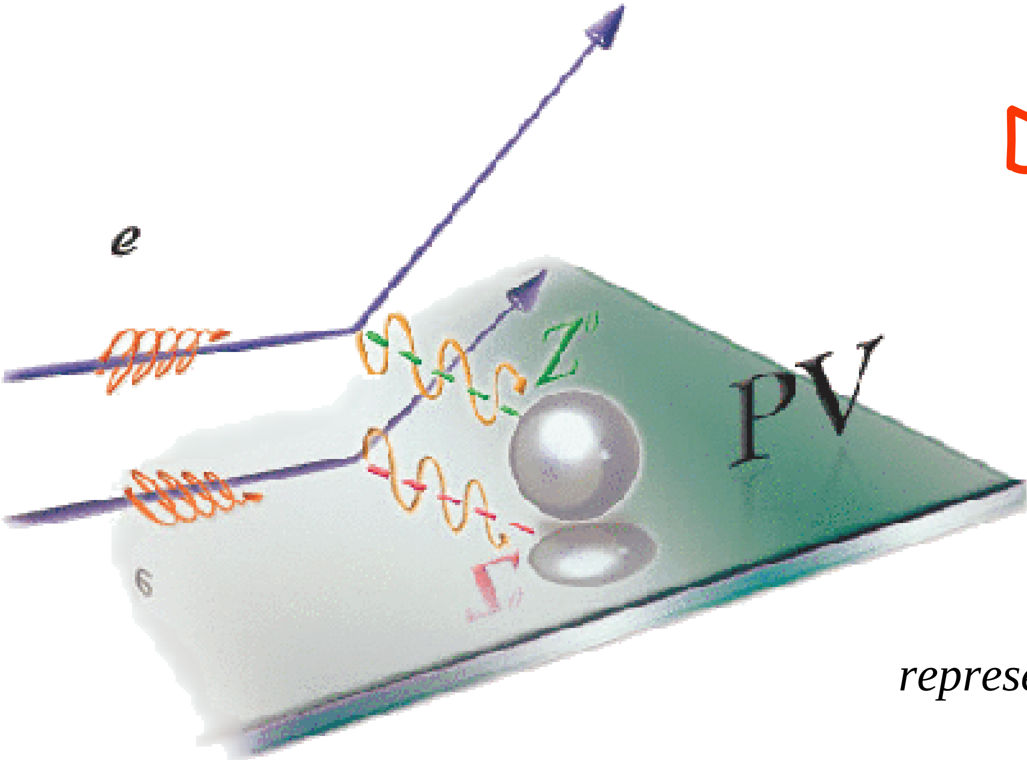
New Results from the HAPPEx Experiments at $Q^2 = 0.1\ GeV/c^2$



David S. Armstrong

College of William & Mary

representing the **HAPPEX Collaboration**

From Parity Violation to Hadronic Structure… (PAVI 2006)   Milos, Greece   May 16 2006

The College of WILLIAM & MARY

Jefferson Lab

Outline

- Parity-violation in electron scattering
- Elastic Vector Strange Form Factors: G^s_E and G^s_M
- $Q^2 = 0.1\ (GeV/c)^2$ as/of early 2005

- Latest results from HAPPEx-II:
  - HAPPEx-hydrogen and HAPPEx-Helium

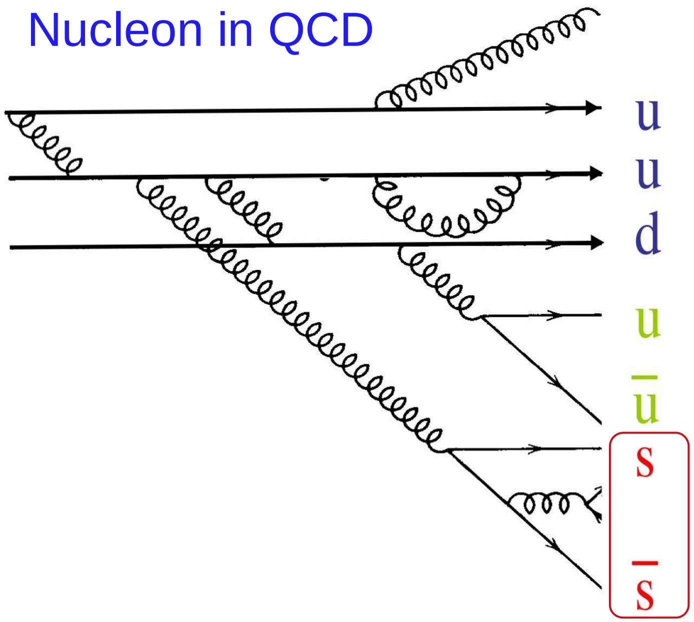
- The present situation at $Q^2 = 0.1\ (GeV/c)^2$
- Implications and Conclusions

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

Francis Bacon 1561-1626

Strangeness in the nucleon

Nucleon in QCD



- $P = uud + u\bar{u} + d\bar{d} + s\bar{s} + g + ...$ (« sea »: $u\bar{u} + d\bar{d} + s\bar{s} + g + ...$)

- s quark: cleanest candidate to study the sea

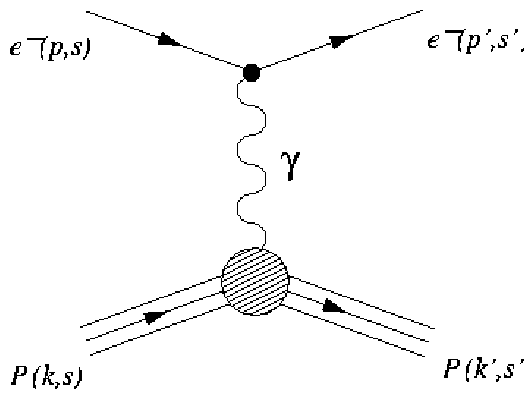
-)How much do virtual $s\bar{s}$ pairs contribute to the structure of the nucleon ?
  - Momentum : 4 % (DIS)
  - Spin : 0 to -10% (polarized DIS)
  - Mass : 0 to 30 % (πN -sigma term)

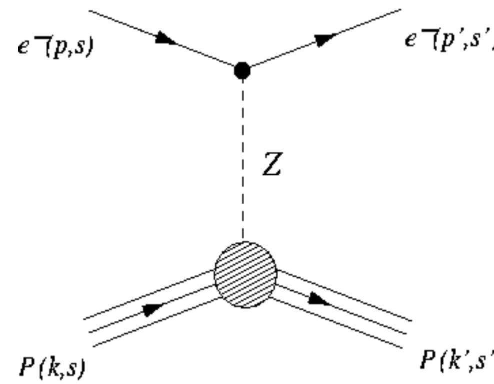
  (large uncertainties on these contributions)

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

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

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 ⇨

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

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

Form Factors

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

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*:

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

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

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

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

* See B. Kubis & R. Lewis nucl-th/0605006 & Randy Lewis' talk at this meeting

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

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

For deuterium:

enhanced G_A^e sensitivity

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^s_E and G^s_M !

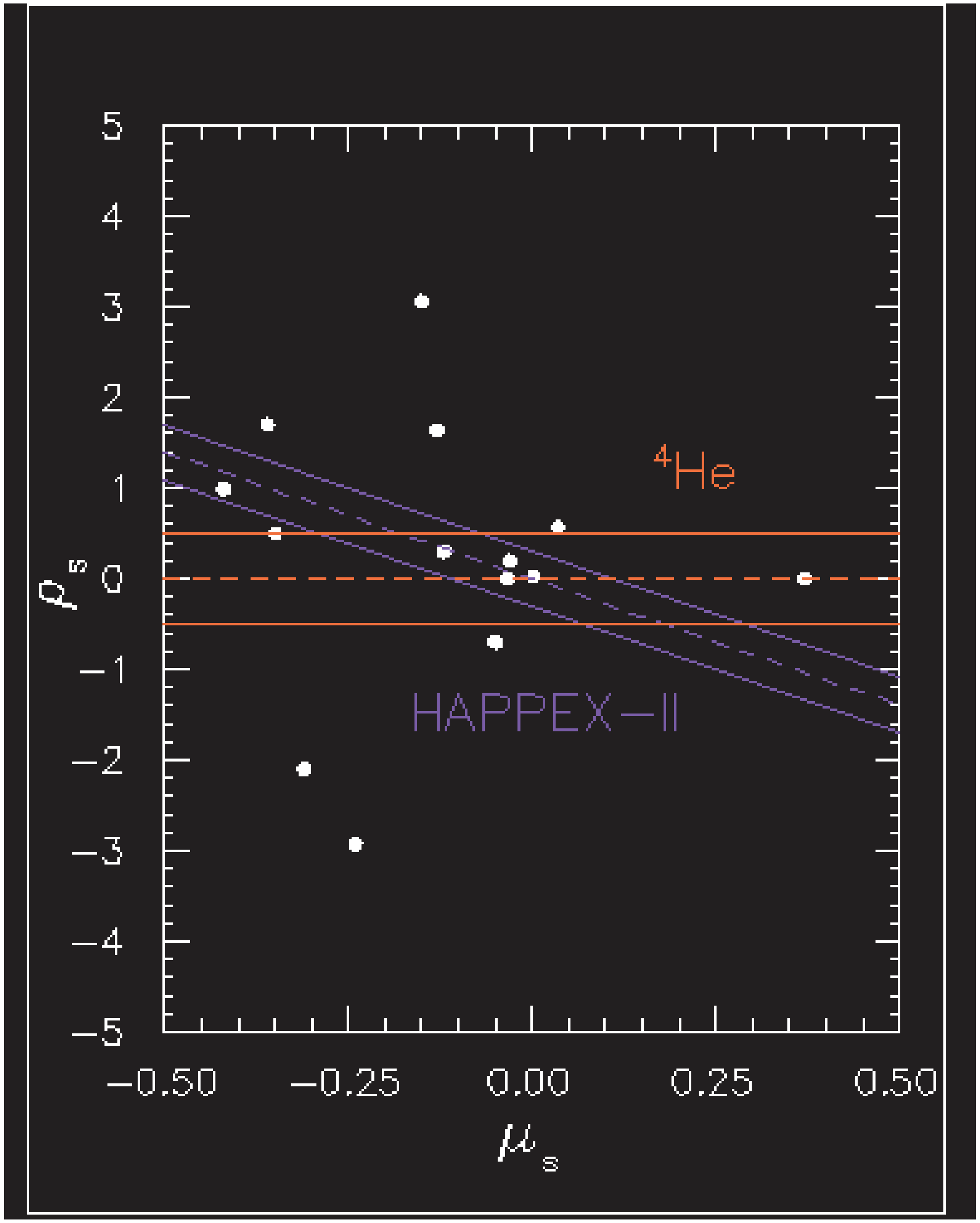
a challenging problem in non-perturbative QCD

