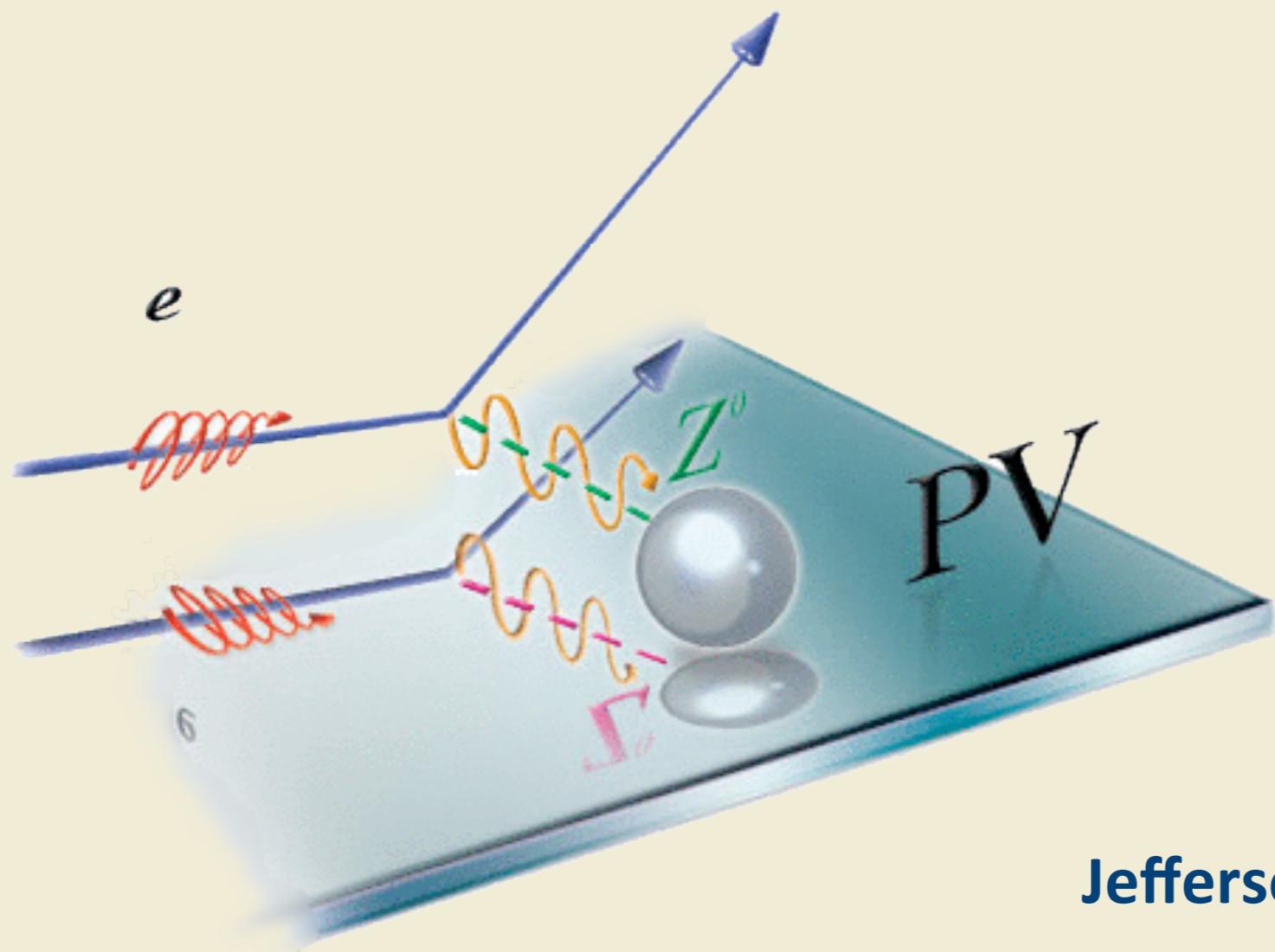


HAPPEX-III and Strangeness Contributions to the Nucleon Vector Form-factors



Kent Paschke

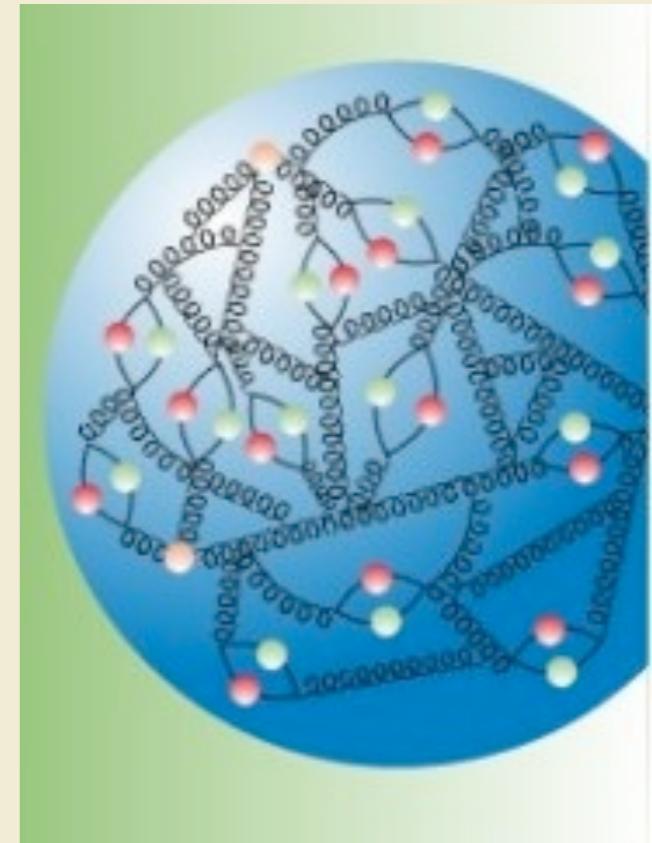
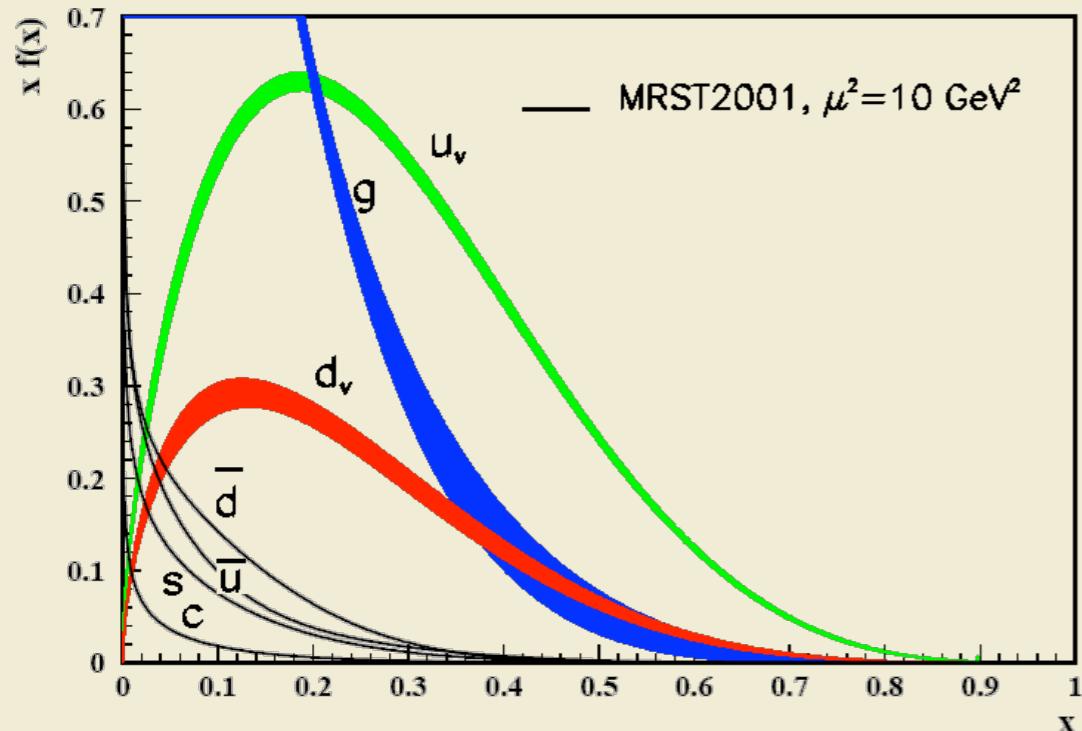
UNIVERSITY of VIRGINIA

HAPPEX Collaboration

Jefferson Lab User's Group Meeting
June 7, 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 $\sim 4\%$

$$\int_0^1 x(s + \bar{s}) dx$$

Mass 0-30%

$$\langle N | s\bar{s} | N \rangle, \Sigma_{\pi N}$$

Spin 0 - -10%

$$\Delta s$$

Magnetic moment,
charge radius

$$\rho_s, \mu_s$$

$$G_E^s, G_M^s$$

Nucleonic Strangeness in Other Arenas

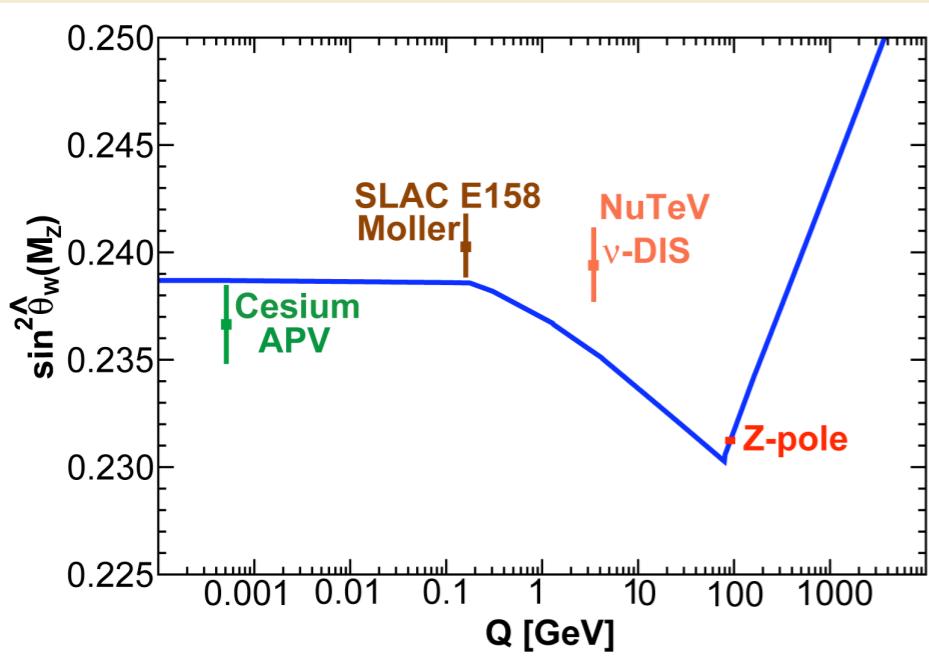
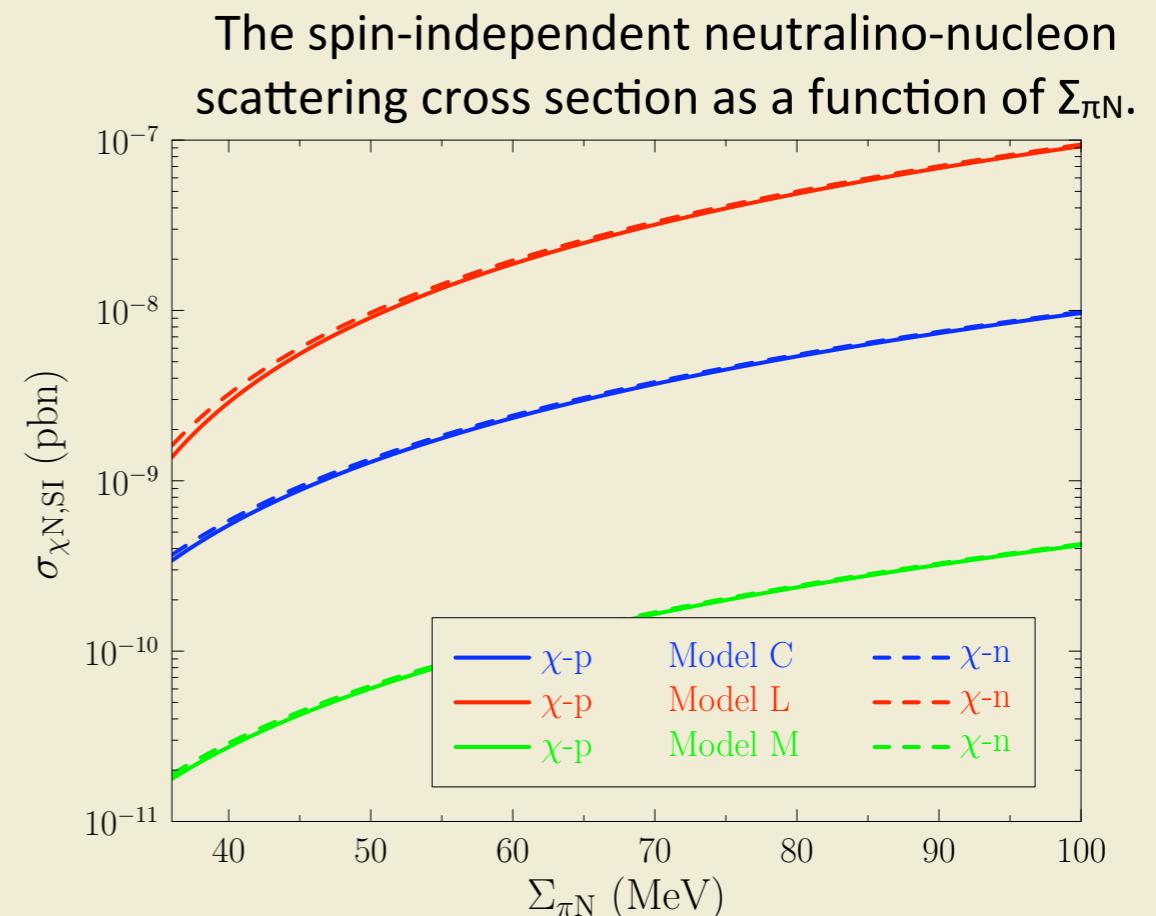
Dark Matter Searches

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



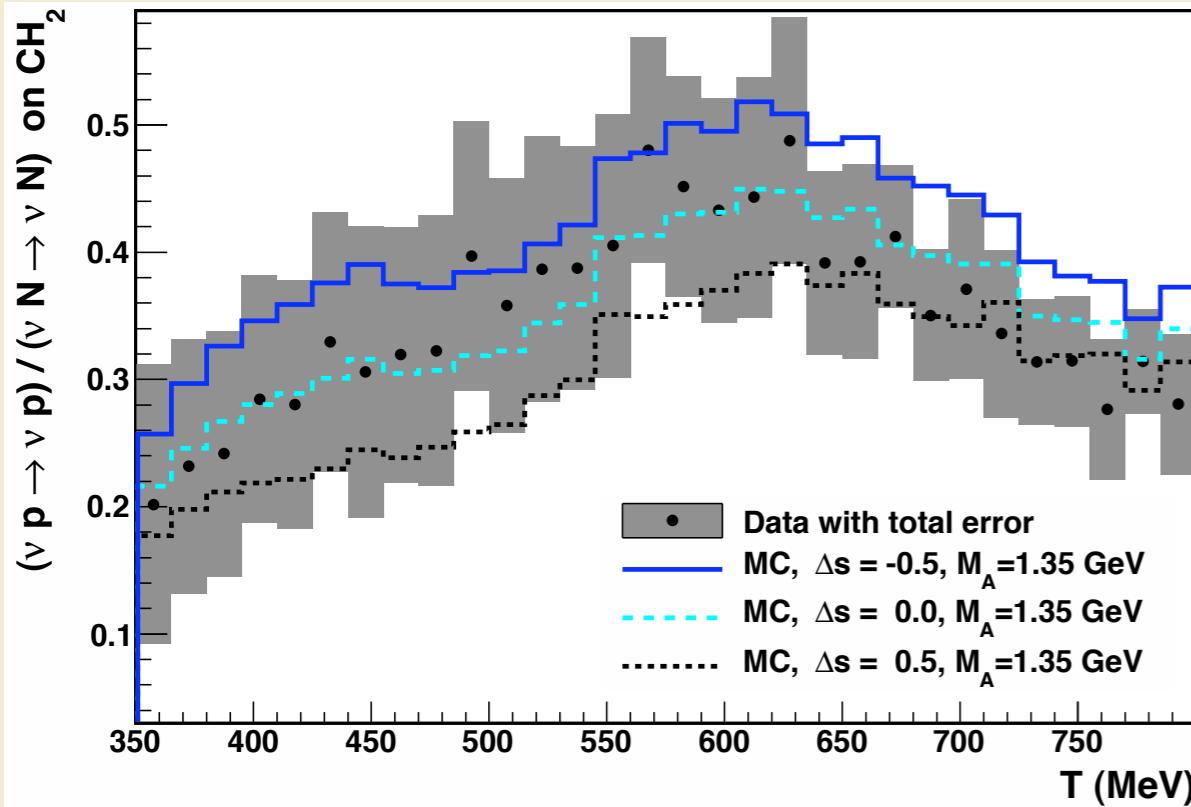
NuTeV Anomaly

NuTeV published a 3σ deviation from the standard model

The leading hypothesis is that a significant fraction is explained by an asymmetry in the strange sea:

$$S - \bar{S}$$

Strange Quarks in Elastic Scattering



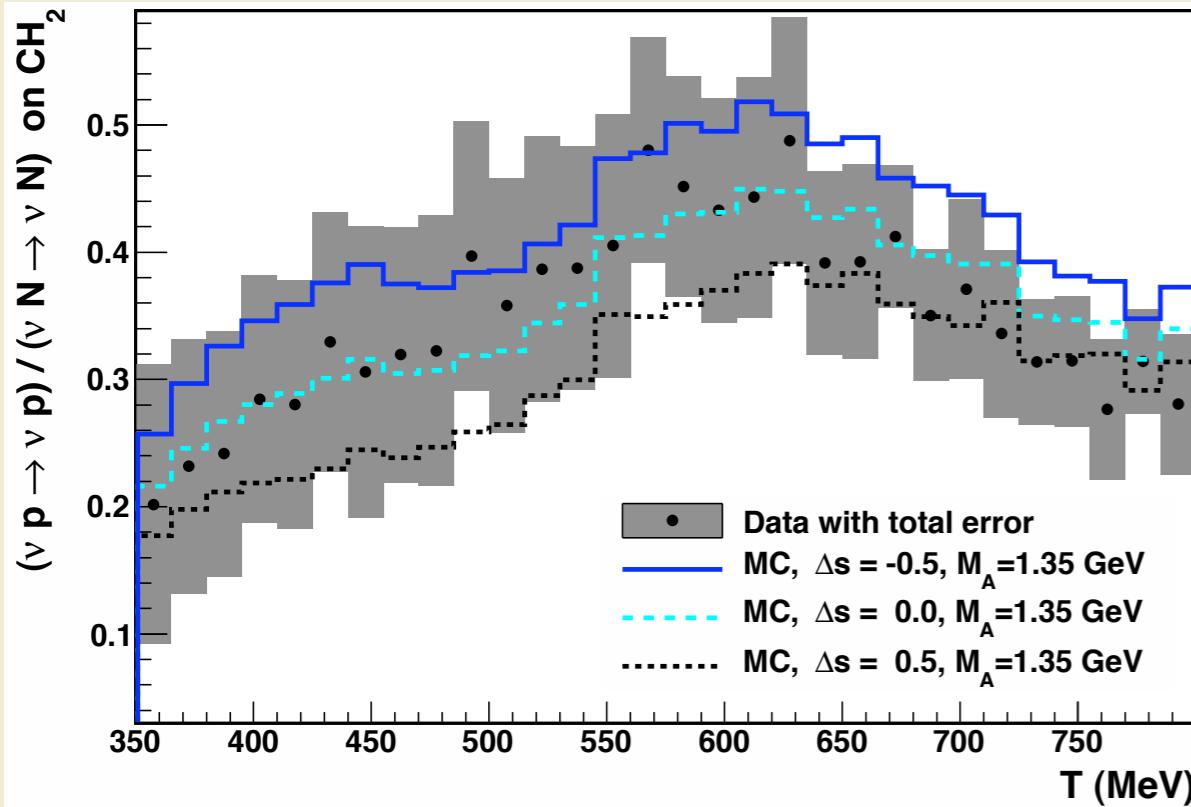
Miniboone Collaboration, Phys.Rev. D82 (2010) 092005

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

Strange Quarks in Elastic Scattering

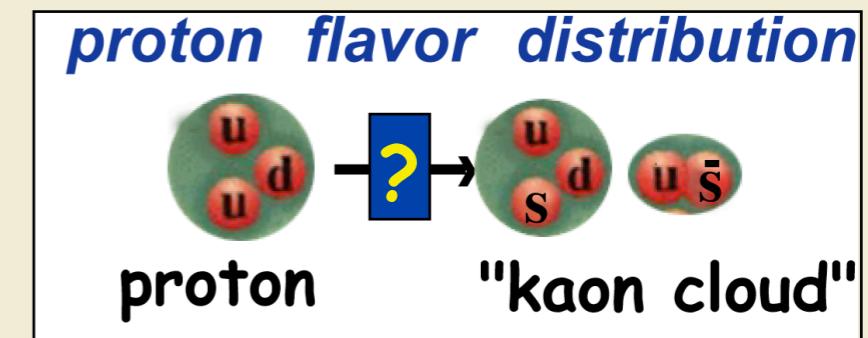
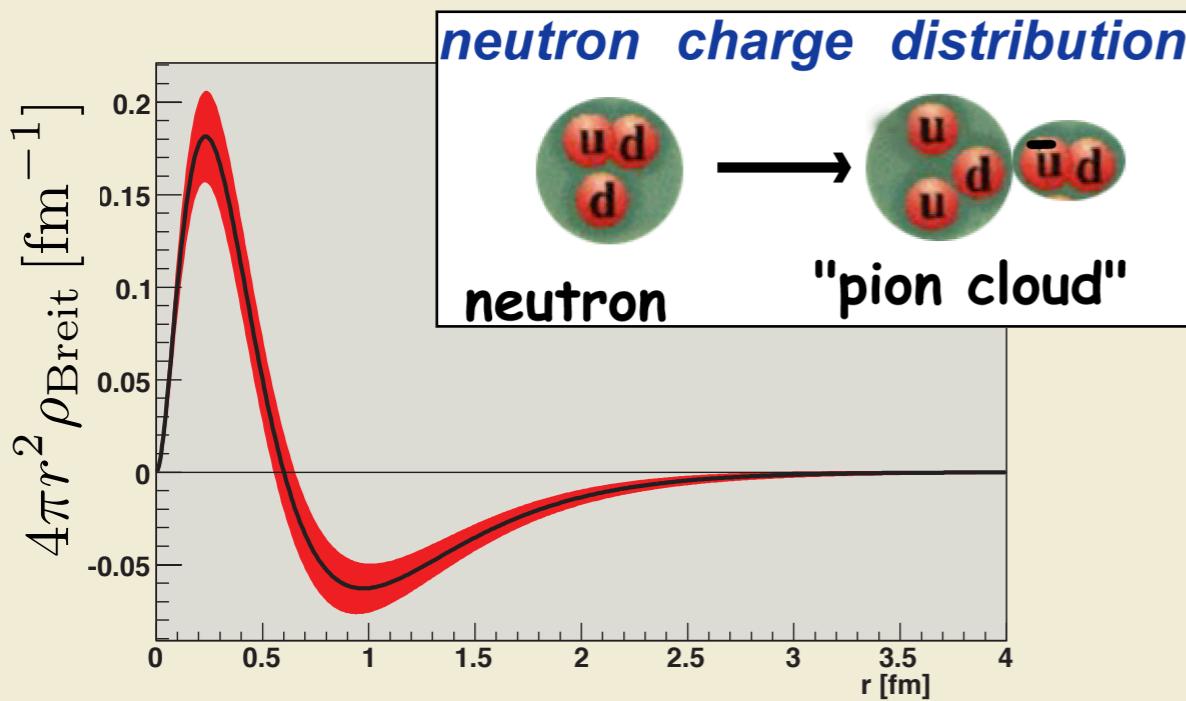


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Also, see fit by Pate *et al.*, Phys.Rev. C78 (2008) 015207

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



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

The diagram illustrates the use of charge symmetry to reduce the number of unknowns. It shows two equations for the charge symmetry form factor G_E^p and G_E^n . The first equation contains terms $G_E^{u,p}$, $G_E^{d,p}$, and G_E^s . The second equation contains terms $G_E^{u,n}$, $G_E^{d,n}$, and G_E^s . Arrows point from the $G_E^{u,p}$ and $G_E^{u,n}$ terms to a central node, indicating they are related by charge symmetry.

Extracting the Strange Form Factor with the Neutral Weak Interaction

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

Two equations and three unknowns

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

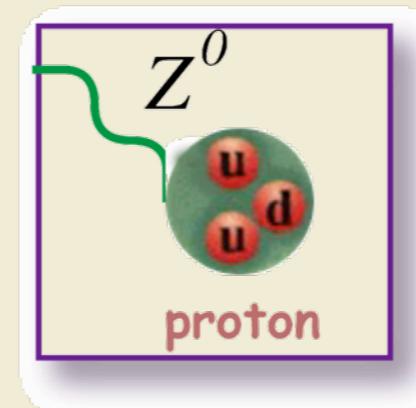
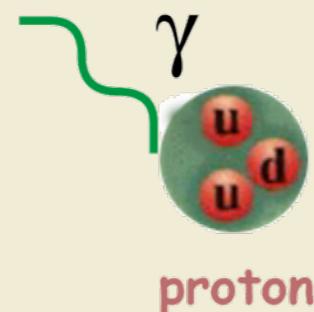
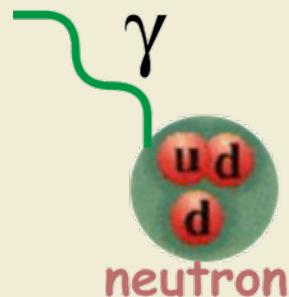
Extracting the Strange Form Factor with the Neutral Weak Interaction

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

Two equations and three unknowns

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

Measure neutral weak proton form-factor



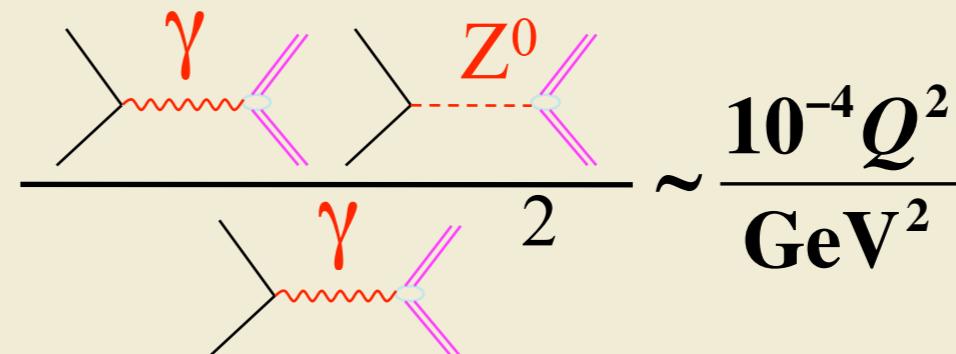
Three equations and three unknowns

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

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



Proton:

$$A = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \right] \frac{A_E + A_M + A_A}{\sigma_p} \sim \text{few parts per million}$$

$$A_E = \epsilon G_E^p G_E^Z$$

$$A_M = \tau G_M^p G_M^Z$$

$$A_A = (1 - 4 \sin^2 \theta_W) \epsilon' G_M^p \tilde{G}_A$$

Forward angle

Backward angle

"Anapole" radiative corrections are problematic

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

Spin=0, T=0 ${}^4\text{He}$: G_E^s only!

