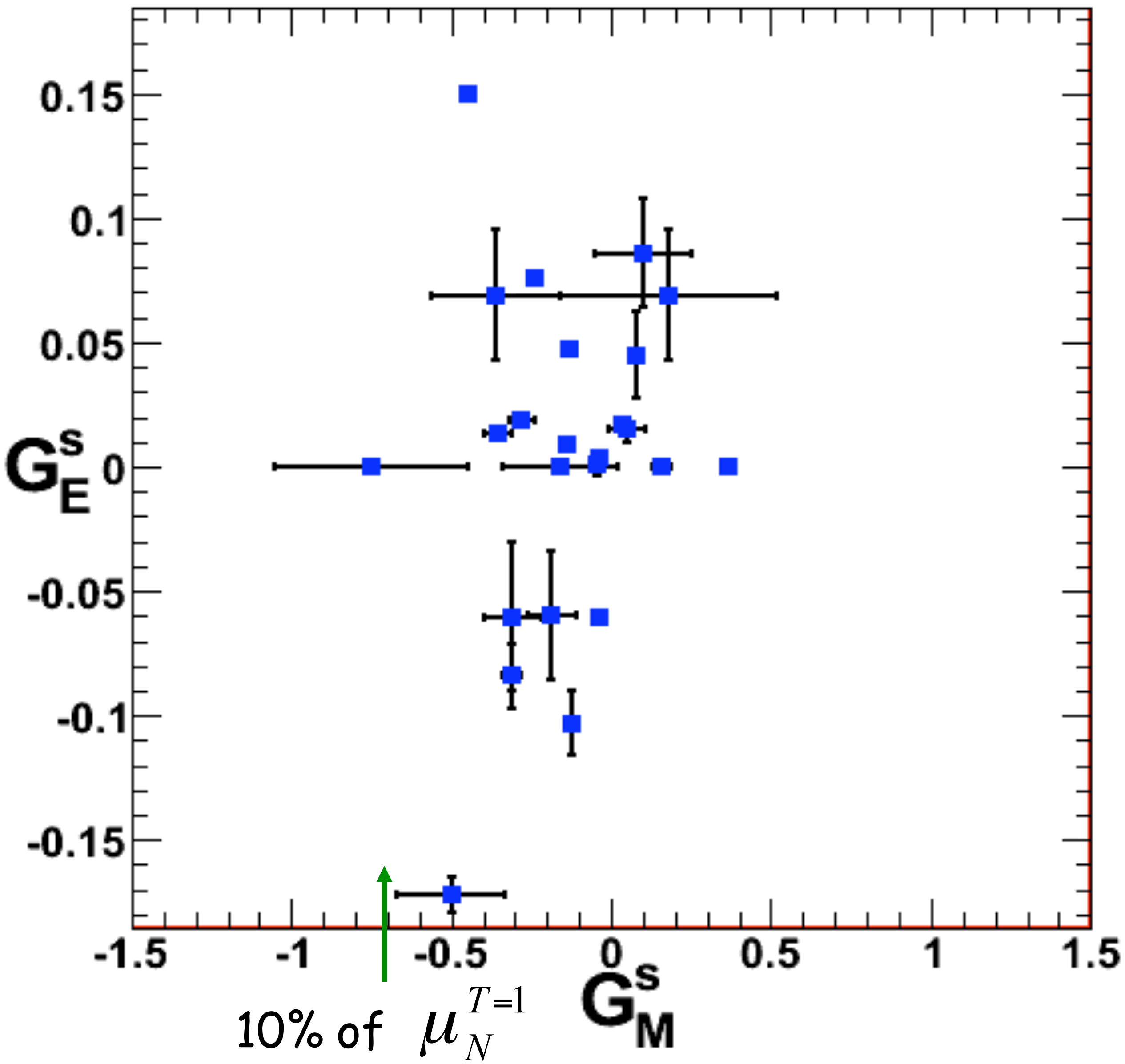
a challenging problem in non-perturbative QCD

What about QCD on the lattice?

- Dong, Liu, Williams PRD **58**(1998)074504
- Lewis, Wilcox, Woloshyn PRD **67**(2003)013003
- Leinweber, *et al.* PRL **94**(2005) 212001; PRL **97** (2006) 022001
- Doi, *et al.* (2009) arXiv:0903.3232 – and see talk CF-3…

Disconnected insertions – technically challenging

Strangeness Models



10% of $\mu_N^{T=1}$

(as/of circa 2005)

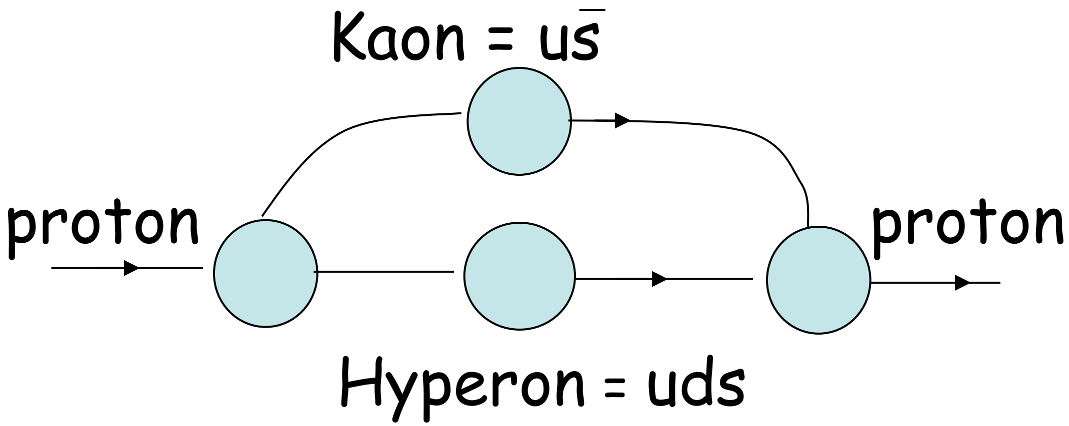
note: caveats…

What would non-zero G^s_E and G^s_M imply?

$G^s_E \neq 0$ ⇒ s and $\bar{s}$ have different spatial distributions in proton

$G^s_M \neq 0$ ⇒ s and $\bar{s}$ have different magnetization distributions in proton

-> contribute to magnetic moment, etc.



Kaon = $u\bar{s}$

proton

proton

Hyperon = uds

(naive model for illustration)

The Axial Current Contribution

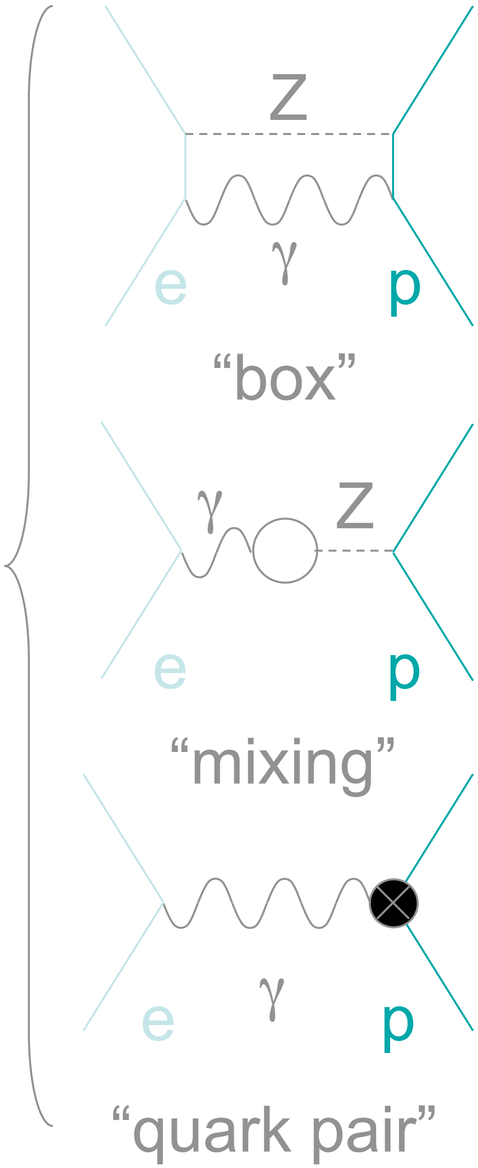
- **Recall:** $A^{PV} \propto \frac{A_E + A_M + A_A}{2\sigma_{unp}}$

$$A_E = \varepsilon(\theta) G_E^{\gamma} G_E^{Z}, \quad A_M = \tau G_M^{\gamma} G_M^{Z}$$

$$A_A = -\left(1 - 4\sin^2\theta_W\right) \varepsilon'(\theta) G_M^{\gamma} G_A^{e}$$

$$G_A^{e} = -\tau_3 (1 + R_A^{T=1}) G_A + \sqrt{3} R_A^{T=0} G_A^{8} + \Delta s$$

  - Effective axial form factor: $G_A^e(Q^2)$
  - related to form factor measured in ν scattering
  - also contains "*anapole*" form factor
  - determine isovector piece by combining proton and neutron (deuteron) measurements



