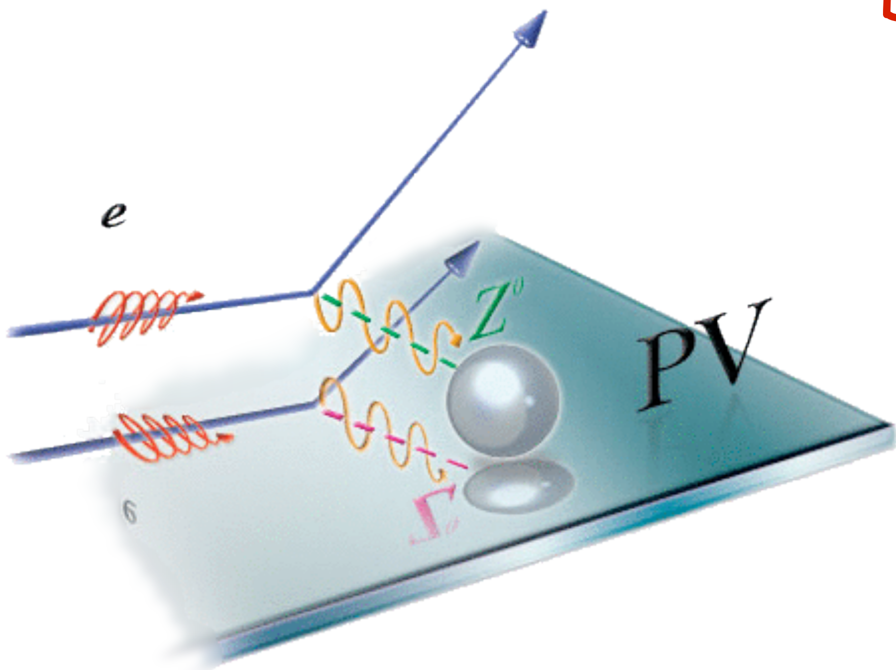
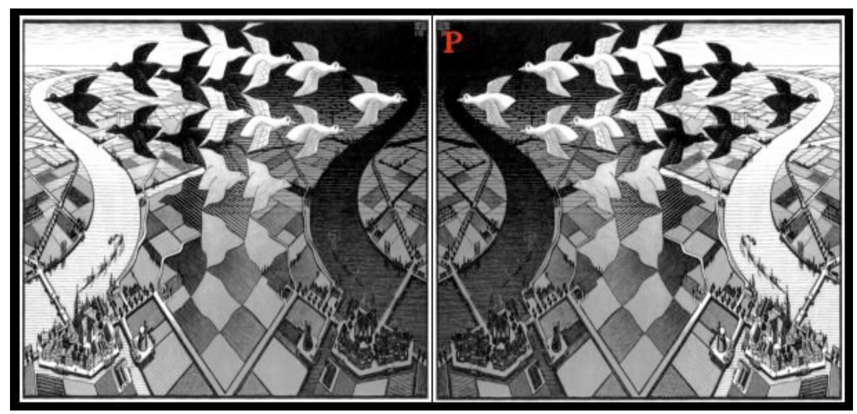
Strangeness in the Nucleon

David S. Armstrong

College of William & Mary

G0 and HAPPEx Collaborations





CAP 2012 Congress
Calgary, Alberta
June 15 2012

The College of WILLIAM & MARY

Jefferson Lab

Outline

- Parity violation in electron scattering
- Vector Strange Form Factors: G_E^s and G_M^s
- World Experimental Effort
- Recent Results:

  HAPPEx-III (forward angle):

  - Separated form factors at $Q^2 = 0.23, 0.63\ (GeV/c)^2$

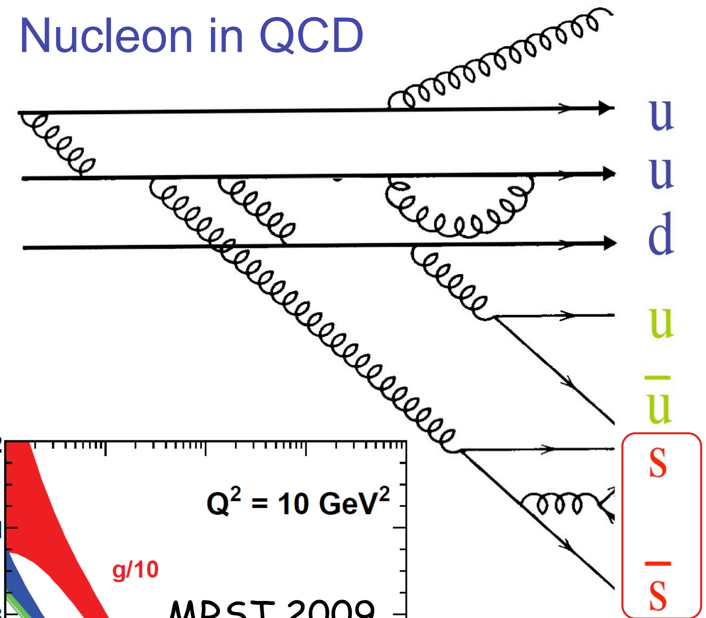
- Implications for Standard Model Tests
- Conclusions

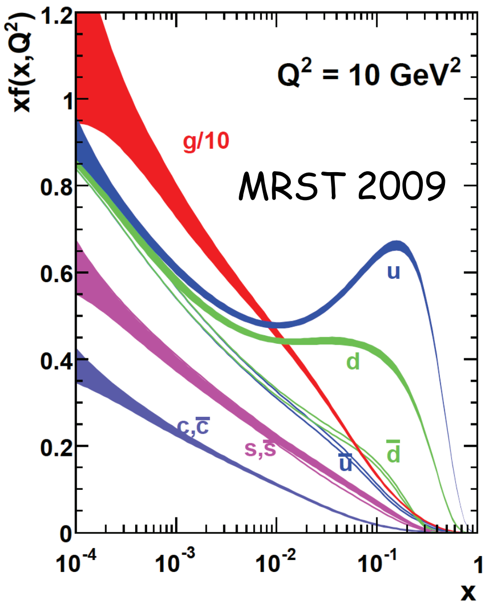
"There is no excellent beauty that hath not some strangeness in the proportion"

Francis Bacon 1561-1626

Strangeness in the nucleon

Nucleon in QCD





- $P = uud + \underbrace{u\bar{u} + d\bar{d} + s\bar{s} + g \; + ...}_{\text{« sea »}}$

- s quark: clean candidate to study the sea

- How much do virtual $s\bar{s}$ pairs contribute to the structure of the nucleon ?
  - Momentum : 4% (DIS)
  - Spin : 0 to -10% (polarized DIS)
  - Mass : 0 to 30% (πN- σ term)
  - *(the latter two are far from settled)*

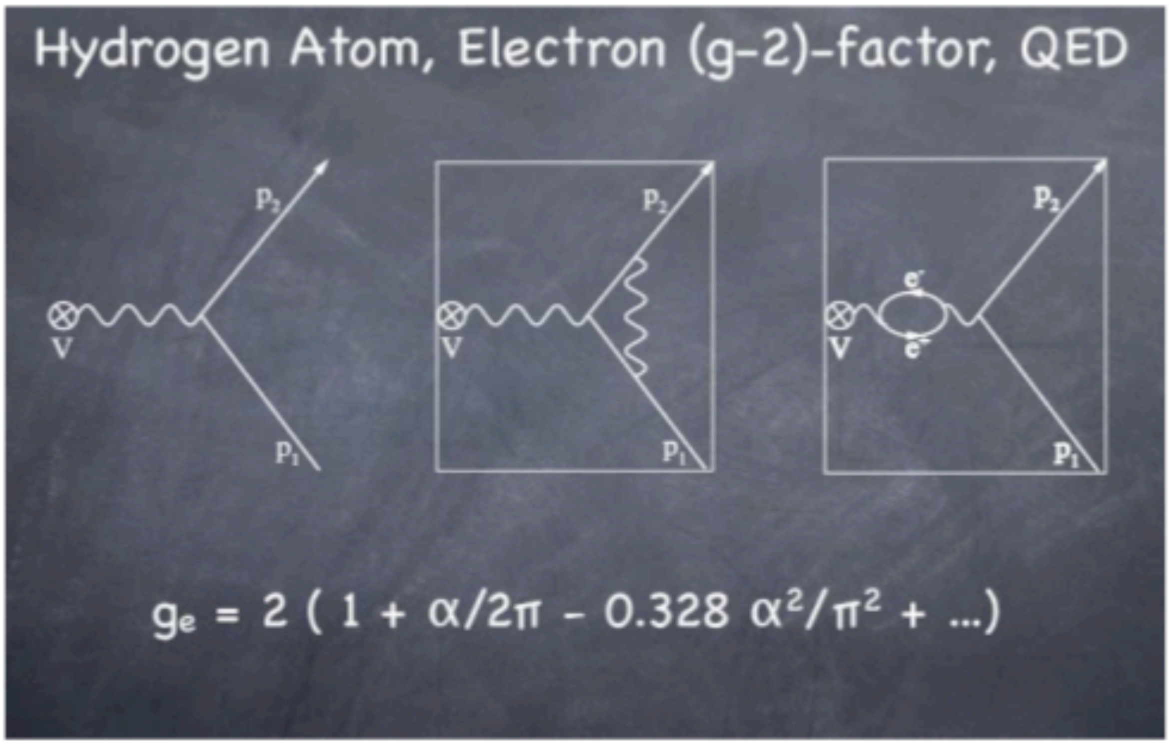
also: OZI violations in $p\bar{p} \rightarrow \dfrac{\phi\gamma}{\omega\gamma}$

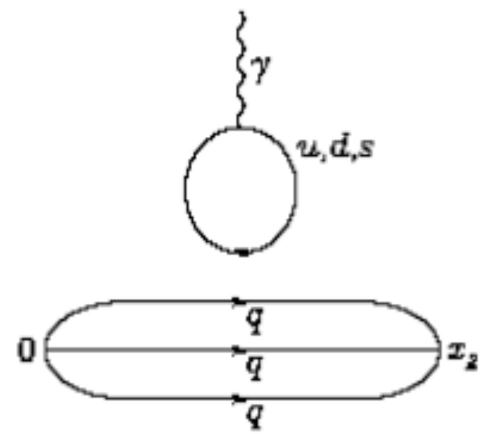
Goal: Determine the contributions of the strange quark sea ($s\bar{s}$) to the charge and magnetization distributions in the nucleon :

Vector "strange form factors": G^s_E and G^s_M

The "Lamb Shift" of QCD

Strangeness contribution is a (QCD) vacuum polarization effect*





Analogy borrowed from A.W. Thomas

Genesis of a Strange Idea

Puzzle: Initial DIS measurements of spin-structure of nucleon (EMC):
valence quarks contribute unexpectedly low fraction to total spin - "Spin Crisis"

Possible reconciliation: large fraction of spin from $s\bar{s}$?
eg. D. B. Kaplan and A. Manohar, Nucl. Phys. B310, 527 (1988).

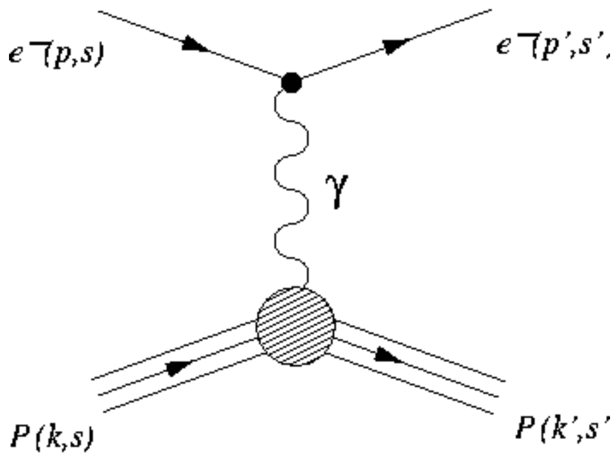
Theoretical realization: not only did available nucleon model calculations allow this, but they also allowed (and in some cases *favored*) large strange quark contributions to *other* properties of nucleon

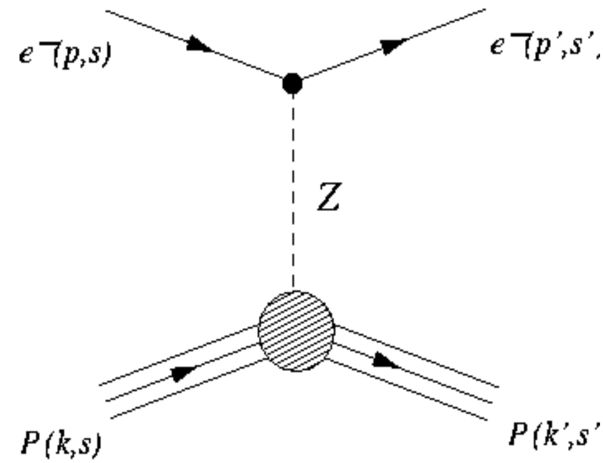
Consternation and excitement: at the time, data gave no constraint on strange contributions to charge distribution and magnetic moment!