Deuterium: Enhanced G_A

The Axial Term and the Anapole Moment

Axial form-factors G_A^p, G_A^n

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

- 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:

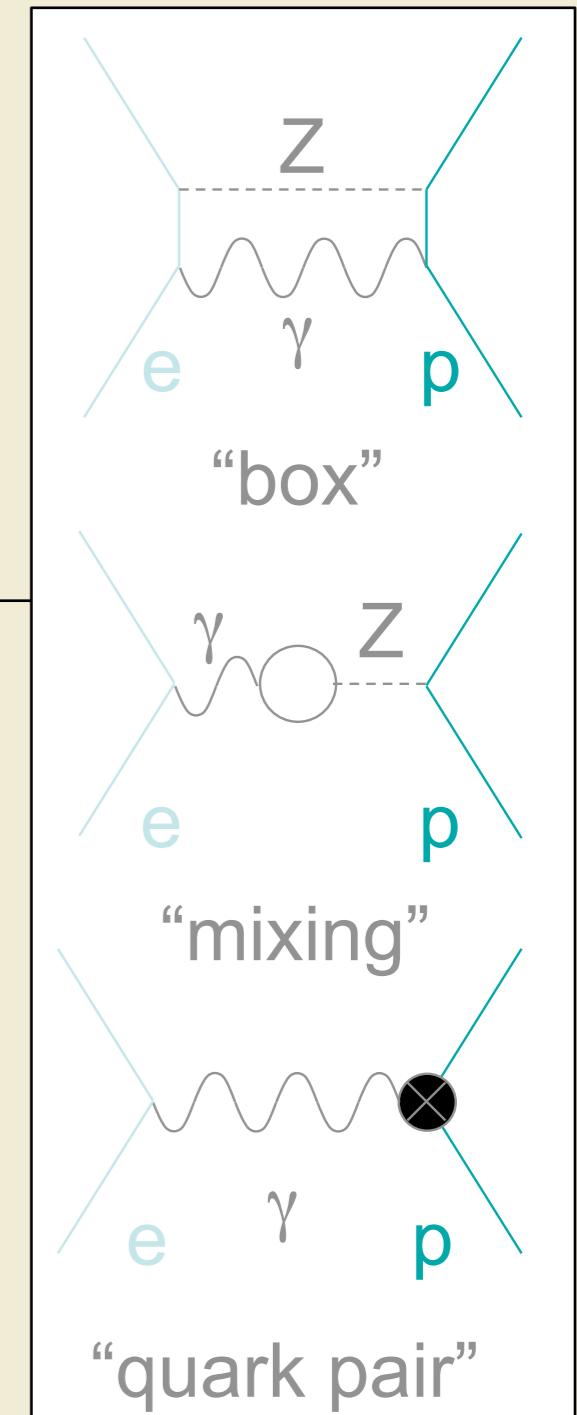
Multiquark weak interaction in $R_A^{(T=1)}, R_A^{(T=0)}$

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

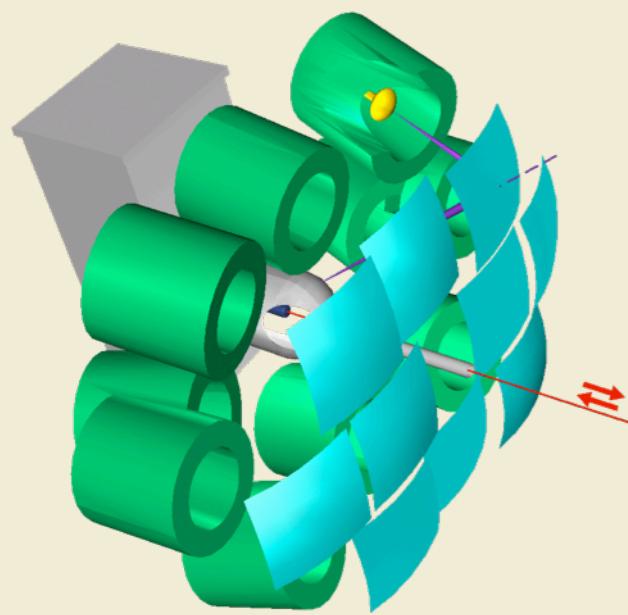
- Model dependent calculation, with large uncertainty
- Dominates Uncertainty in Axial Term

Difficult to achieve tight experimental constraint

Reduced in importance for forward-angle measurements



Experimental Overview



SAMPLE

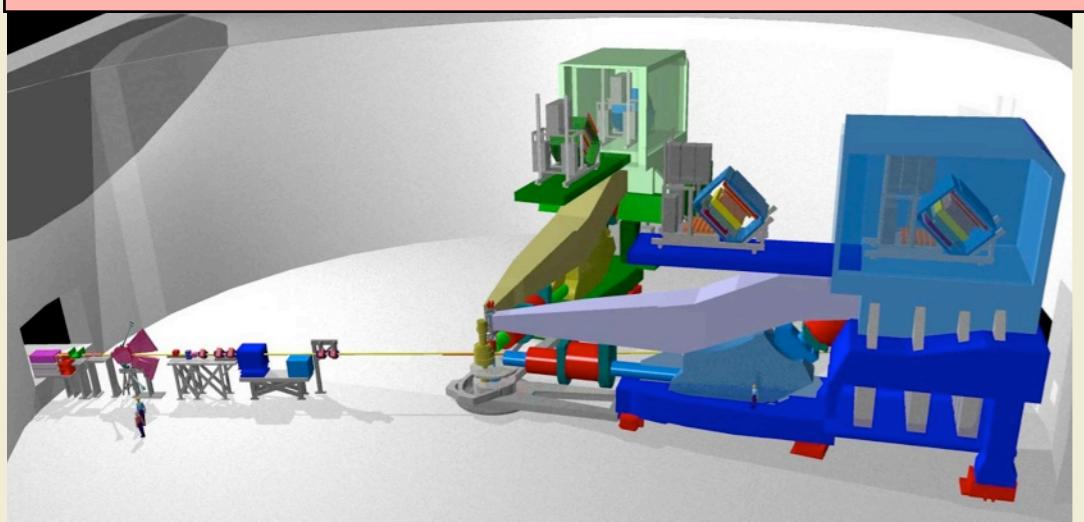
open geometry,
integrating,
back-angle only

HAPPEX

Precision spectrometer,
integrating

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

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

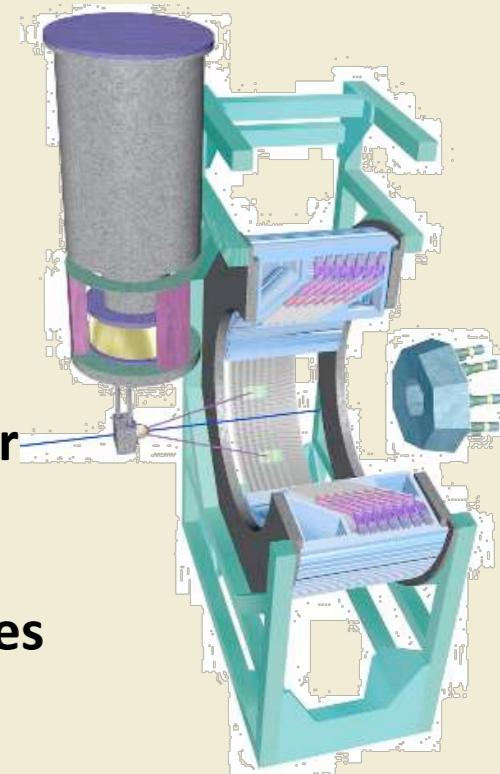


A4

Open geometry

Fast counting calorimeter for
background rejection

Forward and Backward angles

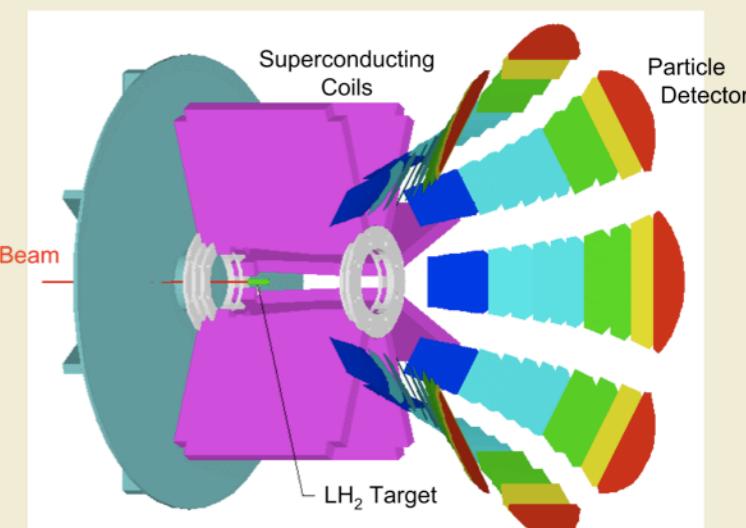


G0

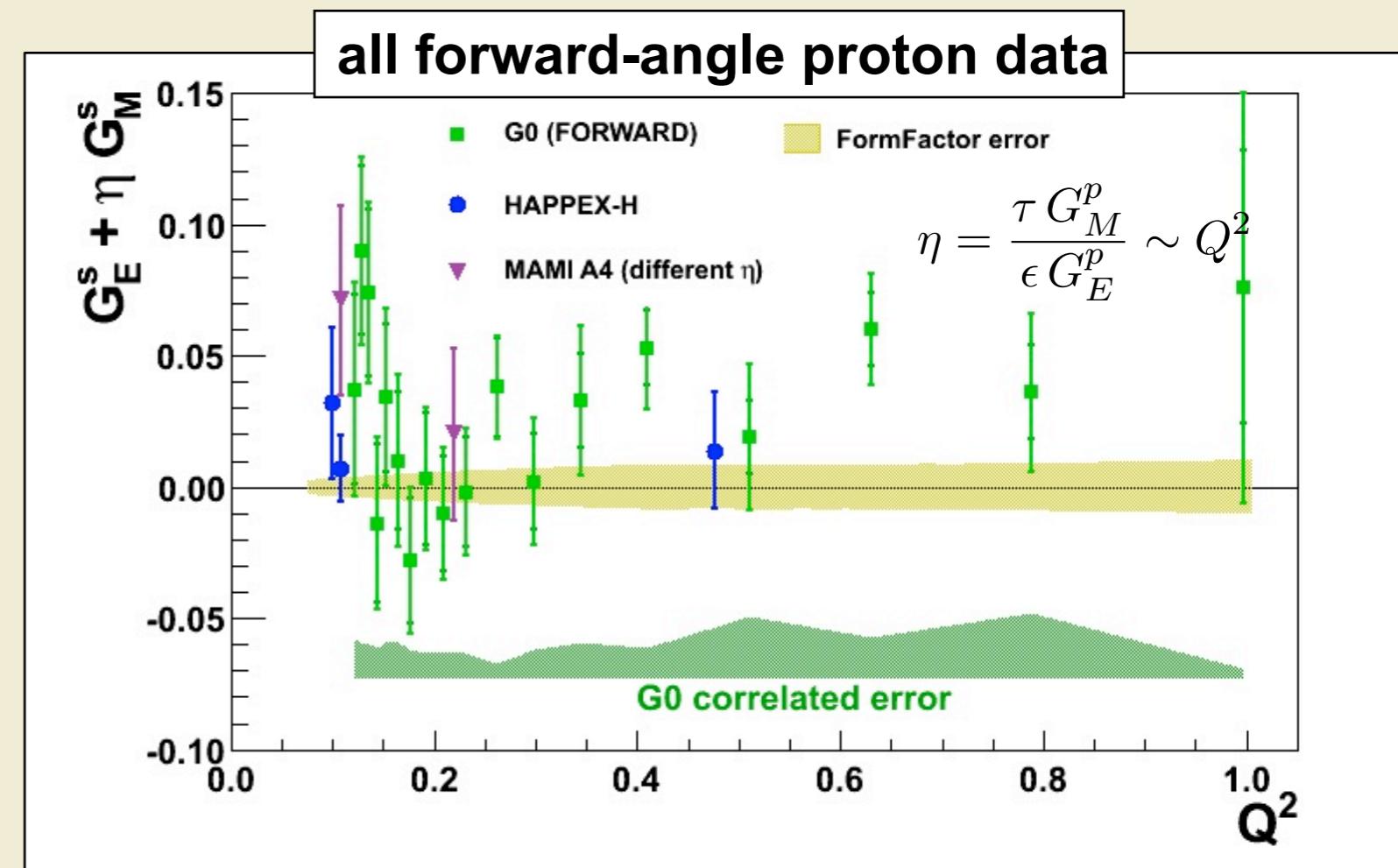
Open geometry

Fast counting with magnetic spectrometer + TOF
for background rejection

Forward and Backward angles over a range of Q^2

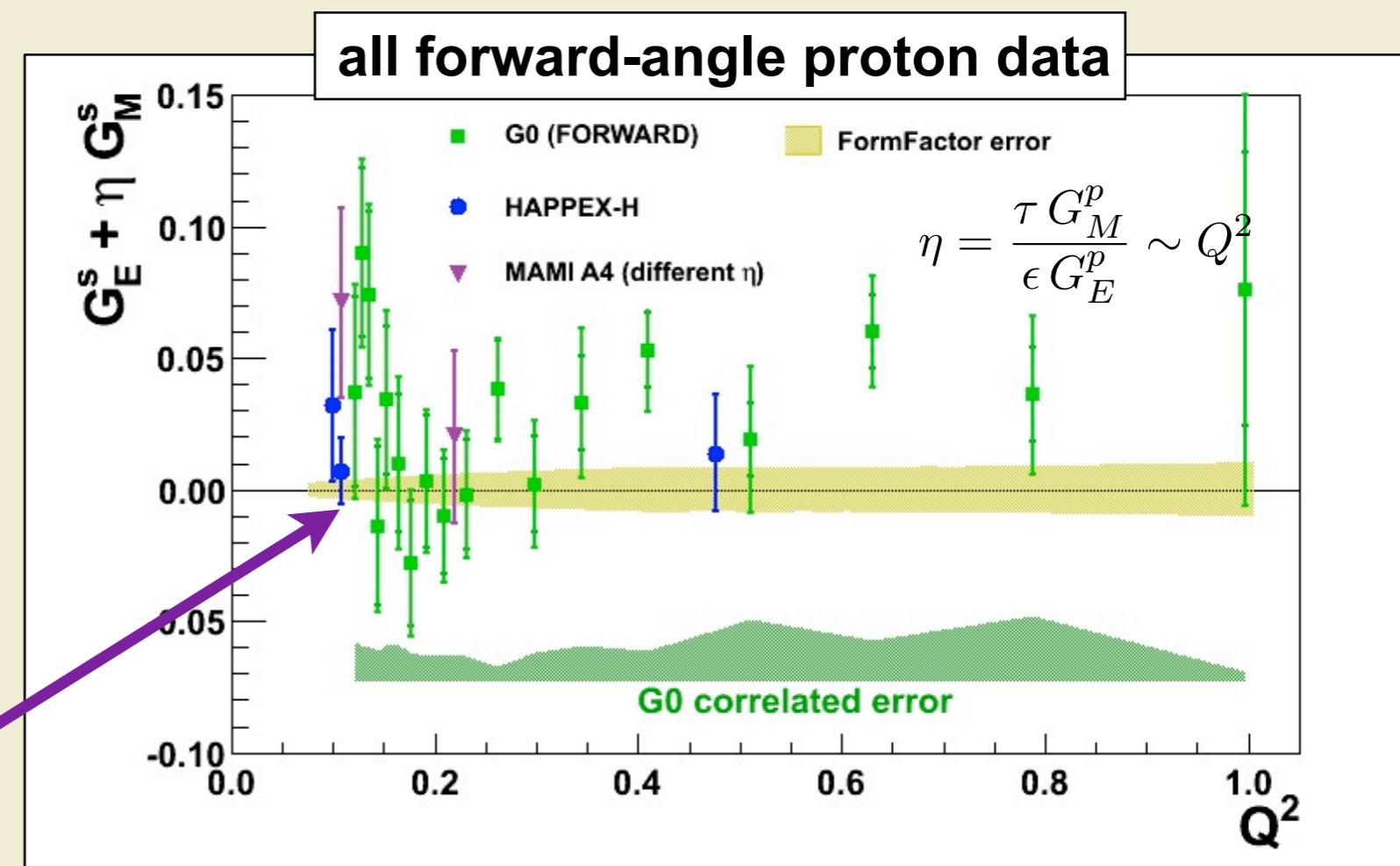
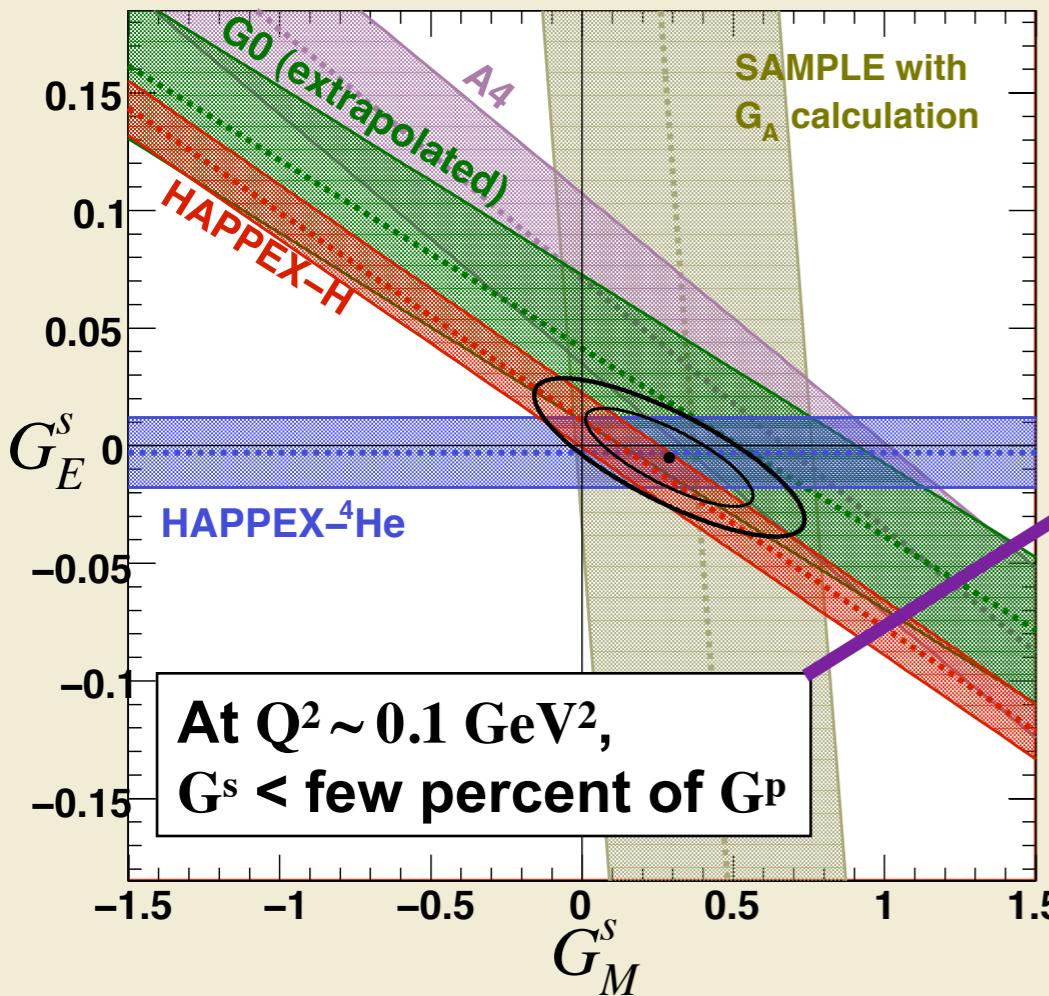


World data on G^s



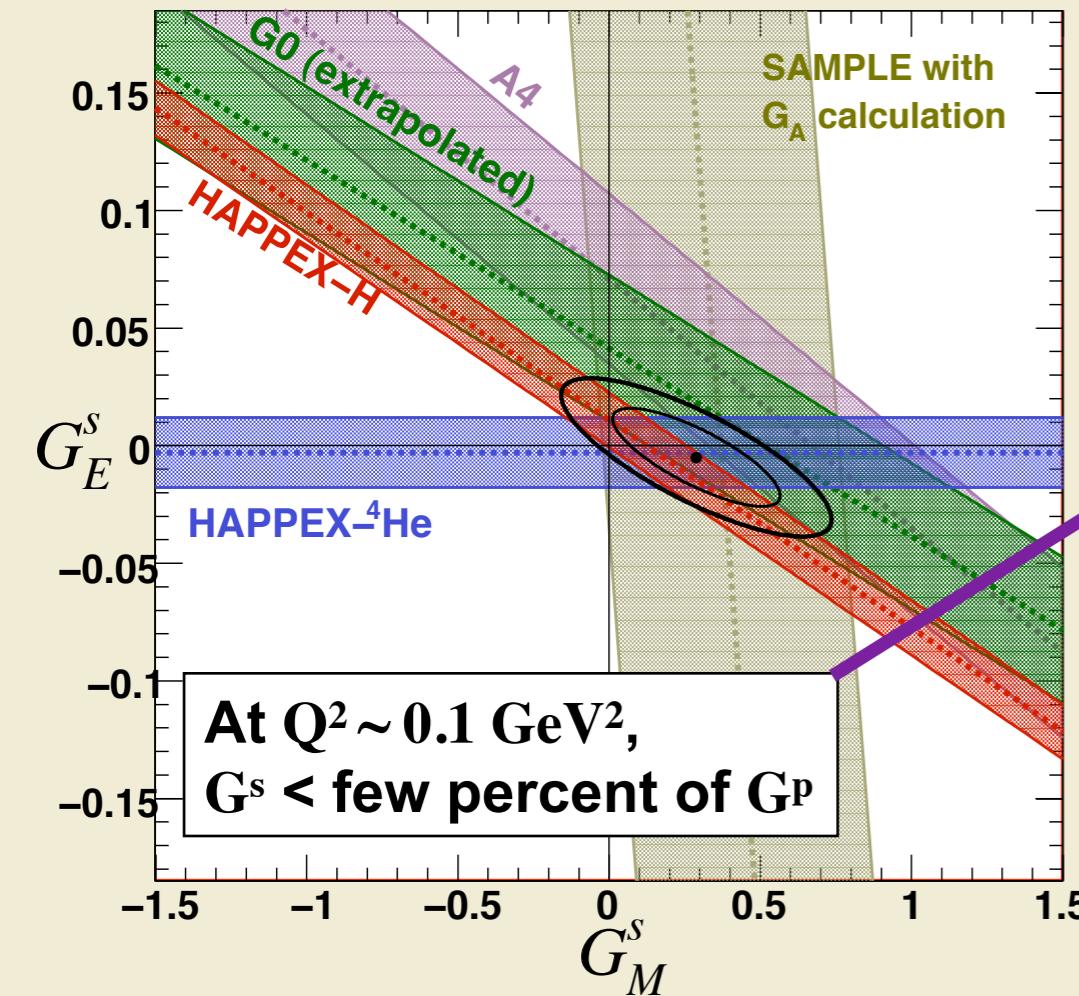
- “Form Factor” error: precision of EMFF (including 2γ) and Anapole correction
- Significant systematic uncertainty in higher Q^2 points

World data on G^s

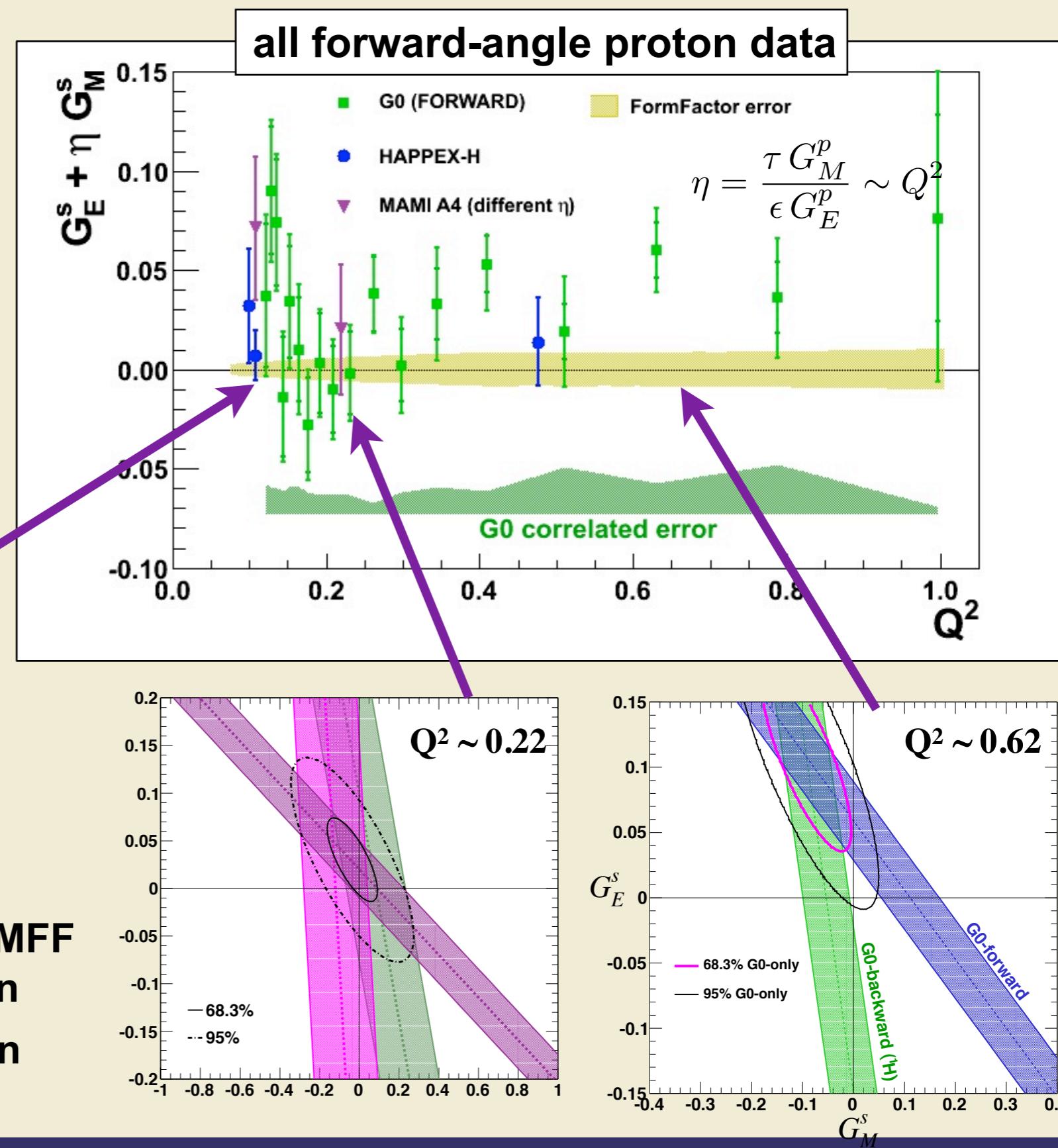


- “Form Factor” error: precision of EMFF (including 2γ) and Anapole correction
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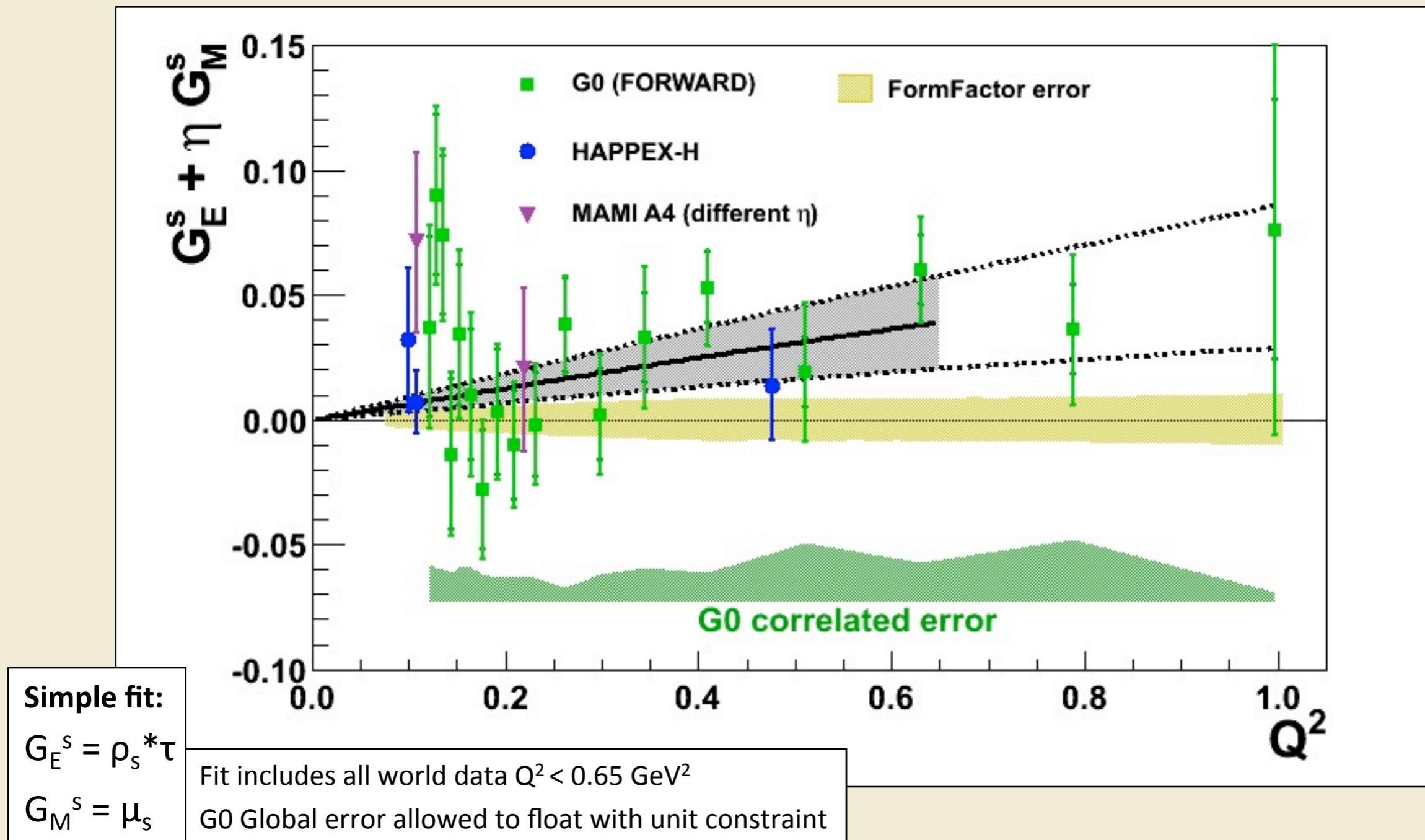
World data on G^S