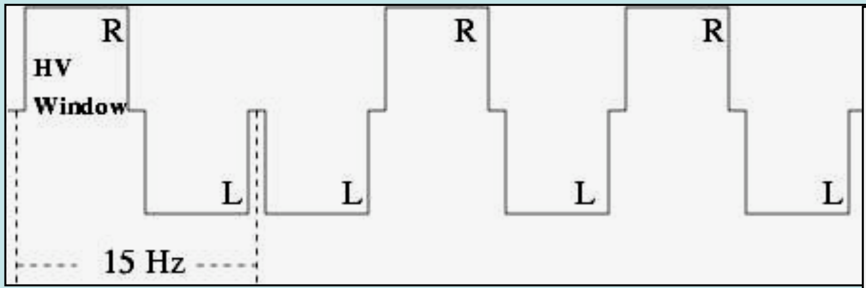
Measurement of P-V Asymmetries

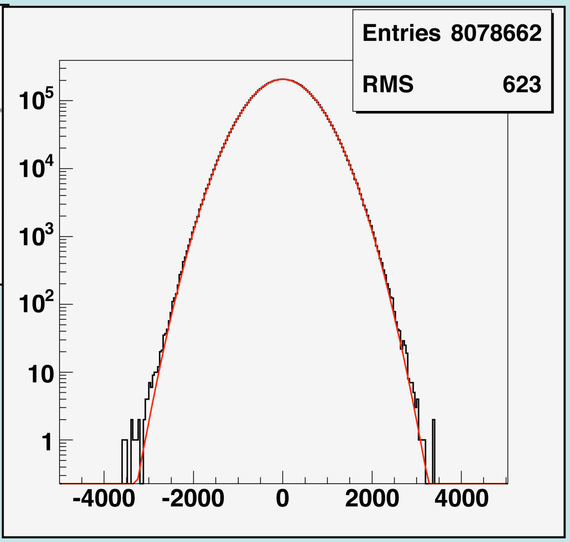
$$A_{LR} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx 10^{-6}$$

e.g. 5% Statistical Precision on 1 ppm
-> requires 4×10^{14} counts

Rapid Helicity Flip: Measure the asymmetry at 10^{-4} level, 10 million times

$$A_{LR} = \frac{N_R - N_L}{N_R + N_L}$$



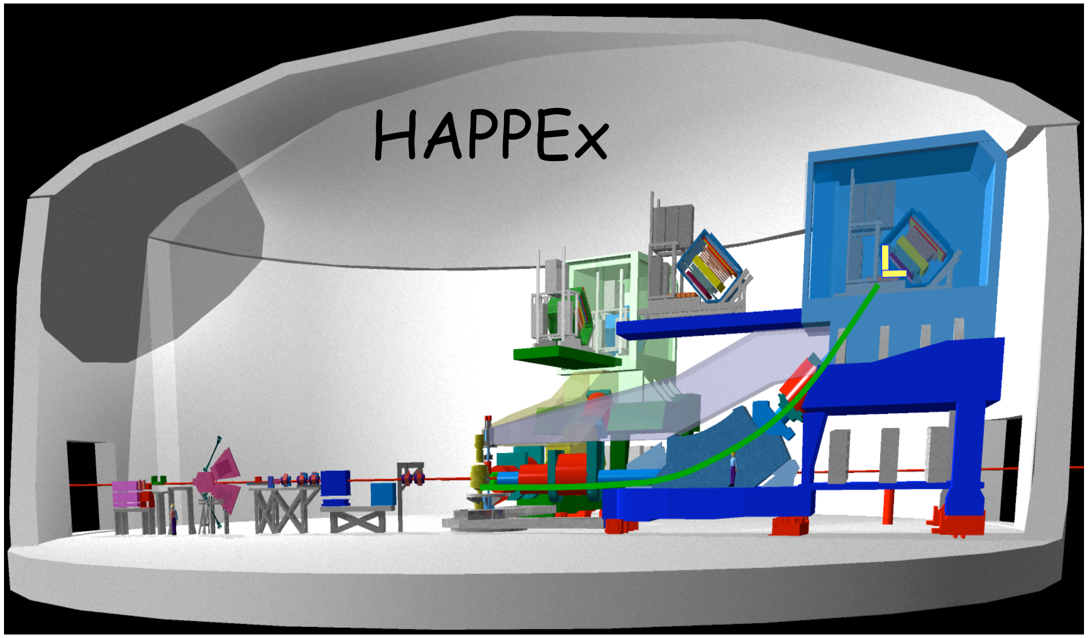


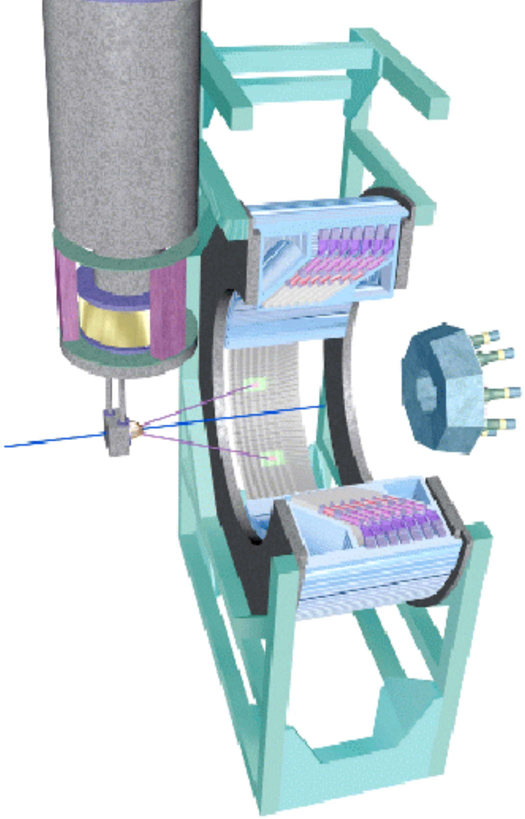
- •High luminosity: thick targets, high beam current
- •Control noise (target, electronics)
- •High beam polarization and rapid flip

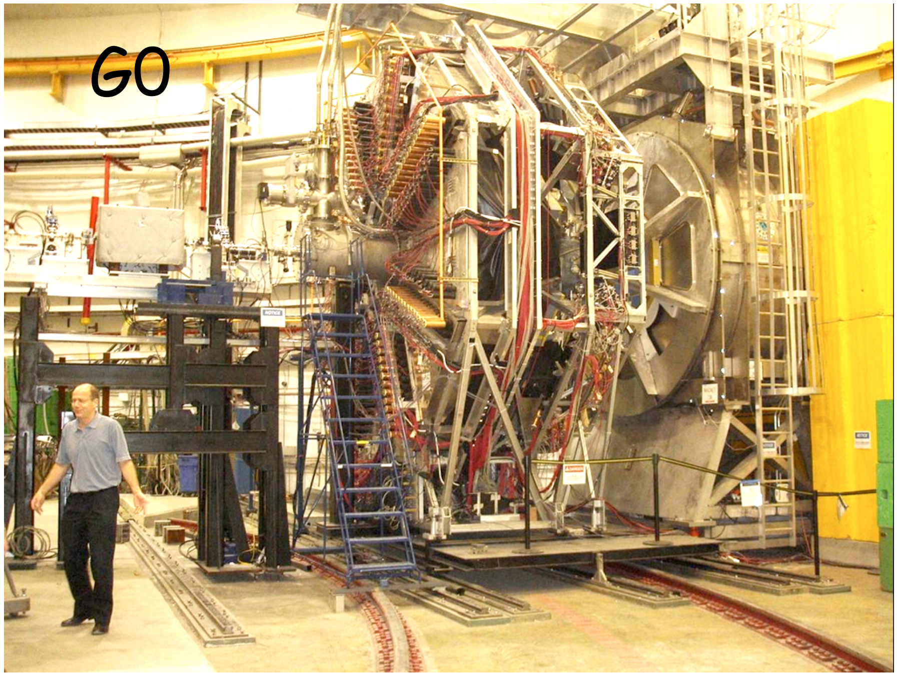
Statistics: high rate, low noise
Systematics: beam asymmetries, backgrounds, helicity-correlated pickup
Normalization: Polarization, linearity, dilution

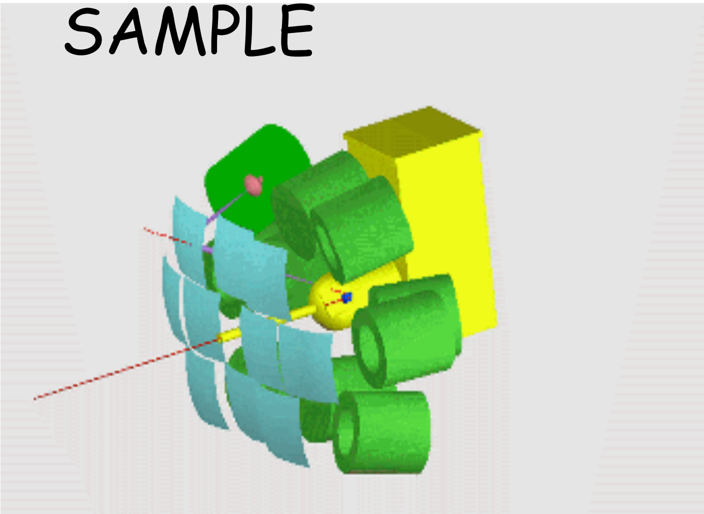
Parity-Violating Electron Scattering Program

