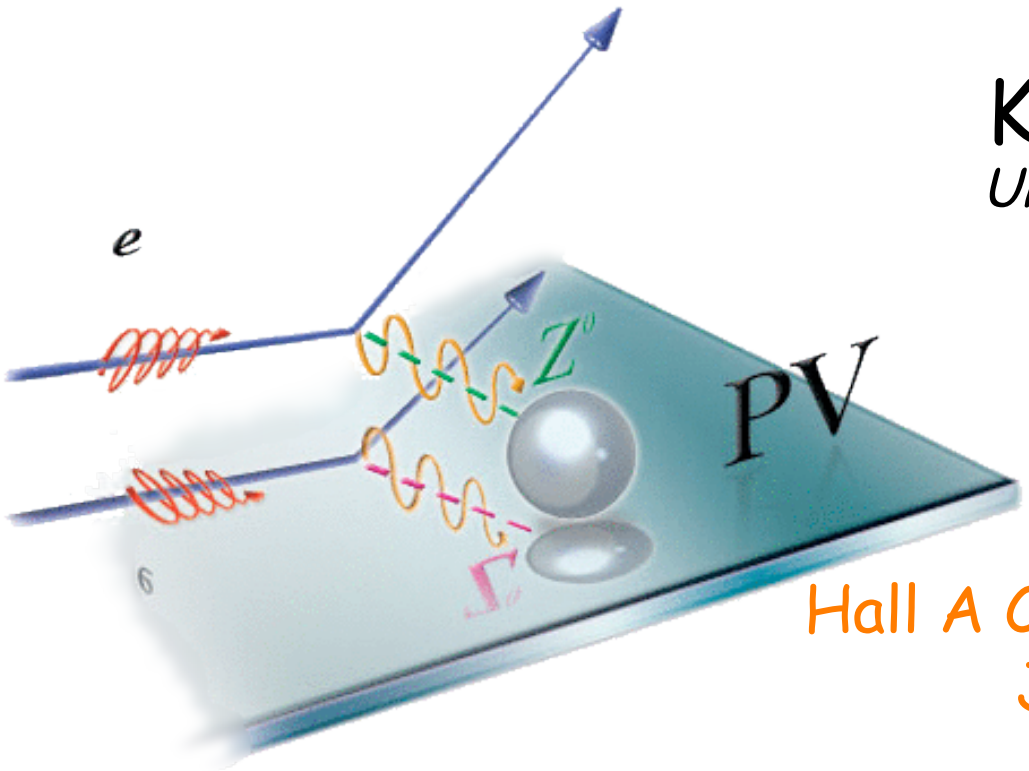
E05-009: HAPPEX-III Update



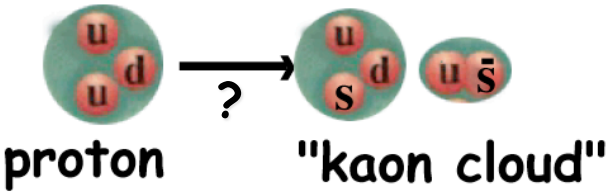
Kent Paschke
University of Virginia

Hall A Collaboration Meeting
June 13, 2008

The Neutral Current and Nucleon Vector Form Factors

Strange quarks exist in the nucleon at short distance scales. Do they play a role in the long-distance interaction of the proton?

proton flavor distribution



Can the quark model really predict static properties?

At very low Q^2, $G^s_{E/M}$ relates to the strange matrix elements of the nucleon (strange radius ρ_s and strange magnetic moment μ_s)

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

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

Using Charge Symmetry:

Remove $G^u_{E,M}$, $G^d_{E,M}$ from G^Z, replace with the well-measured $G^{\gamma,p}_{E,M}$, $G^{\gamma,n}_{E,M}$

$$G^Z_{E/M} = \left(1-4\sin^2\theta_W\right)G^{\gamma p}_{E/M} - G^{\gamma n}_{E/M} - G^s_{E/M}$$

Measuring Strange Vector Form Factors

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{\gamma \quad Z^0}{\gamma^2} \sim \frac{10^{-4} Q^2}{\mathrm{GeV}^2}$$

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

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

$$A_E = \epsilon G_E^p G_E^Z \qquad A_M = \tau G_M^p G_M^Z \qquad A_A = (1 - 4\sin^2\theta_W)\epsilon' G_M^p \tilde{G}_A$$

Forward angle | Backward angle

For a spin=0, T=0 ^{4}He: G^s_E only!

For deuterium: Enhanced G_A

The Axial Term and the Anapole Moment

Axial form-factors G_A^p, G_A^n:

- Determined at Q^2=0 from neutron and hyperon decay parameters (isospin and SU(3) symmetries)
- Q^2 dependence assumes dipole form, fit to ν-DIS and π electroproduction
- Includes also Δs, fit from ν-DIS data

$$\tilde{G}_A^{p,n} = -\tau_3\left(1 + R_A^{T=1}\right)G_A^{(3)} + \sqrt{3}R_A^{T=0}G_A^{(8)} + \Delta s$$

Anapole Moment Correction:

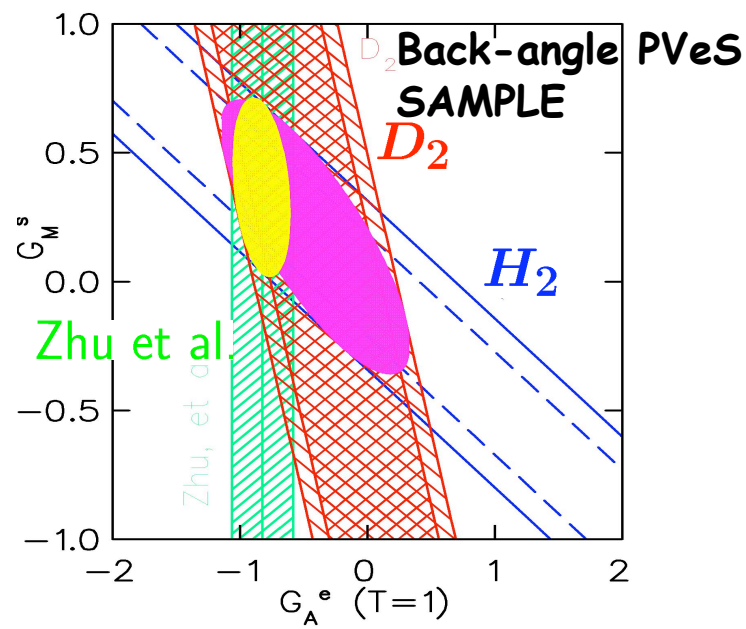
Multiquark weak interaction modifies axial form-factor

Zhu, Puglia, Holstein, Ramsey-Musolf, Phys. Rev. D **62**, 033008

Large uncertainty estimated to account for specific uncalculated terms

Uncertainty dominates axial term

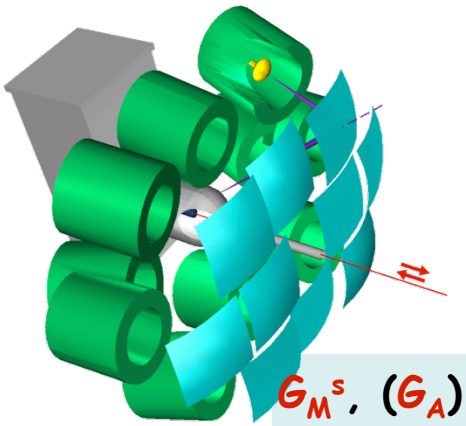
Experimental constraint is very poor



$G^e_A{}^{(T=1)}$ = -0.53 ± 0.57 ± 0.50

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

Experimental Overview



SAMPLE

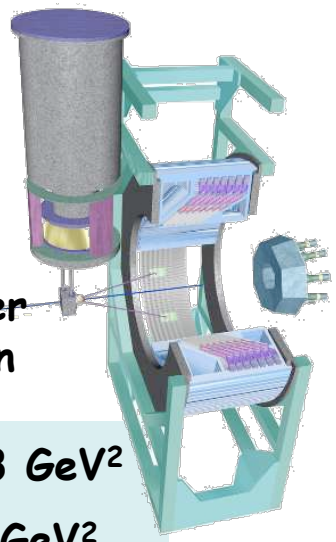
open geometry, integrating

G_M^s, (G_A) at Q^2 = 0.1 GeV^2

A4

Open geometry

Fast counting calorimeter for background rejection



G_E^s + 0.23 G_M^s at Q^2 = 0.23 GeV^2

G_E^s + 0.10 G_M^s at Q^2 = 0.1 GeV^2

G_M^s, G_A^e at Q^2 = 0.23 GeV^2

HAPPEX

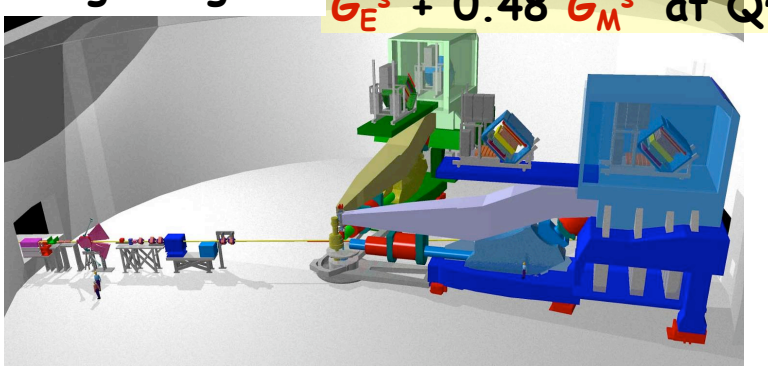
Precision spectrometer, integrating

G_E^s + 0.39 G_M^s at Q^2 = 0.48 GeV^2

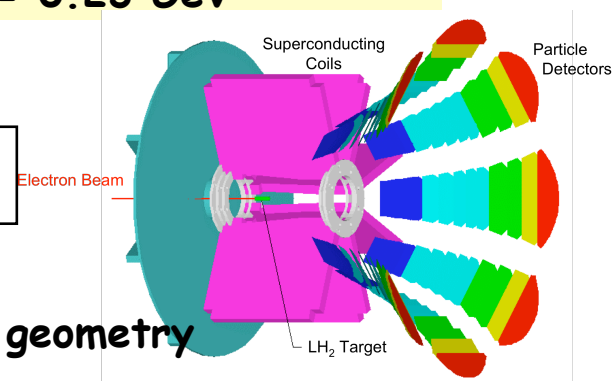
G_E^s + 0.08 G_M^s at Q^2 = 0.1 GeV^2

G_E^s at Q^2 = 0.1 GeV^2 (^{4}He)

