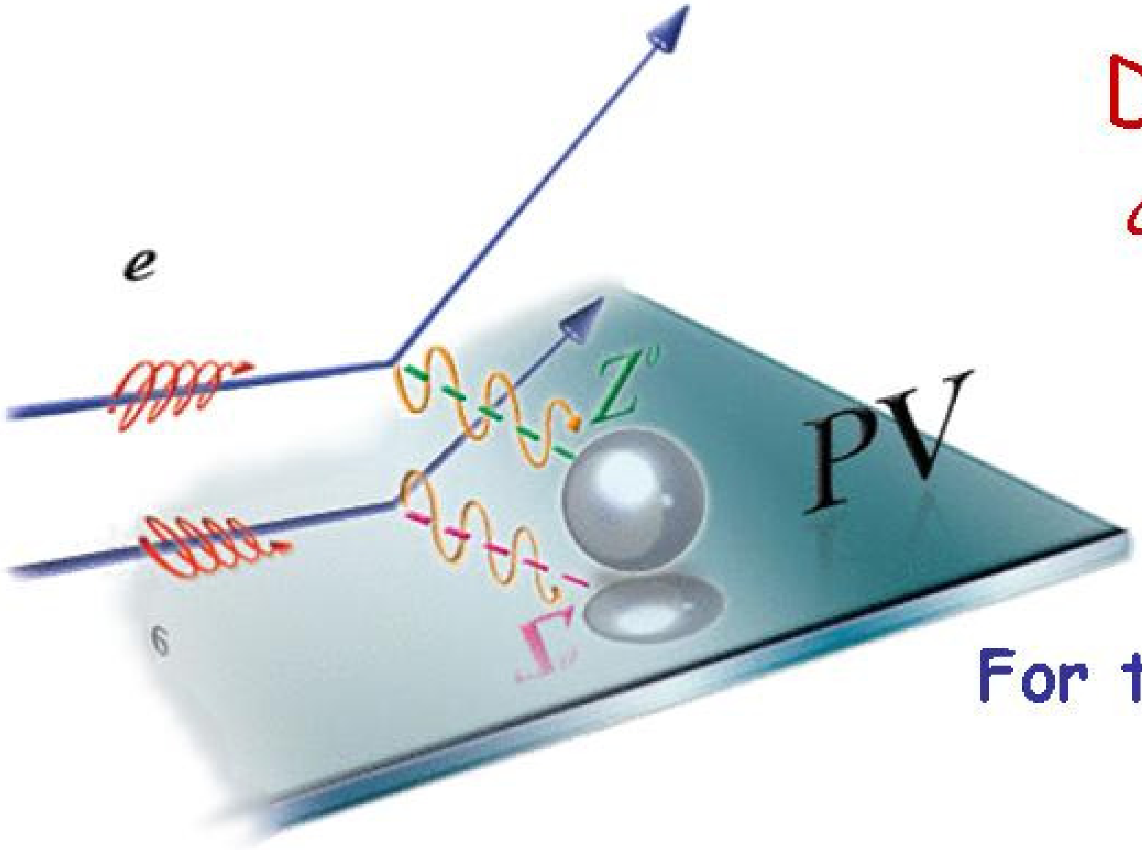
Results from HAPPEX

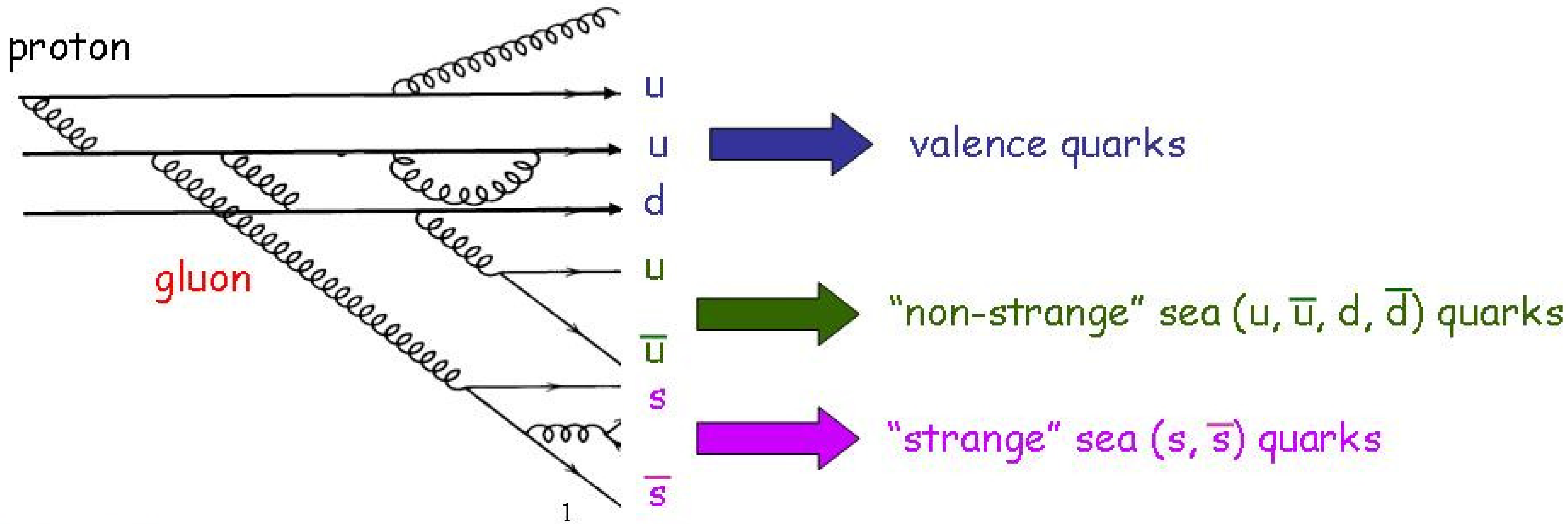


David Armstrong
College of William & Mary

For the HAPPEX Collaboration

August 16 2005 - JLAB/INT Precision Electroweak Interactions Workshop - W&M

What role do strange quarks play in nucleon properties?



Momentum: $\int_0^1 x(s+\bar{s})dx \sim 4\% \text{ (DIS)}$

Spin: $< N | \bar{s}\gamma^5 s | N > \sim -10\% \text{ (polarized DIS)}$

Mass: $< N | \bar{s}s | N > \sim 30\% \text{ } (\pi N \, \sigma\text{-term})$

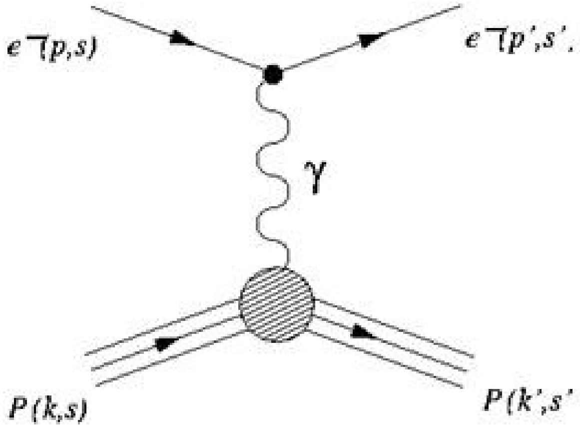
Charge and current: $< N | \bar{s} \, \gamma^\mu \, s | N > = ?? \rightarrow G_E^s \; G_M^s$

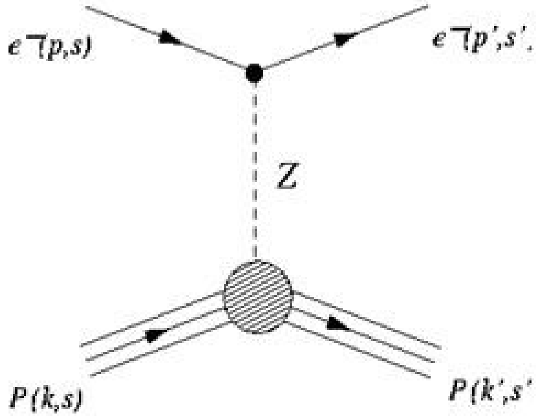
Goal : Determine the contributions of the strange quark sea ($s\bar{s}$) to the electromagnetic properties of the nucleon ("strange form factors").

“ There is no excellent beauty that hath not some strangeness in the proportion ”

Francis Bacon 1561-1626

Parity Violating Electron Scattering → Weak NC Amplitudes





$$M^{EM} = \frac{4\pi\alpha}{Q^2} Q_l \, \ell^{\mu} J_{\mu}^{EM}$$

$$M_{PV}^{NC} = \frac{G_F}{2\sqrt{2}} \left[g_A \ell^{\mu 5} J_{\mu}^{NC} + g_V \ell^{\mu} J_{\mu 5}^{NC} \right]$$

Interference with EM
amplitude makes NC
amplitude accessible

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

Connections to TPE physics

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 → P. Blunden's talk
   - not a concern at present experimental precision.

2. Electromagnetic Form Factors used to extract strange form factors:
   - which form factors to use? → J. Arrington's talk

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.

     → S. Wells' talk, and rest of Wed. AM session

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: $G_E^\gamma = F_1^\gamma + \tau F_2^\gamma$ $\quad G_M^\gamma = F_1^\gamma + F_2^\gamma$

NC vector current 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

Neglecting trivial breaking due to Coulomb force, one expects the neutron to be an isospin rotation of the proton:

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

→ R. Lewis' talk

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

$$\left|\begin{array}{l} G^{\gamma,p}_{E,M} \\ G^{\gamma,n}_{E,M} \\ G^{Z,p}_{E,M} \end{array}\right. \xrightarrow[\text{symmetry}]{\text{Charge}} \left|\begin{array}{l} G^{u}_{E,M} \\ G^{d}_{E,M} \\ G^{s}_{E,M} \end{array}\right. \xrightarrow{\text{Shuffle}} \left|\begin{array}{l} G^{p}_{E,M} \\ G^{n}_{E,M} \\ G^{s}_{E,M} \end{array}\right.$$

Well Measured

$\langle N|\, s\gamma^{\mu} s\, |N\rangle$

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

Theoretical Approaches to Strange Form Factors

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 the lattice?

- Dong, Liu, Williams PRD **58**(1998)074504
- Lewis, Wilcox, Woloshyn PRD **67**(2003)013003
- Leinweber, et al. PRL **94**(2005) 212001

→ *A. Thomas' talk*

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 ± [illegible] (syst) ppm

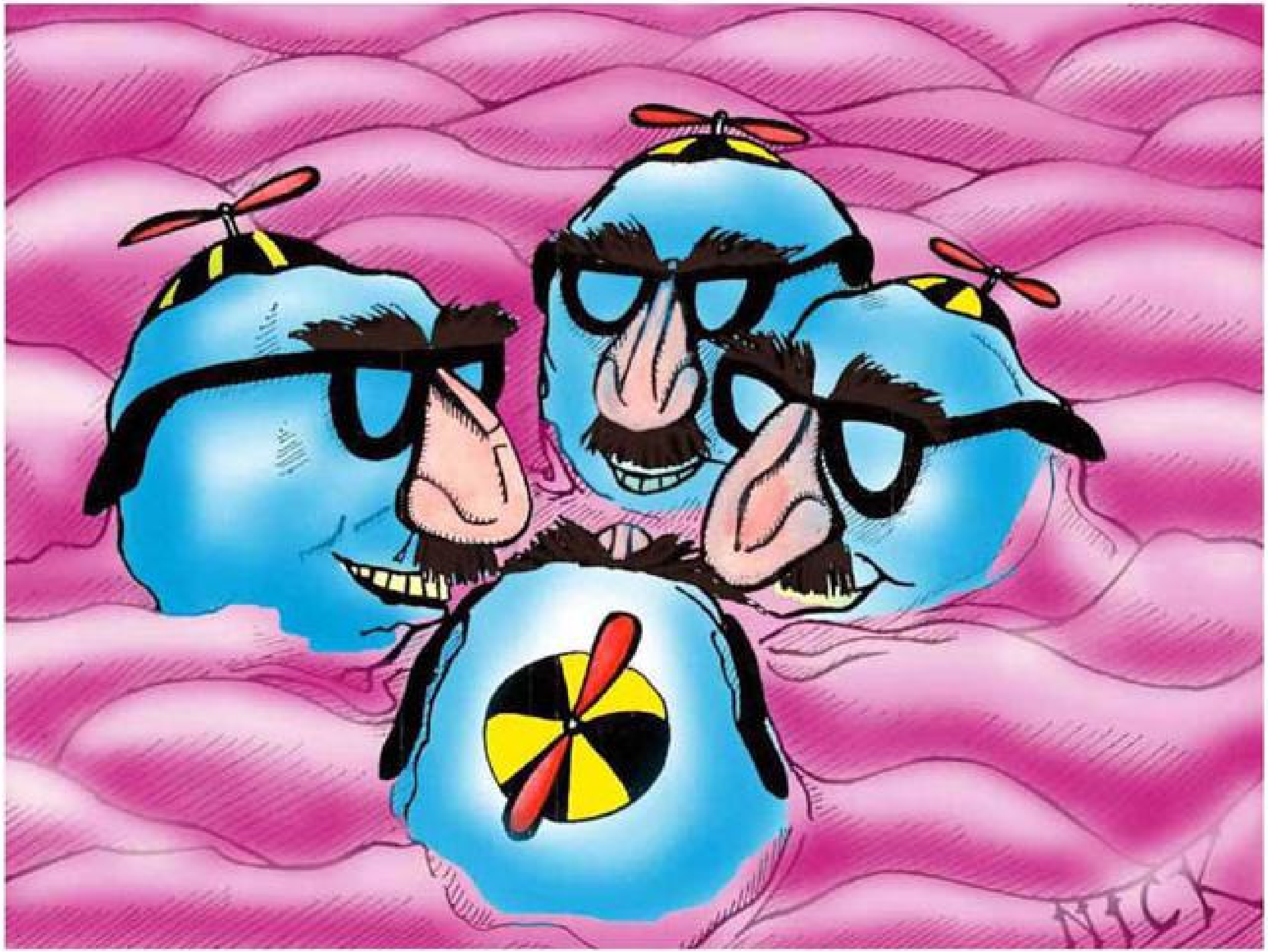
$$\boxed{G^s_E + 0.39 G^s_M = 0.014 \pm 0.020\ (exp) \pm 0.010\ (FF)}$$

"Parity Quality" Beam @ JLab

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

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

...(interlude)...



