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

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University of Virginia

HAPPEX Collaboration

PAVI ’11
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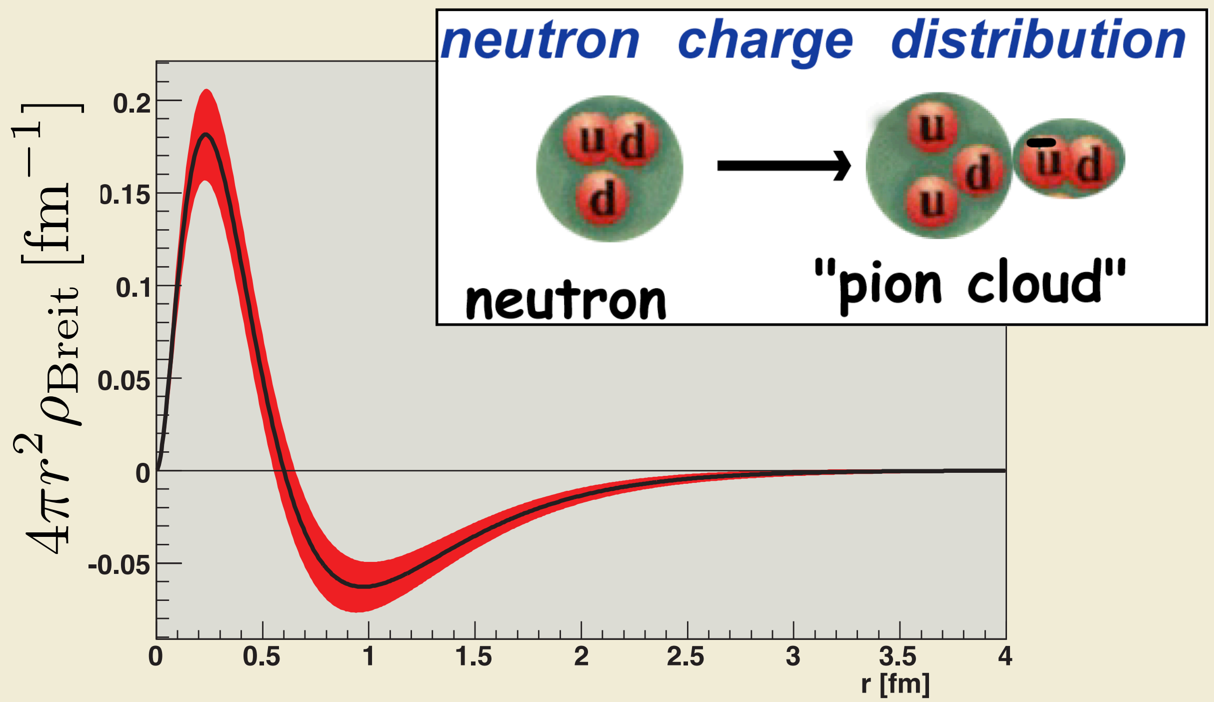
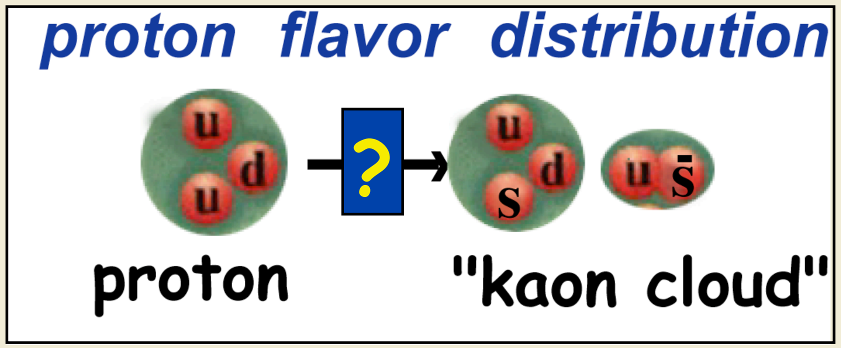
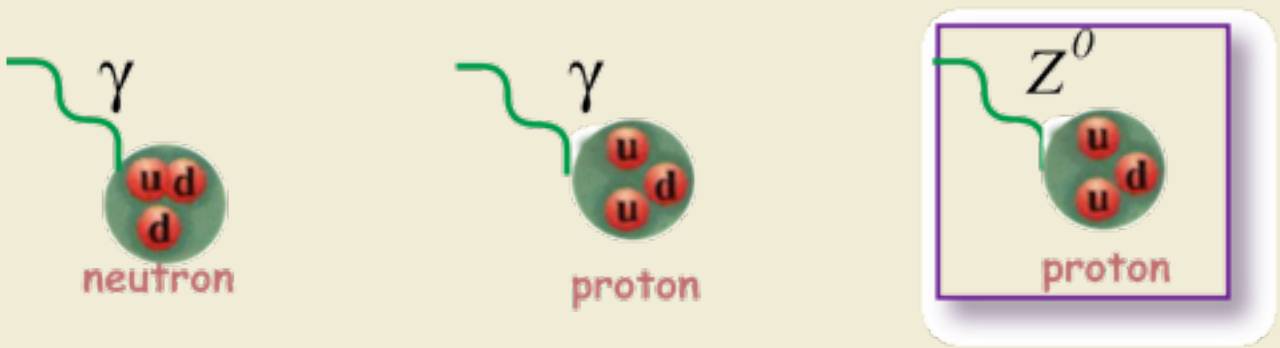
Strange Quarks in Elastic Scattering

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





Measure the neutral weak proton form-factor



Three equations and three unknowns

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

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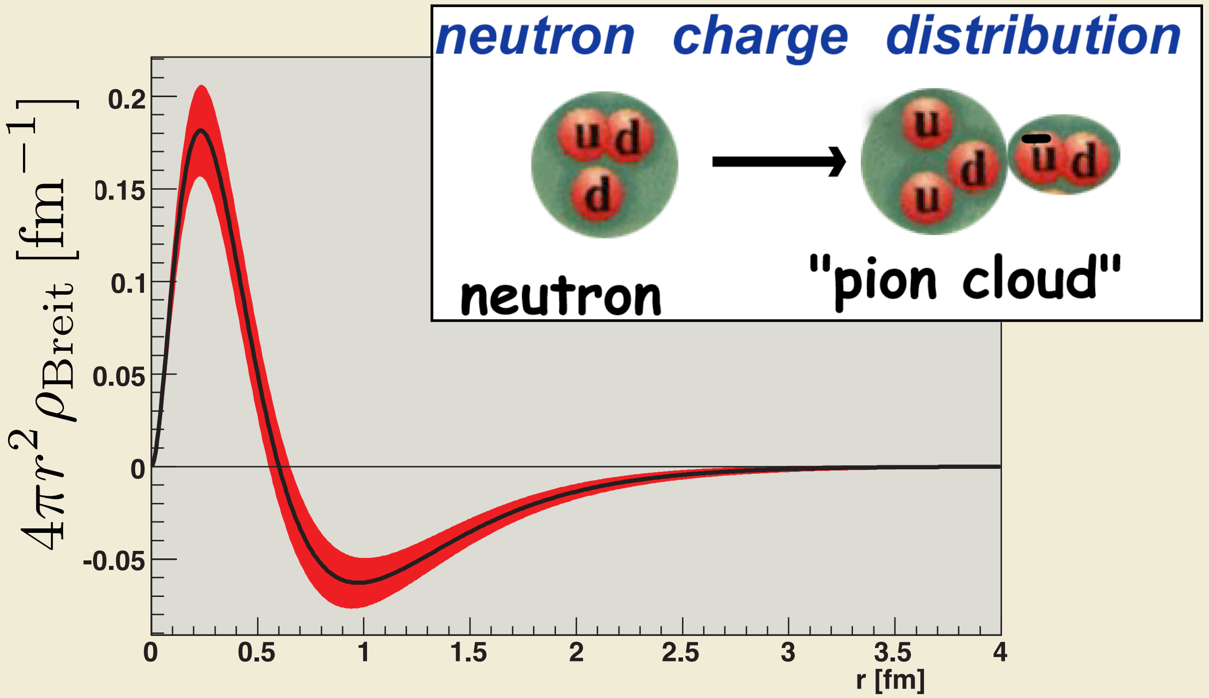

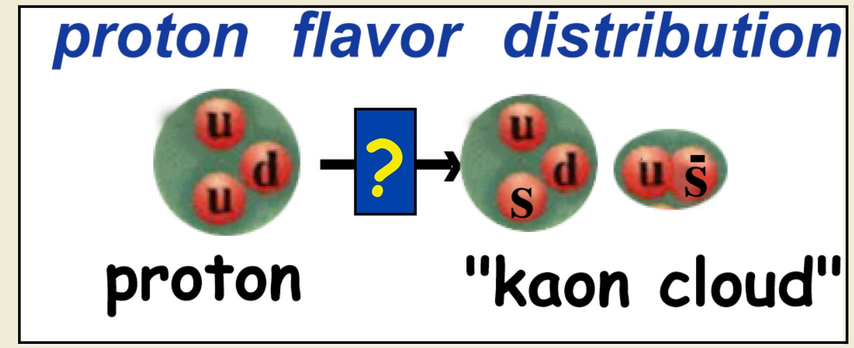

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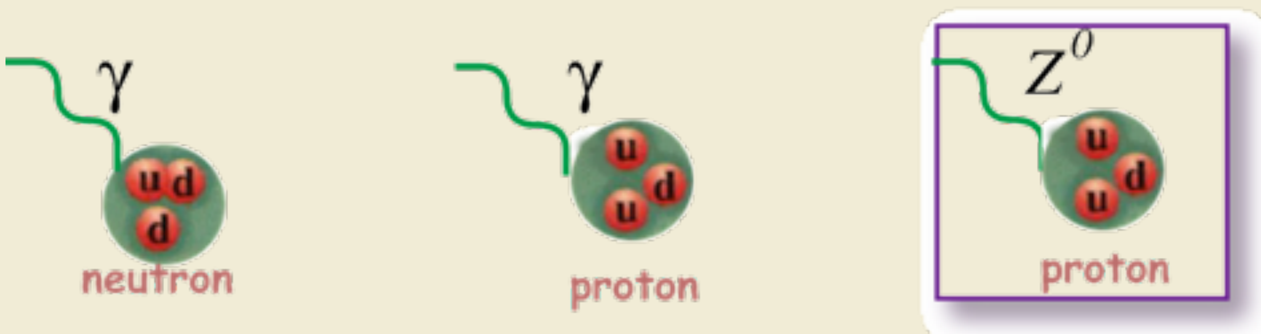

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$$G_E^p = \frac{2}{3} G_E^{u,p} - \frac{1}{3} G_E^{d,p} - \frac{1}{3} G_E^s$$

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

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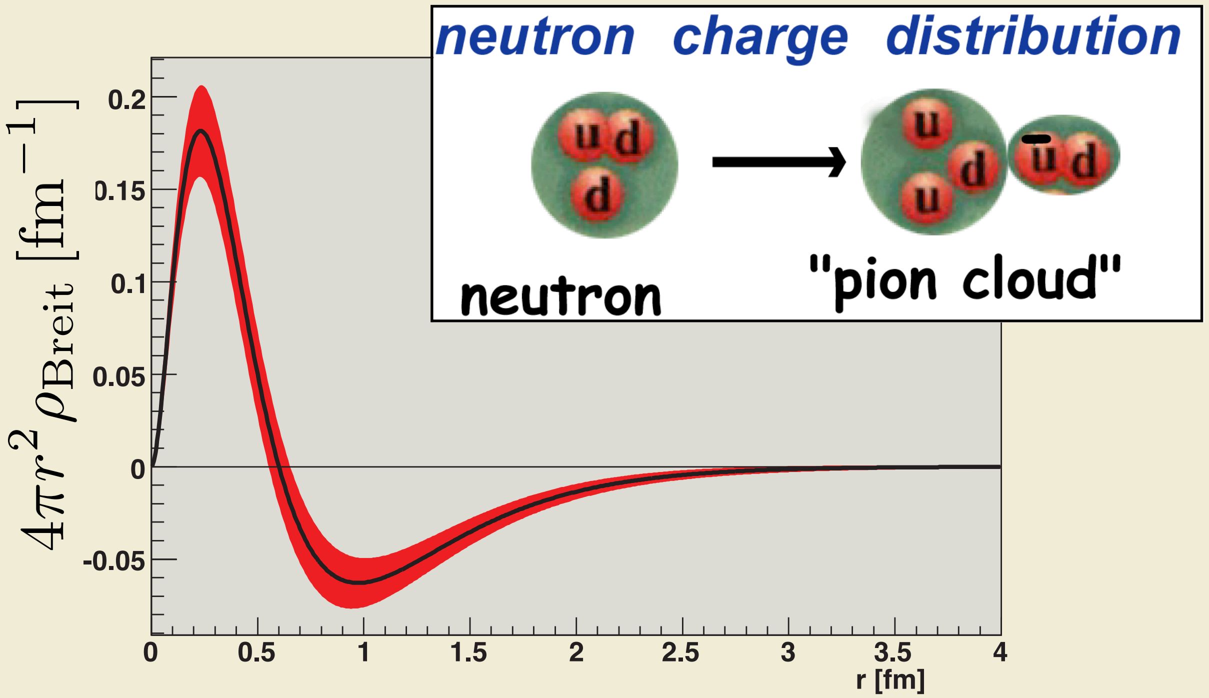

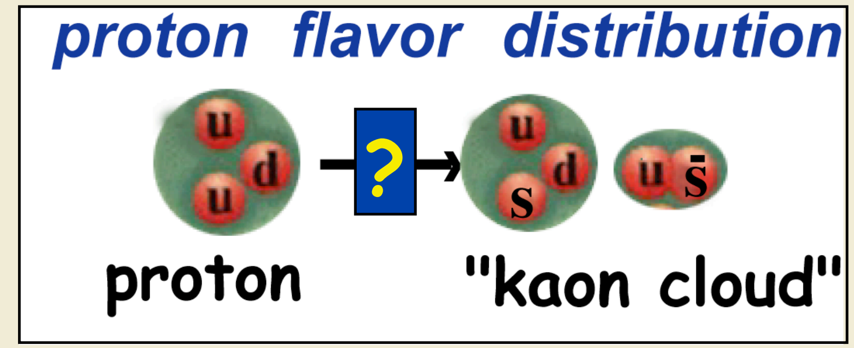

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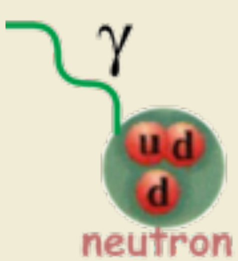

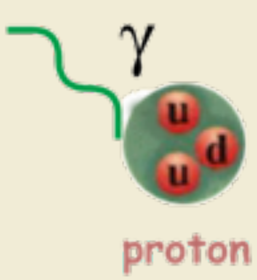

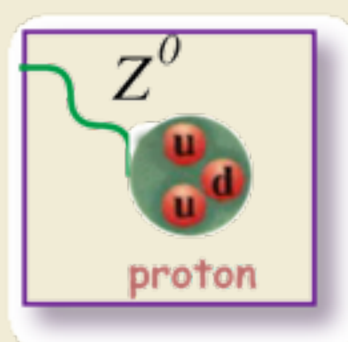

Three equations and three unknowns

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Charge Symmetry

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

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

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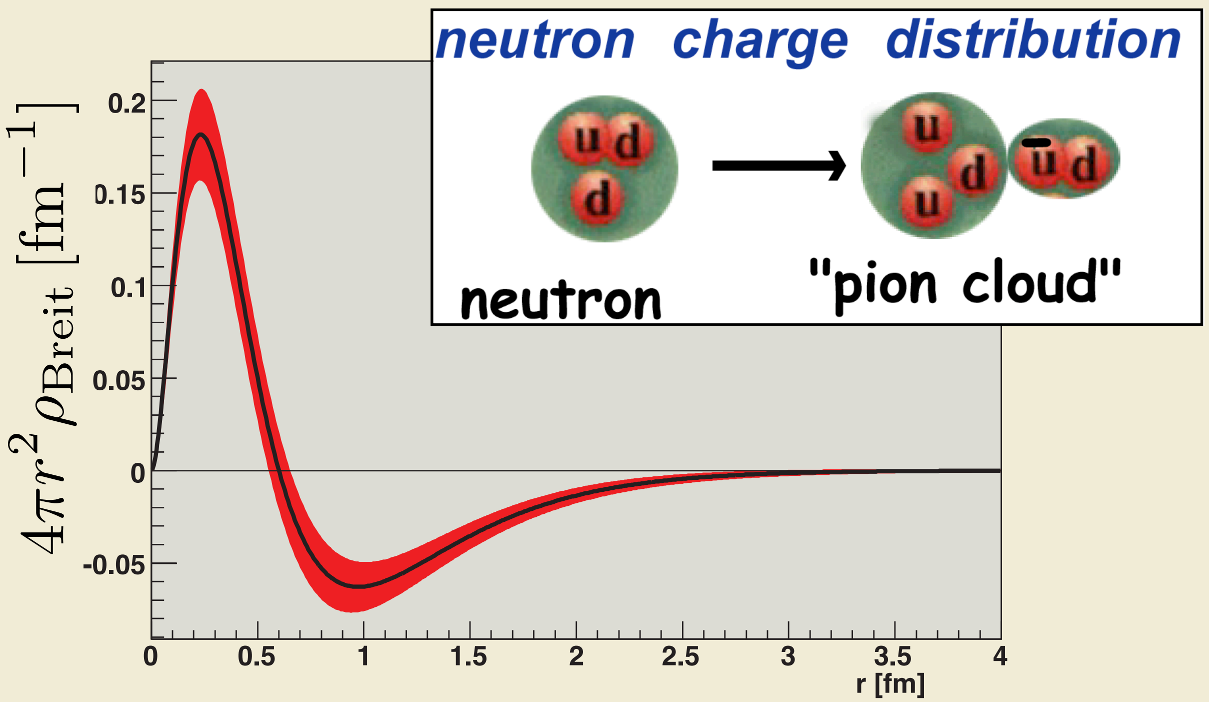

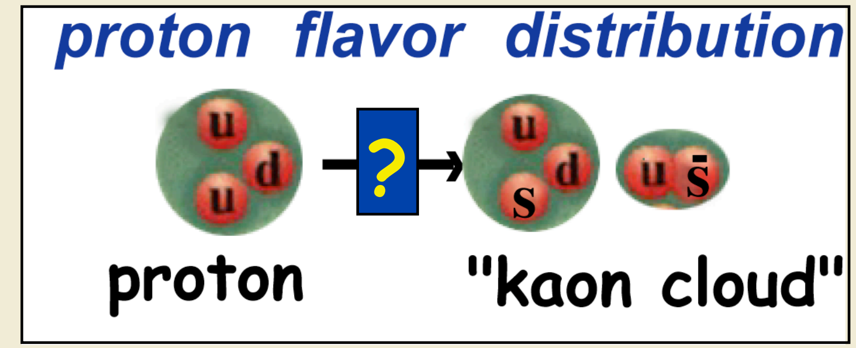

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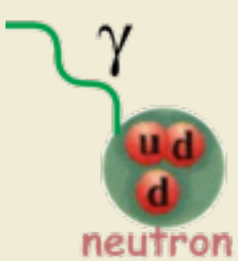

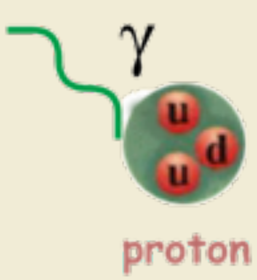

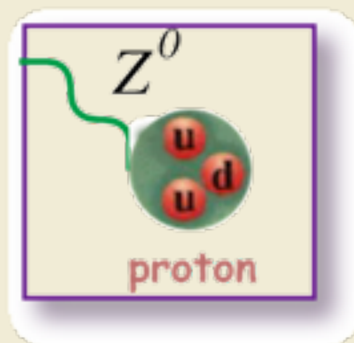

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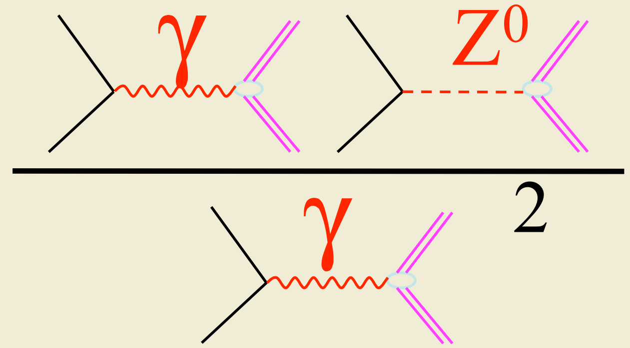
$$G_E^p = \frac{2}{3}G_E^u - \frac{1}{3}G_E^d - \frac{1}{3}G_E^s$$

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

The weak form factor is accessible via parity violation

Measuring Strange Vector Form Factors

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



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

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

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

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

Deuterium: **Enhanced G_A**

The Axial Term and the Anapole Moment

Anapole Moment Correction:

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

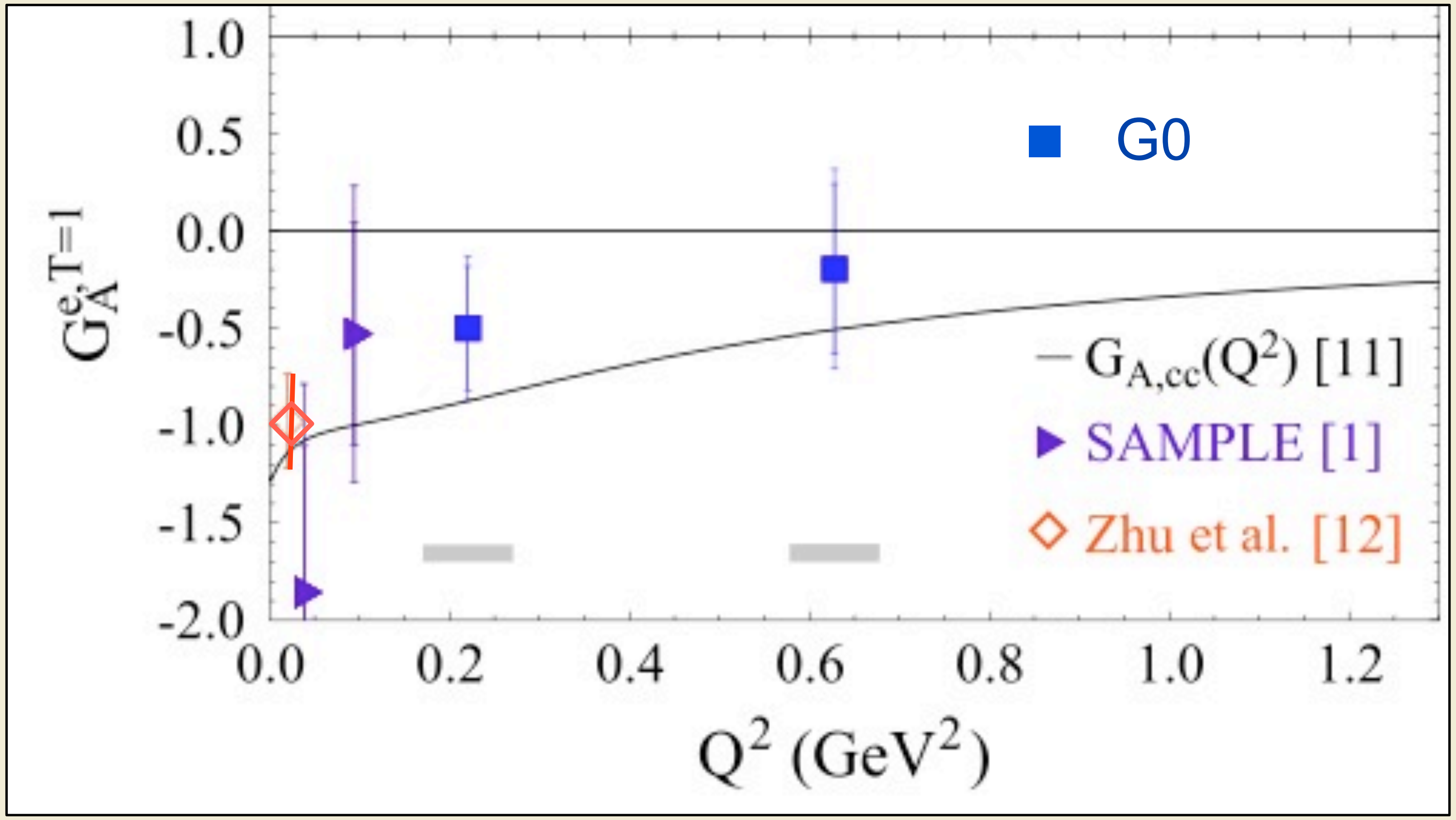
$$\tilde{G}_A^{p,n} = -\tau_3\left(1+R_A^{T=1}\right)G_A^{(3)} + \sqrt{3}R_A^{T=0}G_A^{(8)} + \Delta s$$

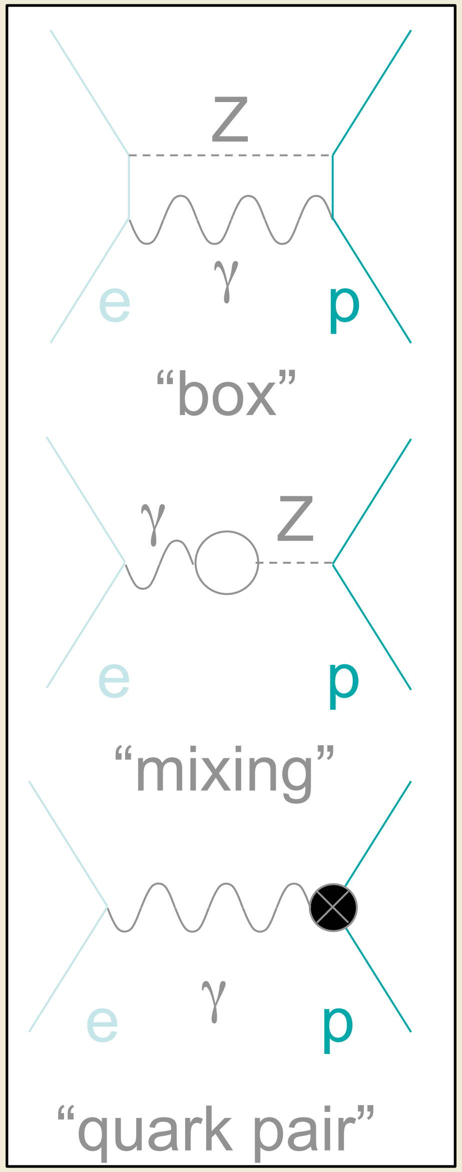
Zhu, Puglia, Holstein, Ramsey-Musolf, Phys. Rev. D **62**, 033008

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

Difficult to achieve tight experimental constraint

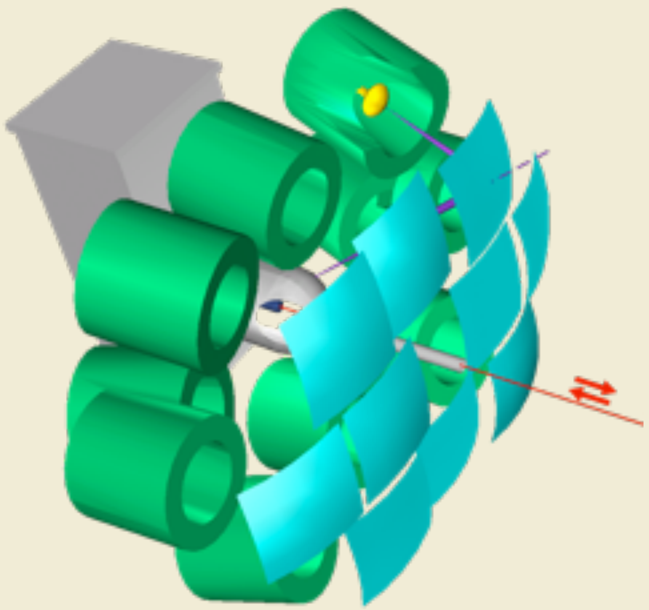
Reduced in importance for forward-angle measurements





- Using experimental determination for axial form factor would increase total FF uncertainty about 70%