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

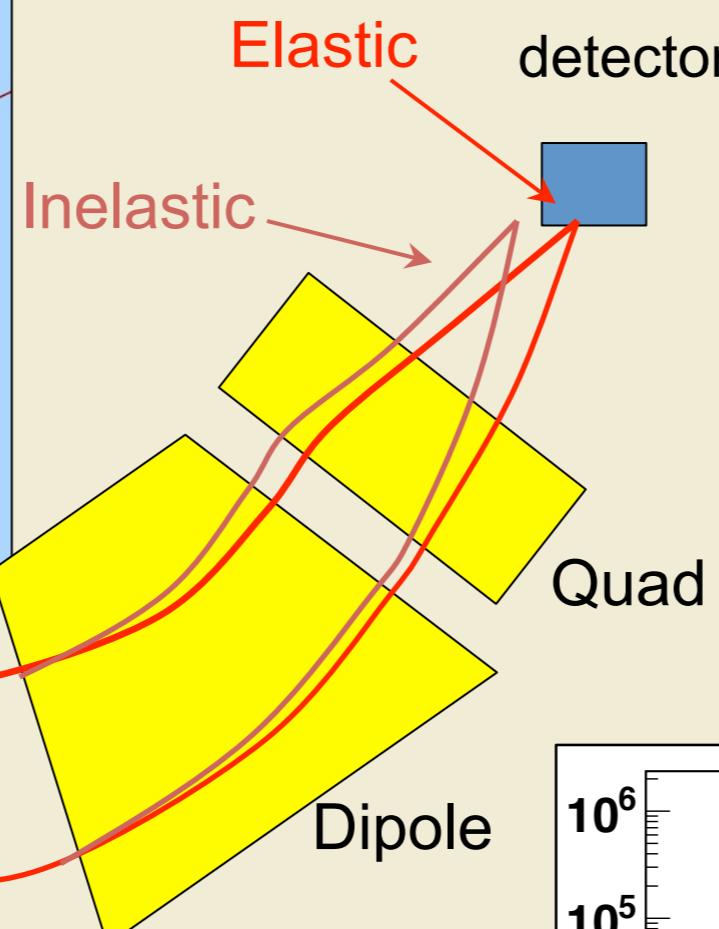
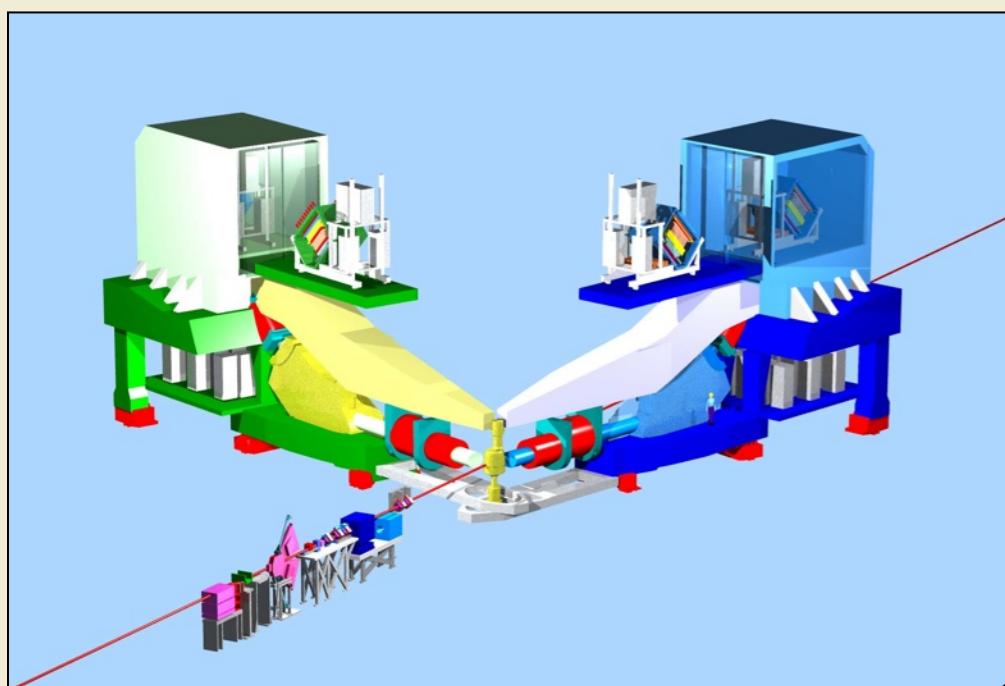


Global fit of all world data

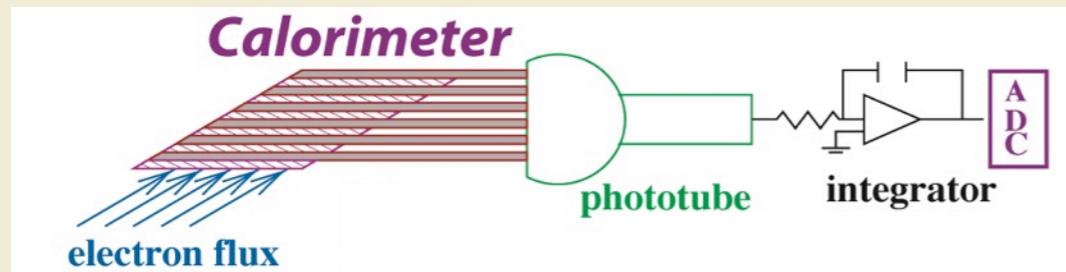


- Data set appears to show consistent preference for positive effect
- Significant contributions at higher Q^2 are not ruled out.

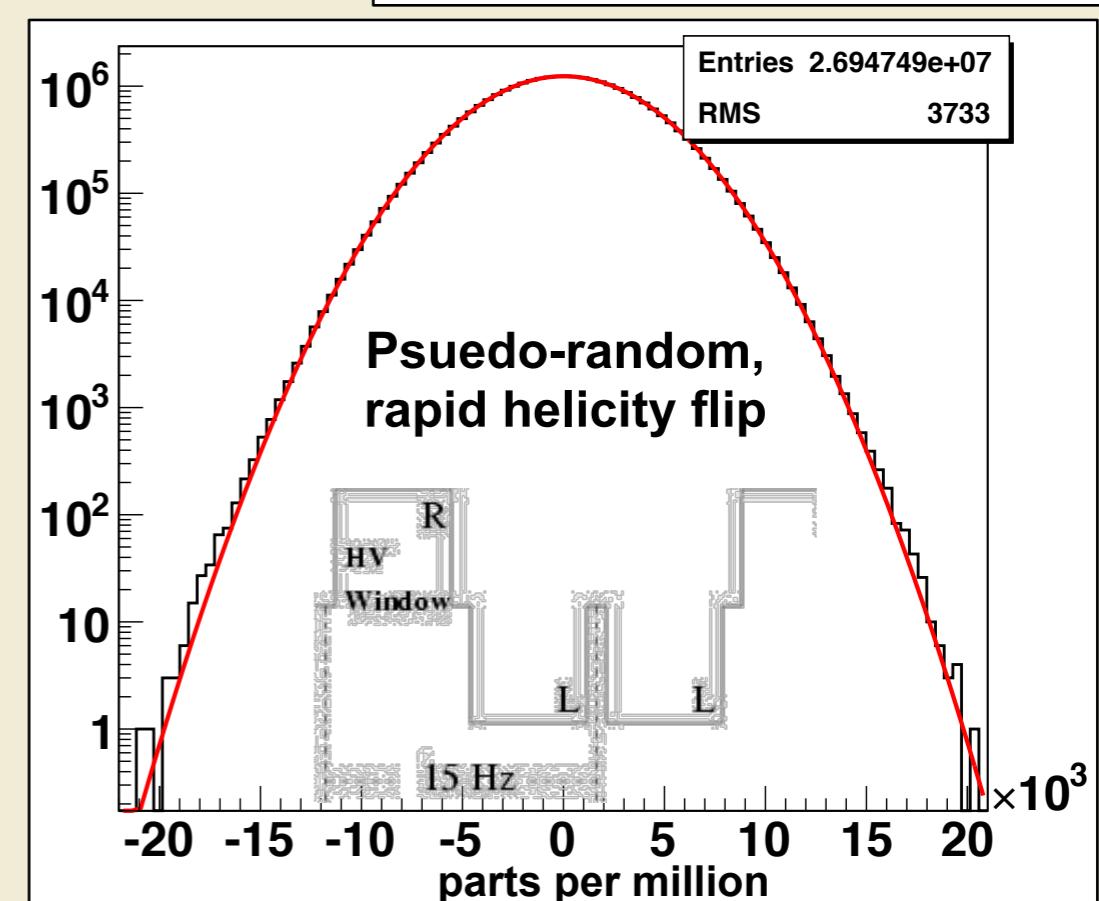
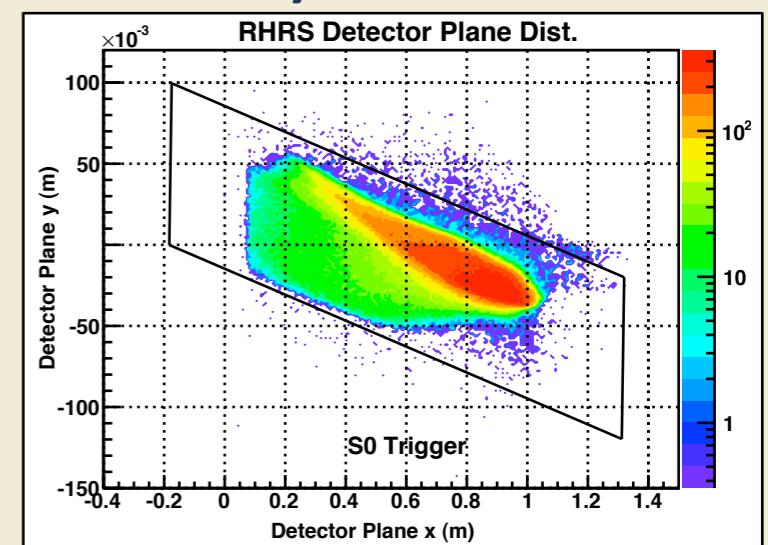
Hall A Parity: Integrating in the High Resolution Spectrometers



Lead - Lucite Cerenkov Shower Calorimeter
• phototube current integrated over fixed time periods



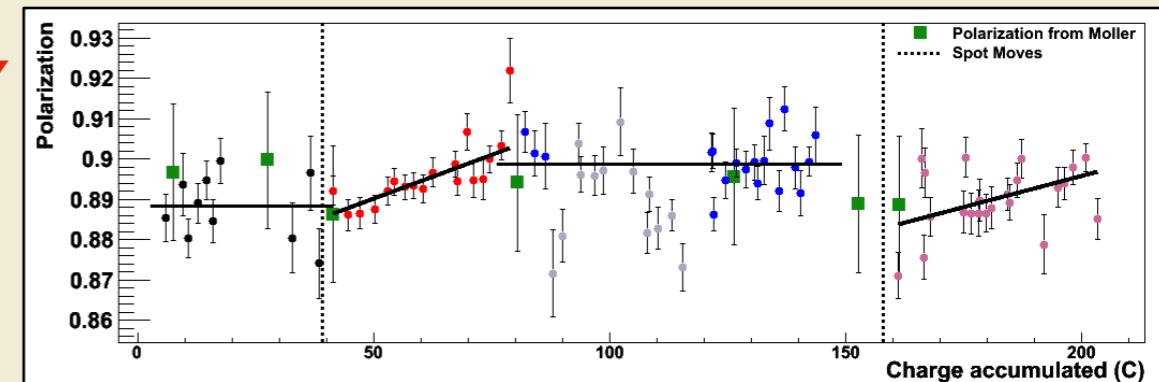
Very clean separation of elastic events by HRS optics
no PID needed; detector sees only elastic events



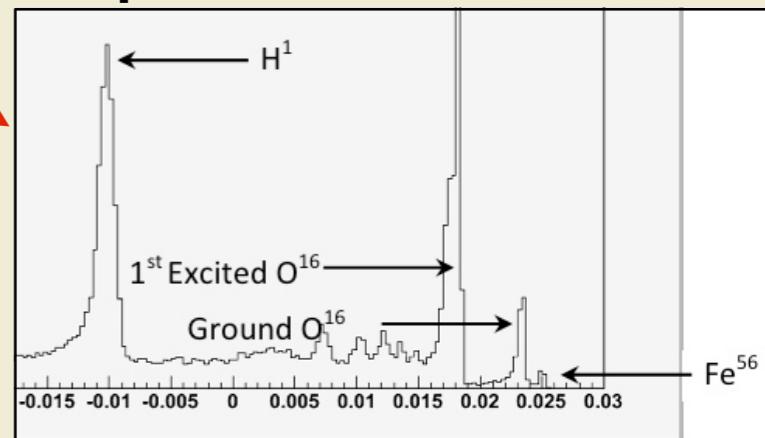
HAPPEX-III Error Budget

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

Compton + Moller polarimeters

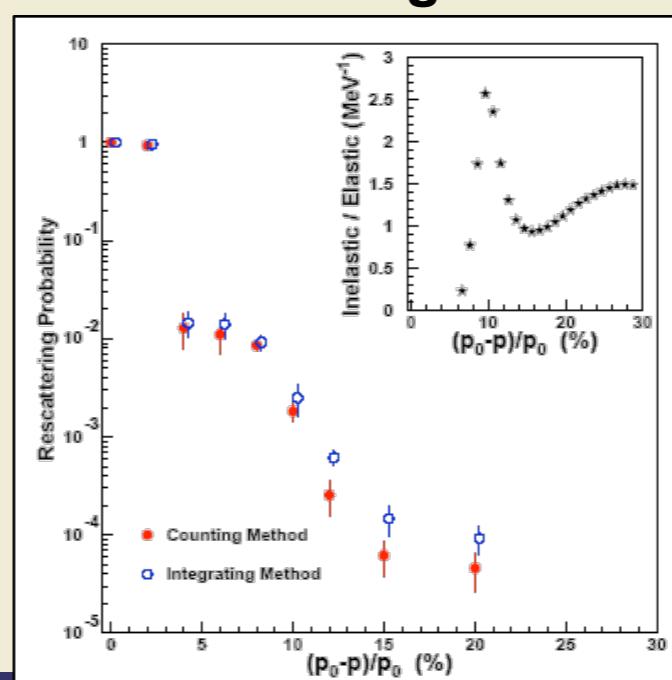
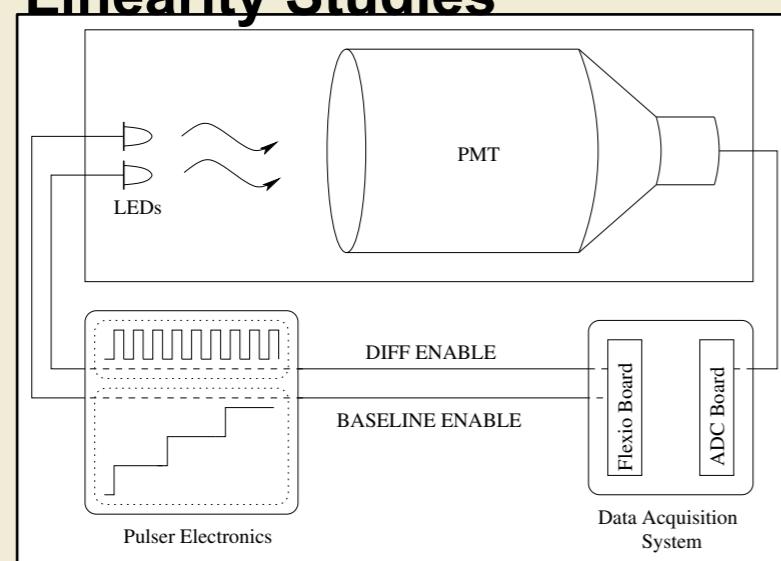


Spectrometer Calibration



HRS Backgrounds

Linearity Studies



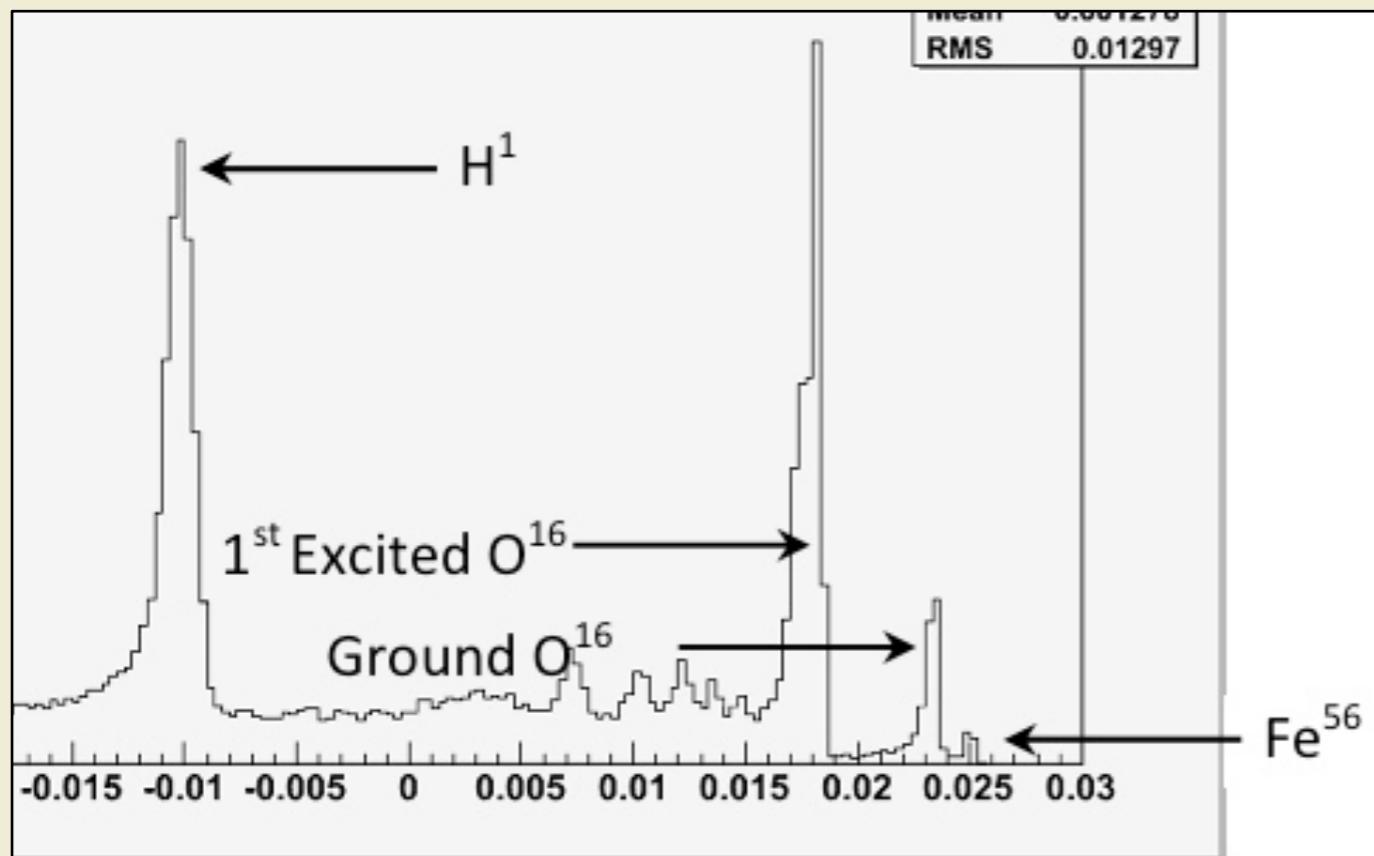
Systematic uncertainties are well controlled - experiment is statistics dominated

Determining Q²

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

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

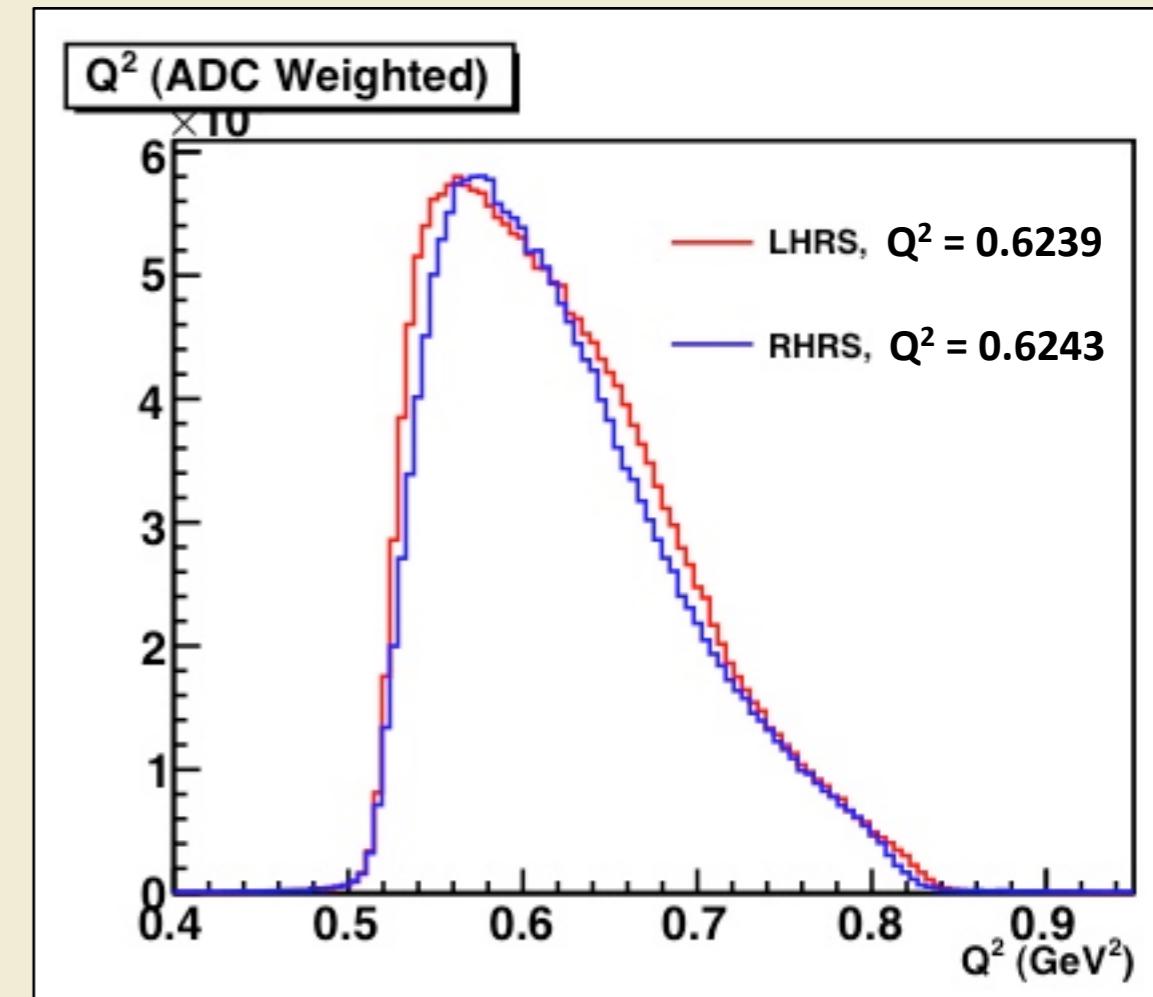
Water cell optics target for central angle



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

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

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

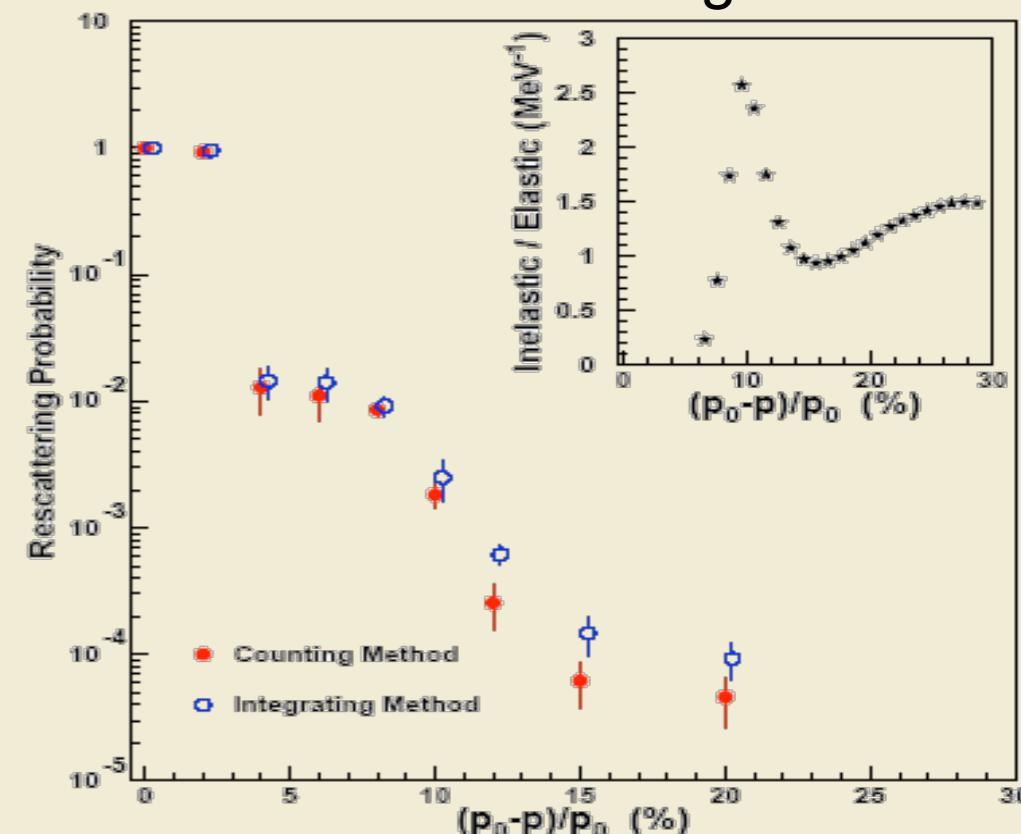


Central Angle	0.45%
Beam Energy, HRS momentum	0.11%
Drifts	0.2%
ADC weighting	0.1%
Total	0.52%

Backgrounds

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

Rescattering probability measured during H-I



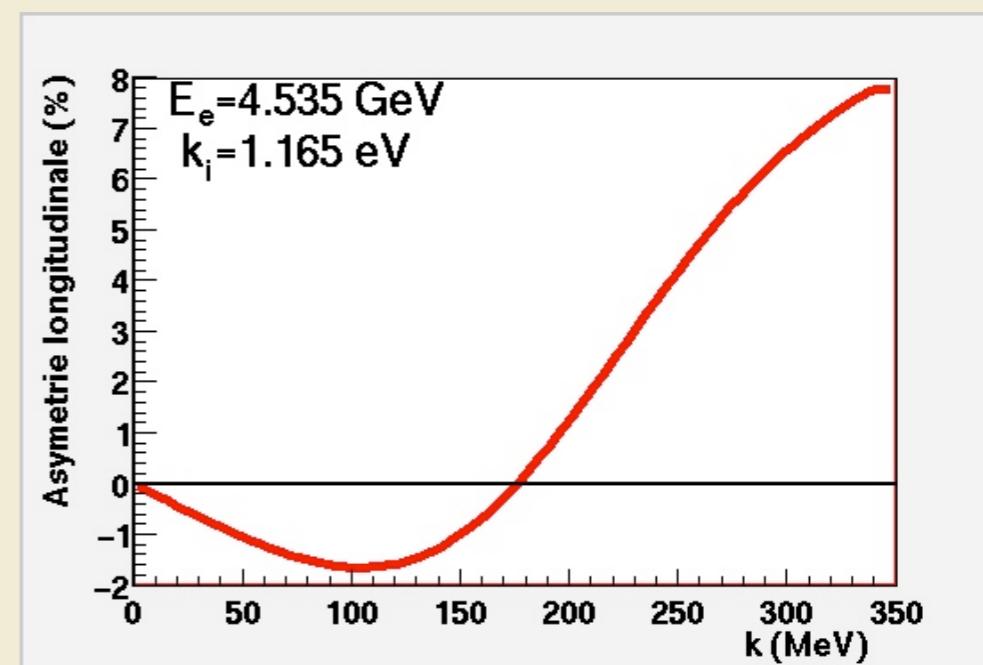
background	f	A	Net Correction	Net Uncertainty
Aluminum (target window)	1.15% (30%)	-34.5 ppm (30%)	125 ppb	126 ppb
Rescattering	0.3% (25%)	-63 ppm (25%)	114 ppb	55 ppb

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

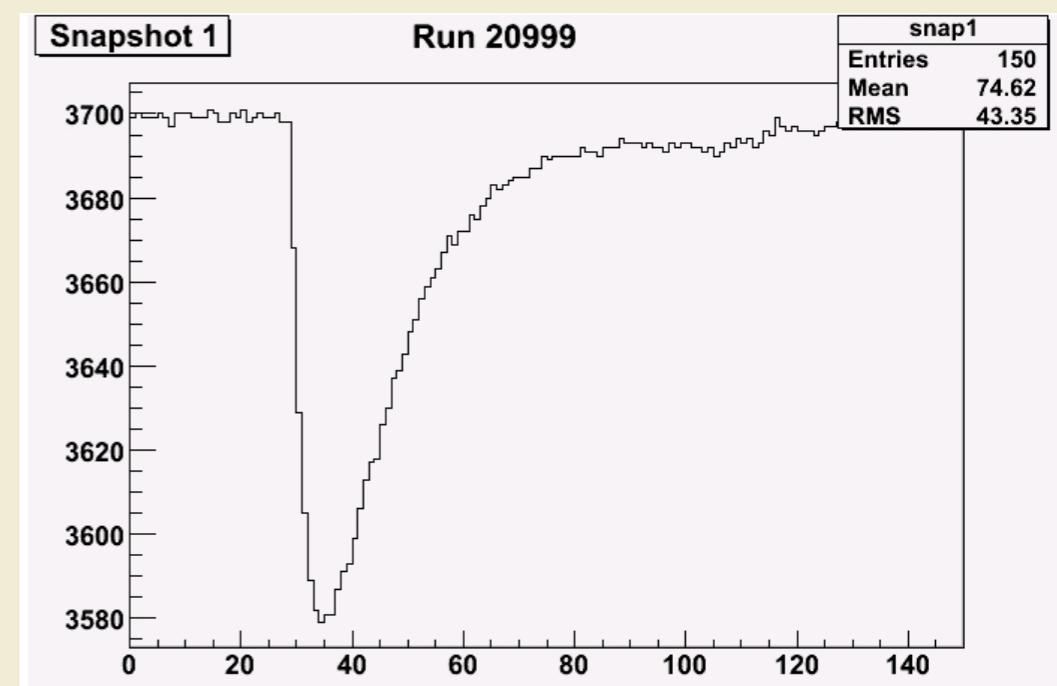
Integrating photon detection:
immune to calibration, pile-up, deadtime,
response function



