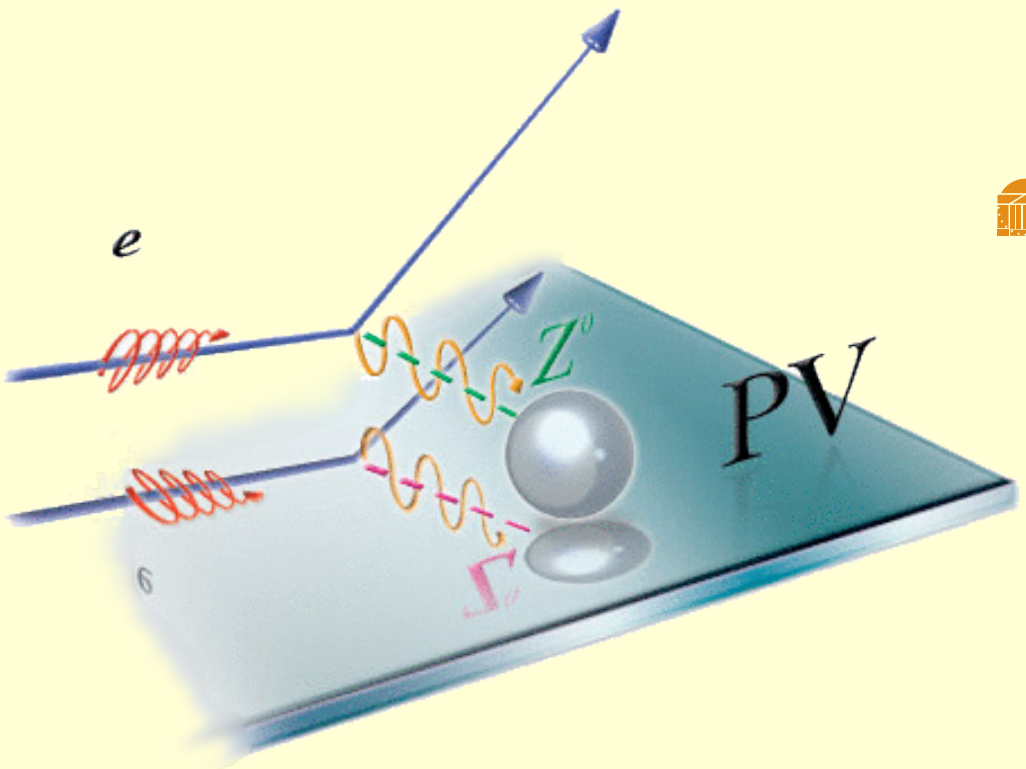
HAPPEX-III and Strangeness Contributions to the Nucleon Vector Form-factors



Kent Paschke

University of Virginia

Jefferson Lab

HAPPEX Collaboration

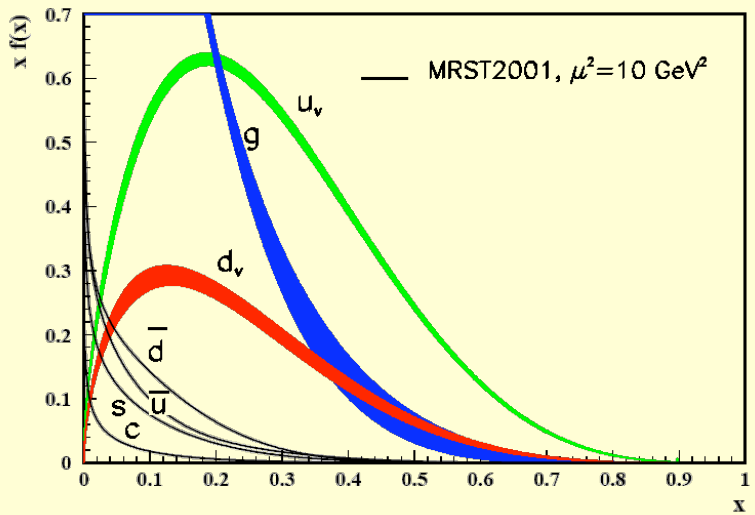
Hall A Collaboration

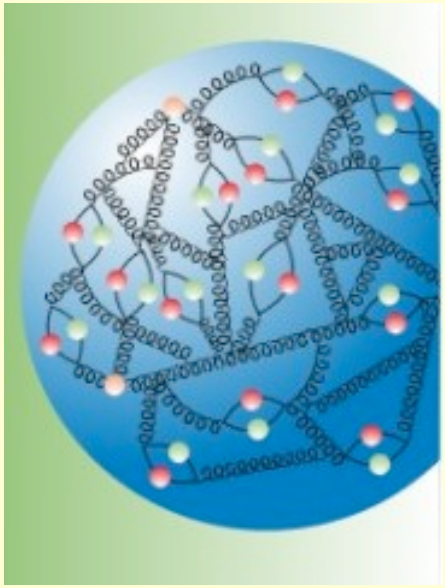
Jefferson Lab

February 18, 2011

Strange Quarks in the Nucleon

Strange quarks exist in the nucleon at short distance scales.





How do they influence the interactions of the nucleon?

Momentum ~ 4% $\int_0^1 x(s+\bar{s})dx$

Mass 0-30% $\langle N|s\bar{s}|N\rangle,\ \Sigma_{\pi N}$

Spin 0 - -10% Δs

Magnetic moment, charge radius ρ_s, μ_s

G_E^s, G_M^s

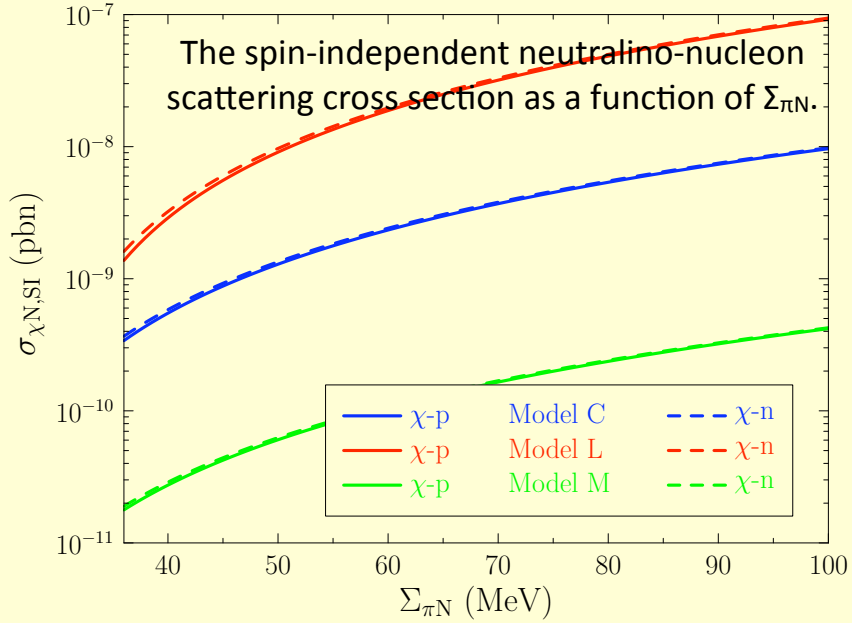
Nucleonic Strangeness in Other Arenas

Dark Matter Searches

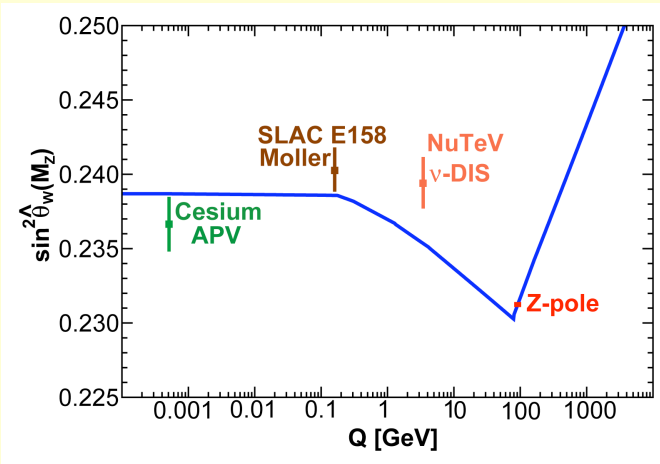
Strange quarks coupling to the Higgs is much higher than that of the u/d flavors.

The spin independent neutralino-nucleon coupling varies by an order of magnitude depending on the strange condensate of the nucleon

The spin dependent neutralino-nucleon coupling depends on Δs



Ellis et al, Phys.Rev. D77 (2008) 065026, arXiv:0801.3656



NuTeV Anomaly

NuTeV published a 3σ deviation from the standard model

The leading hypothesis is that a signficant fraction is explained by an asymmetry in the strange sea: $s - \bar{s}$

Strange Quarks in Elastic Scattering

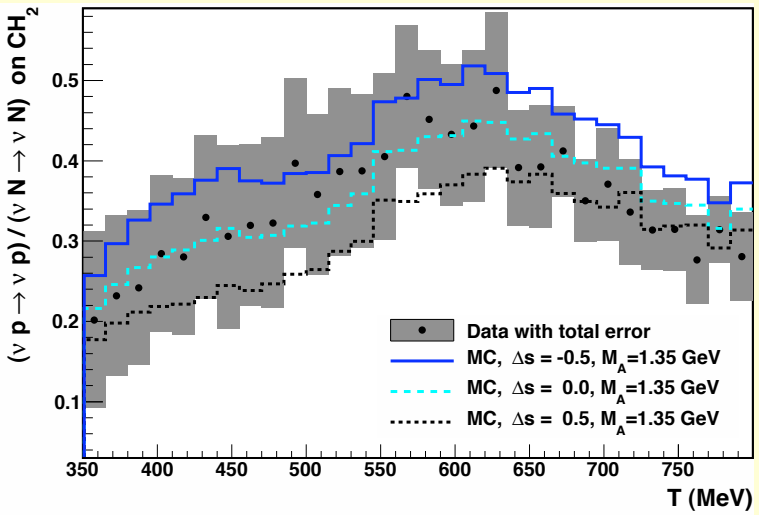


FIG. 12: The ratio of $\nu p \to \nu p / \nu N \to \nu N$ as a function of the reconstructed energy for data and MC with Δs values as labeled.

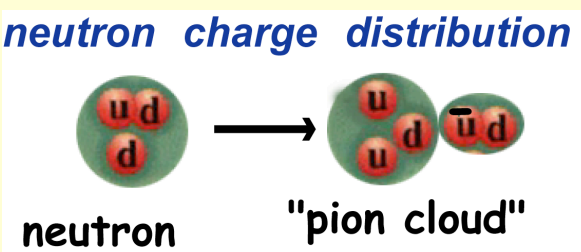
Miniboone Collaboration, Phys.Rev. D82 (2010) 092005

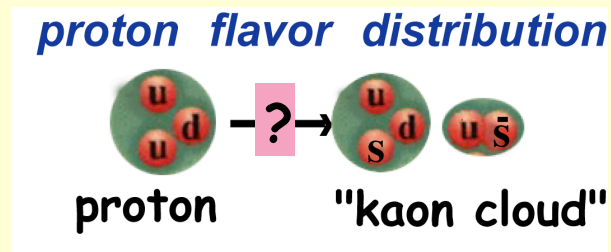
Δs can be fit in neutrino scattering, but this also requires a flavor decomposition of vector electromagnetic form-factors

$$G_E^p = \frac{2}{3} G_E^{u,p} - \frac{1}{3} G_E^{d,p} - \frac{1}{3} G_E^s$$

Also, see fit by Pate *et al.*, **Phys.Rev. C78 (2008) 015207**

Do the strange quarks in the sea play a significant role in the electric/magnetic charge distributions in the nucleon?

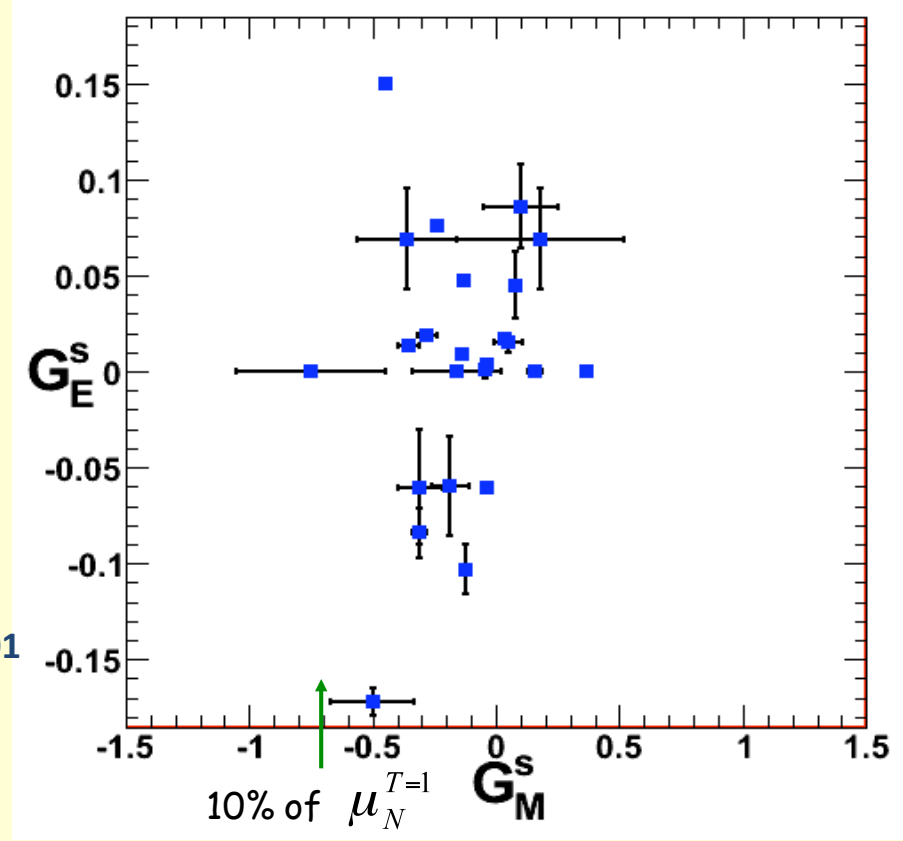




QCD models

Model guidance is unclear:

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, …



Recent significant progress in Lattice QCD:

- Dong, Liu, Williams PRD 58(1998)074504
- Lewis, Wilcox, Woloshyn PRD 67(2003)013003
- Leinweber, et al.,PRL 94(2005) 212001; 97 (2006) 022001
- Lin, arXiv:0707:3844
- Wang et al, Phys.Rev. C79 (2009) 065202
- Doi et al., Phys.Rev. D80 (2009) 094503

these all suggest very small effects

Extracting the Strange Form Factor with the Neutral Weak Interaction

Charge Symmetry

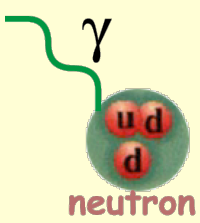
$$G_E^p = \frac{2}{3}G_E^{u,p} - \frac{1}{3}G_E^{d,p} - \frac{1}{3}G_E^s$$

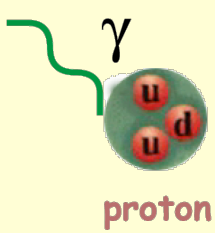
$$G_E^n = \frac{2}{3}G_E^{u,n} - \frac{1}{3}G_E^{d,n} - \frac{1}{3}G_E^s$$

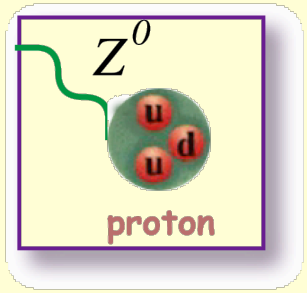
Two equations and three unknowns

Measure neutral weak proton form-factor

Three equations and three unknowns





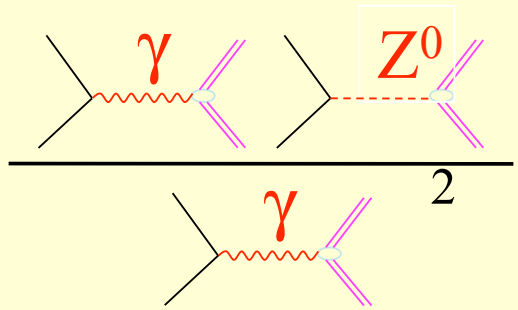


Measuring all three enables separation of up, down and strange contributions

The weak form factor is accessible via parity violation

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

$$\mathbf{G^Z_{E,M} = (1 - 4\sin^2\theta_W) G^p_{E,M} - G^n_{E,M} - G^s_{E,M}}$$

For a spin=0, T=0 ^{4}He: G^s_E only!