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 *and* hep-lat/0601025

⇨ See Ross Young's talk

Strangeness Models (as/of 2000)

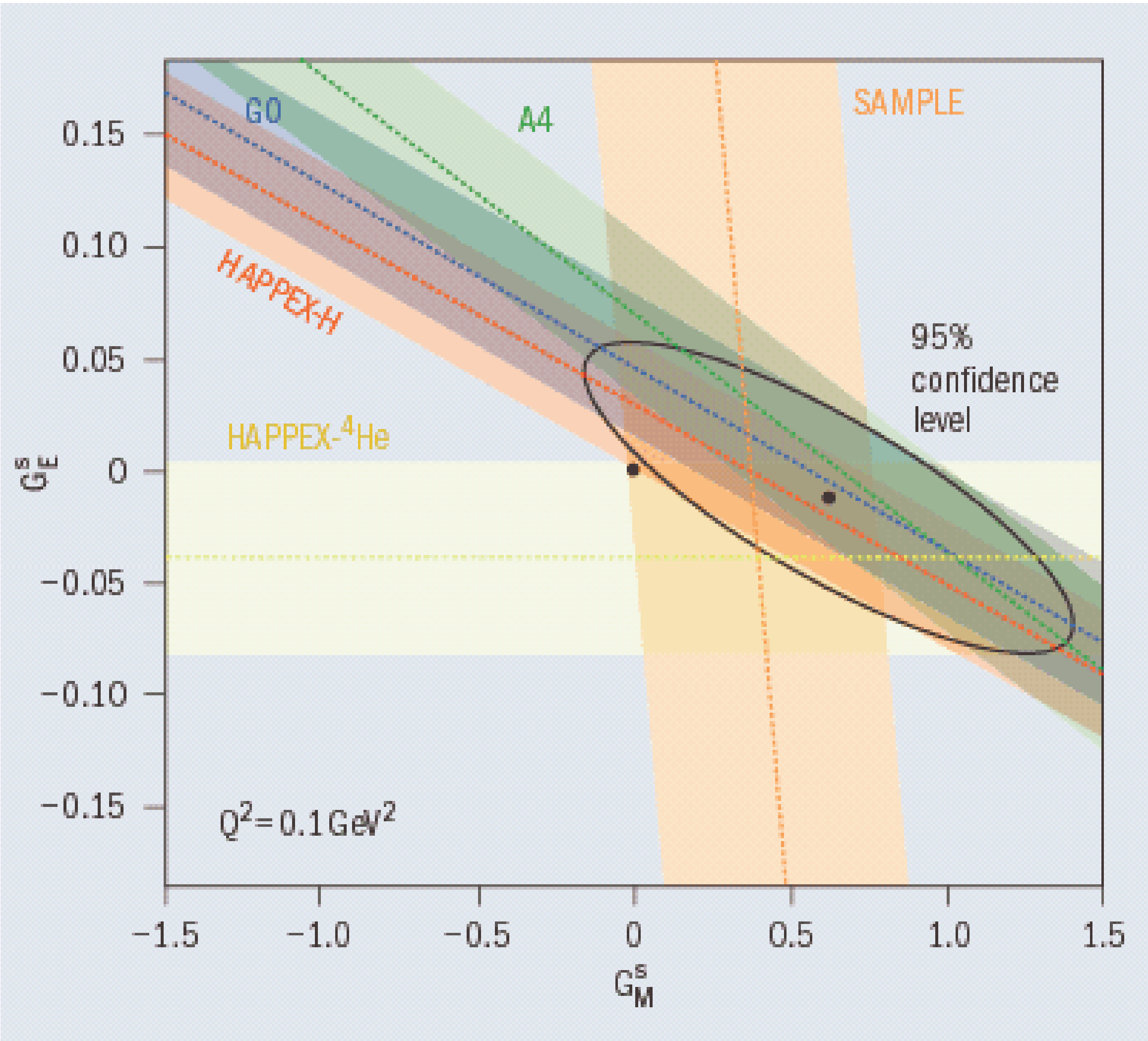


Leading moments of form factors:

$\mu_s = G_M^s(Q^2=0)$

$\rho_s = \partial G_E^s/\partial\tau\ (Q^2=0)$

World Data (early 2005) at $Q^2 \sim 0.1\ GeV^2$



Note : SAMPLE result adopts Zhu *et al.* calculation of G_A^e
PRD 62(2000)033008

G_E^s = -0.12 ± 0.29

G_M^s = 0.62 ± 0.32

Would imply that 5-10% of nucleon magnetic moment is *Strange*

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

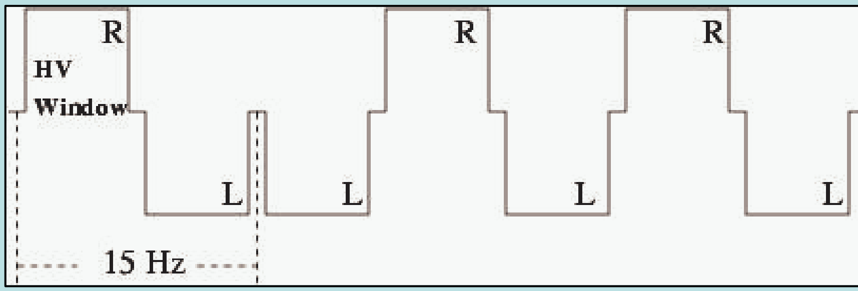
Measurement of P-V Asymmetries

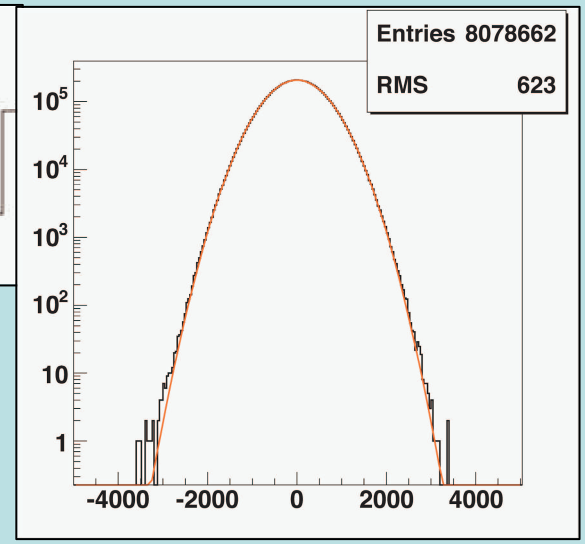
$$A_{LR} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx 10^{-6}$$

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)
- High beam polarization and rapid flip

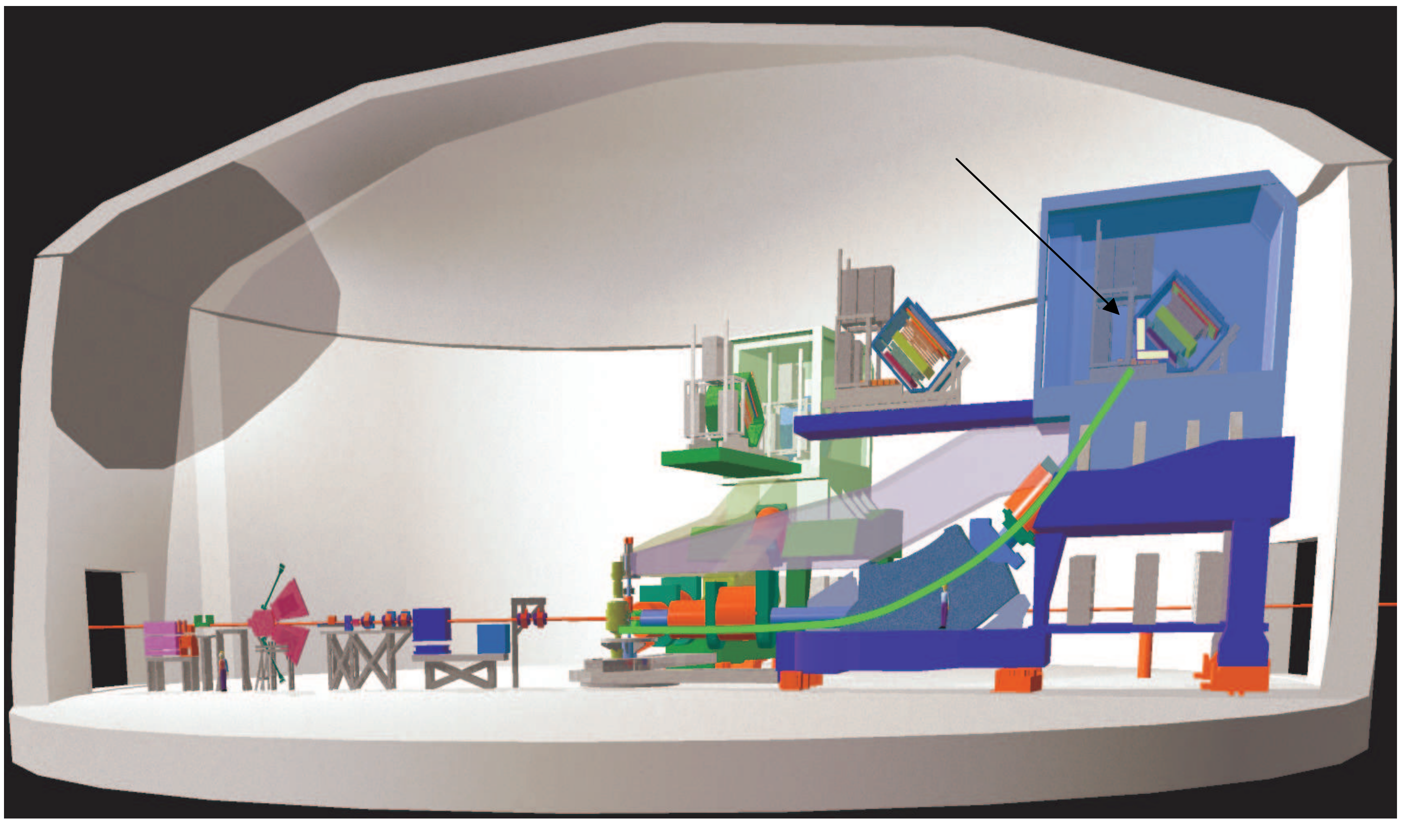
Statistics: high rate, low noise
Systematics: beam asymmetries, backgrounds, Helicity correlated DAQ
Normalization: Polarization, Linearity, Dilution