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

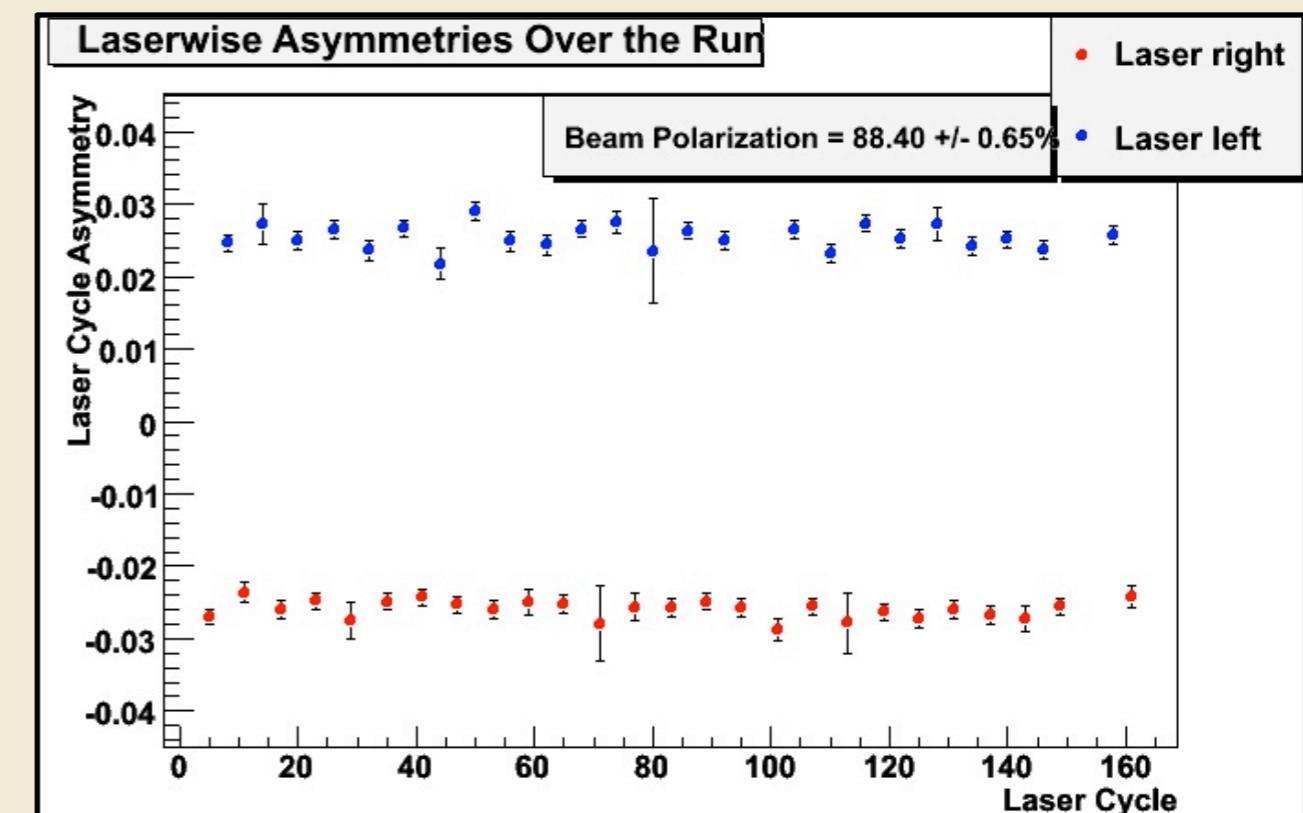
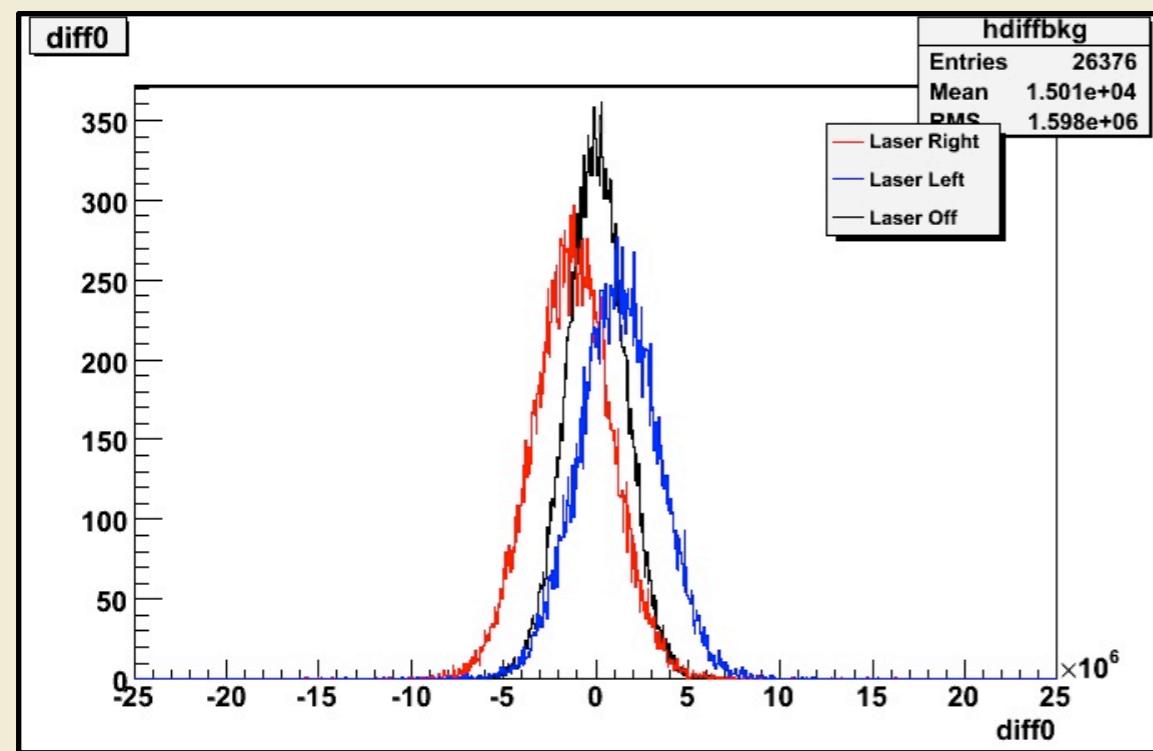
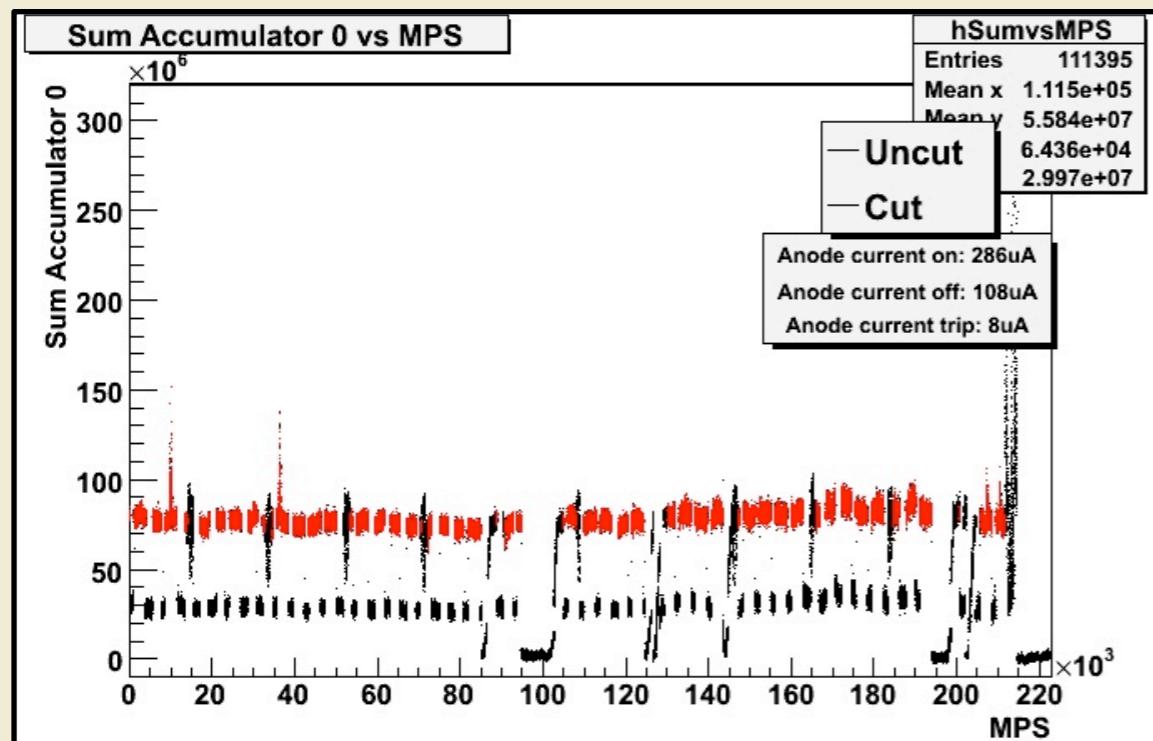
Triggered mode: triggered “snap shot” of
fixed time interval (for calibration)

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



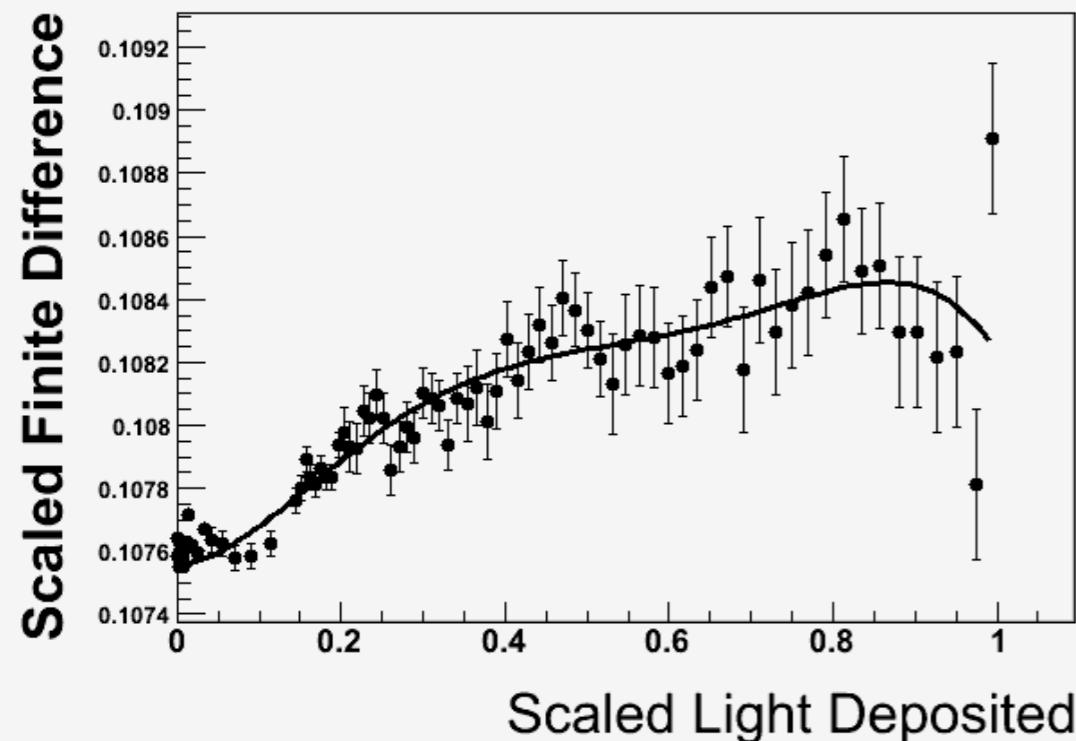
Compton Integrating Analysis, online

Online plots from run 20457



Compton Polarimetry

Graph to Fit

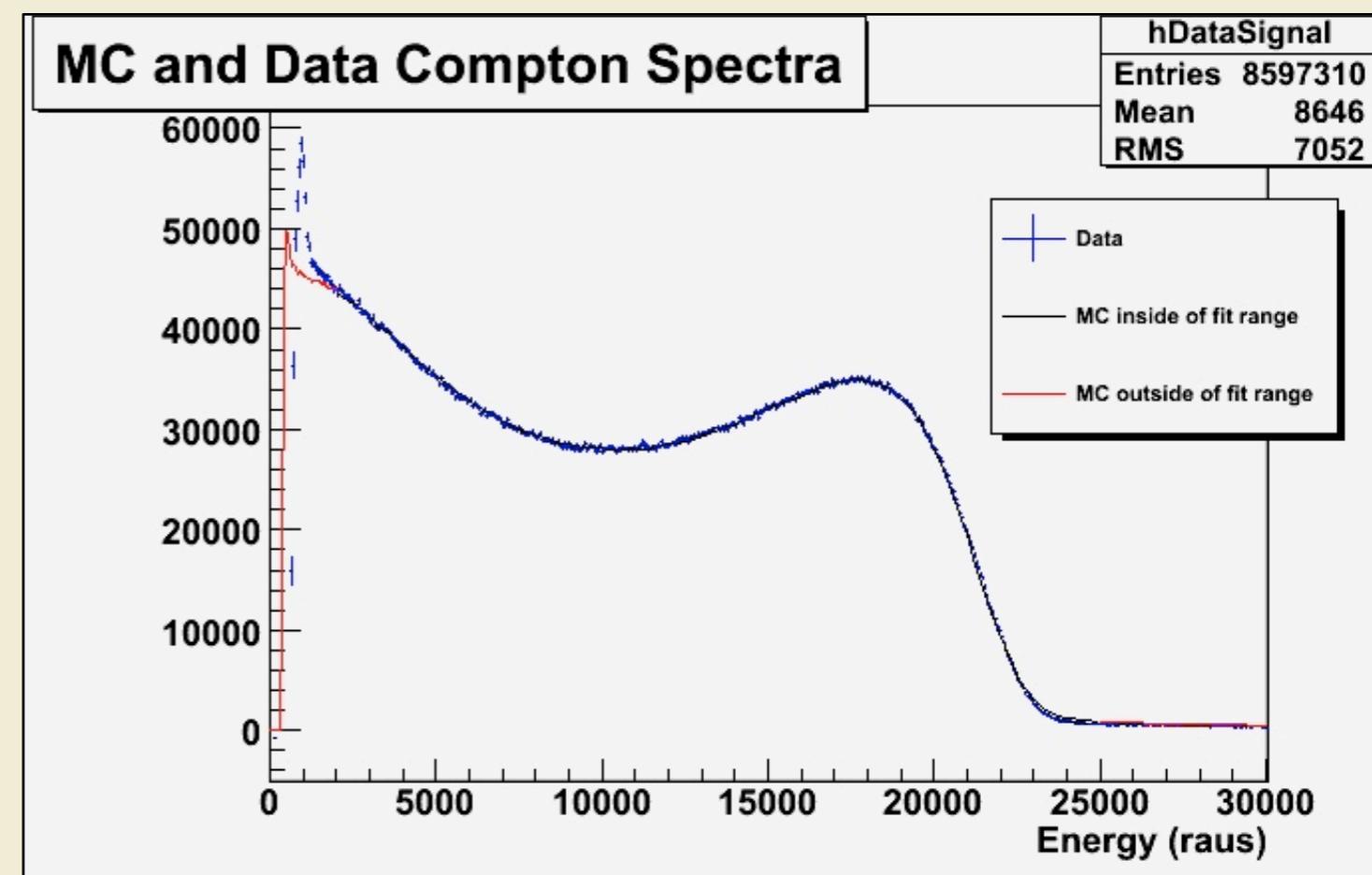


Non-linearity mapped out in with pulsed LED system.

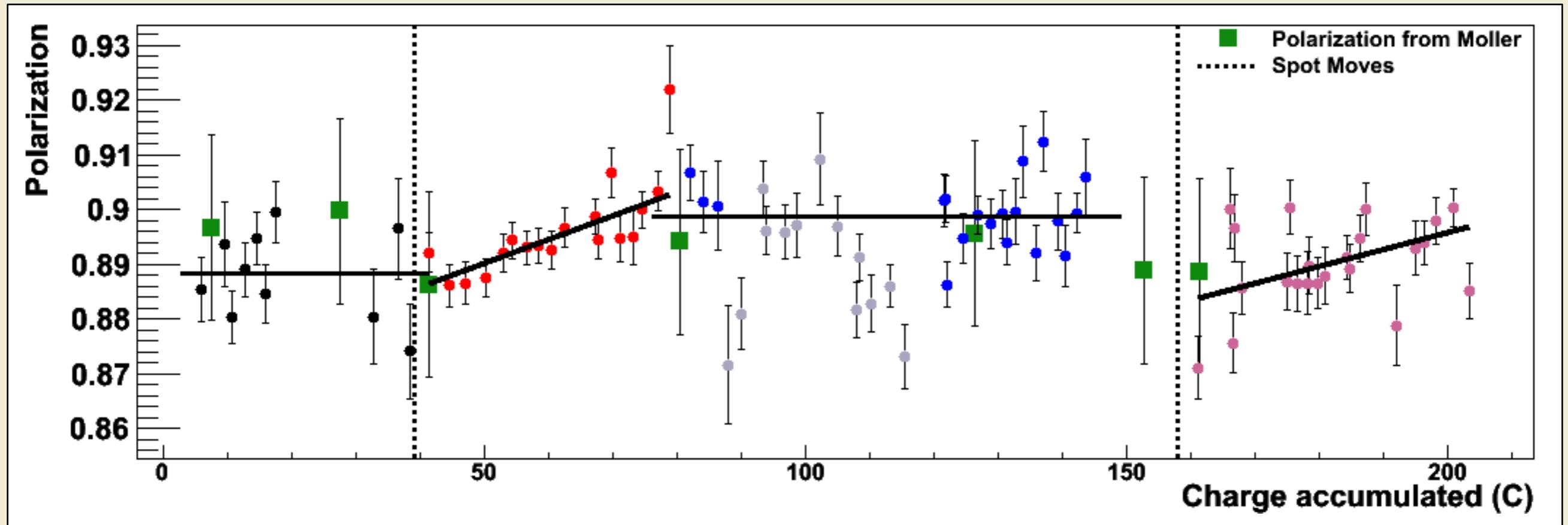
Compton spectrum very well simulated

- linearity
- collimator/detector alignment
- synchrotron light shielding

Analyzing power calculation is not extremely sensitive to these corrections



Polarimetry Summary



Compton: $89.41 \pm 0.96\%$

Moller: $89.22 \pm 1.7\%$

Average: $89.36 \pm 0.84\%$

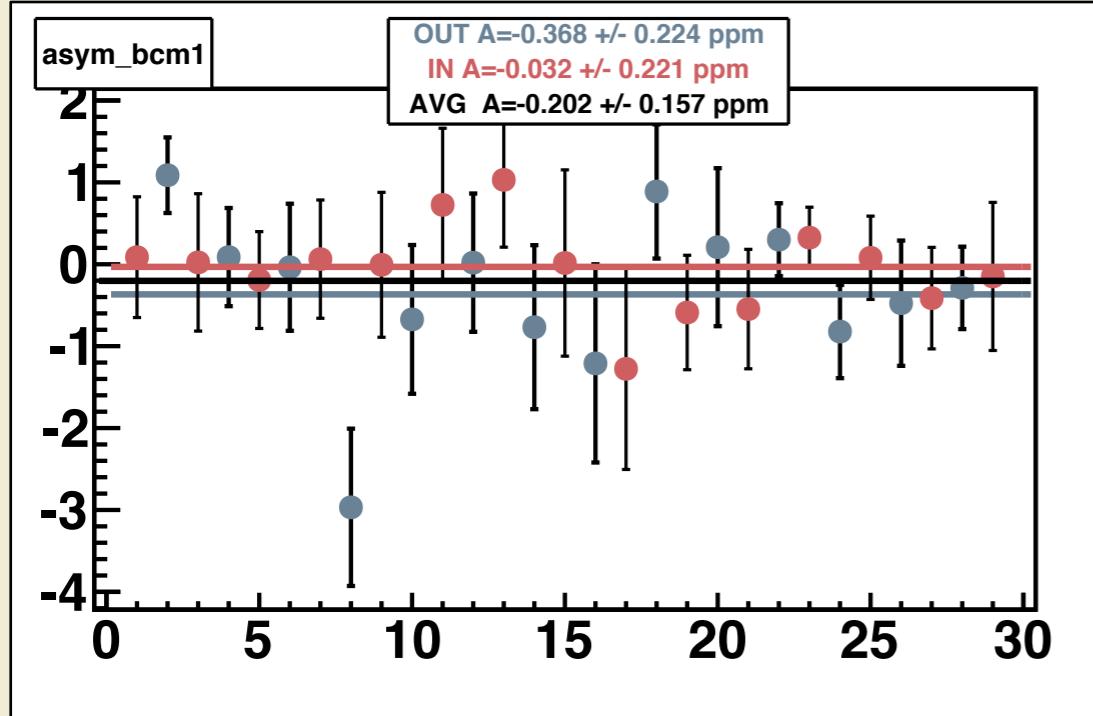
Moller systematic errors

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

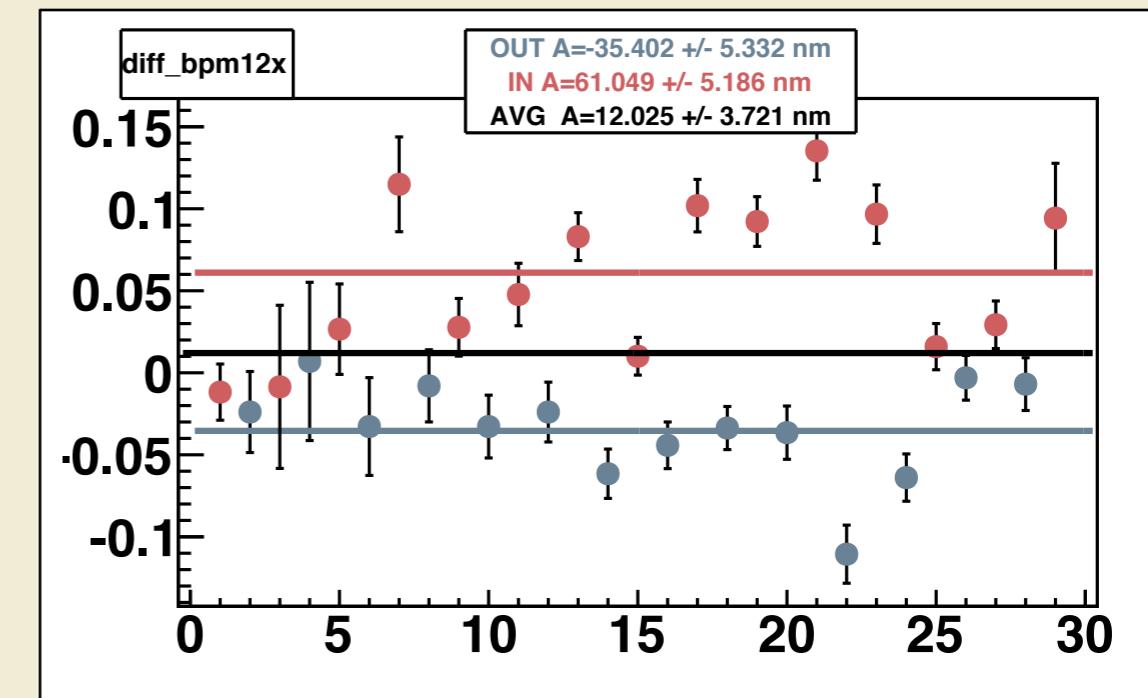
Compton systematic errors

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

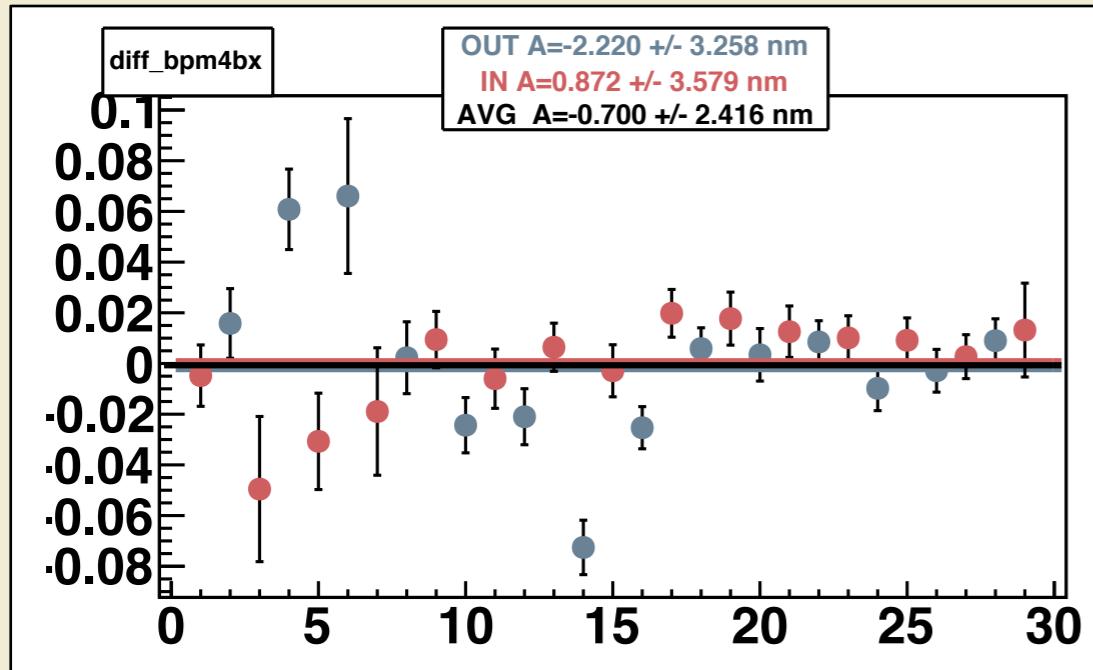
Beam Asymmetries



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

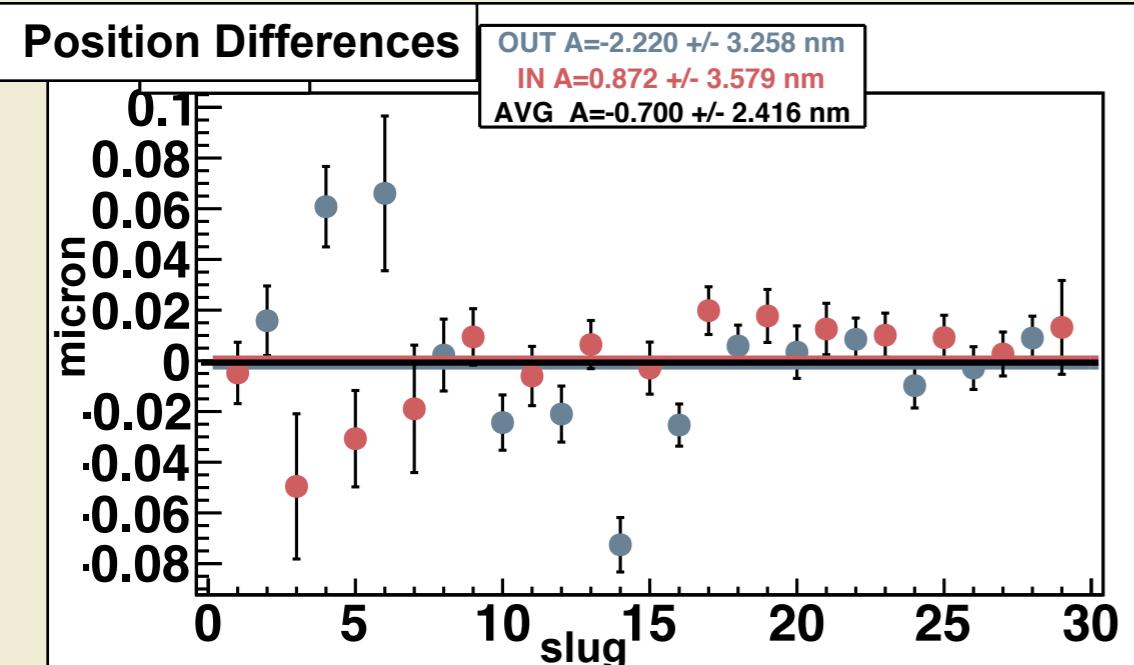
HAPPEX-III Measurement of A_{PV}

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

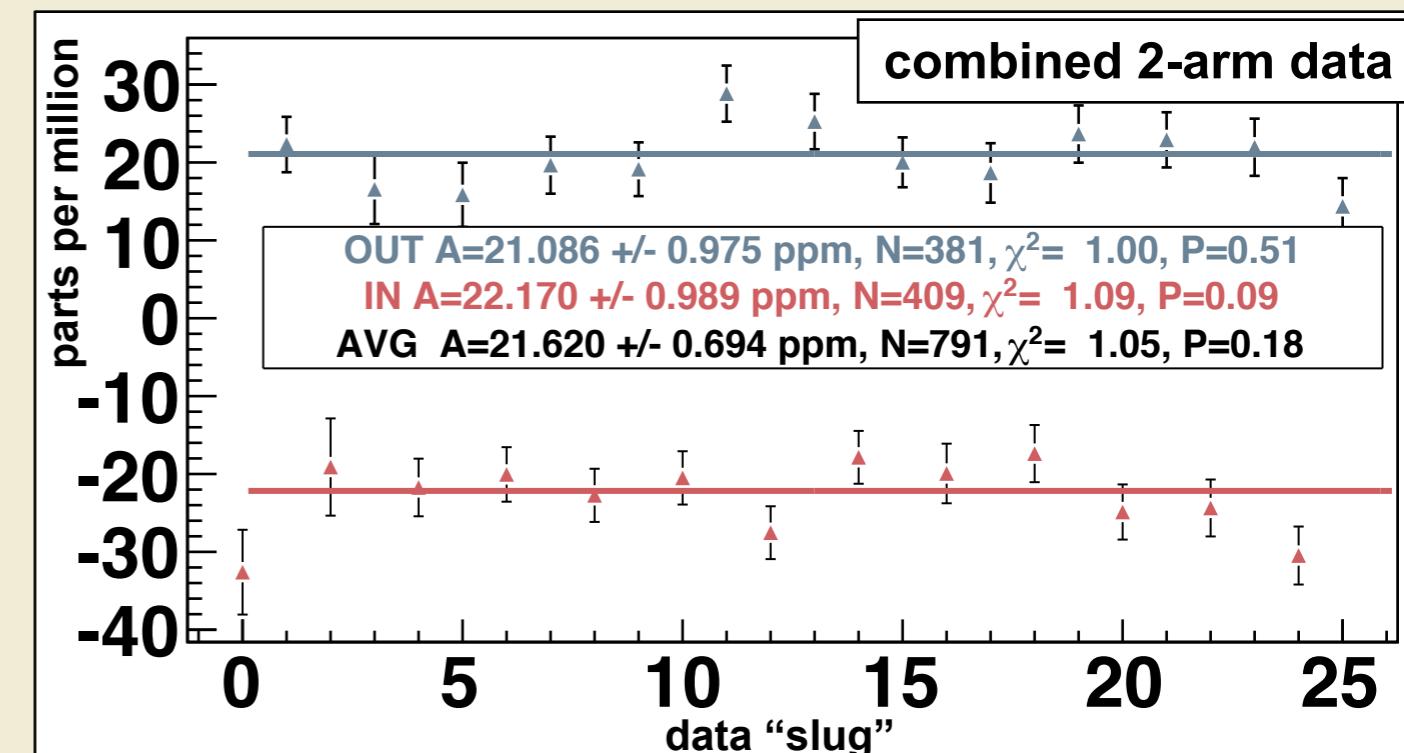
This includes

- 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) \pm 1.5% (syst)

