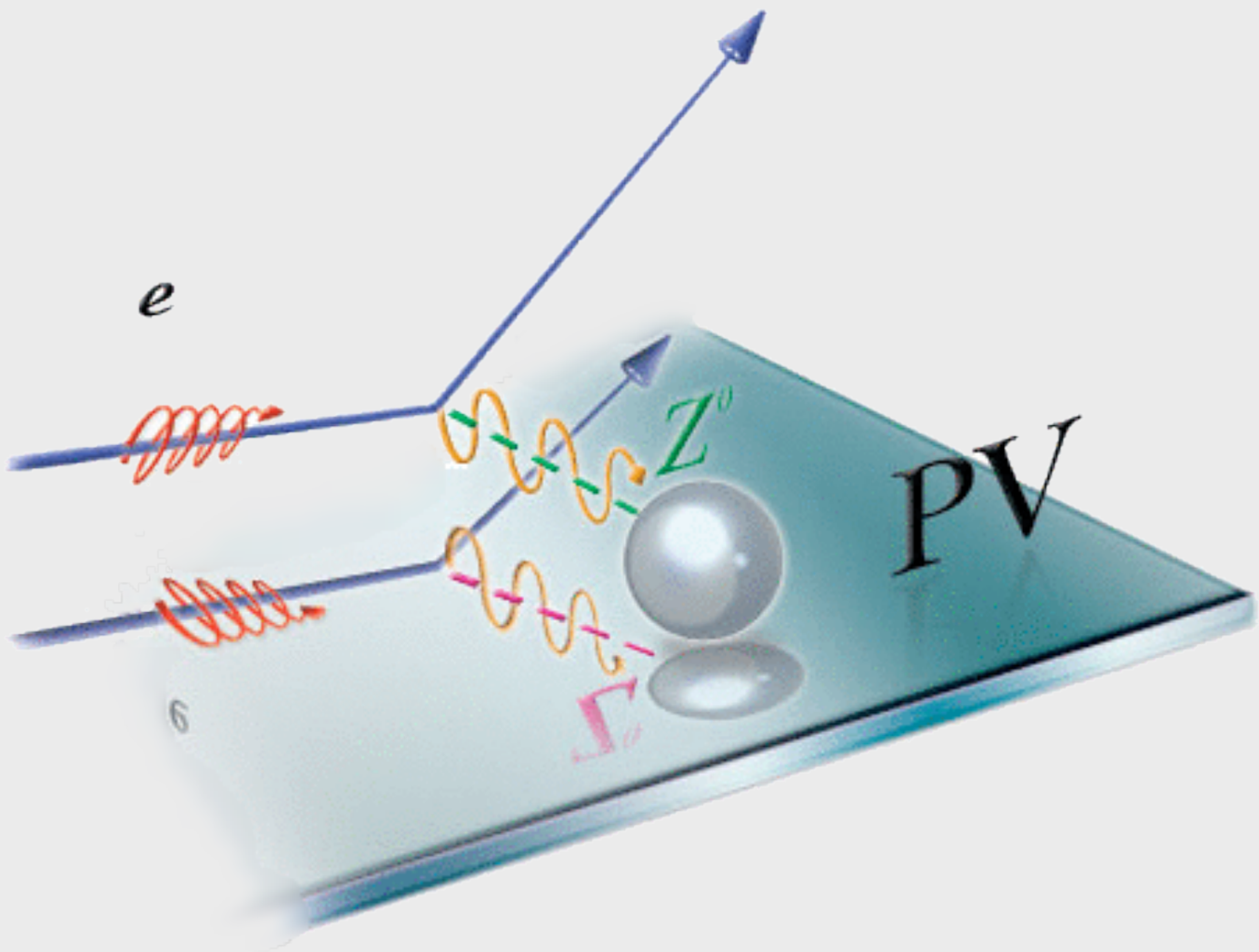
Strangeness Contributions to the Nucleon Vector Form-Factors: Results from HAPPEX-III



Mark Dalton

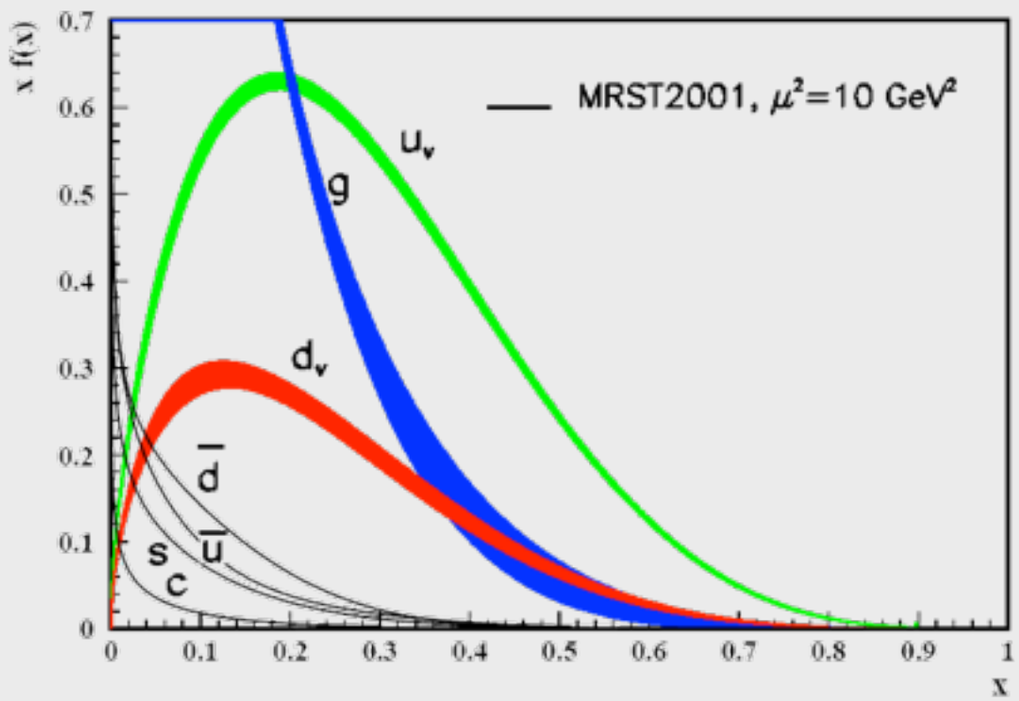
University of Virginia

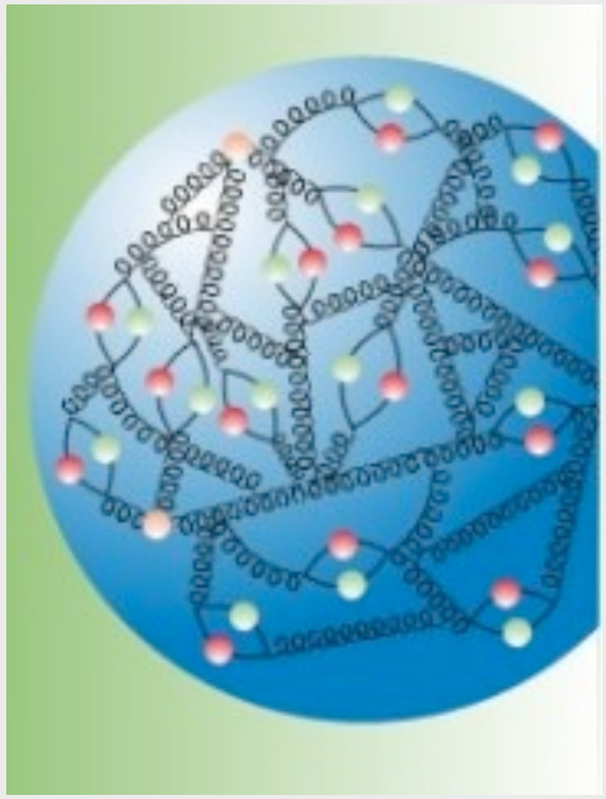
for the
HAPPEX Collaboration

PANIC Conference, MIT
July 25, 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

Extracting the Strange Form Factor with the Neutral Weak Interaction

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

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

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

Extracting the Strange Form Factor with the Neutral Weak Interaction

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

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

Two equations and three unknowns

Extracting the Strange Form Factor with the Neutral Weak Interaction

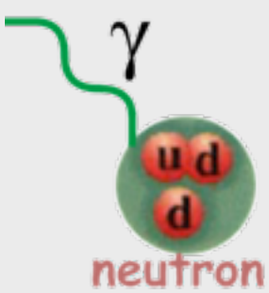
$$G_E^p = \frac{2}{3}G_E^u - \frac{1}{3}G_E^d - \frac{1}{3}G_E^s$$

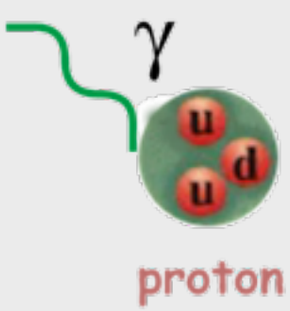
$$G_E^n = \frac{2}{3}G_E^d - \frac{1}{3}G_E^u - \frac{1}{3}G_E^s$$

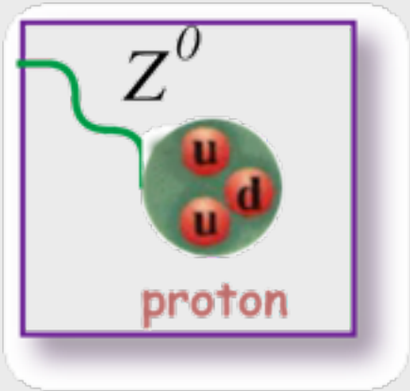
Two equations and three unknowns

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

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{\gamma \quad Z^0}{\gamma^2} \sim \frac{10^{-4} Q^2}{\mathrm{GeV}^2}$$

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

"Anapole" radiative corrections are problematic

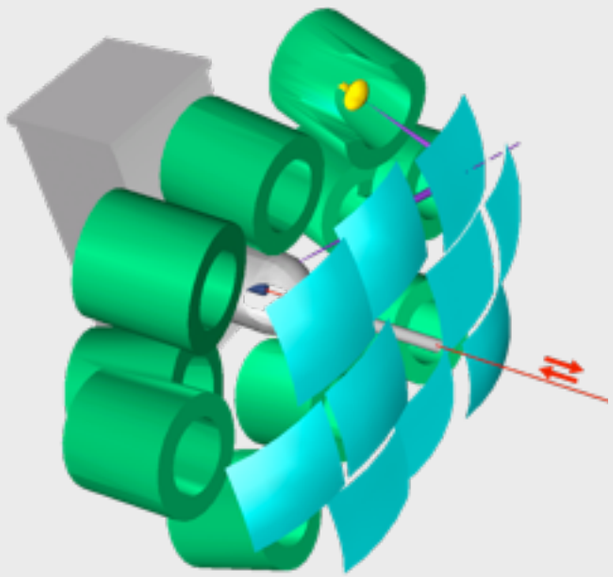
Neutral weak proton form factor

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

Spin=0,T=0 ^{4}He: **G^s_E only!**

Deuterium: **Enhanced G_A**

Experimental Overview



SAMPLE

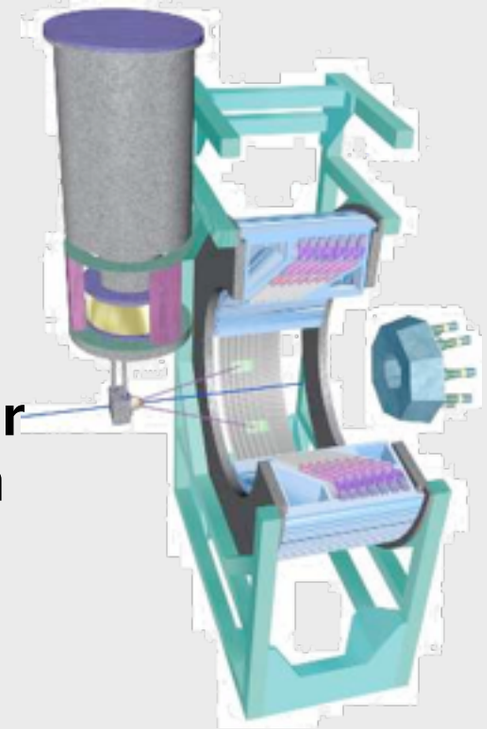
open geometry,
integrating,
back-angle only