Challenge: how to isolate strange vector form factors?

Answer: exploit the weak neutral current as a probe

Parity-Violating Electron Scattering
⇨ Weak NC Amplitudes





scatter electrons of opposite helicities from unpolarized target

Interference: $\sigma \sim |M^{EM}|^2 + |M^{NC}|^2 + 2Re(M^{EM*})M^{NC}$

Interference with EM amplitude makes Neutral Current (NC) amplitude accessible ⇨

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{|M_{PV}^{NC}|}{|M^{EM}|} \sim \frac{Q^2}{(M_Z)^2}$$

Small (~10^{-6}) cross section asymmetry isolates weak interaction

Nucleon Form Factors

Adopt Sachs FF: $G_E^\gamma = F_1^\gamma + \tau F_2^\gamma \qquad G_M^\gamma = F_1^\gamma + F_2^\gamma$

Roughly : Fourier transforms of charge and magnetization

NC and EM probe same hadronic flavor structure, with different couplings:

$$G_{E/M}^\gamma = \frac{2}{3} G_{E/M}^u - \frac{1}{3} G_{E/M}^d - \frac{1}{3} G_{E/M}^s$$

$$G_{E/M}^Z = \left(1 - \frac{8}{3}\sin^2\theta_W\right) G_{E/M}^u - \left(1 - \frac{4}{3}\sin^2\theta_W\right) G_{E/M}^d - \left(1 - \frac{4}{3}\sin^2\theta_W\right) G_{E/M}^s$$

$G^Z_{E/M}$ provide an important benchmark for testing non-perturbative QCD structure of the nucleon

Charge Symmetry

One expects the neutron is ≈ an isospin rotation of the proton:

$$G_{E/M}^{p,u} = G_{E/M}^{n,d}, \qquad G_{E/M}^{p,d} = G_{E/M}^{n,u}, \qquad G_{E/M}^{p,s} = G_{E/M}^{n,s}$$

$$G_{E/M}^{\gamma,p} = \frac{2}{3}G_{E/M}^{u} - \frac{1}{3}G_{E/M}^{d} - \frac{1}{3}G_{E/M}^{s} \;\rightarrow\; G_{E/M}^{\gamma,n} = \frac{2}{3}G_{E/M}^{d} - \frac{1}{3}G_{E/M}^{u} - \frac{1}{3}G_{E/M}^{s}$$

$G^{g,p}_{E,M}$, $G^{g,n}_{E,M}$, $G^{Z,p}_{E,M}$	Charge symmetry →	$G^{u}_{E,M}$, $G^{d}_{E,M}$, $G^{s}_{E,M}$	Shuffle →	$G^{p}_{E,M}$, $G^{n}_{E,M}$ ← Well Measured; $G^{s}_{E,M}$ ← <N| sγ^μ s |N>

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{M_Z M_\gamma}{|M_\gamma|^2} = -\frac{G_F Q^2}{\sqrt{2}\pi\alpha} \mathrm{F}\left(G_{E/M}^{p}, G_{E/M}^{n}, G_{E/M}^{s}, G_A\right)$$

Isolating individual form factors: vary *kinematics* or *target*

For a proton:

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

~ few parts per million

$$A_E = \varepsilon\, G_E^p G_E^Z, \qquad A_M = \tau\, G_M^p G_M^Z, \qquad A_A = -\left(1 - 4\sin^2\theta_W\right)\varepsilon' G_M^p G_A^e$$

Forward angle — Backward angle

For ^{4}He: G_E^s alone

$$A_{PV} = \frac{G_F Q^2}{\pi\alpha\sqrt{2}}\left[\sin^2\theta_W + \frac{G_E^s}{2(G_E^p + G_E^n)}\right]$$

For deuteron:

enhanced G_A^e sensitivity

$$A_d = \frac{\sigma_p A_p + \sigma_n A_n}{\sigma_d}$$

Theoretical Approaches to Strange Form Factors

Models - a non-exhaustive list:

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

- no consensus on magnitudes or even *signs* of G_E^s and G_M^s !

Only model-independent statement: $G_E^s(Q^2=0)=0$

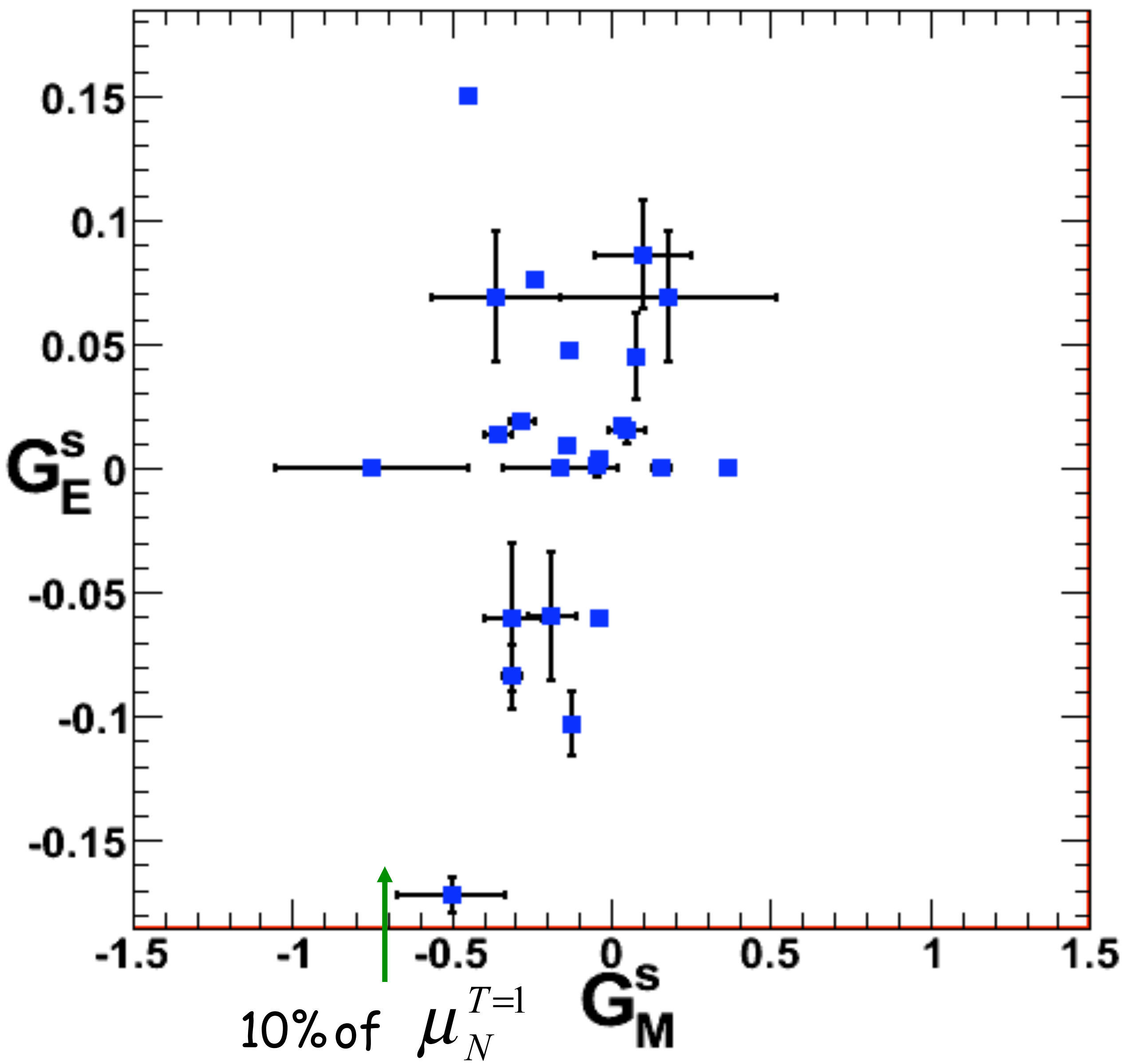
a challenging problem in non-perturbative QCD

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; PRL **97** (2006) 022001
- Doi, *et al.* PRD **80** (2009) 094503

Disconnected insertions – technically challenging

Strangeness Models



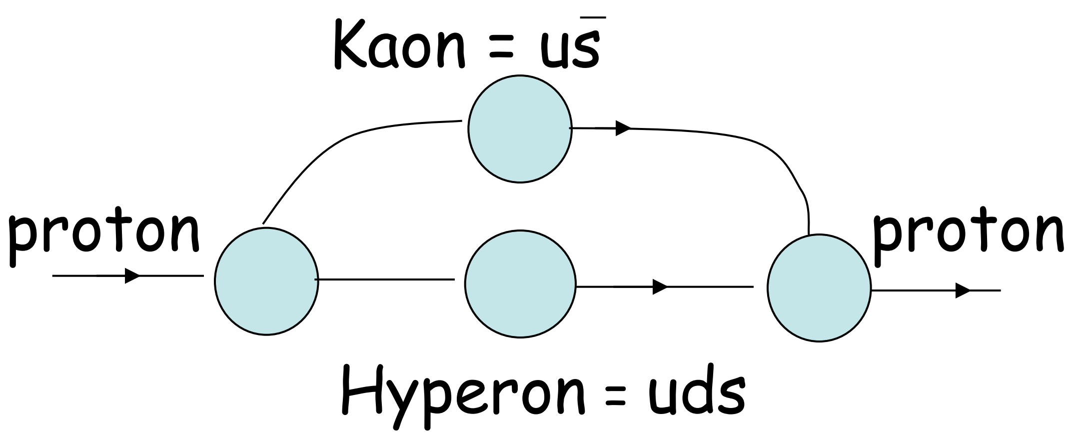
(as/of circa 2005)

note: caveats…

What would non-zero strange form factors imply?

$G^s_E \neq 0$ ⟹ s and $\bar{s}$ have different spatial distributions in proton

$G^s_M \neq 0$ ⟹ s and $\bar{s}$ have different magnetization distributions in proton
-> contribute to magnetic moment, etc.



