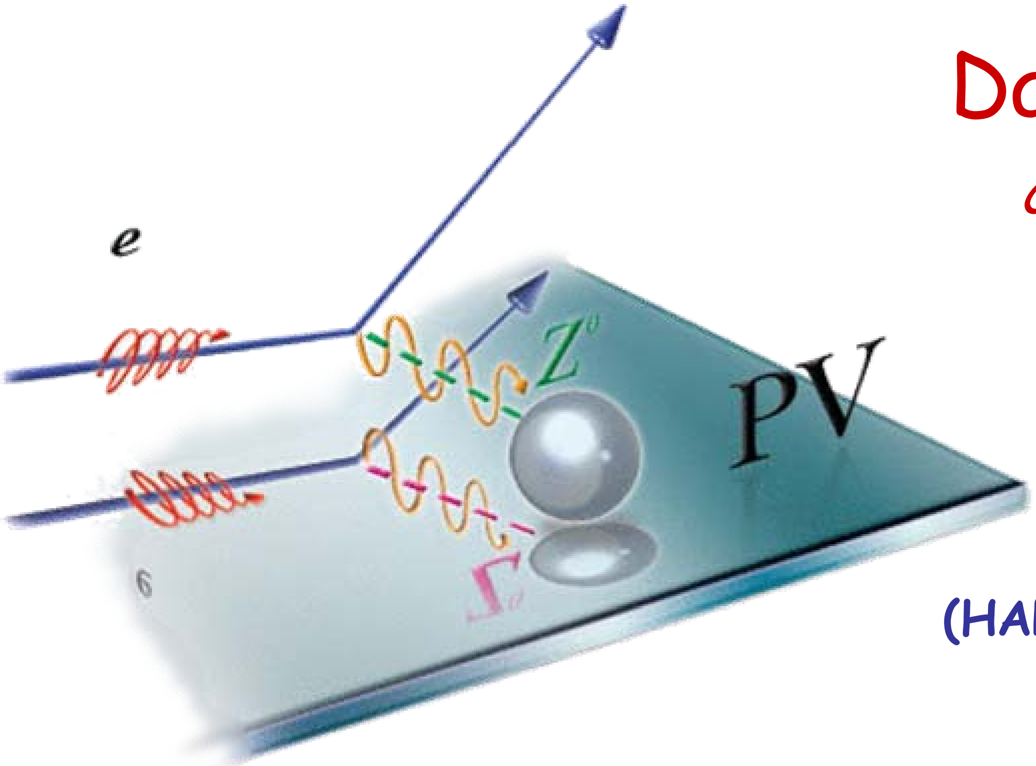
Parity-Violating Electron Scattering & Strangeness in the Nucleon



David S. Armstrong

College of William & Mary

(HAPPEX and G0 Collaborations)

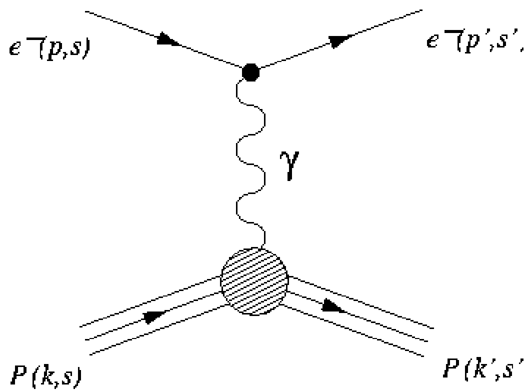
Workshop on Intersections of Nuclear Physics with Neutrinos and Electrons
Jefferson Lab May 4 2006

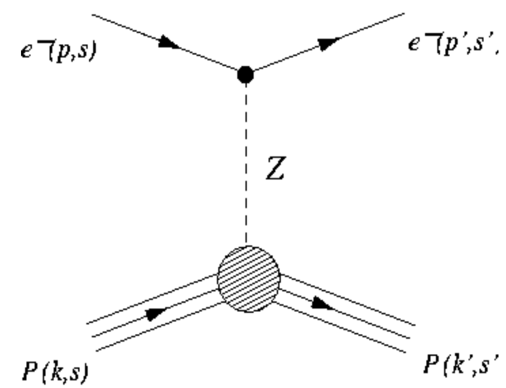
Outline

- Parity-violation in electron scattering
- Elastic Vector Strange Form Factors: G^s_E and G^s_M
- First generation results: HAPPEX-I, SAMPLE, PV-A4
- Latest results:
  - G0 (forward-angle)
  - HAPPEX-II and HAPPEX-Helium

- The present situation at $Q^2 = 0.1\ (GeV/c)^2$
- The future…

Parity Violating Electron Scattering → Weak NC Amplitudes





$$M^{EM} = \frac{4\pi\alpha}{Q^2} Q_\ell \, \ell^\mu J_\mu^{EM} \qquad M_{PV}^{NC} = \frac{G_F}{2\sqrt{2}} \left[g_A \ell^{\mu 5} J_\mu^{NC} + g_V \ell^\mu J_{\mu 5}^{NC} \right]$$

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

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

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

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

Form Factors

$$J_\mu^{EM} = \sum_q \mathrm{Q}_q \left\langle \overline{N} \left| \overline{u}_q \gamma_\mu u_q \right| N \right\rangle = \overline{N}\left[\gamma_\mu F_1^\gamma + \frac{i\sigma_{\mu\nu} q^\nu}{2M_N} F_2^\gamma \right] N$$

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

(Roughly: Fourier transforms of charge and magnetization)

NC probes 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 new benchmark for testing non-perturbative QCD structure of the nucleon

Charge Symmetry

One expects the neutron to be an isospin rotation of the proton*:

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

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

$G^{\gamma,p}_{E,M}$	Charge symmetry →	$G^{u}_{E,M}$	Shuffle →	$G^{p}_{E,M}$ ← Well Measured
$G^{\gamma,n}_{E,M}$		$G^{d}_{E,M}$		$G^{n}_{E,M}$ ← Well Measured
$G^{Z,p}_{E,M}$		$G^{s}_{E,M}$		$G^{s}_{E,M}$ ← $\langle N \vert \bar{s}\gamma^{\mu} s \vert N \rangle$

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

*Neglecting trivial breaking due to Coulomb force

Isolating the form factors: vary the 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

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

Forward angle — Backward angle

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

$$G_A^e = -G_A + \Delta s + \eta F_A + R^e$$

For ^{4}He: G_E^s alone (but only available at low Q^2)

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

For deuterium:

enhanced G_A^e sensitivity

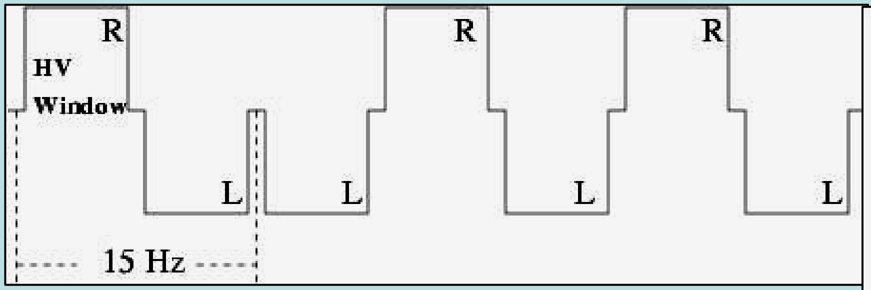
Measurement of P-V Asymmetries

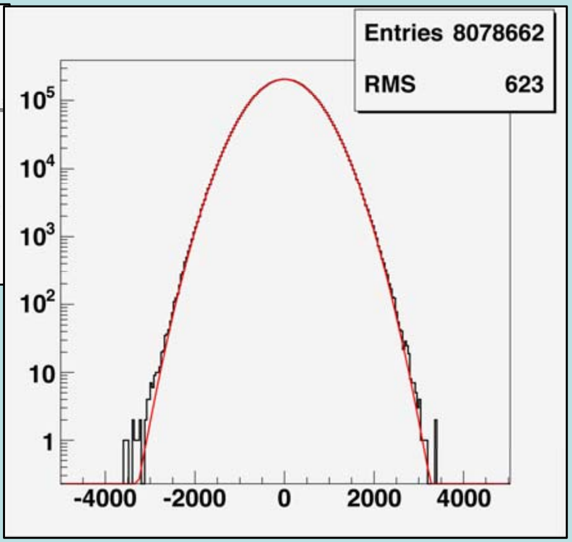
$$A_{LR} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx 10^{-6}$$

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)
- Polarized source uses optical pumping of strained photocathode: high polarization and rapid flip

Statistics: high rate, low noise
Systematics: beam asymmetries, backgrounds, Helicity correlated DAQ
Normalization: Polarization, Linearity, Background

Early History: Tests of Weinberg-Salam-Glashow

- C. Prescott, *et al.* SLAC E122 DIS on deuterium

  Phys. Lett. 77B, 3 47 (1978), Phys. Lett. 84B, 524 (1979)

- W. Heil, *et al.* Mainz quasielastic ^{9}Be

  Nucl. Phys. B327, 1 (1989)

- P. Souder, *et al.* MIT/Bates ^{12}C elastic

  PRL 65, 694 (1990)

HAPPEX (first generation)

Hydrogen Target: E=3.3 GeV, θ=12.5°, Q^2=0.48 $(GeV/c)^2$

$$A^{PV} = \left[\frac{-G_F M_p^2 \tau}{\pi\alpha\sqrt{2}}\right]\left\{(1-4\sin^2\theta_W) - \frac{[\varepsilon G_E^{p\gamma}(G_E^{n\gamma}+\boxed{G_E^s}) + \tau G_M^{p\gamma}(G_M^{n\gamma}+\boxed{G_M^s})]}{\varepsilon(G_E^{p\gamma})^2 + \tau(G_M^{p\gamma})^2}\right\} - A_A$$

A^{PV} = -14.92 ppm ± 0.98 (stat) ppm ± 0.56 (syst) ppm

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

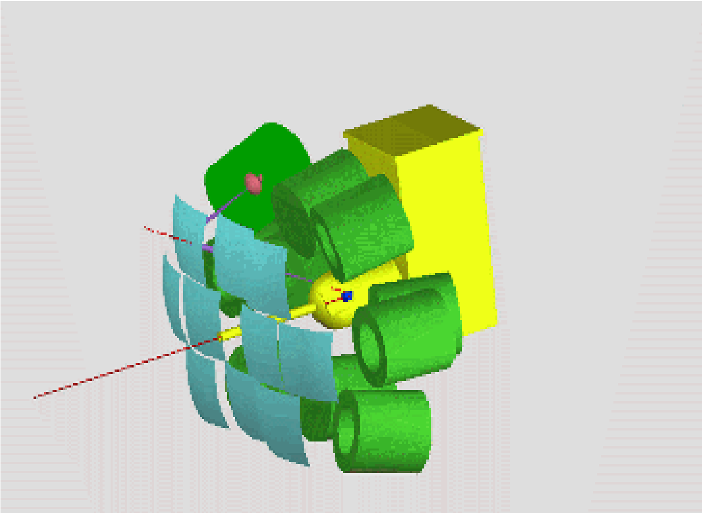
"Parity Quality" Beam @ JLab

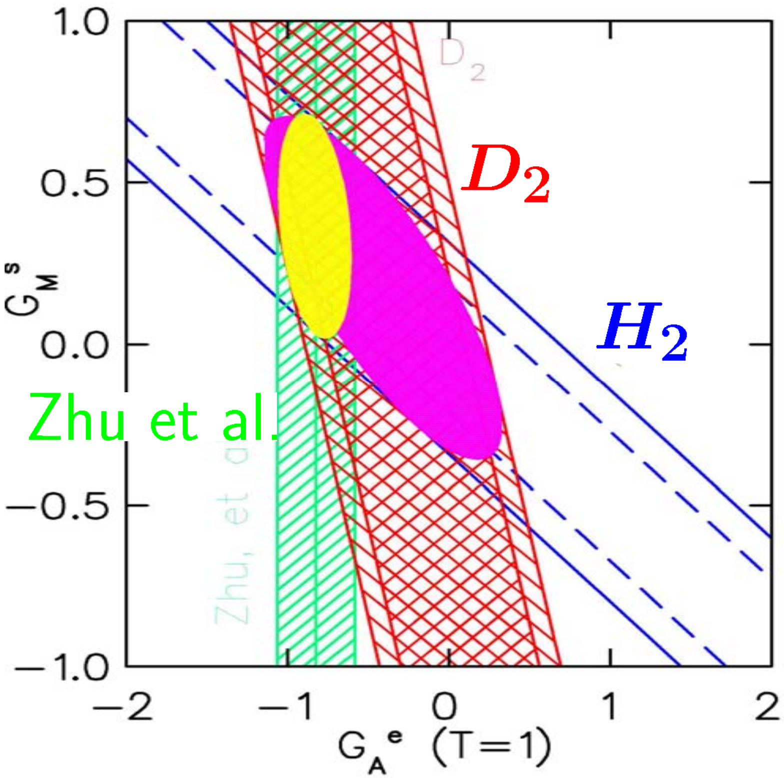
Phys. Rev. Lett. 82,1096 (1999);
Phys. Lett. B509, 211 (2001);
Phys. Rev. C 69, 065501 (2004)

A_A suppressed by ε' $(1 - 4\sin^2\theta_w)$ where $\varepsilon' = [\tau(1+\tau)(1-\varepsilon^2)]^{\frac{1}{2}}$ $\approx$ (0.08)(0.08) here.