HAPPEX (second generation)

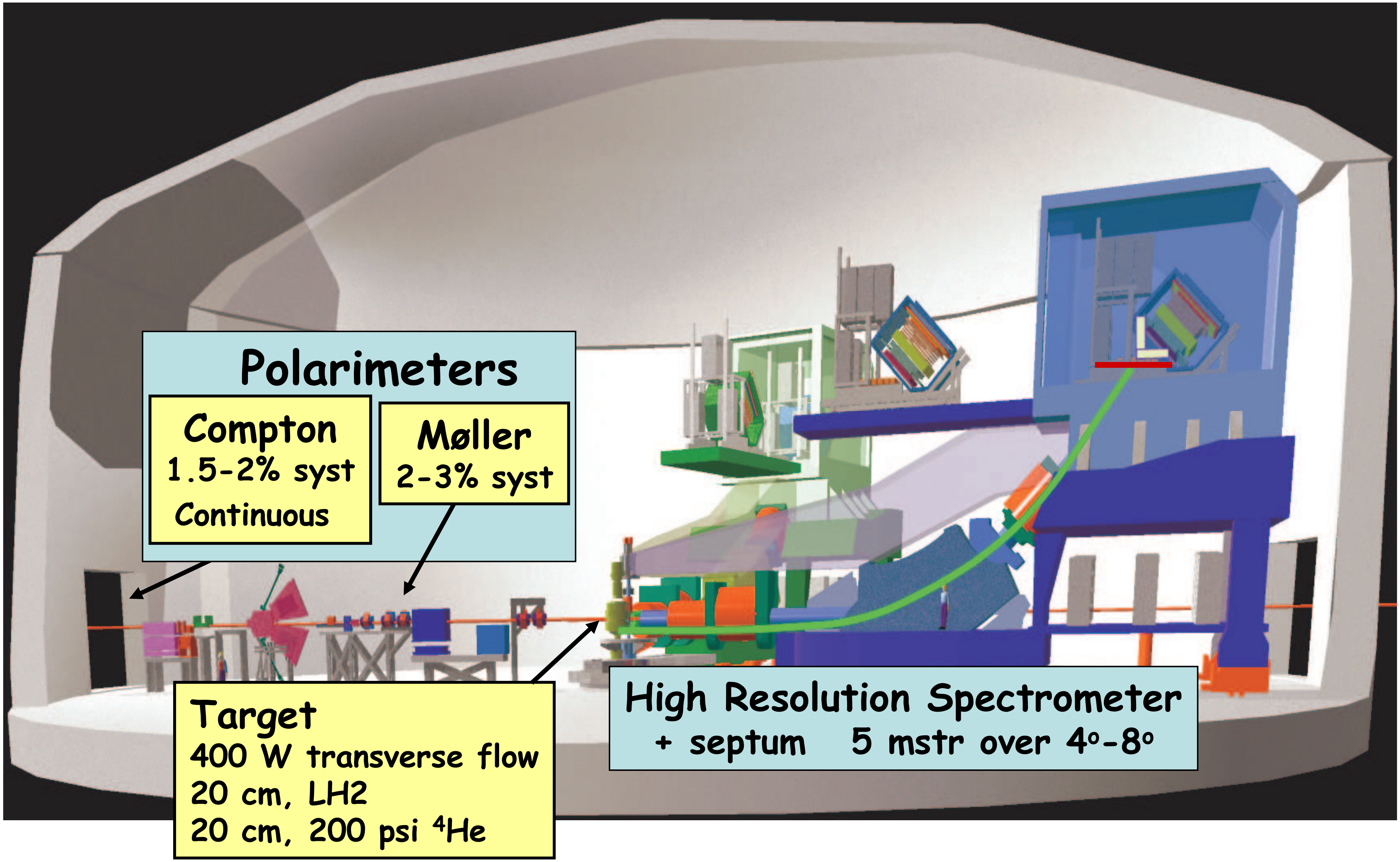
E=3 GeV θ=6° Q^2= 0.1 $(GeV/c)^2$

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

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



Hall A



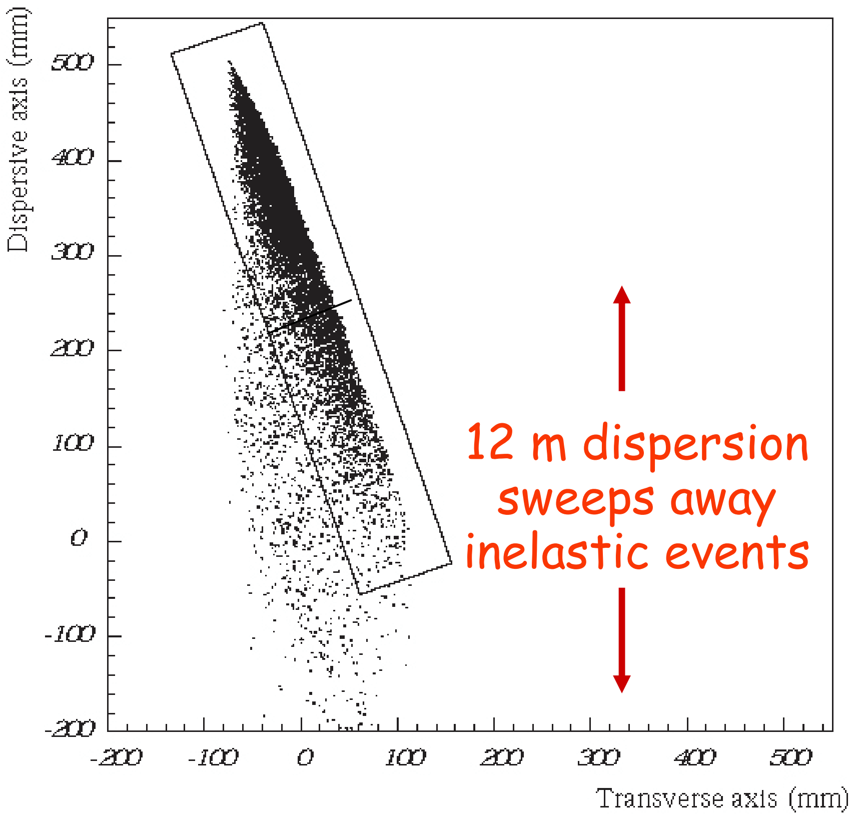
Polarimeters
Compton
1.5-2% syst
Continuous
Møller
2-3% syst
Target
400 W transverse flow
20 cm, LH2
20 cm, 200 psi ⁴He
High Resolution Spectrometer
+ septum   5 mstr over 4°-8°

Summary of Data Runs: HAPPEX-II

June 2004	HAPPEX-He • about 3M pairs at 1300 ppm => δA_{stat} ~ 0.74 ppm
June – July 2004	HAPPEX-H • about 9M pairs at 620 ppm => δA_{stat} ~ 0.2 ppm
July-Sept 2005	HAPPEX-He • about 35M pairs at 1130 ppm => δA_{stat} ~ 0.19 ppm
Oct – Nov 2005	HAPPEX-H • about 25M pairs at 540 ppm => δA_{stat} ~ 0.105 ppm

High Resolution Spectrometers

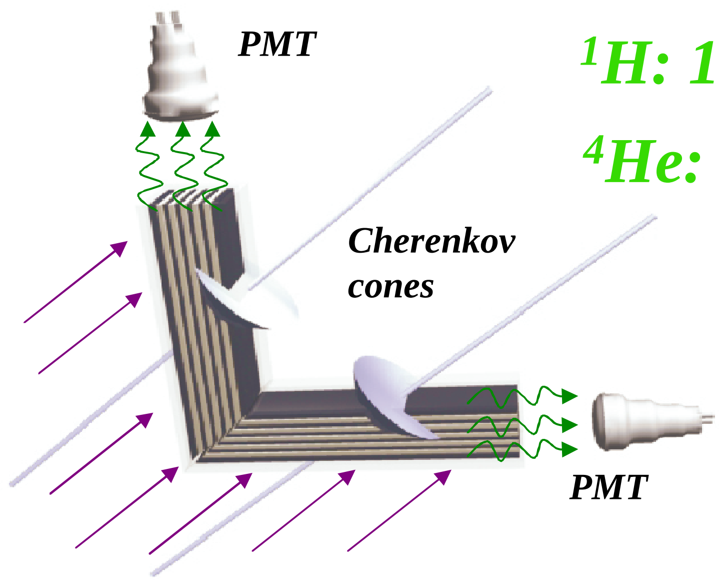
Clean separation of elastic events by HRS optics → Locate detector over elastic line and integrate the flux



Elastic Rate:

^{1}H: 120 MHz

^{4}He: 12 MHz



Brass-Quartz Integrating Cerenkov Shower Calorimeter

Large dispersion & heavy shielding reduce backgrounds at focal plane

Correcting Beam Asymmetries

$$A_{raw} = A_{det} - A_Q + \Sigma_{i=1,5}\beta_i \Delta x_i$$

Slopes from
- **natural beam jitter (regression)**
- **beam modulation (dithering)**

Independent methods provide a cross-check.
Each is subject to different systematic errors.