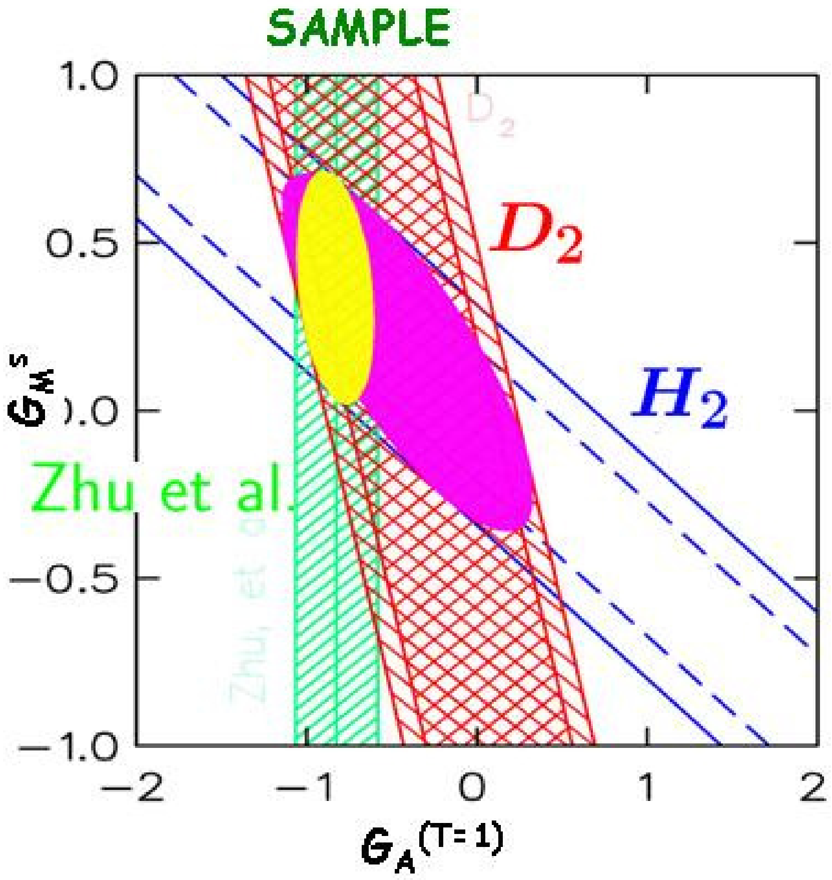
At a resolution of 10^{-24} metres, isolated clumps of
Strange Matter pop briefly out of the quantum foam
to debate the possible existence of ~~Particle~~ Physicists.
Hadronic

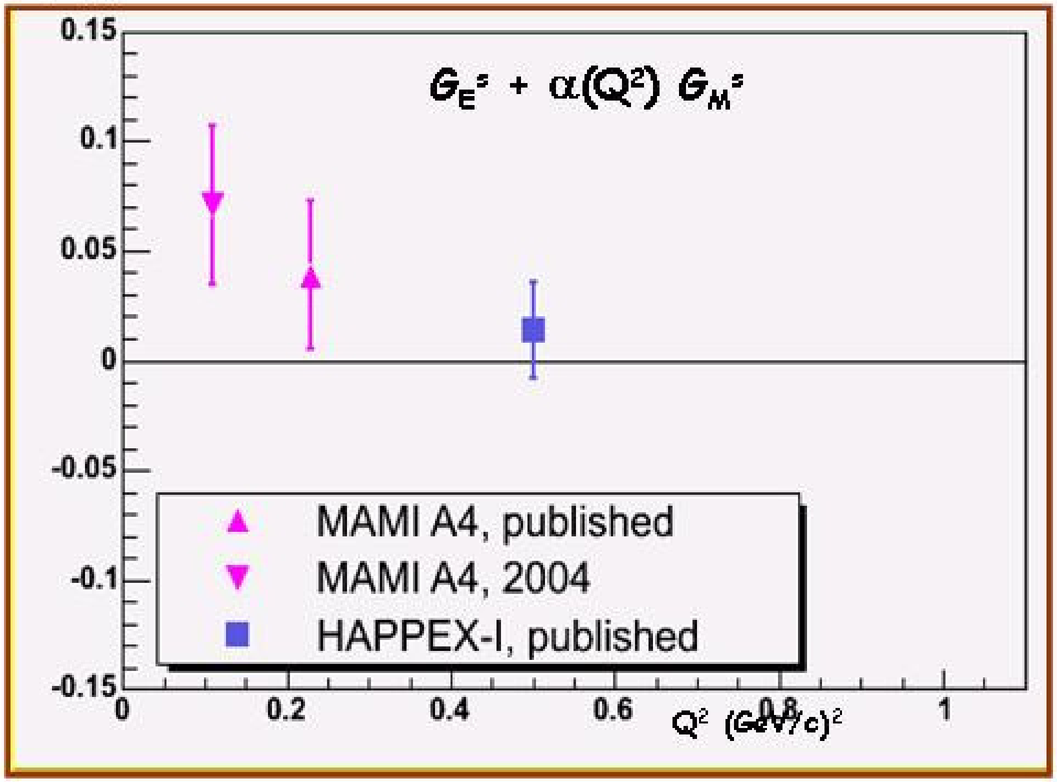
Other Measurements

SAMPLE (MIT/Bates):
measured $G_M^s + \beta G_A$
at Q^2=0.1 GeV^2

PAVI-A4 (Mainz):
measured $G_E^s + \alpha G_M^s$
at Q^2 = 0.23, 0.1
GeV^2

→ S. Taylor's talk

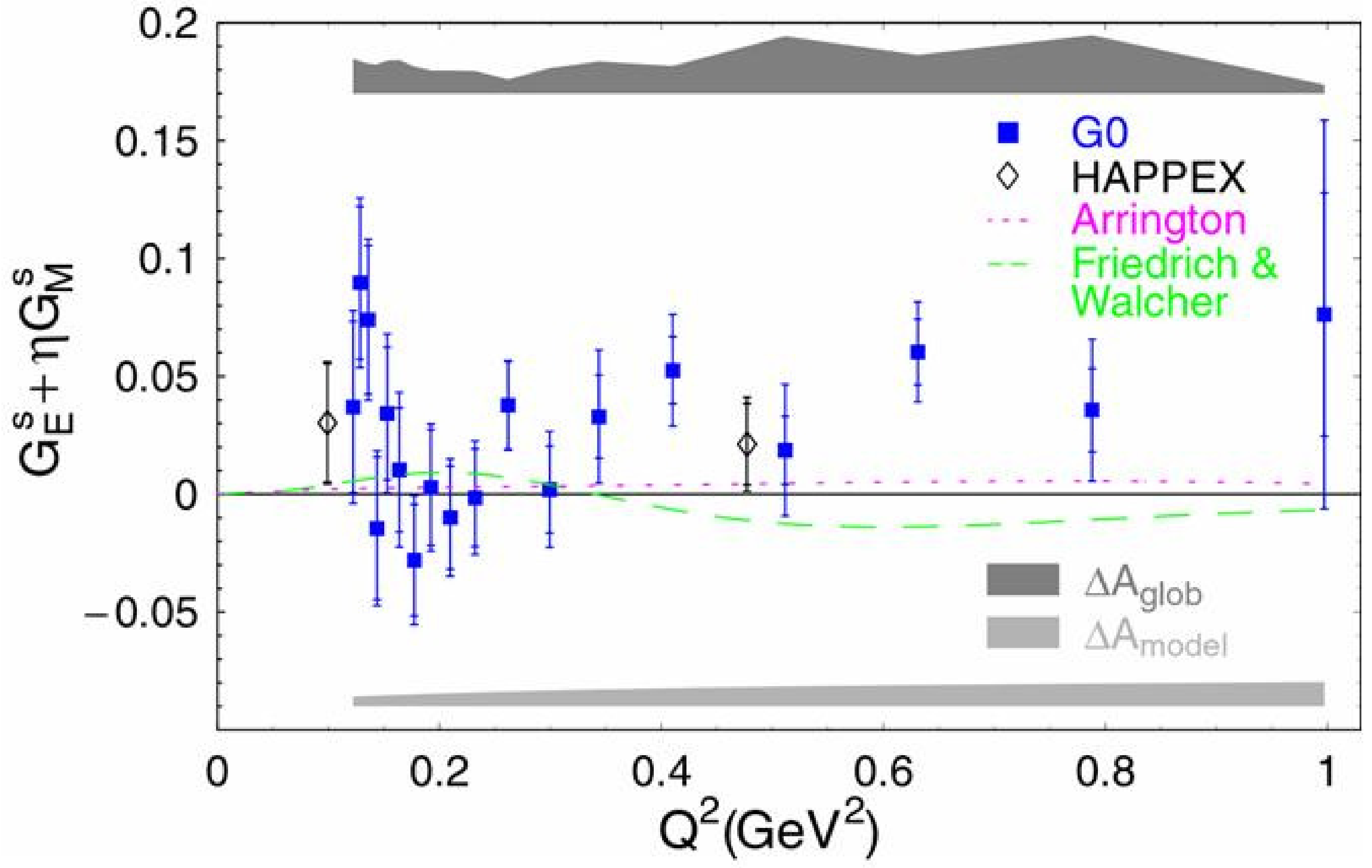




Other Measurements cont'd

G0 at JLab/Hall C
measured $G_E^s + \alpha G_M^s$
at $Q^2 = 0.12 \rightarrow 1.0\ GeV^2$

→ S. Pate's talk



HAPPEX (second generation)

E=3 GeV θ=6° 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)	Syst. Error (ppm)	sensitivity
^1H	-1.4	0.08 (5.7%)	0.04 (2.9%)	$\delta\,(G^s_E+0.08G^s_M) = 0.010$
^4He	+7.8	0.18 (2.2%)	0.18 (2.1%)	$\delta\,(G^s_E) = 0.015$

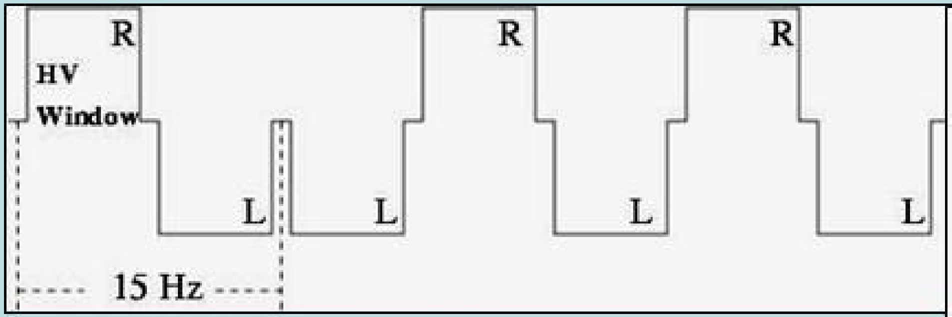
Measurement of P-V Asymmetries

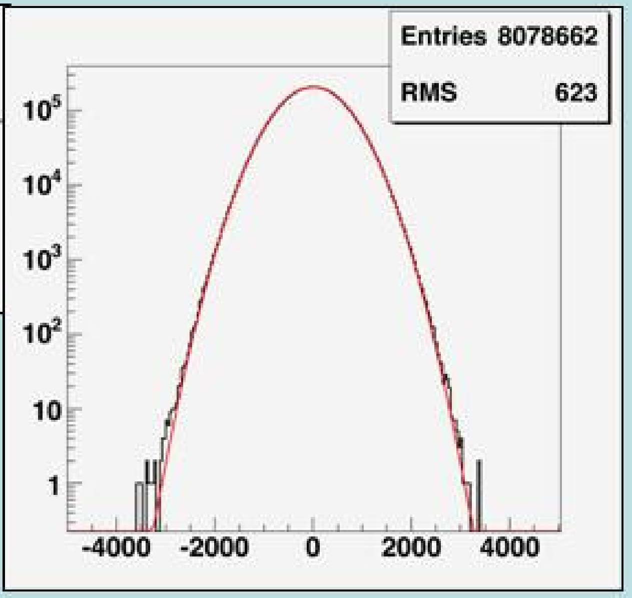
$$A_{LR} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx 10^{-6}$$

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

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

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





- Analog integration of rates ~100 MHz
- 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

Apparatus Upgrade

HAPPEX-I precision:
~ 1 ppm, 15%

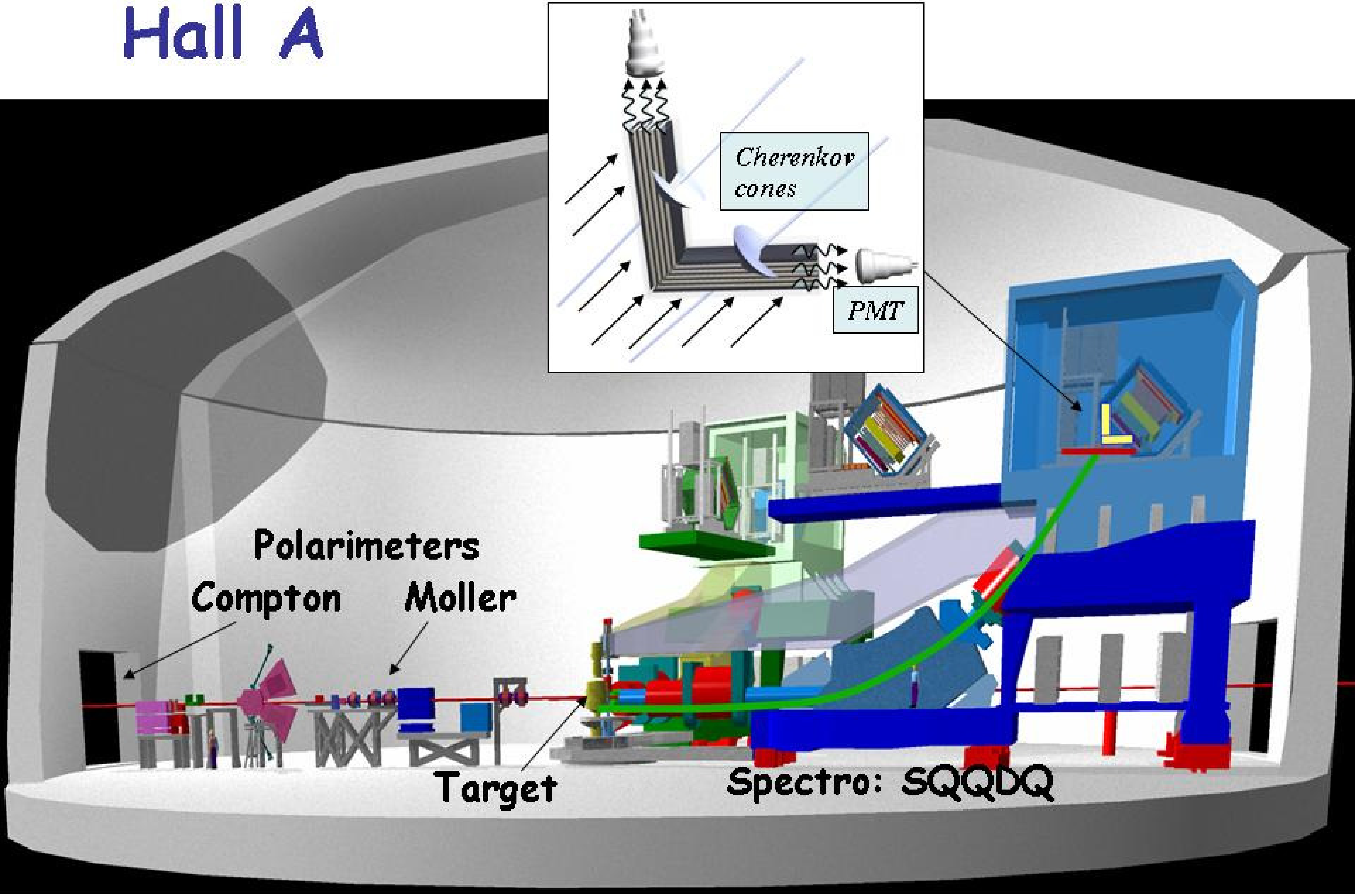
HAPPEX-H precision ~ 50 ppb
HAPPEX-He precision ~ 2%

- **High Luminosity** => High I and P_e (superlattice), thick new targets, rad-hard integrating det., improved DAQ.
- **Small forward angle** => new Septum magnets
- **Accurate Normalization** => improved polarimetry, new focal plane profile scanner
- **High systematic accuracy** => improved polarized source, close attention to beam optics, luminosity monitor.