SAMPLE (MIT/Bates)

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

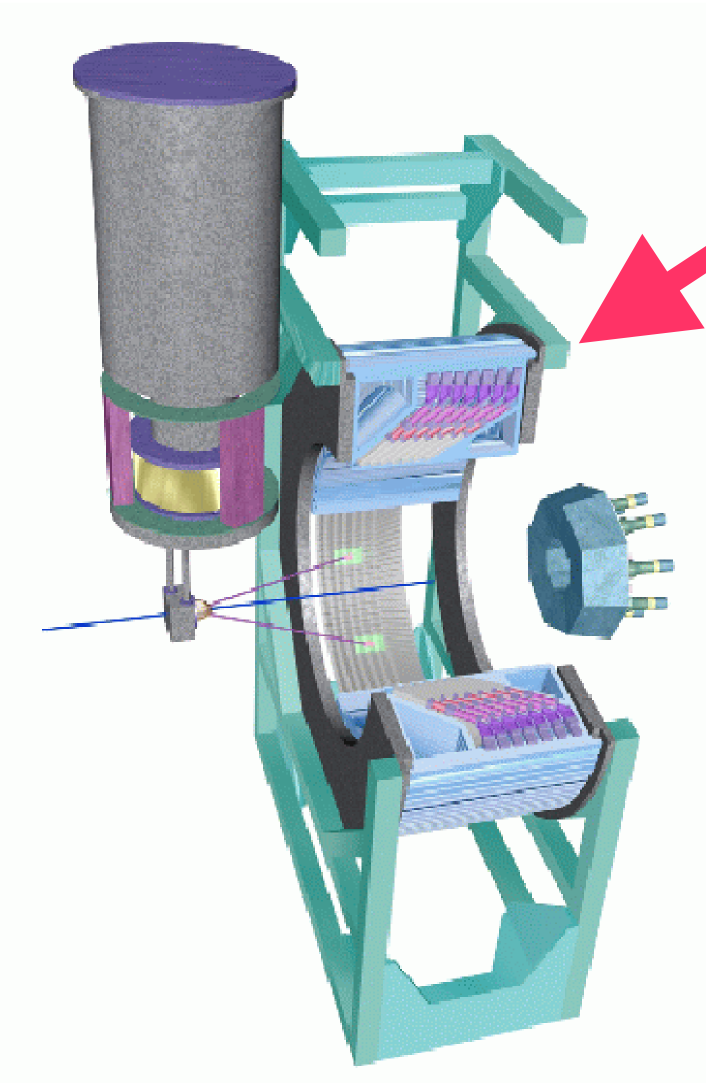
$G^e_A{}^{(T=1)}$ = -0.53 ± 0.57 ± 0.50

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

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

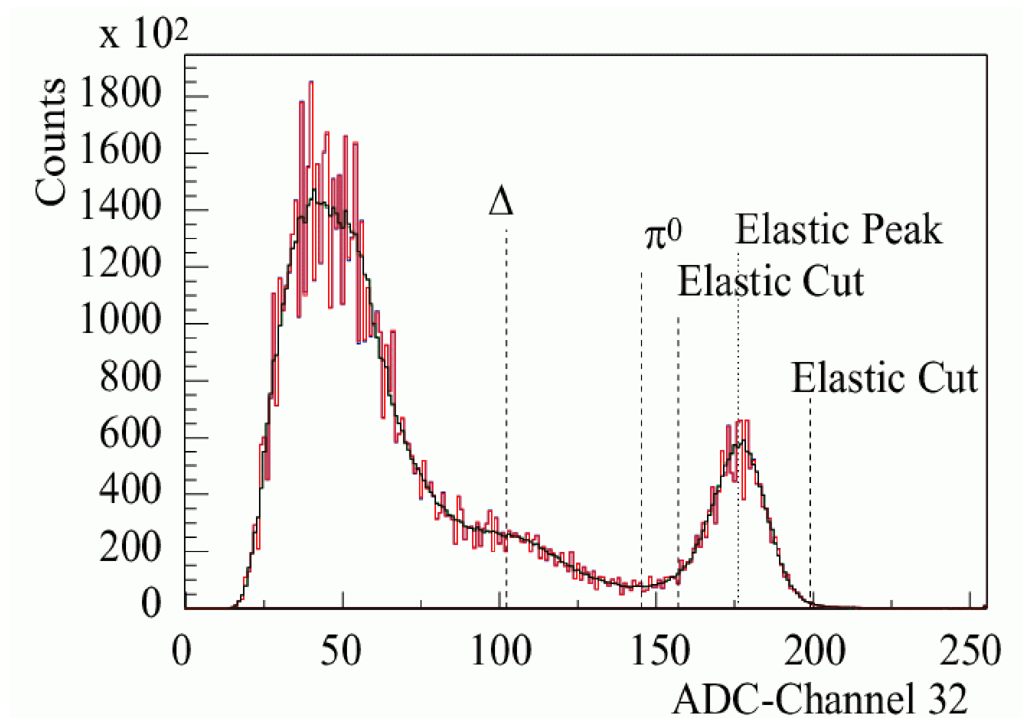
$G^s_M = 0.37 \pm 0.20_{Stat} \pm 0.36_{Syst} \pm 0.07_{FF}$

PV-A4 at Mainz



Fast PbF_2 calorimeter

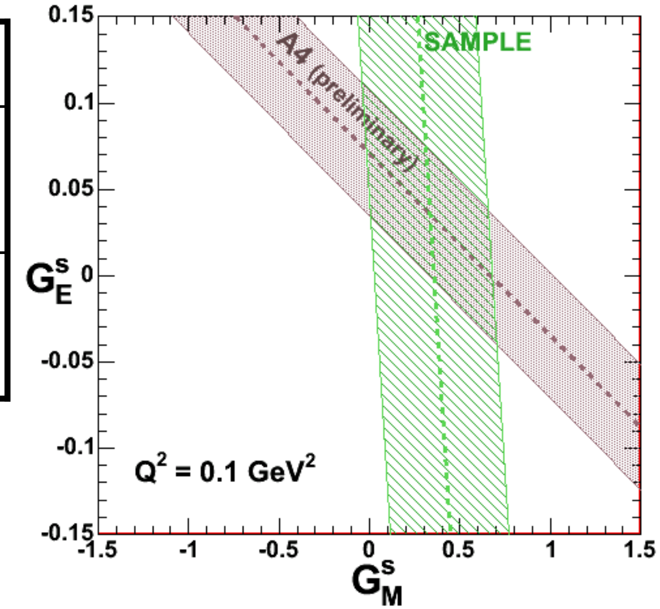
- 1022 crystals in 146 frames
- θ = 30-40^o , φ = 0-360^o

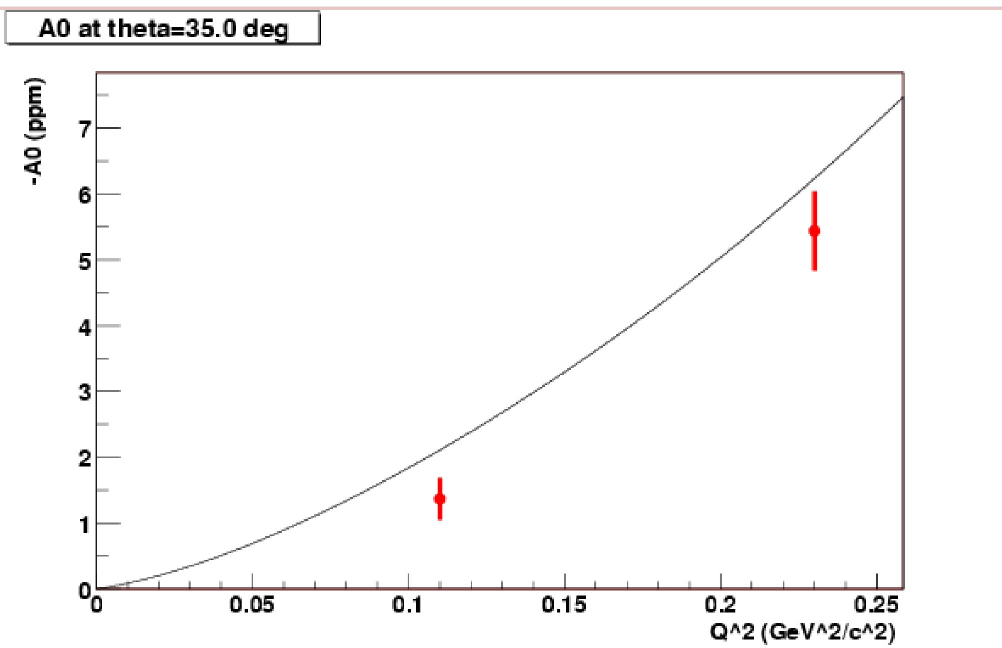


For Q^2=0.108 $(GeV/c)^2$, 16× 10^6 histograms → 10^{13} elastic scattering events

PV-A4 (MAMI/Mainz)

Q^2 (GeV^2)	$A \pm$ stat $\pm$ syst (ppm)	$G_E^s + \alpha G_M^s$
0.230	$-5.44 \pm 0.54 \pm 0.26$	$G_E^s + 0.225\ G_M^s = 0.039 \pm 0.034$
0.101	$-1.36 \pm 0.29 \pm 0.13$	$G_E^s + 0.106\ G_M^s = 0.071 \pm 0.036$





"Evidence for Strange Quark Contributions to the Nucleon's Form Factors at Q2 = 0.1 GeV^2"
PRL 94, 152001 (2006)

Back Angle runs underway to separate G^s_M, G_A at additional points…

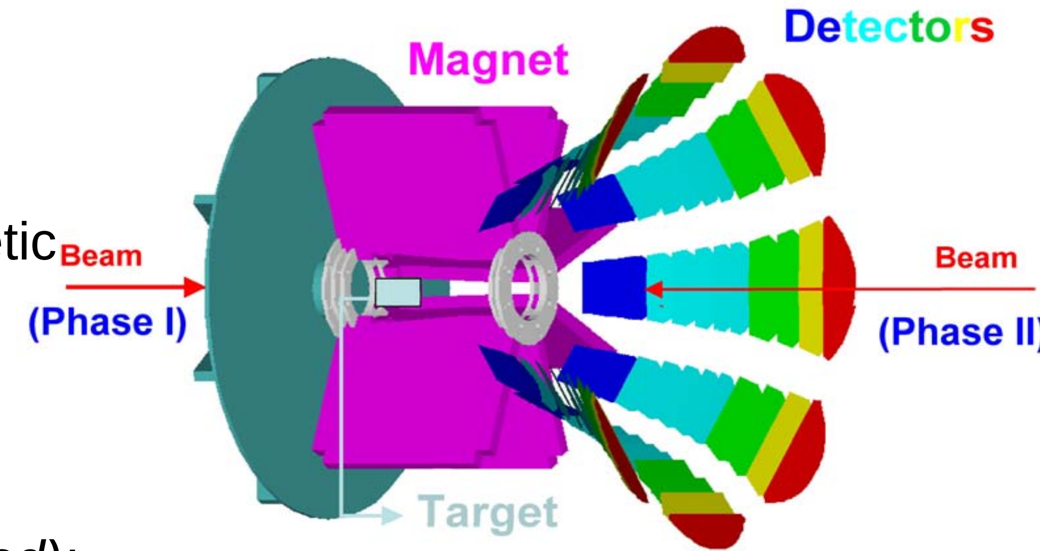
G^0 (JLab – Hall C)

- LH_2/LD_2 target (20 cm)

  $L = 2.\ 10^{38}\ cm^{-2}\ s^{-1}$

- Superconducting toroidal magnetic spectrometer

- 16 “Rings” divided into 8 octants



Forward angle mode *(completed):*

- LH_2: $E_e = 3.0$ GeV

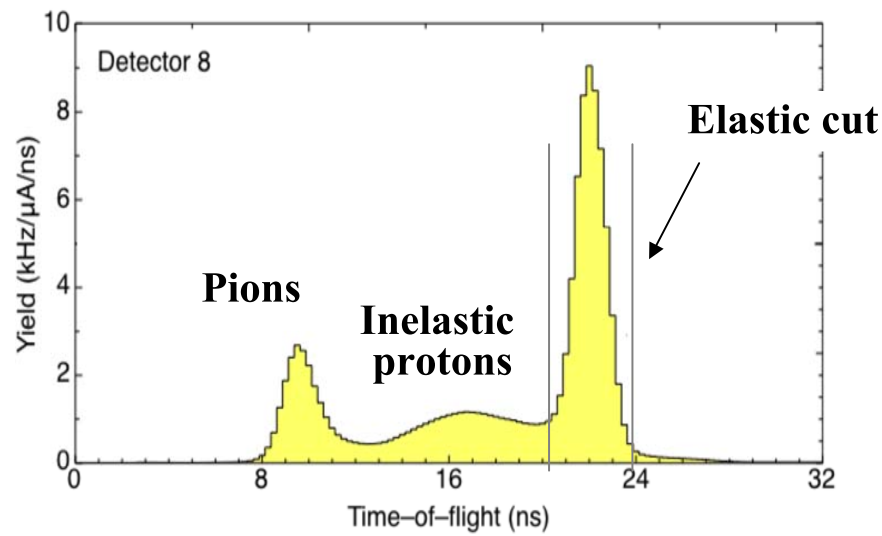
  Recoil proton detection ($52^o < \theta_p < 76^o$)