(naive model for illustration)

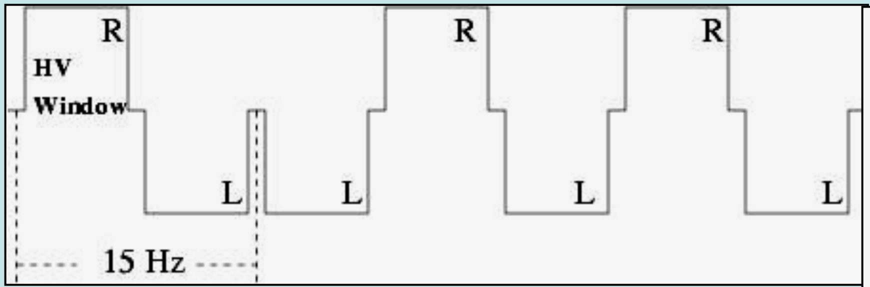
Measurement of P-V Asymmetries

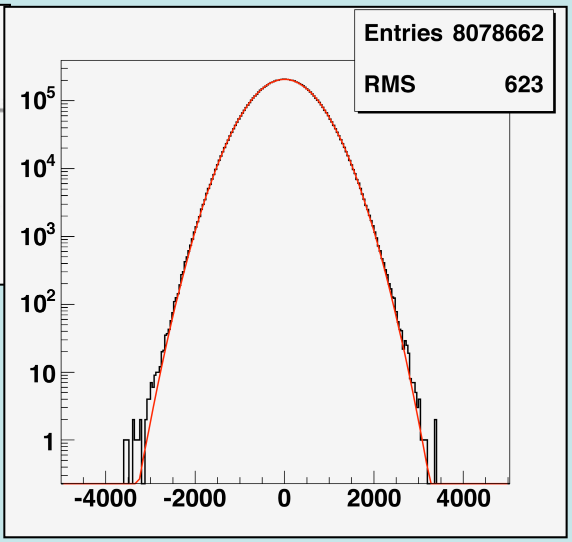
$$A_{LR} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx 10^{-6}$$

e.g. 5% Statistical Precision on 1 ppm
-> requires 4×10^{14} counts

Rapid Helicity Flip: Measure the asymmetry at 10^{-4} level, 10 million times

$$A_{LR} = \frac{N_R - N_L}{N_R + N_L}$$





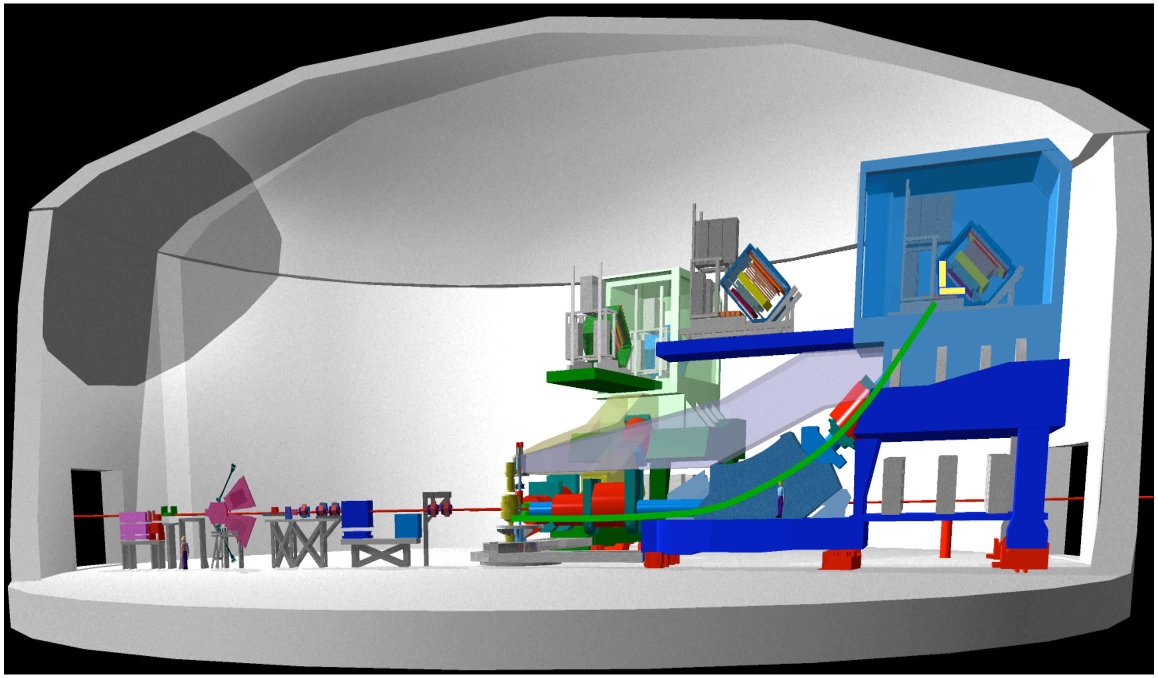
- High luminosity: thick targets, high beam current
- Control noise (target, electronics)
- High beam polarization and rapid flip

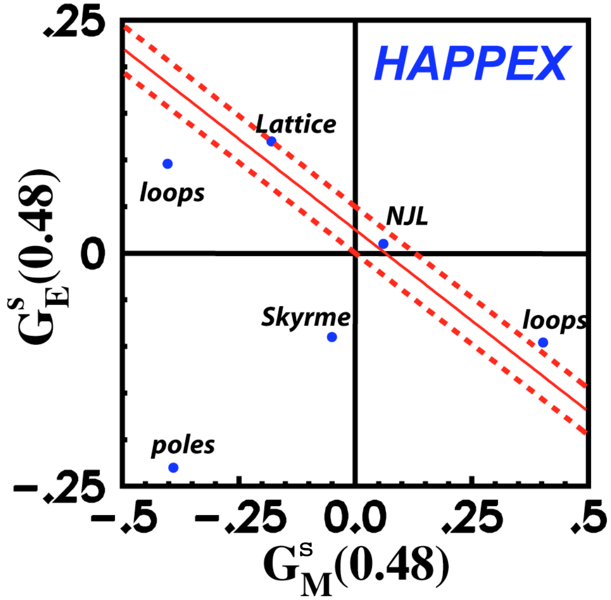
Parity-Violating Electron Scattering Program

Expt/Lab	Target/Angle	Q^2 (GeV^2)	A_{pv} (ppm)	Sensitivity	Complete
SAMPLE/Bates					
SAMPLE I	LH_2/145	0.1	-6	$G_M + 0.4G_A$	2000
SAMPLE II	LD_2/145	0.1	-8	$G_M + 2G_A$	2004
SAMPLE III	LD_2/145	0.04	-4	$G_M + 3G_A$	2004
HAPPEx/JLab					
HAPPEx	LH_2/12.5	0.47	-15	$G_E + 0.39G_M$	1999
HAPPEx II	LH_2/6	0.11	-1.6	$G_E + 0.1G_M$	2006, 2007
HAPPEx He	^4He/6	0.11	+6	G_E	2006, 2007
HAPPEx III	LH_2/14	0.63	-24	$G_E + 0.5G_M$	2011
PV-A4/Mainz					
	LH_2/35	0.23	-5	$G_E + 0.2G_M$	2004
	LH_2/35	0.11	-1.4	$G_E + 0.1G_M$	2005
	LH_2/145	0.23	-17	$G_E + \eta G_M + \eta' G_A$	2009
	LH_2/35	0.63	-28	$G_E + 0.64G_M$	(2009)
G0/JLab					
Forward	LH_2/35	0.1 to 1	-1 to -40	$G_E + \eta G_M$	2005
Backward	LH_2/LD_2/110	0.23, 0.63	-12 to -45	$G_E + \eta G_M + \eta' G_A$	2009

HAPPEx-I JLab (Hall A)

Hydrogen Target: E= 3.3 GeV θ=12.5° Q^2=0.48 $(GeV/c)^2$





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

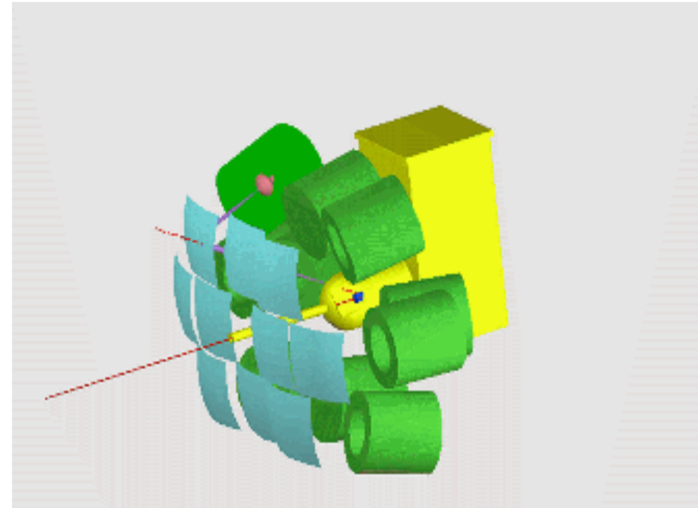
$$G^s_E + 0.39G^s_M = 0.014 \pm 0.020\ (exp) \pm 0.010\ (FF)$$

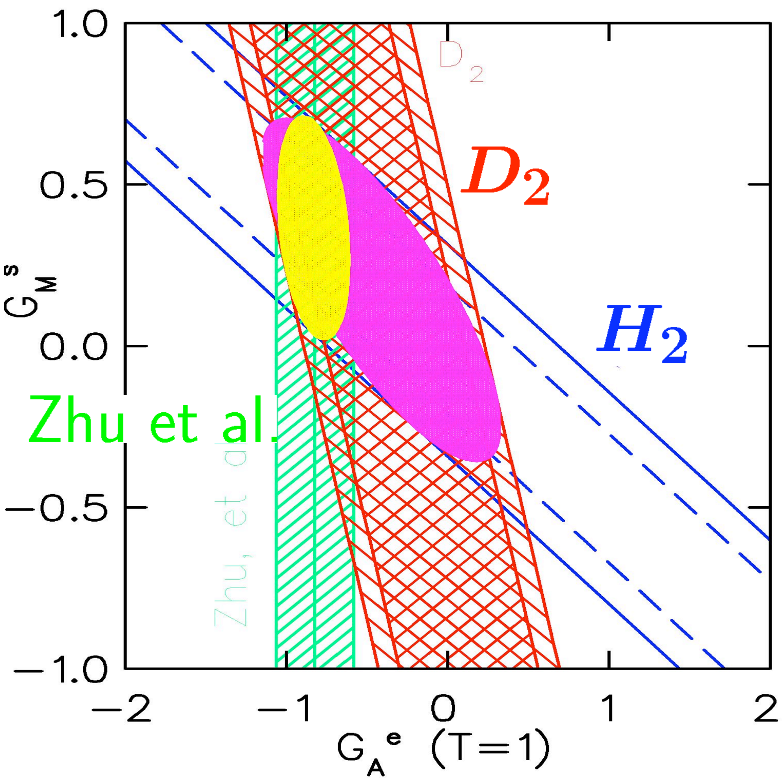
Phys. Rev. Lett. 82,1096 (1999);
Phys. Lett. B509, 211 (2001);
Phys. Rev. C 69, 065501 (2004)

SAMPLE (MIT/Bates)

Backward angle (θ=150°), integrating

$Q^2(\mathrm{GeV}^2)$	A_{PV} (ppm)	$A_0 + \alpha G^s_M + \beta G^e_A(T=1)$
$0.1, LH_2$	$-5.61 \pm 0.67 \pm 0.88$	$-5.56 + 3.37 G^s_M + 1.54 G^e_A$
$0.1, LD_2$	$-7.06 \pm 0.73 \pm 0.72$	$-7.06 + 0.72 G^s_M + 1.66 G^e_A$
$0.03, LD_2$	$-3.51 \pm 0.57 \pm 0.58$	$-2.14 + 0.27 G^s_M + 0.76 G^e_A$





$G_M{}^s$ = 0.23 ± 0.36 ± 0.40

$G^e{}_A{}^{(T=1)}$ = -0.53 ± 0.57 ± 0.50

E.J. Beise *et al.*, Prog Nuc Part Phys 54 (2005)

If theory [Zhu *et al.* Phys. Rev. D 62, 033008 (2000)] for $G^e{}_A{}^{(T=1)}$ used to constrain $G^S{}_M$:

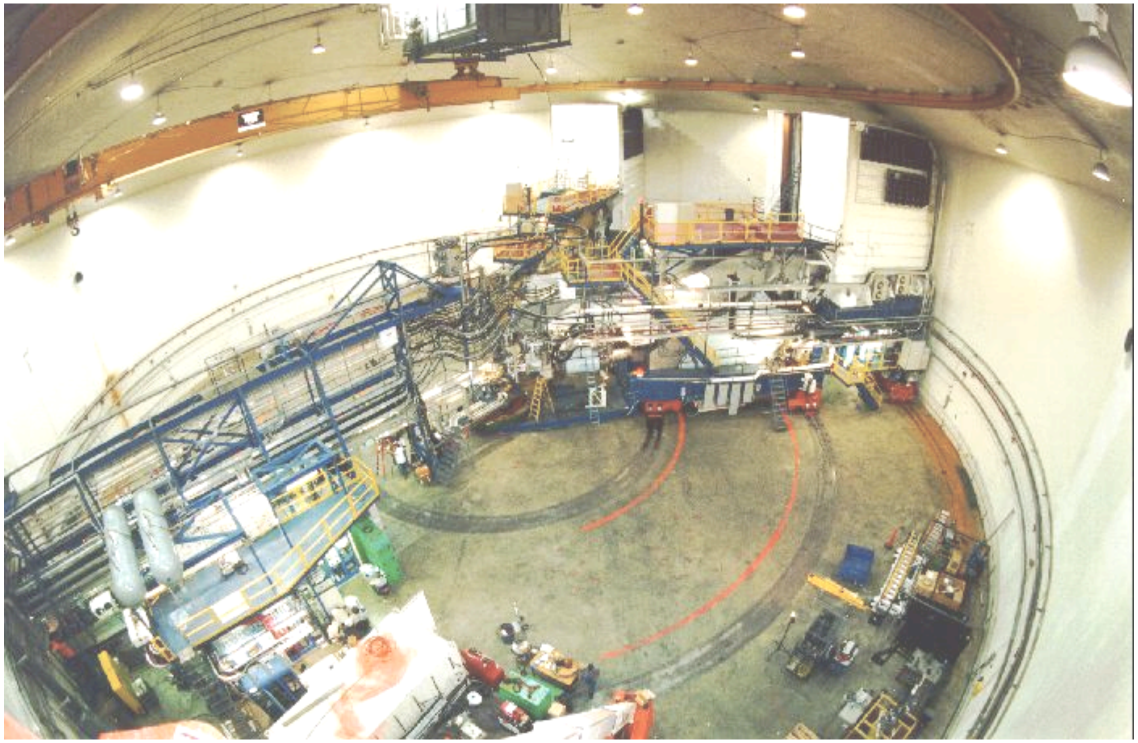
$$G^s{}_M = 0.37 \pm 0.20_{Stat} \pm 0.36_{Syst} \pm 0.07_{FF}$$

HAPPEx-II

E=3 GeV θ=6° Q^2= 0.1 (GeV/c)^2

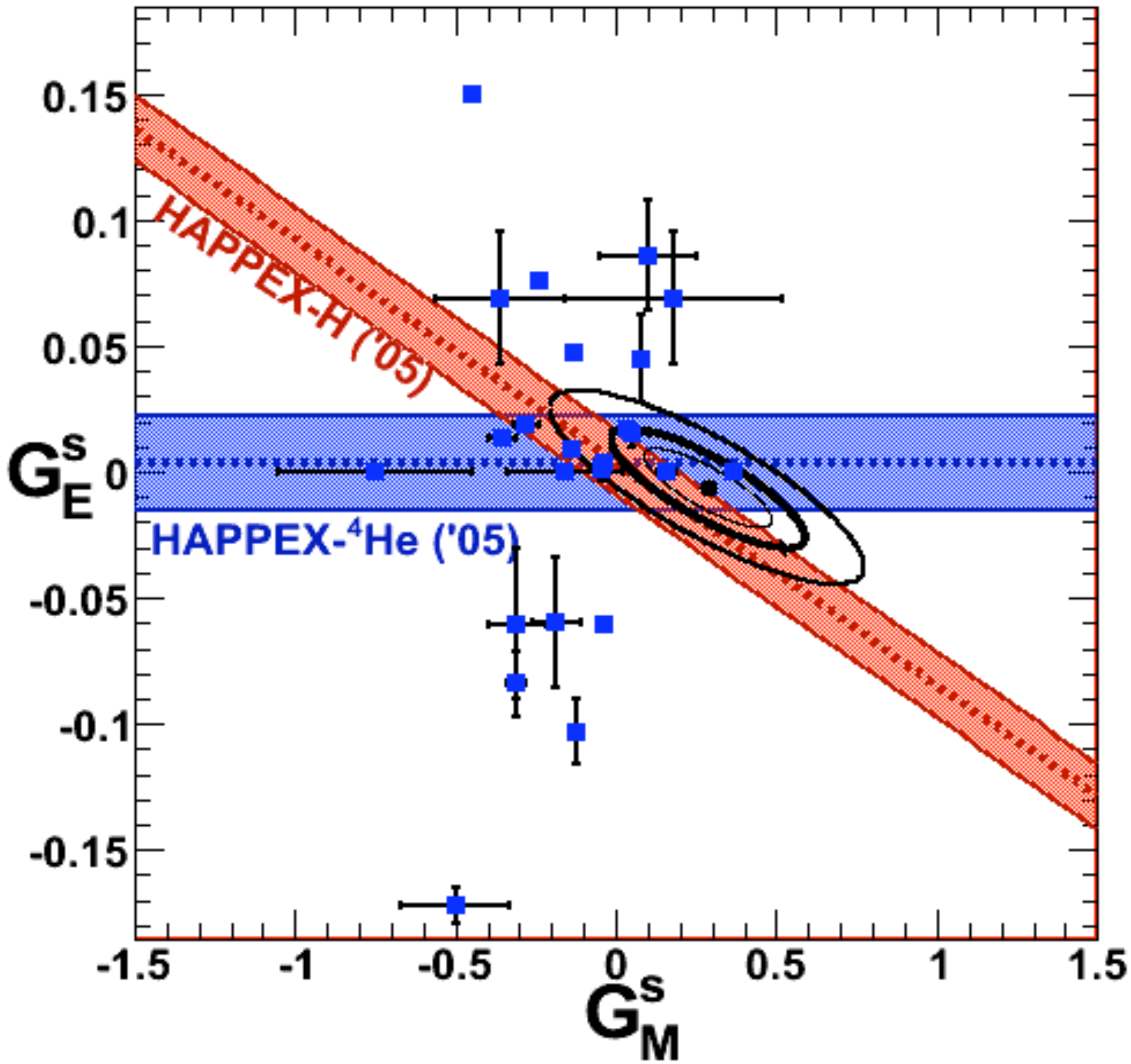
- **Hydrogen** : $G_E^s + \eta G_M^s$
- **^{4}He**: Pure G_E^s : $A^{PV} = -\frac{A_0}{2}\left(2\sin^2\theta_W + \frac{G_E^s}{G_E^{p\gamma} + G_E^{n\gamma}}\right)$

2 runs: 2004 & 2005



A. Acha, et al. PRL 98(2007)032301

HAPPEx data at Q^2 ~0.1 GeV^2



Including all data at $Q^2 \approx 0.1$

$$G_M^s = 0.28 \pm 0.20$$

21% of $\mu_N^{T=0}$

$$\langle r^2 \rangle_E^p = 0.766 \pm 0.012\, fm^2$$

$$\langle r^2 \rangle_E^s = 0.002 \pm 0.015\, fm^2$$

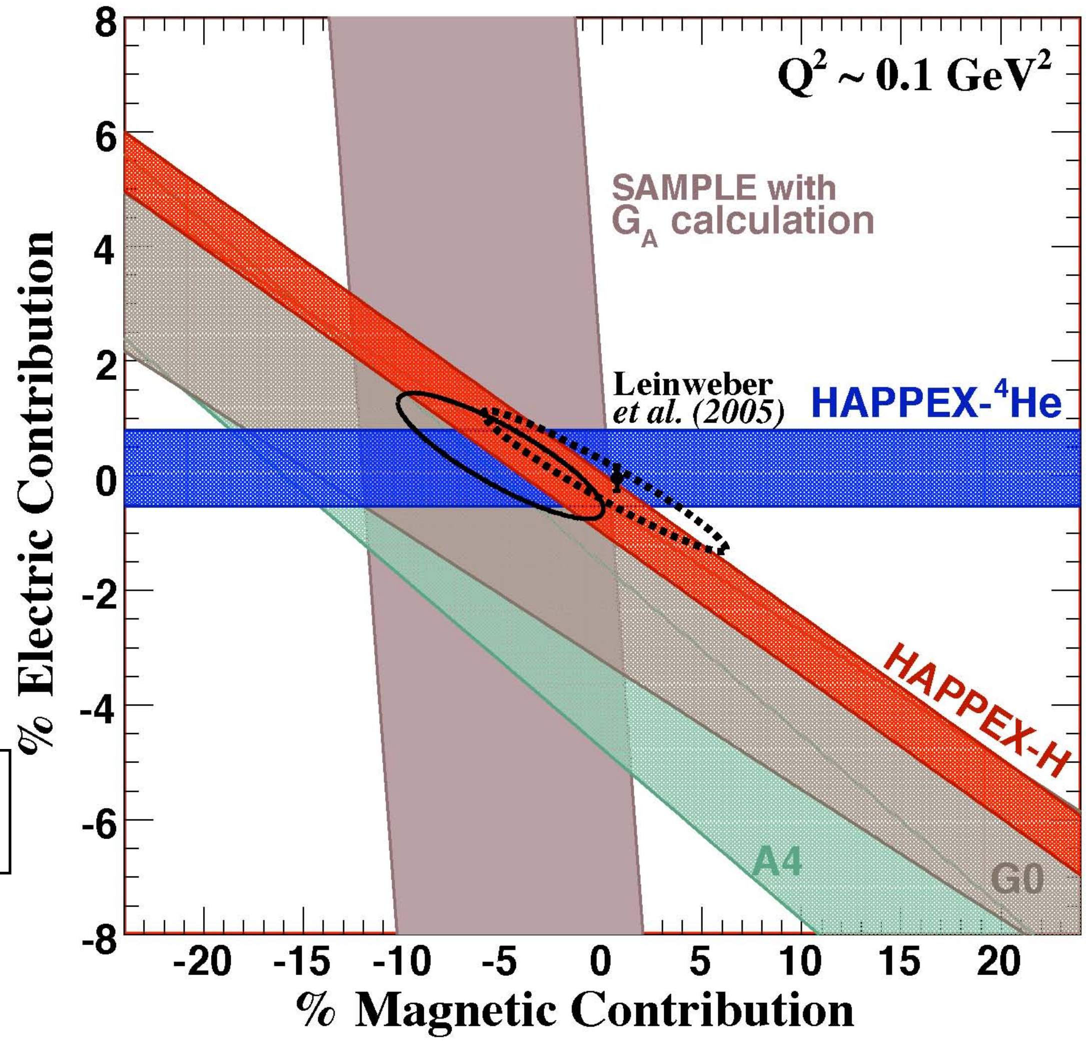
Summary of data at Q^2 =0.1 GeV^2

Solid ellipse:
K. Paschke, priv. comm.
[≈ J. Liu et al.
PRC 76, 025202 (2007)]
uses theoretical constraints
on the axial form factor

Dashed ellipse:
R.D. Young et al.
PRL 97 (2006) 102002,
does not constrain G_A
with theory

note: Placement of SAMPLE band
on depends on choice for G_A

$$\% \text{ contrib} = \frac{G^s_{E,M}}{G^p_{E,M}} \times \left(-\frac{1}{3}\right) \times 100$$



Theoretical Refinements

1. Two Boson exchange: *eg.* H.Q. Zhou, C.W. Kao and S.N. Yang
   Phys.Rev.Lett.99:262001 (2007); Phys.Rev.C **79**:062501 (2009)

   γZ box dominates the two boson effects at HAPPex, PVA4 kinematics

   $\longrightarrow$ reduces extracted $G^s_E + \eta\, G^s_M$

   (not yet put into global fits)

2. Charge-symmetry breaking effects:

   Hydrogen: B. Kubis & R. Lewis Phys. Rev. C **74**:015204 (2006)

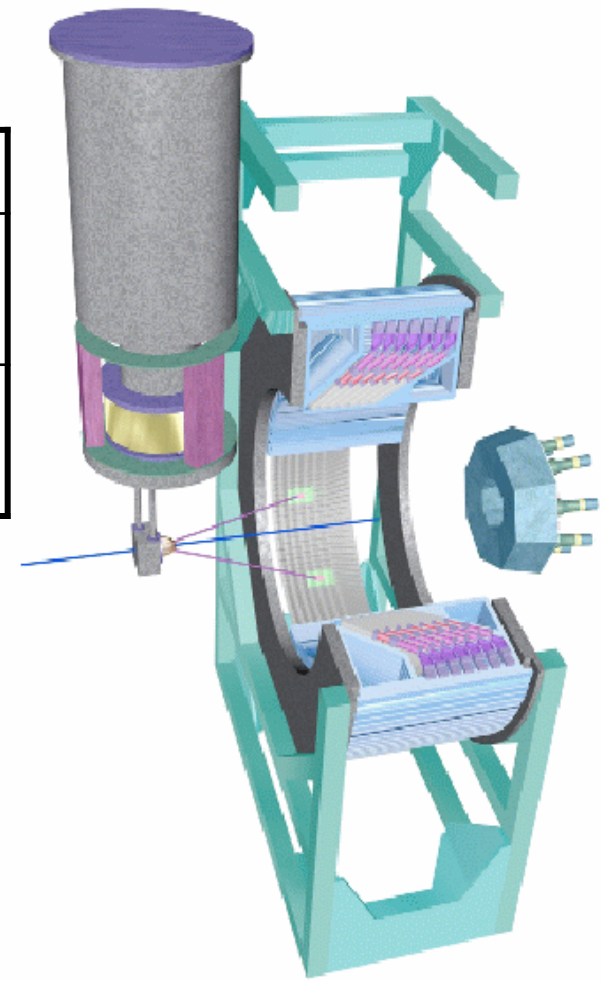
   ^{4}He: Viviani, Schiavilla, Kubis, Lewis, et al.
   Phys.Rev.Lett. **99**:112002 (2007)

still only a (modest) fraction of smallest experimental statistical errors.

