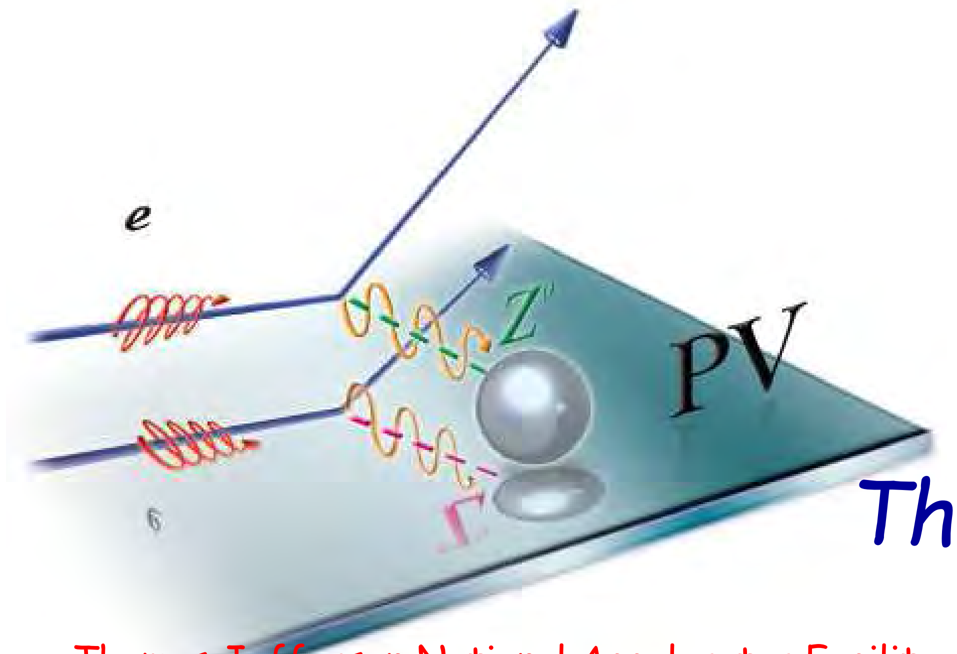
Parity-Violating Electron Scattering and Strangeness in the Nucleon: Results from HAPPEX-II



Bryan Moffit
College of William and Mary

The HAPPEX Collaboration

Thomas Jefferson National Accelerator Facility - Argonne National Laboratory - CSU, Los Angeles - College of William and Mary - Duke - DSM/DAPNIA/SPhN CEA Saclay - FIU - Harvard - INFN, Rome - INFN, Bari - IAE, Beijing - IPT Kharkov - Jozef Stefan Institute - Kent State - MIT - NPIRAS, St. Petersburg - ODU - Rutgers - Smith College - Syracuse - Temple - U. Blaise Pascal - U. of Illinois Urbana-Champaign - UMass, Amherst - U. of Kentucky - U. of Virginia - UST, Heifei

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Strange Quarks in the Nucleon

Spin - polarized DIS $\langle N|\bar{s}\gamma^\mu\gamma^5 s|N\rangle$

Inclusive: Δs = -0.10 $\pm$ 0.06

uncertainties from SU(3), extrapolation

Semi-inclusive: Δs = 0.03 $\pm$ 0.03

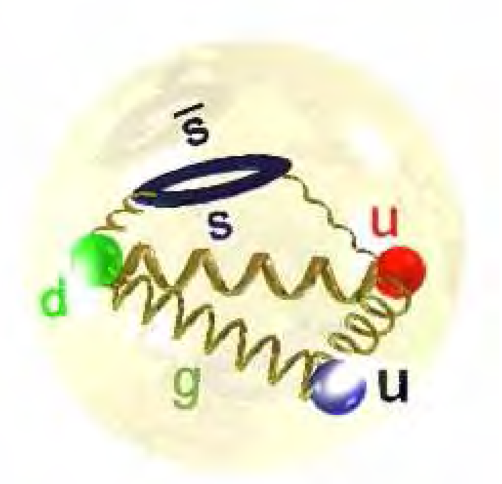
fragmentation function

Strange Mass $\langle N|\bar{s}s|N\rangle$

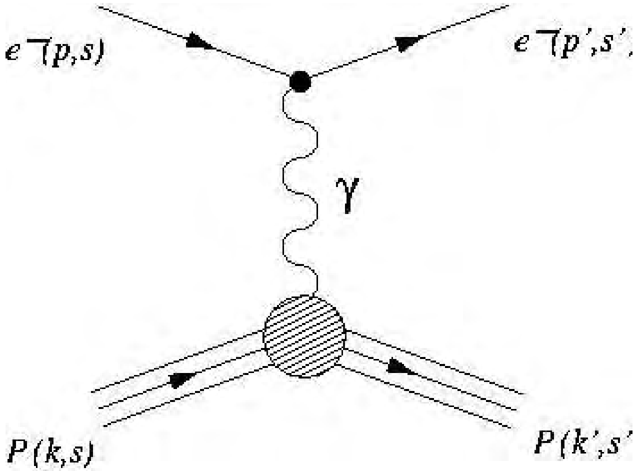
πN scattering: 0-30%

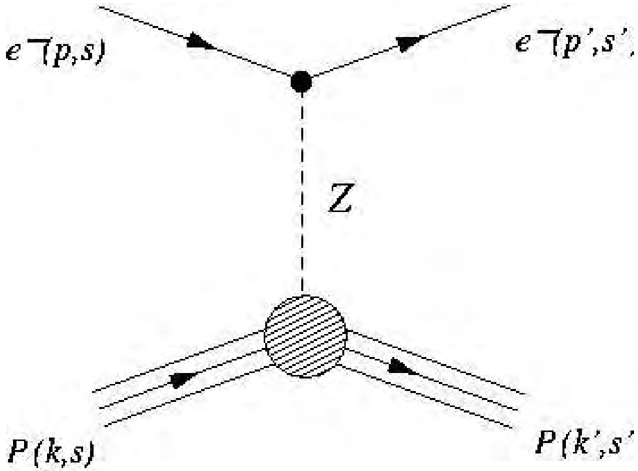
Strange vector FF $\langle N|\bar{s}\gamma^\mu s|N\rangle$

Strange sea is well-known, but contributions to nucleon matrix elements are somewhat unsettled



Parity-Violating Electron Scattering





$$\mathcal{M}^{EM} = \frac{4\pi\alpha}{Q^2} Q_l l^\mu J^{EM}_\mu \qquad \mathcal{M}^{NC}_{PV} = \frac{G_F}{2\sqrt{2}} \left[g_A l^{\mu 5} J^{NC}_\mu + g_V l^\mu J^{NC}_{\mu 5} \right]$$

Interference with EM amplitude makes NC amplitude accessible

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

Parity-Violating Electron Scattering

For a proton:

$$A_{PV} = \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{A_E + A_M + A_A}{\sigma_p}$$

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

Forward angle   Backward angle

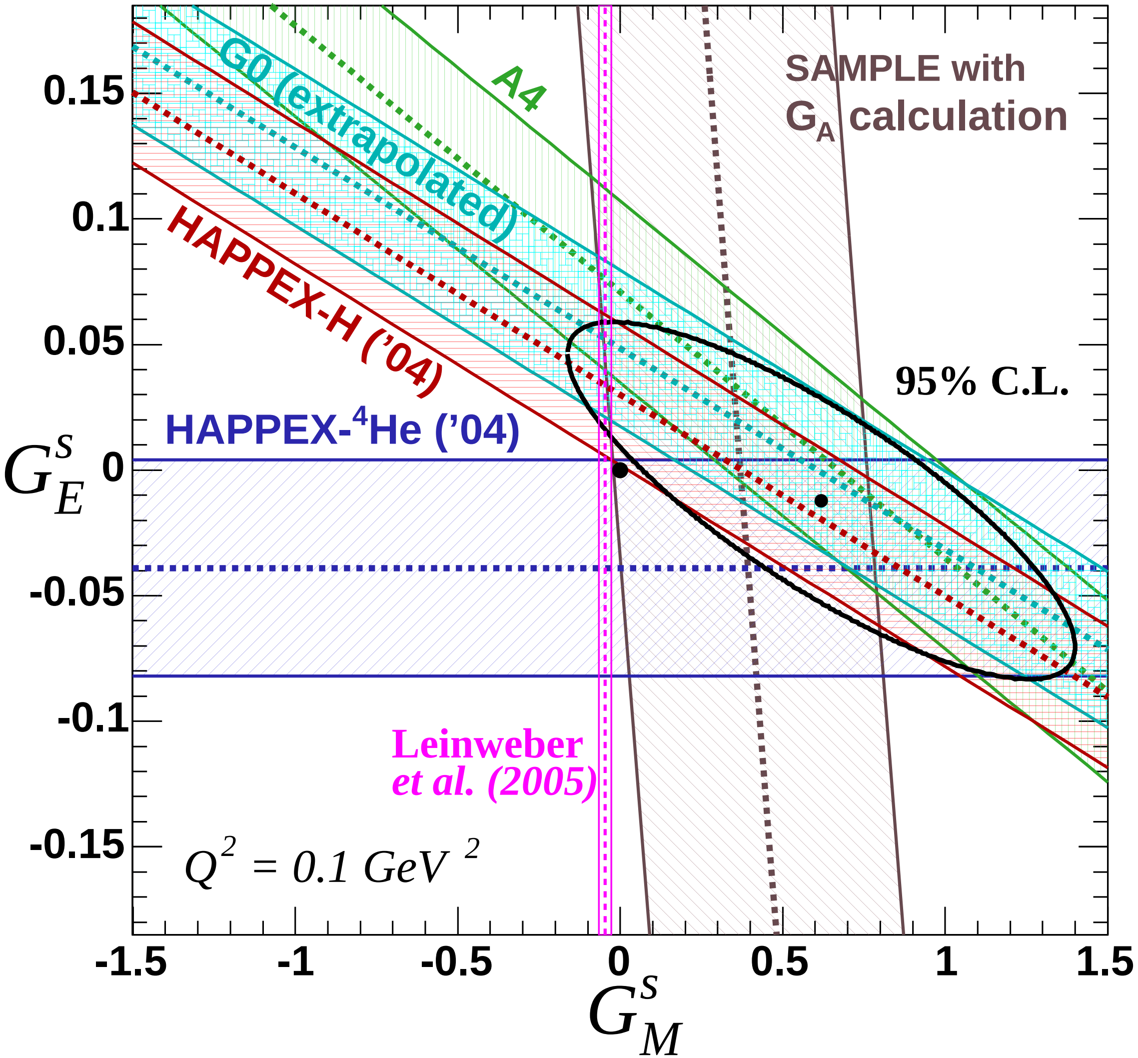
$$G_{E,M}^Z = (1 - 4\sin^2\theta_W) G_{E,M}^p - G_{E,M}^n - G_{E,M}^s$$

For ^{4}He:

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

World Data at $Q^2 \sim 0.1\ GeV^2$

Extrapolated G0 from
Q^2=[0.12,0.16] GeV^2



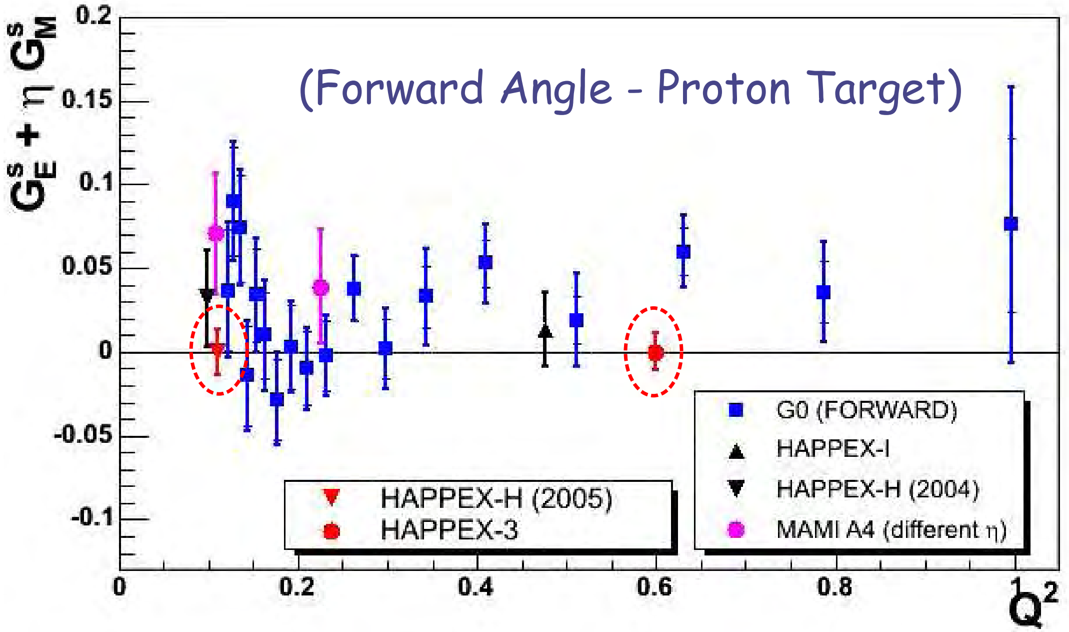
Note: excellent agreement of world data set

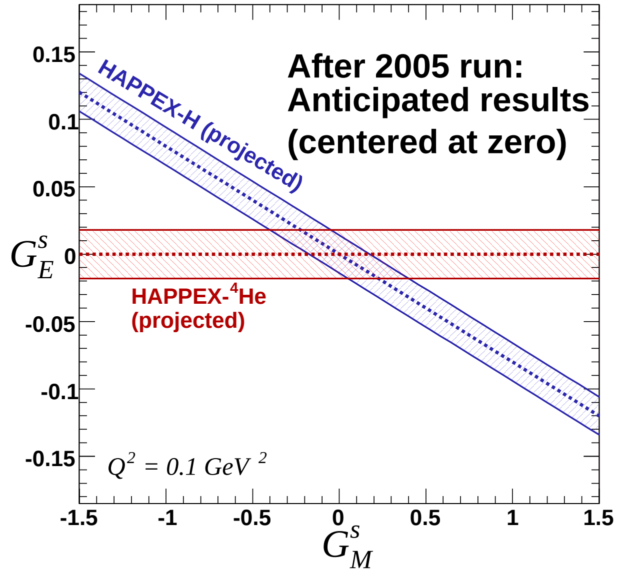
G_E^s = -0.12 ± 0.29

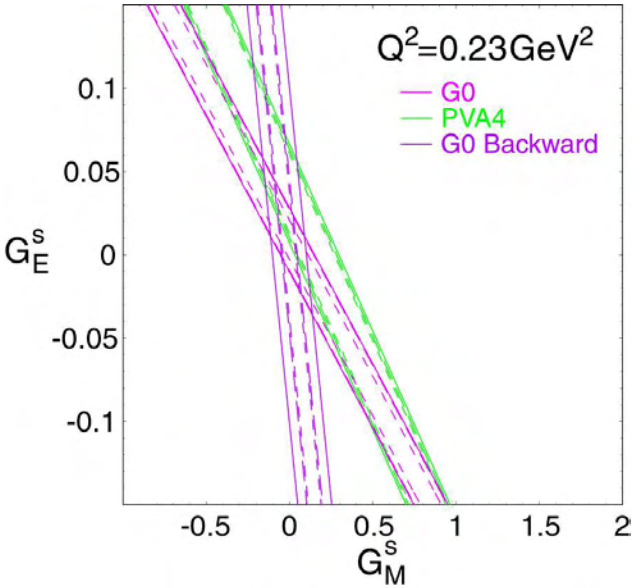
G_M^s = 0.62 ± 0.32

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

World Data







- Suggested large values at $Q^2 \sim 0.1\ GeV^2$
  - HAPPEX-II, H and He (2005)
- Large possible cancellation at $Q^2 \sim 0.2\ GeV^2$
  - G^0 backangle
  - A4 backangle
- Possible large values at Q^2>0.4 GeV^2
  - G^0 backangle
  - HAPPEX-III
  - A4 backangle

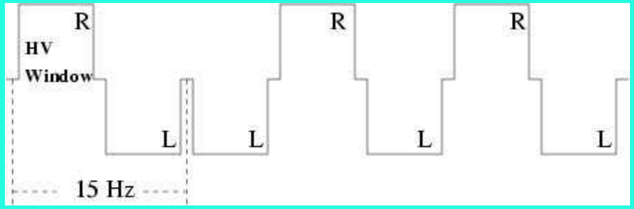
Measurement of PV Asymmetries

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

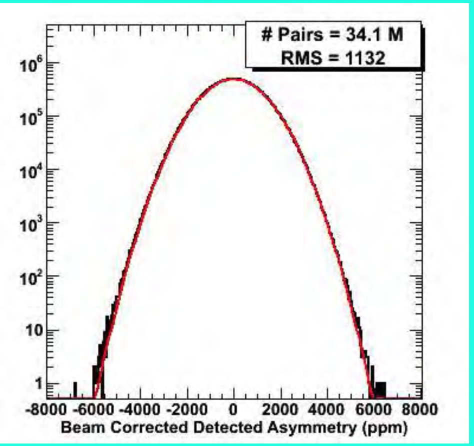
5% Statistical Precision on 1ppm
→ requires 4×10^{14} counts

Rapid Helicity Flip:
Measure the asymmetry at few 10^{-4} level, 30 million times

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

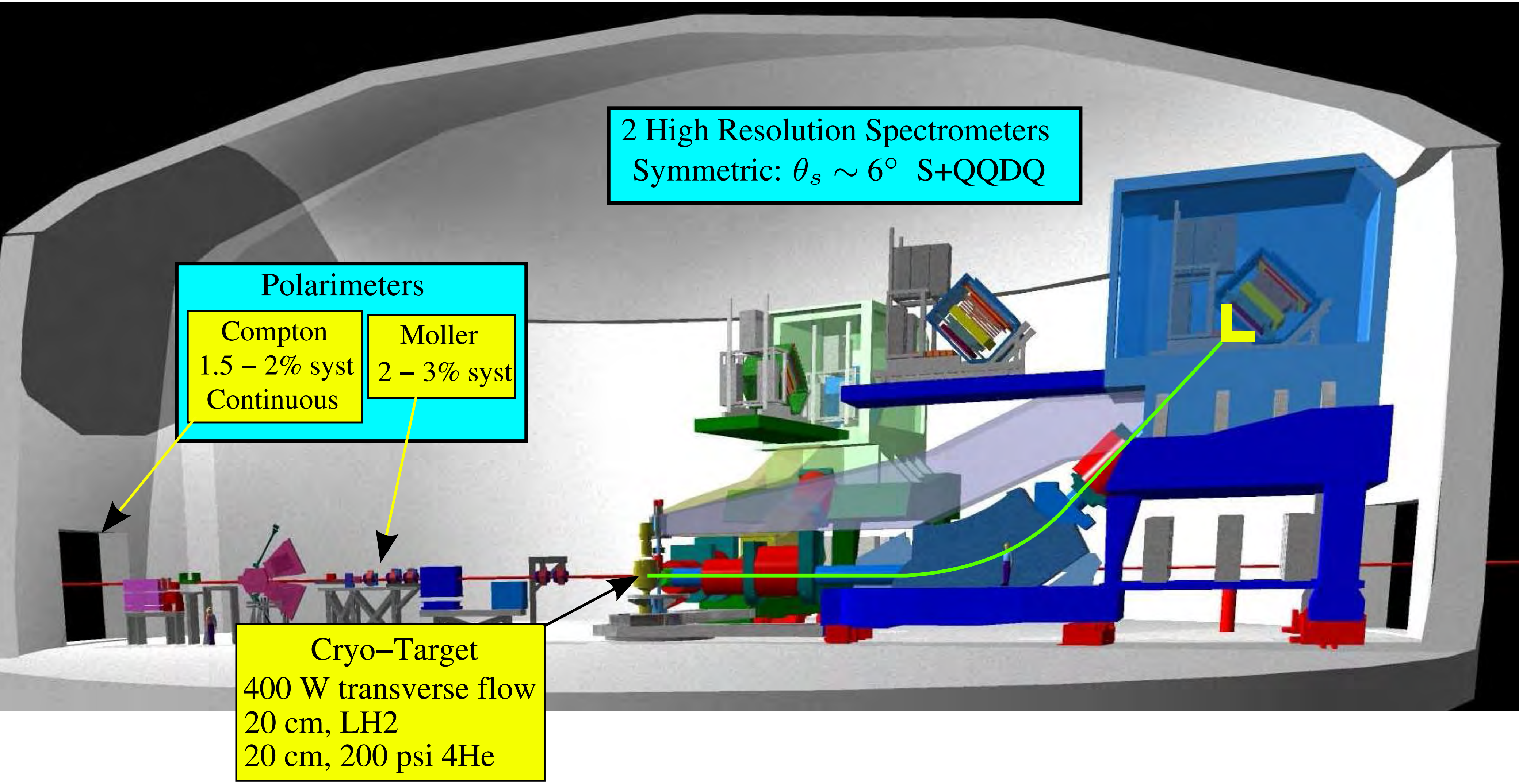


- Analog integration over entire window (33 ms) (detectors, beam current and position monitors)
- RMS: Control noise (target, electronics)
- Mean: Minimize and accurately correct for false asymmetries



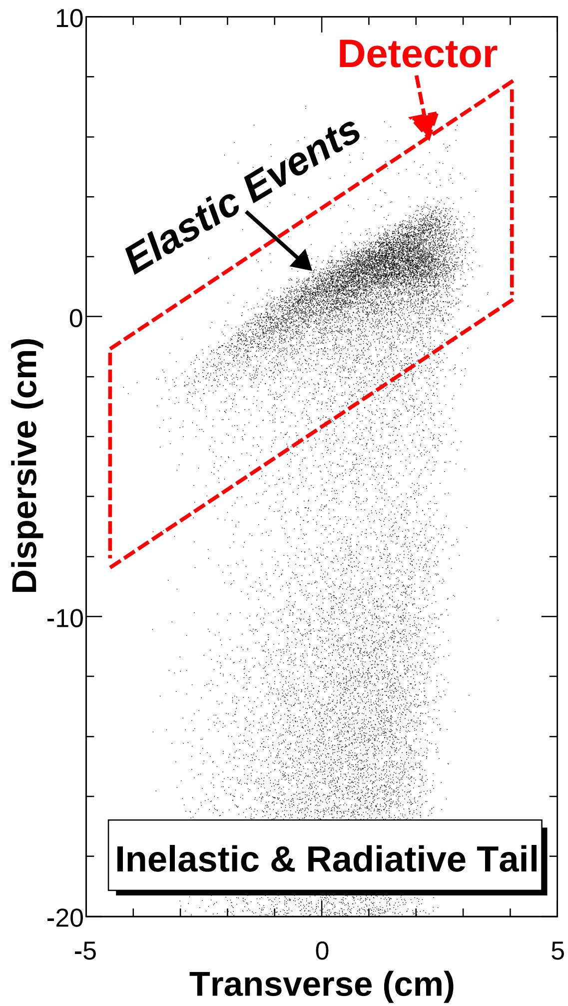
Statistics:	High rate, Low noise
Systematics:	Beam asymmetries, Backgrounds
Normalization:	Polarization, Linearity, Backgrounds

