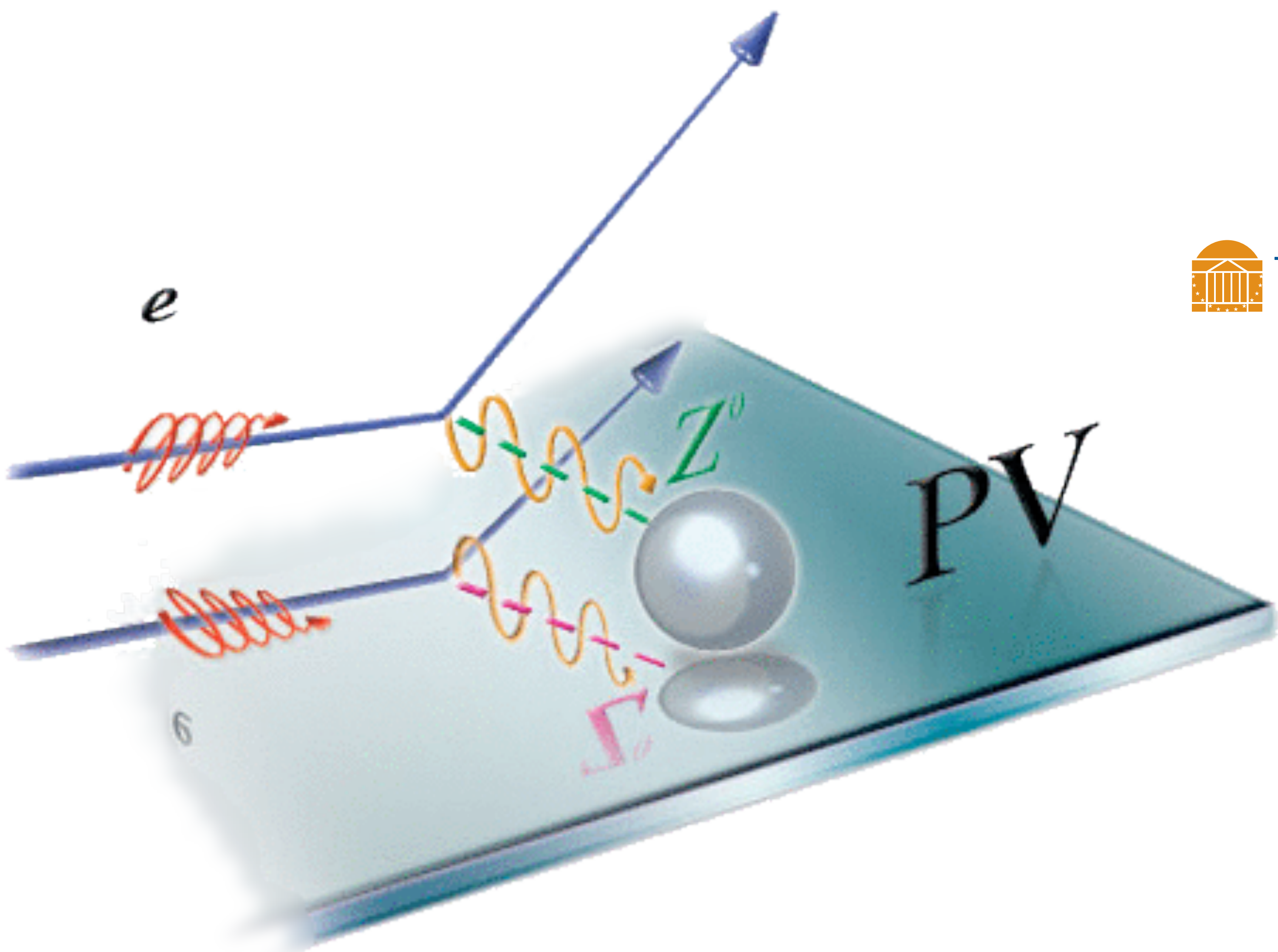
HAPPEX-III and Strangeness Contributions to the Nucleon Vector Form-factors



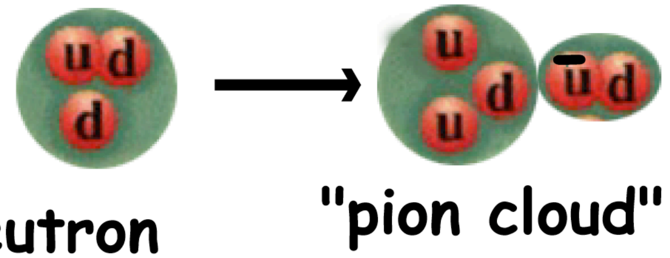
Kent Paschke

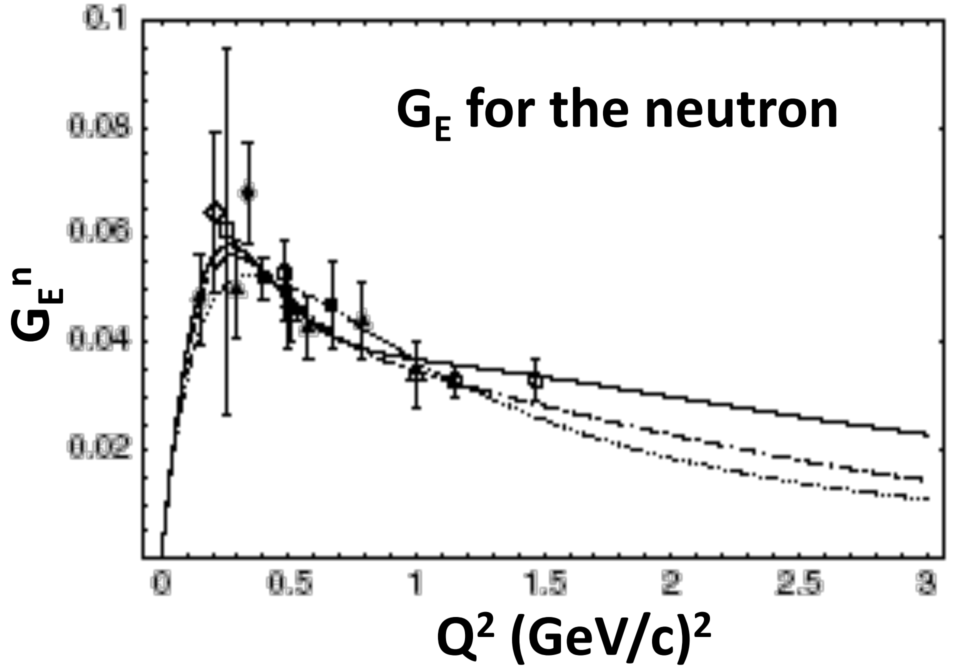
University of Virginia

PAVI '09
Bar Harbor, Maine
June 22, 2009

The Neutral Current and Nucleon Vector Form Factors

neutron charge distribution





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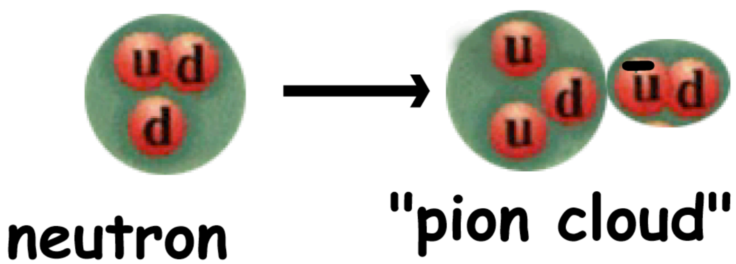
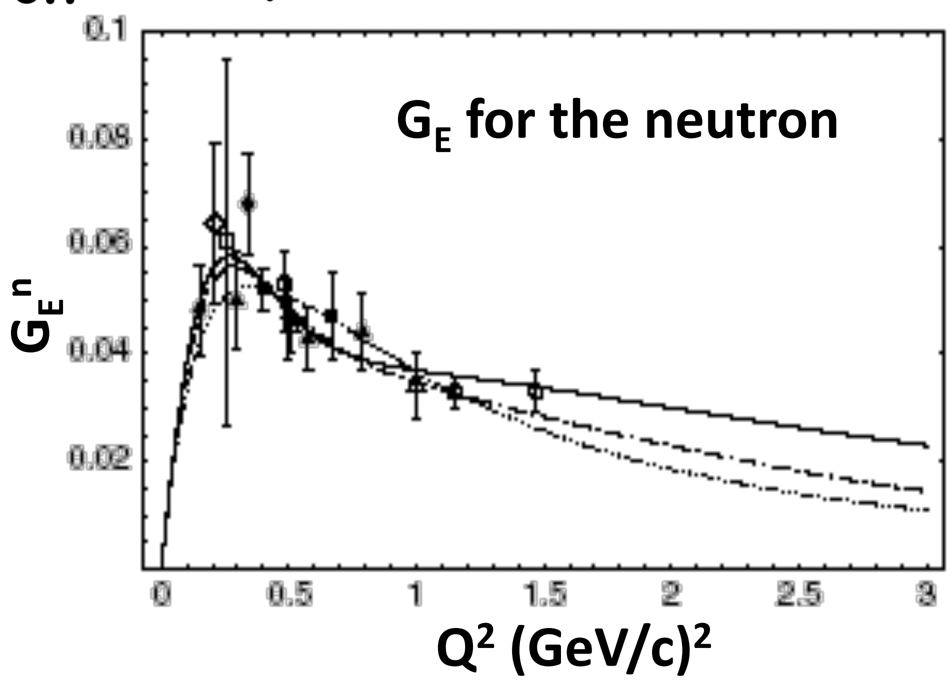
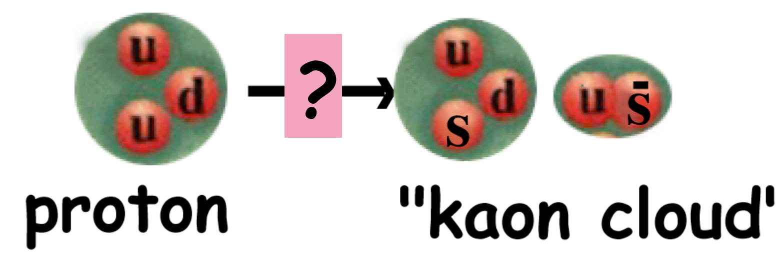




Strange quarks exist in the nucleon at short distance scales. Do they play a role in the elastic proton scattering?

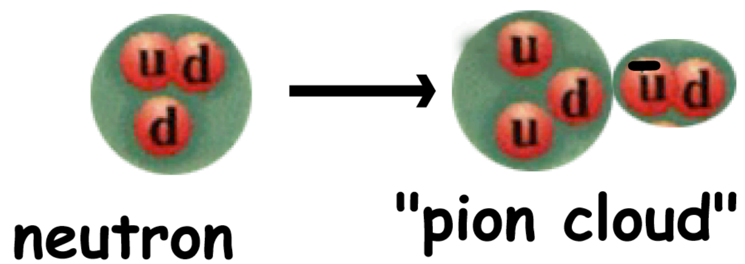
proton flavor distribution

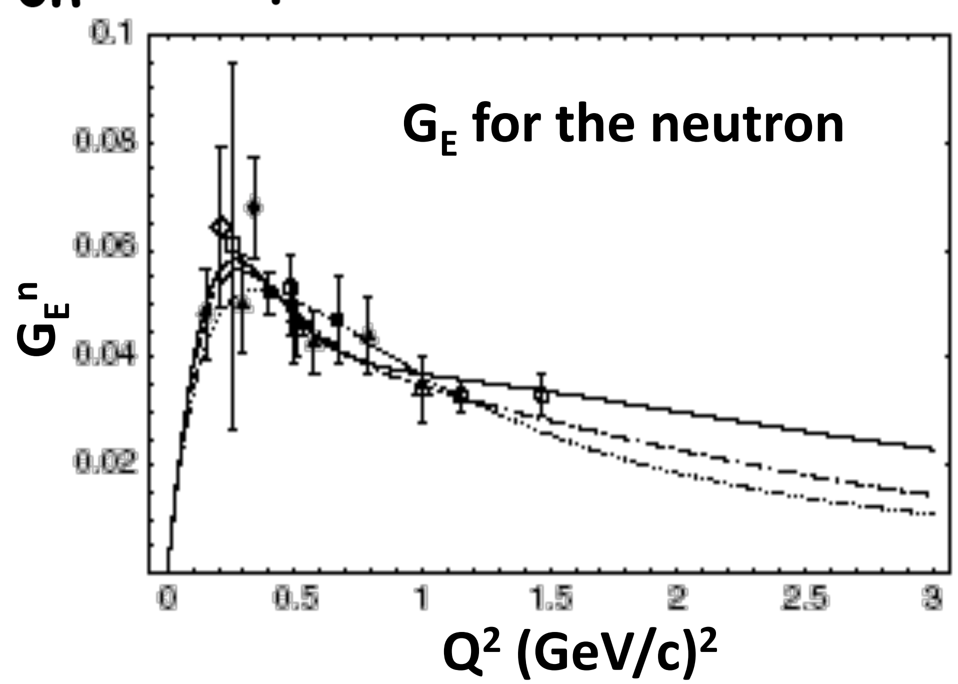


At very low Q^2, $G^s_{E/M}$ relates to the strange matrix elements of the nucleon (strange radius and strange magnetic moment)

The Neutral Current and Nucleon Vector Form Factors

neutron charge distribution





Strange quarks exist in the nucleon at short distance scales. Do they play a role in the elastic proton scattering?

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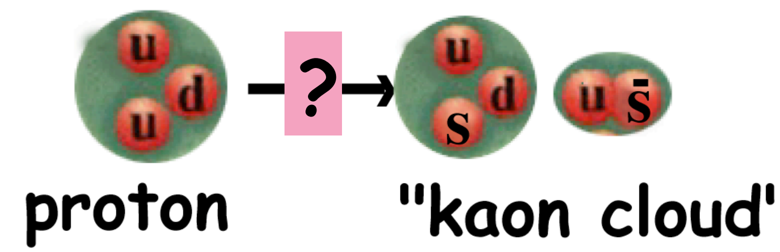
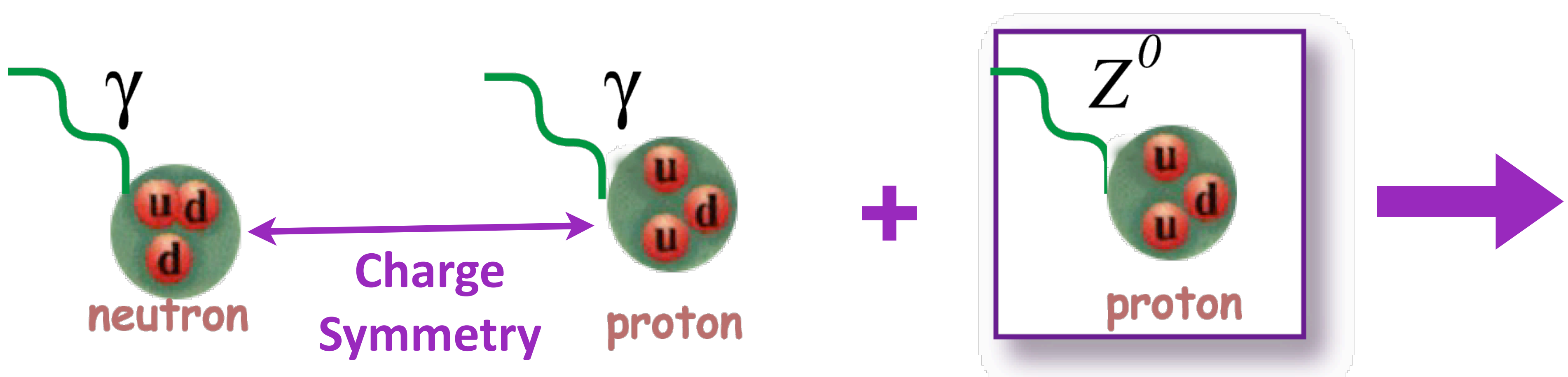


At very low Q^2, $G^s_{E/M}$ relates to the strange matrix elements of the nucleon (strange radius and strange magnetic moment)

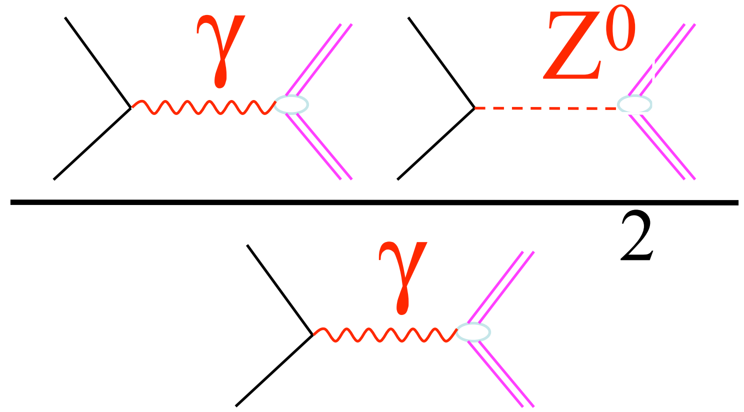
Assume 3 quark flavor contributions to vector form factors: G^u, G^d, G^s



3 equations with 3 unknowns

Measuring Strange Vector Form Factors

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto$$



$$\sim \frac{10^{-4} Q^2}{\mathrm{GeV}^2}$$

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

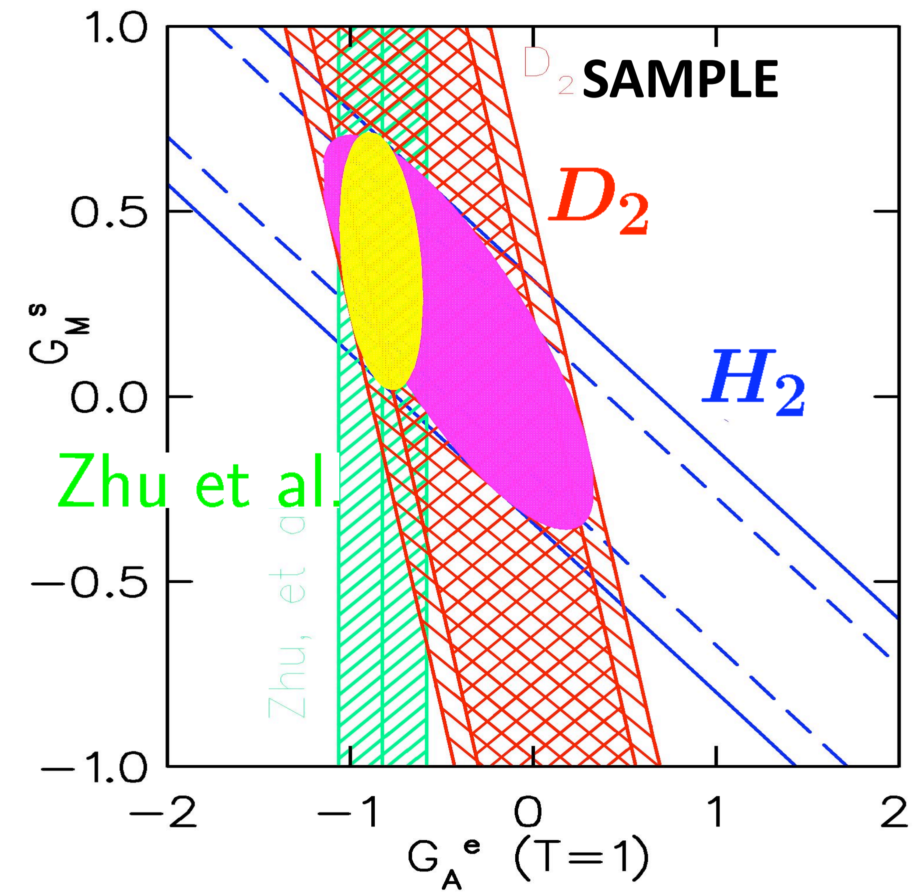
$$\tilde{G}_A^{p,n} = -\tau_3\left(1 + R_A^{T=1}\right)G_A^{(3)} + \sqrt{3}R_A^{T=0}G_A^{(8)} + \Delta s$$

Anapole Moment Correction:

Multiquark weak interaction modifies axial form-factor

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

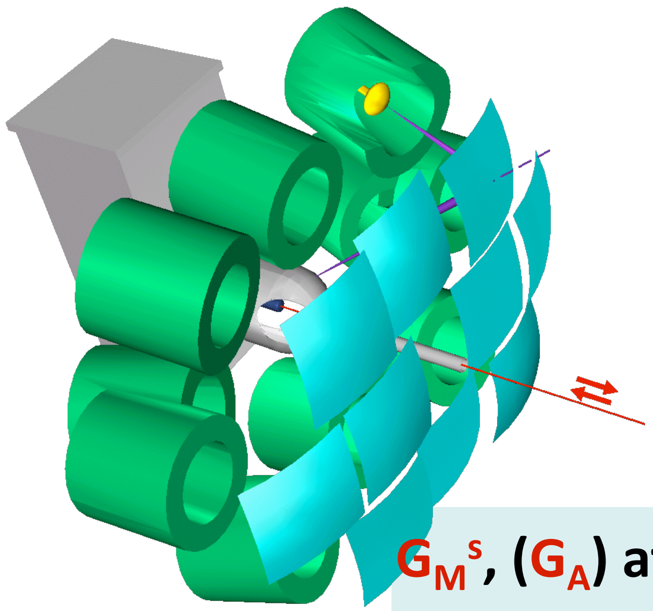
- **Large uncertainty estimated to account for specific uncalculated terms**
- **Uncertainty dominates axial term**
- **Difficult to achieve tight experimental constraint**



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

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

Experimental Overview

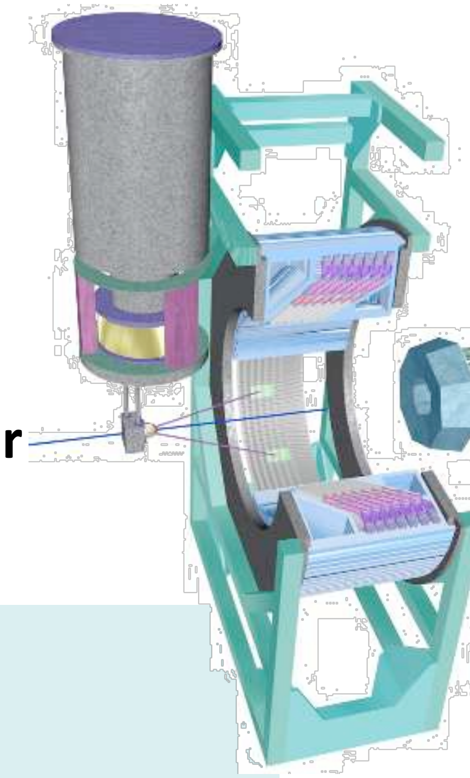


SAMPLE

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

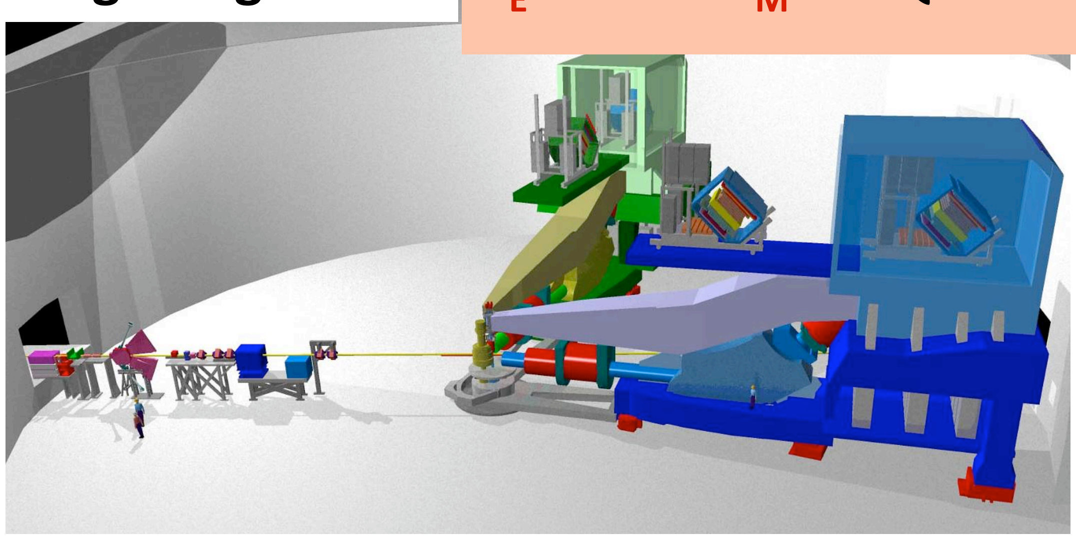
Precision spectrometer, integrating

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

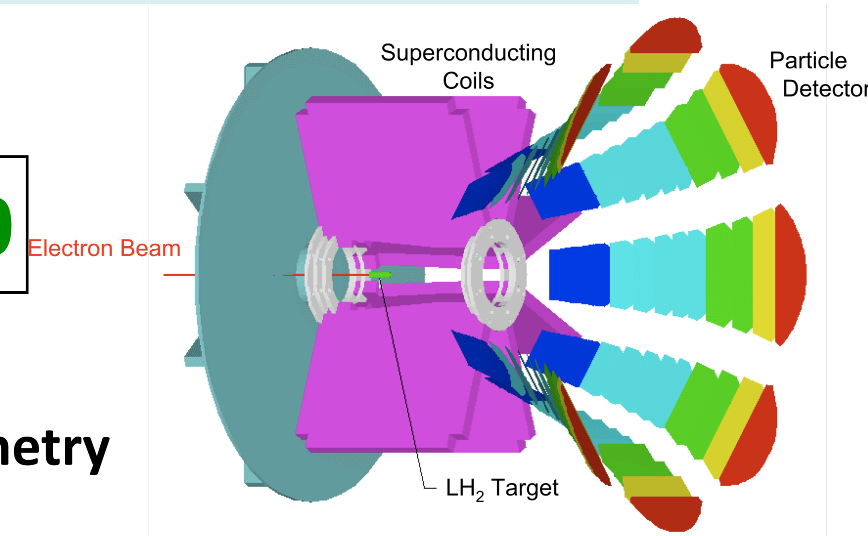
$G_E^s + 0.08\, G_M^s$ at $Q^2 = 0.1$ GeV^2