First Run, 2004

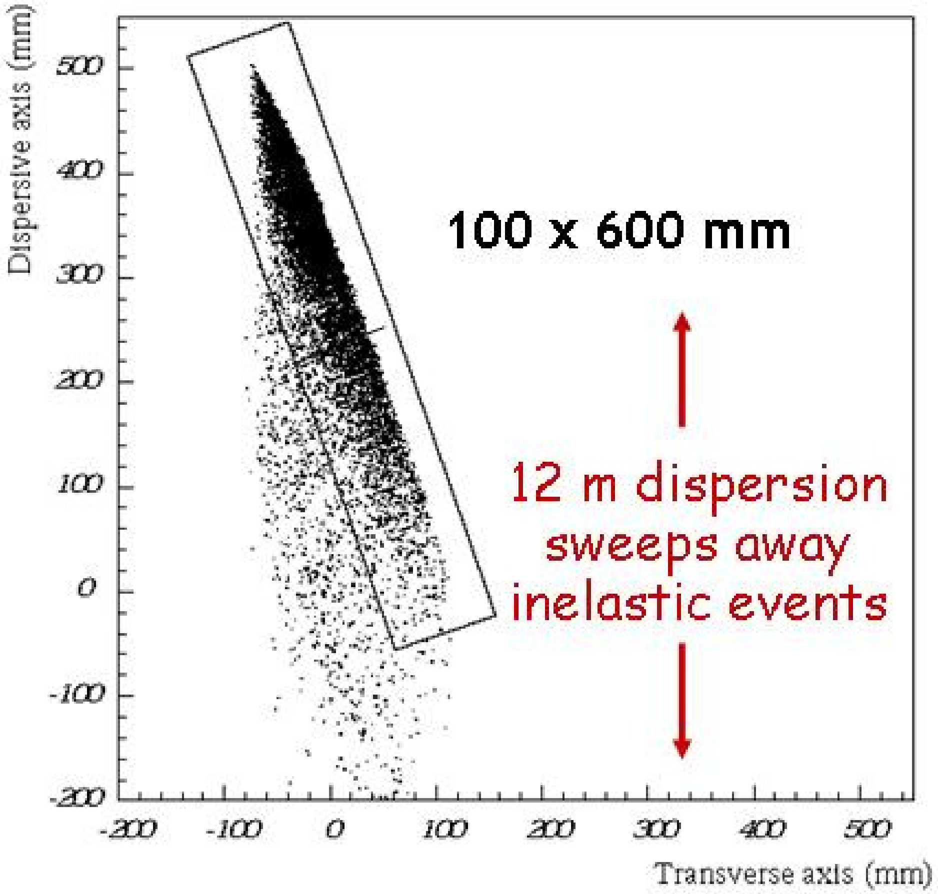
June 8 - June 22	HAPPEX-He · about 3M pairs at 1300 ppm => $\delta A_{stat} \sim 0.7$ ppm
June 24 - July 26	HAPPEX-H · about 8M pairs at 600 ppm => $\delta A_{stat} \sim 0.2$ ppm
Second run started July 15 '05 *(underway right now...)*	

Hall A


Cherenkov cones
PMT
Polarimeters
Compton
Moller
Target
Spectro: SQQDQ

High Resolution Spectrometers

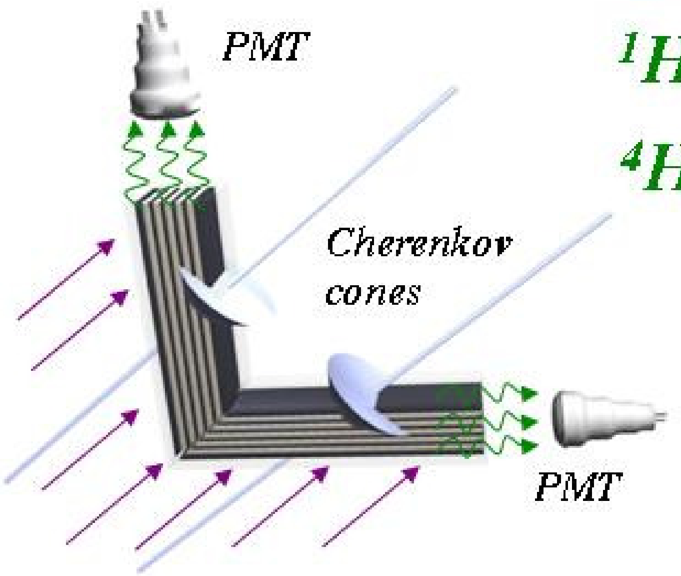
Very clean separation of elastic events by HRS optics → Overlap the elastic line above the focal plane and integrate the flux



Elastic Rate:

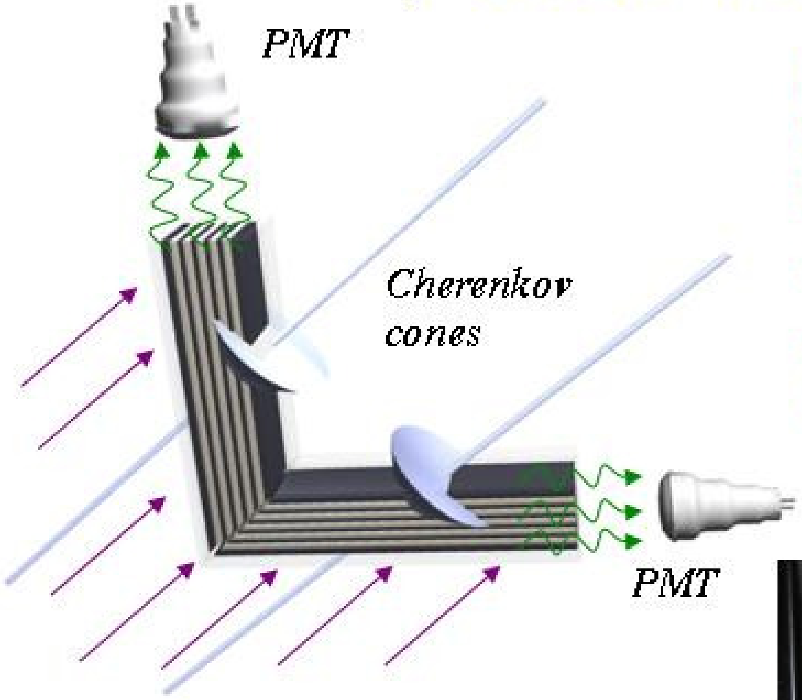
^{1}H: 120 MHz

^{4}He: 30 MHz



Large dispersion and heavy shielding reduce backgrounds at the focal plane

Focal Plane Detectors



Brass-Quartz Integrating Cerenkov Shower Calorimeter

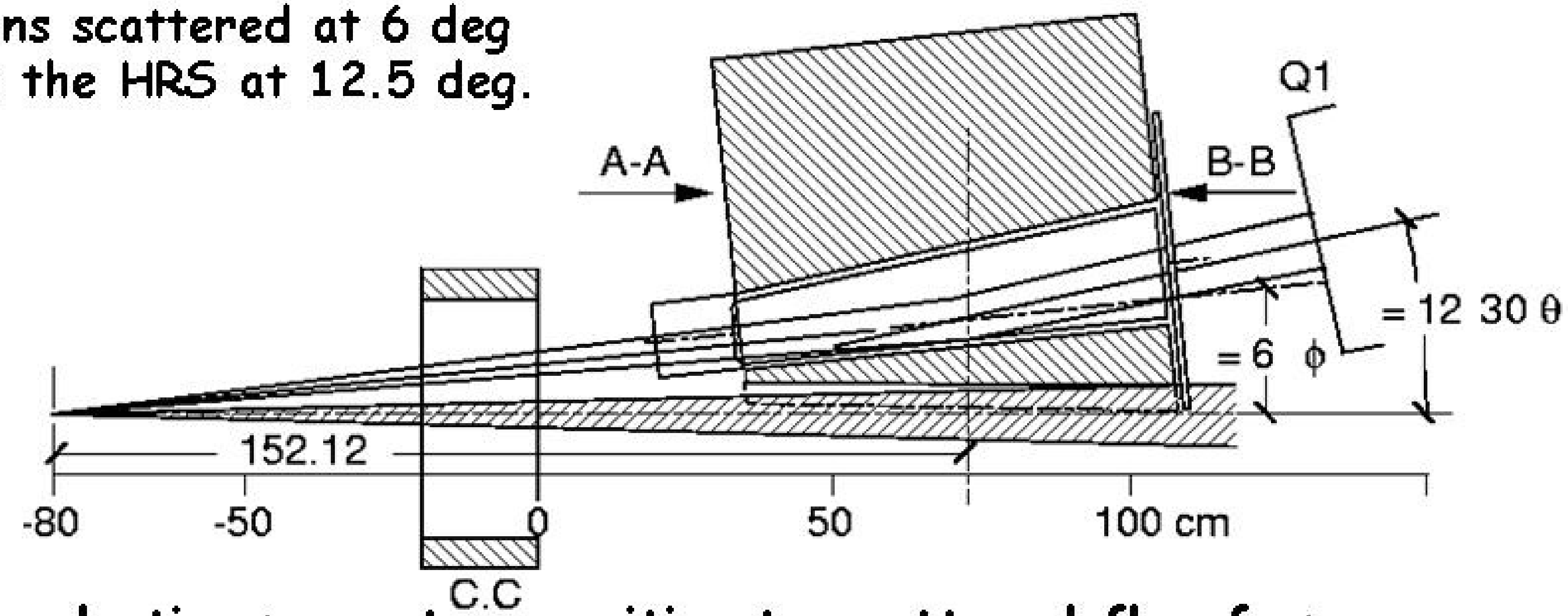
- Insensitive to background
- Directional sensitivity
- High-resolution
- Rad hard

Two segment "L"-shape covers hydrogen elastic peak

Smaller 4He elastic peak requires only ½ single-segment detector

Septum Magnets

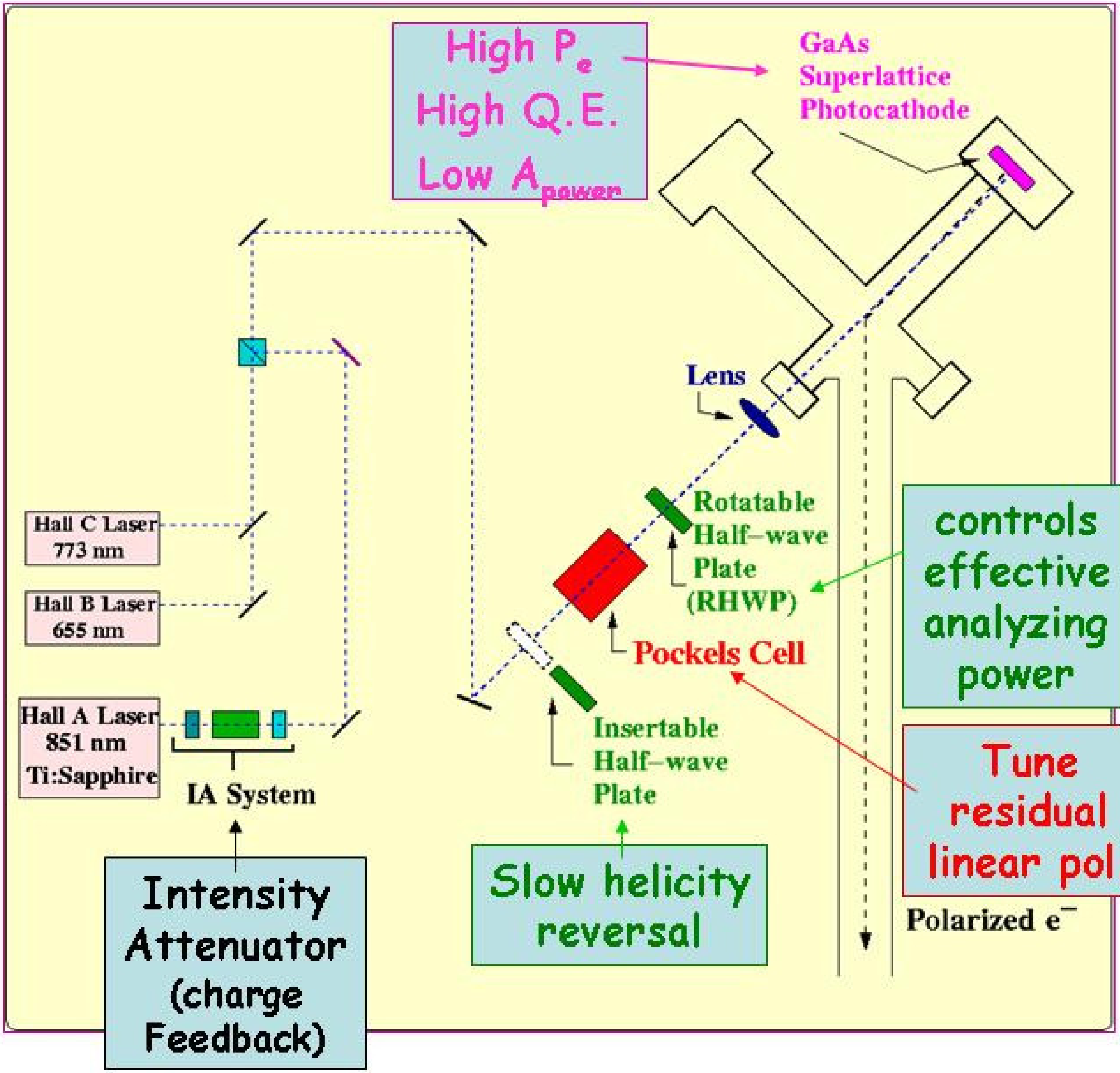
Electrons scattered at 6 deg
sent to the HRS at 12.5 deg.



