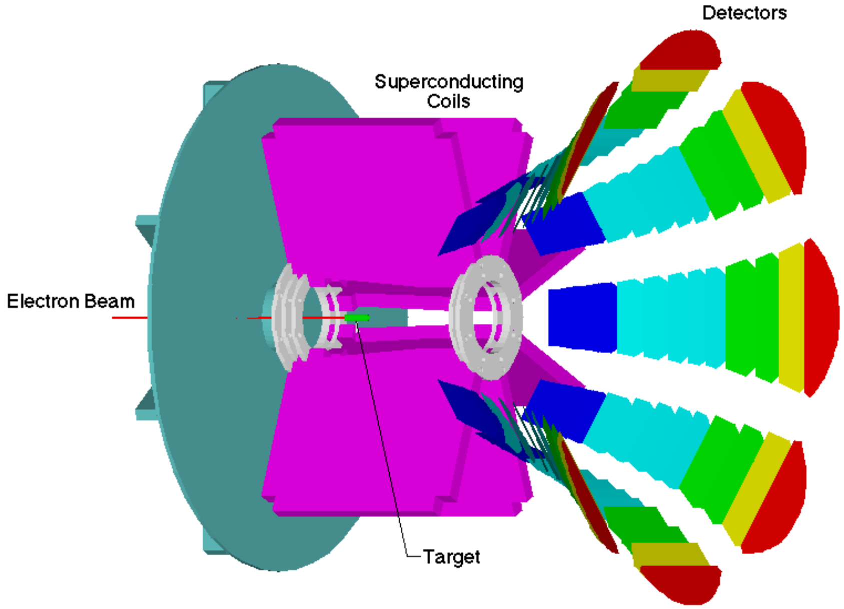
Parity-Violating Electron Scattering on Hydrogen and Deuterium at Backward Angles: G0 Experiment

David S. Armstrong
College of William & Mary

For the G0 Collaboration



PAVI 09 Bar Harbor MA

June 22-26 2009

The College of WILLIAM & MARY

Jefferson Lab

Outline

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

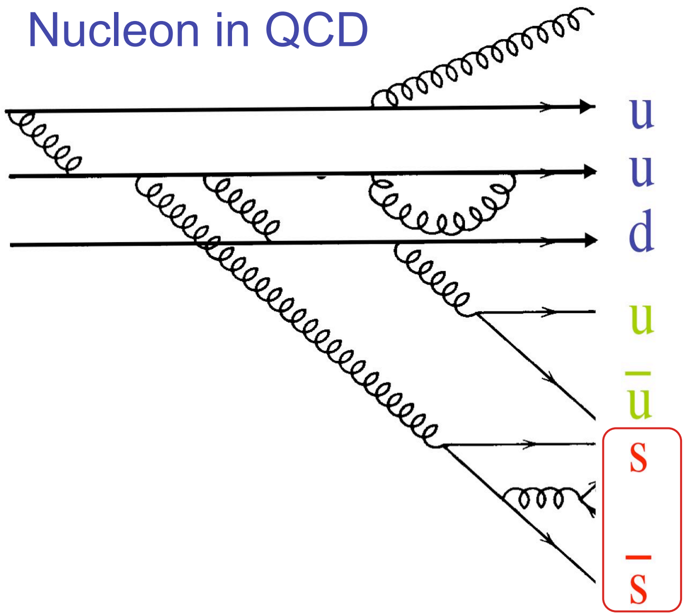
- Results from G0 at backward angles:
  - Separated form factors at Q^2 = 0.23, 0.63 $(GeV/c)^2$
  - Other physics results
- Implications & Conclusions