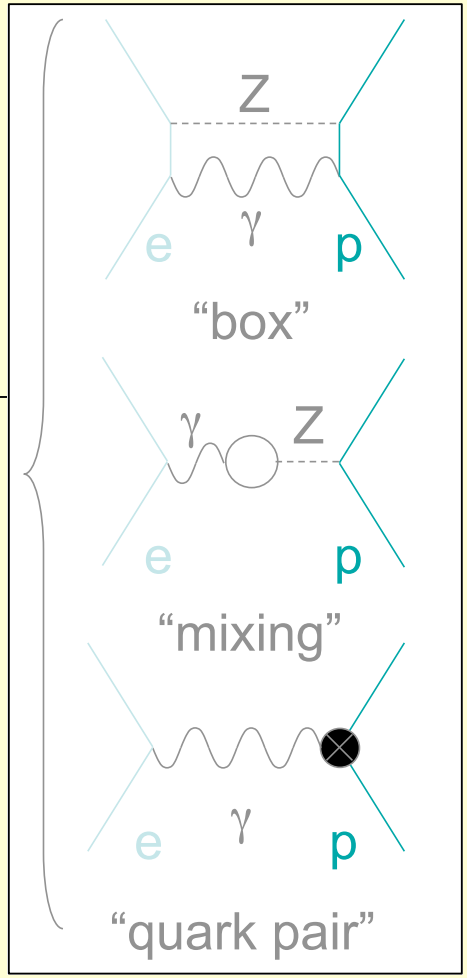
For deuterium: Enhanced G_A

The Axial Term and the Anapole Moment

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

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 often assumed to be dipole form, fit to ν DIS and π electroproduction
- Includes also Δs, fit from ν-DIS data



Anapole Moment Correction:

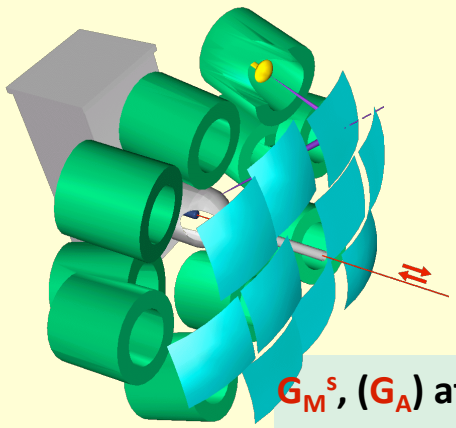
Multiquark weak interaction in $R_A^{(T=1)}$, $R_A^{(T=0)}$

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

- Model dependent calculation with large uncertainty
- Uncertainty dominates axial term

Difficult to achieve tight experimental constraint

Experimental Overview



SAMPLE

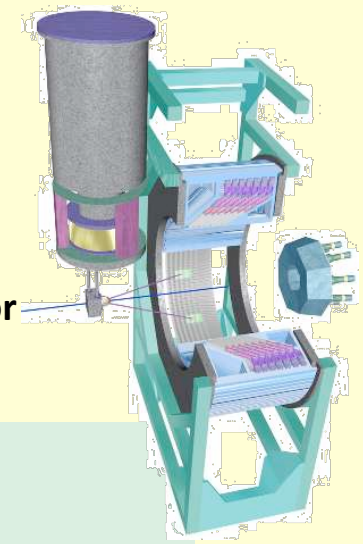
open geometry, integrating

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

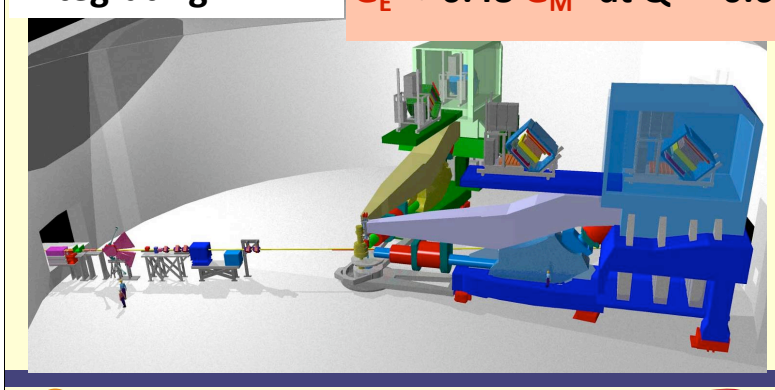
Precision spectrometer, integrating

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

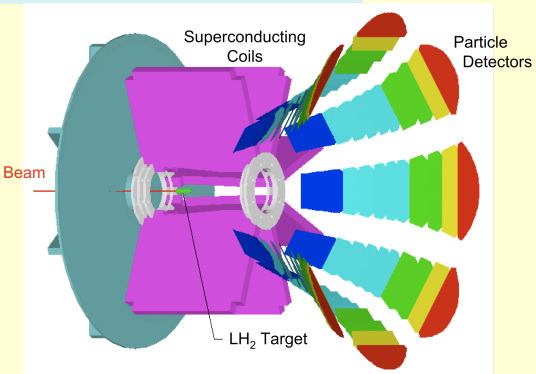
G_E^s + 0.08 G_M^s at Q^2 = 0.1 GeV^2

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



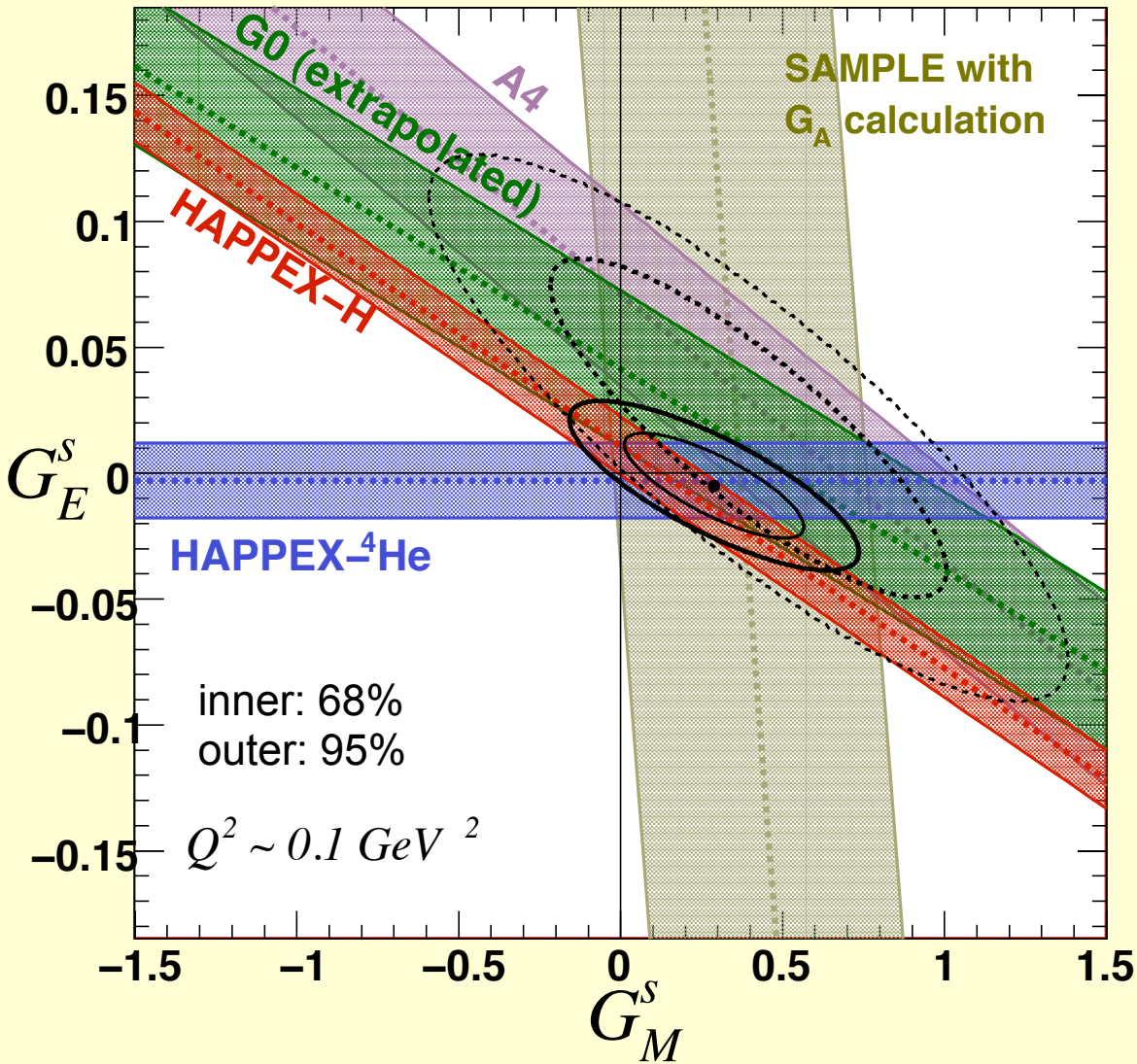
Open geometry

Fast counting with magnetic spectrometer + TOF for background rejection

G_E^s + η 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

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



G_M^s = 0.28 +/- 0.20

G_E^s = -0.006 +/- 0.016

~3% +/- 2.3% of G_M^p

~0.2 +/- 0.5% of G_E^p

HAPPEX-only fit suggests something even smaller:

G_M^s = 0.18 +/- 0.27

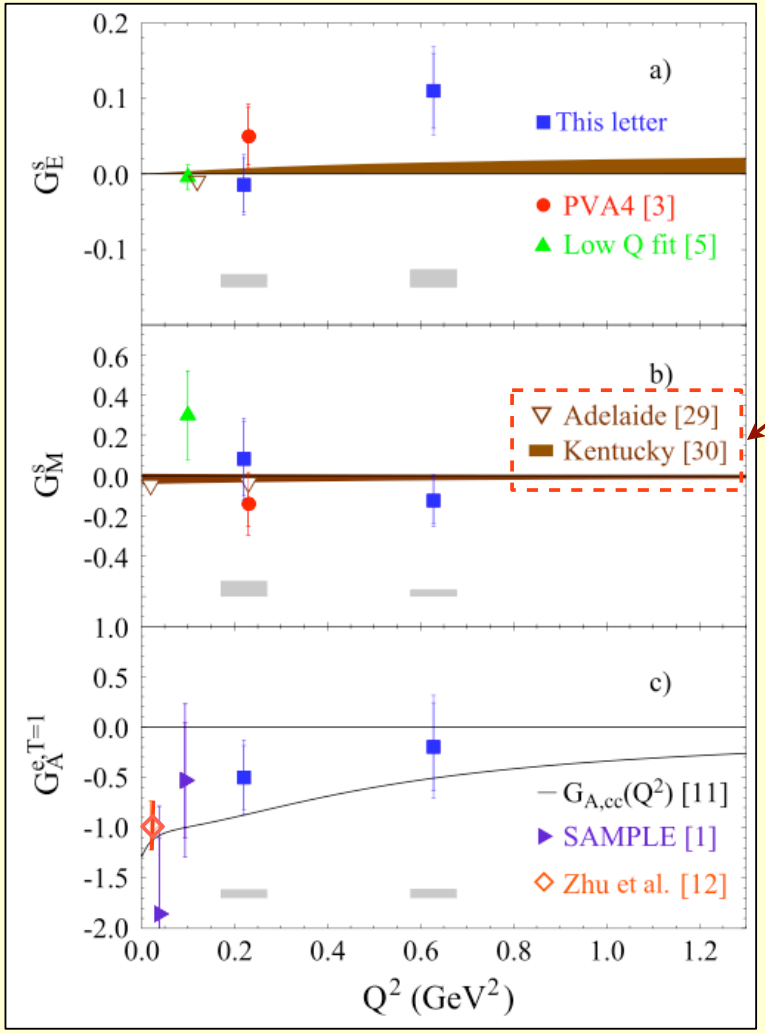
G_E^s = -0.005 +/- 0.019

Caution: the combined fit is approximate. Correlated errors and assumptions not taken into account. More comprehensive fit results can be found in:

Young *et al.*, Phys.Rev.Lett. 97 (2006) 102002, nucl-ex/0604010

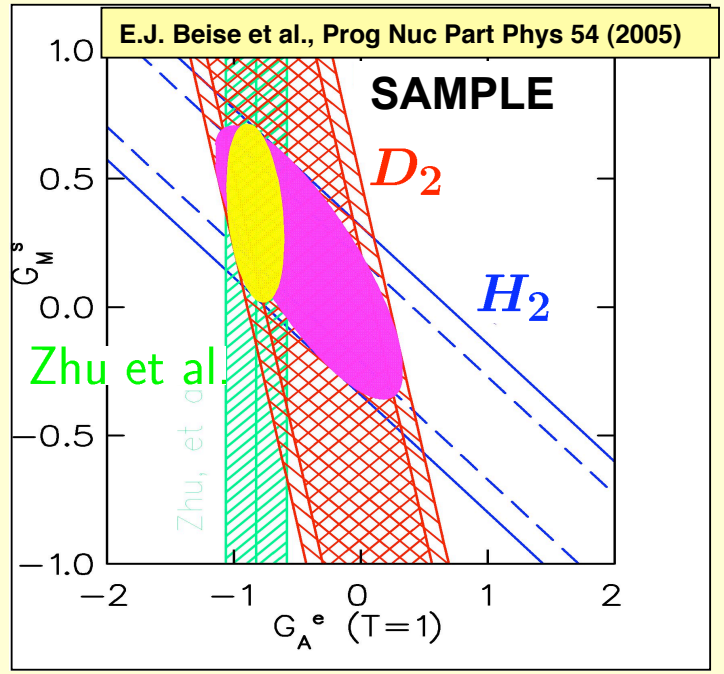
Liu *et al.*, Phys.Rev. C76 (2007) 025202, arXiv:0706.0226

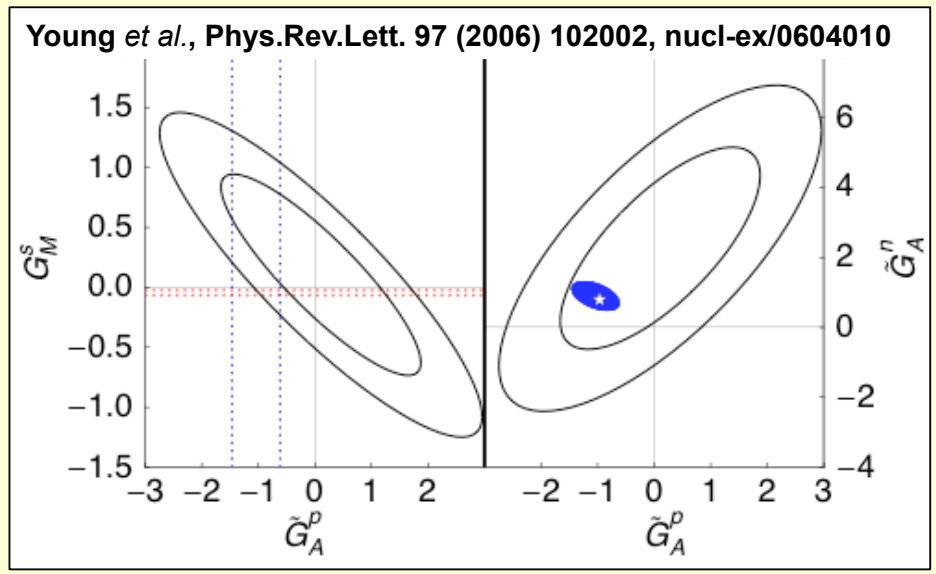
Form Factor Separation



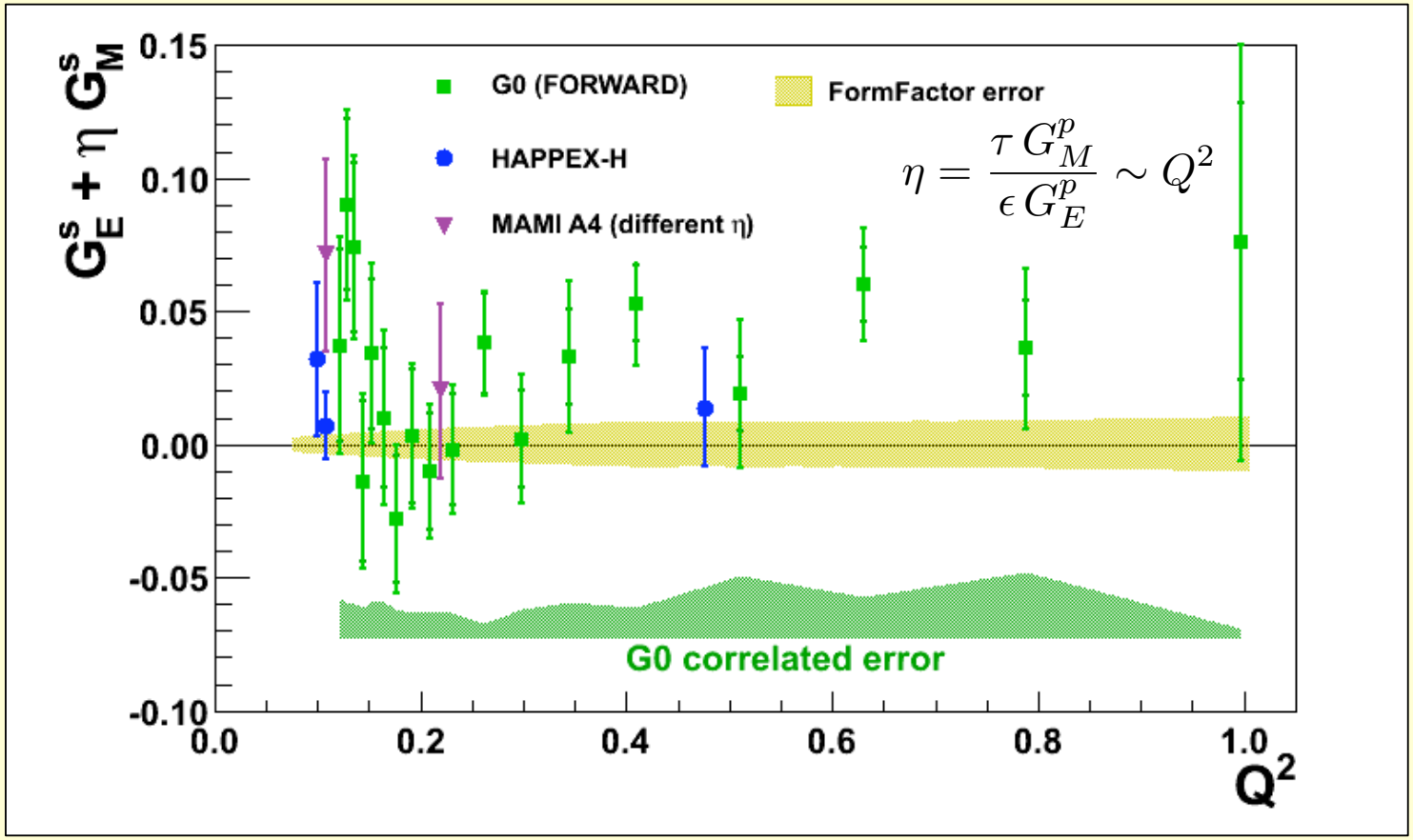
G0 Backward Scattering, **PRL 104, 012001 (2010)**