Hall A

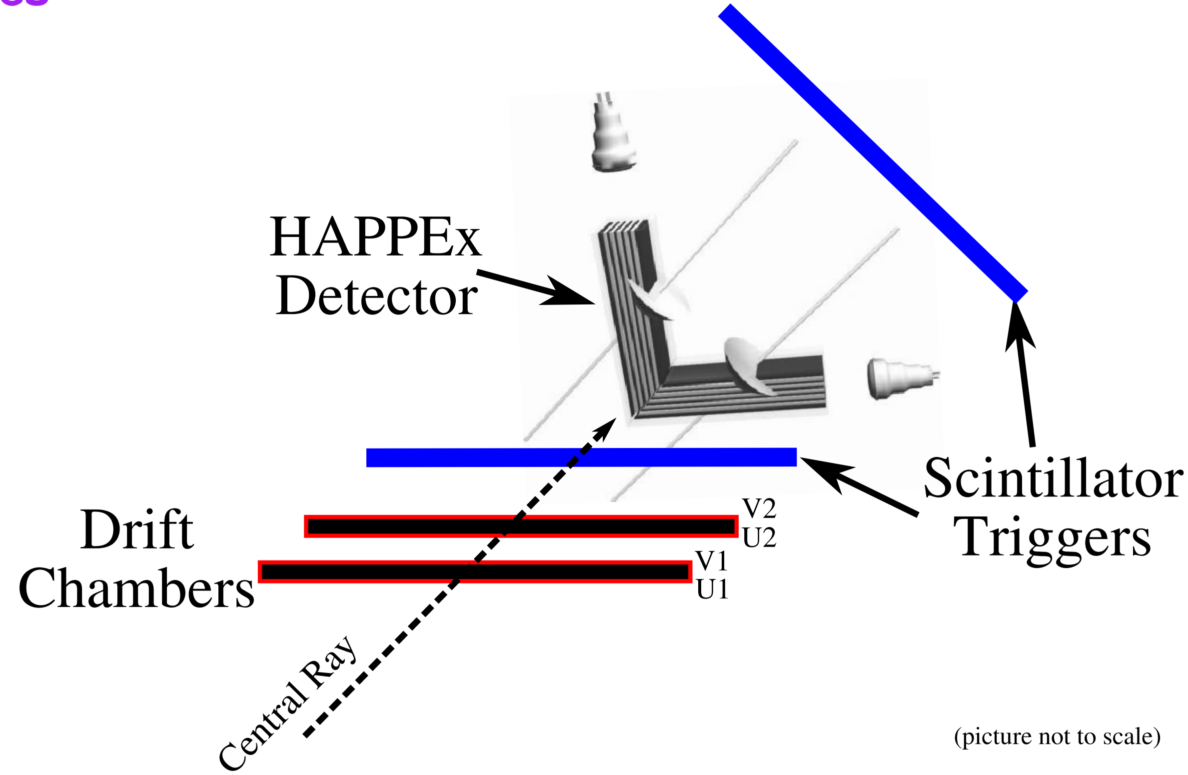

2 High Resolution Spectrometers
Symmetric: $\theta_s \sim 6^\circ$ S+QQDQ
Polarimeters
Compton
1.5 – 2% syst
Continuous
Moller
2 – 3% syst
L
Cryo–Target
400 W transverse flow
20 cm, LH2
20 cm, 200 psi 4He

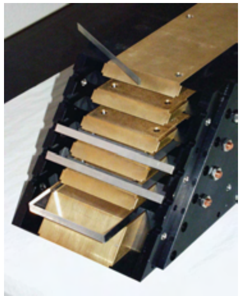
Focal Plane Detectors

Clean Separation of
elastic events by HRS optics



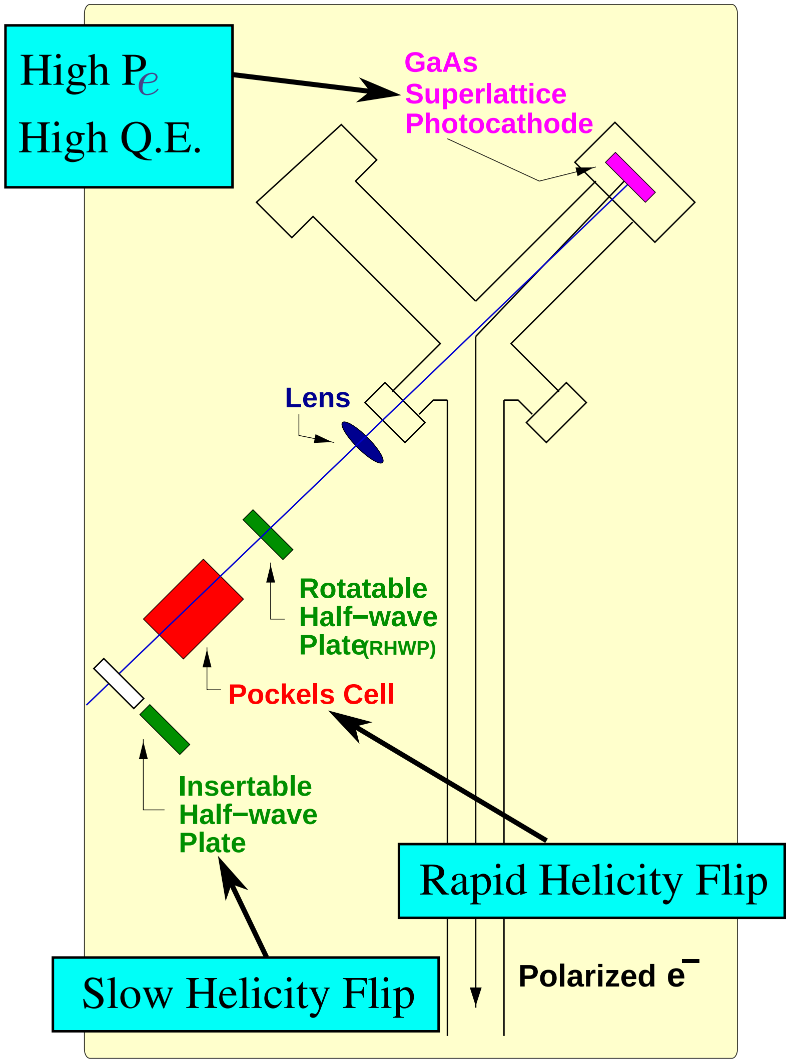
Overlap the elastic line above the
focal plane and integrate the flux





Brass-Quartz
Cerenkov Shower Calorimeter

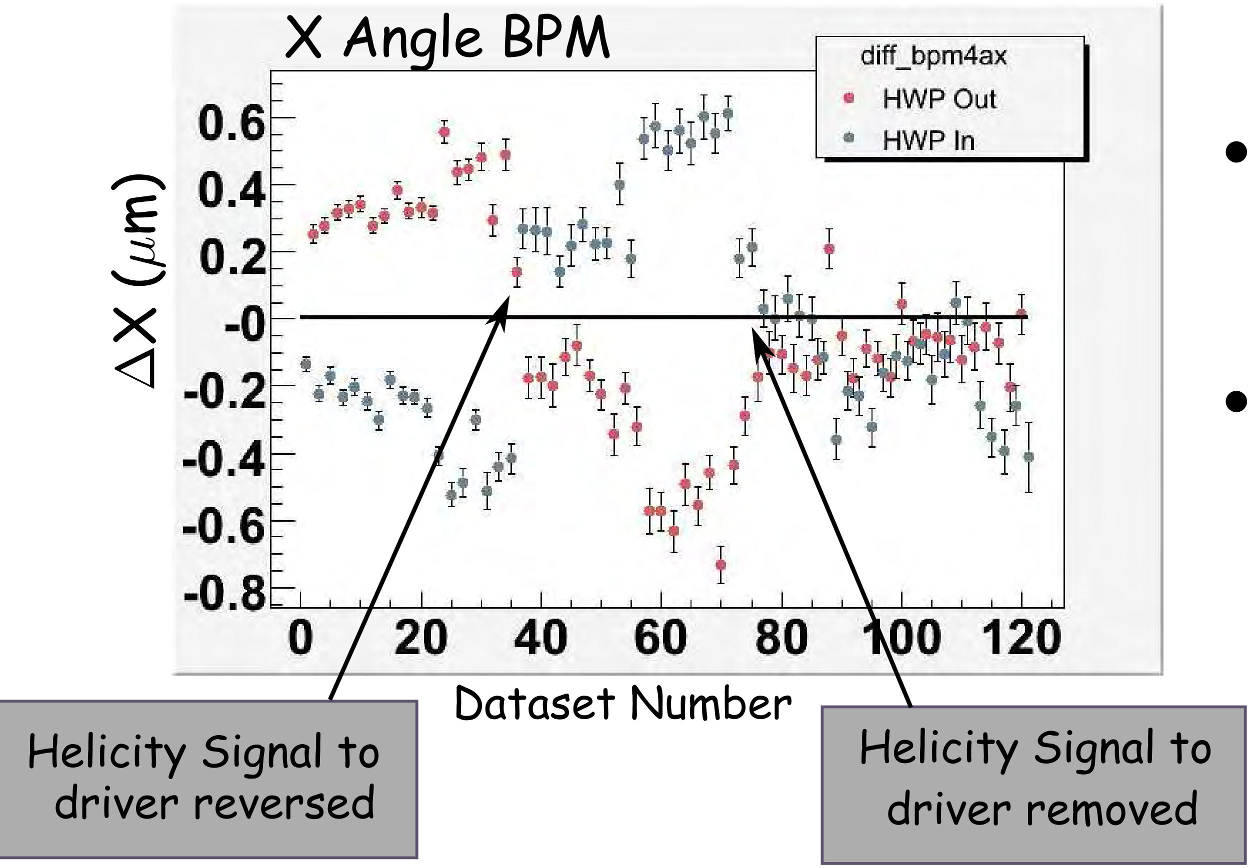
Polarized Source



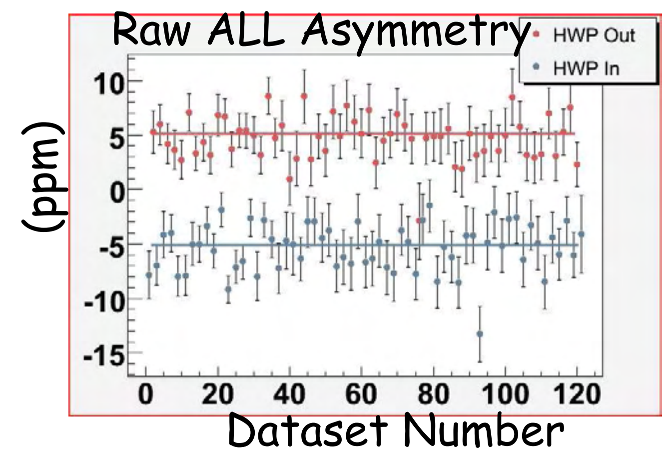
- Optical pumping of solid state photocathode
- High Polarization (>85%)
- Pockels cell allows rapid helicity flip (30 Hz)
- Slow helicity flip (1/day) to check answer and further cancel beam asymmetries
- Careful configuration to reduce beam asymmetries