"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

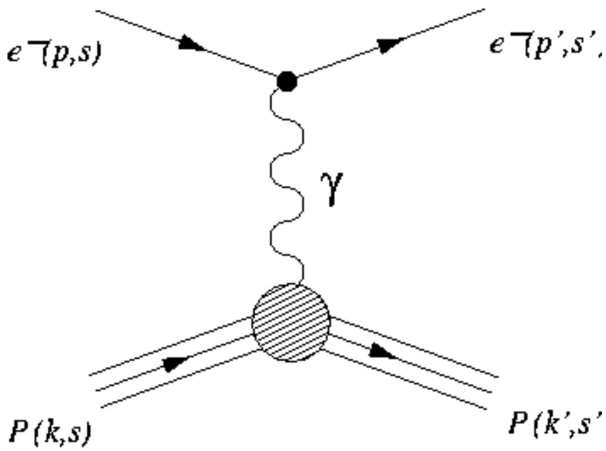
- How much do virtual $s\bar{s}$ pairs contribute to the structure of the nucleon ?
  - Momentum : 4% (DIS)
  - Spin : 0 to -10% (polarized DIS)
  - Mass : 0 to 30% (πN-sigma term)
  - (significant uncertainties on the latter two)

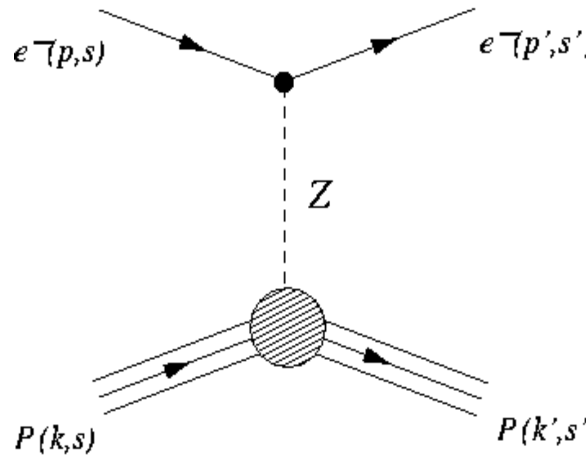
also: OZI violations in $p\bar{p} \rightarrow \frac{\phi\gamma}{\omega\gamma}$

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

Parity Violating Electron Scattering
⇒ Weak NC Amplitudes





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 ($\sim 10^{-6}$) 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 to be an isospin rotation of the proton*:

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

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

$G^{\gamma,p}_{E,M}$, $G^{\gamma,n}_{E,M}$, $G^{Z,p}_{E,M}$ —Charge symmetry→ $G^{u}_{E,M}$, $G^{d}_{E,M}$, $G^{s}_{E,M}$ —Shuffle→ $G^{p}_{E,M}$, $G^{n}_{E,M}$, $G^{s}_{E,M}$

Well Measured ($G^{p}_{E,M}$, $G^{n}_{E,M}$)

$\langle N|\, \bar{s}\gamma^{\mu} s\, |N\rangle$ ($G^{s}_{E,M}$)

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

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

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

$$G^Z_{E,M} = (1-4\sin^2\theta_W)(1+R_V^p)G^p_{E,M} - (1_3 + R_V^n)G^n_{E,M} - G^s_{E,M}$$

$$G_A^e = -\tau_3(1+R_A^{T=1})G_A + \sqrt{3}R_A^{T=0}G_A^8 + \Delta s$$

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 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: $G_E^s(Q^2=0)=0$