A4

Open geometry

Fast counting calorimeter for background rejection

Forward and Backward angles

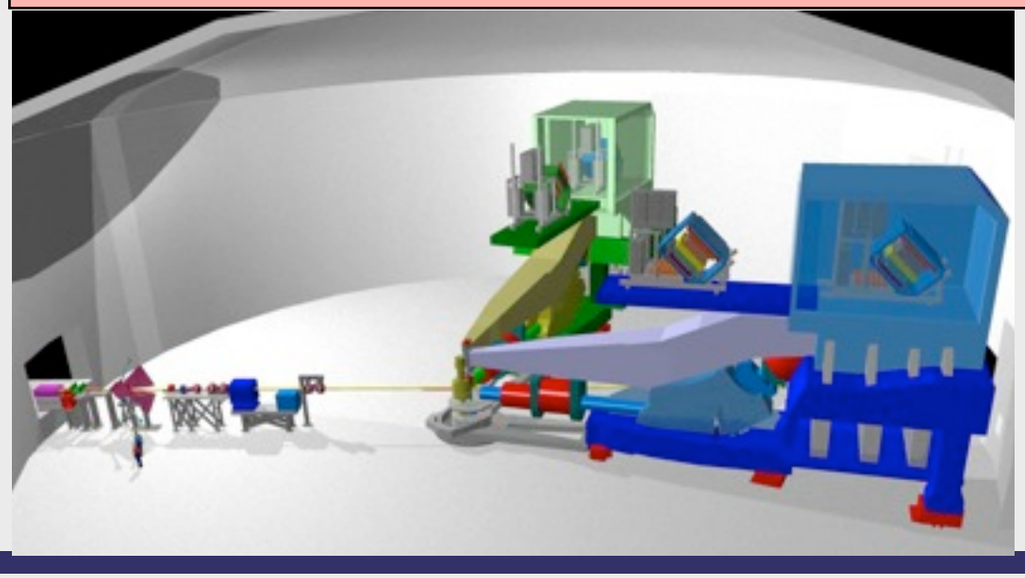


HAPPEX

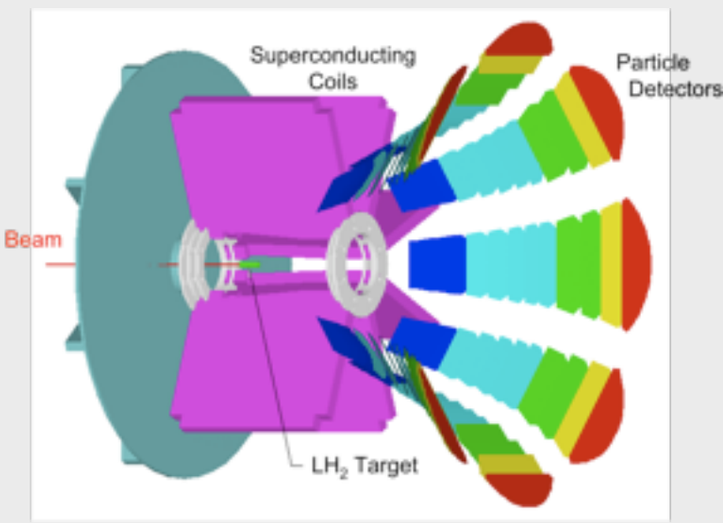
Precision spectrometer, integrating

Forward angle, also ^{4}He at low Q^2

HAPPEX-3: $G_E^s + 0.52\ G_M^s$ at $Q^2 = 0.62\ GeV^2$



G0

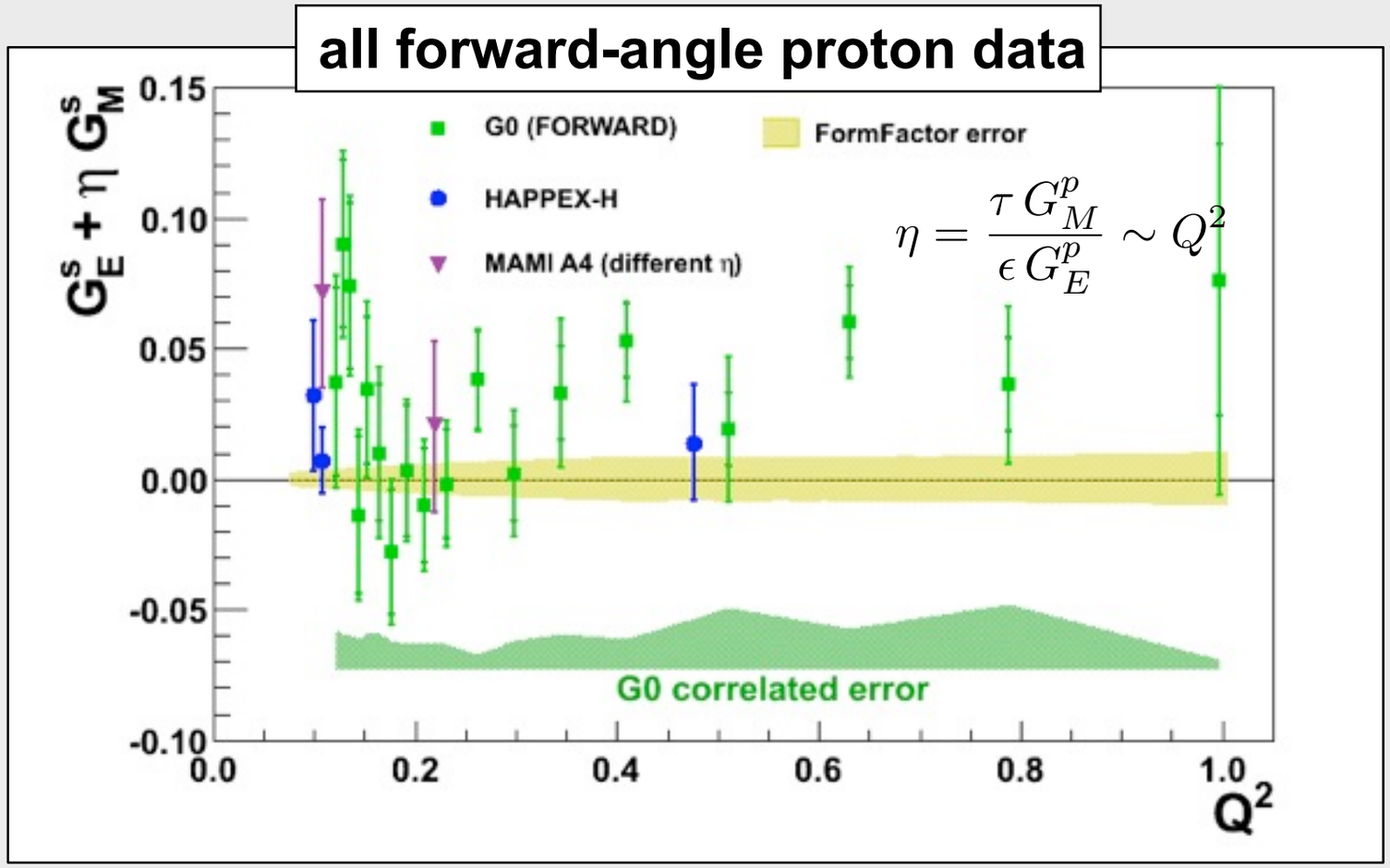


Open geometry

Fast counting with magnetic spectrometer + TOF for background rejection

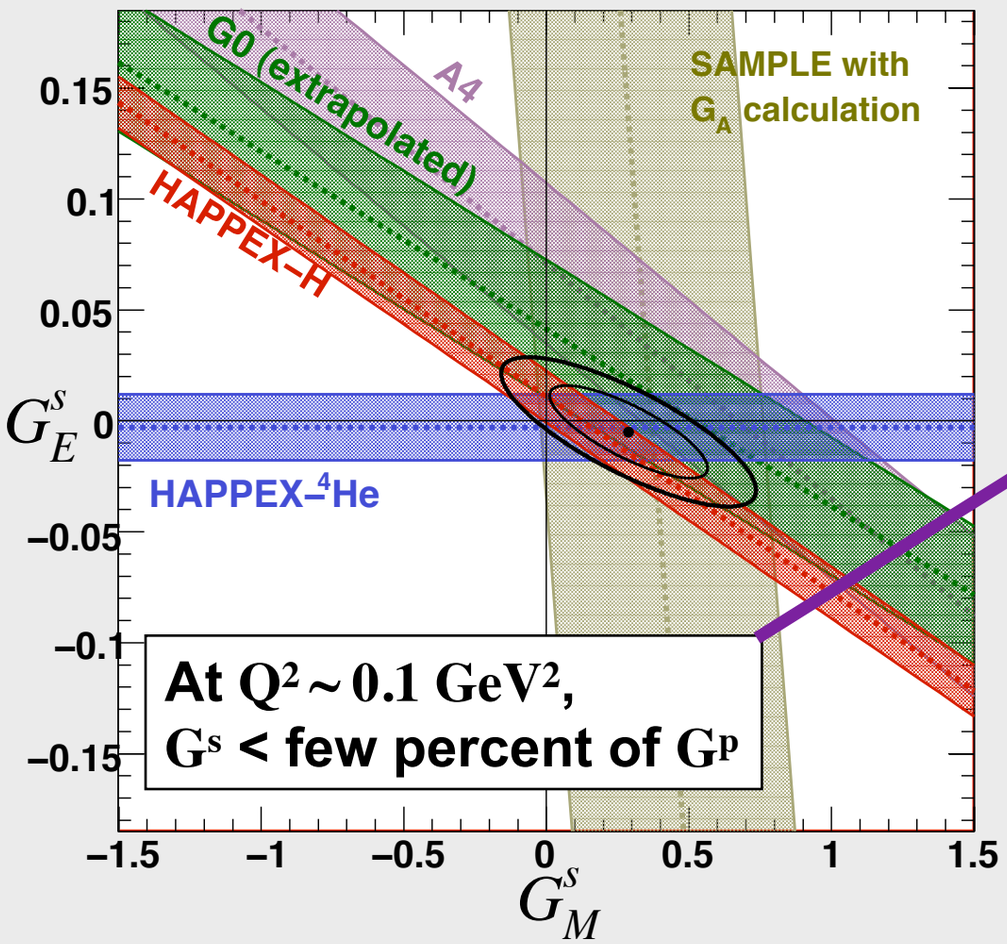
Forward and Backward angles over a range of Q^2

World data on G^s

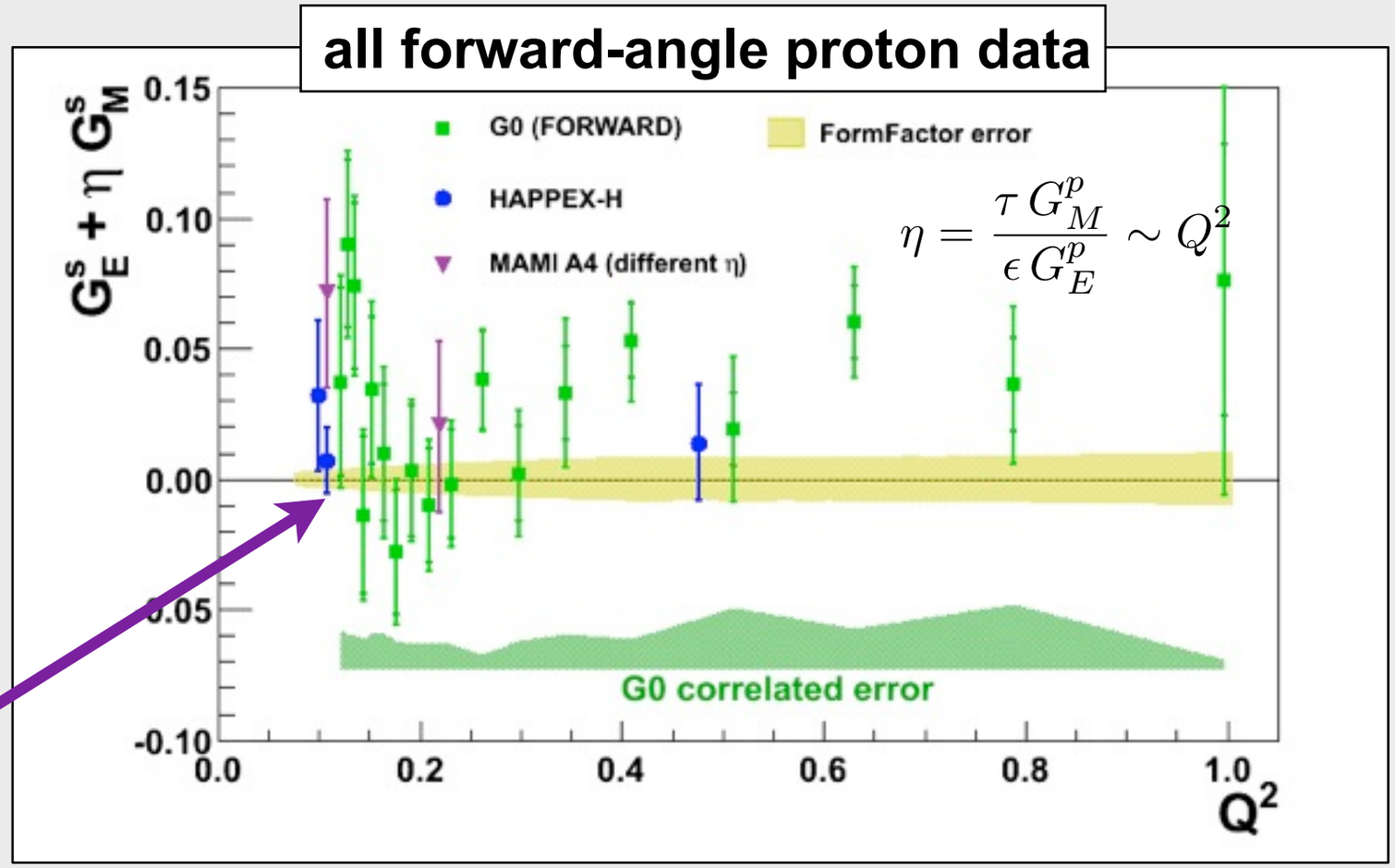


- "Form Factor" error: precision of EMFF (including 2γ) and Anapole correction
- Significant systematic uncertainty in higher Q^2 points

World data on G^s



At $Q^2 \sim 0.1$ GeV^2,
G^s < few percent of G^p



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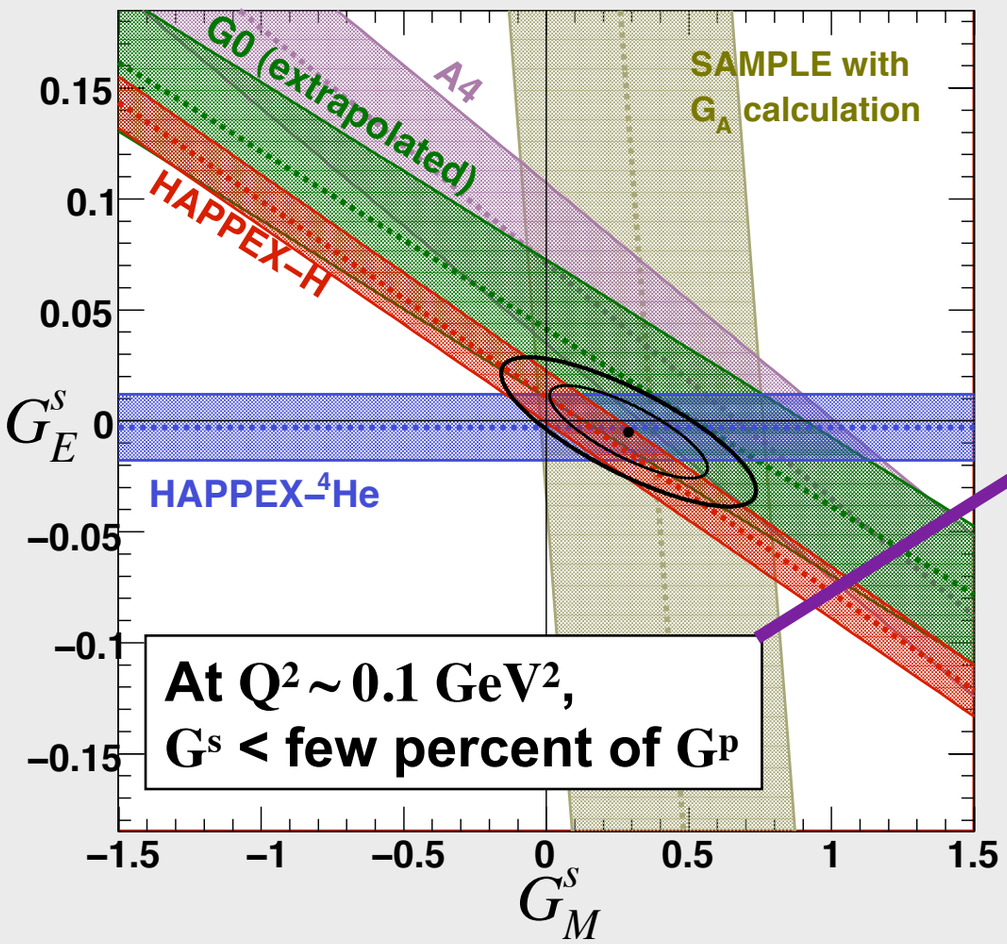
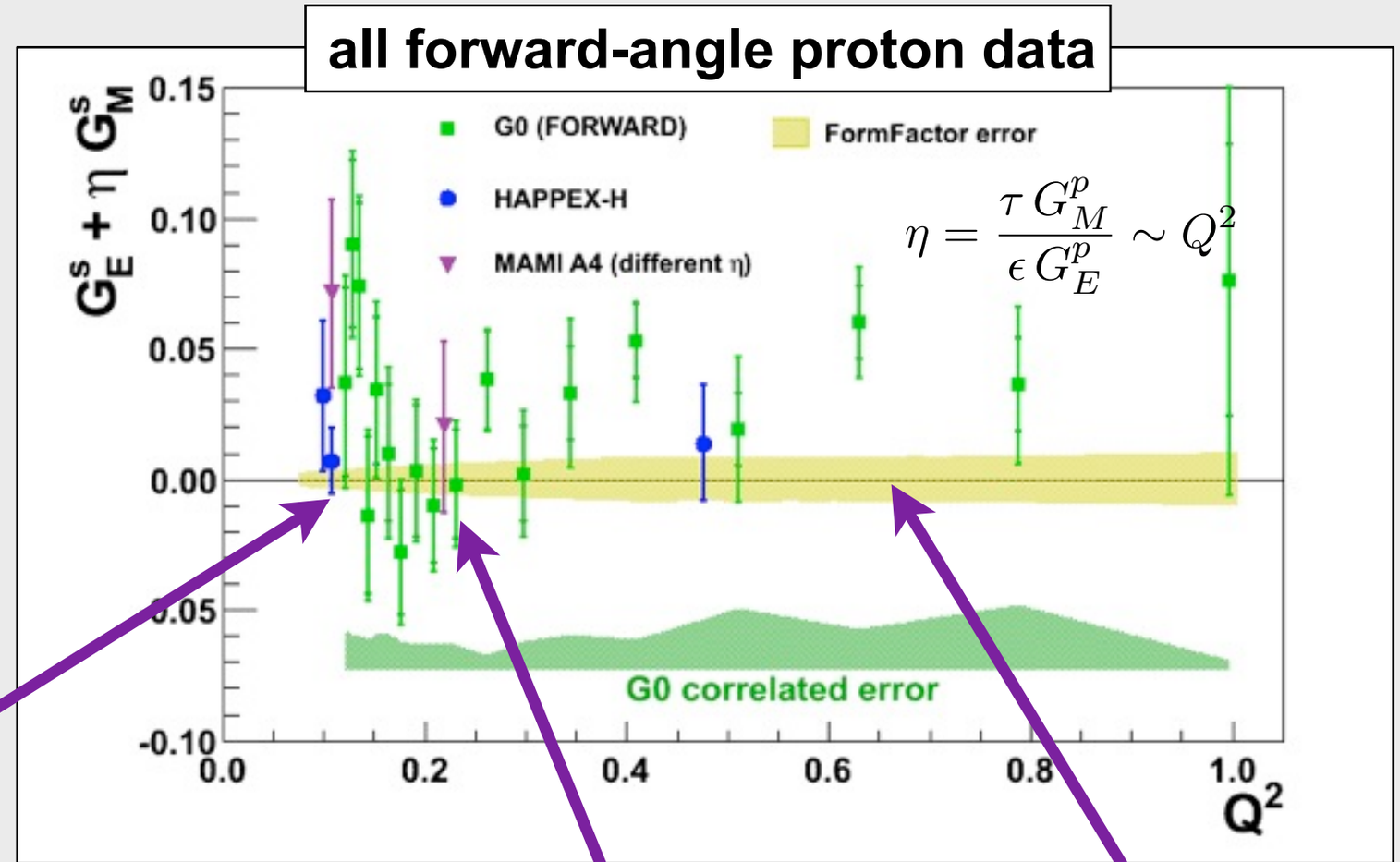
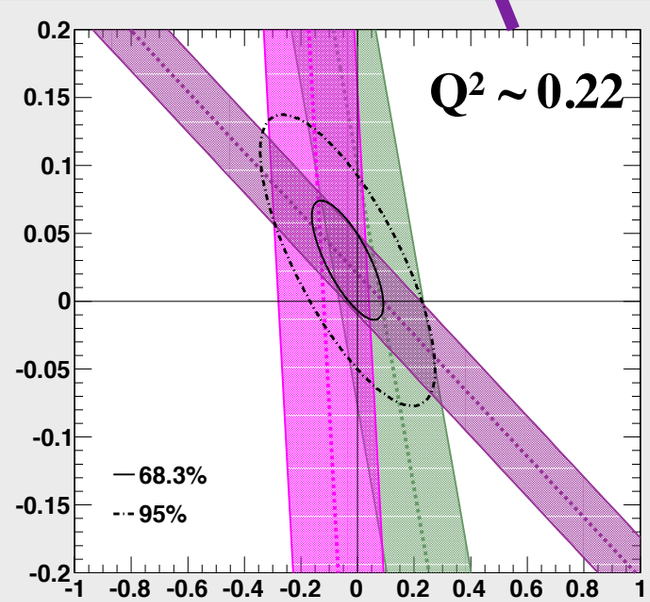
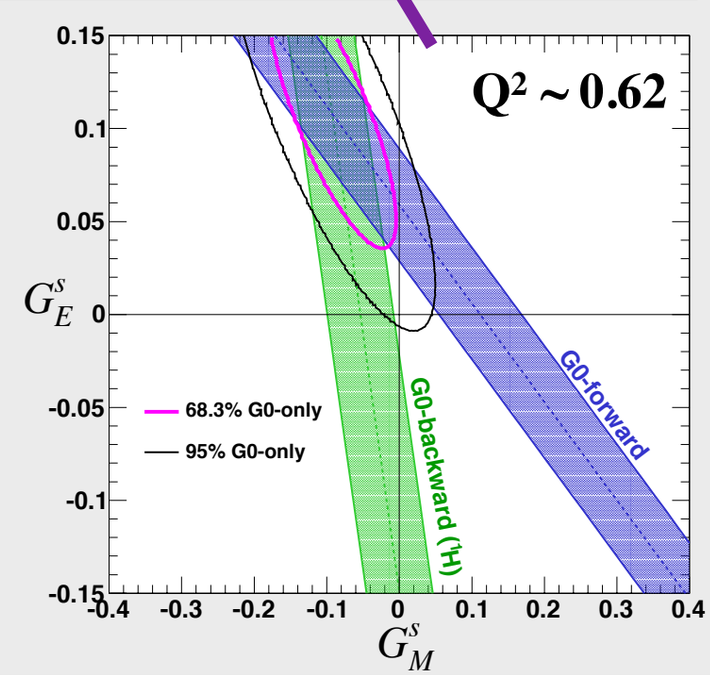
World data on G^s