QCD lattice suggests very small effects



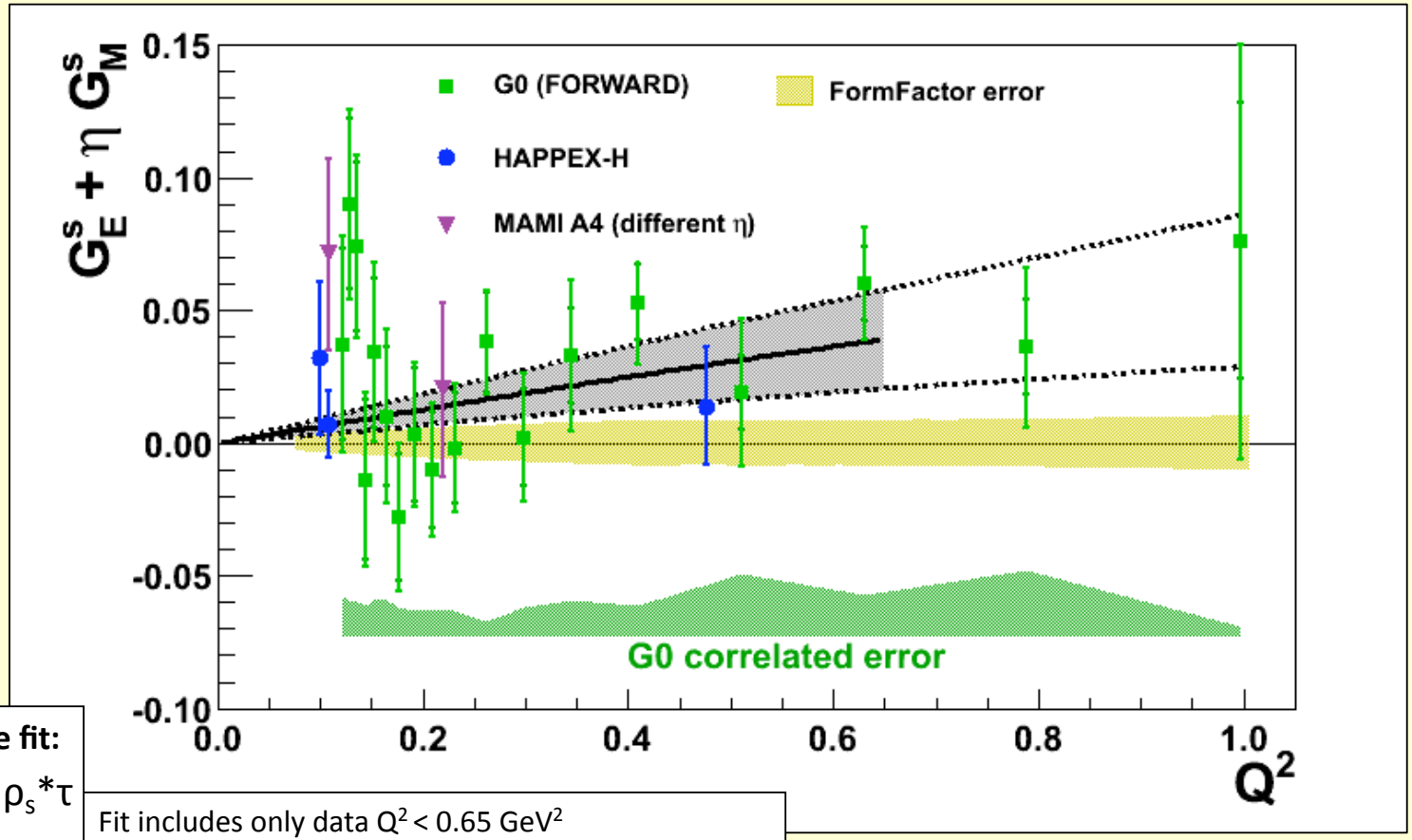


Forward-angle proton scattering



- "Form Factor" error: precision of EMFF (including 2γ) and Anapole correction
- Using experimental determination for axial form factor would increase total FF uncertainty about 50%
- Note: recent lattice results indicate values smaller than these FF uncertainties

Forward-angle proton scattering



Simple fit:

$G_E^s = \rho_s * \tau$

$G_M^s = \mu_s$

Fit includes only data $Q^2 < 0.65$ GeV^2

G0 Global error allowed to float with unit constraint

- **Data set appears to show consistent preference for positive effect**
- **Significant contributions at higher Q^2 are not ruled out.**

(fit suggests $G_E^s + \eta G_M^s(\text{at } Q^2 = 0.62) = 0.038$)

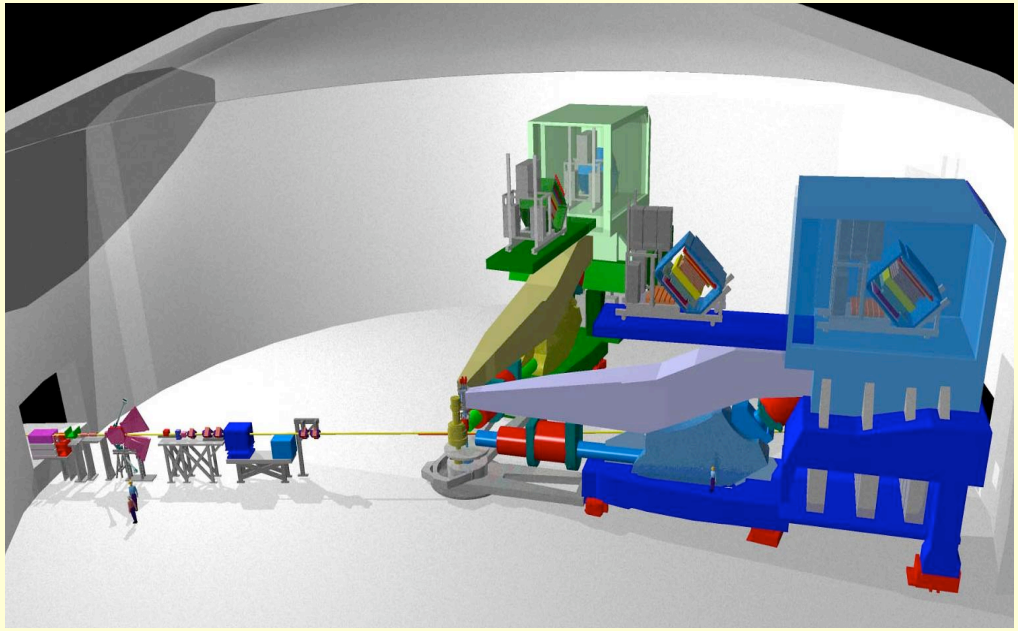
HAPPEX: Built around the HRS

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° minimum angle
- ~3 GeV maximum E'

Statistical FOM suitable for forward-angle PVeS studies

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

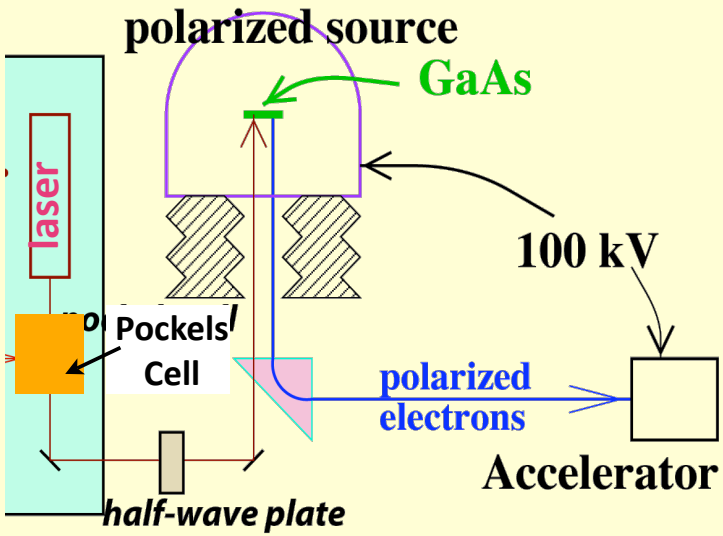


- Very clean isolation of elastic signal with low backgrounds
- Low Q^2 precision range extended and optimized with septum magnet for 6° scattering

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

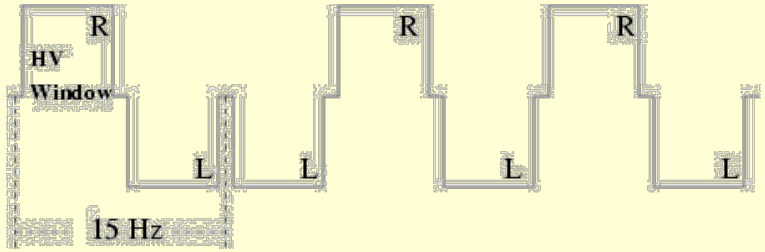
- Insensitive to problematic anapole moment
- ^{4}He interpretability very robust

Goal: Small Asymmetry, Measured to a Few Percent

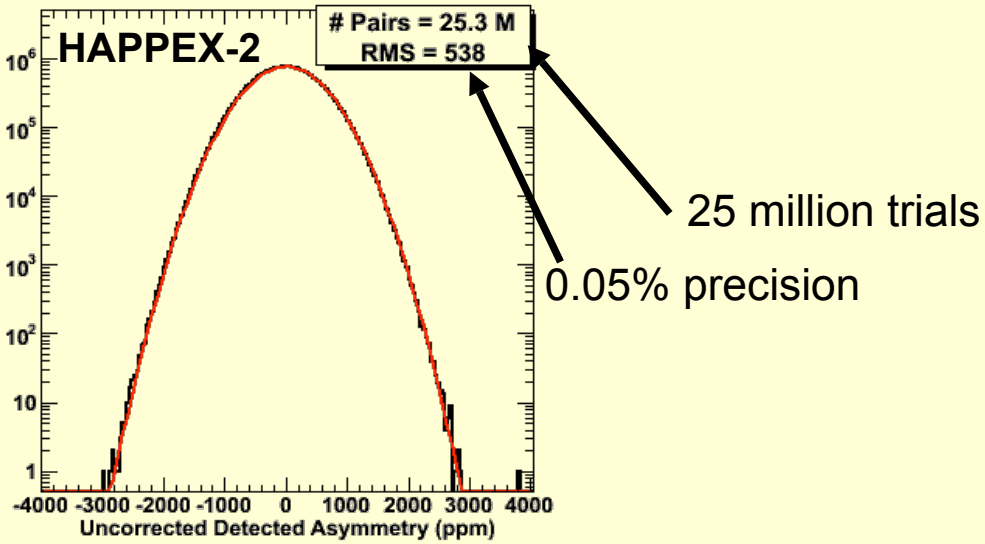


photoemission electron source: laser polarization determines electron polarization

Psuedo-random, rapid helicity flip

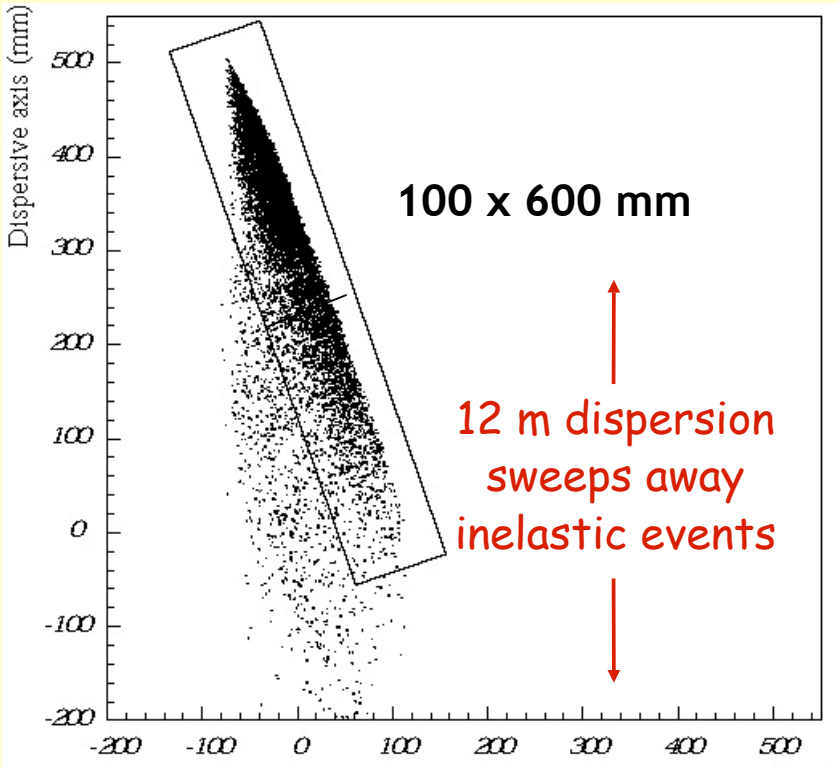


Measure the asymmetry to high precision, millions of times



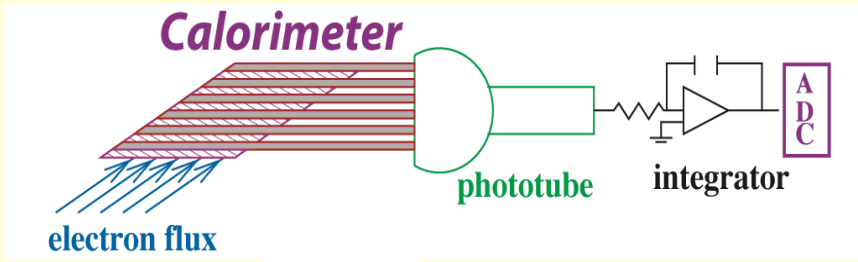
Elastic measurements in the HRS

Very clean separation of elastic events by HRS optics



Large dispersion and heavy shielding reduce backgrounds at the focal plane

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

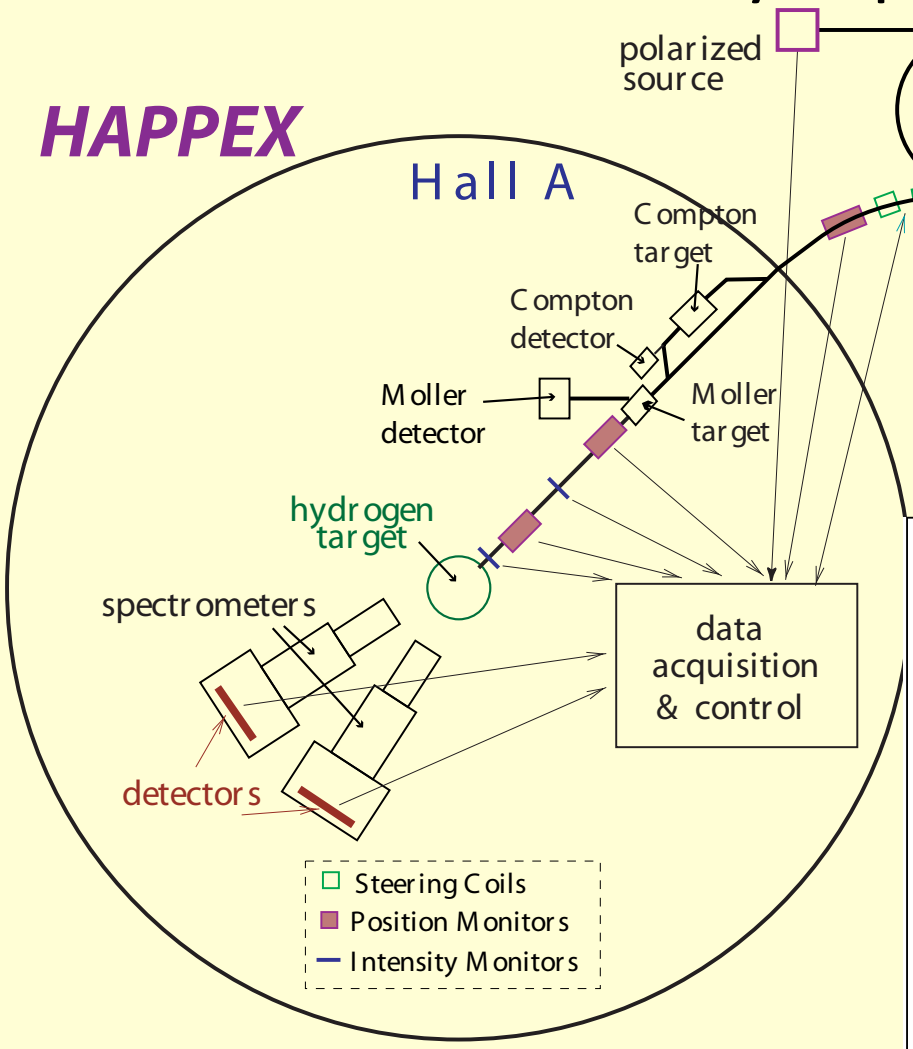


Analog integration enables very high flux detection with minimal rate-dependent corrections

- **no PID needed; detector sees only elastic events**
- **Phototube current integrated over fixed time periods**

First PVeS experiment at JLab

Hall A Proton Parity Experiment (E91-010)



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

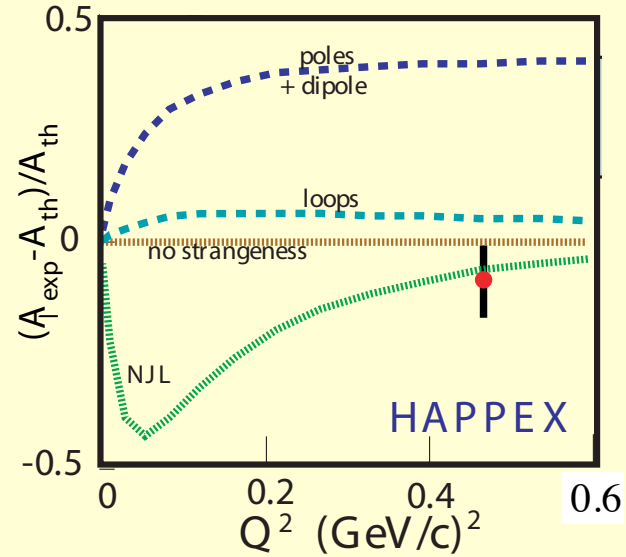
- High polarization from strained cathode
- Beam intensity asymmetry measurement and feedback
- optimization of polarized source and beam transport for control of position asymmetries
- Beam modulation to extract position/ energy sensitivity
- Precision Compton polarimetry
- Low noise analog flux integration

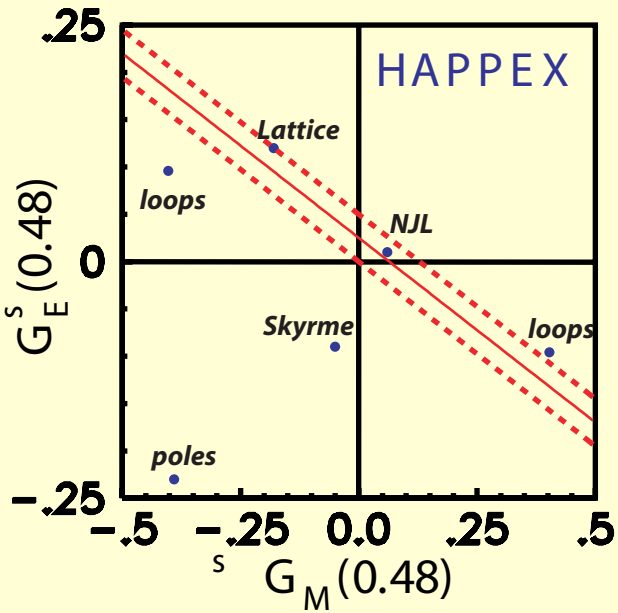
HAPPEX Results

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)