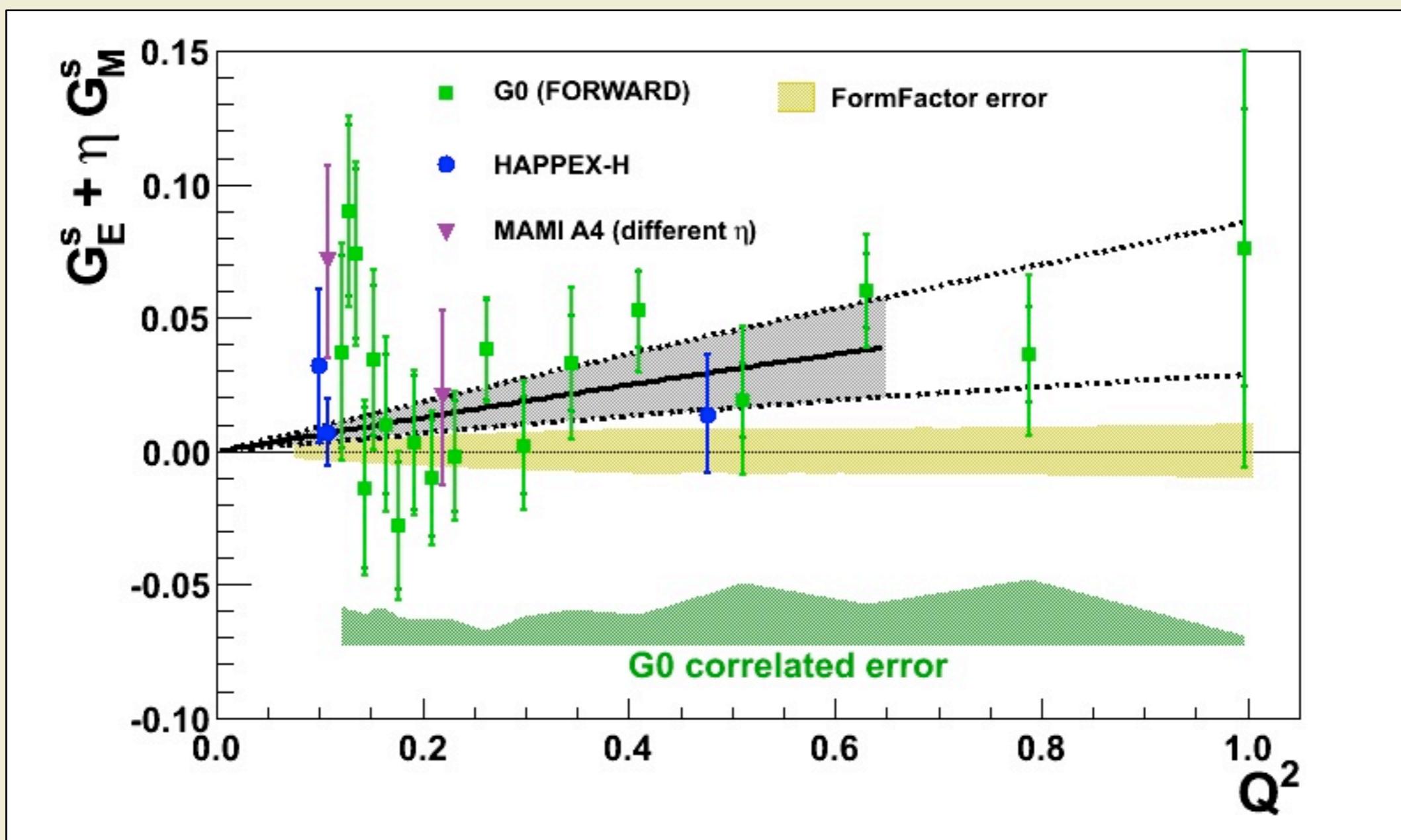
total correction \sim 2.5% + polarization

Analysis Blinded \pm 2.5 ppm

HAPPEX-III Result

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

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

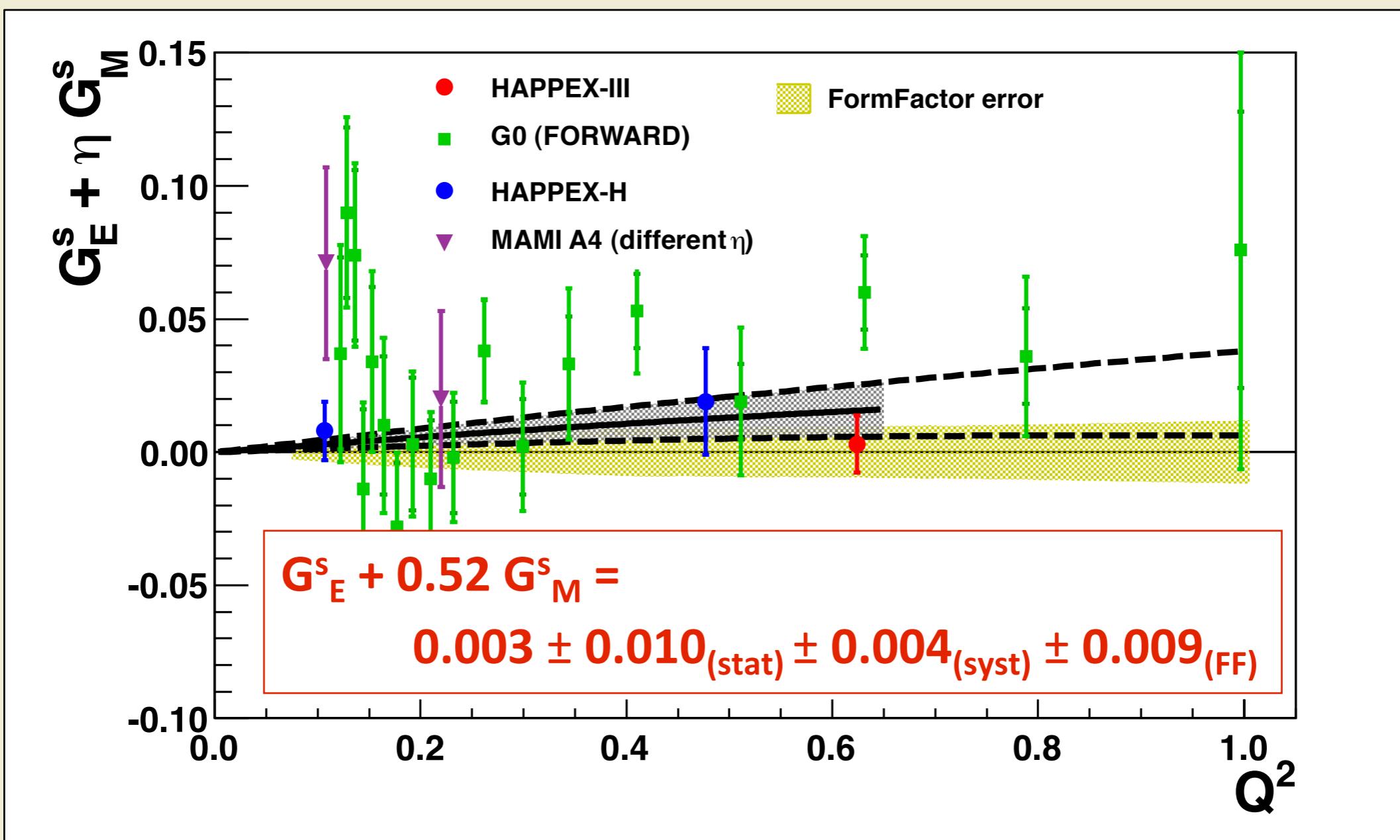


HAPPEX-III Result

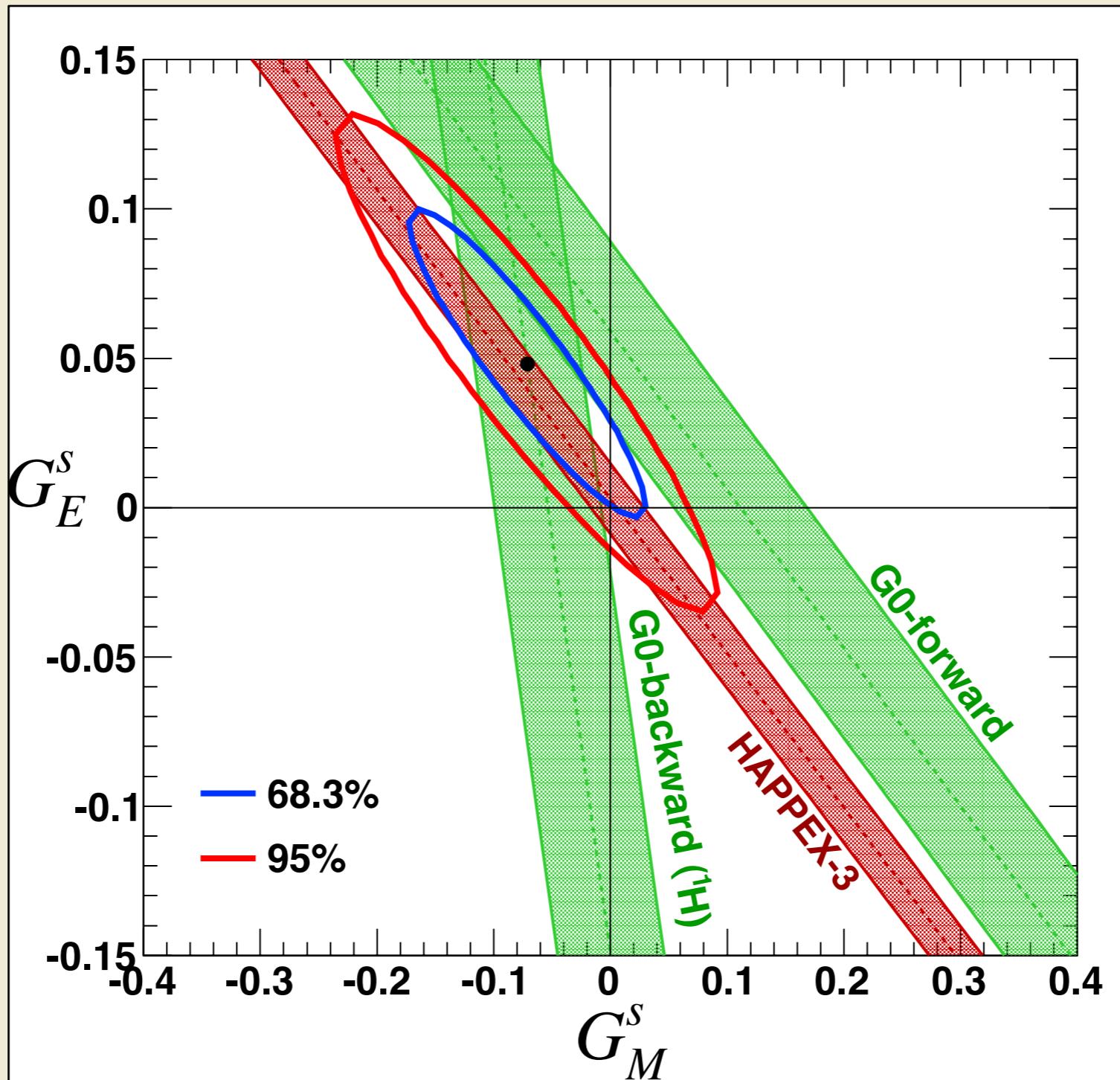
$A_{PV} = -23.803 \pm 0.778 \text{ (stat)} \pm 0.359 \text{ (syst) ppm}$

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

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

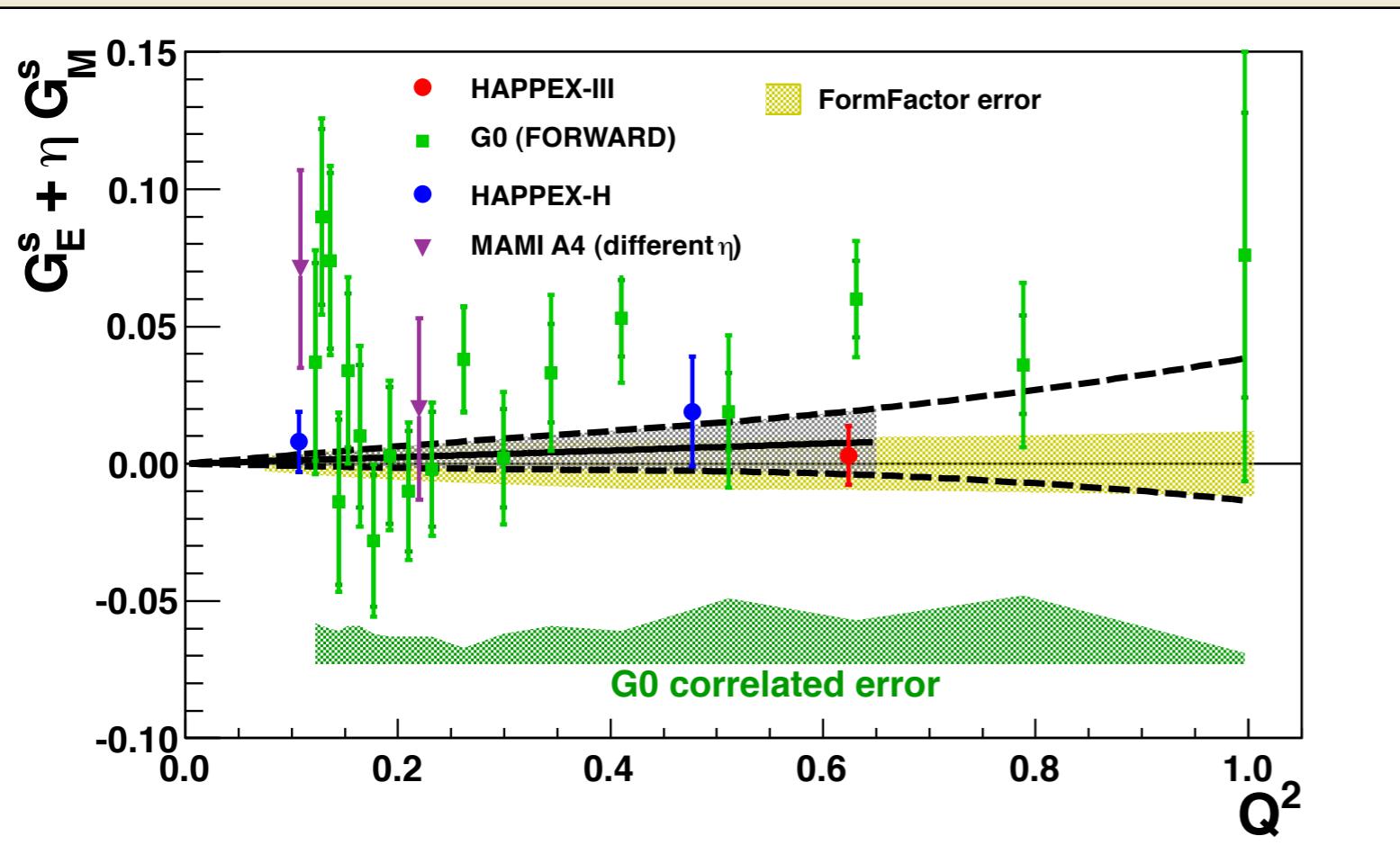
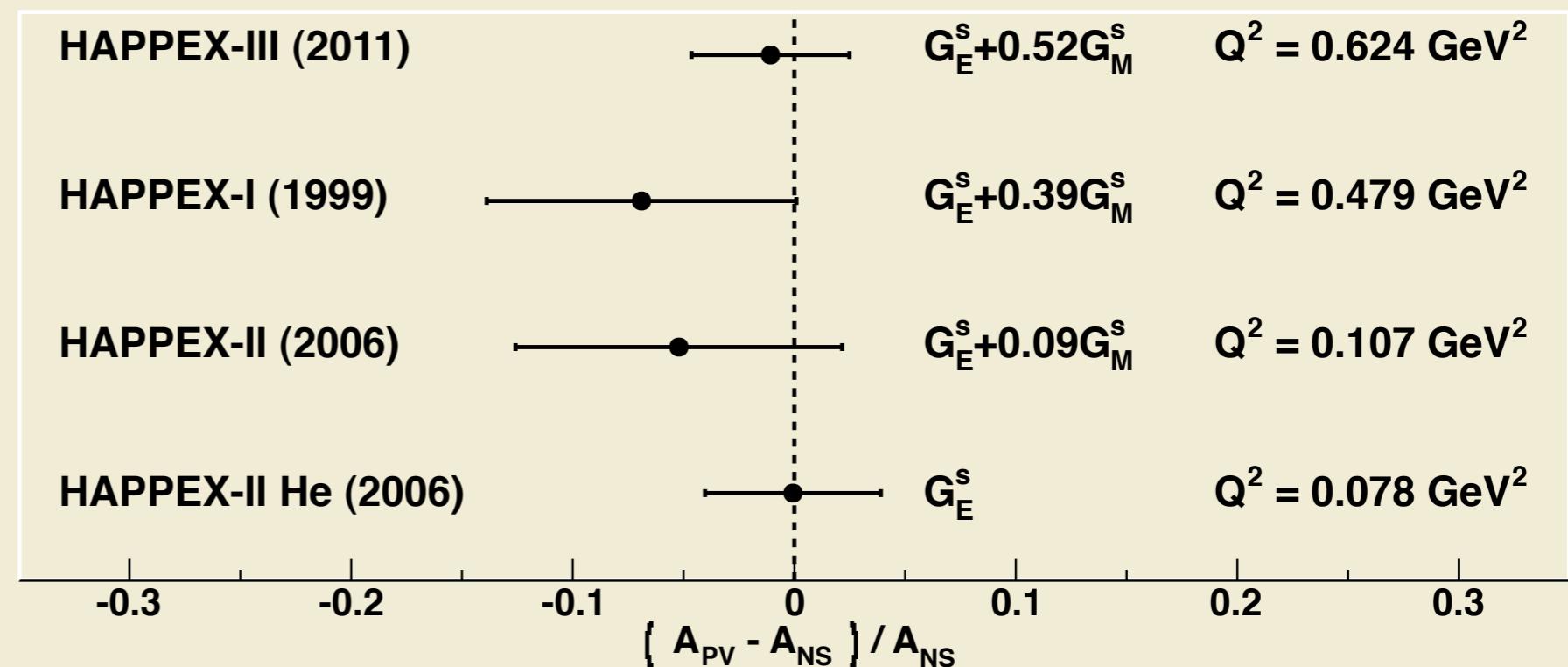


$Q^2 = 0.62 \text{ GeV}^2$ in combination



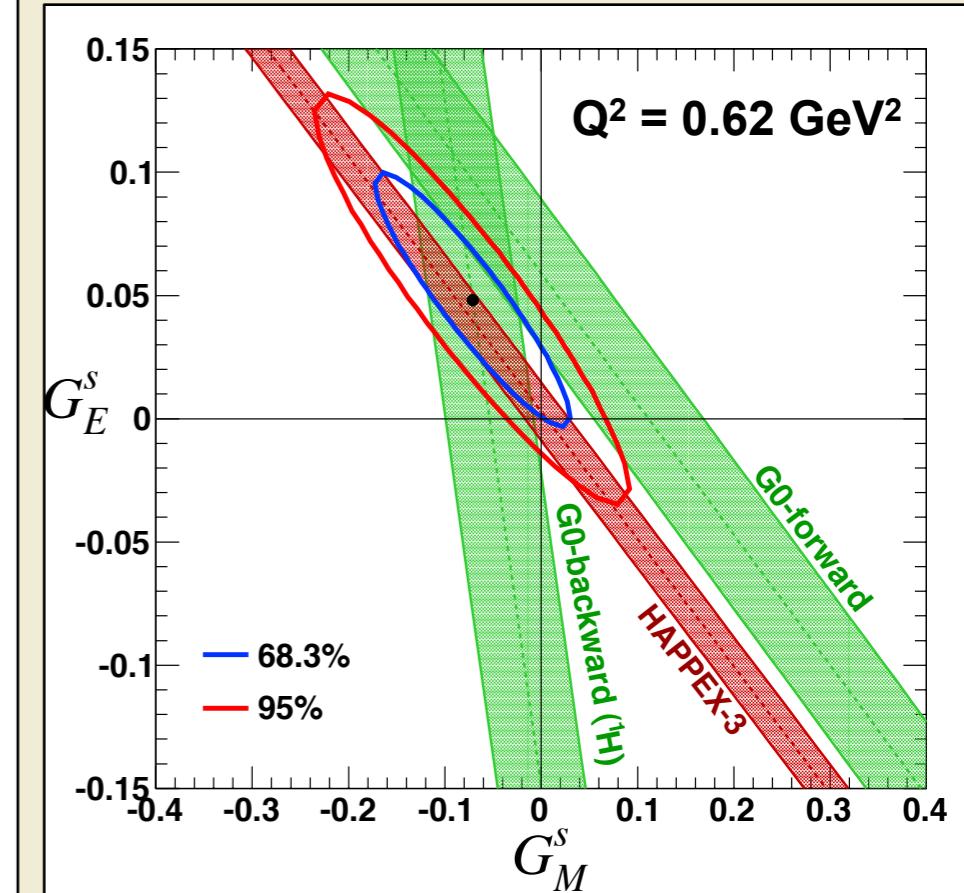
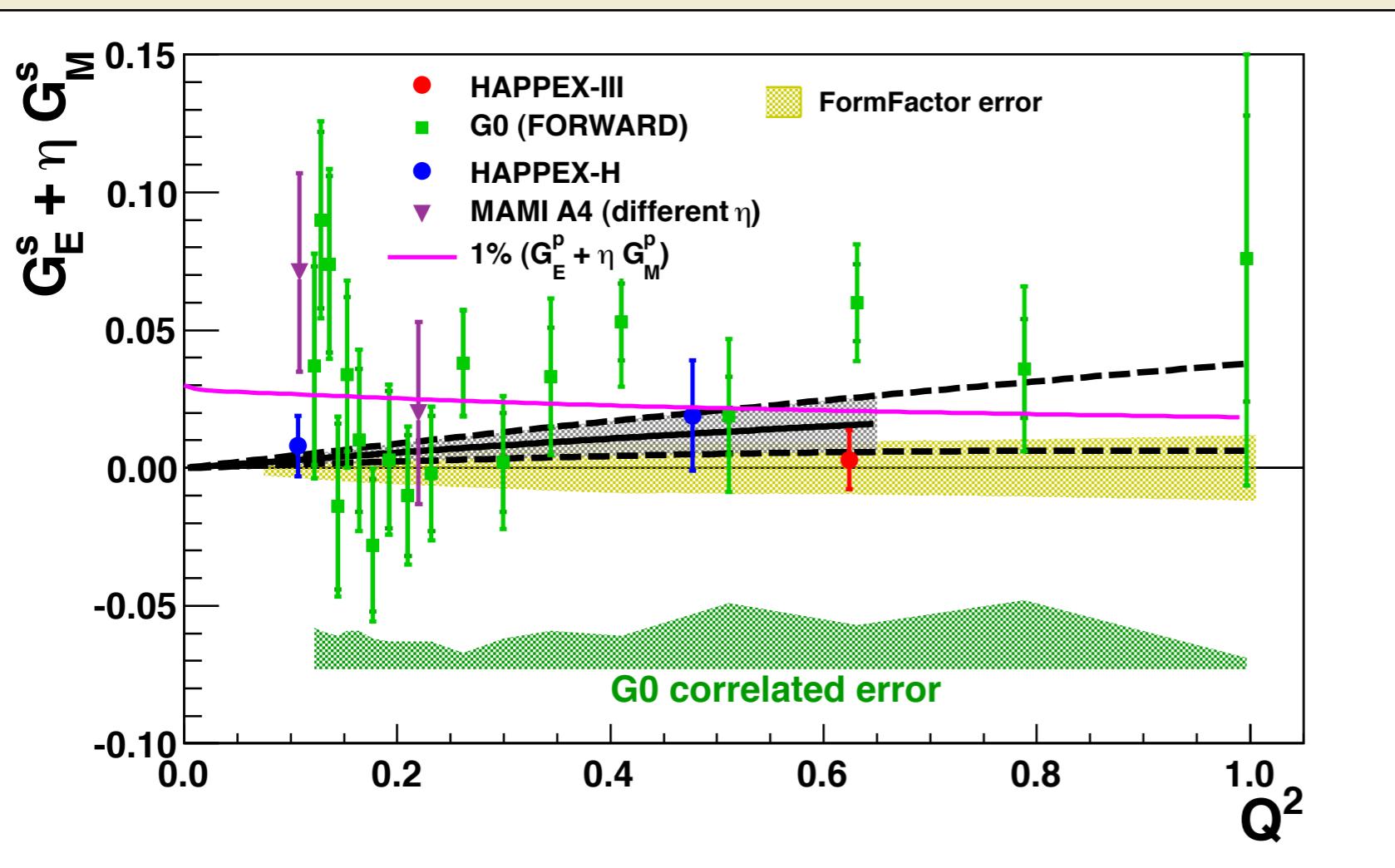
Combined fit includes form-factor
uncertainties, experimental bands do not