Beam Position Differences, Helium

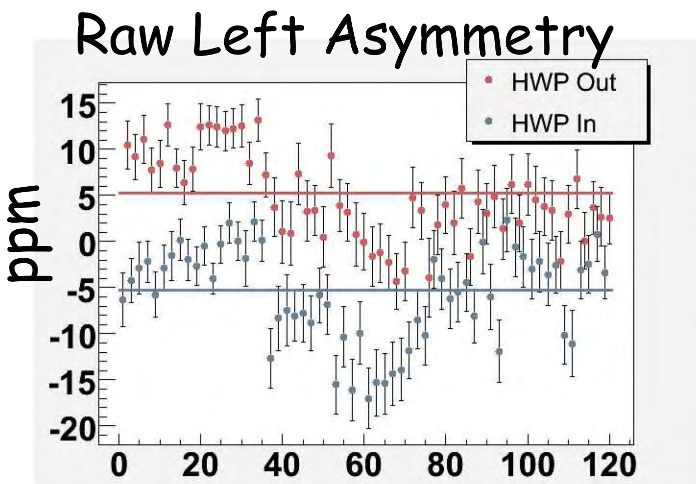
Position Difference Goal: 3 nanometers!

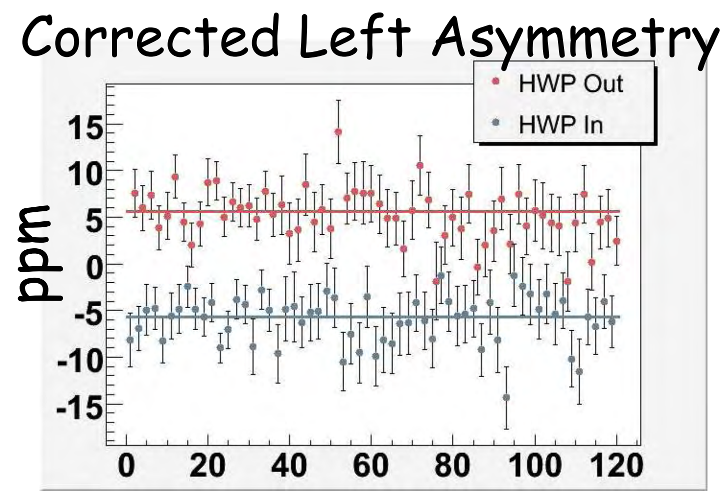


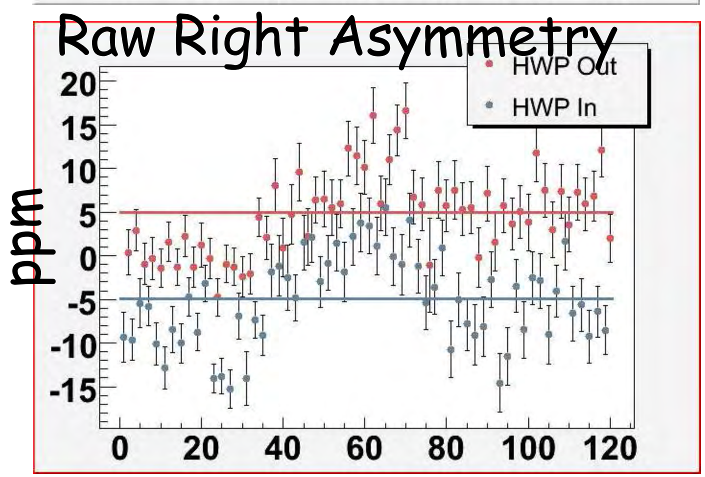
- Problem clearly identified as beam steering from electronic cross-talk
- Tests verify no helicity-correlated pickup in DAQ at sub ppb level
- Mostly cancel in average over both detectors

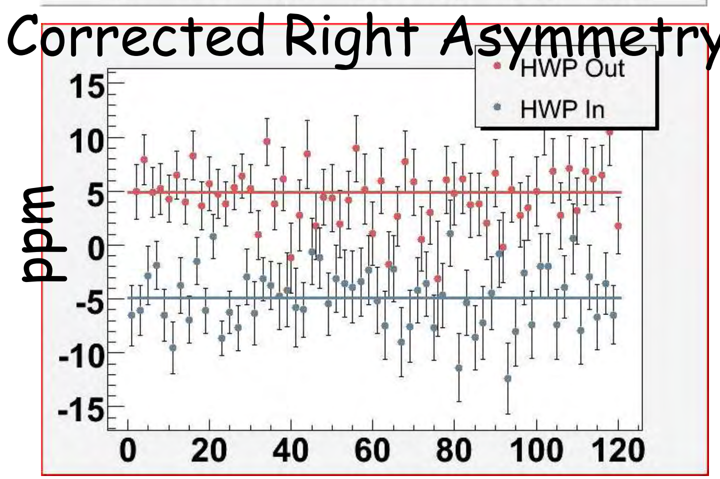


Beam Position Corrections- Helium









Beam Asymmetries:

X Target:	-5 nm
X Angle:	-28 nm
Y Target:	-21 nm
Y Angle:	1 nm

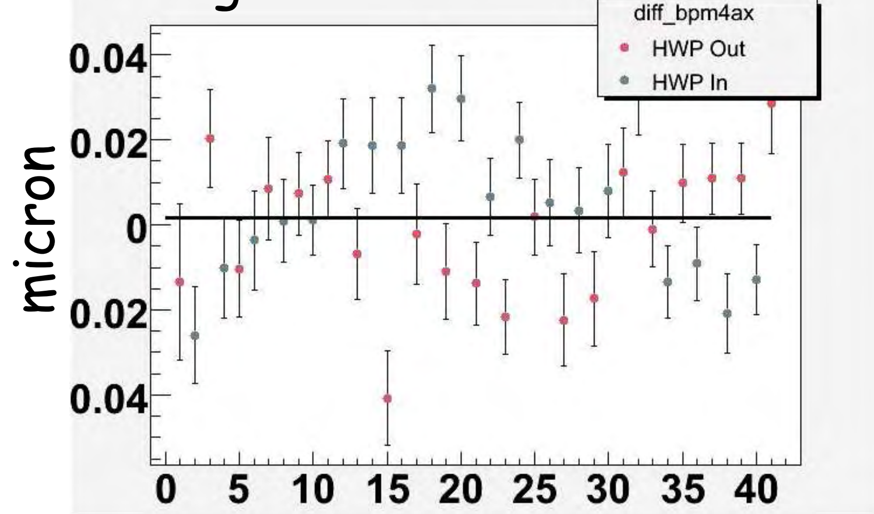
Total Corrections:

Left:	-0.370 ppm
Right:	0.080 ppm
All:	0.120 ppm

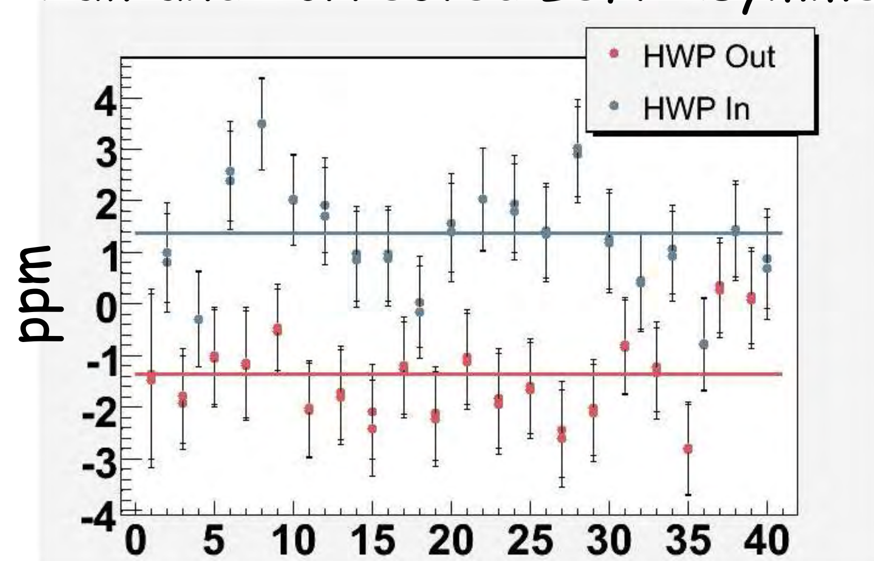
(A_{raw} = 5.253 $\pm$ 0.191 ppm)

Beam Position Corrections- Hydrogen

X angle BPM



Raw and Corrected Left Asymmetry



Surpassed Beam Goals
for Hydrogen Run

Energy -0.25 ppb
X Target: 1 nm
X Angle: -2 nm
Y Target: -1 nm
Y Angle: <1 nm

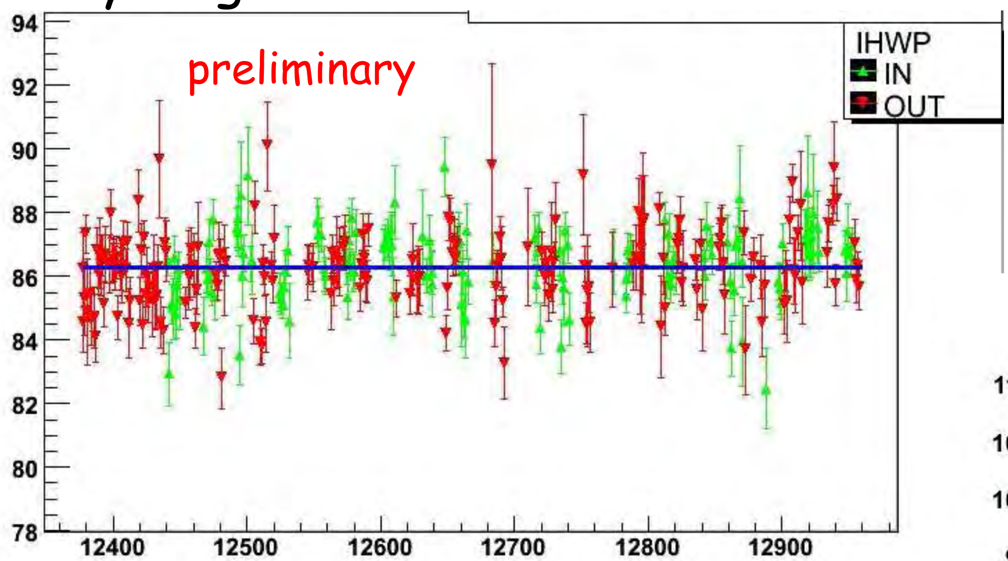
← Raw and Corrected for
Left Arm Only! Superimposed!