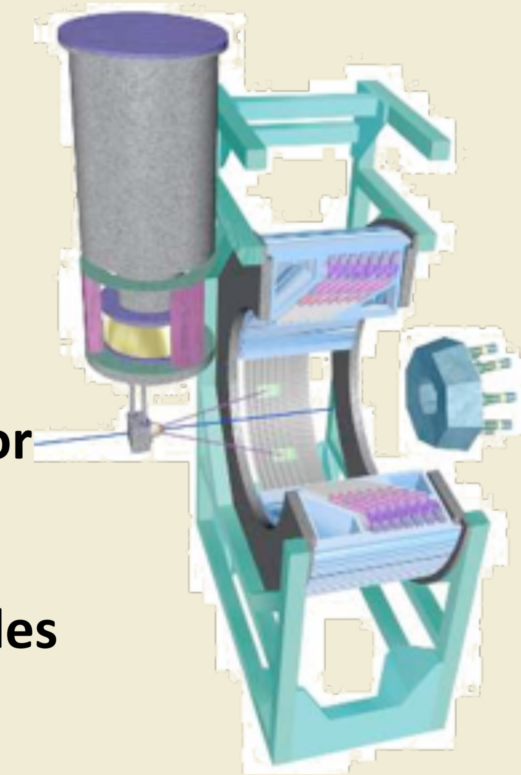
Experimental Overview



SAMPLE

open geometry,
integrating,
back-angle only

A4



Open geometry

Fast counting calorimeter for background rejection

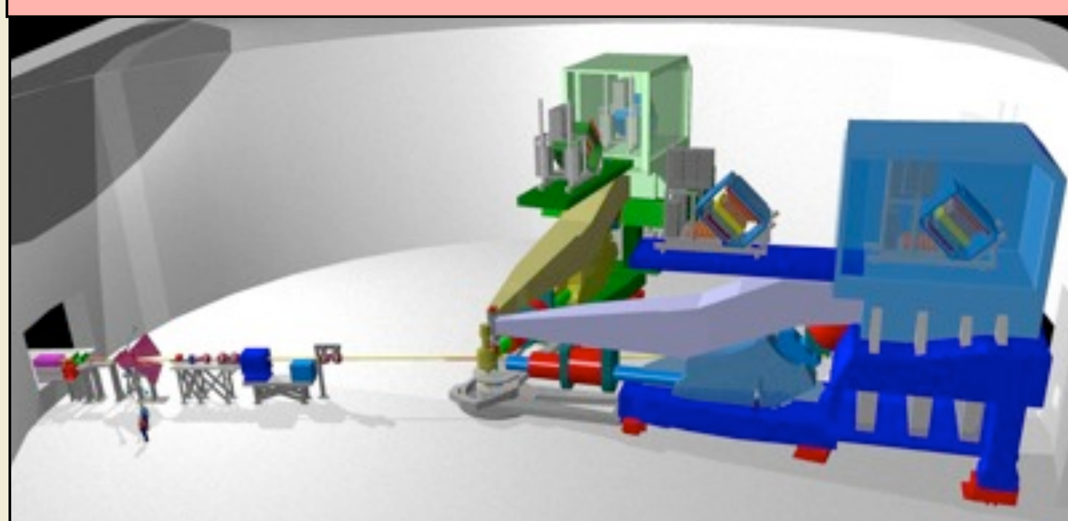
Forward and Backward angles

HAPPEX

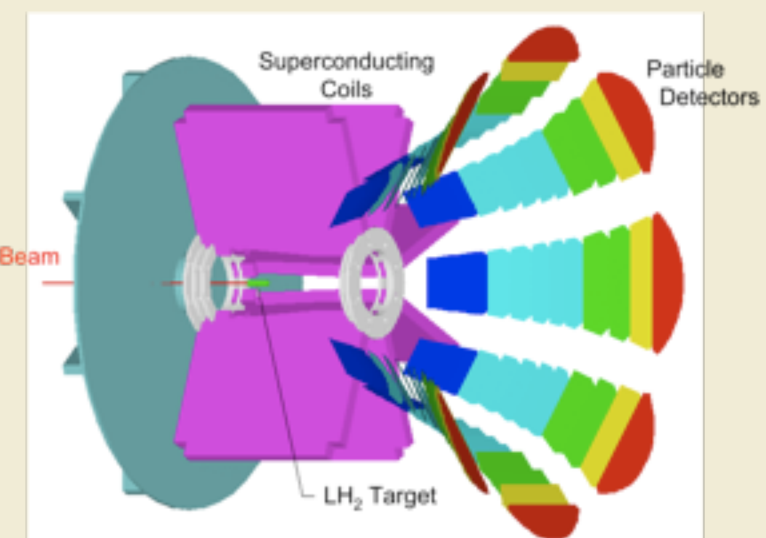
Precision spectrometer, integrating

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

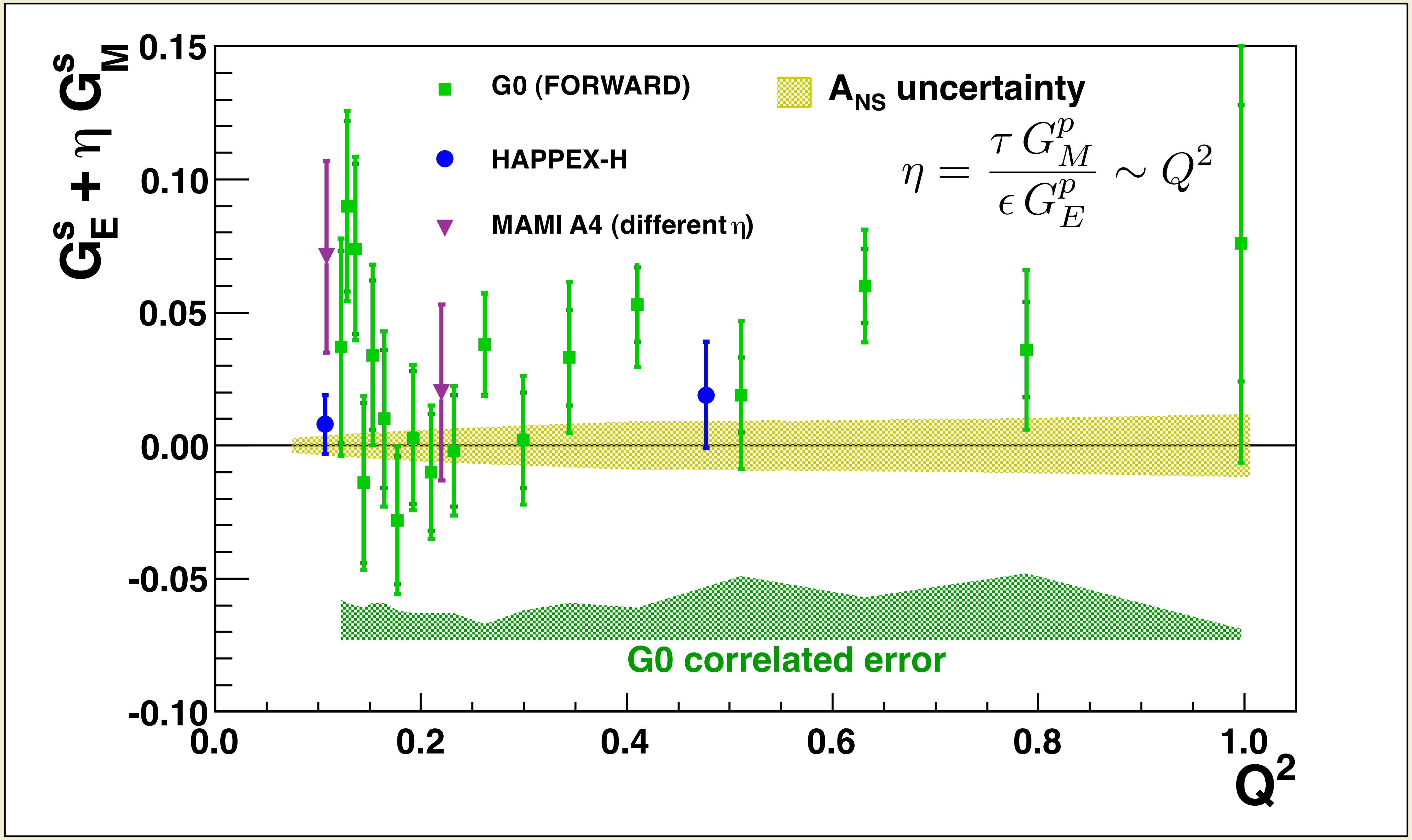


Open geometry

Fast counting with magnetic spectrometer + TOF for background rejection

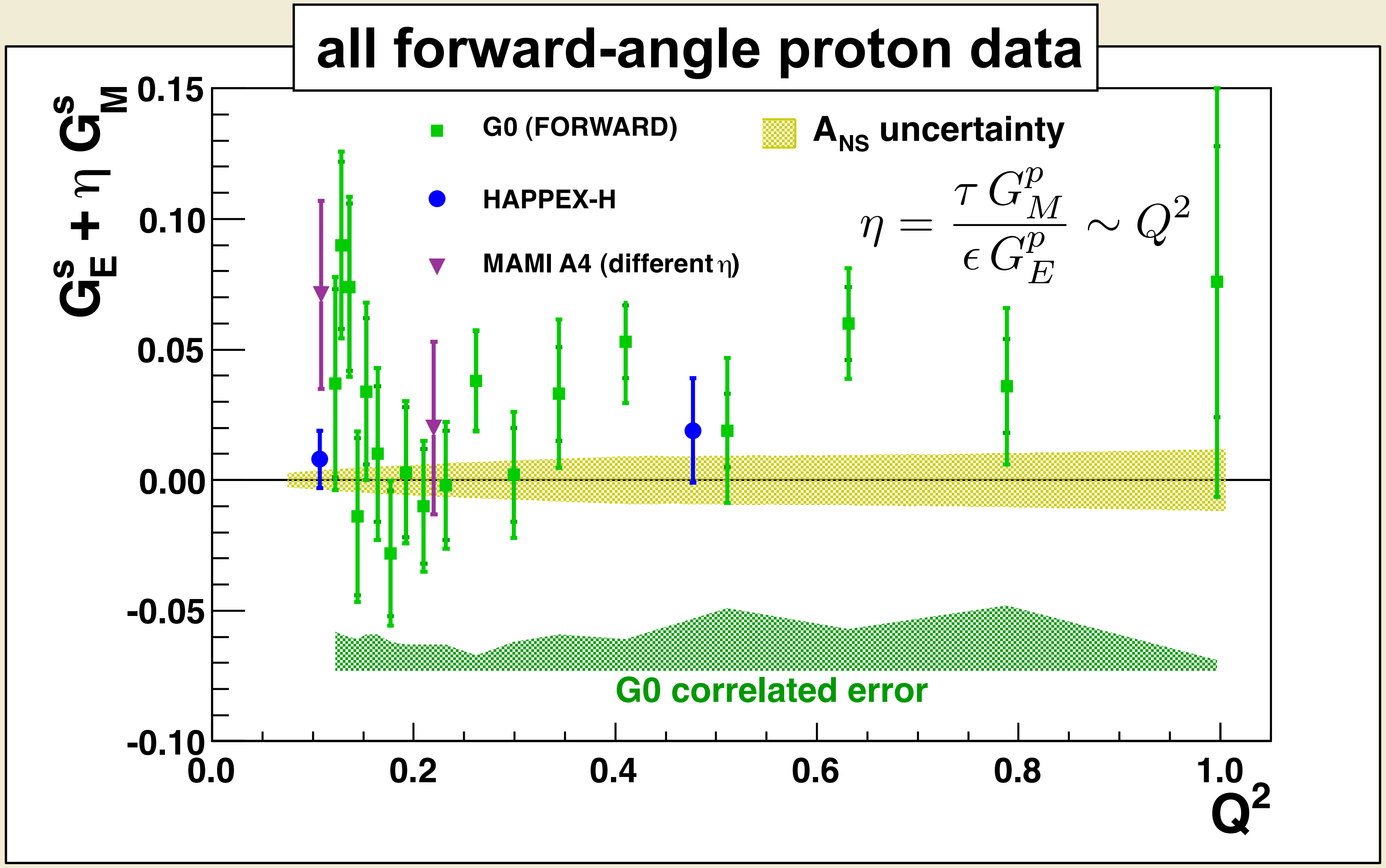
Forward and Backward angles over a range of Q^2

Forward-angle proton scattering



- "Form Factor" error: precision of EMFF (including 2γ) and Anapole correction

World data on G^s



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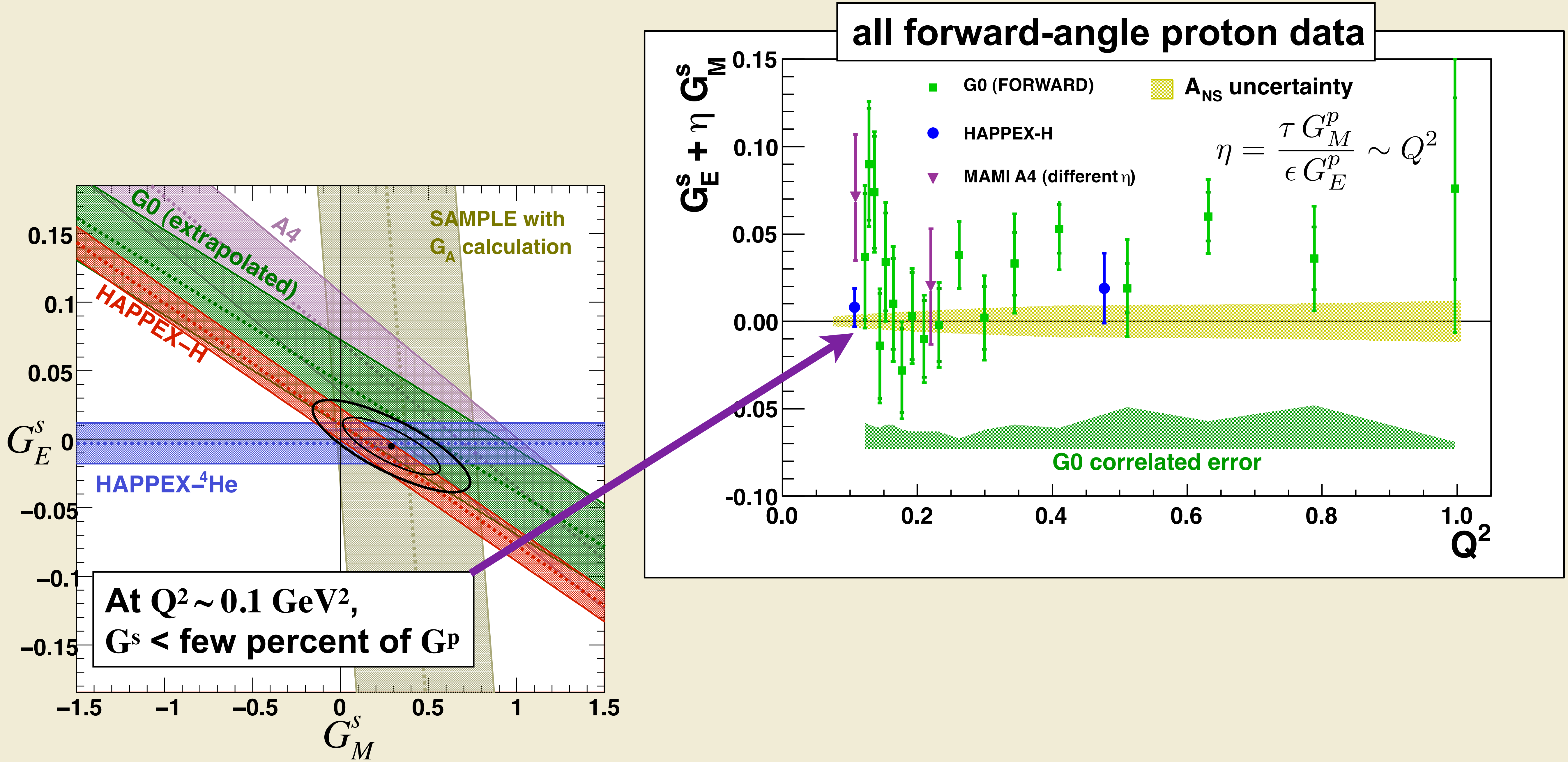
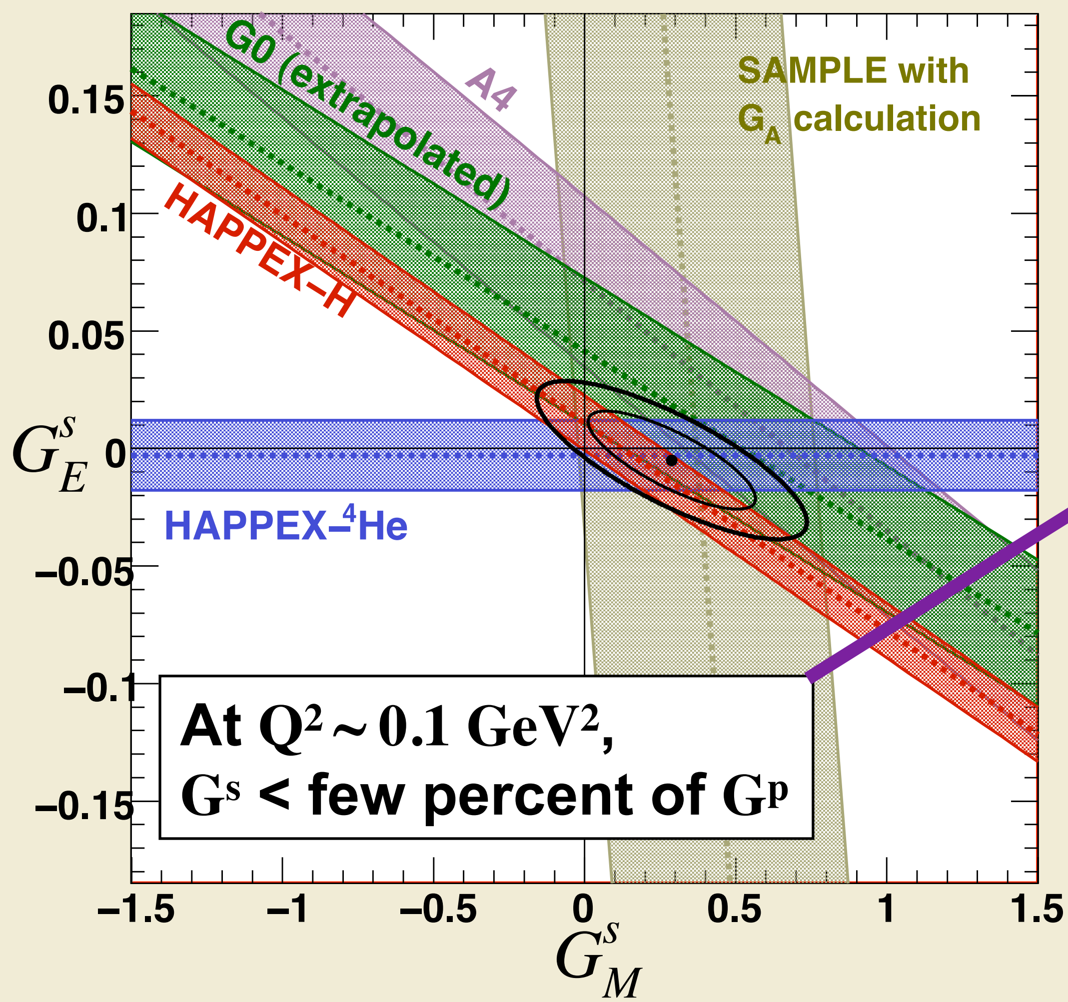
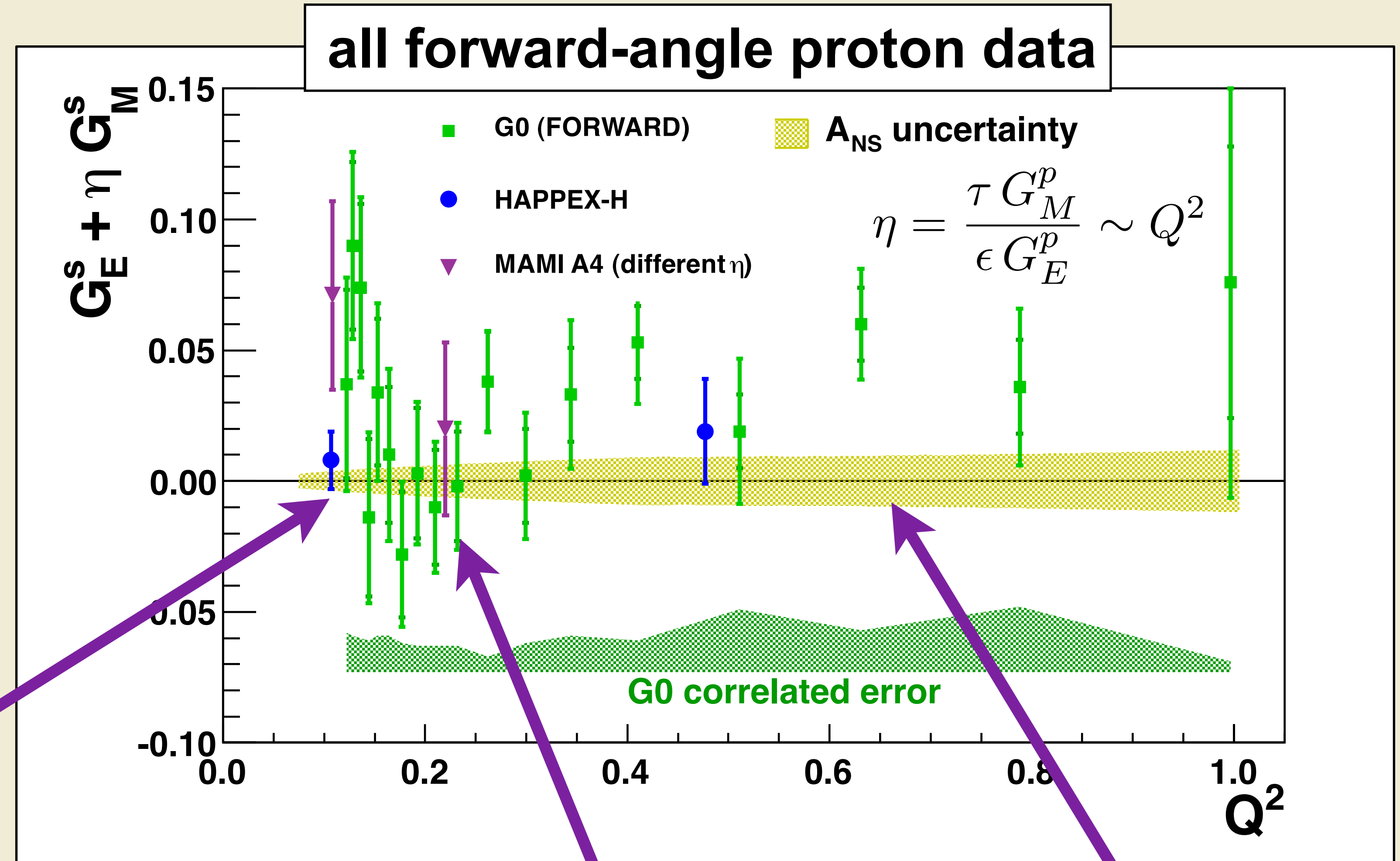
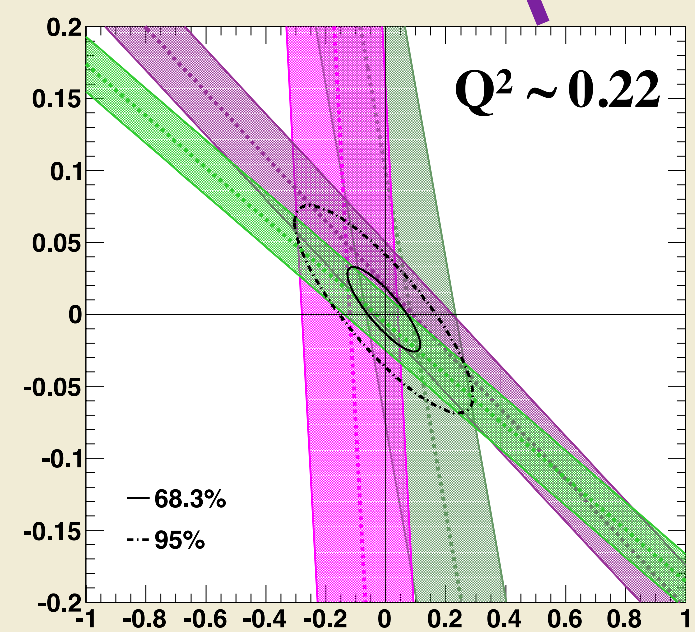


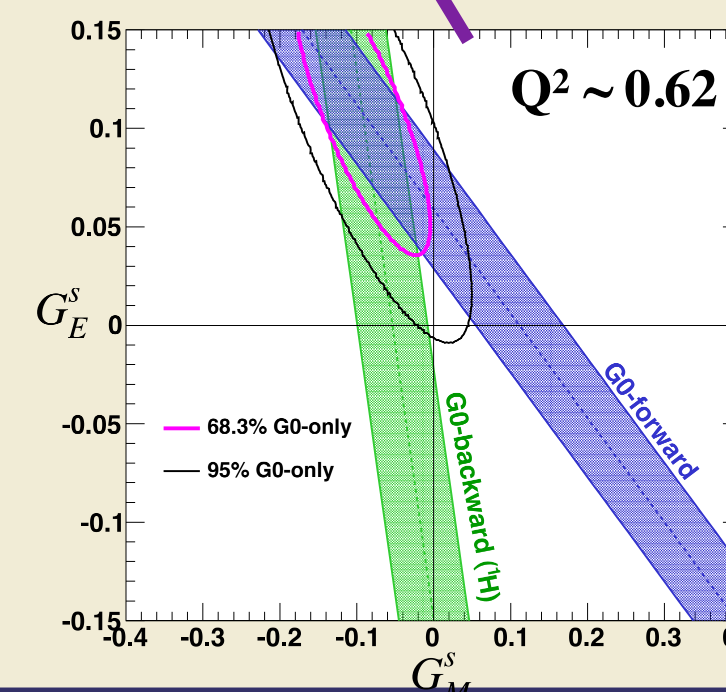
World data on G^s



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



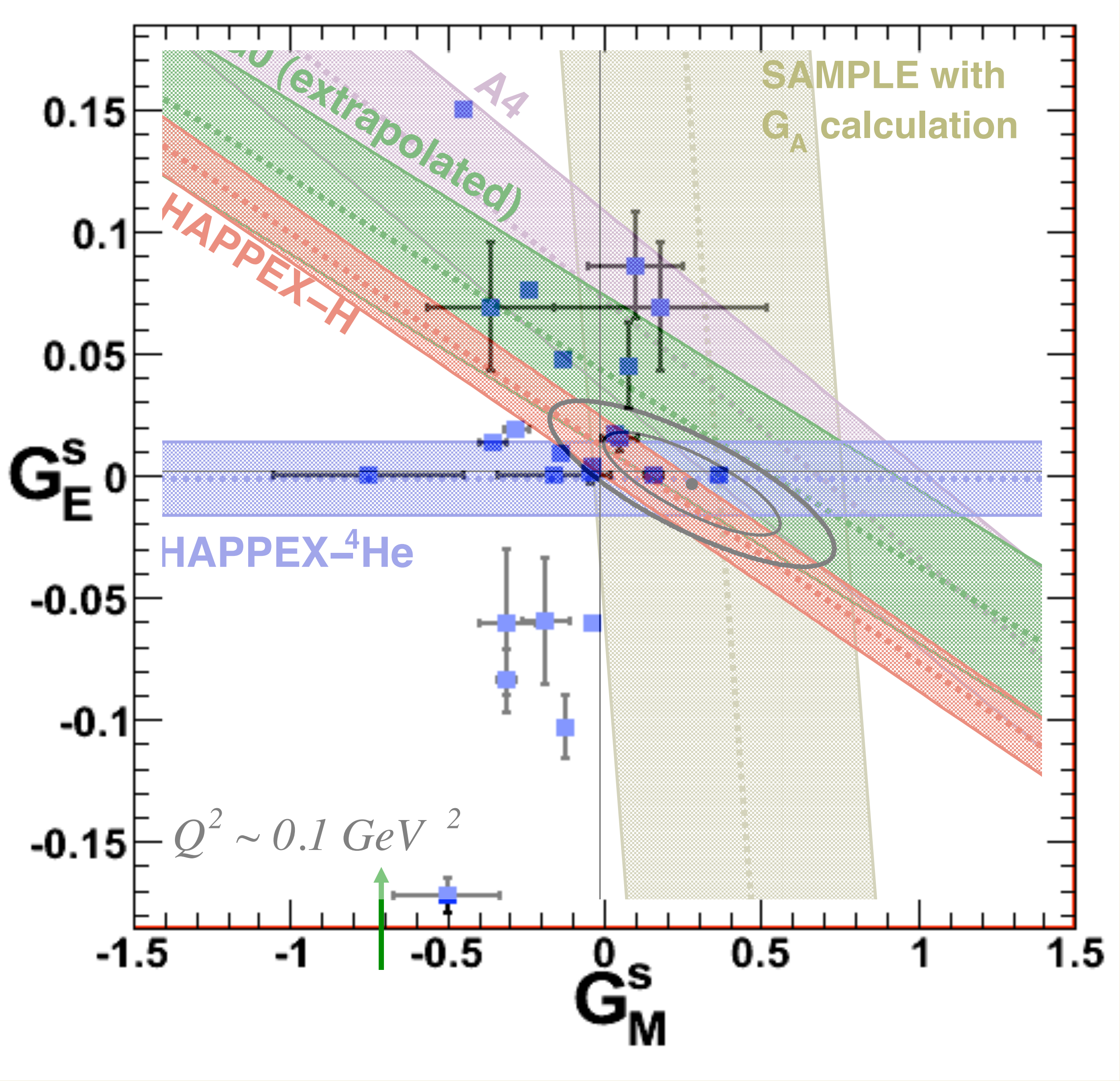




QCD models

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, …

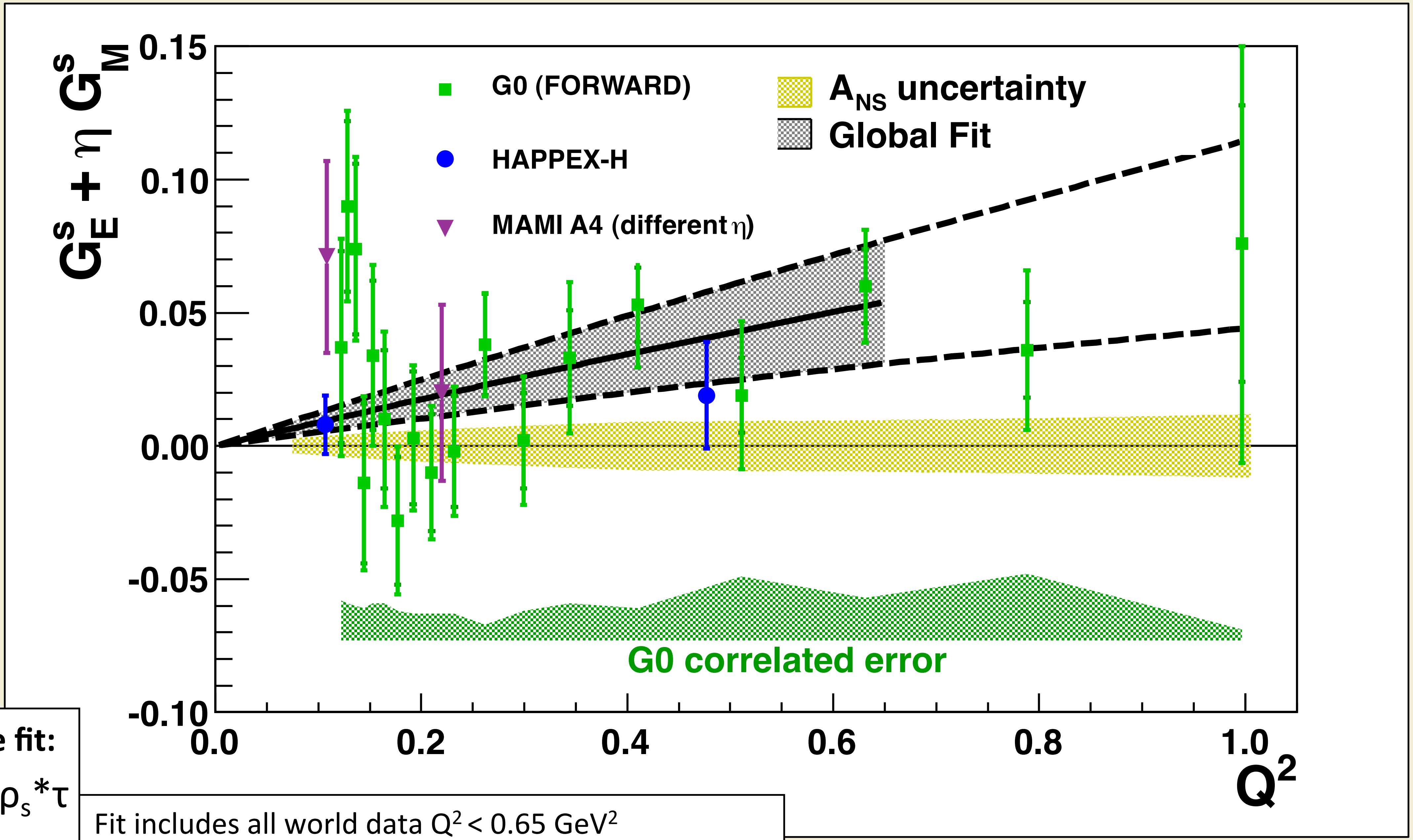


Recent significant progress in Lattice QCD:

- 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

Global fit of all world data



Simple fit:

$G_E^s = \rho_s * \tau$

$G_M^s = \mu_s$

Fit includes all world data $Q^2 < 0.65\ \mathrm{GeV}^2$

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.**

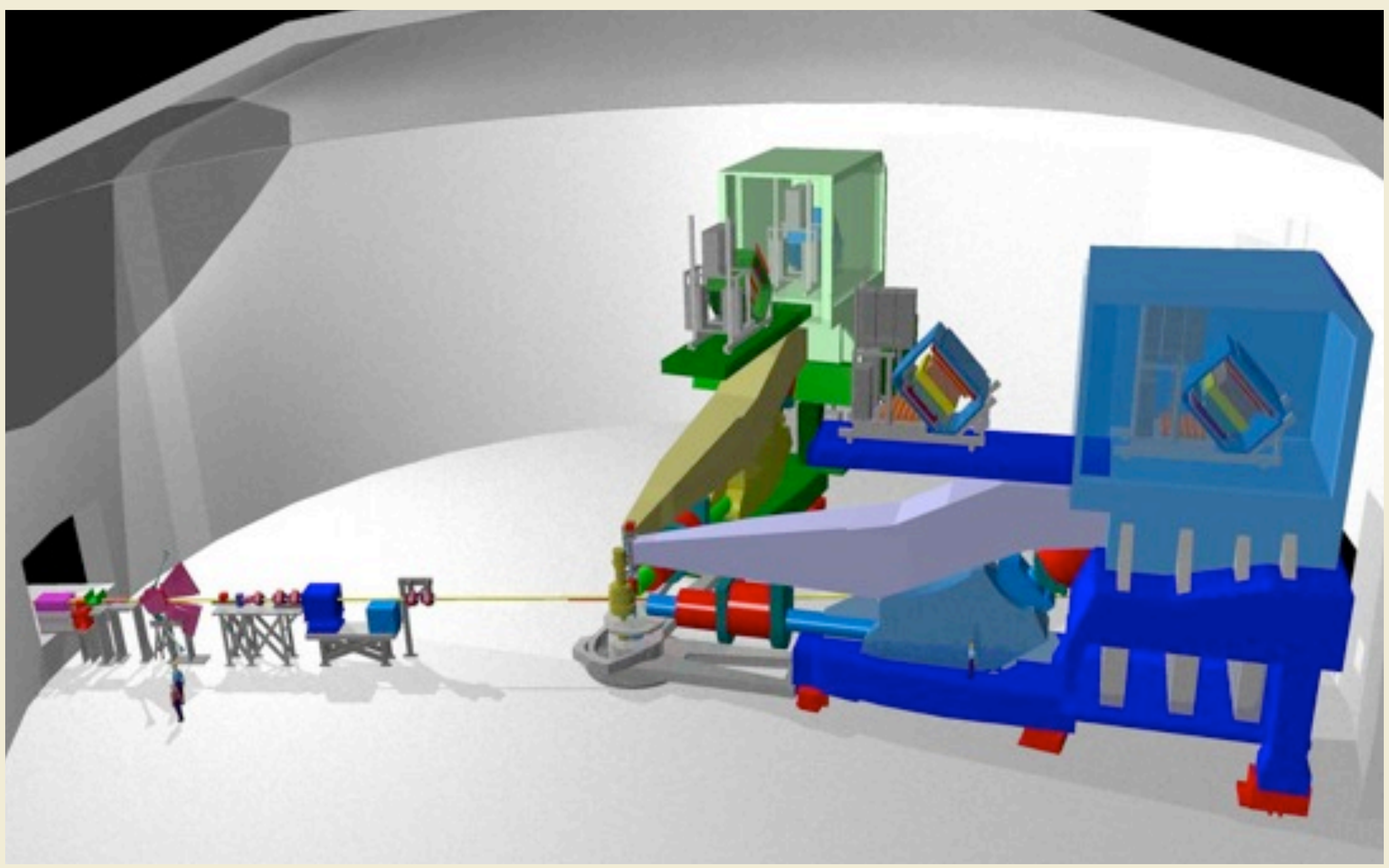
HAPPEX: Built around the HRS

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

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

Statistical FOM suitable for forward-angle PVeS studies

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



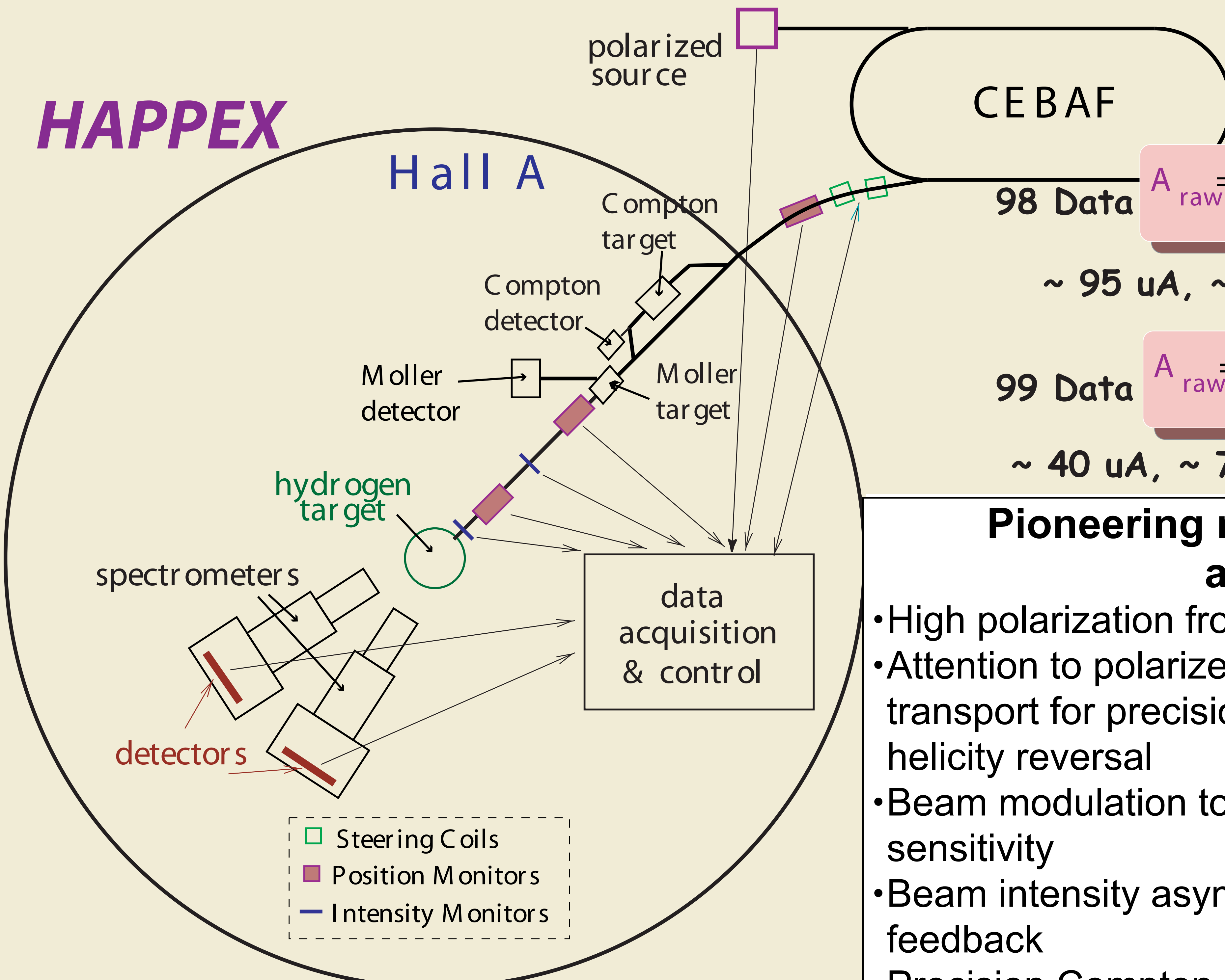
- Very low backgrounds
- Very clean isolation of ^{4}He elastic
- Low Q^2 range extended with septum magnet for 6^o scattering