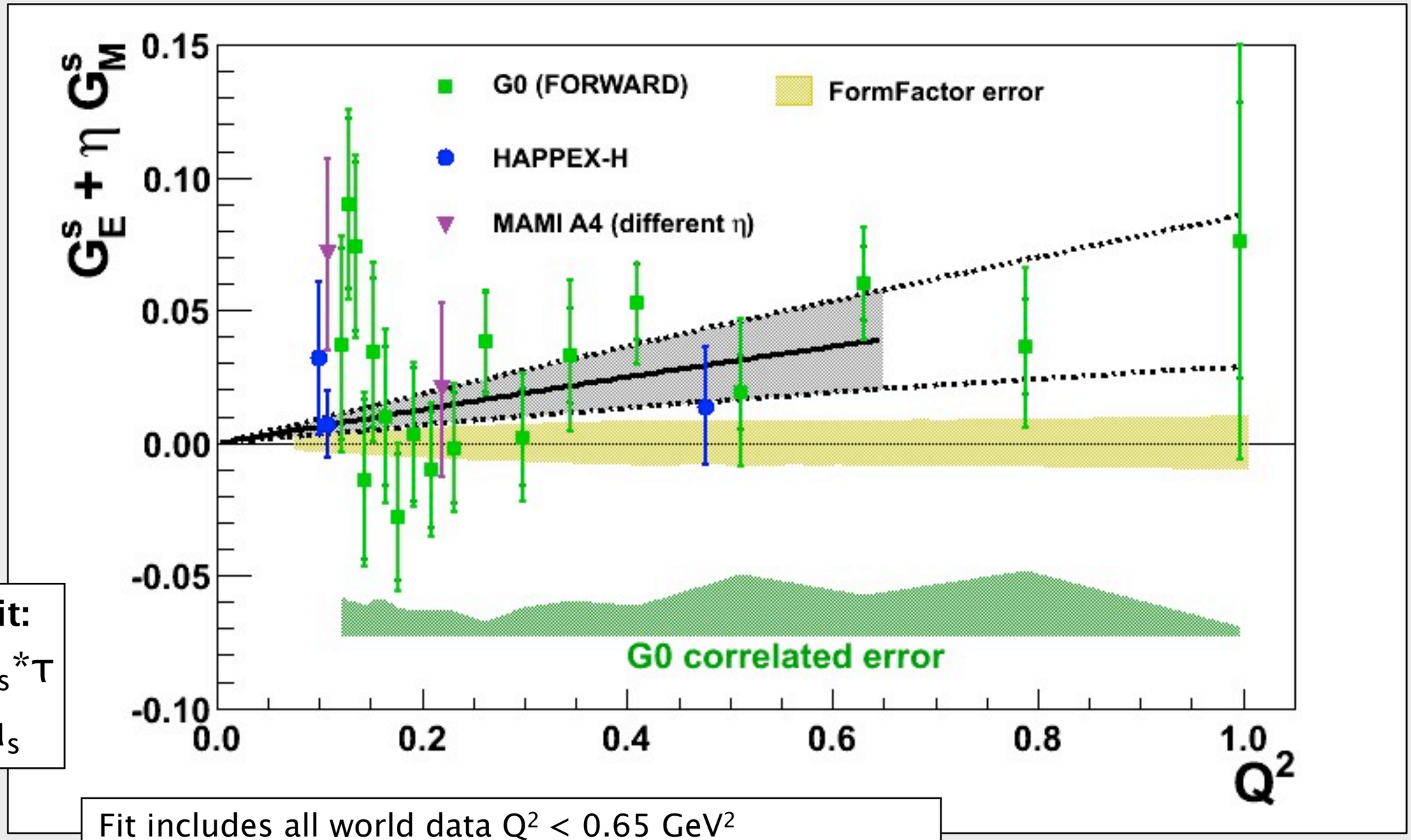






- "Form Factor" error: precision of EMFF (including 2γ) and Anapole correction
- Significant systematic uncertainty in higher Q^2 points

Global fit of all world data



Simple fit:

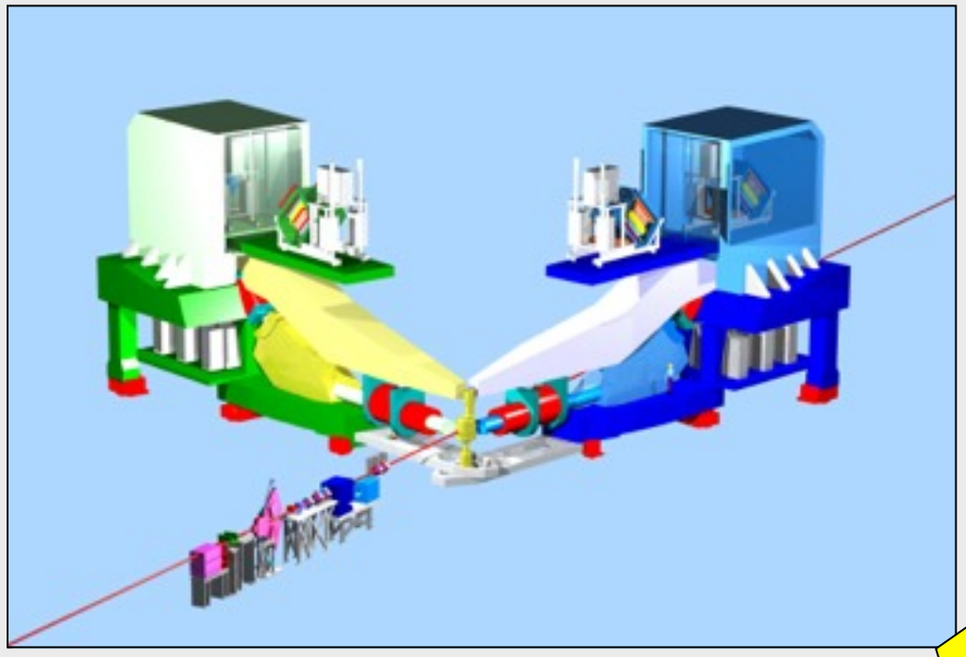
$G_E^s = \rho_s * \tau$

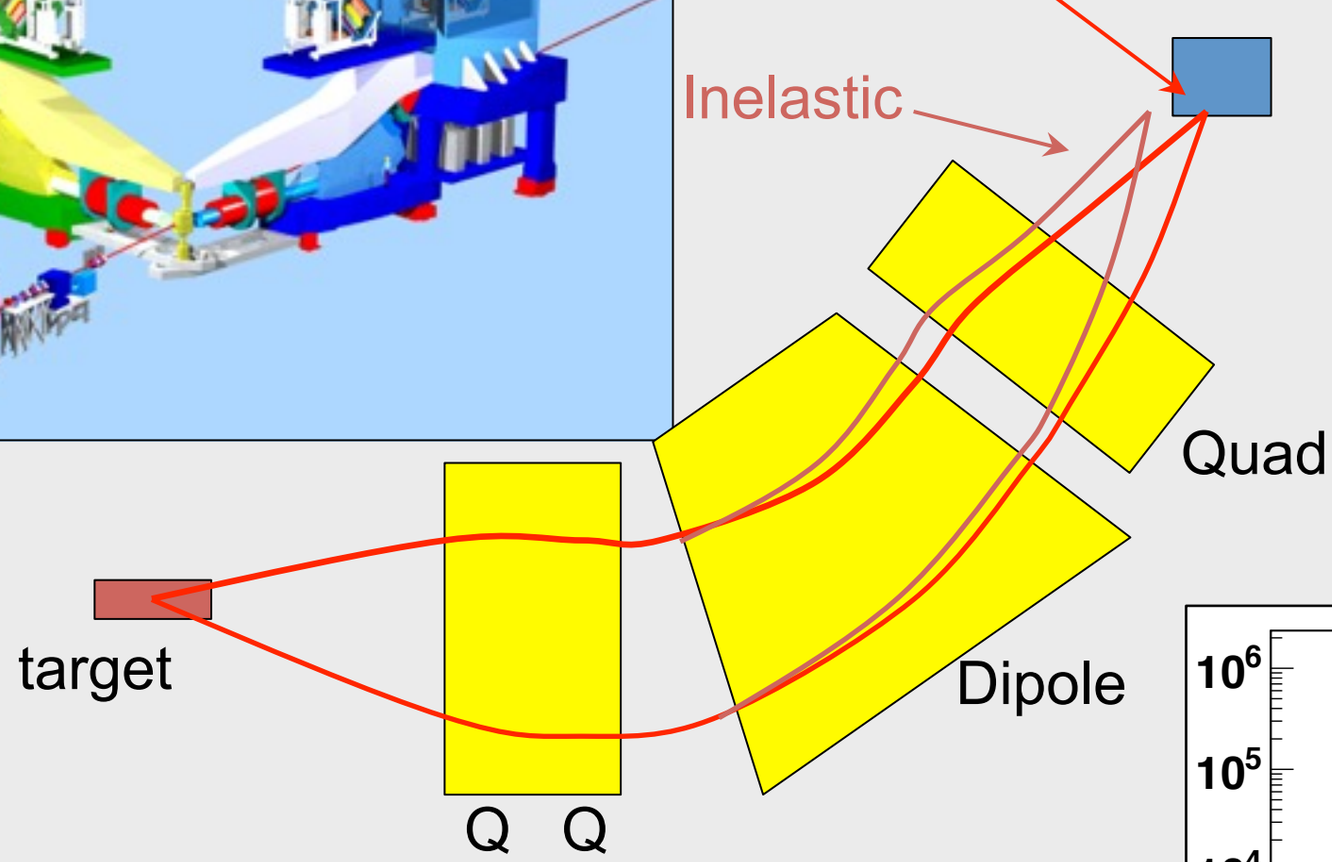
$G_M^s = \mu_s$

Fit includes all world 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.**

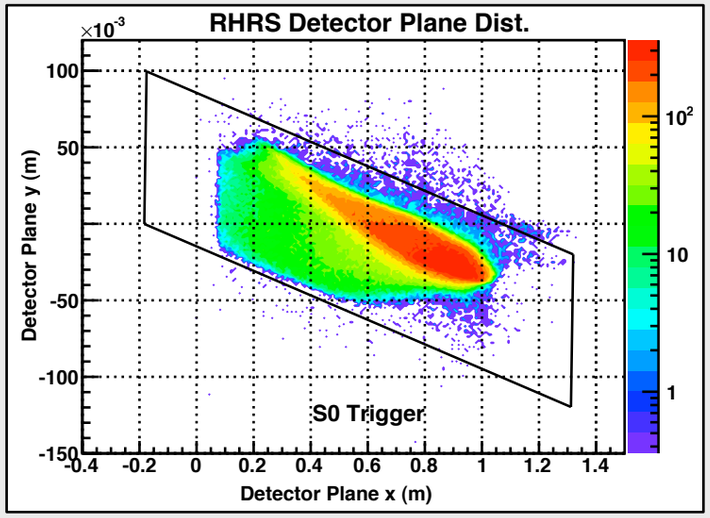
Integrating in the High Resolution Spectrometers





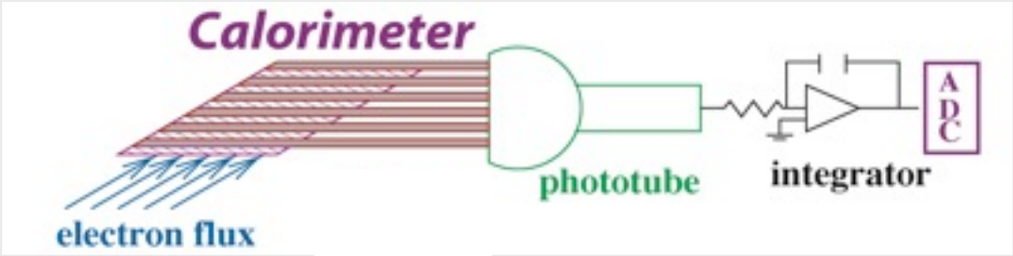
Very clean separation of elastic events by HRS optics

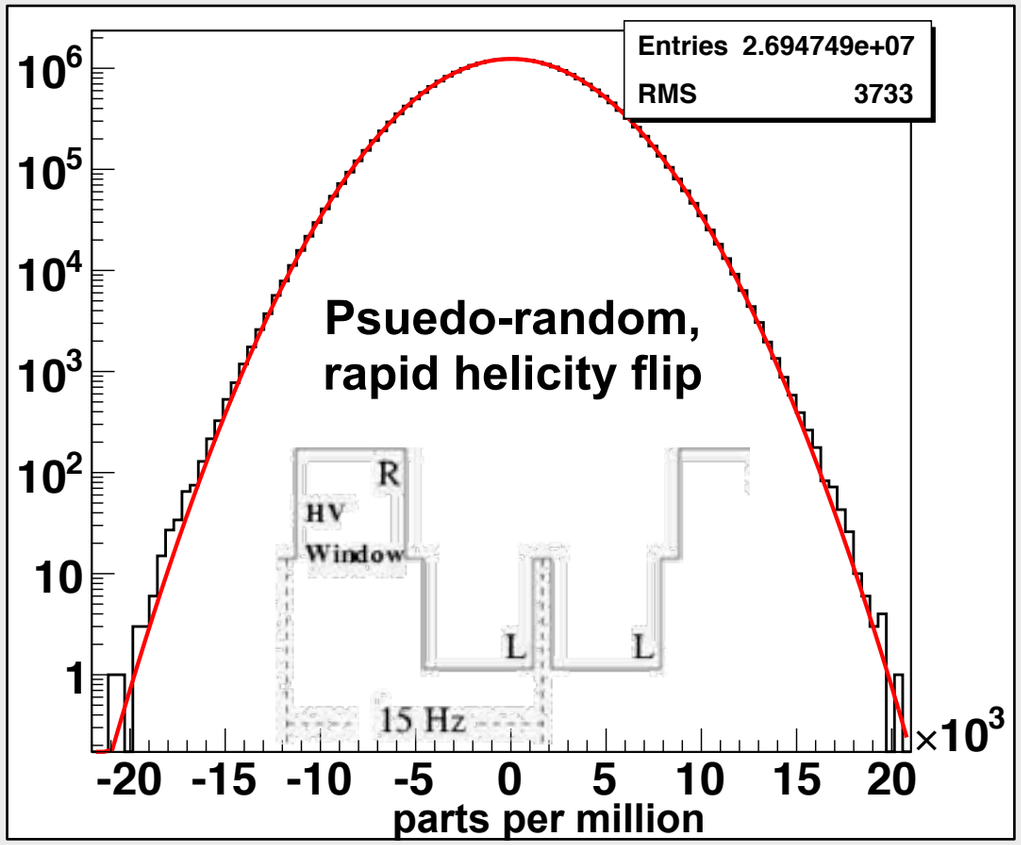
no PID needed; detector sees only elastic events



Lead – Lucite Cerenkov Shower Calorimeter

phototube current integrated over fixed time periods

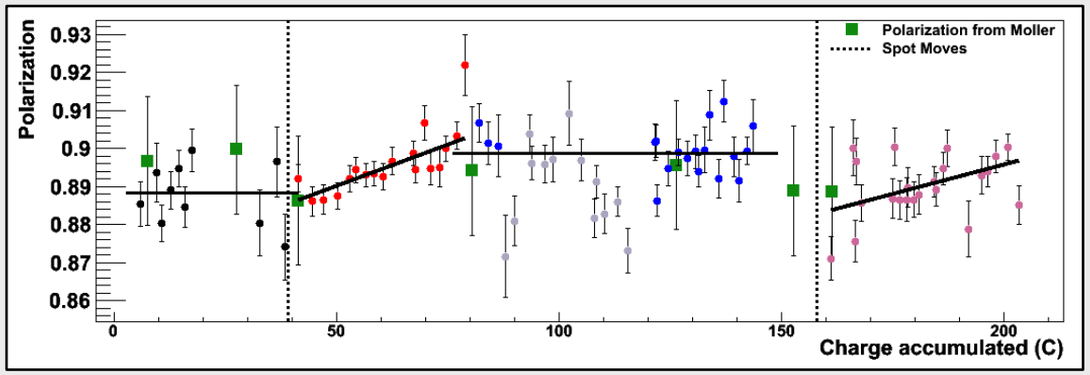




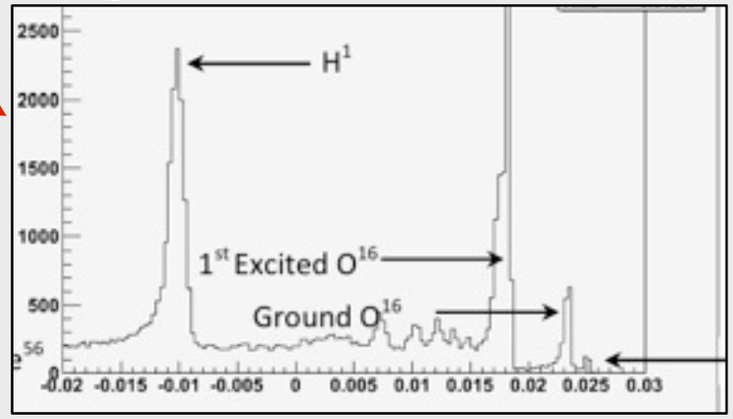
HAPPEX-III Error Budget

	δA_{PV} (ppm)	δA_{PV} / A_{PV}
Polarization	0.20	0.8%
Q^2	0.18	0.8%
Backgrounds	0.19	0.8%
Linearity	0.12	0.5%
Finite	0.05	0.2%
False	0.04	0.2%
Total	0.369	1.51%
Statistics	0.778	3.27%
Total	0.857	3.60%

