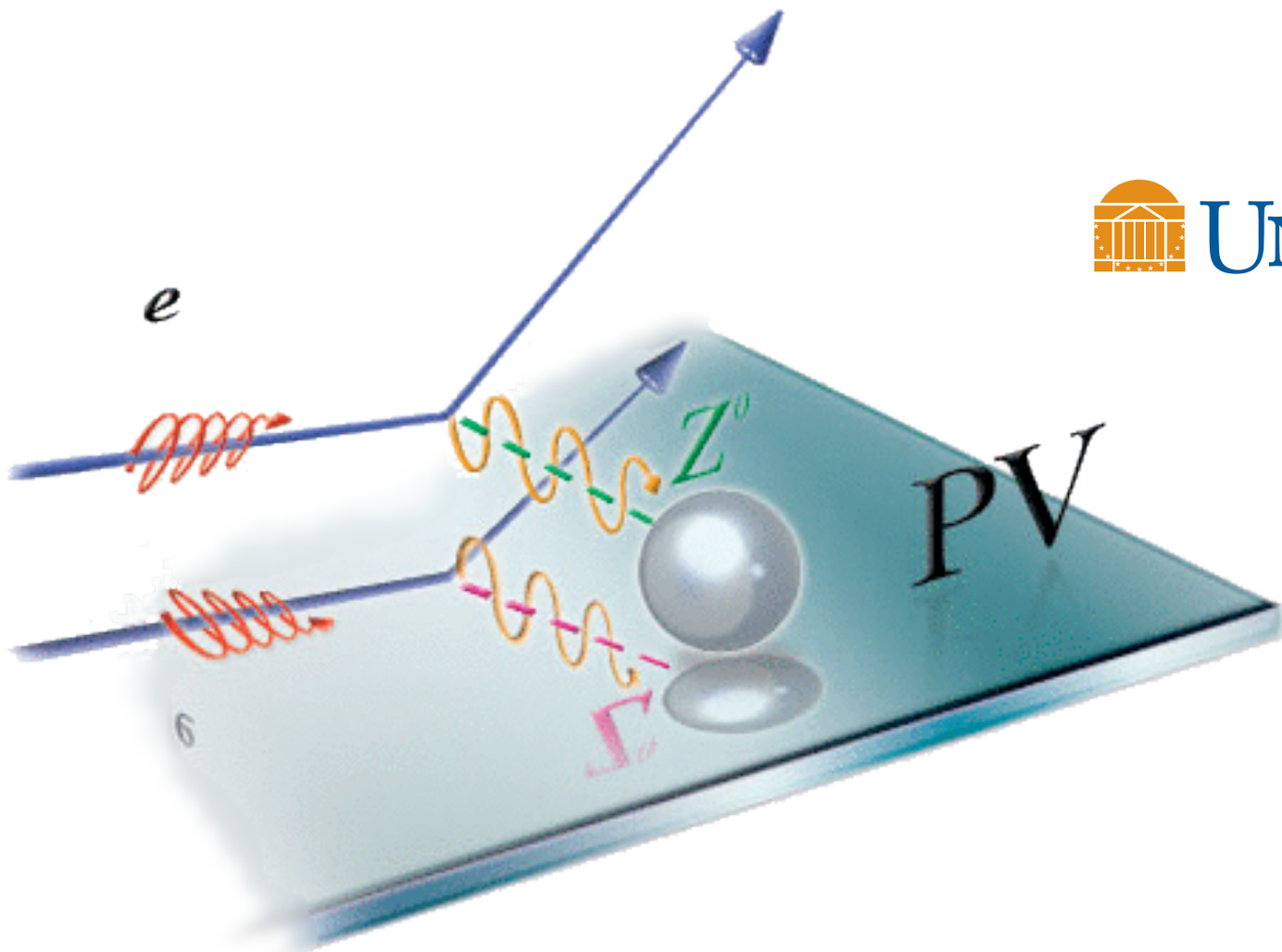
HAPPEX: Measuring Strange Quark Contributions to the Charge and Magnetic Distributions of the Proton

Kent Paschke

UNIVERSITY of VIRGINIA

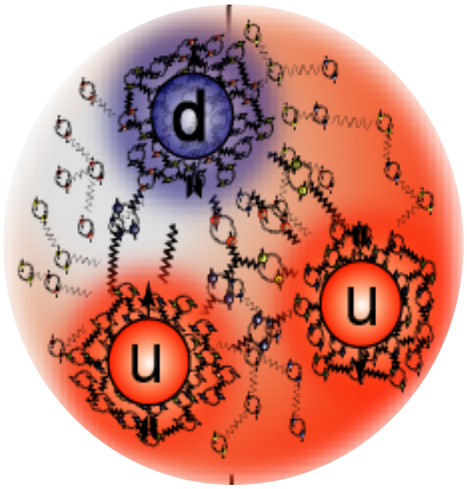


MENU 2010
Williamsburg, VA
June 2, 2010

The Sea in the Nucleon

The nucleon contains three quarks… embedded in a teeming sea of gluons and additional quarks and anti-quarks.

The sea is dominated by the three light quark flavors: up, down, strange



Quark sea contributions to nucleon static properties are unsettled

strangeness contribution must be from the sea

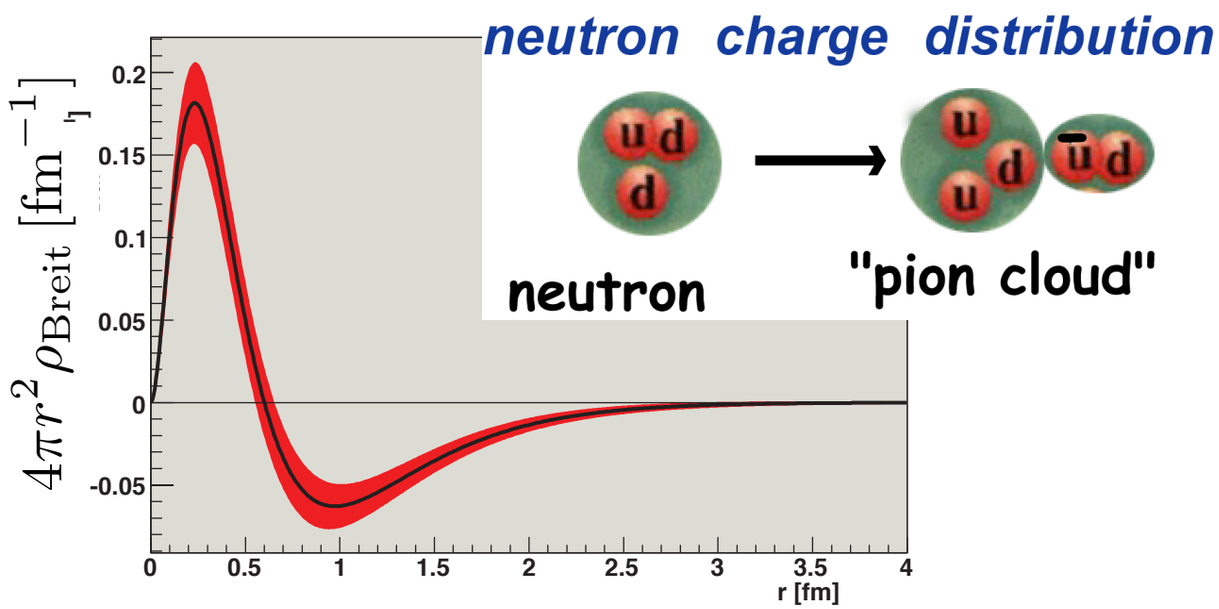
Spin polarized DIS
Δs = 0.0-0.10

Strange mass
πN scattering: 0-30%

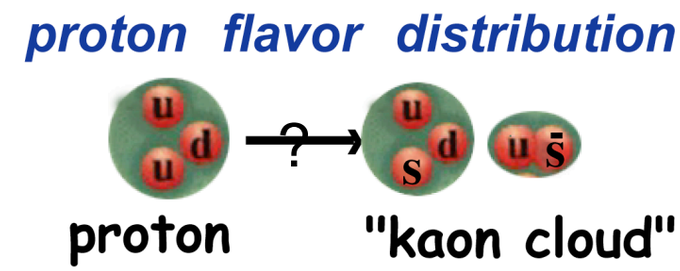
Strange charge radius and magnetic moment

Goal: Determine the contributions of the strange quark sea ($\bar{s}s$) to the charge and magnetization distributions in the nucleon : "strange form factors" G^s_E and G^s_M

Expectations for Nucleon Strangeness



might the strange quark behave in the same way?



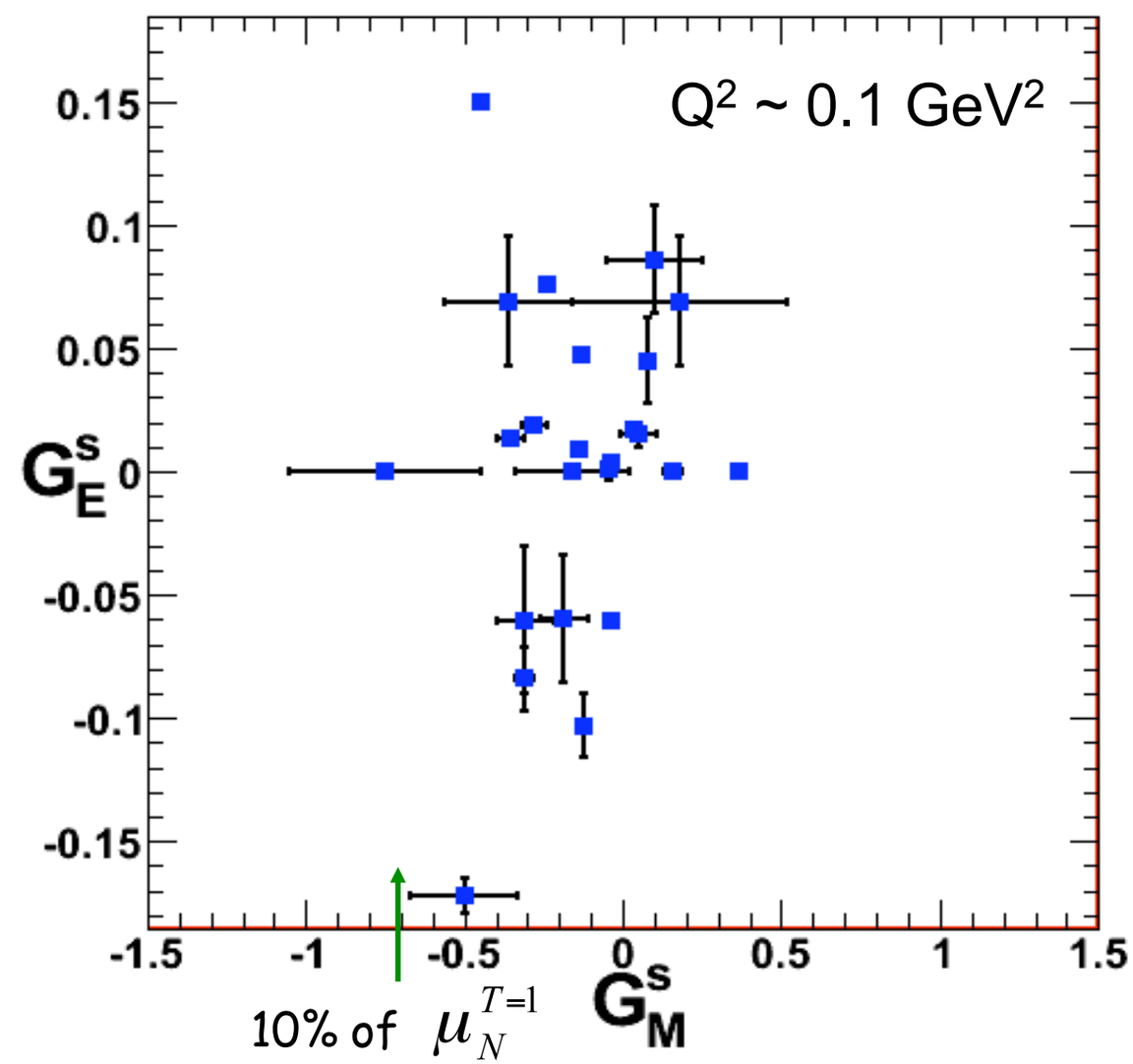
Models - a non-exhaustive list:

kaon loops, vector dominance, Skyrme model, chiral quark model, dispersion relations, NJL model, quark-meson coupling model, chiral bag model, HBChPT, chiral hyperbag, QCD equalities, …

What about QCD on the lattice?