Total correction for beam position asymmetry on Left, Right, or ALL detector: 0.010 ppm

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

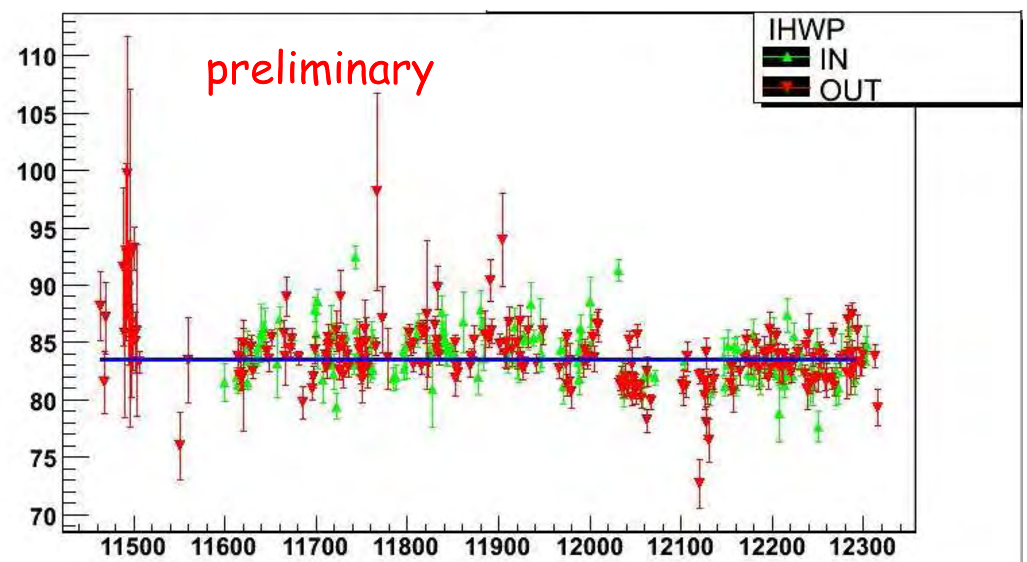
Compton Polarimetry (results)

Hydrogen: 86.7 ± 2 %



New developements in γ & e^{-} analyses. Anticipate <2% systematic uncertainty.

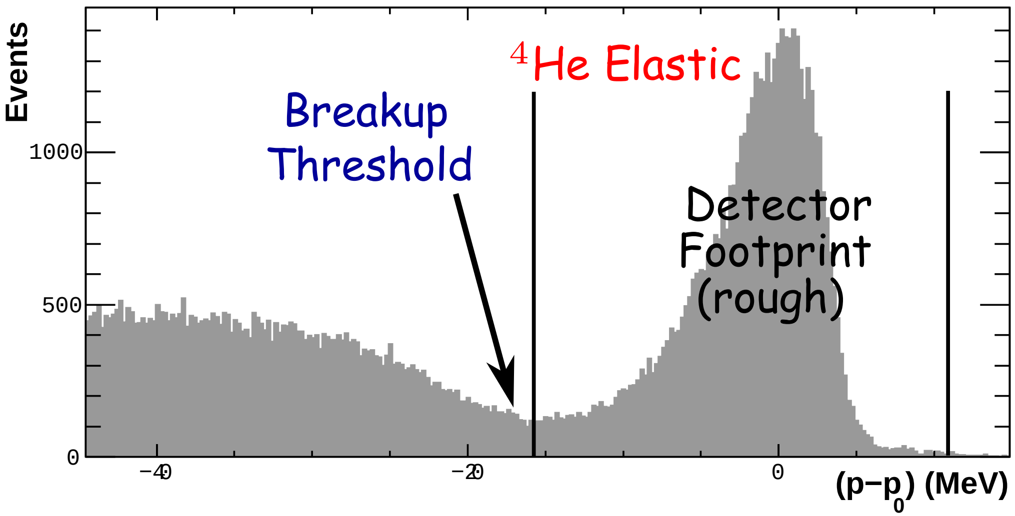
Helium: 84.0 ± 2.5 %



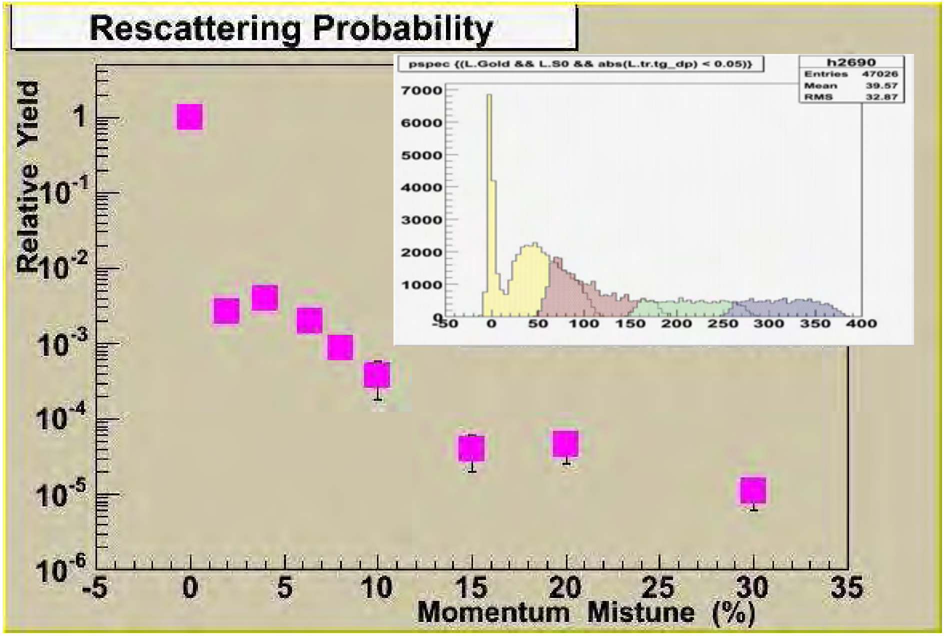
Helium ran with lower beam energy, making analysis significantly more challenging.

Backgrounds

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



Dipole field scan to measure the probability of rescattering inside the spectrometer



Helium:

Helium QE in detector:	0.15 +/- 0.15%
Helium QE rescatter:	0.25 +/- 0.15%
Al fraction:	1.8 +/- 0.2%

Hydrogen:

Al fraction:	0.75 +/- 0.25%
Hydrogen Tail + Delta rescatter	< 0.1%

Total systematic uncertainty contributions: ~40 ppb (Helium), ~15 ppb (Hydrogen)

Q^2 Central Scattering Angle

4-Momentum Transfer Squared

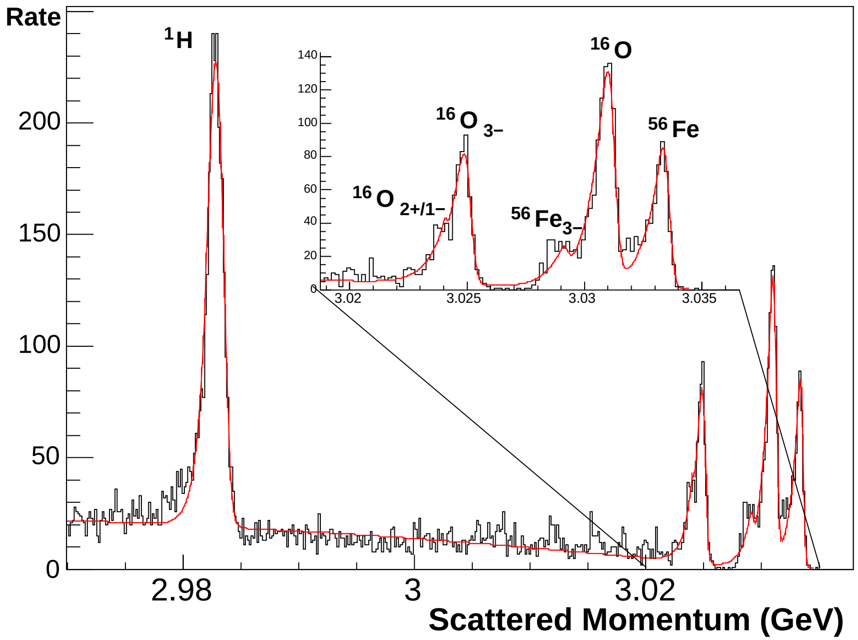
$$Q^2 = 2EE'(1 - \cos\theta)$$

$$\delta\theta_{survey} \simeq 1\% \quad \Rightarrow \quad \delta Q^2 \simeq 2\%$$ (Goal δQ^2: 1%)

Nuclear Recoil Method:

Water Cell (Steel Windows)

$$E' = \frac{E - \frac{1}{2m}(m^{*2} - m^2)}{1 + \frac{E}{m}(1 - \cos\theta)}$$



$$\delta\theta_{nuclei} \simeq 0.3\% \quad \Rightarrow \quad \delta Q^2 \simeq 0.7\%$$