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

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

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

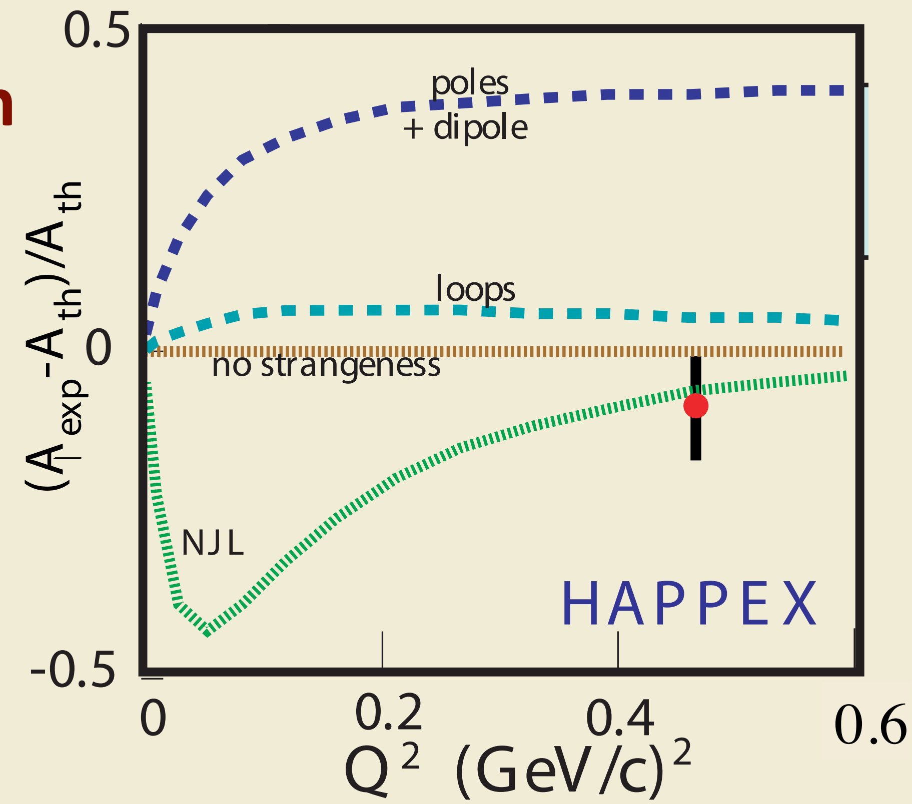
HAPPEX Results

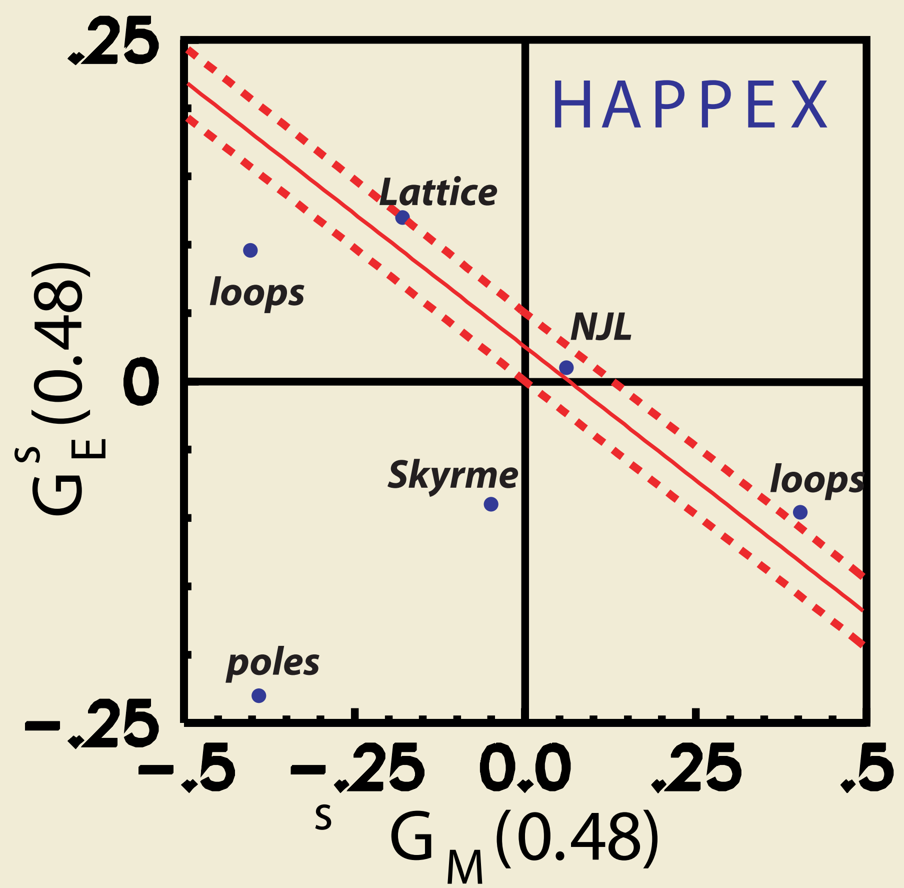
ep at Q^2=0.5 $(GeV/c)^2$, 12.3 degrees

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

$G^s_E + 0.392\, G^s_M$ =

0.014 ± 0.020 (exp) ± 0.010 (FF)



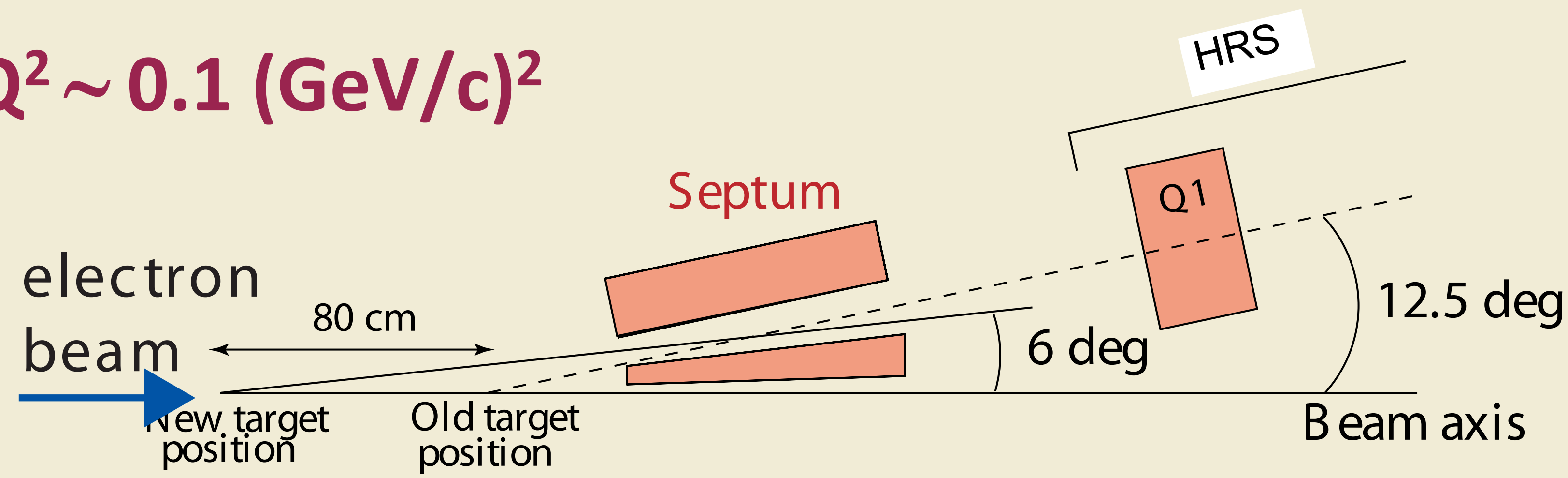


Statistics limited. Leading systematic is polarimetry

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

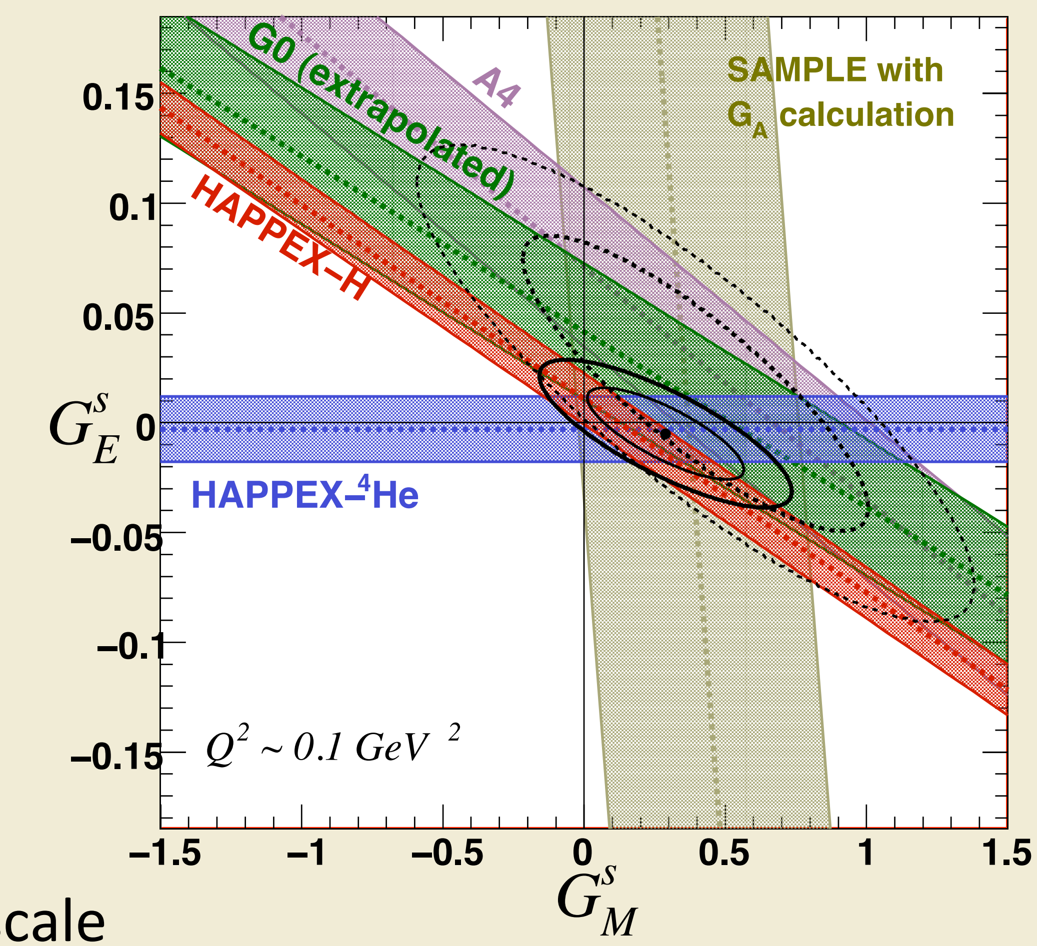


- **Hydrogen** : $G^s_E + \alpha\, G^s_M$

- **^{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%)



Statistics limited. Leading systematics are polarimetry, Q^2 scale

HAPPEX-III

Challenges similar to original HAPPEX, but seeking higher precision

Configuration:

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

Kinematics: E = 3.48 GeV, θ=13.7°, E' = 3.14 GeV, Q^2 = 0.624 GeV^2, ε=0.967

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

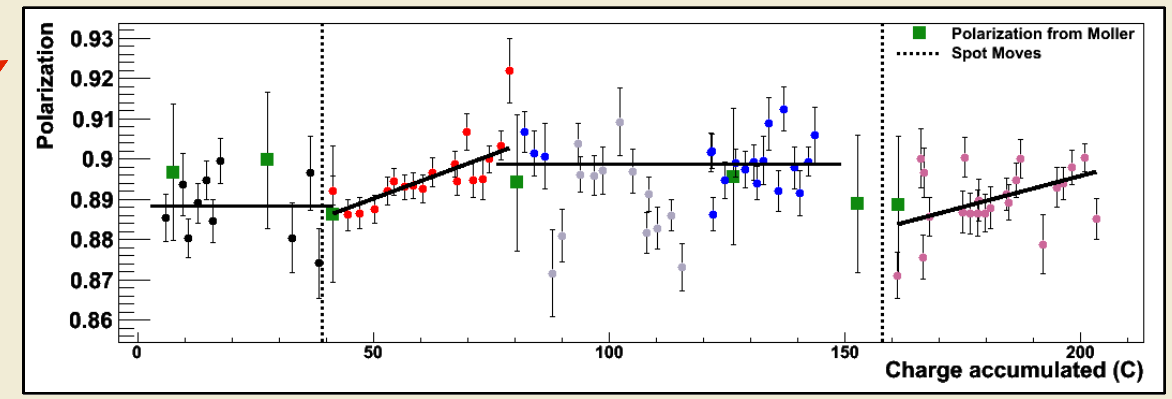
A_{PV} (assuming no strange vector FF): A_{PV}^{NS} = -24.06 ppm ± 0.73 ppm

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

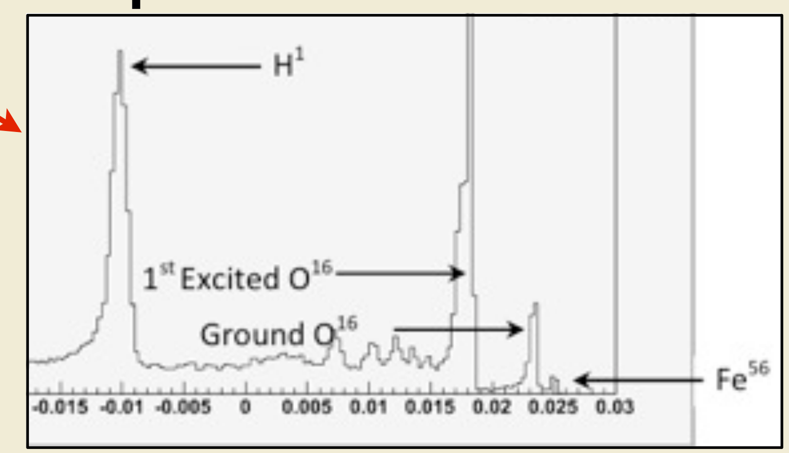
HAPPEX-III Error Budget

	δA_{PV} (ppm)	$\delta A_{PV} / A_{PV}$
Polarization	0.20	0.9%
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	0.362	1.52%
Statistics	0.778	3.27%
Total Experimental	0.858	3.60%

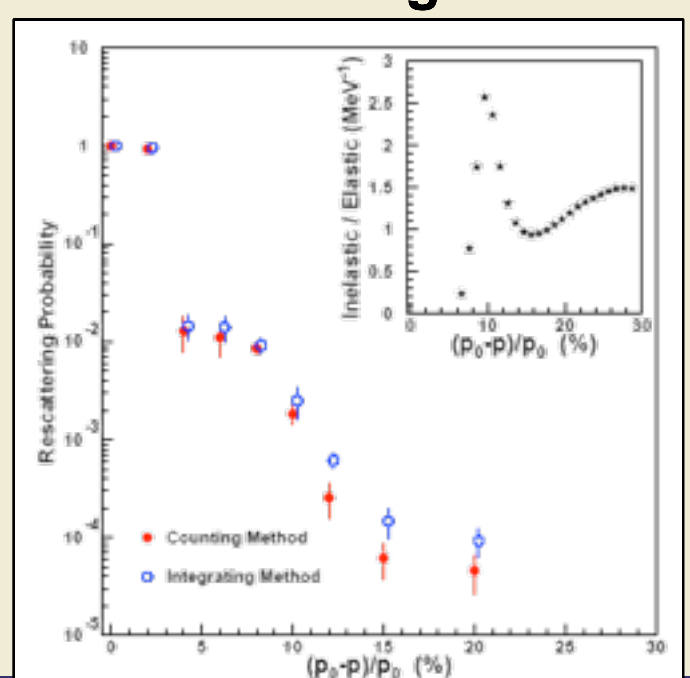
Compton + Moller polarimeters



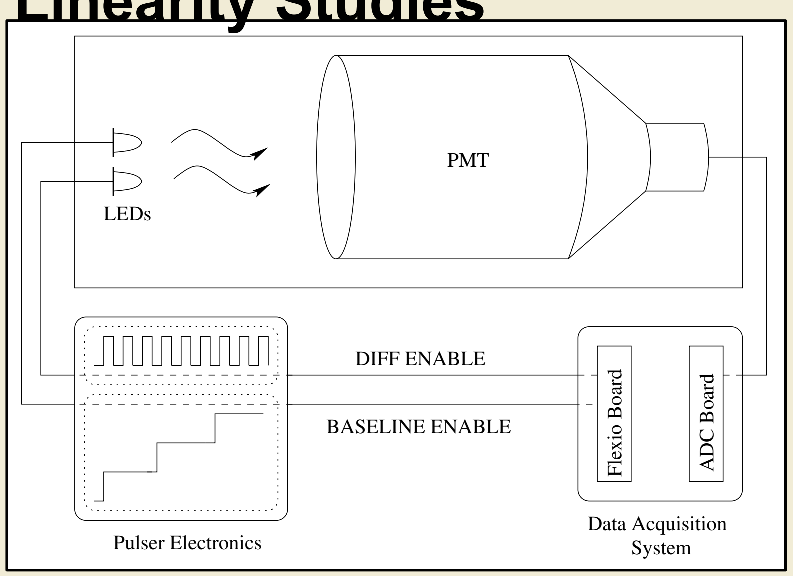
Spectrometer Calibration



HRS Backgrounds



Linearity Studies

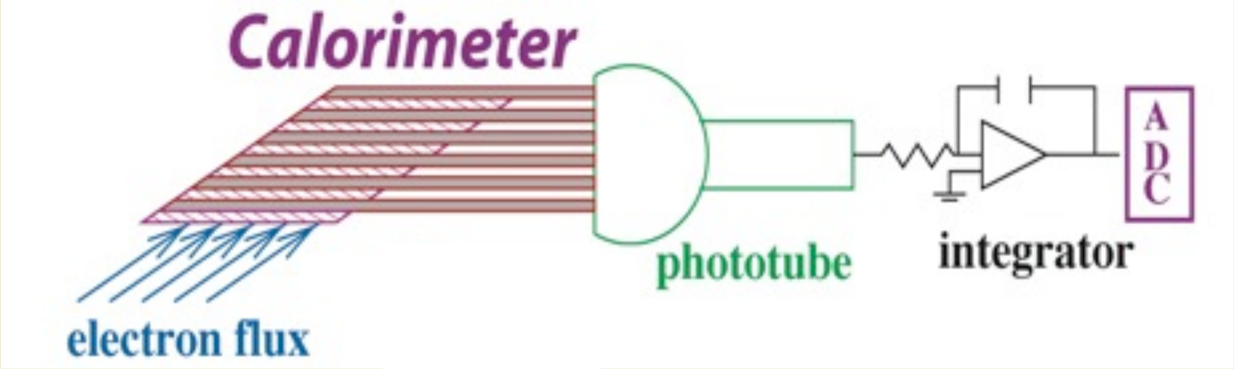


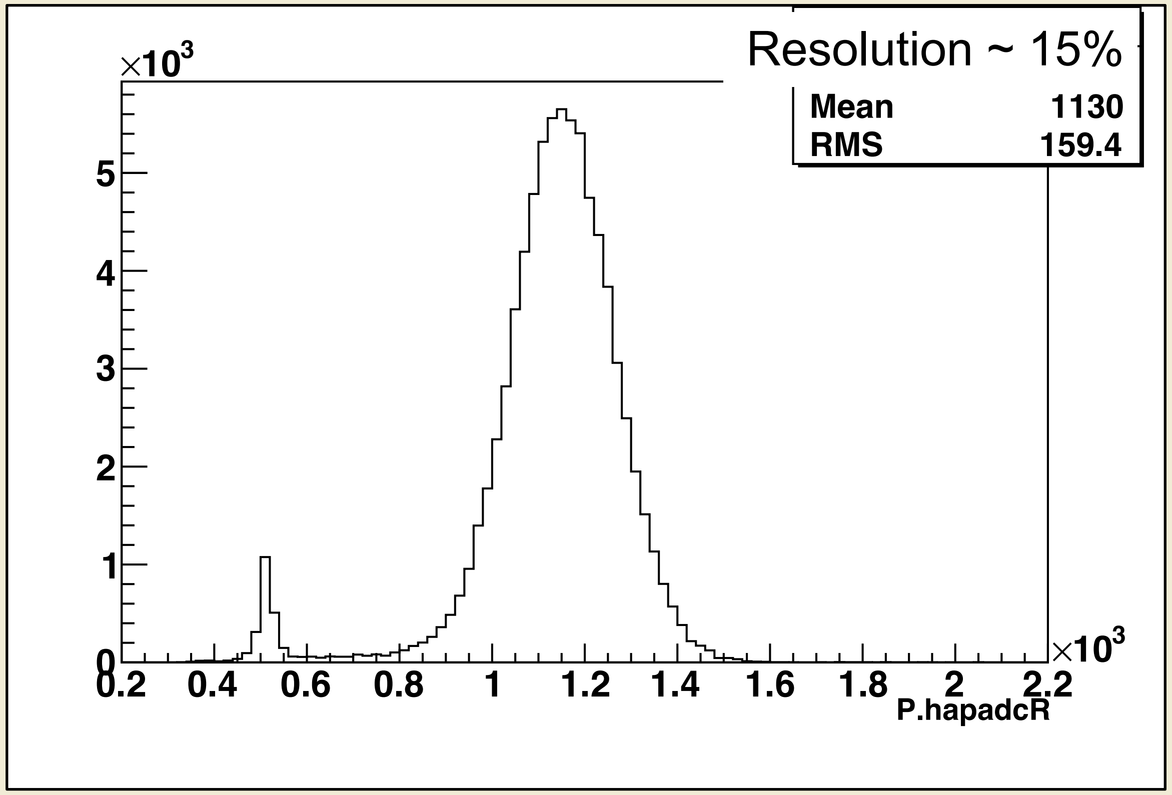
Systematic uncertainties are well controlled - experiment is statistics dominated