- 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, PRC 79(2009)065202
- Doi et al., hep-lat 0903.3232

these suggest very small effects



Flavor-separating the Vector Form Factors

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

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

Flavor-separating the Vector Form Factors

Charge Symmetry

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

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

Flavor-separating the Vector Form Factors

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

Two equations and three unknowns

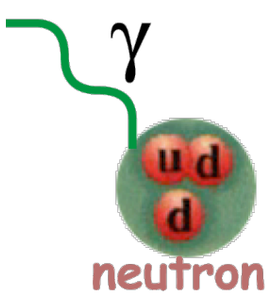
Flavor-separating the Vector Form Factors

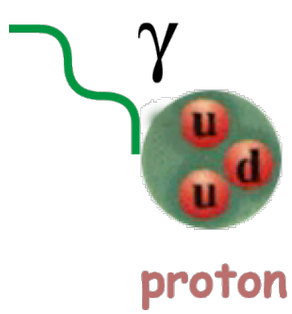
$$G_E^p = \frac{2}{3}G_E^u - \frac{1}{3}G_E^d - \frac{1}{3}G_E^s$$

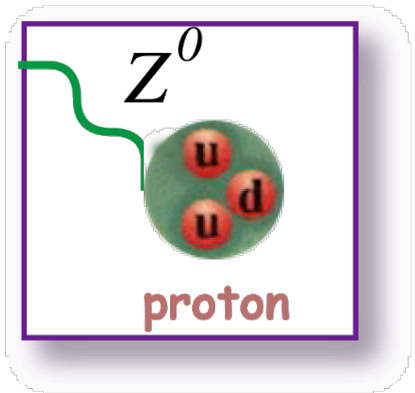
$$G_E^n = \frac{2}{3}G_E^d - \frac{1}{3}G_E^u - \frac{1}{3}G_E^s$$

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

$$G_E^{p,Z} = \left(1 - \frac{8}{3}\sin^2\theta_W\right)G_E^u - \left(1 - \frac{4}{3}\sin^2\theta_W\right)G_E^u - \left(1 - \frac{4}{3}\sin^2\theta_W\right)G_E^u$$

Measuring Strange Vector Form Factors

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

Interference with $\mathcal{EM}$ amplitude makes Neutral Current ($\mathcal{NC}$) amplitude accessible

For a proton:

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

$$A_E = \epsilon\, G_E^p G_E^Z \qquad A_M = \tau\, G_M^p G_M^Z \qquad A_A = (1 - 4\sin^2\theta_W)\epsilon'\, G_M^p \underline{\tilde{G}_A}$$

Forward angle | Backward angle

Difficult radiative corrections accompany the axial form-factor

For spin=0,T=0 (^{4}He):

G^s_E only!

nuclear corrections:
forward angle, low Q^2 only

For deuterium:

Enhanced G_A

Back-angle quasi-elastic.

The Axial Term and the Anapole Moment

Axial form-factors G_A^p, G_A^n:

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

- **Biggest uncertainty comes from radiative corrections**

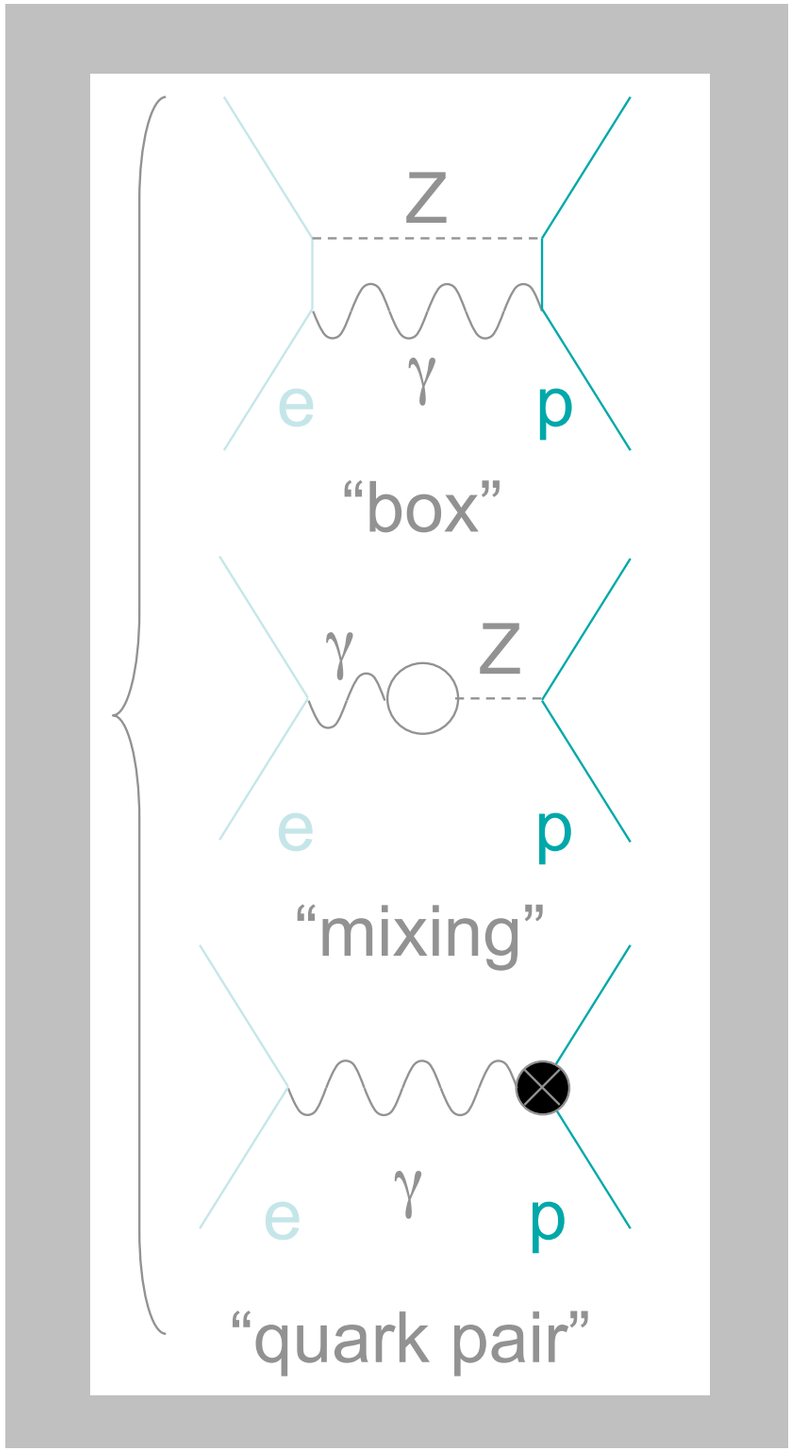
Anapole Moment Correction:

Multiquark weak interaction modifies axial form-factor

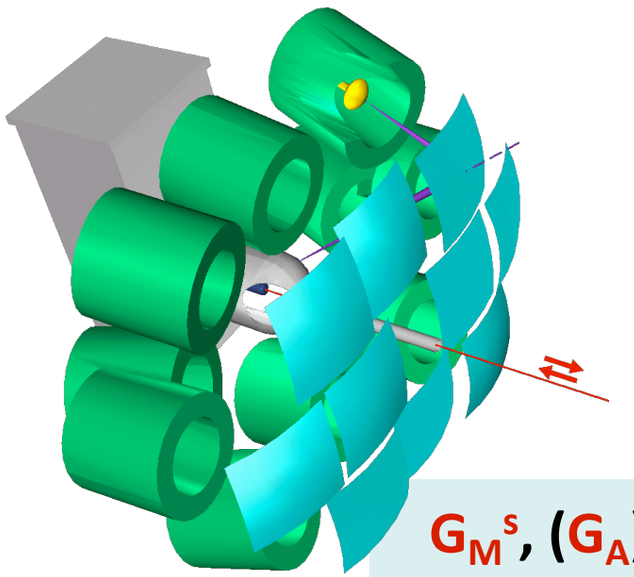
Zhu, Puglia, Holstein, Ramsey-Musolf, Phys. Rev. D **62**, 033008

- **Large uncertainty estimated to account for specific uncalculated terms**
- **Uncertainty dominates axial term**
- **Difficult to achieve tight experimental constraint**

This adds a new degree of freedom to the strange quark extraction (really, two, for both isoscaler and isovector anapole terms)