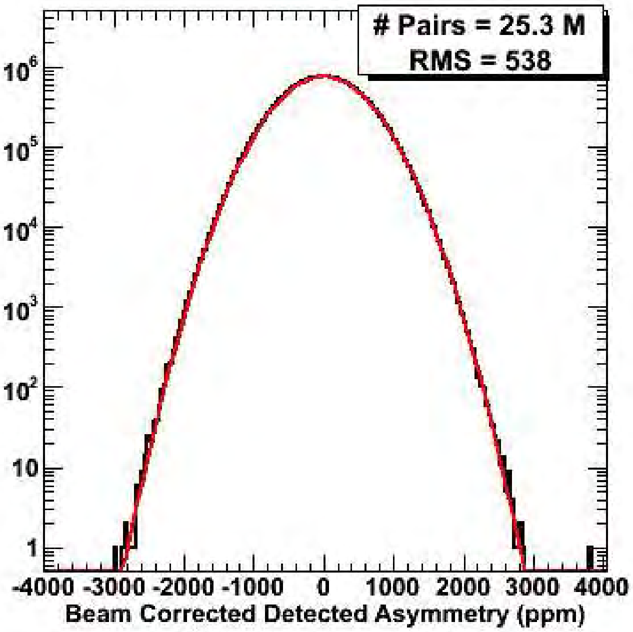
^{1}H Preliminary Results

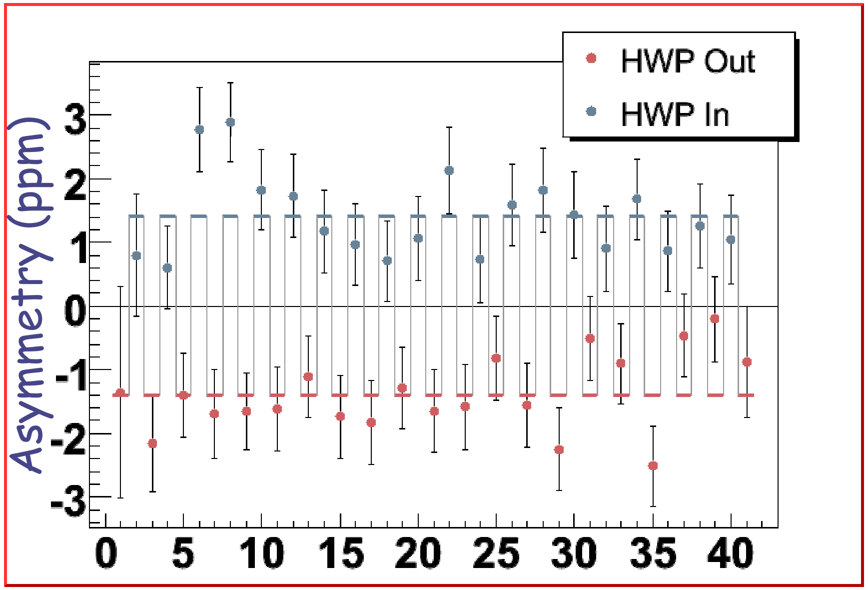
Raw Parity Violating Asymmetry

$\sim$ 25 M pairs, width $\sim$540 ppm

A_{raw} correction $\sim$ 11 ppb

Helicity Window Pair Asymmetry





Slug

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

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

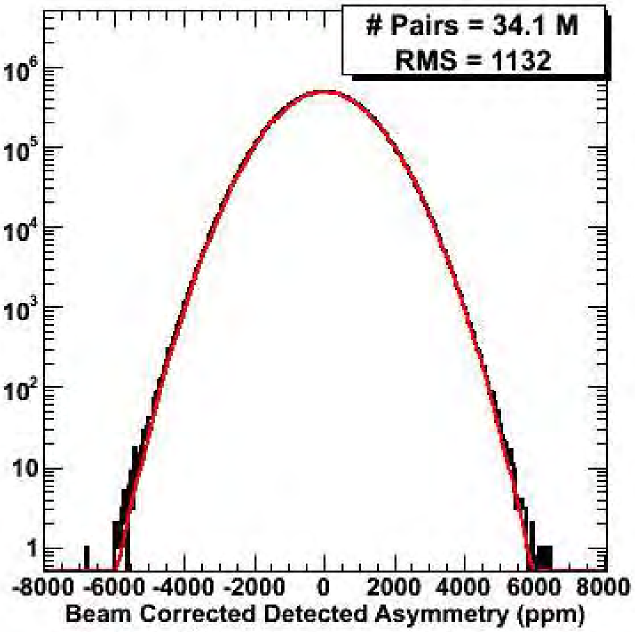
^{4}He Preliminary Results

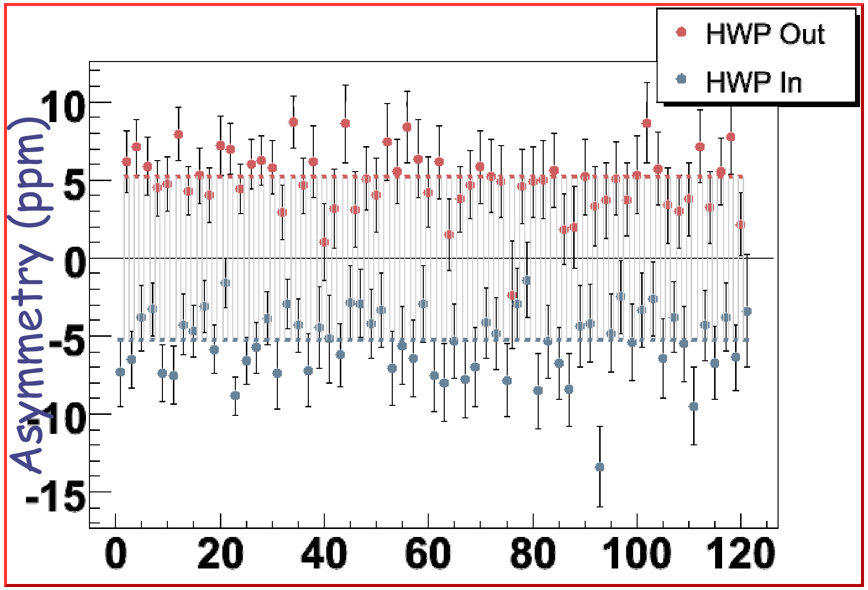
Raw Parity Violating Asymmetry

$\sim$ 30 M pairs, width $\sim$1130 ppm

A_{raw} correction $\sim$ 0.12 ppm

Helicity Window Pair Asymmetry





Slug

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

A_{raw} = 5.253 $\pm$ 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

$$G_E^s = 0.004 \pm 0.014_{(stat)} \pm 0.013_{(syst)}$$

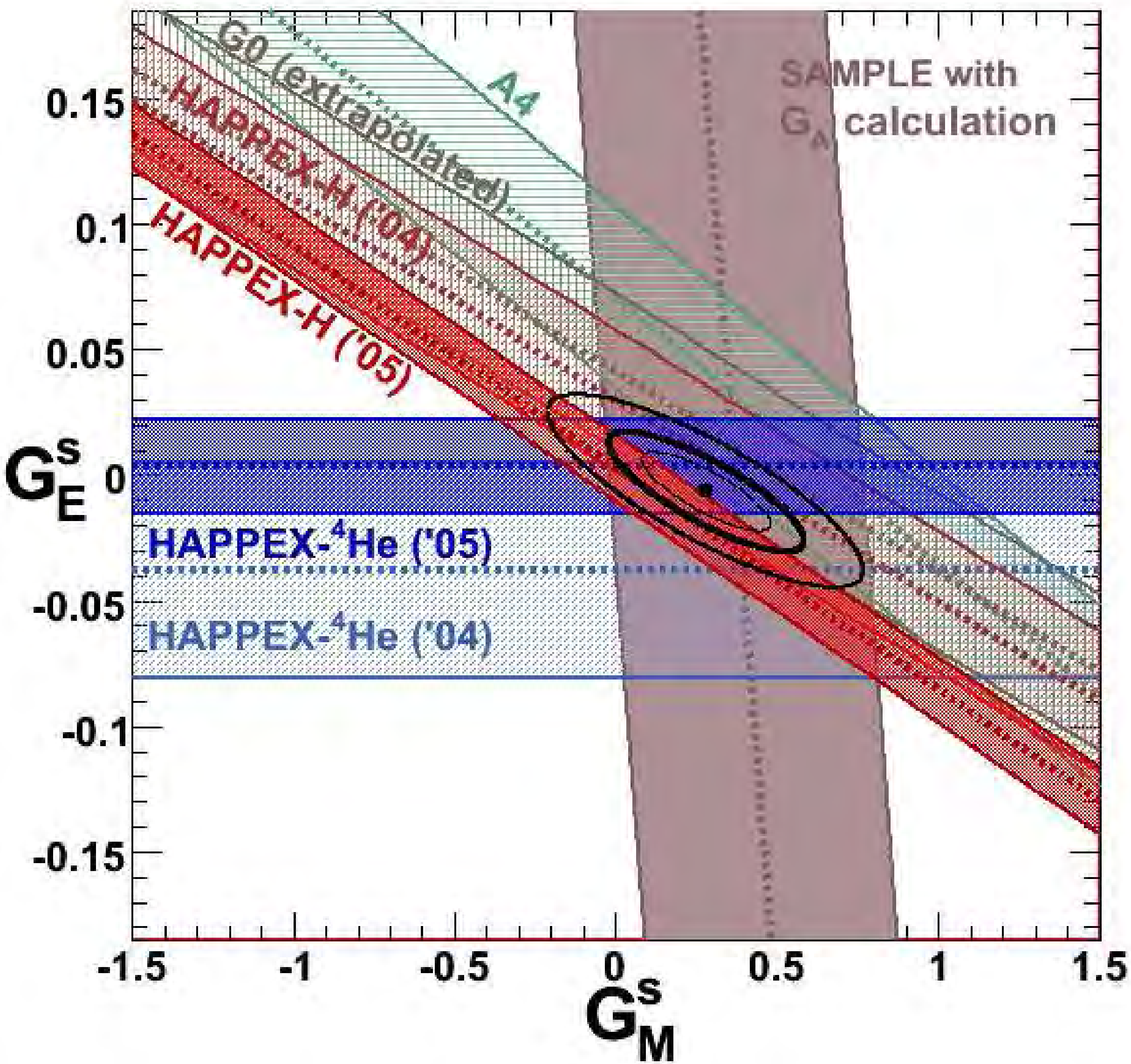
HAPPEX-H:

$Q^2 = 0.1089 \pm 0.0011\ (GeV/c)^2$
$A_{PV} = -1.60 \pm 0.12\ (stat) \pm 0.05\ (syst)$ ppm

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

$$G_E^s + 0.088\, G_M^s =$$
$$0.004 \pm 0.011_{(stat)} \pm 0.005_{(syst)} \pm 0.004_{(FF)}$$

World Data... $Q^2 \sim 0.1\ GeV^2$



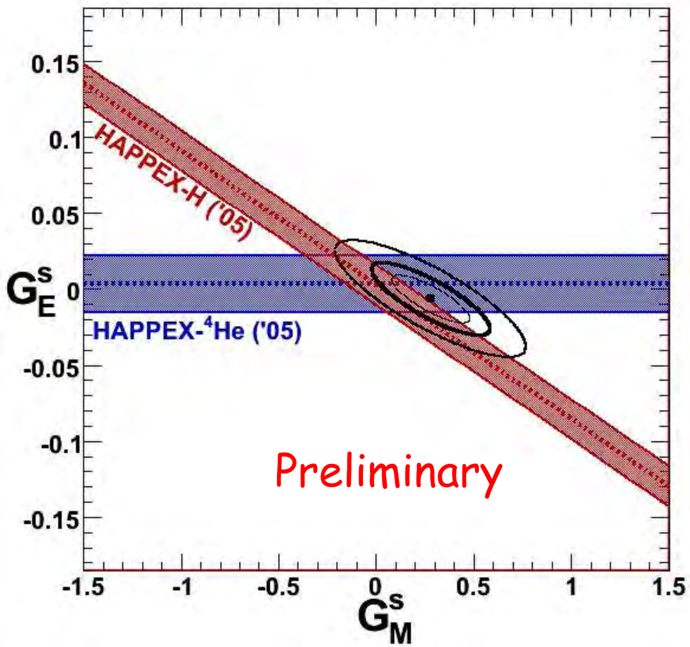
G^s_M = 0.28 $\pm$ 0.20
G^s_E = -0.006 $\pm$ 0.016

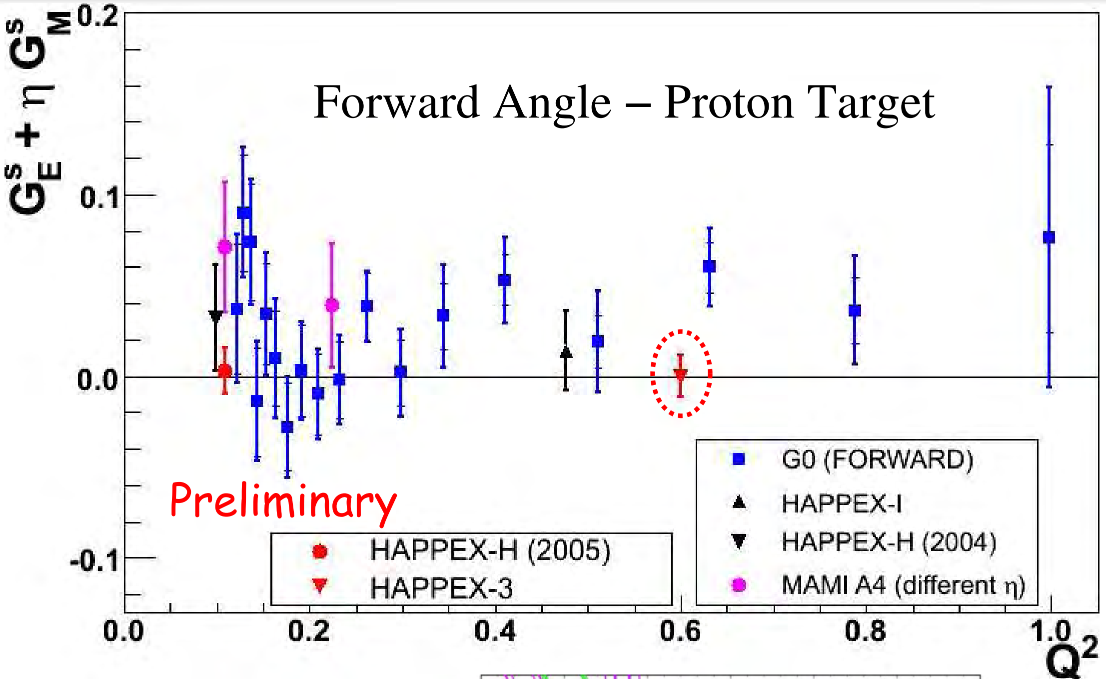
$\sim$ 3% $\pm$ 2.3% of proton magnetic moment