Expt/Lab	Target/ Angle	Q^2 (GeV^2)	A_{phys} (ppm)	Sensitivity	Status
SAMPLE/Bates					
SAMPLE I	LH_2/145	0.1	-6	$G_M + 0.4G_A$	2000
SAMPLE II	LD_2/145	0.1	-8	$G_M + 2G_A$	2004
SAMPLE III	LD_2/145	0.04	-4	$G_M + 3G_A$	2004
HAPPEx/JLab					
HAPPEx	LH_2/12.5	0.47	-15	$G_E + 0.39G_M$	1999
HAPPEx II	LH_2/6	0.11	-1.6	$G_E + 0.1G_M$	2006, 2007
HAPPEx He	^4He/6	0.11	+6	G_E	2006, 2007
HAPPEx III	LH_2/14	0.63	-24	$G_E + 0.5G_M$	(2009)
PV-A4/Mainz					
	LH_2/35	0.23	-5	$G_E + 0.2G_M$	2004
	LH_2/35	0.11	-1.4	$G_E + 0.1G_M$	2005
	LH_2/145	0.23	-17	$G_E + \eta G_M + \eta' G_A$	2009
	LH_2/35	0.63	-28	$G_E + 0.64G_M$	(2009)
G0/JLab					
Forward	LH_2/35	0.1 to 1	-1 to -40	$G_E + \eta G_M$	2005
Backward	LH_2/LD_2/110	0.23, 0.63	-12 to -45	$G_E + \eta G_M + \eta' G_A$	2009


HAPPEx

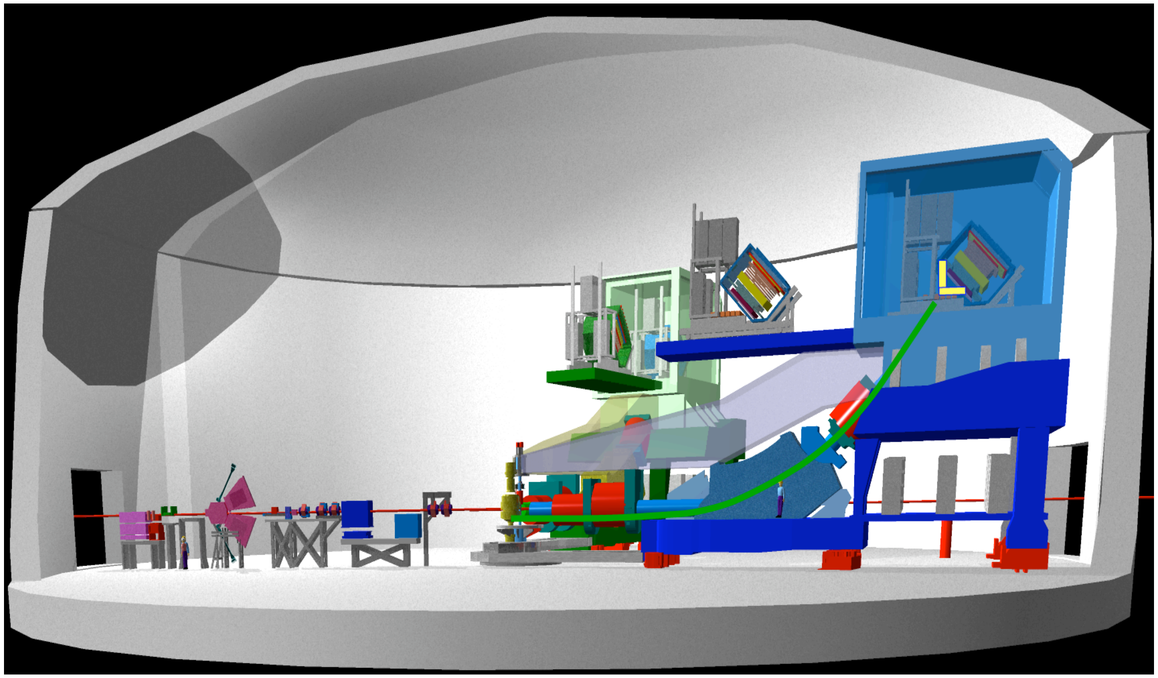

PV-A4


GO


SAMPLE

HAPPEX-I Jlab/Hall-A

Hydrogen Target: $E = 3.3\ \mathrm{GeV}$ $\theta = 12.5°$ $Q^2 = 0.48\ (\mathrm{GeV}/c)^2$



$A^{PV} = -14.92\ \mathrm{ppm} \pm 0.98\ (\mathrm{stat})\ \mathrm{ppm} \pm 0.56\ (\mathrm{syst})\ \mathrm{ppm}$

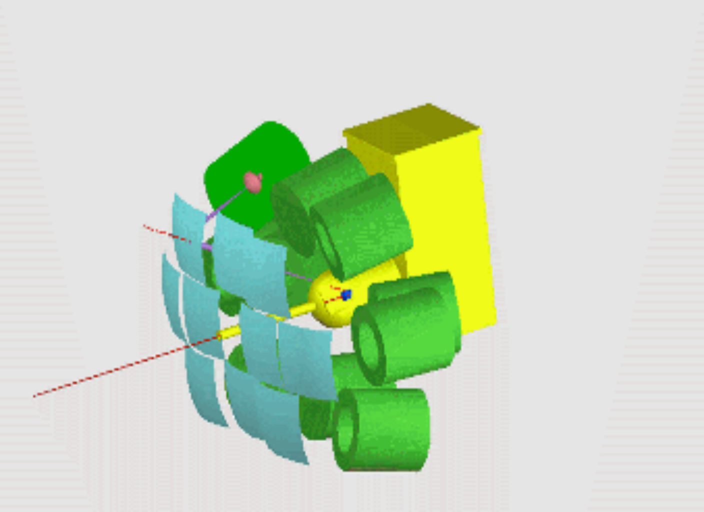
$$\boxed{G^s_E + 0.39 G^s_M = 0.014 \pm 0.020\ (exp) \pm 0.010\ (FF)}$$

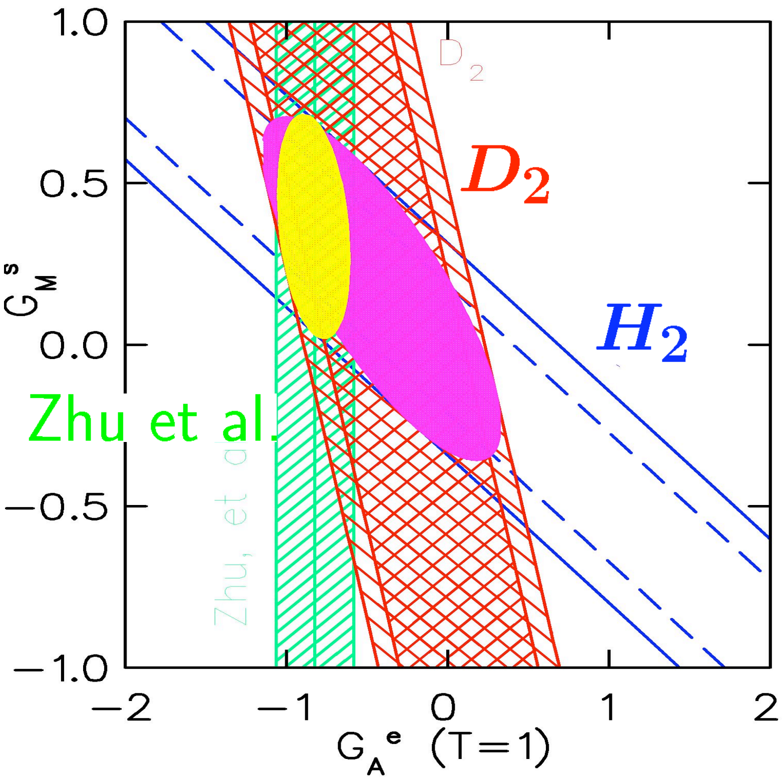
Phys. Rev. Lett. 82,1096 (1999);
Phys. Lett. B509, 211 (2001);
Phys. Rev. C 69, 065501 (2004)

SAMPLE (MIT/Bates)

Backward angle (θ=150°), integrating

Q^2(GeV^2)	A_{PV} (ppm)	$A_0 + \alpha G^s_M + \beta G^e_A(T=1)$
$0.1, LH_2$	$-5.61 \pm 0.67 \pm 0.88$	$-5.56 + 3.37 G^s_M + 1.54 G^e_A$
$0.1, LD_2$	$-7.06 \pm 0.73 \pm 0.72$	$-7.06 + 0.72 G^s_M + 1.66 G^e_A$
$0.03, LD_2$	$-3.51 \pm 0.57 \pm 0.58$	$-2.14 + 0.27 G^s_M + 0.76 G^e_A$





G_M^s = 0.23 ± 0.36 ± 0.40

$G_A^{e\,(T=1)}$ = -0.53 ± 0.57 ± 0.50

E.J. Beise *et al.*, Prog Nuc Part Phys 54 (2005)

Results of Zhu *et al.* commonly used to constrain G^s_M result:

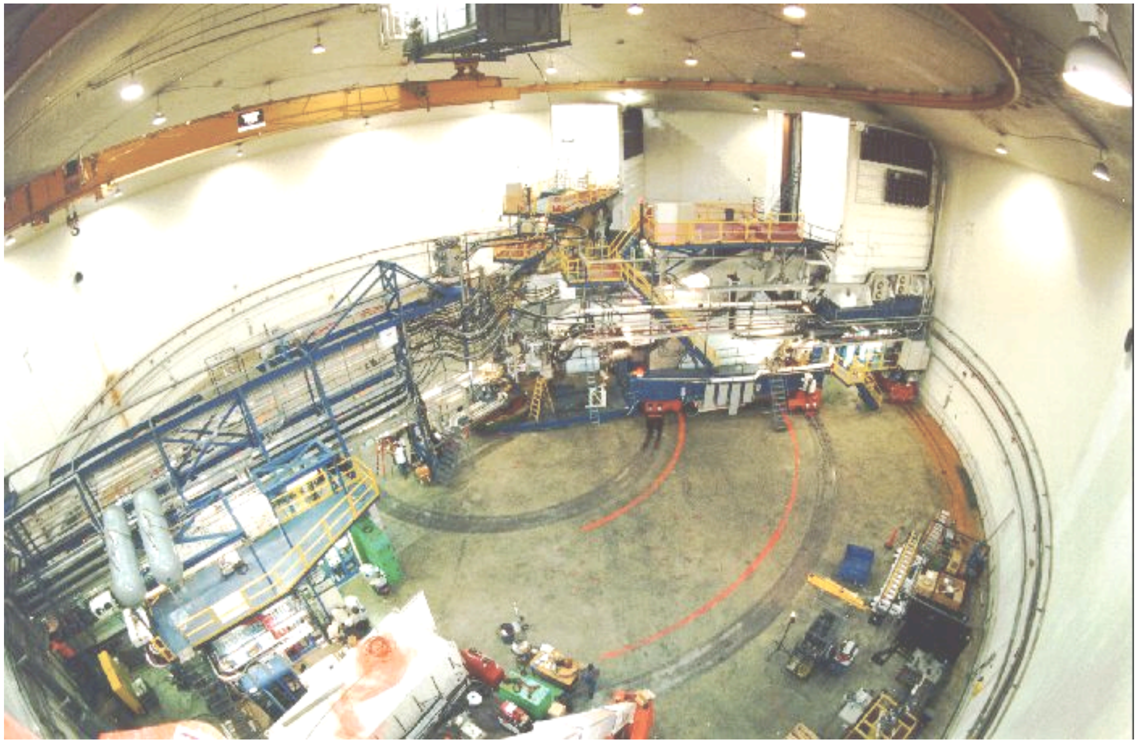
$G^s_M = 0.37 \pm 0.20_{Stat} \pm 0.36_{Syst} \pm 0.07_{FF}$

HAPPEX-II

E=3 GeV $\theta=6°$ Q^2= 0.1 $(\text{GeV}/c)^2$

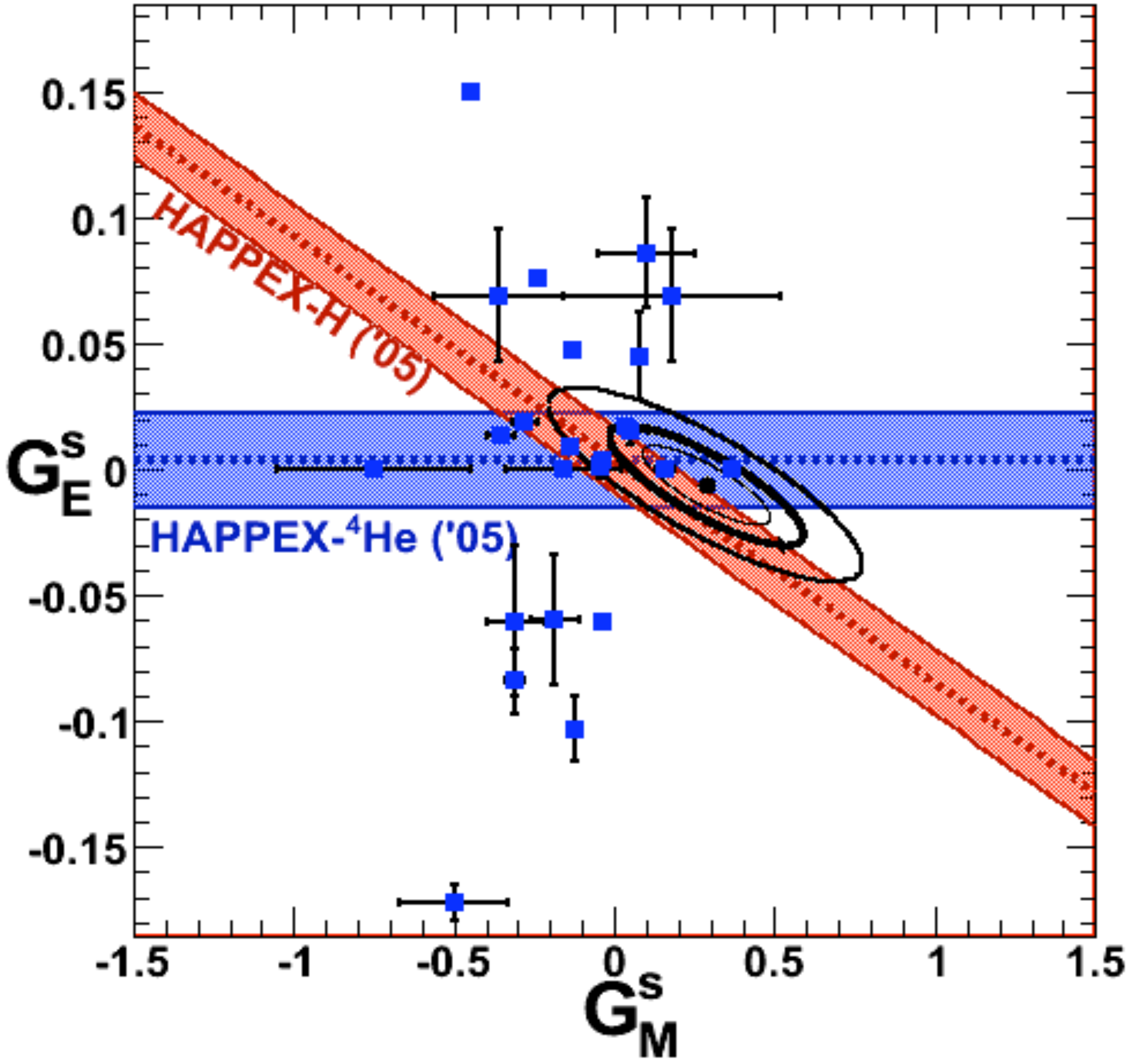
- **Hydrogen** : $G_E^s + \eta G_M^s$
- **^{4}He**: Pure G_E^s : $A^{PV} = -\frac{A_0}{2}\left(2\sin^2\theta_W + \frac{G_E^s}{G_E^{p\gamma} + G_E^{n\gamma}}\right)$

2 runs: 2004 & 2005



A. Acha, et al. PRL 98(2007)032301

World Data near Q^2 ~0.1 GeV^2



$$G_M^s = 0.28 \pm 0.20$$

21% of $\mu_N^{T=0}$

$$\langle r^2 \rangle_E^p = 0.766 \pm 0.012\, fm^2$$

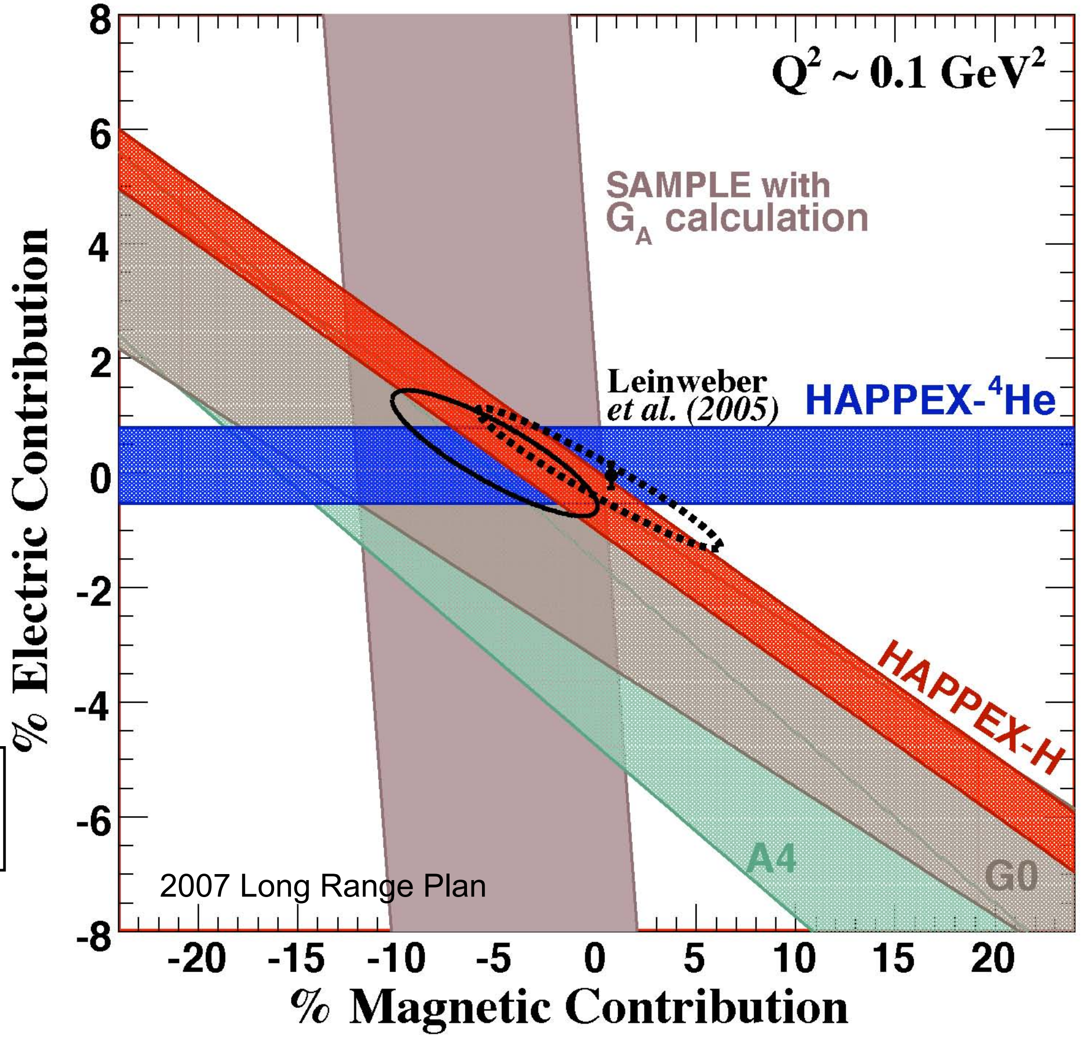
$$\langle r^2 \rangle_E^s = 0.002 \pm 0.015\, fm^2$$