Experimental Overview



SAMPLE

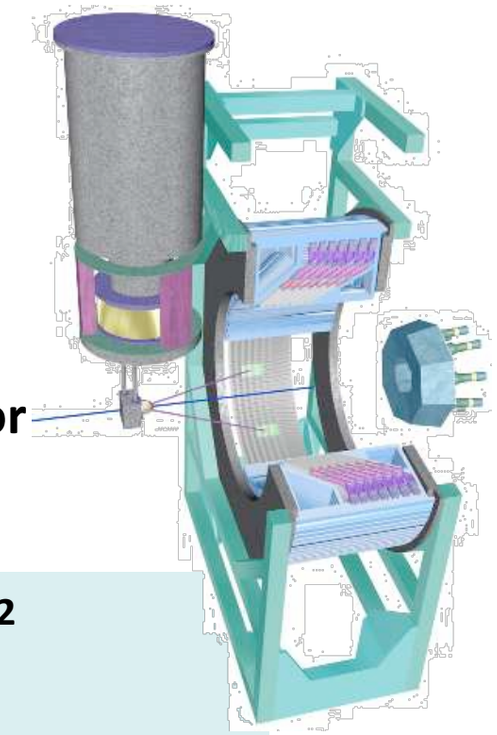
open geometry, integrating

G_M^s, (G_A) at Q^2 = 0.1 GeV^2

A4

Open geometry

Fast counting calorimeter for background rejection



G_E^s + 0.23 G_M^s at Q^2 = 0.23 GeV^2

G_E^s + 0.10 G_M^s at Q^2 = 0.1 GeV^2

G_M^s, G_A^e at Q^2 = 0.23 GeV^2

HAPPEX

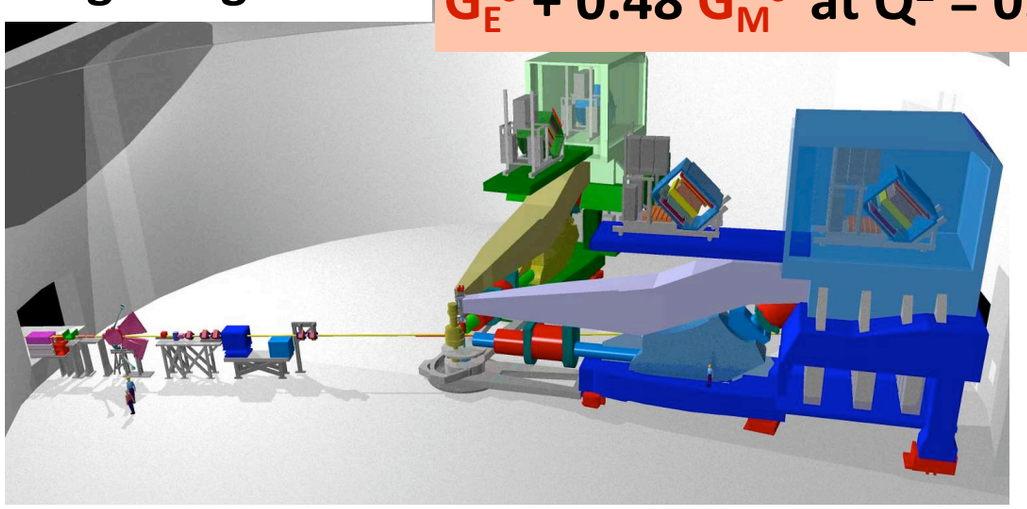
Precision spectrometer, integrating

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

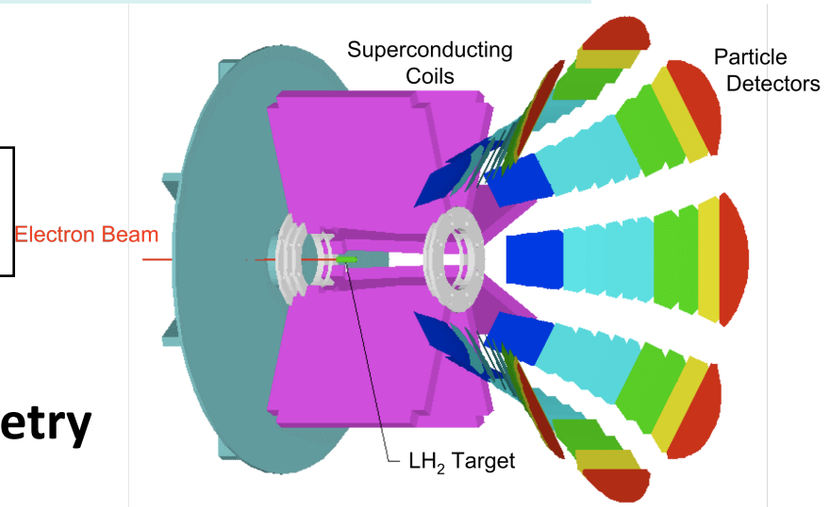
G_E^s + 0.08 G_M^s at Q^2 = 0.1 GeV^2

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

G_E^s + 0.48 G_M^s at Q^2 = 0.62 GeV^2



G0



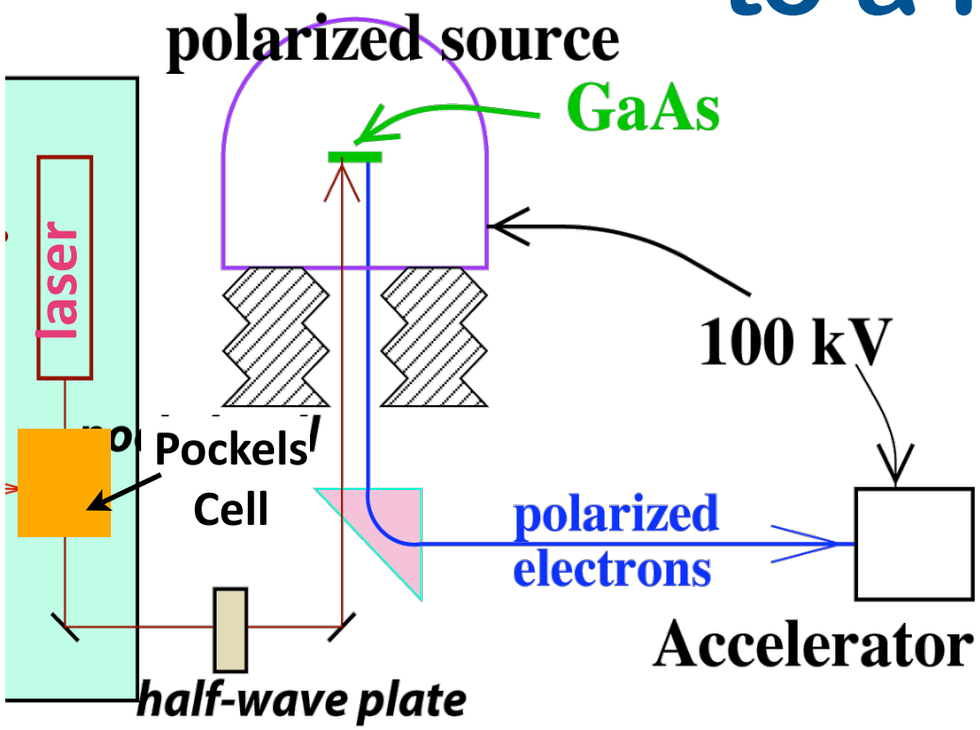
Open geometry

Fast counting with magnetic spectrometer + timing for background rejection

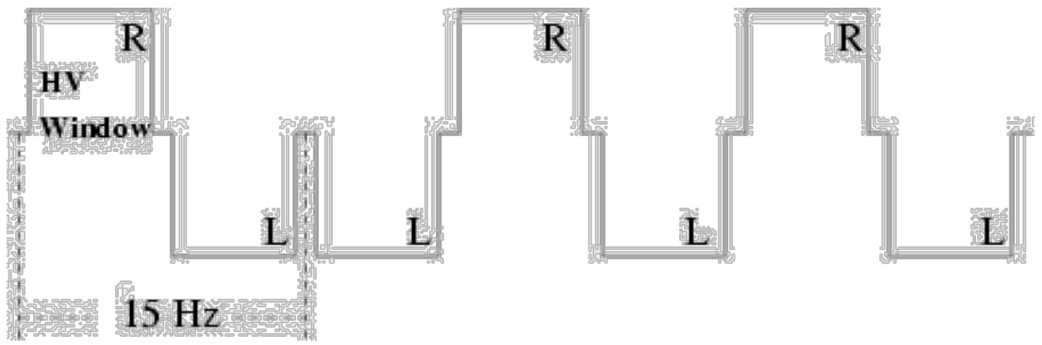
G_E^s + η G_M^s over Q^2 = [0.12,1.0] GeV^2

G_M^s, G_A^e at Q^2 = 0.23, 0.62 GeV^2

Goal: Small Asymmetry Measured to a Few Percent



Psuedo-random, rapid helicity flip



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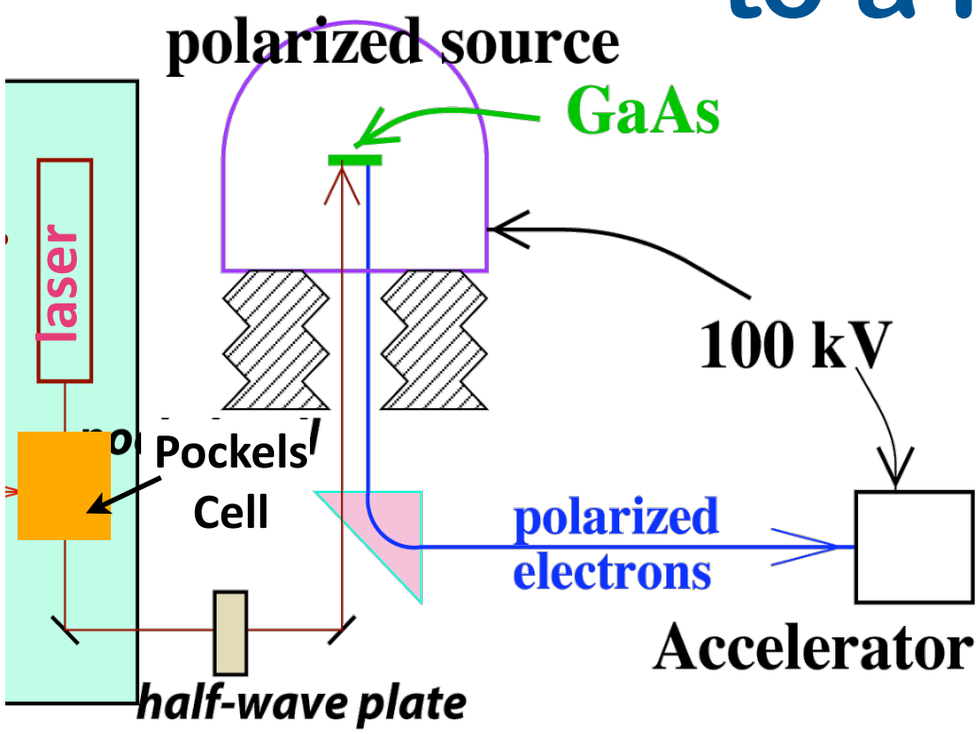
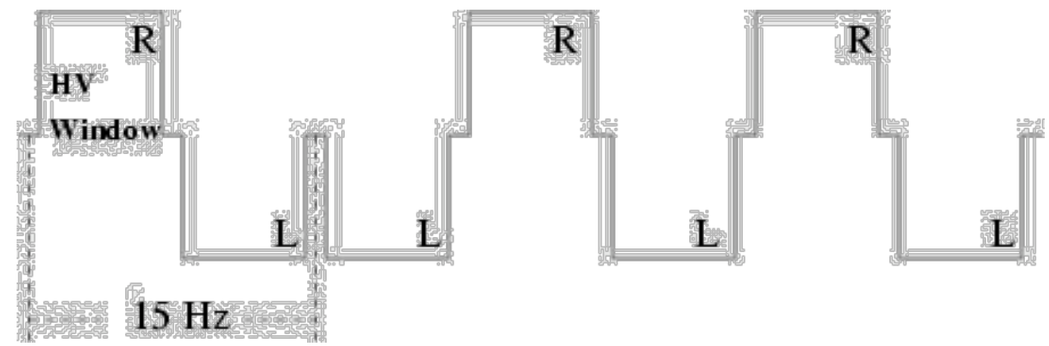
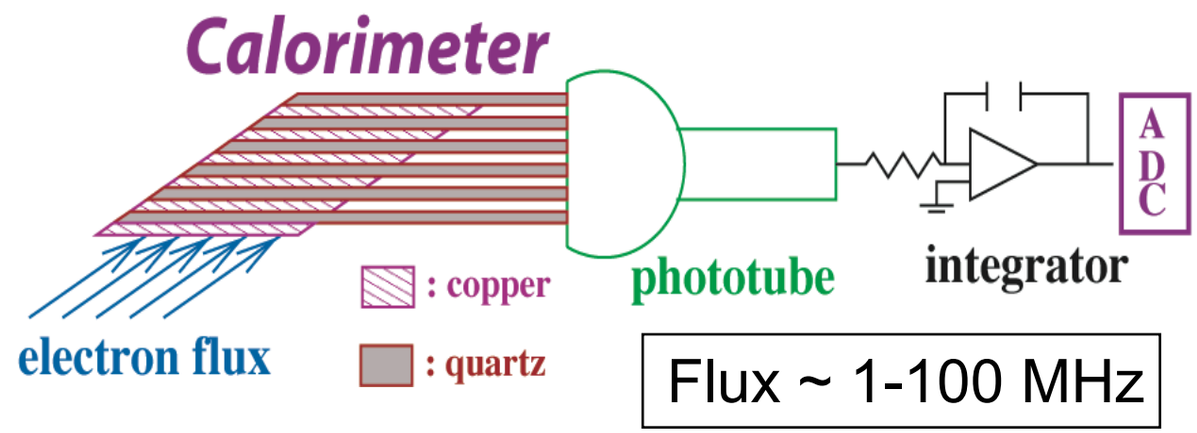