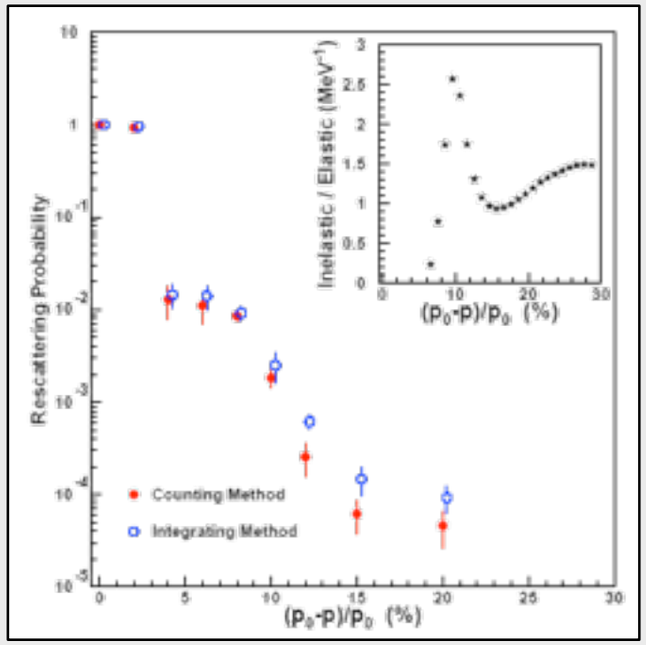
Compton + Moller polarimeters



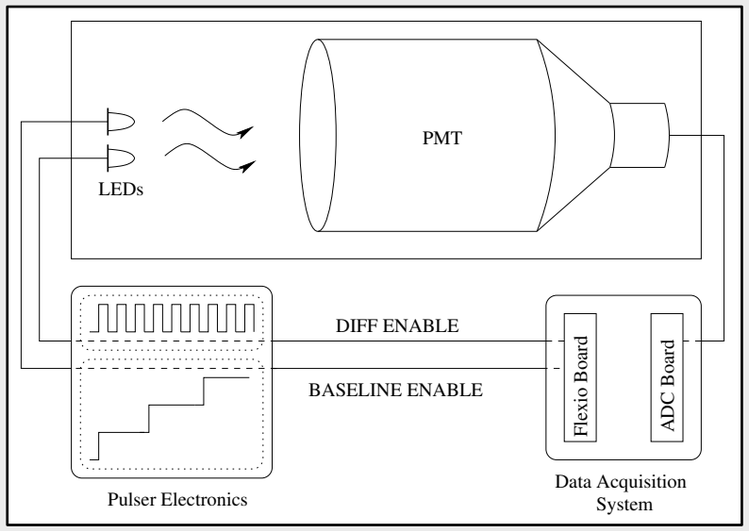
Spectrometer Calibration



HRS Backgrounds



Linearity Studies

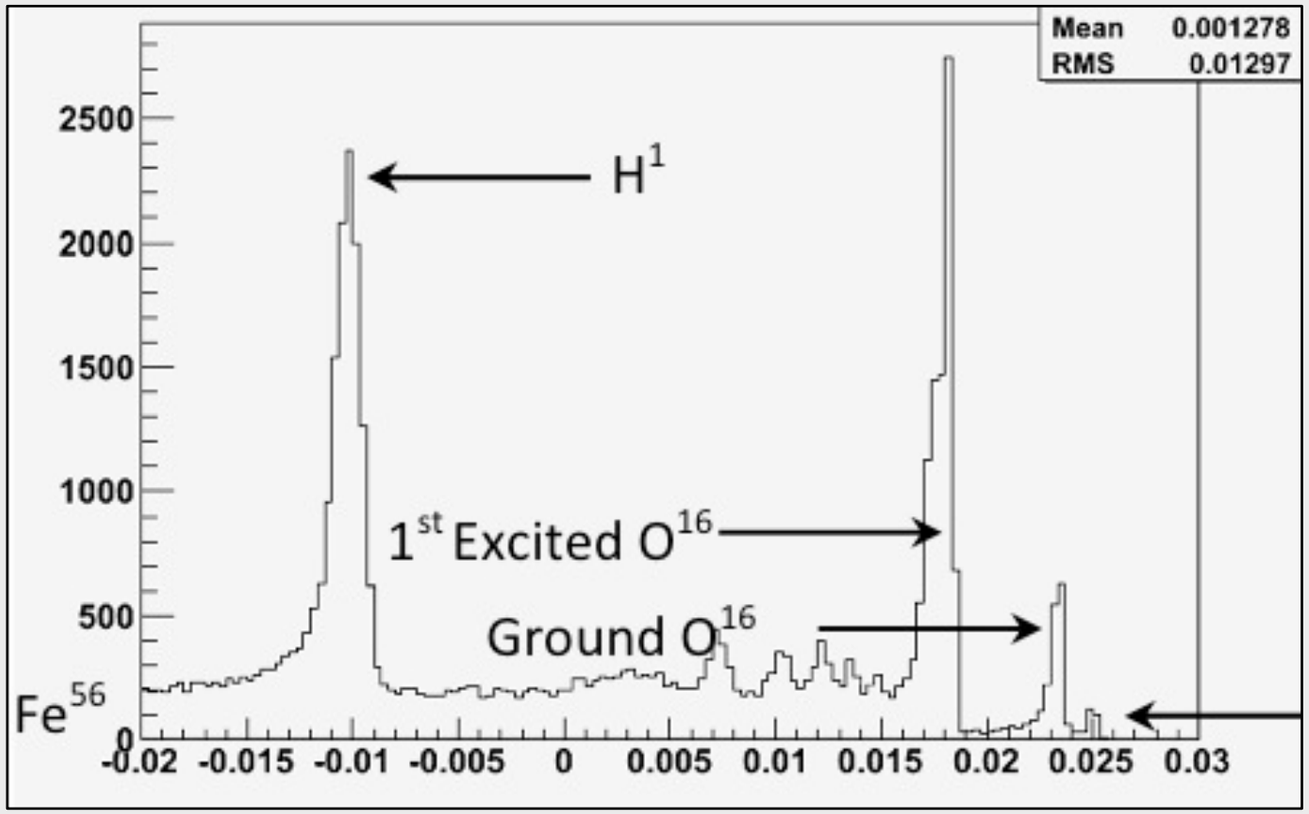


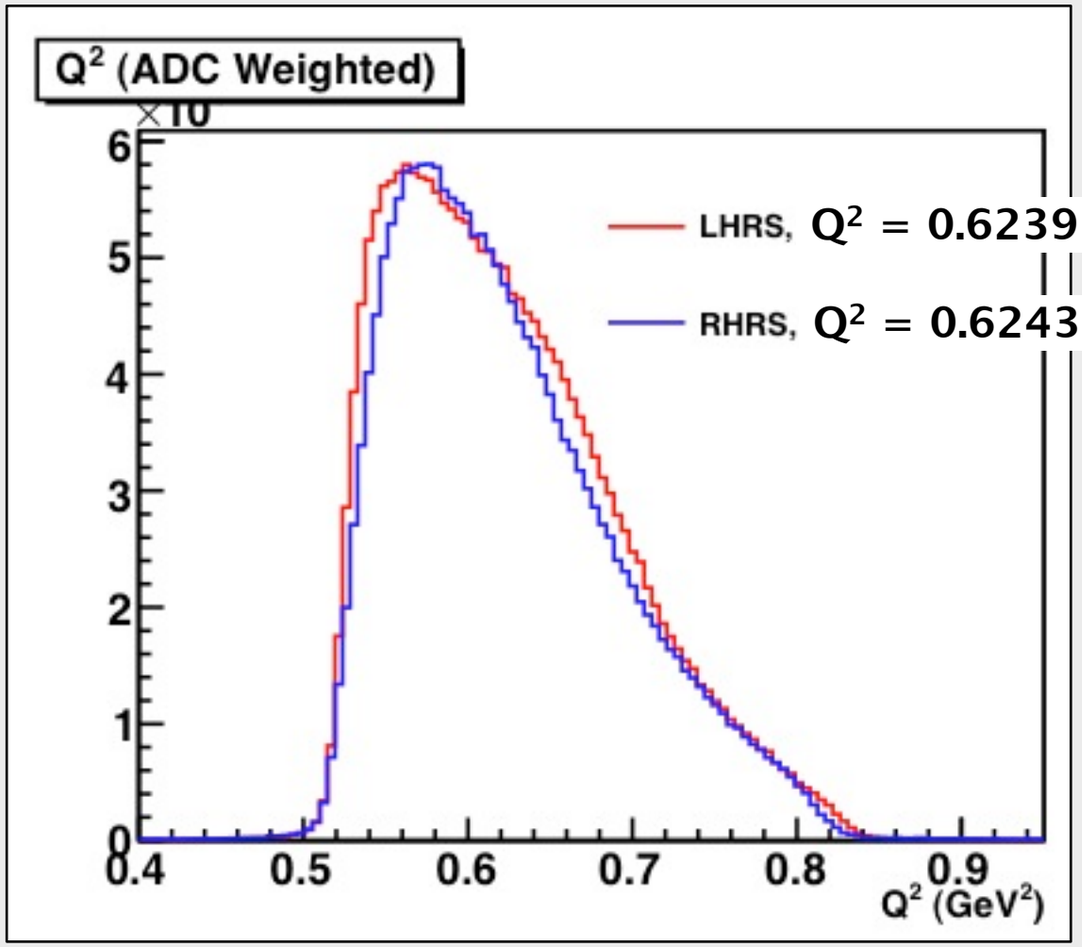
Systematic uncertainties are well controlled - experiment is statistics dominated

Determining Q^2

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

$\delta\theta \sim 0.55$ mrad (0.23%)

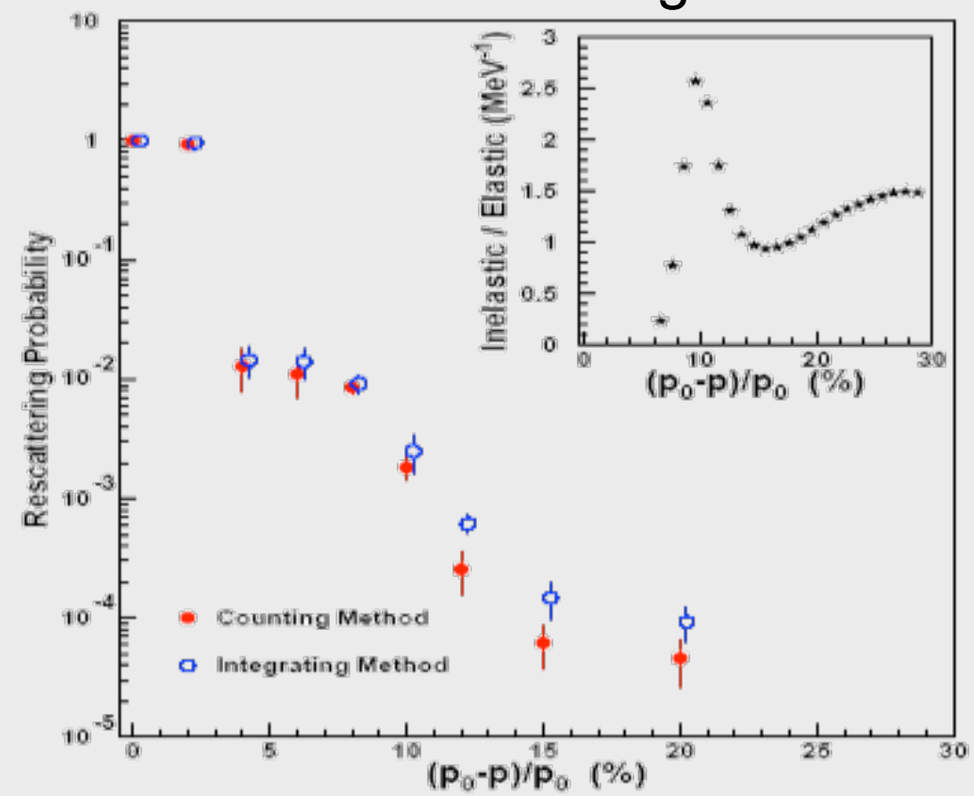
$Q^2 = 0.6241 \pm 0.0032$ (0.52%)

Central Angle	0.45%
Beam Energy, HRS momentum	0.11%
Drifts	0.2%
ADC weighting	0.1%
Total	**0.52%**

Backgrounds

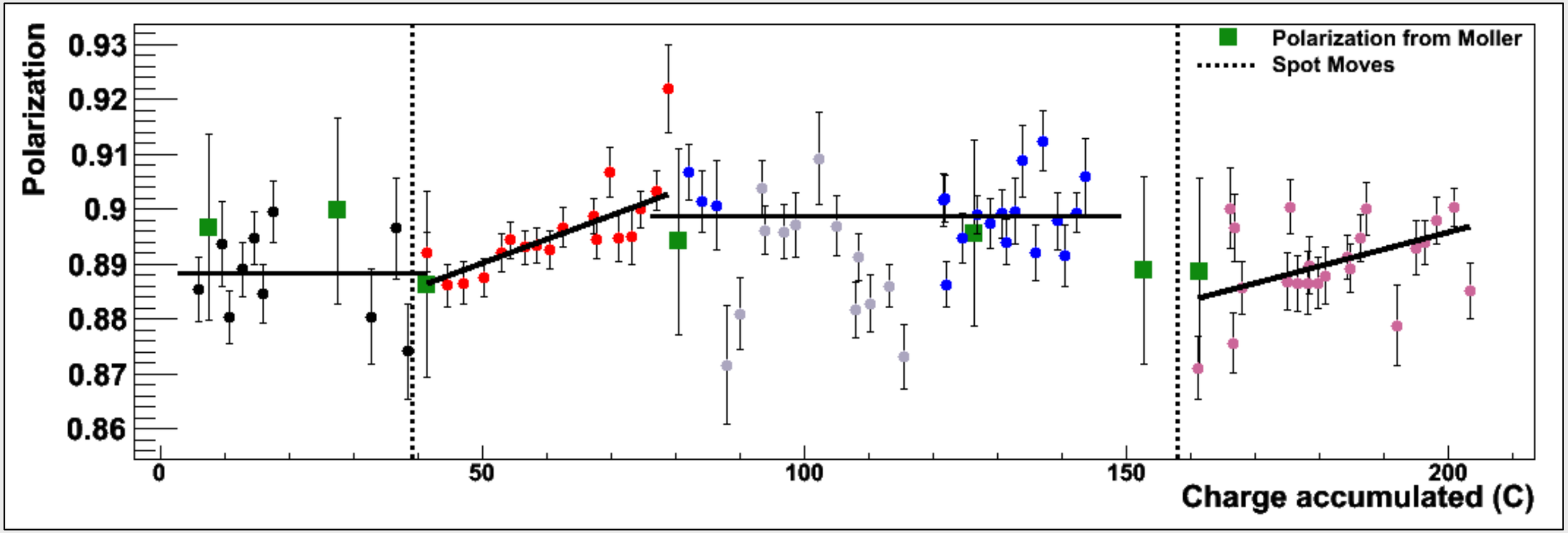
- Aluminum from target windows
- Signal from inelastic electrons scattering inside spectrometer

Rescattering probability measured during H-I



background	fraction	Asymmetry	Net Correction	Net Uncertainty
Aluminum (target window)	1.15% (30%)	-34.5 ppm (30%)	125 ppb	126 ppb
Rescattering	0.3% (25%)	-63 ppm (25%)	114 ppb	55 ppb