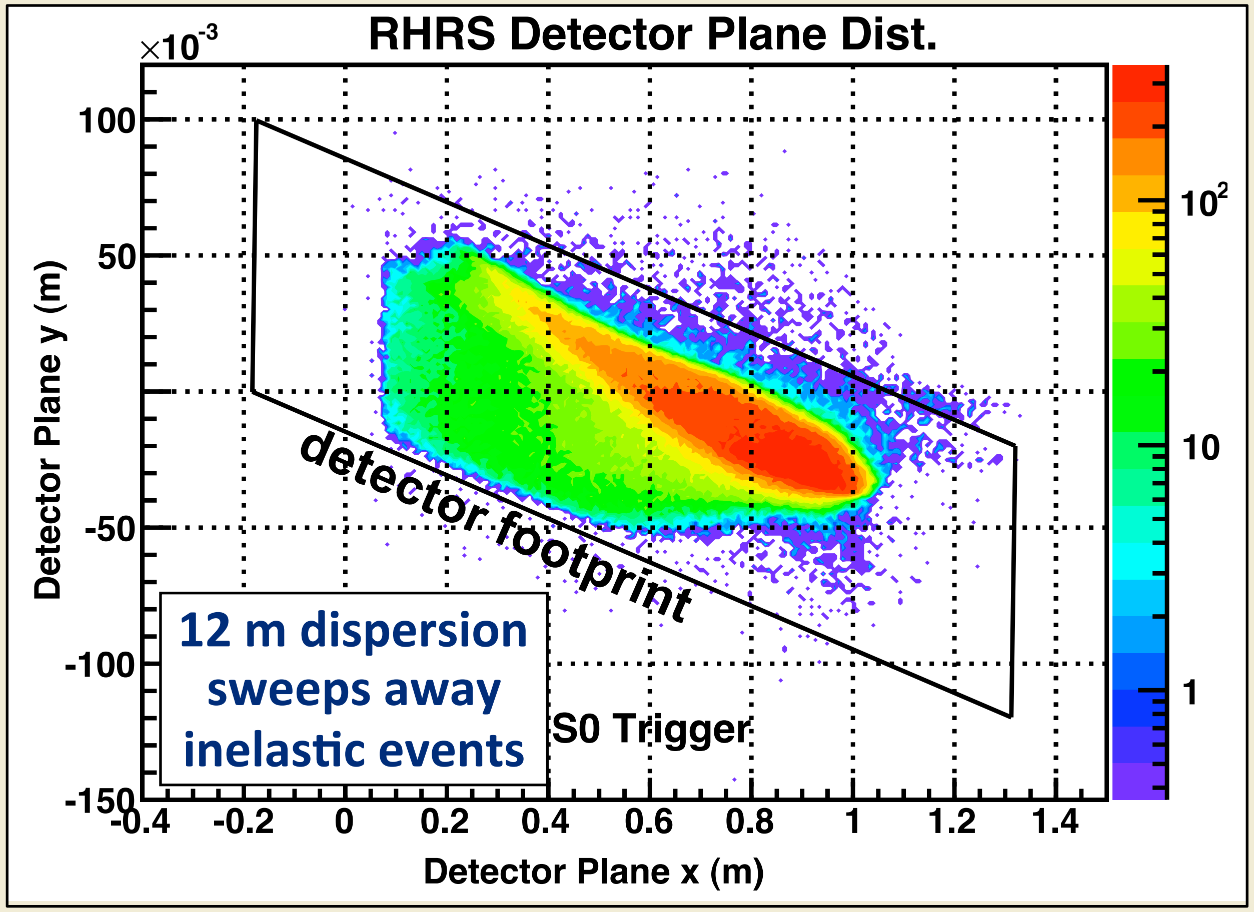
Integrating Detector

Lead - Lucite Cerenkov Shower Calorimeter

- Insensitive to background
- Directional sensitivity
- High-resolution

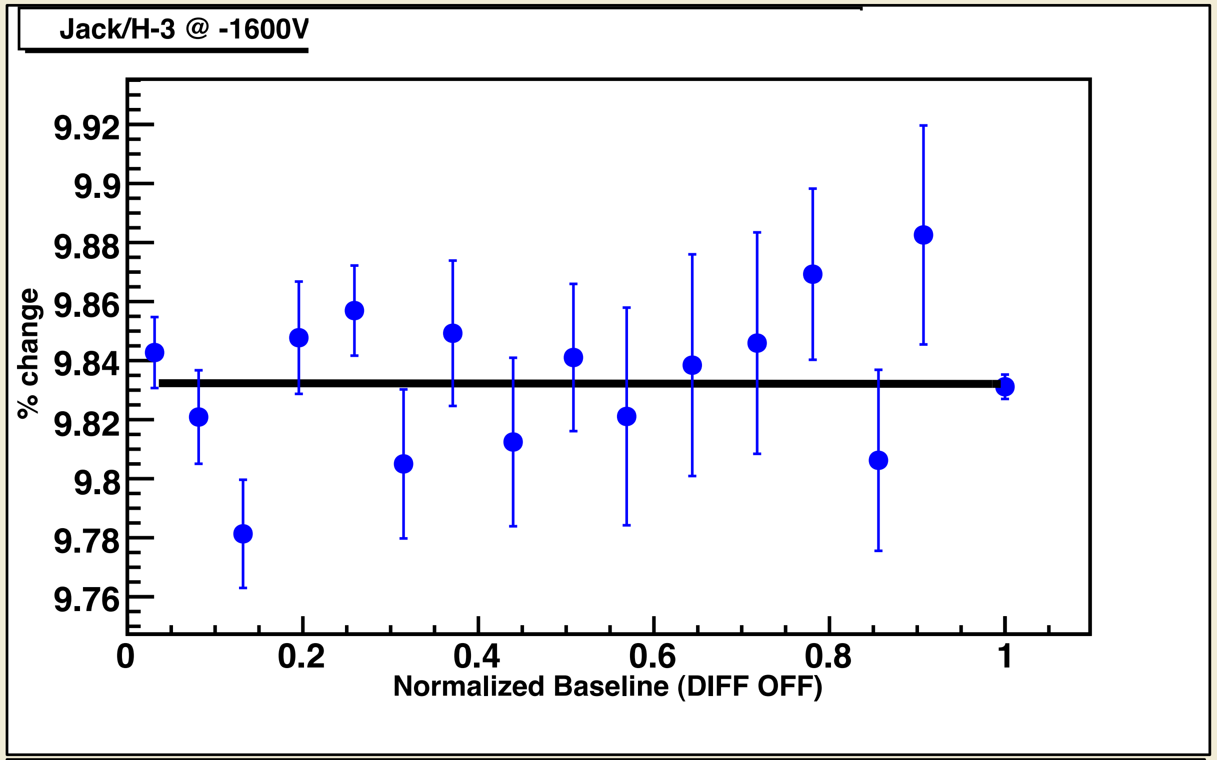


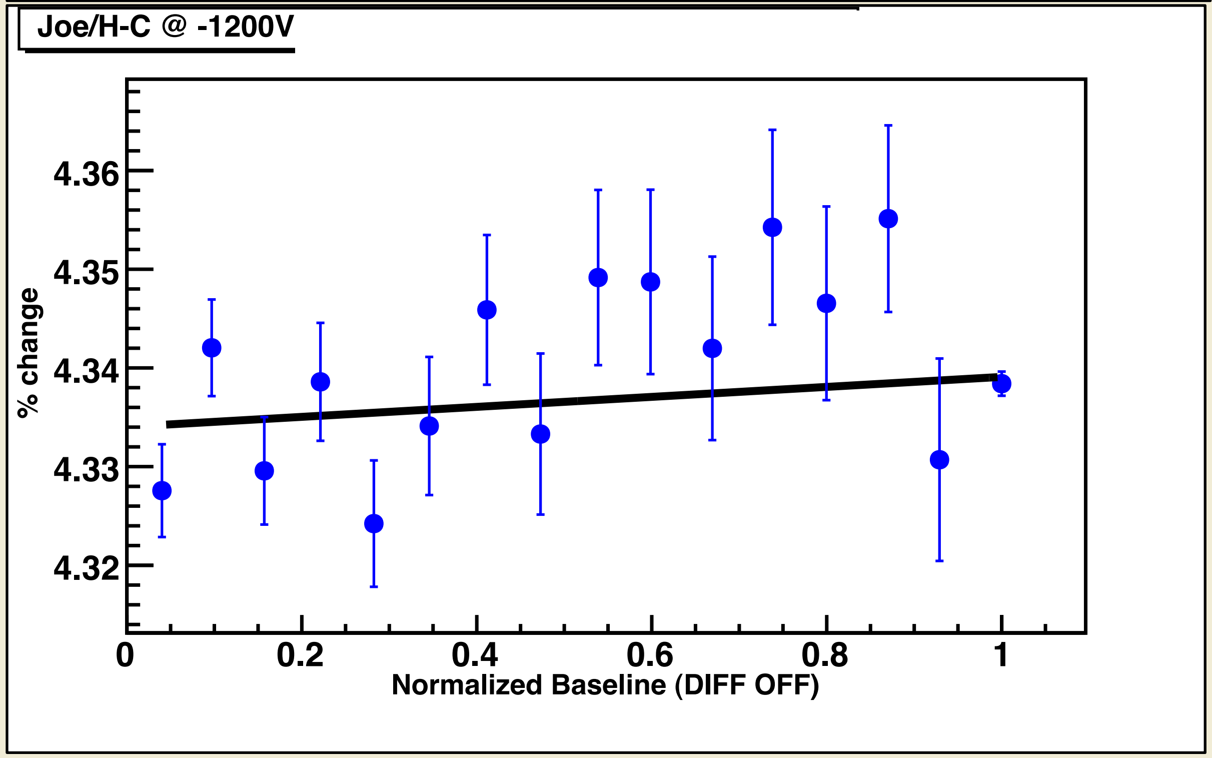


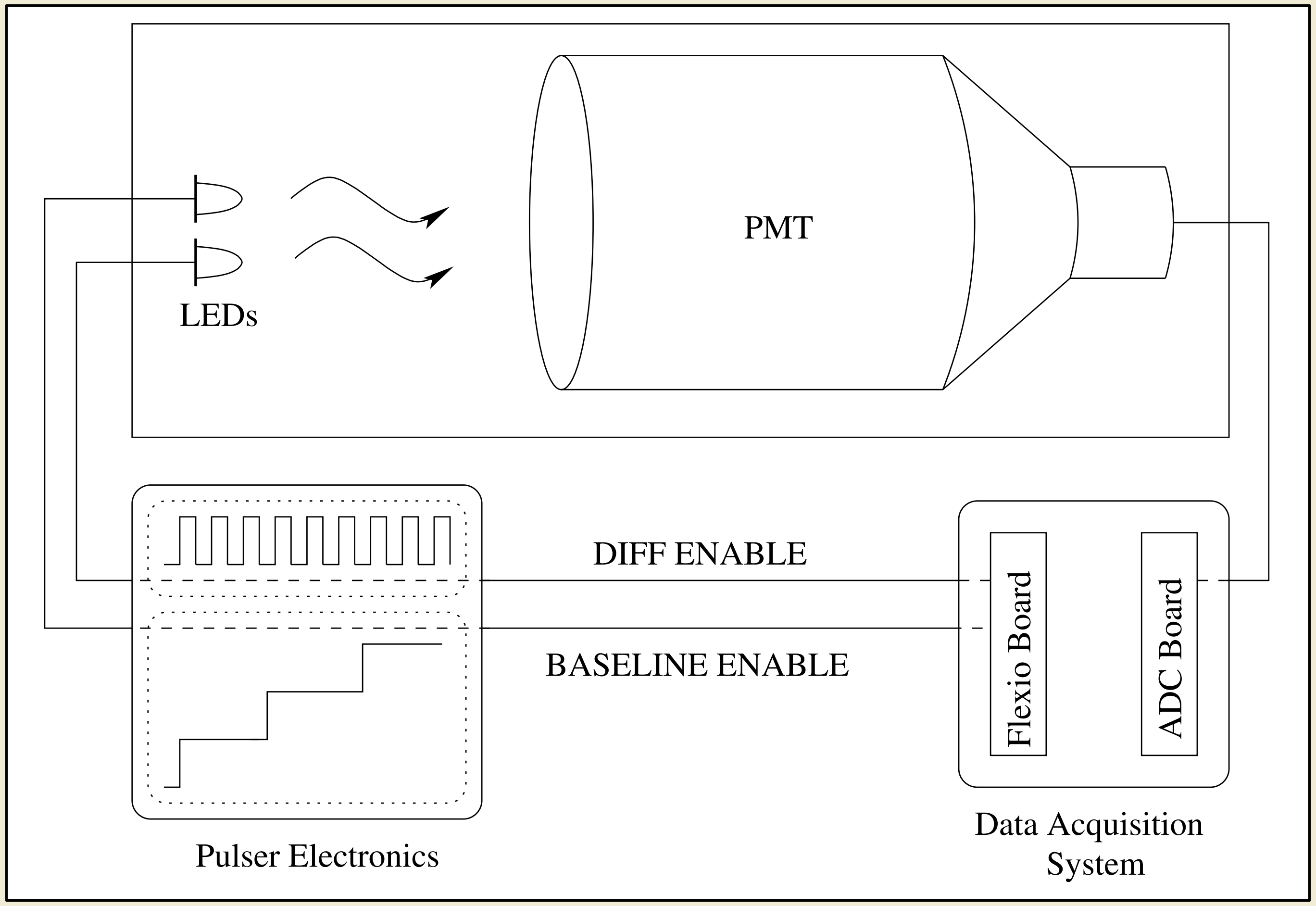


Detector Linearity

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

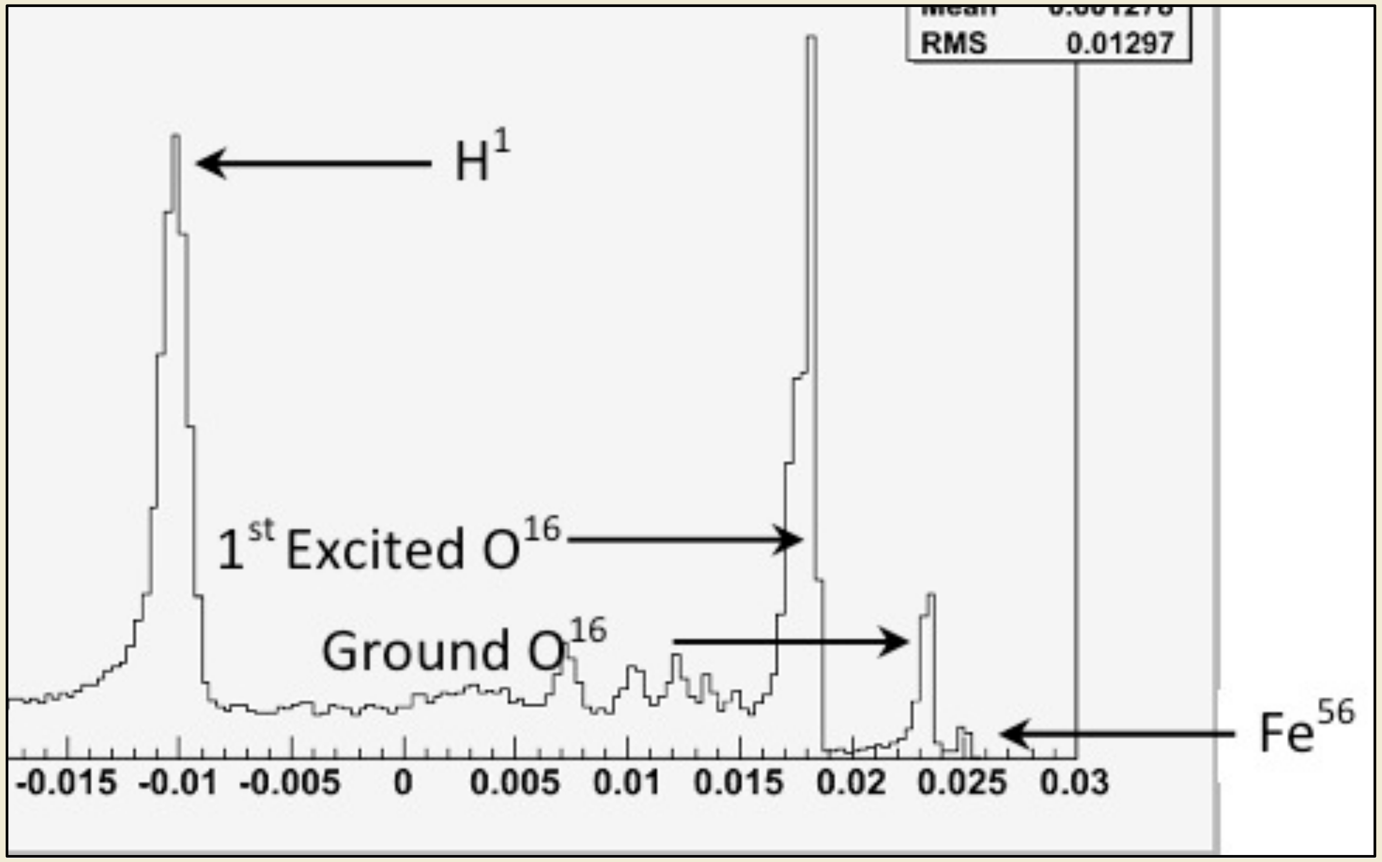
Phototube and readout non-linearity bounded at the 0.5% level

Determining Q2

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

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

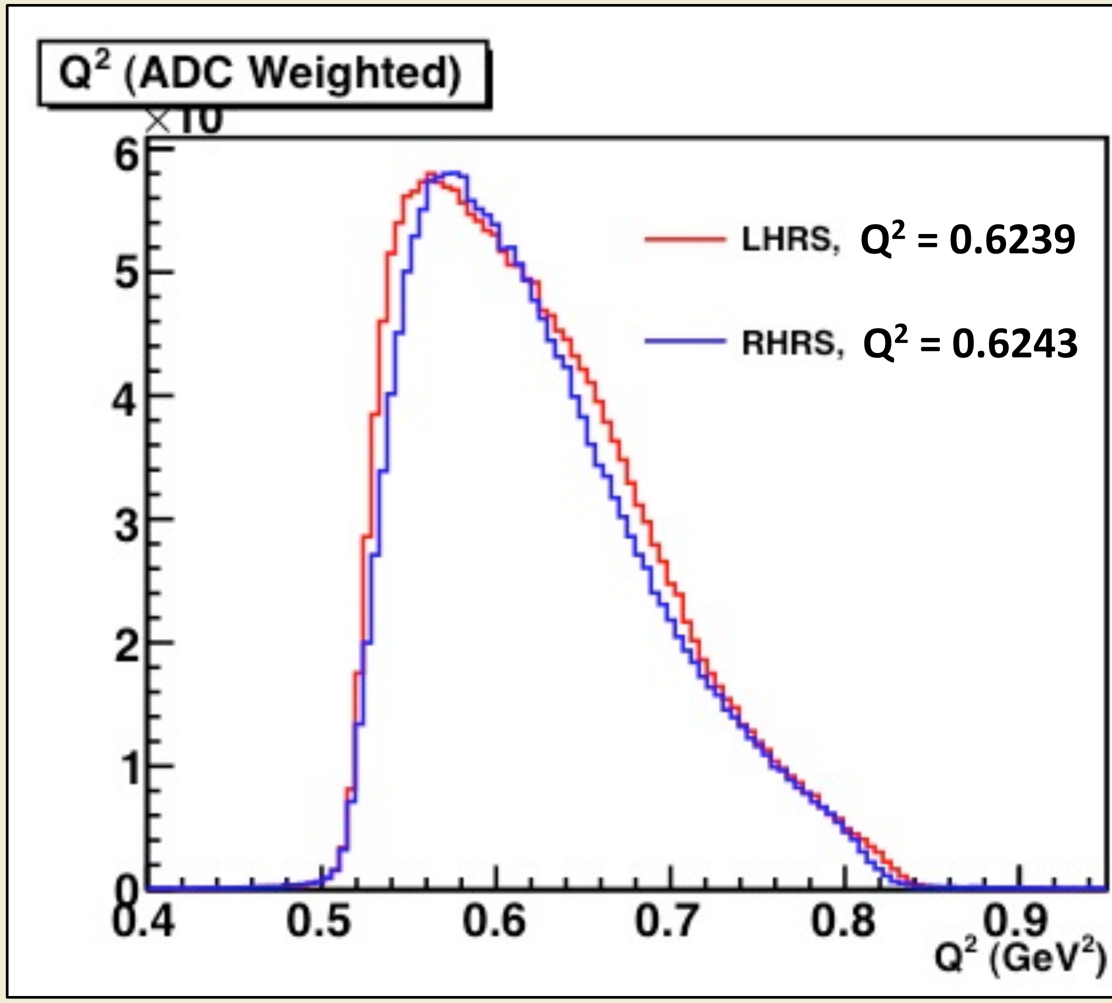
Water cell optics target for central angle



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

δθ ~ 0.55 mrad (0.23%)

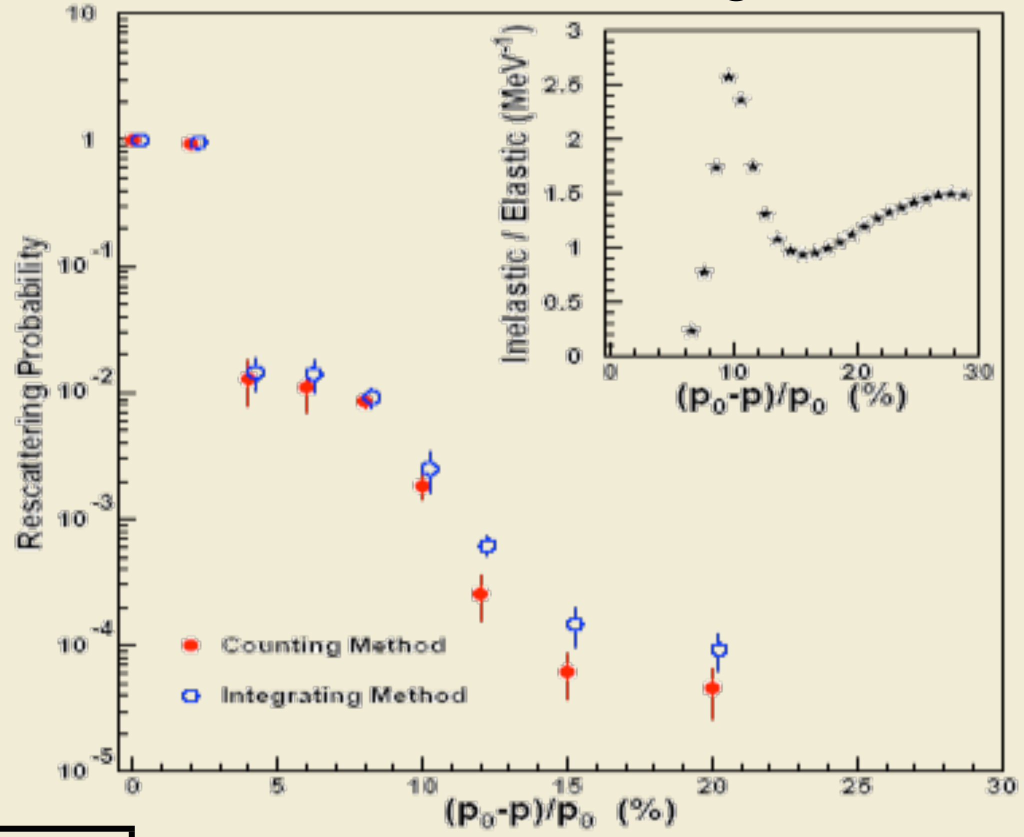
$Q^2 = 0.6241 \pm 0.0032$ (0.52%)



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

Backgrounds

Rescattering probability measured during H-I



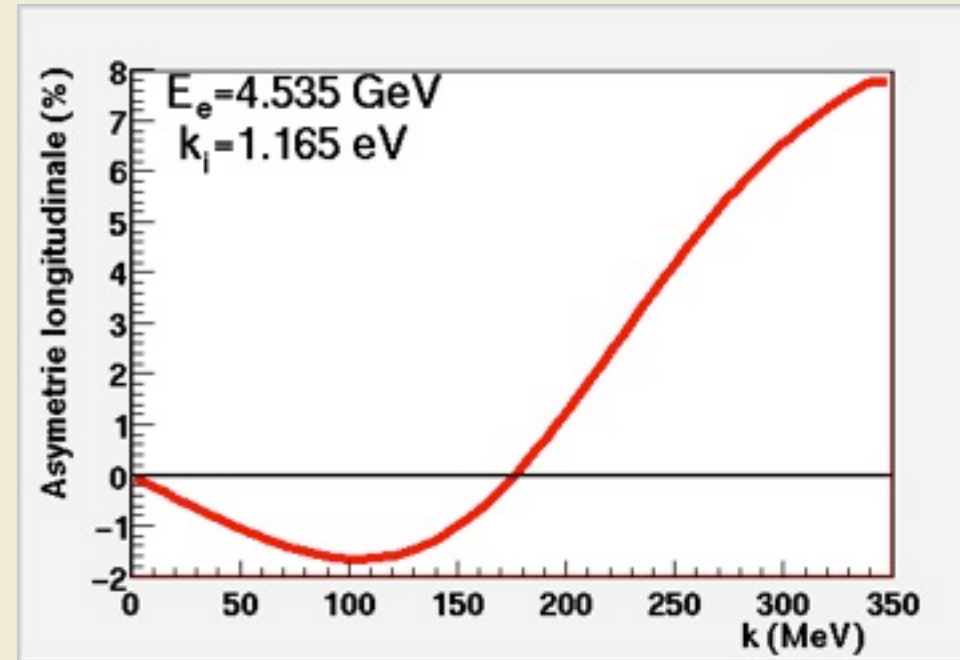
- Aluminum from target windows
- Signal from inelastic electrons scattering inside spectrometer

background	f	A	Net Correction	Net Uncertainty
Aluminum (target window)	1.15% (30%)	-34.5 ppm (30%)	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

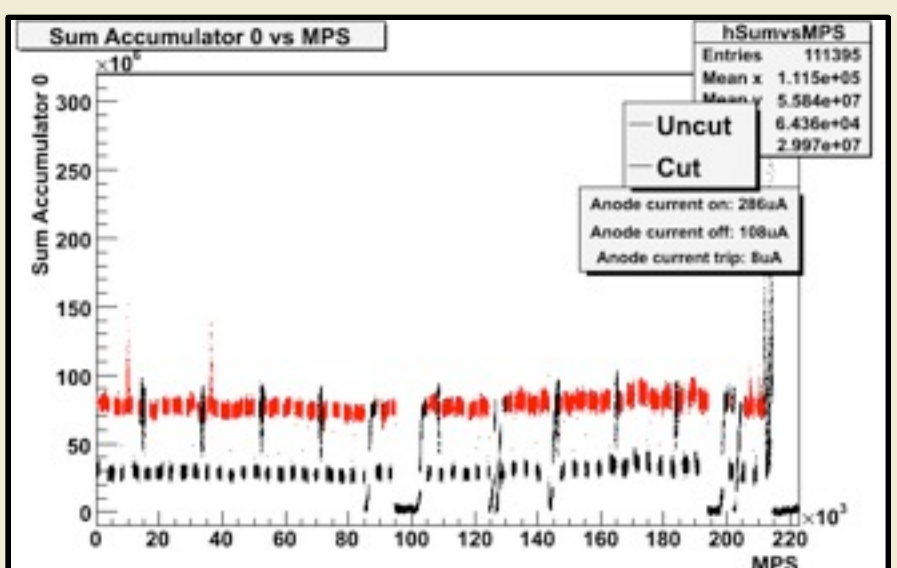
Photon self-triggered analysis has been limited in accuracy, and required electron coincidence measurements for calibration

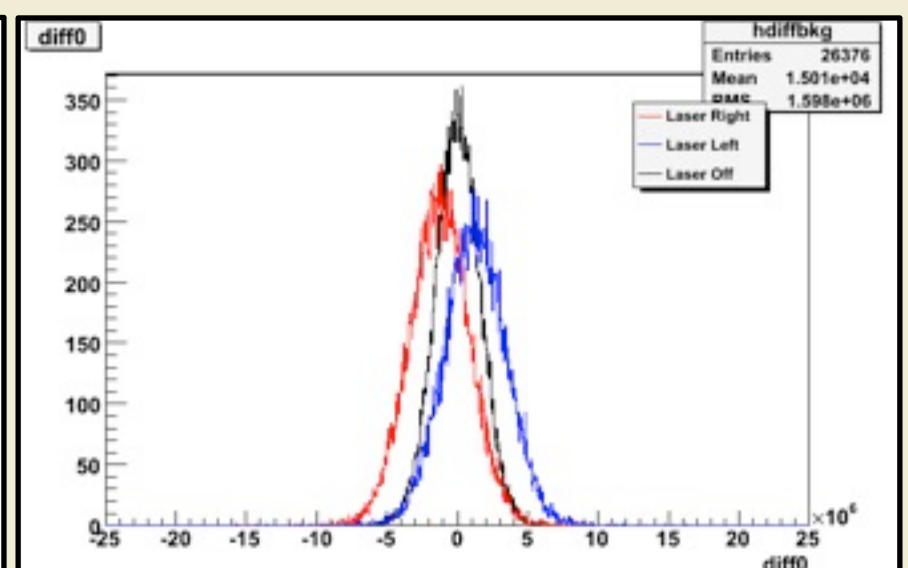


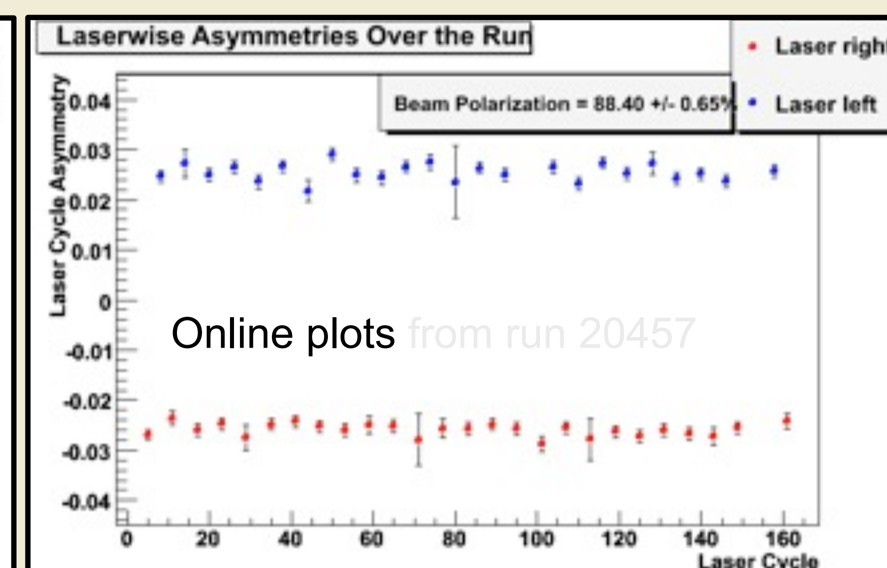
Integrating photon detection:

immune to calibration, pile-up, deadtime, response function

New DAQ, with SIS 2230 Flash ADC: **Accumulator readout: all FADC samples are summed on board for entire helicity window**

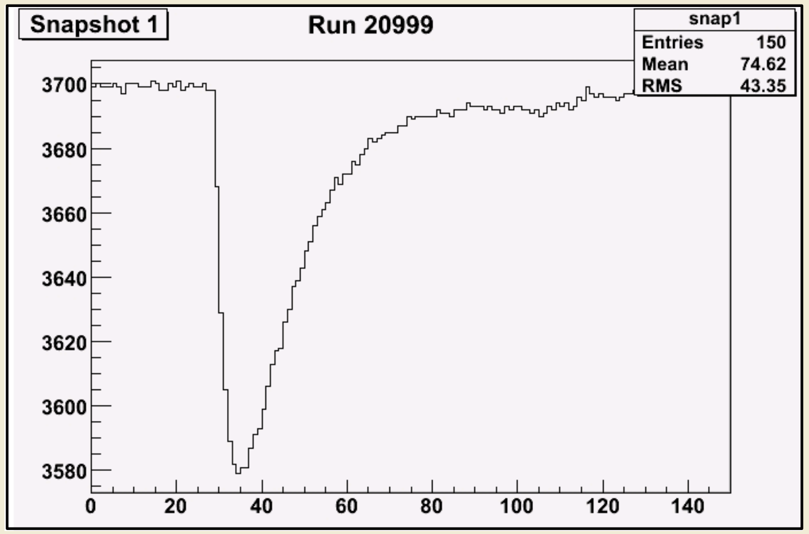






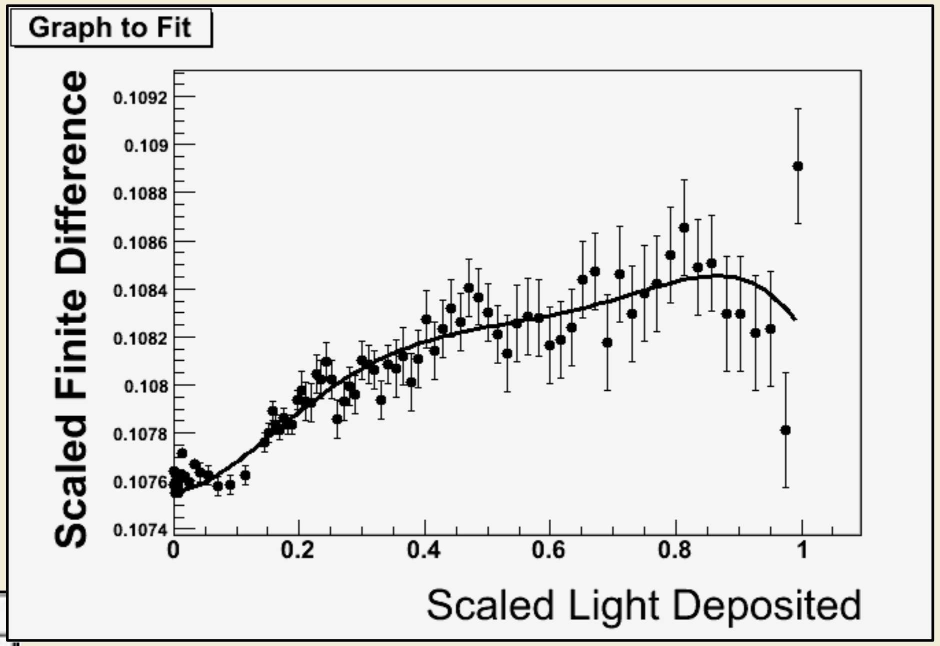
Compton Polarimetry

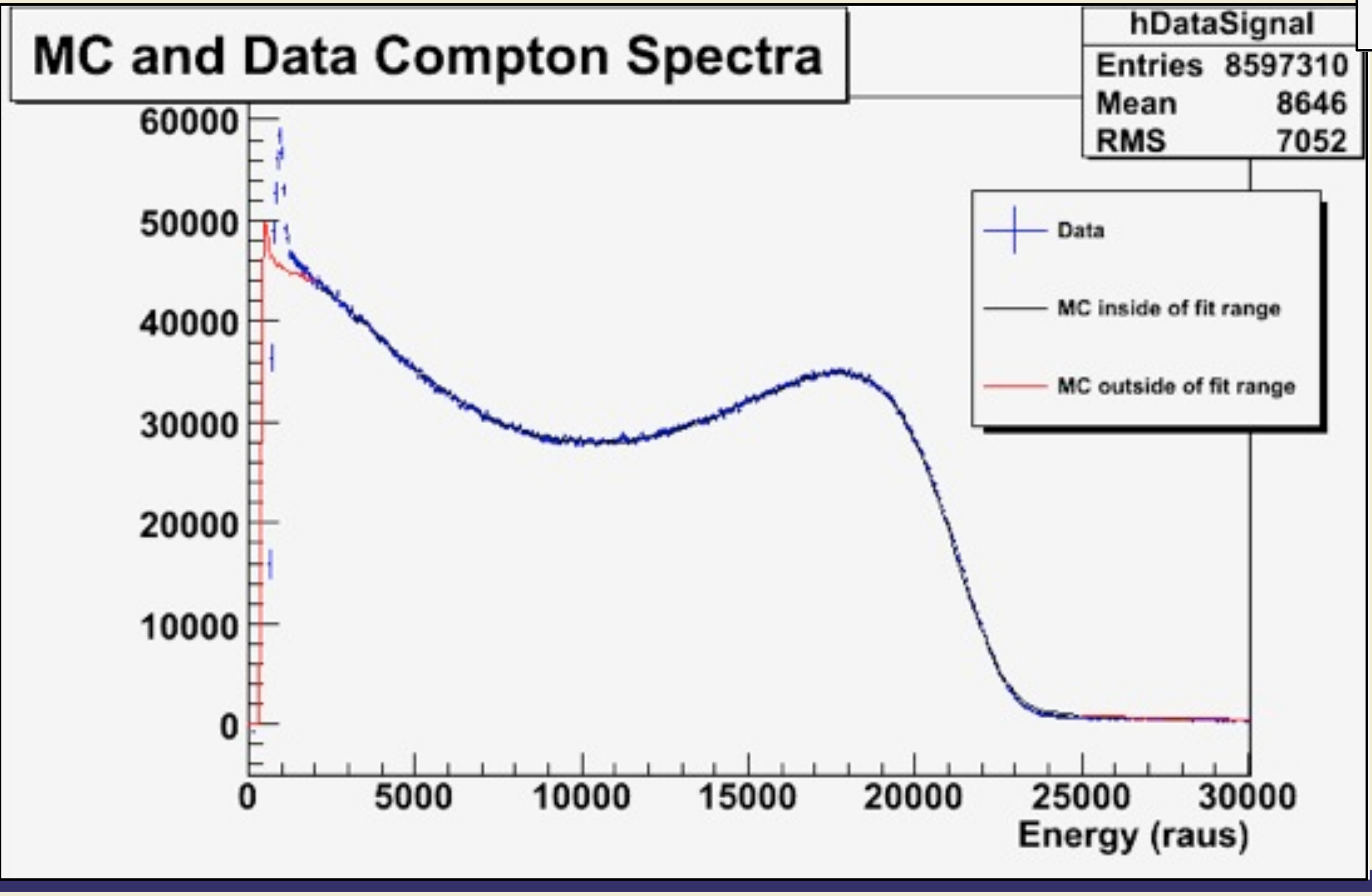
Triggered mode: triggered "snap shot" of fixed time interval (for calibration)



Pulse-size non-linearity mapped by pulsed LED system

Combined with beam and beam+laser to make rate-dependent correction



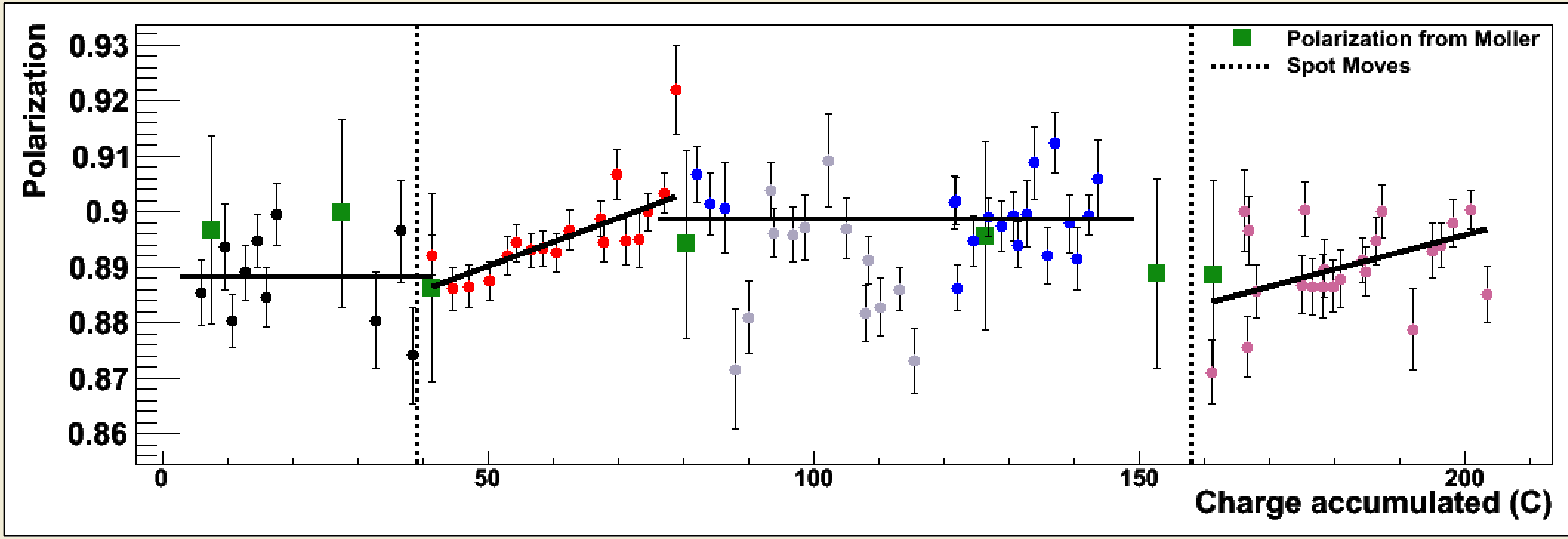


Compton spectrum very well simulated
- **energy deposition in detector**
- **linearity**
- **collimator/detector alignment**
- **synchrotron light shielding**