- Superconducting magnets, sensitive to scattered flux from the target.

- Sweep *Magnet*, to sit inside the scattering chamber, is being built to protect bore tube from *Moller* flux in 2005

Polarized Source



High P_e
High Q.E.
Low A_{power}

controls effective analyzing power

Tune residual linear pol.

Slow helicity reversal

Intensity Attenuator (charge Feedback)

- Optical pumping of solid-state photocathode
- High Polarization
- Pockels cell allows rapid helicity flip
- Careful configuration to reduce beam asymmetries.
- Slow helicity reversal to further cancel beam asymmetries

Correcting Beam Asymmetries

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

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
- Sensitive to highly-correlated beam motion

"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

Raw Asymmetry Corrections

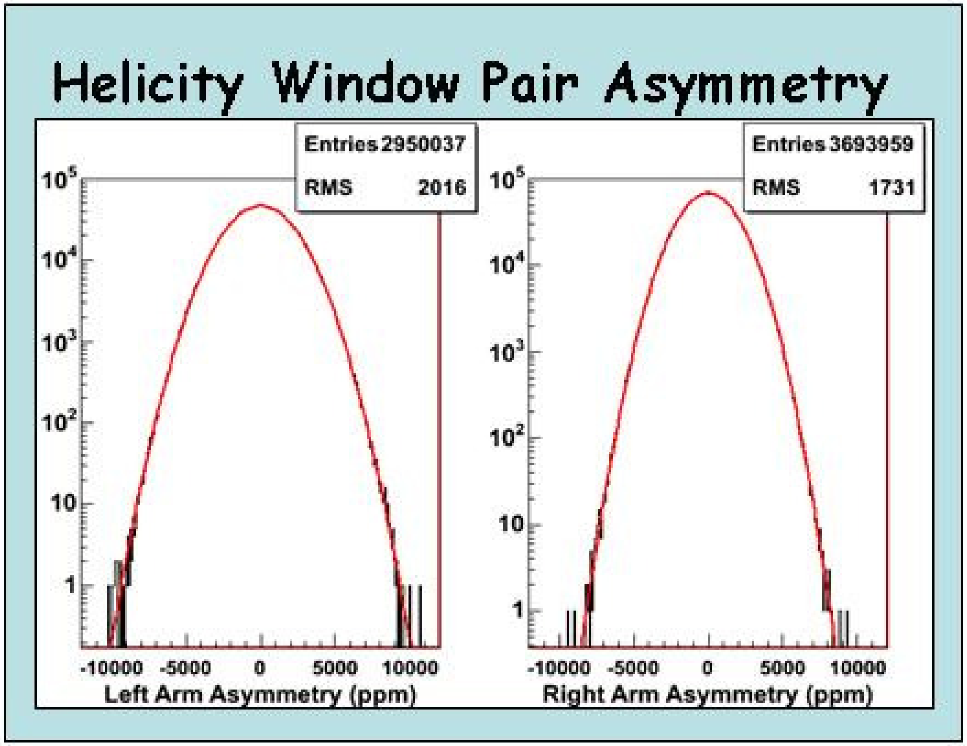
Hydrogen, '04 run	Magnitude	Approximate Correction	Uncertainty Estimate
Charge Asymmetry	-2.6 ppm	-2.6 ppm	5 ppb
Energy Asymmetry	22 ppb	-120 ppb	12 ppb
Position Difference	-4 nm	<5 ppb	Negligible
Angle Difference	-7 nrad	60 ppb	30 ppb

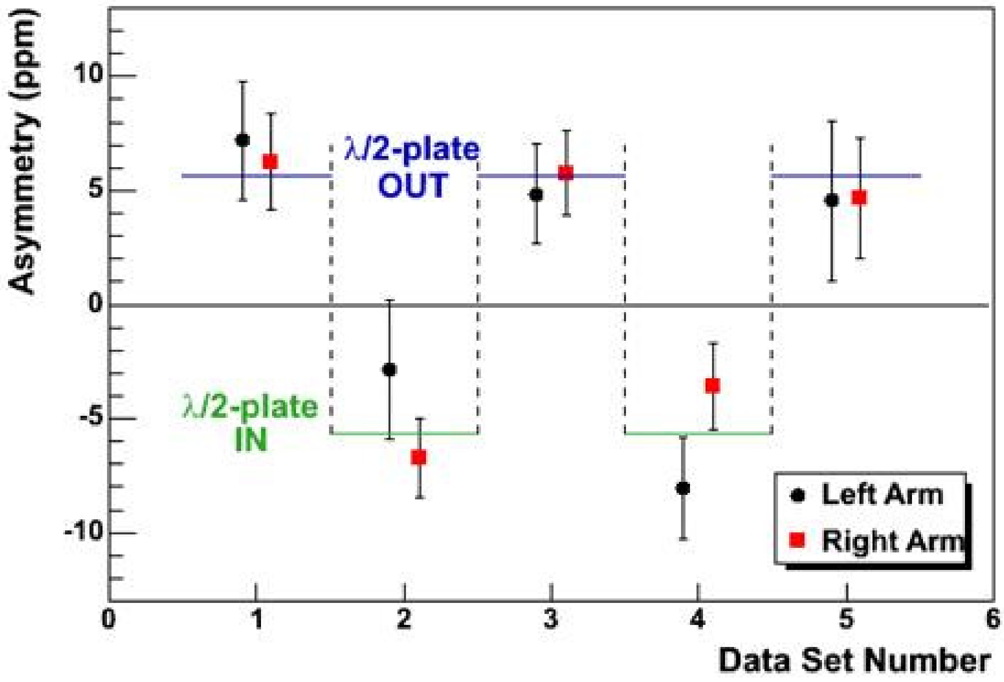
^{4}He Results

Raw Parity-Violating Asymmetry

3.3 M pairs, total width ~1300 ppm

A_{raw} correction < 0.2 ppm


Helicity Window Pair Asymmetry



$Q^2 = 0.091\ (GeV/c)^2$

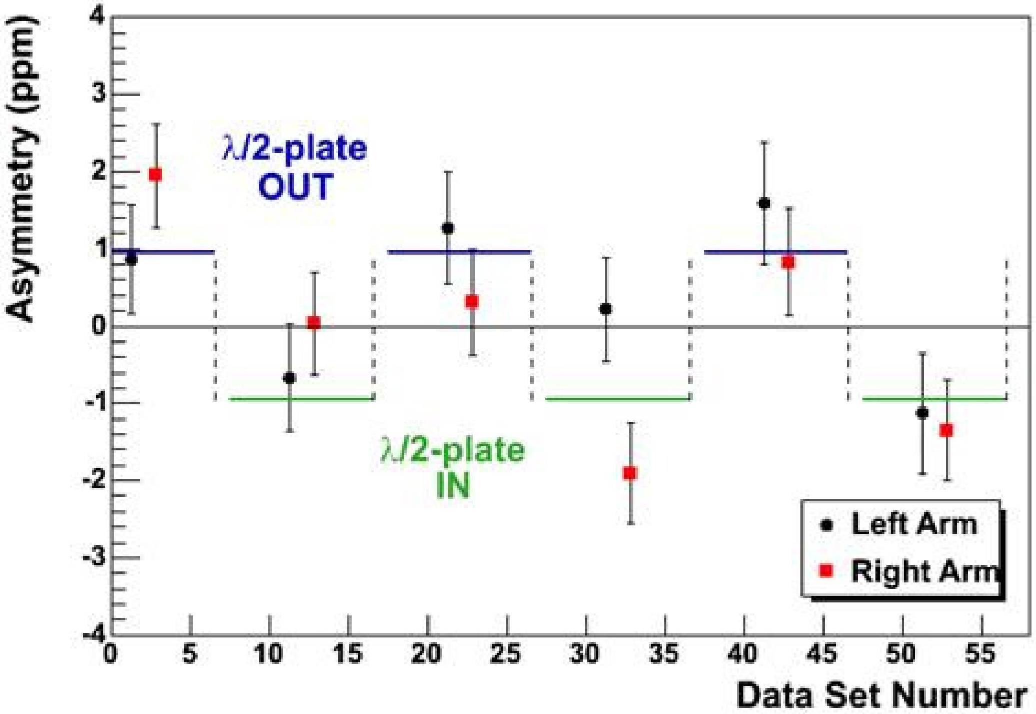
$A_{raw} = 5.63$ ppm ± 0.71 ppm (stat)