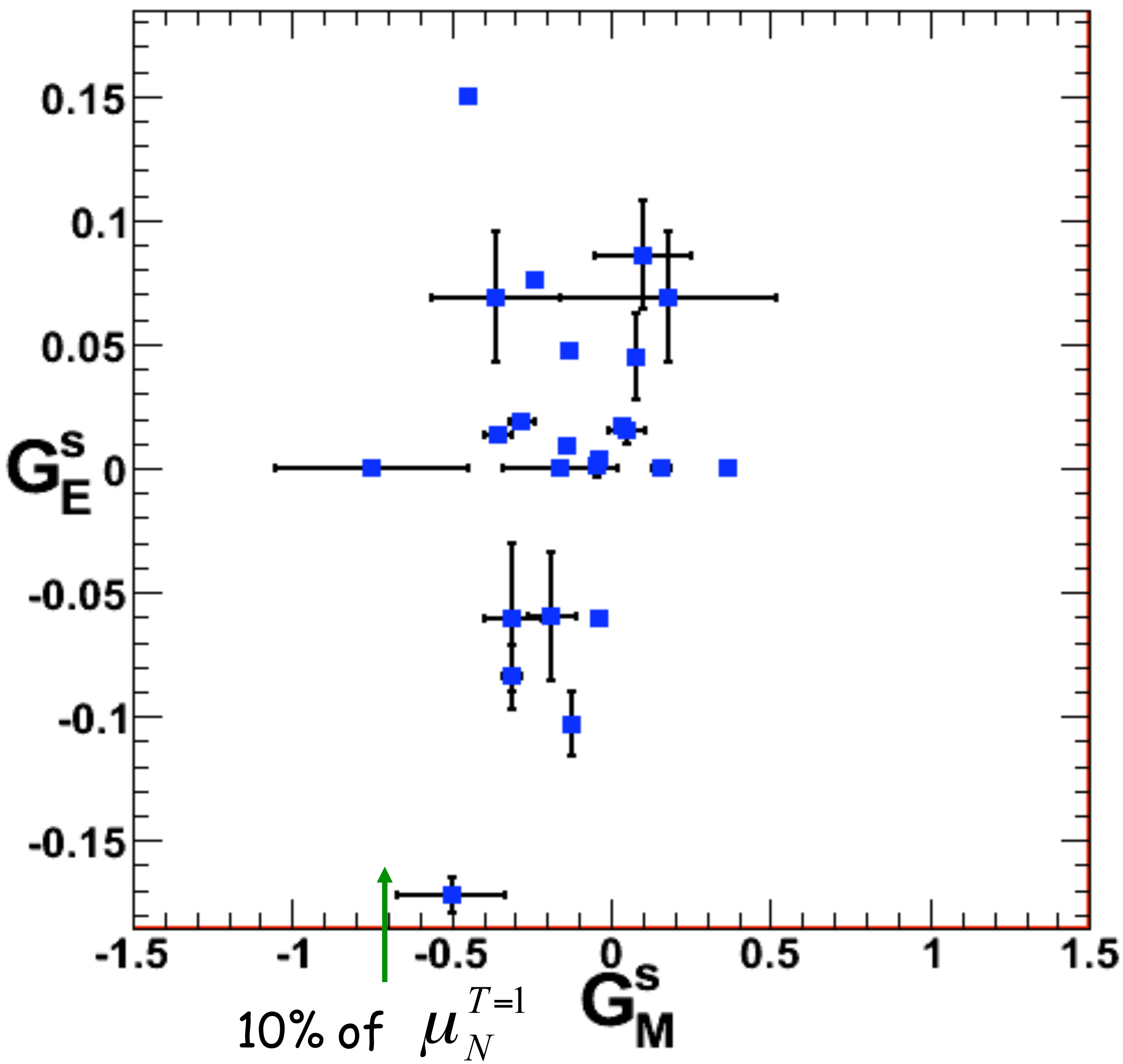
a challenging problem in non-perturbative QCD