Analyzing power calculation is rather insensitive to these corrections

M. Friend *et al.*, arXiv:1108.3116, arXiv:1108.3096

Polarimetry Summary



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

Average: 89.36 ± 0.84%

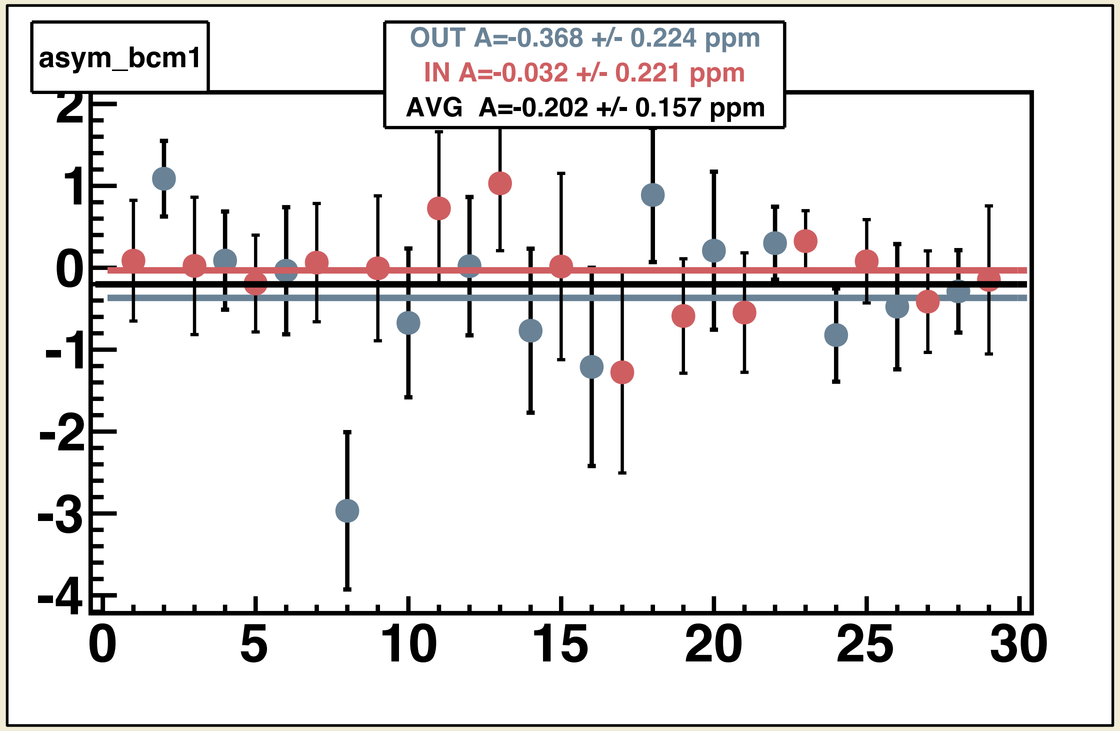
Moller systematic errors

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

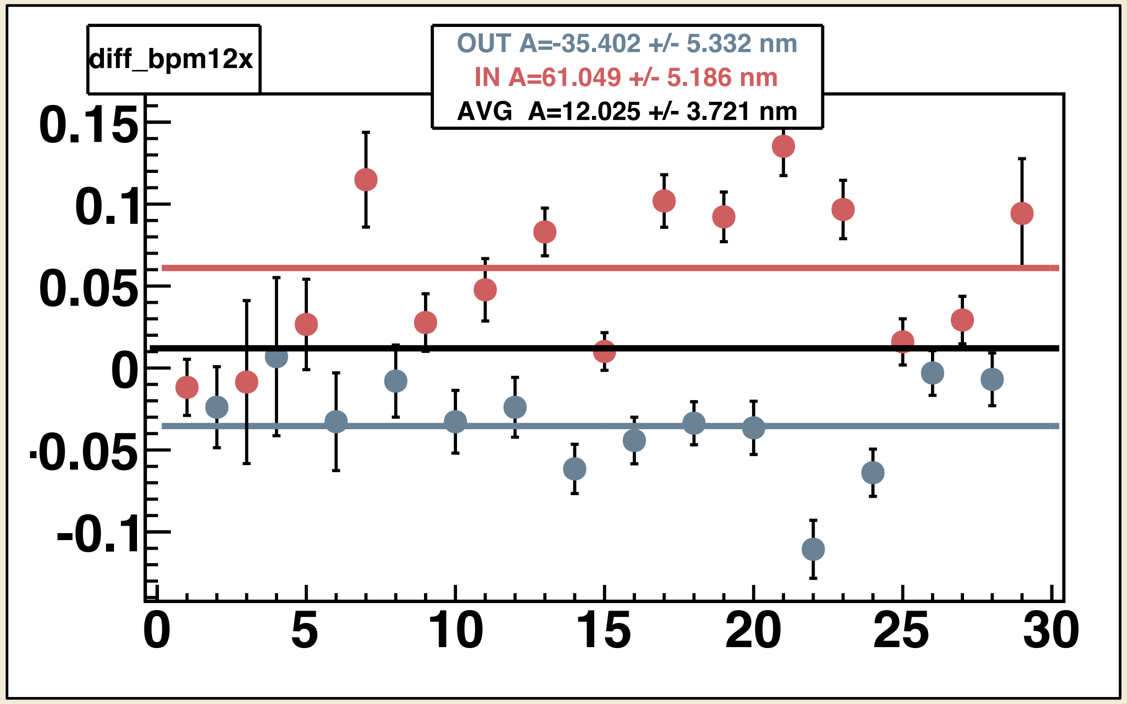
Compton systematic errors

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

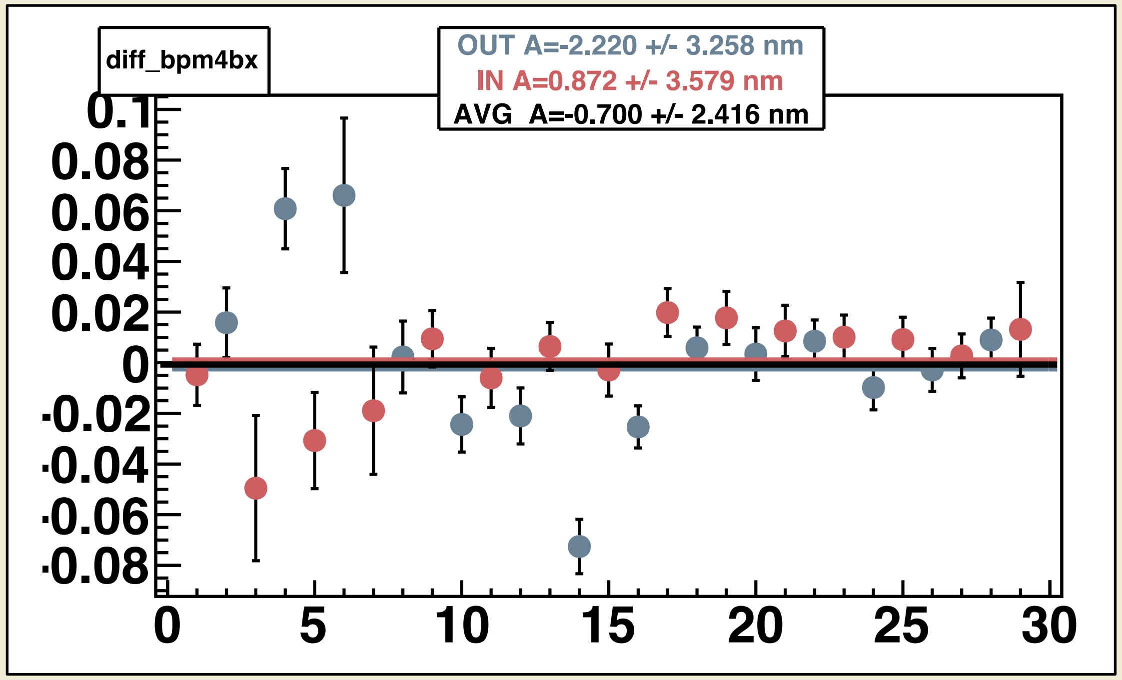
Beam Asymmetries



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



Implies energy asymmetry at 3 ppb



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

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

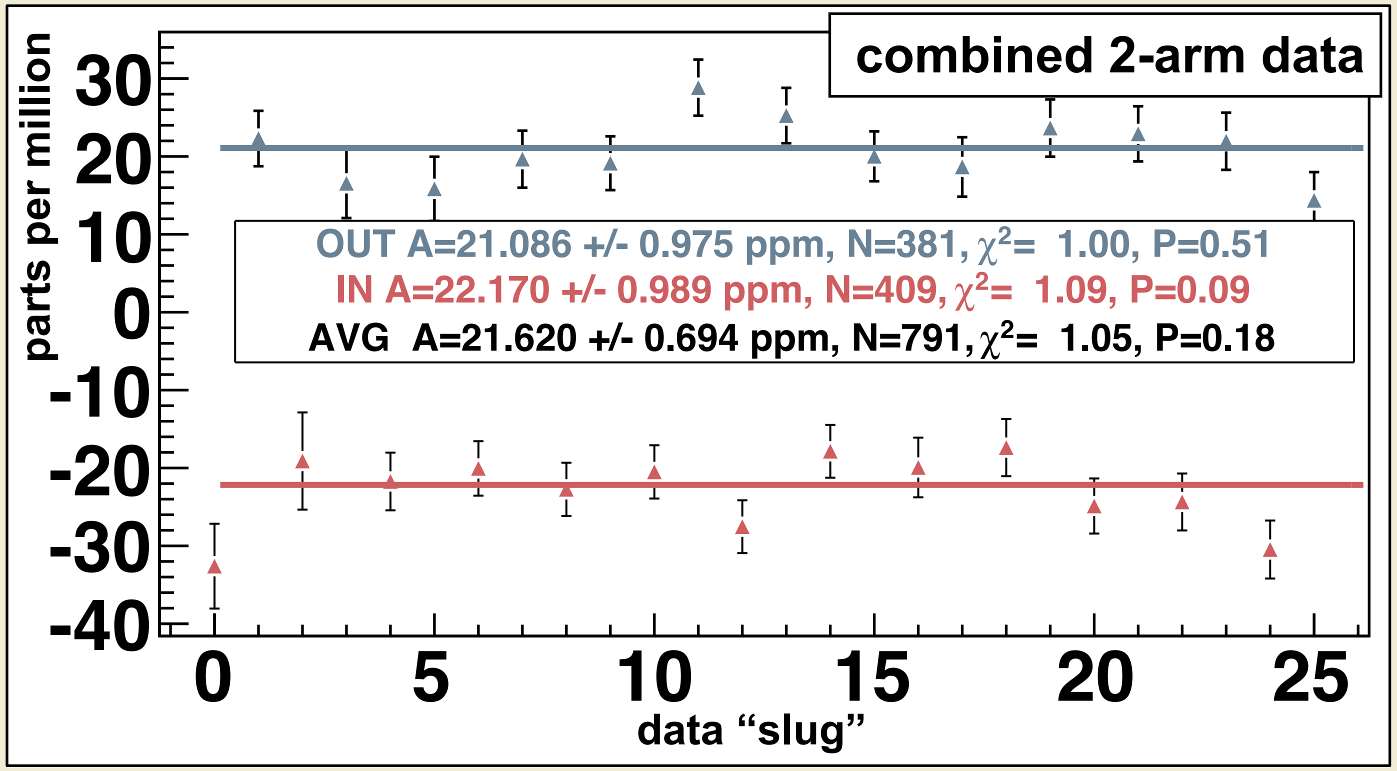
Total Correction for dx, dE:
-0.016 ppm (0.07%)

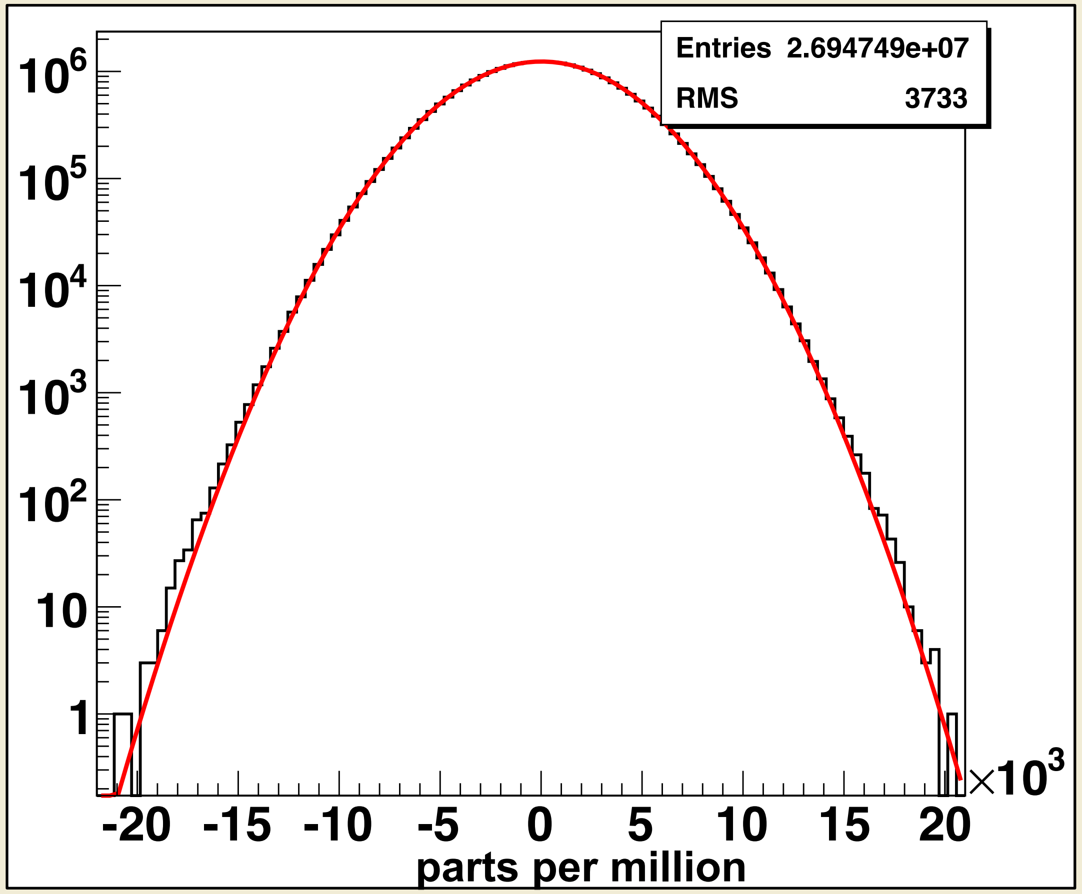
HAPPEX-III Measurement of A_{PV}

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

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

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





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

3.27% (stat)± 1.5% (syst)

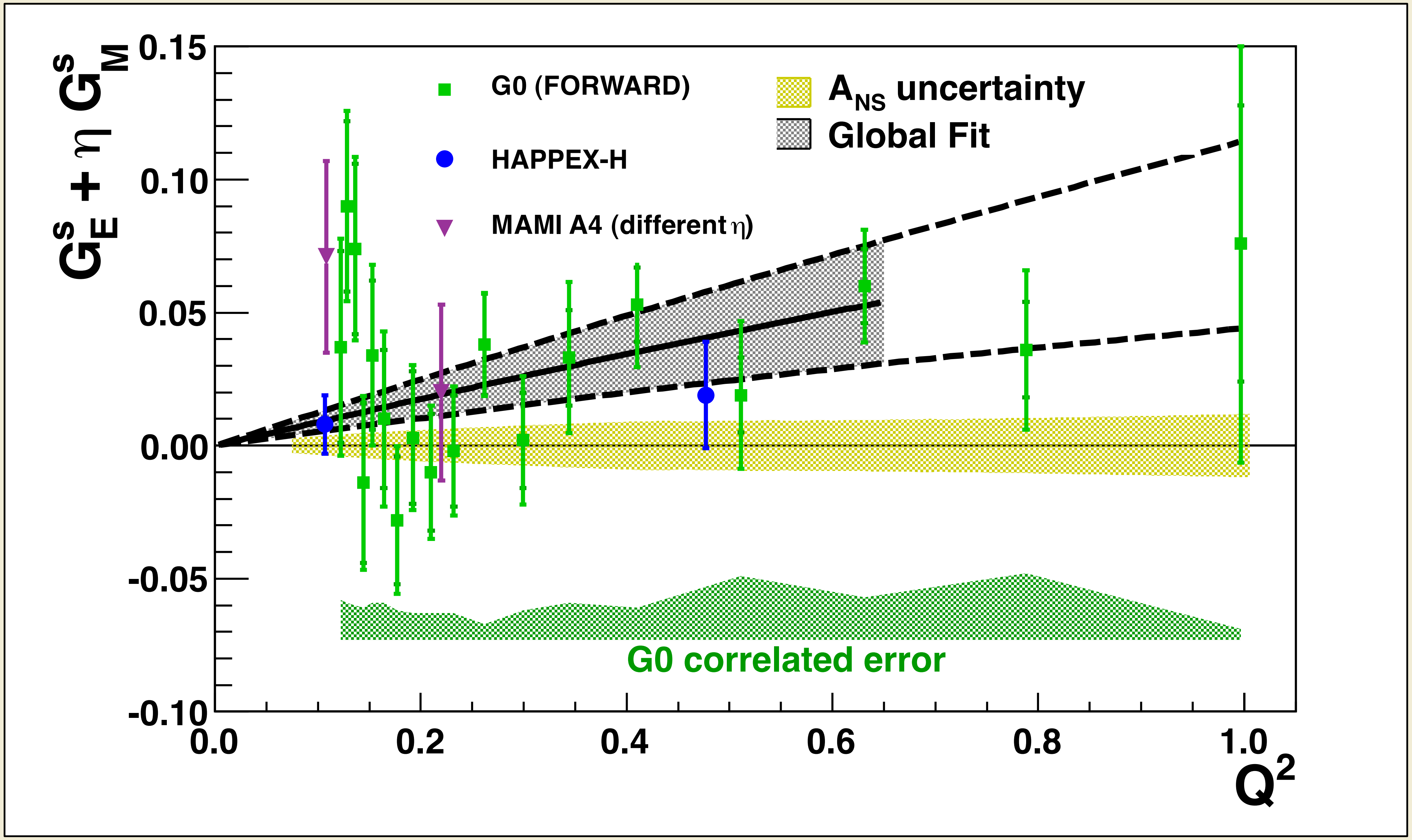
total correction ~2.5% + polarization

Analysis Blinded ± 2.5 ppm

HAPPEX-III Result

$A_{PV} = -23.803 \pm 0.778 \ (stat) \pm 0.362 \ (syst) \ ppm$

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

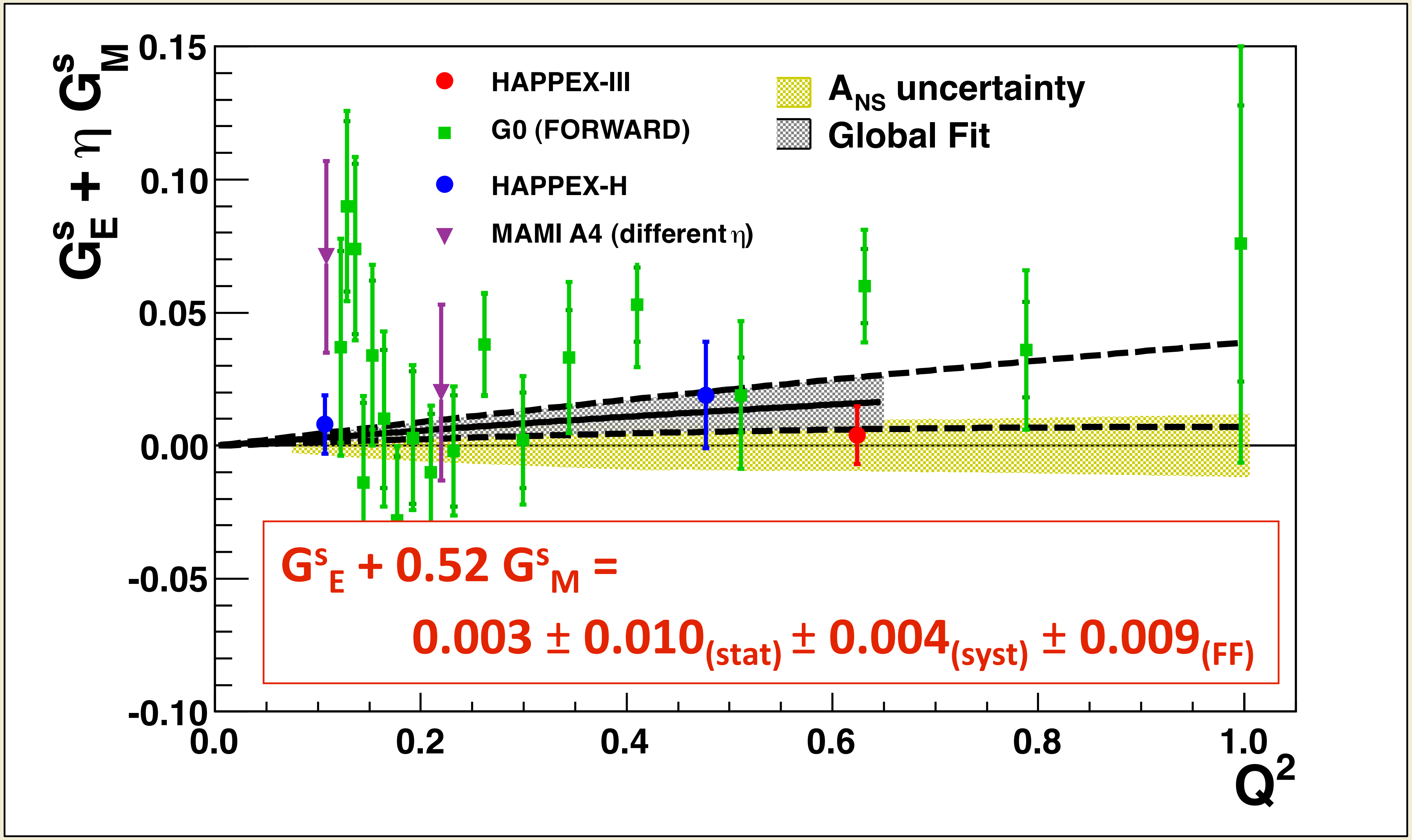


HAPPEX-III Result

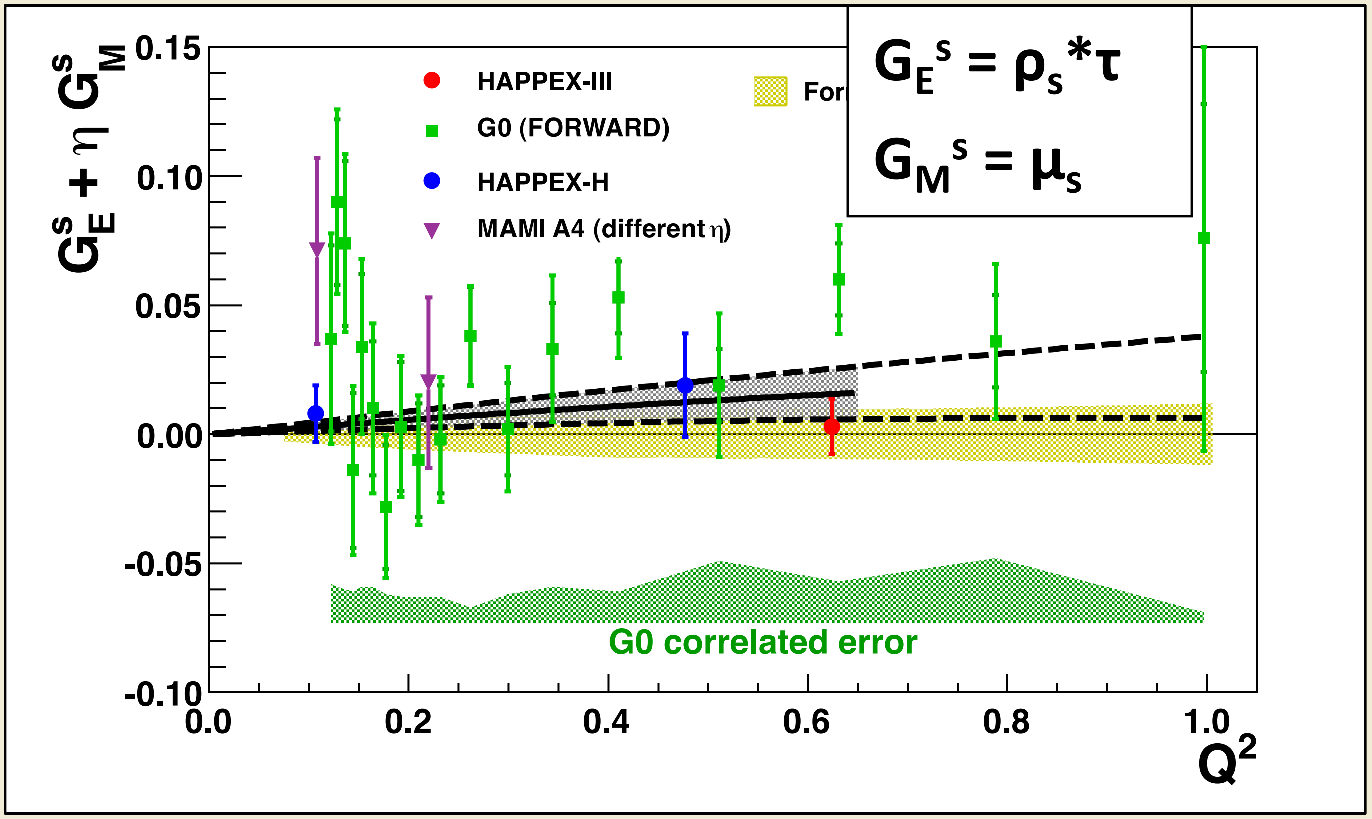
$A_{PV} = -23.803 \pm 0.778\ (stat) \pm 0.359\ (syst)\ ppm$

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

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

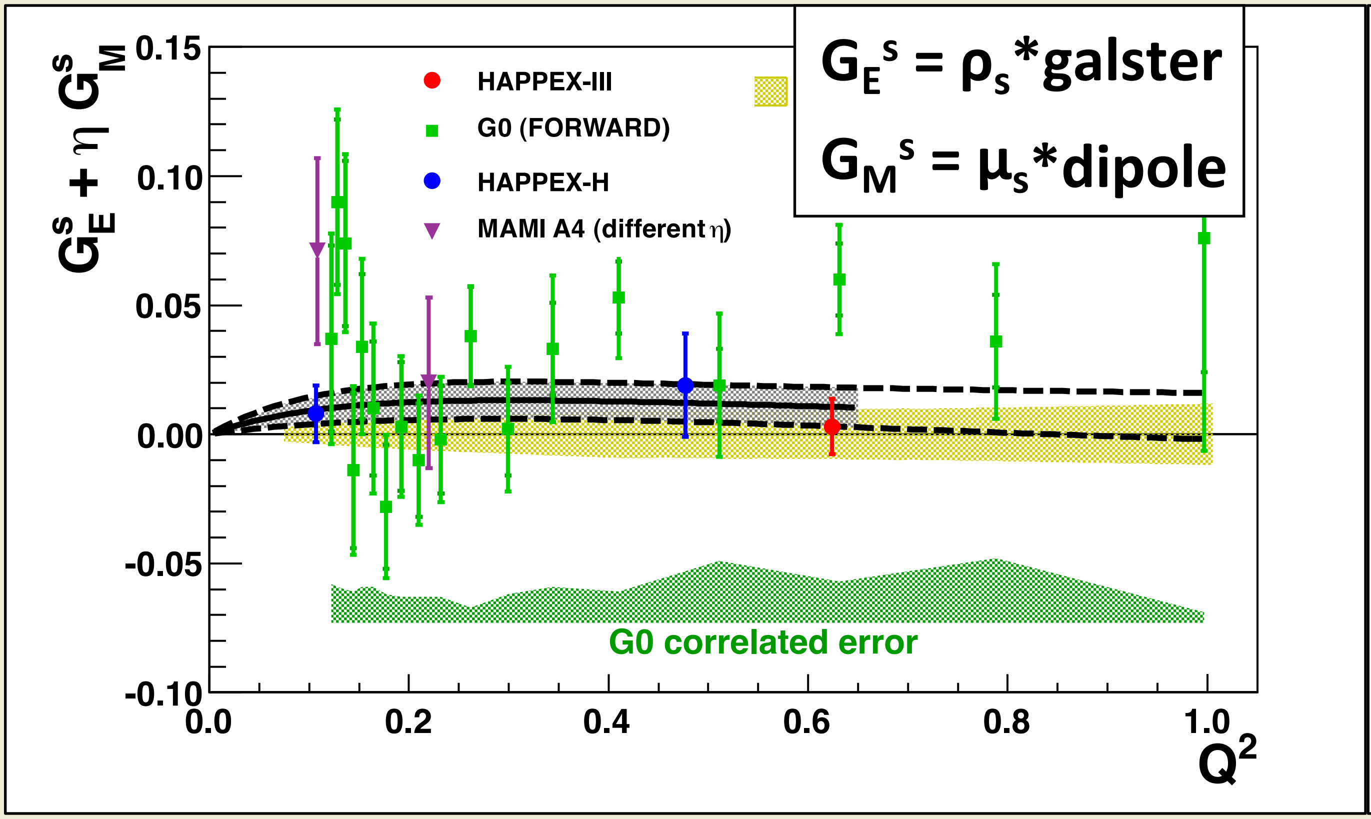


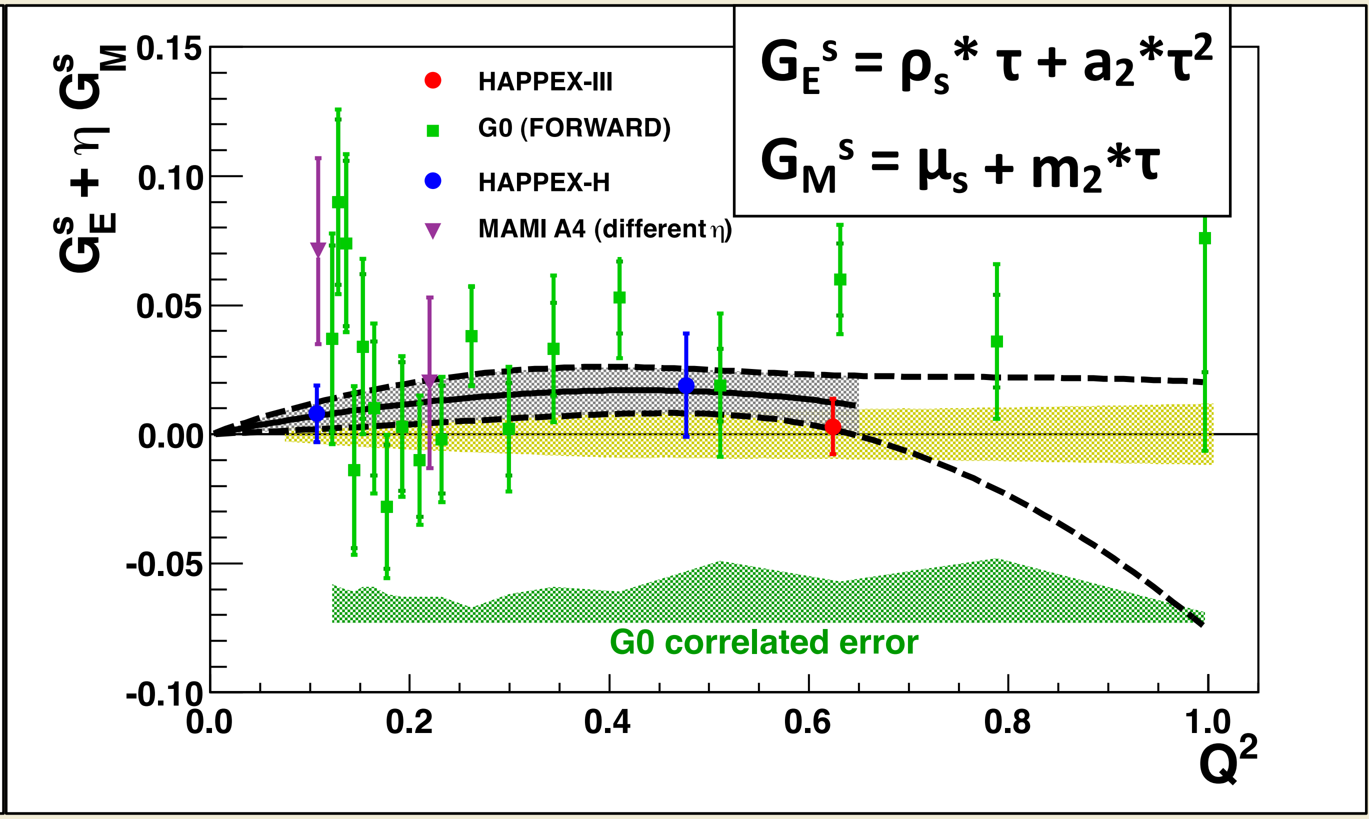
Parameterizations



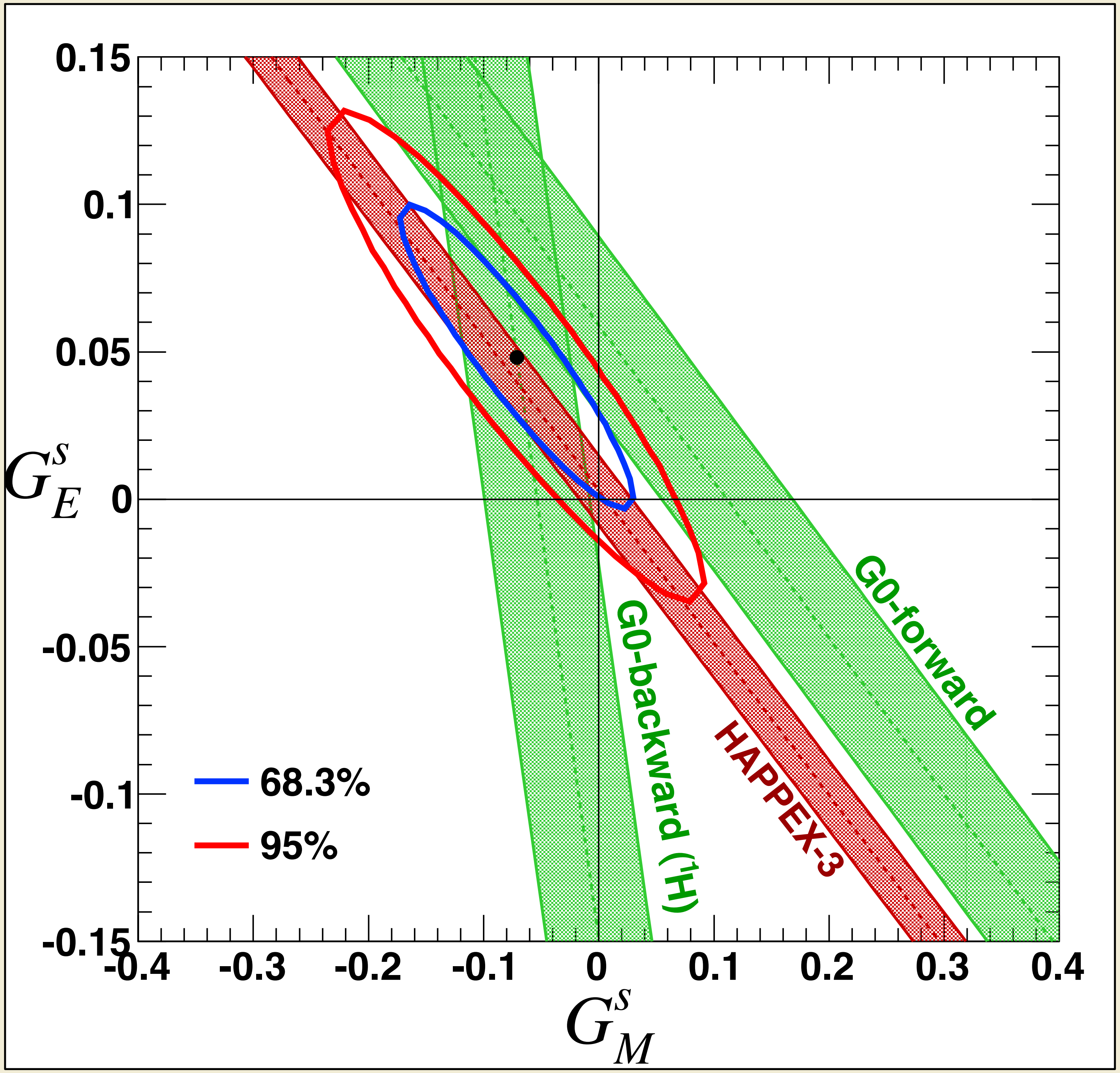
Fit includes all world data $Q^2 < 0.65$ GeV^2
G0 Global error allowed to float with unit constraint