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

$G_E^s + \eta\, G_M^s$ over $Q^2 = [0.12, 1.0]$ GeV^2

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

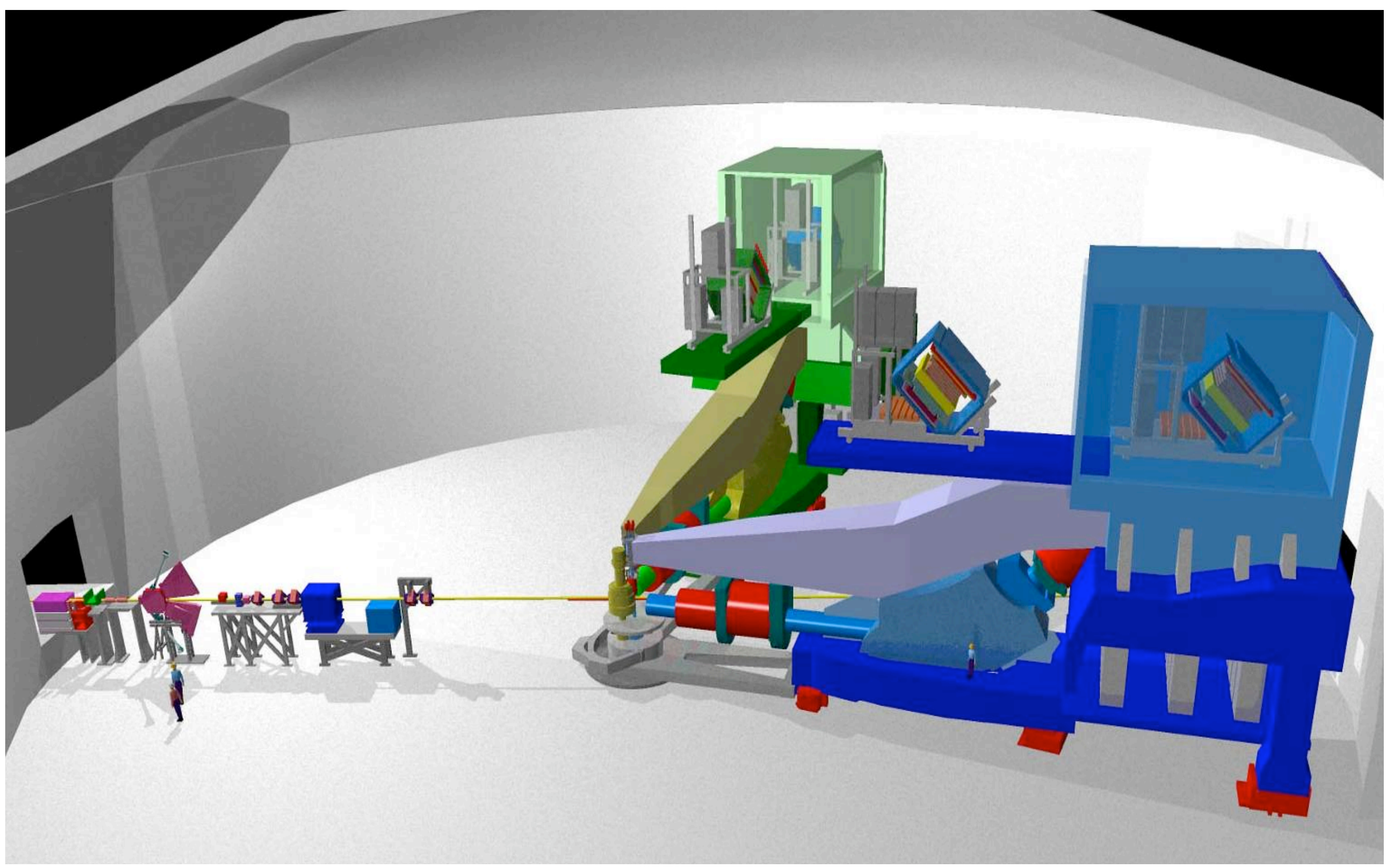
HAPPEX: Built around the HRS

HRS: twin high-resolution spectrometers, built for (e,e'p) studies.

- Limited acceptance (~5-8 msr) but very clean. (Plenty of acceptance in forward angles.)
- 12.5^o minimum angle
- ~3 GeV maximum E'

Statistical FOM suitable for forward-angle PVeS studies

- Hydrogen, Deuterium from $Q^2 \sim [0.25\ GeV^2 - 1.0\ GeV^2]$
- Helium-4 at $Q^2 \sim [0.05\ GeV^2 - 0.15\ GeV^2]$



- Very low backgrounds
- Very clean isolation of ^4He elastic
- Low Q^2 precision range extended and optimized with septum magnet for 6^o scattering

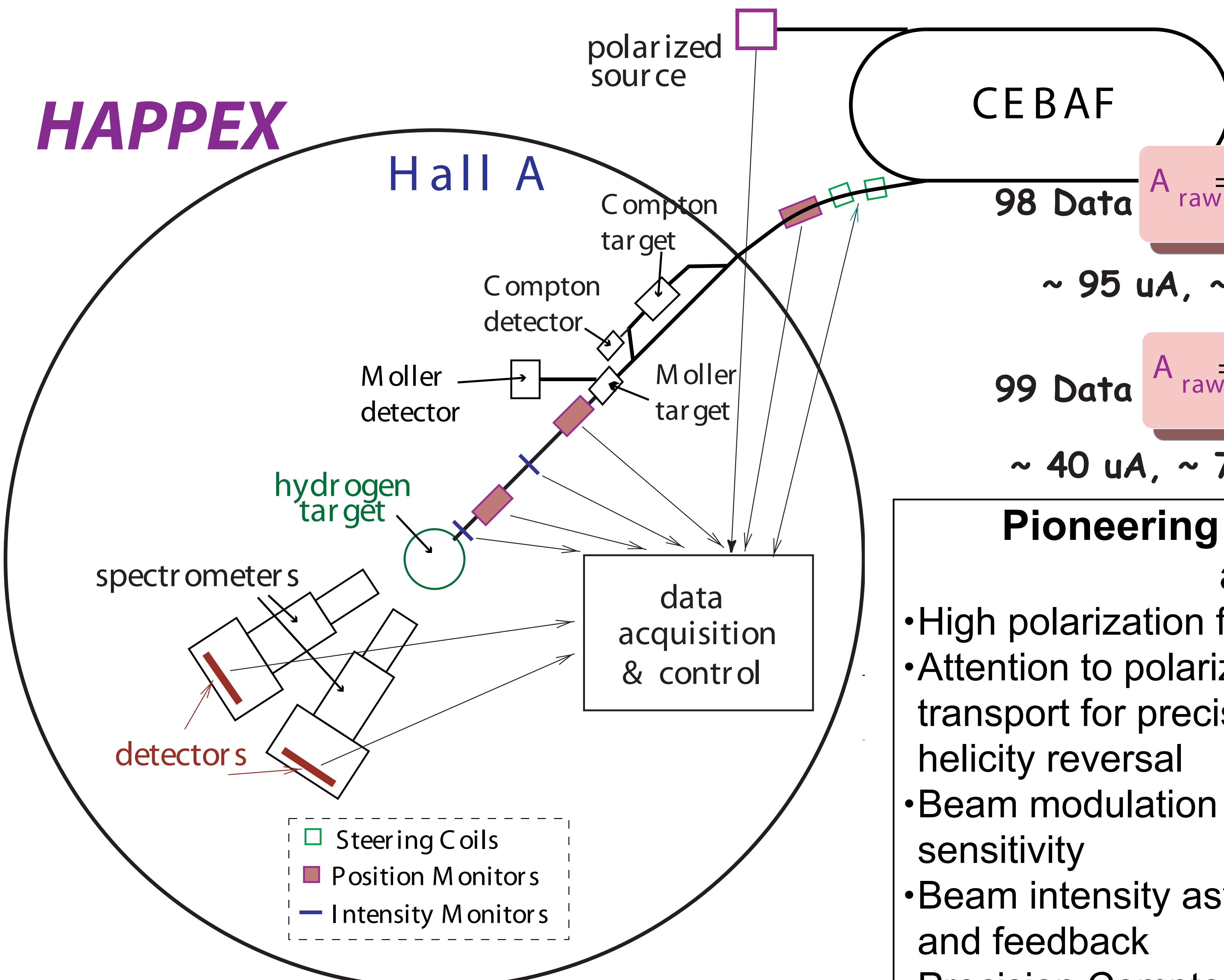
Forward-angle program plays a primary role in strange-quark studies

- Insensitive to problematic anapole moment
- ^4He interpretability very robust

First PVeS experiment at JLab

Hall A Proton Parity Experiment (E91-010)

HAPPEX



98 Data A_{raw}=-5.64 ± 0.75 (ppm)

~ 95 uA, ~ 38% polarization

99 Data A_{raw}=-10.45 ±0.75 (ppm)

~ 40 uA, ~ 70% polarization

Pioneering new technologies at JLab

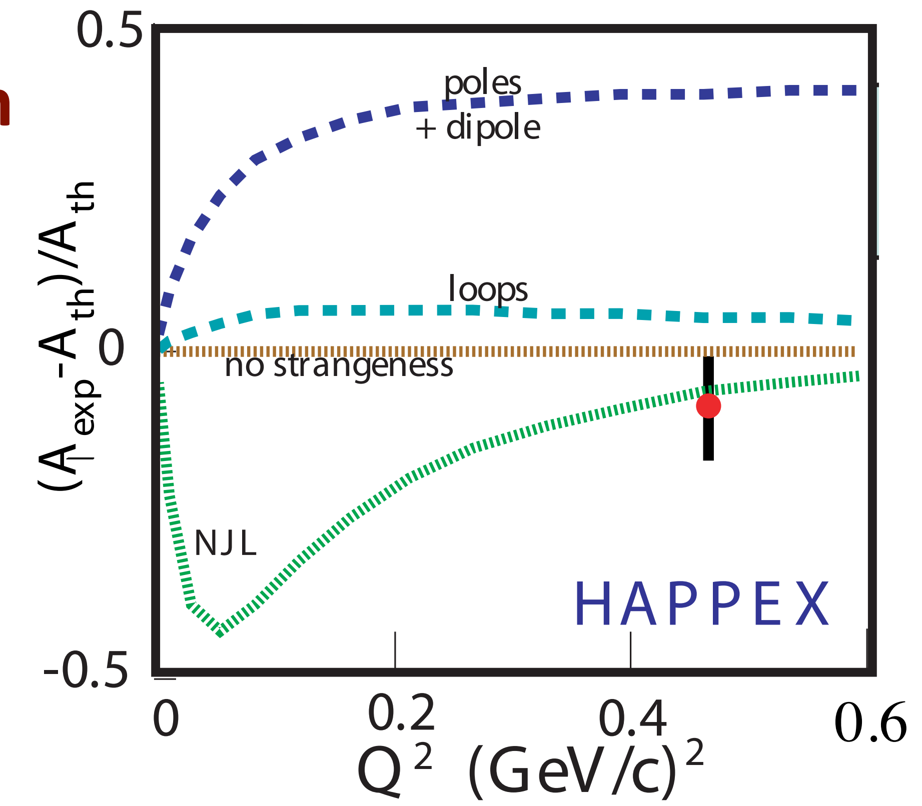
- High polarization from strained cathode
- Attention to polarized source and beam transport for precision and stability under helicity reversal
- Beam modulation to extract position/energy sensitivity
- Beam intensity asymmetry measurement and feedback
- Precision Compton polarimetry
- Low noise analog flux integration

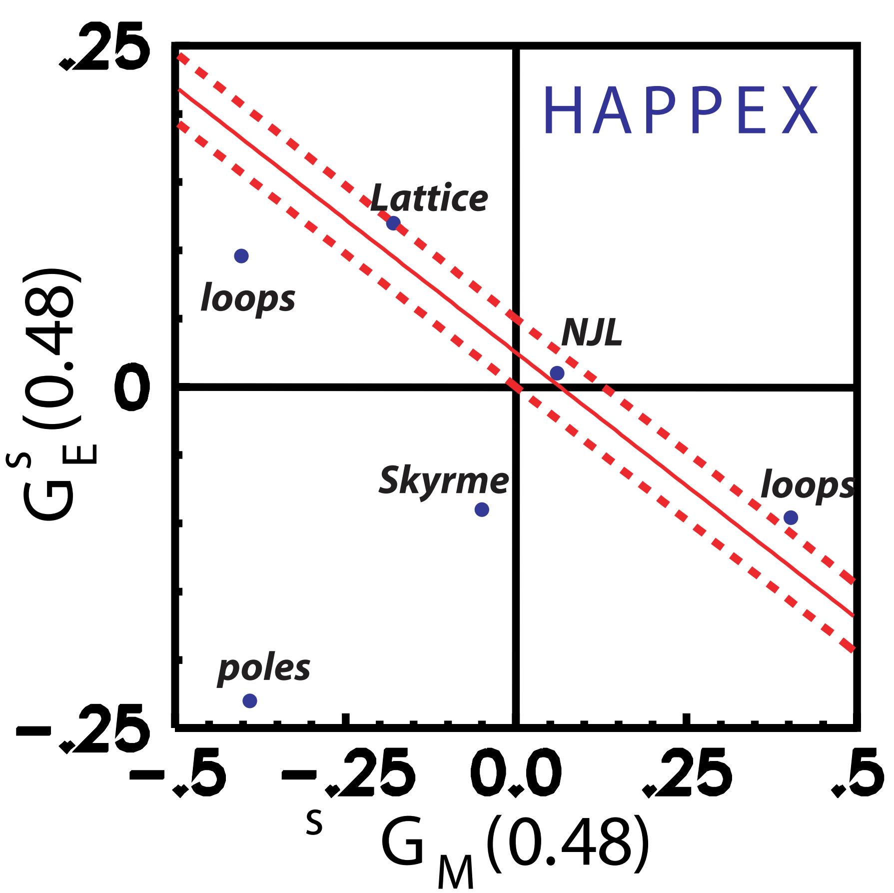
HAPPEX Results

ep at Q^2=0.5 (GeV/c)^2, 12.3 degrees

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

$G^s_E + 0.392\, G^s_M$ =
0.014 ± 0.020 (exp) ± 0.010 (FF)





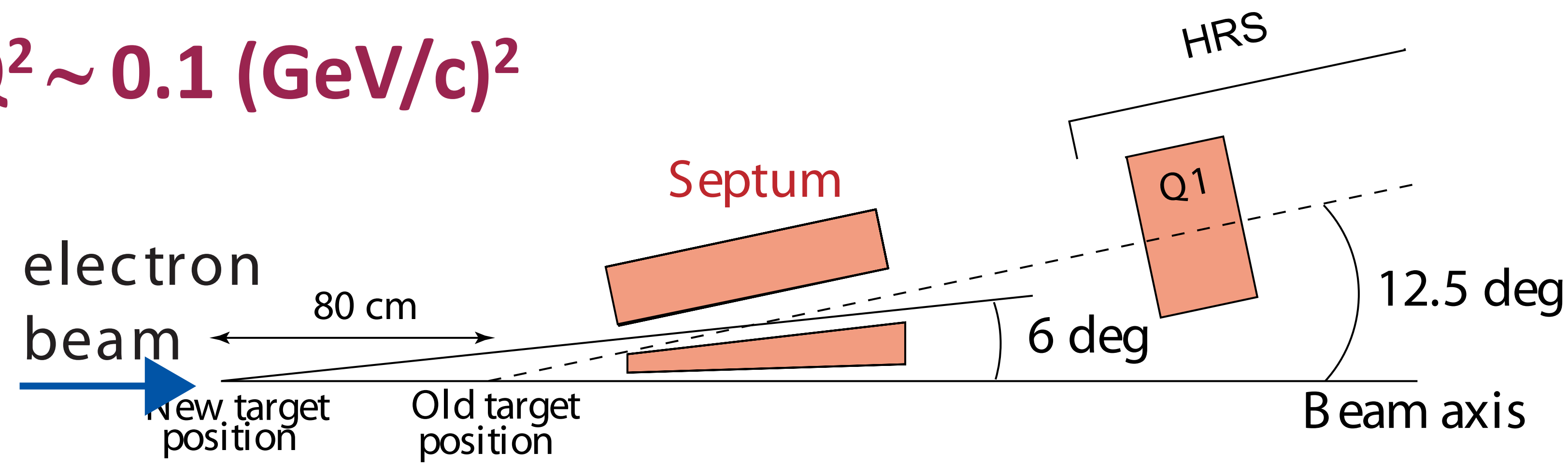
Statistics limited. Leading systematic is polarimetry

Axial form factor contribution: 0.56 ± 0.23 ppm
(includes anapole limits by Zhu *et al*)

Phys. Rev. Lett. 82:1096-1100,1999;
Phys. Lett. B509:211-216,2001;
Phys. Rev. C 69, 065501 (2004)

HAPPEX-II / HAPPEX-He

θ=6 deg, E ~ 3 GeV, Q^2 ~ 0.1 $(GeV/c)^2$



- **Hydrogen** : $G^s_E + \alpha\, G^s_M$
- **^{4}He**: Pure G^s_E :

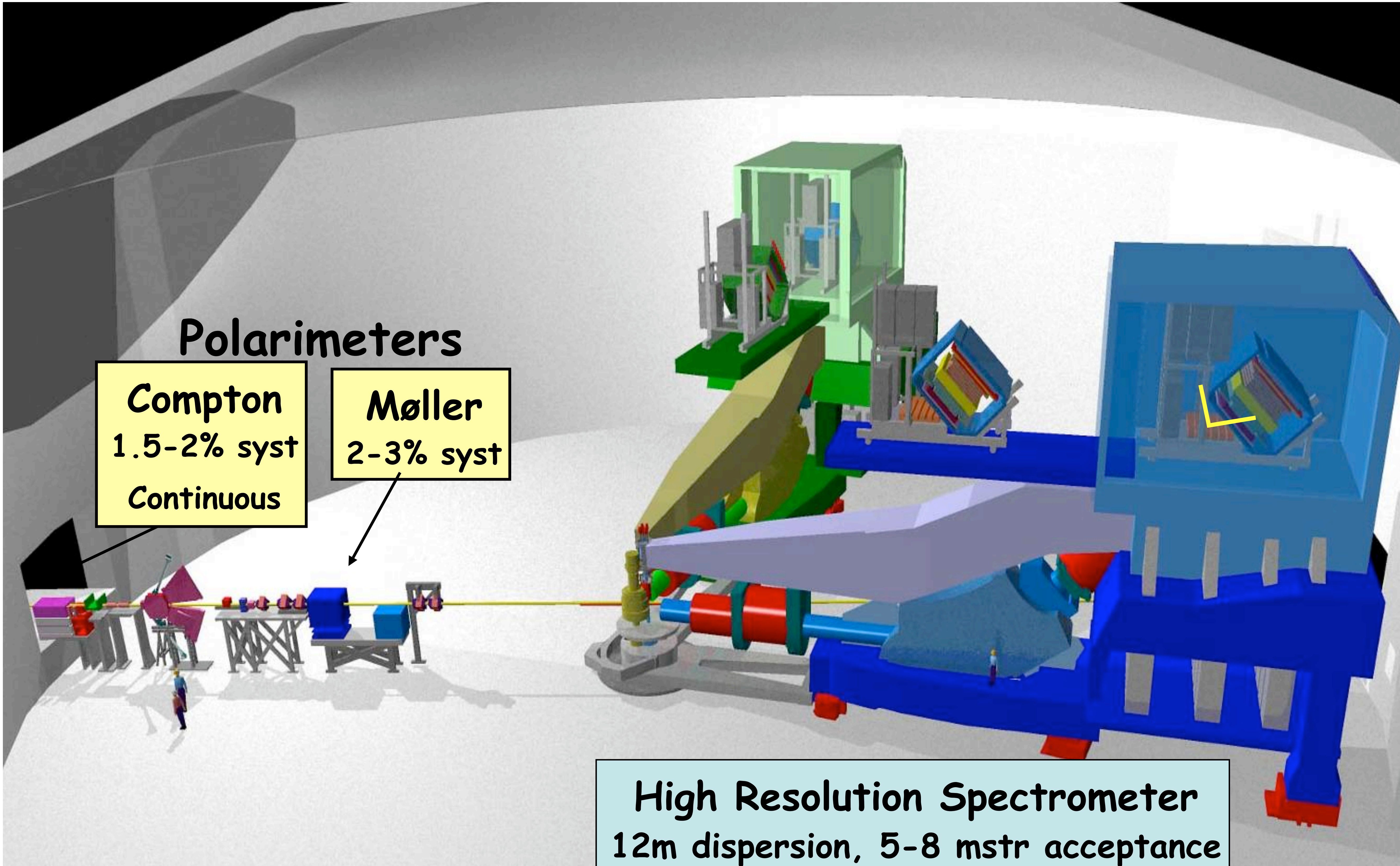
$$A^{PV} = -\frac{A_0}{2}\left(2\sin^2\theta_W + \frac{G_E^s}{G_E^{p\gamma} + G_E^{n\gamma}}\right)$$

target	A_{PV} $G^s = 0$ (ppm)	Stat. Error (ppm)
^{1}H	-1.7	8%
^{4}He	6.4	4%

High absolute precision (~100 ppb)