^1H Results

Raw Parity-Violating Asymmetry

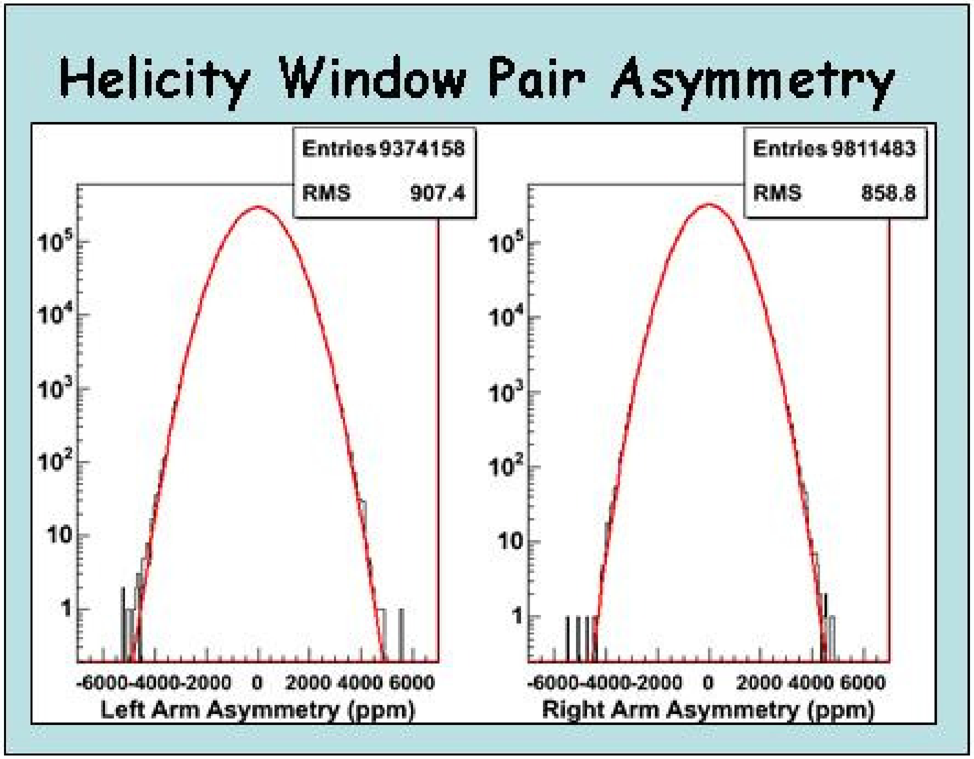
9.5 M pairs, total width ~620 ppm

A_{raw} correction ~ 0.06 ppm

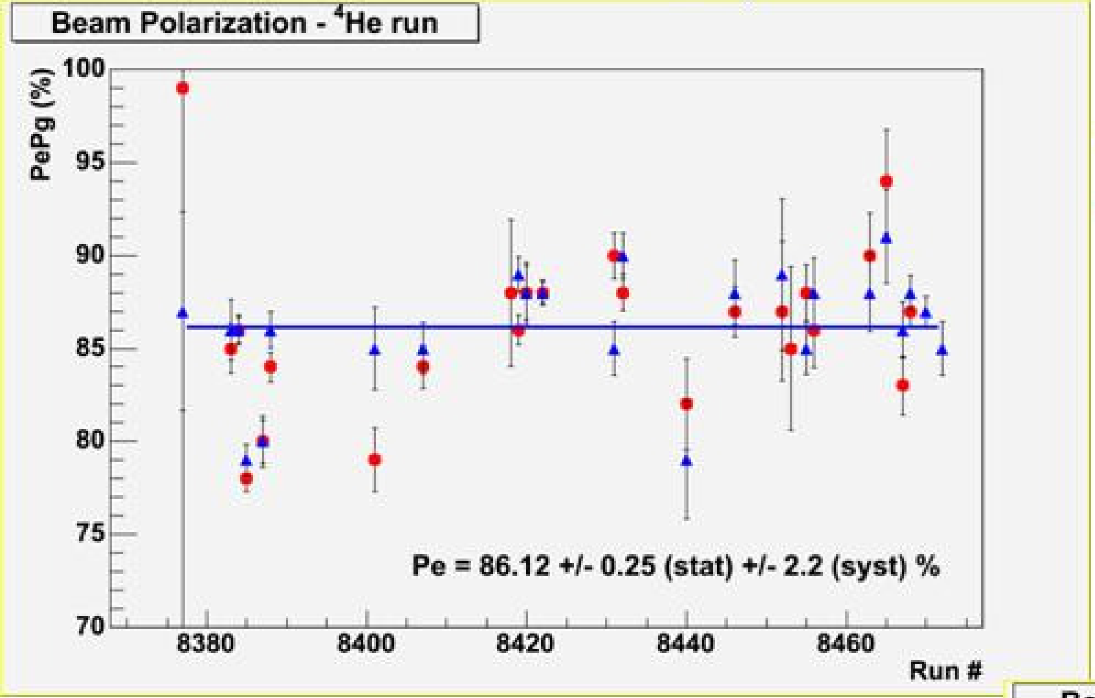


$Q^2 = 0.099\ (GeV/c)^2$

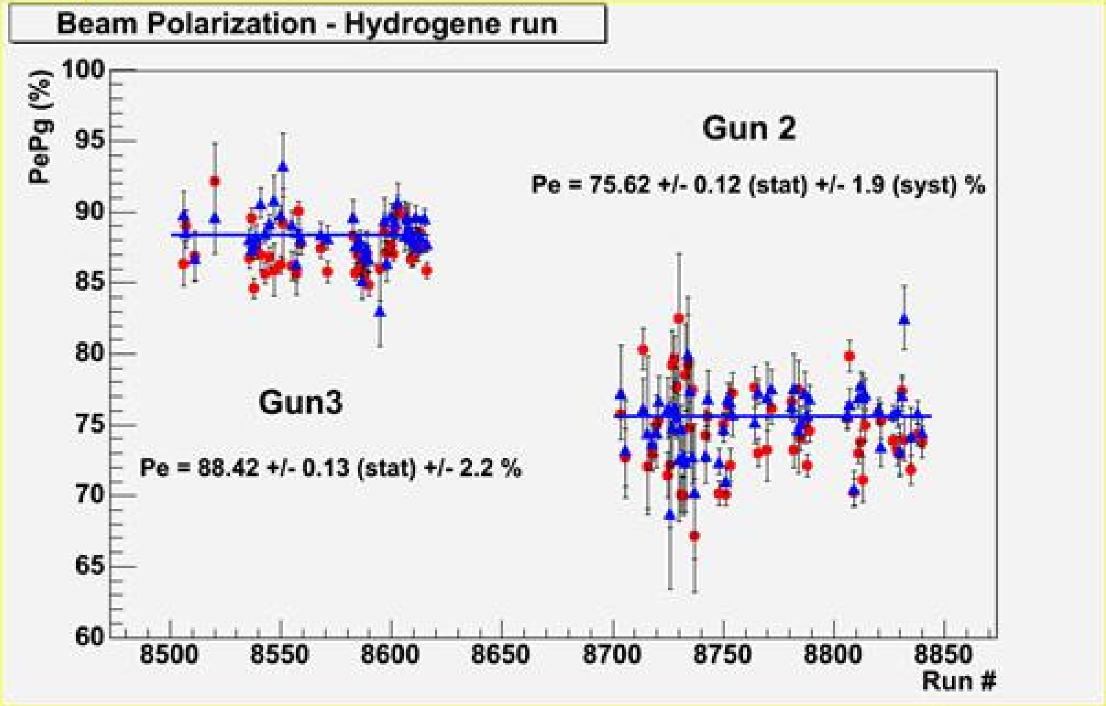
$A_{raw} = -0.95$ ppm ± 0.20 ppm (stat)


Helicity Window Pair Asymmetry

Compton Polarimetry



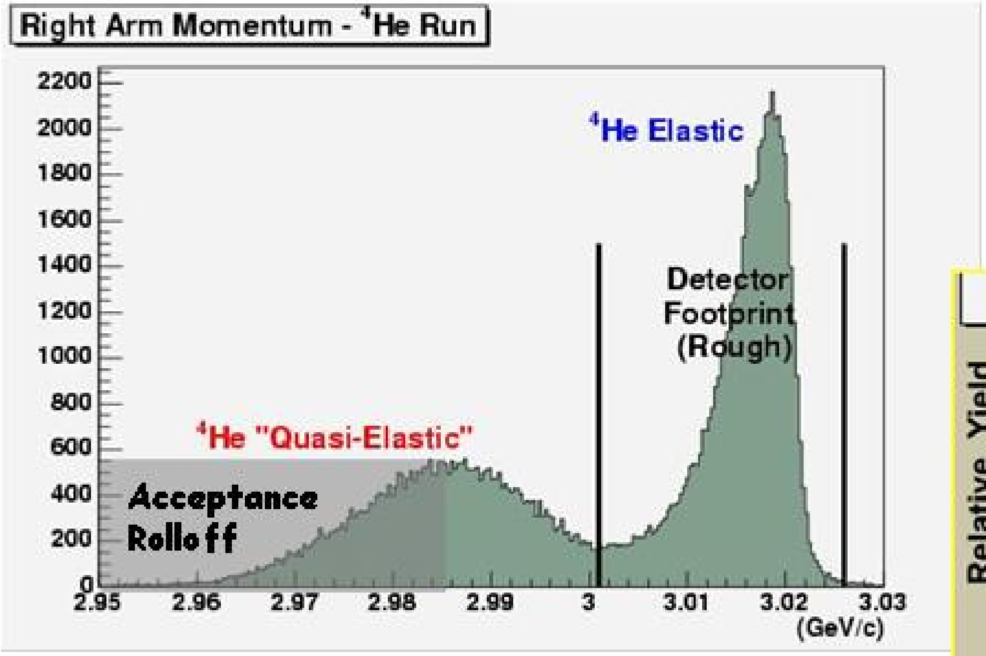
- **photon**
- **electron**



Superlattice:
P_e=85-89% !

Background

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

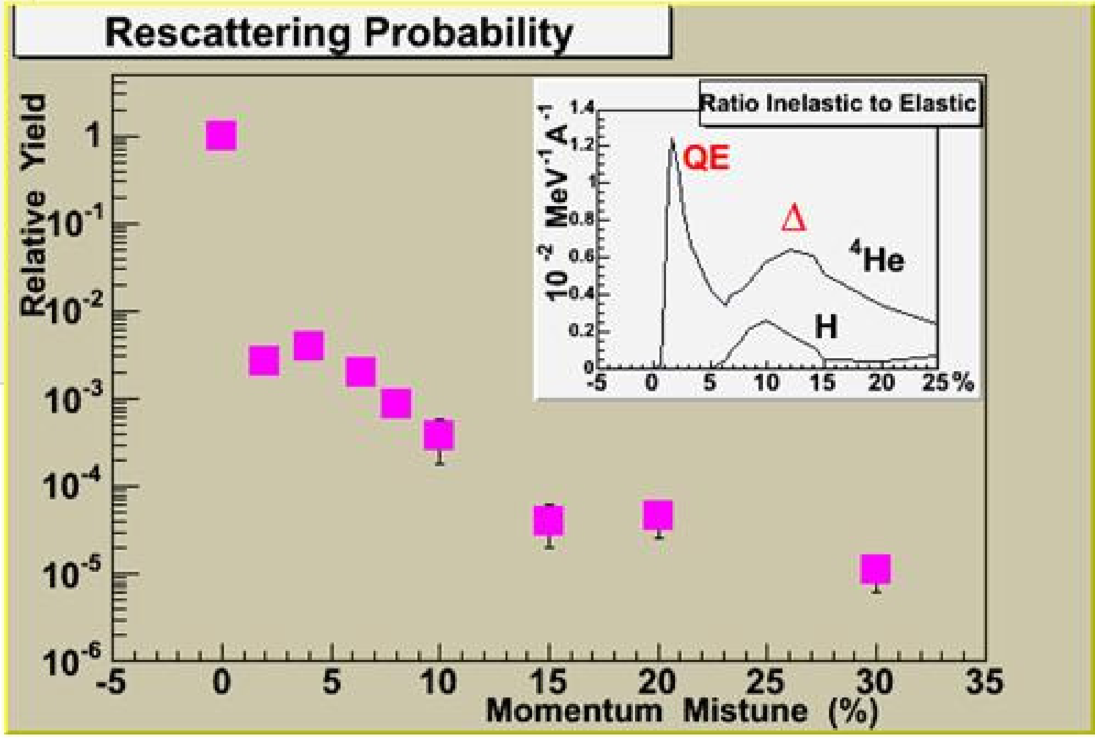


Helium QE in detector: 1.6 +/- 0.8%
Helium QE rescatter: 0.6 +/- 0.6%

Hydrogen Tail + Delta rescatter: <0.2%

Dedicated run with Al Dummy
for Al window QE background: <1%

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



Determining Q^2

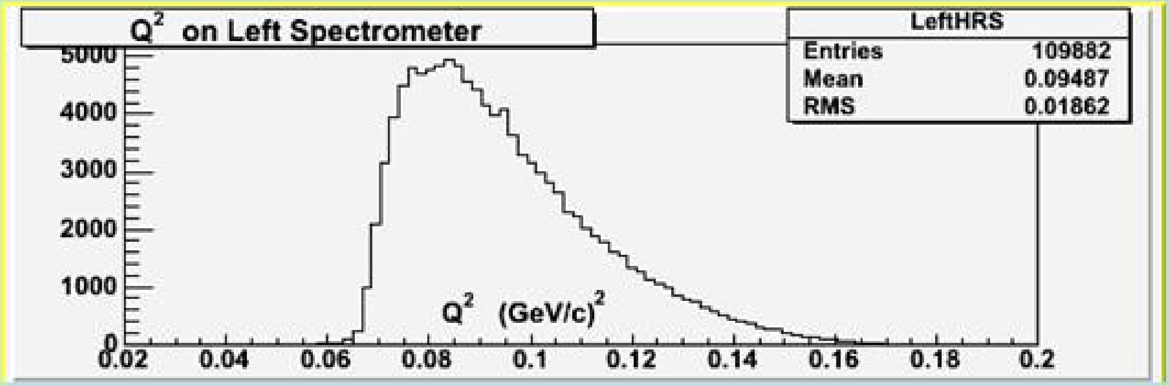
Asymmetry explicitly depends on Q^2:

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

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

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

Effective Kinematics

$\langle Q^2 \rangle \sim 0.09\ (\mathrm{GeV}/c)^2$

measured at low current with Drift Chambers

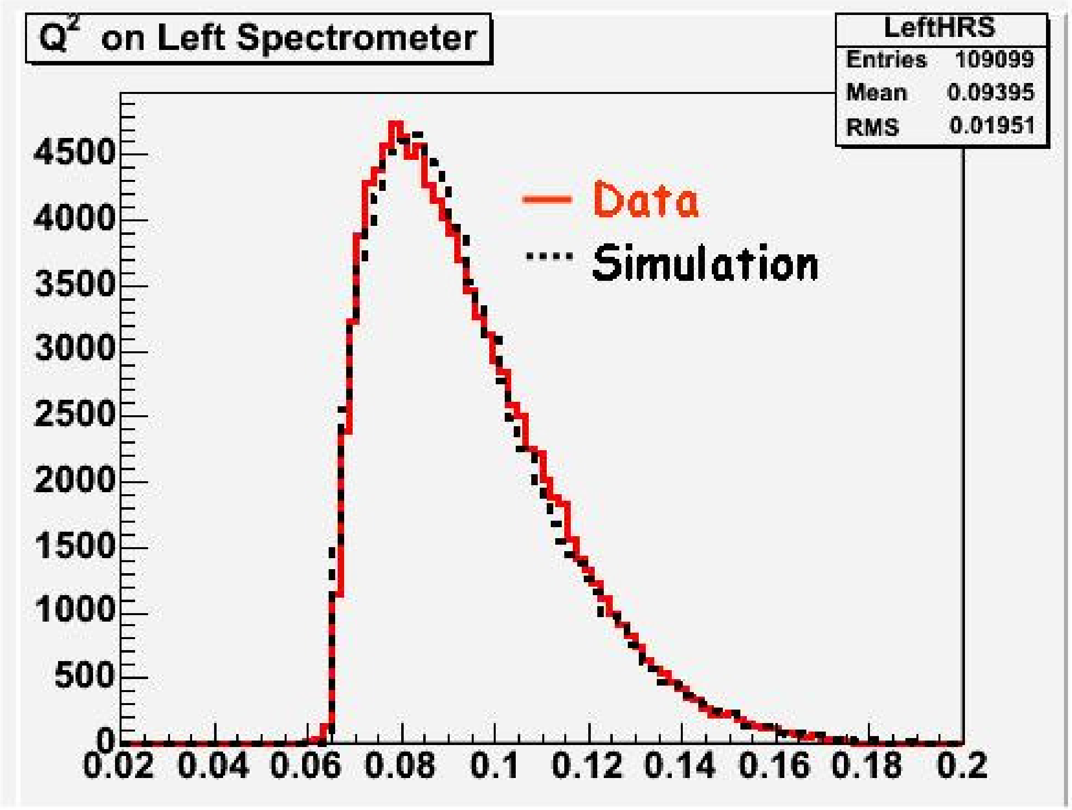
EMFF dependence of Hydrogen requires a correction factor to relate measured asymmetry to central kinematics

External radiative corrections are nearly irrelevant: finite detector acceptance is important.