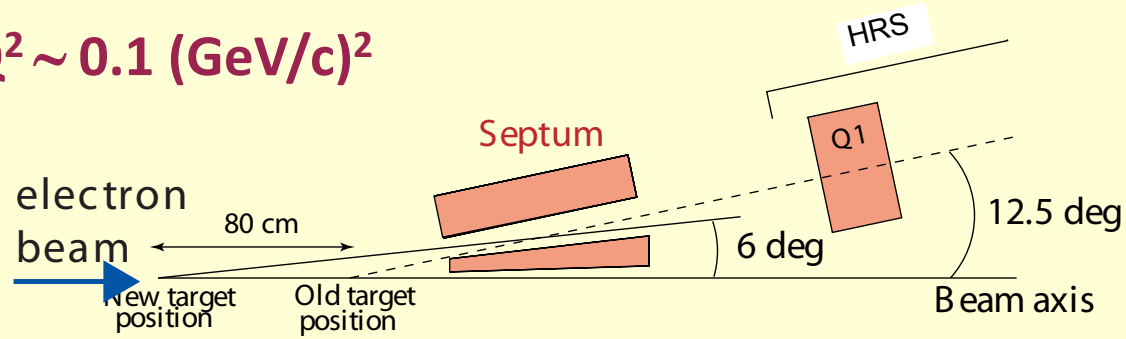


Statistics limited. Leading systematic is polarimetry

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

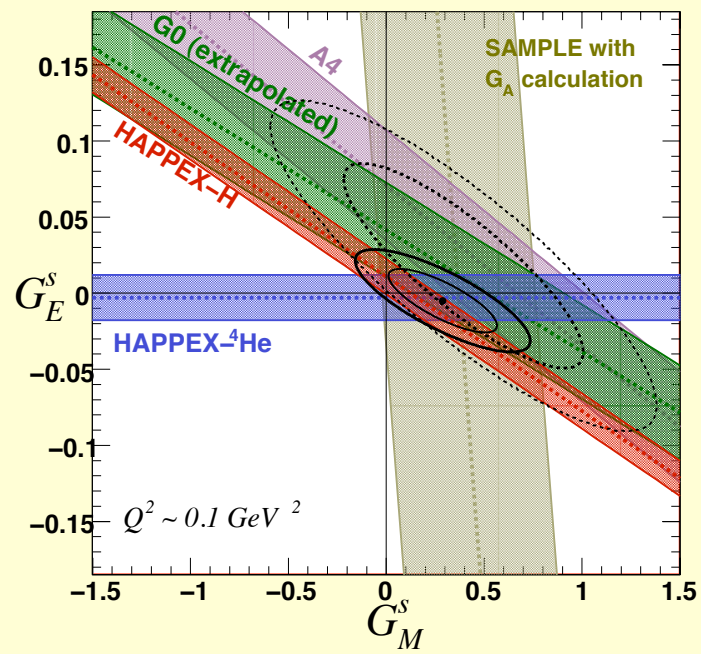


- **Hydrogen** : $G^s_E + \alpha G^s_M$

- **^{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)	Statistical Error
^{1}H	-1.7	0.11 ppm (8%)
^{4}He	6.4	0.23 ppm (4%)



HAPPEX-III

Challenges similar to original HAPPEX, but seeking higher precision

Configuration:

- 25 cm cryogenic Hydrogen Target
- 100 μA
- 89% polarization

Kinematics: E = 3.484 GeV, θ=13.7°, E' = 3.14 GeV, Q^2 = 0.624 GeV^2

Sensitive to $G_E^s + 0.52\, G_M^s$

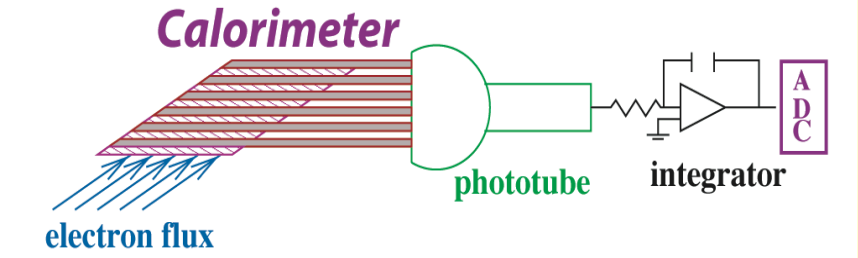
A_{PV} (assuming no strange vector FF): A_{PV}^{NS} = -24.2 ppm ± 0.66 ppm

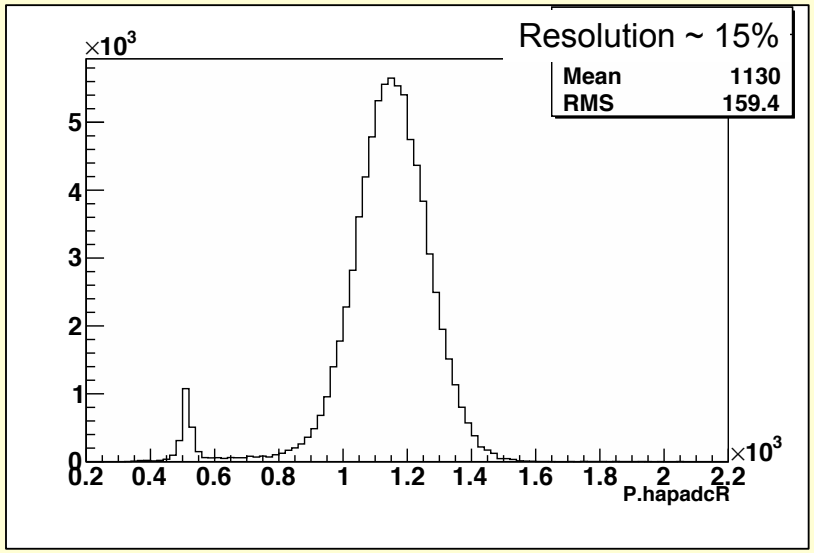
- **precision alignment for Q^2 uncertainty**
- **1% polarimetry**
- **backgrounds**
- **linearity**

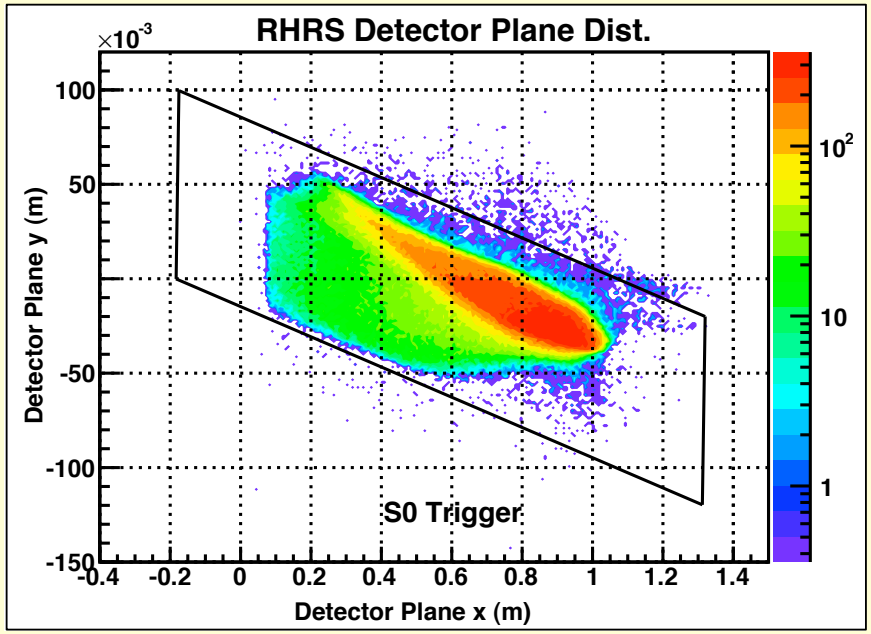
Integrating Detector

Lead - Lucite Cerenkov Shower Calorimeter

- Insensitive to background
- Directional sensitivity
- High-resolution

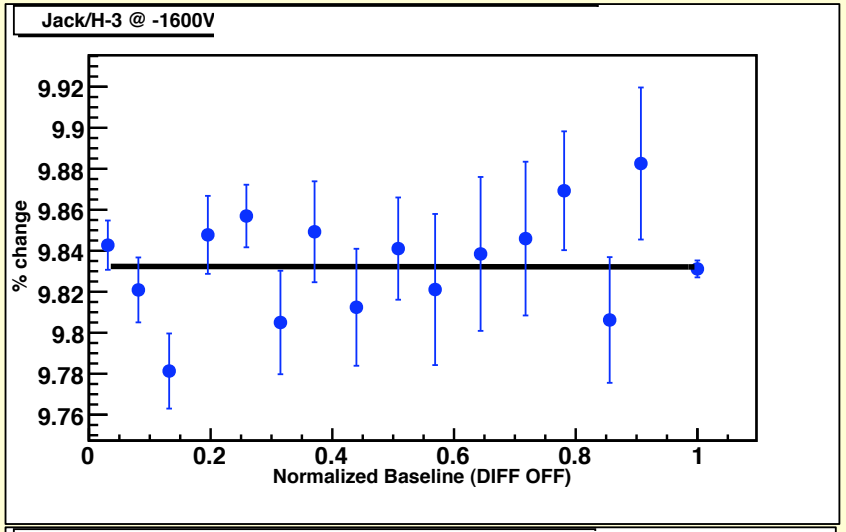


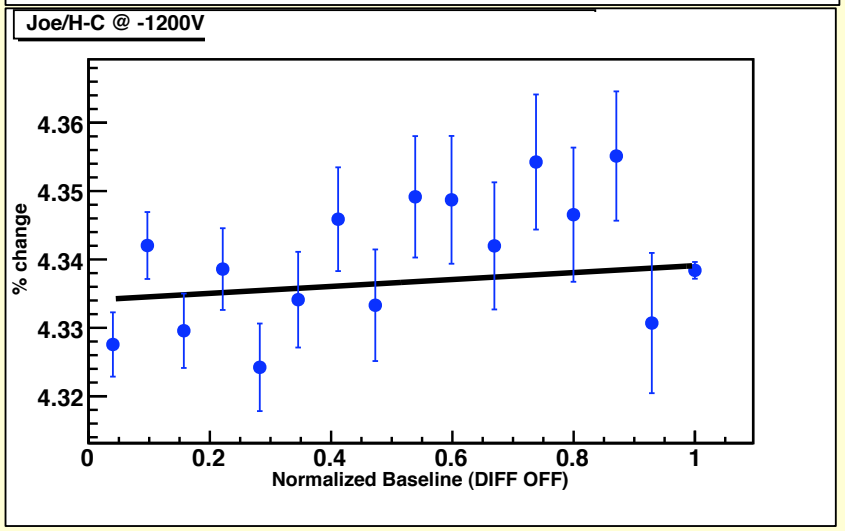


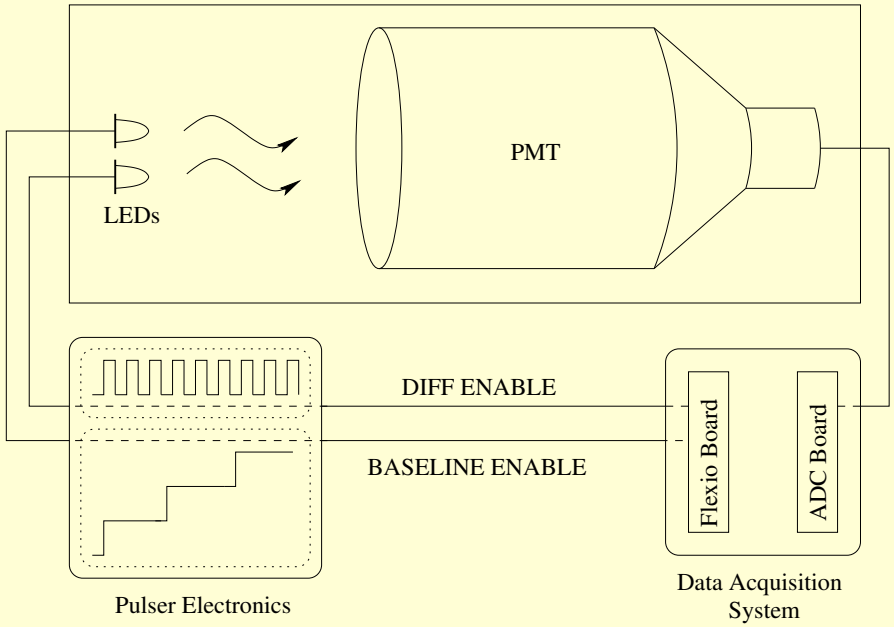


Detector Linearity

Studied *in situ* and on bench with LED system optimized to linearity for differential rates of similar pulses







Measurements taken in short deviations from high rate, to maintain consistent thermal properties

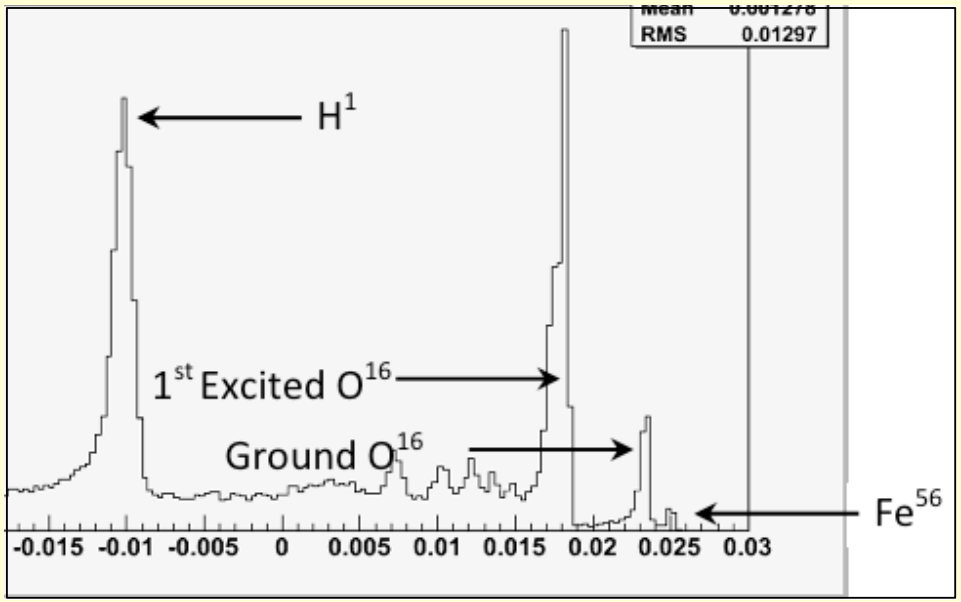
Phototube and readout non-linearity bounded at the 0.5% level

Determining Q2

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

Goal: $\delta Q^2 < 0.5\%$

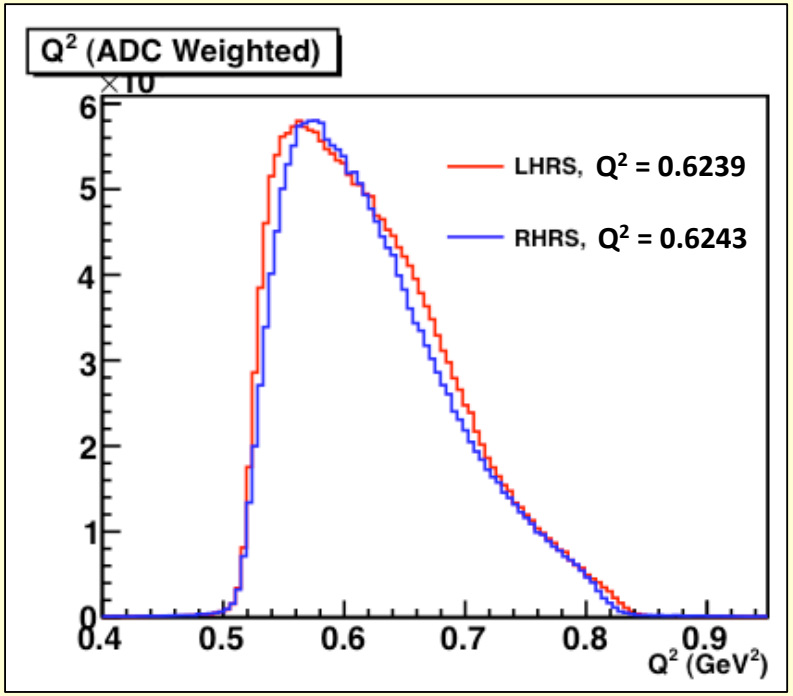
Water cell optics target for central angle



δp between elastic and inelastic peaks reduces systematic error from spectrometer calibration

$\delta\theta \sim 0.4$ mrad (0.2%)

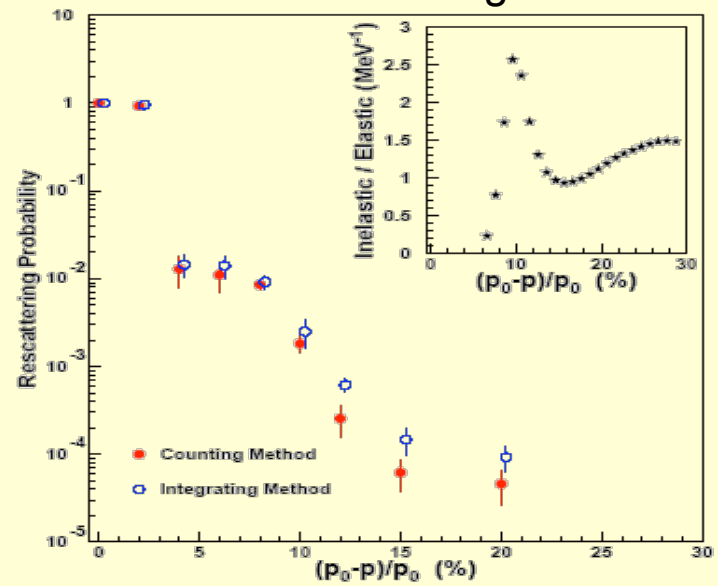
$Q^2 = 0.6241 \pm 0.0027$ (0.44%)



Central Angle	0.32%
Beam Energy, HRS momentum	0.11%
optics	0.16%
Drifts	0.2%
ADC weighting	0.1%
Total	**0.44%**

Backgrounds

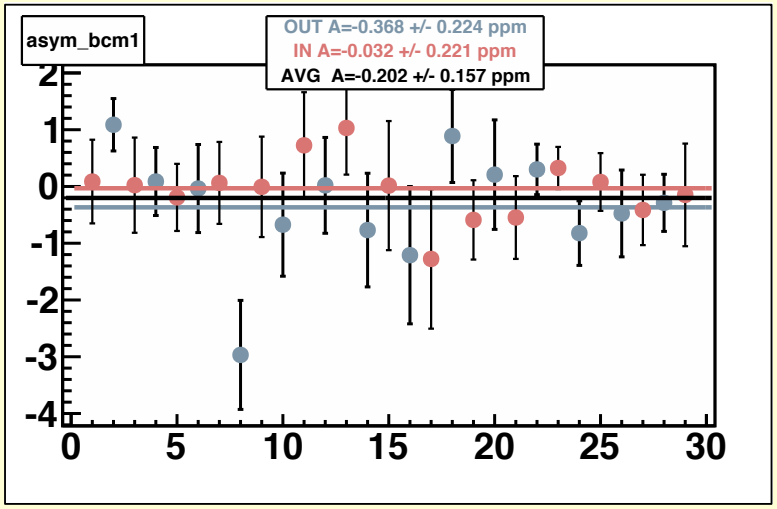
Rescattering probability measured during H-I