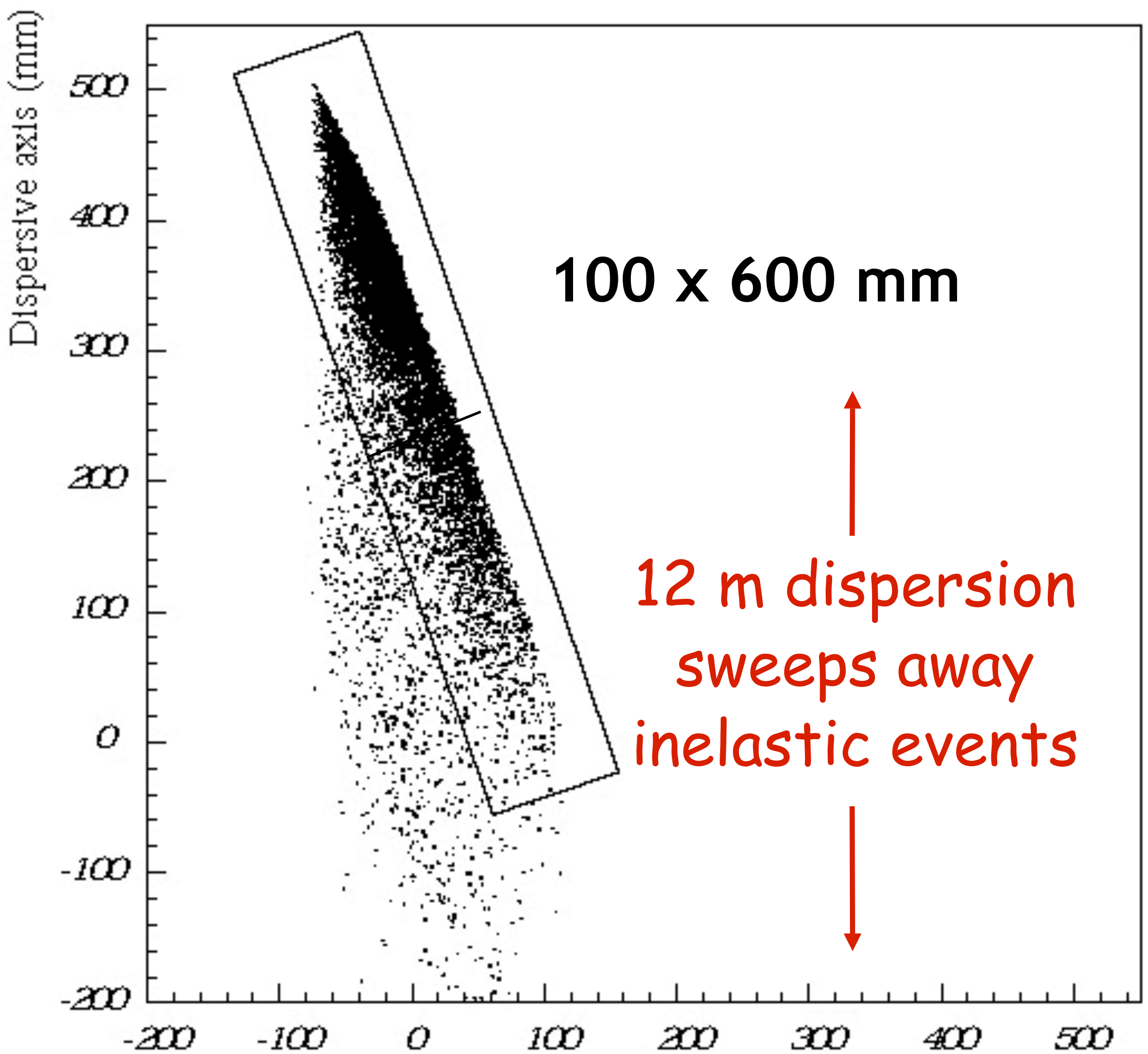
High relative precision (~4%)

Hall A

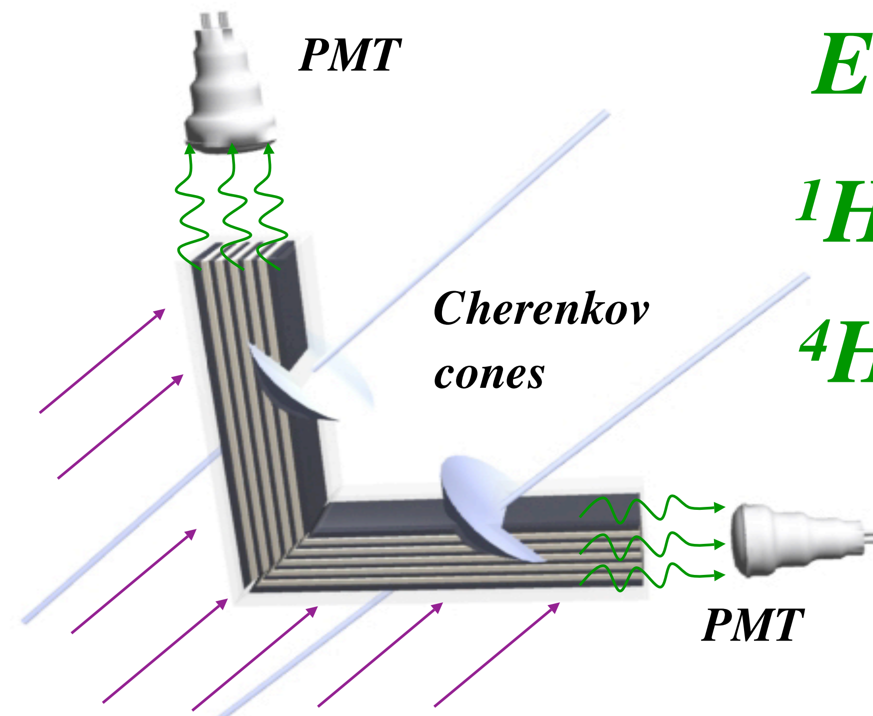

Polarimeters
Compton
1.5-2% syst
Continuous
Møller
2-3% syst
High Resolution Spectrometer
12m dispersion, 5-8 mstr acceptance

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



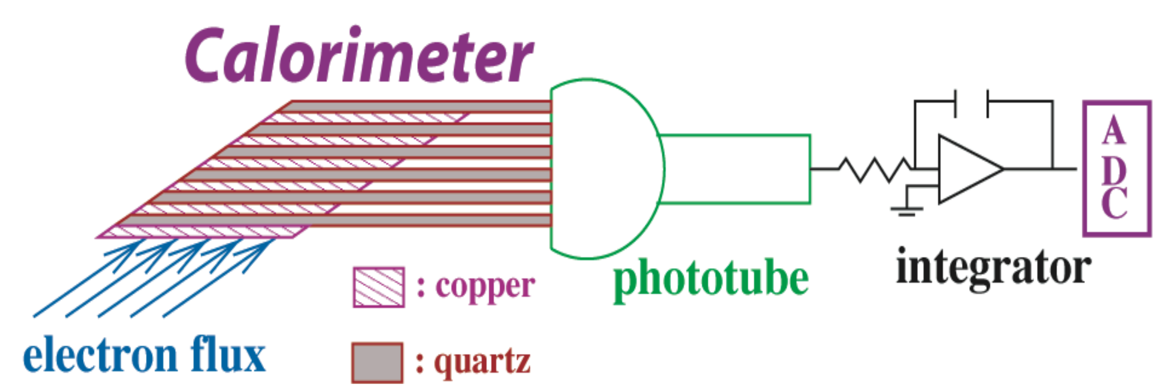
Elastic Rate:

^{1}H: 120 MHz

^{4}He: 12 MHz

Brass-Quartz Integrating Cerenkov Shower Calorimeter

- Insensitive to background
- Directional sensitivity
- High-resolution
- Rad hard

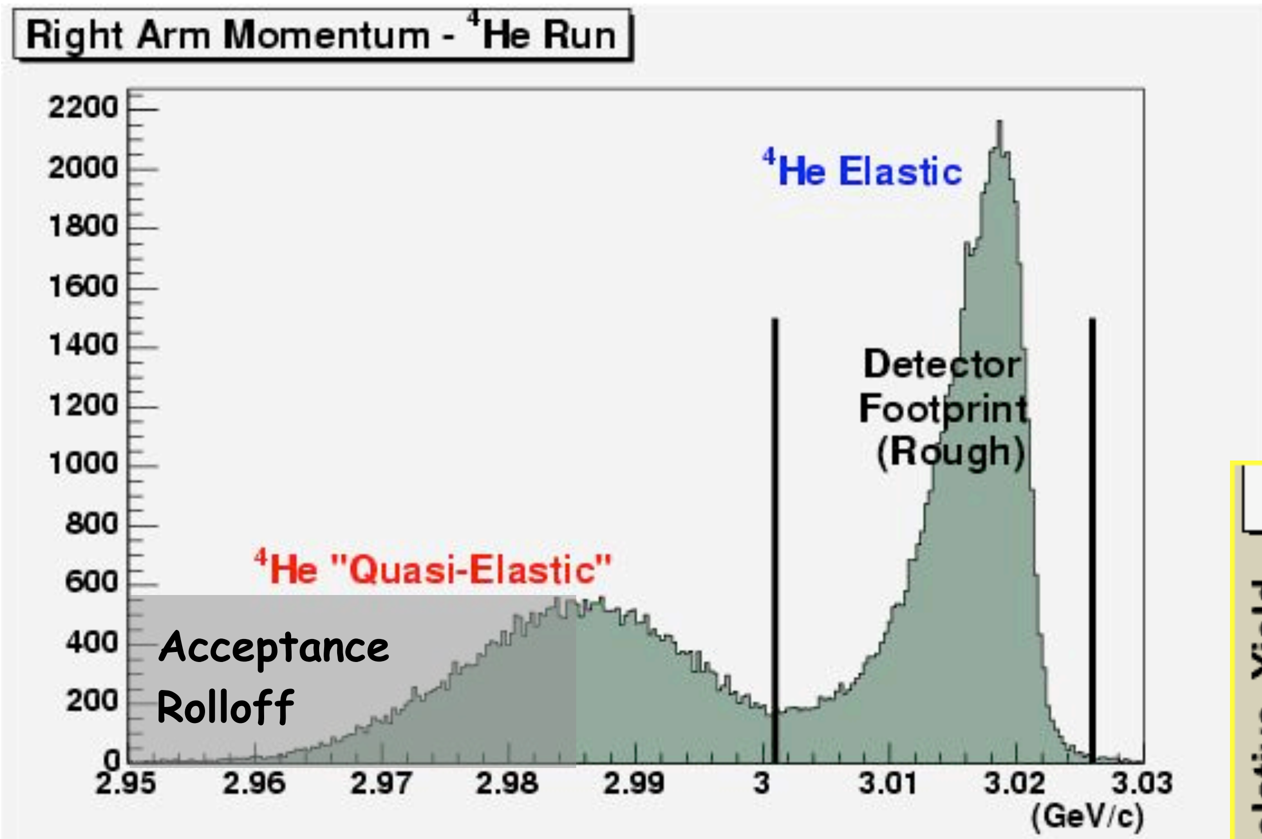


Analog integration enables very high flux detection

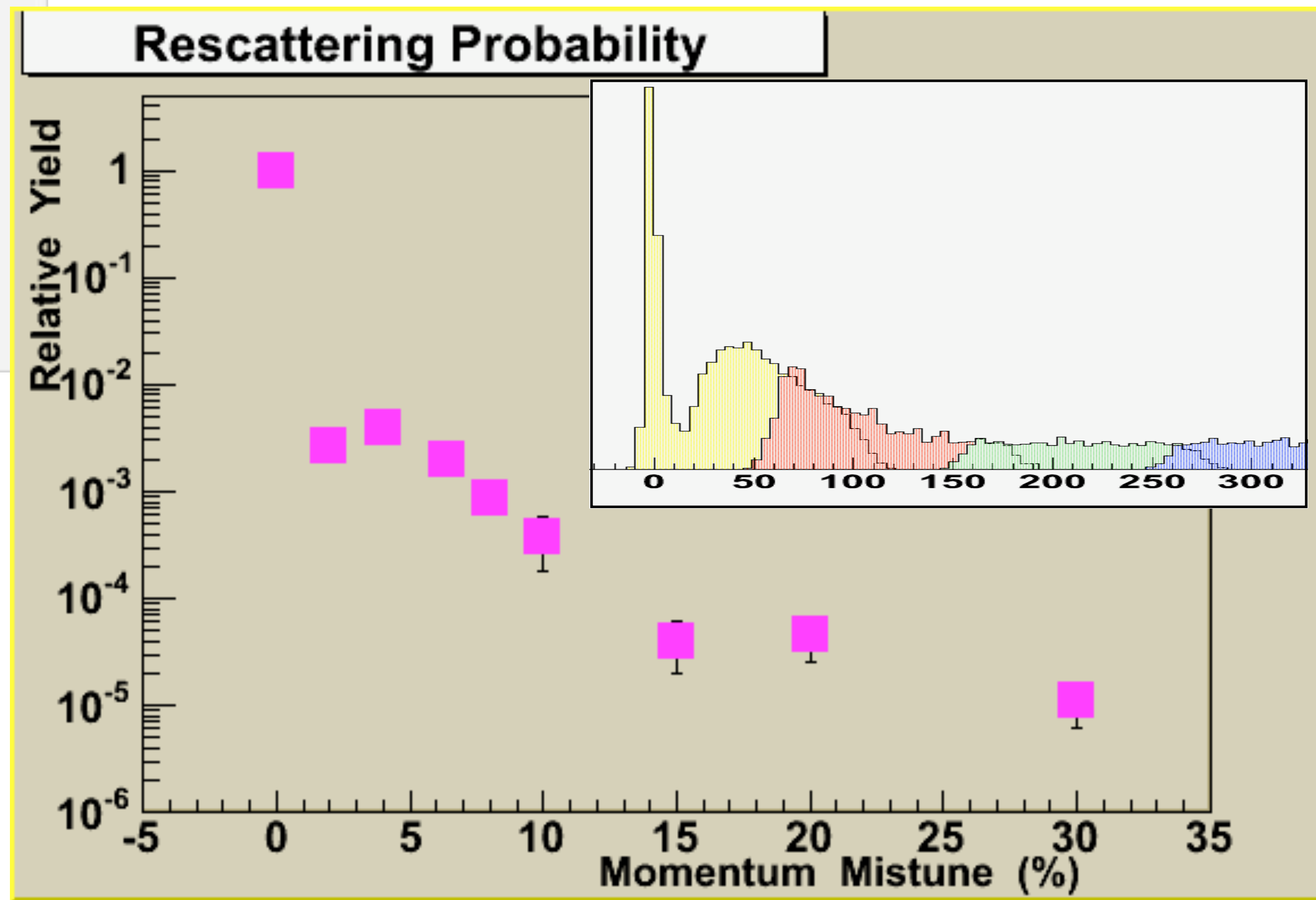
- Phototube current integrated over fixed time periods.

Background

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 +/- 25 %

Hydrogen Tail + Delta rescatter: <0.1%

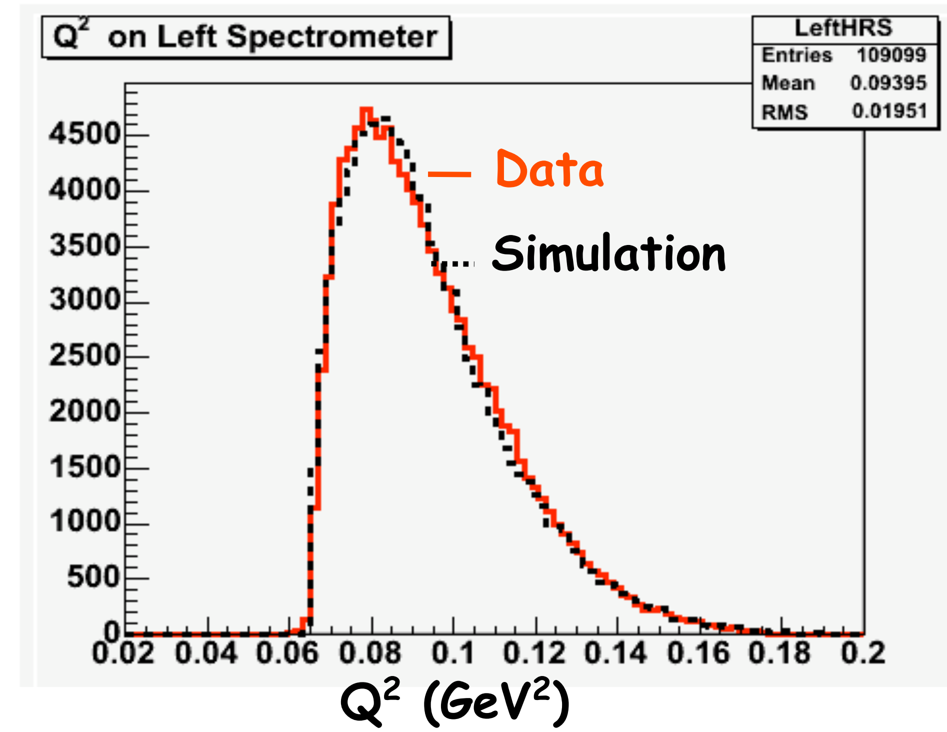
Total systematic uncertainty contribution ~40 ppb (Helium), ~15 ppb (Hydrogen)

Determining Q^2

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

Goal: $\delta Q^2 < 1.0\%$

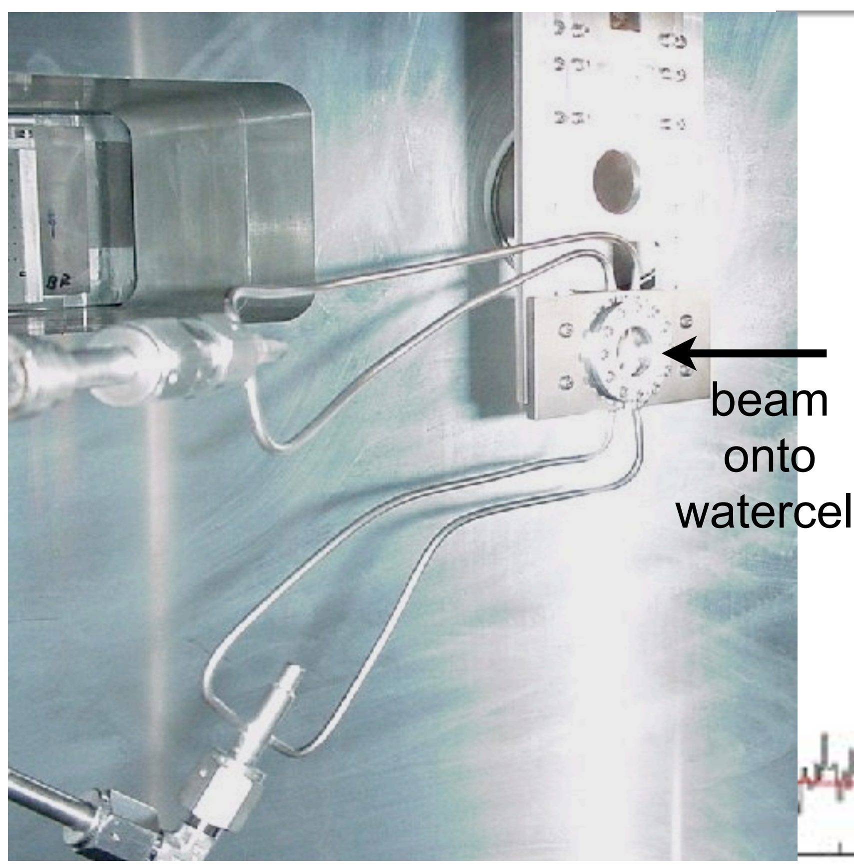
- **Central scattering angle must be measured to $\delta\theta < 0.5\%$**
- **Asymmetry distribution must be averaged over finite acceptance (uncertainty evaluated with simulation)**

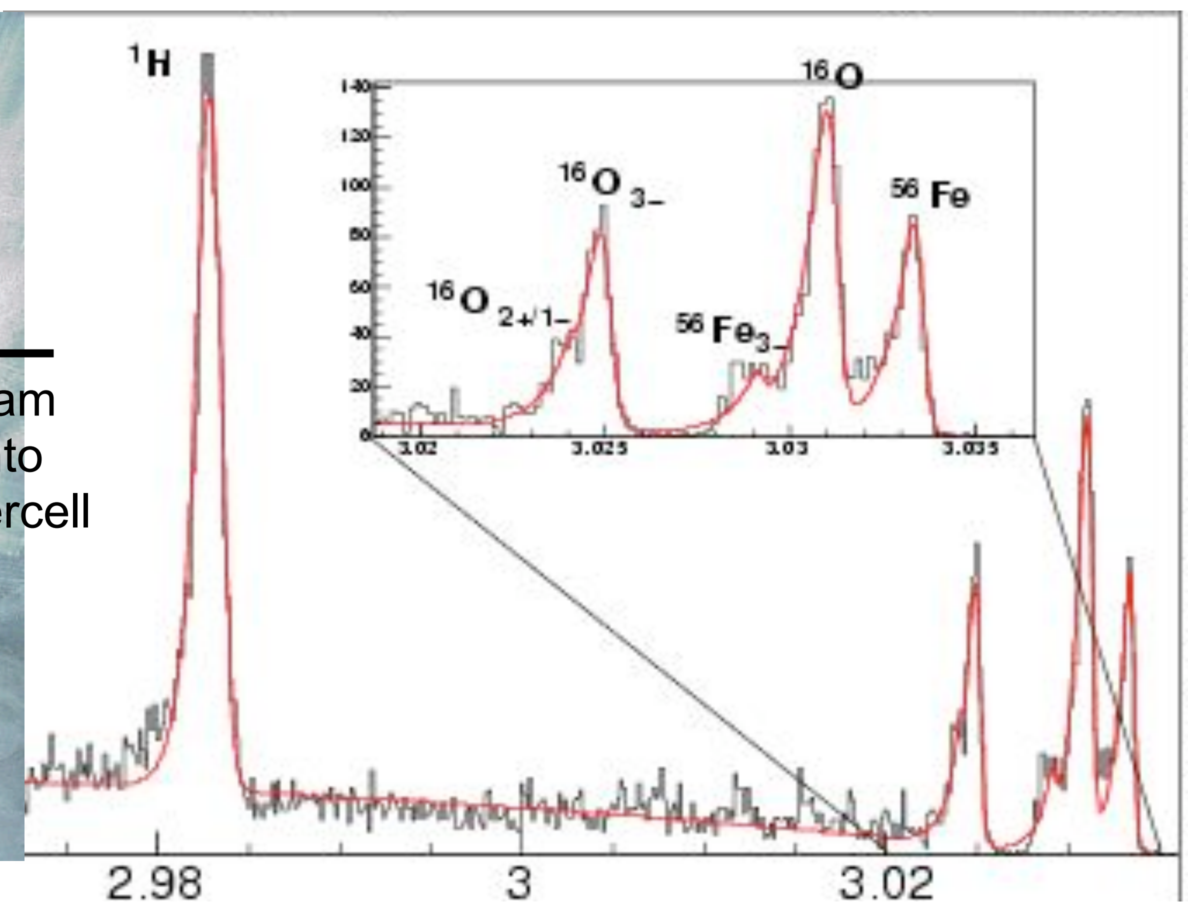


Novel Water cell optics target for central angle

- **δp between elastic and excited state peaks reduces systematic error from spectrometer calibration**
- **$\delta\theta$ ~ 0.3%**

  -> δQ^2 ~ 0.7%



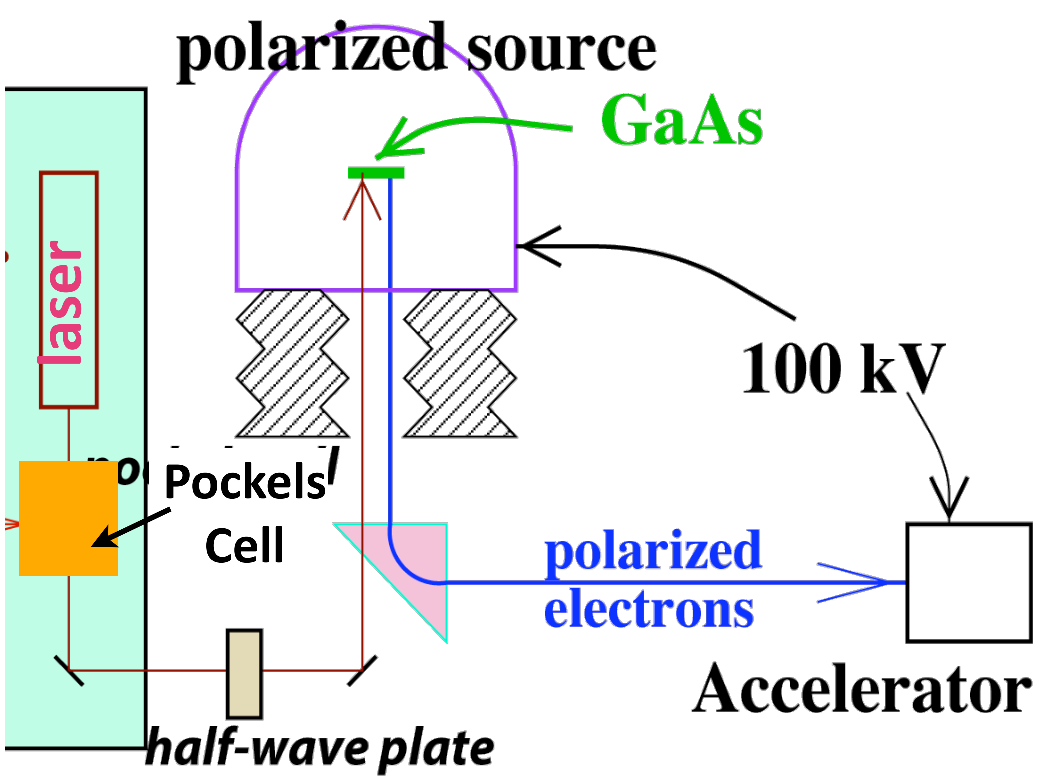


Helcity-Correlated Beam Asymmetries

$$A_{raw} = A_{det} - A_Q + \alpha\Delta_E + \Sigma\beta_i\Delta x_i$$

Sensitivity of flux measurement to changes in beam trajectory or energy are measured, to correct for helicity-correlated trajectory/energy changes

Corrections must be kept small!