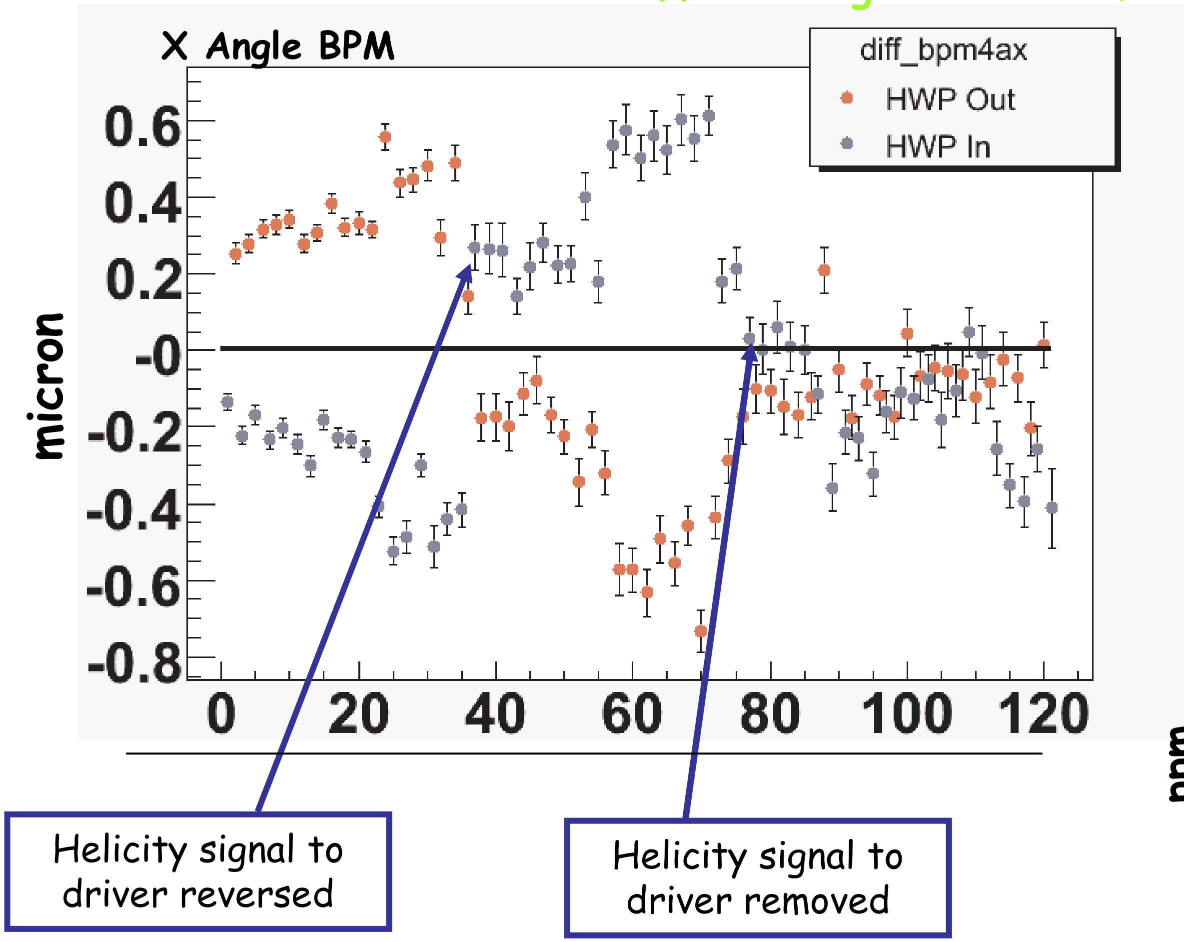
Regression:
- Natural beam motion, measure $dA/d\Delta x_i$
- Simultaneous fit establishes independent sensitivities
- By definition, removes correlation of asymmetry to beam *monitors*
- Sensitive to highly correlated beam motion and electronics noise

"Dithering":
- Induce non-HC beam motion with coils, measure dS/dC_i, dx_i/dC_i
- Relate slopes to dS/dx_i
- Not compromised by correlated beam motion
- Robust, clear signals for failures
- Sensitive to non-linearities

⇨ See Kent Paschke's talk

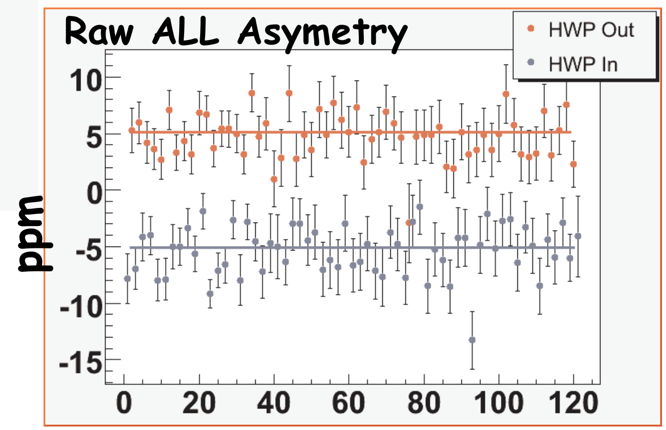
Beam Position Differences, Helium

Position difference goal: 3 nanometers!



All's well that ends well

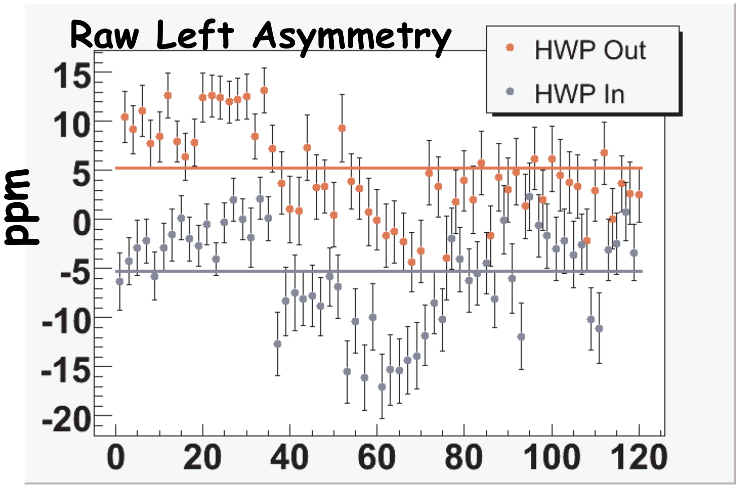
- Problem clearly identified as beam steering from electronic cross-talk
- No helicity-correlated electronics noise in Hall DAQ at < ppb level
- Large position differences ≈cancel in average over both detectors

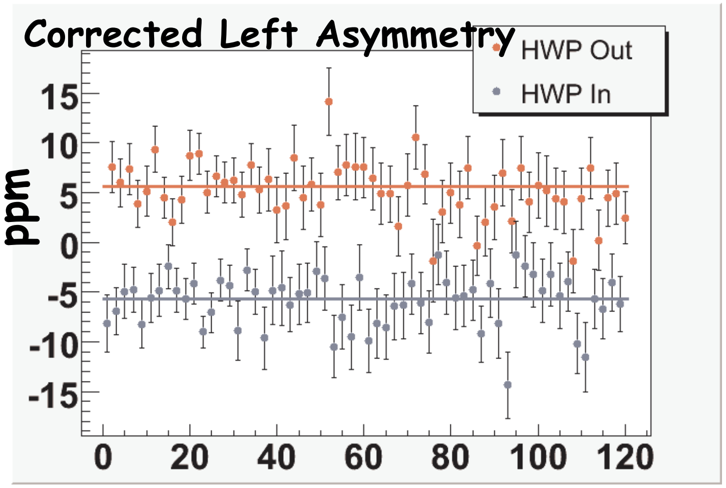


Problem: Helicity signal deflecting the beam through electronics "pickup"