G_E^s + 0.48 G_M^s at Q^2 = 0.62 GeV^2



G0



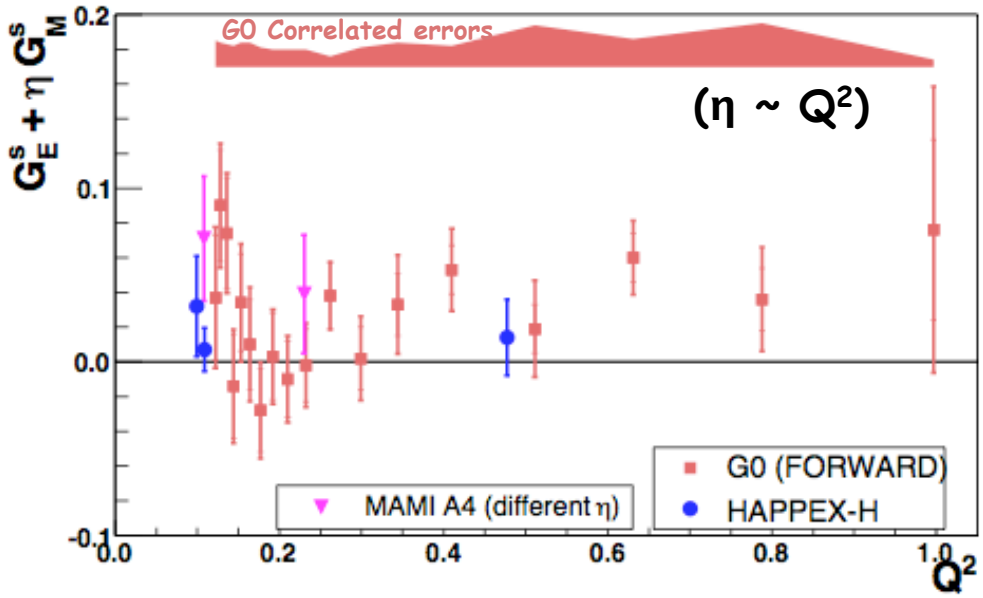
Open geometry

Fast counting with magnetic spectrometer + TOF for background rejection

G_E^s + ηG_M^s over Q^2 = [0.12,1.0] GeV^2

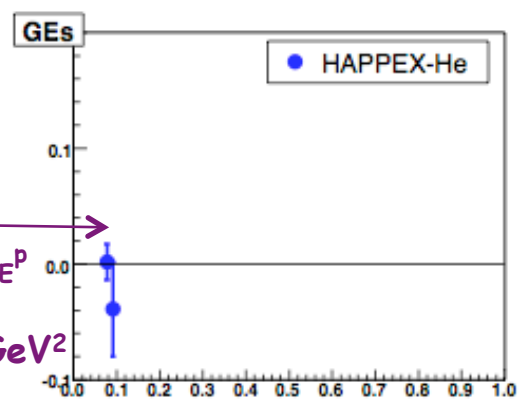
G_M^s, G_A^e at Q^2 = 0.23, 0.62 GeV^2

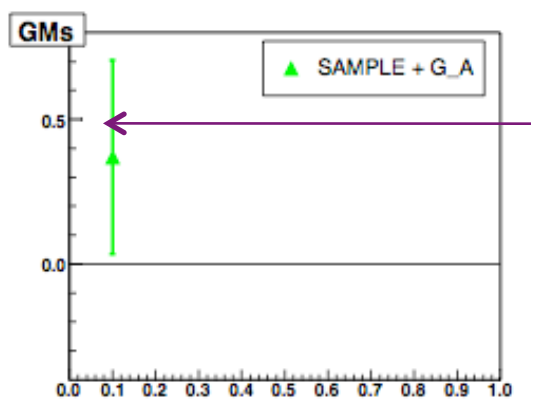
World data (on G_E^s, G_M^s)



The data is consistent, with systematic preference for a positive result...

...but not conclusive



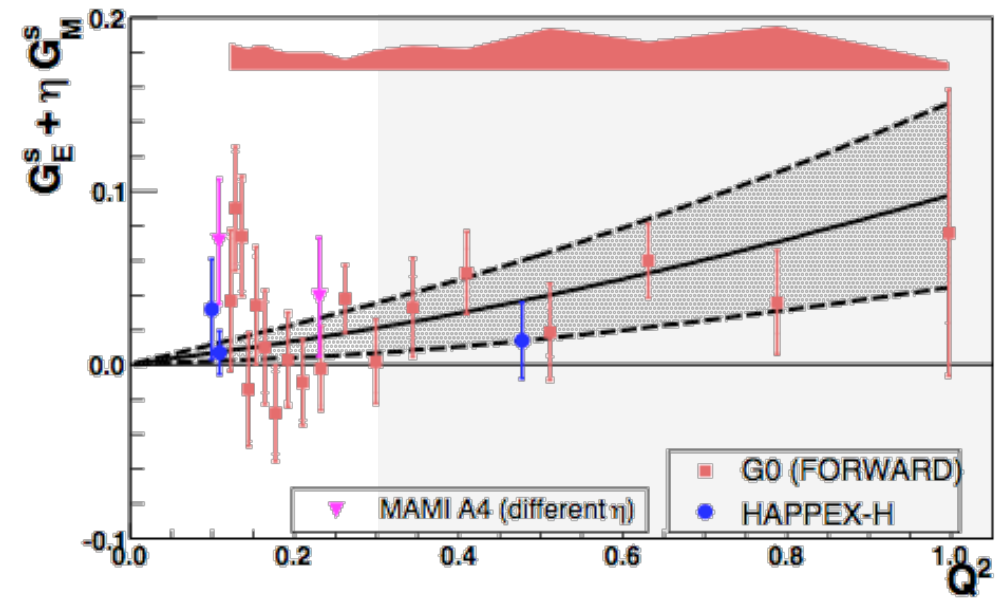


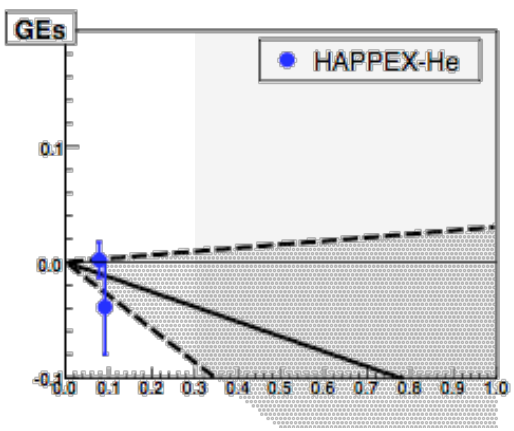
1% of G_E^p at Q^2=0.1GeV²

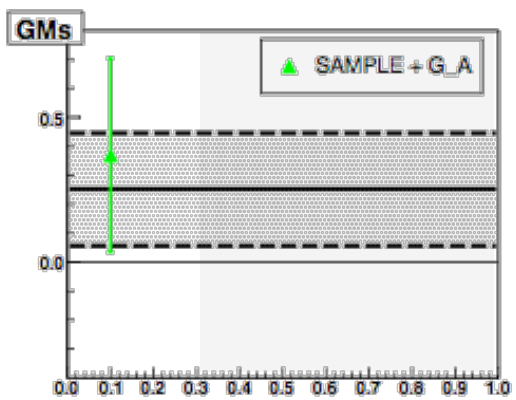
6% of proton magnetic moment

High Q^2 and back-angle results assume anapole moment correction is under control

A Simple Fit







Simple fit:

$G_E^s = \rho_s * \tau$

$G_M^s = \mu_s$

Includes only data $Q^2 < 0.3$ GeV^2

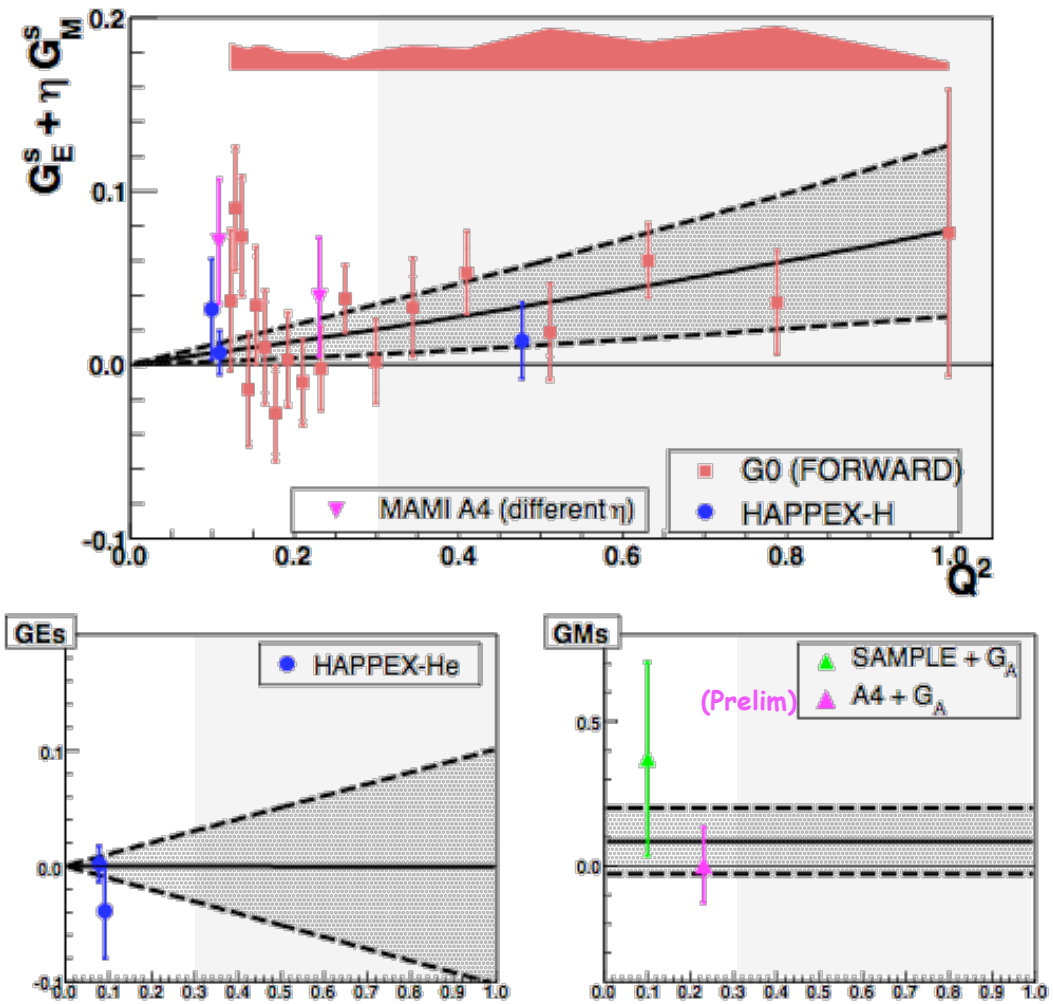
Similar to R. Young fit, but no care taken to re-parse experimental reports

Quantitative values should NOT be taken very seriously, but sizeable contributions at higher Q^2 are not definitively ruled out.

Are they even suggested?

- **Q^2 evolution unknown**
- **G0 results for Q^2>0.4 deviate by ~17% from s=0, but systematics dominated (f_B ~ 20%, δA_B~40-60%)**

Preliminary A4 results

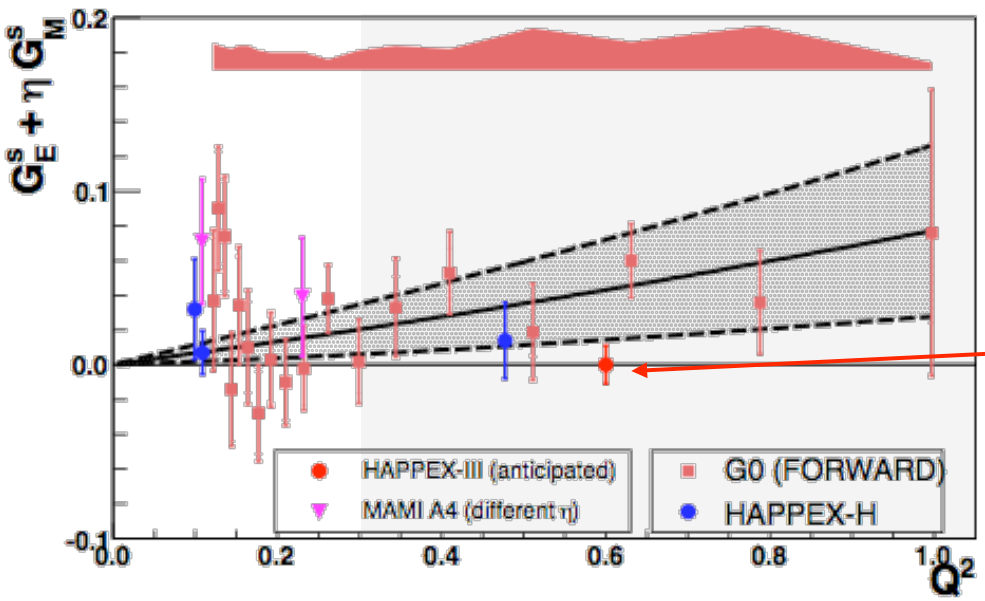


Preliminary A4 back angle proton results released

From: Frank Maas, MENU07, FZ Julich, Sept 10, 2007

Consistent with zero strangeness... but this fit precision requires assumptions on anapole corrections

Definitive precision at higher Q^2



Forward angle HAPPEX advantages:

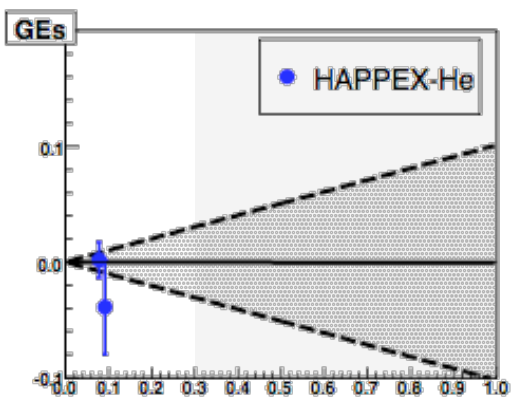
- low background
- low systematic error
- small axial contribution

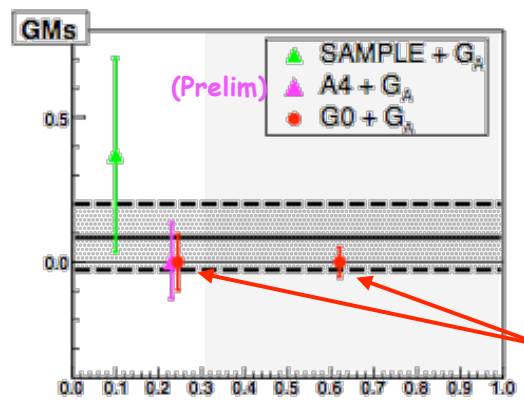
HAPPEX-III (2009)

$\sigma(G_E^s + 0.48\, G_M^s) \sim 0.011$

- high precision
- enhanced G_M^s sensitivity

$\delta A/A \sim 4\%$





G0 (backangle)

G_e^s, G_M^s, $G_A^p = G_A^n$

Improvements since HAPPEX-I

- P^2L (statistical power)
  - Now 100 μA at 80% polarization is routine.
  - Target thickness: 20cm
- Precision polarimetry
  - Compton improvements: $\delta(P_{beam}) = 1\%$
- Q^2 determination
  - Nuclear Recoil method: $\delta(Q^2) = 0.5\%$

A_{PV} (assuming no strange vector FF) at $Q^2 = 0.6\ GeV^2$:

$A_{PV}^{NS} = -22.1$ ppm $\pm$ 0.62 ppm (form factor/radiative correction)

Anticipated results:

$\delta A_{PV} = 0.55$ ppm (stat) $\pm$ 0.33 ppm (syst)

$\delta(G^s_E + 0.48\ G^s_M) = 0.0070$ (stat) $\pm$ 0.0042 (syst) $\pm$ 0.0079 (FF)

Experimental Error Budget

	$\delta A_{PV} / A_{PV}$	$\delta(G_E^s + 0.48 G_M^s)$	
Polarization	1.0%	0.0028	*
Q^2 Measurement	0.8%	0.0022	*
Backgrounds	0.3%	0.0009	*
Linearity	0.6%	0.0017	*
Finite Acceptance	0.3%	0.0009	*
False Asymmetries	0.3%	0.0009	"easy" (big A_{pv})
Total Systematic	1.5%	0.0042	
Statistics	2.5%	0.0070	
Total Experimental	2.9%	0.0082	