  ⇨ $0.12 \le Q^2 \le 1.0\ (GeV/c)^2$

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

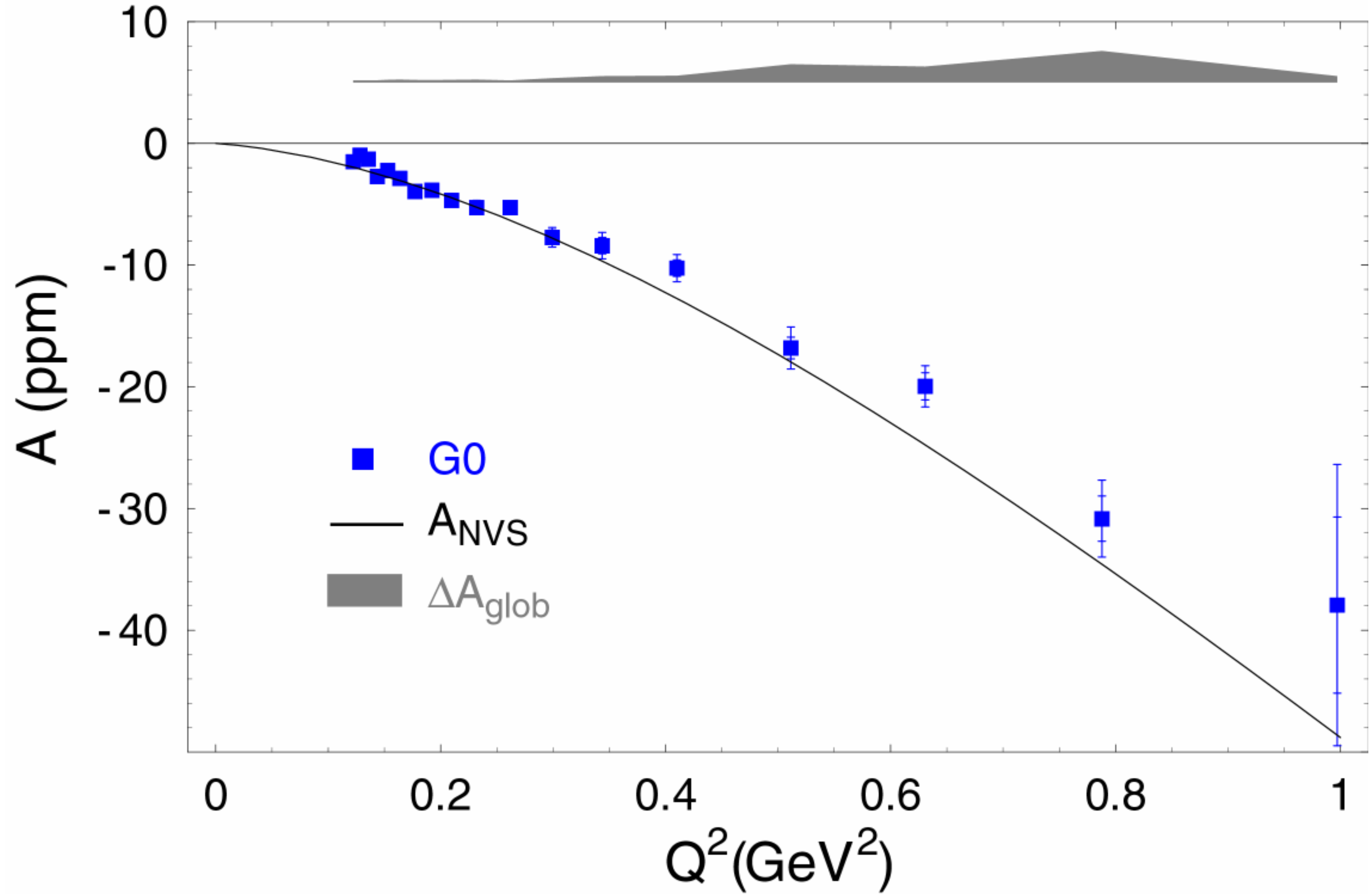
  Histograms built each 33 ms

E99-016, E01-115 and E01-116

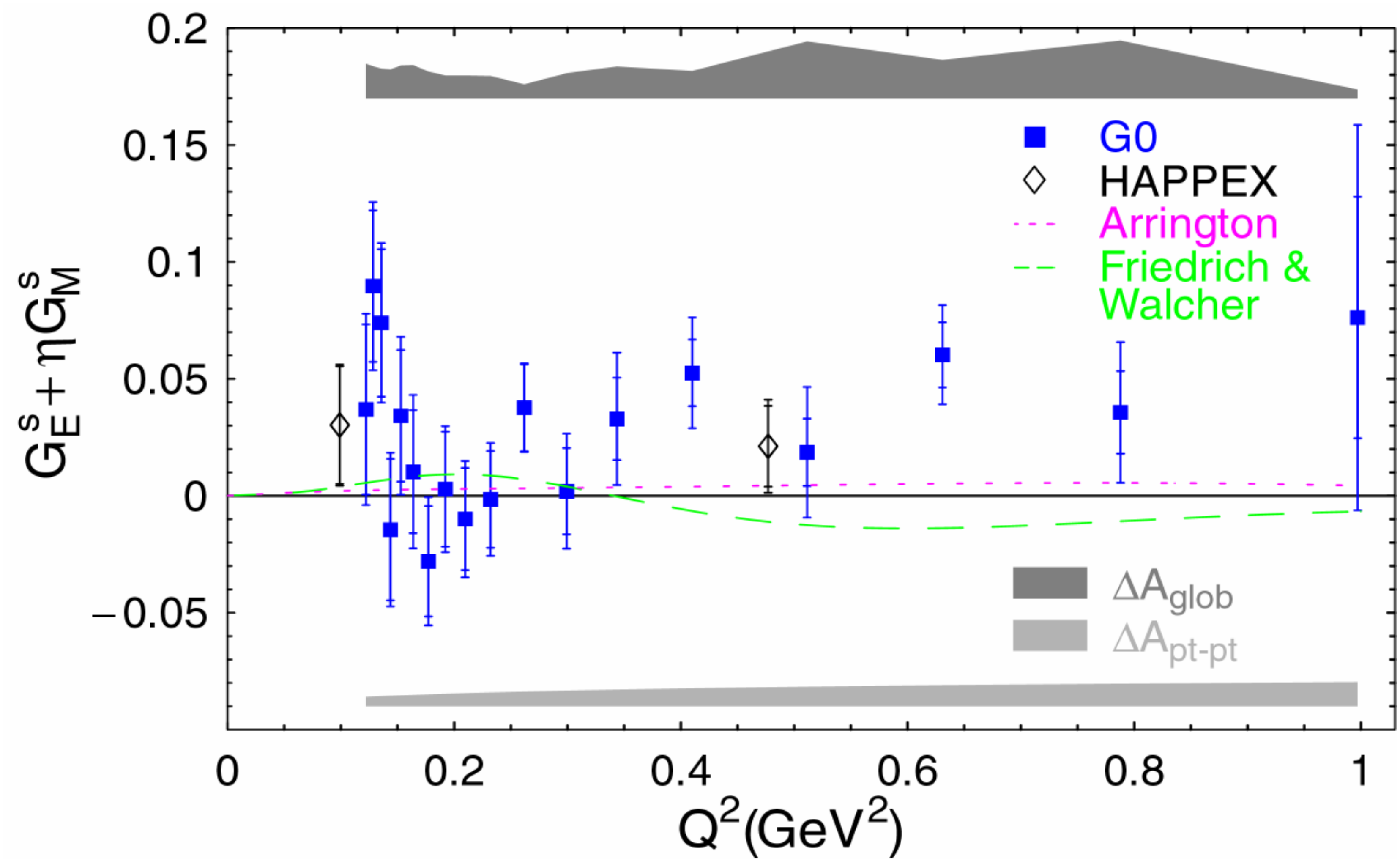


G0 Asymmetries (Forward-Angle)

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



G0: Forward-angle results



$G^s_E = G^s_M = 0$: Hypothesis excluded at 89% C.L.

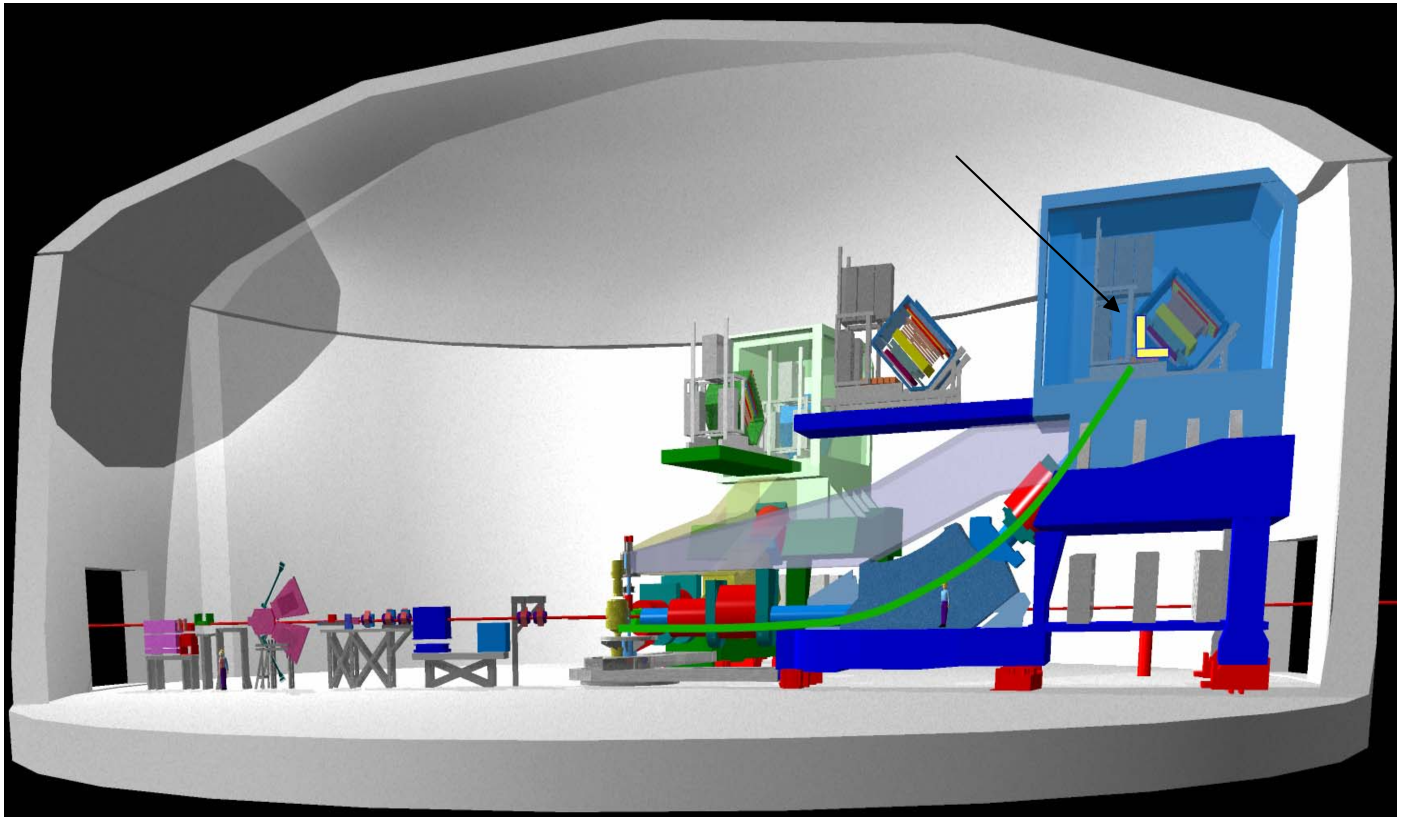
D.S. Armstrong *et al.*, PRL 95, 092001 (2005)

HAPPEX (second generation)

E=3 GeV θ=6° Q^2= 0.1 (GeV/c)^2

New results: just released *(P. Souder at Dallas APS meeting)*

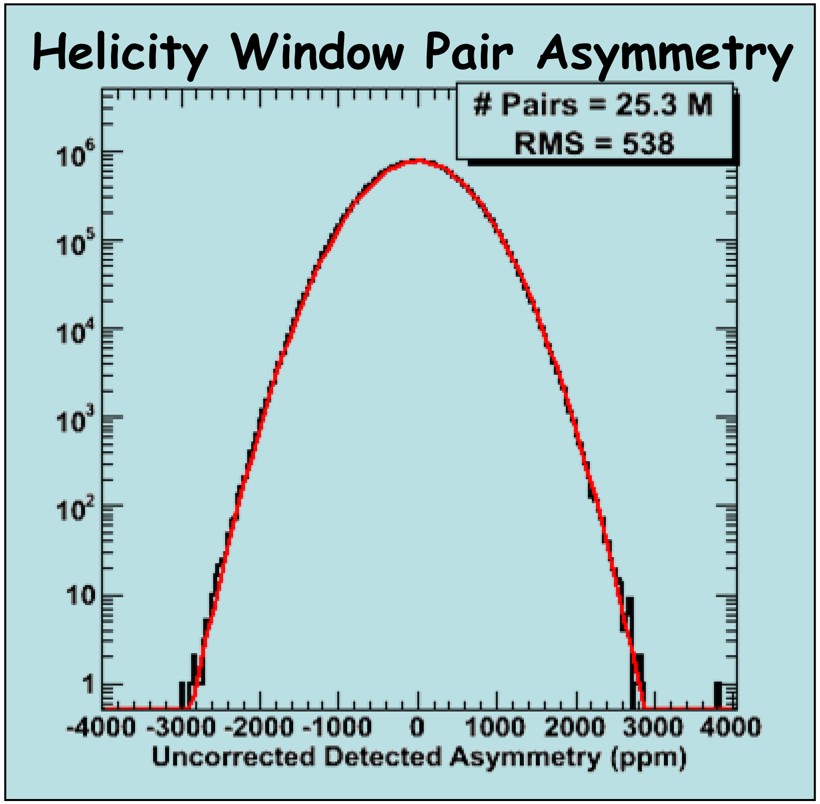
- **Hydrogen** : $G^s_E + \alpha\, G^s_M$
- **^{4}He**: Pure G^s_E : $A^{PV} = -\frac{A_0}{2}\left(2\sin^2\theta_W + \frac{G_E^s}{G_E^{p\gamma} + G_E^{n\gamma}}\right)$