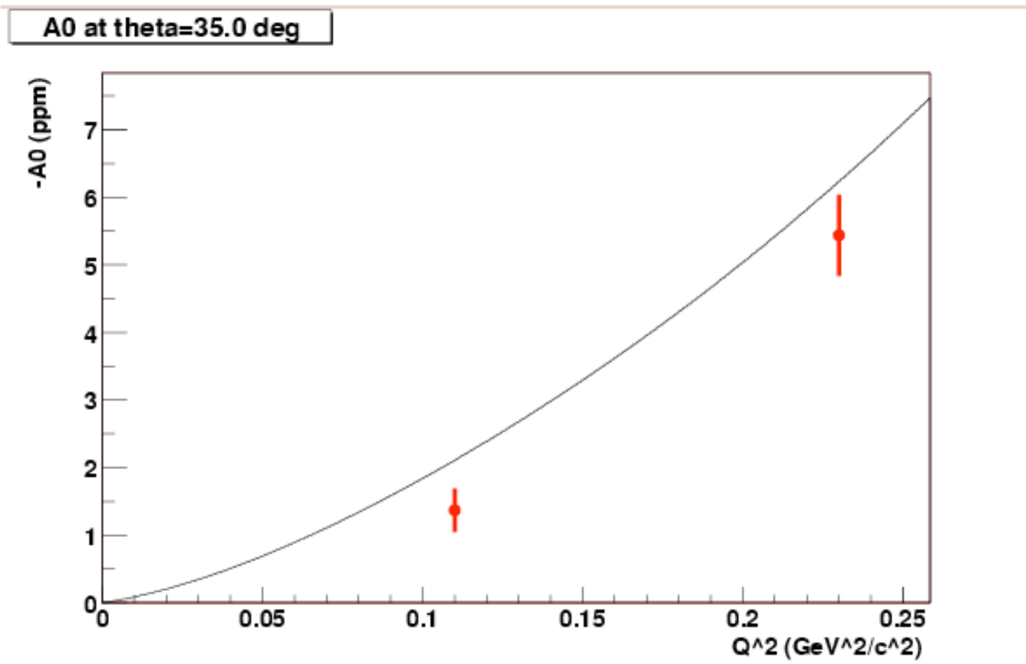
(not yet put into global fits)

PV-A4: Forward angle (MAMI)

Q^2 (GeV^2)	A_{PV} ± stat ± syst (ppm)	$G_E^s + \eta G_M^s$
0.230	-5.44 ± 0.54 ± 0.26	$G_E^s + 0.225\, G_M^s$ = 0.039 ± 0.034
0.110	-1.36 ± 0.29 ± 0.13	$G_E^s + 0.106\, G_M^s$ = 0.071 ± 0.036

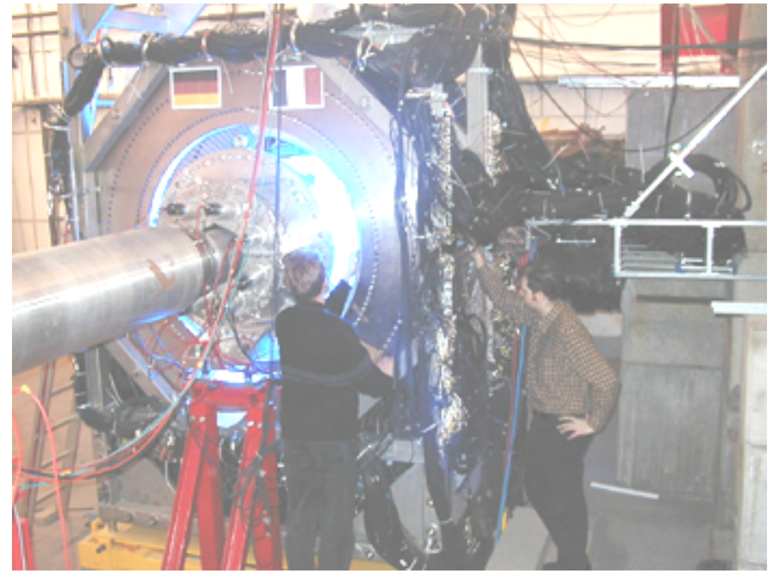


Counting – fast energy histograms



"Evidence for Strange Quark Contributions to the Nucleon's Form Factors at Q^2 = 0.1 GeV^2"
F. Maas et al. PRL 94, 152001 (2006)

PV-A4: Backward angle

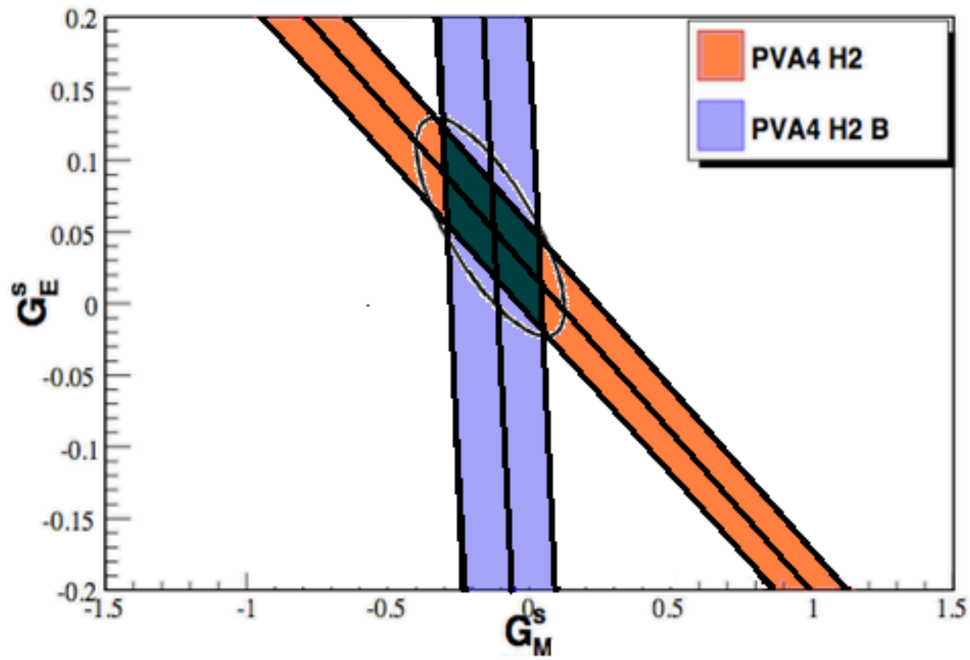


$\theta = 145°$ $Q^2 = 0.22\ (GeV/c)^2$

$A_{meas} = -17.23 \pm 0.82 \pm 0.89$ ppm

$G^s_E = 0.050 \pm 0.038 \pm 0.019$
$G^s_M = -0.14 \pm 0.11 \pm 0.11$

(uses theoretical constraint of Zhu et al., for the axial FF)



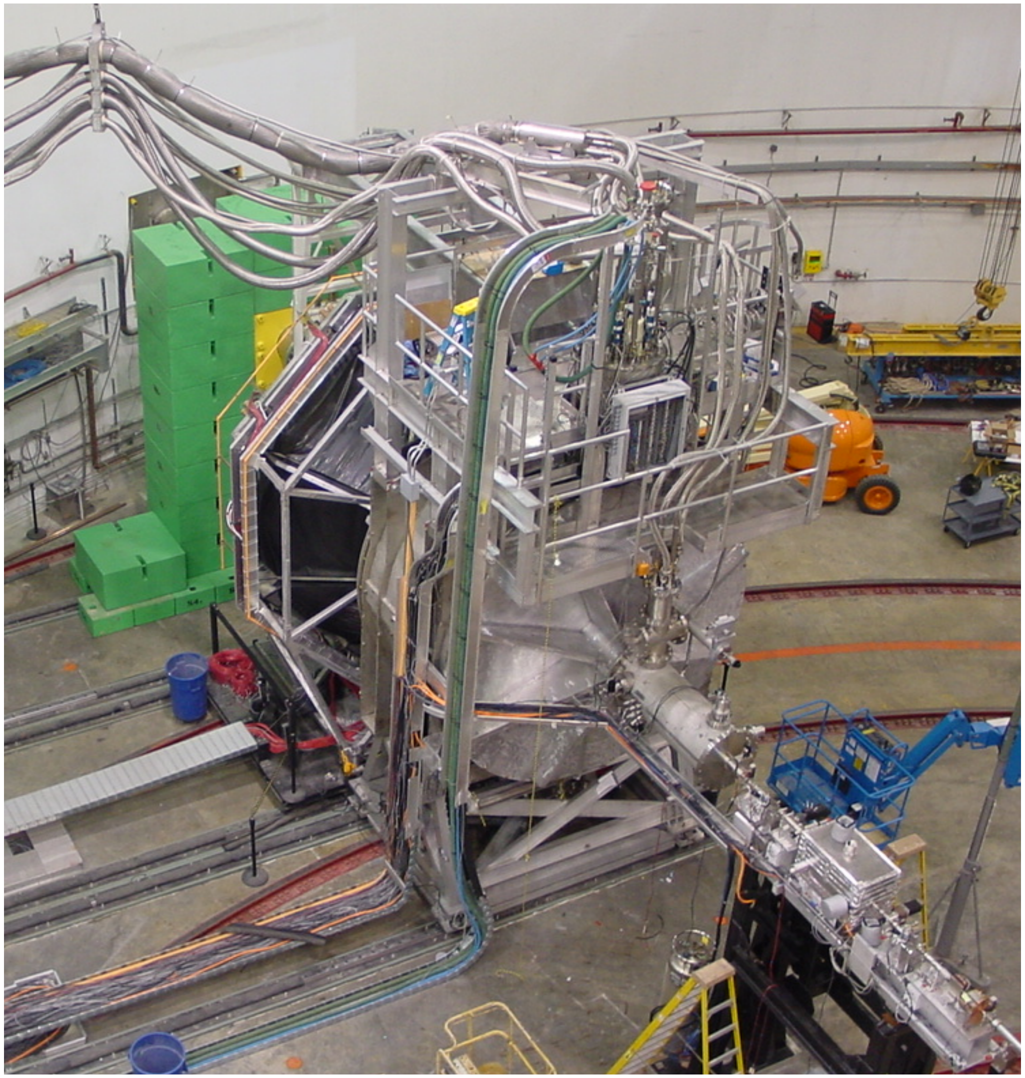
% contribution to proton:
electric: 3.0 ± 2.5 %
magnetic: 2.9 ± 3.2 %

S. Baunack et al., PRL 102 (2009) 151803

Deuterium results at same Q^2 – results expected soon....