Psuedo-random, rapid helicity flip





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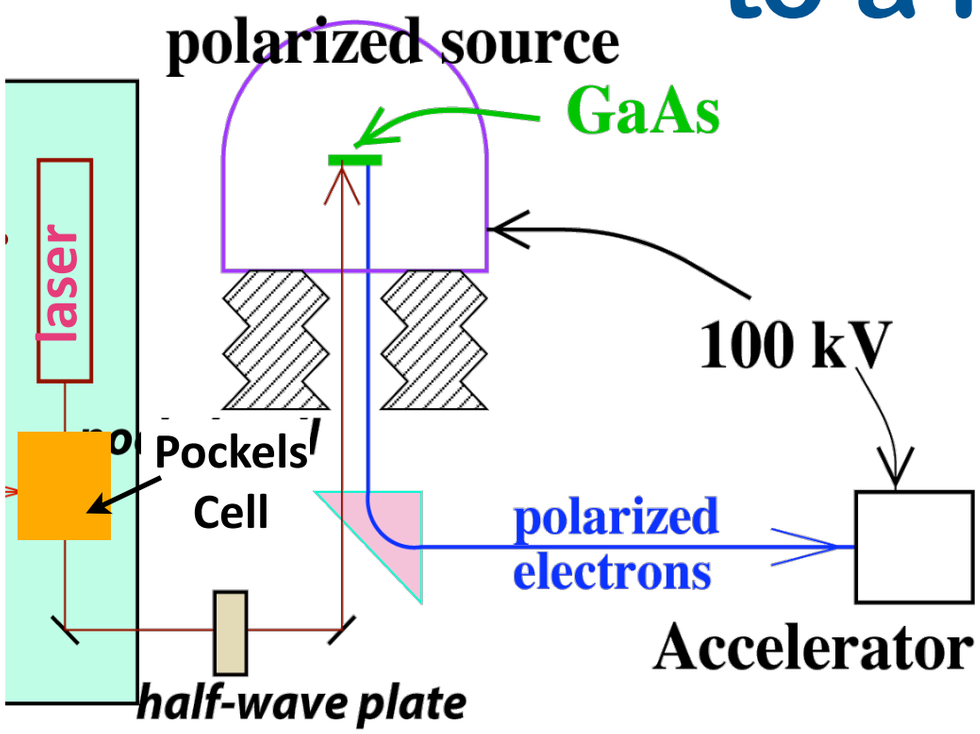

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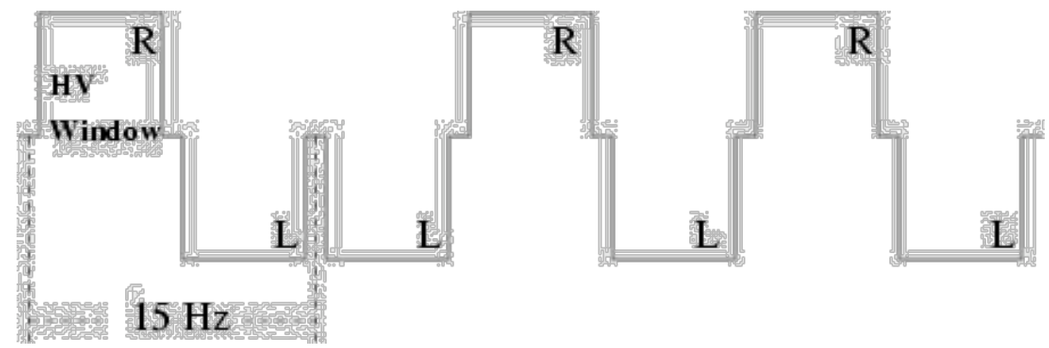
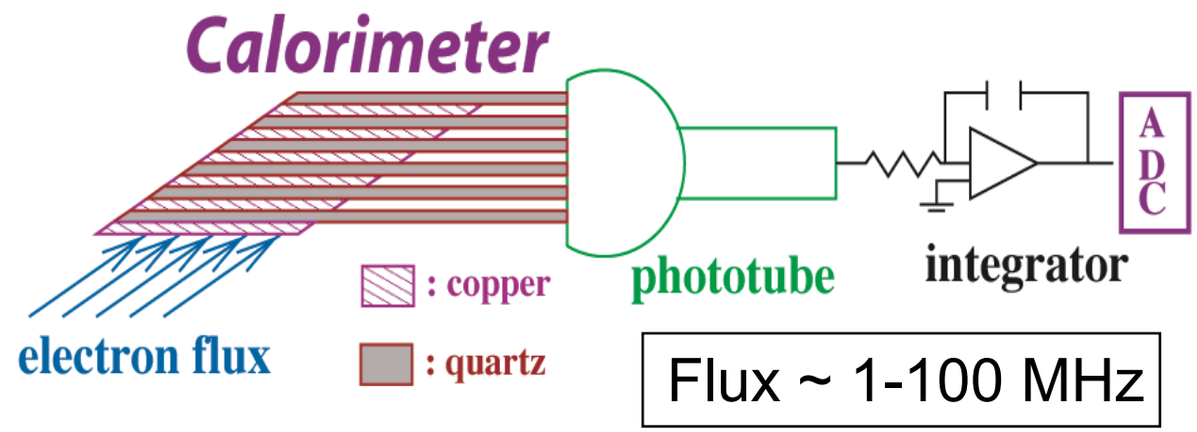
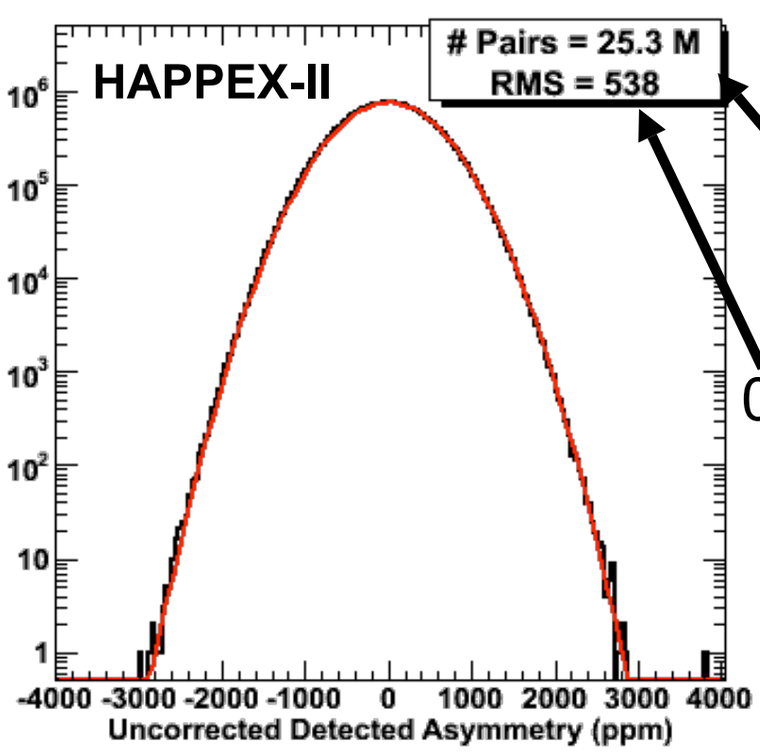




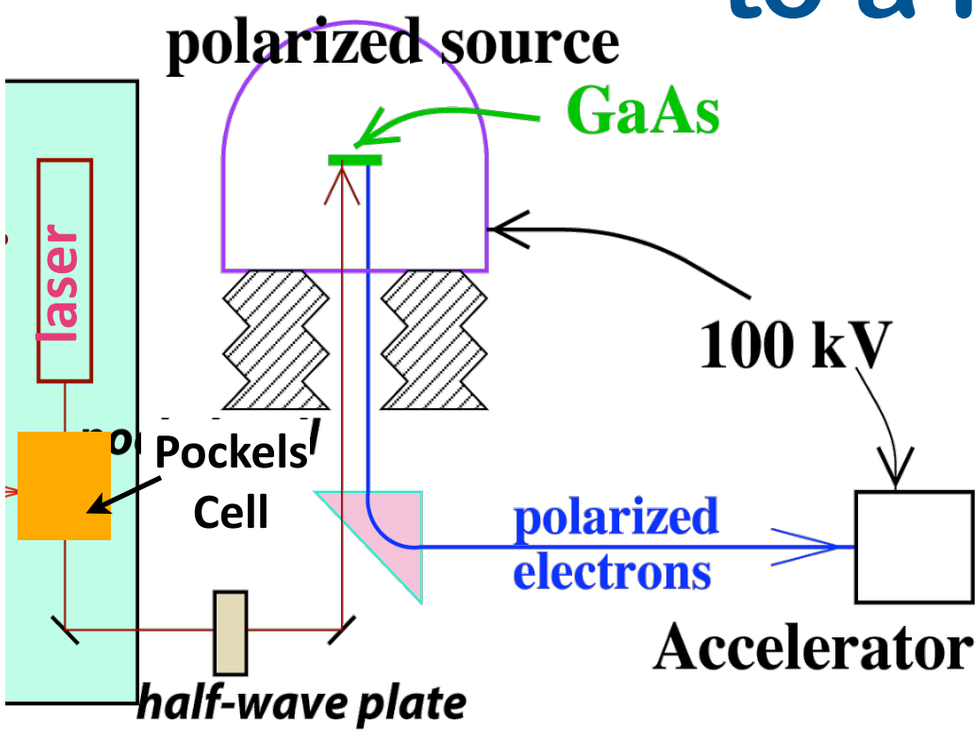
Measure the asymmetry to high precision, millions of times