Polarimetry Summary



Compton: 89.41± 0.96%
Moller: 89.22 ± 1.7%

Average: 89.36 ± 0.84%

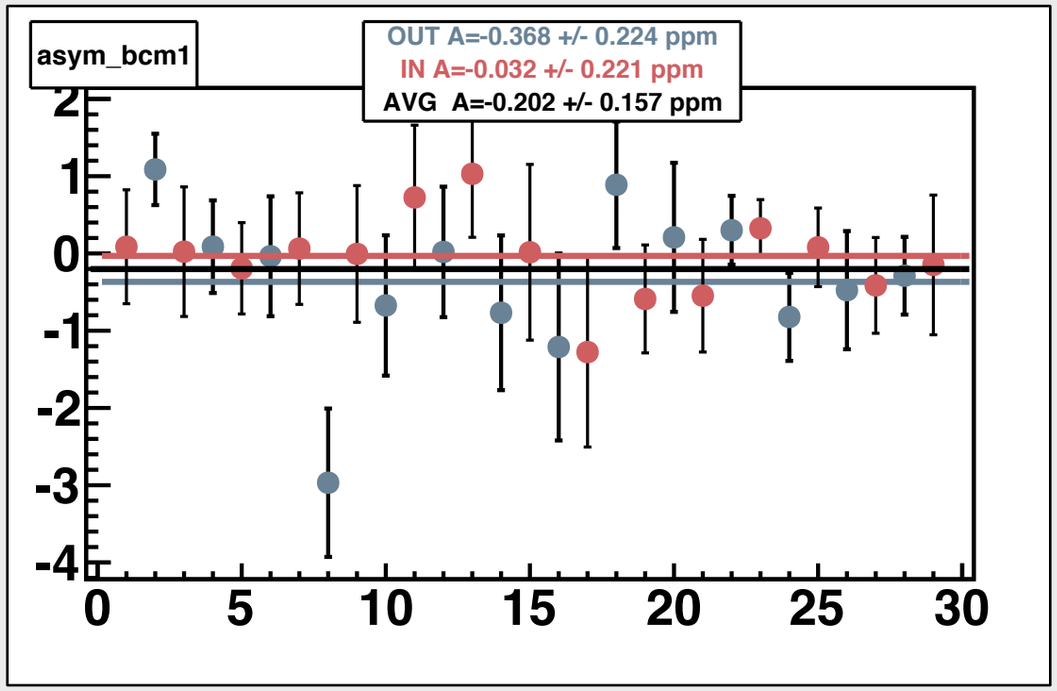
Moller systematic errors

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

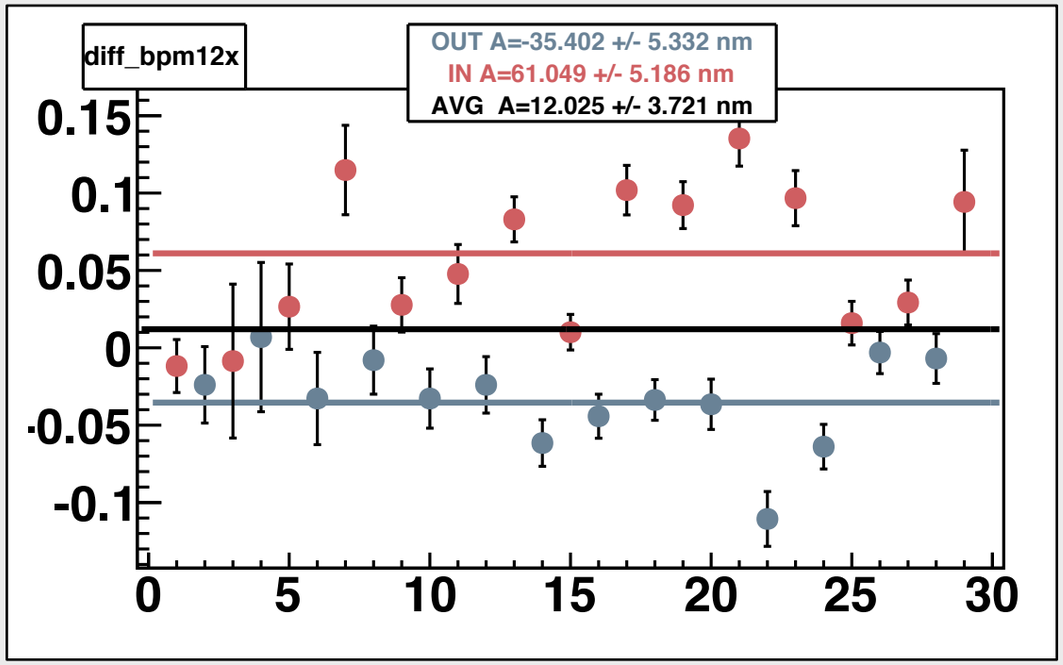
Compton systematic errors

laser polarization	0.80%
Analyzing Power	0.33%
Asymmetry	0.43%
TOTAL	**0.96%**

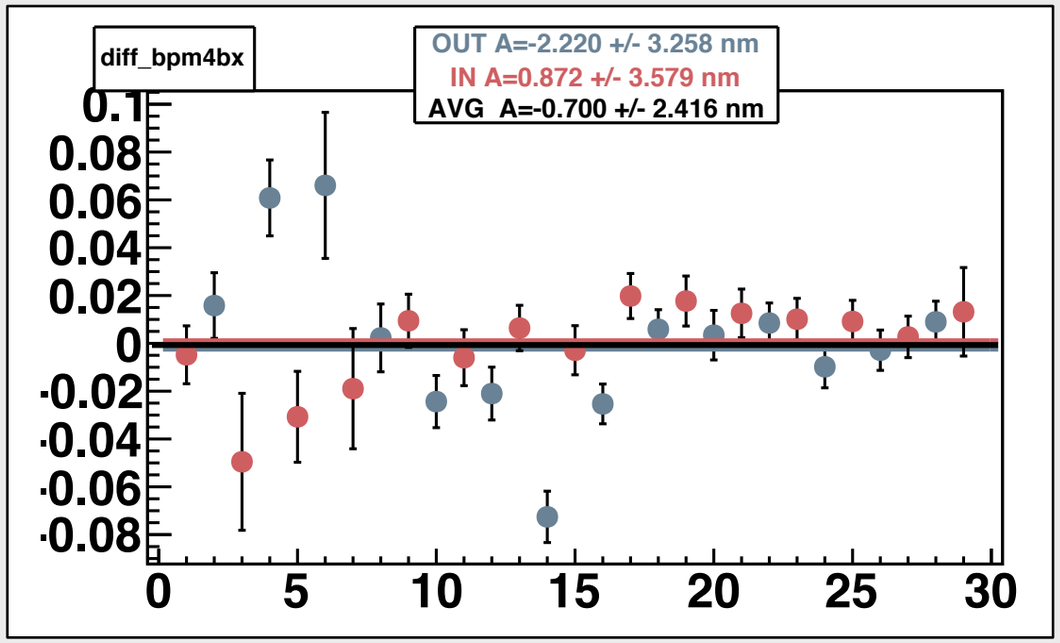
Beam Asymmetries



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:
-0.016 ppm (0.07%)

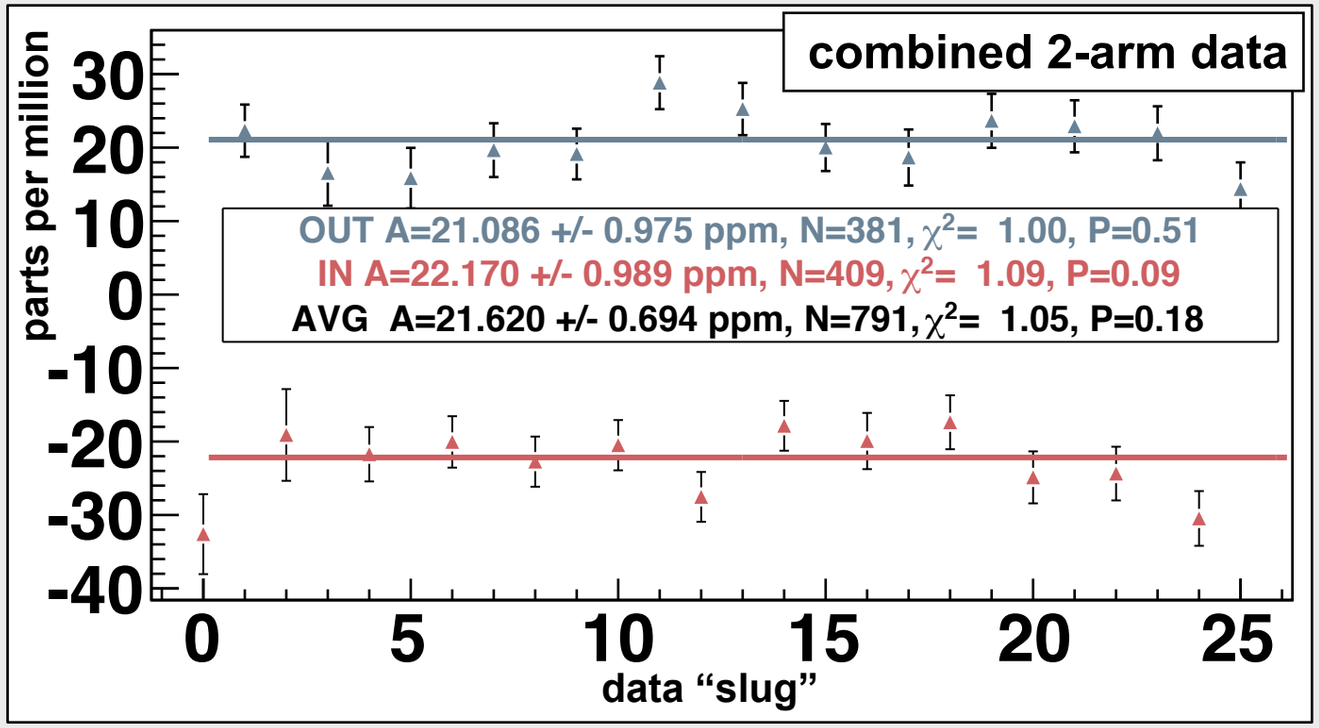
Trajectory at target averages to <3nm,<0.5nrad

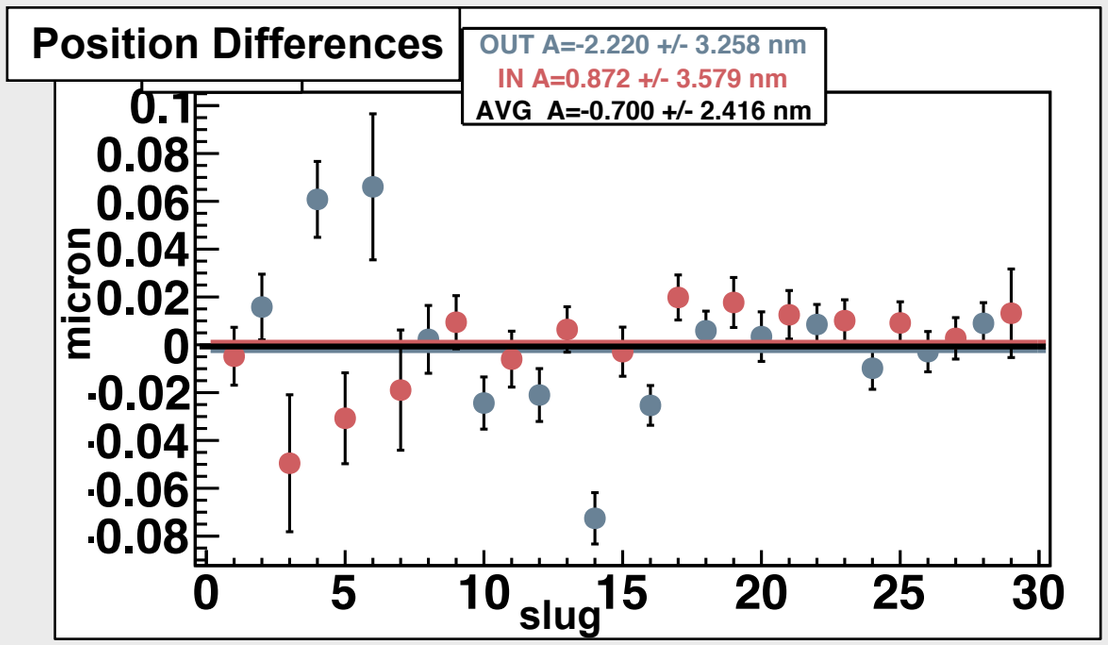
HAPPEX-III Measurement of A_{PV}

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

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

OUT / IN from "slow" spin reversals to cancel systematics





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

Corrections are then applied:
- backgrounds (1.0%)
- acceptance averaging (0.5%)
- beam polarization (11%)

3.27% (stat)± 1.5% (syst)