Models need "bumps" to find significant strange effects





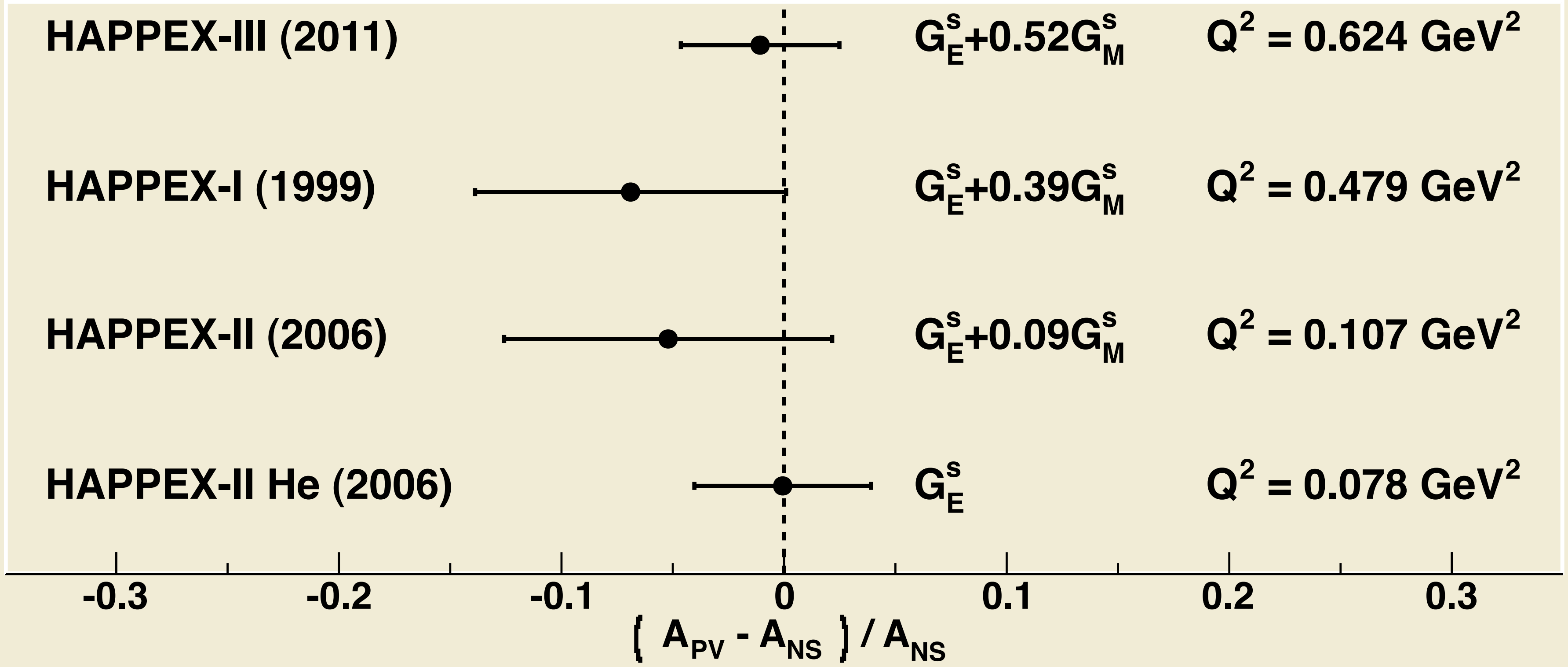
Q^2 = 0.62 GeV^2 in combination

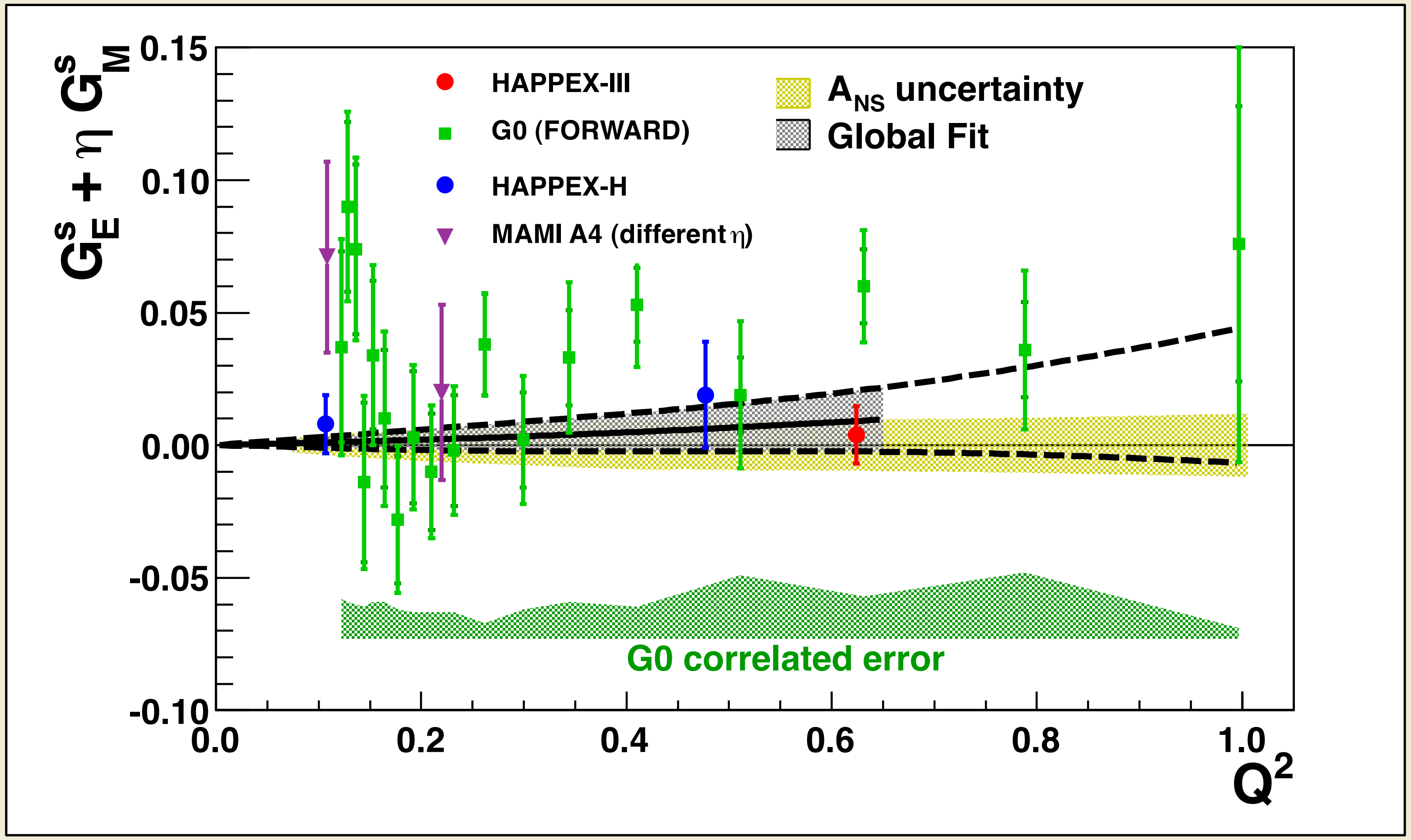


Zhu constraint is used for axial form-factor

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

Considering only the 4 HAPPEX measurements

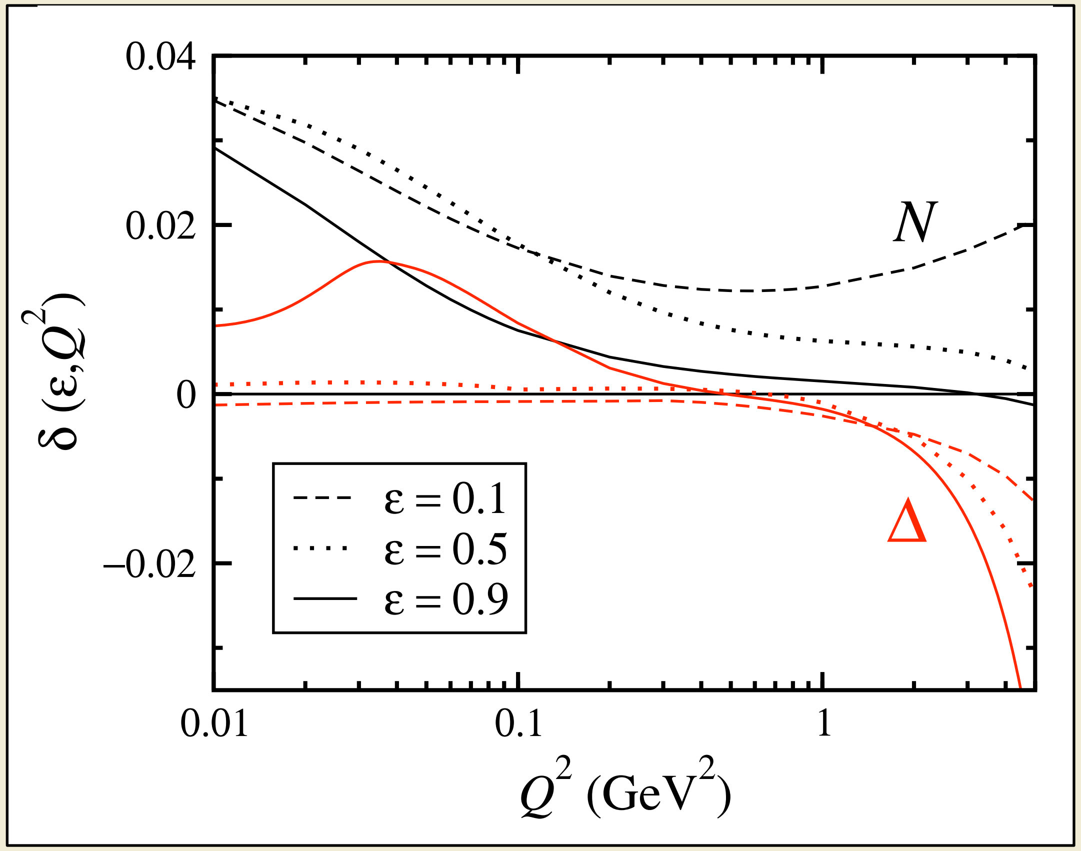




- High precision
- Small systematic error
- ε>0.95 - relatively clean theoretical interpretation

γZ box contributions

$$A_{\rm PV} = (1+\delta)A^0_{\rm PV} \equiv \left(\frac{1+\delta_{Z(\gamma\gamma)}+\delta_{\gamma(Z\gamma)}}{1+\delta_{\gamma(\gamma\gamma)}}\right) A^0_{\rm PV}$$

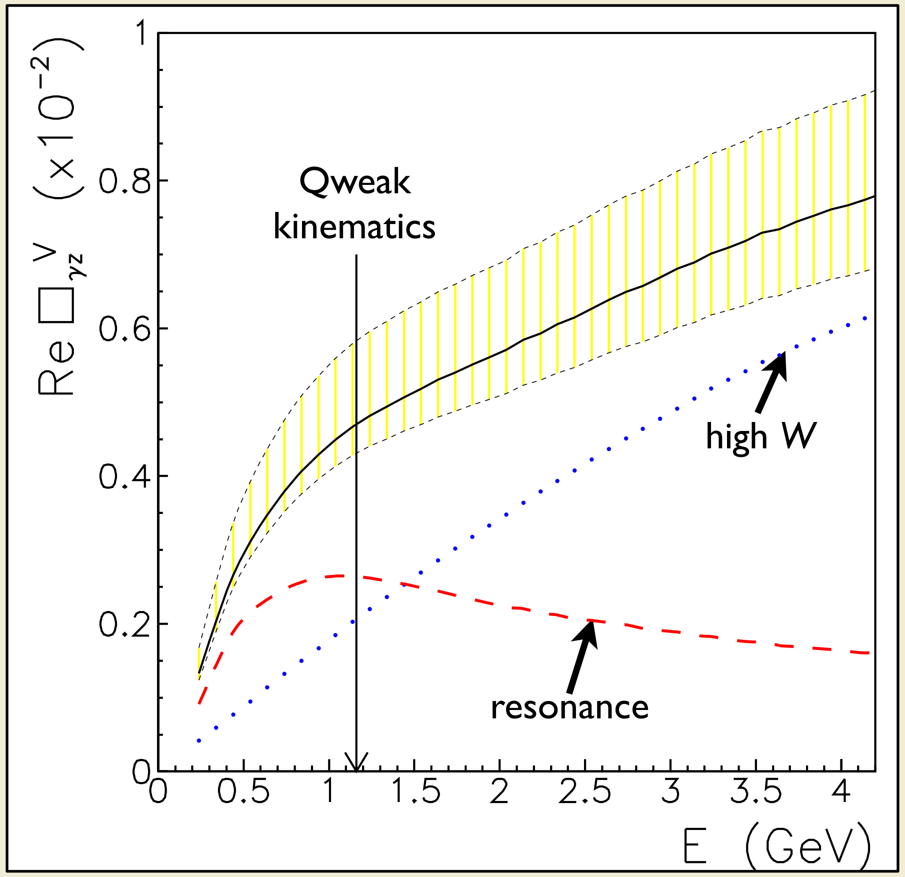


Tjon, Blunden, Melnitchouk (2009)

Also results from Zhou, Kao, Yang, Nagata (2010)

At Q^2 = 0.6 GeV^2 **~10^{-3} for A_{PV} for H-III**

$$Q^p_W = (1+\Delta\rho+\Delta_e)(1-4\sin^2\theta_W(0)+\Delta'_e) + \Box_{WW}+\Box_{ZZ}+\Box_{\gamma Z}(0)\ ,$$



Sibirtsev, Blunden, Melnitchouk, Thomas (2010)

Also results from: Rislow, Carlson (2010),
Gorchtein, Horowitz, M. Ramsey-Musolf(2011)

At Q^2 = 0.6 GeV^2, Qweak only about 20% of asymmetry: **0.15% for A_{PV} for H-III**

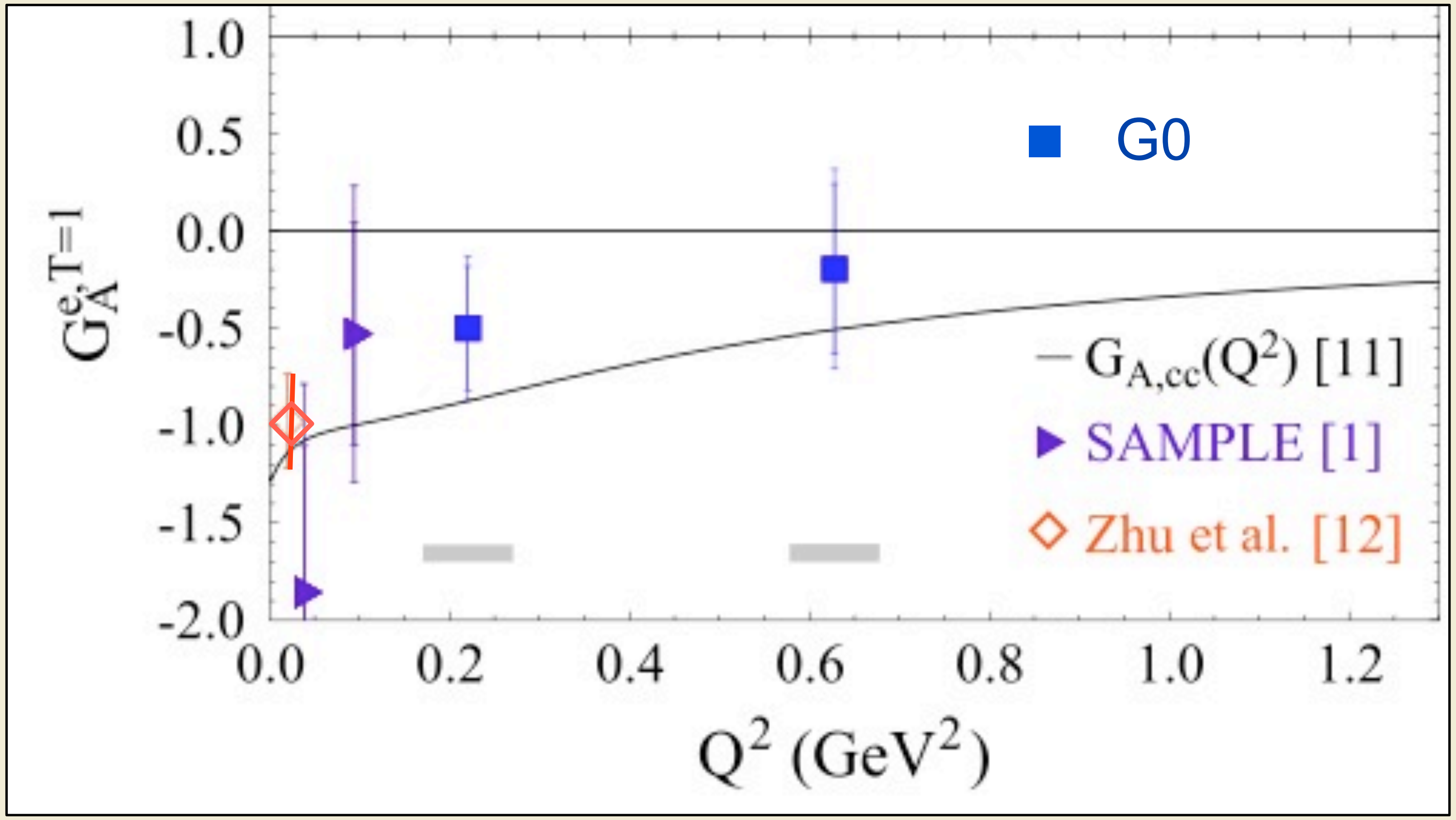
The Axial Term and the Anapole Moment

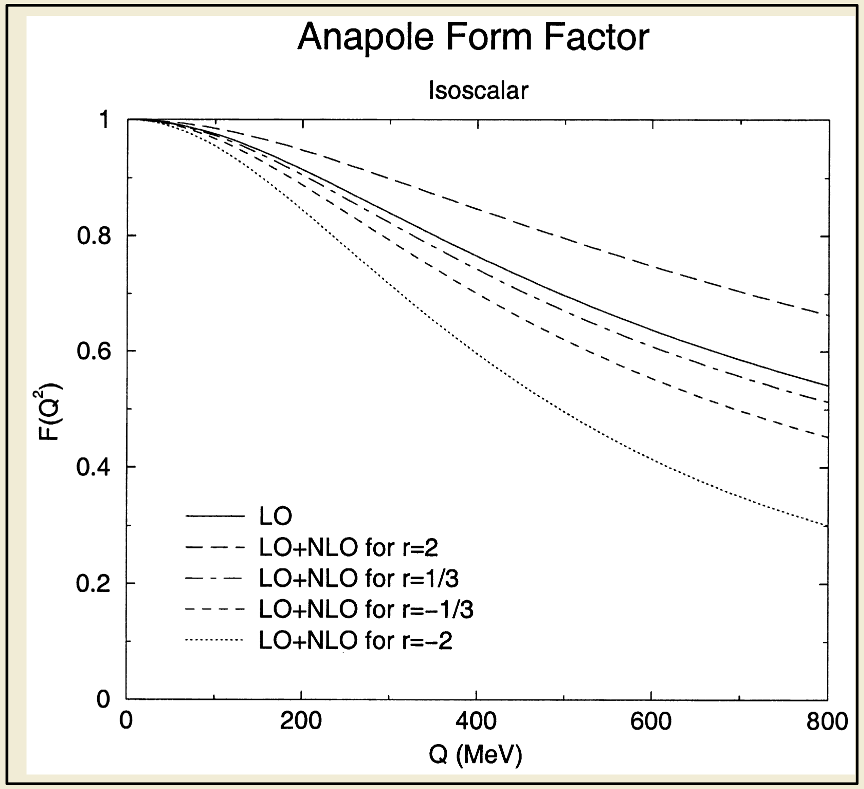
Anapole Moment Correction:

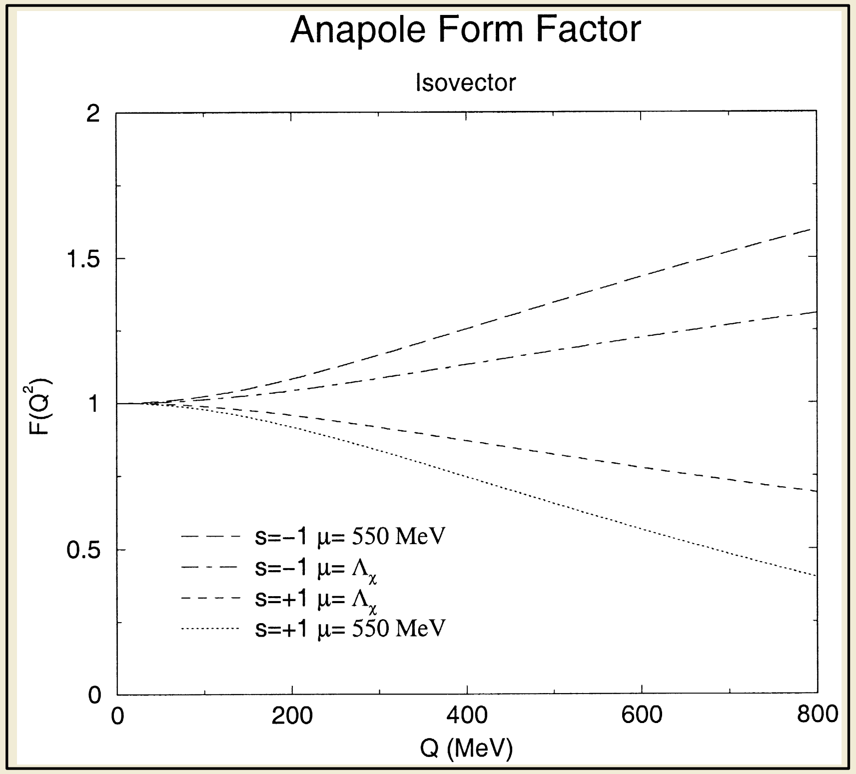
Multiquark weak interaction in $R_A^{(T=1)}$, $R_A^{(T=0)}$

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

How does the correction change with Q^2?



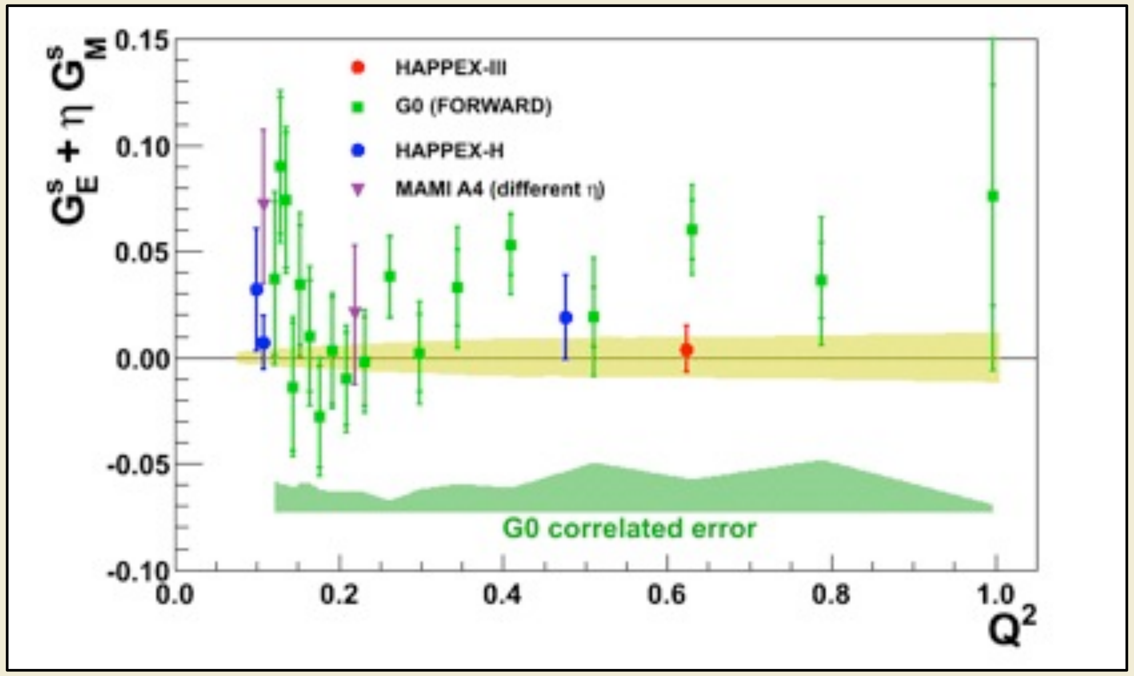




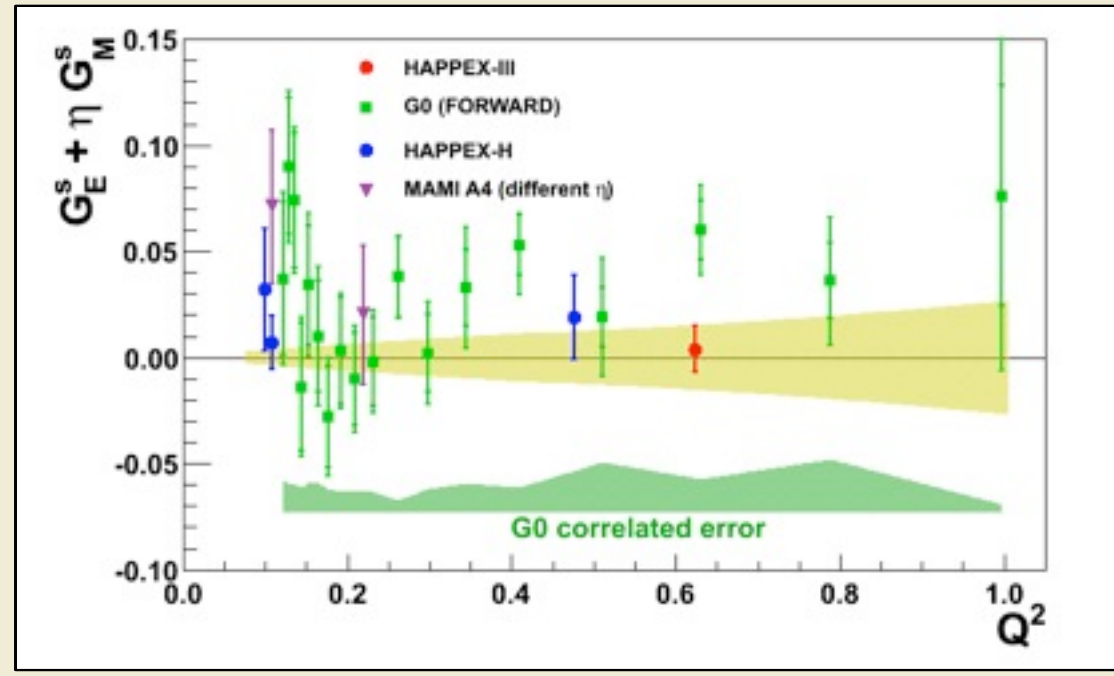
Maekawa, Phys Lett B 488(2000)

The Anapole Moment

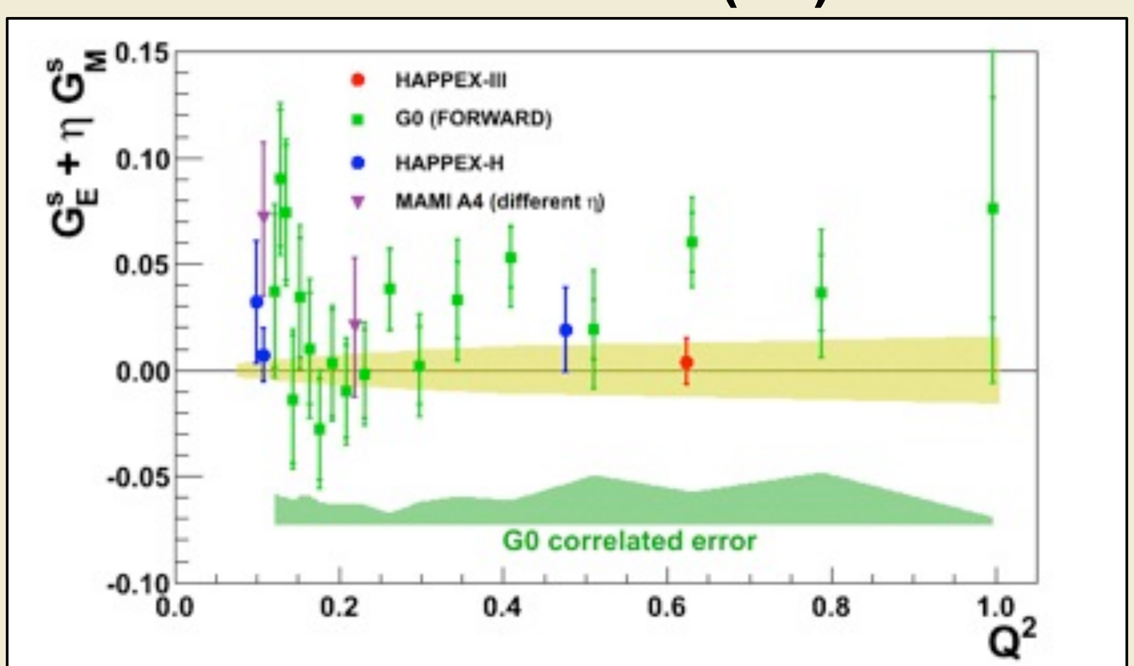
Zhu error bar, correction scales with $F_A(Q^2)$