Large beam deflections even when Pockels cell is off

Beam Position Corrections, Helium





Beam Asymmetries

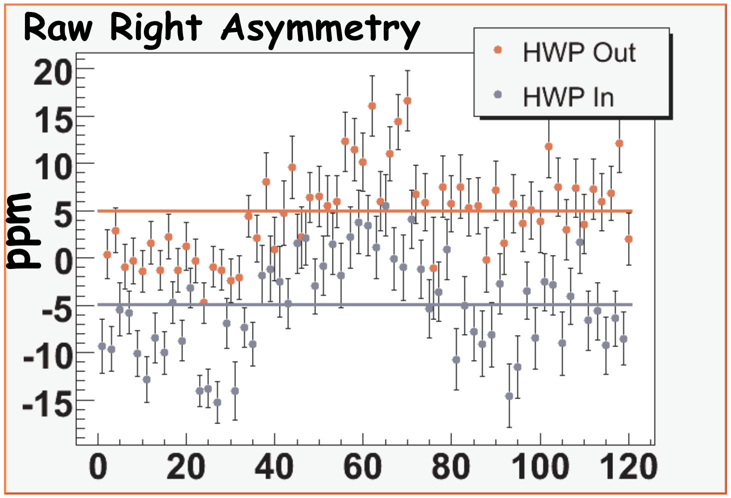
Energy: -3ppb

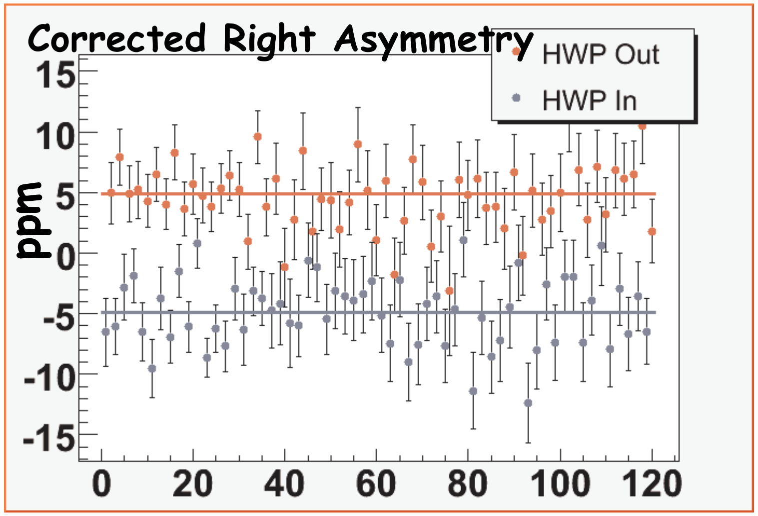
X Target: -5 nm

X Angle: -28 nm

Y Target :-21 nm

Y Angle: 1 nm





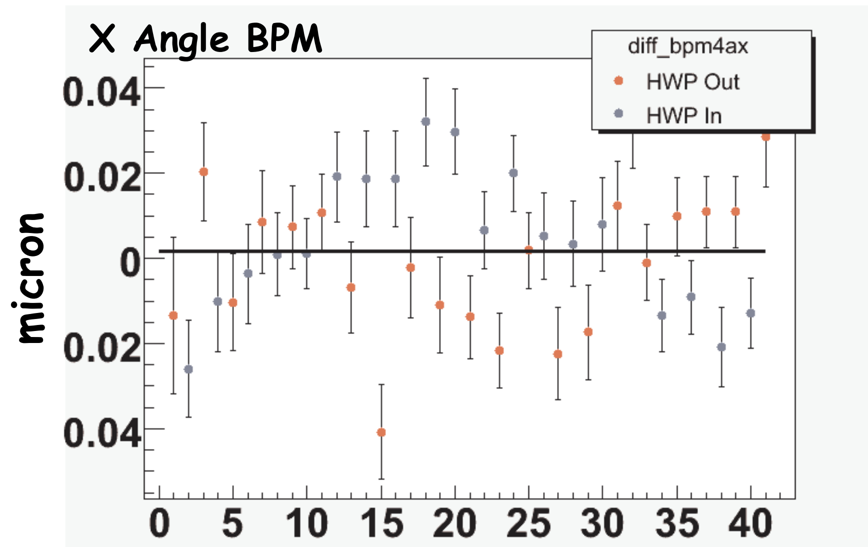
Total Corrections:

Left: -370 ppb

Right: 80 ppb

All: 120 ppb

Beam Position Corrections, Hydrogen



Surpassed Beam Asymmetry Goals for Hydrogen Run

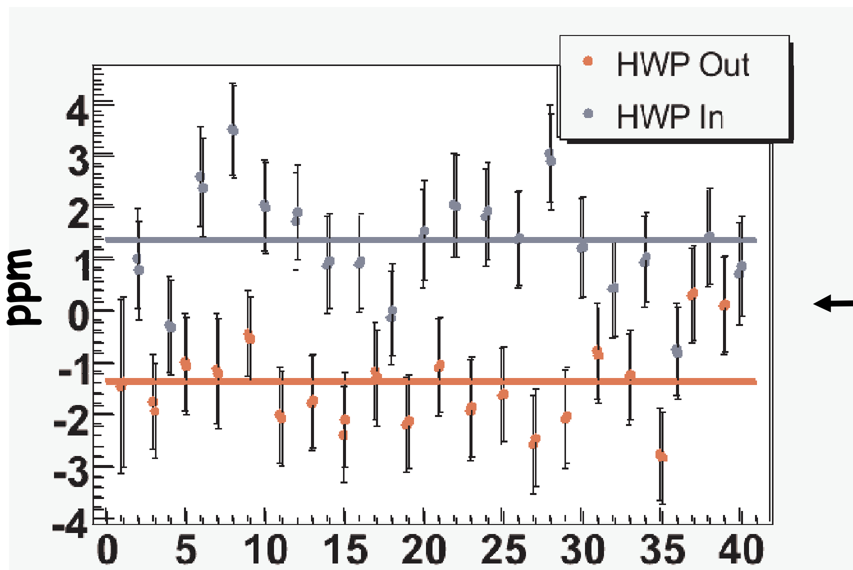
Energy: -0.25 ppb

X Target: 1 nm

X Angle: 2 nm

Y Target : 1 nm

Y Angle: <1 nm



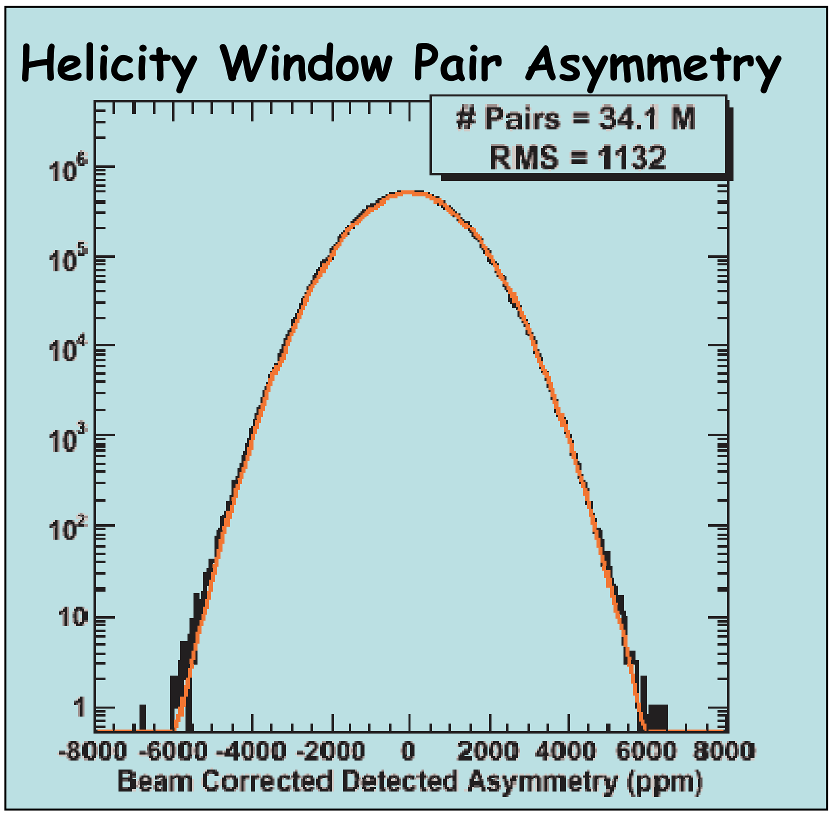
Corrected and Raw, Left arm alone, Superimposed!

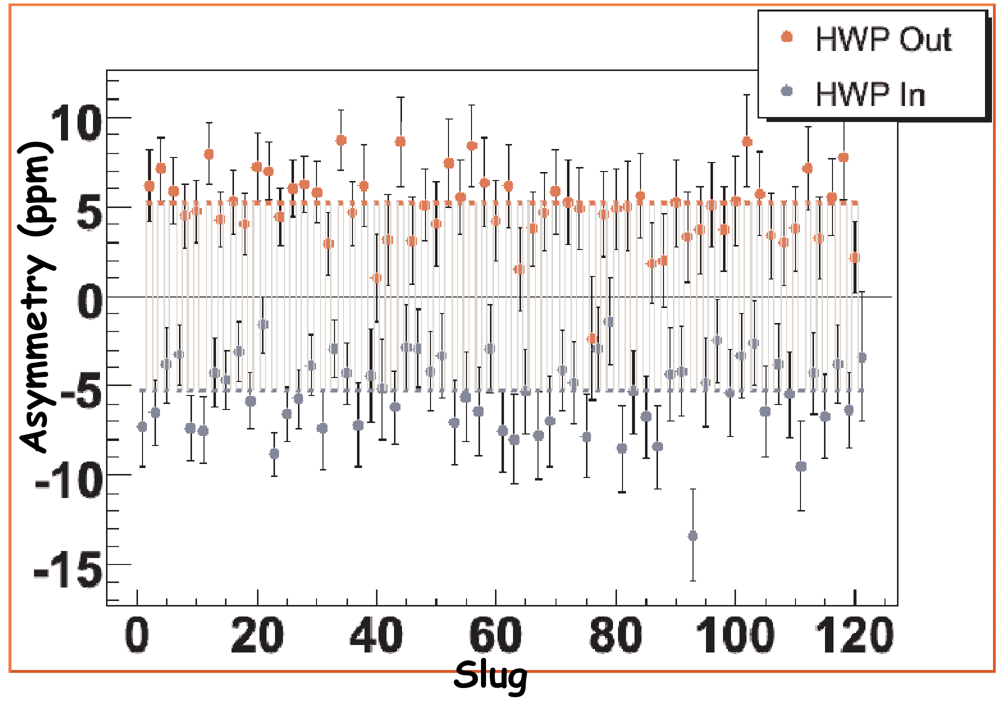
Total correction for beam position asymmetry on Left, Right, or ALL detector: 10 ppb