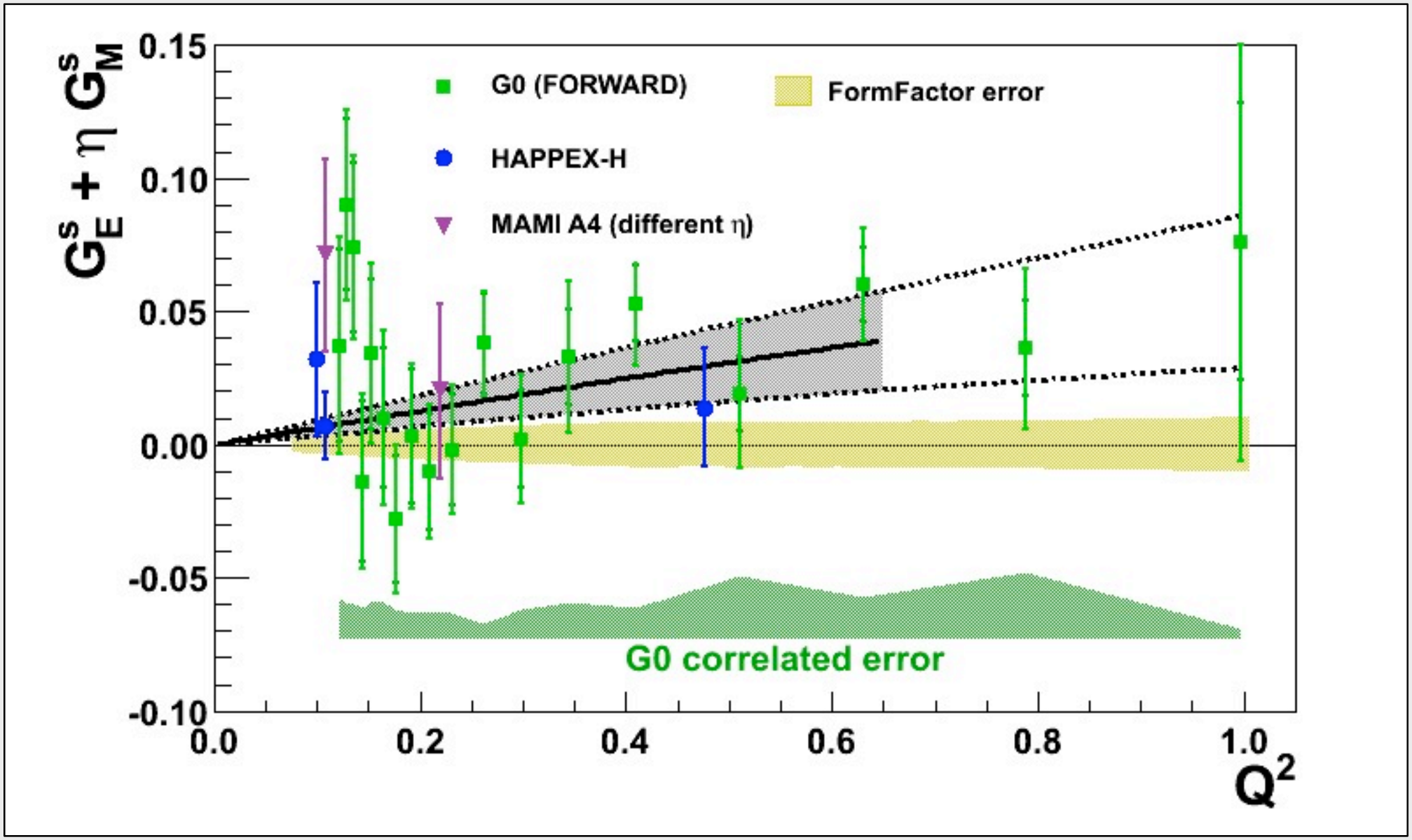
total correction ~2.5% + polarization

Analysis Blinded ± 2.5 ppm

HAPPEX-III Result

$A_{PV} = -23.803 \pm 0.778$ (stat) ± 0.359 (syst) ppm

$Q^2 = 0.6241 \pm 0.0032\ (GeV/c)^2$



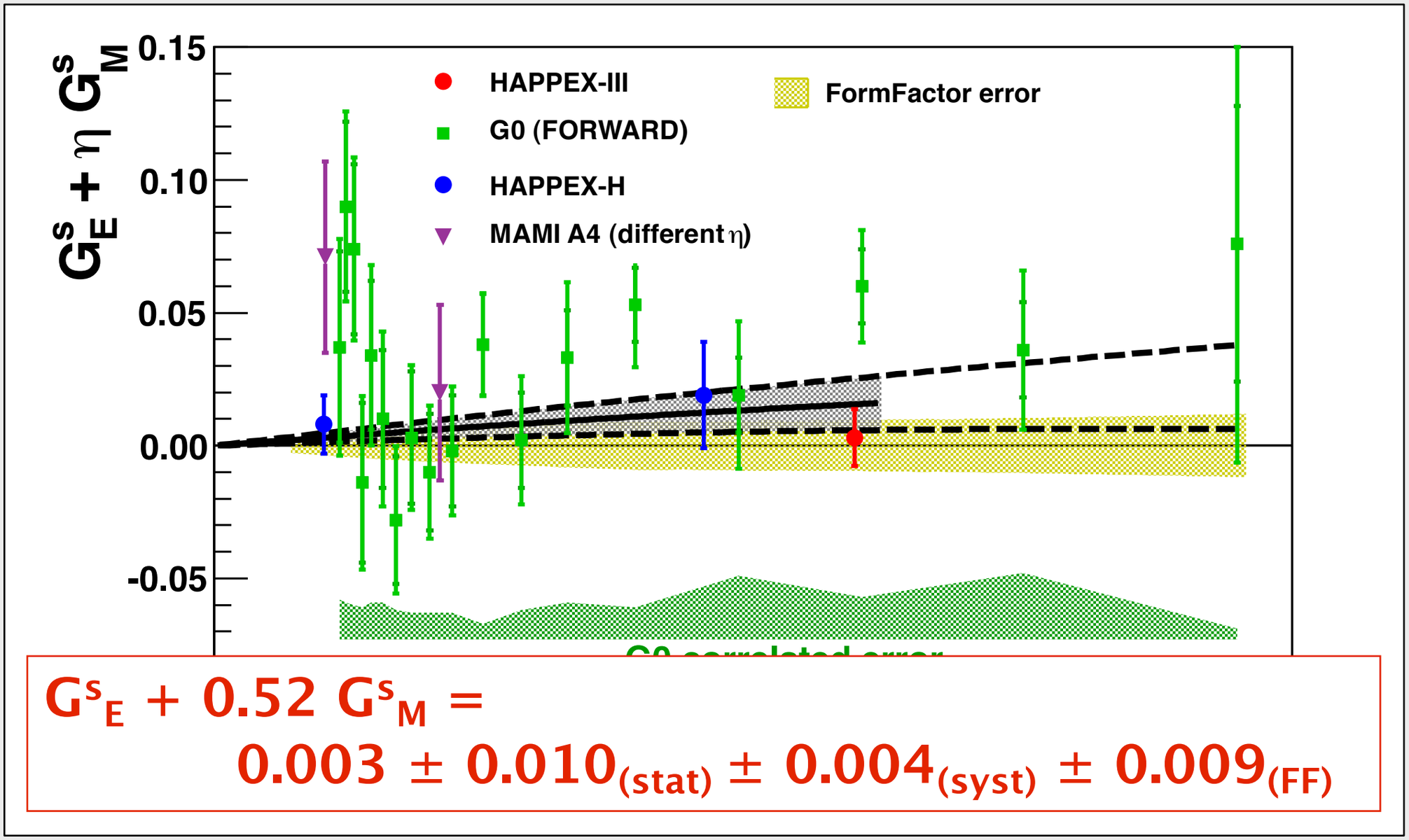
HAPPEX-III Result

$A_{PV} = -23.803 \pm 0.778\ (stat) \pm 0.359\ (syst)\ ppm$

$Q^2 = 0.6241 \pm 0.0032\ (GeV/c)^2$

$A(G^s=0) = -24.062\ ppm \pm 0.734\ ppm$

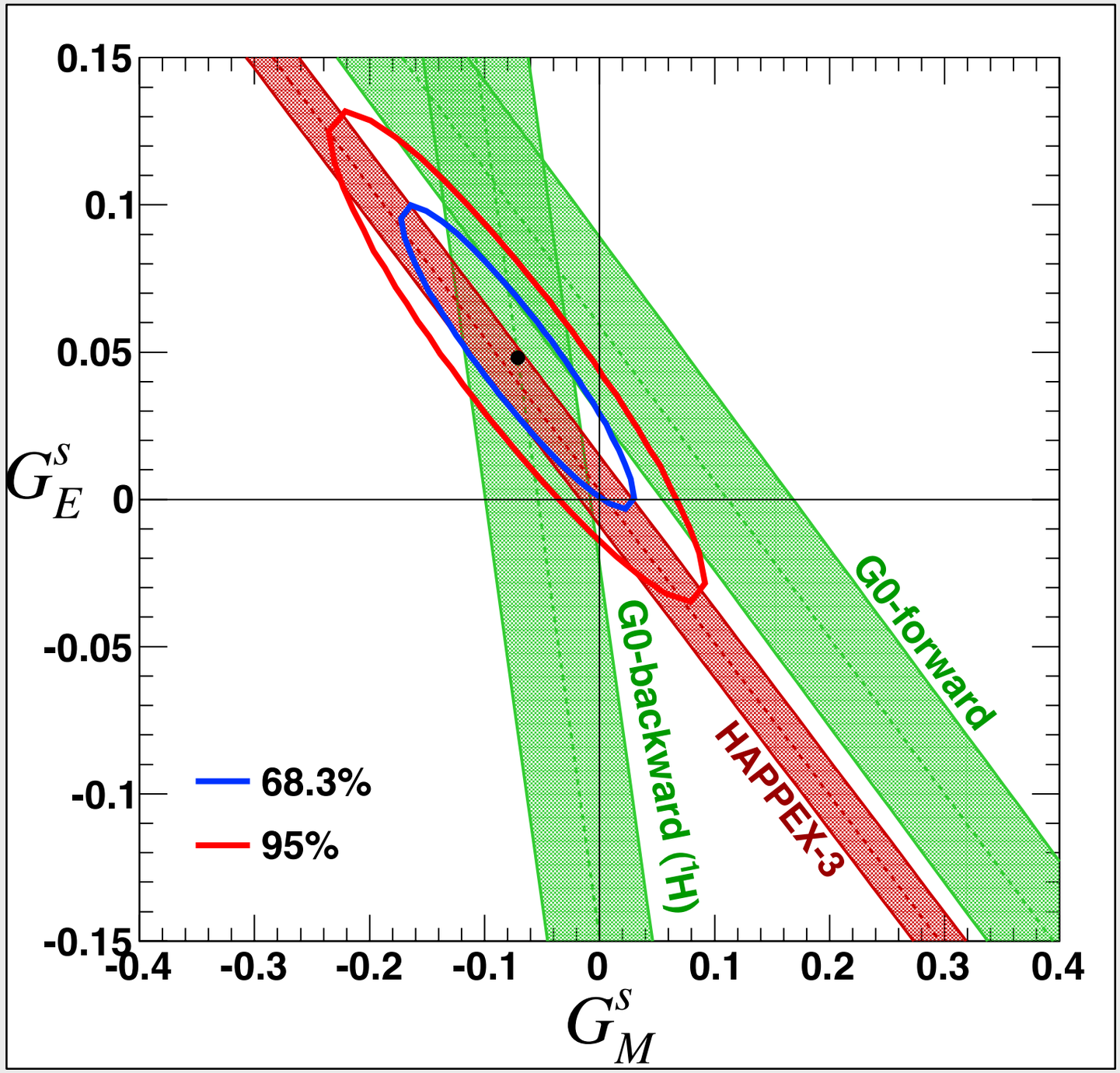
arXiv: 1107.0913v1



$G^s_E + 0.52\ G^s_M =$

$0.003 \pm 0.010_{(stat)} \pm 0.004_{(syst)} \pm 0.009_{(FF)}$

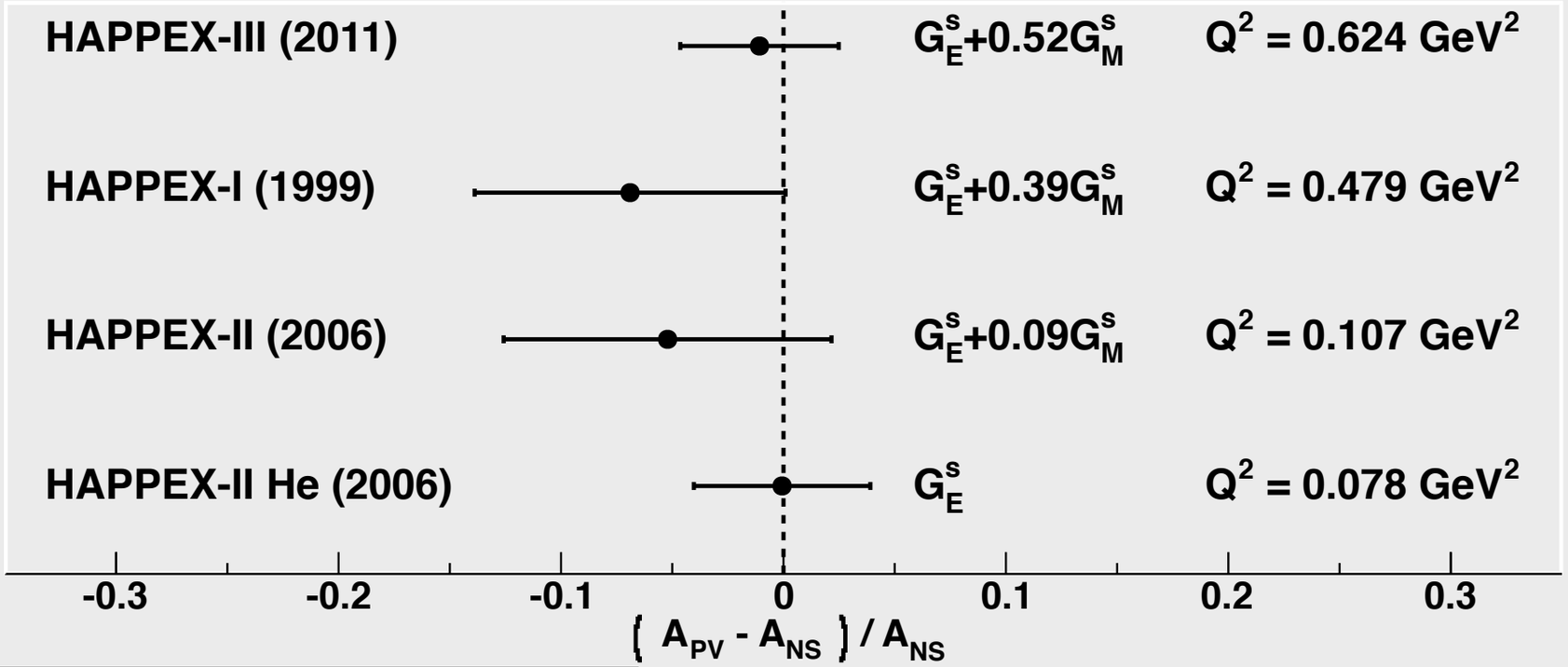
Q^2 = 0.62 GeV^2 in combination

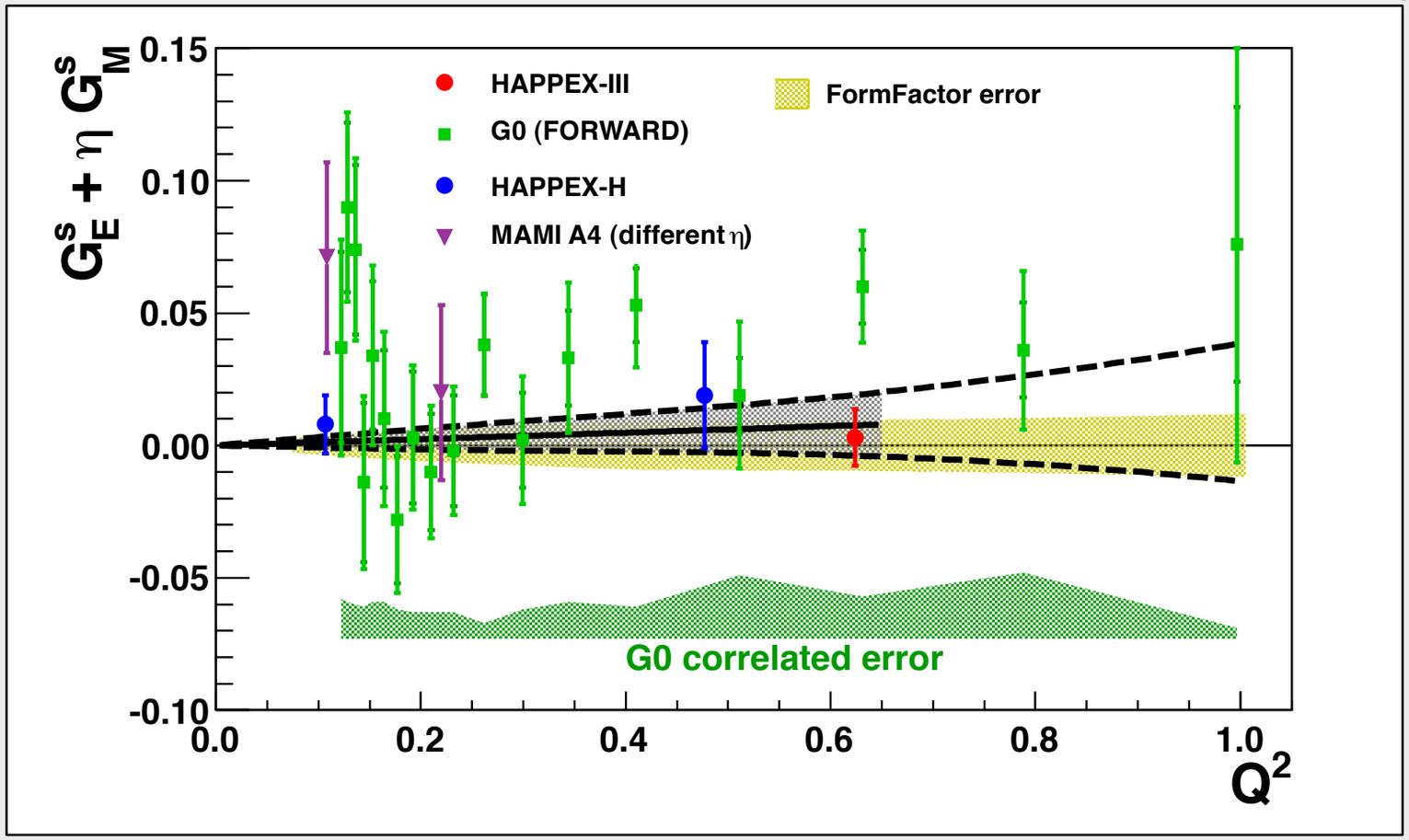


Zhu constraint is used for axial form-factor

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

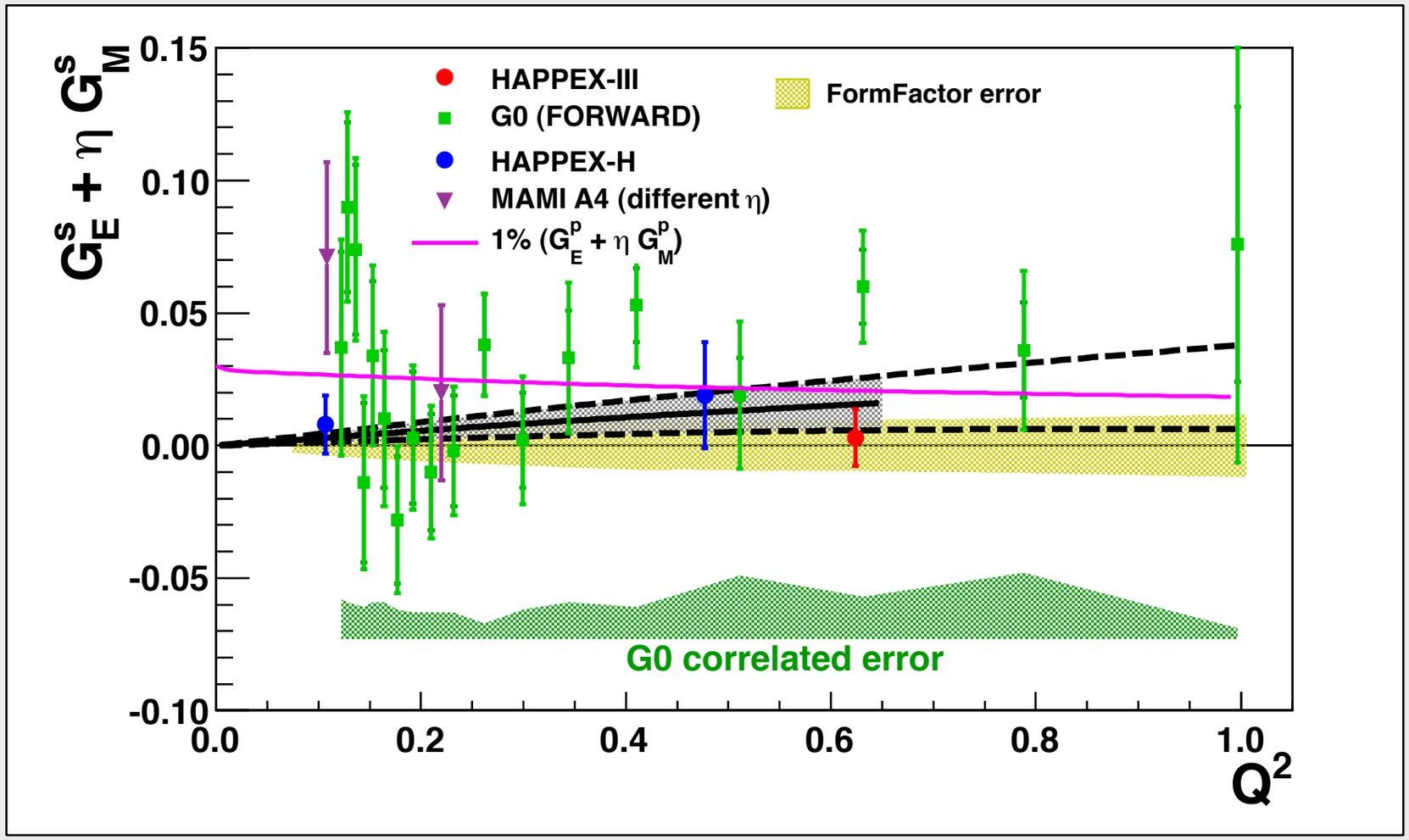
Considering only the 4 HAPPEX measurements