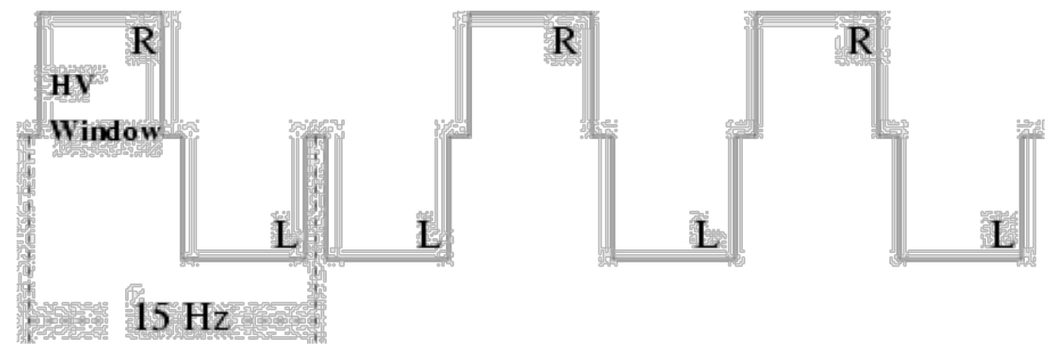
25 million trials

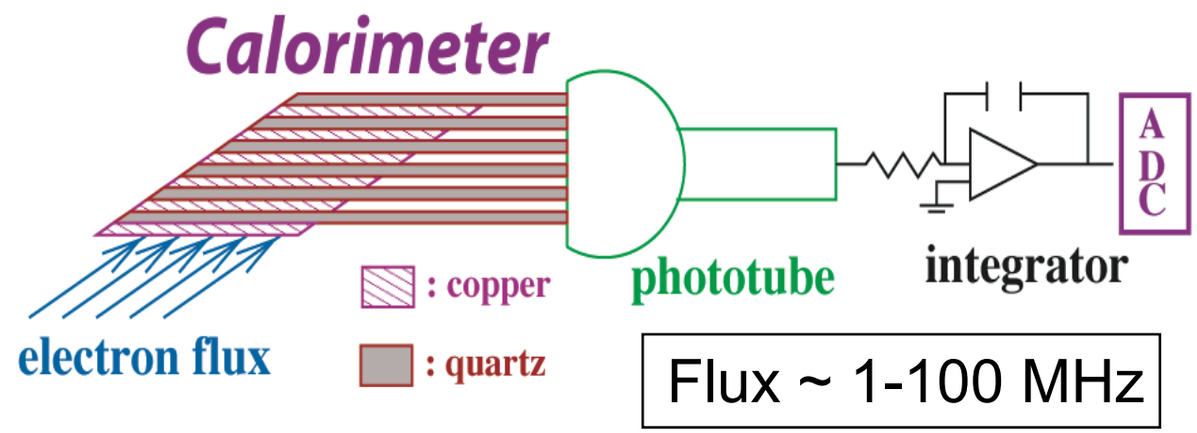
0.05% precision

Goal: Small Asymmetry Measured to a Few Percent



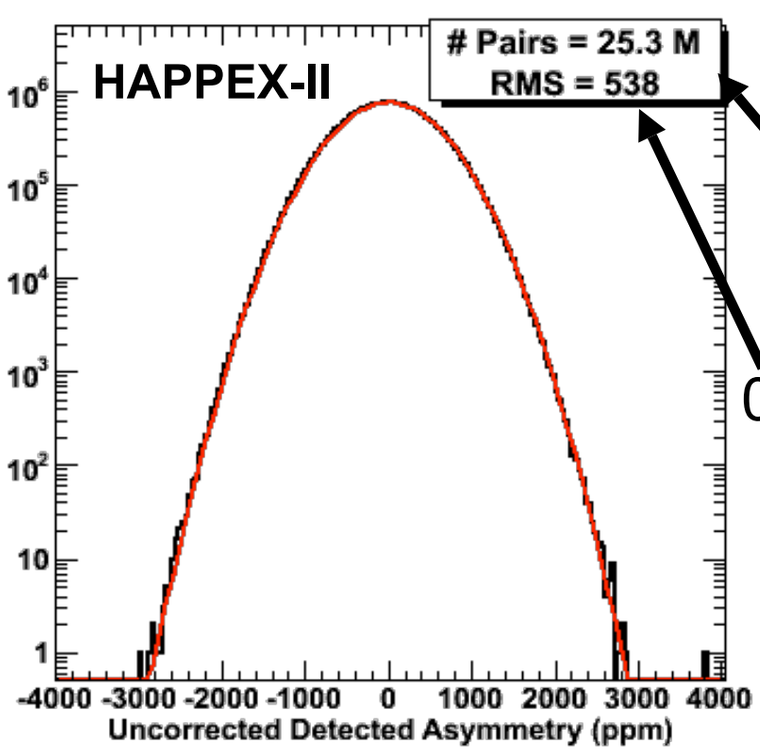
Psuedo-random, rapid helicity flip





Flux ~ 1-100 MHz

Measure the asymmetry to high precision, millions of times



25 million trials

0.05% precision

50 MHz @ 15 Hz

σ_A ~ 540 ppm

$$\delta(A_{PV}) = \frac{540\,\text{ppm}}{\sqrt{25 \times 10^6}} \sim 110\,\text{ppb}$$

Experimental Techniques for PVeS

Statistical Precision

- High beam current, high polarization
- High power cryotargets with small density fluctuations
- Large acceptance
- Precision beam monitoring
- Large acceptance, or very forward angle, spectrometer
- Integrating Detection: low noise, linear

Systematic Accuracy - False Asymmetries

- Large acceptance or very forward angle
- Spectrometers: separate background channels, minimize re-scattered backgrounds (especially magnetized material)
- Helicity-correlated beam asymmetries small: $\Delta I / I$ < 1 ppm, $\Delta x \sim 1$ nm, $\Delta E/E \sim 1$ ppb
- Measurements of sensitivity to beam position changes
- sign flips (g-2, laser optics)

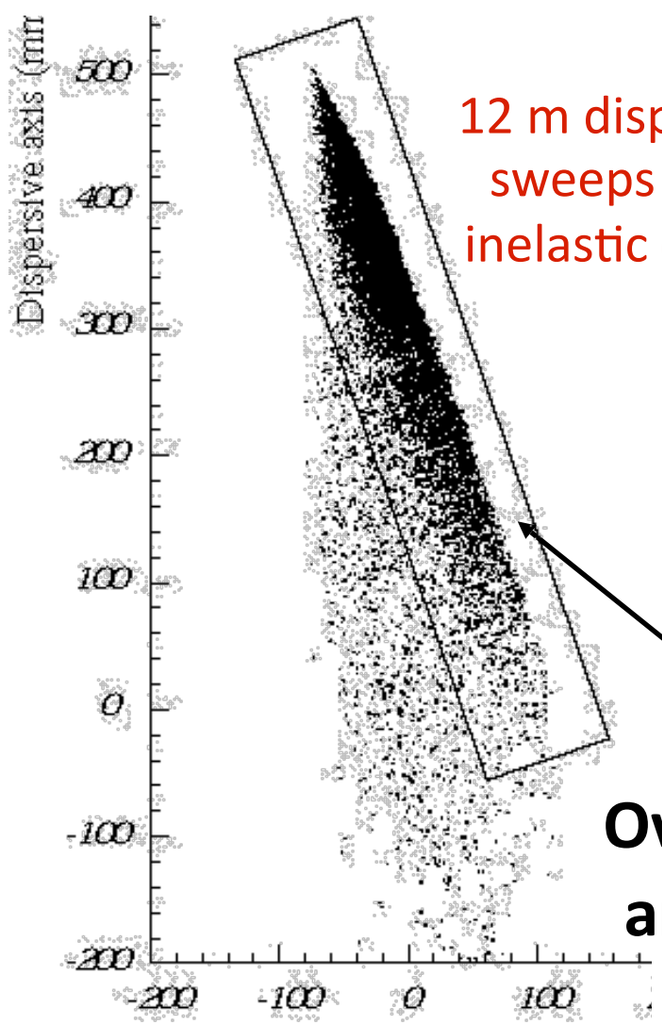
Systematic Accuracy - Normalization

- beam polarimetry
- absolute energy scale and angle measurement (Q^2)
- detector linearity
- background dilutions

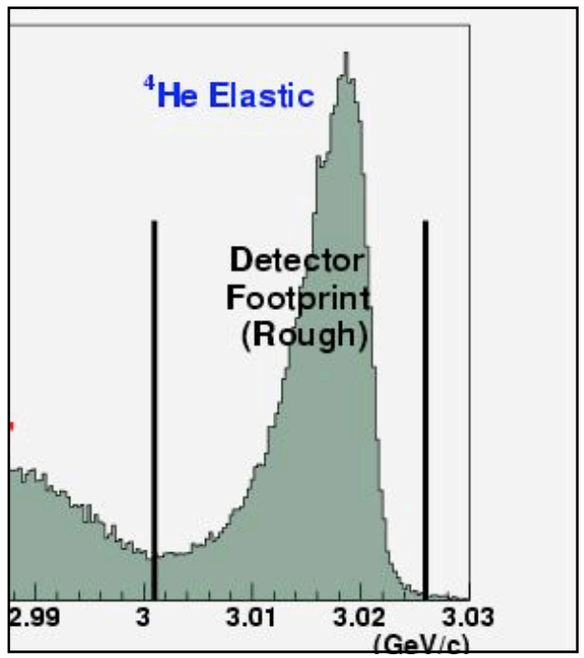
HAPPEX at JLab

HRS: twin high-resolution spectrometers

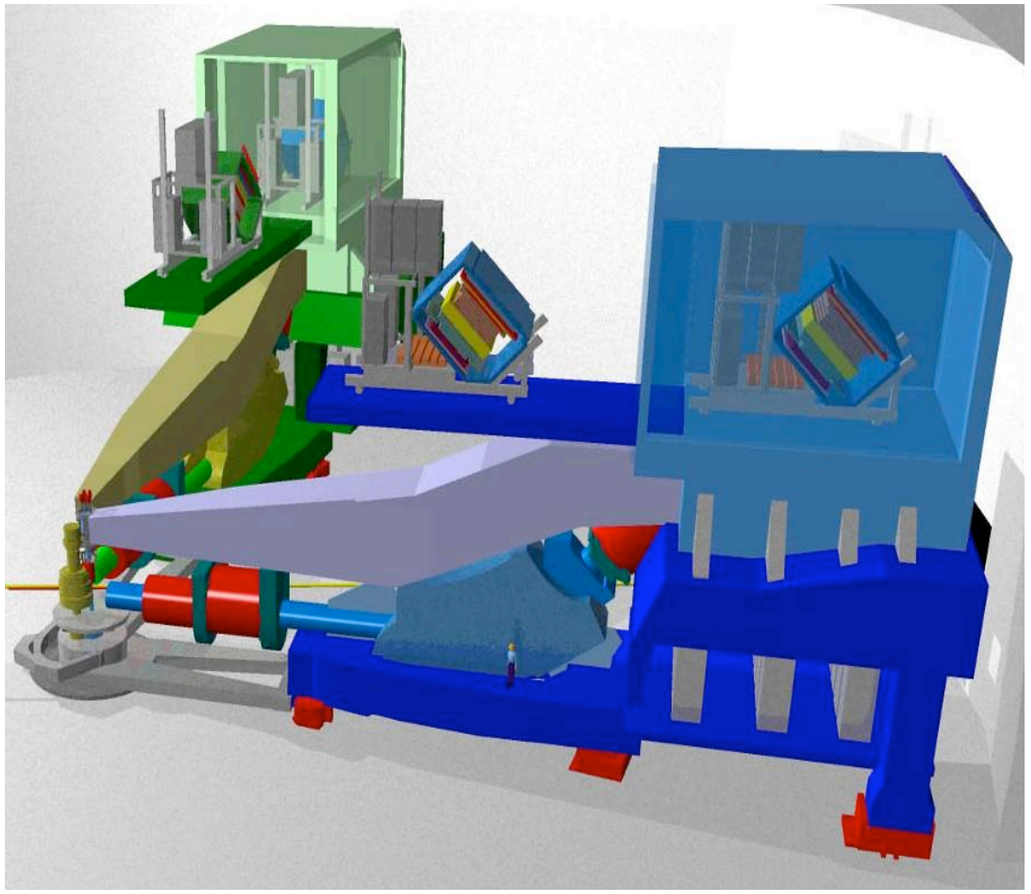
- Limited acceptance (~5-8 msr) but very clean.
- **Statistical FOM suitable for forward-angle studies**
- 6-14° angles, 2.8-3.5 GeV
- 500 kHz - 50 MHz signal rates: analog integration



12 m dispersion sweeps away inelastic events



Overlap the elastic line and integrate the flux

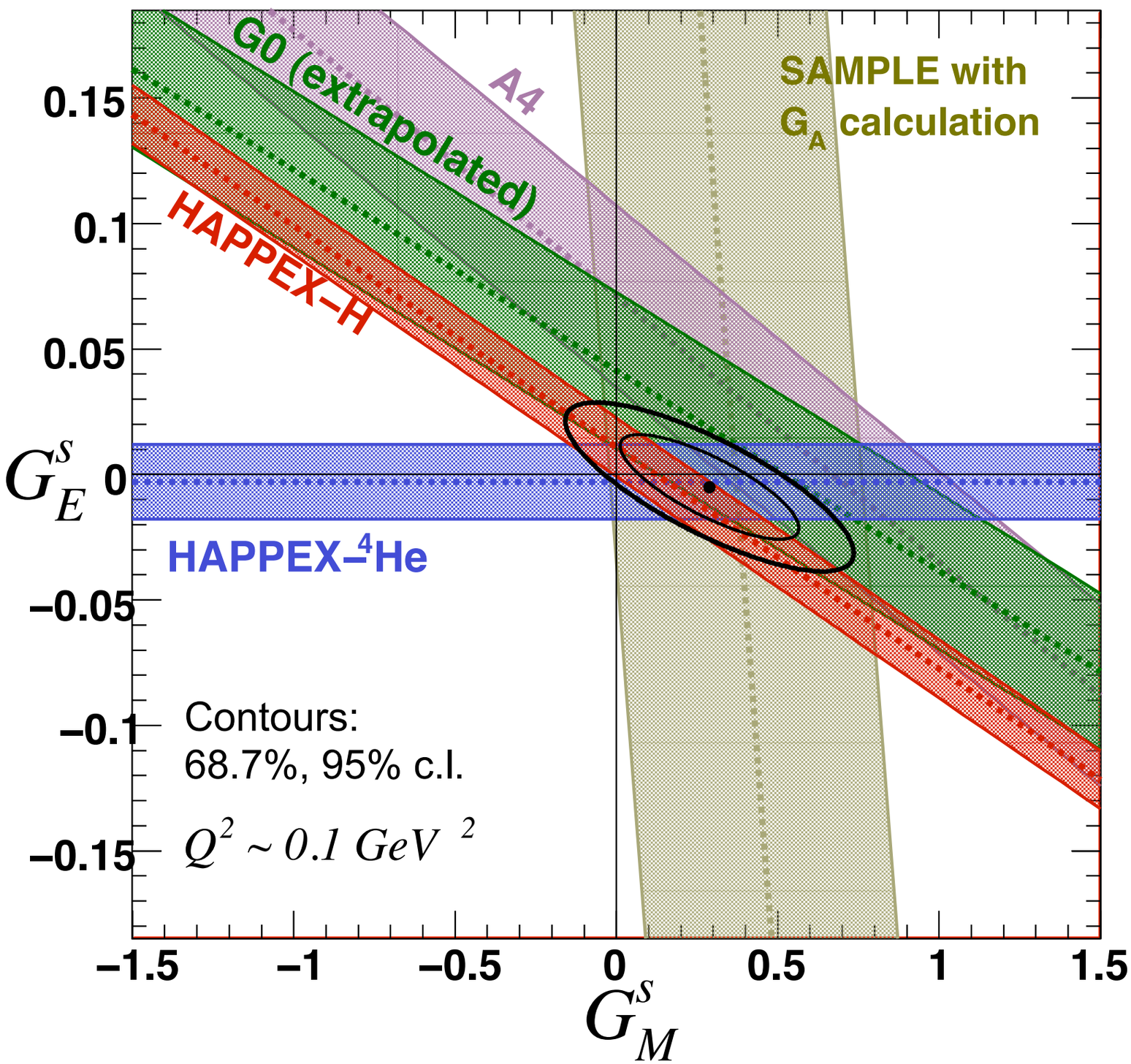


- **H_2** at $Q^2 \sim 0.1, 0.5, 0.62$ GeV^2
- **Helium-4** at $Q^2 \sim 0.1$ GeV^2