Considering only the 4 HAPPEX measurements



- High precision
- Small systematic error
- Clean theoretical interpretation

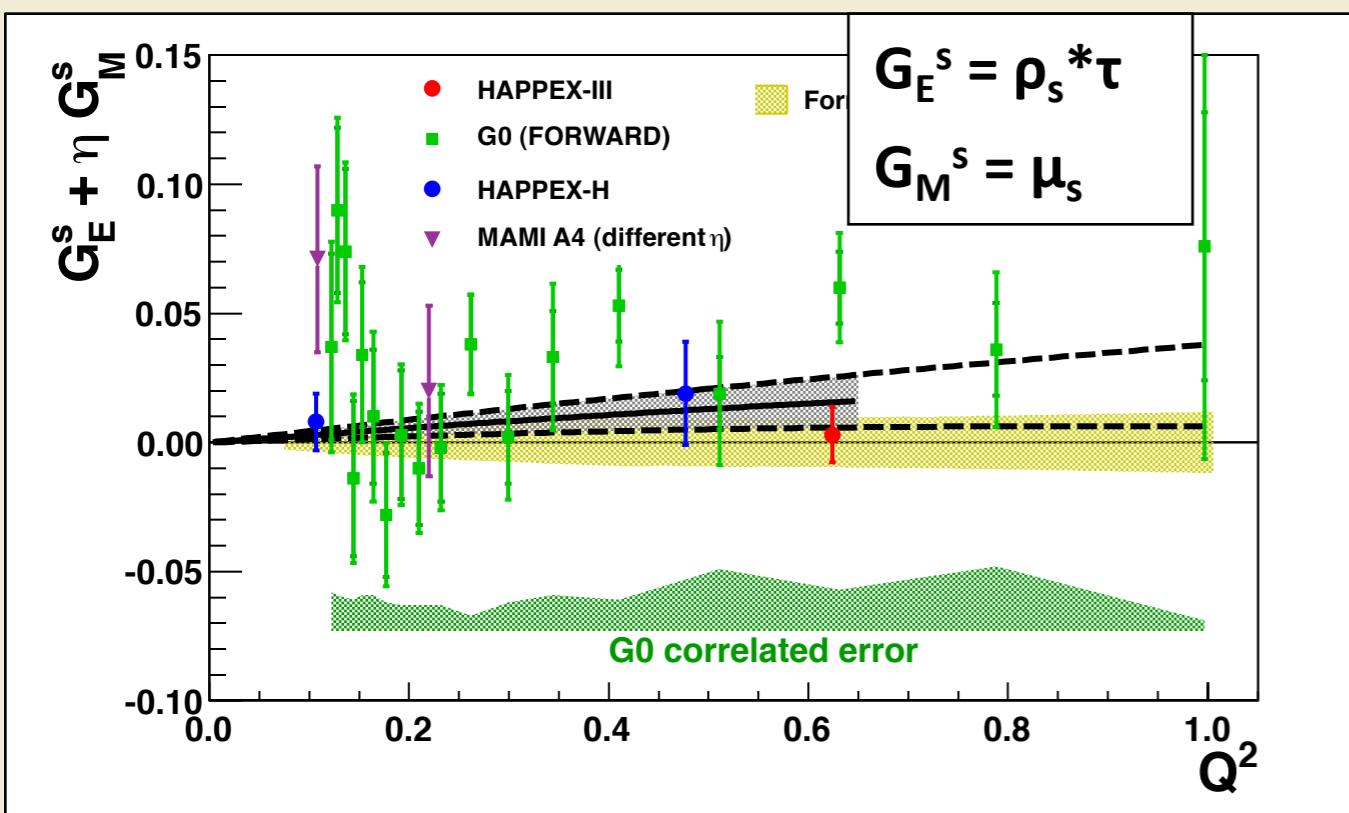
Strange Vector Form Factors Are Small



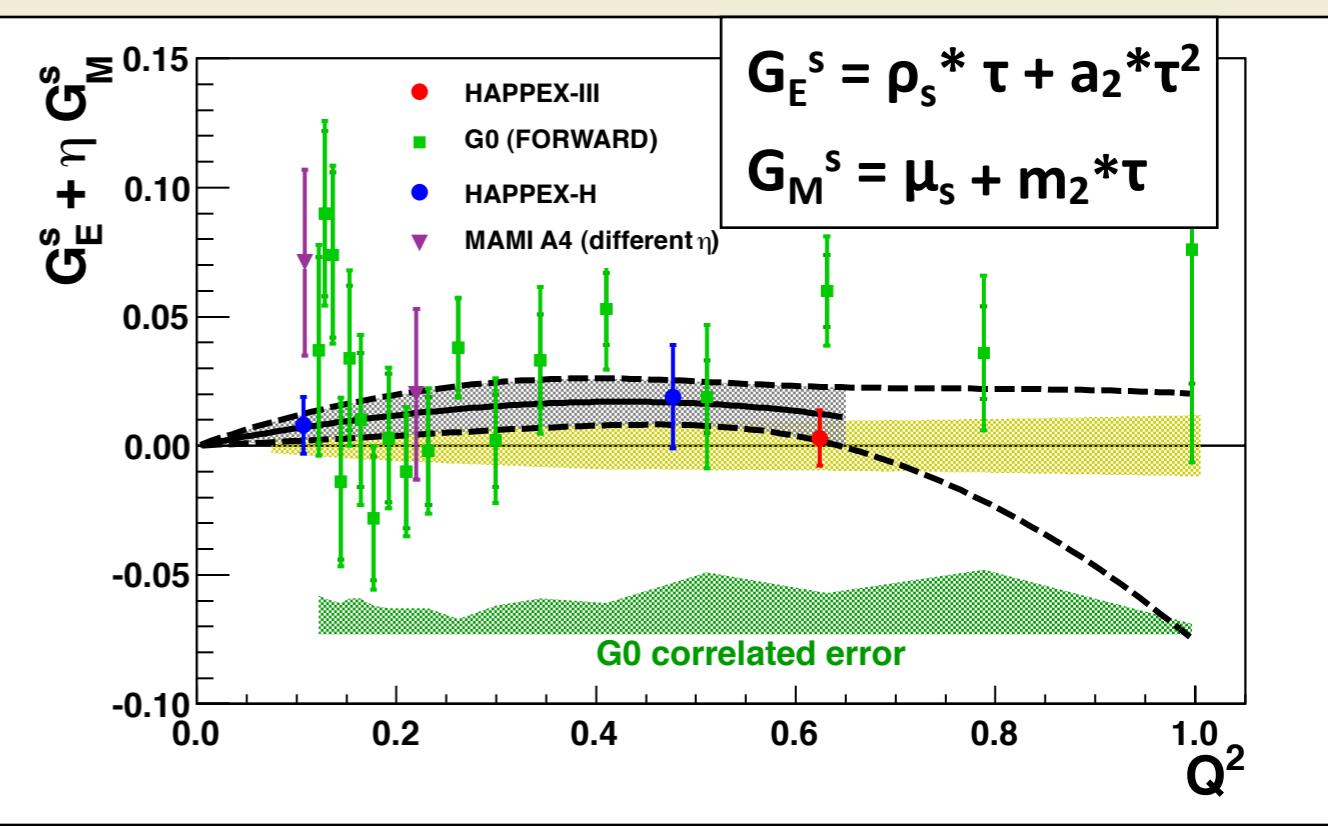
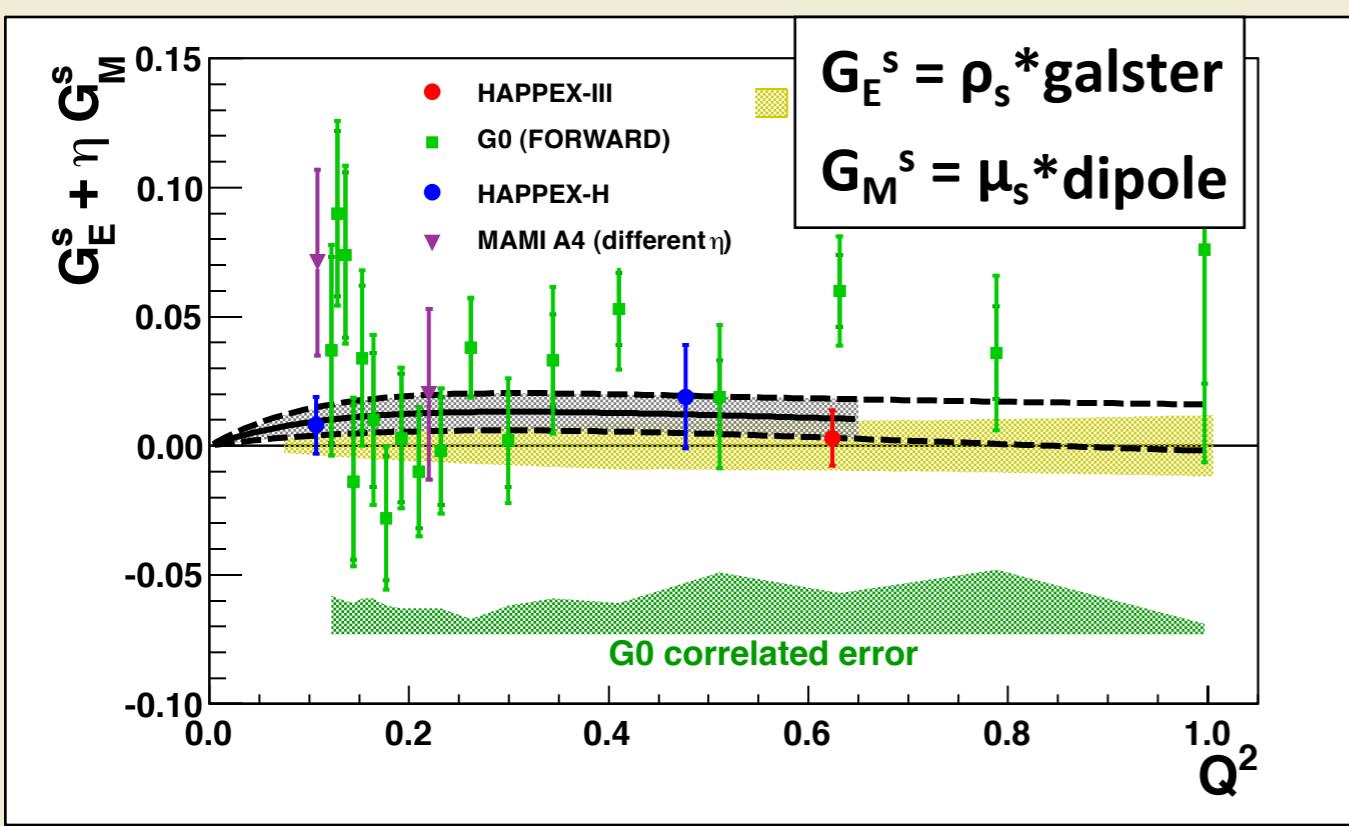
- HAPPEX-III provides a clean, precise measure of A_{PV} at $Q^2=0.62 \text{ GeV}^2$, and finds that it is consistent with no strangeness contribution to the long-range electromagnetic interaction of the nucleon
- Recent lattice results indicate values smaller than these FF uncertainties
- Further improvements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

Backup

Parameterizations

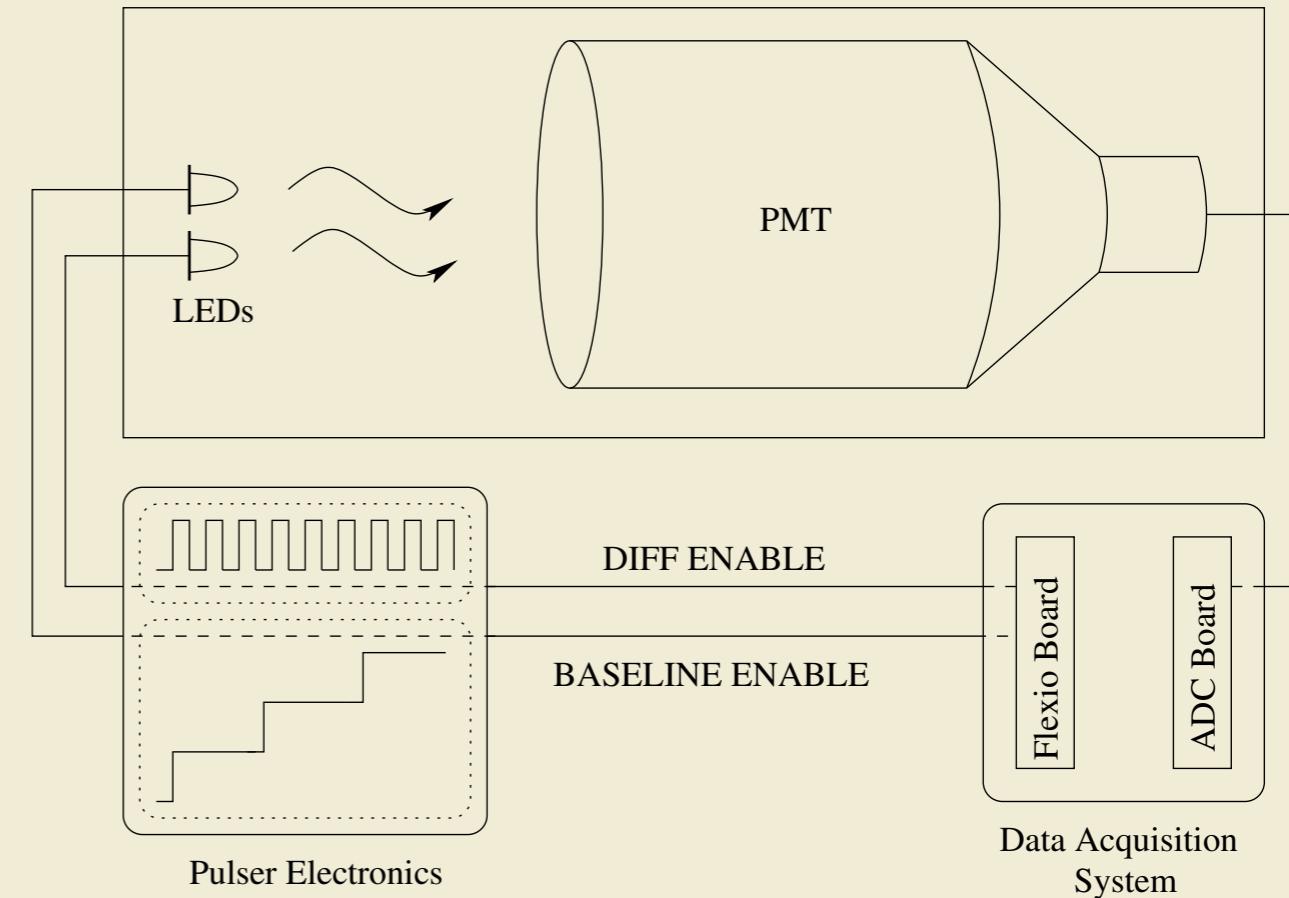
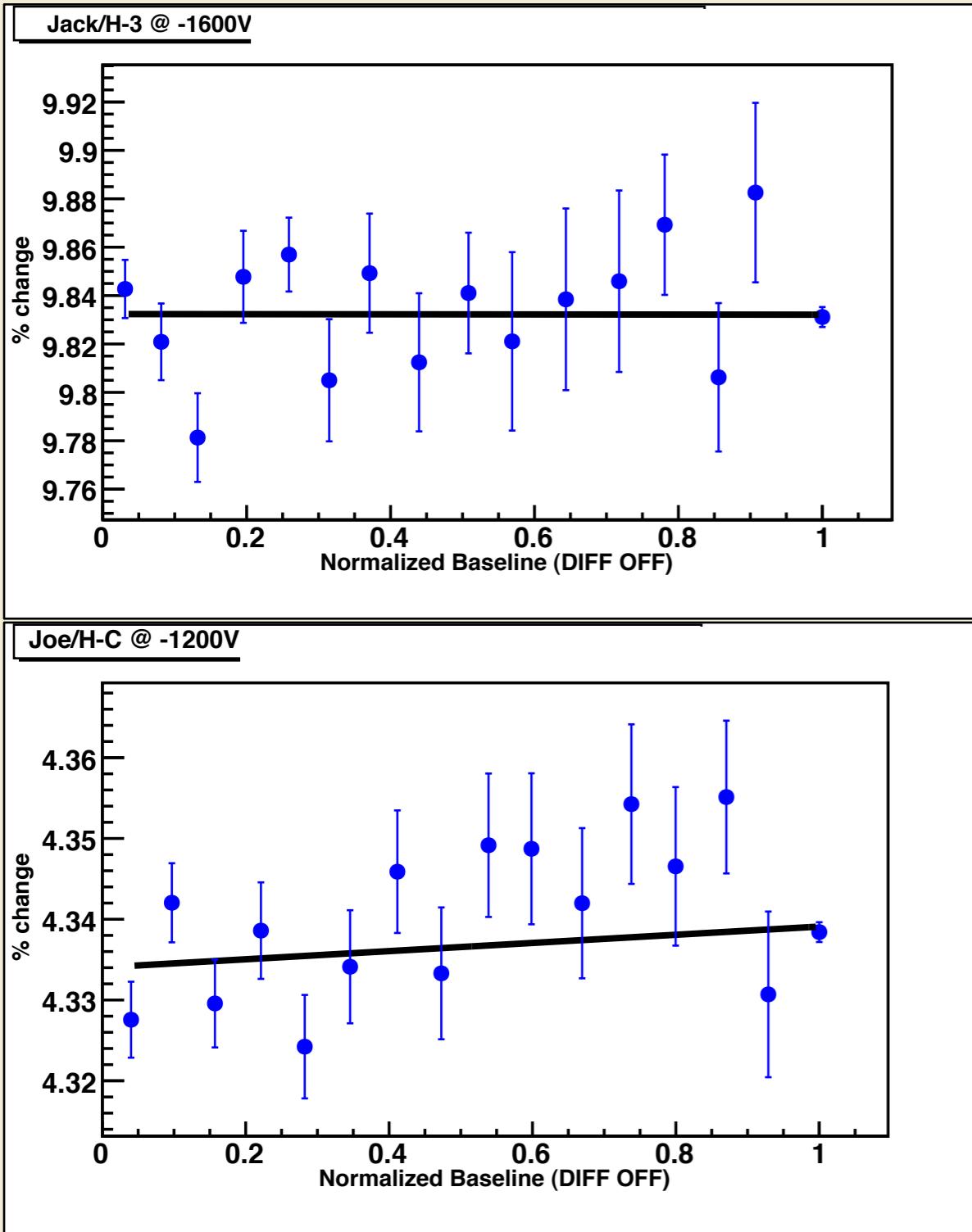


Fit includes all world data $Q^2 < 0.65 \text{ GeV}^2$
G0 Global error allowed to float with unit constraint



Detector Linearity

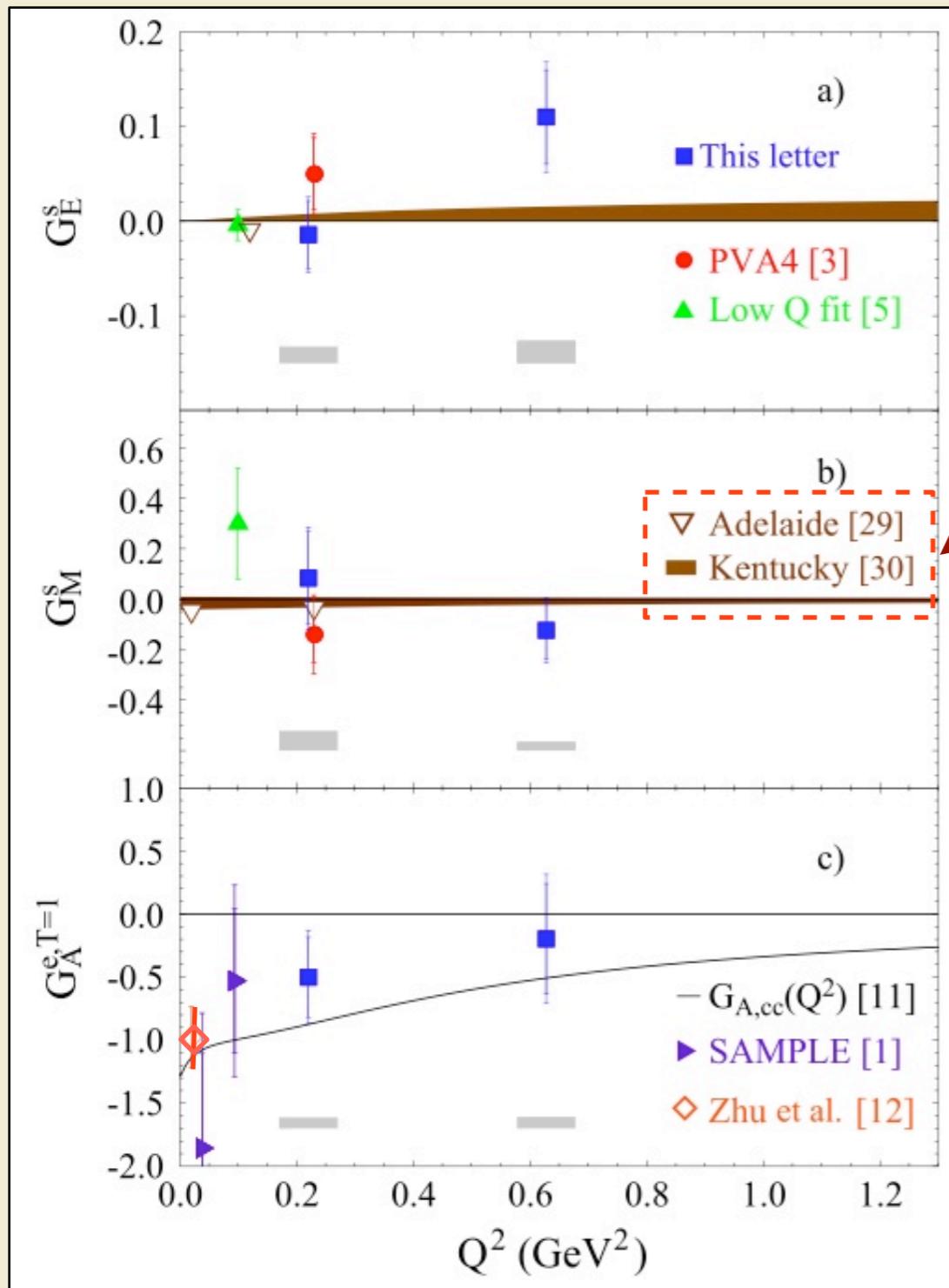
Studied *in situ* and on bench with LED system optimized to linearity for differential rates of similar pulses



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

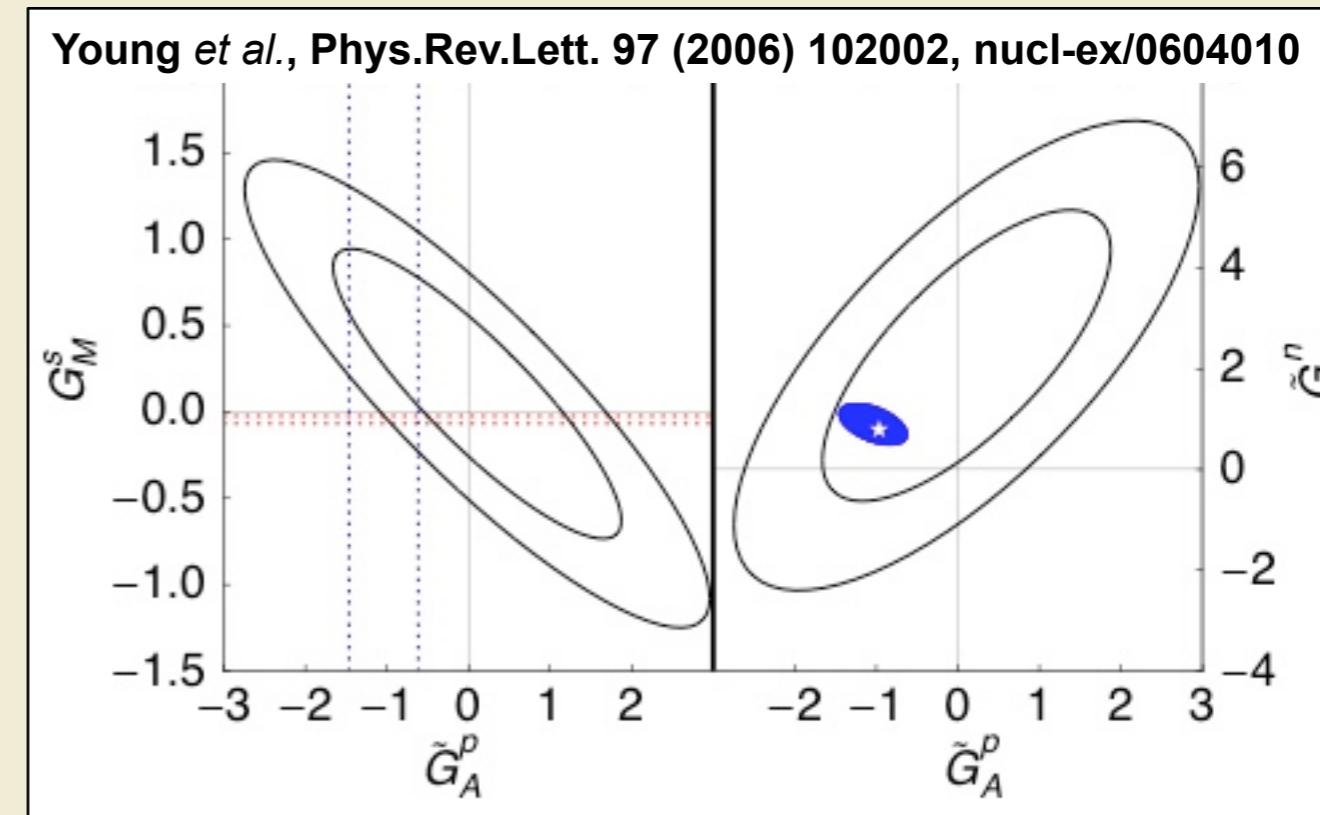
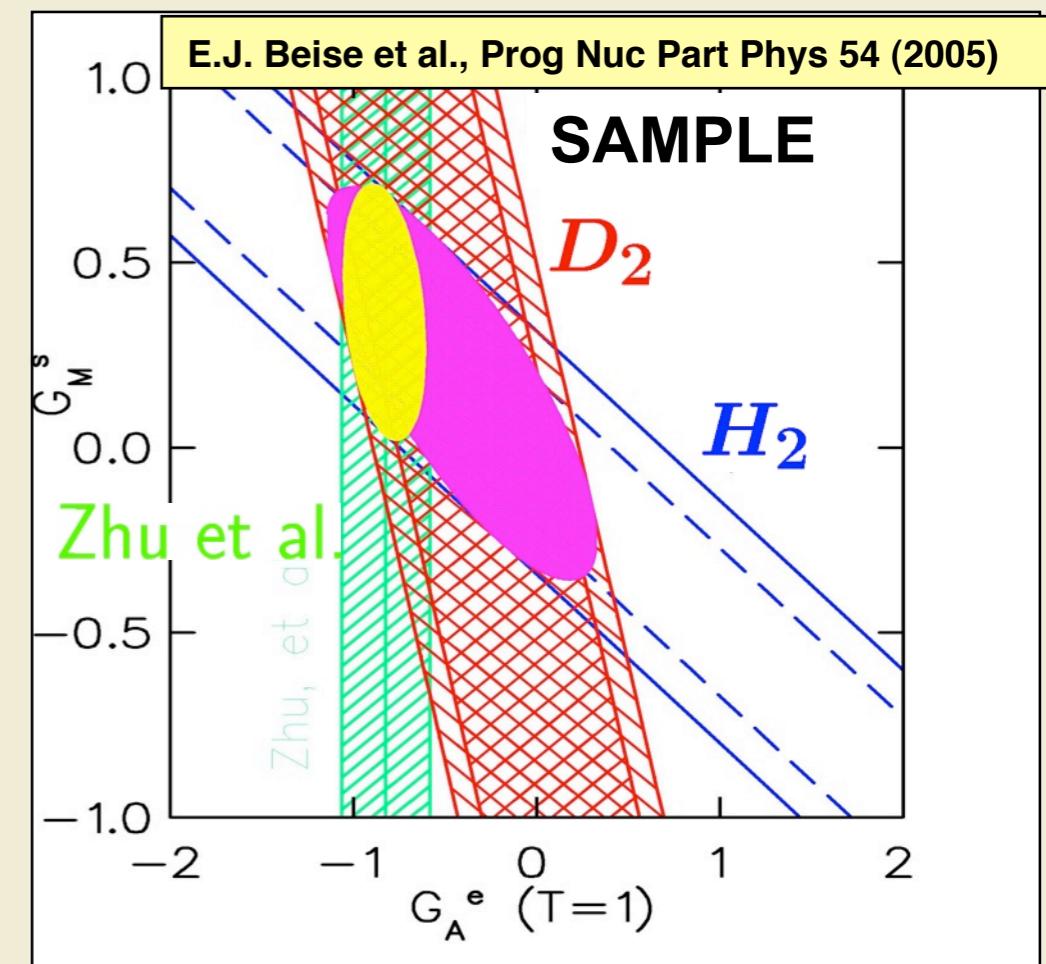
Phototube and readout non-linearity bounded at the 0.5% level

Form Factor Separation



G0 Backward Scattering, PRL 104, 012001 (2010)

QCD lattice
suggests
very small
effects



QCD models

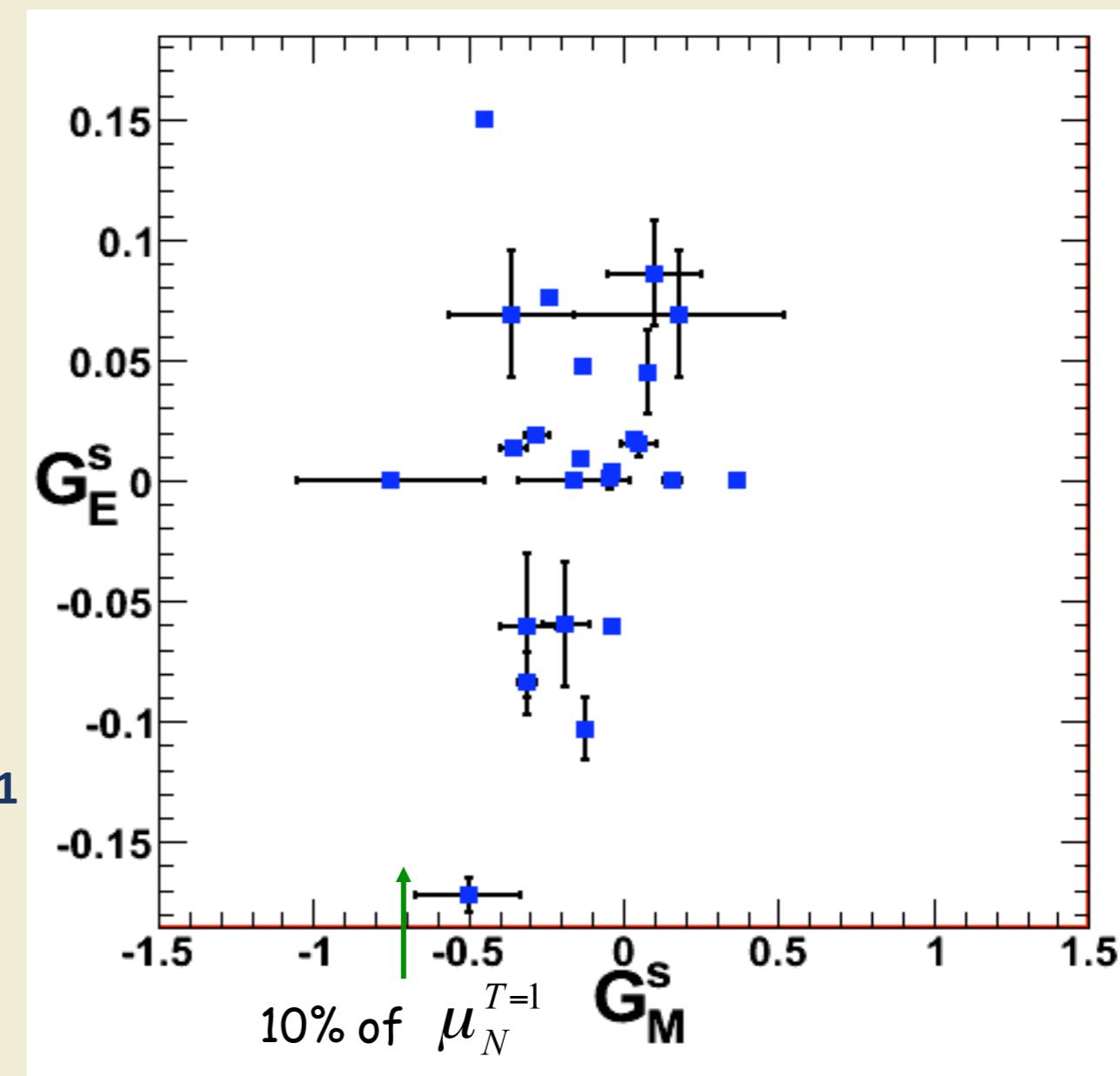
Model guidance is unclear:

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



The Axial Term and the Anapole Moment

Axial form-factors G_A^p, G_A^n

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

- 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

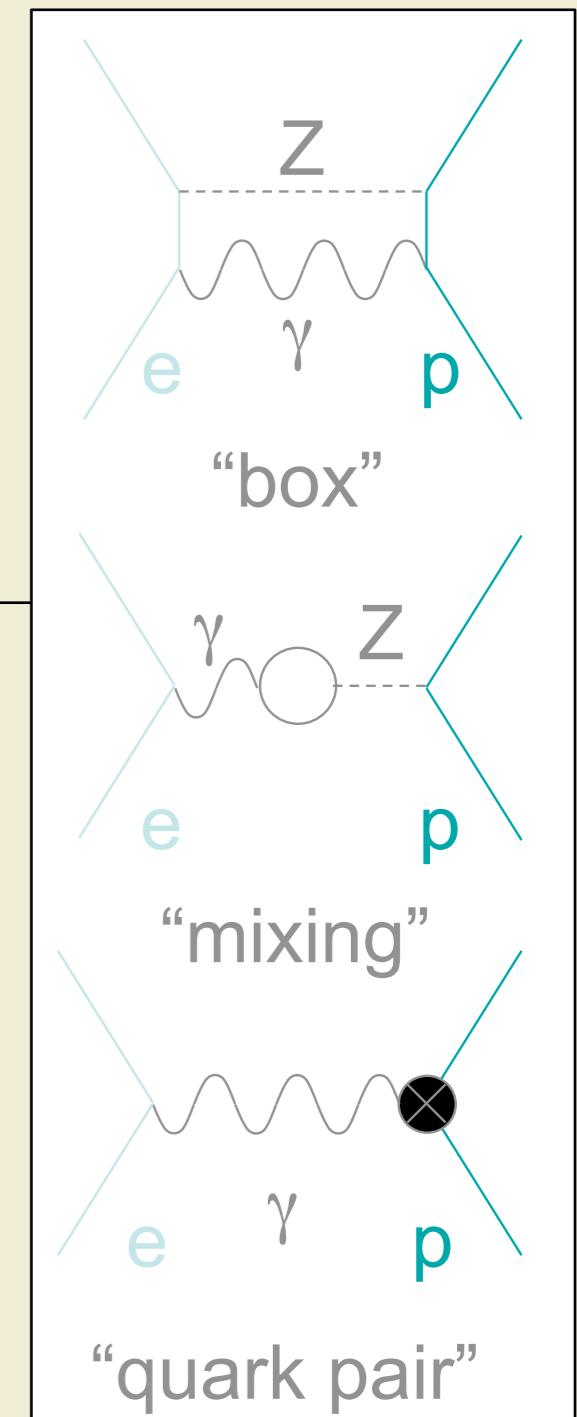
Anapole Moment Correction:

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

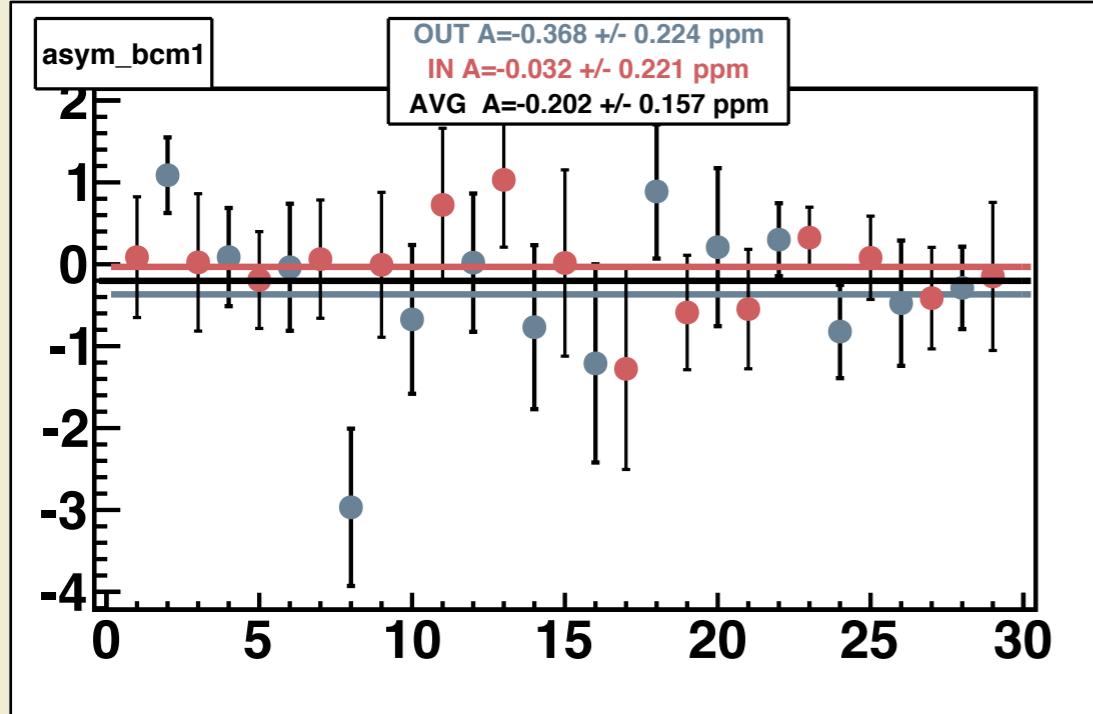
Zhu, Puglia, Holstein, Ramsey-Musolf, Phys. Rev. D **62**, 033008

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

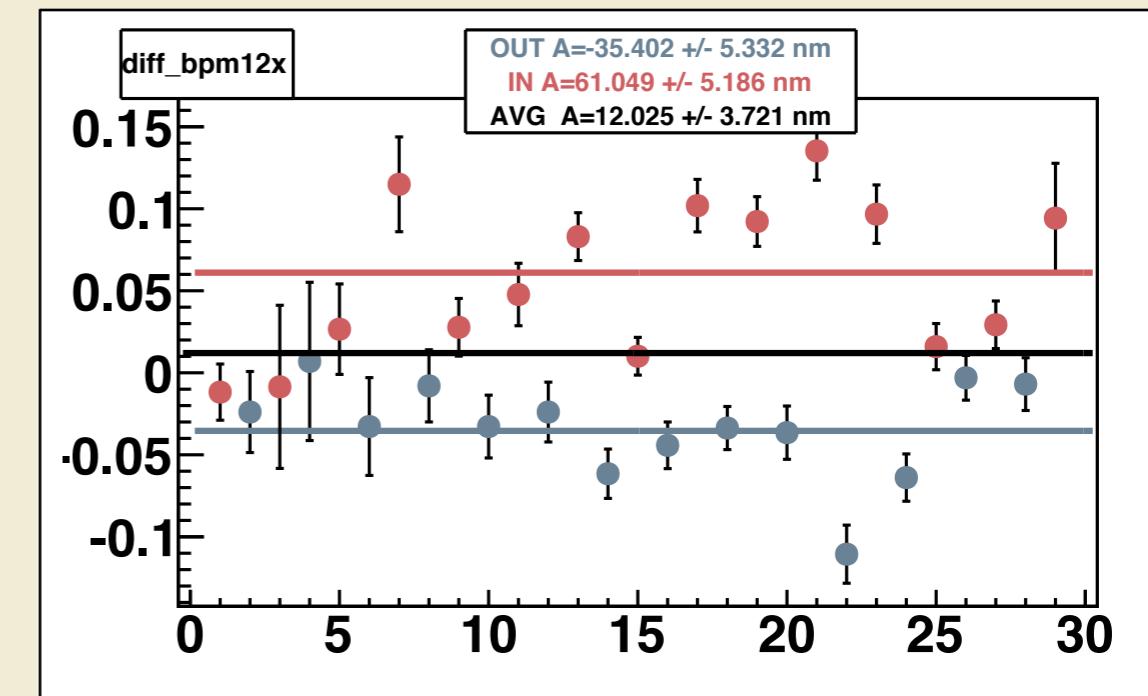
Difficult to achieve tight experimental constraint



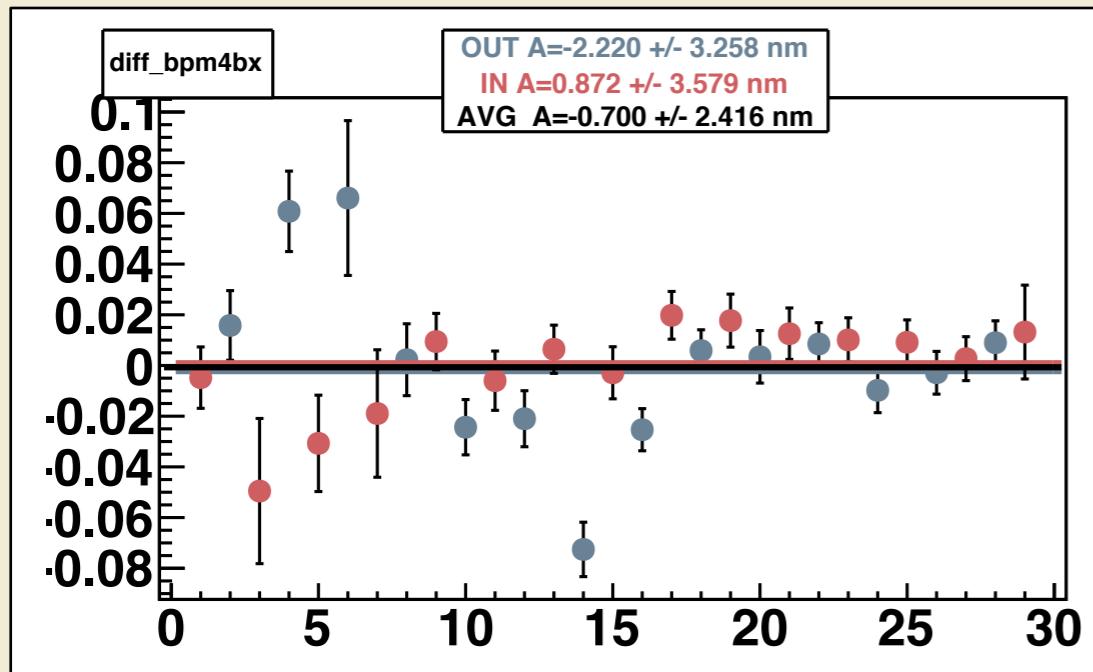
Beam Asymmetries



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



Implies energy asymmetry at 3 ppb

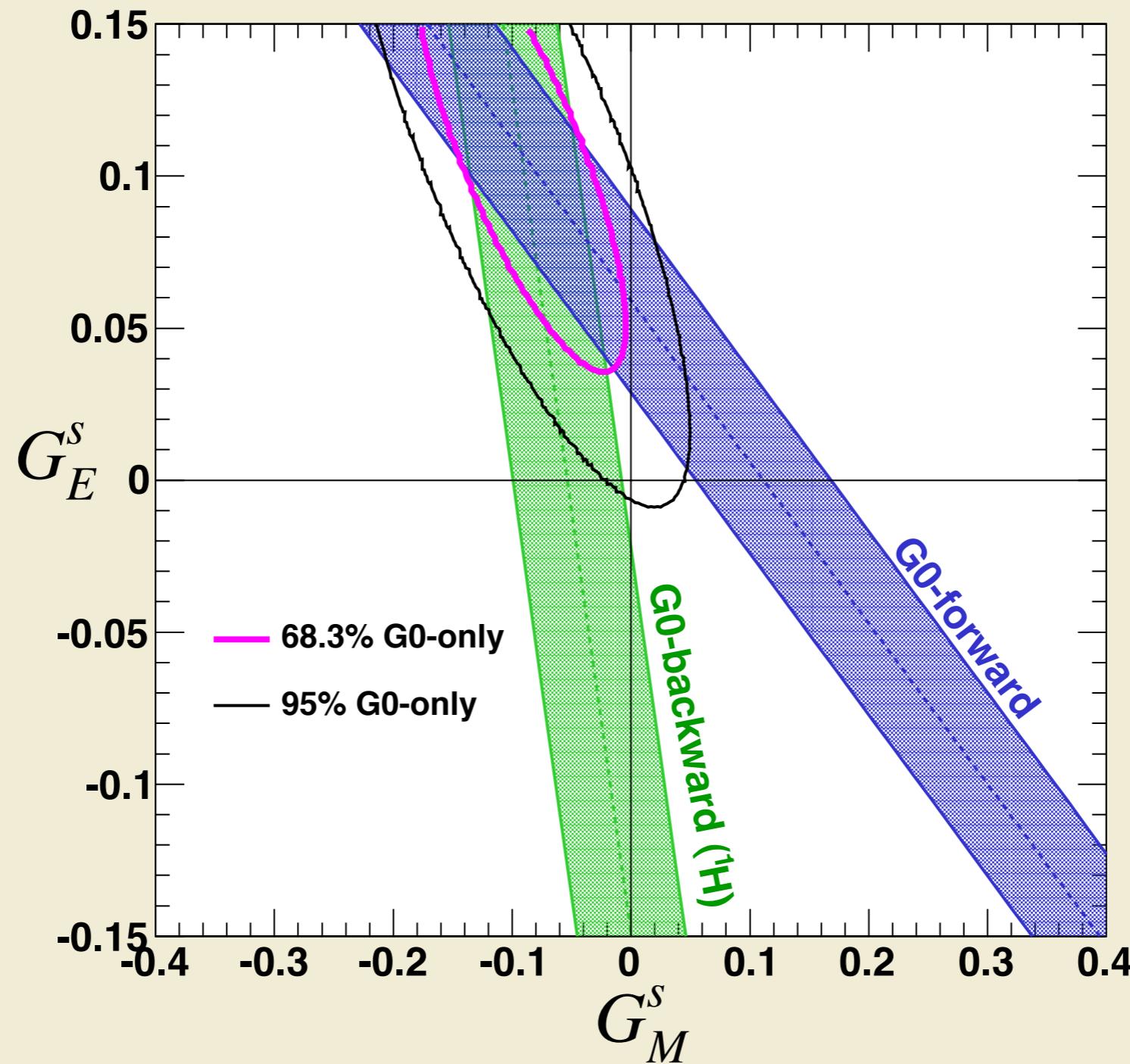


Individual detector response measured
to be at the level of 5 ppb/nm

Total Correction: -0.010 ppm (0.05%)

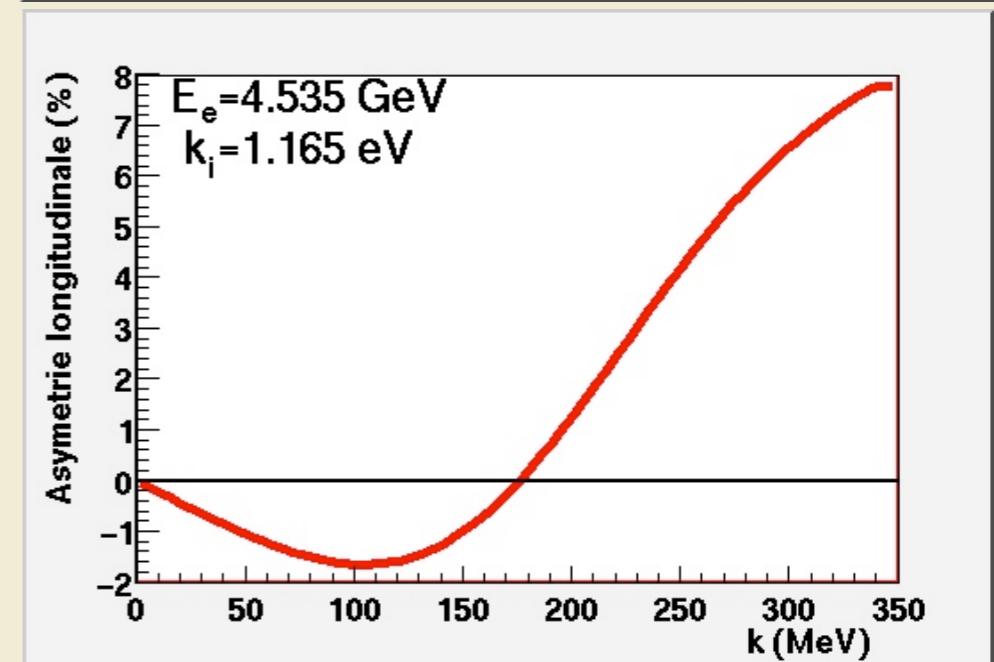
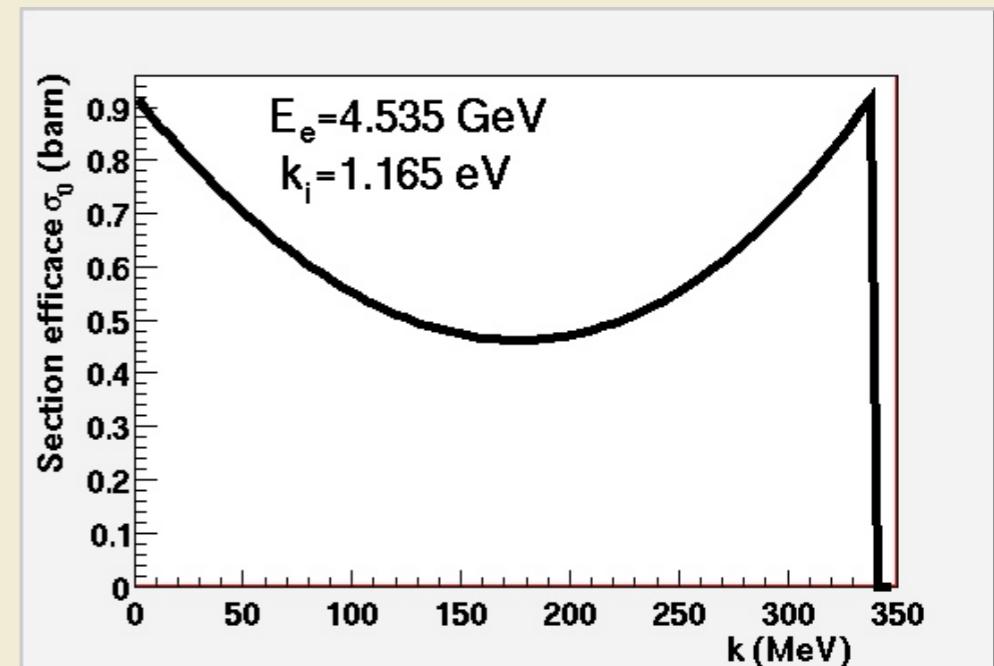
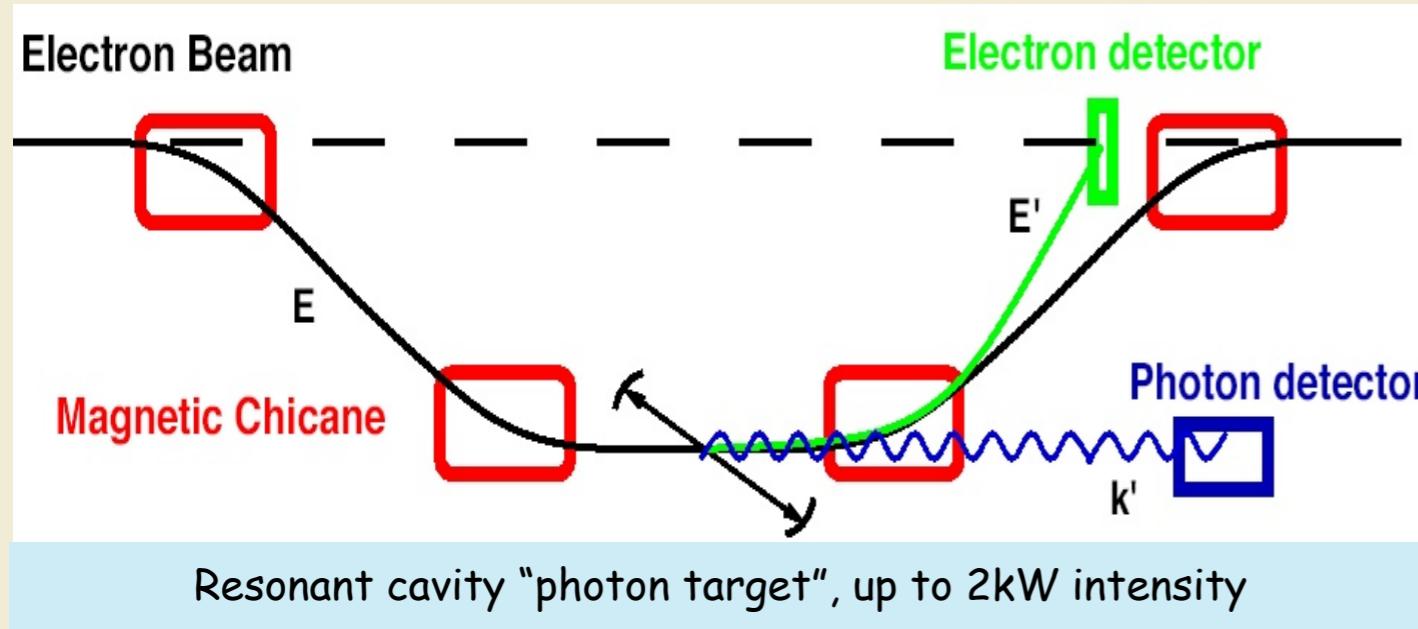
Trajectory at target averages to <3nm,<0.5nrad

$Q^2 = 0.62 \text{ GeV}^2$ in combination



Zhu constraint is used
for axial form-factor

Hall A Compton Polarimeter



$$A_{\text{exp}} = \frac{n^+ - n^-}{n^+ + n^-} = P_\gamma \times P_e \times \langle A_{\text{th}} \rangle$$

Calibration of the analyzing power
is usually the leading uncertainty

measure asymmetry independently in:

- momentum analyzed electrons
- photons in calorimeter

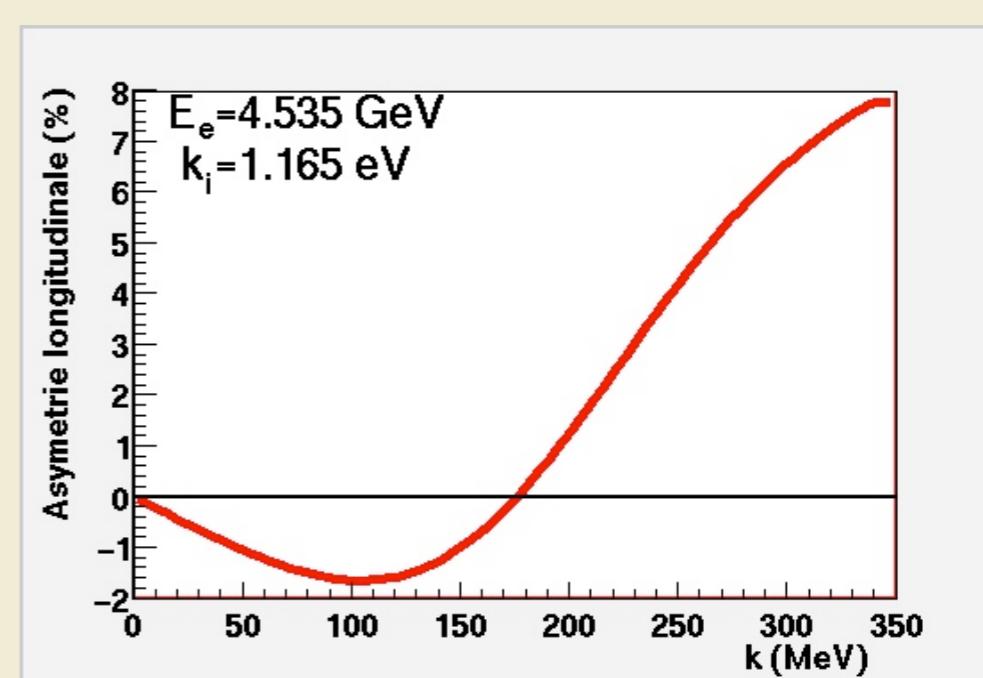
Electron detector achieved 1% accuracy for HAPPEX-2,
but system was broken for HAPPEX-3

Integrating Photon Analysis

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

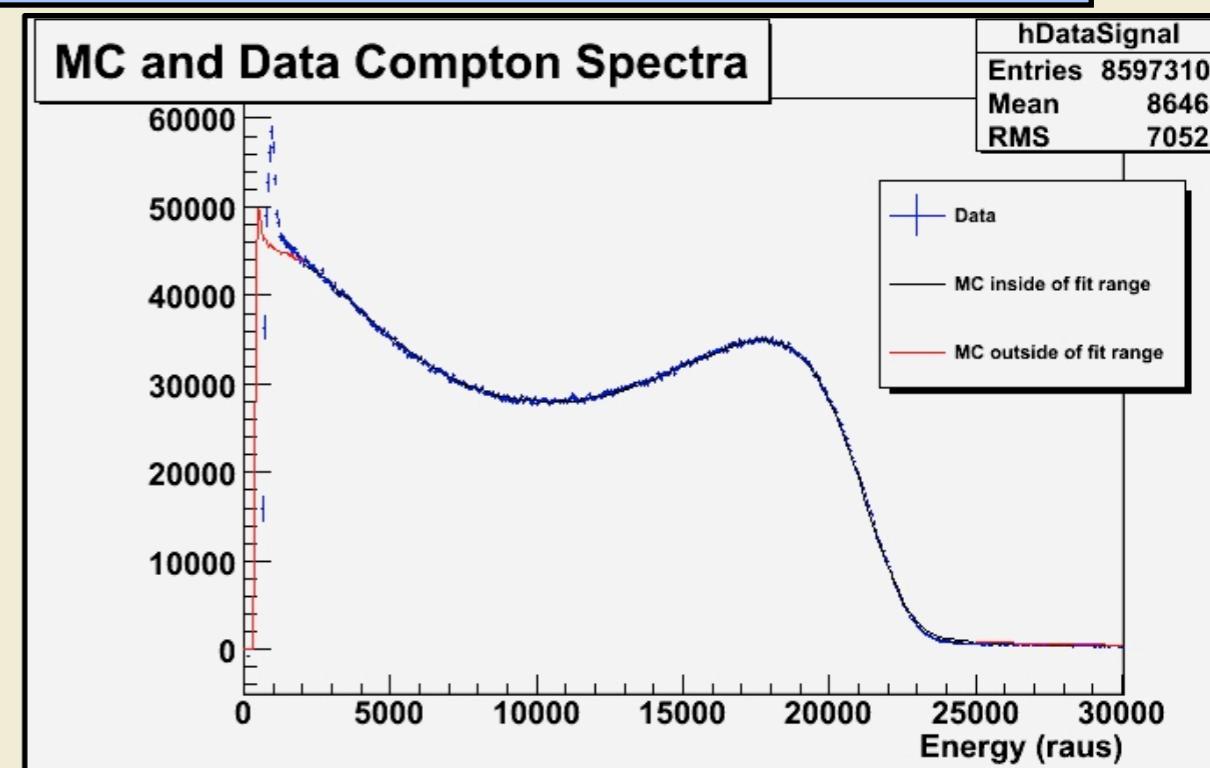
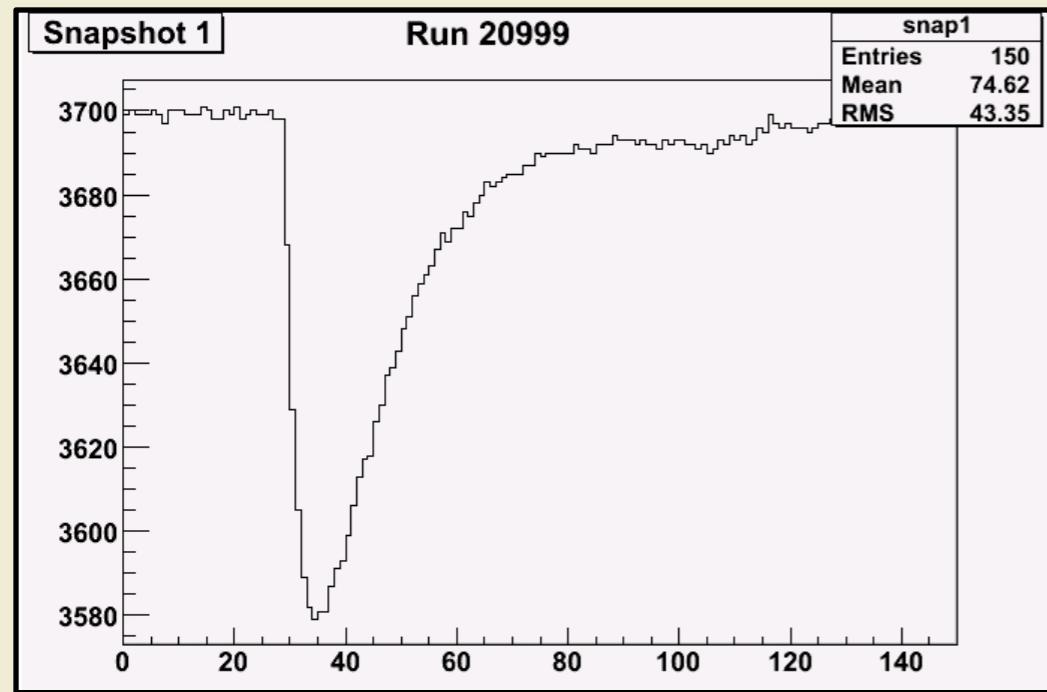
Photon self-triggered analysis has been limited in
accuracy, and required electron coincidence
measurements for calibration