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; PRL **97** (2006) 022001

situation is unsettled

Strangeness Models



note: caveats…

The Axial Current Contribution

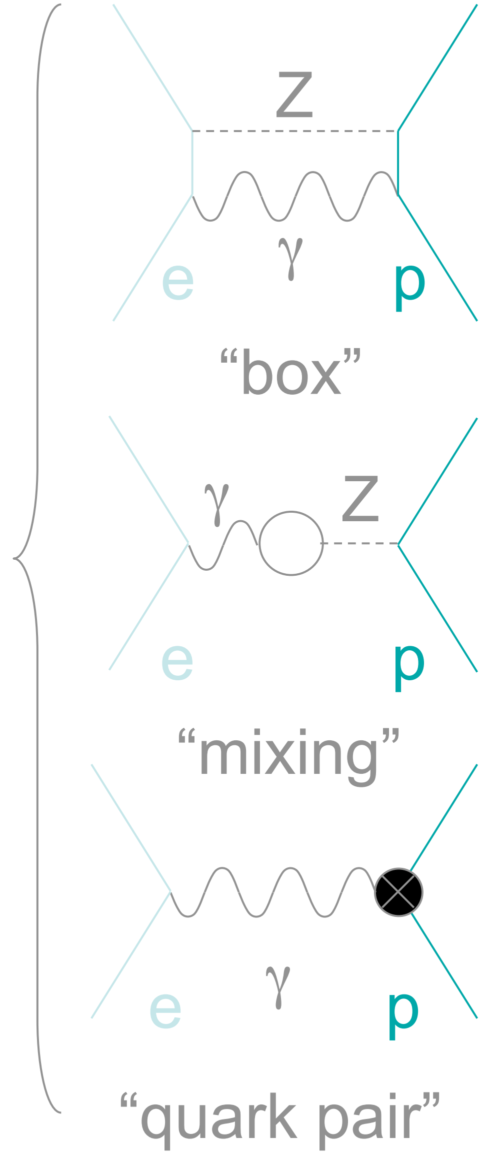
- Recall: $$A^{PV} \propto \frac{A_E + A_M + A_A}{2\sigma_{unp}}$$

$$A_E = \varepsilon(\theta) G_E^\gamma G_E^Z, \; A_M = \tau G_M^\gamma G_M^Z$$

$$A_A = -\left(1 - 4\sin^2\theta_W\right) \varepsilon'(\theta) G_M^\gamma G_A^e$$

$$G_A^e = -\tau_3 (1 + R_A^{T=1}) G_A + \sqrt{3} R_A^{T=0} G_A^8 + \Delta s$$

- Effective axial form factor: $G_A^e(Q^2)$
- related to form factor measured in neutrino scattering
- also contains "*anapole*" form factor
- determine isovector piece by combining proton and neutron (deuteron) measurements



Parity-Violating Electron Scattering Program

Expt/Lab	Target/ Angle	Q^2 (GeV^2)	A_{phys} (ppm)	Sensitivity	Status
SAMPLE/Bates					
SAMPLE I	LH_2/145	0.1	-6	$\mu_s + 0.4G_A$	2000
SAMPLE II	LD_2/145	0.1	-8	$\mu_s + 2G_A$	2004
SAMPLE III	LD_2/145	0.04	-4	$\mu_s + 3G_A$	2004
HAPPEx/JLab					
HAPPEx	LH_2/12.5	0.47	-15	$G_E + 0.39G_M$	2001
HAPPEx II, III	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	LH_2/14	0.63	-24	$G_E + 0.5G_M$	(2009)
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