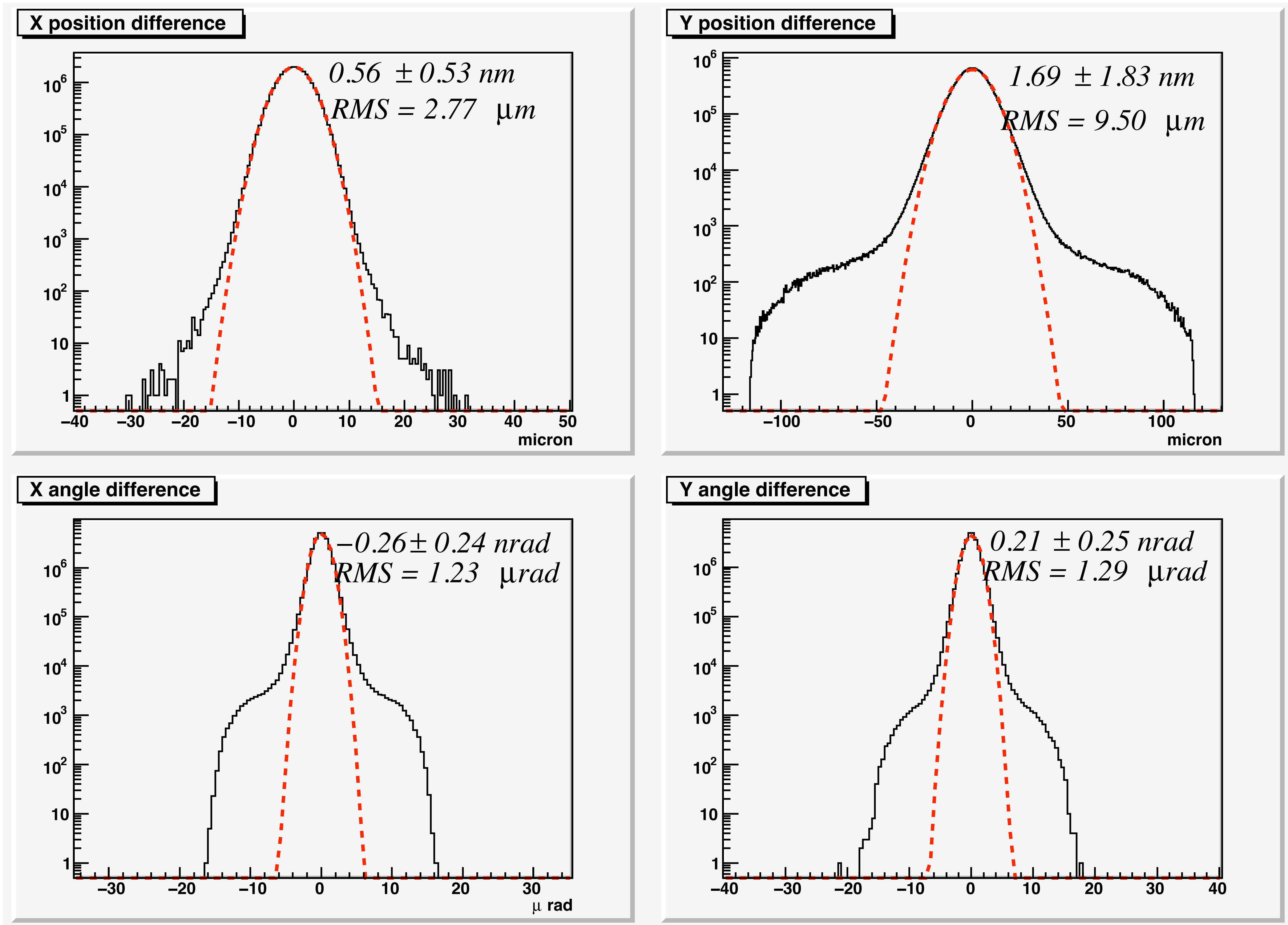
- Electrons are created in polarized source through spin-selective photoemission from a semiconductor. **The uniformity of laser polarization between the two helicity states is critical**

- At design electron transport optics, the e- beam phase space stays smooth, with minimal projections to large positions. **The beam transport optics must be carefully tuned to avoid blowing up small helicity-correlated differences.**

Close collaboration between the experimenters and beam physicists and a vigorous R&D program on the laser optics led to unprecedented success

Helicity Correlated Position Differences

Over the ~20 million pairs measured in HAPPEX-II, the average position was not different between the two helicity states by more than 1 nanometer

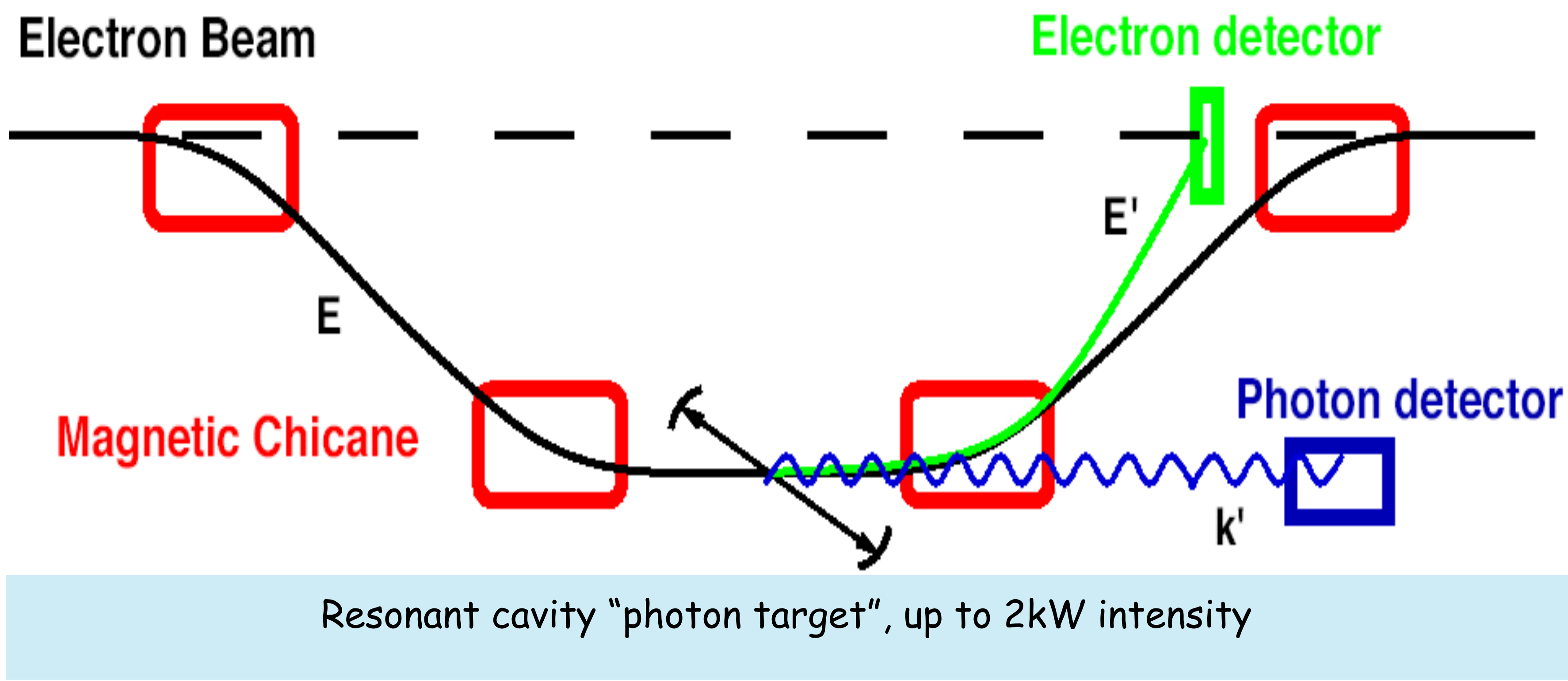


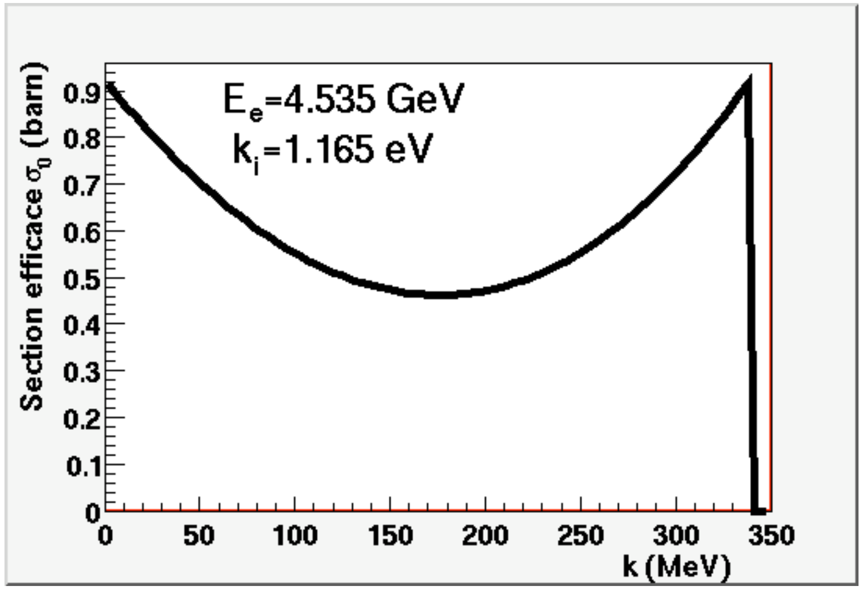
This was still the leading source of systematic uncertainty in the proton asymmetry

Hall A Compton Polarimeter

$$A_{\exp} = \frac{n^+ - n^-}{n^+ + n^-} = P_\gamma \times P_e \times < A_{th} >$$

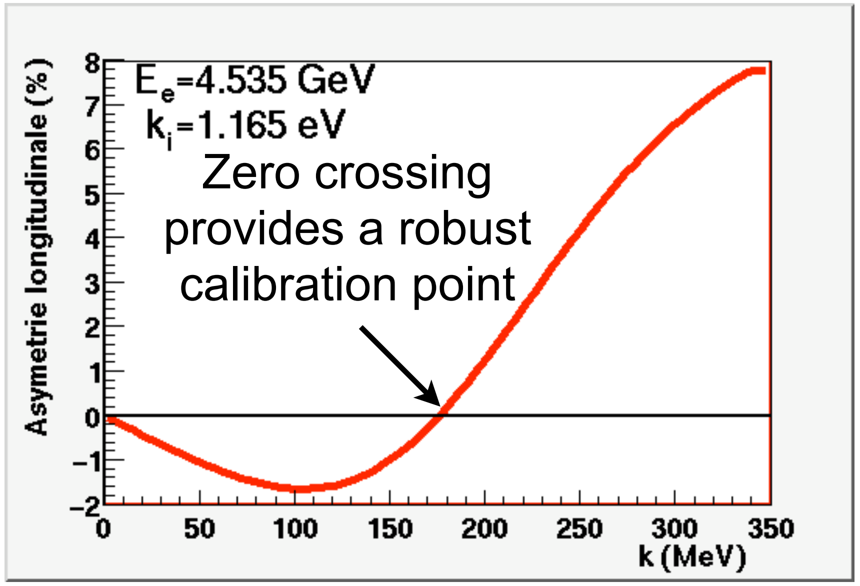
Limiting uncertainty due to calibration of analyzing power





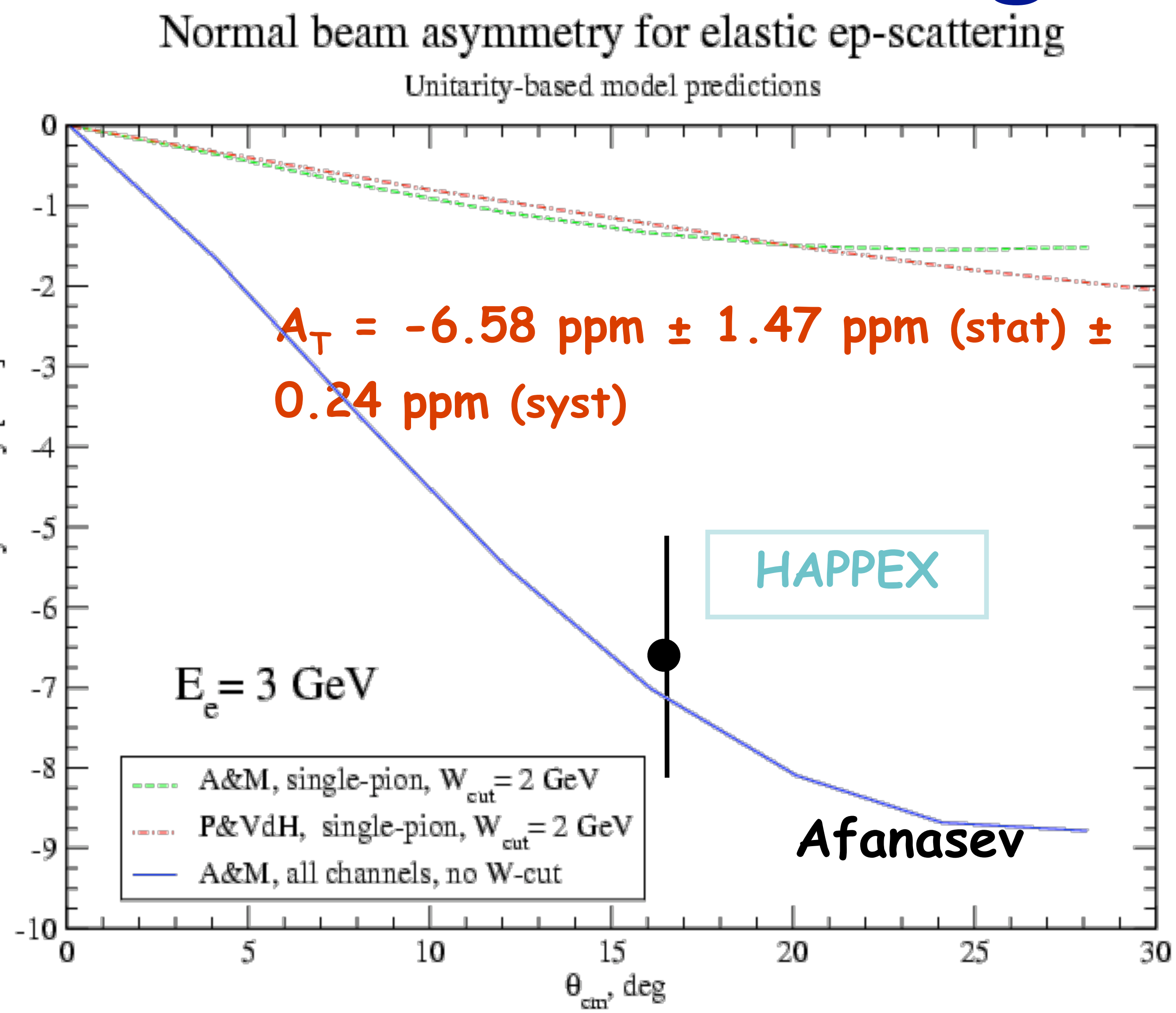
measure asymmetry independently in:

- momentum analyzed electrons
- photons in calorimeter



- Requires 10^{-10} halo at 5mm from primary beam
- Best precision now ~1.5% at E_b~3 GeV (harder at low E_b)
- 1% is within reach

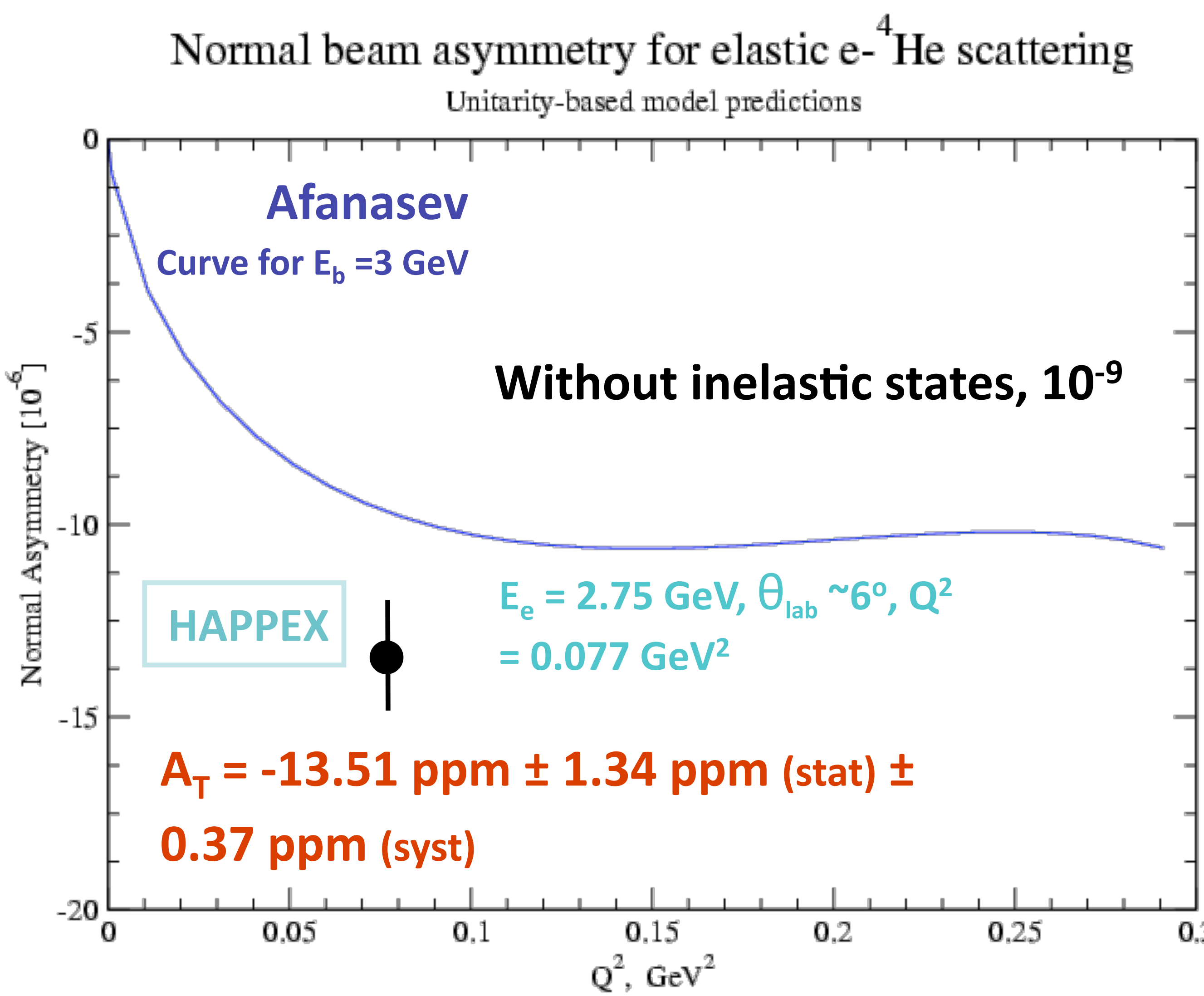
Transverse Single-Spin Asymmetry A_T



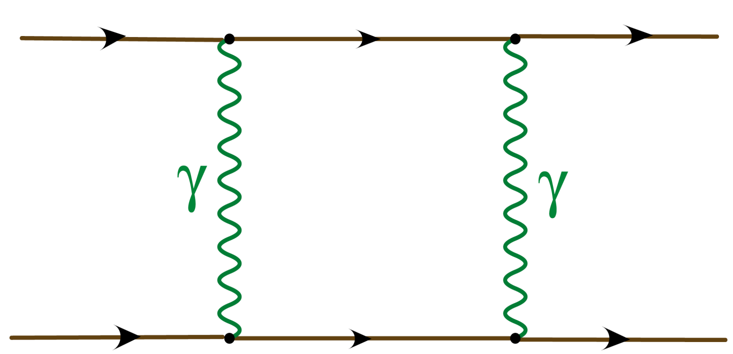
Beam normal single-spin asymmetry in elastic electron scattering

$$A_T \propto \vec{S}_e \cdot (\vec{k}_e \times \vec{k}'_e)$$

Potential systematic error in A_{PV} if imperfect cancellation over acceptance



Clear signal from 2-photon exchange processes, dominated by excited intermediary states



HAPPEX-II 2005 Results

HAPPEX-^{4}He:

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

$$A_{PV} = +6.40 \pm 0.23\ (stat) \pm 0.12\ (syst)\ ppm$$

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

$$G^s_E = 0.002 \pm 0.014_{(stat)} \pm 0.013_{(syst)}$$

HAPPEX-H:

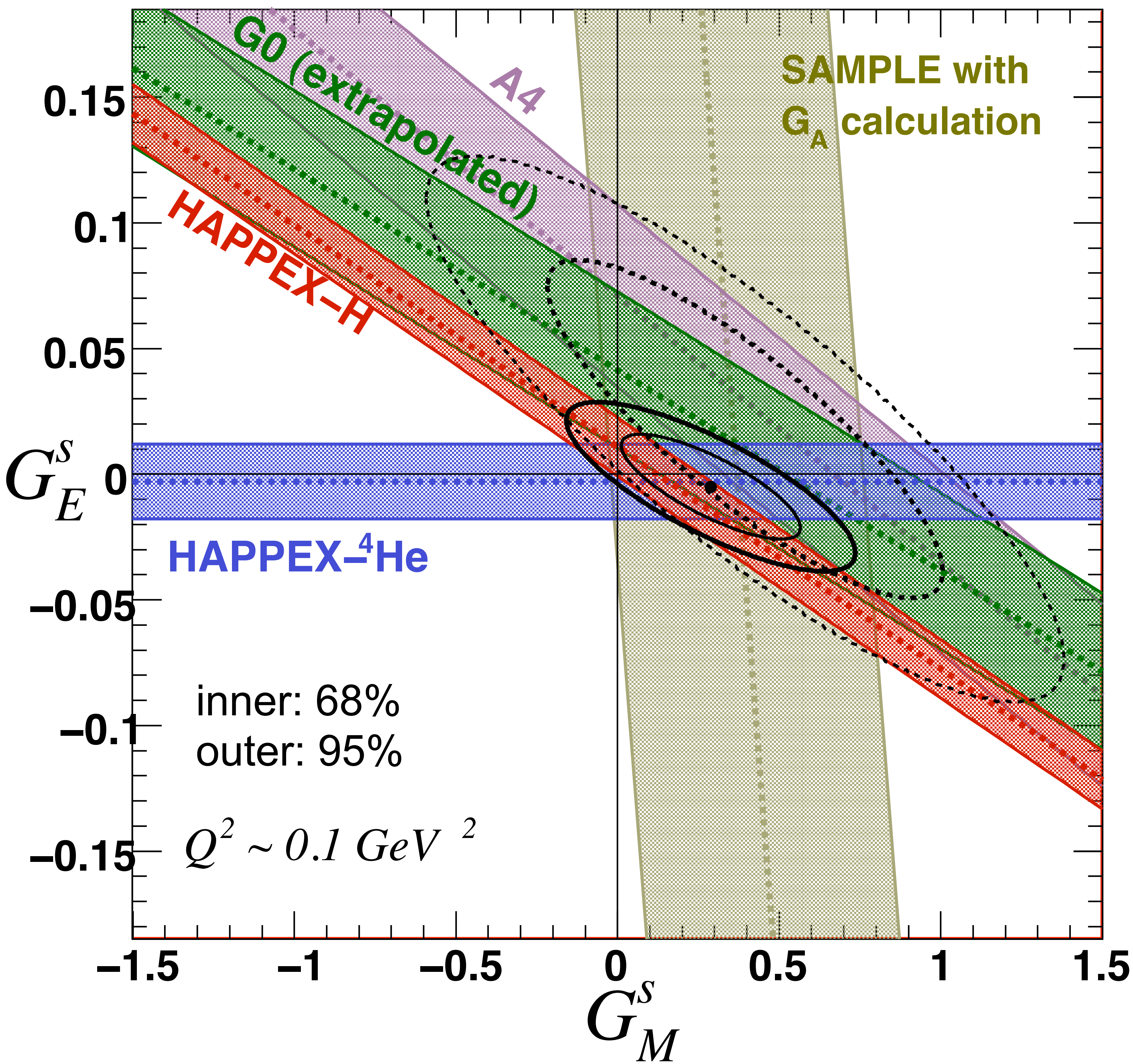
$$Q^2 = 0.1089 \pm 0.0011\ (GeV/c)^2$$

$$A_{PV} = -1.58 \pm 0.12\ (stat) \pm 0.04\ (syst)\ ppm$$

$$A(G^s=0) = -1.66\ ppm \pm 0.05\ ppm$$

$$G^s_E + 0.09\ G^s_M = 0.007 \pm 0.011_{(stat)} \pm 0.004_{(syst)} \pm 0.005_{(FF)}$$