* small improvement over H-II

* significant improvement over H-II

Extraction of SVFF from A_{PV}

Including radiative corrections, A_{PV} from hydrogen is:

$$A_{PV} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left\{\left(1-4\sin^2\theta_W\right)\left(1+R_V^p\right)-\left(1+R_V^n\right)\boxed{\frac{\varepsilon G_E^p G_E^n+\tau G_M^p G_M^n}{\varepsilon\left(G_E^p\right)^2+\tau\left(G_M^p\right)^2}}\right\}$$

$$+\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left(1+R_V^{(0)}\right)\frac{\varepsilon G_E^p}{\varepsilon\left(G_E^p\right)^2+\tau\left(G_M^p\right)^2}G_E^s$$

$$+\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left(1+R_V^{(0)}\right)\frac{\tau G_M^p}{\varepsilon\left(G_E^p\right)^2+\tau\left(G_M^p\right)^2}G_M^s$$

$$+\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\frac{\left(1-4\sin^2\theta_W\right)\varepsilon' G_M^p}{\varepsilon\left(G_E^p\right)^2+\tau\left(G_M^p\right)^2}\boxed{\left(\xi_A^{T=1}G_A^{(3)}+\xi_A^{T=0}G_A^{(8)}+\xi_A^{(0)}G_A^s\right)}$$

Electromagnetic FF

Axial FF (G_A^Z)

Axial FF: $\delta(A_{PV})$ = 0.33 ppm

EMFF: dominated by G^n_M, δ(APV) = 0.53 ppm

Total: $\delta(A_{PV})$ = 0.62 ppm, 2.8%

Estimated Precision

	$\delta A_{PV} / A_{PV}$	$\delta(G_E^s + 0.48 G_M^s)$
Total Systematic	1.5%	0.0042
Statistics	2.5%	0.0070
Total Experimental	2.9%	0.0082
Axial FF	1.5%	0.0042
EM FF	2.4%	0.0067
Total FF	2.8%	0.0079
TOTAL:	4.0%	0.011

HAPPEX Interpretation Issues

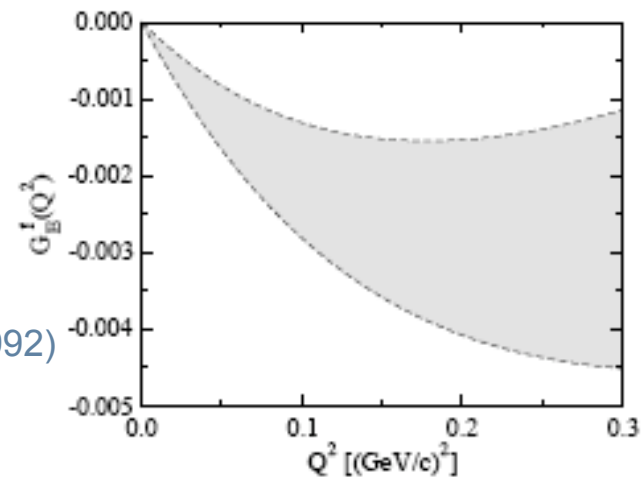
PROTON

Old Story: theoretical CSB estimates indicate <1% violations

Size of charge symmetry breaking effects <1% in low-E n,p observables:

- n - p mass difference = $(m_n - m_p)/m_n$ ~ 0.14%
- $\Delta A = A_n - A_p$ in elastic n+p, p+n Vigdor et al., PRC 46, 410 (1992)
- A_{FB} in n + p -> d + π^0 Opper et al., PRL 91 (2003) 212302

nucl-th/070305



For vector FF: theoretical estimates indicate < 1% violations:
Miller PRC **57**, 1492 (1998) Lewis & Mobed, PRD **59**, 073002(1999)

New Story: effects could be large as statistical error on HAPPEx data!
χPBT + vector meson mixing, B. Kubis & R. Lewis Phys. Rev. C **74** (2006) 015204

Contribution from $G^{u/d}$ **~0.004-0.009**

HAPPEX-II: $G^s_E + 0.09\, G^s_M = 0.007$ **+/- 0.011** +/- 0.004 +/- 0.005 (FF)

Contribution at higher Q^2 is undetermined, but could reasonably be comparable

HAPPEX Interpretation Issues

^{4}He

Old Story: Nuclear effects all << 1%, no explicit correction made.

- ^{4}He g.s. pure isospin state: Ramavataram, Hadjimichael, Donnelly PRC 50(1994)1174
- No D-state admixture: Musolf & Donnelly PL B318(1993)263
- Meson exchange corrections small: Musolf, Schiavilla, Donnelly PRC 50(1994)2173

New Story: Nuclear admixture + nucleon CSB ~ 1%

HAPPEX-^{4}He: $\delta A_{PV}/A_{PV}$(stat) **~ 3.5%**

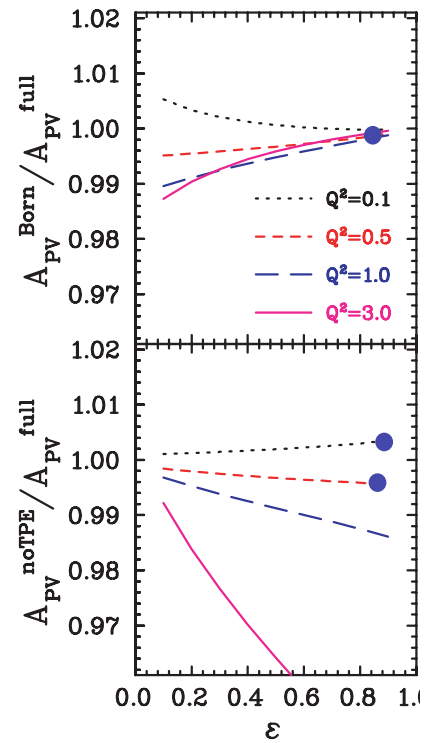
Viviani, Schiavilla, Kubis, Lewis, Girlanda, Keivsky, Marcucci, Rosati, nucl-th/070305

Two photon effects and extraction of $G^s_{E,M}$

EMFF must be corrected for two-photon effects, and errors in extracted form-factors are correlated.

Arrington and Sick, Phys Rev C 76 035201 (2007)

ε > 0.95 at Q2~0.1, 0.6 so δA/A<0.5%

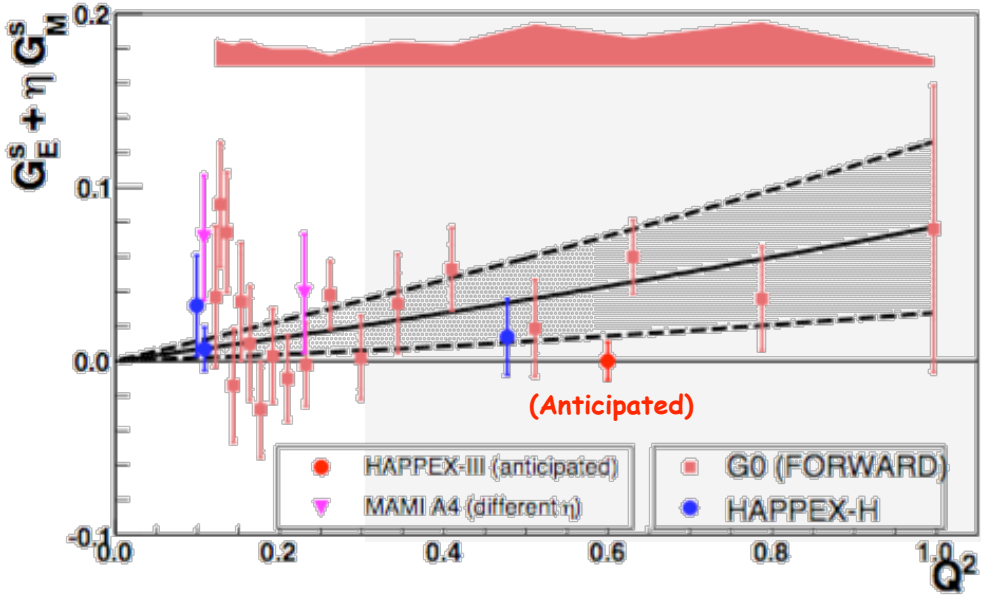


Preparations

- **Detector** - Examine HAPPEX-I detectors, refurbish or rebuild (W&M).
- **Polarimetry** – Review e^- analysis (also, complete upgrade).
- **Linearity** - LED studies of phototubes/bases.
- **Q^2** - verify cross-sections and plan angle measurement.
- **Finite Acceptance** – simulation.
- **Backgrounds** – simulation and target design.
- **Rapid Flip** - >200 Hz flip rates are considered for QWeak, PREX. HAPPEX-III may benefit as well.

HAPPEX-III installation now appears on tentative schedule!

Summary



- Significant and accessible (~10% magnetic) contributions still allowed.

- Precision data at middle Q^2 can finish the question of large contributions to the static properties, in a way that back angle measurements (with limited precision and high anapole sensitivities) cannot independently do.

Now on tentative schedule: experiment on track to run August 2009

Nathan Isgur: Zero may be the MOST interesting of the possible results!

Charge Symmetry Breaking: effects in proton could be large as statistical error on high-precision HAPPEx data, and not well constrained at higher Q^2
EMFF uncertainties: (including 2γ) limit to few percent precision

Strangeness interpretation would require additional theoretical and empirical input! Further improvements in precision will measure G^Z, but may not distinguish source.