$\sim$ 0.2% $\pm$ 0.5% of Electric distribution

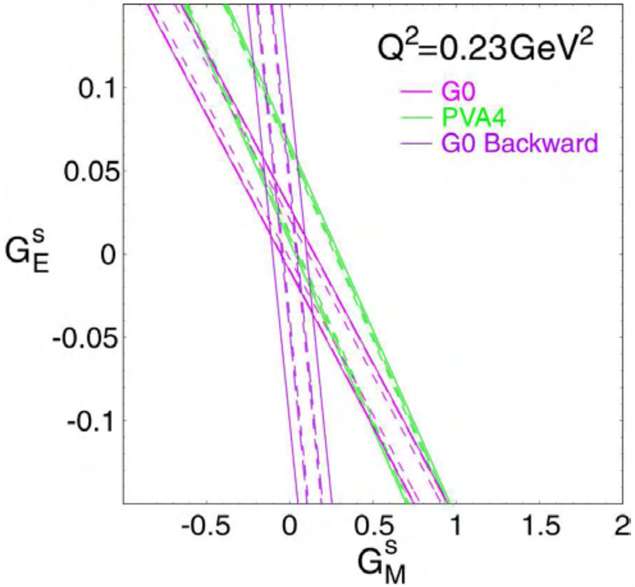
HAPPEX-only fit suggests something even smaller:
G^s_M = 0.12 $\pm$ 0.24
G^s_E = -0.002 $\pm$ 0.017

Summary and Outlook





- Suggested large values at $Q^2 \sim 0.1$ GeV^2
  - Tightly constrained
- Large possible cancellation at $Q^2 \sim 0.2$ GeV^2
  - Very unlikely given constraint at 0.1 GeV^2
  - G^0 backangle at low Q^2 maintains sensitivity to discover G_M^s
- Possible large values at Q^2>0.4 GeV^2
  - G^0 backangle, Running Now!
  - HAPPEX-III - 2008



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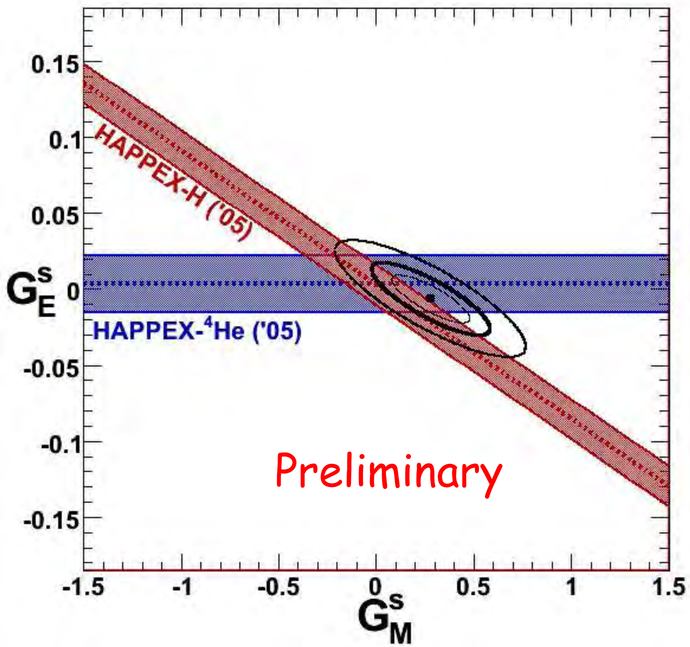
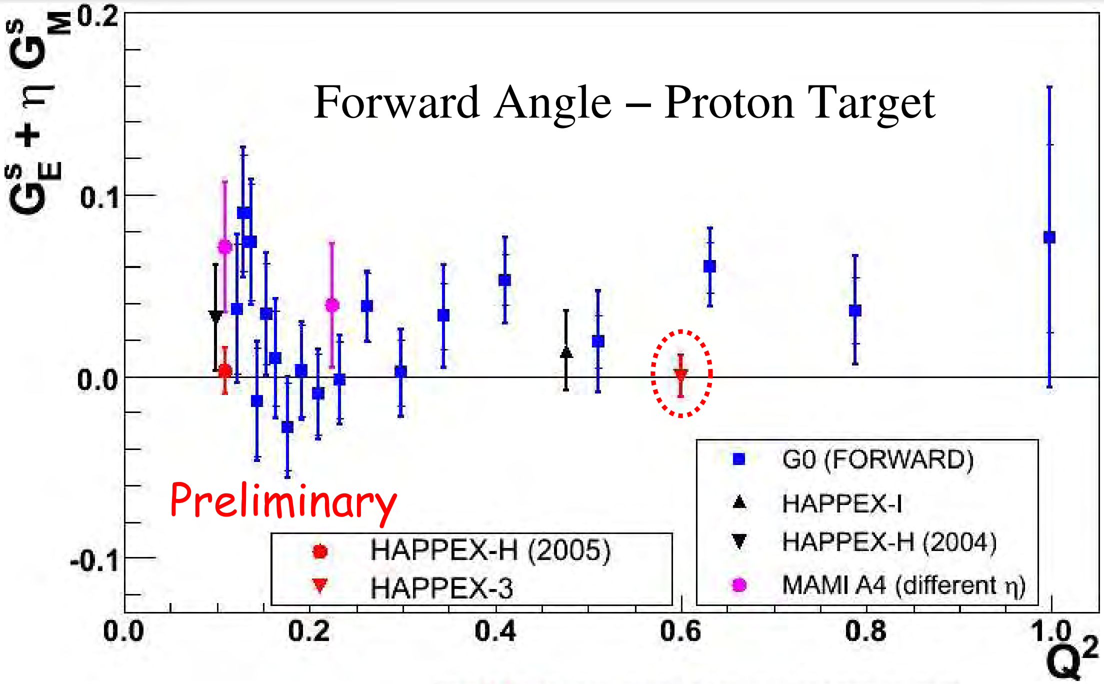
Summary and Outlook





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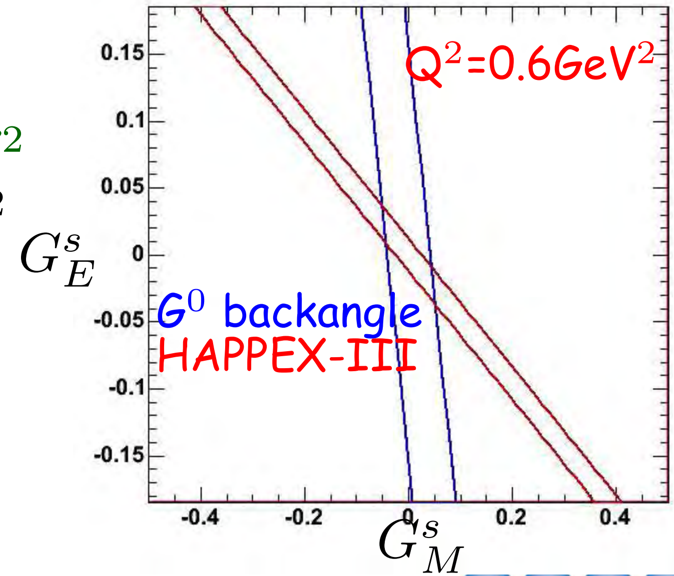


Extra Slides

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

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

Q^2 Error Summary

Error Source	Error	Percent Error in Q^2
Scattering Angle	0.01°	0.4 %
HRS Momentum Scale	5 MeV	0.2 %
Beam Energy	3 MeV	0.1 %
Matrix Elements:		
At Z = 0		0.3 %
Z dependence		0.1 %
ADC Weighting		He: 0.1 % H: 0.5 %
Drifts in Time		0.6 %
Rate Dependence		He: 0.3 % H: 0.1 %
Total Systematic Error		He: 0.9 % H: 1.0 %
Statistical Error		$\leq$0.1 %
TOTAL ERROR		He: 0.9 % H: 1.0 %
Contribution to δA_{PV} (syst)		He: 58 ppb H: 16 ppb

Correcting Beam Asymmetries

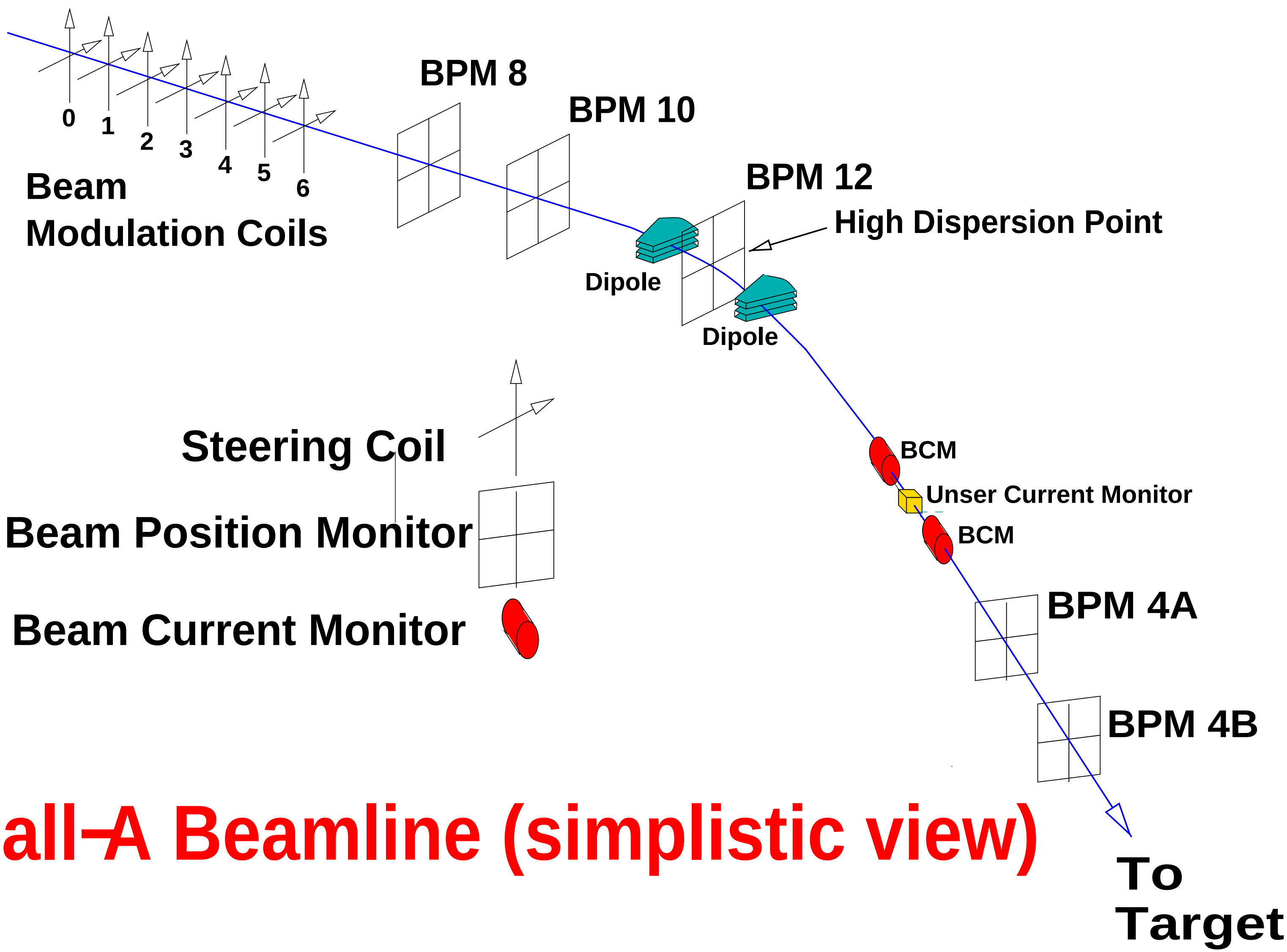
$$A_{\rm raw} = A_{\rm det} - A_{\rm Q} + \sum_{i=1}^{5} \beta_i \Delta x_i$$