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

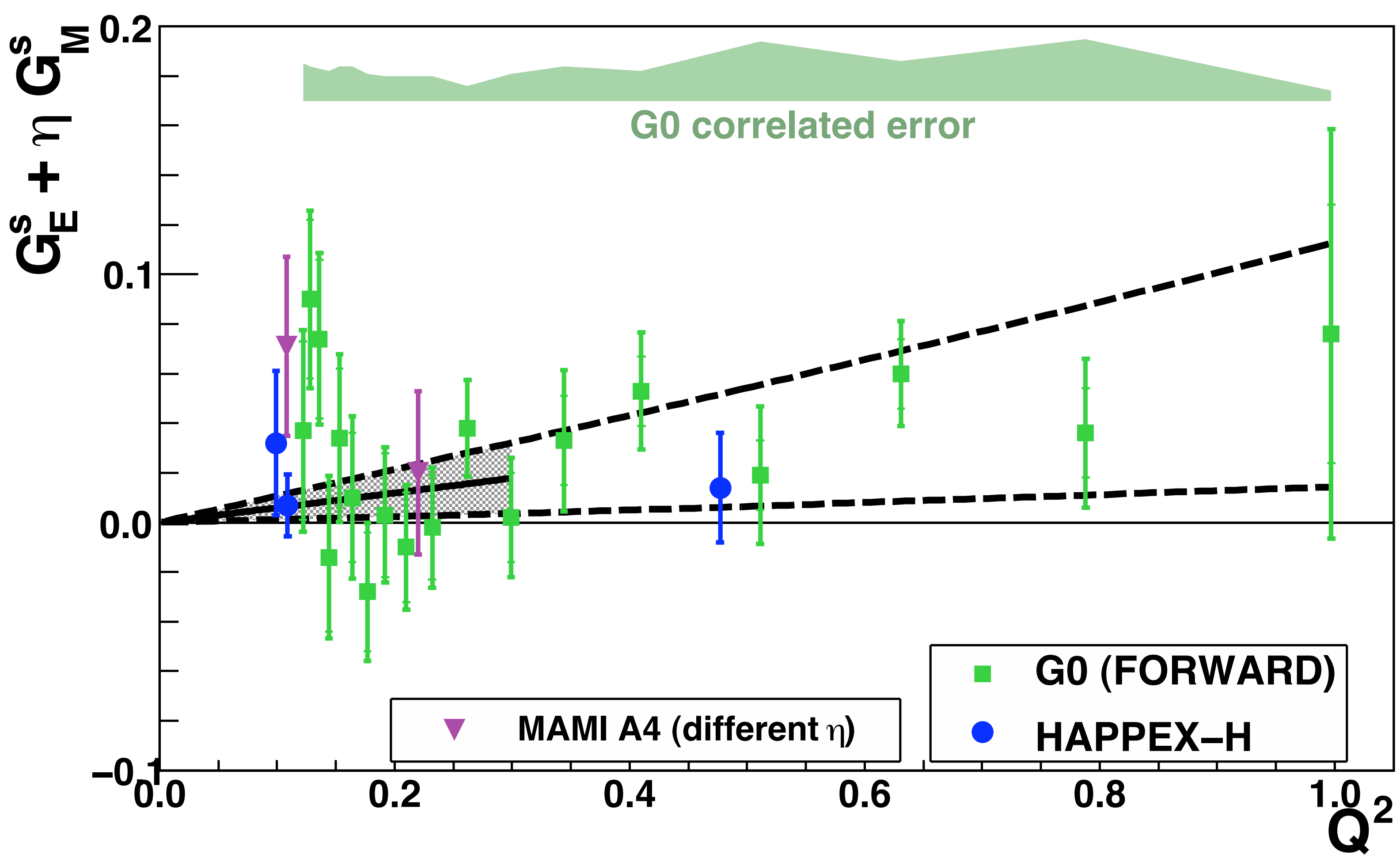
HAPPEX-only fit suggests something even smaller:

G_M^s = 0.18 +/- 0.27

G_E^s = -0.005 +/- 0.019

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

World Data vs. Q^2



Simple fit:

$G_E^s = \rho_s * \tau$

$G_M^s = \mu_s$

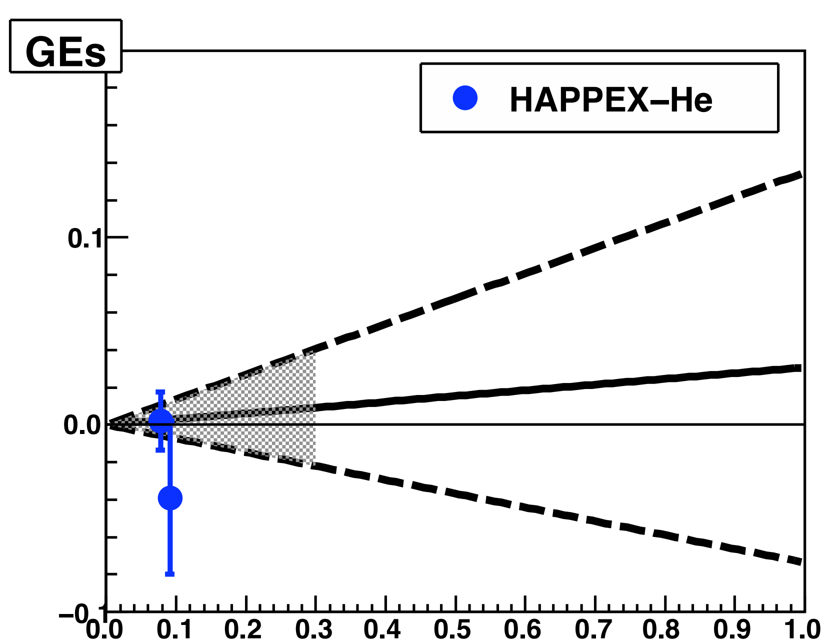
Includes only data $Q^2 < 0.3$ GeV^2

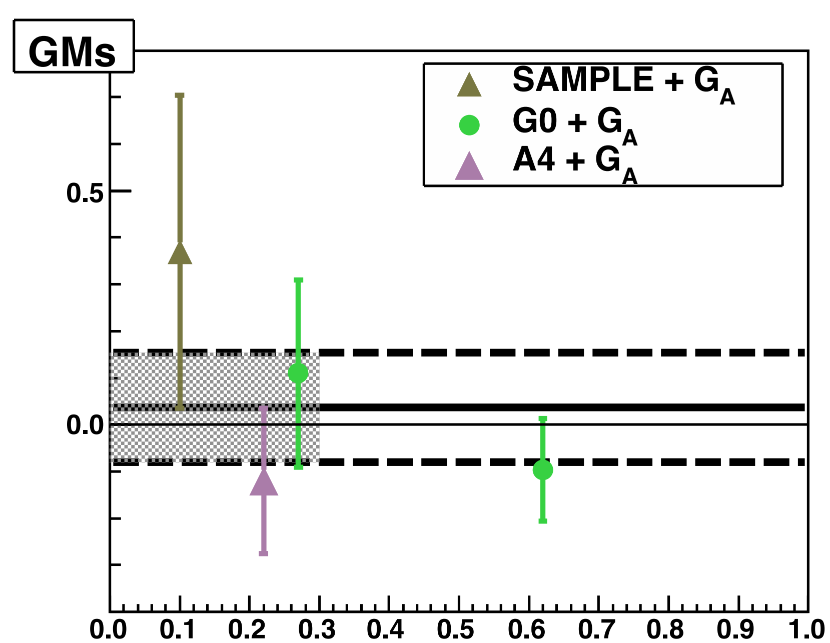
Includes backangle results as constraint on G_M^s only.

G0 Backangle is best guess, picked from plots

G0 Global error allowed to float with unit constraint

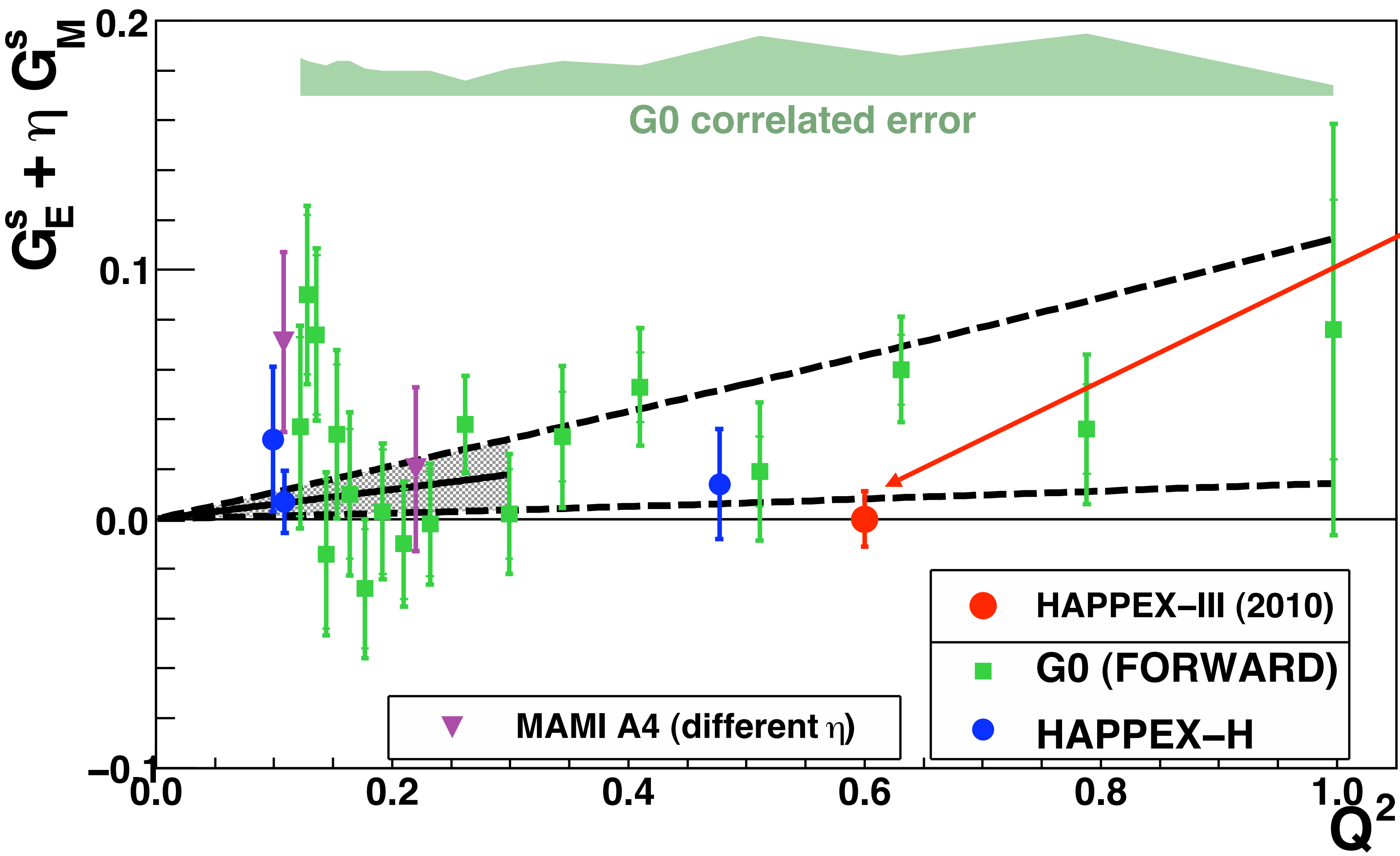
Nothing intelligent done with form factors, correlated errors, etc.





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

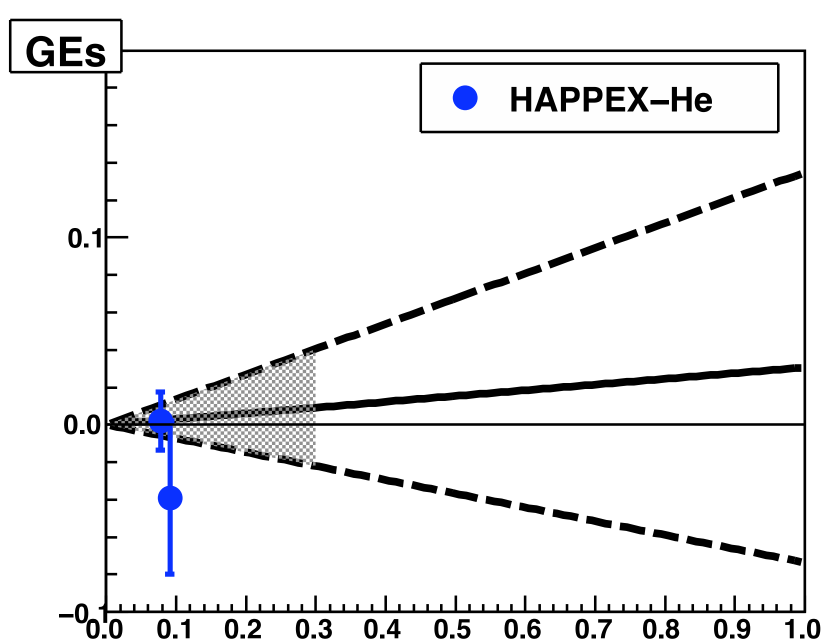
HAPPEX-III

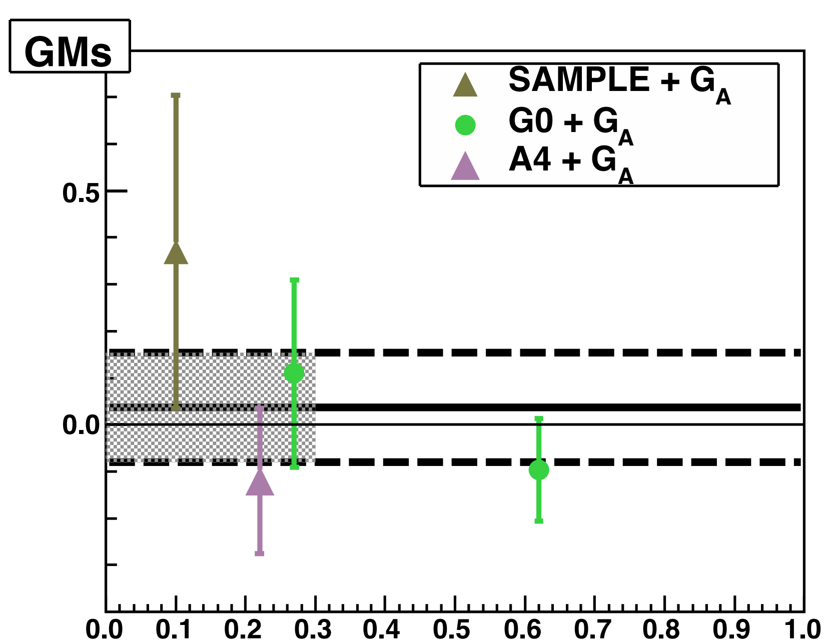


HAPPEX-III (running 2009)

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

World data suggests central value 4σ from zero





Outline of HAPPEX-III

Improvements since HAPPEX-I

- P^2L (statistical power): HAPPEX-I had 100 μA and 38% polarization, or 35 μA and 71% pol
  - Now high current at 80% polarization is routine.
  - Target 15cm -> 25 cm
- Precision polarimetry: HAPPEX-I: $\delta(P_{beam}) = 3.2\%$
  - $\delta(P_{beam}) = 1\%$
- Q^2 determination: HAPPEX-I: $\delta(Q^2) = 1.2\%$
  - Nuclear Recoil method: $\delta(Q^2) = 0.5\%$

A_{PV} (assuming no strange vector FF) at $Q^2 = 0.62$ GeV^2 :

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

Anticipated results:

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

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

Precision at the level of interpretability:

Anapole correction: $\delta A = 0.33$ ppm, EMFF (mostly G_M^n) $\delta A \sim 0.53$ ppm

Two photon effects (through EMFF), CSV may be comparable

HAPPEX-III 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

Interpretation Issues

PROTON

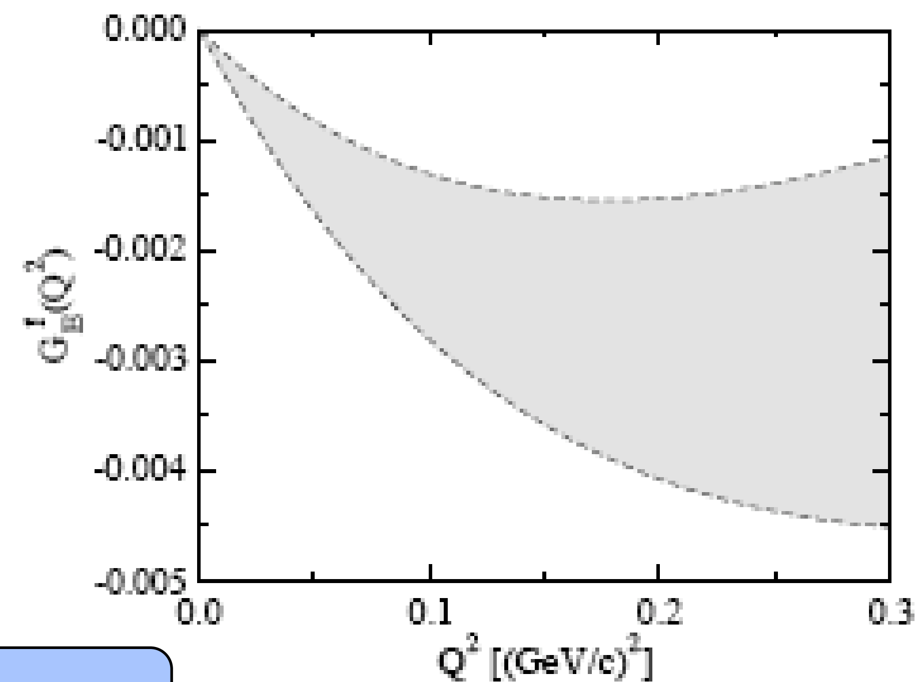
Old Story: theoretical CSB estimates indicate <1% violations

Miller PRC **57**, 1492 (1998)

Lewis & Mobed, PRD **59**, 073002(1999)

New Story: effects could be large as statistical error on HAPPEx data!

χPBT, B. Kubis & R. Lewis   Phys. Rev. C **74** (2006) 015204



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

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

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

Helium-4

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

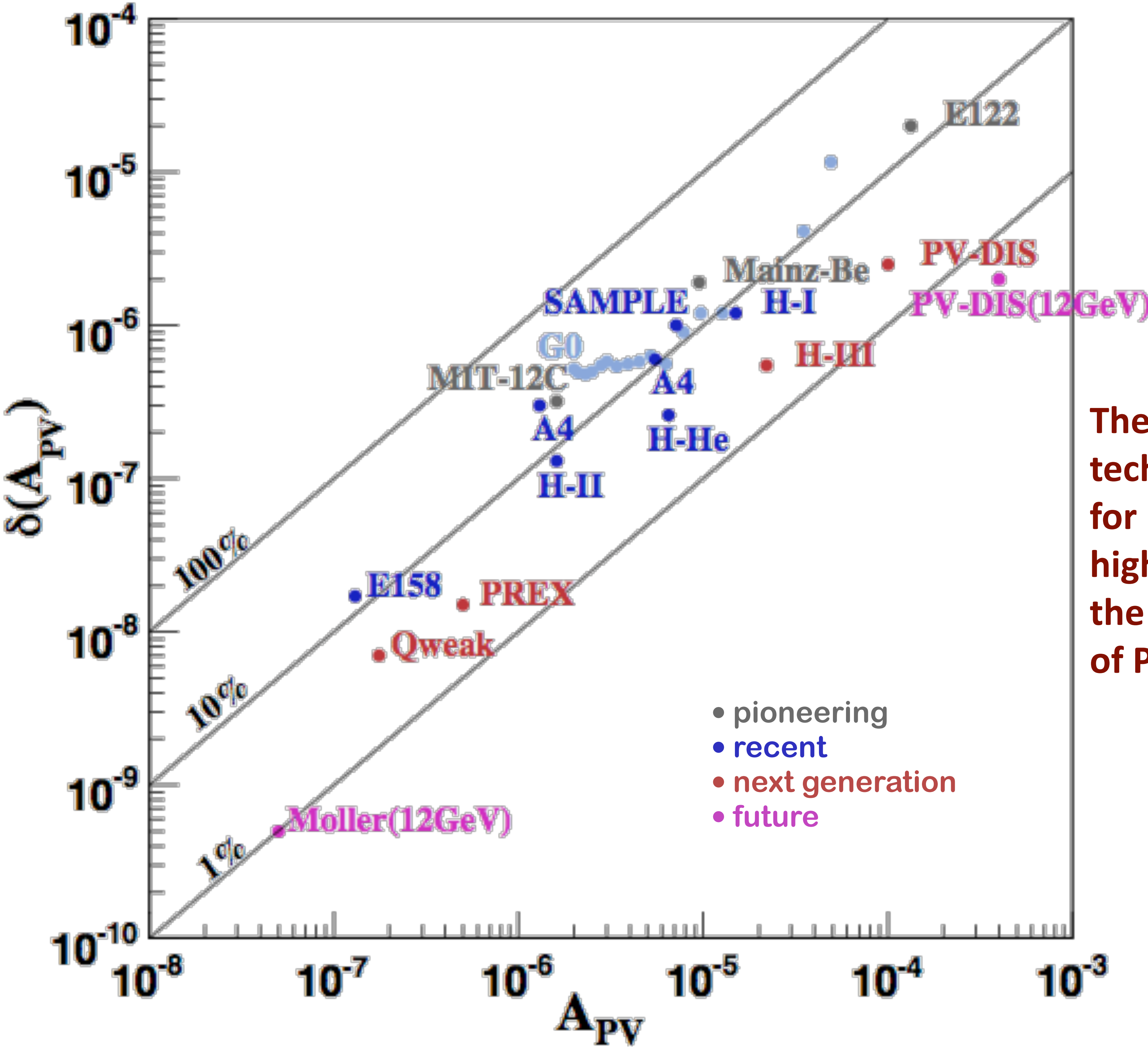
New Story: Nuclear admixture + nucleon CSB ~ 1% ... about 1/4 HAPPEX-He error bar

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

$$\Gamma \equiv -2\frac{F^{(1)}(q)}{F^{(0)}(q)} - \frac{4G_E^{u/d}}{\left(G_E^p + G_E^n\right)} + \frac{2G_E^s}{\left(G_E^p + G_E^n\right)} = 0.006 \pm 0.037$$