G^0 (JLab – Hall C)

- Superconducting toroidal magnetic spectrometer



Forward angle mode:

LH_2: E_e = 3.0 GeV

Recoil proton detection

➩ $0.12 \leq Q^2 \leq 1.0$ $(GeV/c)^2$

Backward angle mode:

E_e = 362, 687 MeV

LH_2, LD_2 electron detection

(quasi)elastic at ~108°

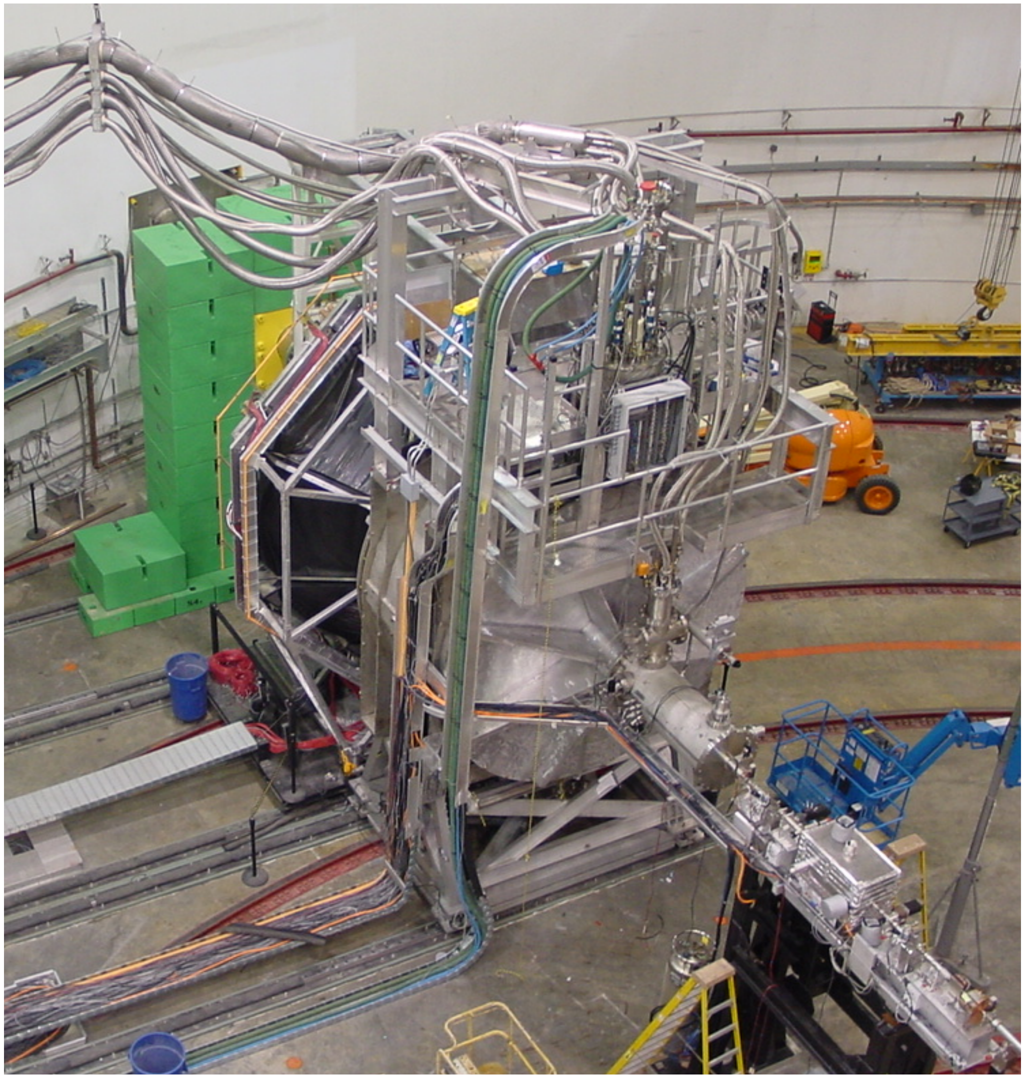
Q^2 = 0.22 GeV^2, 0.63 GeV^2

G^0 (JLab – Hall C)

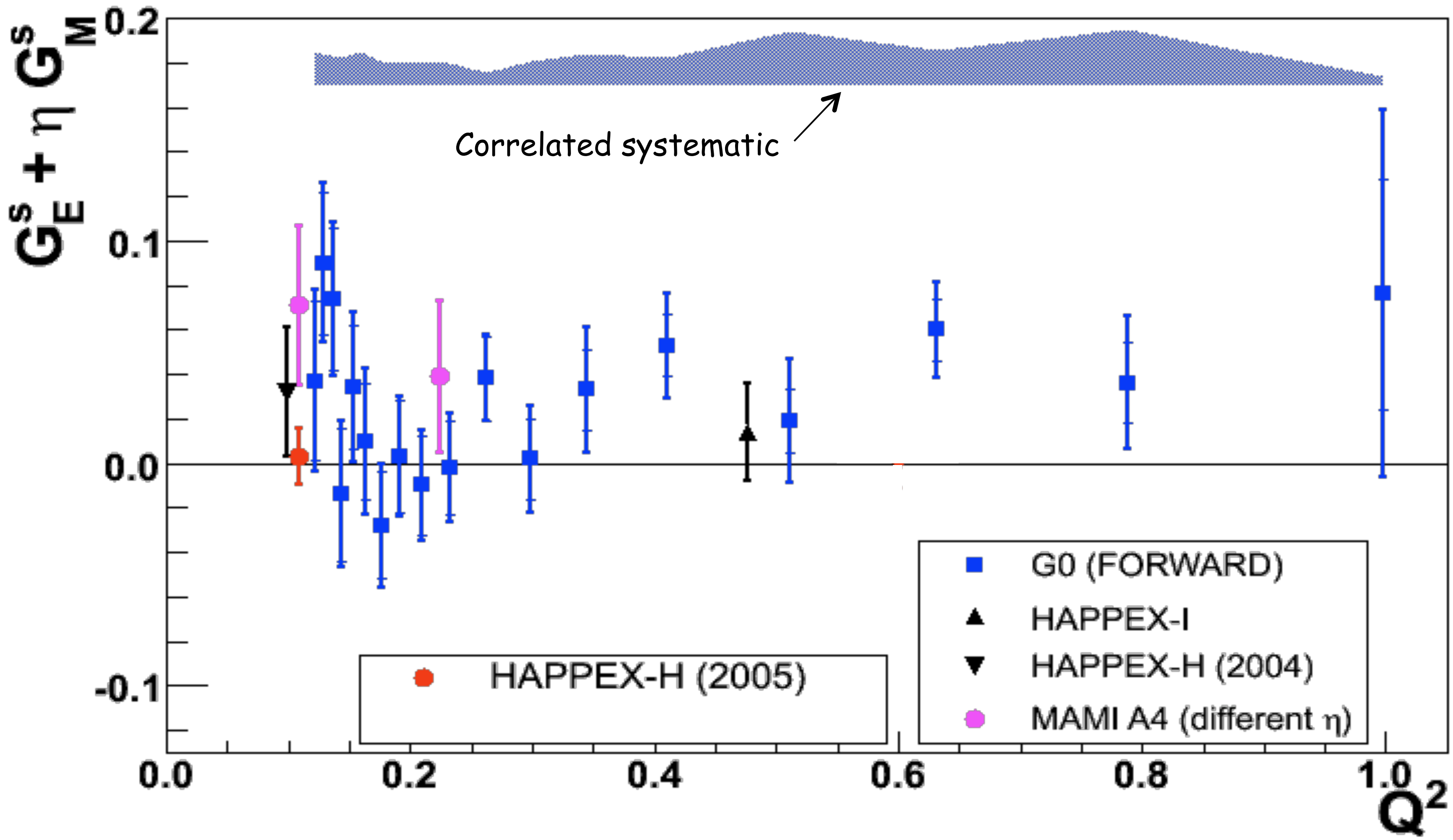
Major Canadian Content:

U. Manitoba, U, Winnipeg,
TRIUMF, UNBC

also several Canadians at
U.S. institutions eg.
D. Beck (spokesperson), B. Quinn,
D. Armstrong



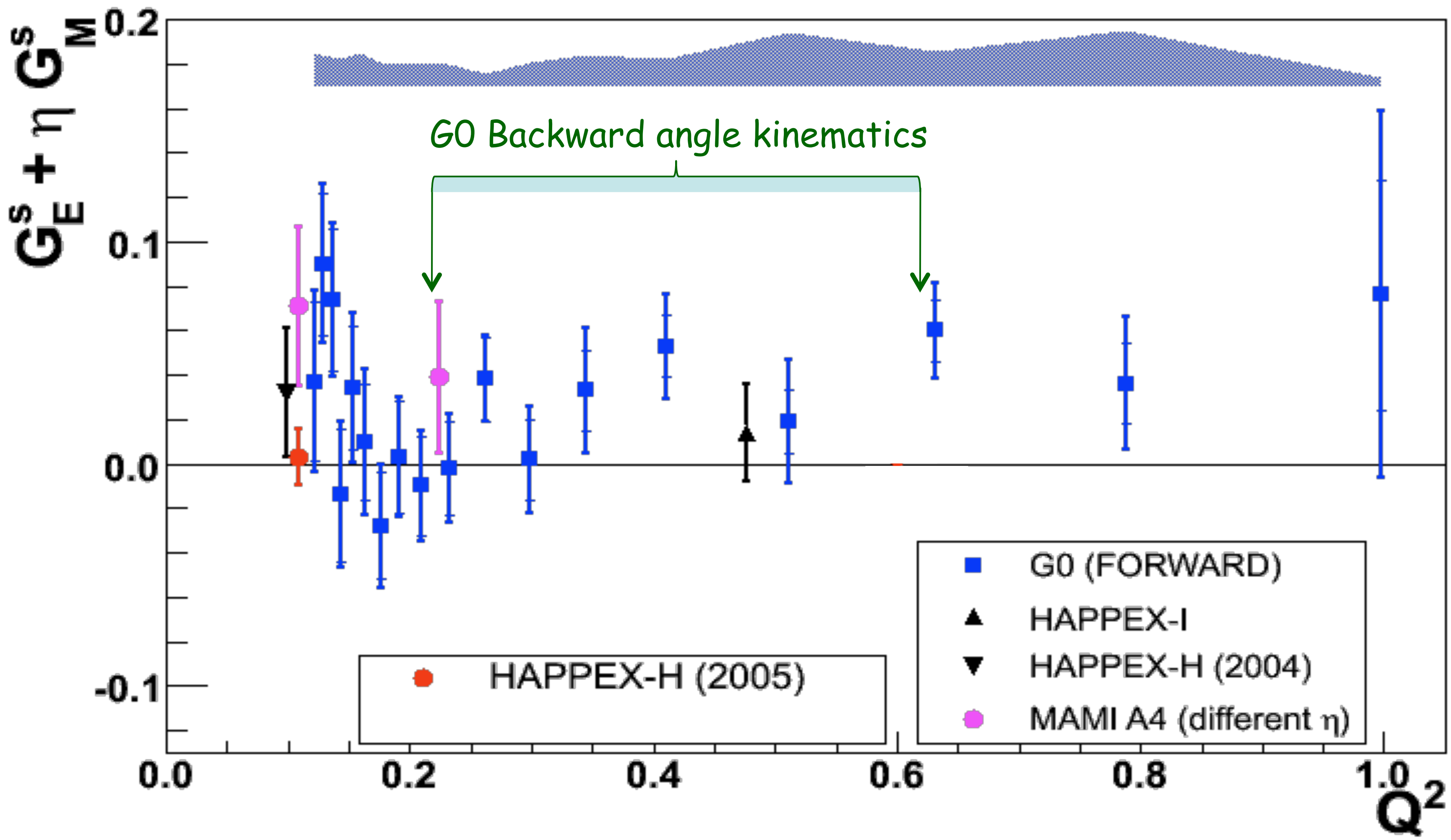
G0: Forward-angle results



$G_E^s = G_M^s = 0$ Hypothesis excluded at 89% C.L.