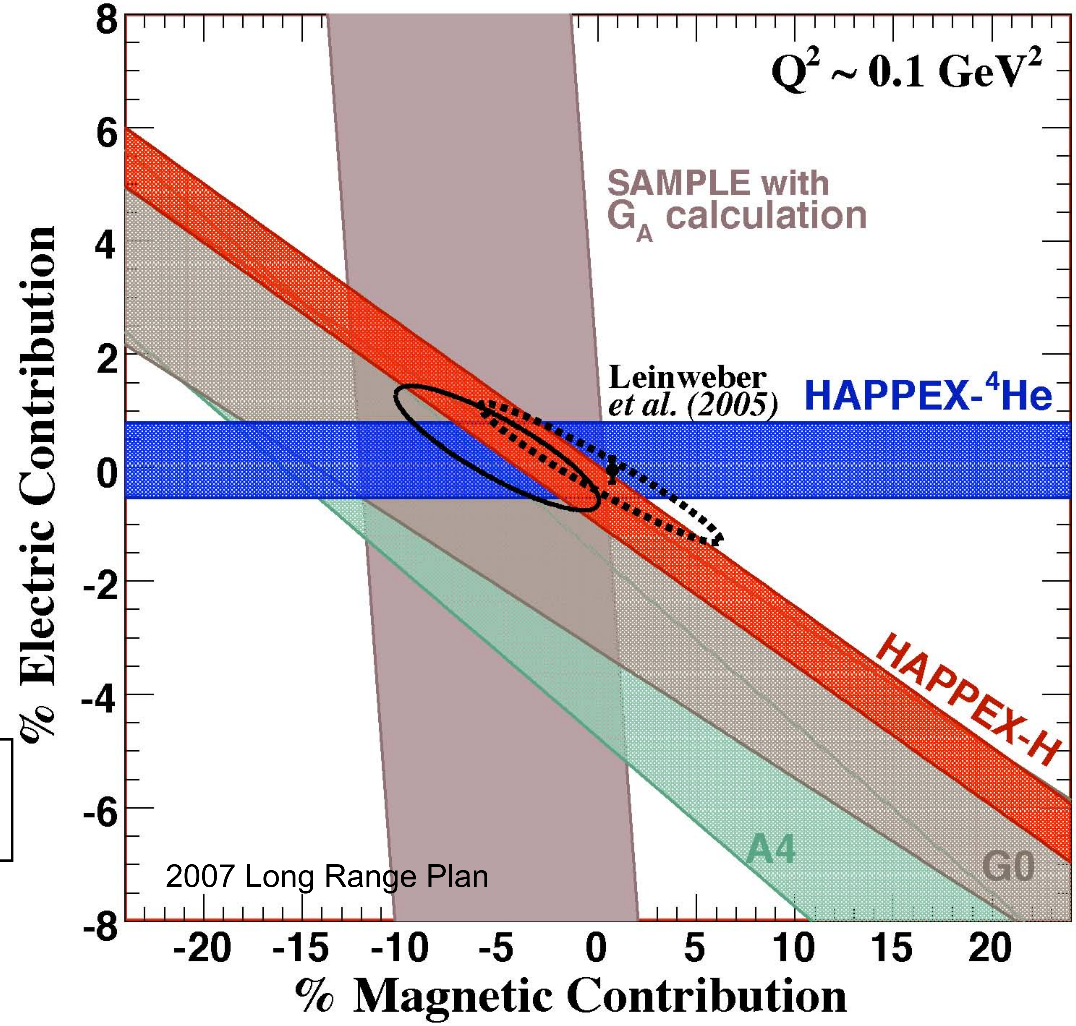
Summary of data at Q^2 =0.1 GeV^2

Solid ellipse:
K. Pashke, private comm, [same as J. Liu, et al PRC 76, 025202 (2007)], uses theoretical constraints on the axial form factor

Dashed ellipse:
R. 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

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



(thanks to K. Pashke, R. Young)

G0 Collaboration

California Institute of Technology, Carnegie Mellon University,
College of William and Mary, Grinnell College,
Institut de Physique Nucléaire d'Orsay,
Laboratoire de Physique Subatomique et de Cosmologie-Grenoble,
Louisiana Tech University, New Mexico State University, Ohio University,
Thomas Jefferson National Accelerator Facility, TRIUMF, University of Illinois,
University of Kentucky, University of Manitoba, University of Maryland,
University of Winnipeg, University of Zagreb, Virginia Tech,
Yerevan Physics Institute

Graduate Students:

C. Capuano (W&M), A. Coppens (Manitoba), C. Ellis (Maryland), J. Mammei (VaTech), M. Muether (Illinois), J. Schaub (New Mexico State), M. Versteegen (Grenoble); S. Bailey (Ph.D. Jan. 07 W&M)

Analysis Coordinator: Fatiha Benmokhtar (Maryland & CMU)

Spokesperson: Doug Beck (UIUC)