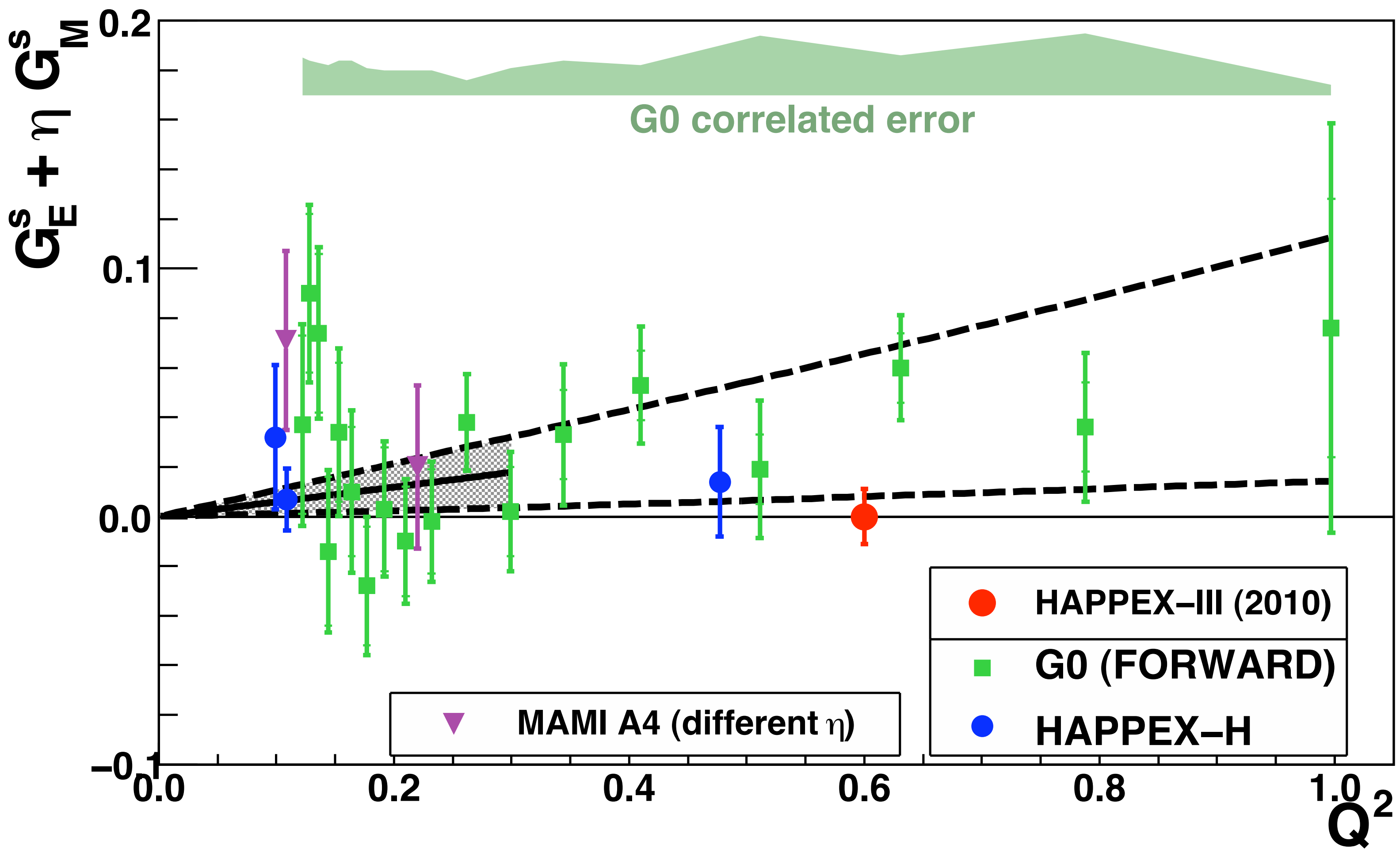
~0.001-0.002   0.008 ± 0.003

PVeS is now a precision tool at JLab

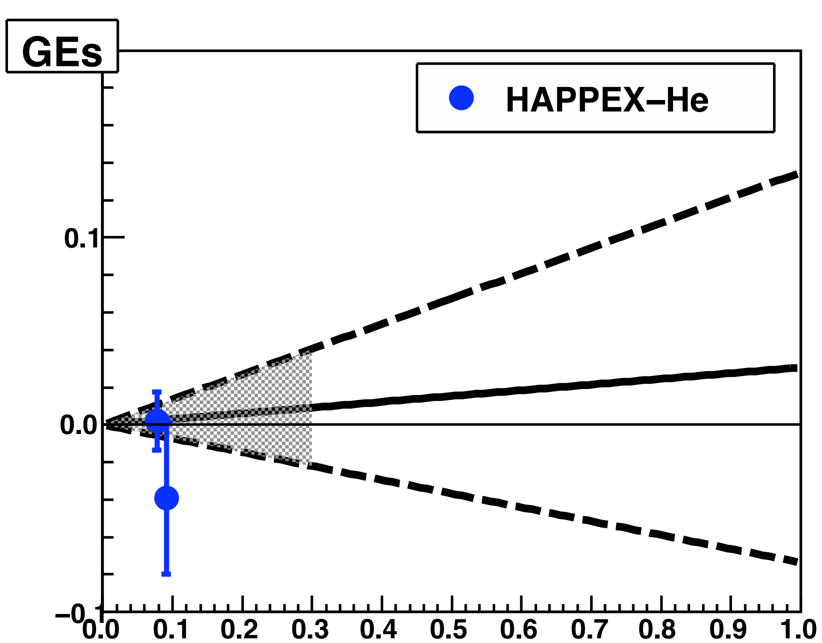


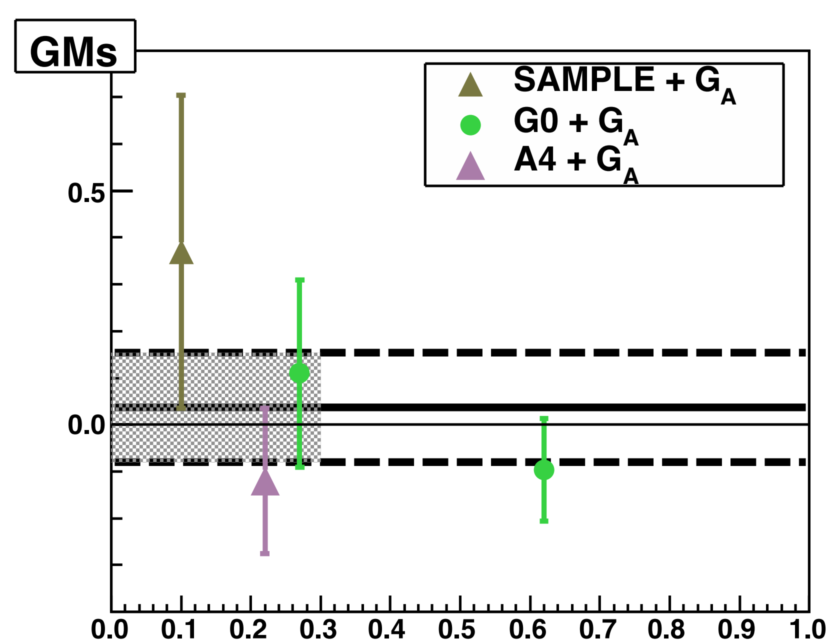
The HAPPEX program has driven technical developments essential for high relative precision and high absolute precision, setting the stage for the next generation of PVeS experiments

Summary



- Significant and accessible contributions are still allowed.
- Precision data at middle Q^2 can finish the question of large contributions to the vector form-factors





Further improvements in precision would require additional theoretical and empirical input for interpretation

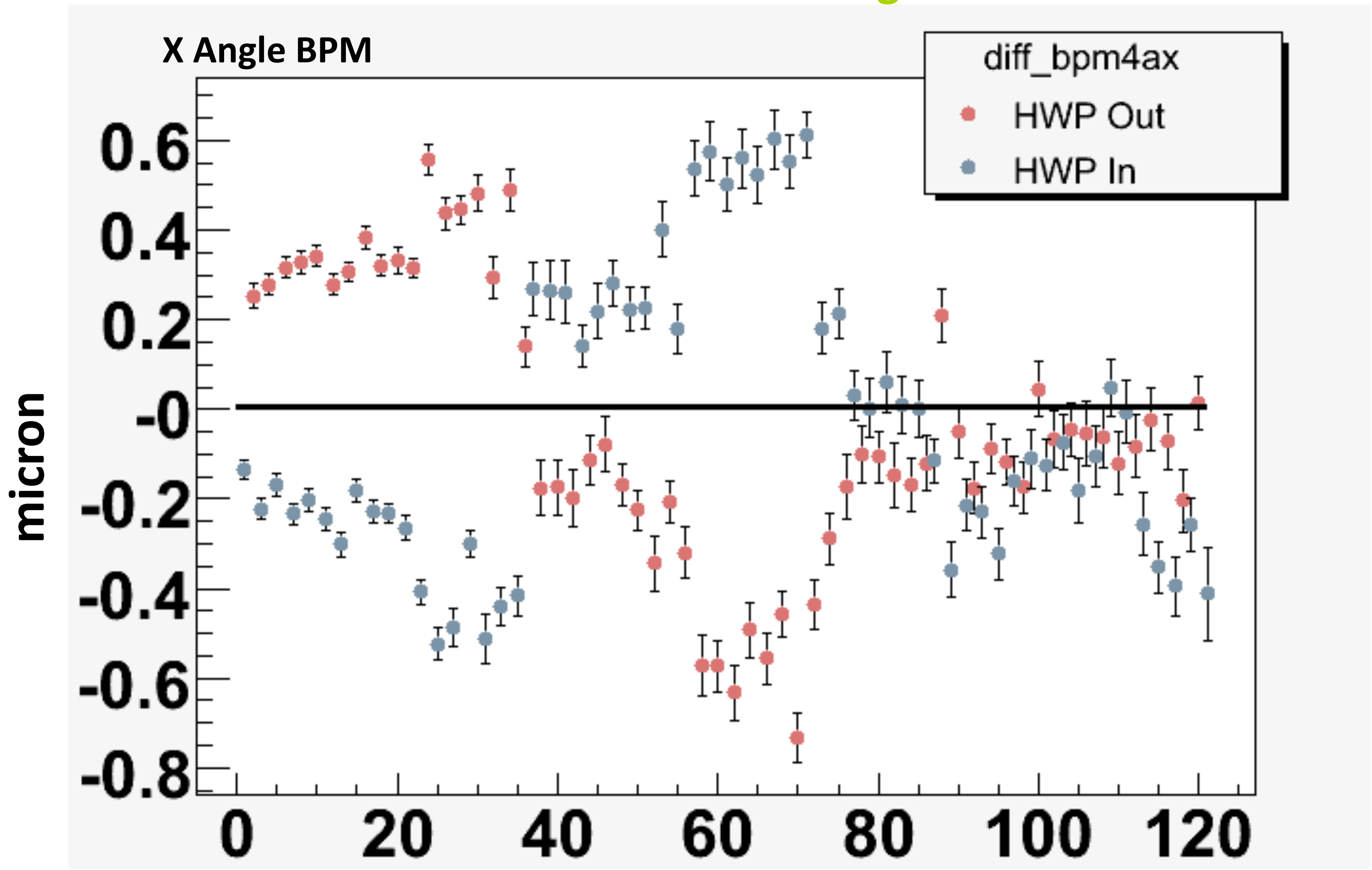
Charge Symmetry Breaking: effects in proton could be large as statistical error on high-precision HAPPEx data, and not well constrained at higher Q^2

EMFF uncertainties: (including 2γ) limit to few percent precision

Anapole term: ultimately limit backangle precision on G_M^s

Beam Position Differences, Helium 2005

Position difference goal: 3 nanometers!



Problem: Helicity signal deflecting the beam through electronics “pickup”

Large beam deflections even when Pockels cell is off

Beam Position Differences, Helium 2005

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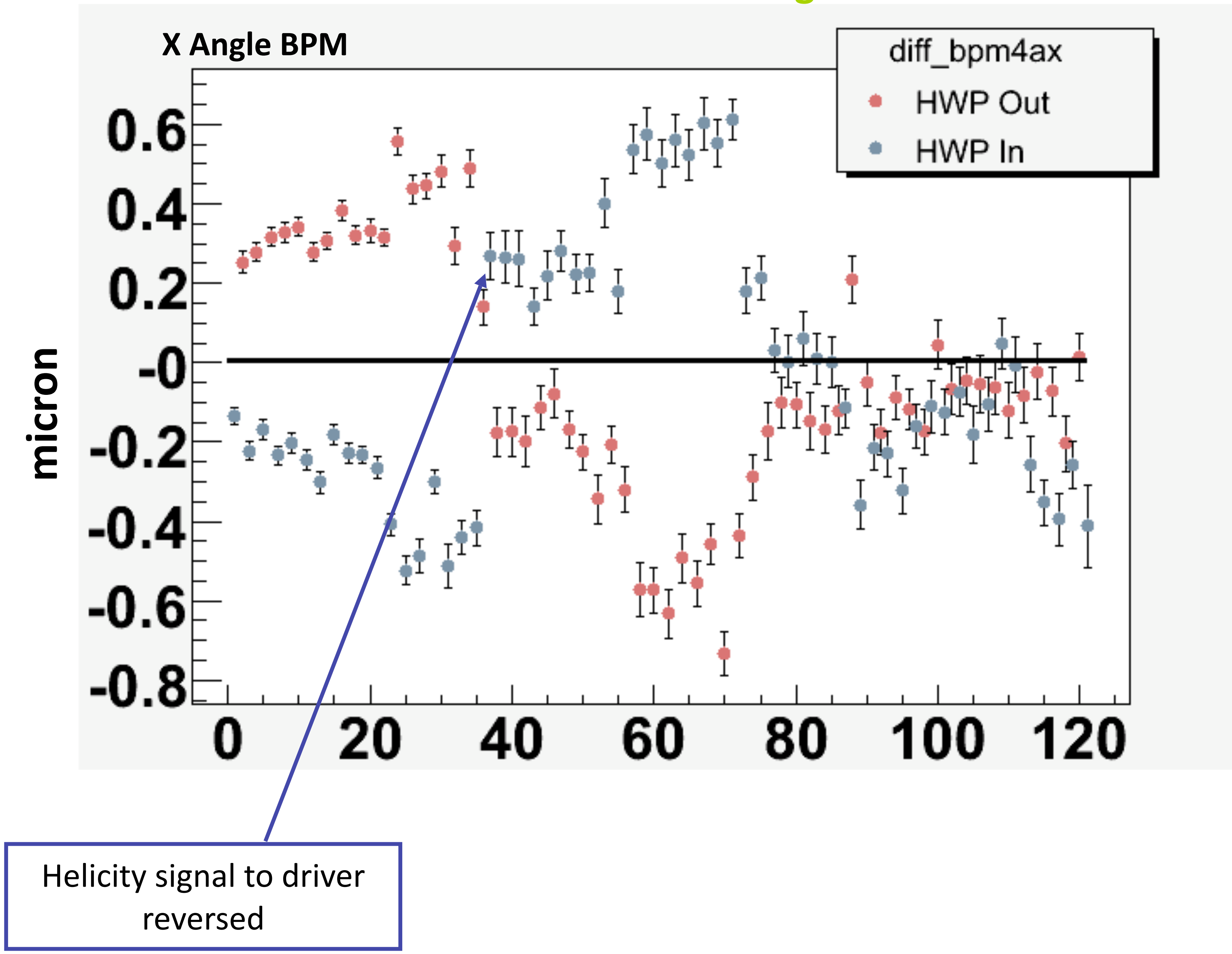

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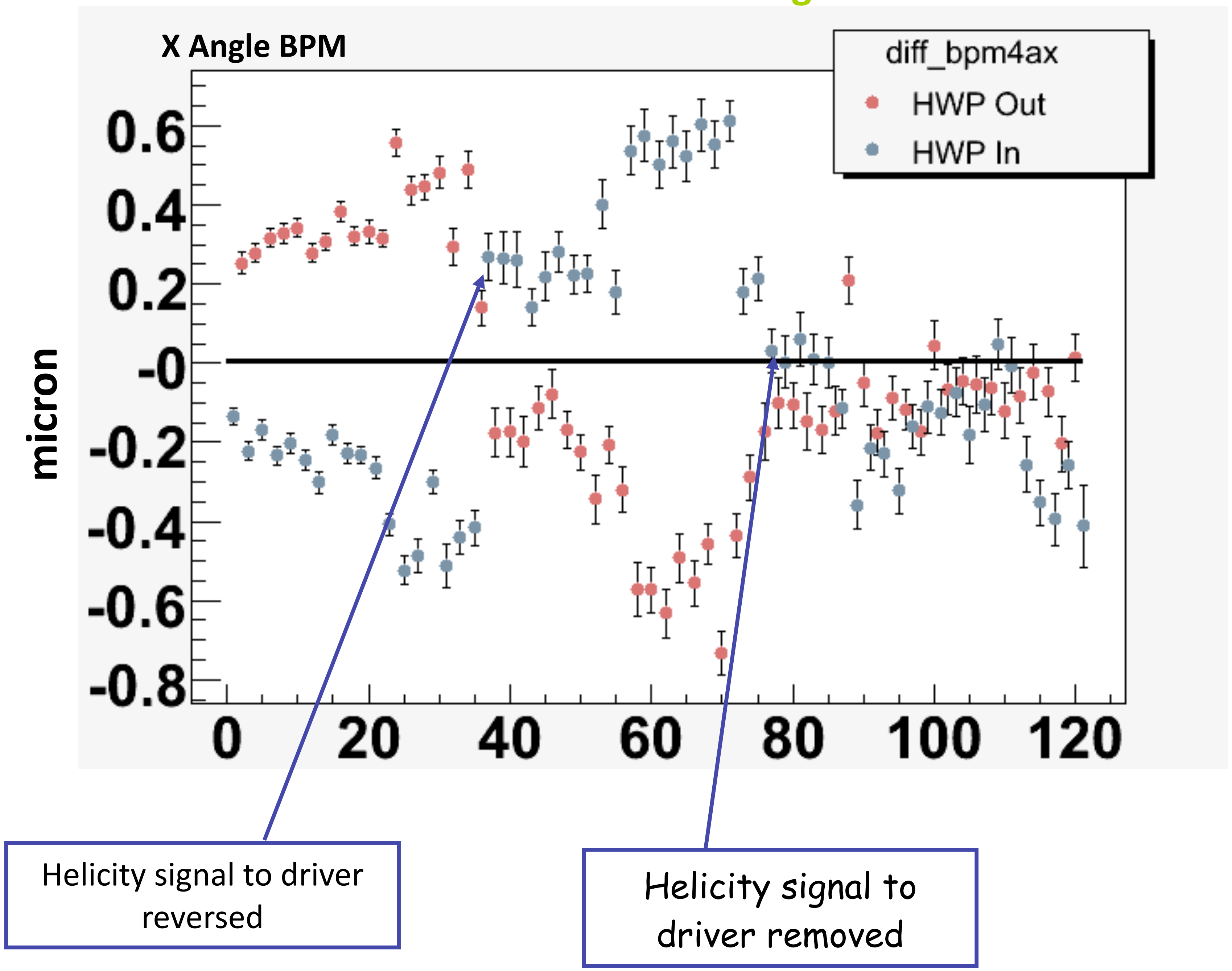

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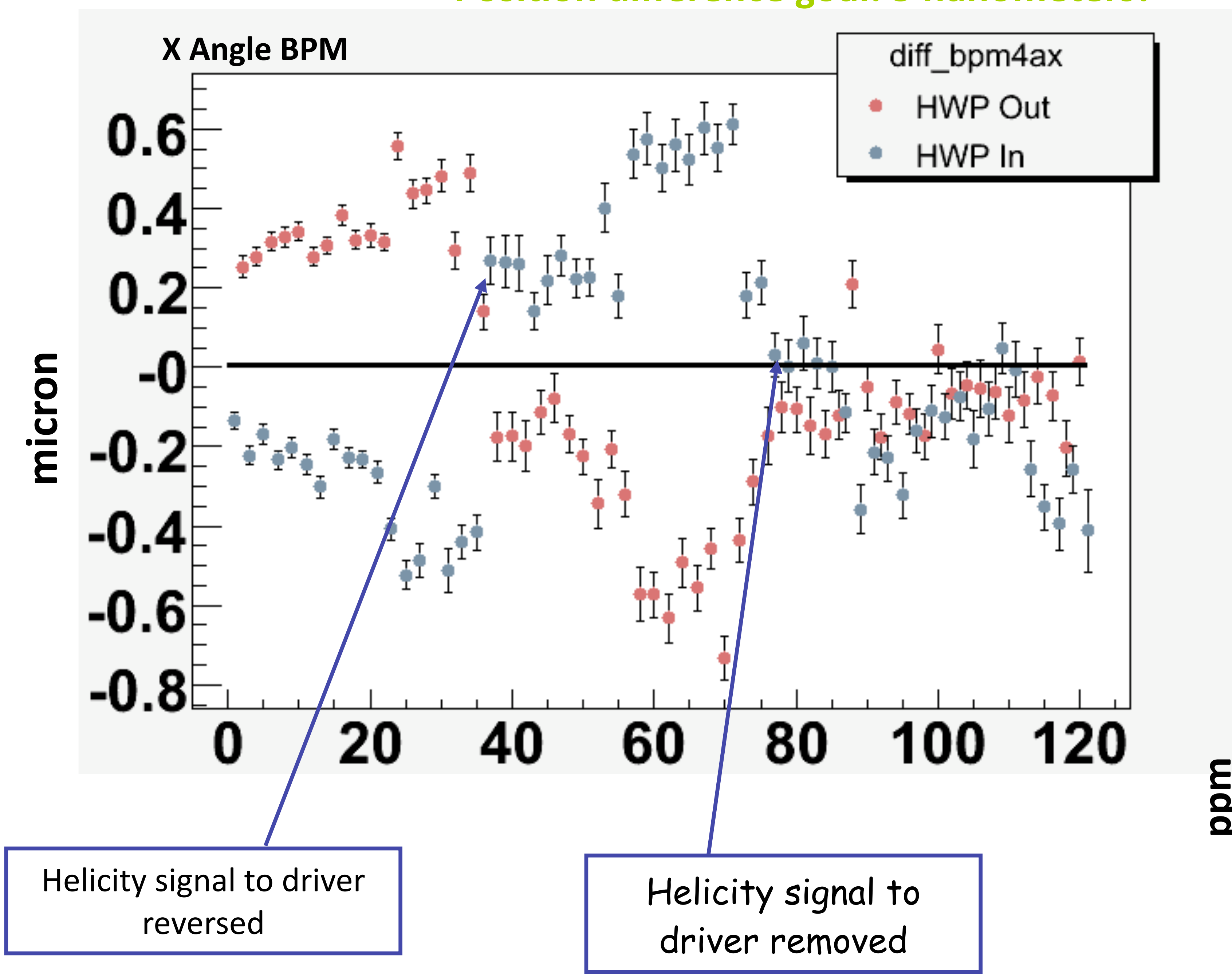
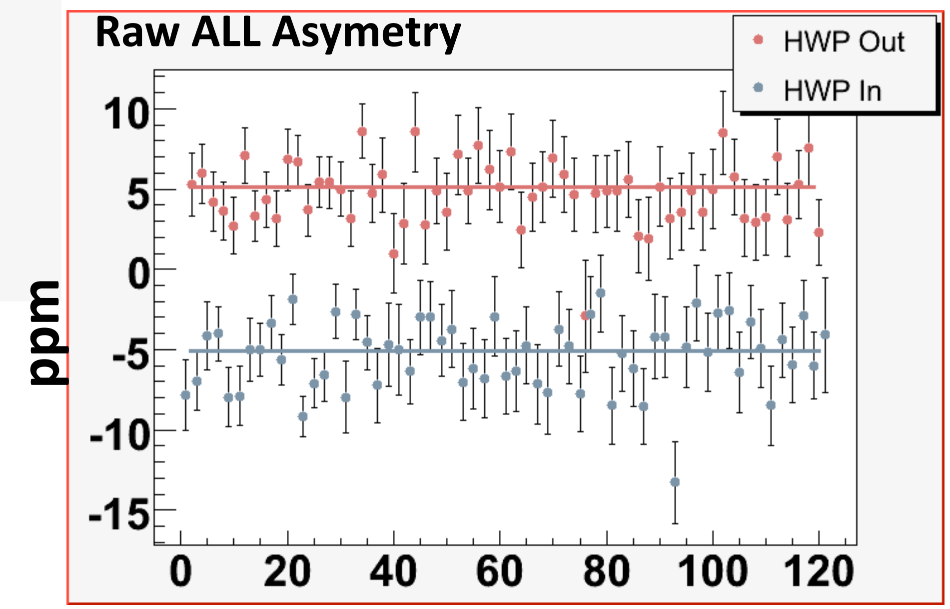