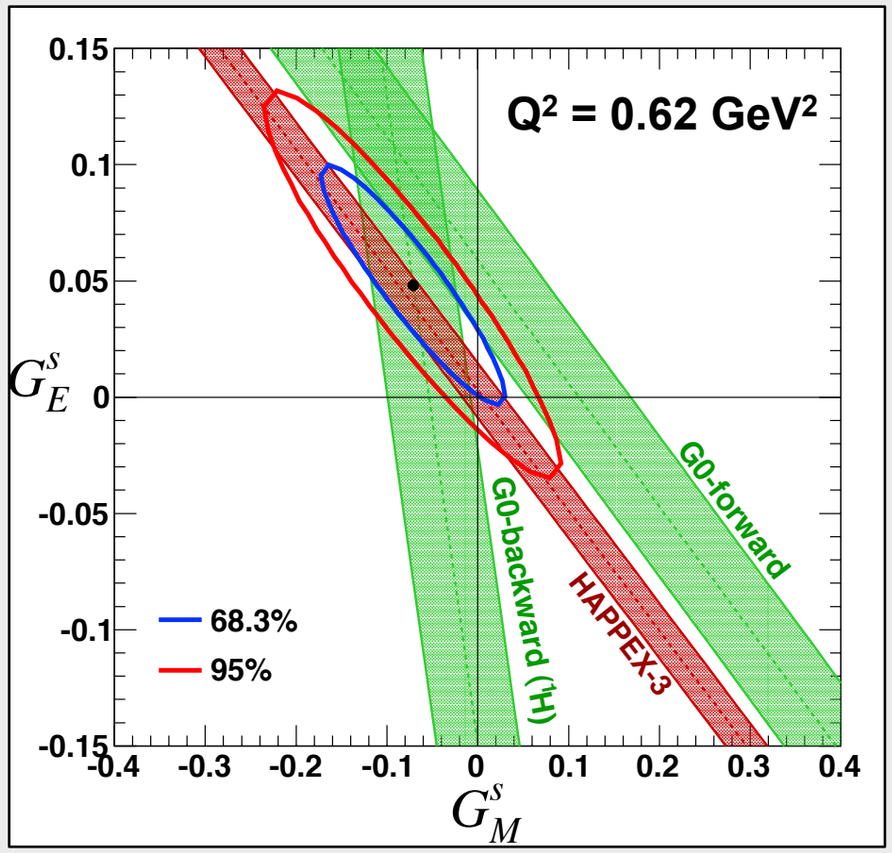




- High precision
- Small systematic error
- Clean theoretical interpretation

Strange Vector Form Factors Are Small



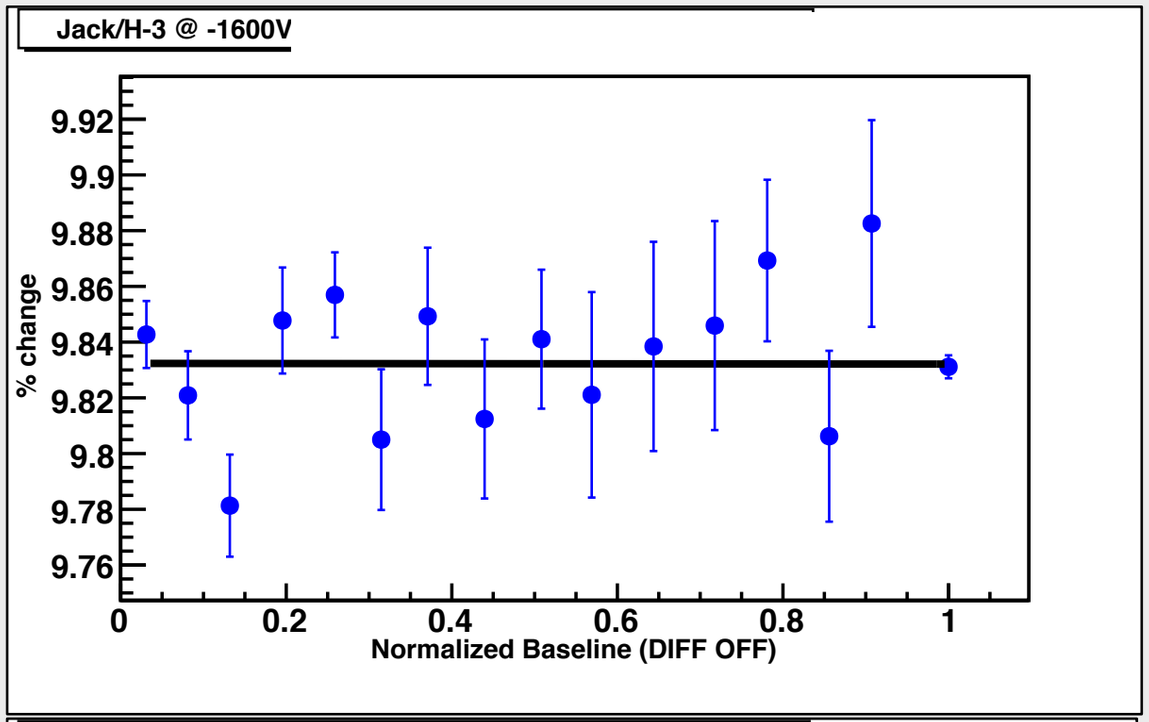


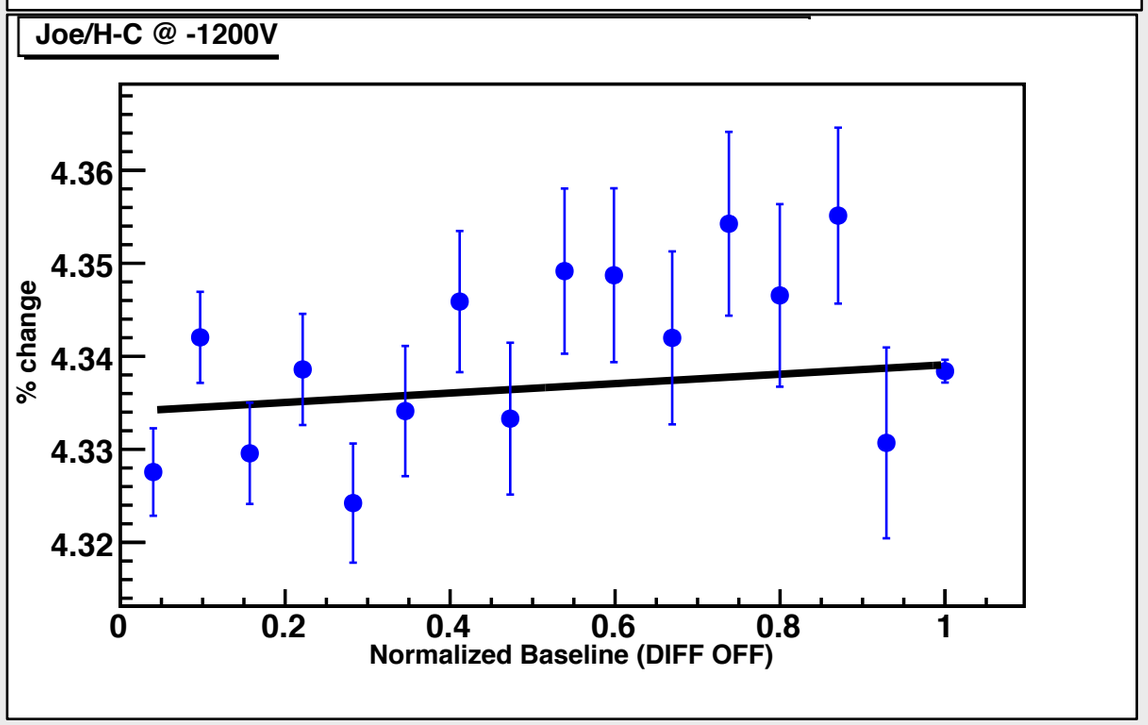
- HAPPEX-III provides a clean, precise measure of A_{PV} at Q^2=0.62 GeV^2, and finds that it is consistent with no strangeness contribution to the long-range electromagnetic interaction of the nucleon
- Recent lattice results indicate values smaller than these FF uncertainties
- Further improvements in precision would require additional theoretical and empirical input for interpretation

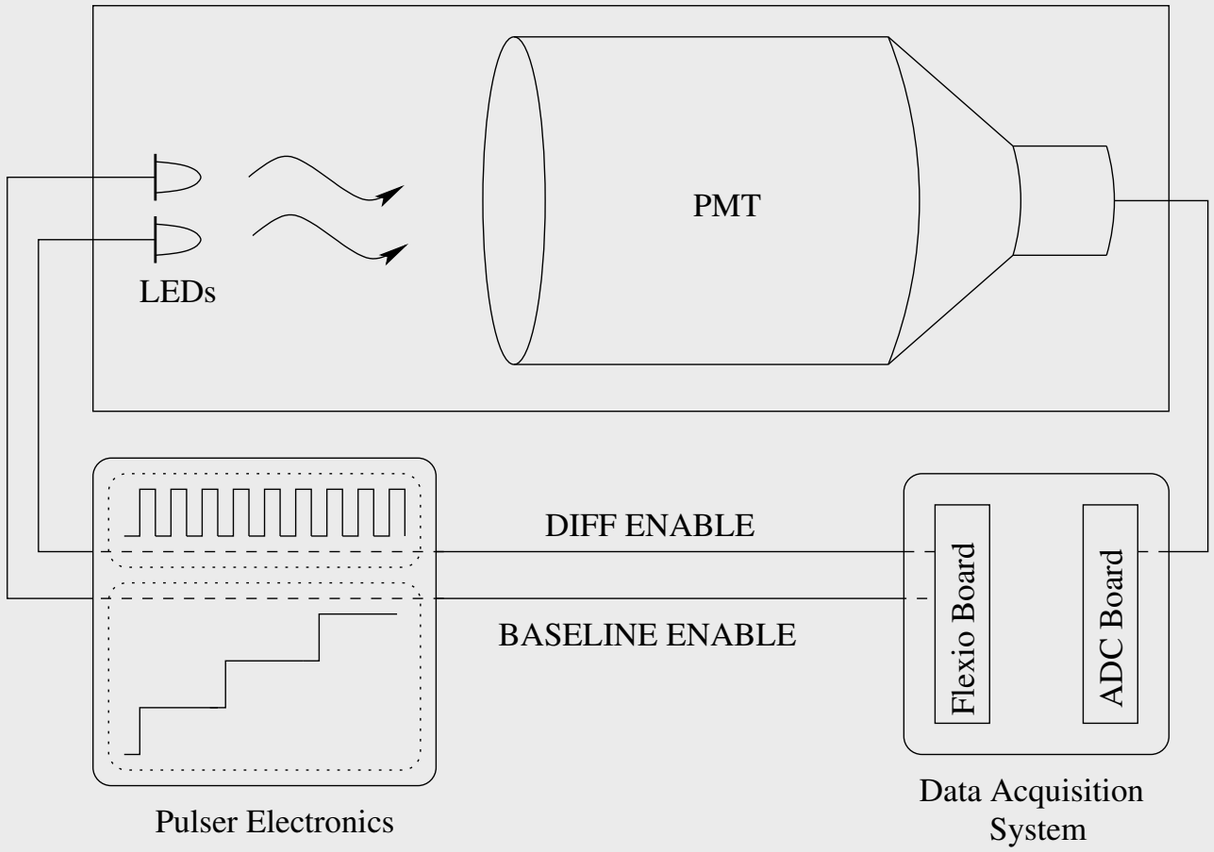
Backup

Detector Linearity

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



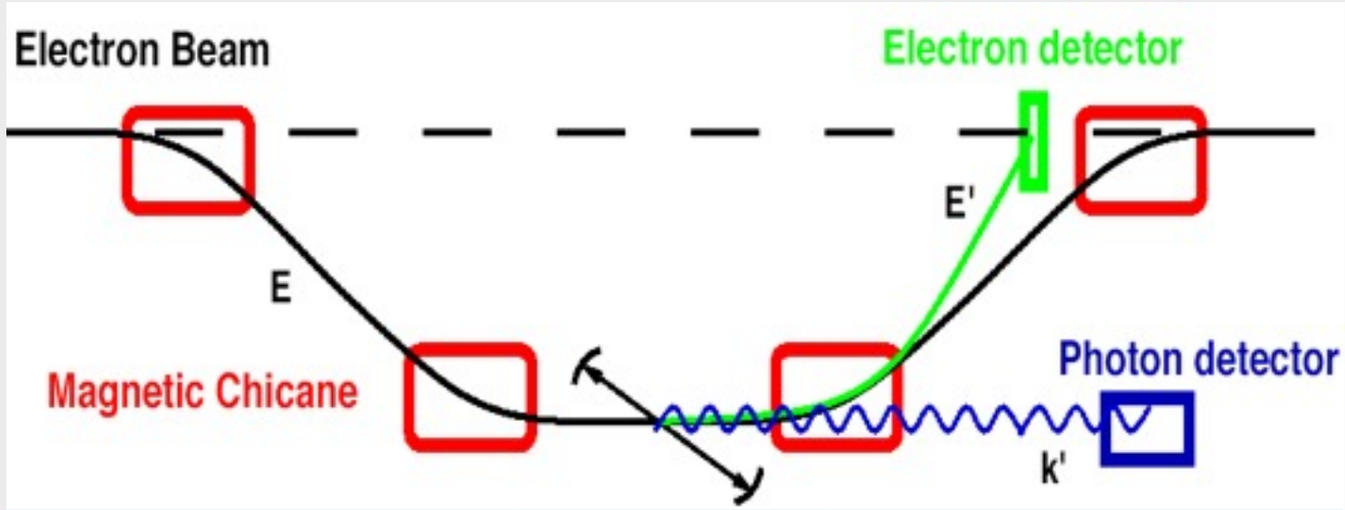




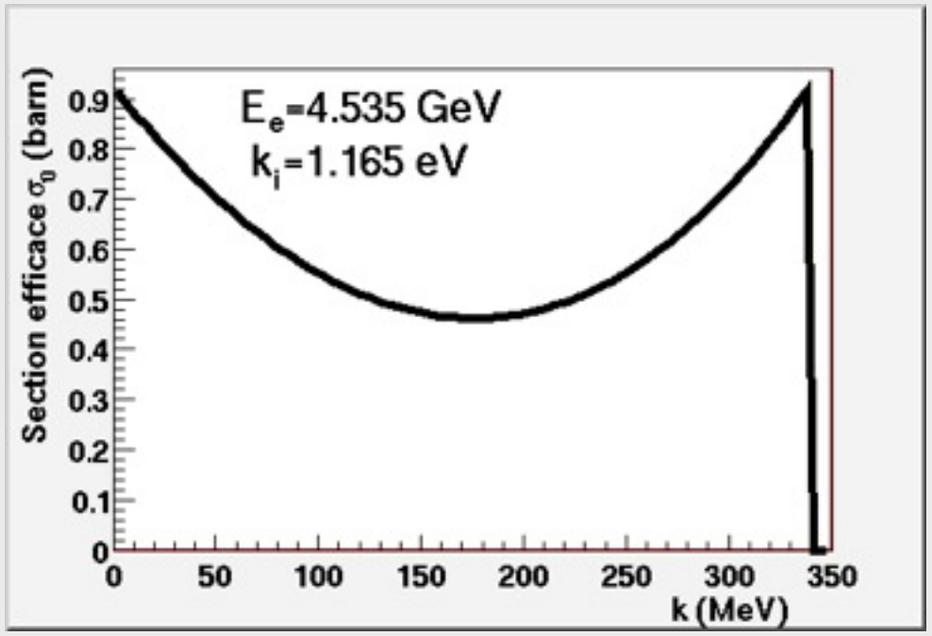
Measurements taken in short deviations from high rate, to maintain consistent thermal properties

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

Hall A Compton Polarimeter

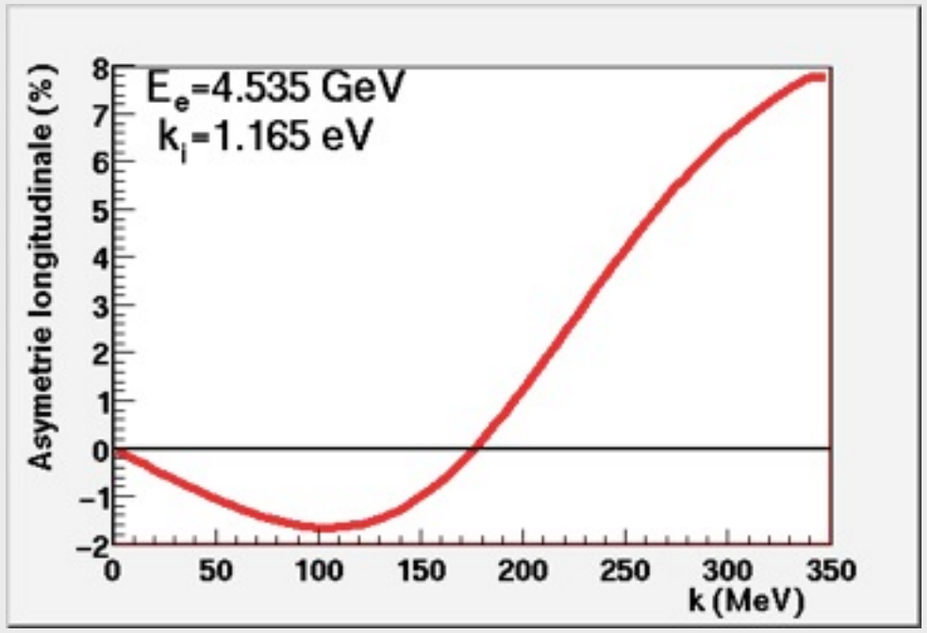


Resonant cavity "photon target", up to 2kW intensity



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

Calibration of the analyzing power is usually the leading uncertainty



measure asymmetry independently in:

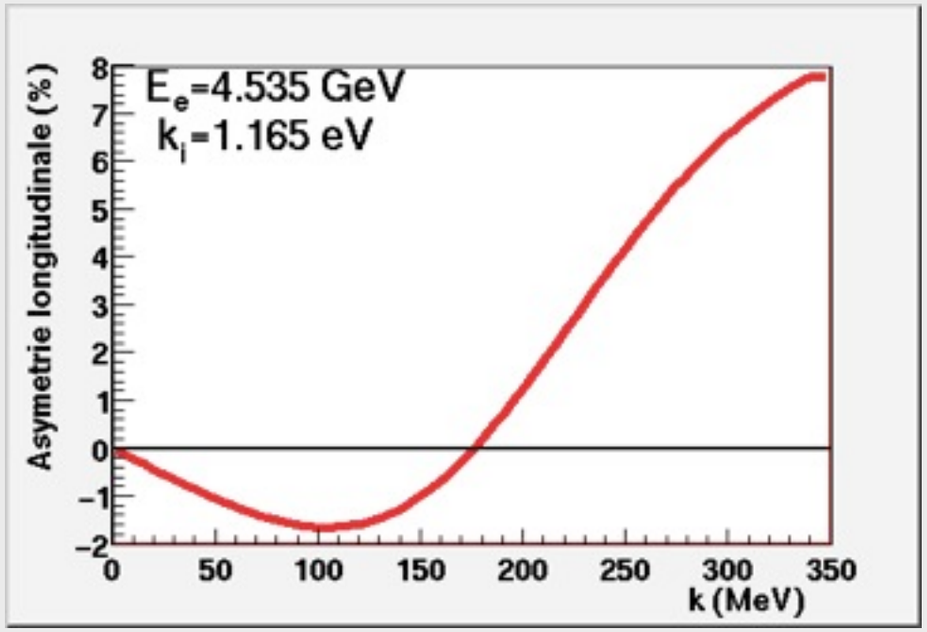
- **momentum analyzed electrons**
- **photons in calorimeter**

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

Compton Polarimetry

Electron detector achieved 1% accuracy for HAPPEX-2, but e-det system was not functioning for HAPPEX-3

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

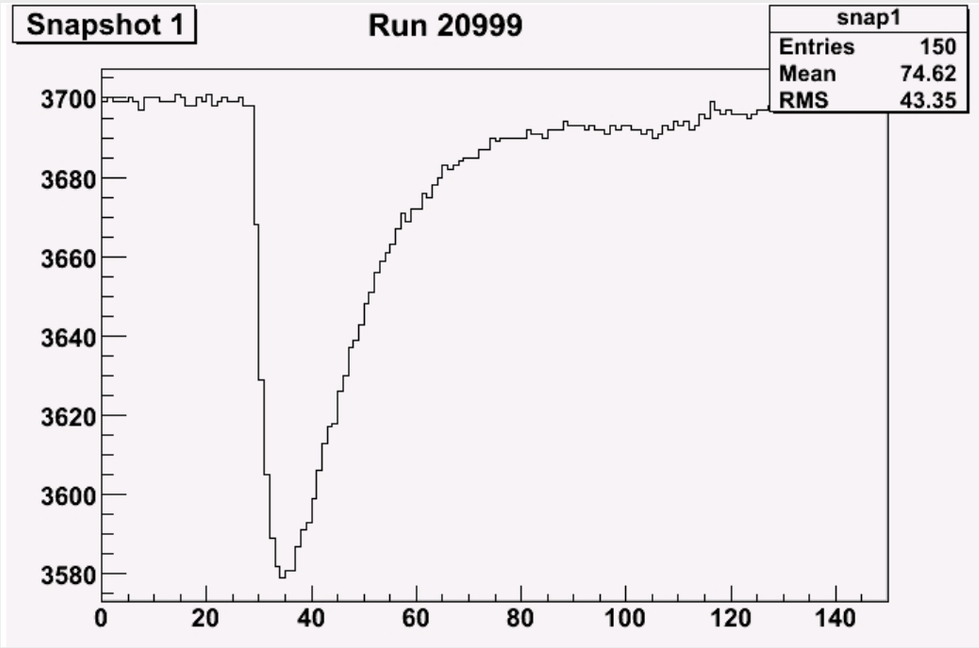


Integrating photon detection:
immune to calibration, pile-up, deadtime, response function