$$A_v = C\, A_{meas}$$

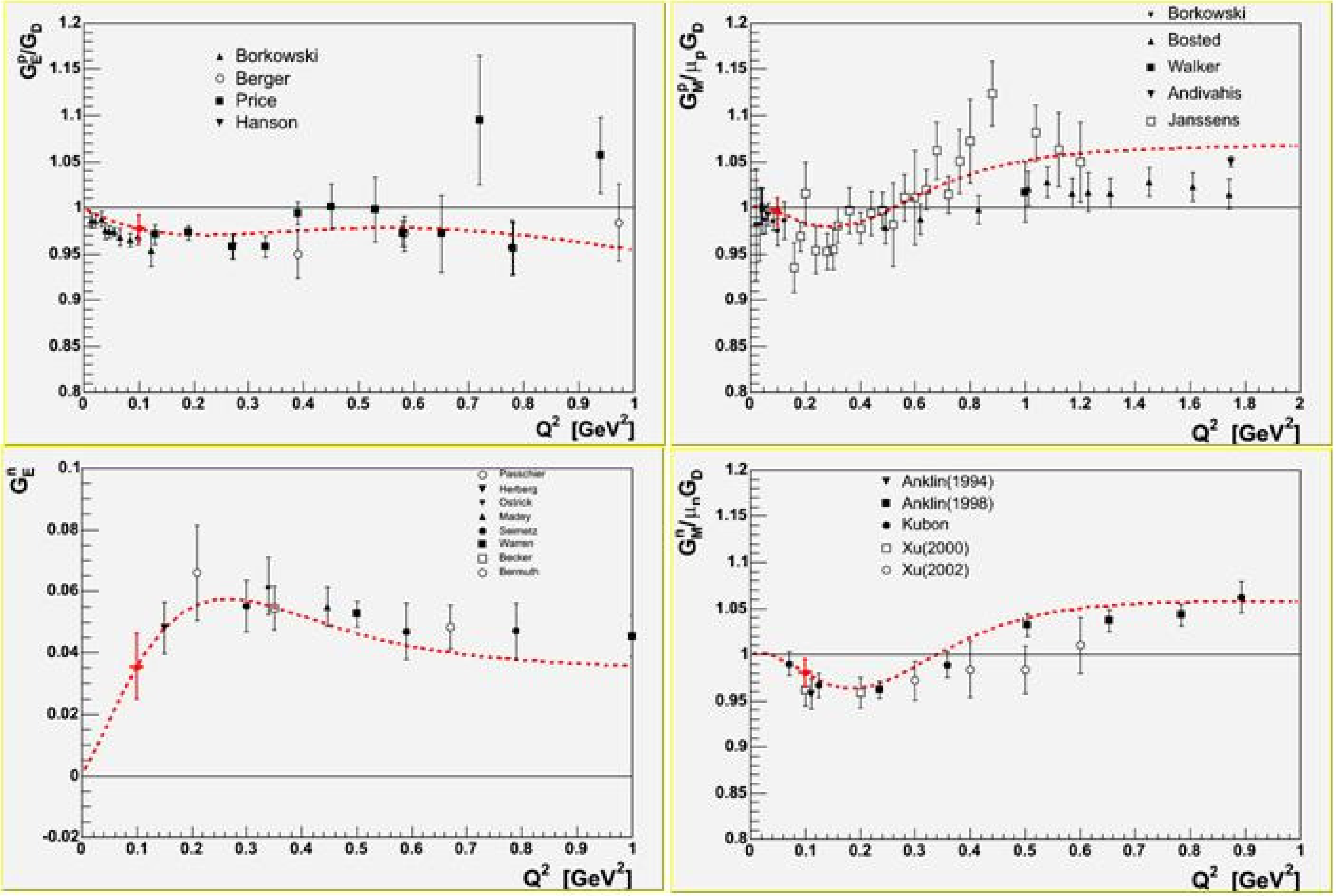
$C_{hydro} = 0.976 +/- 0.006$

$C_{helium} = 1.000 +/- 0.001$



EM Form Factors

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



FF	Error
G_E^p	2.5%
G_M^p	1.5%
G_E^n	30%
G_M^n	1.5%
$G_A^{(3)}$	-
$G_A^{(8)}$	-

2004 HAPPEX-II Results

HAPPEX-^{4}He:

$$Q^2 = 0.091\ (\mathrm{GeV/c})^2$$

$$A_{PV} = +6.72 \pm 0.84\ (\mathrm{stat}) \pm 0.21\ (\mathrm{syst})\ \mathrm{ppm}$$

$$A(G^s=0) = +7.507\ \mathrm{ppm} \pm 0.075\ \mathrm{ppm}$$

$$G^s_E = -0.039 \pm 0.041_{(\mathrm{stat})} \pm 0.010_{(\mathrm{syst})} \pm 0.004_{(\mathrm{FF})}$$

HAPPEX-H:

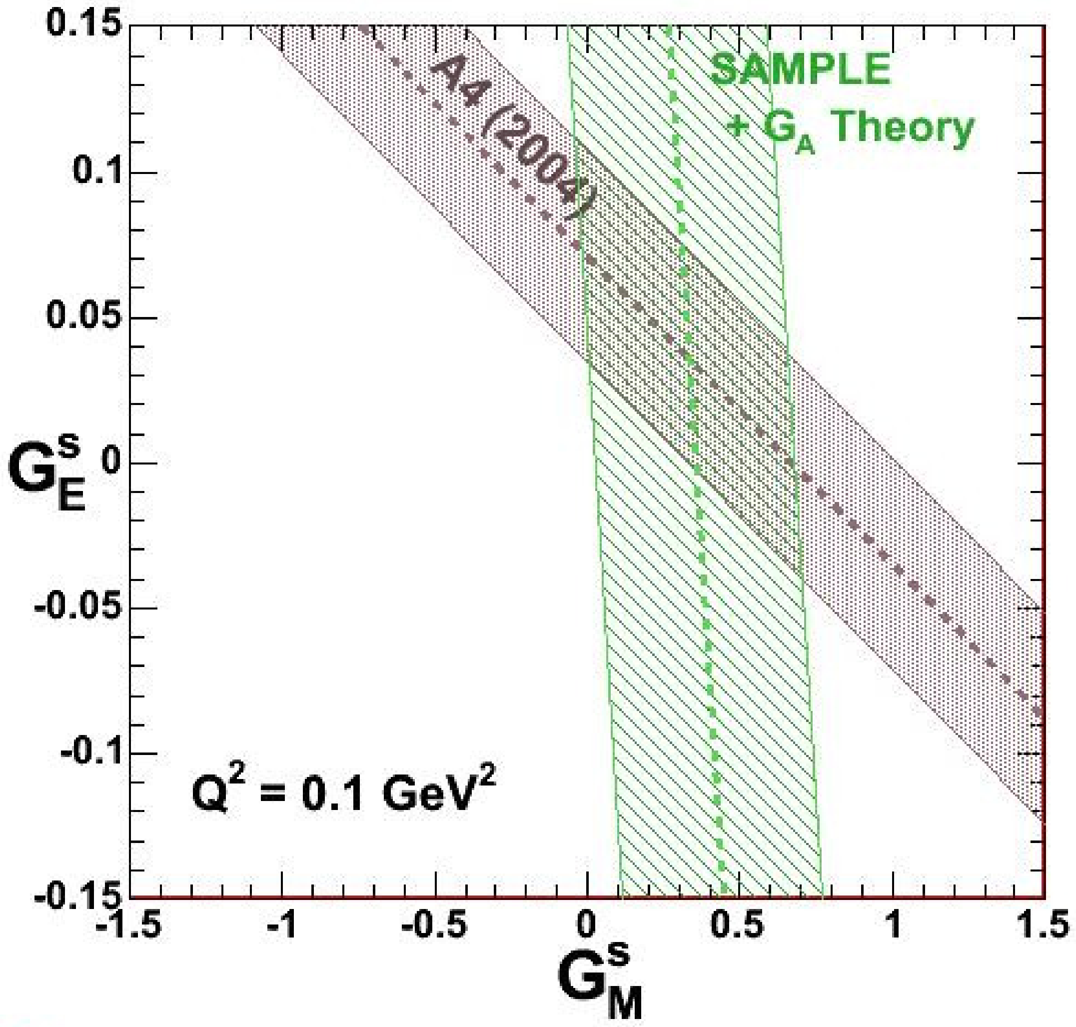
$$Q^2 = 0.099\ (\mathrm{GeV/c})^2$$

$$A_{PV} = -1.14 \pm 0.24\ (\mathrm{stat}) \pm 0.06\ (\mathrm{syst})\ \mathrm{ppm}$$

$$A(G^s=0) = -1.440\ \mathrm{ppm} \pm 0.105\ \mathrm{ppm}$$

$$G^s_E + 0.08\, G^s_M = 0.032 \pm 0.026_{(\mathrm{stat})} \pm 0.007_{(\mathrm{syst})} \pm 0.011_{(\mathrm{FF})}$$

2004 HAPPEX-II Results

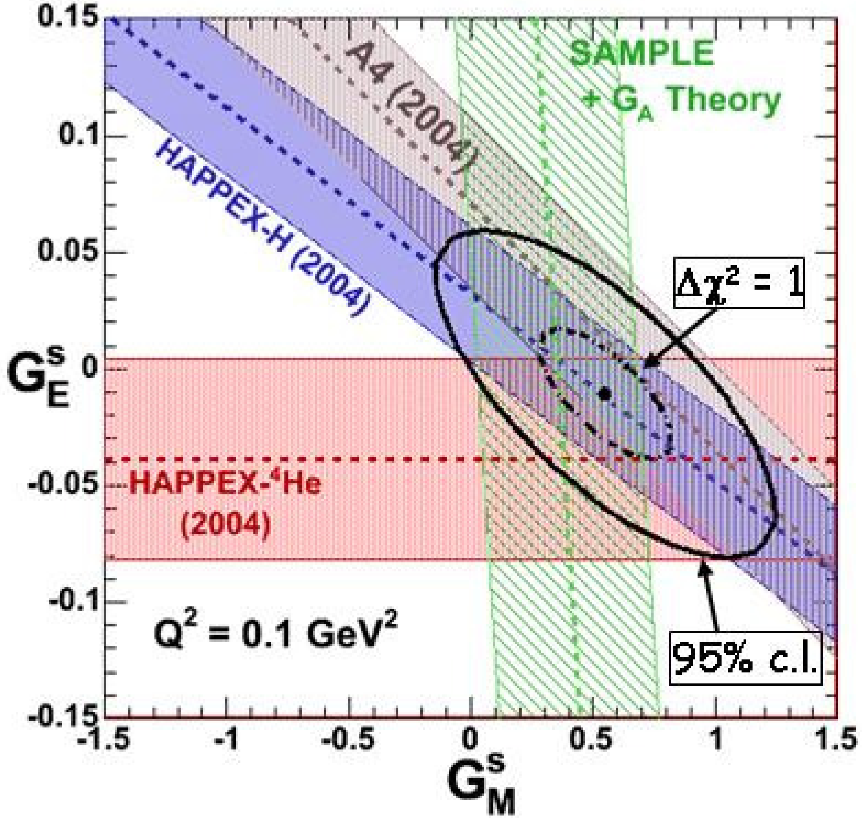


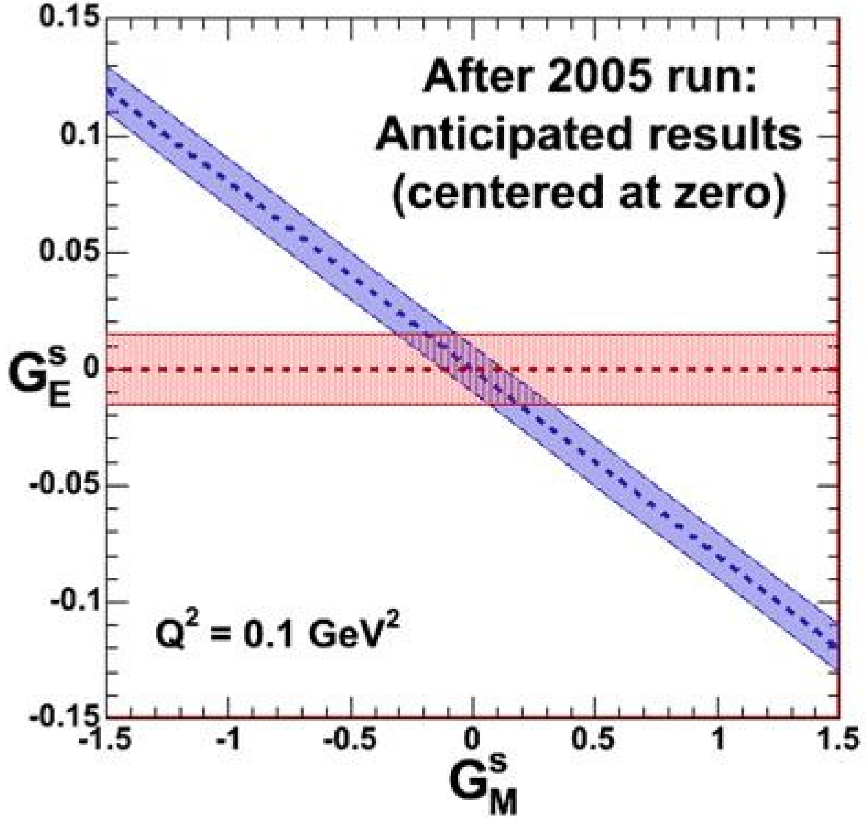
$$G^s_E = -0.039 \pm 0.041_{(stat)} \pm 0.010_{(syst)} \pm 0.004_{(FF)}$$

$$G^s_E + 0.08\, G^s_M = 0.032 \pm 0.026_{(stat)} \pm 0.007_{(syst)} \pm 0.011_{(FF)}$$

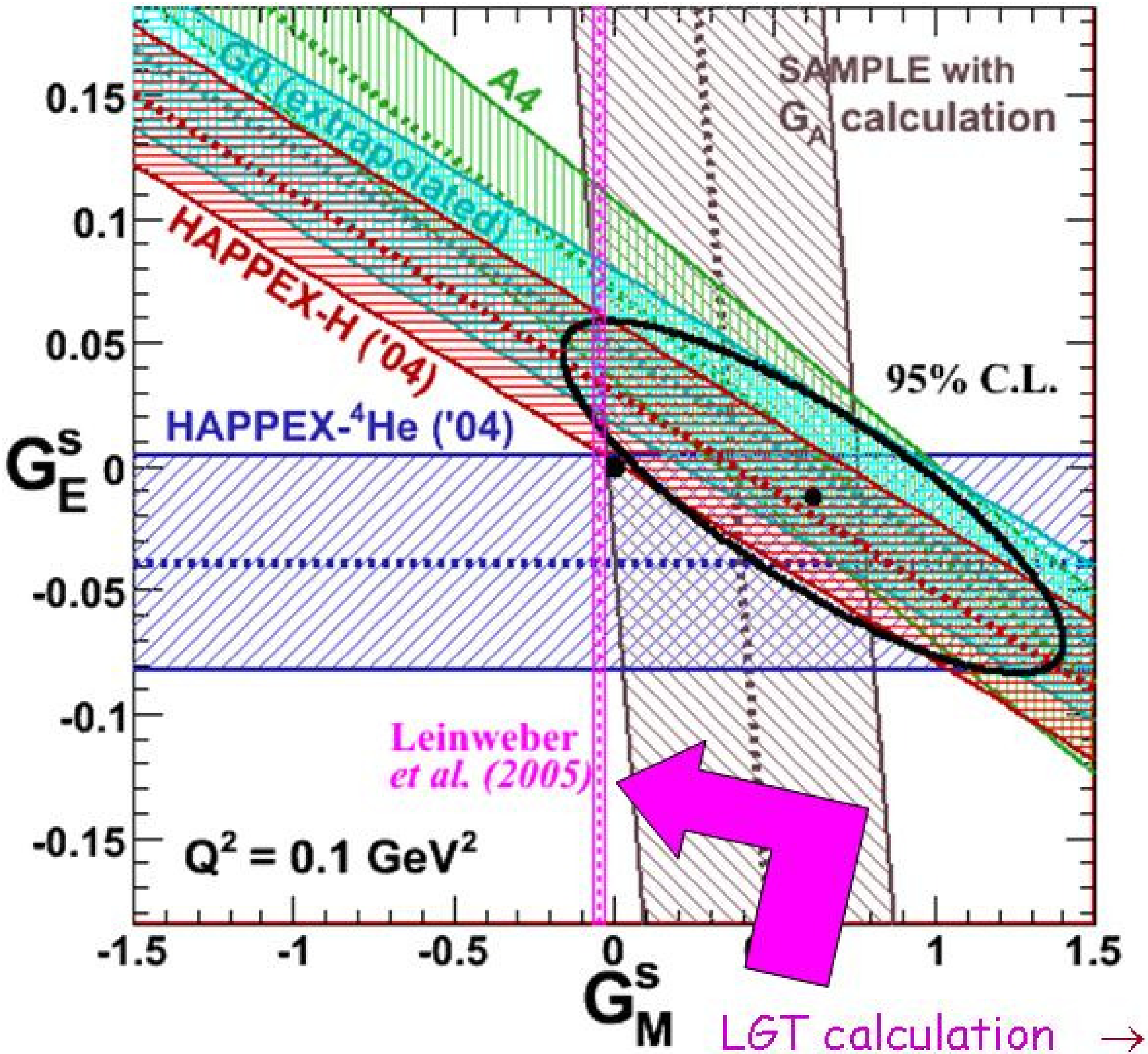
The near future

- '04 run has demonstrated control over systematic errors
- Expected to achieve full proposed precision in 2005 (underway)
- Suggestions of positive G_M^s from 2004 data set will be well tested by final HAPPEX-II result