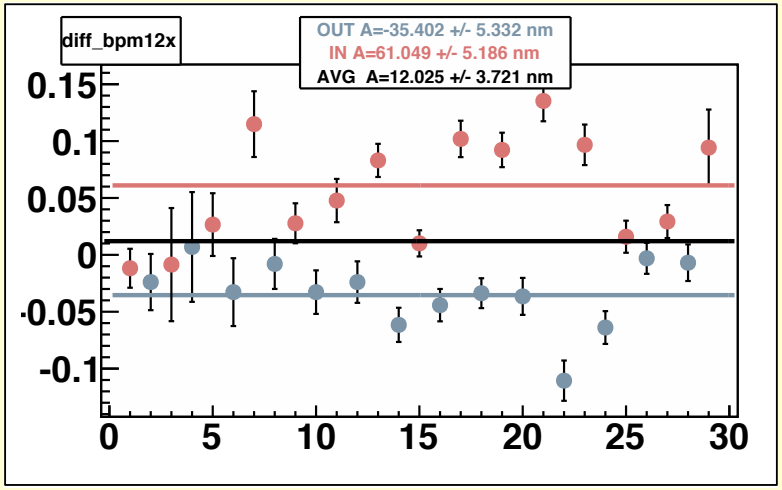
- Aluminum from target windows
- Signal from inelastic electrons scattering inside spectrometer

background	f	A	Net Correction	Net Uncertainty
Aluminum (target window)	1.15% (30%)	-34.5 ppm (30%)	126 ppb	127 ppb
Rescattering	0.3% (25%)	-63 ppm (25%)	114 ppb	55 ppb

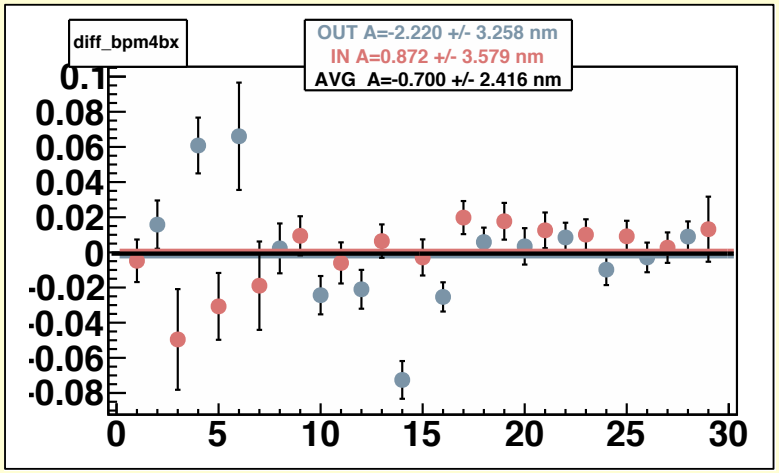
Beam Asymmetries



Charge asymmetry (with feedback) averages to 200 parts per billion



Implies energy asymmetry at 3 ppb

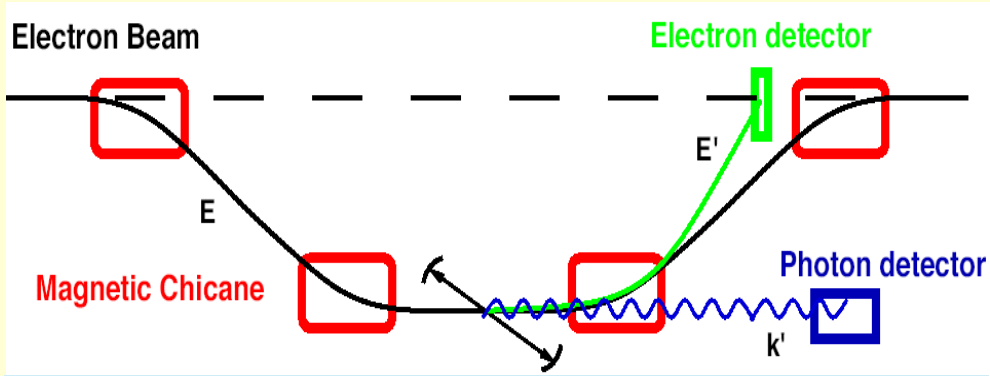


Individual detector response measured to be at the level of 5 ppb/nm

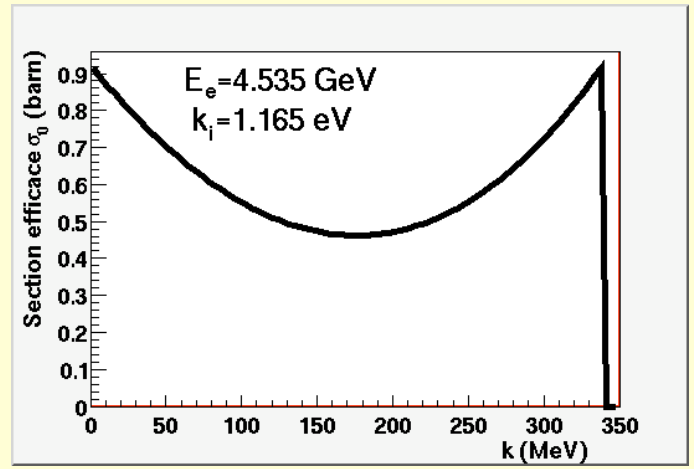
Total Correction: -0.010 ppm (0.05%)

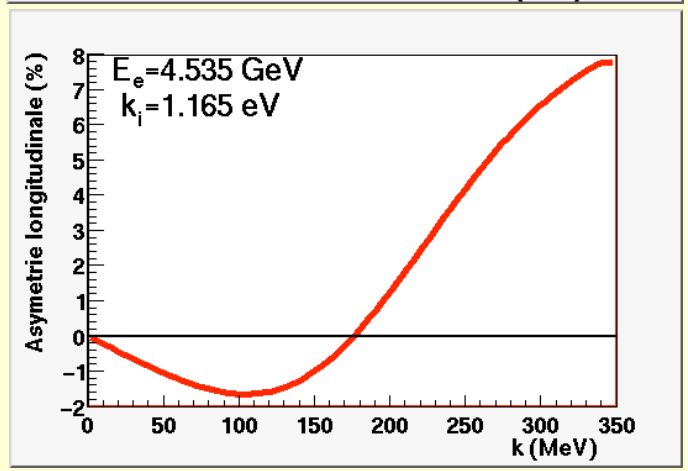
Trajectory at target averages to <3nm,<0.5nrad

Hall A Compton Polarimeter



Resonant cavity "photon target", up to 2kW intensity





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

Calibration of the analyzing power is usually the leading uncertainty

measure asymmetry independently in:

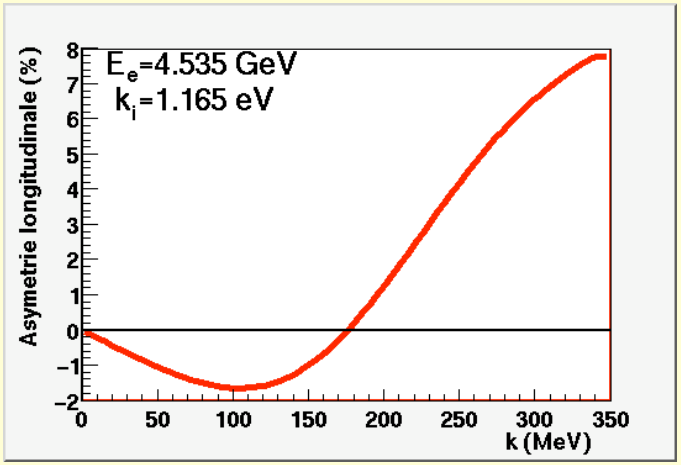
- **momentum analyzed electrons**
- **photons in calorimeter**

Electron detector achieved 1% accuracy for HAPPEX-2, but system was broken for HAPPEX-3

Integrating Photon Analysis

Electron detector achieved 1% accuracy for HAPPEX-2, but system was broken for HAPPEX-3

Photon self-triggered analysis has been limited in accuracy, and required electron coincidence measurements for calibration

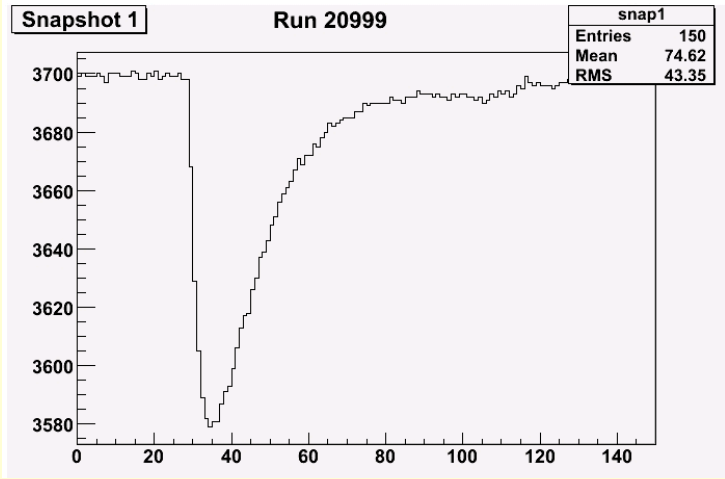


Integrating photon detection:
immune to calibration, pile-up, deadtime, response function

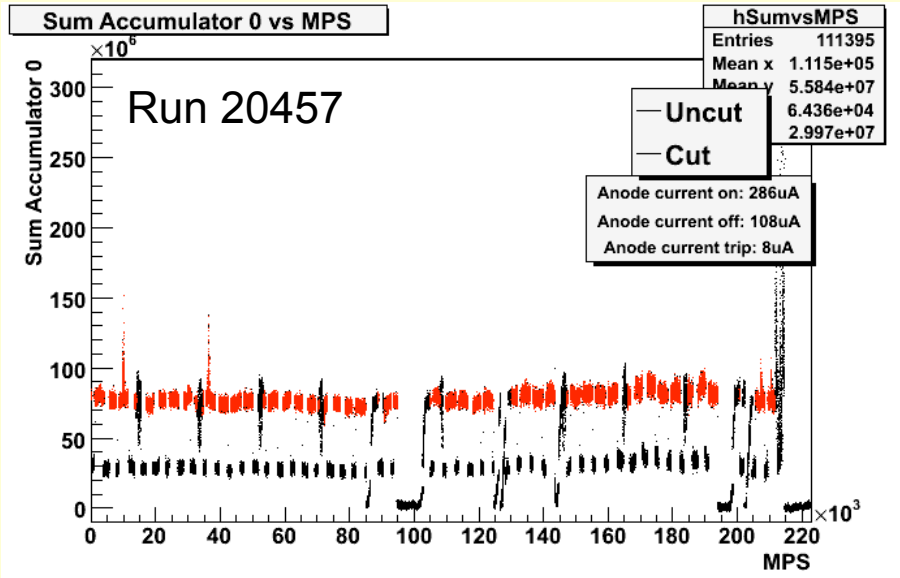
New DAQ, with SIS 2230 Flash ADC read out in two modes:

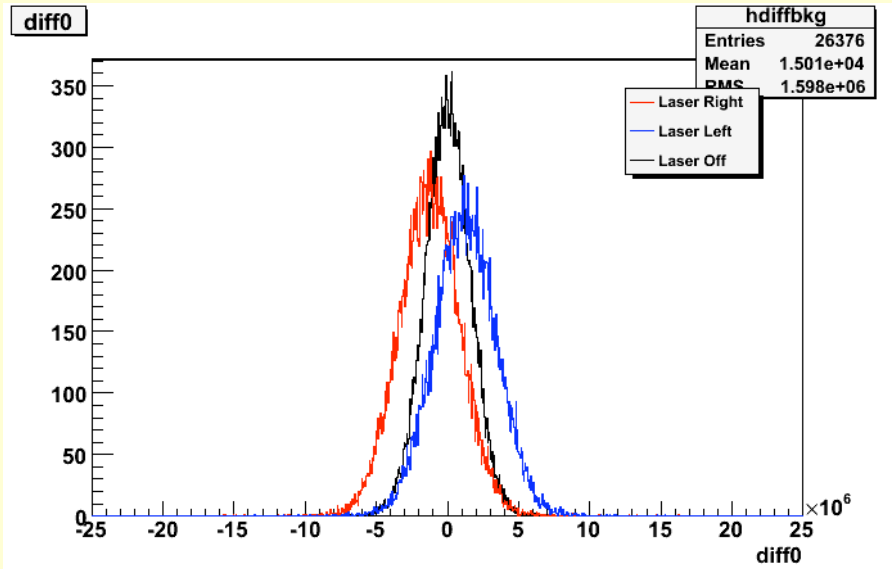
Accumulator readout: all FADC samples are summed on board for entire helicity window

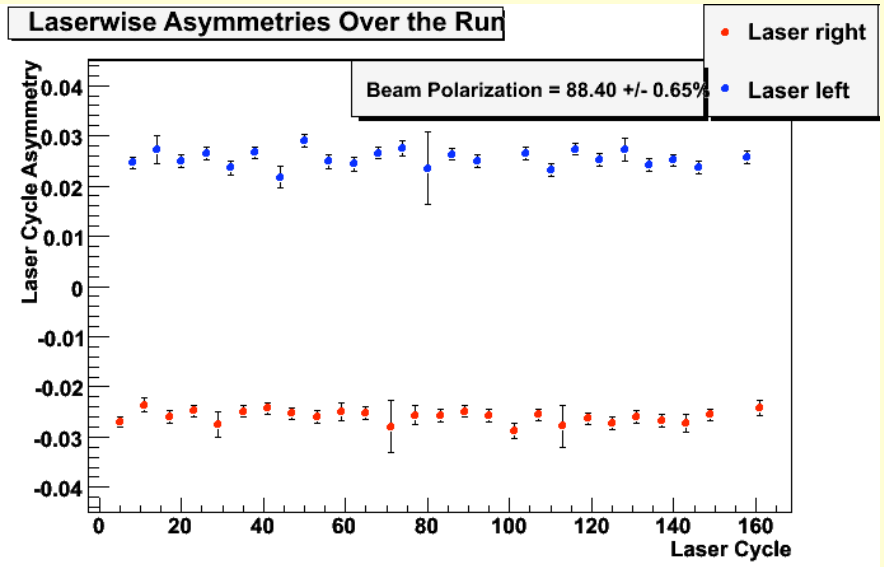
Triggered mode: triggered "snap shot" of fixed time interval (for calibration)

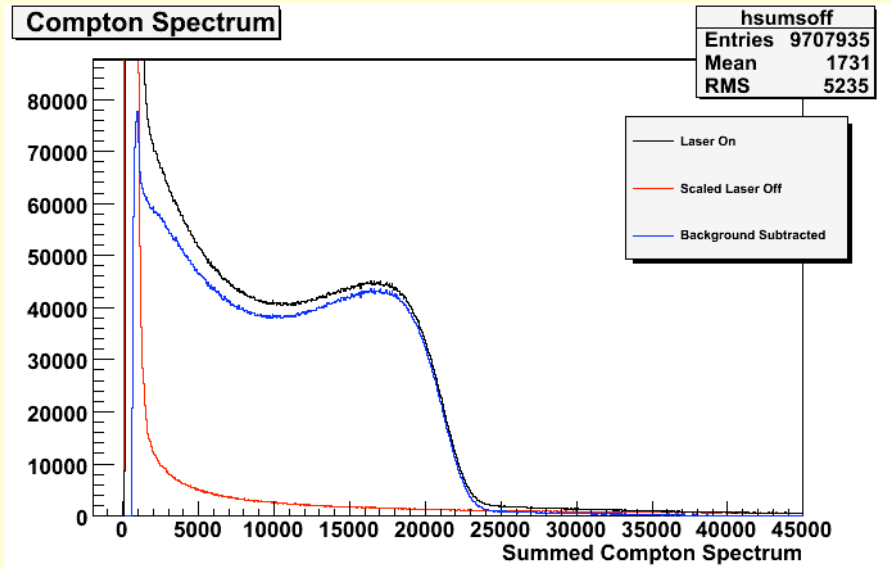


Integrating Analysis, online plots

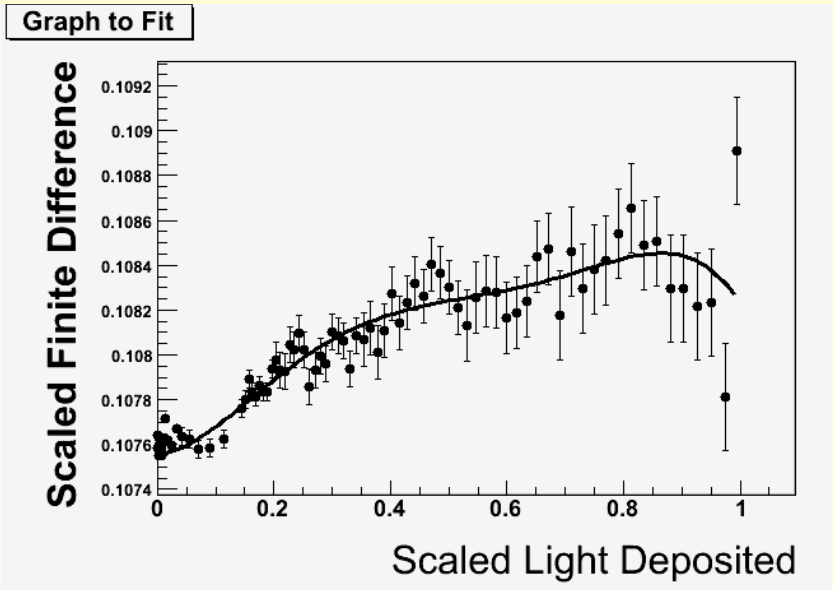








Compton Polarimetry

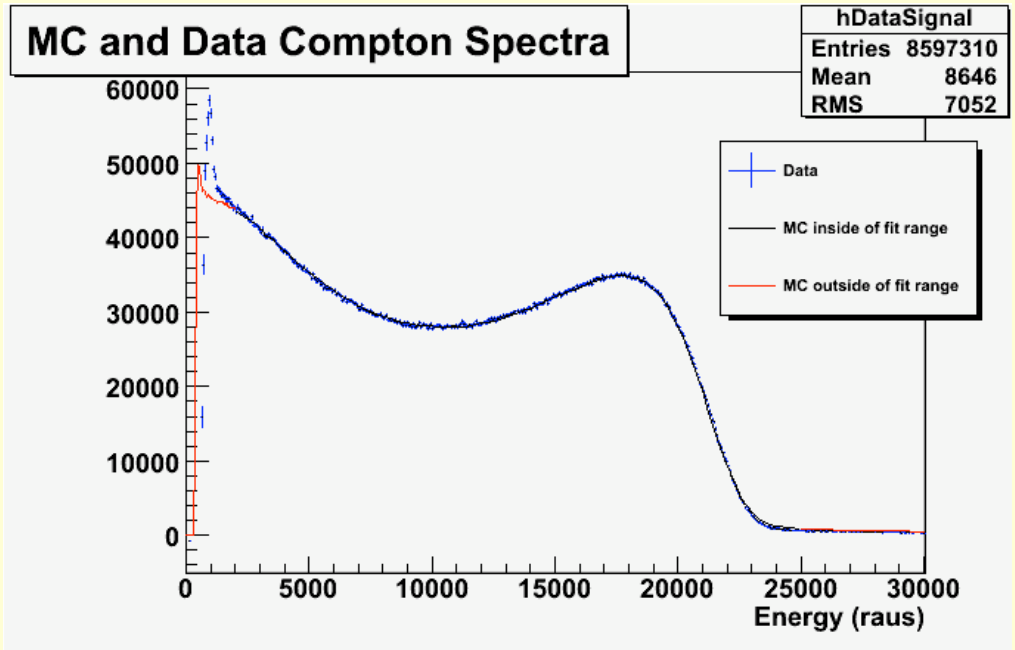


Non-linearity mapped out in with pulsed LED system.