Summary of data at $Q^2 = 0.1\ \mathrm{GeV}^2$

Solid ellipse:
K. Paschke, priv. comm.
[≈ J. Liu et al.
PRC 76, 025202 (2007)]
uses theoretical constraints
on the axial form factor

Dashed ellipse:
R.D. Young et al.
PRL 97 (2006) 102002,
does not constrain G_A
with theory

note: Placement of SAMPLE band on depends on choice for G_A



(figure: thanks to K. Paschke, R. Young)

$$\%\ \text{contrib} = \frac{G^s_{E,M}}{G^p_{E,M}} \times \left(-\frac{1}{3}\right) \times 100$$

Theoretical Refinements

1. Two Boson exchange: H.Q. Zhou, C.W. Kao and S.N. Yang
   Phys.Rev.Lett.99:262001 (2007); Phys.Rev.C79:062501 (2009)

   γZ box dominates the two boson effects at HAPPex, PVA4 kinematics

   → reduces extracted $G^s_E + \beta\, G^s_M$

   (not yet put into global fits)

2. Charge-symmetry breaking effects:

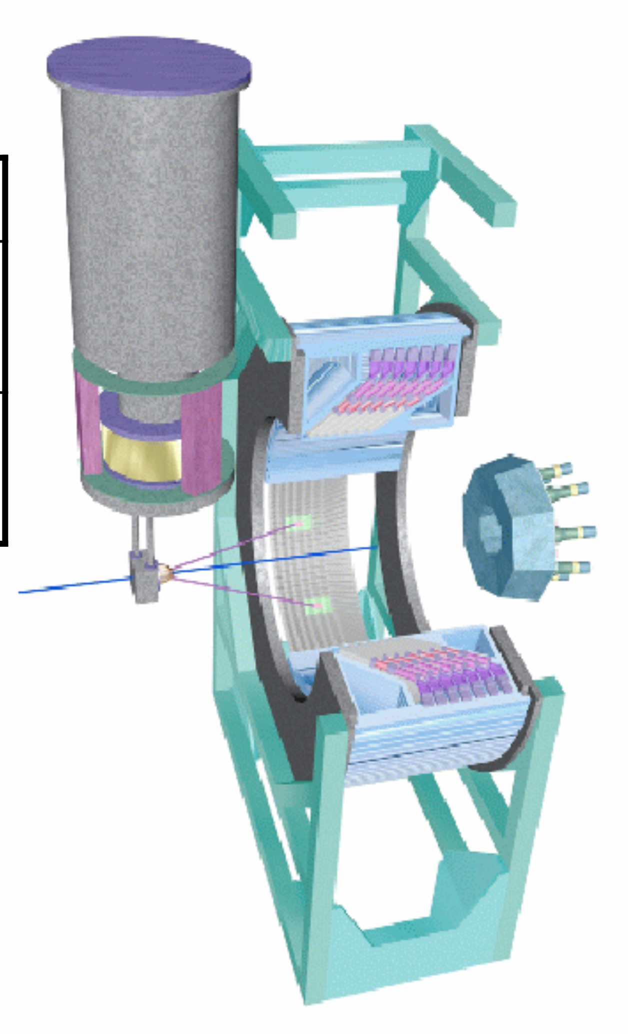
   Hydrogen: B. Kubis & R. Lewis Phys. Rev. C 74 (2006) 015204
   ^{4}He: Viviani, Schiavilla, Kubis, Lewis, et al.
   Phys.Rev.Lett.99:112002,2007

   still only a (modest) fraction of smallest experimental statistical errors.

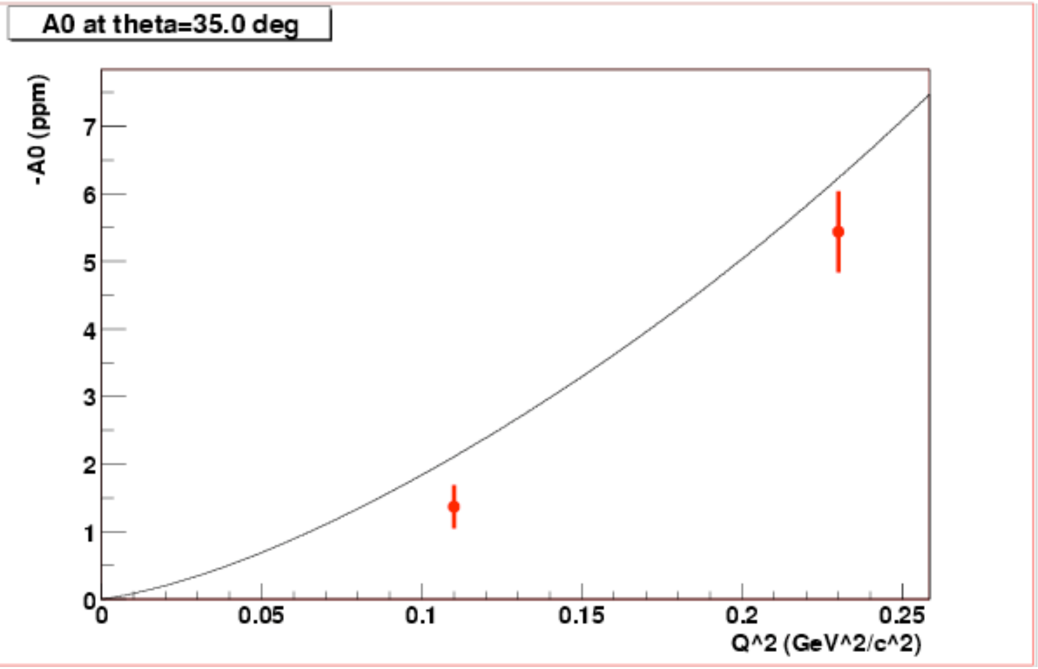
   (not yet put into global fits)

PV-A4 (MAMI/Mainz)

Q^2 (GeV^2)	A ± stat ± syst (ppm)	$G_E^s + \eta G_M^s$
0.230	-5.44 ± 0.54 ± 0.26	$G_E^s + 0.225\, G_M^s$ $= 0.039 \pm 0.034$
0.110	-1.36 ± 0.29 ± 0.13	$G_E^s + 0.106\, G_M^s$ $= 0.071 \pm 0.036$

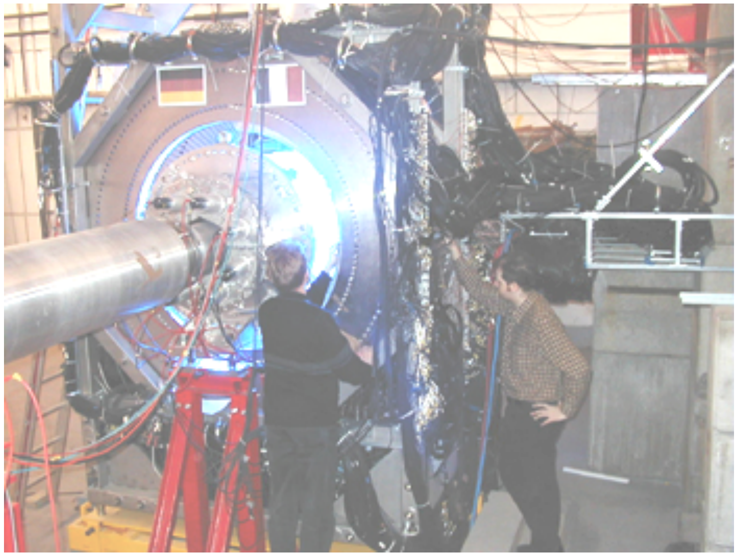


Counting – fast energy histograms



"Evidence for Strange Quark Contributions to the Nucleon's Form Factors at Q^2 = 0.1 GeV^2"
F. Maas et al. PRL 94, 152001 (2006)

New results from PV-A4
(MAMI/Mainz)



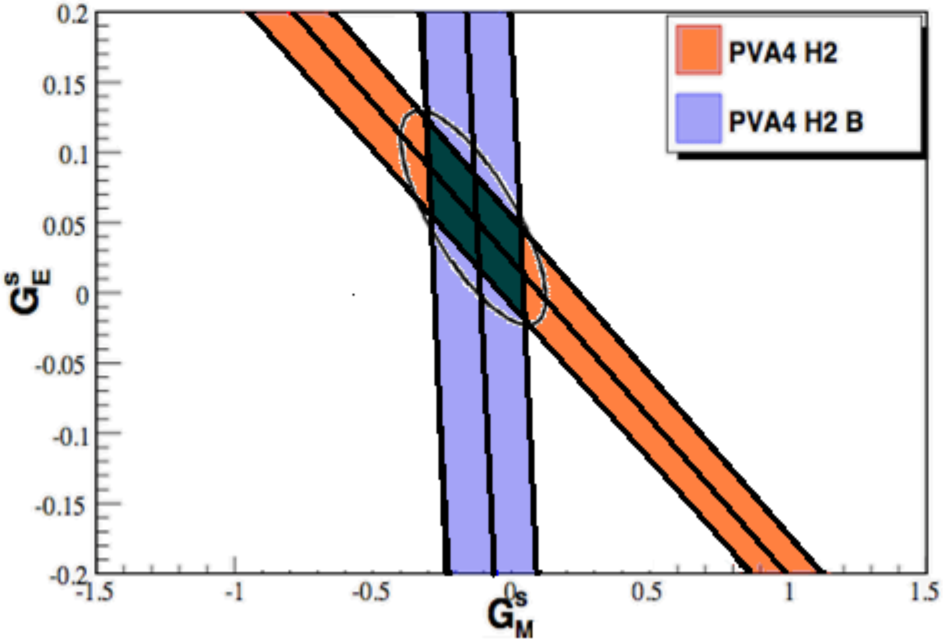
$\Theta = 145°$

$Q^2 = 0.22\ (\mathrm{GeV}/c)^2$

$A_{meas} = -17.23 \pm 0.82 \pm 0.89$ ppm

$G^s_E = 0.050 \pm 0.038 \pm 0.019$
$G^s_M = -0.14 \pm 0.11 \pm 0.11$

(use theoretical constraint of Zhu et al., for the axial FF)



% contribution to proton:

electric: 3.0 ± 2.5 %
magnetic: 2.9 ± 3.2 %

S. Baunack et al., PRL 102 (2009) 151803

Deuterium results at same Q2 – still being analyzed….