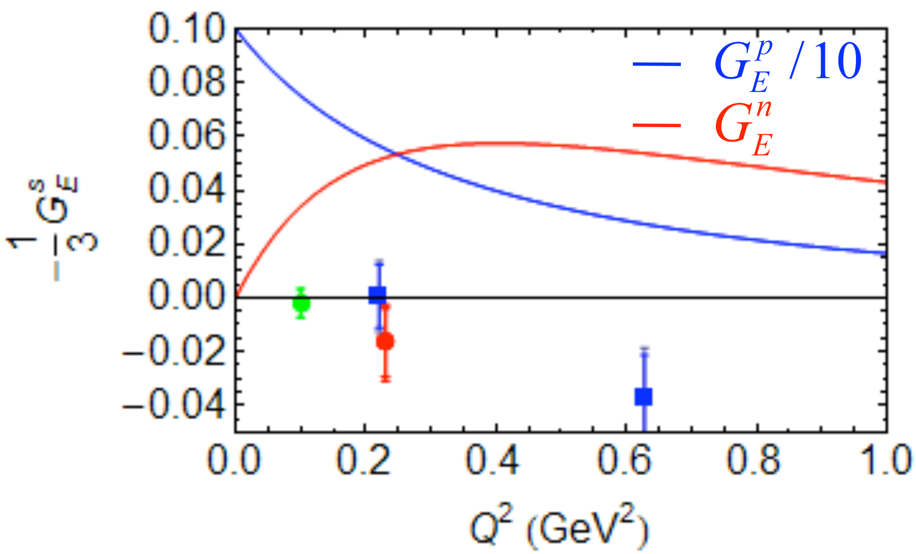
D.S. Armstrong *et al.*, PRL 95, 092001 (2005)

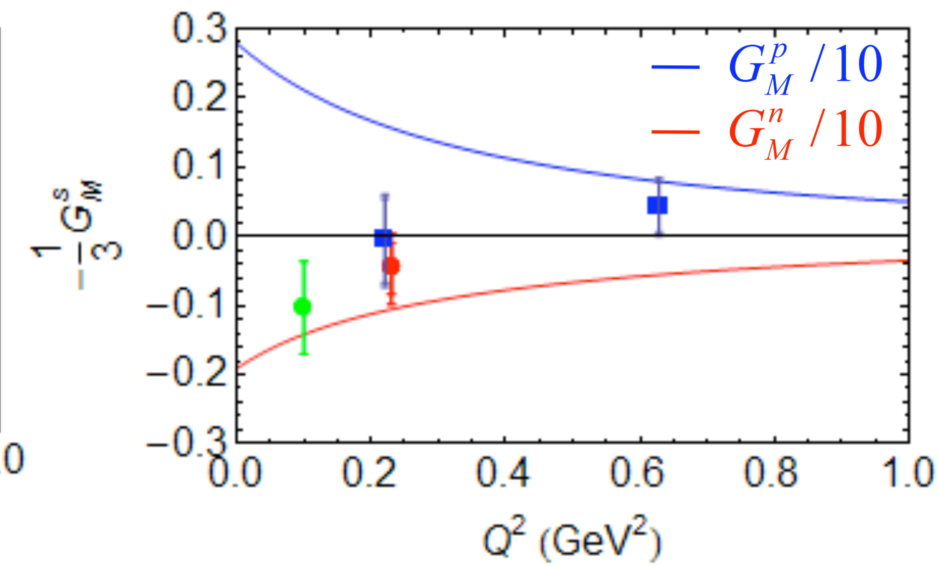
Forward Angle Results



G0 Backward Angle results

D. Androic *et al.* PRL **104**(2010)012001





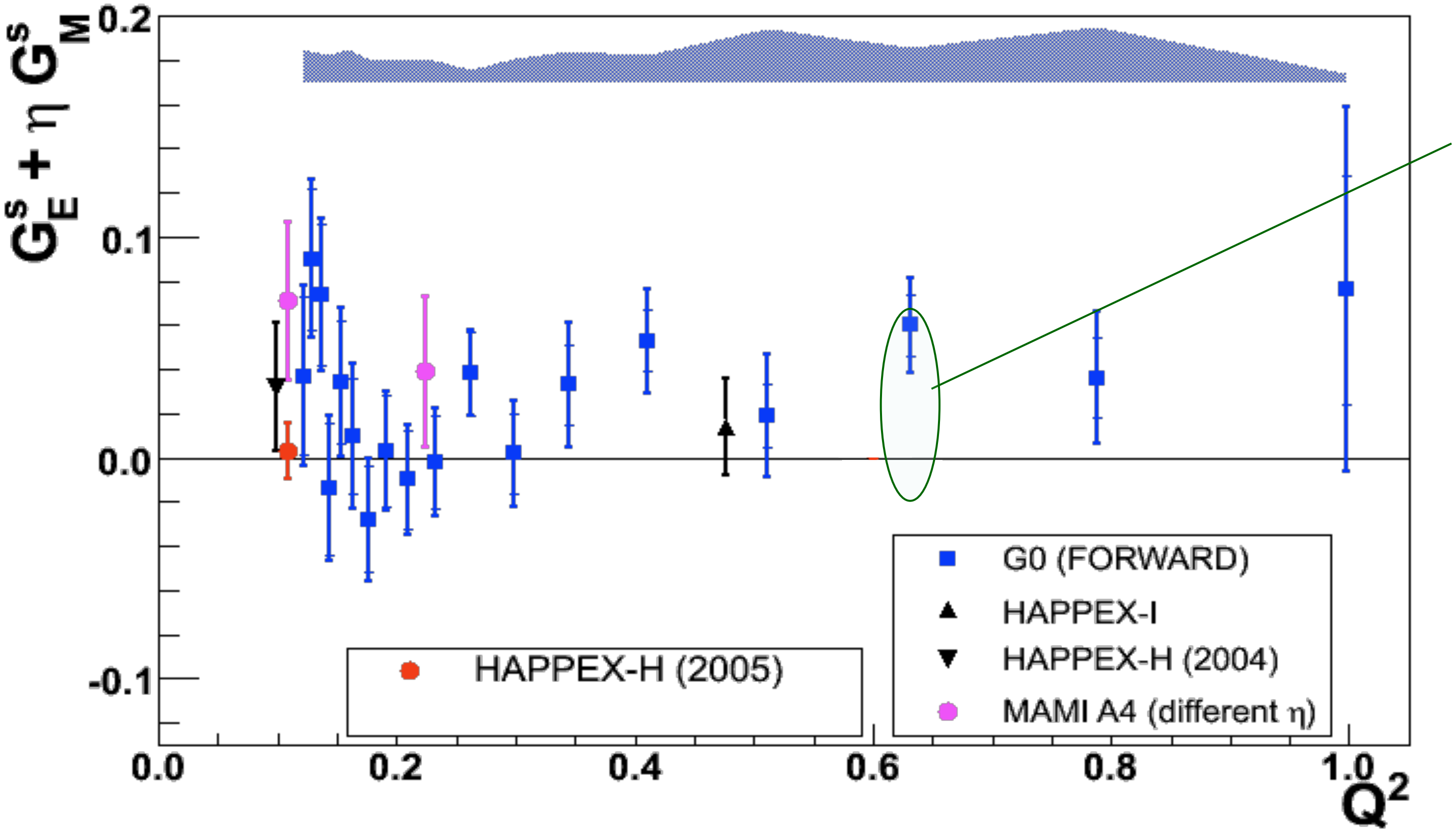
G0 , PVA4, world data at 0.1

Strange form factors
contribute at most a few % to
overall vector form factors…

except maybe near Q^2 = 0.6…

HAPPEX-III

Data-taking 2009



A higher precision repeat of HAPPEx-I, at somewhat higher Q^2

(0.624 GeV^2 – heart of the G0 "signal")

- 100 μA beam current, 89.6% polarization, 25 cm lH2 target

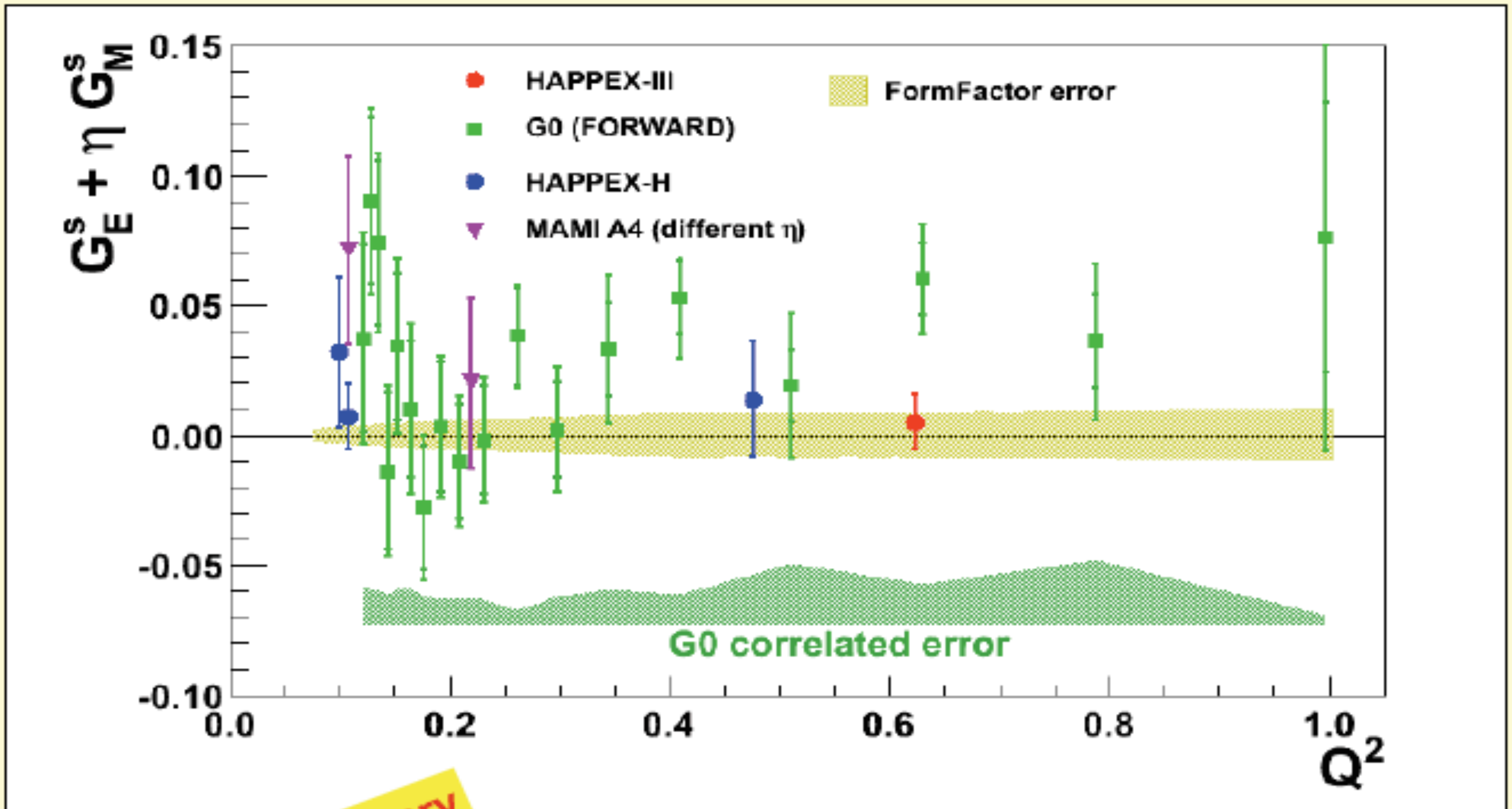
(c.f. 35 μA at 70% polarization, 15 cm target for HAPPEx-I)