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

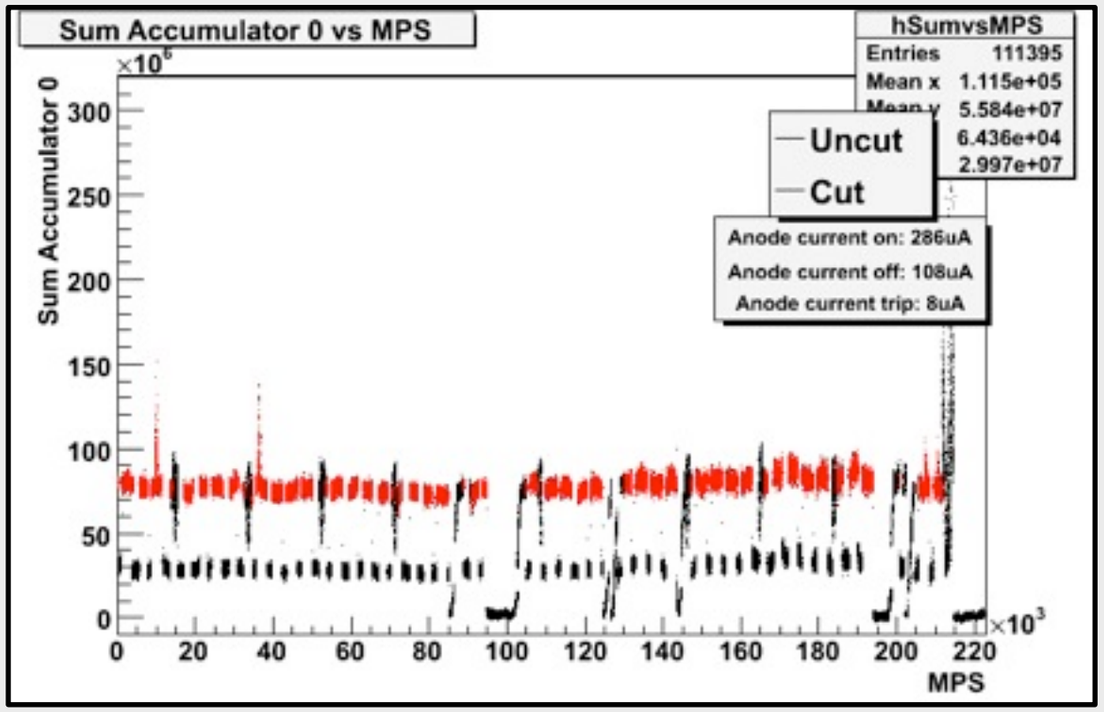
Triggered mode: triggered "snap shot" of fixed time interval (for calibration)

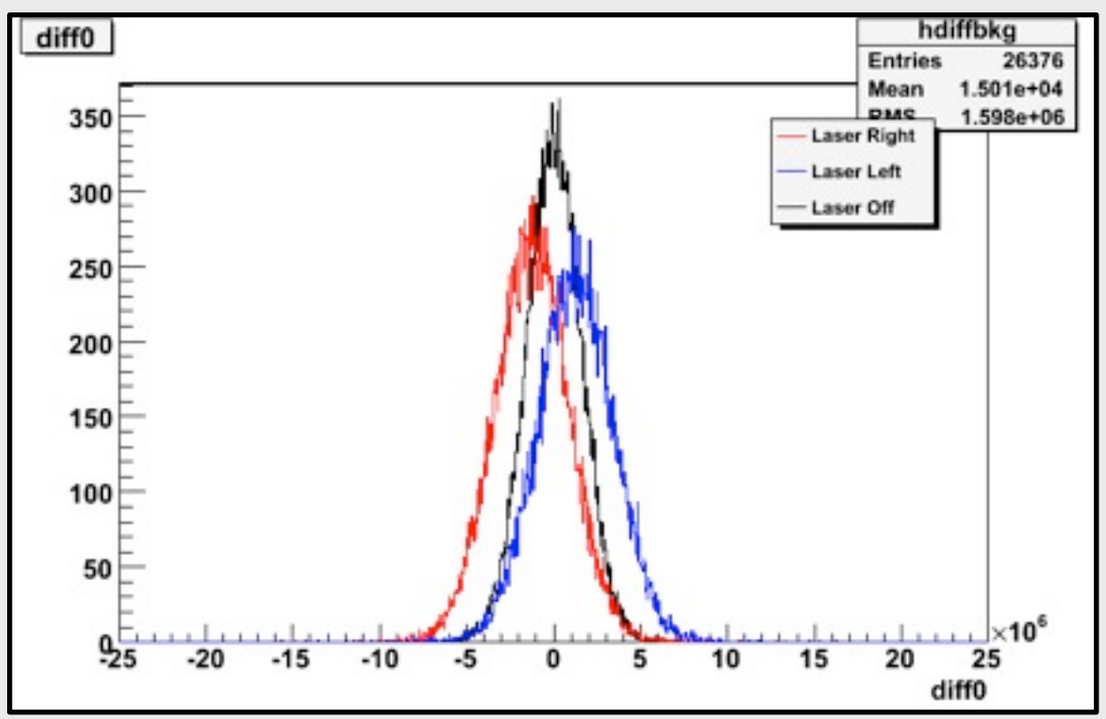
Accumulator readout: all FADC samples are summed on board for entire helicity window

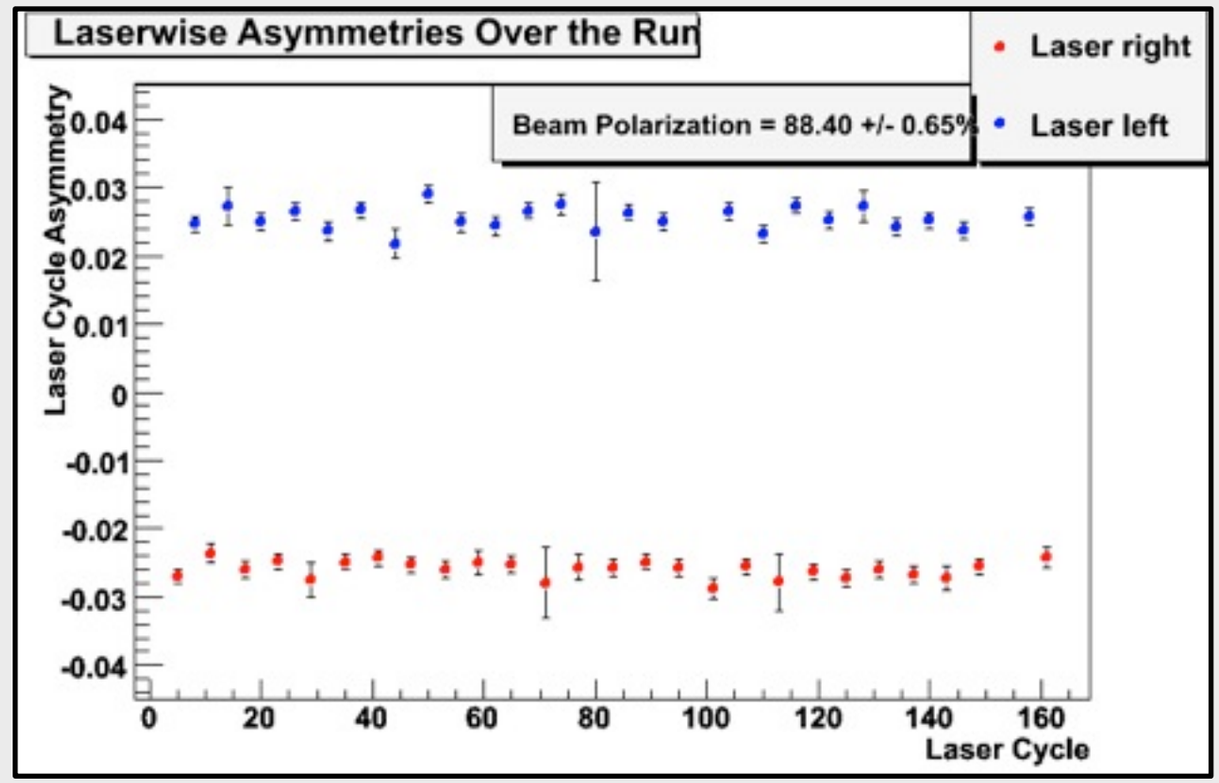


Compton Integrating Analysis, online

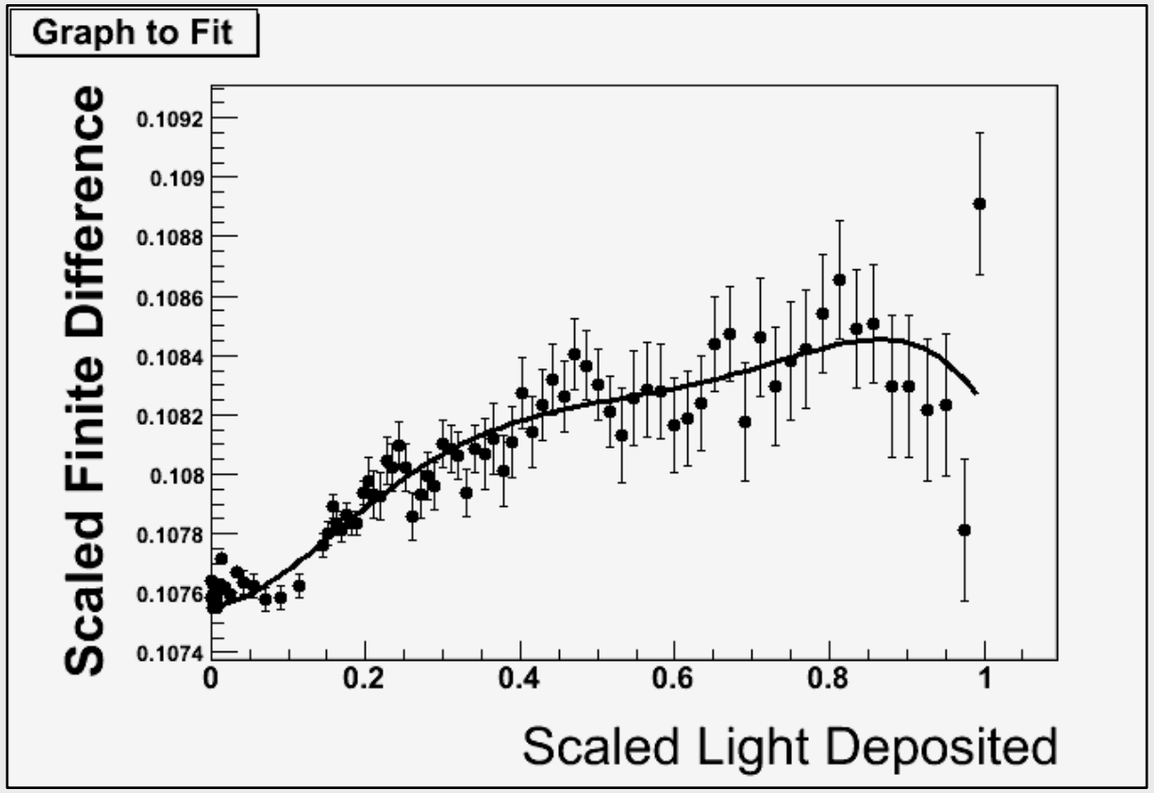
Online plots from run 20457







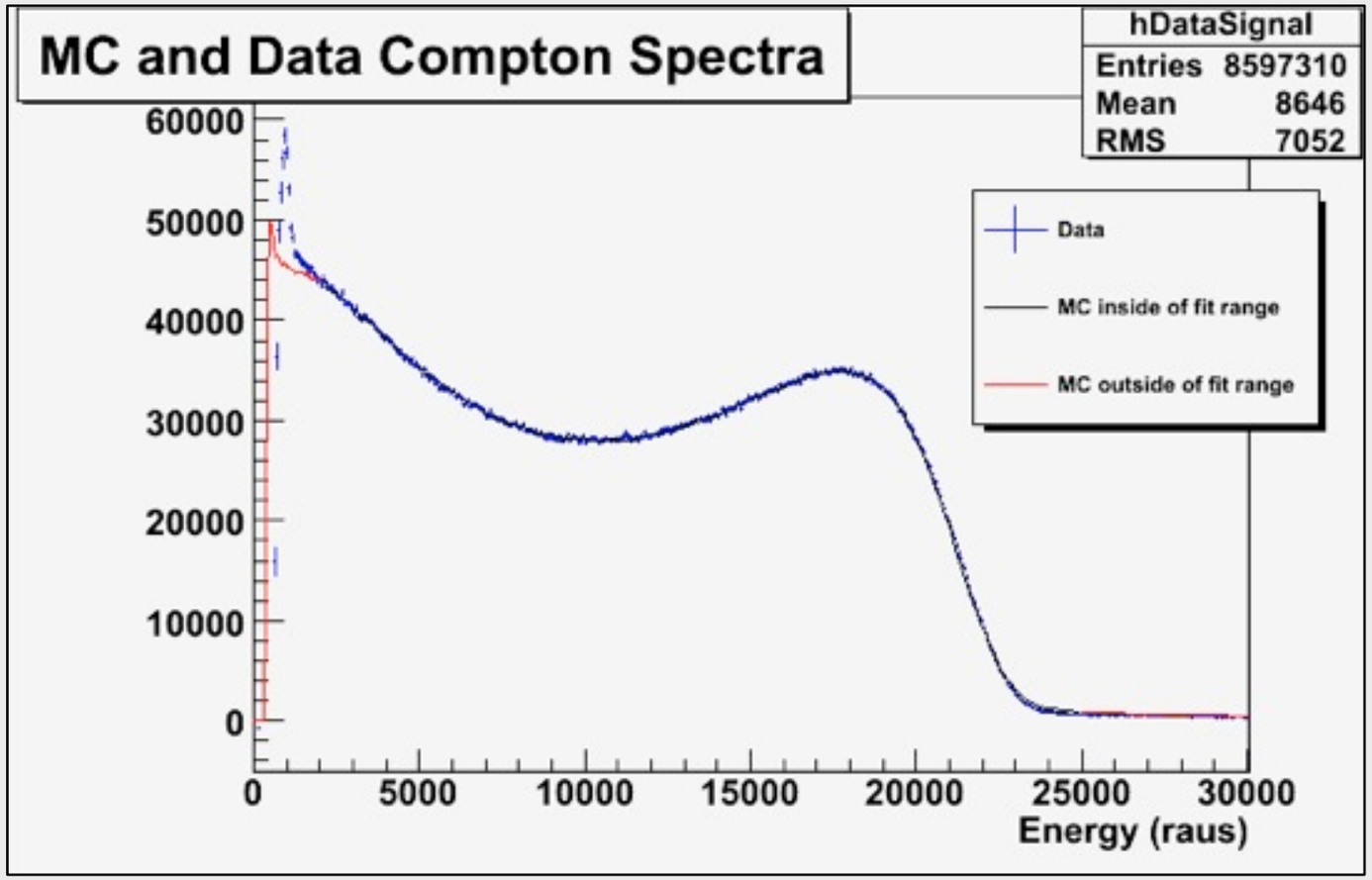
Compton Polarimetry



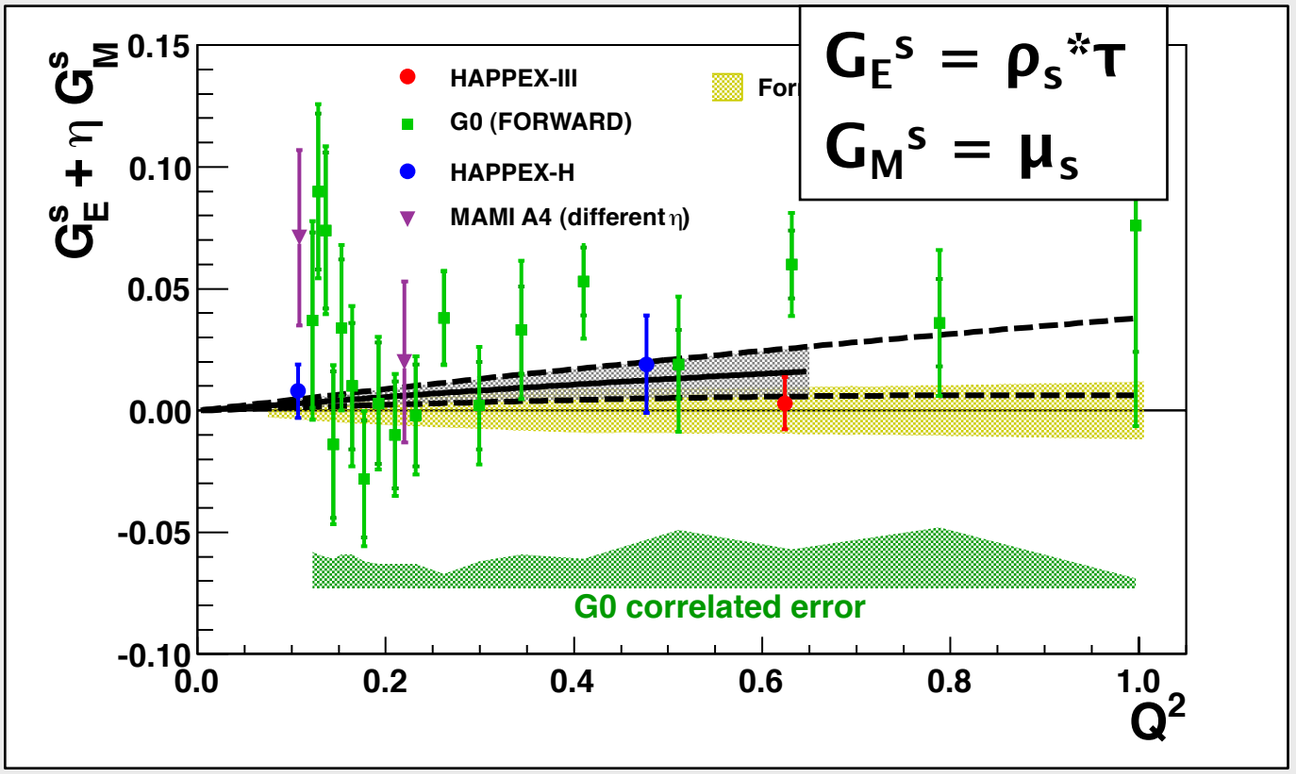
Non-linearity mapped out in with pulsed LED system.

Compton spectrum very well simulated
- **linearity**
- **collimator/detector alignment**
- **synchrotron light shielding**

Analyzing power calculation is not extremely sensitive to these corrections



Parameterizations



Fit includes all world data $Q^2 < 0.65$ GeV^2
G0 Global error allowed to float with unit constraint