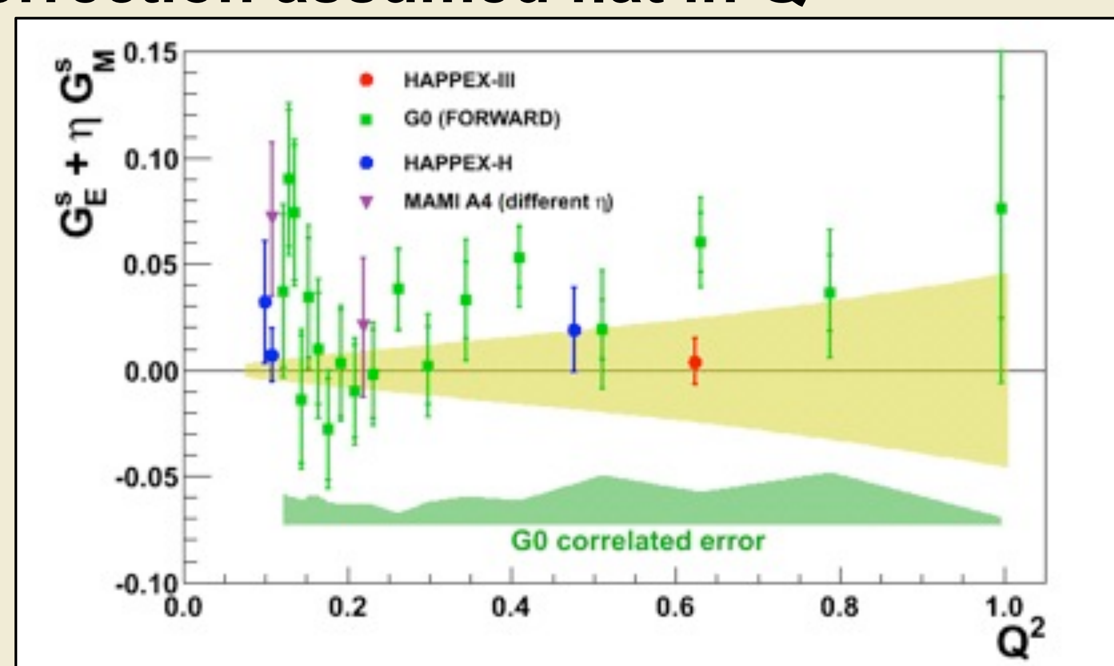
Zhu error bar, correction assumed flat in Q^2



approx G0 experimental error bar, correction scales with $F_A(Q^2)$



approx G0 experimental error bar, correction assumed flat in Q^2



Charge Symmetry Violation

PROTON

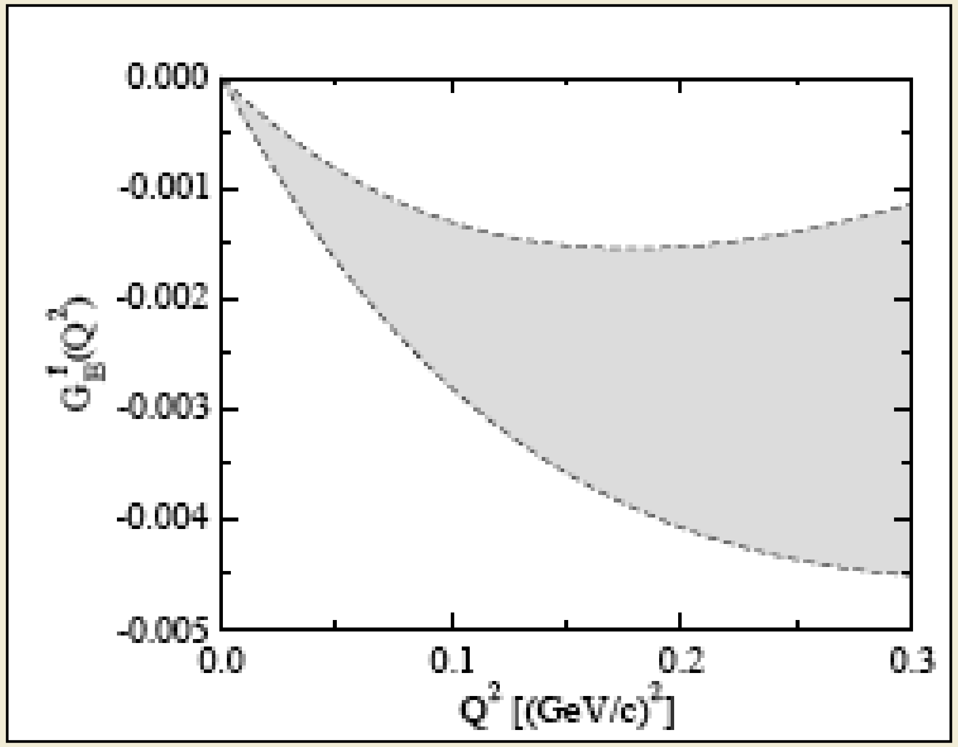
Old Story: theoretical CSB estimates indicate <1% violations

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

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

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

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



Contribution from $G^{u/d}$ ~ **0.004-0.009** near H-II error bar

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

Correction at higher Q^2 not constrained

Helium-4

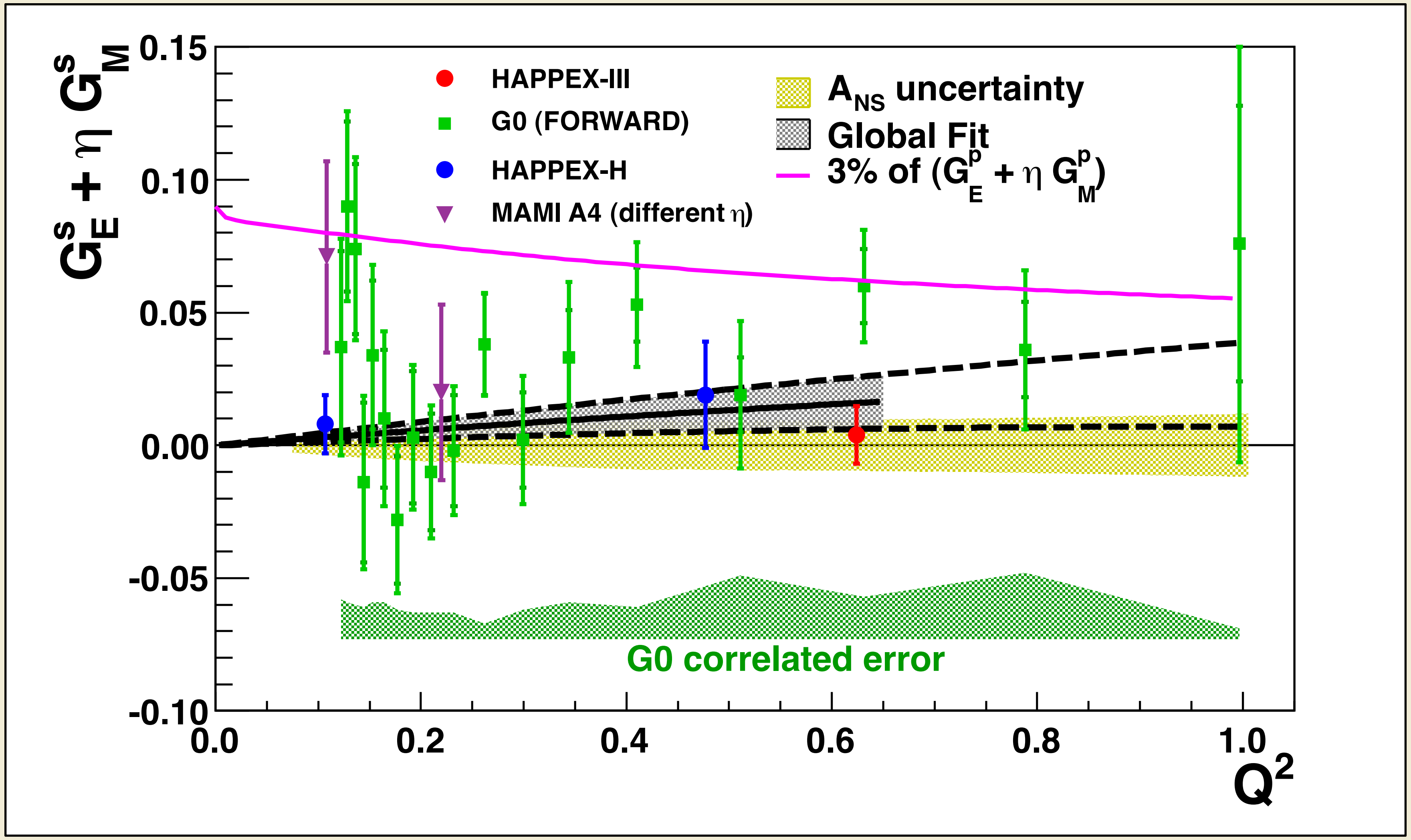
Old Story: Nuclear effects all << 1%, no explicit correction made.

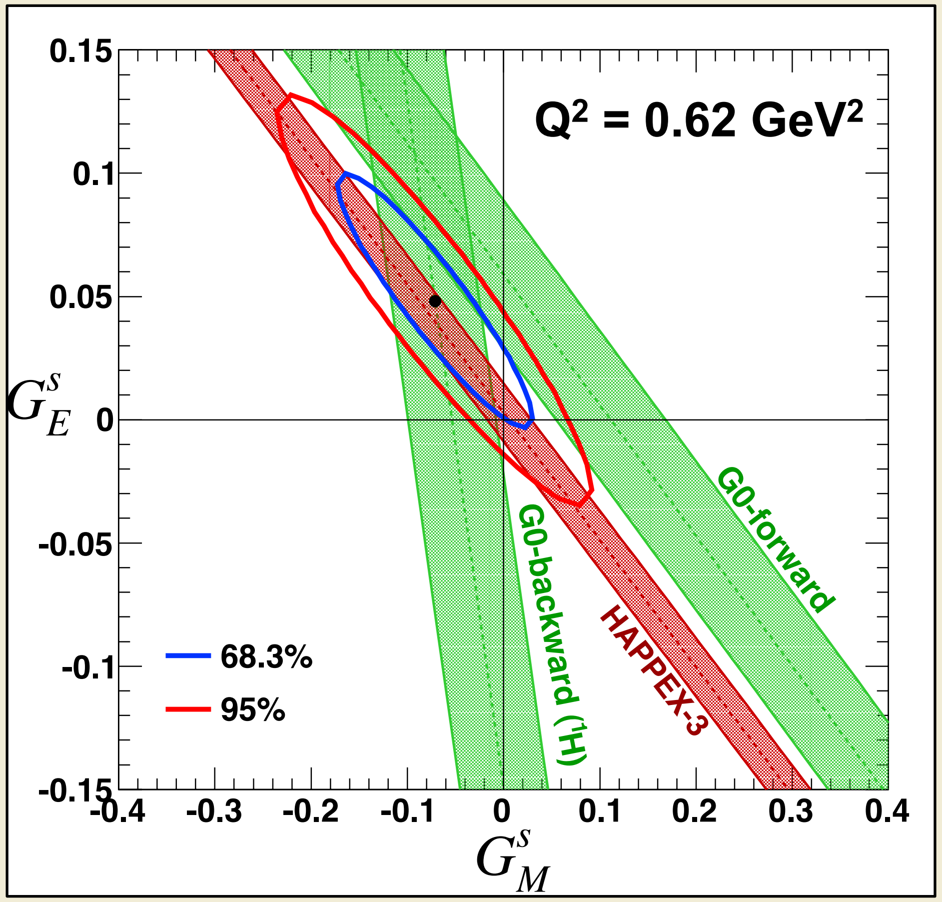
- ^{4}He g.s. pure isospin state: Ramavataram, Hadjimichael, Donnelly PRC 50(1994)1174
- No D-state admixture: Musolf & Donnelly PL B318(1993)263
- Meson exchange corrections small: Musolf, Schiavilla, Donnelly PRC 50(1994)2173

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

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

Strange Vector Form Factors Are Small

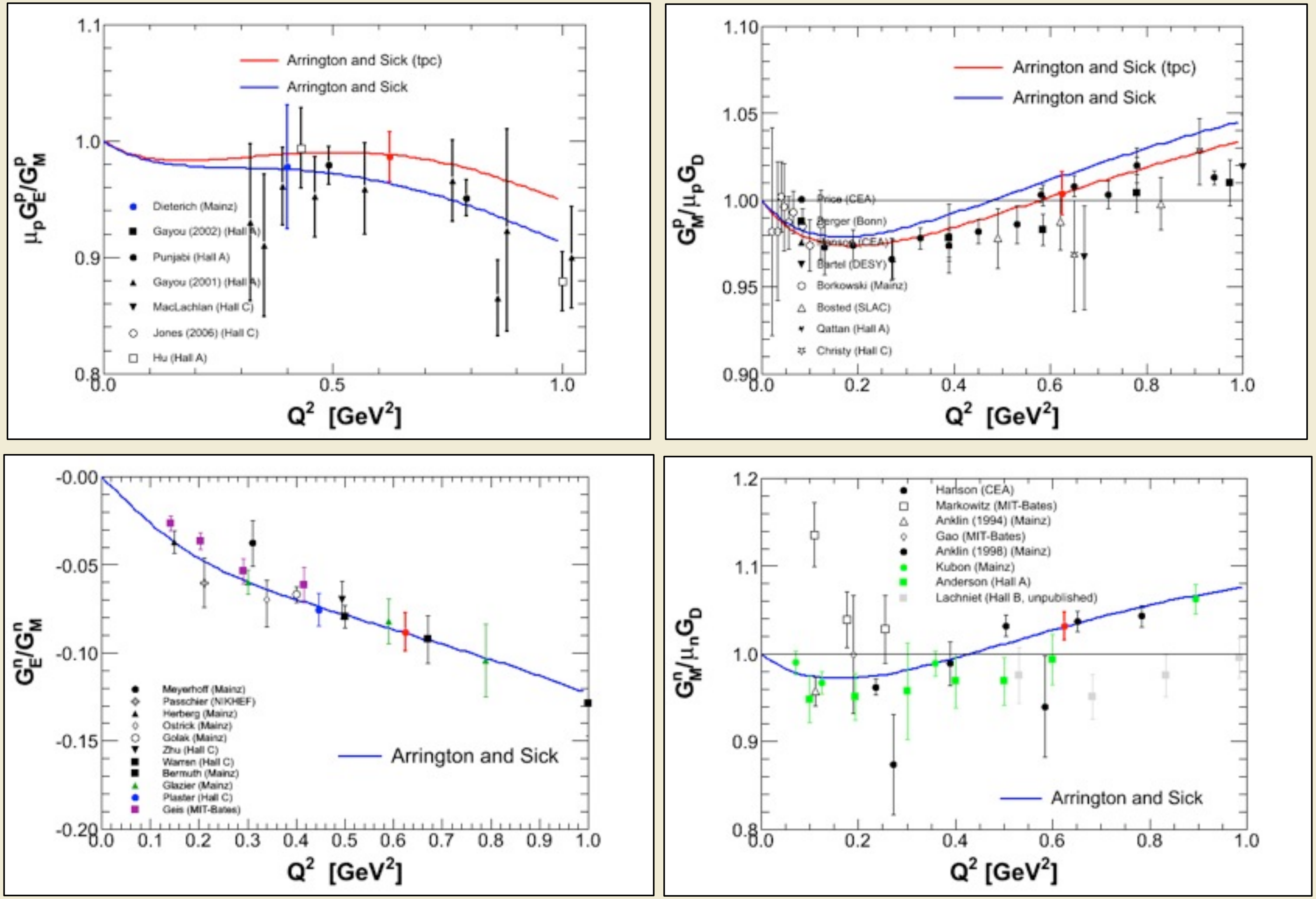




- HAPPEX-III provides a clean, precise measure of A_{PV} at Q^2=0.62 GeV^2, and finds that it is consistent with no strangeness contribution to the long-range electromagnetic interaction of the nucleon
- Recent lattice results indicate values smaller than these FF uncertainties
- Further improvements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

Backup

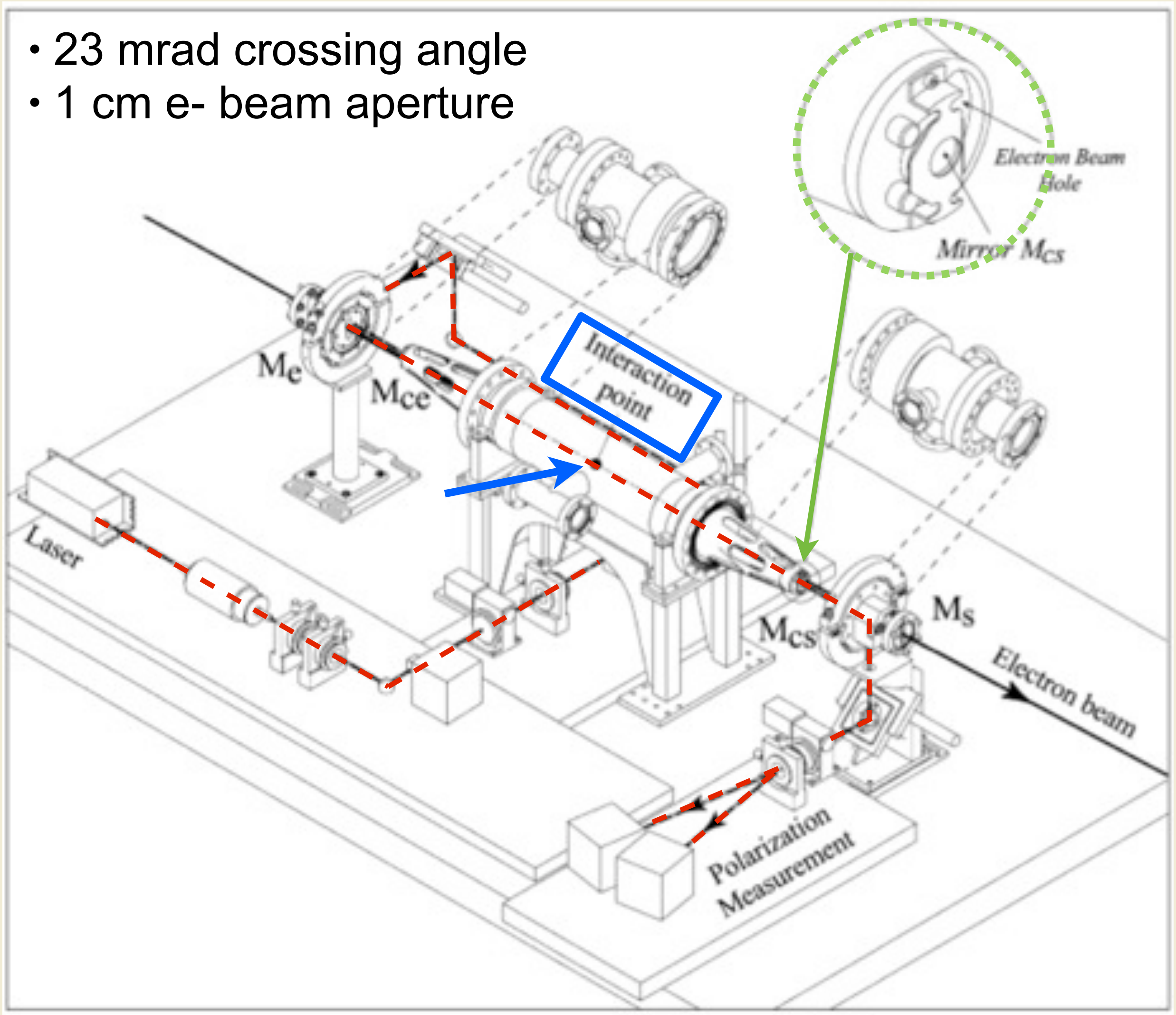
EMFF

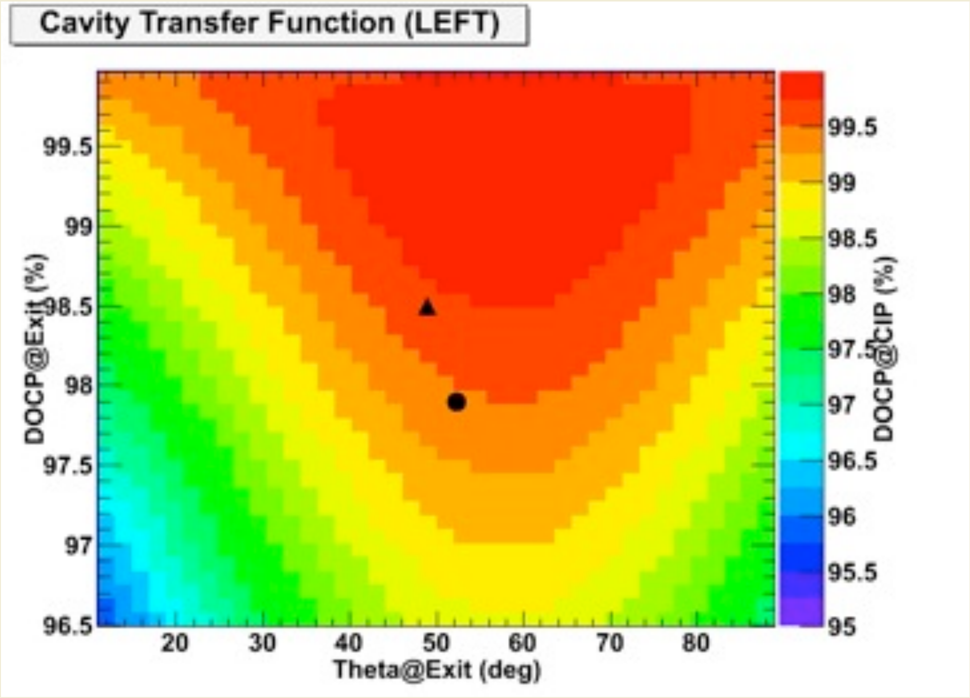


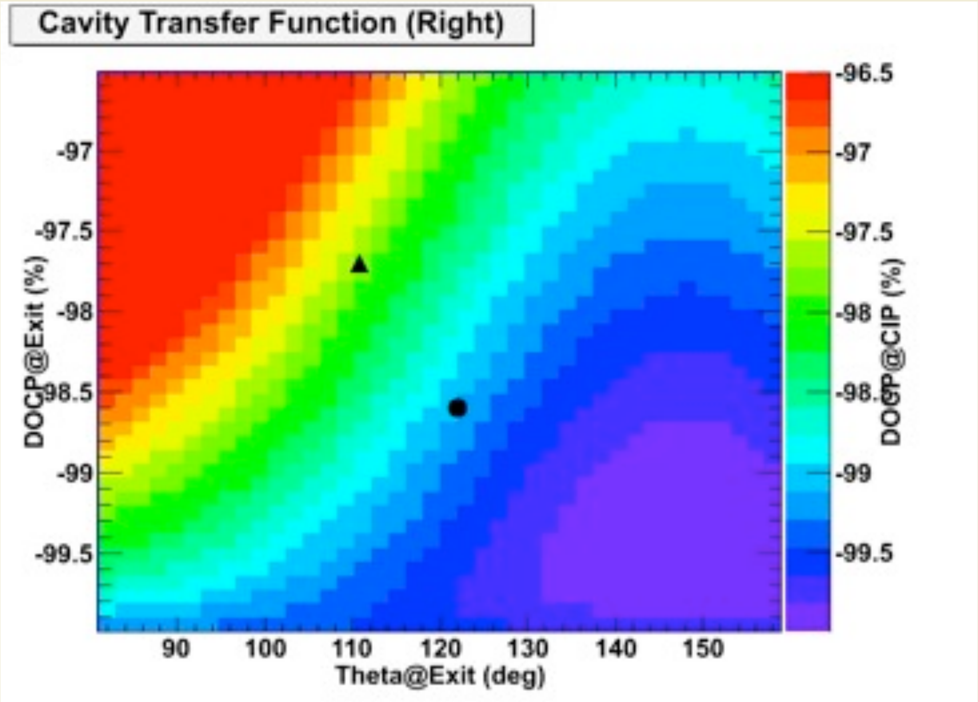
G_E^p	0.3%
G_M^p	1.1%
G_E^n	1.6%
G_M^n	1.4%
σ_{red}	1.1%
R_{Ana}	0.6%
Total	2.7%

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

Compton Polarimetry, Transfer Function





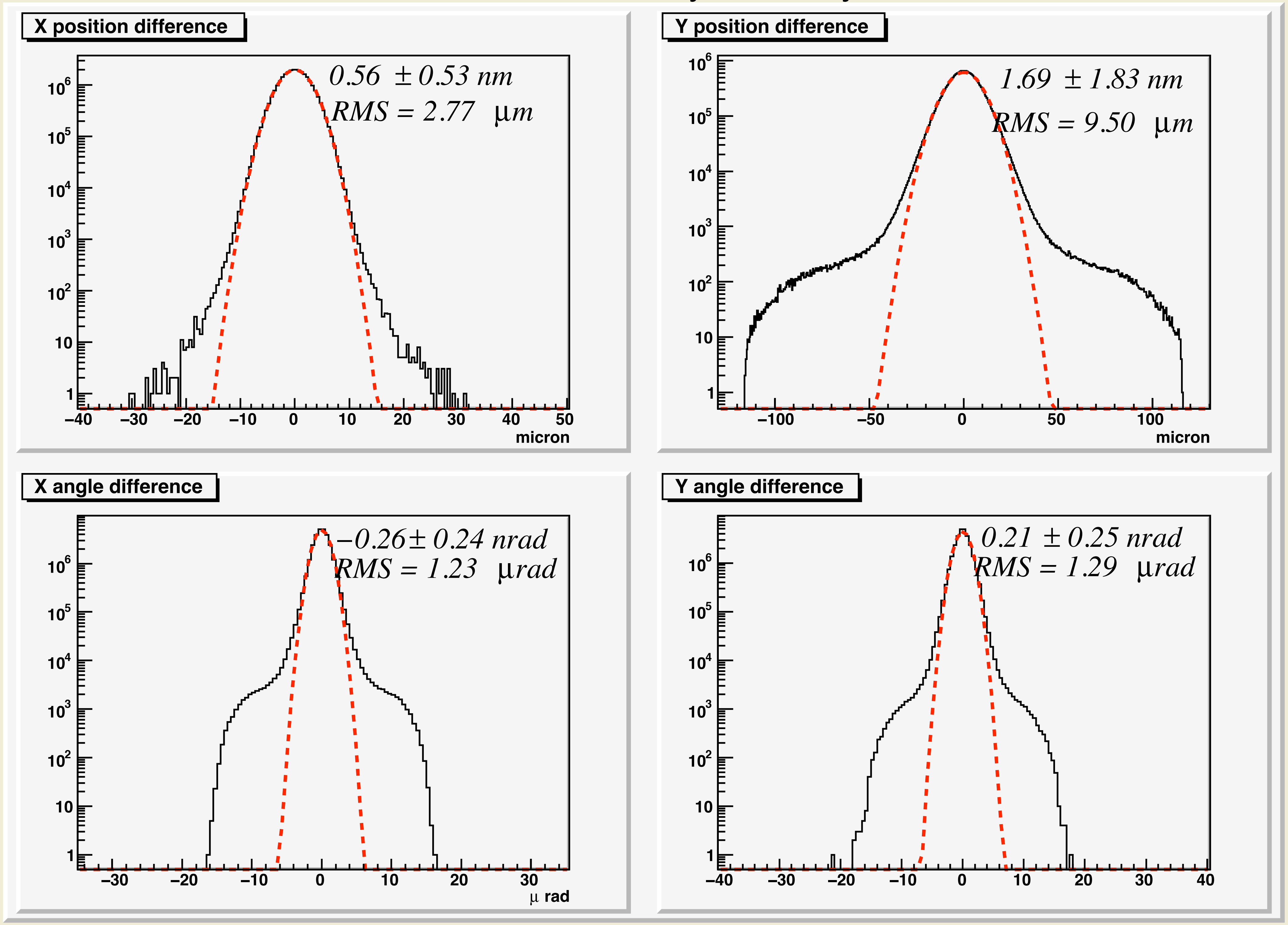



```
LEFT:
          AVERAGE:                  97.90%, 52.3 degrees   :   99.44%
          WithoutCavity:            98.46%, 48.9 degrees   :   99.65%

RIGHT:
          AVERAGE:                  -97.81%, 122.02 degrees   :   -98.59%
          WithoutCavity:            -97.67%, 110.78 degrees   :   -97.72%
```

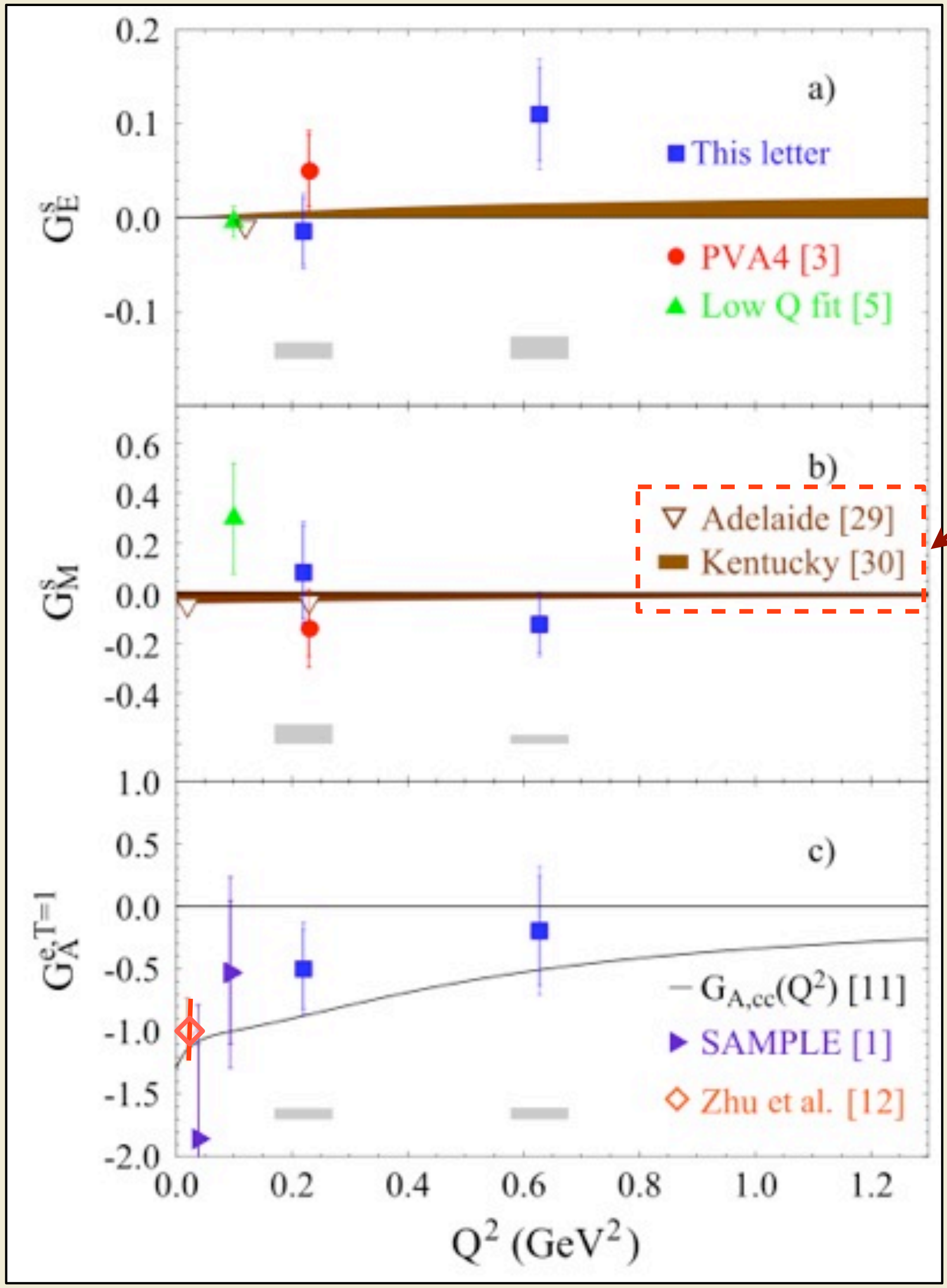
Helicity Correlated Position Differences

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



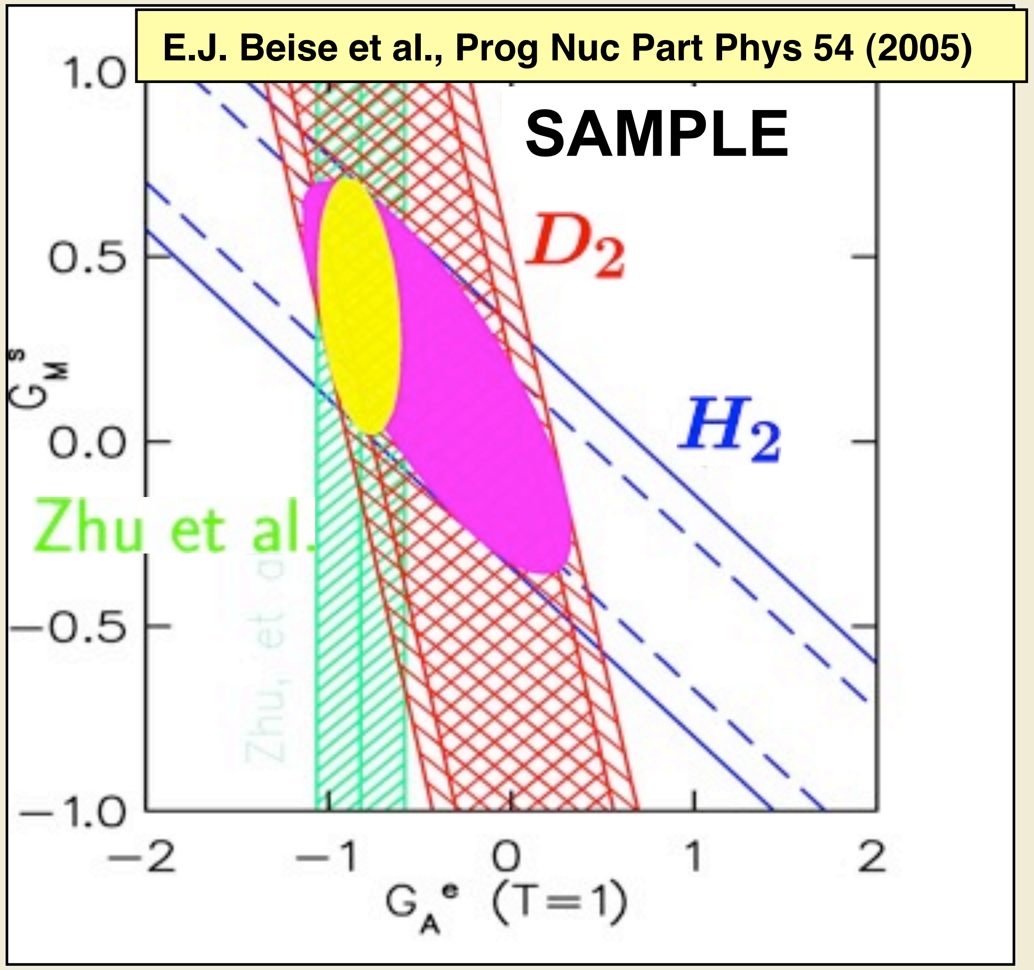
This was still the leading source of systematic uncertainty in the proton asymmetry