G^0 (JLab – Hall C)

- Superconducting toroidal magnetic spectrometer

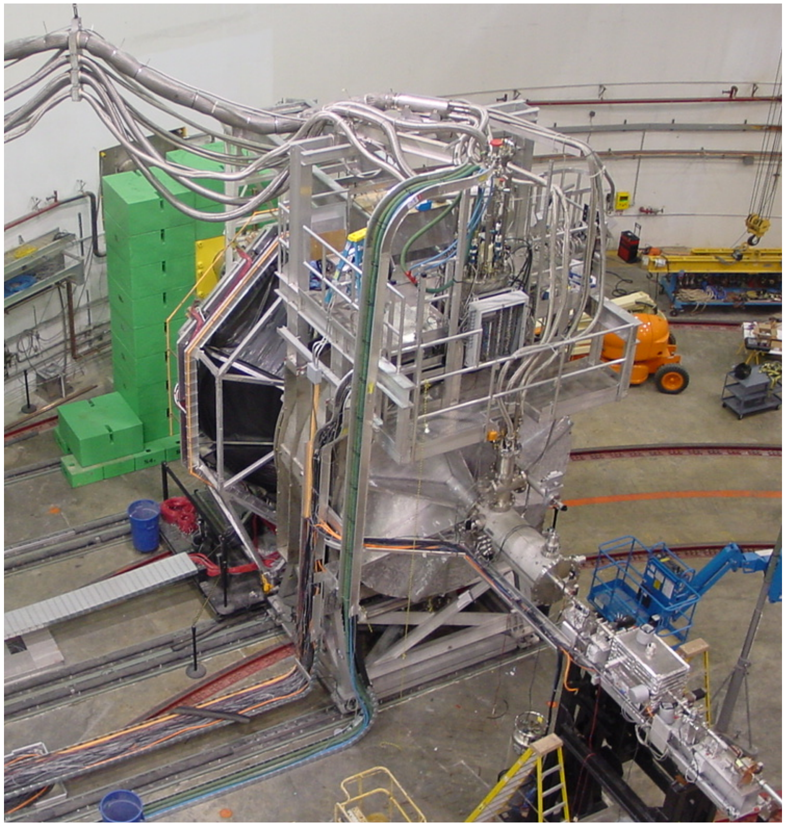
Forward angle mode

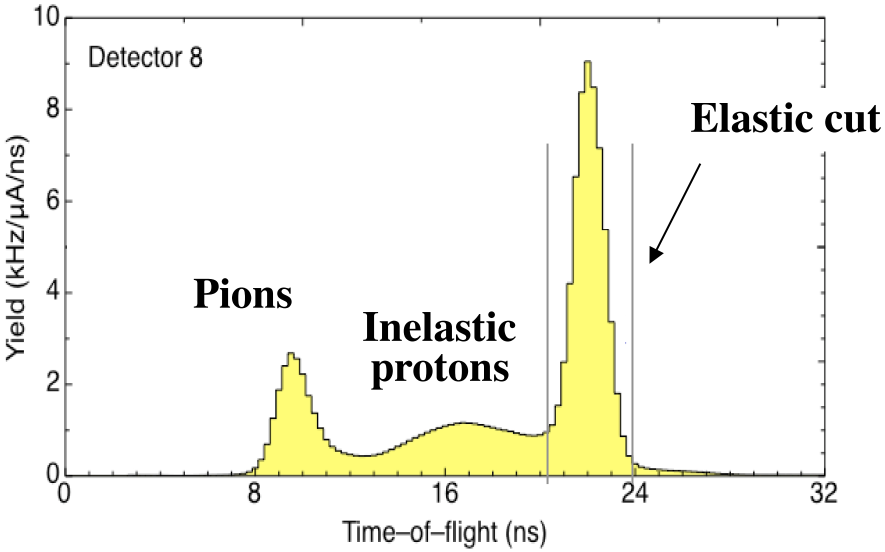
- LH_2: E_e = 3.0 GeV

  Recoil proton detection

  ➯ $0.12 \leq Q^2 \leq 1.0$ $(GeV/c)^2$

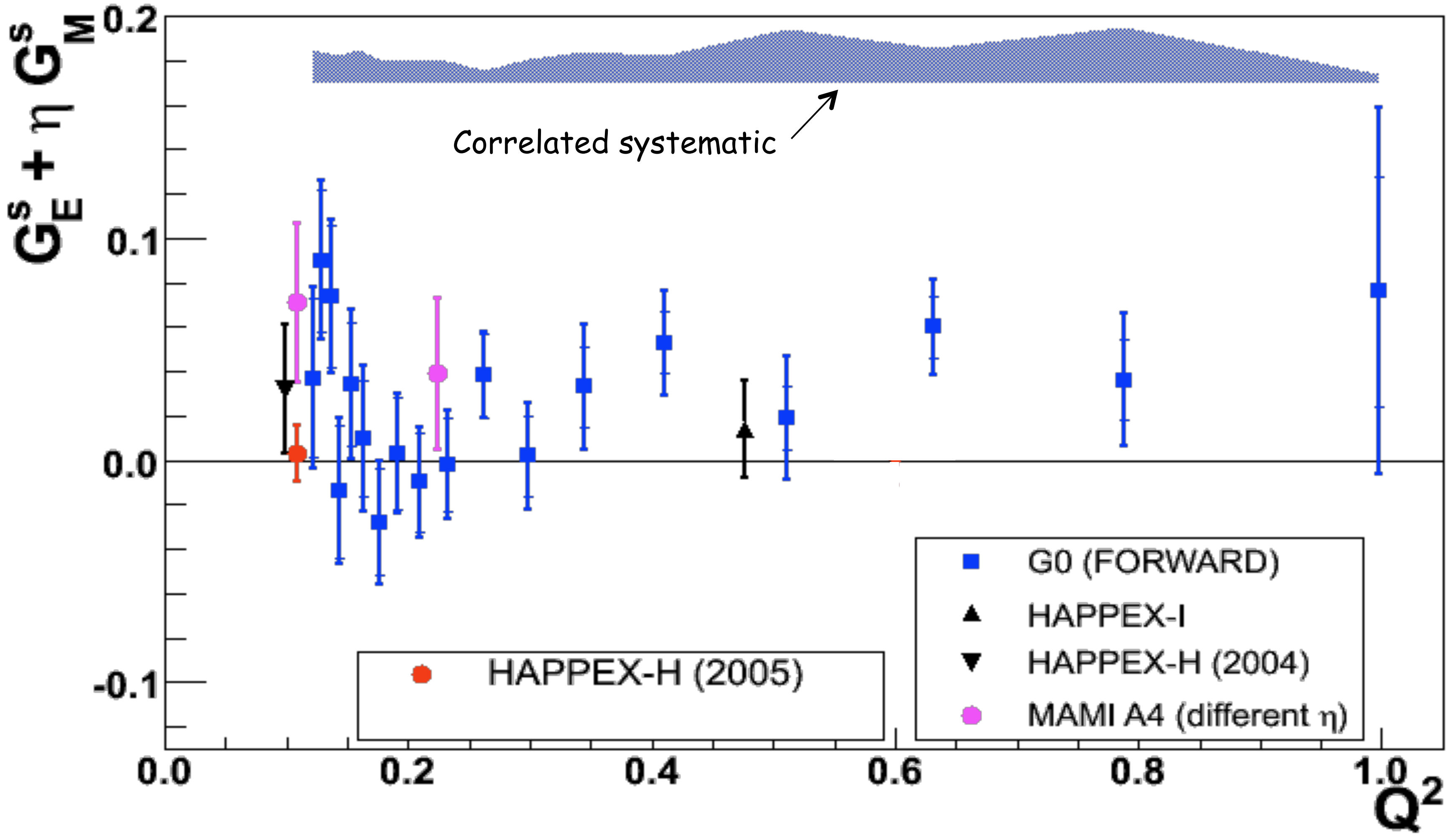
- Counting experiment – separate backgrounds via time-of-flight