- Highest statistical precision at specific kinematics
- Very clean isolation of ^{4}He elastic
- Very low backgrounds ($f \sim 1.5\%$)

clean measurement of G_M^s, G_E^s

Precision Data at Q^2 ~0.1 GeV^2 shows small G^s



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

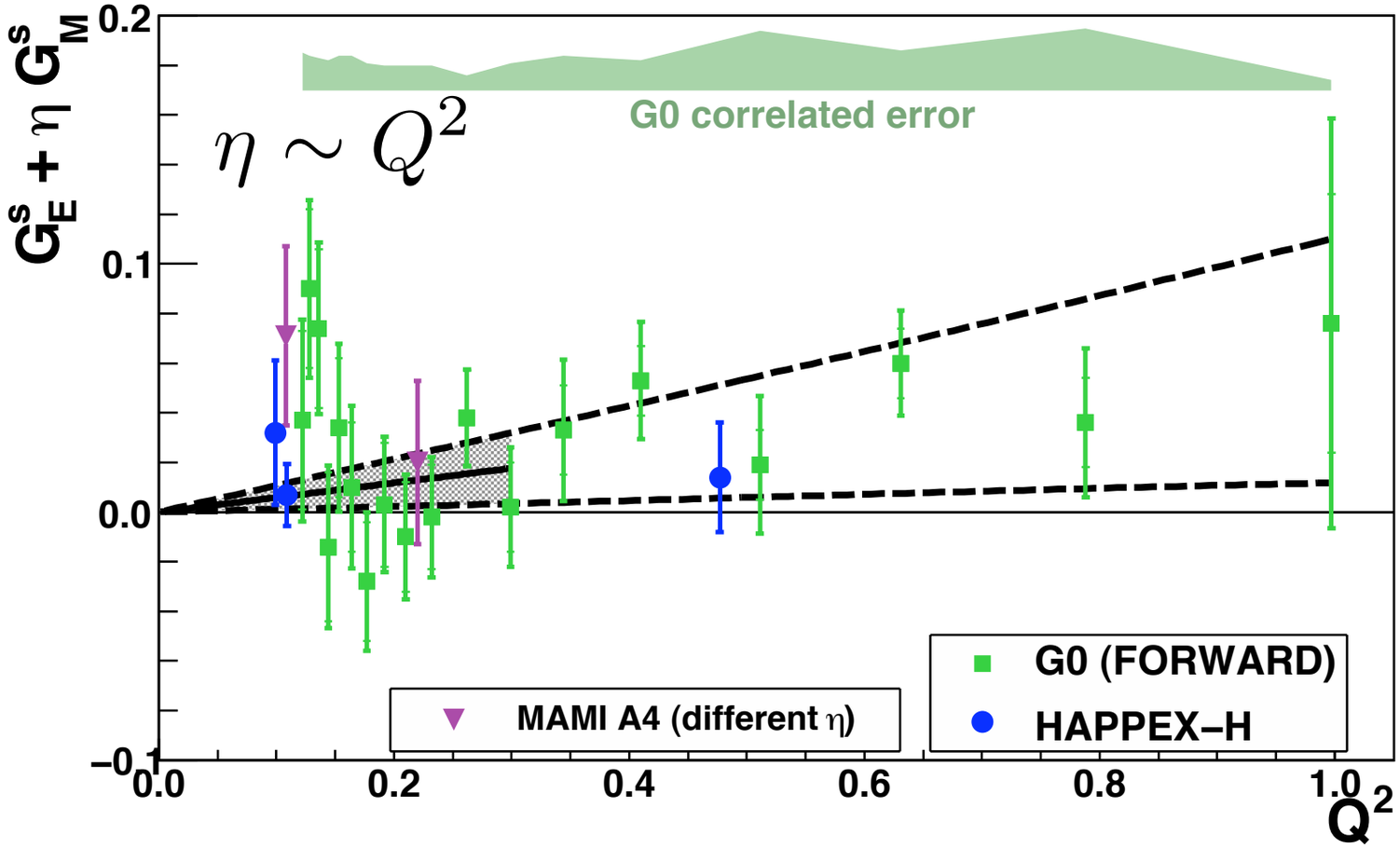
~0.2 +/- 0.5% of G_E^P

Excellent consistency between data sets

Caution: the combined fit is approximate. Correlations due to common assumptions or sources of error are not taken into account.

For a more rigorous treatment, see published fits by:
R. Young et al., Phys. Rev. Lett 97, 102002 (2006)
or
J.Liu et al., Phys. Rev. C 76, 025202 (2007)

World Data vs. Q^2



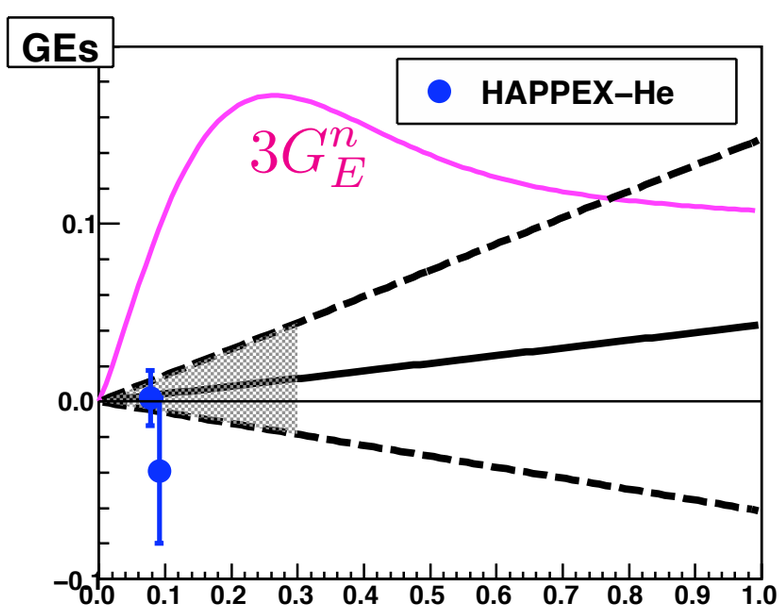
Simple fit to "leading order" in Q^2

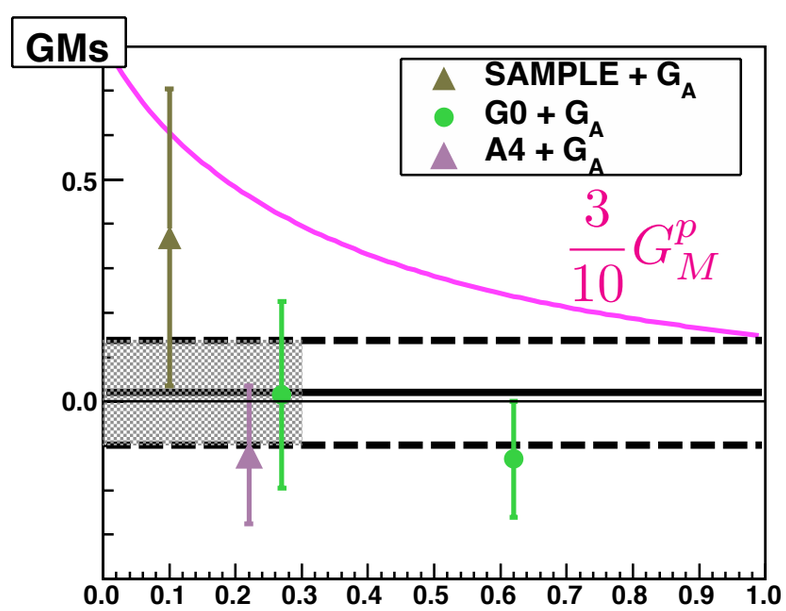
$$G_E^s = \rho_s * \tau$$

$$G_M^s = \mu_s$$

Includes only data $Q^2 < 0.3$ GeV^2

Sizeable contributions at higher Q^2 are not still not definitively ruled out.





G0 Global error allowed to float with unit constraint

Zhu et al axial constraints are used

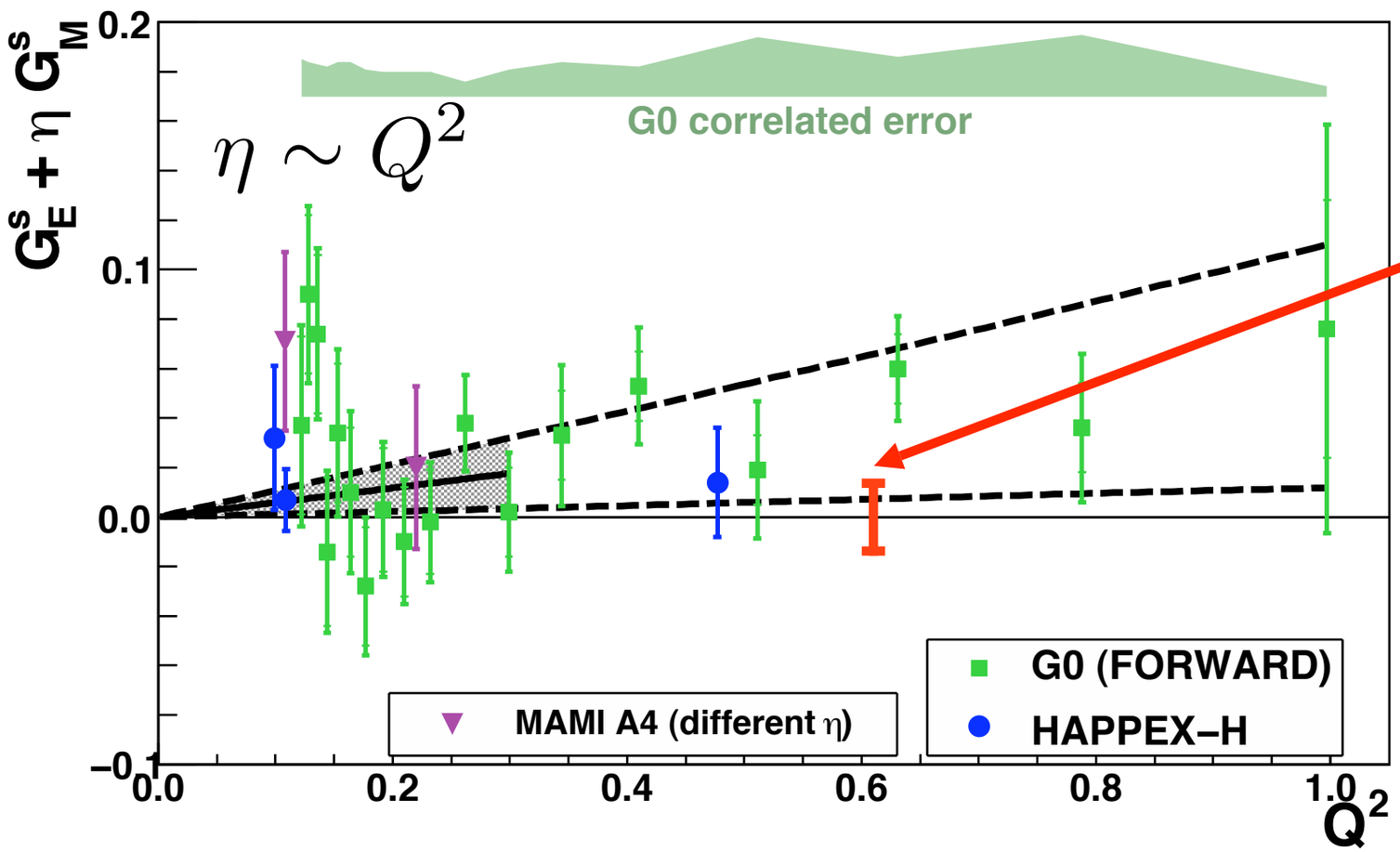
Includes backangle results as constraint on G_M^s only (neglects correlations with G_E^s from extraction)