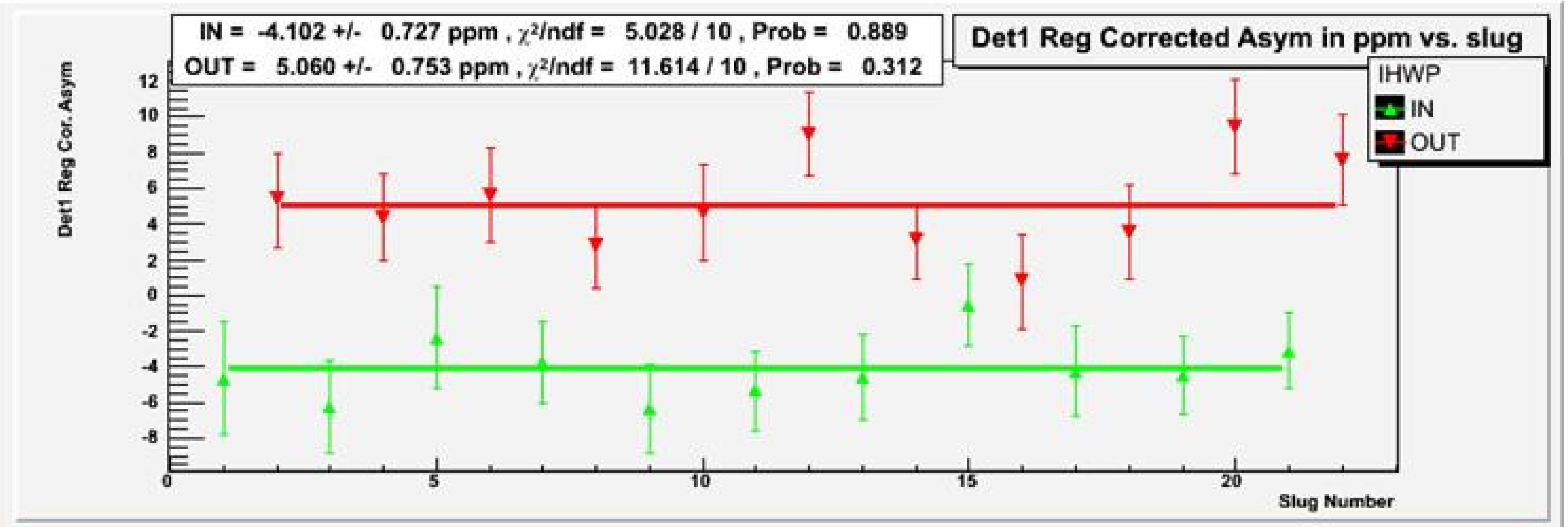
The world data at $Q^2 = 0.1$



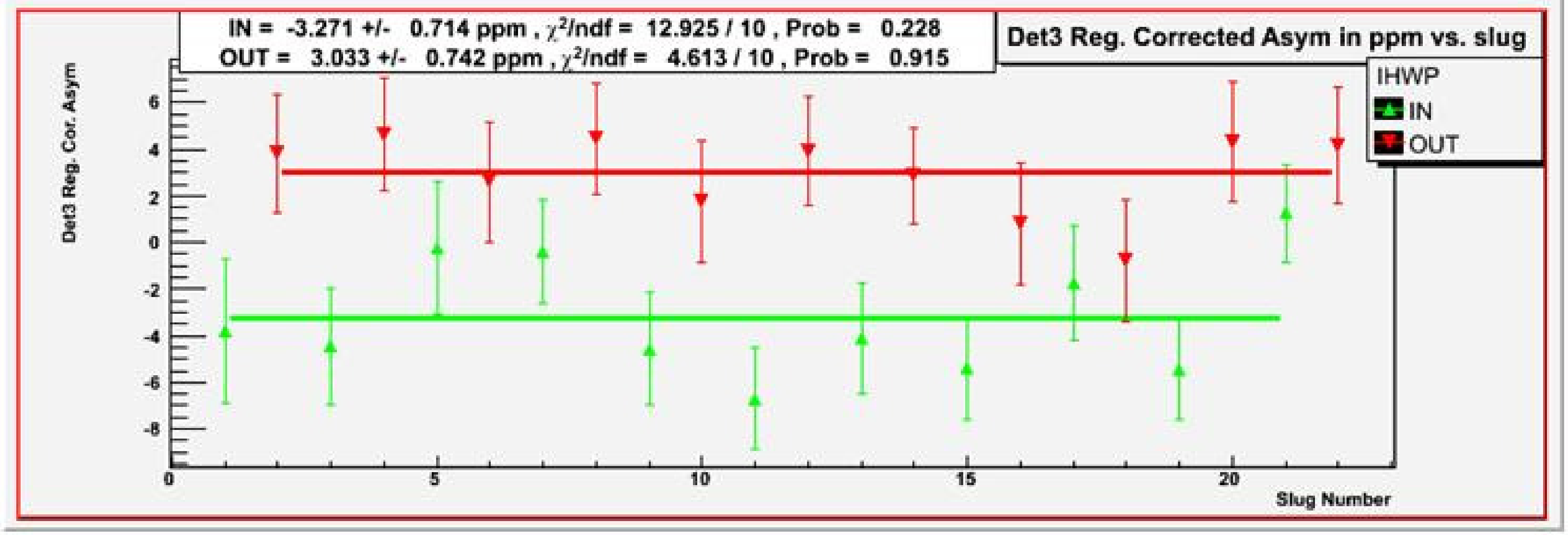
LGT calculation → A. Thomas talk

2005 HAPPEX-Helium   Online Results

- Asymmetry is "blinded".
- Each $\lambda/2$ setting is ~ 10 hrs of data.

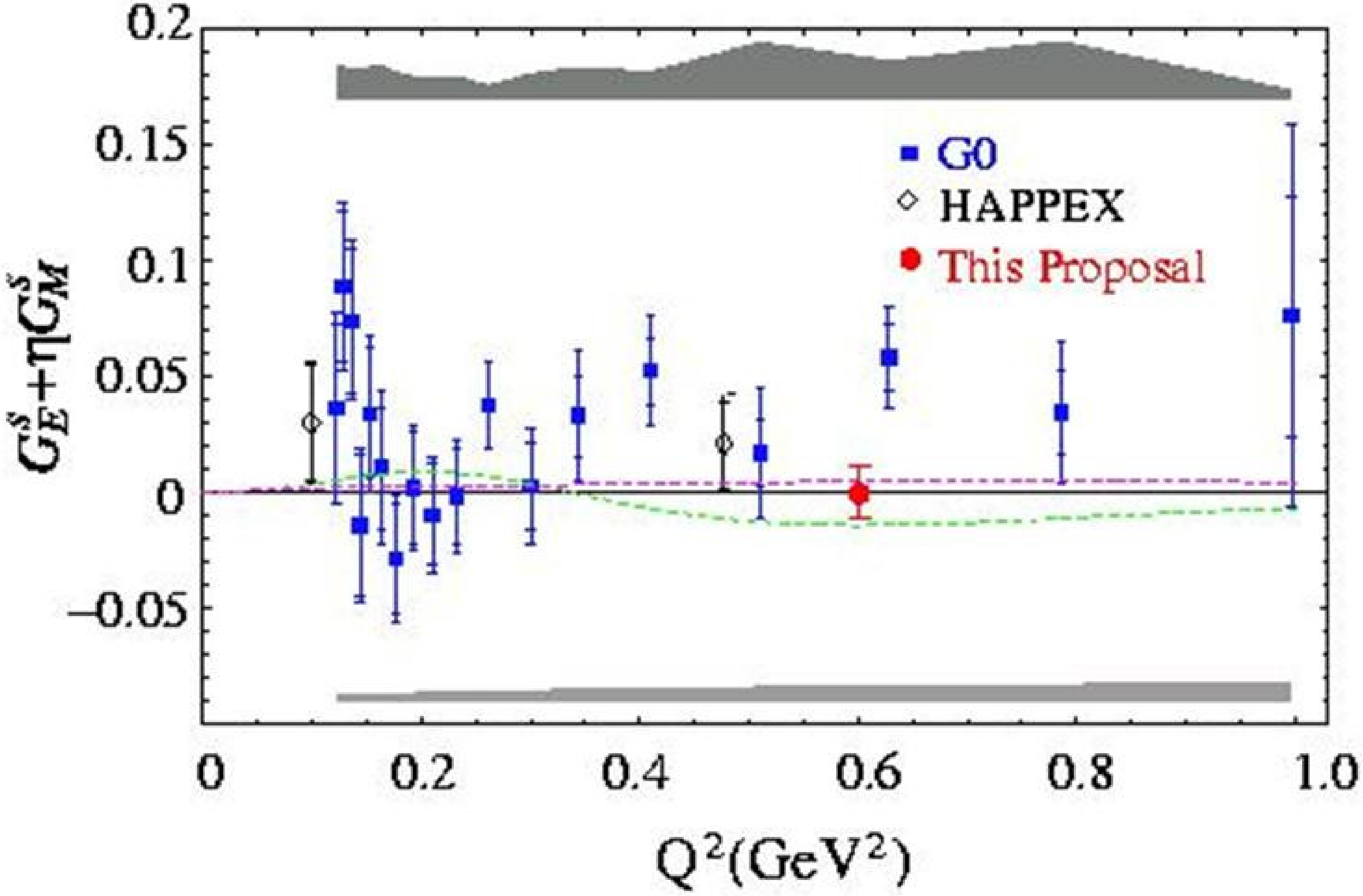


Left Arm



Right Arm

New Proposal: HAPPEX at higher Q^2

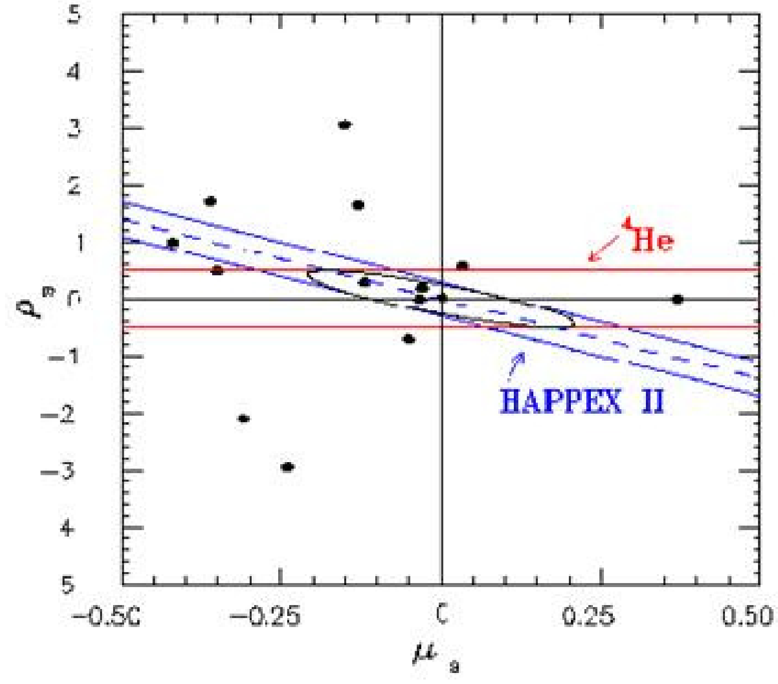


Paschke & Souder, submitted to PAC28

Conclusions

- Marvelous consistency of present data, esp. at Q^2=0.1 *GeV*^{2}.
- Q^2 = 0.1 *GeV*^{2} data suggest that G^s_M is non-zero and positive.
- 2005 HAPPEx-hydrogen & helium results should clarify situation:
  pushing the precision frontier…
- Future run at Q^2 = 0.6 *GeV*^{2} (if approved) of compelling interest
  given forward-angle *G0* results.