HAPPEX-III Collaboration

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F. Bataru, Z.-E. Meziani, B. Sawatzky, P. Solvignon, and H. Yao - *Temple University*

H. Benaoum, R. Holmes, and P.A. Souder, Z. Ahmed ,A. Rakhman - *Syracuse University*

R. Carlini, J.-P. Chen, R.J. Feuerbach, J. Grames, D.W. Higinbotham, C.W. de Jager, R. Michaels, B. Reitz, J. Roche, and A. Saha - *TJNAF*

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D. Lhuillier and C. Munoz-Camacho - *CEA Saclay, DAPNIA/SPhN*

P. Markowitz - *Florida International University*

P. Reimer and X. Zheng - *Argonne National Laboratory*

R. Wilson - *Harvard University*

Axial Form Factor

Axial Form Factor: Uncertainty dominated by "anapole moment"

$$R_A^{T=1} = -0.06 \pm 0.024$$

$$R_A^{T=0} = 0.01 \pm 0.014$$

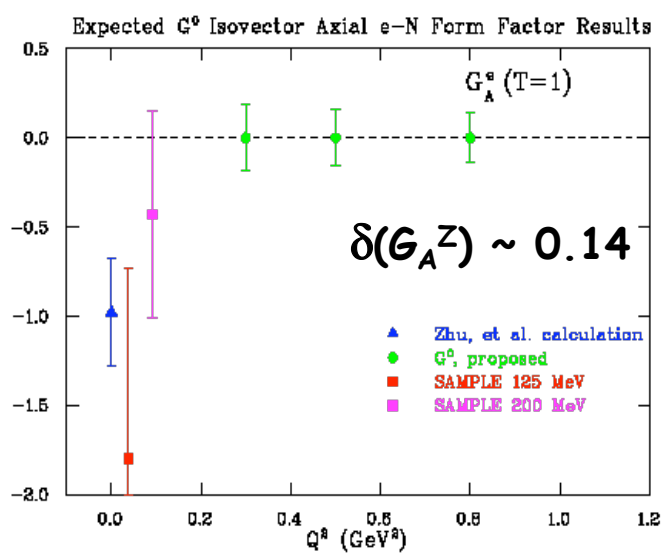
[Zhu *et al* , 2000]

Assume dipole FF, with M_A = 1.001 GeV

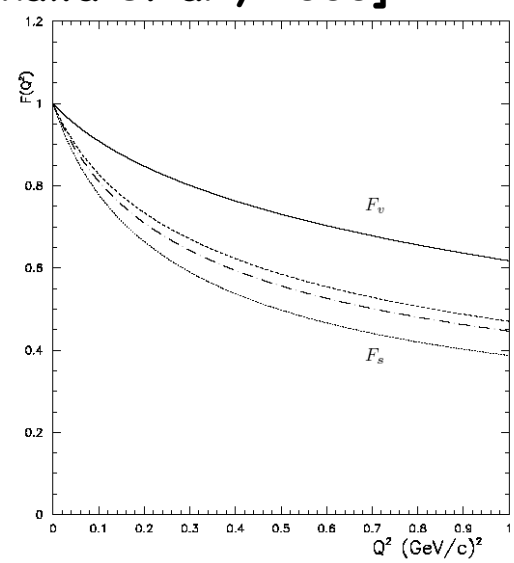
⇨ **$\delta(G_A^Z) \sim 0.12$, $\delta(A_{PV}) = 0.33$ ppm**

Compatible with Phys. Rev. *C* 69, 065501 (2004)

E04-115 G0 Backward Angle



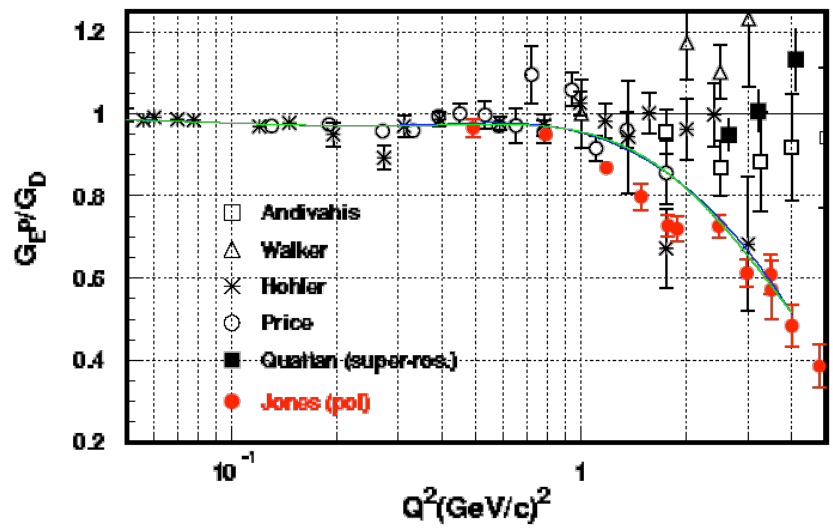
[Maekawa *et al* , 2000]



EM Form Factors

	uncertainty	$d(A_{PV})/A_{PV}$
G^p_M	2%	negligible
G^p_E	1.5%	0.24 ppm
G^n_E	8%	0.26 ppm
G^n_M	2%	0.44 ppm
Total		0.53 ppm

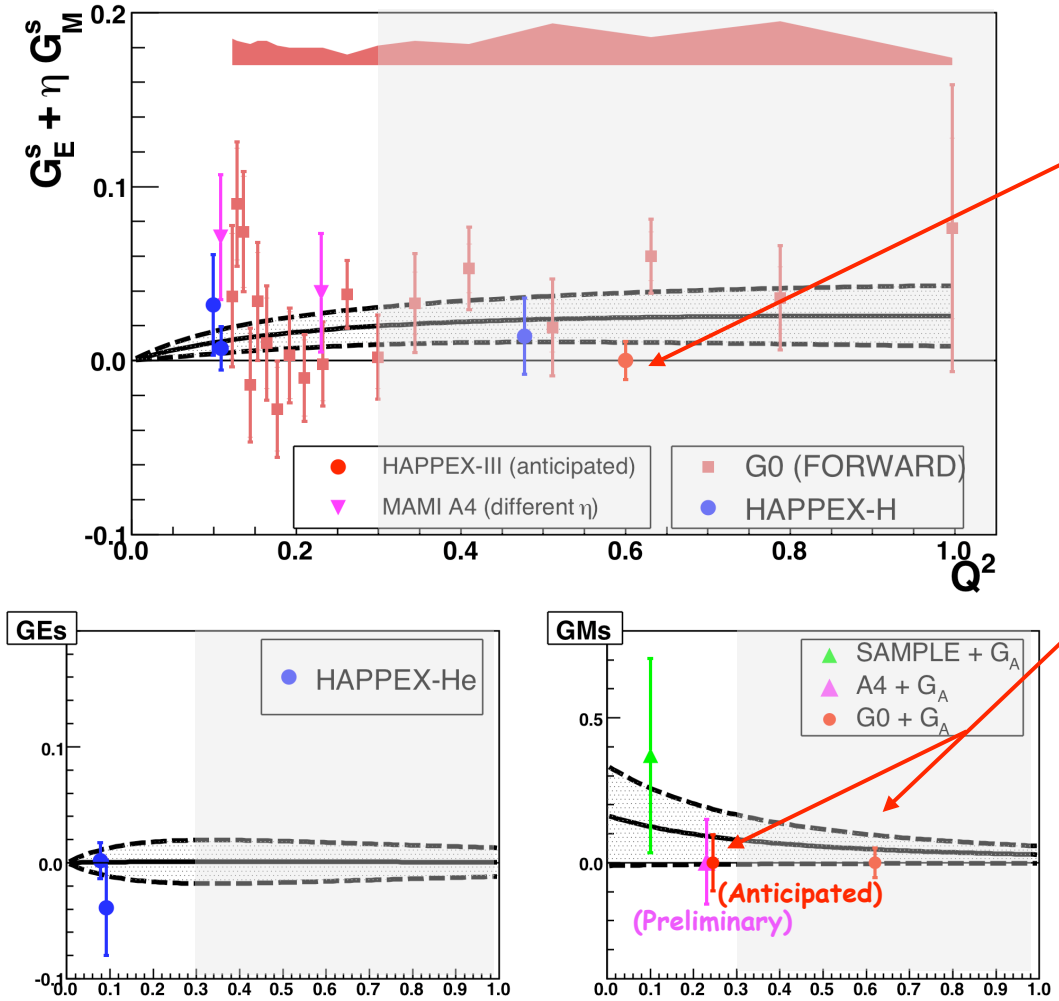
But: 2-photon effects can complicate this picture at 2-4% level



Experimental constraint:

E04-116 in Hall B (approved): precision comparison of elastic positron-proton and electron-proton scattering, with very good coverage at this Q2

Dependence on Q^2 evolution assumption



HAPPEX-III (2009)

$\sigma(G_E^s + 0.48\ G_M^s) \sim 0.011$

G0 (backangle)

$G_e^s,\ G_M^s\ ,G_A^p=G_A^n$

Fit with with dipole fall-off:

$G_E^s = \rho_s * G_{galster}$

$G_M^s = \mu_s * G_{dipole}$

Includes only data $Q^2 < 0.3\ GeV^2$

A Global Fit: R.D. Young, et al.