G0: Forward-angle results

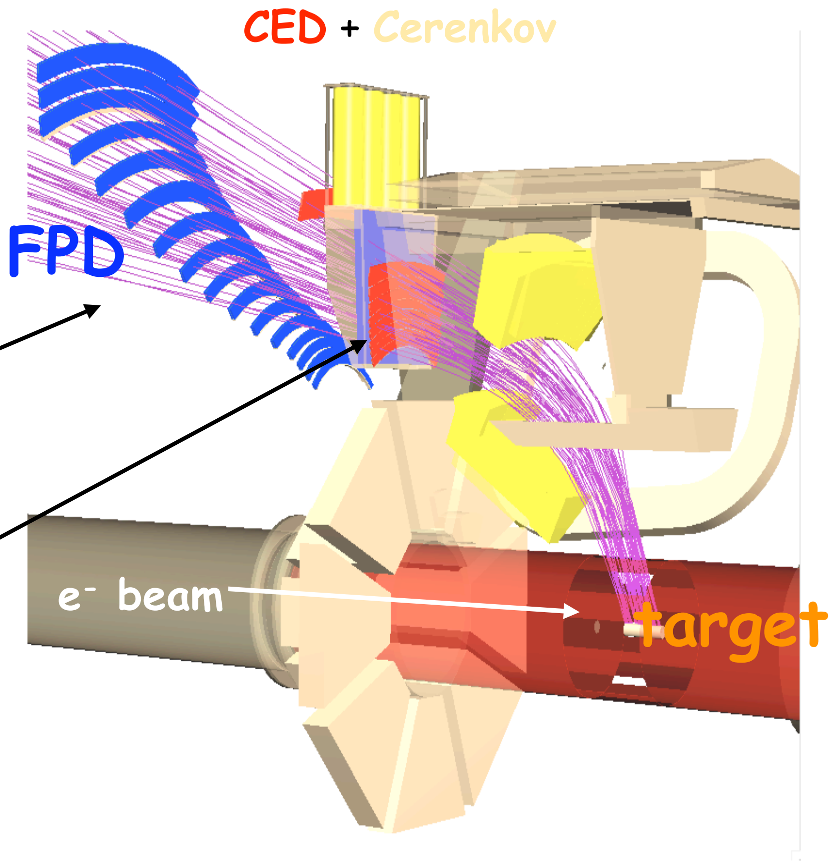
EM form factors:
J.J.Kelly, PRC **70,**
068202 (2004)



$G_E^s = G_M^s = 0$ Hypothesis excluded at 89% C.L.

D.S. Armstrong *et al.*, PRL 95, 092001 (2005)

G0 Back Angle Apparatus: schematic



Single Octant Schematic

🟫 🟨 Shielding

FPD: Focal Plane Detector

CED: Cryostat Exit Detector

Kinematic separation of elastic, inelastic

- Polarized electron beam at 362, 687 MeV
- Target: 20 cm LH_2, LD_2
- (quasi)elastic, inelastic scattering at ~108°
- Electron/pion separation using aerogel Cerenkov

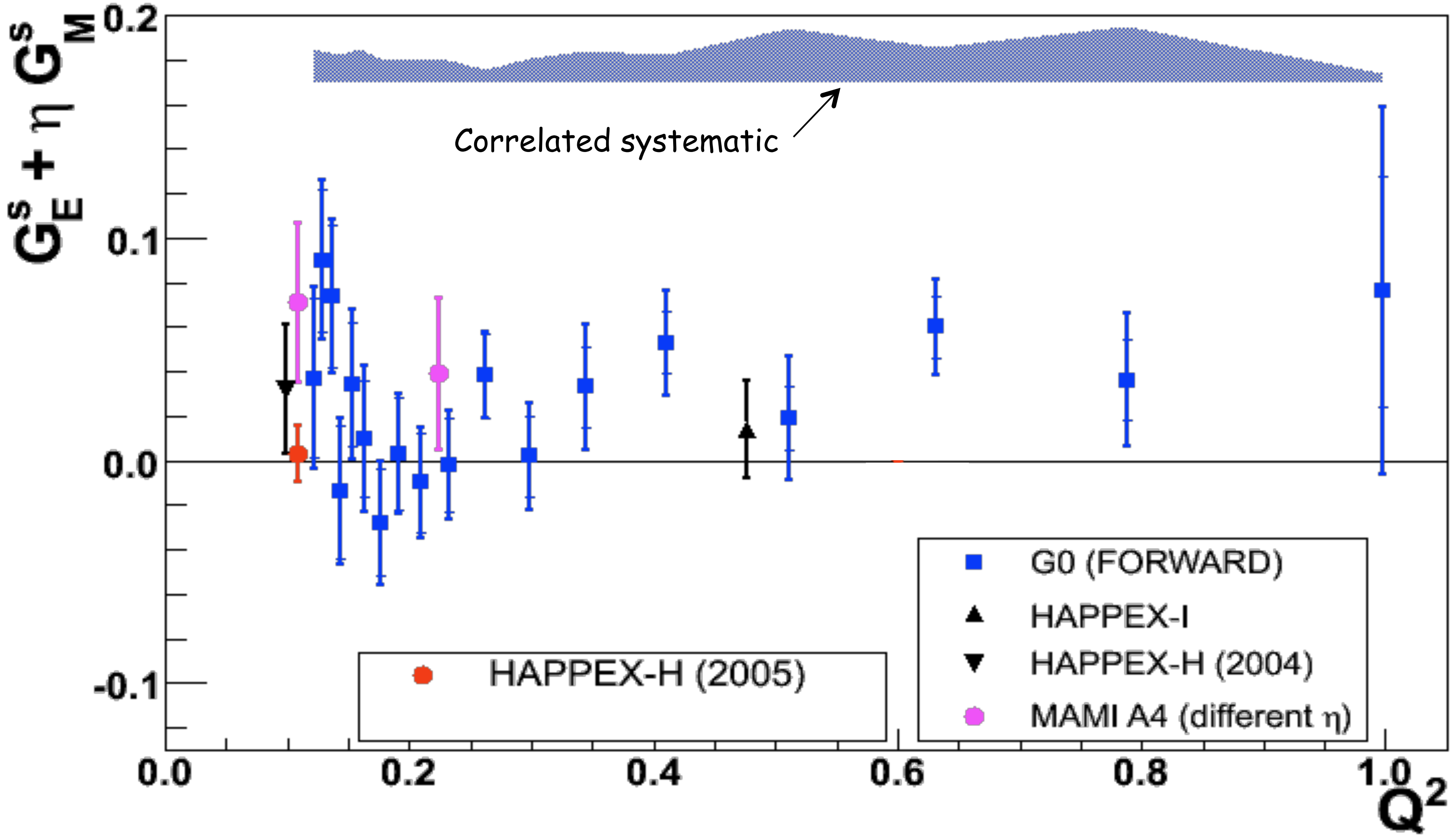
G0 Asymmetries

(backward angle measurements)

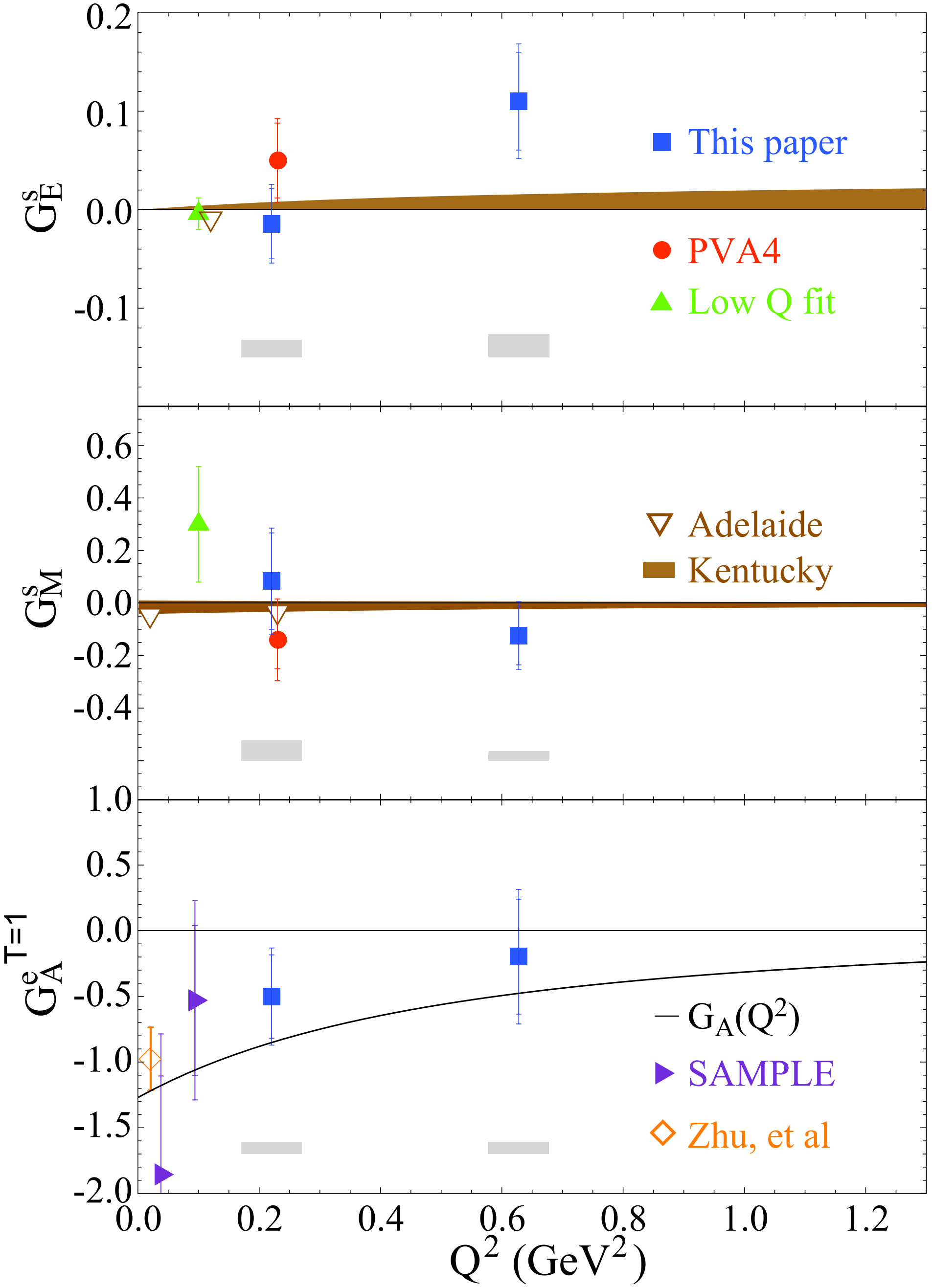
Set	Asymmetries *(ppm)*	Stat *(ppm)*	Sys pt *(ppm)*	Sys Global *(ppm)*	Total *(ppm)*
H 362	-11.416	0.872	0.268	0.385	0.990
D 362	-17.018	0.813	0.411	0.197	0.932
H 687	-46.14	2.43	0.84	0.75	2.68
D 687	-55.87	3.34	1.98	0.64	3.92