All's well that ends well

- Problem clearly identified as beam steering from electronic cross-talk
- Tests verify no helicity-correlated electronics noise in Hall DAQ at sub ppb level
- Large position differences mostly cancel in average over both detectors



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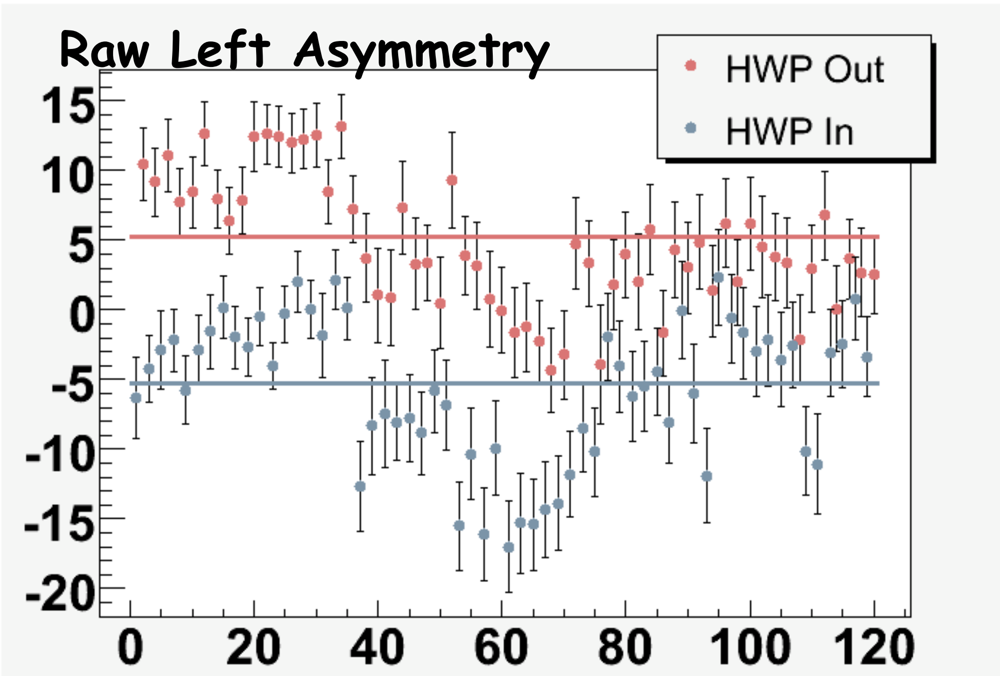
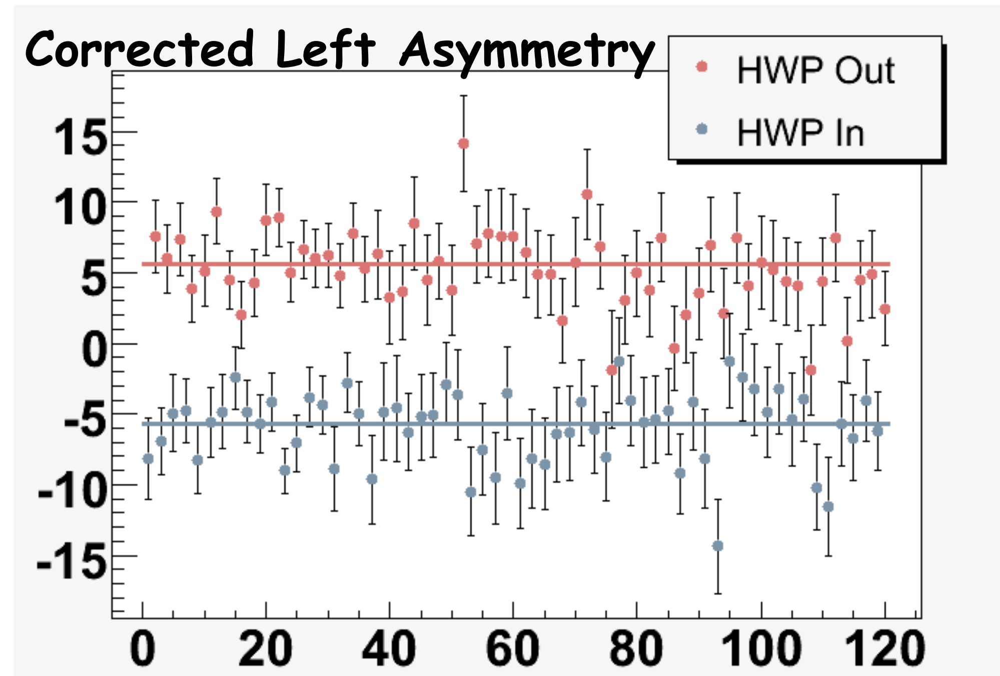
Beam Position Corrections, Helium 2005





Beam Asymmetries

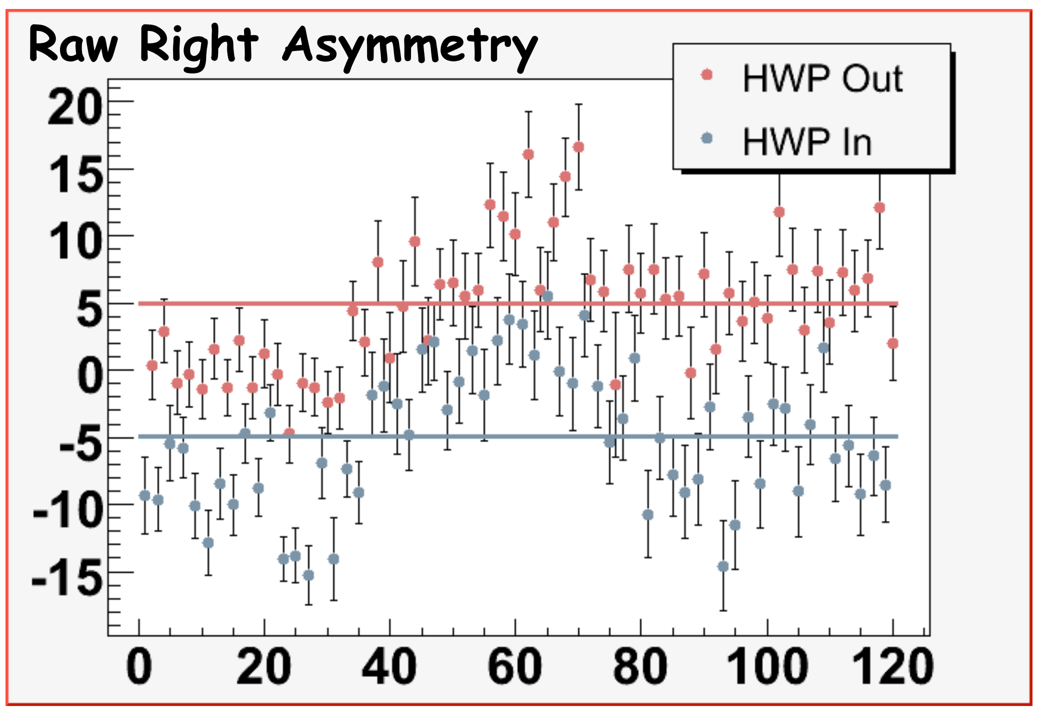
Energy: -3ppb

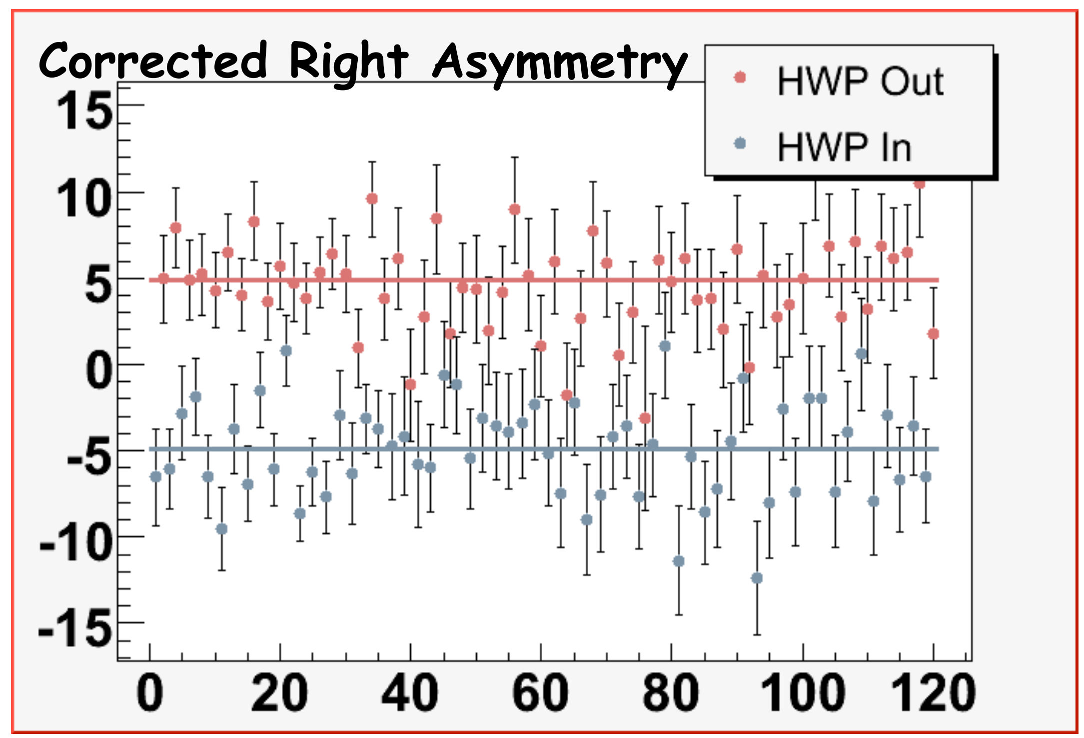
X Target: -5 nm

X Angle: -28 nm

Y Target :-21 nm

Y Angle: 1 nm





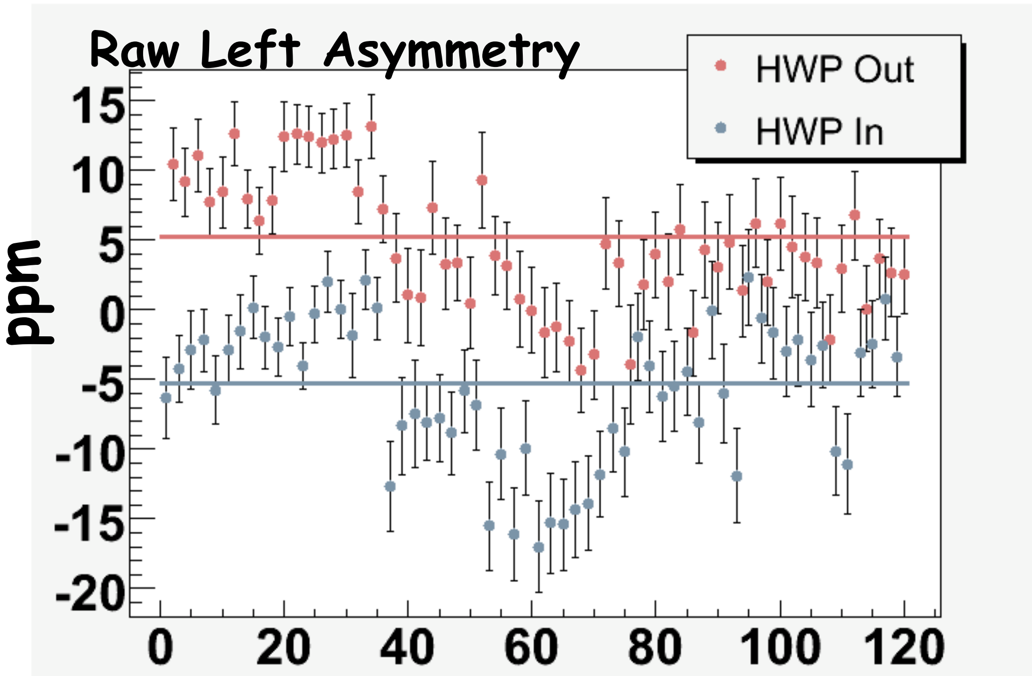
Total Corrections:

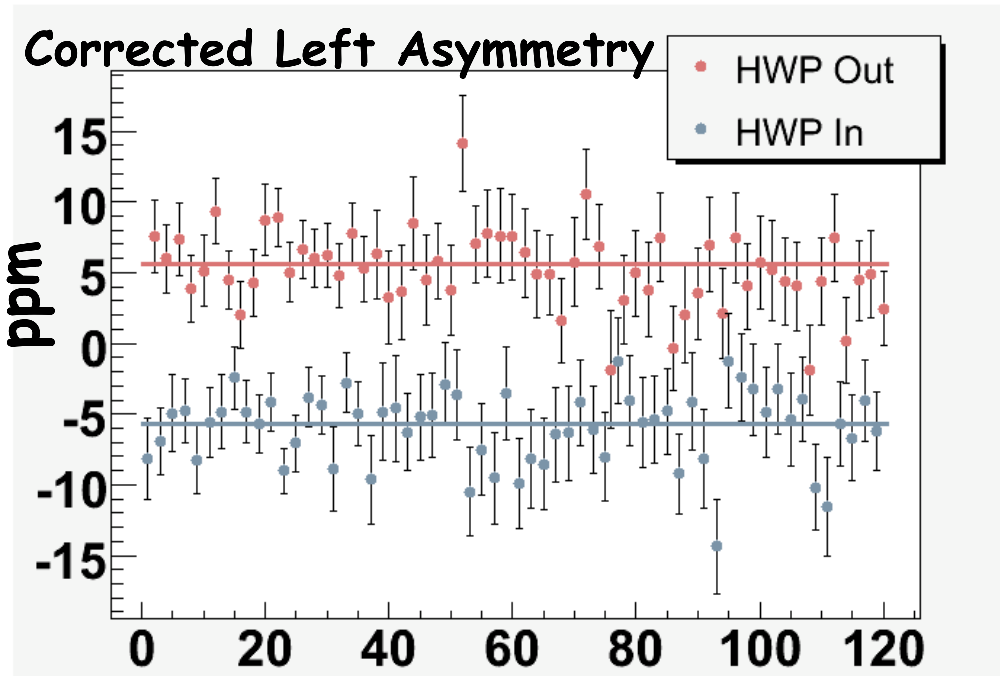
Left: -370 ppb

Right: 80 ppb

All: 120 ppb

Beam Position Corrections, Helium 2005





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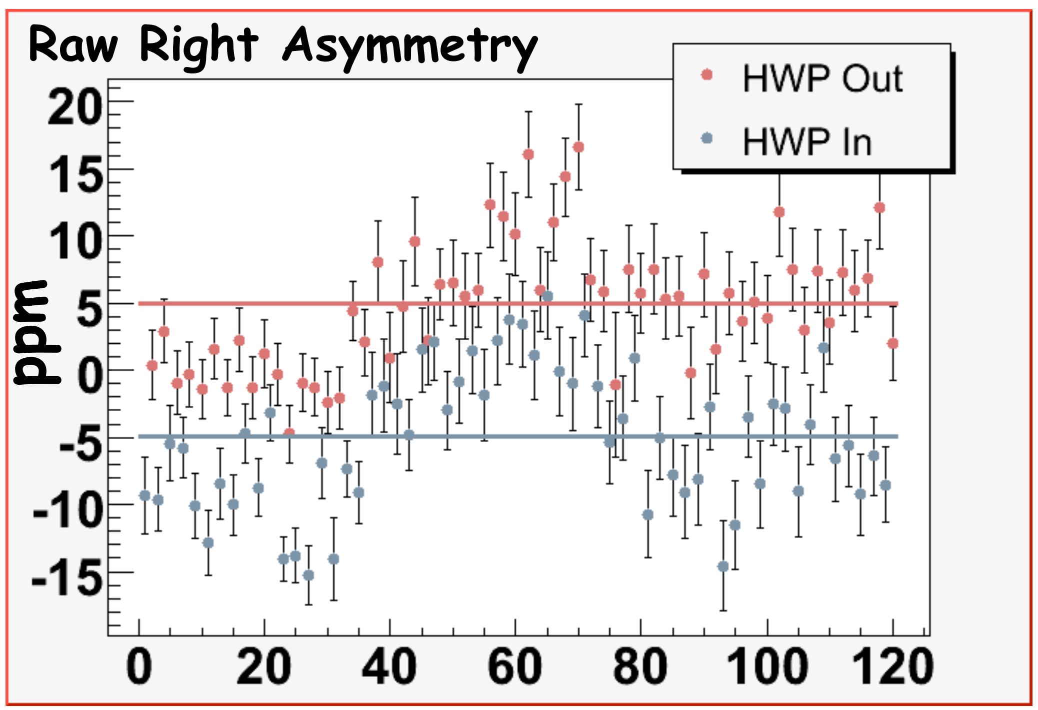

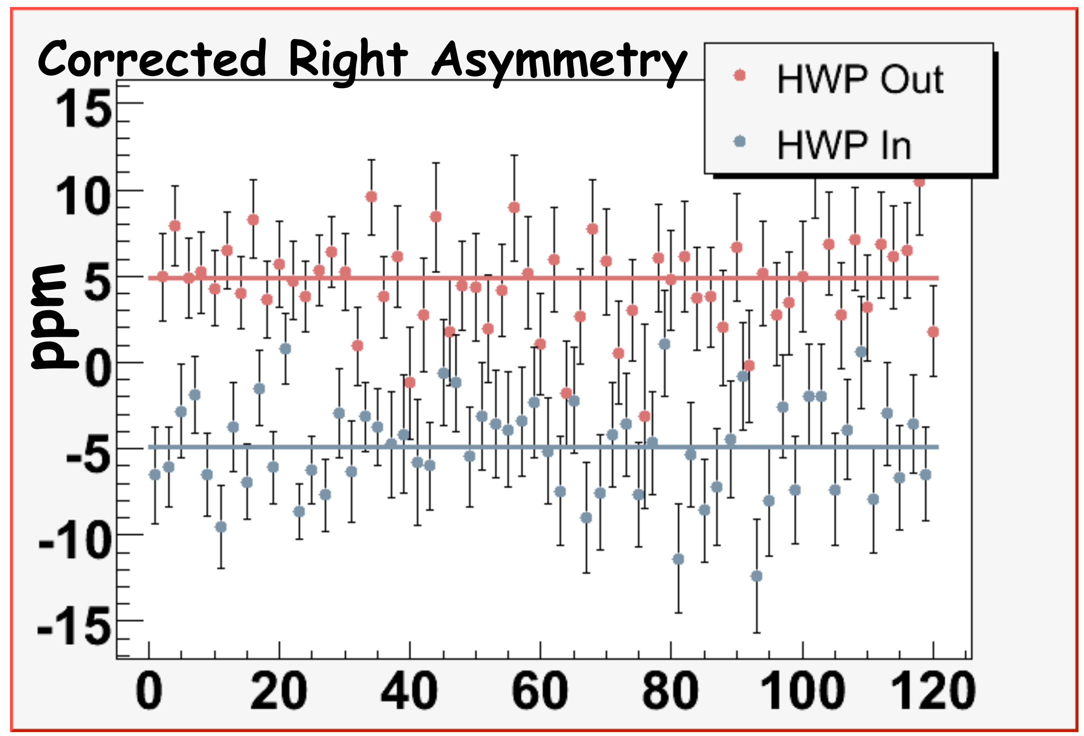

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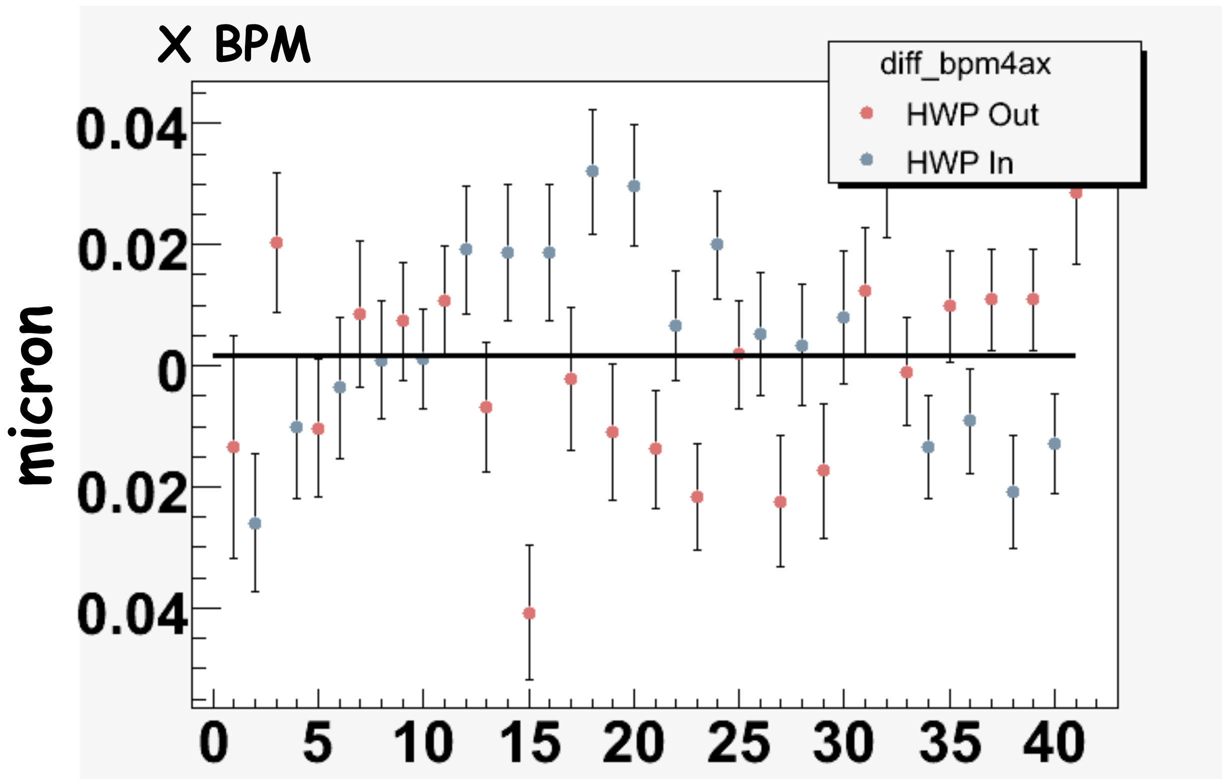
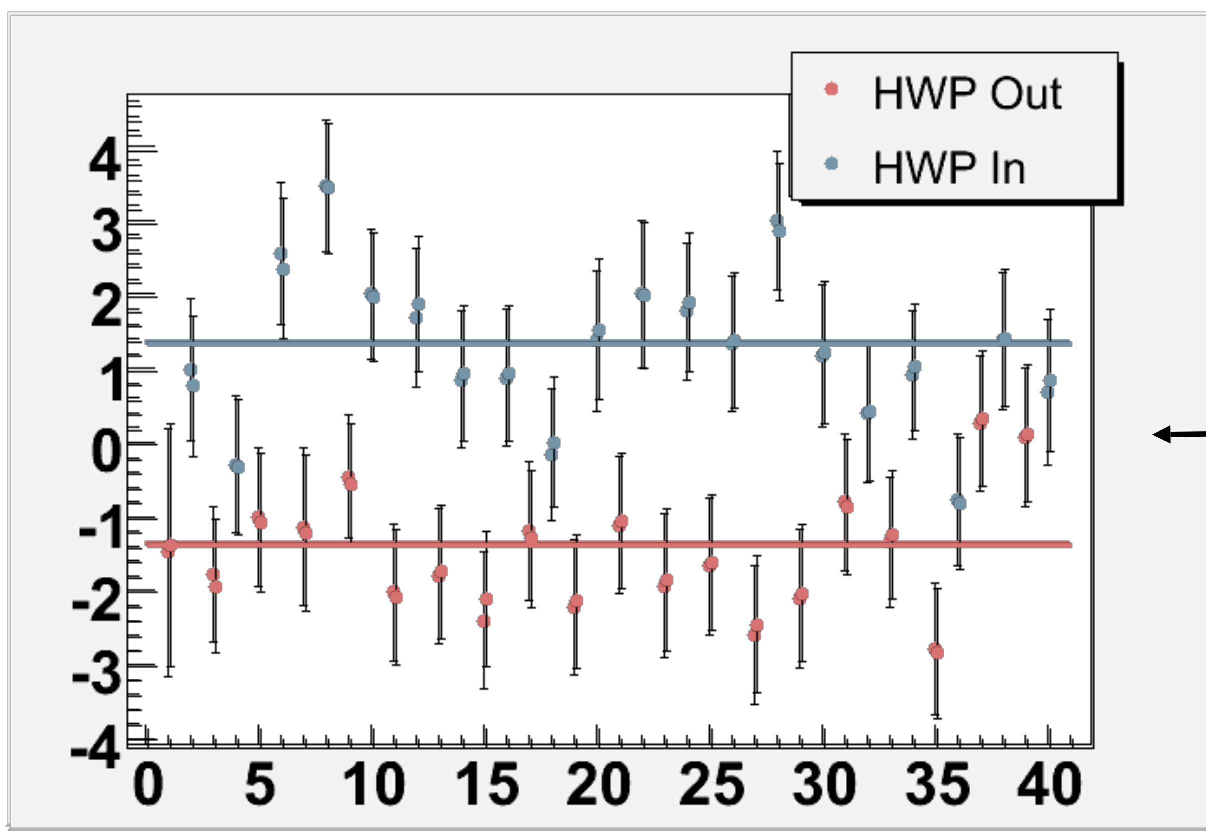
Beam Position Corrections, Hydrogen 2005