- all data $Q^2 < 0.3$,
- leading moments of G_E^s, G_M^s
- Float G_A^e separately for neutron and proton

Fit described in:
Phys.Rev.Lett. 97 (2006) 102002

Result: zero, with a range of $\pm 3\%$ of G_M^p, $\pm 1\%$ of G_E^p

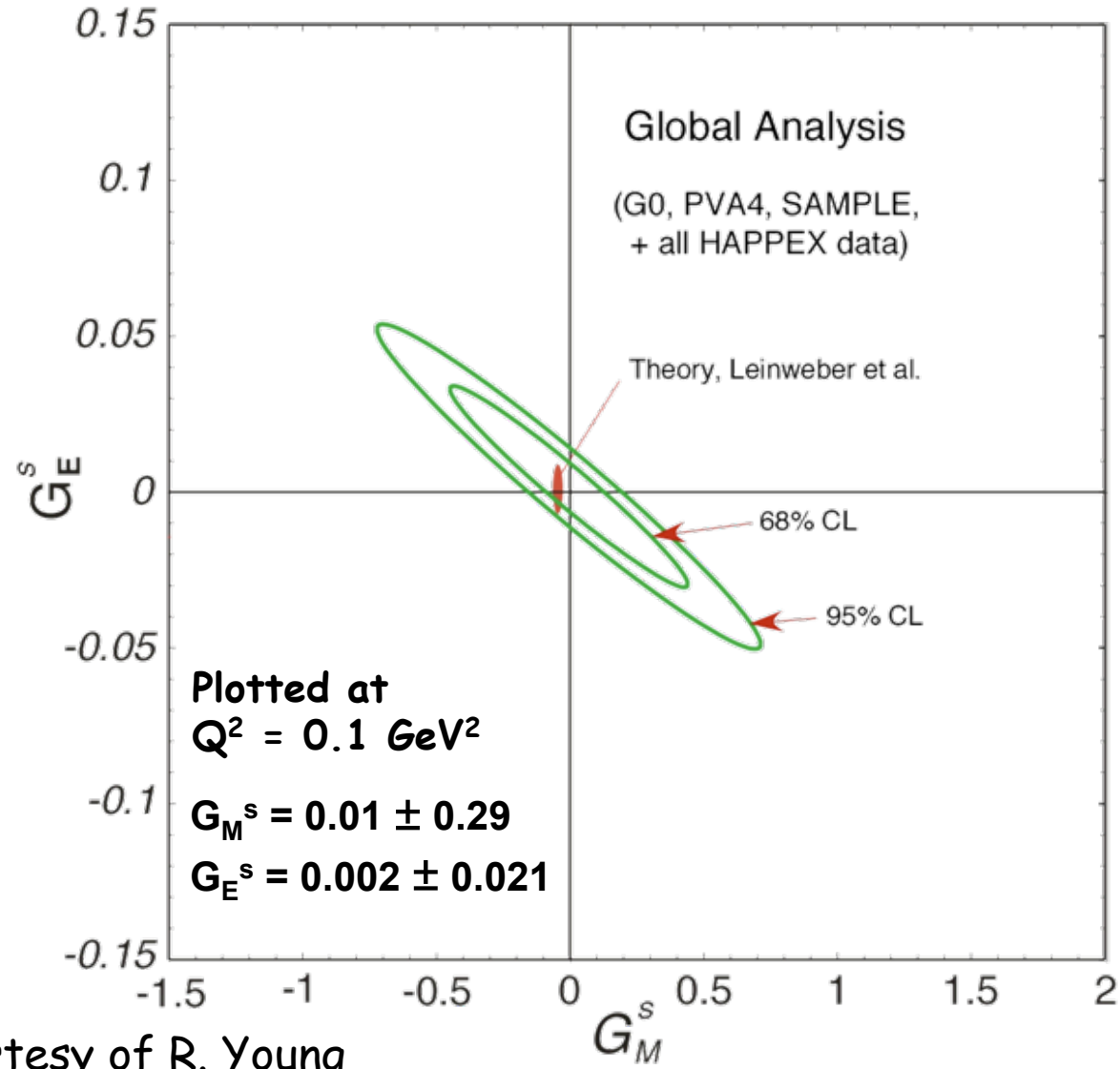


Figure: courtesy of R. Young

Constraint on Anapole Moment

all data $Q^2 < 0.3$, leading moments of G_E^s, G_M^s

Constraint on G_A^e is included

Result: non-zero pull but consistent with zero.

Max (1σ):
5% of G_M^p,
1% of G_E^p

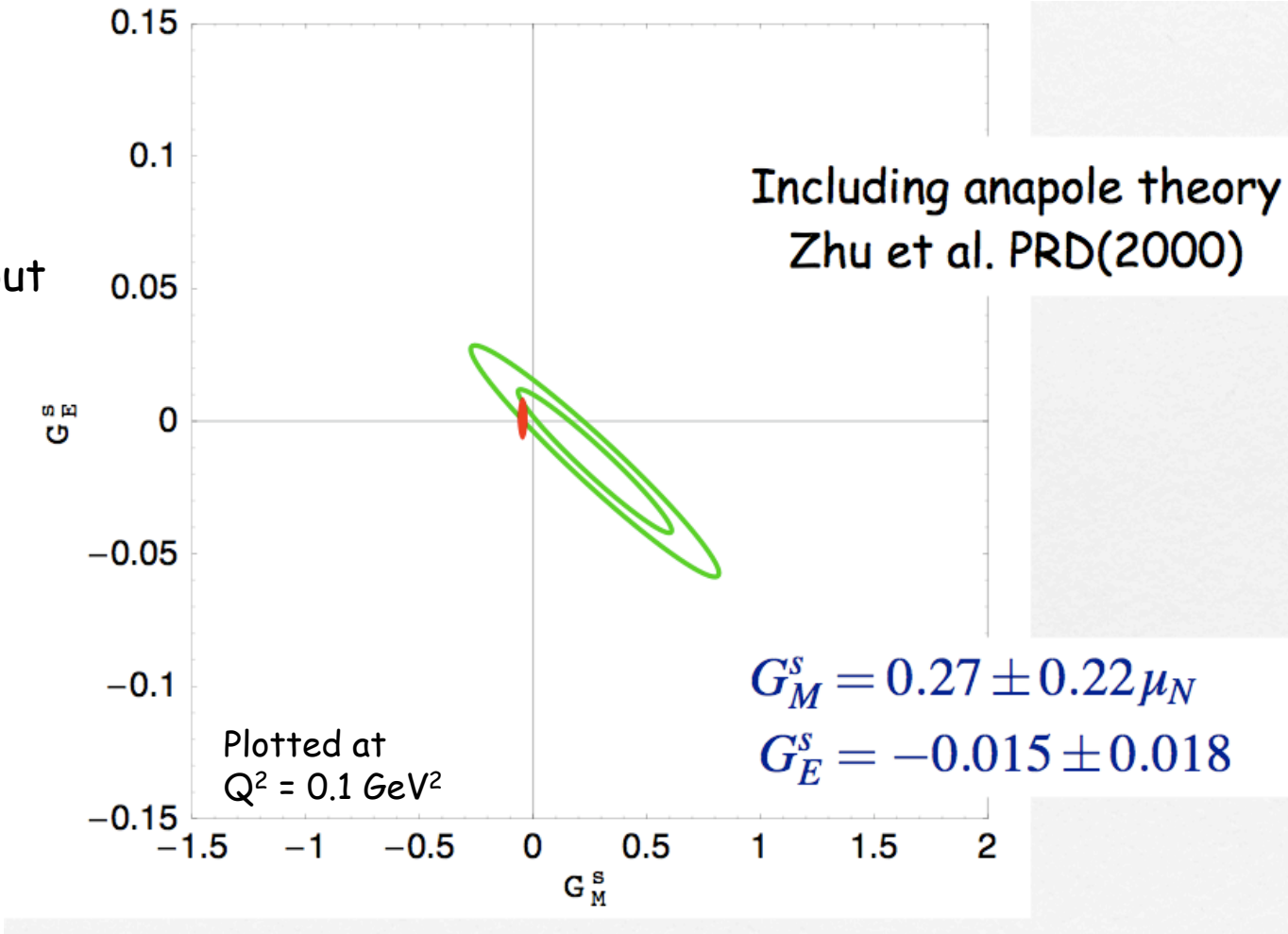


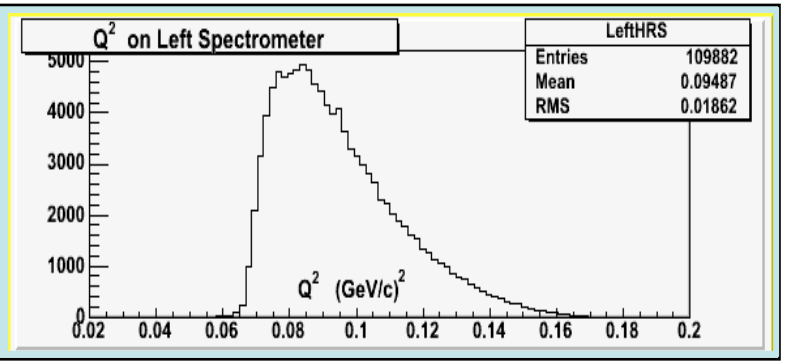
Figure: courtesy of R. Young

Measuring Q^2

Goal: $\delta_{Q^2} < 0.5\%$

- Central scattering angle must be measured to $\delta\theta < 0.25\%$
- Asymmetry distribution must be averaged over finite acceptance

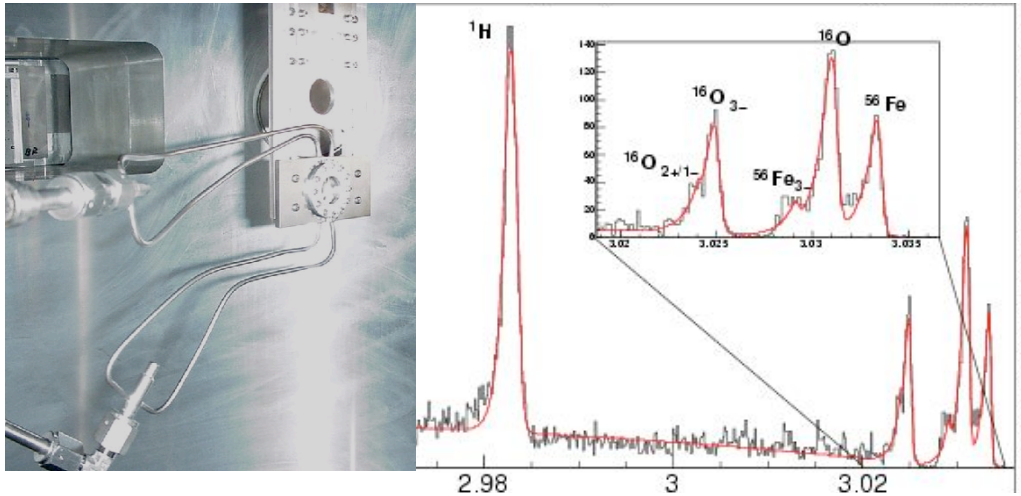
Q2 measured using standard HRS tracking package, with reduced beam current



Nuclear recoil, using water cell optics target: δp between elastic and excited state peaks reduces systematic error from spectrometer calibration.