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

"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

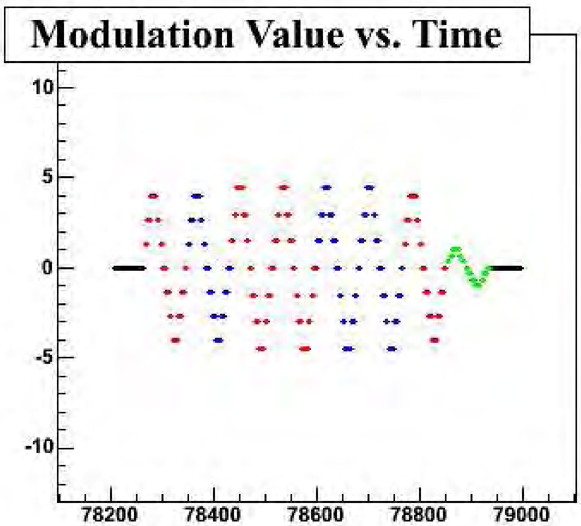
"Dithering"
- Induce non-HC beam motion with coils, measure dS/dC_i, dx/dC_i
- Relate slopes to dS/dx_i
- Not compromised by correlated beam motion
- Robust, clear signals for failures
- Sensitive to non-linearities

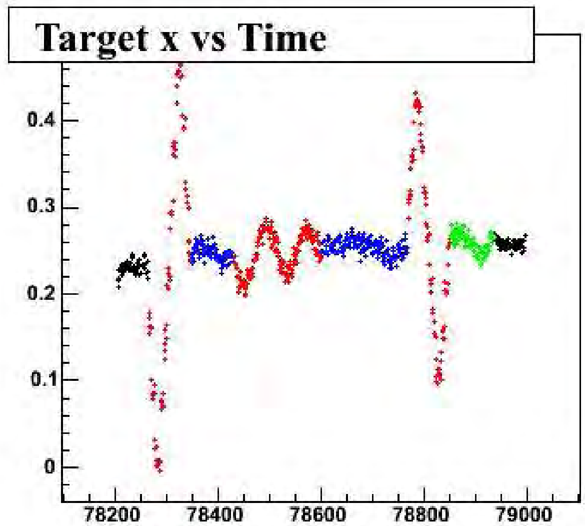
Beam Modulation

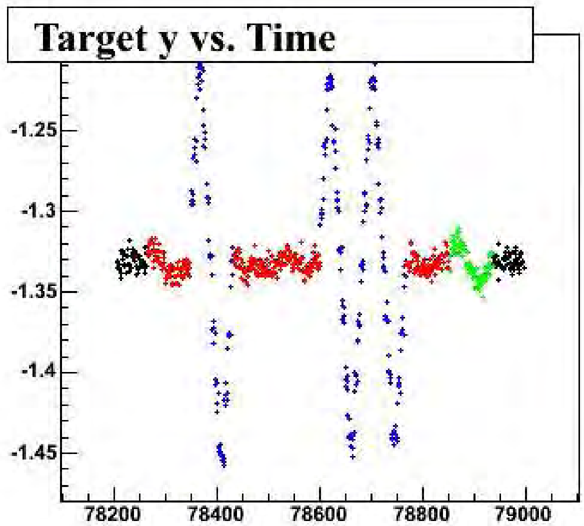


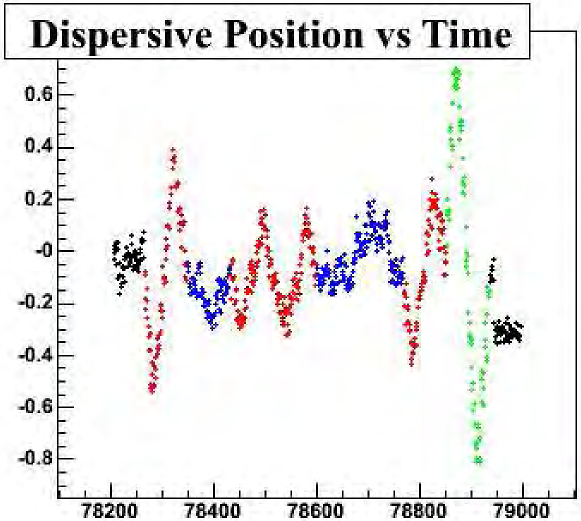
Hall-A Beamline (simplistic view)

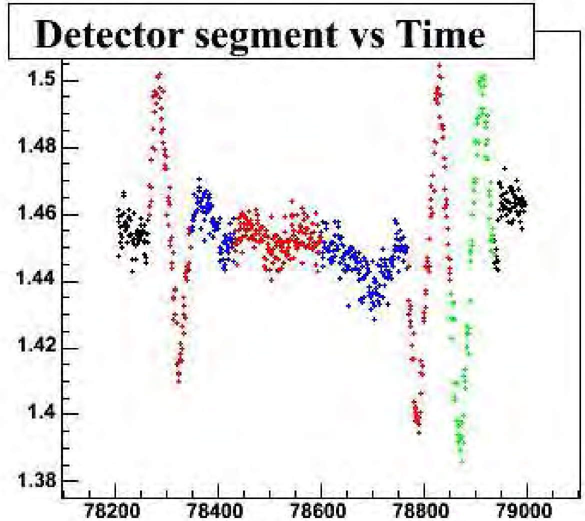
Beam Modulation

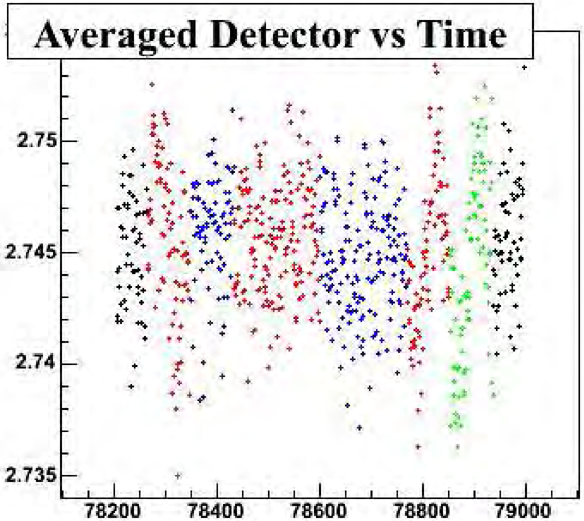




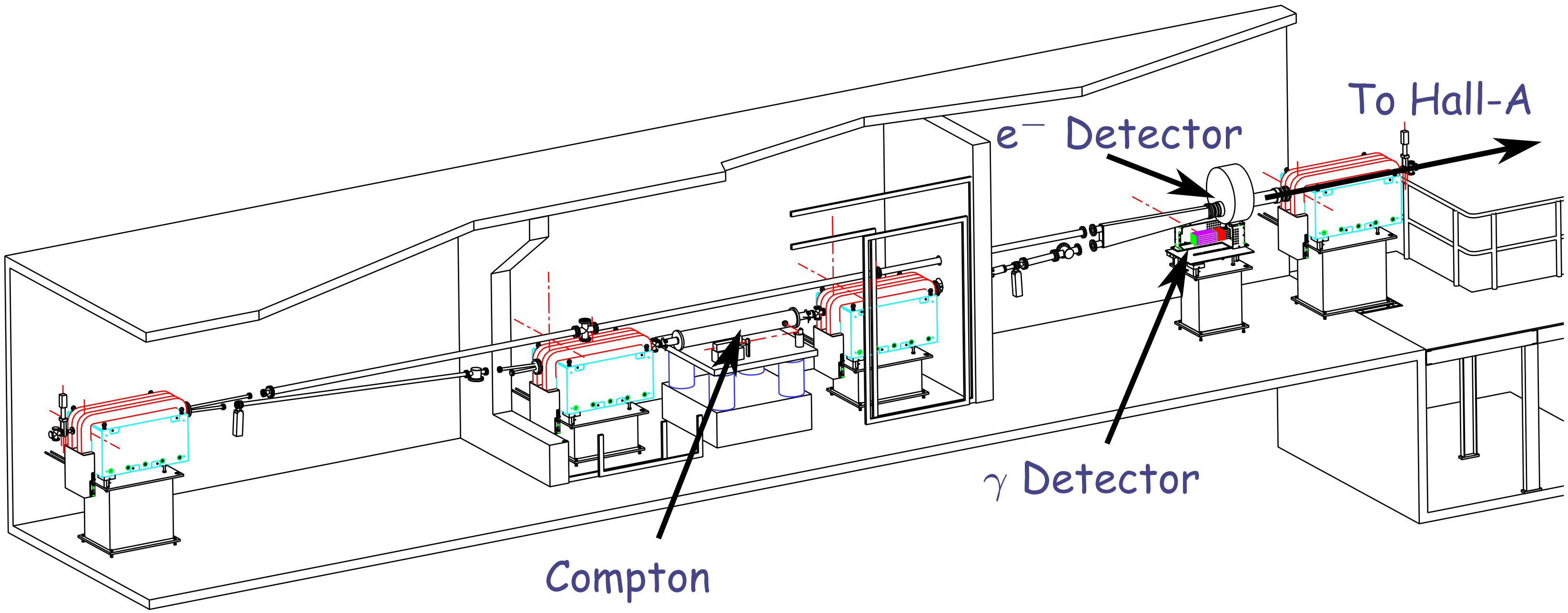








Compton Polarimetry



- Non-invasive, continuous polarimetry
- 2% systematic error at 3 GeV
- Independent photon and electron analyses
- Cross-checked with Hall A Møller, 5 MeV Mott