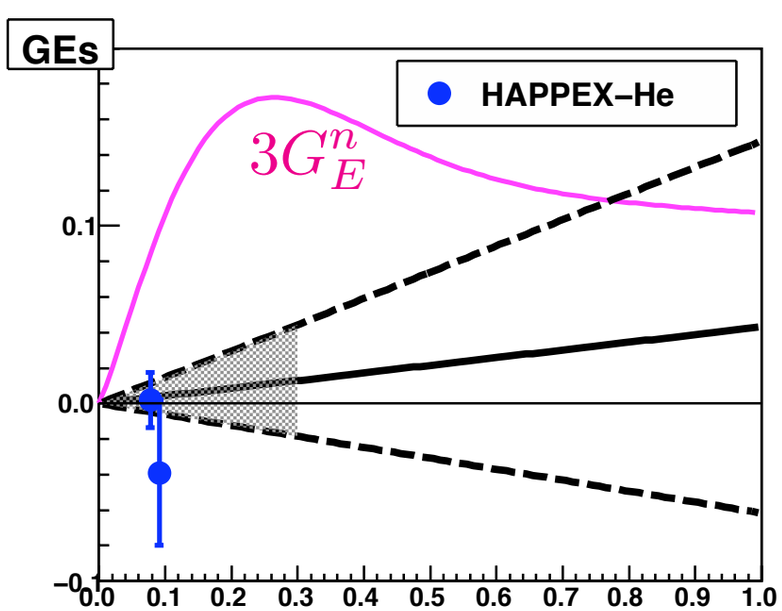
Sources of correlated error, such as electromagnetic form factor assumptions are neglected

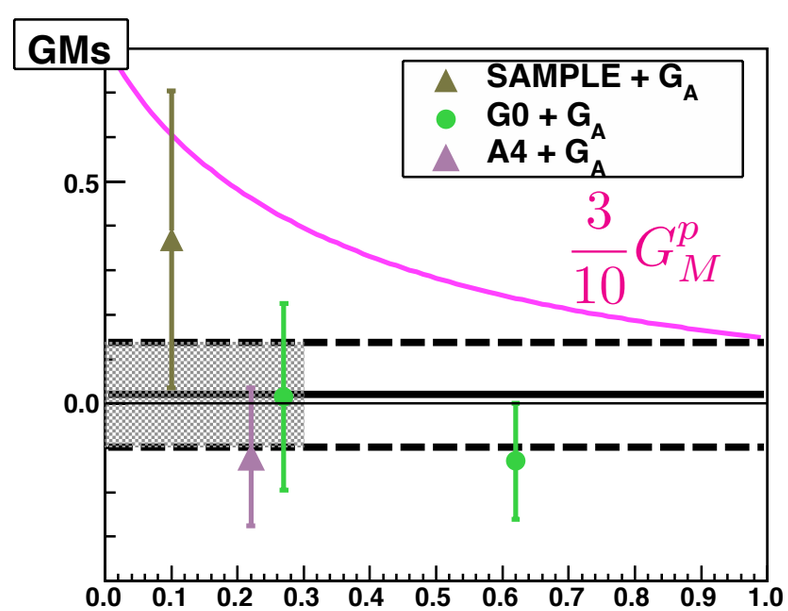
Again, a more careful fit with somewhat different assumptions is available::

R. Young et al., Phys. Rev. Lett 97, 102002 (2006)

Expected data at higher Q^2







HAPPEX-III

$Q^2 \sim 0.62\ GeV^2$

Data taking completed in 2009

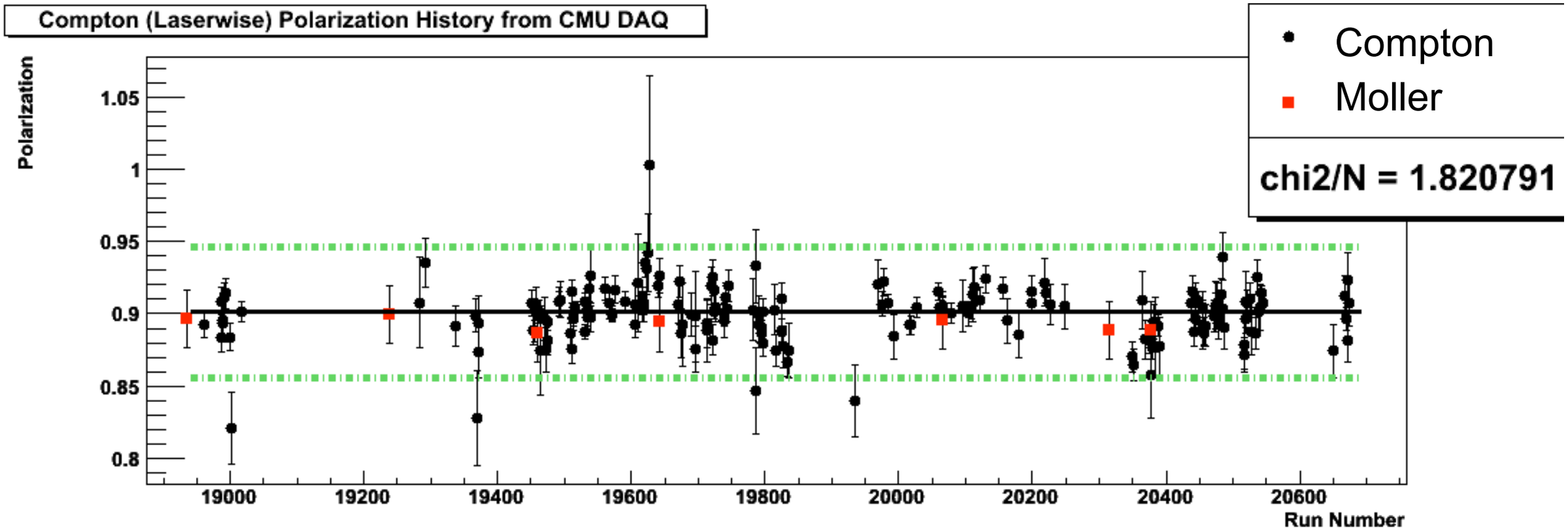
$\delta(G_E^s + 0.48\ G_M^s) \sim 0.015$

Statistics-limited error bar, with leading systematic error from polarimetry

Analysis proceeding similarly to HAPPEX-I :

K. A. Aniol et. al., Phys. Rev. C69, 065501(2004)

Beam Polarization for HAPPEX-III

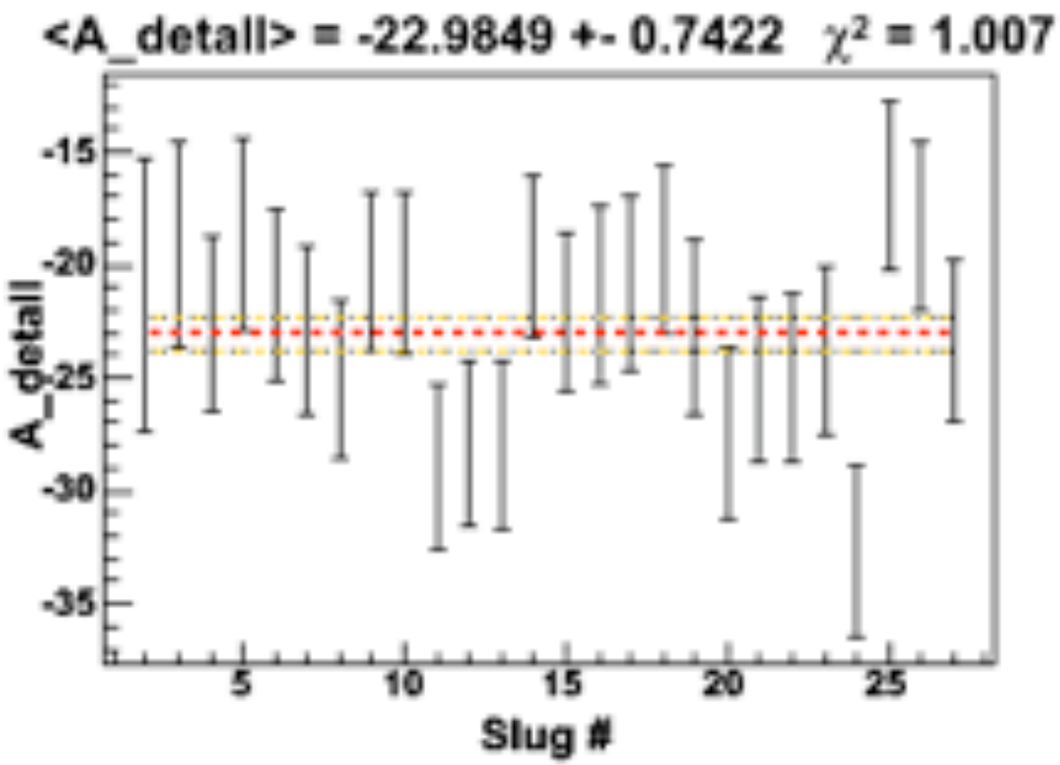


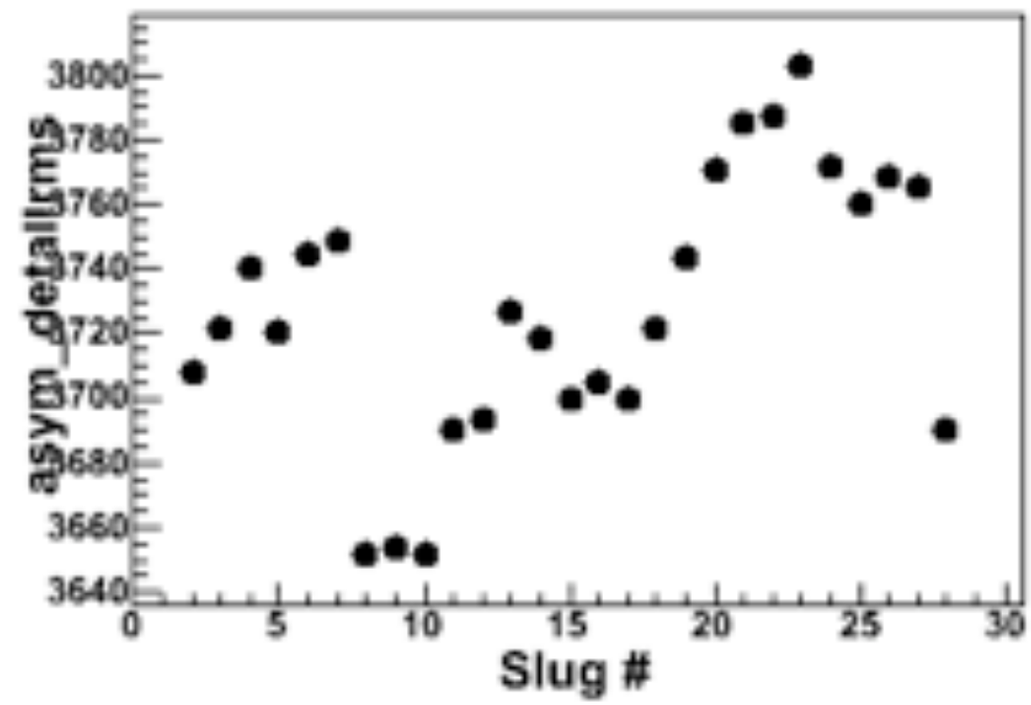
- Energy-weighted integration minimizes calibration uncertainties
- Non-statistical jitter dominated by background instabilities
- Analysis still in progress