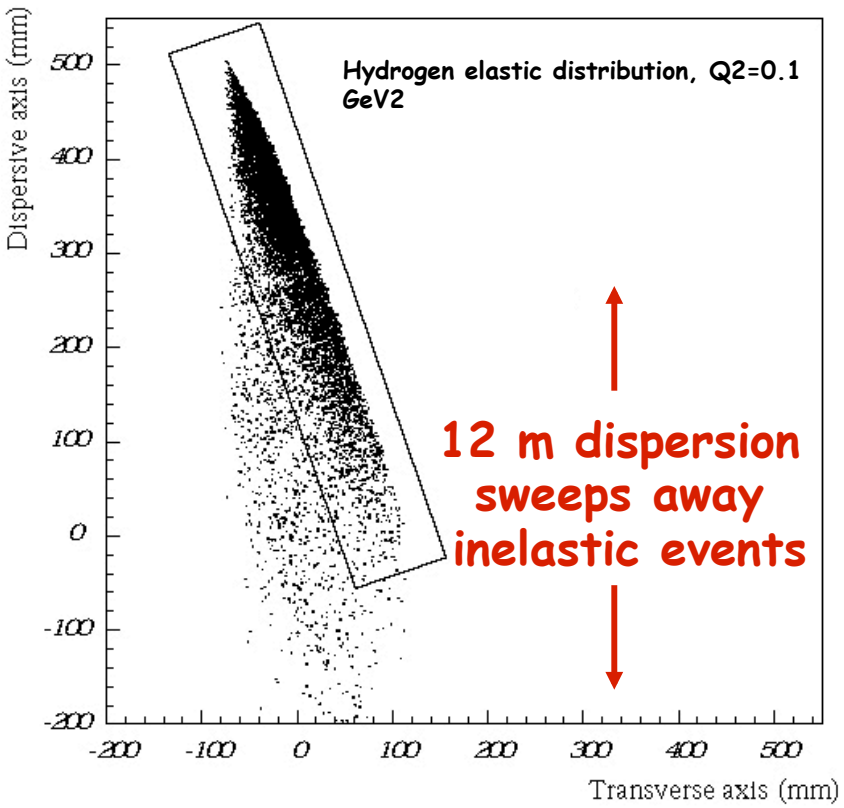
At $Q^2 \sim 0.1$ GeV^2 (6°) in 2004:

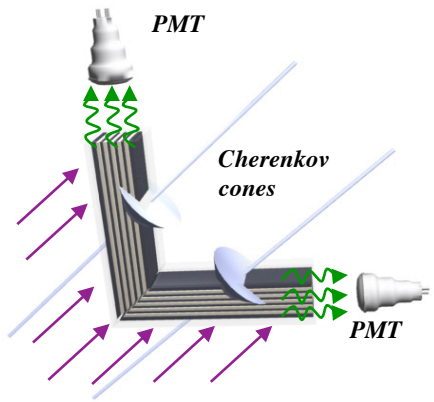
Achieved $\delta\theta \sim 0.3\%$



High Resolution Spectrometers

Very clean separation of elastic events by HRS optics → Overlap the elastic line above the focal plane and integrate the flux





Large dispersion and heavy shielding reduce backgrounds at the focal plane: typically $\Sigma f_i < 1.5\%$

Standard detector package used to track individual electrons to measure kinematics, study background, in dedicated low-current studies.

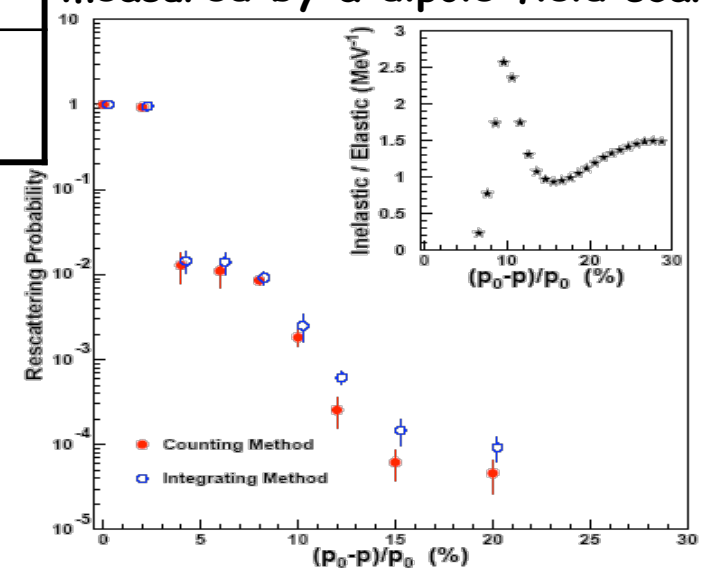
PR-05-109: HAPPEX High-Q^2

Background

		Al Quasi-elastic	Spectrometer Rescatter
HAPPEX-I (0.48 GeV^2)	fraction	1.4%	0.2%
	$d(A_{PV})/A_{PV}$	0.3%	0.1%
This proposal (0.6 GeV^2)	fraction	1.4%	0.4%
	$d(A_{PV})/A_{PV}$	0.3%	0.1%

G0: typical dilution factor at high Q^2 ~ 20%

The probability of rescattering inside the spectrometer as measured by a dipole field scan

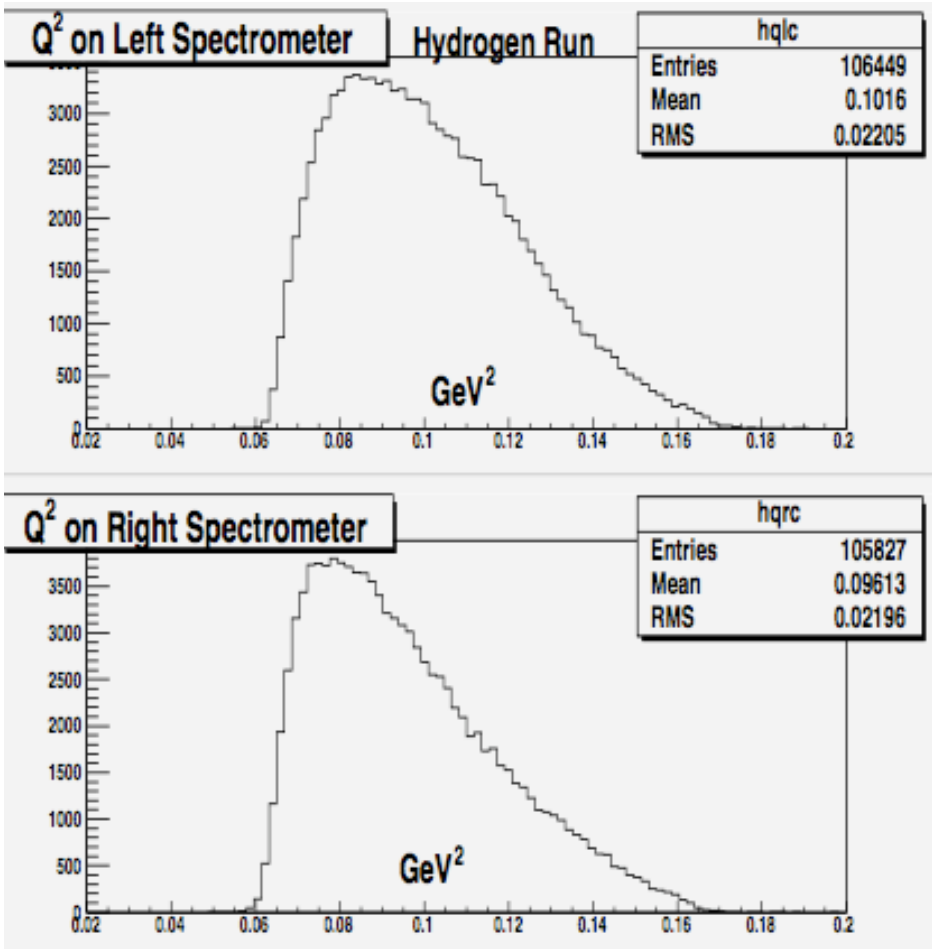


Measured using:

- Dedicated runs at very low current using track reconstruction of the HRS
- Dedicated integrating runs

Q^2 coverage

HAPPEX-II (2004) Q^2 coverage



GO Q^2 coverage, by detector

Det	Q^2 (GeV^2)
1	0.122
2	0.128
3	0.136
4	0.144
5	0.153
6	0.164
7	0.177
8	0.192
9	0.210
10	0.232
11	0.262
12	0.299
13	0.344
14 a	0.410
15 a	0.511
15 b	0.631
15 c	0.788
14 b	0.997

HAPPEX High-Q^2

Configuration:

- 20 cm cryogenic Hydrogen Target
- 100 mA
- 80% polarization

Kinematics: E = 3.42 GeV, q=13.7o, E' = 3.1 GeV, Q2 = 0.6 GeV2

Rate: 1.1 MHz per arm (3700 ppm width per arm, 2600 ppm per pair)

APV (assuming no strange vector FF):

APVNS = -22.1 ppm ± 0.62 ppm (form factor/radiative correction)

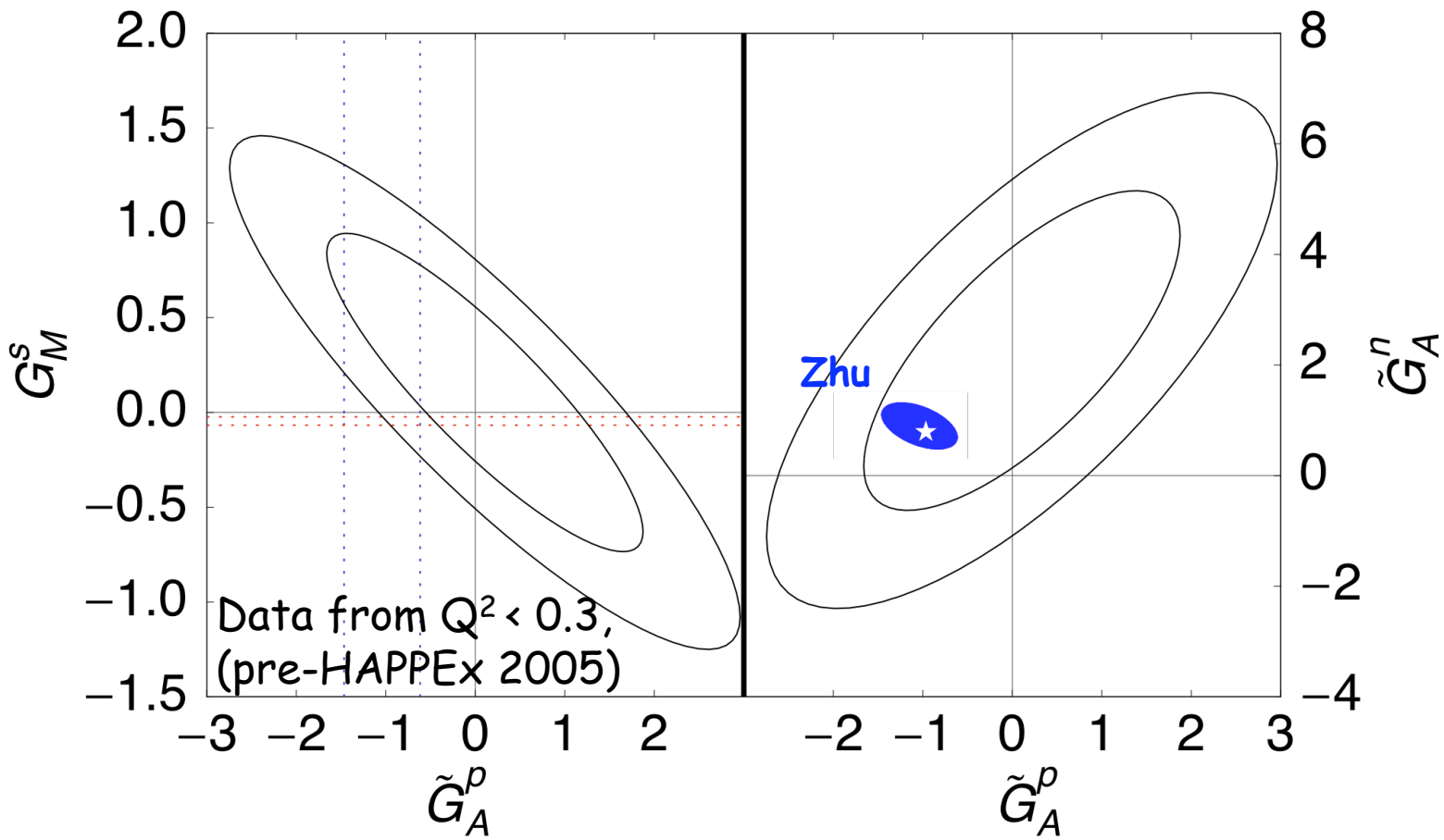
Anticipated results:

dAPV = 0.55 ppm (stat) ± 0.33 ppm (syst)

d(GsE + 0.48 GsM) = 0.0070 (stat) ± 0.0042 (syst) ± 0.0079 (FF)

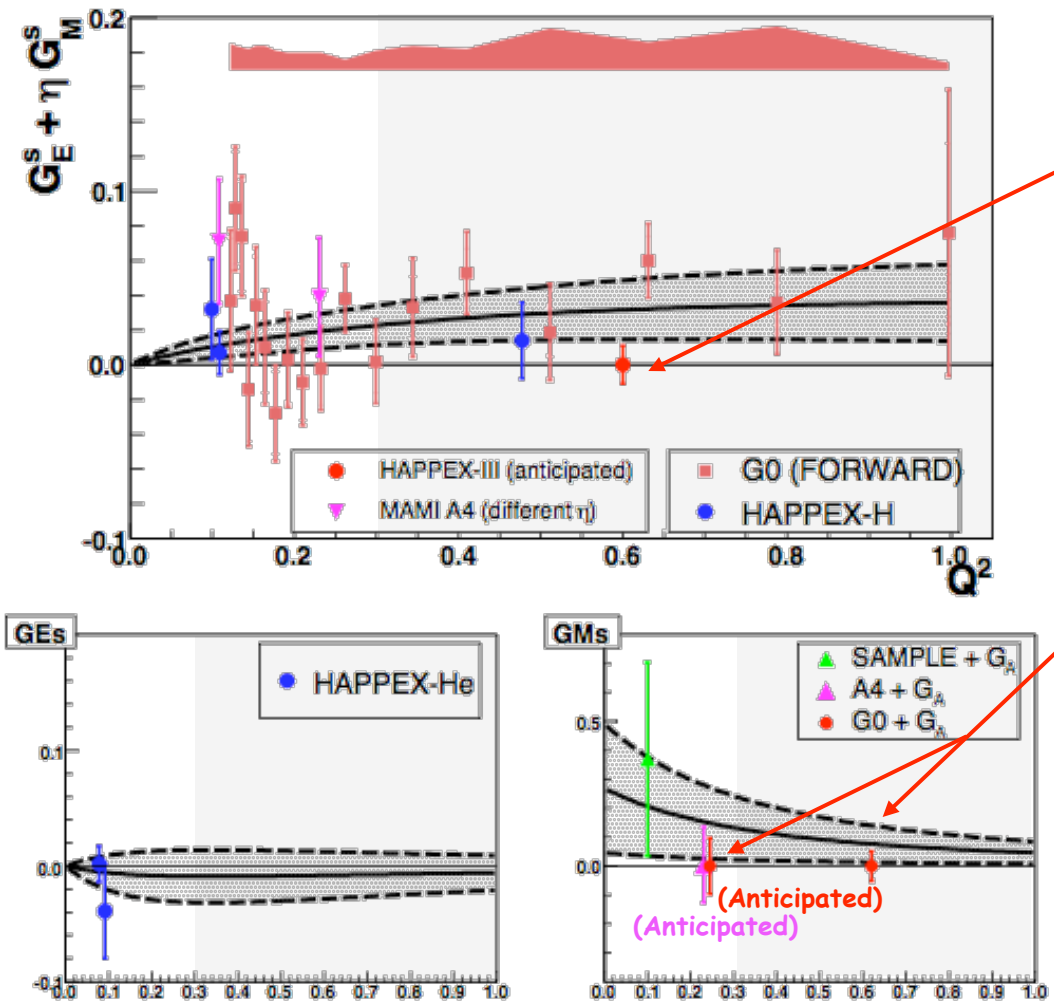
Effect of "floating" effective axial FF

$$\tilde{G}_A^{p,n} = G_A^e = -\tau_3(1+R_A^{T=1})G_A + \sqrt{3}R_A^{T=0}G_A^8 + \Delta s$$



R.D. Young, et al., Phys.Rev.Lett. 97 (2006) 102002

Impact depends on Q^2 evolution assumption



HAPPEX-III (2009)

$\sigma(G_E^s + 0.48\ G_M^s) \sim 0.01$

G0 (backangle)

G_e^s, G_M^s ,$G_A^p = G_A^n$

Fit with with dipole fall-off:

$G_E^s = \rho_s * G_{galster}$

$G_M^s = \mu_s * G_{dipole}$

Includes only data $Q^2 < 0.3\ GeV^2$