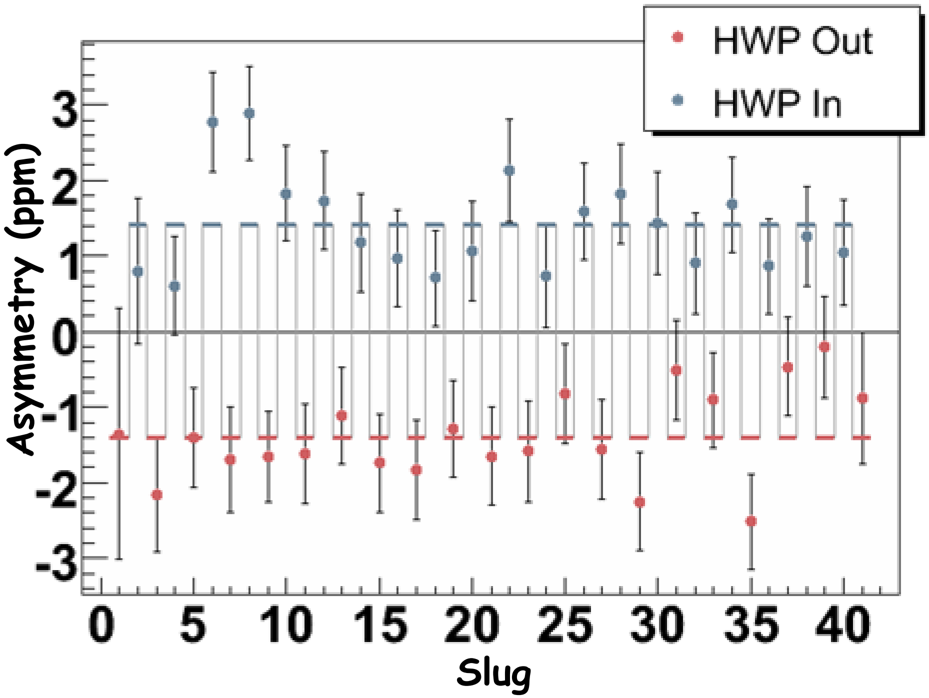


^{1}H Preliminary Results

Raw Parity Violating Asymmetry

A_{raw} correction ~11 ppb





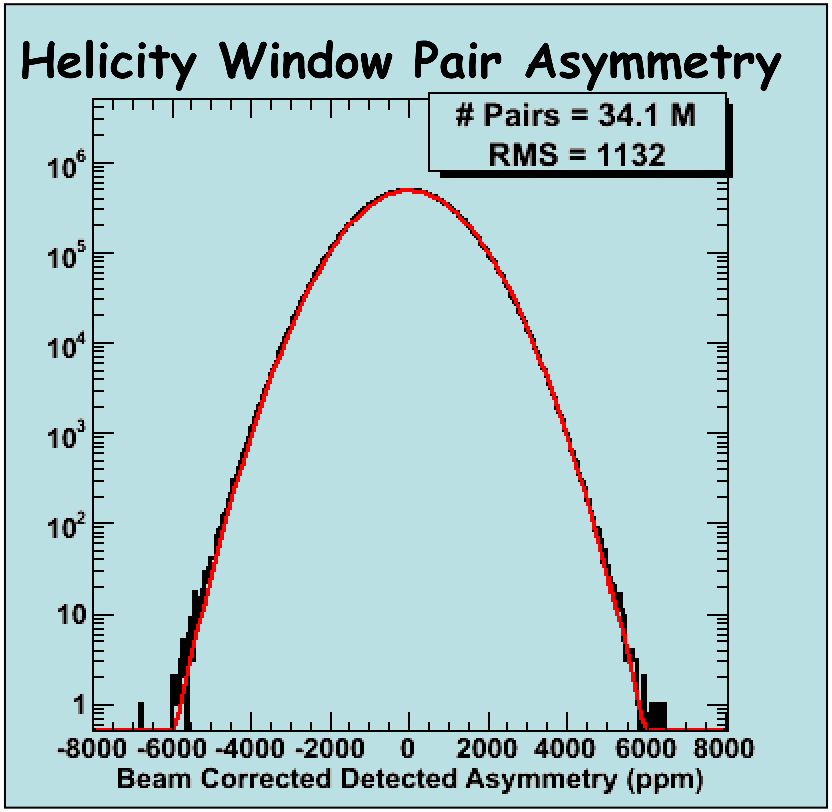
$Q^2 = 0.1089 \pm 0.0011 GeV^2$

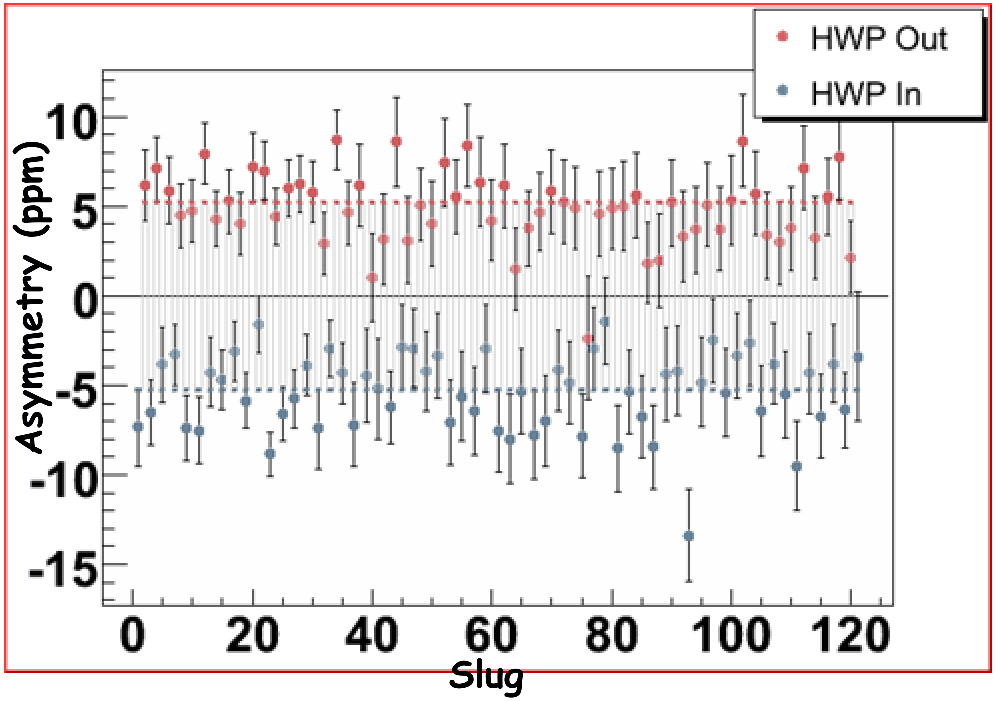
$A_{raw} = -1.418$ ppm $\pm$ 0.105 ppm (stat)

^{4}He Preliminary Results

Raw Parity Violating Asymmetry

A_{raw} correction ~ 0.12 ppm





$Q^2 = 0.07725 \pm 0.0007\ GeV^2$

$A_{raw} = 5.253$ ppm $\pm$ 0.191 ppm (stat)

HAPPEX-II 2005 Preliminary Results

HAPPEX-^{4}He:

$$Q^2 = 0.0772 \pm 0.0007\ (GeV/c)^2$$

$$A_{PV} = +6.43 \pm 0.23\ (stat) \pm 0.22\ (syst)\ ppm$$

$$A(G^s{=}0) = +6.37\ ppm$$

$$G^s_E = 0.004 \pm 0.014_{(stat)} \pm 0.013_{(syst)}$$

HAPPEX-H:

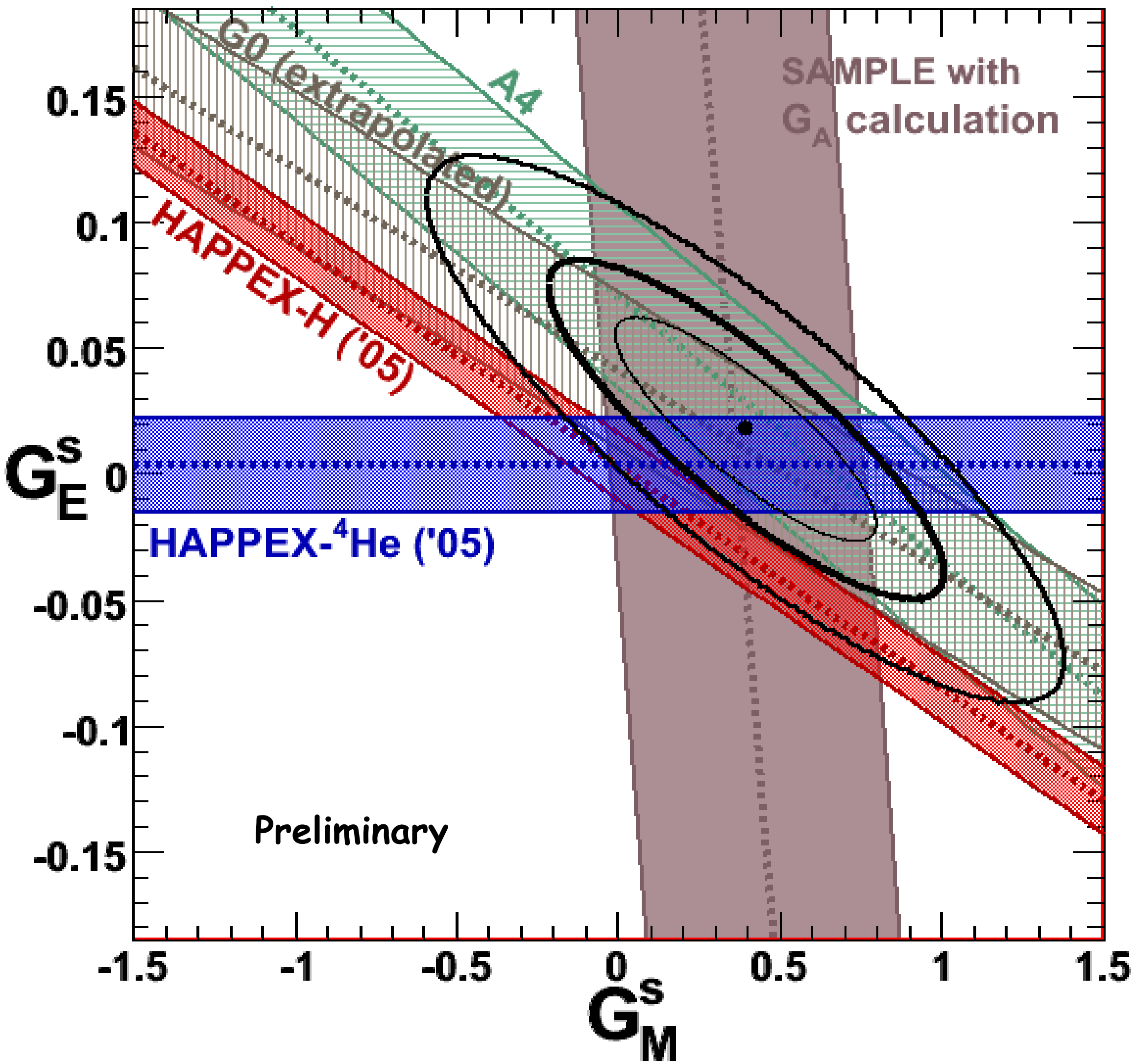
$$Q^2 = 0.1089 \pm 0.0011\ (GeV/c)^2$$

$$A_{PV} = -1.60 \pm 0.12\ (stat) \pm 0.05\ (syst)\ ppm$$

$$A(G^s{=}0) = -1.640\ ppm \pm 0.041\ ppm$$

$$G^s_E + 0.088\ G^s_M = 0.004 \pm 0.011_{(stat)} \pm 0.005_{(syst)} \pm 0.004_{(FF)}$$