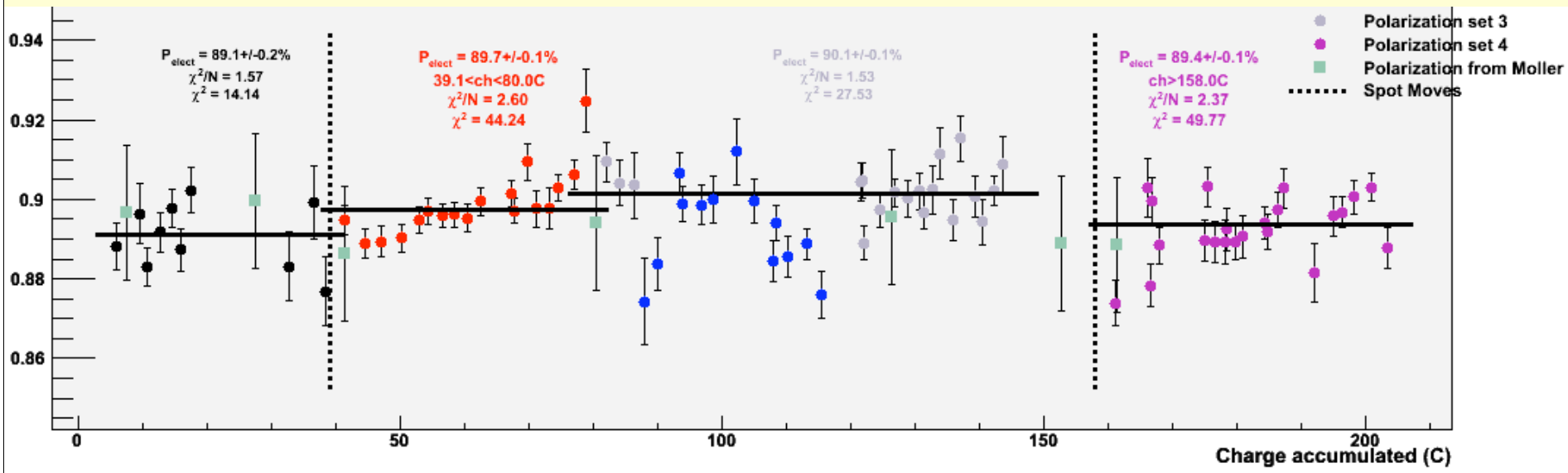
Compton spectrum very well simulated

- **linearity**
- **collimator/detector alignment**
- **synchrotron light shielding**

Analyzing power calculation is not extremely sensitive to these corrections



Polarimetry Summary



Compton: 89.68 ± 0.95%
Moller: 89.22 ± 1.7%

Average: 89.59 ± 0.76%

Moller systematic errors

Target	1.5%
Analyzing Power	0.3%
Levchuk	0.2%
Background	0.3%
Deadtime	0.3%
other	0.5%
TOTAL	**1.7%**

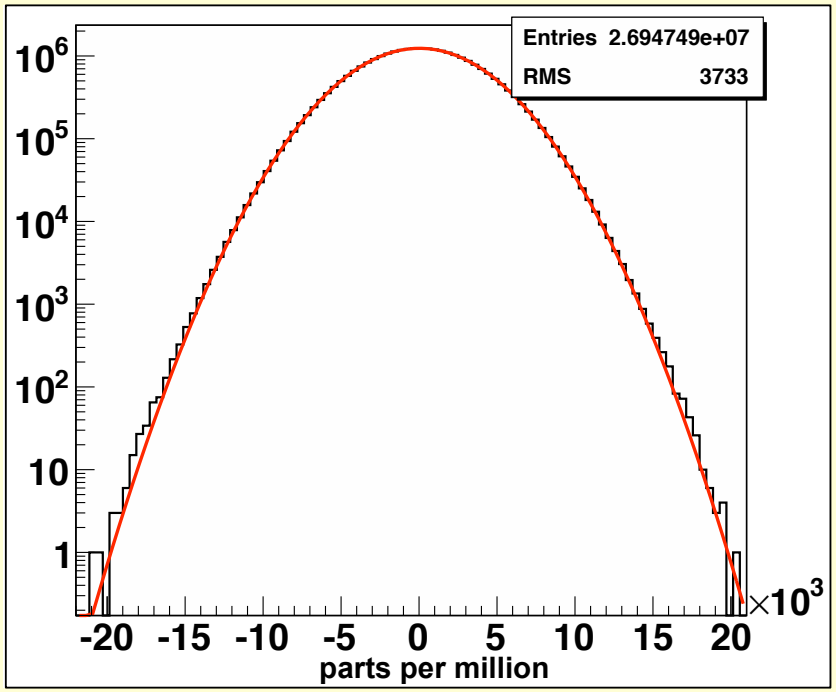
Compton systematic errors

laser polarization	0.8%
non-linearity	0.3%
gain	0.3%
gaps	0.2%
other	0.2%
TOTAL	**0.95%**

HAPPEX-III Error Budget

	δA_{PV} (ppm)	$\delta A_{PV} / A_{PV}$
Polarization	0.202	0.85%
Q^2 Measurement	0.160	0.67%
Backgrounds	0.194	0.82%
Linearity	0.129	0.54%
Finite Acceptance	0.048	0.20%
False Asymmetries	0.041	0.17%
Total Systematic	0.353	1.49%
Statistics	0.776	3.27%
Total Experimental	0.853	3.59%

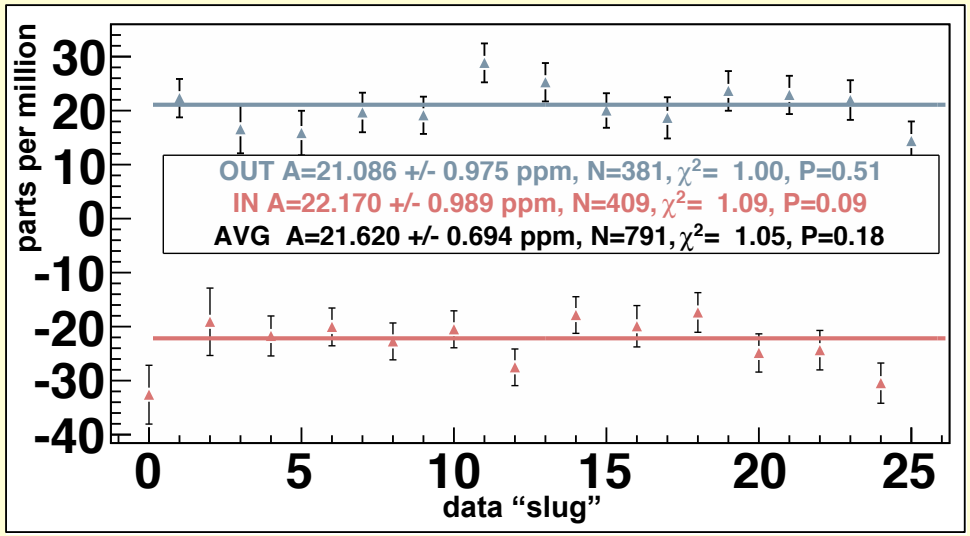
HAPPEX-III Measurement of A_{PV}



$$A_{RAW} = -21.591 \pm 0.688 \text{ (stat) ppm}$$

This includes
- beam asymmetry correction (-0.01 ppm)
- charge normalization (0.20 ppm)

This is corrected for
- backgrounds (1.1%)
- acceptance averaging (0.5%)
- beam polarization (11%)



Analysis Blinded ± 2.5 ppm

3.26% (stat)± 1.49% (syst)
total correction ~2.5% + polarization

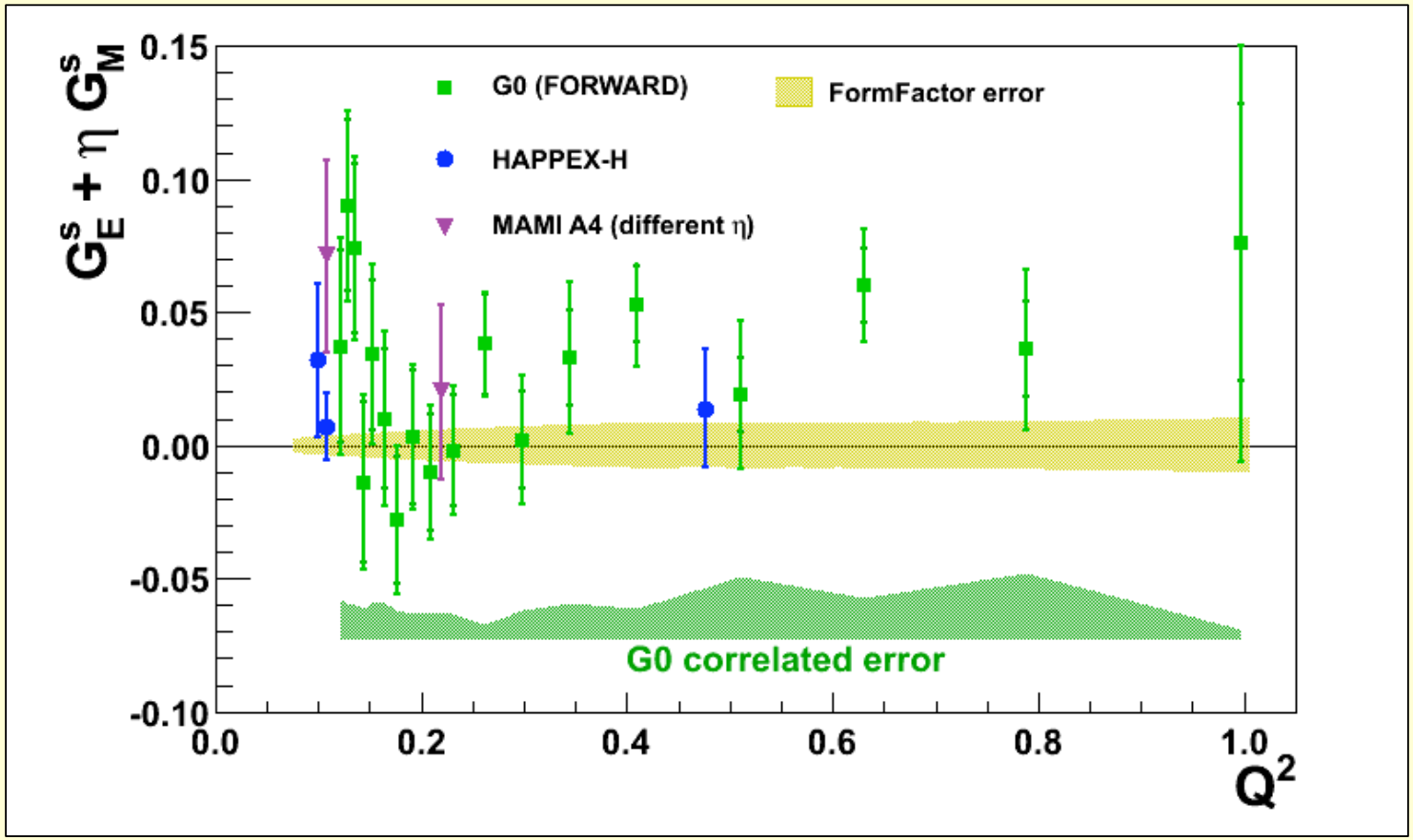
preliminary

$$Q^2 = 0.6241 \pm 0.0028 \text{ (GeV/c)}^2$$

$$A_{PV} = -23.742 \pm 0.776 \text{ (stat)} \pm 0.353 \text{ (syst) ppm}$$

HAPPEX-III Results

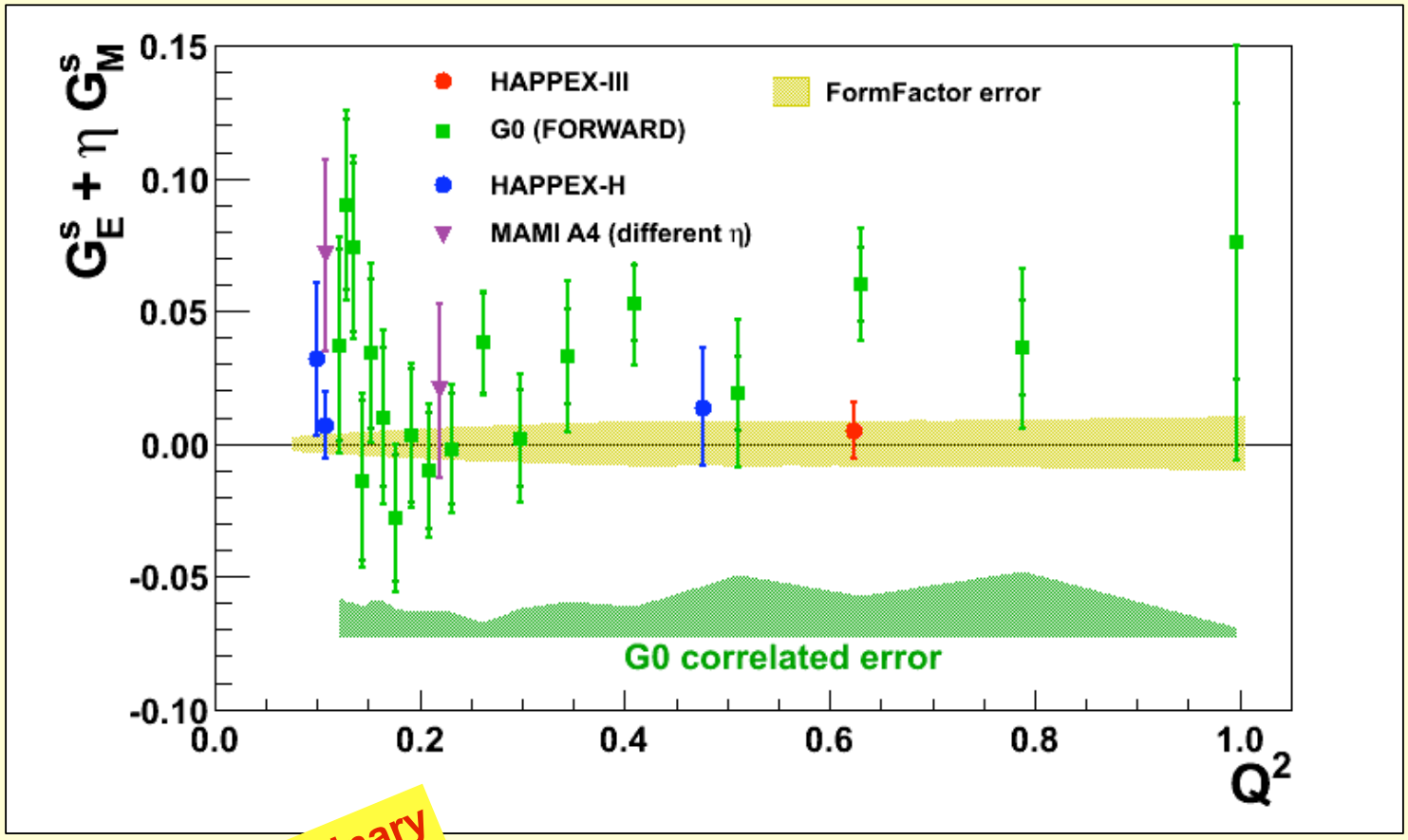
$$A_{PV} = -23.742 \pm 0.776\ (stat) \pm 0.353\ (syst)\ ppm$$