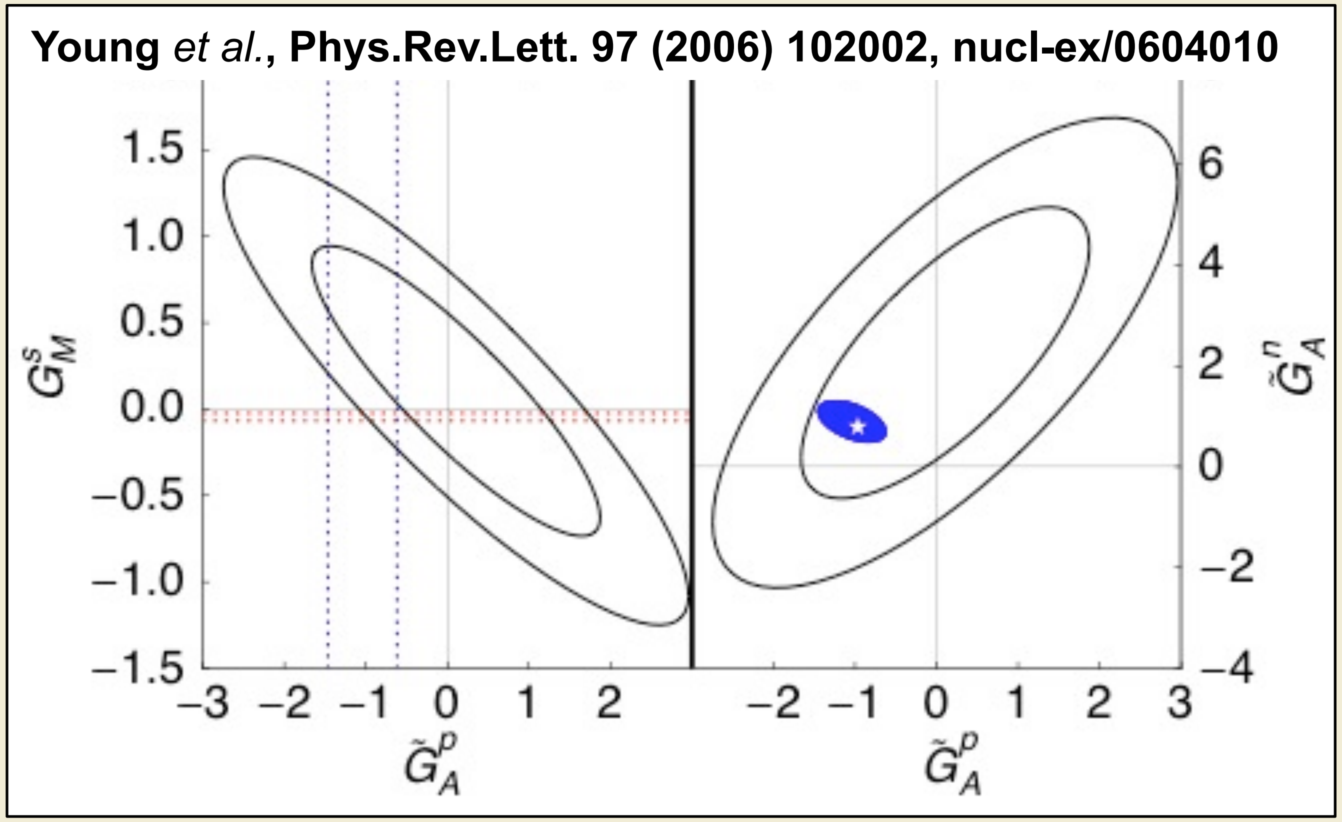
Form Factor Separation



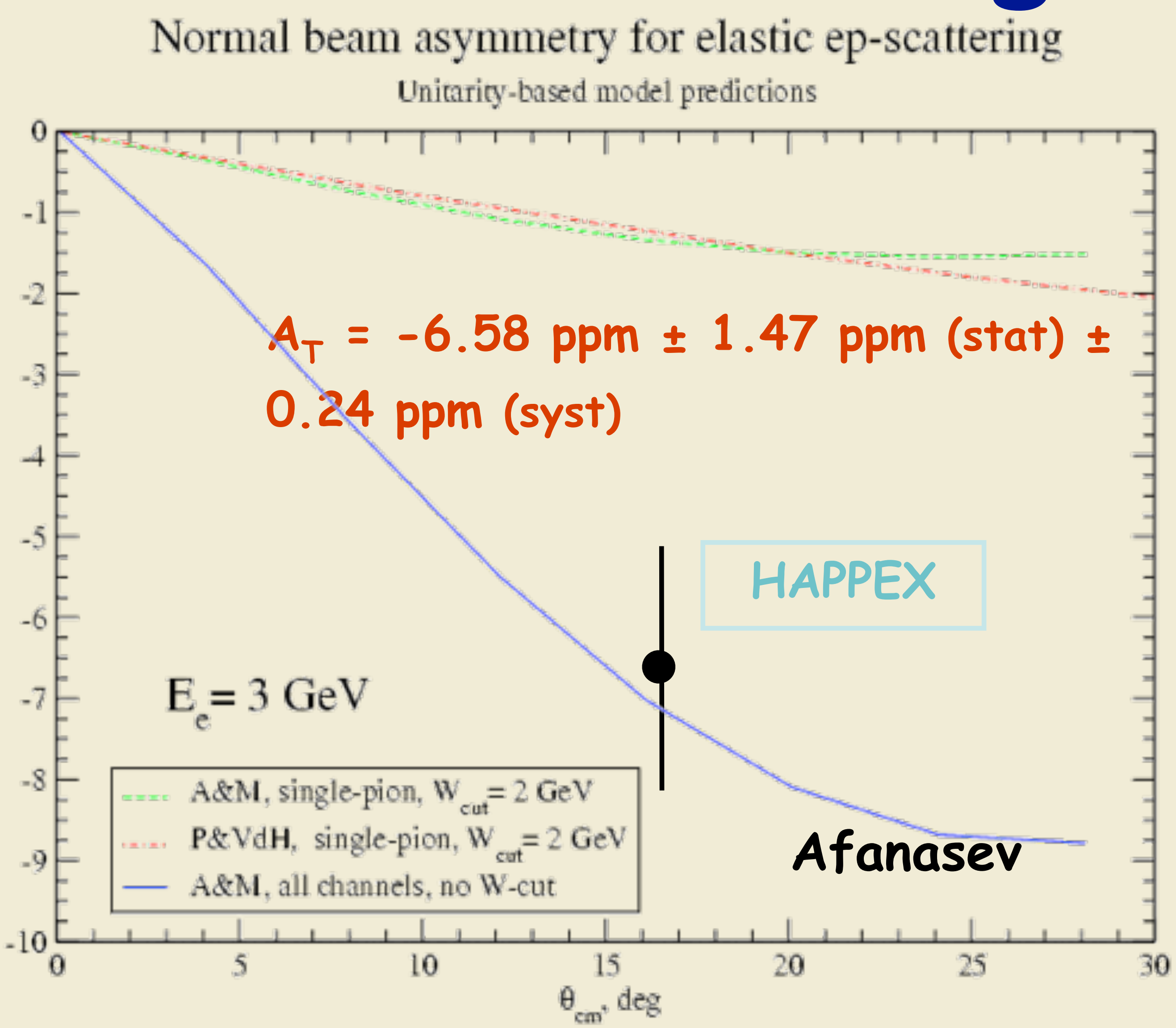
G0 Backward Scattering, **PRL 104, 012001 (2010)**

QCD lattice suggests very small effects

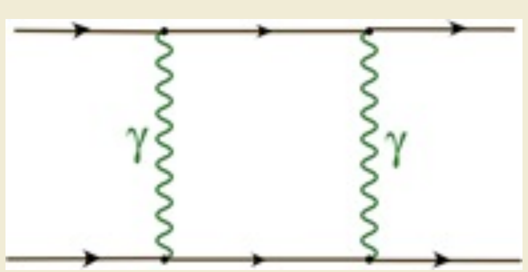




Transverse Single-Spin Asymmetry A_T



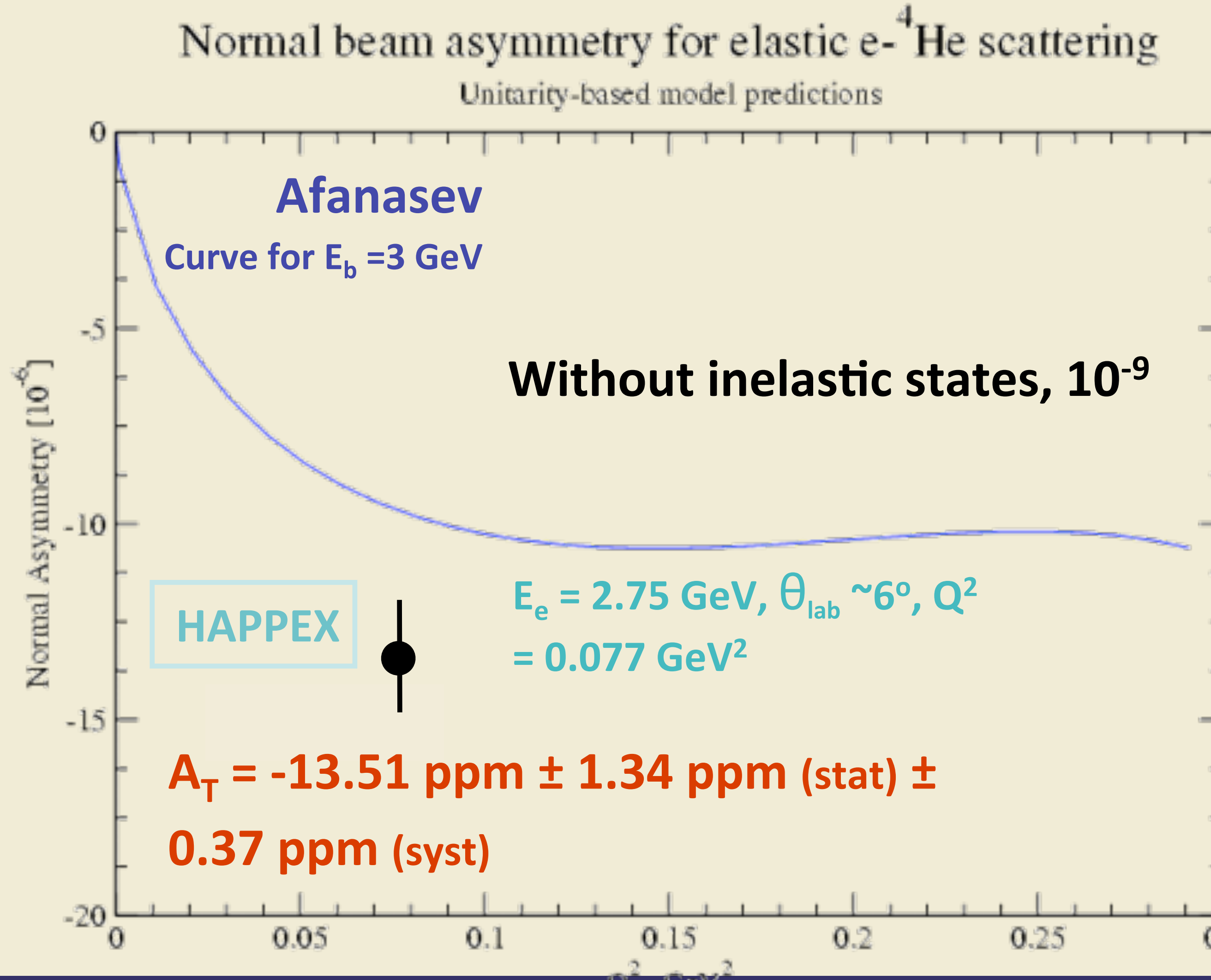
Clear signal from 2-photon exchange processes, dominated by excited intermediary states



Beam normal single-spin asymmetry in elastic electron scattering

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

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

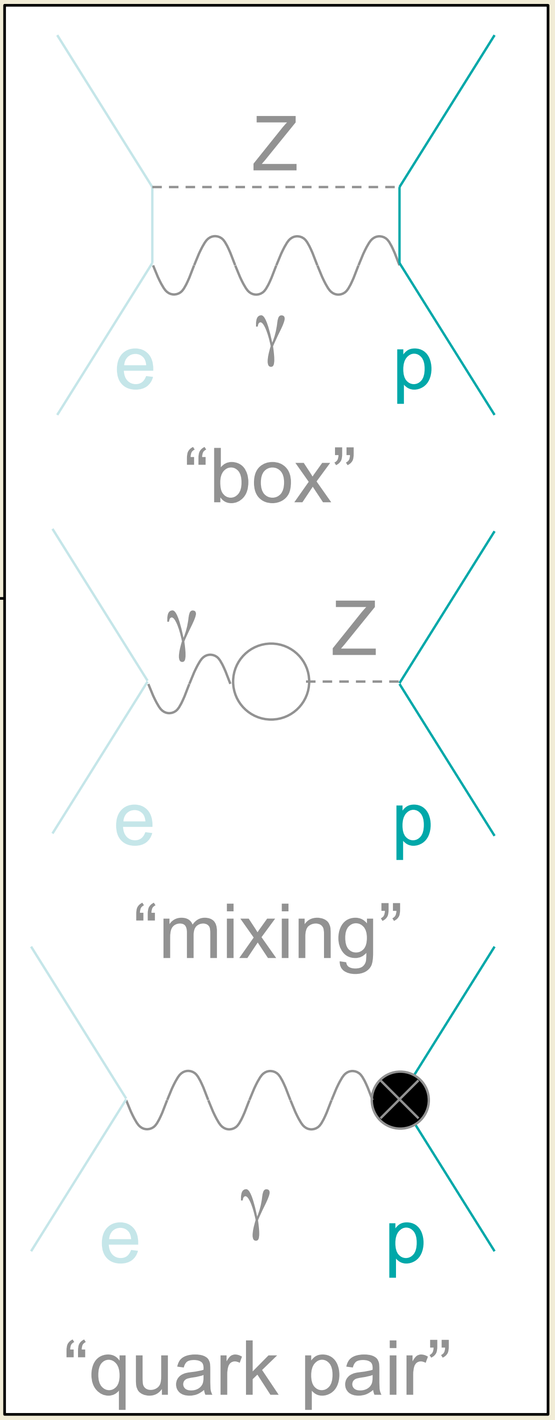


The Axial Term and the Anapole Moment

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:

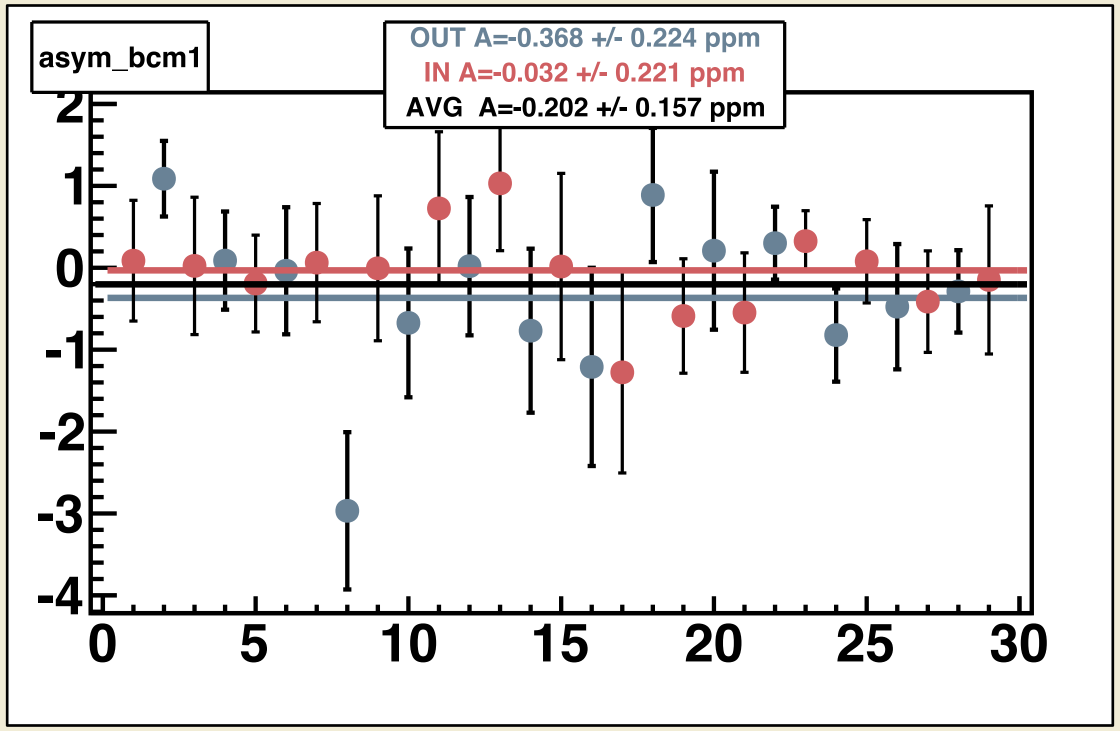
Multiquark weak interaction in $R_A^{(T=1)}$, $R_A^{(T=0)}$

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

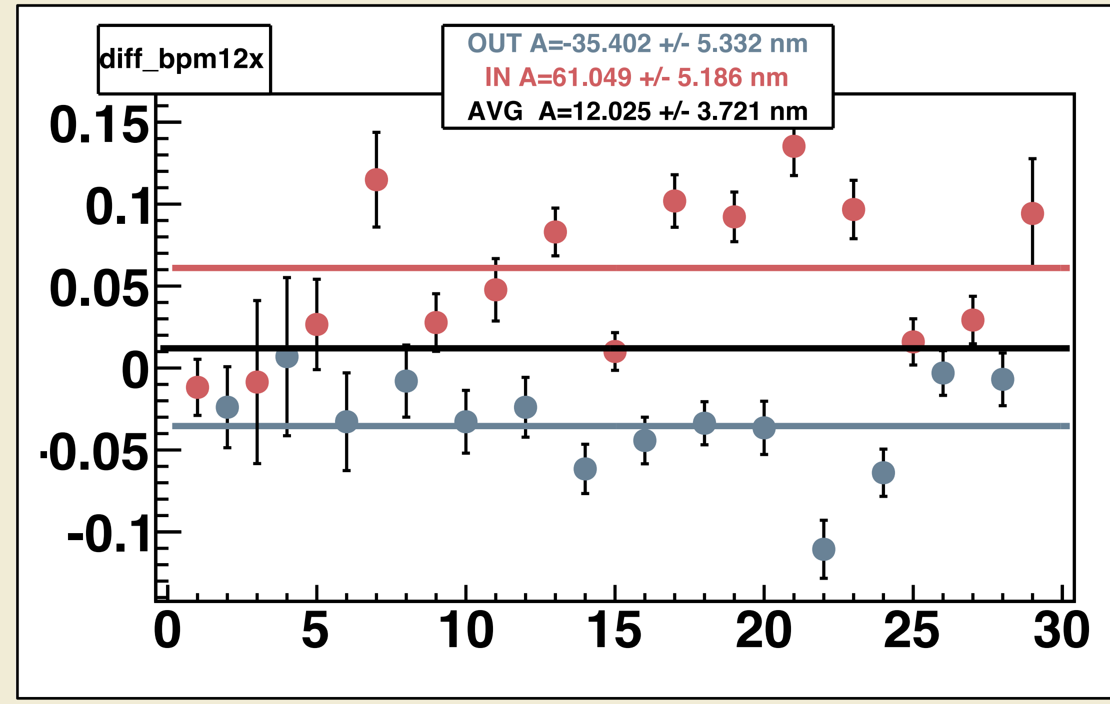
- Model dependent calculation with large uncertainty
- Uncertainty dominates axial term

Difficult to achieve tight experimental constraint

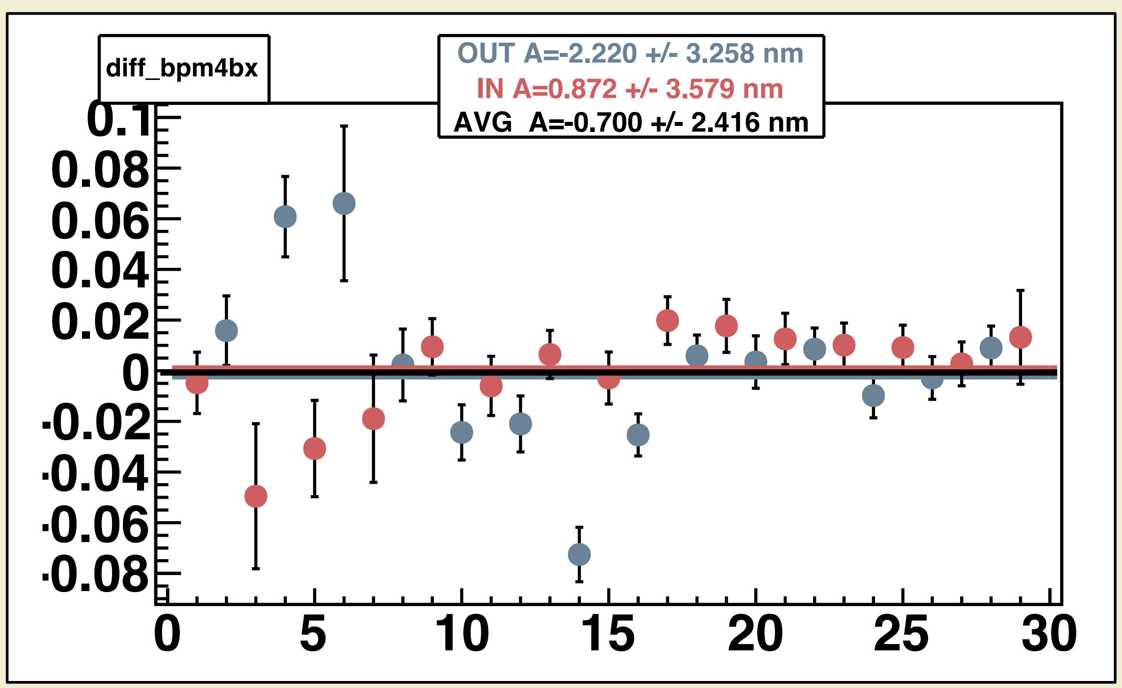
Beam Asymmetries



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



Implies energy asymmetry at 3 ppb

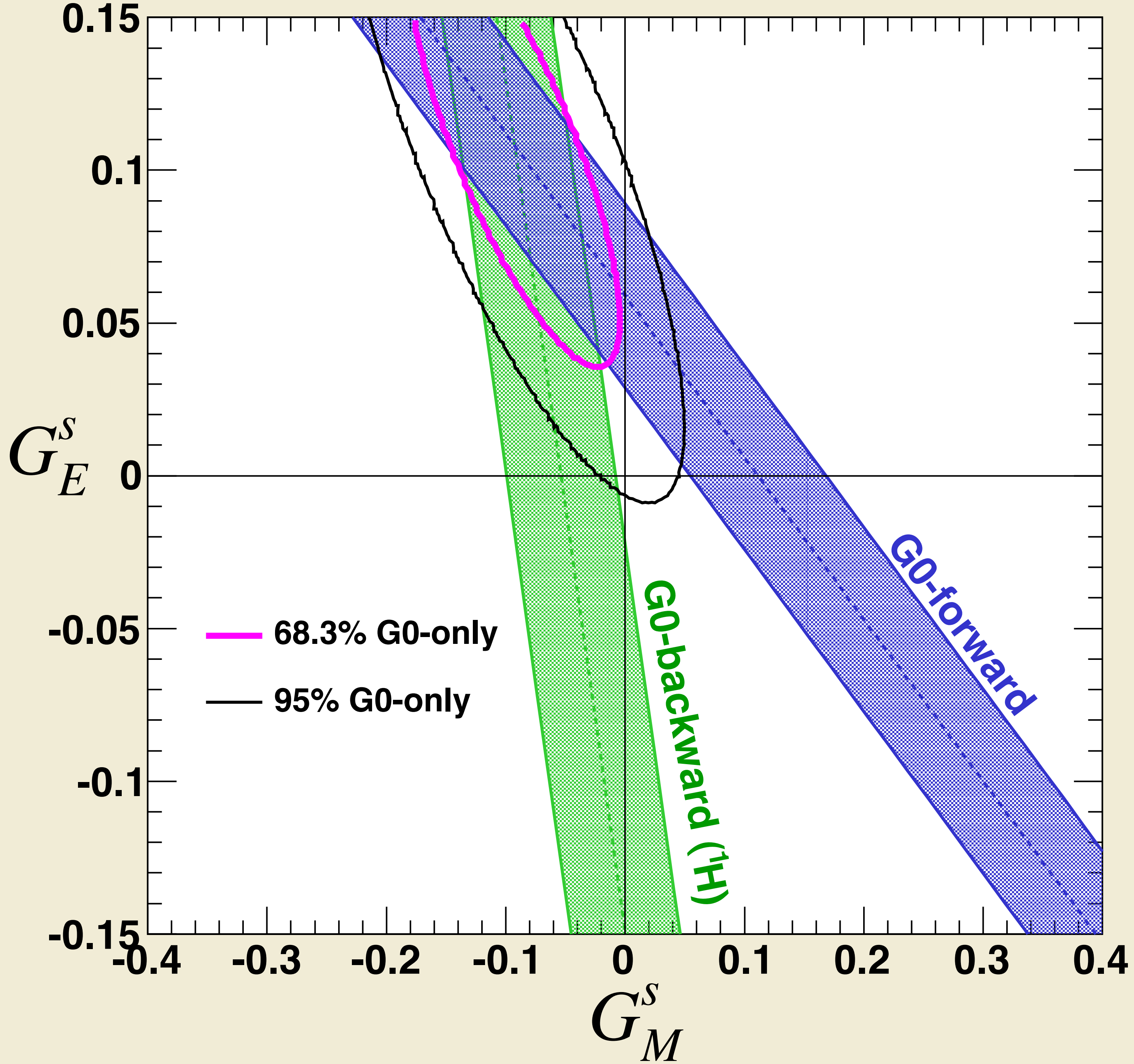


Trajectory at target averages to <3nm,<0.5nrad

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

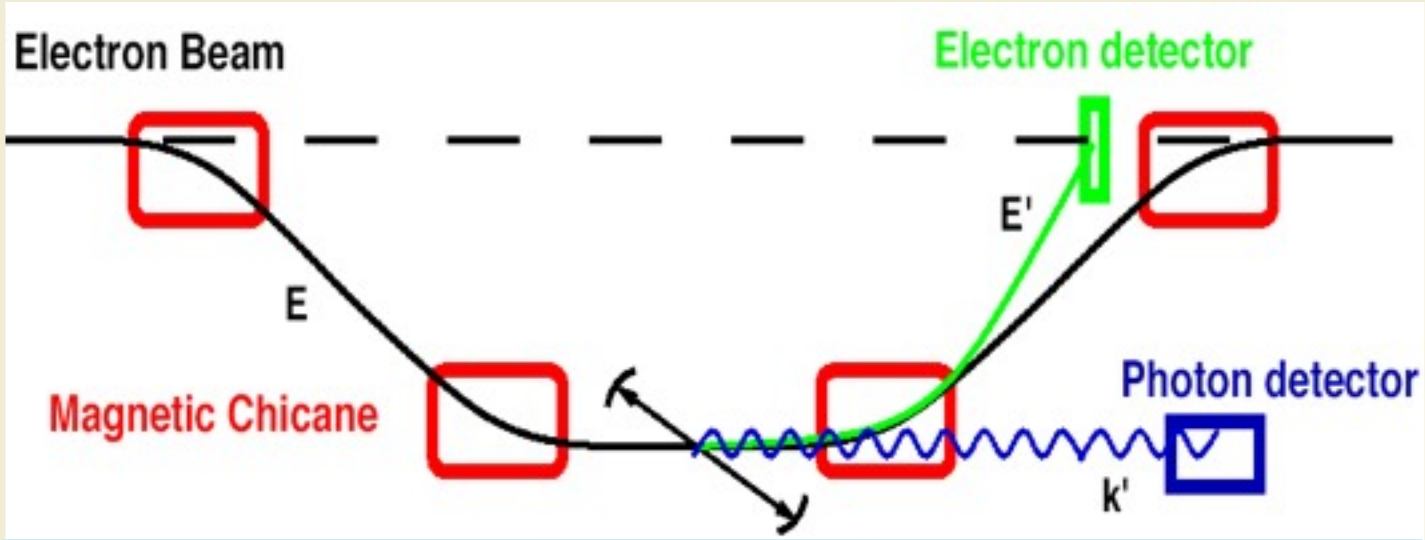
Total Correction: -0.010 ppm (0.05%)

Q^2 = 0.62 GeV^2 in combination



Zhu constraint is used for axial form-factor

Hall A Compton Polarimeter



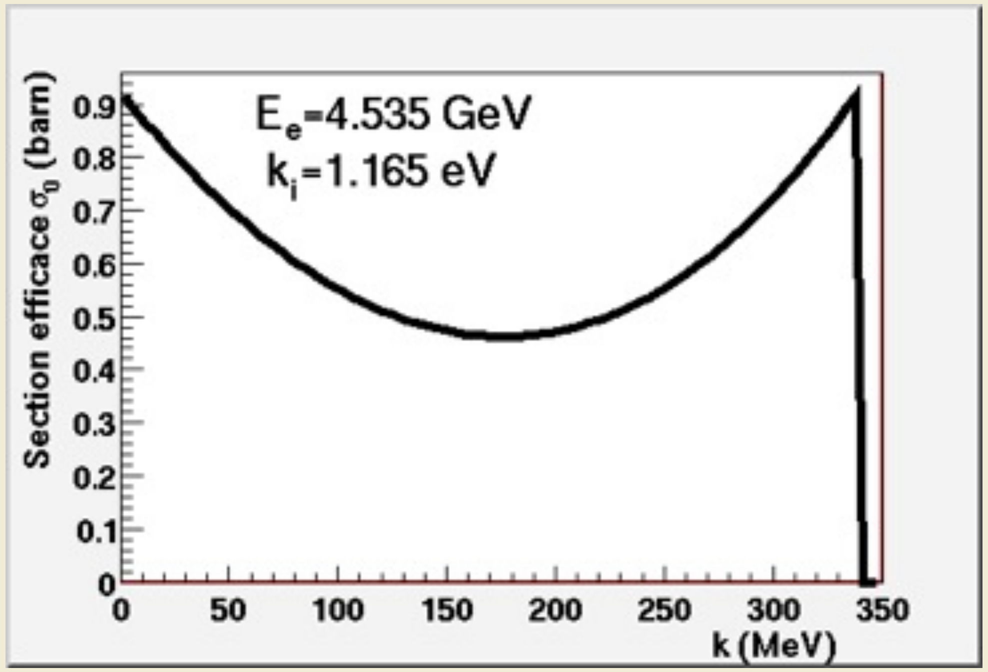
Resonant cavity "photon target", up to 2kW intensity

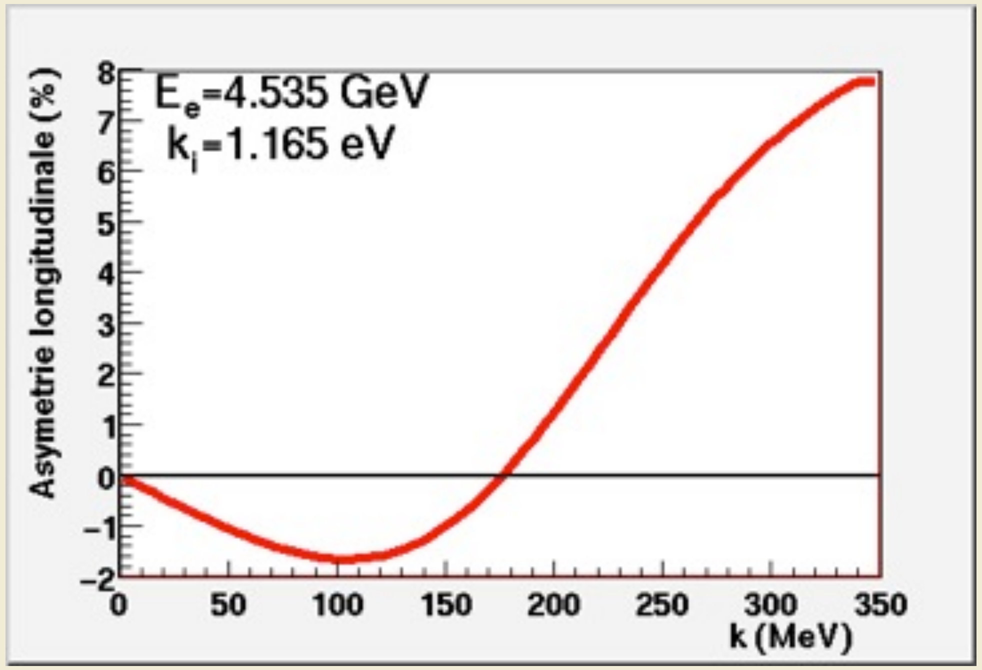
$$A_{exp} = \frac{n^+ - n^-}{n^+ + n^-} = P_\gamma \times P_e \times < A_{th} >$$

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