Compton: <P> ~ 90%
Moller: <P> ~ 89%

Expected systematic error
1-2% on each

HAPPEX-III analysis underway





(Blinded) asymmetry analysis nearly complete

Background, Q^2, polarimetry, PMT linearity analyses underway

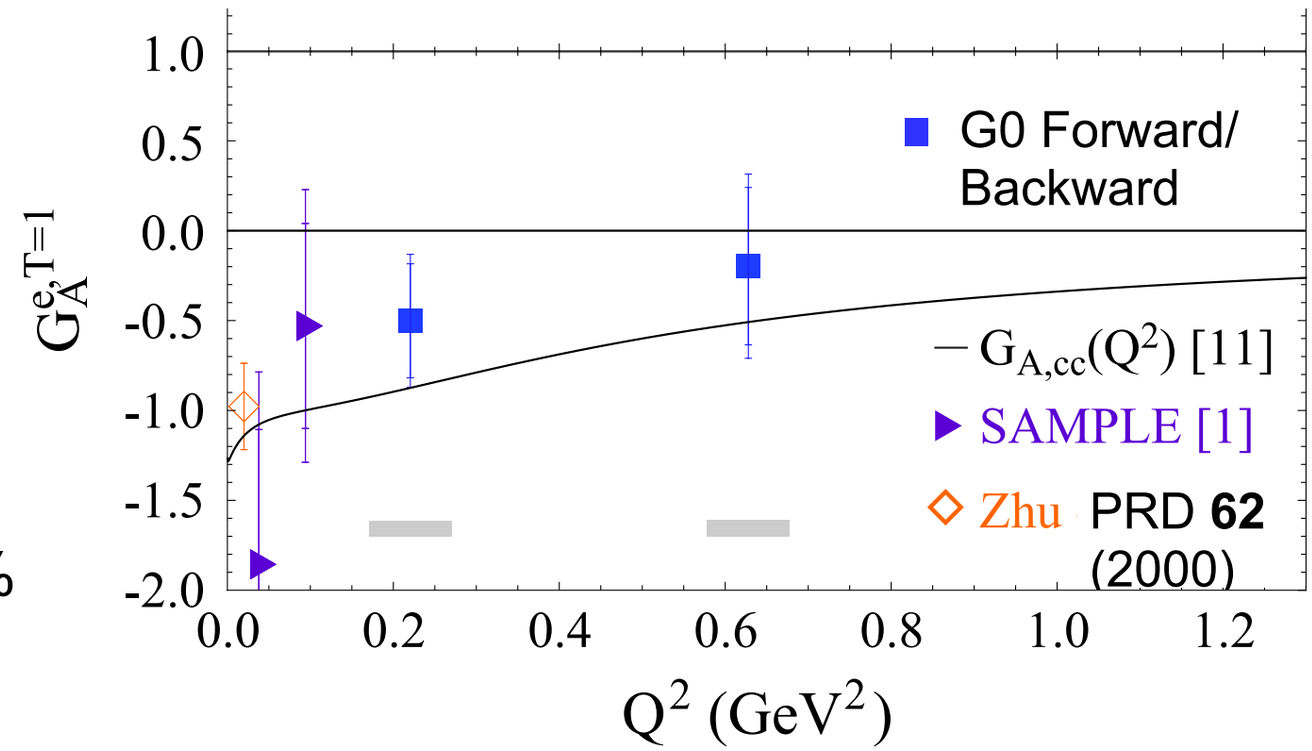
Results expected Fall 2010

Outlook for improved precision

Anapole correction and other ϒϒ and ϒZ box

The uncertainties in the axial form-factor continue to complicate interpretation in terms of $G^s_{E/M}$

Anapole uncertainty contribution to H-III: 1.5%



Charge Symmetry Breaking

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-II data

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

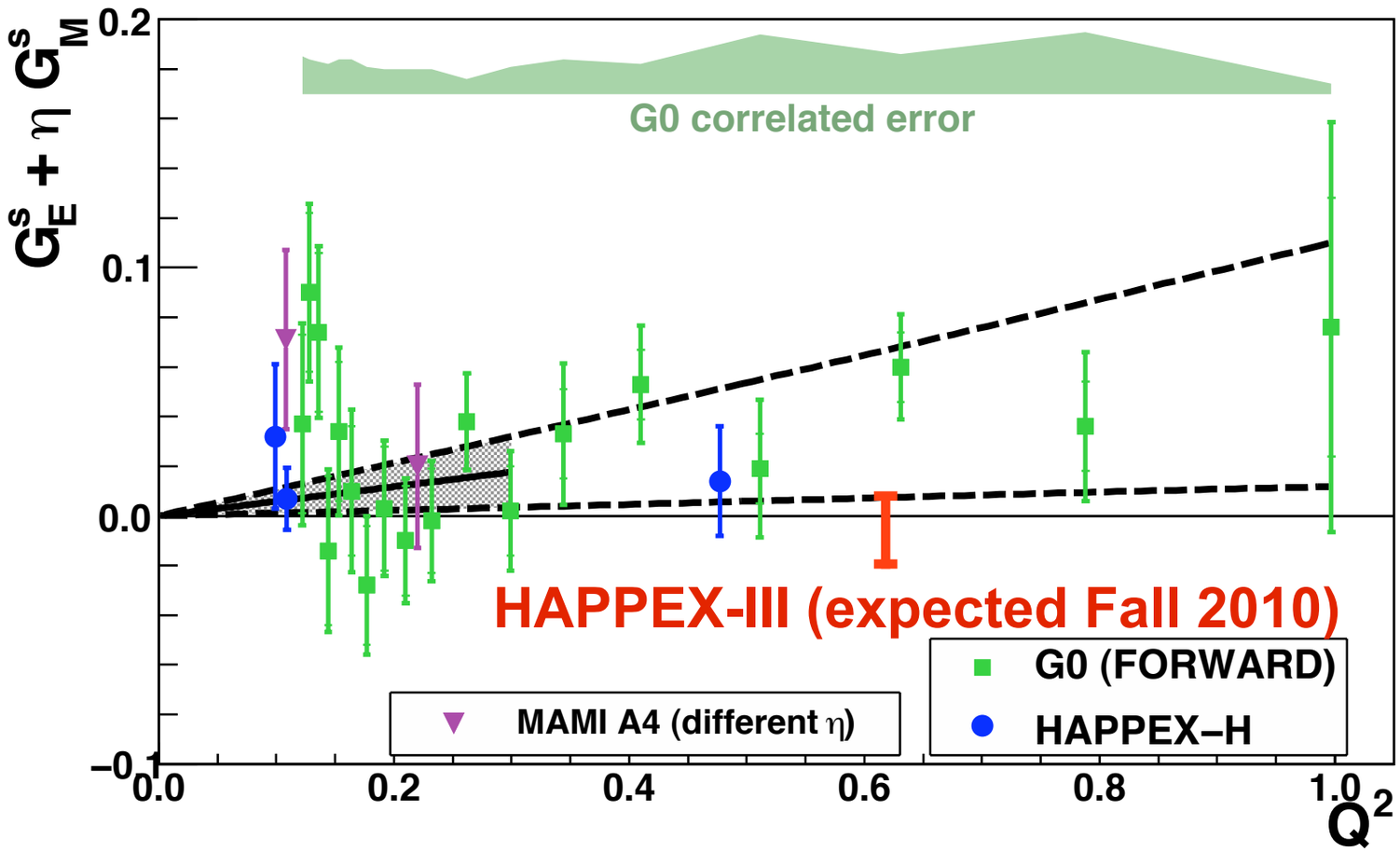
New improvements on precision (in the forward angle) may test charge symmetry

Electromagnetic Form Factors

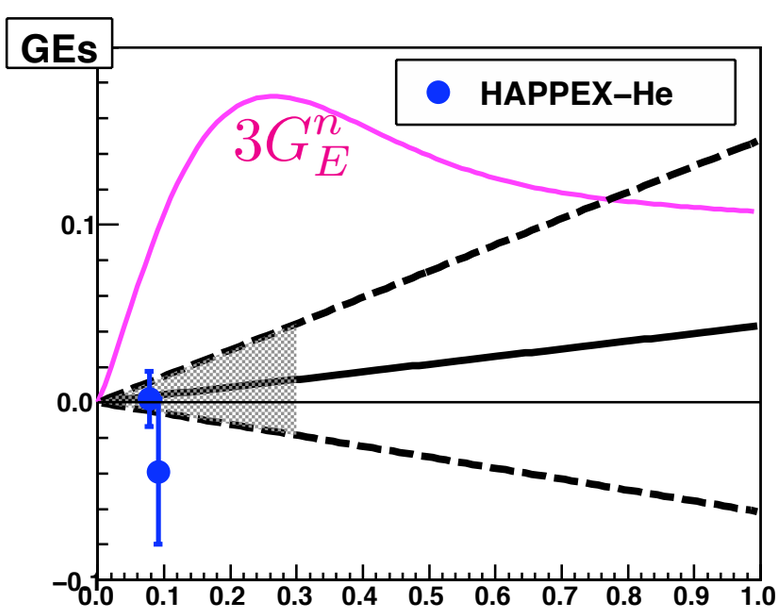
Limited to few percent precision (including 2-γ uncertainties)

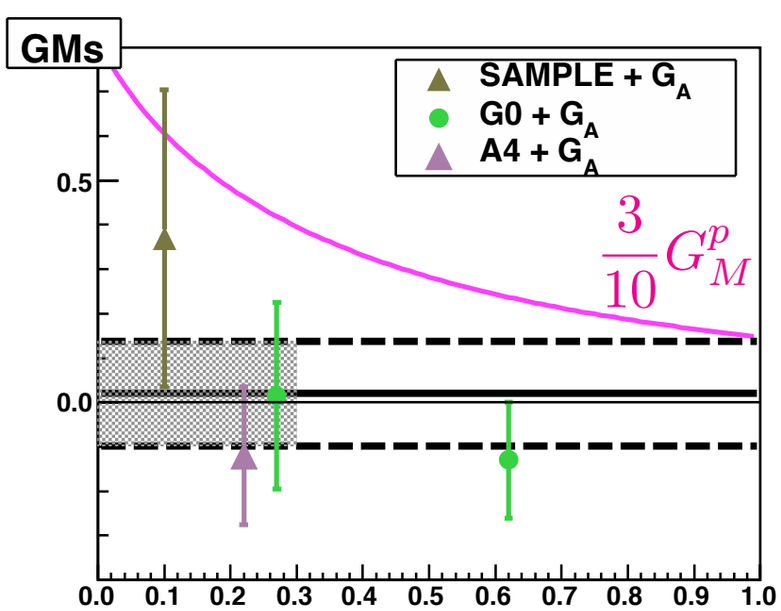
Further improvements in precision would require additional theoretical and empirical input for interpretation

Summary



- Significant and accessible contributions are still allowed... but the range has been narrowed.
- No more than a few percent of the neutron charge or proton magnetic moment can be due to strange quarks
- Precision data at middle Q^2 can finish the question of large contributions to the vector form-factors





Further improvements in precision would require additional theoretical and empirical input for interpretation