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

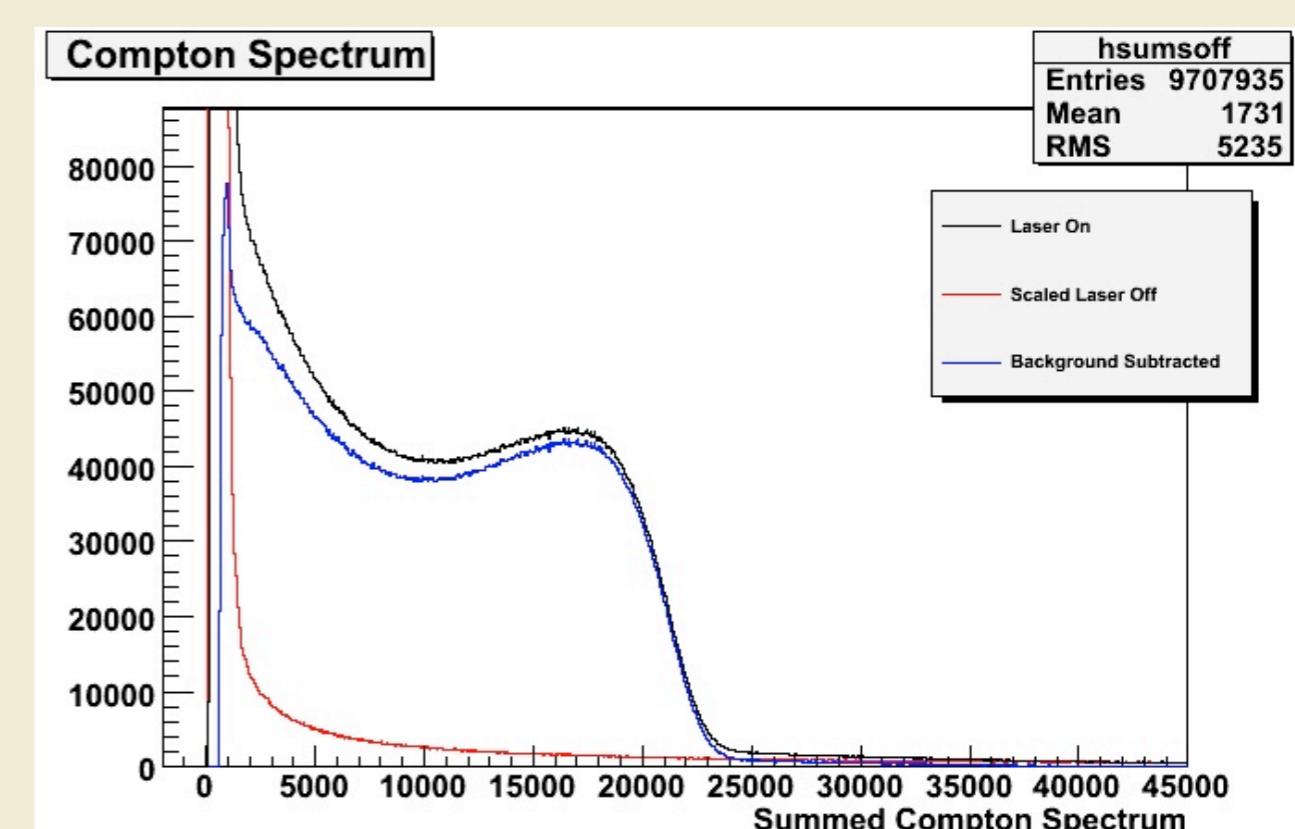
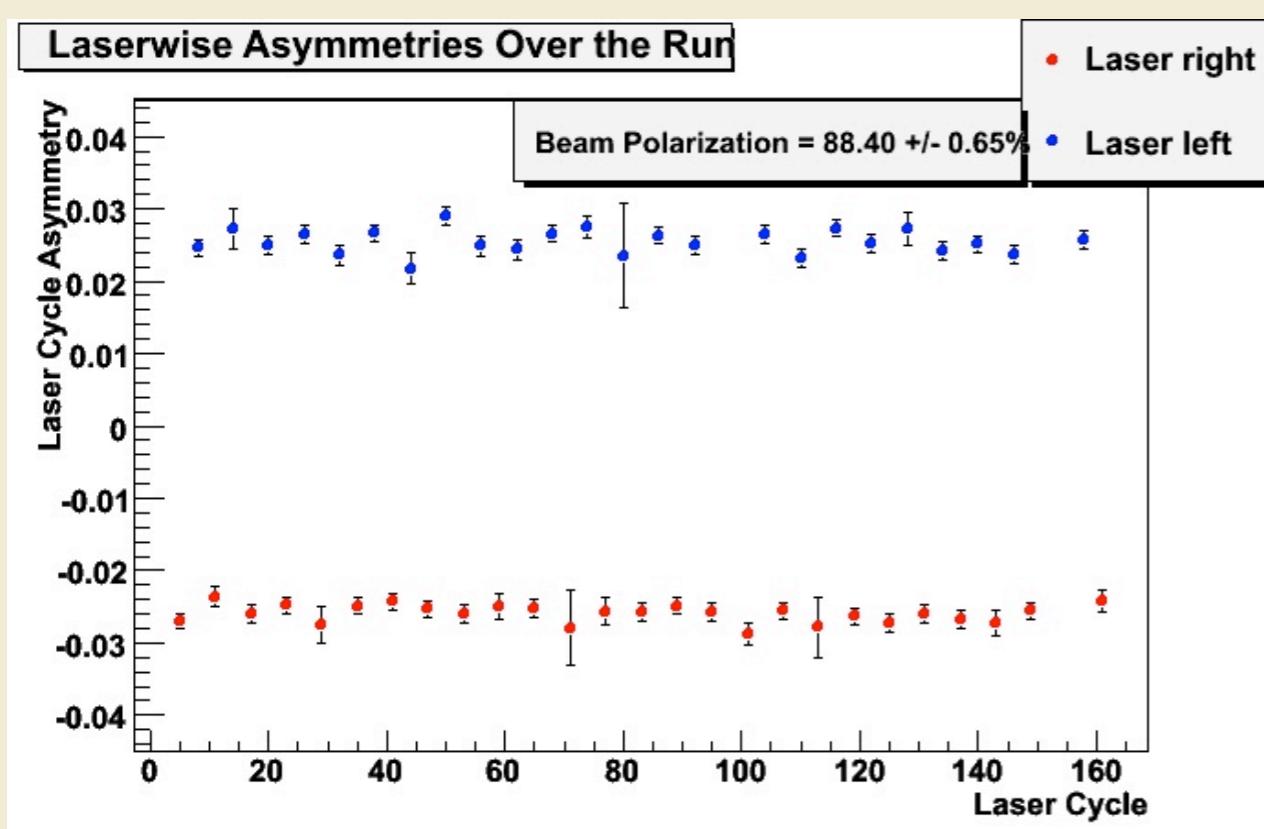
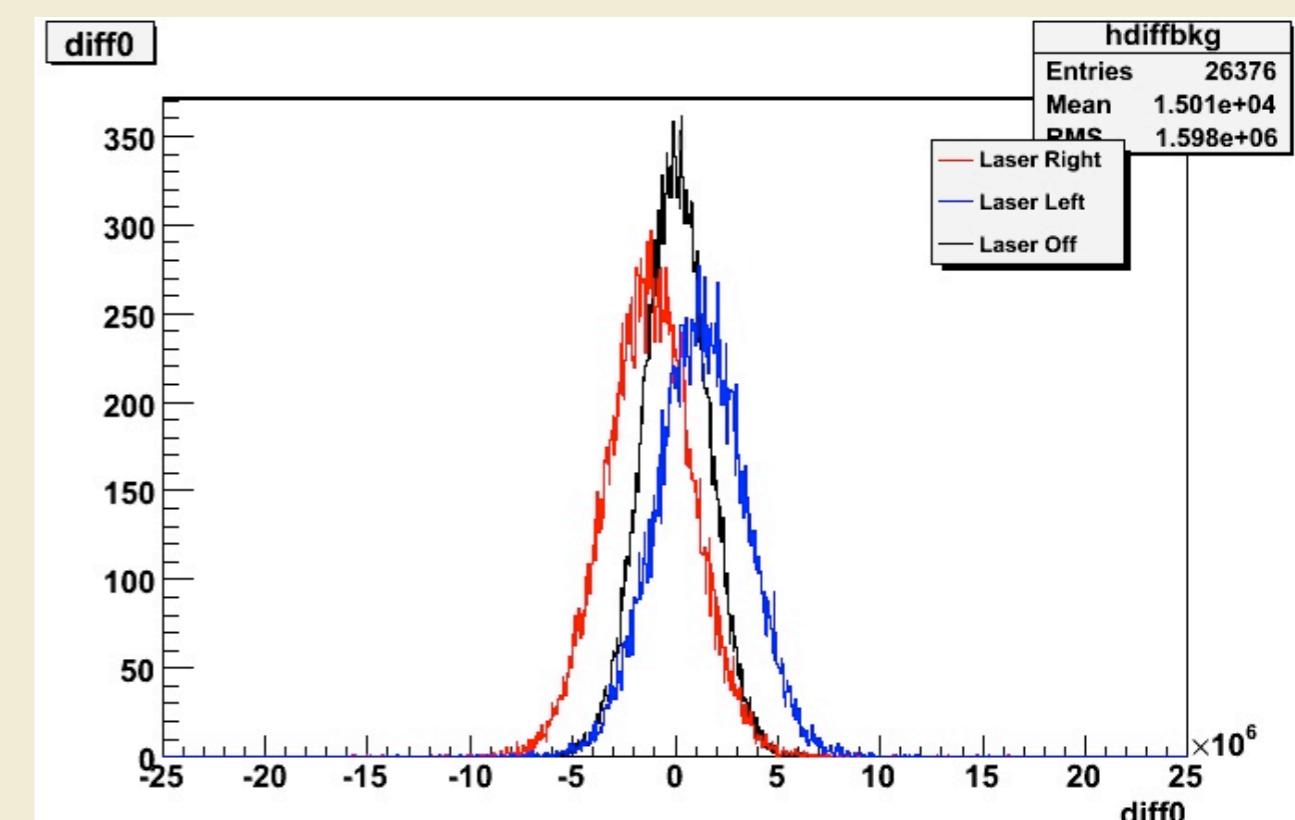
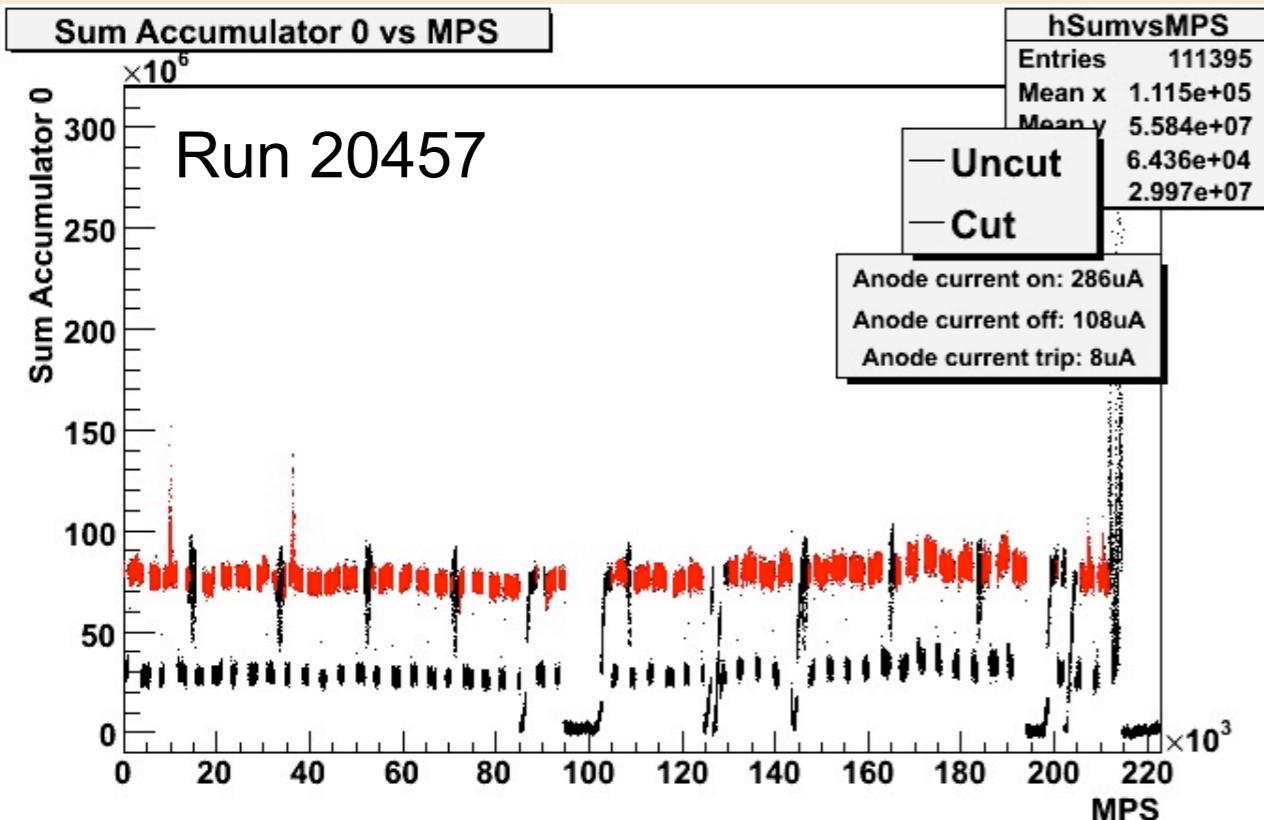


New DAQ, with SIS 2230 Flash ADC read out in two modes

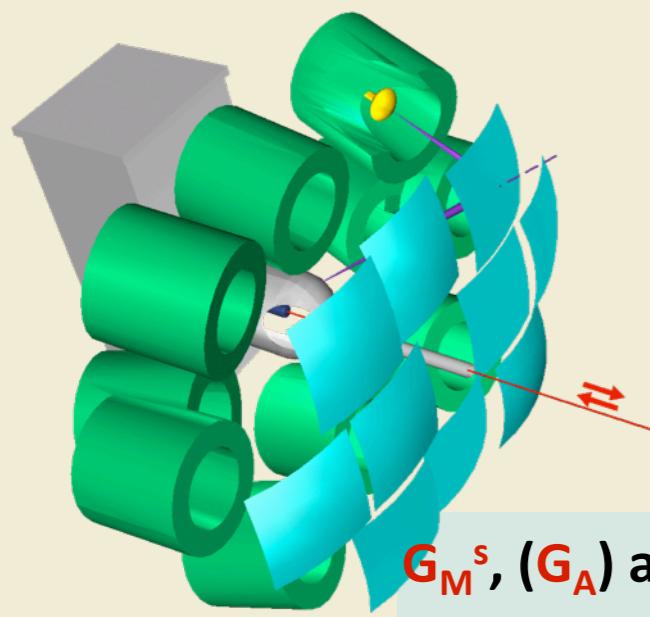
Triggered mode: triggered “snap shot” of fixed time interval (for calibration)



Integrating Analysis, online plots



Experimental Overview



SAMPLE

open geometry,
integrating

$G_M^s, (G_A)$ at $Q^2 = 0.1 \text{ GeV}^2$

HAPPEX

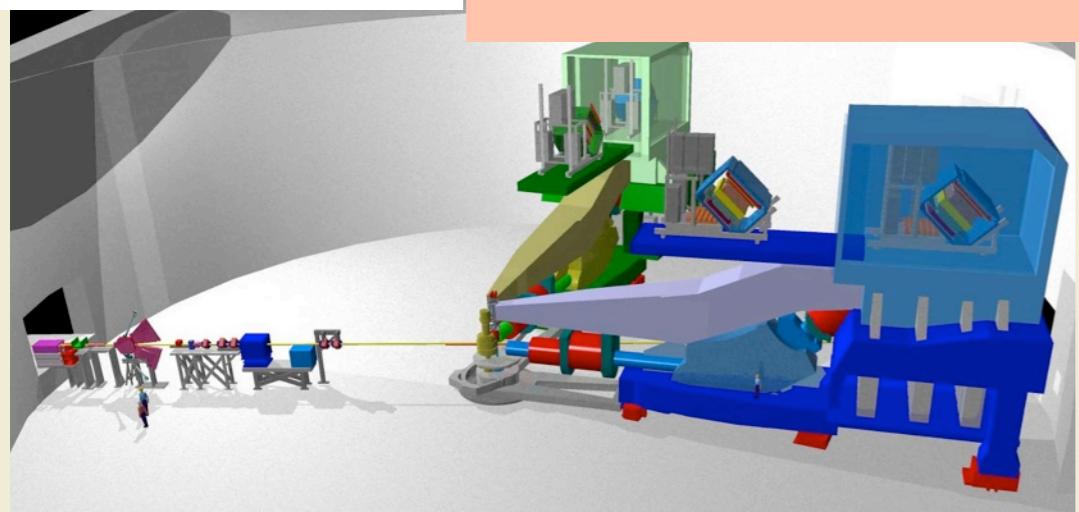
Precision
spectrometer,
integrating

$G_E^s + 0.39 G_M^s$ at $Q^2 = 0.48 \text{ GeV}^2$

$G_E^s + 0.08 G_M^s$ at $Q^2 = 0.1 \text{ GeV}^2$

G_E^s at $Q^2 = 0.1 \text{ GeV}^2$ (${}^4\text{He}$)

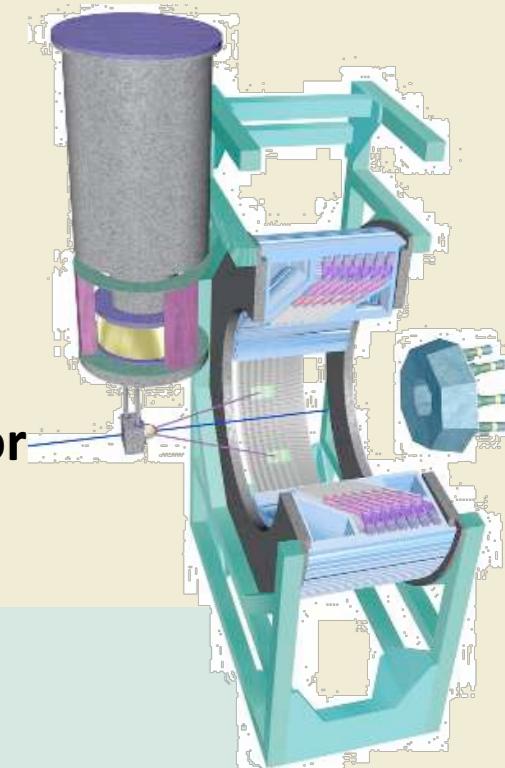
$G_E^s + 0.48 G_M^s$ at $Q^2 = 0.62 \text{ GeV}^2$



A4

Open geometry

Fast counting calorimeter for
background rejection



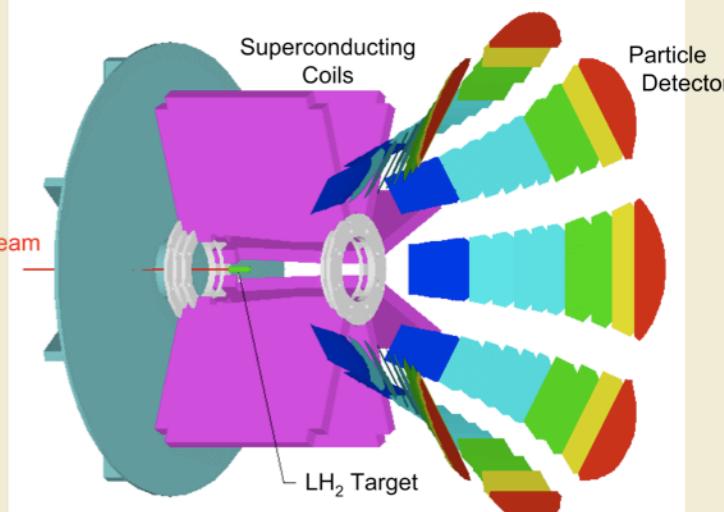
$G_E^s + 0.23 G_M^s$ at $Q^2 = 0.23 \text{ GeV}^2$

$G_E^s + 0.10 G_M^s$ at $Q^2 = 0.1 \text{ GeV}^2$

G_M^s, G_A^e at $Q^2 = 0.23 \text{ GeV}^2$

G0

Open geometry



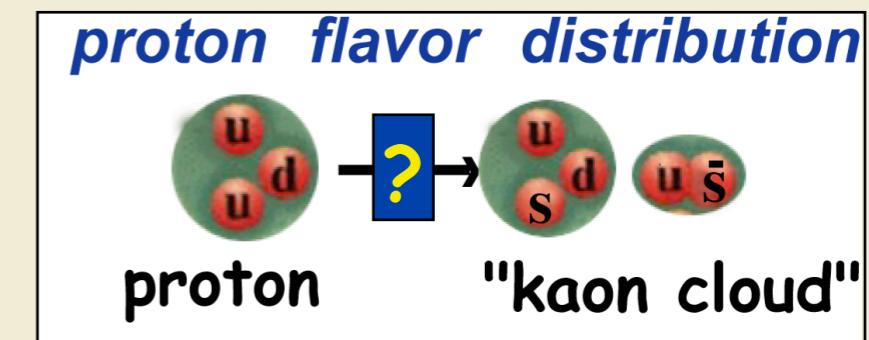
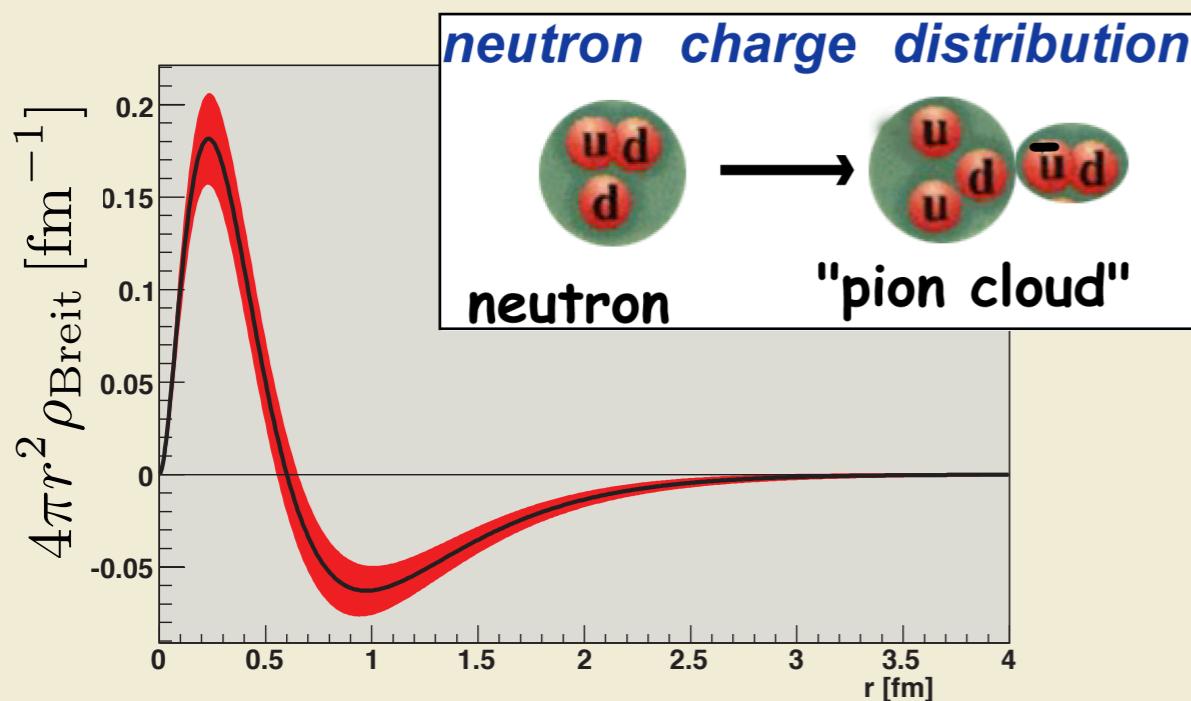
Fast counting with magnetic spectrometer + TOF
for background rejection

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

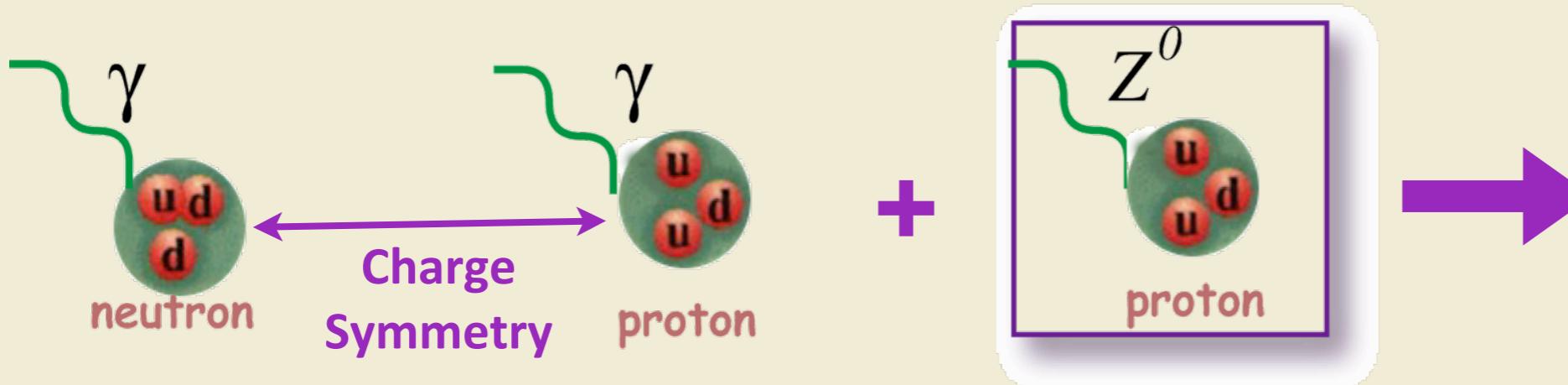
G_M^s, G_A^e at $Q^2 = 0.23, 0.62 \text{ GeV}^2$

The Neutral Current and Nucleon Vector Form Factors

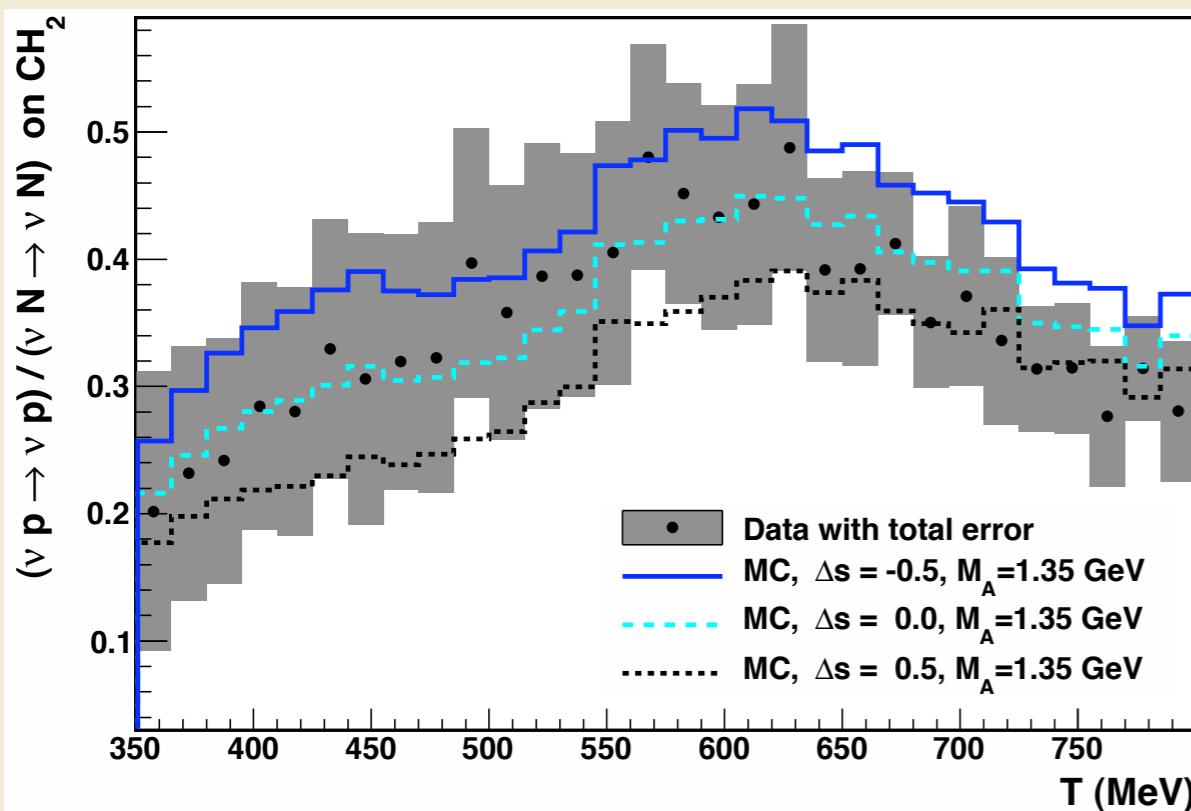
Strange quarks exist in the nucleon at short distance scales.
Do they play a role in elastic proton scattering?



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



Strange Quarks in Elastic Scattering



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

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

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