HAPPEX-III Results

preliminary

$$A_{PV} = -23.742 \pm 0.776\ (stat) \pm 0.353\ (syst)\ ppm$$

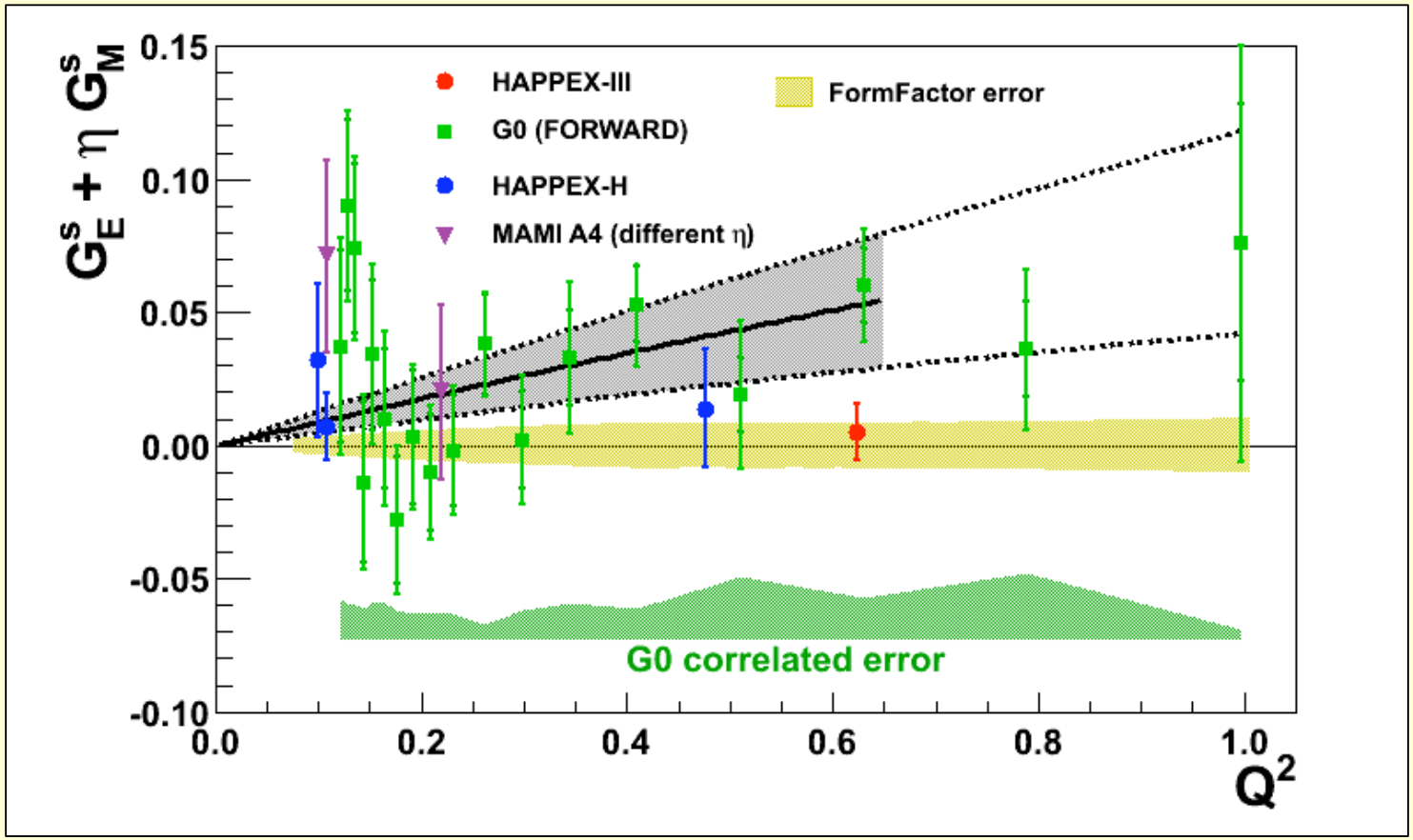


preliminary

$A(G^s=0)$ = -24.158 ppm ± 0.663 ppm

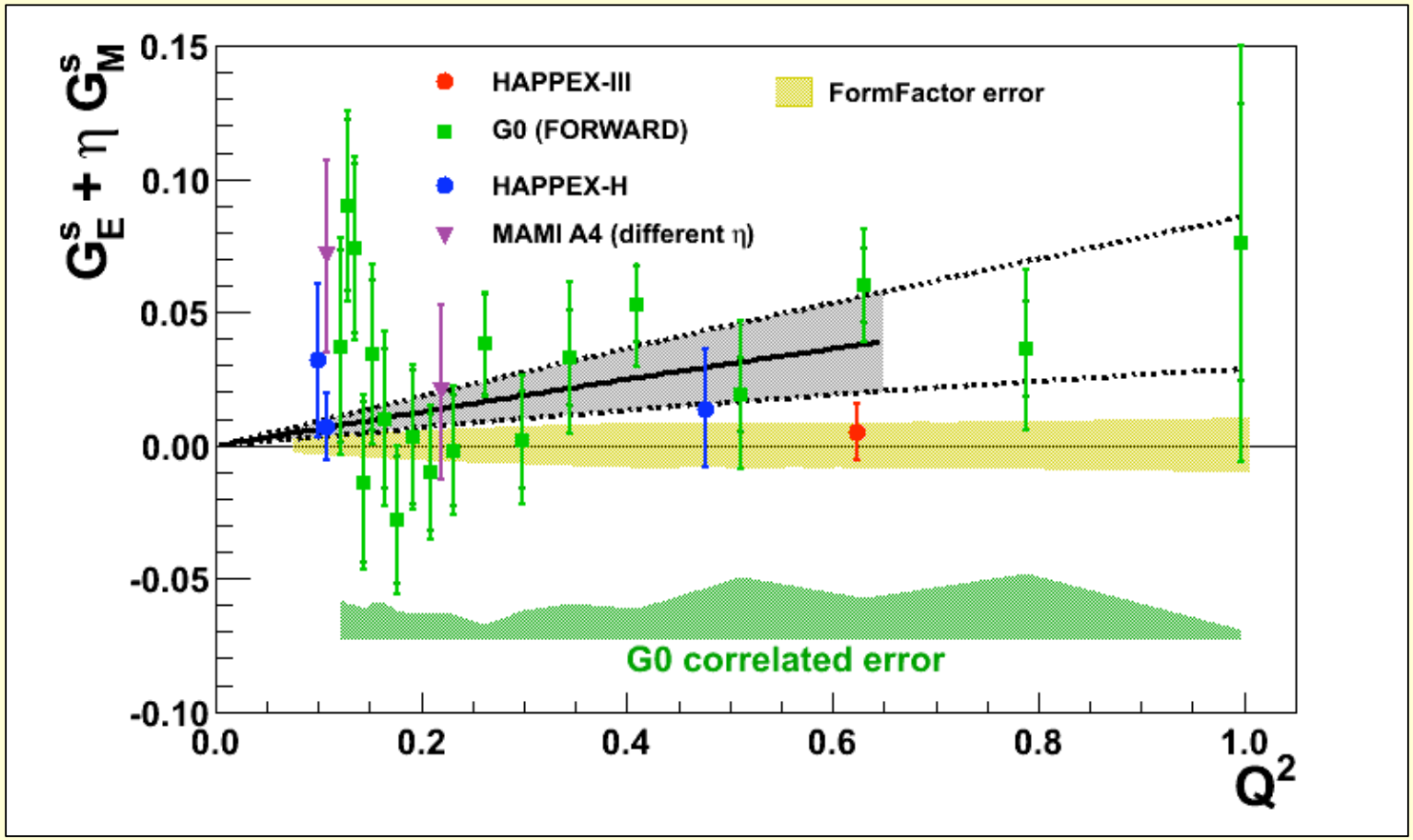
$$G^s_E + 0.52\ G^s_M = 0.005 \pm 0.010_{(stat)} \pm 0.004_{(syst)} \pm 0.008_{(FF)}$$