Many slides shamelessly stolen from various colleagues: K. Kumar, M. Pitt, E. Beise,
D. Beck, and especially K. Paschke…



^{4}He
HAPPEX II
ρ_s
μ_s
5
4
3
2
1
0
−1
−2
−3
4
5
−0.50
−0.25
0
0.25
0.50

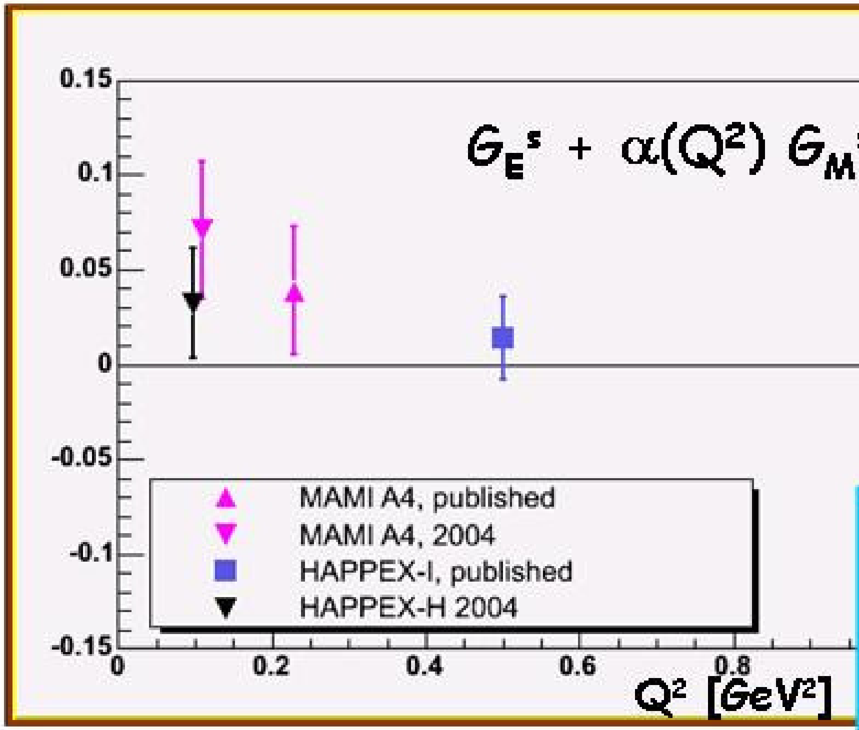
Error Budget-Helium

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

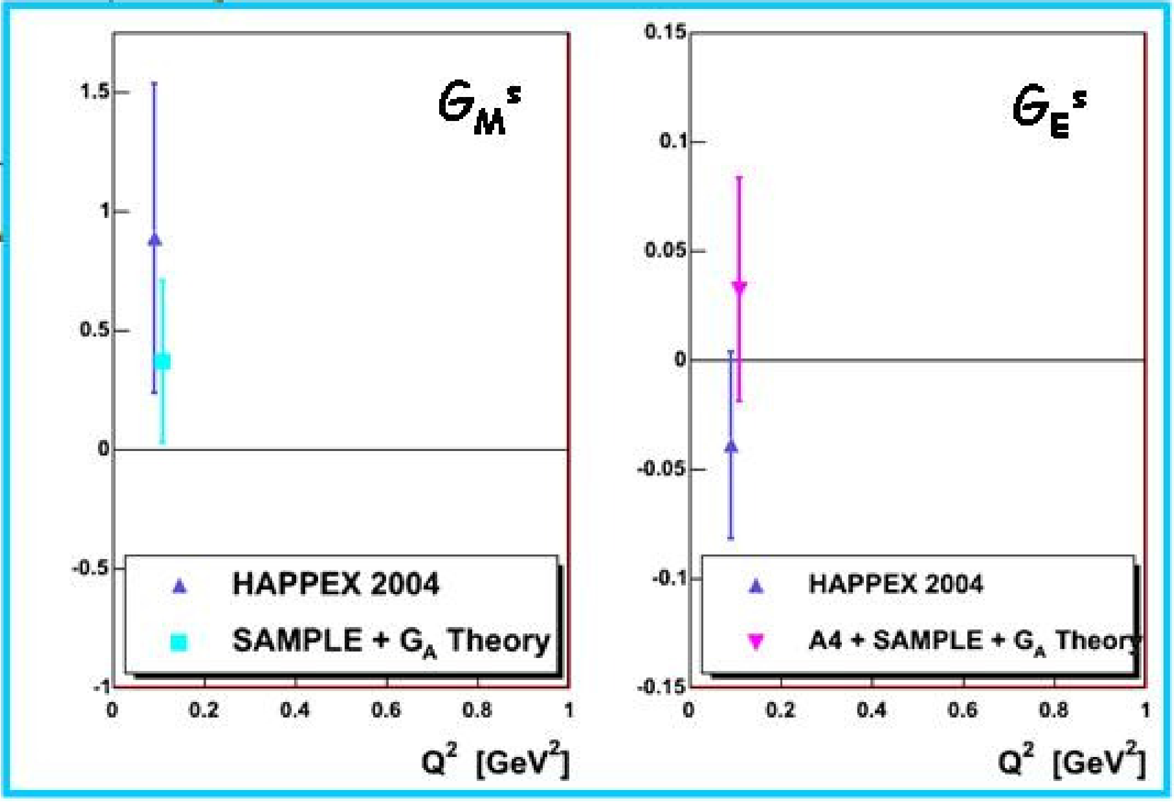
Error Budget-Hydrogen

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

Present results, and looking ahead



HAPPEX-H 2004 result joins the trend at low Q^2



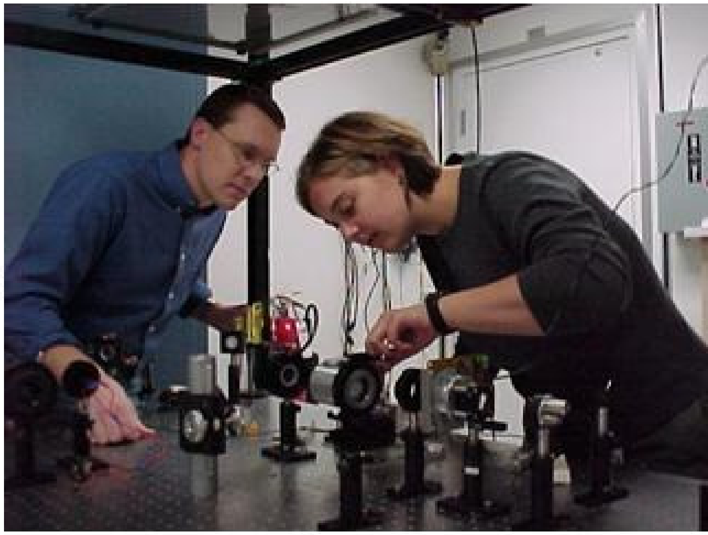
The situation is suggestive, but still ambiguous!

Final anticipated HAPPEX precision has the potential to provide a clear answer.

Controlling Position Differences

Identify and control sources of position differences

- Intrinsic birefringence gradient in the Pockels cell
- Steering from distortions due to piezo-electric deformation of the Pockels cell
- Analyzing power gradients
- *Plus*: vacuum window, QE hole, transmission, upstream gradients, beam loading, current limit…



T.B. Humensky *et. al.*, NIM A 521, 261 (2004)

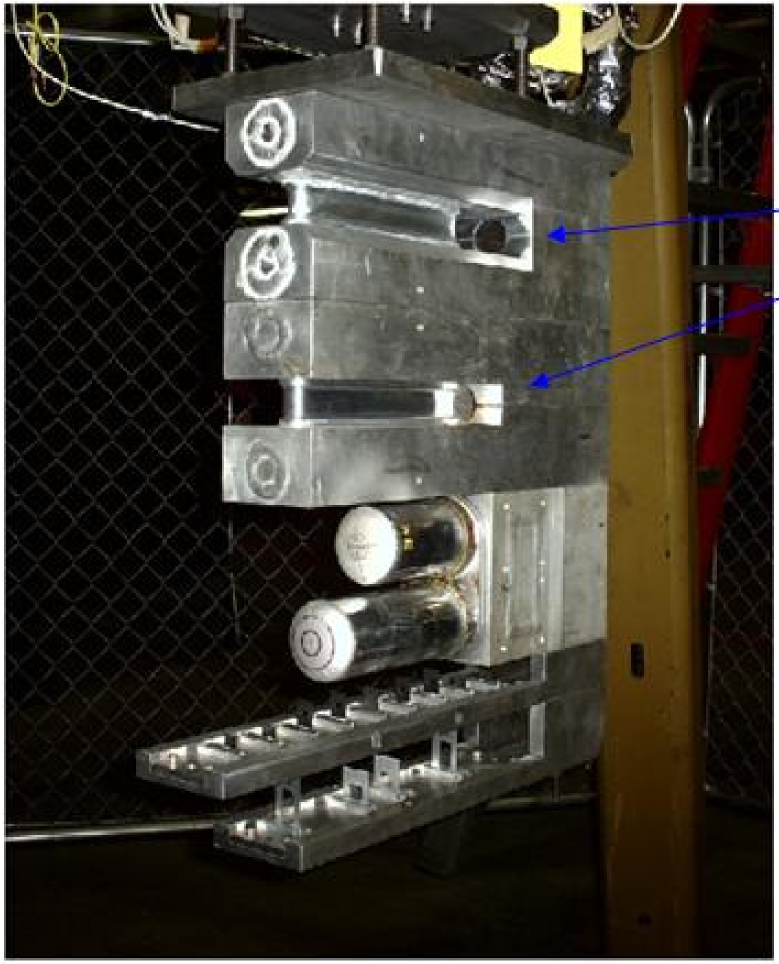
G.D. Cates, Proceedings from PAVI '04

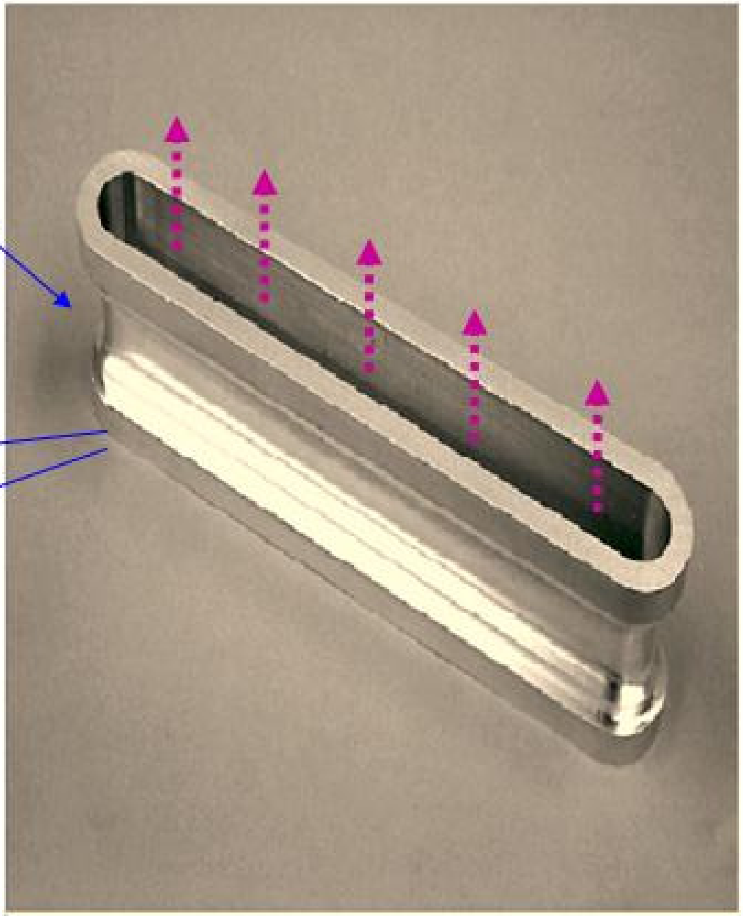
Close Collaboration with the Electron Gun Group in analyzing causes and developing solutions

Laser Test Stand studies and Electron Beam studies have been crucial for developing an understanding of these effects.

Target

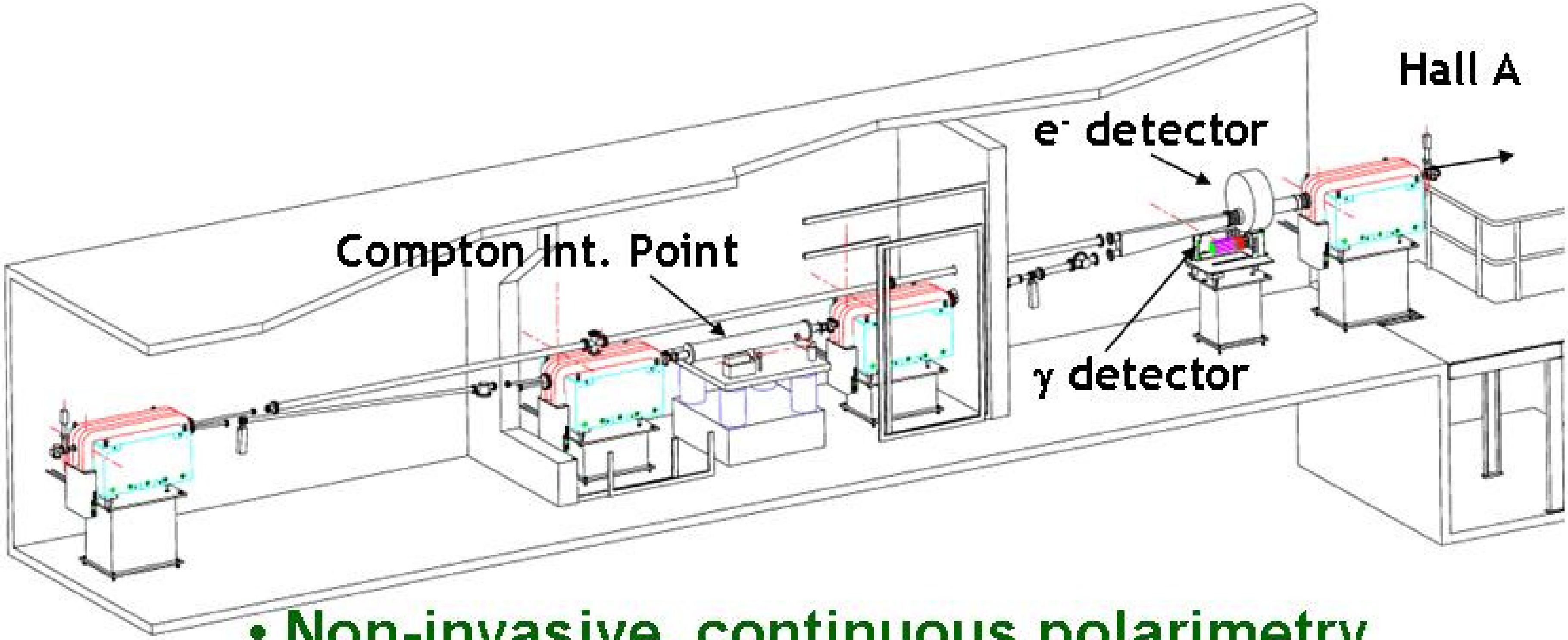
New "race track" design - 20 cm
(transverse cryogen flow)





20 cm LH_2
20 cm ^4He gas cell
Cold (6.6K), dense (230 psi)
Al walls 3-7 mils thick

COMPTON POLARIMETRY



- Non-invasive, continuous polarimetry
- 2% systematic error at 3 GeV
- Independent photon and electron analyses
- Cross-checked with Hall A Moller, 5 MeV Mott
- Requires ~10^{-10} halo, 5mm from primary beam

Measuring Central Angle

Novel Water Cell optics target developed

δp between elastic and excited state peaks reduced systematic error from spectrometer calibration

$\delta\theta \sim 0.3\%$ -> $\delta Q^2 \sim 0.7\%$

$$E' = \frac{E_0 - \frac{1}{2}\left(m^{*2} - m^2\right)}{1 + \frac{E_0}{m(1-\cos\theta)}}$$