^{4}He Preliminary Results

Raw Parity Violating Asymmetry

A_{raw} correction ~ 0.12 ppm





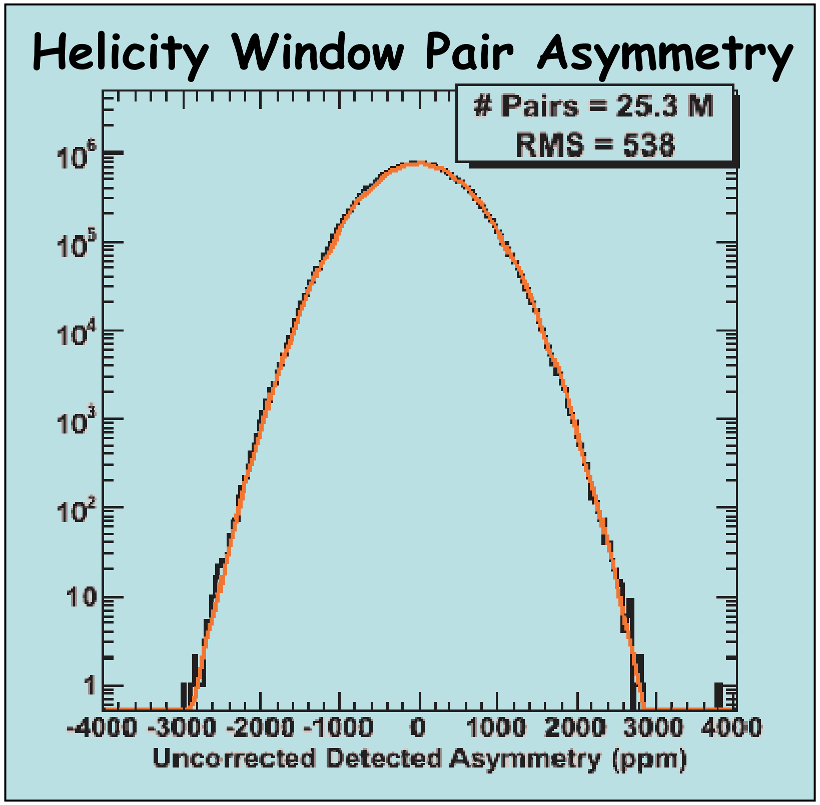
Q^2 = 0.07725 ± 0.0007 GeV^2

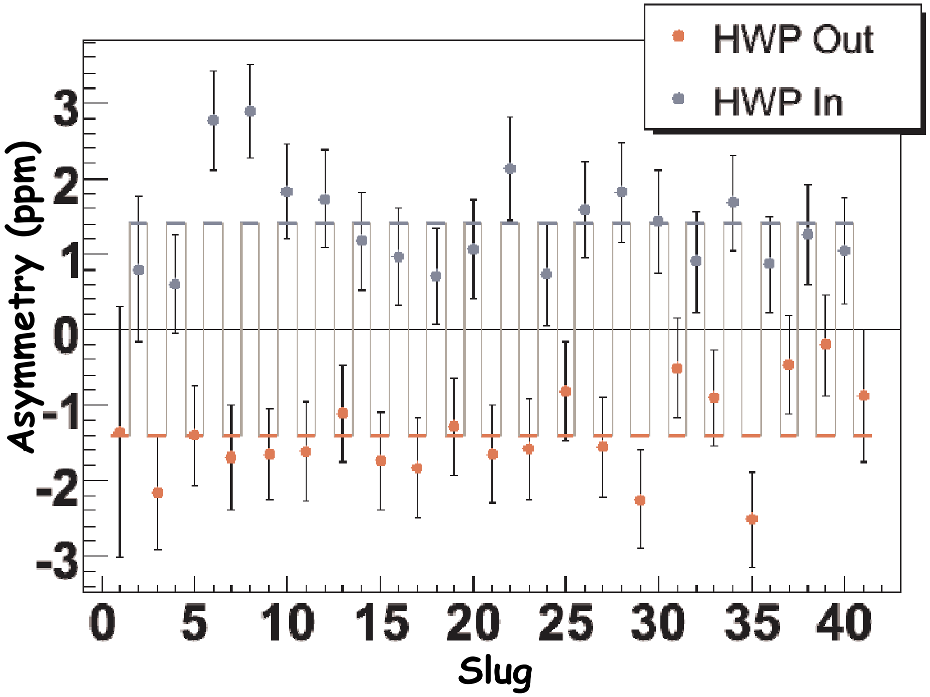
A_{raw} = 5.253 ppm ± 0.191 ppm (stat)

^{1}H Preliminary Results

Raw Parity Violating Asymmetry

A_{raw} correction ~11 ppb

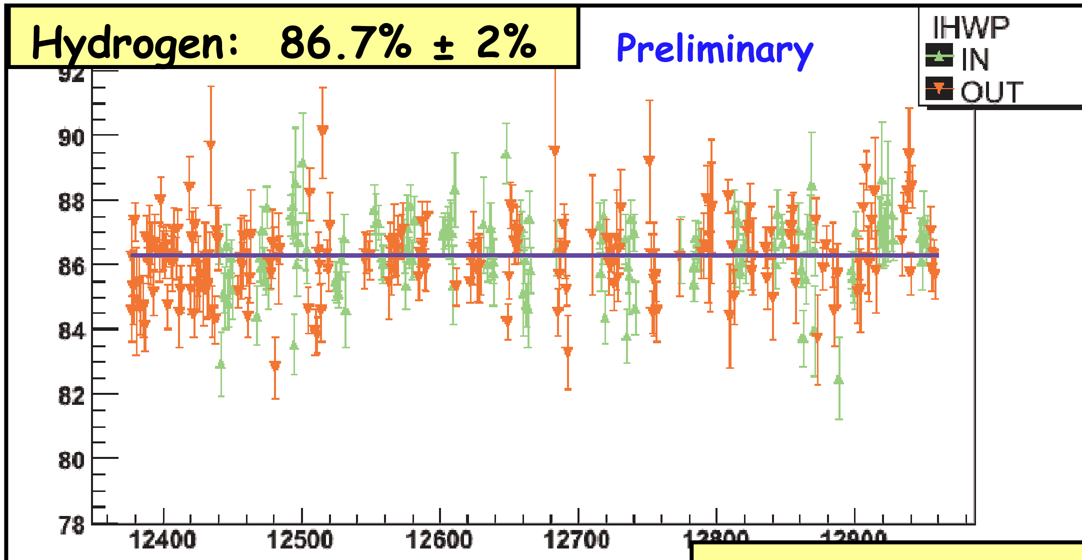




Q^2 = 0.1089 ± 0.0011GeV^2

A_{raw} = -1.418 ppm ± 0.105 ppm (stat)

Compton Polarimetry

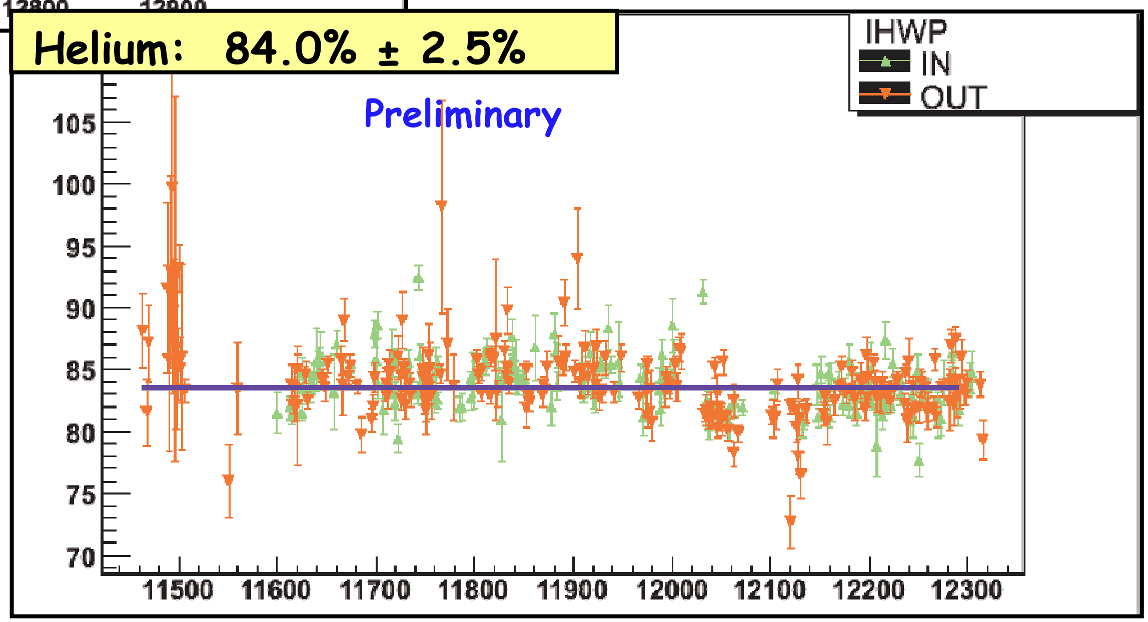


Continuous, non-invasive

Here : Electron Detector analysis

Cross-checked with Møller, Mott polarimeters

also: independent electron analysis



Helium ran with lower beam energy, making the analysis significantly more challenging.

New developments in both photon and electron analyses in preparation: anticipate <2% systematic uncertainty

Miscellany

- Backgrounds: ⇨ Bryan Moffit's talk

Dilutions:	2.2% (^4He)	0.8% (^1H)
Systematic	60 ppb (^4He)	16 ppb (^1H)

- Q^2 & effective kinematics: $\delta Q^2 < 1.0\%$ ⇨ Bryan Moffit's talk

- Two-photon exchange corrections:
  small ⇨ Marc Vanderhaeghan's talk (no explicit correction made)
- Transverse asymmetry:
  measured directly in dedicated runs, ≈cancels in left-right sum;
  Systematic: 4 ppb (^1H) 8 ppb (^4He) ⇨ Lisa Kaufmann's talk

- Electromagnetic Form Factors: use Friedrich & Walcher parameterization, Eur. Phys. J. A, **17**, 607 (2003), and BLAST data for G_E^n
- Axial Form Factor: highly suppressed for ^1H (not present for ^4He)
- Vector Electroweak Radiative Corrections: Particle Data Group

- Blinded Analysis

^{4}He: Nuclear Effects

$0^+ \to 0^+$ T=0 transition

- Any one-body electroweak operator *O*: (eg Fetter and Walecka)

$$\langle J,T|O|J,T\rangle = \Sigma\, \psi_{J,T}(\alpha,\alpha')\, \langle\alpha'|O|\alpha\rangle \qquad |\alpha\rangle = \text{complete set}$$

one-body density matrix element *(nuclear structure)* single-particle matrix element *(nucleon structure)*

- Asymmetry involves ratio of weak/EM matrix elements (G_E^s and $G_E^{T=0}$);
  Single term in J,T in transition; *O* same in weak and EM except for couplings
  $\to$ same one-body density matrix elements in numerator/denominator
  $\to$ nuclear structure cancels, only nucleon form factors remain

This result is EXACT, *if* :

- ^{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

- Nuclear effects all << 1%, no explicit correction made.