Surpassed Beam Asymmetry Goals for Hydrogen Run

Energy: -0.25 ppb

X Target: <1 nm

Y Target: <2 nm

X Angle : <0.5 nrad

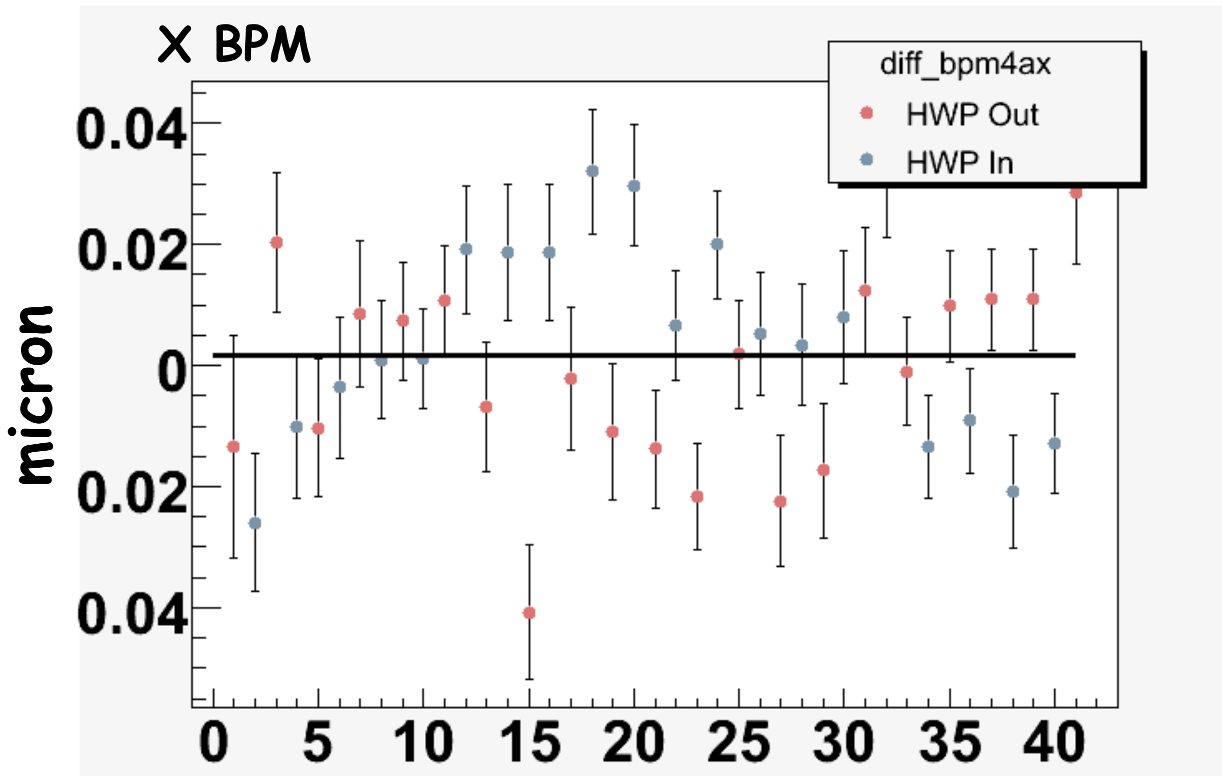
Y Angle: <0.5 nrad

Corrected and Raw, Left arm alone,

Superimposed!

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

Beam Position Corrections, Hydrogen 2005



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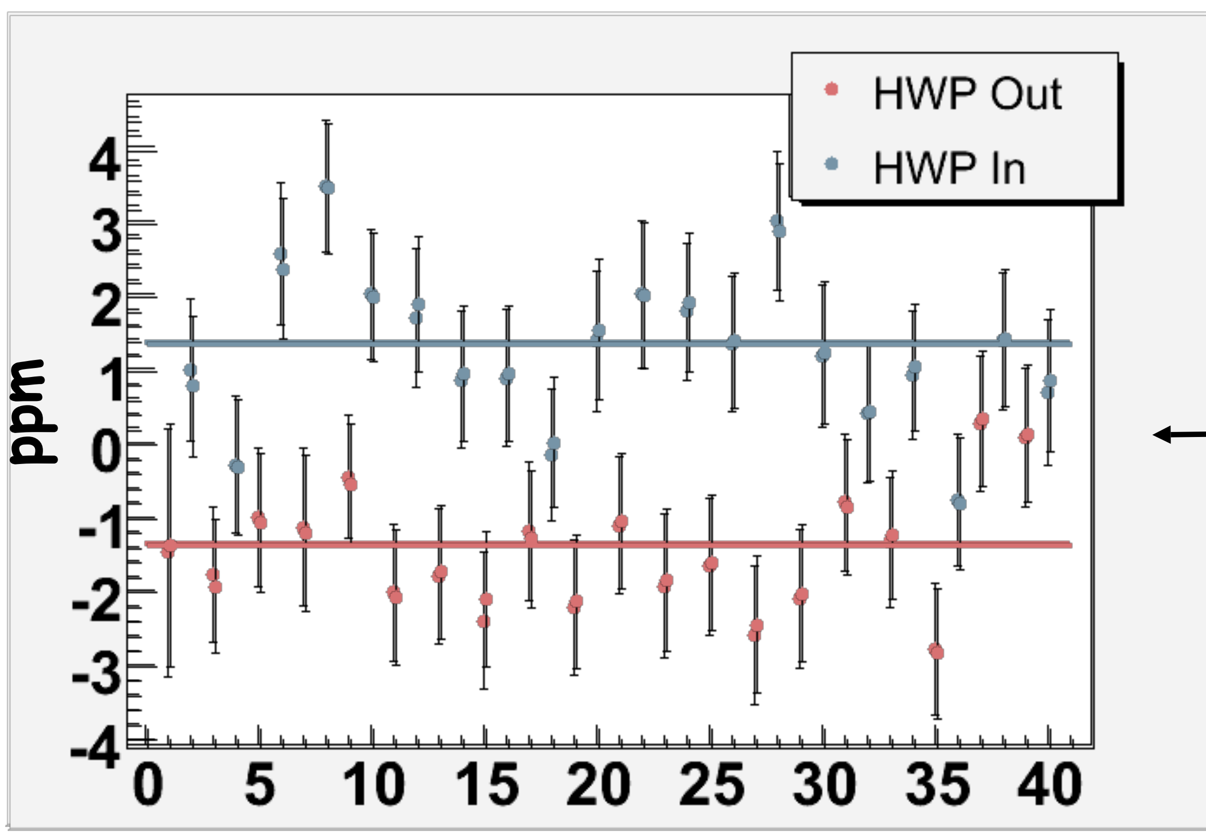

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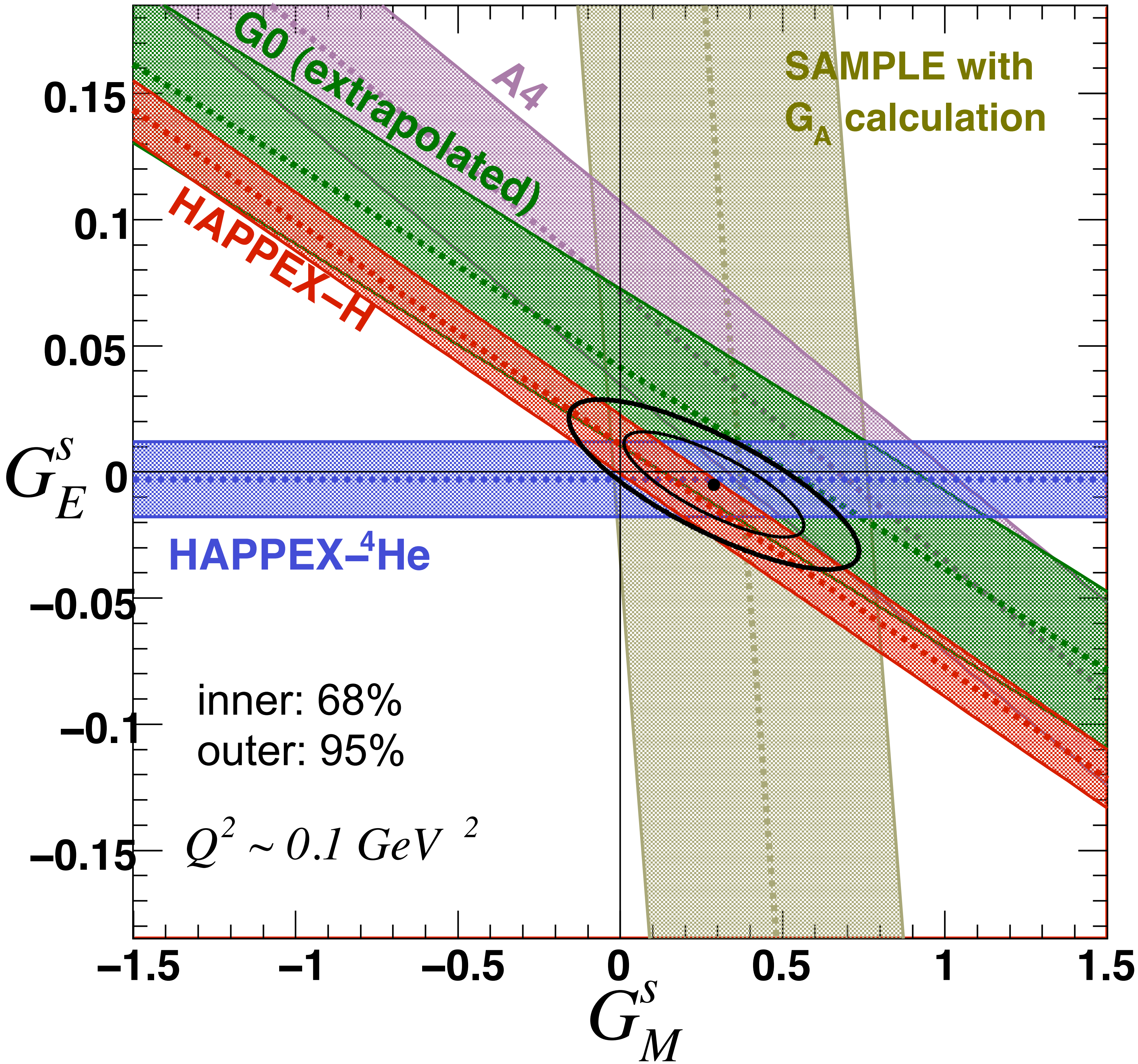
World Data near Q^2 ~0.1 GeV^2



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 = 0.18 +/- 0.27

G_E^s = -0.005 +/- 0.019

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

^{4}He: Nuclear Effects

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

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

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

$|\alpha\rangle$ = 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
  $\rightarrow$ same one-body density matrix elements in numerator/denominator
  $\rightarrow$ 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
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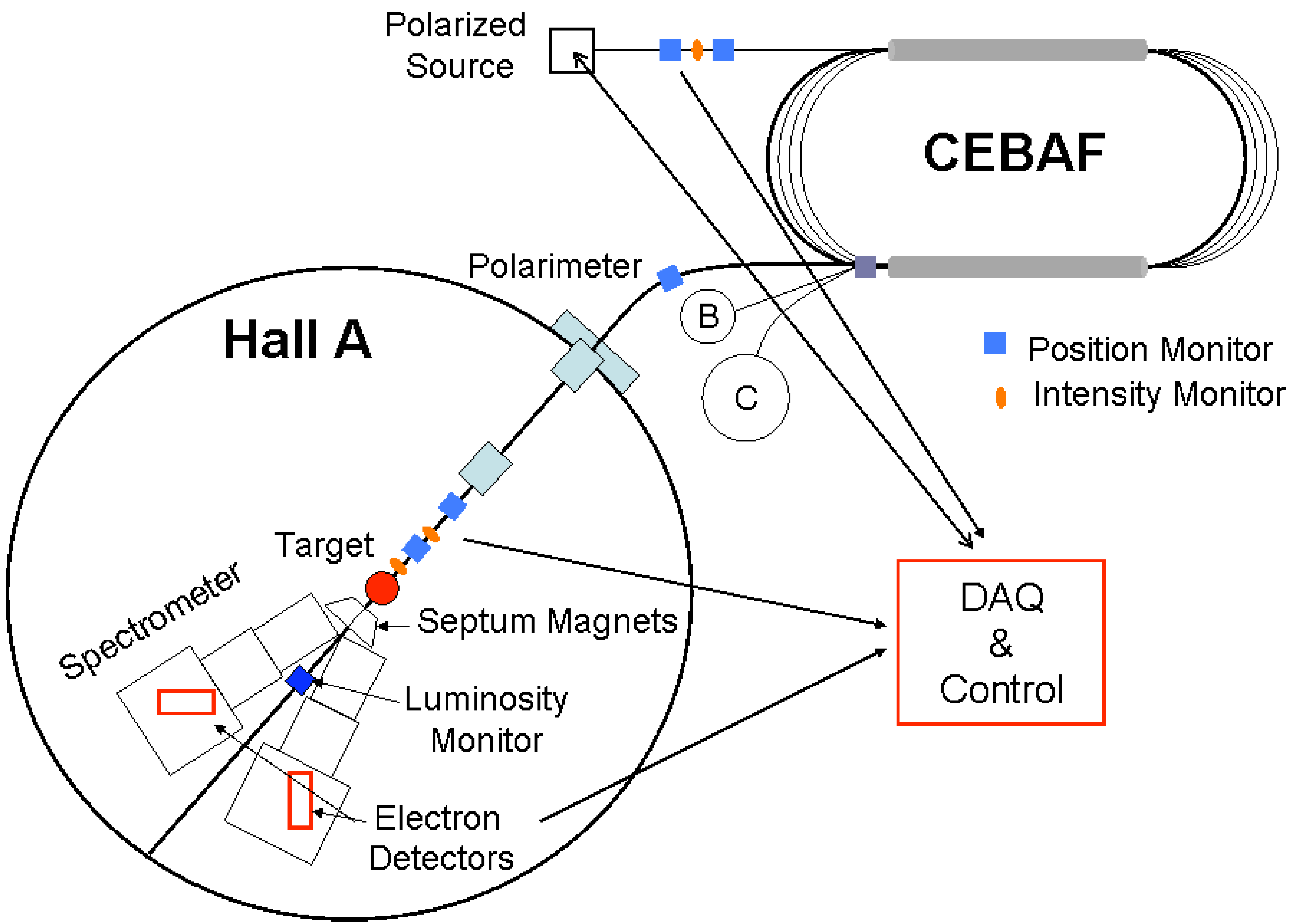
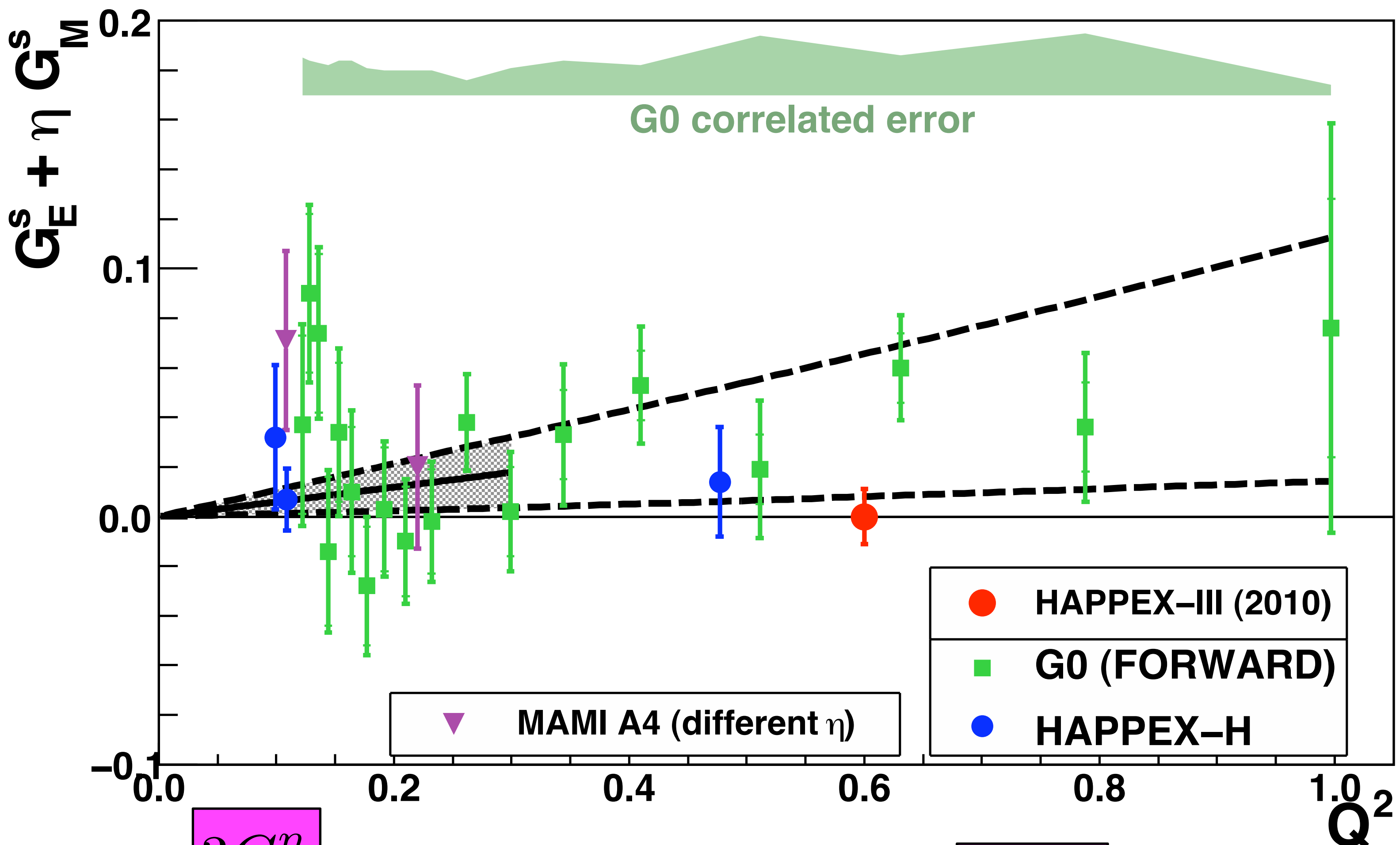

Polarized
Source
CEBAF
Polarimeter
Hall A
B
C
Position Monitor
Intensity Monitor
Target
Spectrometer
Septum Magnets
Luminosity
Monitor
Electron
Detectors
DAQ
&
Control

Summary



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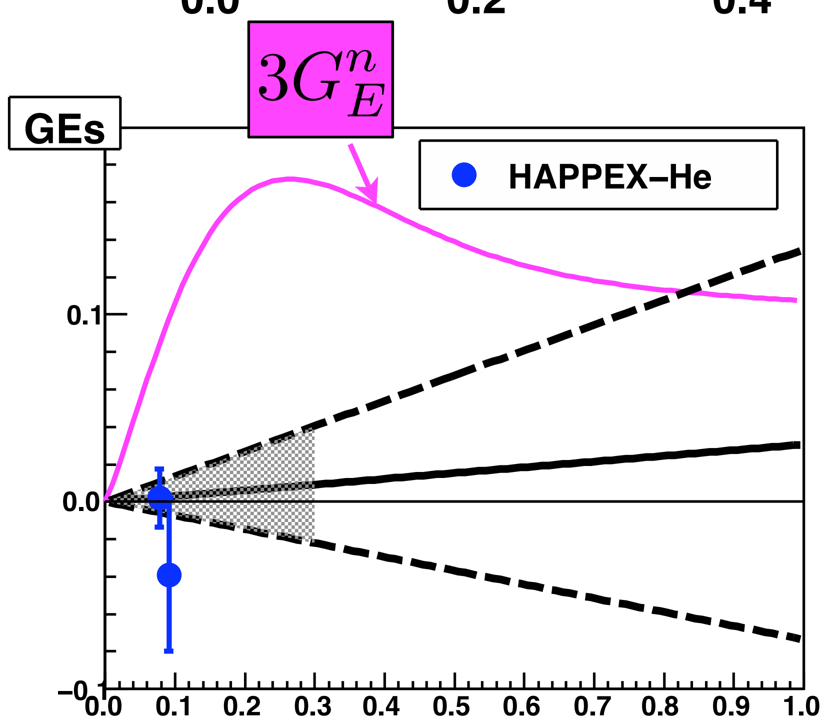

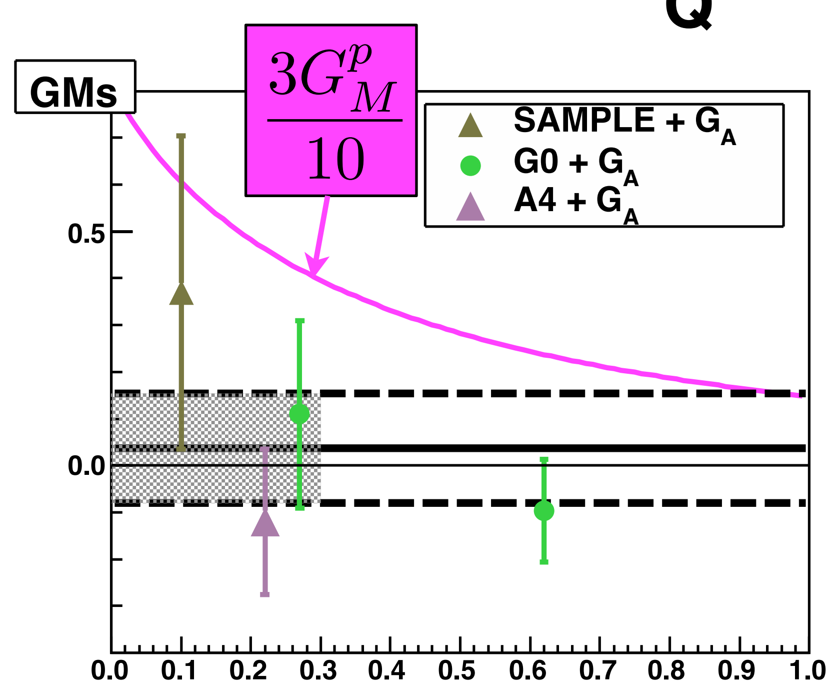

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Beam Modulation