HAPPEX-II 2005 Preliminary Results

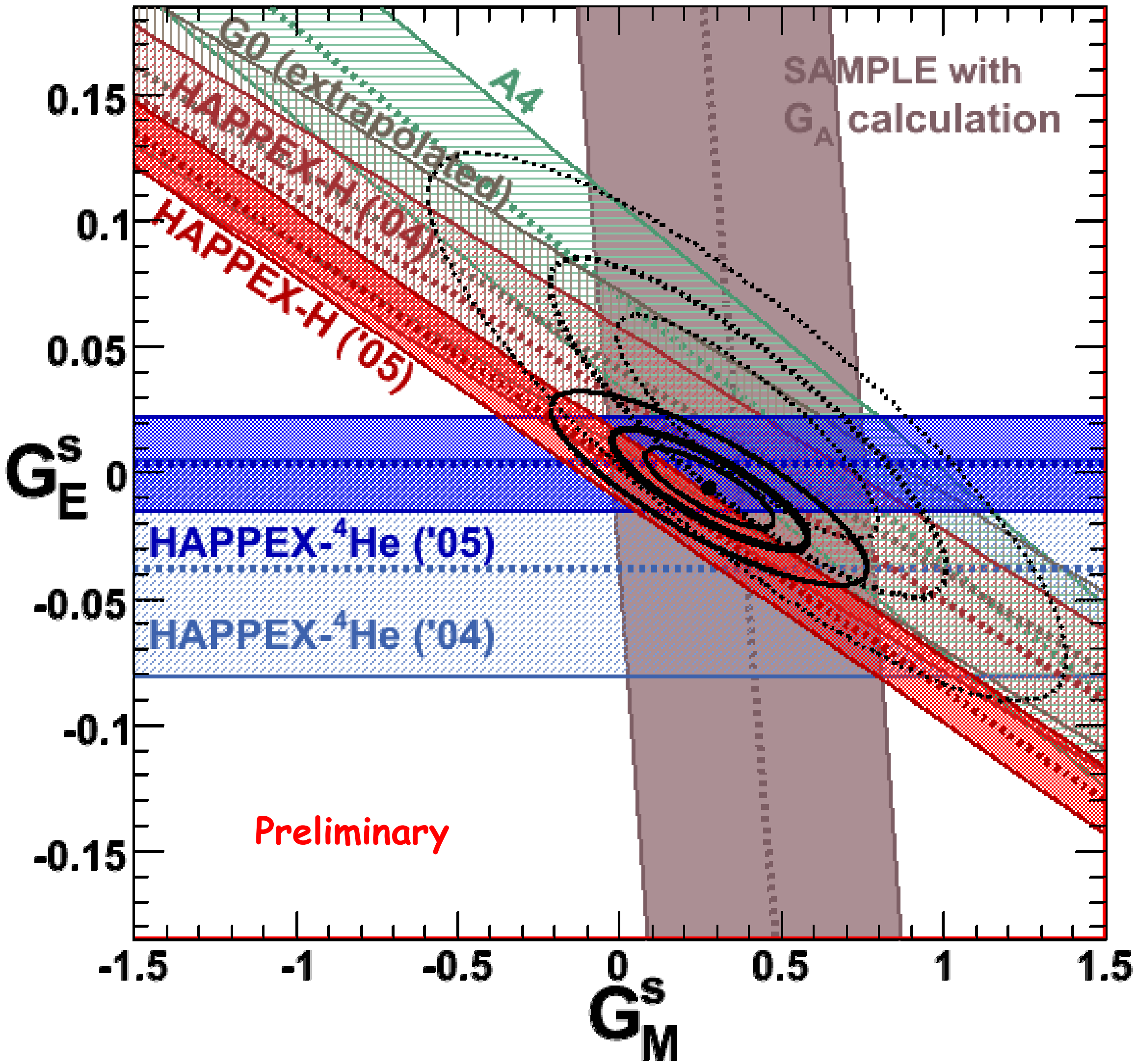


Three bands:

1. Inner: Project to axis for 1-D error bar
2. Middle: 68% probability contour
3. Outer: 95% probability contour

Caution: the combined fit is approximate. Correlated errors and assumptions not taken into account

World Data near Q^2 ~0.1 GeV^2



G_M^s = 0.28 +/- 0.20

G_E^s = -0.006 +/- 0.016

~3% +/- 2.3% of proton magnetic moment

~0.2 +/- 0.5% of electric distribution

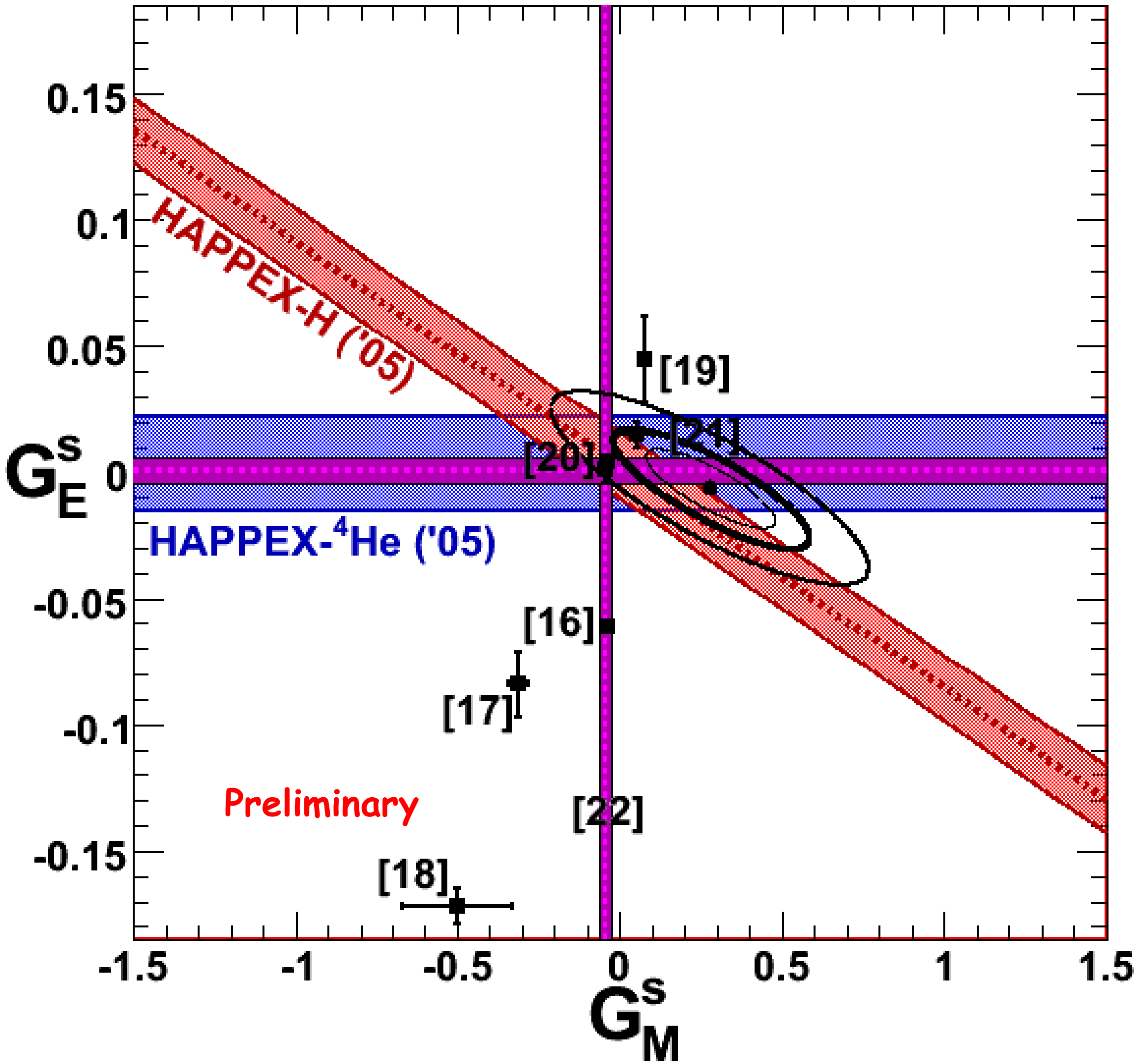
HAPPEX-only fit suggests something even smaller:

G_M^s = 0.12 +/- 0.24

G_E^s = -0.002 +/- 0.017

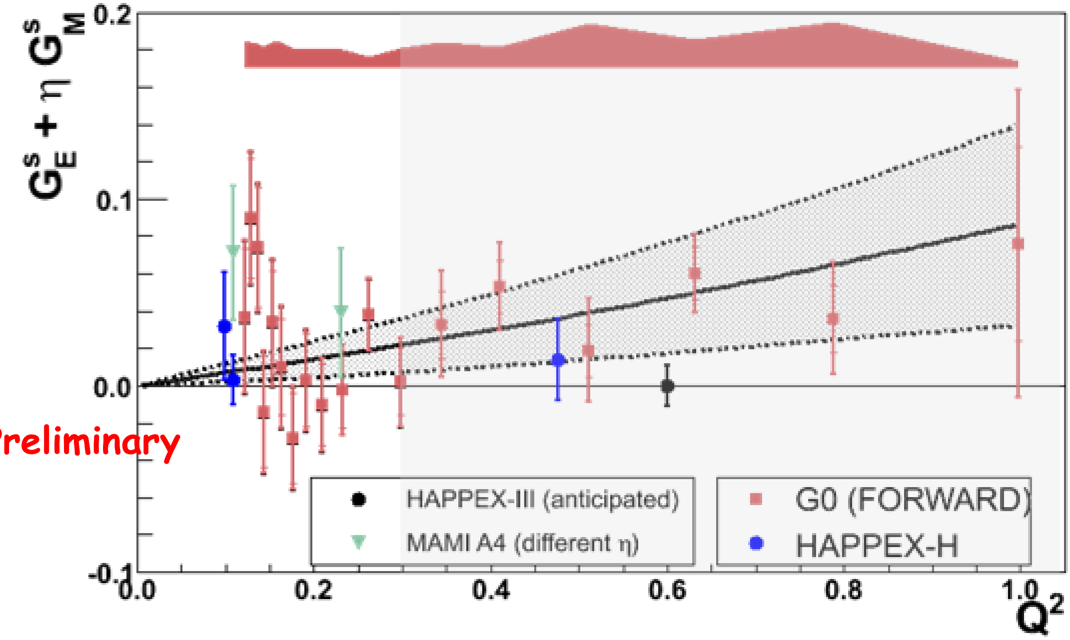
Caution: the combined fit is approximate. Correlated errors and assumptions not taken into account

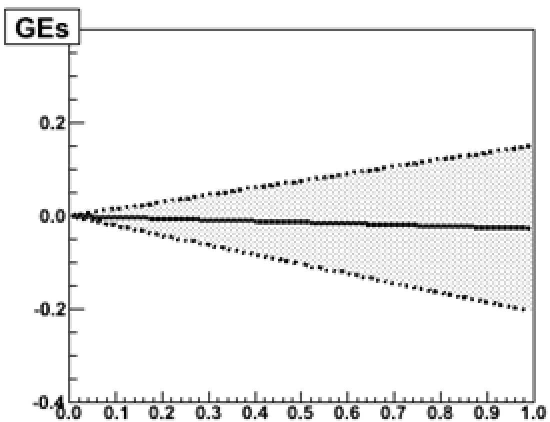
World data consistent with state of the art theoretical predictions

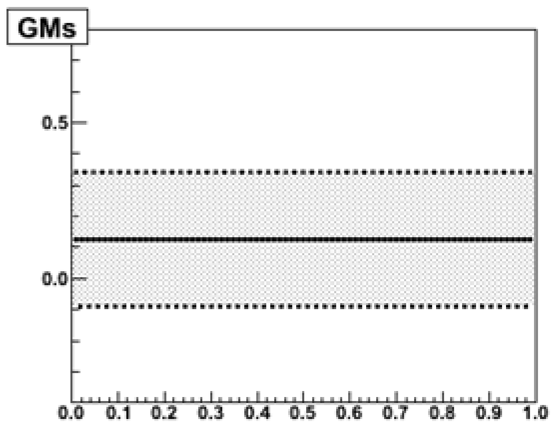


16. **Skyrme Model** - N.W. Park and H. Weigel, Nucl. Phys. *A* **451**, 453 (1992).
17. **Dispersion Relation** - H.W. Hammer, U.G. Meissner, D. Drechsel, Phys. Lett. B **367**, 323 (1996).
18. **Dispersion Relation** - H.-W. Hammer and Ramsey-Musolf, Phys. Rev. *C* **60**, 045204 (1999).
19. ***Chiral Quark Soliton Model*** - *A.* Sliva *et al.*, Phys. Rev. D **65**, 014015 (2001).
20. ***Perturbative Chiral Quark Model*** - V. Lyubovitskij *et al.*, Phys. Rev. *C* **66**, 055204 (2002).
21. **Lattice** - R. Lewis *et al.*, Phys. Rev. D **67**, 013003 (2003).
22. ***Lattice + charge symmetry*** - Leinweber et al, Phys. Rev. Lett. **94**, 212001 (2005) & hep-lat/0601025

A Simple Fit (for a simple point)







Simple fit:

GEs = r_s*τ

GMs = mu_s

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

Includes SAMPLE constrainted with G_A theory and HAPPEX-He 2004, 2005

G0 Global error allowed to float with unit constraint

Nothing intelligent done with form factors, correlated errors, etc.