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

HAPPEX-II 2005 Preliminary Results

HAPPEX-^{4}He:

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

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

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

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

HAPPEX-H:

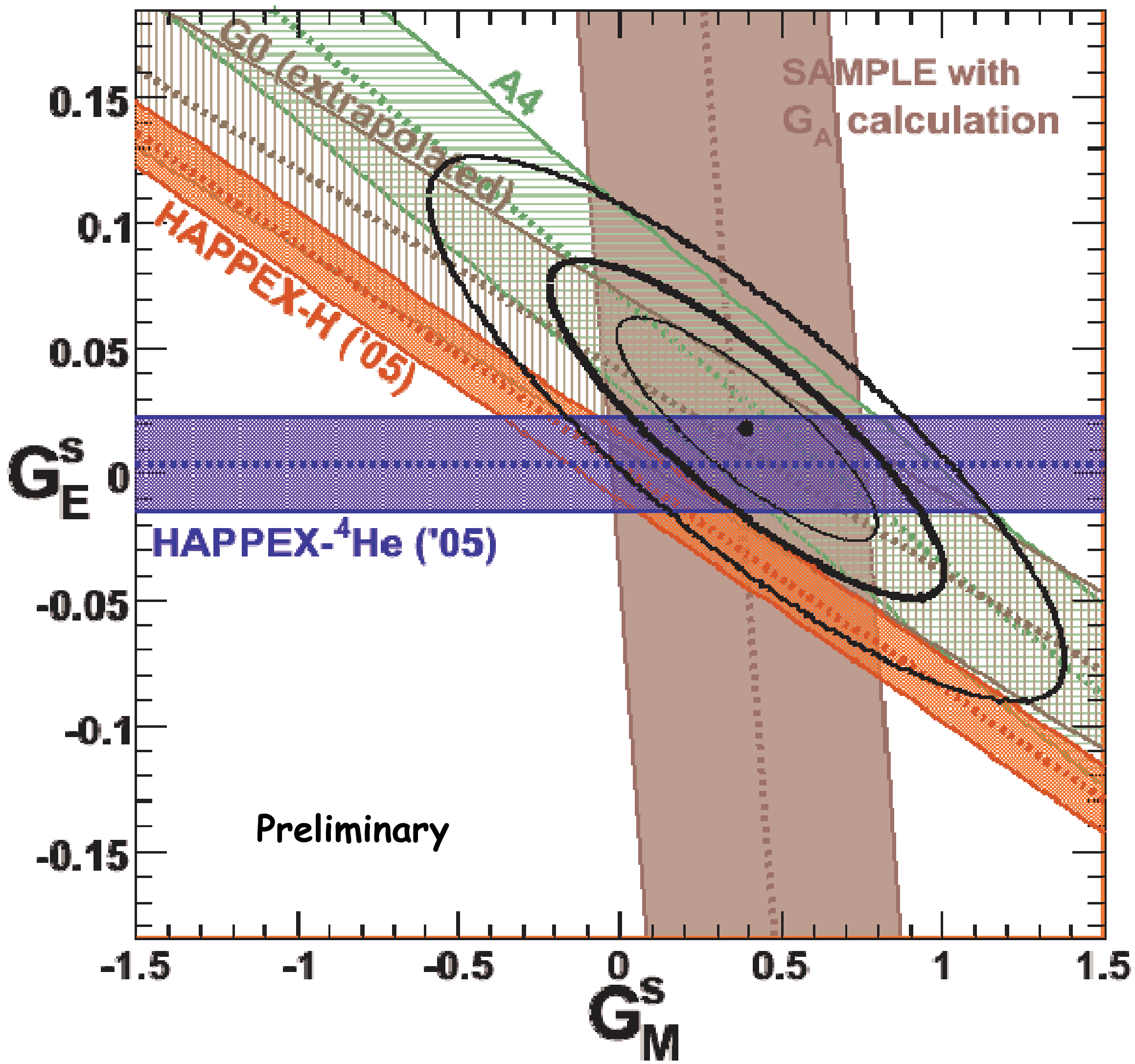
$Q^2 = 0.1089 \pm 0.0011\ (\mathrm{GeV}/c)^2$

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

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

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

HAPPEX-II 2005 Preliminary Results

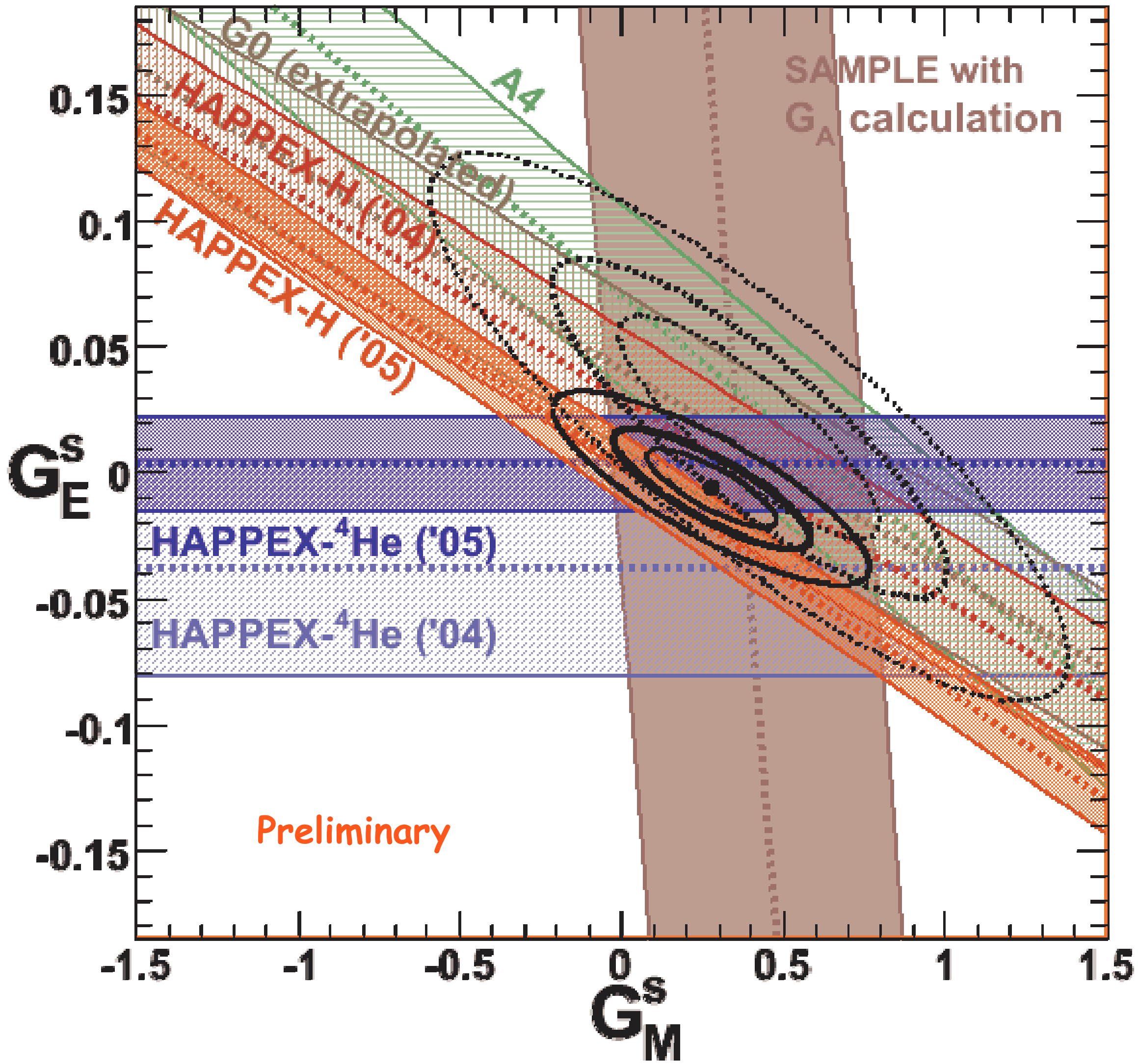


Three bands:

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

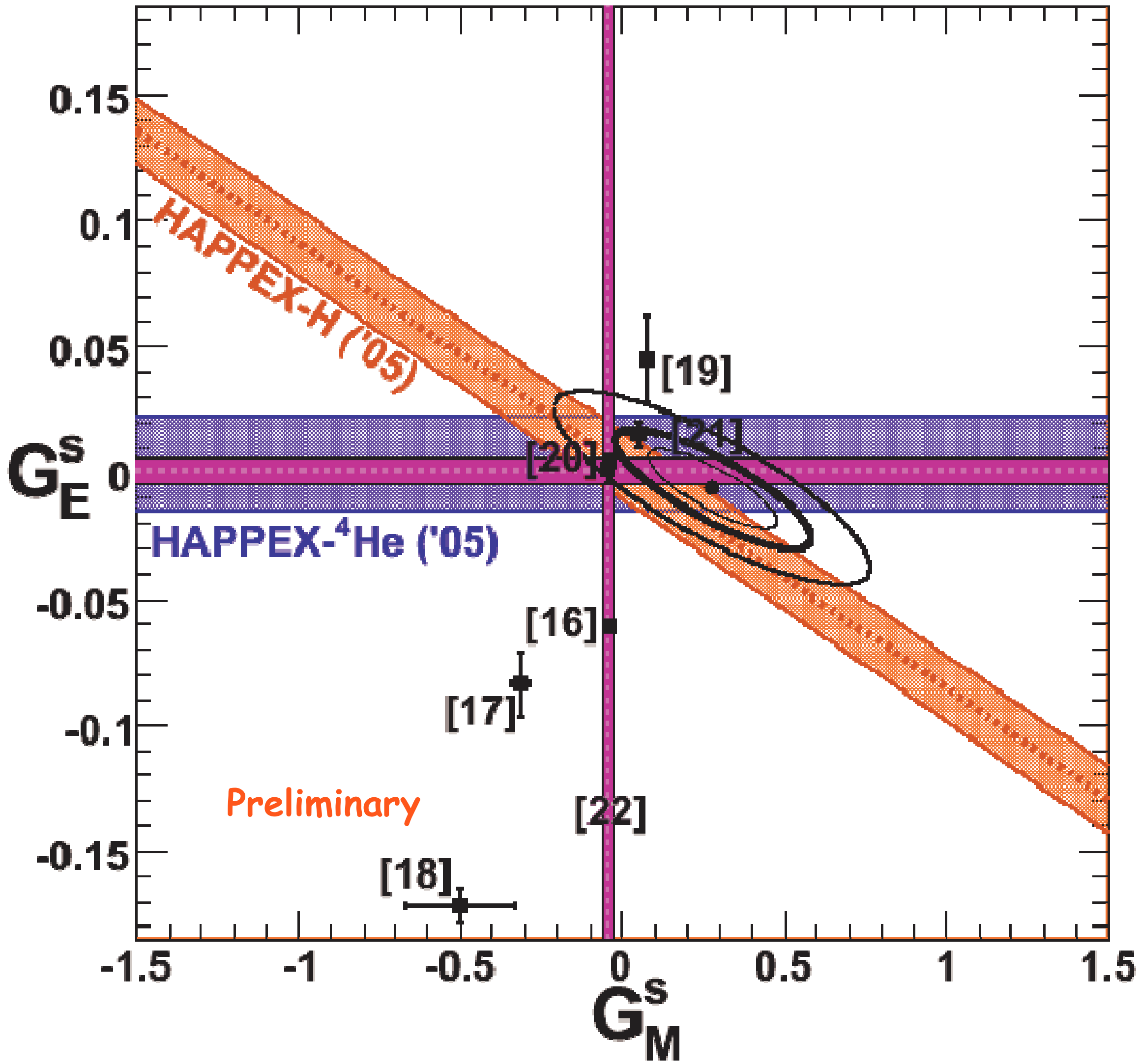
HAPPEX-only fit suggests something even smaller:

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

See Ross Young's talk

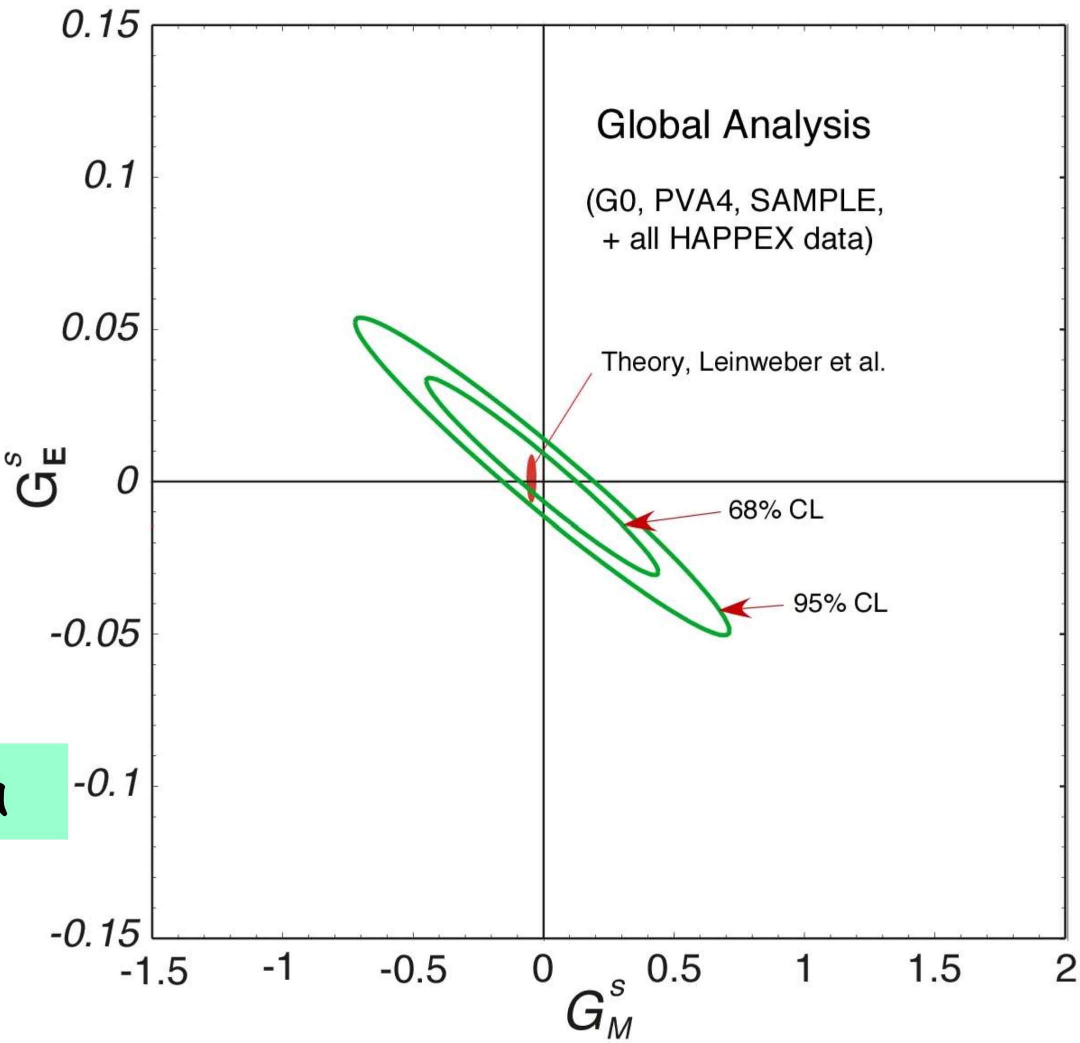
A Global Fit: R.D. Young, et al. nucl-ex/0604010

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

- Kelly's EMF

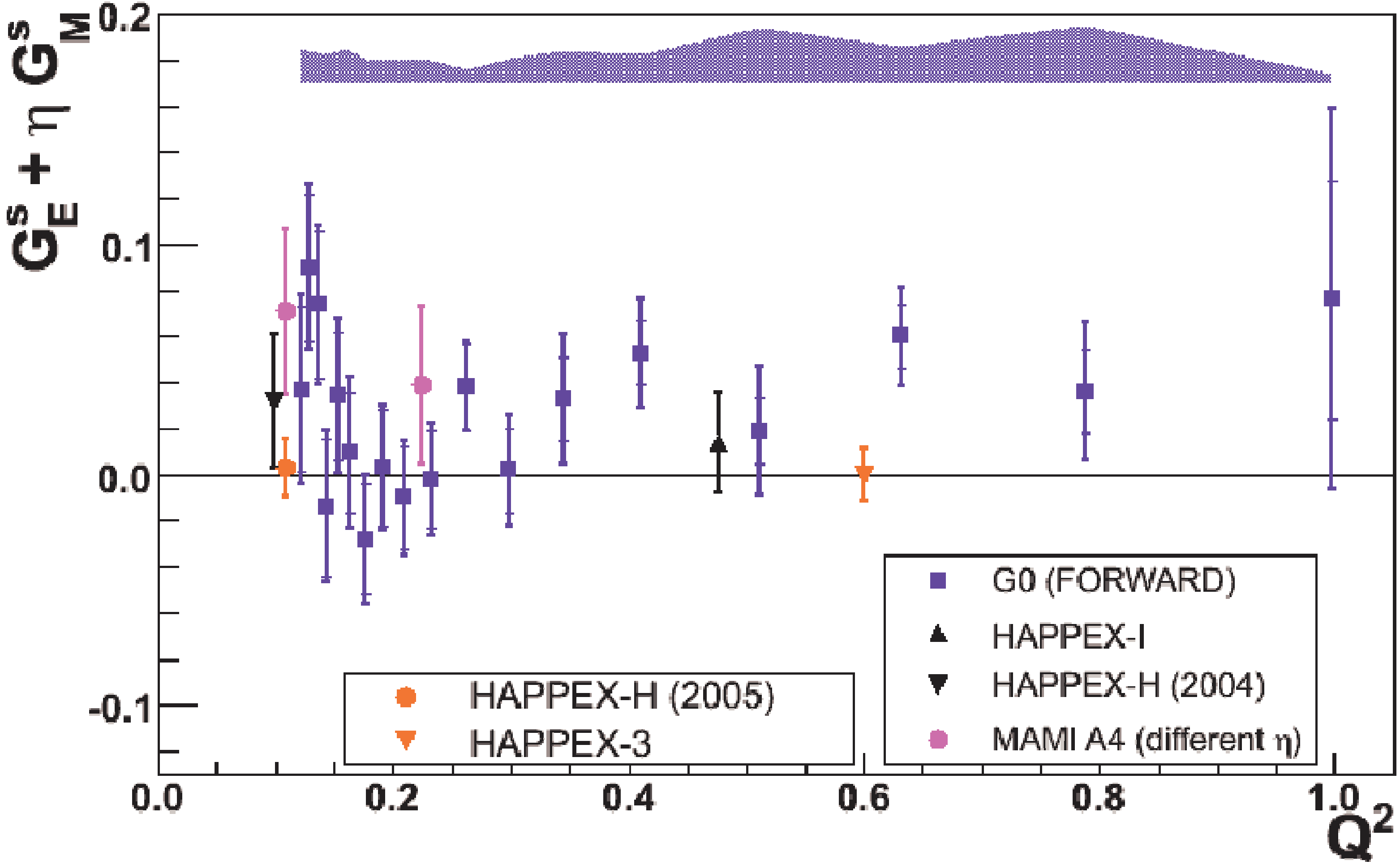
- Float G_A^e separately for neutron and proton

With HAPPEx-2005 data



Figures: courtesy of R. Carlini, R. Young

Future: HAPPEX-3 (2008)



Paschke & Souder, E05-109

Conclusions

- *Marvelous* consistency of data.
- $Q^2 = 0.1$ GeV^2 : G^s_M and G^s_E consistent with zero;
  constraining axial FF to Zhu *et al.* theory favors positive G^s_M

  ^{4}He: best fractional error in PV experiment to date (< 4%)
  no axial contamination → uniquely determines G^s_E

  ^{1}H: < 100 ppb error on *A*, unprecedented "parity quality"
- Still room (& hints?) for non-zero values at higher Q^2

Future of Strangeness form factors:

- G0 Backward: will allow G^s_M and G^s_E separation at two Q^2
- Mainz: PV-A4 backward-angle program well underway
- HAPPEx-III: high precision forward-angle @ $Q^2 = 0.6$ GeV^2