- Precision (0.8%) beam polarimetry with Moller and Compton polarimeters

HAPPEX-III Results

preliminary

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



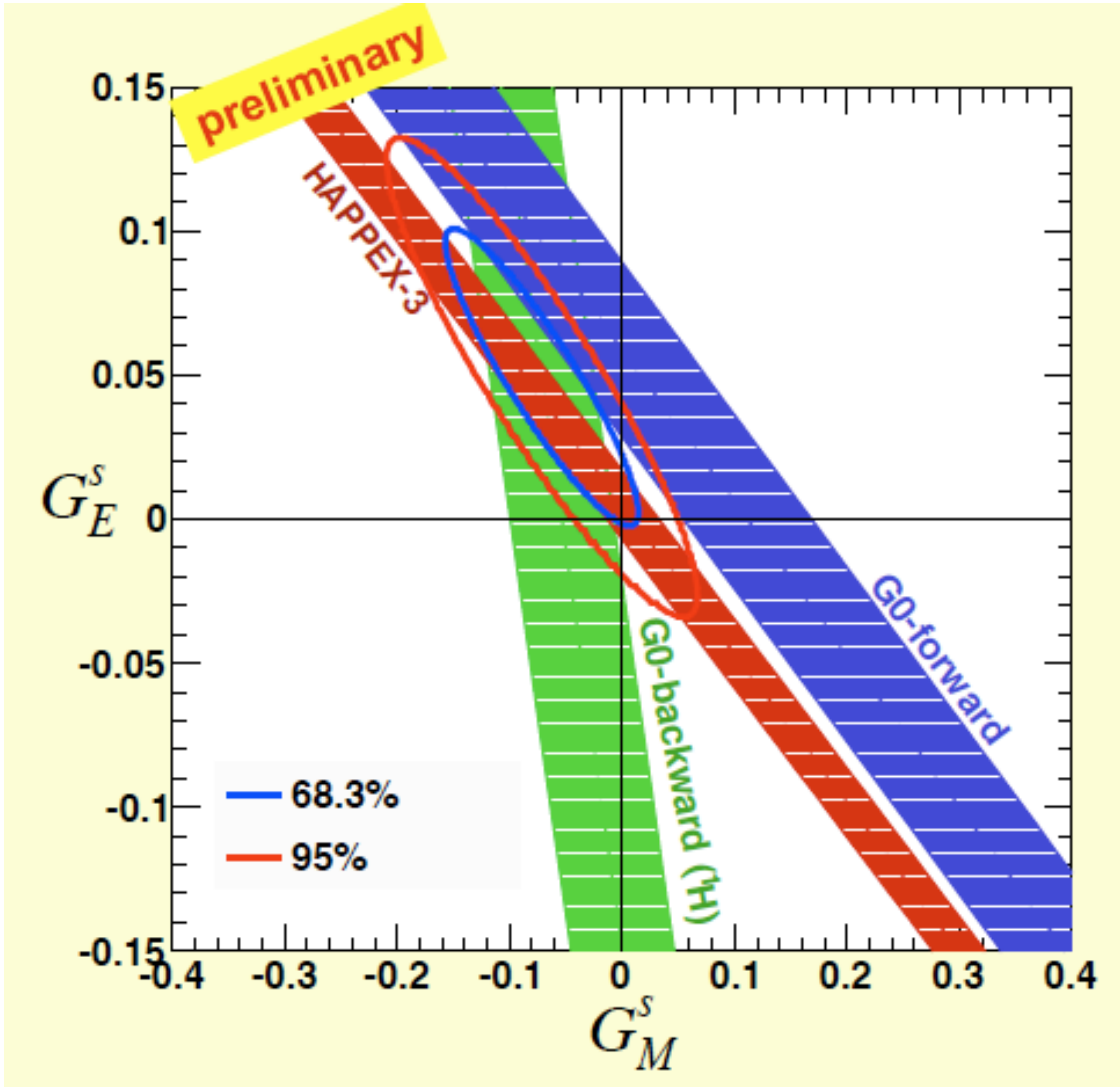
preliminary

$A(G^s=0) = -24.158\ ppm \pm 0.663\ ppm$

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

Z. Ahmed et al., PRL 108(2012)102001.

Separated Form Factors at Q^2=0.63



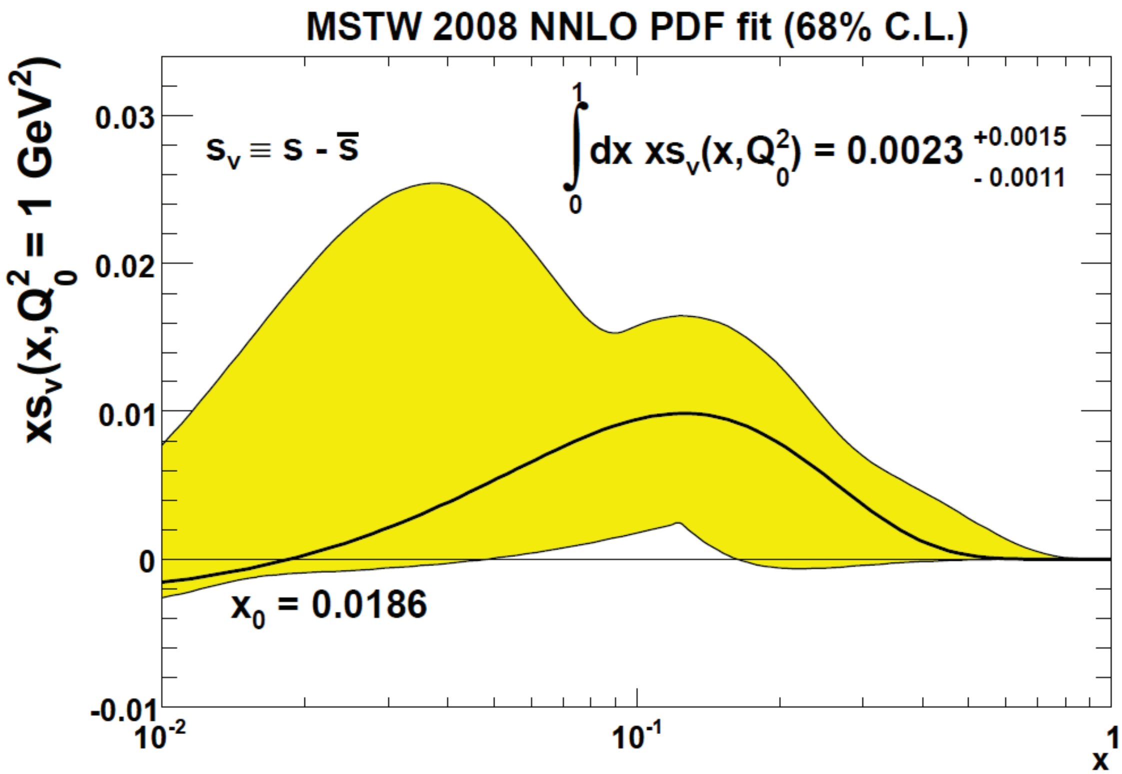
Z. Ahmed et al., PRL 108(2012)102001

Interpretation…

Suggestions from PDF fits of strange asymmetry ⇨

Small G_E^s indicates no corresponding *spatial* asymmetry – the s and s bar are produced with very similar spatial distributions

Small G_M^s indicates *either* that s $\bar{s}$ are produced spin-aligned, *and/or* that their magnetizations are not random with respect to nucleon spin orientation



ATLAS has new results that further constrain strange asymmetry

Beyond Strangeness:
Parity-Violating Electron Scattering as a Standard Model Test

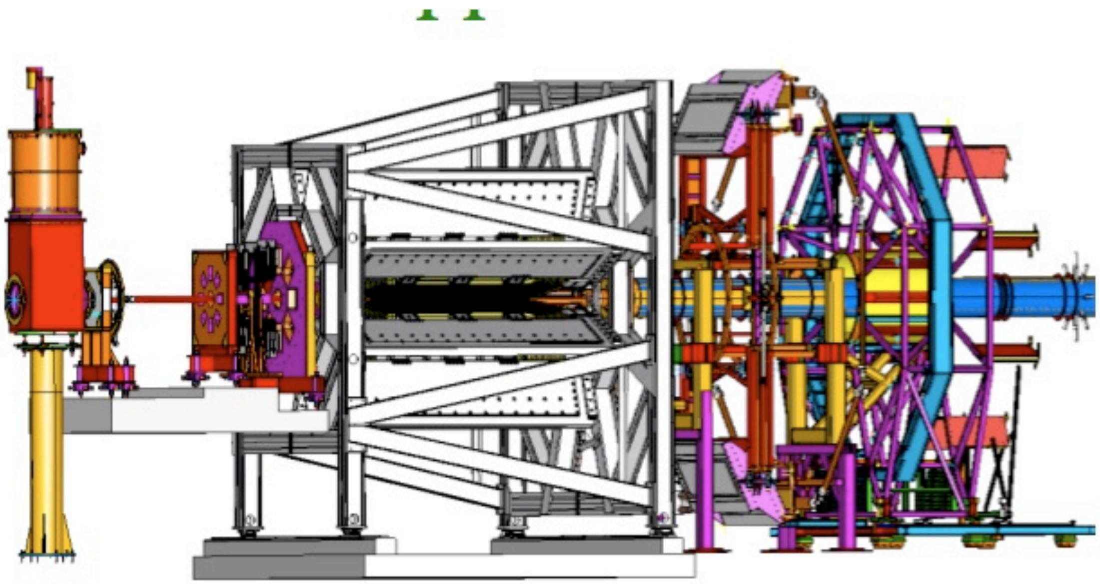
revisit History: SLAC E122 (Prescott, et al). first PV electron scattering experiment – seminal test of electroweak Standard Model

at low Q^2 & forward angles: $A_{PV} \propto Q_w^p = (1 - 4\sin^2\theta_W)$

Q_w^p : Weak charge of the proton – precise Standard Model prediction, poorly tested experimentally

Experiment at JLab; just completed data-taking (May 2012)

Strange form factors crucial input (extrapolation to Q^2=0)



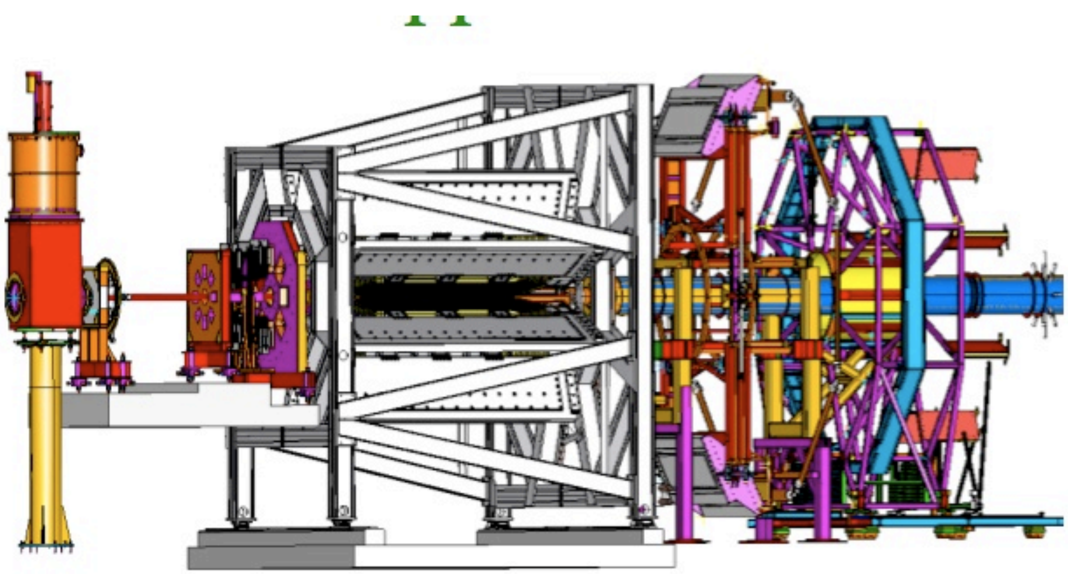
Beyond Strangeness:
Parity-Violating Electron Scattering as a Standard Model Test

revisit History: SLAC E122 (Prescott, et al). first PV electron scattering experiment - seminal test of electroweak Standard Model

at low Q^2 & forward angles: $A_{PV} \propto Q_w^p = (1 - 4 \sin^2\theta_W)$

Q_w^p : Weak charge of the proton – precise Standard Model prediction, poorly tested experimentally

Major Canadian Content:
U. Manitoba, U. Winnipeg, TRIUMF, UNBC



Talks yesterday:
P. Wang, J. Pan, V. Tvaskis

Summary

- Comparison of electromagnetic and weak neutral elastic form factors allows determination of strange quark contribution
  - large distance dynamics of the sea
- Separated form factors at three different Q^2
- G_E^s , G_M^s small, consistent with zero
- Important input for Standard Model test (QWeak)

- Next steps:

  - Mainz PVA4 results at Q^2 =0.63 expected soon (similar kinematics to HAPPEx-III)
  - global fits to all 36 asymmetries, including 2-boson & CSV effects, consistent electromagnetic form factors
  - no plans on pushing experimental effort further… lattice?

"Do not infest your mind with beating on the strangeness of this business" - W. Shakespeare (The Tempest)

Backup slides

At a resolution of 10^{-24} metres, isolated clumps of Strange Matter pop briefly out of the quantum foam to debate the possible existence of ~~Particle Physicists~~.

Hadron Physicists