Quantitative values should NOT be taken very seriously, but some clear, basic points:

- **The world data are consistent.**
- **Rapid Q^2 dependence of strange form-factors is not required.**
- **Sizeable contributions at higher Q2 are not definitively ruled out. (To be tested by HAPPEX-III, G0 and A4 backangle.)**

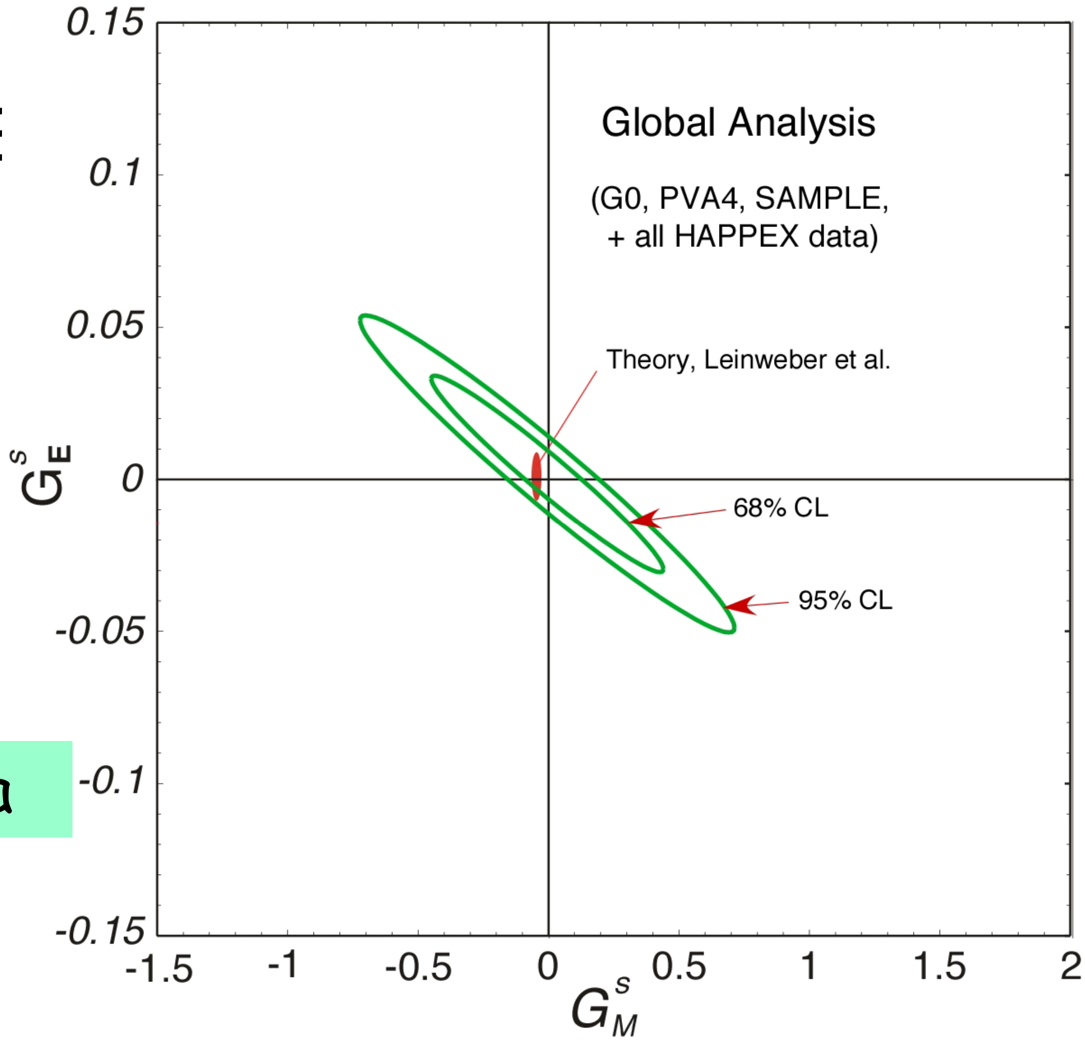
A Global Fit: R.D. Young, et al. nucl-ex/0604010

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

- Reanalysis of SAMPLE nuclear corrections
- Kelly's EMF

- Float G_A^e separately for neutron and proton

With HAPPEx-2005 data



Figures: courtesy of R. Carlini

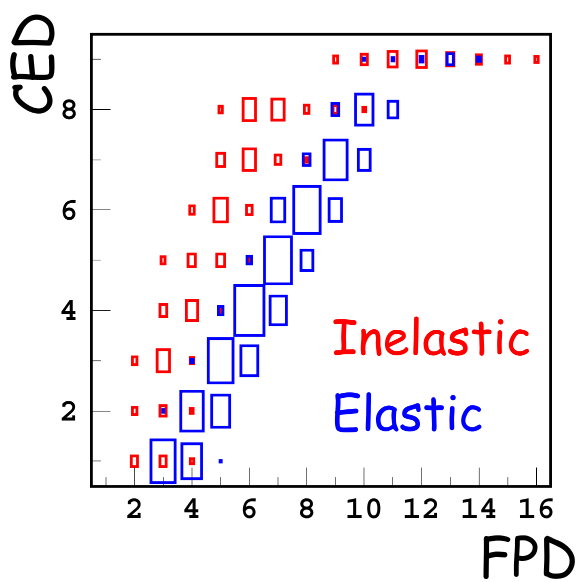
G^0 : Backward Angle

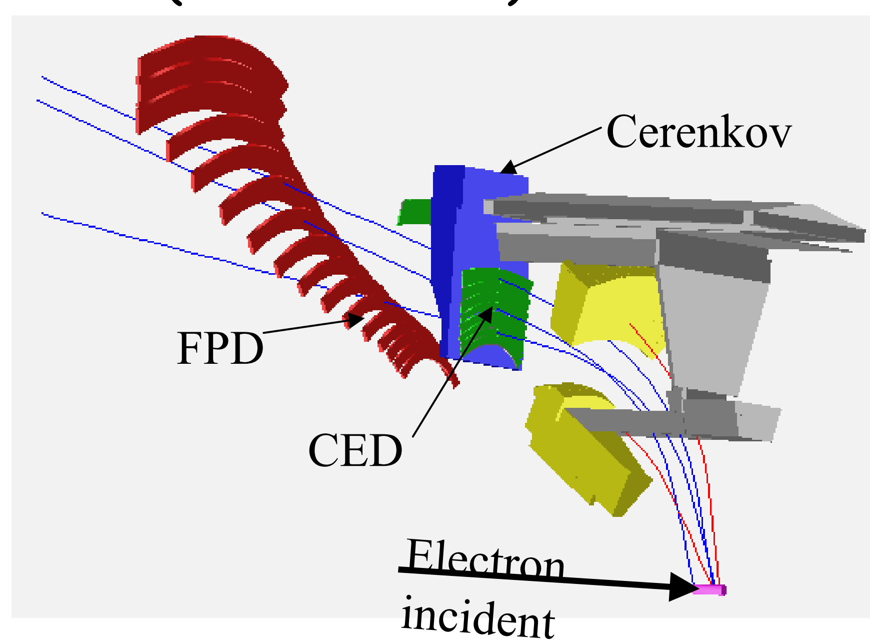
- Detect scattered electrons at $\theta_e \sim 110^\circ$
  $\rightarrow$ Need separate runs at E = 362, 687 MeV
  for Q^2 = 0.23, 0.63 $(GeV/c)^2$
  for both LH_2 and LD_2 targets
- Get G^s_M and G_A

Additional detectors:
- Cryostat Exit Detectors (CED) to separate elastic/inelastic e^-
- Cerenkov detectors for π rejection

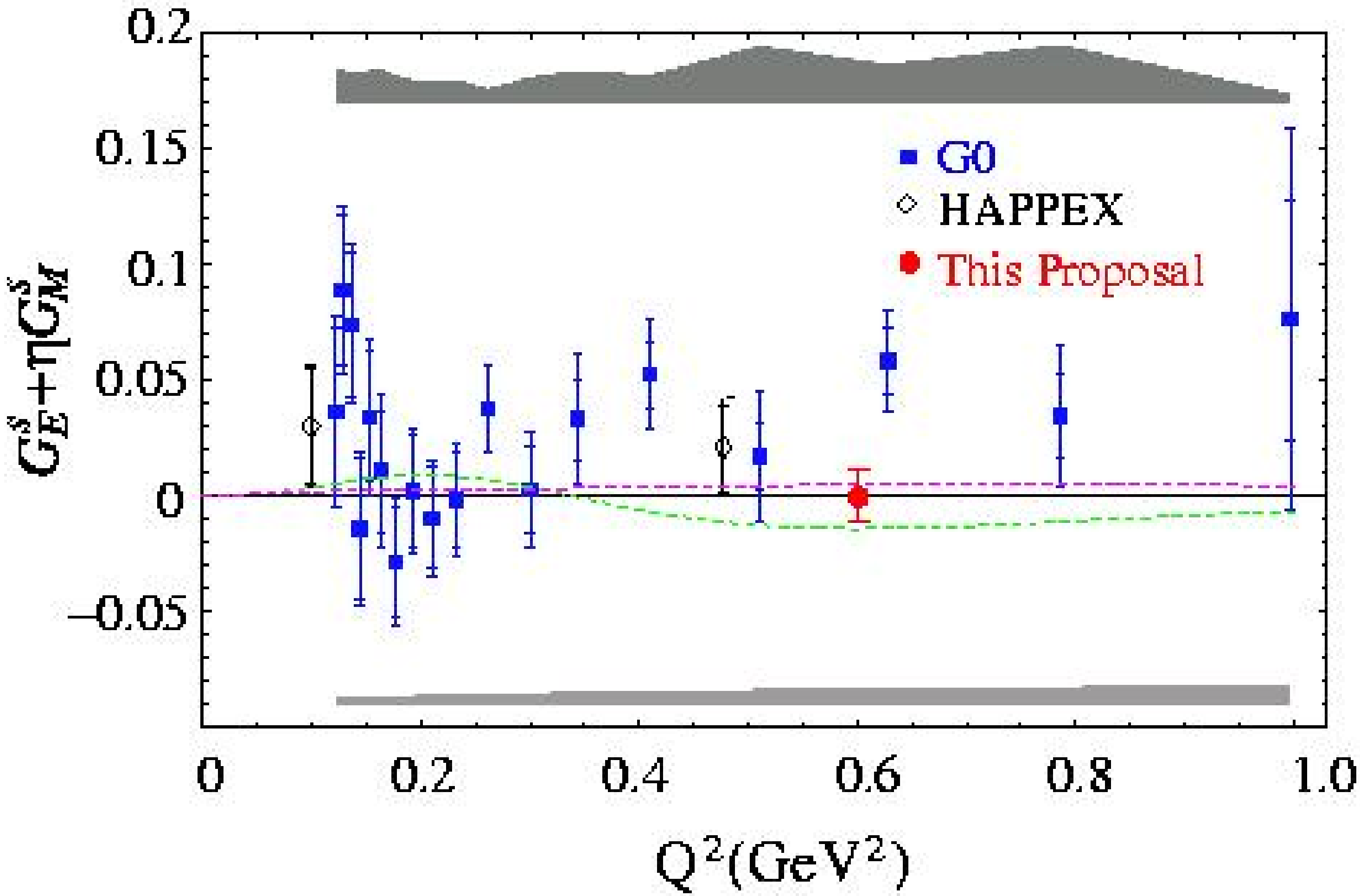
First Run – just completed (last weekend)

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





HAPPEX-III (2008)



Paschke & Souder, E05-109

Conclusions

- *Marvelous* consistency of data, *esp.* at Q^2=0.1 GeV^2.
- Q^2 = 0.1 GeV^2 data: G^s_M and G^s_E consistent with zero;
  constraining axial FF to Zhu *et al.* theory favors positive G^s_M
- Still room (& hints?) for non-zero values at higher Q^2

Future:

- G0 Backward: will allow G^s_M and G^s_E separation at two Q^2
- Mainz: PV-A4 backward-angle program underway
- HAPPEx-III: high precision forward-angle @ Q^2 = 0.6 GeV^2
- Qweak: Standard Model test at low Q^2 (2009)

Backup Slides

Two Photon Exchange

1. Beyond single boson exchange in electroweak interference:
   - $\gamma\gamma$ and γZ box and crossing diagrams.
   - effects appear small at large ε and small Q^2
   - not a concern at present experimental precision.

2. Electromagnetic Form Factors used to extract strange form factors:
   - which form factors to use?

3. Transverse Asymmetry/Beam normal asymmetry/Vector analyzing power:
   - ☹ "background" to PV measurements, if electron beam not 100% longitudinal and detectors not perfectly symmetric.
   - ☺ interesting in its own right – imaginary parts of TPE.

Validity of charge symmetry assumption

$$u \leftrightarrow d$$

$$G_{E,M}^{u,p} = G_{E,M}^{d,n} \qquad G_{E,M}^{d,p} = G_{E,M}^{u,n} \qquad G_{E,M}^{s,p} = G_{E,M}^{s,n}$$

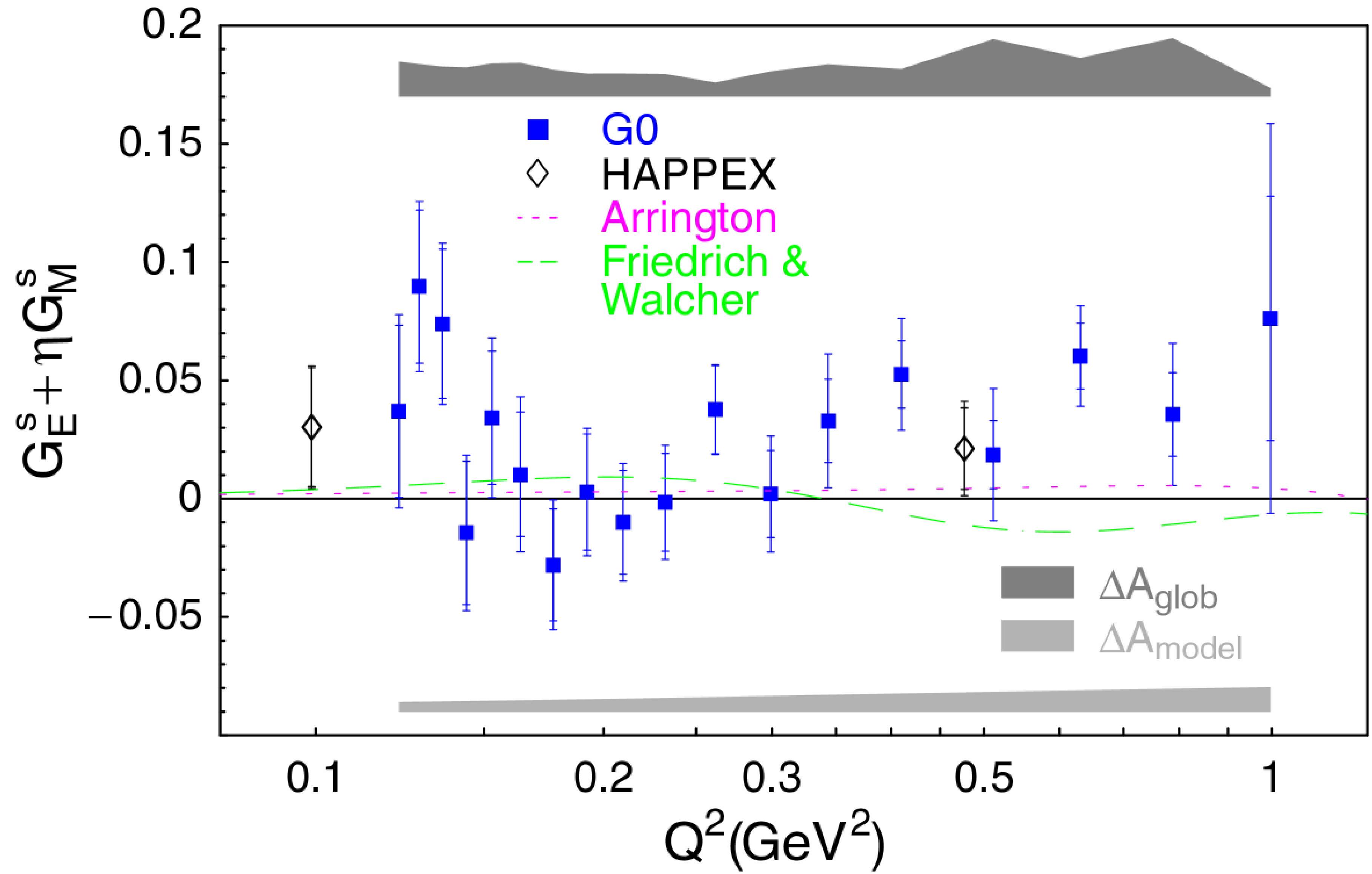
Size of charge symmetry breaking effects in some n,p observables:

- n - p mass difference $\rightarrow$ $(m_n - m_p)/m_n$ ~ 0.14%
- polarized elastic scattering $\vec{n}$ + p, $\vec{p}$+n $\Delta A = A_n - A_p = (33 \pm 6) \times 10^{-4}$
  Vigdor et al, PRC 46, 410 (1992)
- Forward backward asymmetry $n + p \rightarrow d + \pi^0$ $A_{fb} \sim (17 \pm 10) \times 10^{-4}$
  Opper et al., nucl-ex 0306027 (2003)

$\rightarrow$ For vector form factors theoretical CSB estimates indicate < 1% violations (unobservable with currently anticipated uncertainties)

Miller PRC 57, 1492 (1998) Lewis & Mobed, PRD 59, 073002(1999)

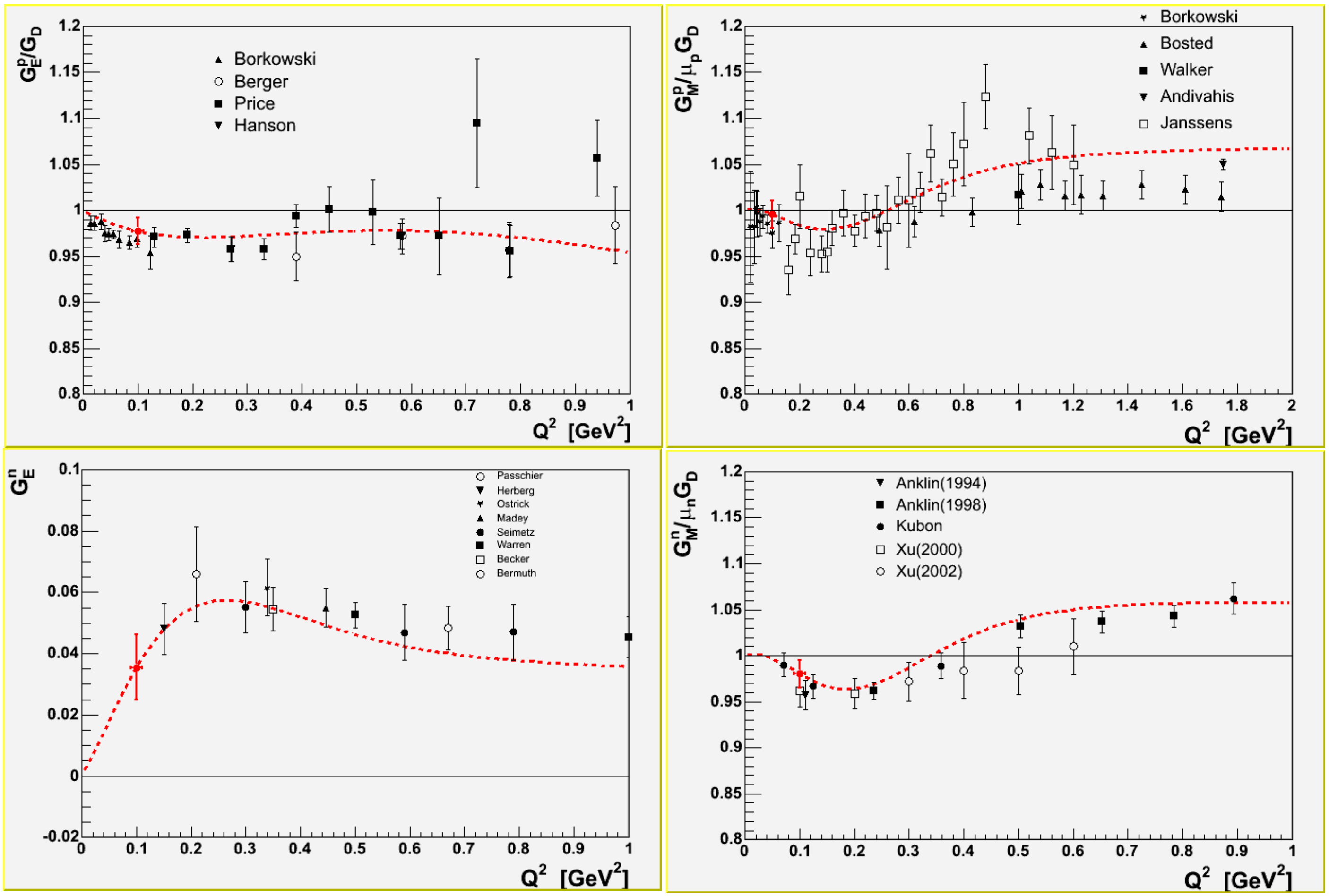
Strange Quark Contribution to Proton



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

EM Form Factors

Electromagnetic form factors parameterized as by:
Friedrich and Walcher, Eur. Phys. J. A, **17**, 607 (2003)



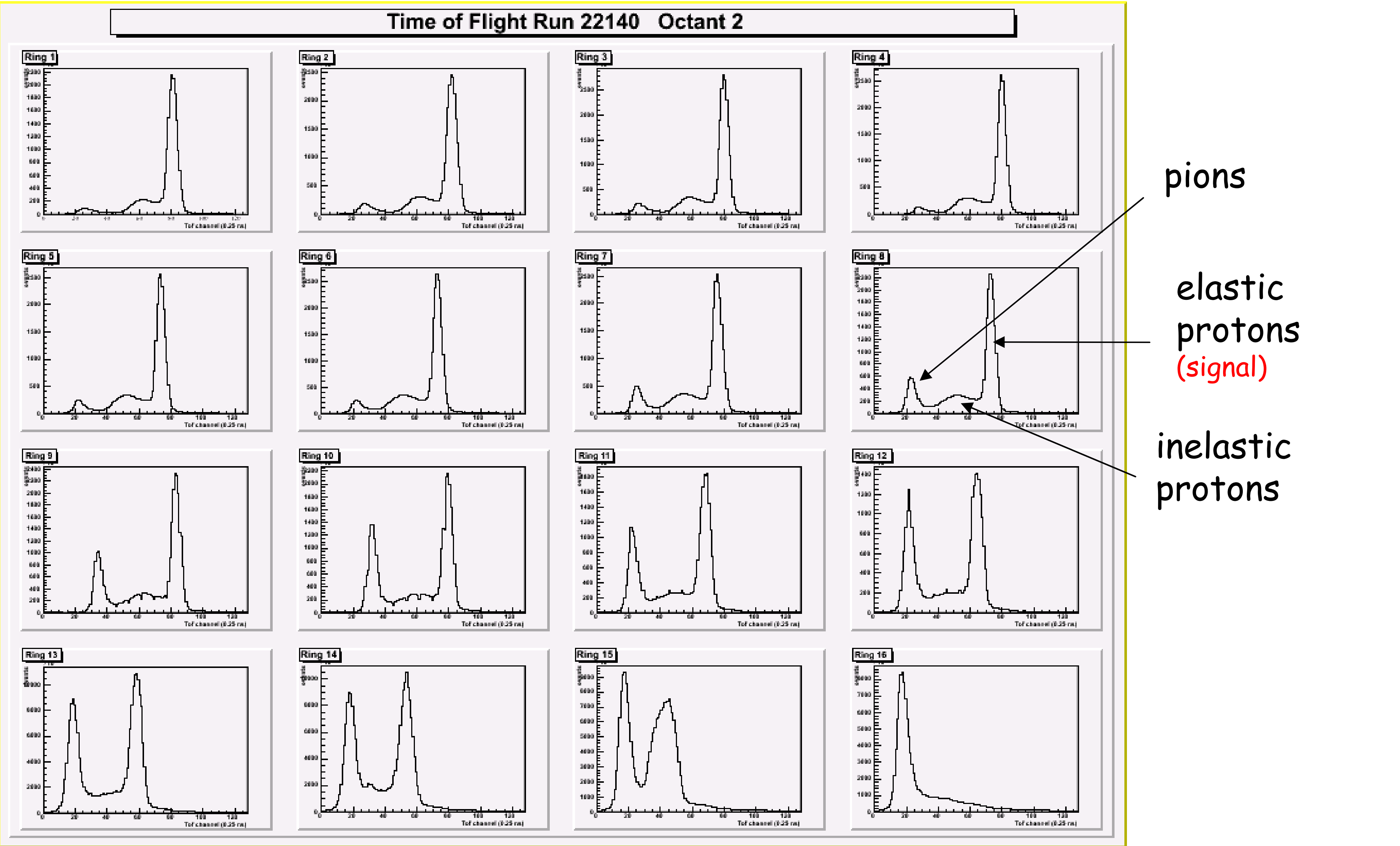
GEn from BLAST:

Claimed uncertainty at 7-8%

FF	Error
G_E^p	2.5%
G_M^p	1.5%
G_E^n	10%
G_M^n	1.5%
$G_A^{(3)}$	-
$G_A^{(8)}$	-

Time of Flight Spectra

Time of flight spectra for all
16 detectors of a single octant
- recorded every 33 ms



Positive Background Asymmetries

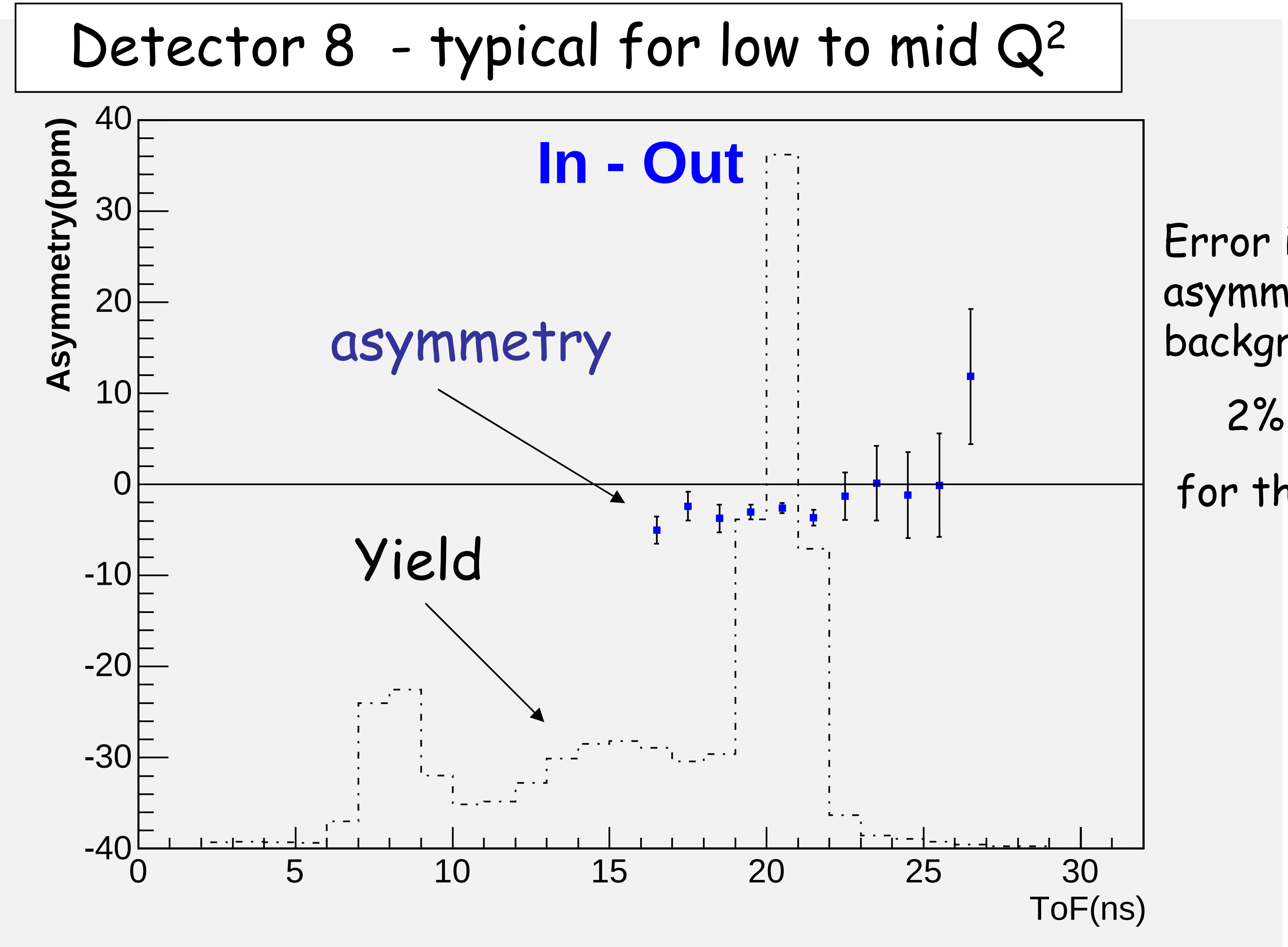
- Det. 12-16 see smoothly varying peak in background asymmetries
  - maximum magnitude ~ +45 ppm