See Fatiha Benmokhtar's talk: CF-4

Forward Angle Results - reminder



G0 Backward Angle Results



Combined with interpolation of
G0 forward measurements

assumes:

$$G_{A,NS}^{T=0}\left(Q^2\right) = R_A^{T=0}\,\frac{3F-D}{2}\,G_A^{dipole}\left(Q^2\right)$$

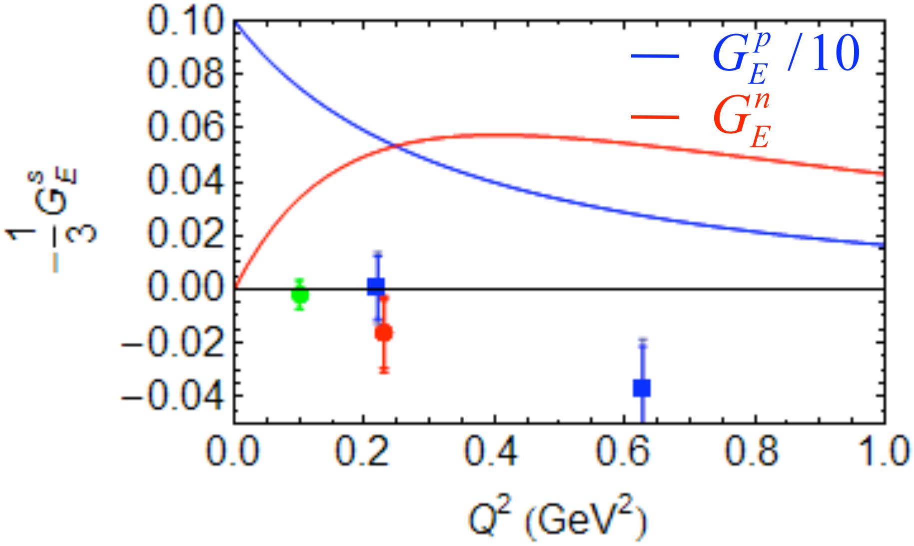
$$G_{A,NS}^{T=0}\left(Q^2=0\right) = 0.070$$

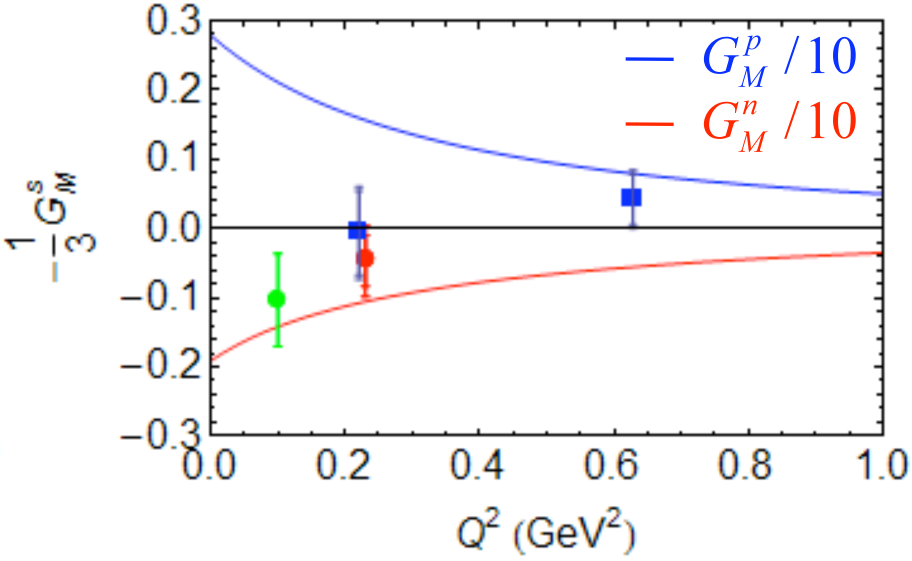
Also assumes: no CSV

▨ = Global systematic

D. Androic *et al.* arXiv :0909.5107

Contributions to Overall Form Factors



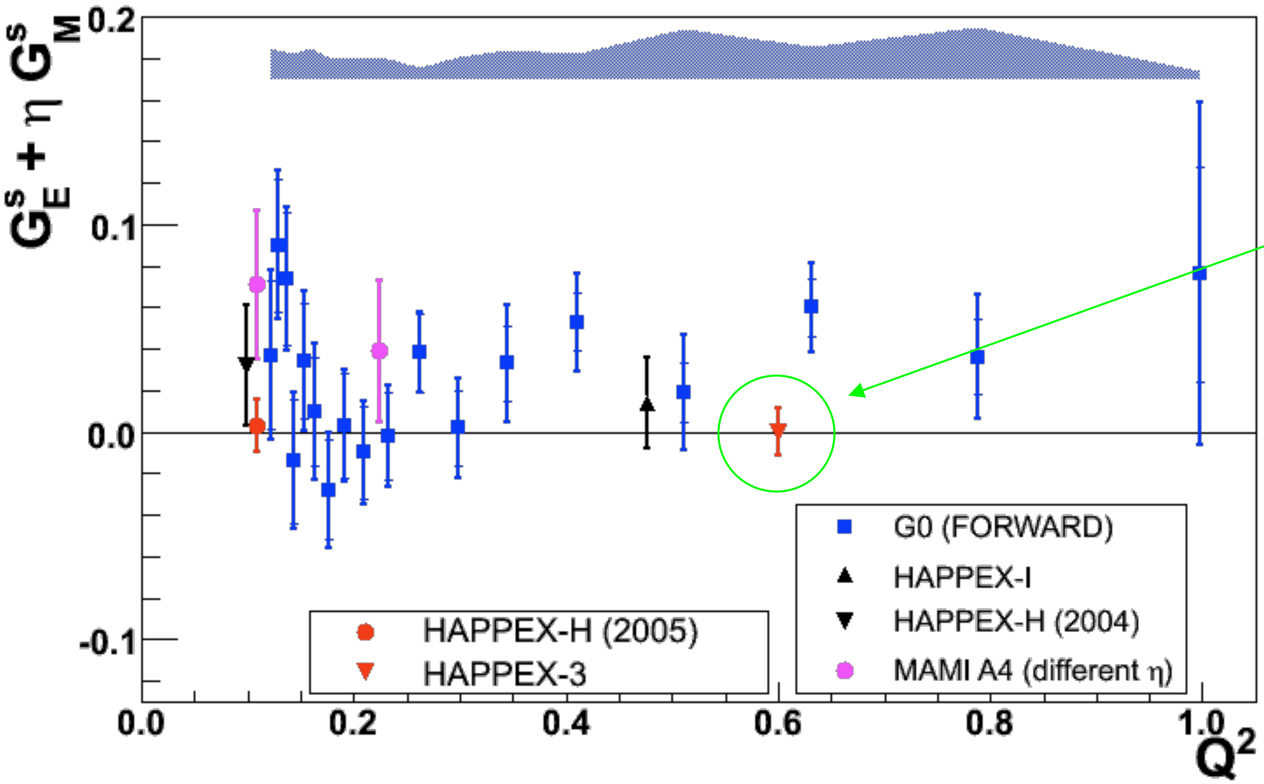


Advertisement: other physics from G0

- First measurement of neutral current NΔ transition around $Q^2 = 0.3\ GeV^2$
  (See Carissa Capuano's talk BD-9, Wed. evening)

- First measurement of PV asymmetry in inclusive π^- production at low Q^2
  (related to anomalous $\Delta S = 1$ hyperon decays)
- Two-photon exchange seen via beam-normal single spin asymmetries
  (See Juliette Mammei's talk BF-6, Wed. evening)

HAPPEX-III Spokepersons: K. Paschke & P. Souder



Running now!
Finishes Oct 28
2009

A higher precision repeat of HAPPEx-I, at slightly higher Q^2
(0.63 GeV^2 – matches G0 backward data point)

- 100 μA beam current, 89% polarization (c.f. 35 μA at 70% polarization for HAPPEx-I)
- If central value from G0 holds, could see ≈ 5σ non-zero strange quark signal.

PV-A4 also now taking data at ≈ same Q^2

Summary

- Comparison of electromagnetic and weak neutral elastic form factors allows determination of strange quark contribution
  - large distance scale dynamics of the sea
- Separated form factors at three Q^2
- Small positive G_E^s at highest Q^2, G_M^s consistent with zero, small quenching of G_A^e, consistent with theory

- Next steps:
  - newer data very soon at $Q^2 = 0.63$ (HAPPEx-III, PV-A4)
  - global fits to all 36 asymmetries, including 2-boson & CSV effects, consistent electromagnetic form factors
  - no plans on pushing experimental effort further… lattice?

"Do not infest your mind with beating on the strangeness of this business" - W. Shakespeare (The Tempest)