Fit, without any HAPPEX



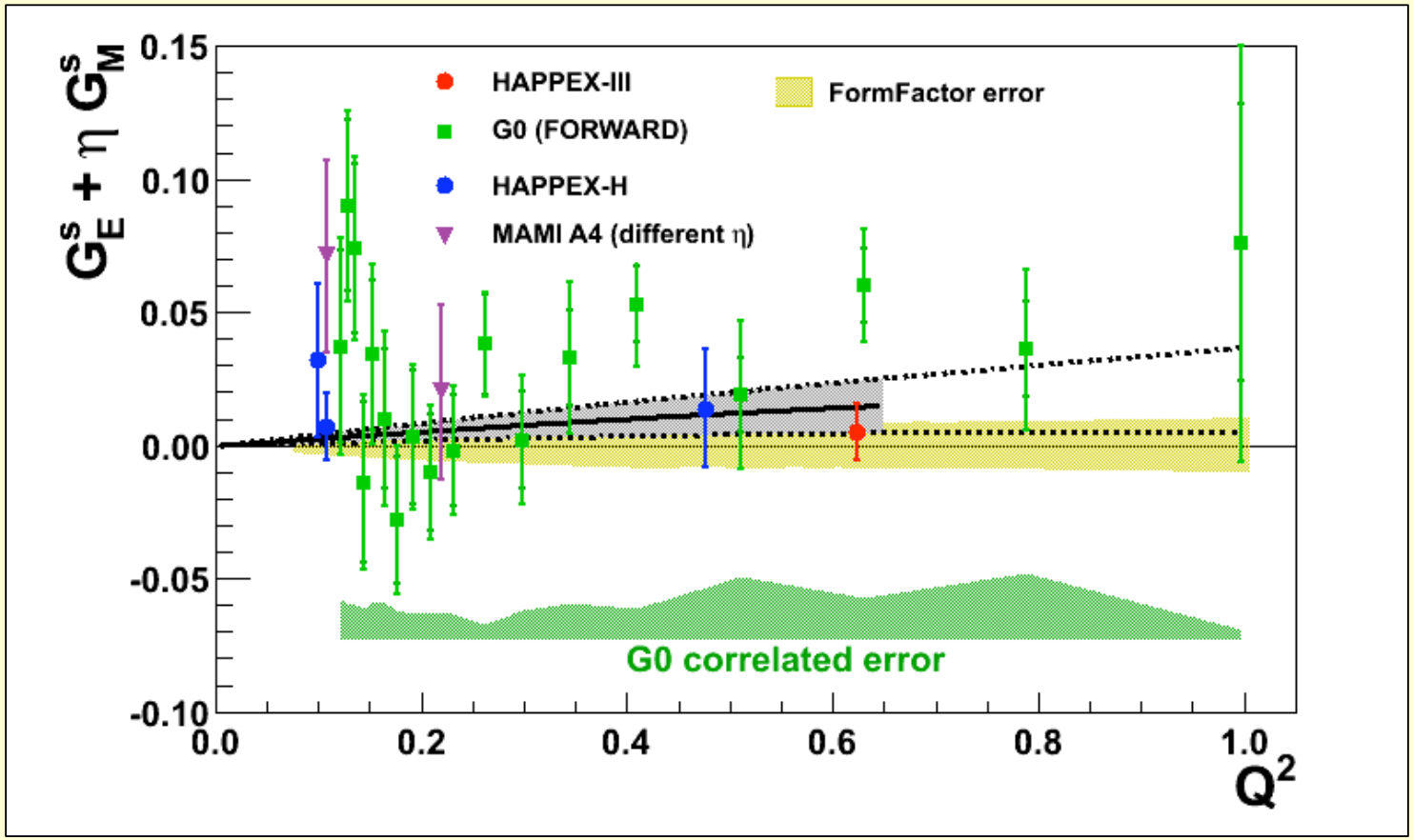
Fit excluding all HAPPEX data

Fit before HAPPEX-III



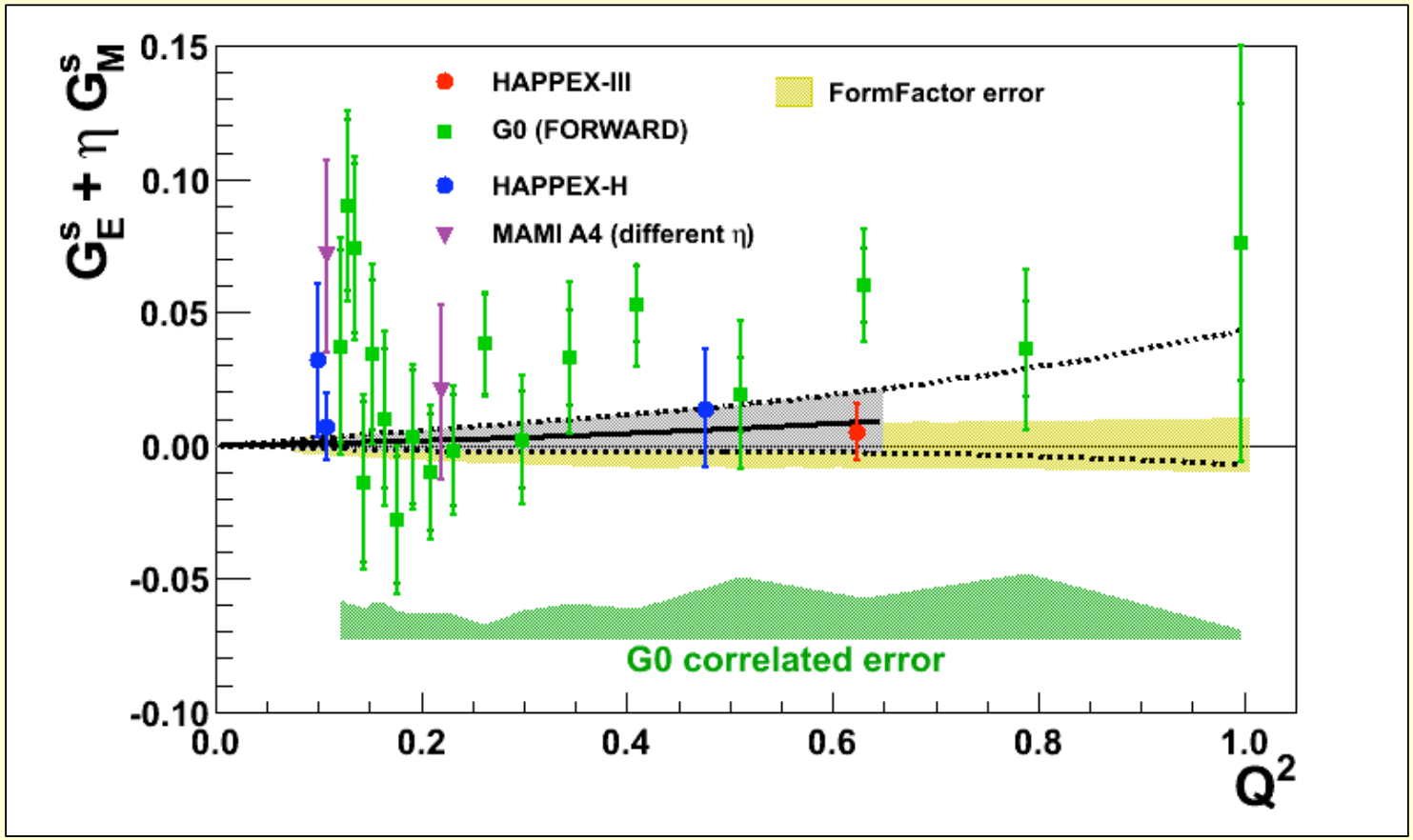
Fit of all data, except HAPPEX-3

Fit, World Data



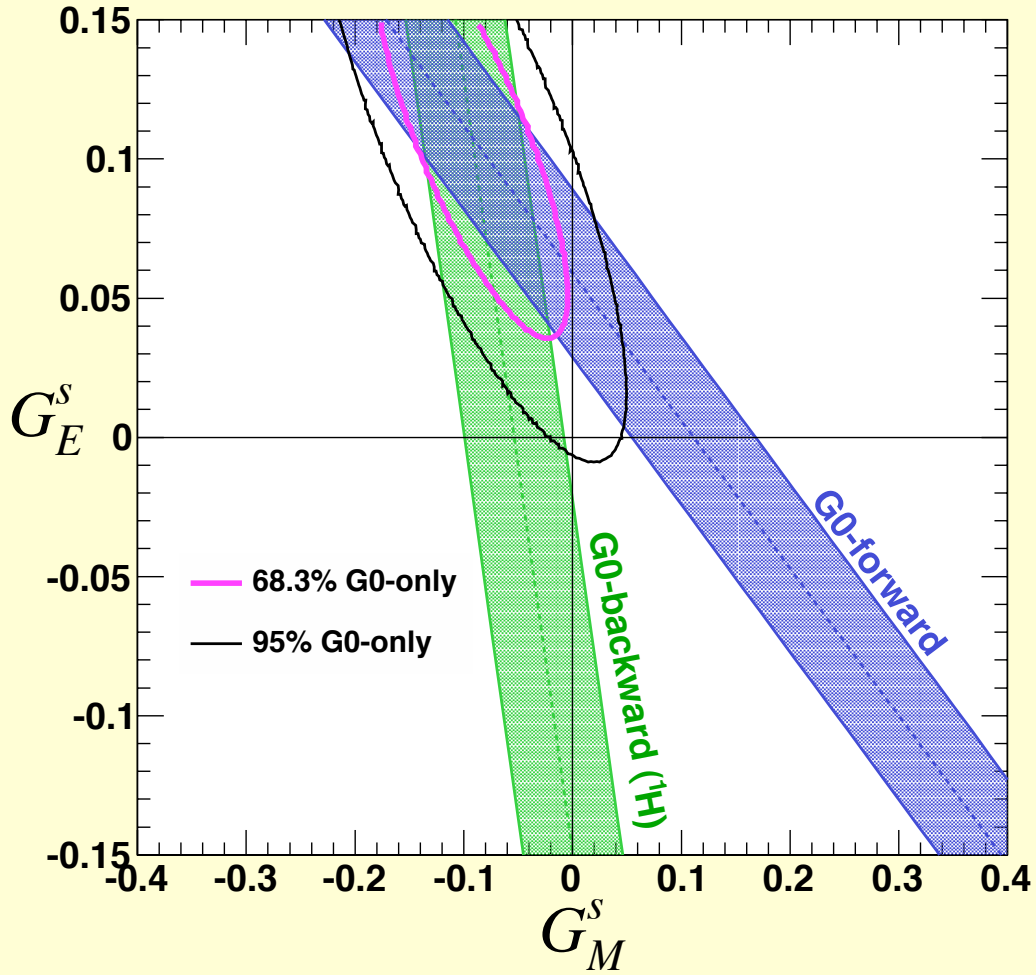
Fit incorporating HAPPEX-III

Fit, only HAPPEX



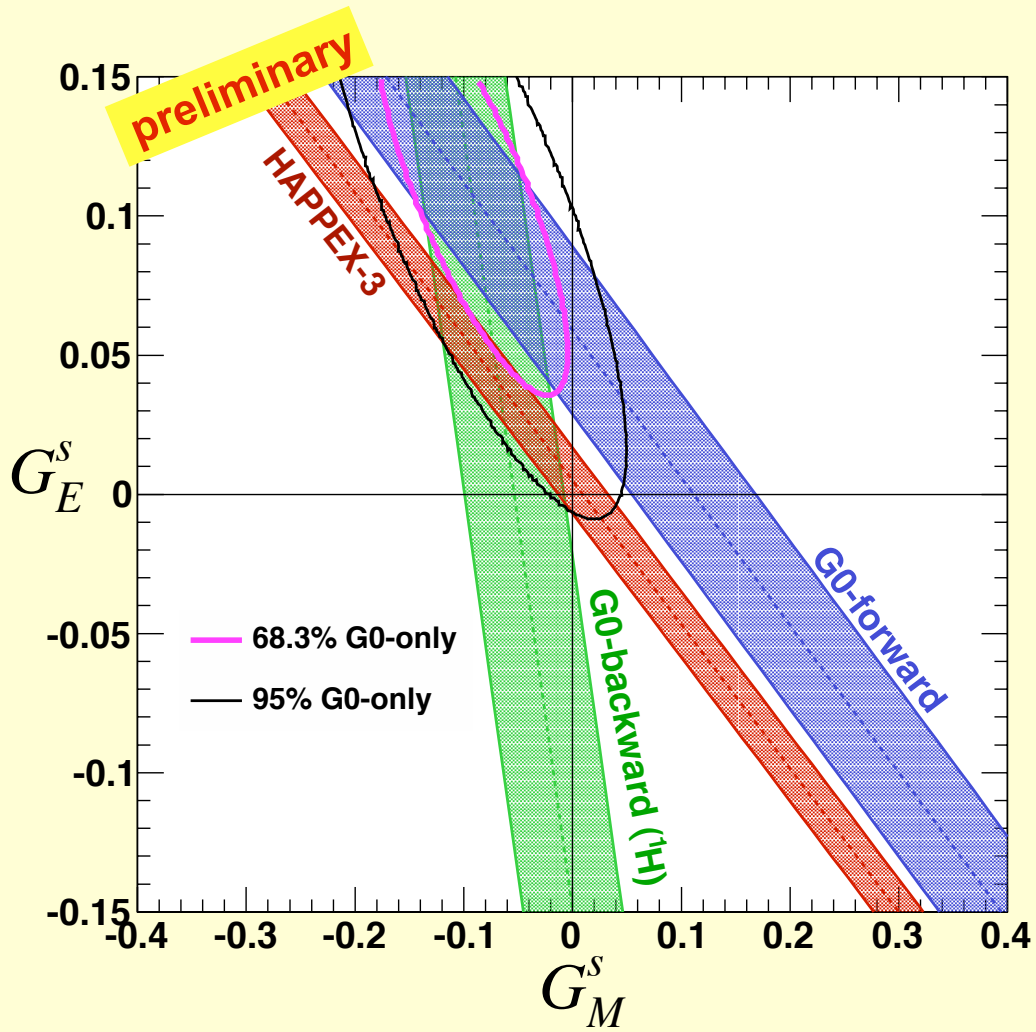
Fit of only the HAPPEX results

$Q^2 = 0.62\ GeV^2$ in combination



Zhu constraint is used for axial form-factor

Q^2 = 0.62 GeV^2 in combination



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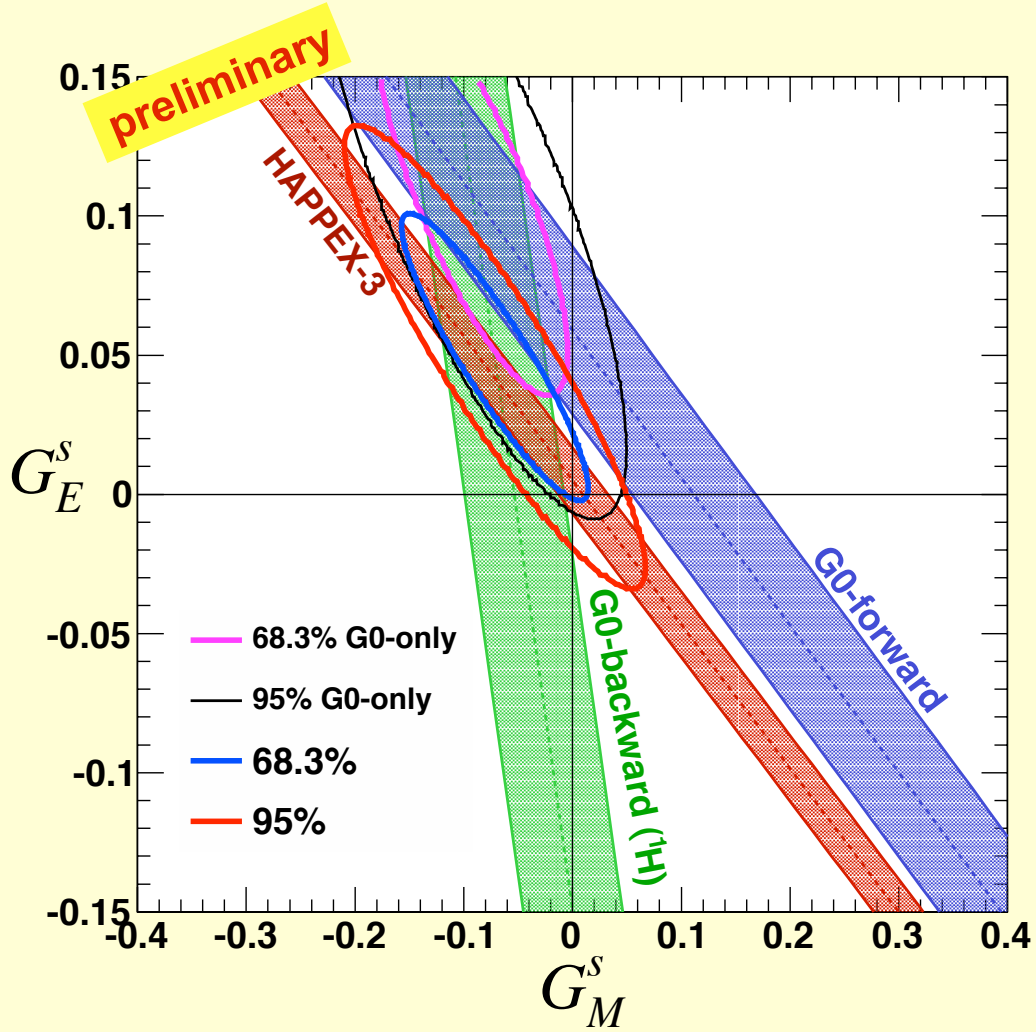
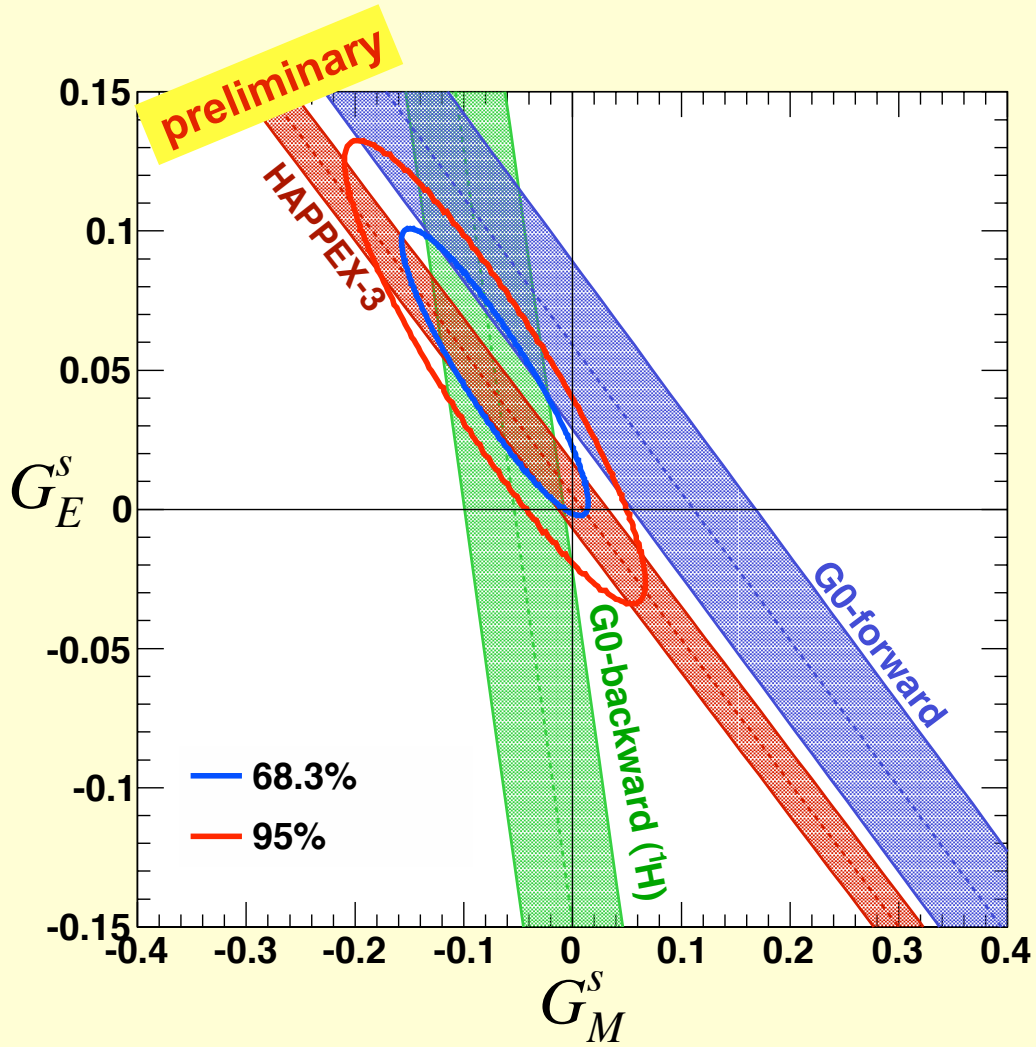
Q^2 = 0.62 GeV^2 in combination



Zhu constraint is used for axial form-factor

Combined fit includes form-factor uncertainties, experimental bands do not

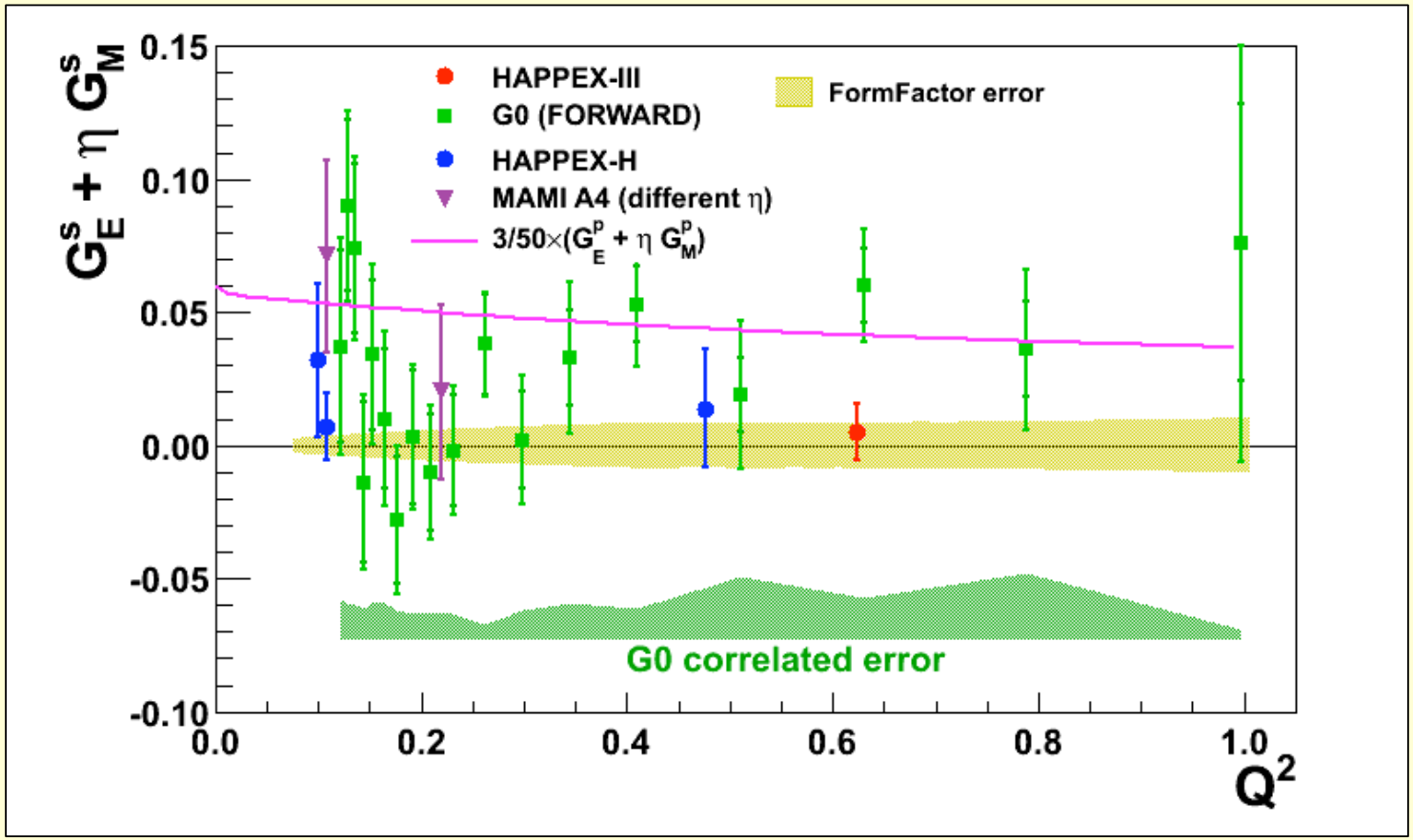
$Q^2 = 0.62\ GeV^2$ in combination



Zhu constraint is used for axial form-factor

Combined fit includes form-factor uncertainties, experimental bands do not

Summary



- HAPPEX-III provides a clean, precise measure of APV at Q2=-.62, and finds that it is consistent with $G_E^s+0.53G_M^s = 0$.
- World data exhibits a preference towards positive contributions, while maintaining statistical consistency (1.5σ) with the HAPPEX results
- Further improvements in precision would require additional theoretical and empirical input for interpretation

Backups

Charge Symmetry Breaking

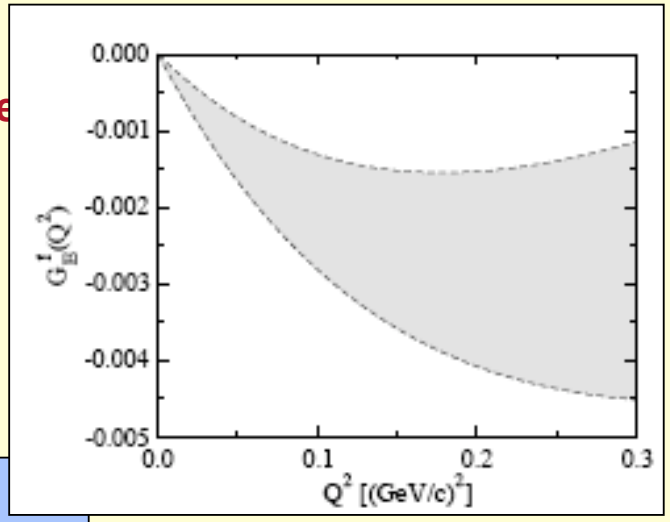
Most theoretical CSB estimates indicate <1% violations

Miller PRC 57, 1492 (1998)

Lewis & Mobed, PRD 59, 073002(1999)

Recent calculations suggest that effects could be large as the statistical error on HAPPEx-II data

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

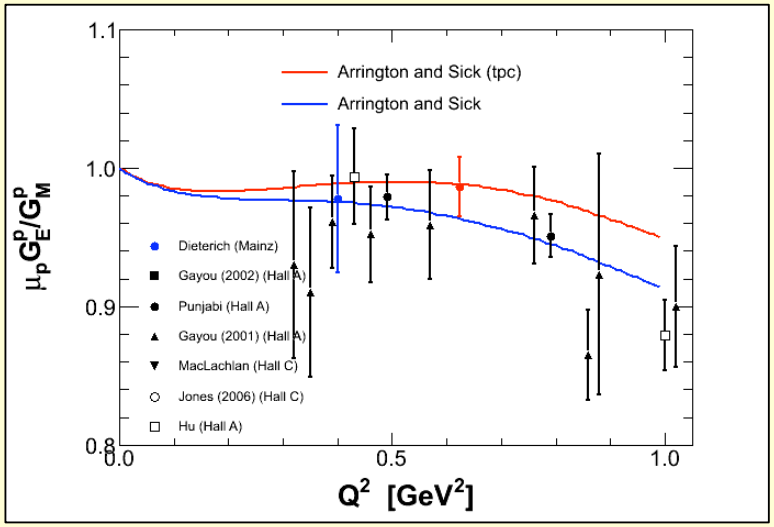


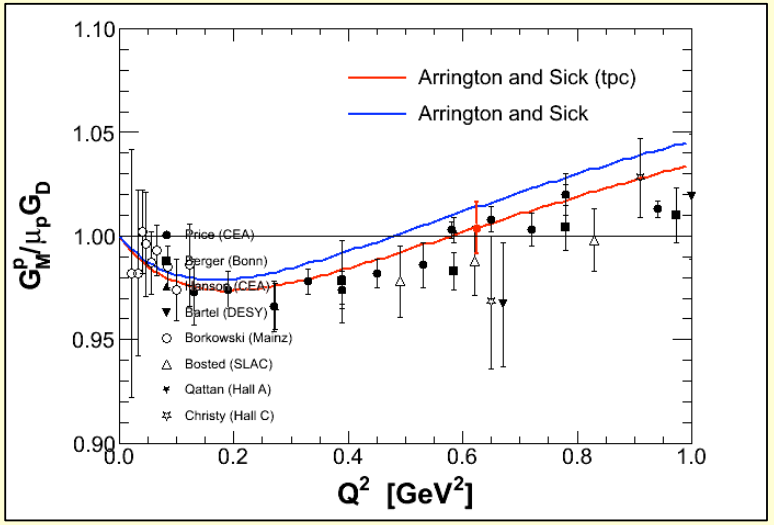
Contribution from $G^{u/d}$ ~ **0.004-0.009**

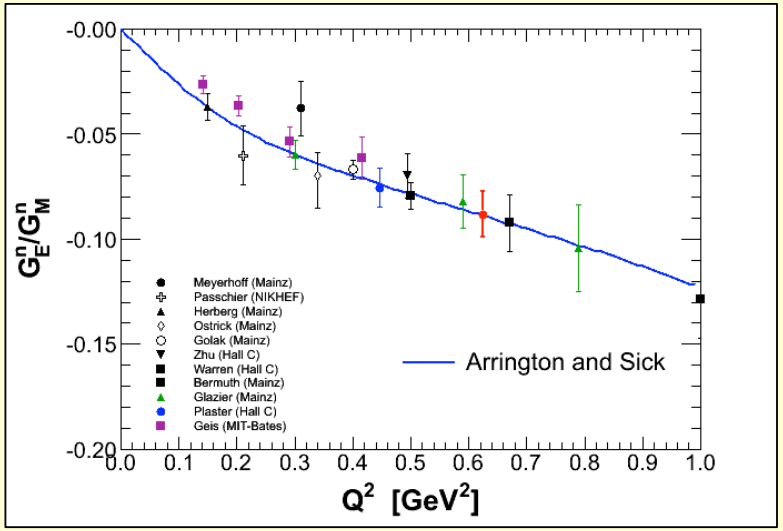
HAPPEX-II: $G^s_E + 0.09\, G^s_M = 0.007 +/- 0.011 +/- 0.004 +/- 0.005$ (FF)

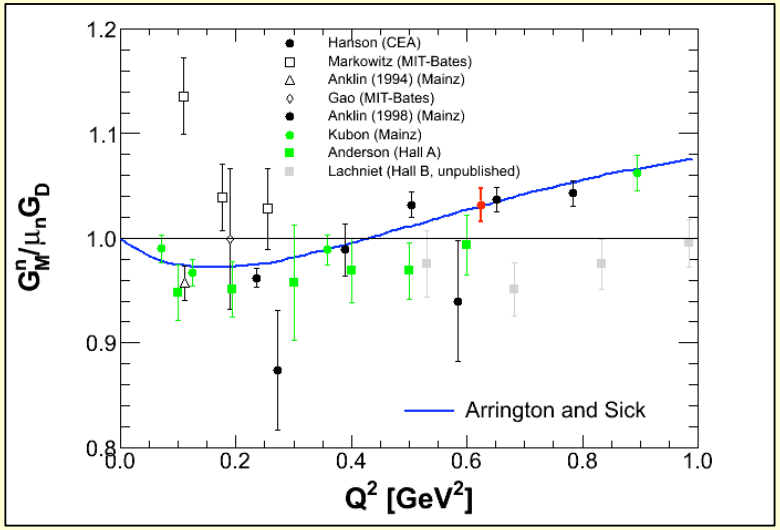
Contributions at higher Q^2 is not determined

EMFF









G_E^p	0.3%
G_M^p	1.1%
G_E^n	1.6%
G_M^n	1.4%
σ_{red}	1.1%
R_{Ana}	0.6%
Total	2.7%

Arrington and Sick, Phys.Rev. C76 (2007) 035201, nucl-th/0612079