- Source is protons from hyperon weak decay scattering inside spectrometer
  - GEANT simulation with generator for hyperon production based on CLAS data
  - simulate both Λ and $\Sigma^{+,0}$ decays
    - polarization transfer for Λ 100%
    - assume 70% for Σ^{+}
    - Σ^{0} asymmetry scaled by further factor of $-1/3$ (CG coefficient)
  - simulation explains source; use measured data for actual analysis

"Side-band" background correction

- Asymmetry and yield measured on either side of elastic peak

  -> smooth interpolation is simple



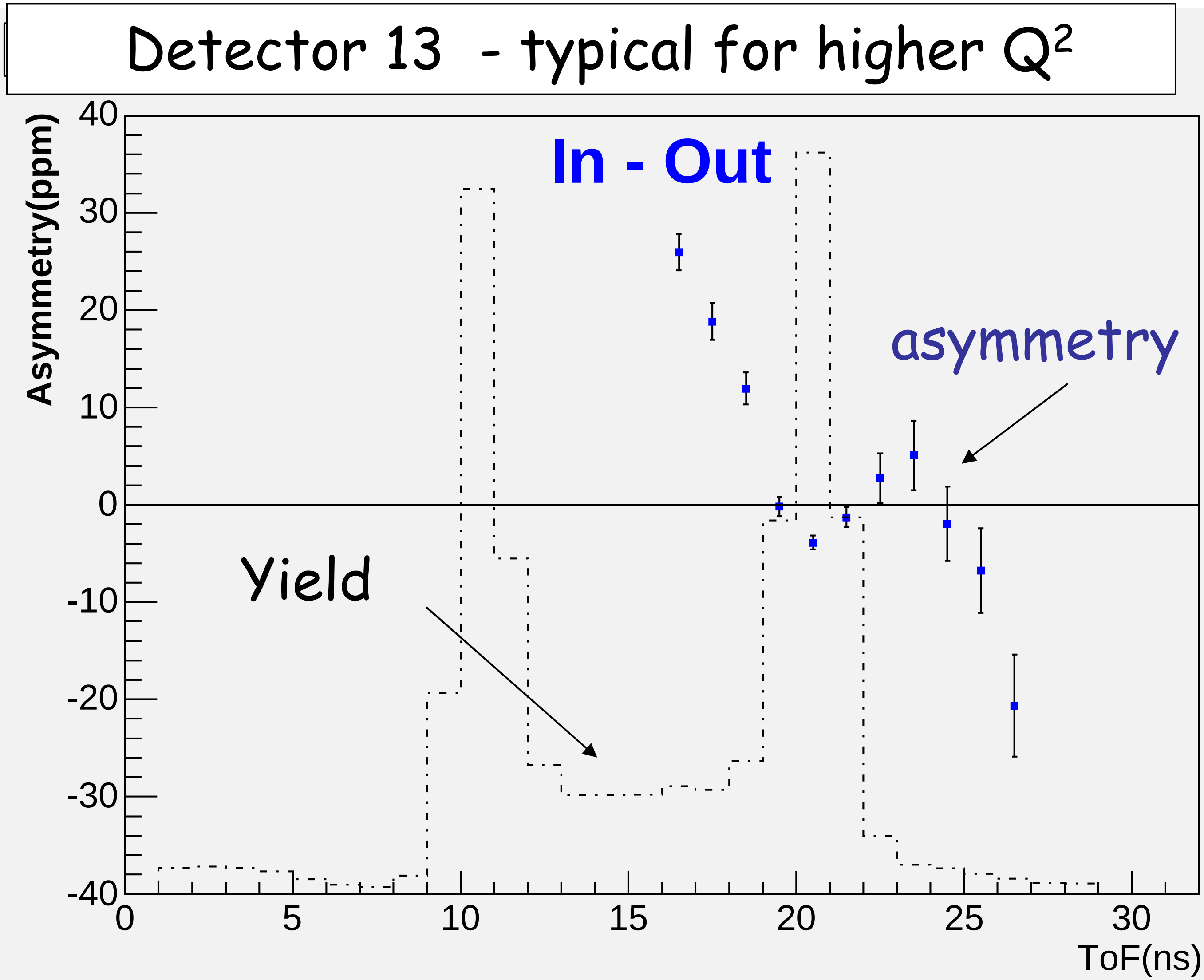
Error in elastic asymmetry due to background is

2% - 5%

for these detectors

"Side-band" background correction @ larger Q^2

- Background asymmetry 'large' & varying significantly under elastic peak

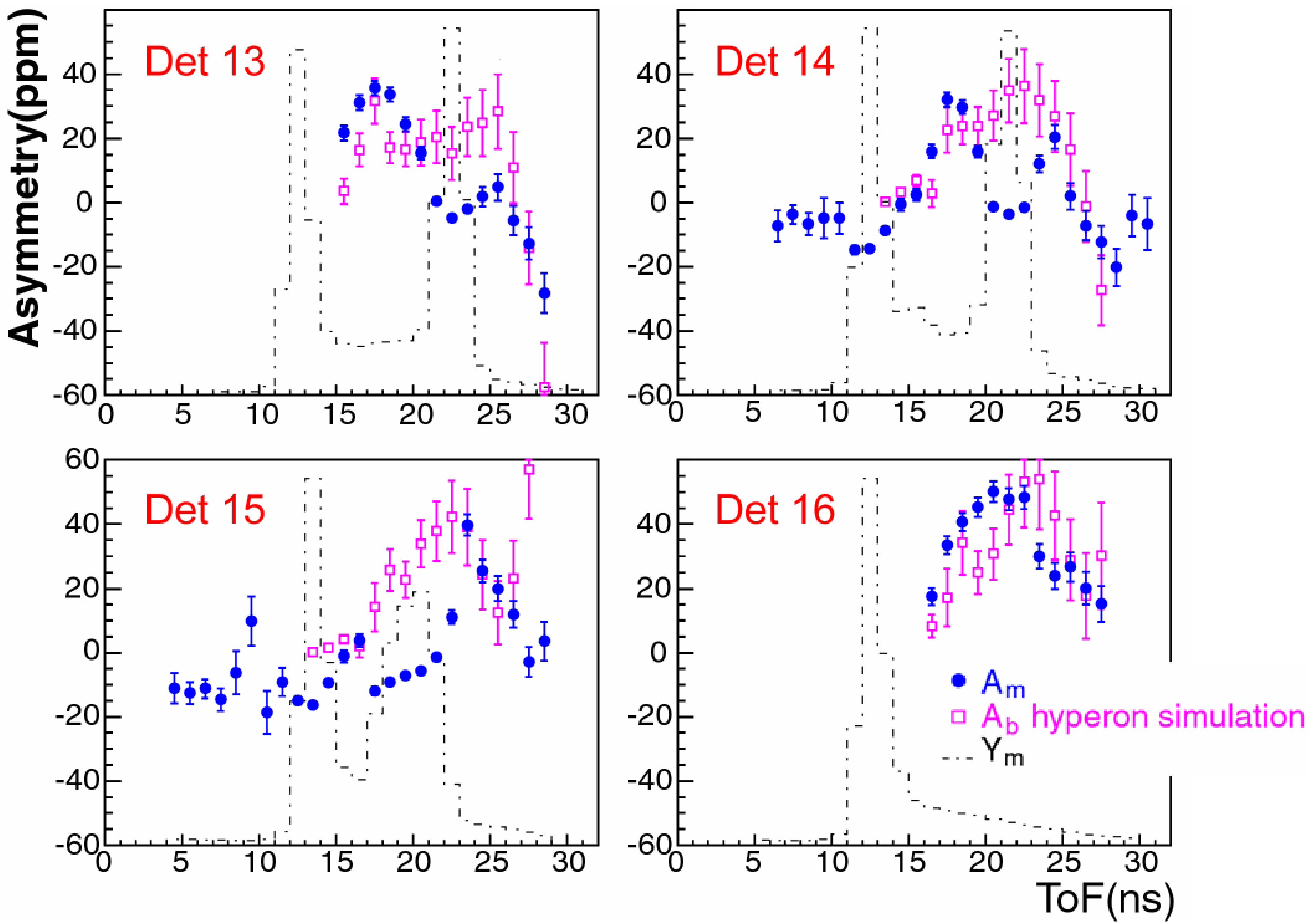


Error in elastic asymmetry due to background dominates here

7% - 20% error

(depending on detector)

Positive Background Asymmetries: GEANT



G0: Asymmetry with EW Radiative Corrections

- Full form of asymmetry used to extract $G_E^s + \eta G_M^s$

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

$$\left(\varepsilon G_E^p G_E^n + \tau G_M^p G_M^n\right)\left(1 + R_V^n\right) - \left(\varepsilon G_E^p G_E^s + \tau G_M^p G_M^s\right)\left(1 + R_V^{(0)}\right) -$$

$$\varepsilon'\left(1 - 4\sin^2\theta_W\right) G_M^p G_A^e \Big\}$$

where

$$G_A^e = -G_A^p\left(1 + R_A^{T=1}\right) + \left[\frac{1}{2}\left(3F - D\right)R_A^{T=0} + \Delta s\left(1 + R_A^{(0)}\right)\right] G_A^{dip}$$

and

$$G_A^p = g_A G_A^{dip} = \left(F + D\right) G_A^{dip} = \frac{g_A}{\left(1 + Q^2/\Lambda_A^2\right)^2}$$

Simple Fits to World Hydrogen Data

- Fit $G_E^s(Q^2) + \eta(Q^2, E_i) G_M^s(Q^2) =$

$$\frac{4\pi\alpha\sqrt{2}}{G_F Q^2} \frac{\varepsilon G_E^{p\,2} + \tau G_M^{p\,2}}{\varepsilon G_E^p \left(1 + R_V^{(0)}\right)} \left(A_{phys} - A_{NVS}(Q^2, E_i)\right)$$

with simple forms for G_M^s , G_E^s

$$G_E^s(Q^2) = \frac{c_2 Q^4}{1 + d_1 Q^2 + d_2 Q^4 + d_3 Q^6}$$

à la Kelly

$$G_M^s(Q^2) = \frac{G_M^s(Q^2 = 0)}{\left(1 + Q^2 / \Lambda_M^{s\,2}\right)^2}$$

with

$$G_M^s(Q^2 = 0) = 0.81$$

from Q^2 = 0.1 GeV^2 plot, dipole ff

HAPPEx

Error Budget-Helium

2005

False Asymmetries	48 ppb
Polarization	192 ppb
Linearity	58 ppb
Radiative Corrections	6 ppb
Q^2 Uncertainty	58 ppb
Al background	32 ppb
Helium quasi-elastic background	24 ppb
Total	216 ppb

2004

False Asymmetries	103 ppb
Polarization	115 ppb
Linearity	78 ppb
Radiative Corrections	7 ppb
Q^2 Uncertainty	66 ppb
Al background	14 ppb
Helium quasi-elastic background	86 ppb
Total	205 ppb

Error Budget-Hydrogen

2005

False Asymmetries	17 ppb
Polarization	37 ppb
Linearity	15 ppb
Radiative Corrections	3 ppb
Q^2 Uncertainty	16 ppb
Al background	15 ppb
Rescattering Background	4 ppb
Total	49 ppb

2004

False Asymmetries	43 ppb
Polarization	23 ppb
Linearity	15 ppb
Radiative Corrections	7 ppb
Q^2 Uncertainty	12 ppb
Al background	16 ppb
Rescattering Background	32 ppb
Total	63 ppb

Determining Q^2

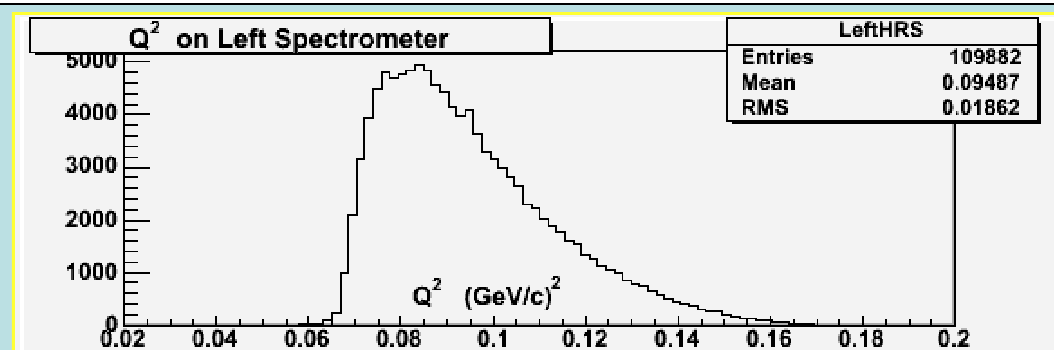
Asymmetry explicitly depends on Q^2:

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

$$Q^2 = 2EE'\left(1-\cos\theta\right)$$

Goal: $\delta_{Q^2} < 1\%$

Q^2 measured using standard HRS tracking package, with reduced beam current



- Central scattering angle must be measured to $\delta\theta < 0.5\%$
- Asymmetry distribution must be averaged over finite acceptance