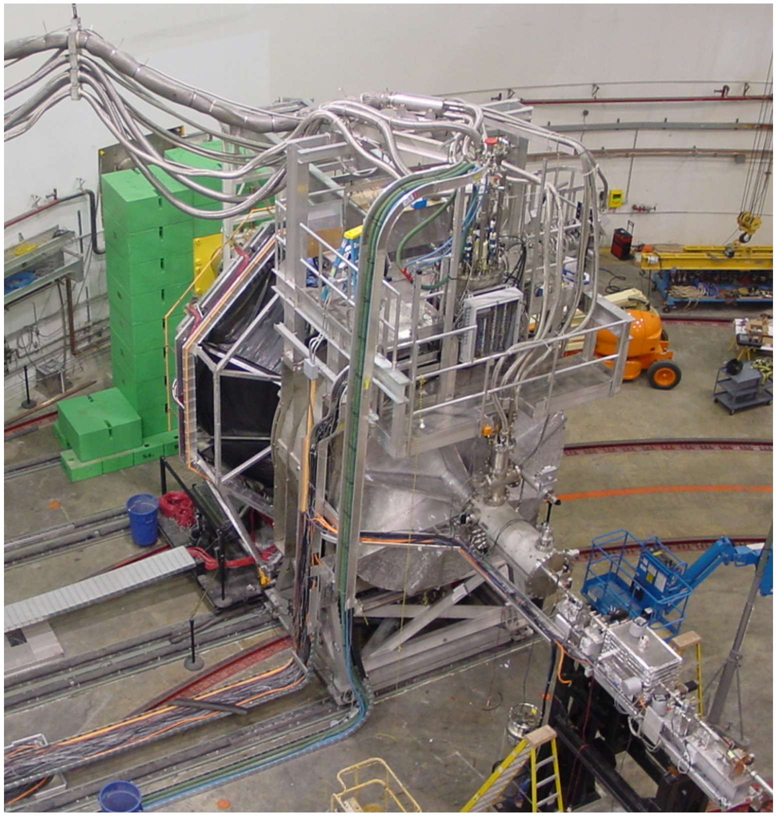
G0 Collaboration

California Institute of Technology, Carnegie Mellon University,
College of William and Mary, Grinnell College,
Institut de Physique Nucléaire d'Orsay,
Laboratoire de Physique Subatomique et de Cosmologie-Grenoble,
Louisiana Tech University, New Mexico State University, Ohio University,
Thomas Jefferson National Accelerator Facility, TRIUMF, University of Illinois,
University of Kentucky, University of Manitoba, University of Maryland,
University of Winnipeg, University of Zagreb, Virginia Tech,
Yerevan Physics Institute

Grad Students

G^0 (JLab – Hall C)

- Superconducting toroidal magnetic spectrometer
- 16 "Rings" of detectors



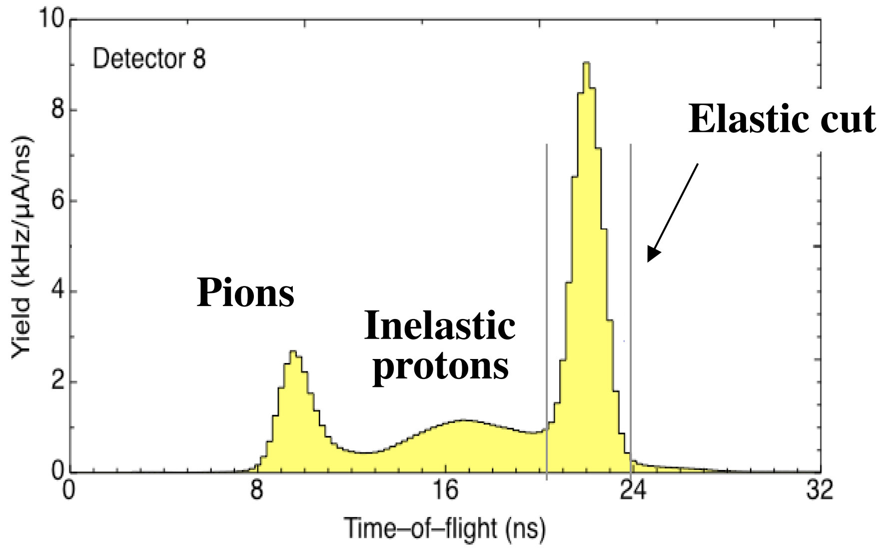
Forward angle mode *(completed):*

- LH_2: $E_e = 3.0$ GeV

  Recoil proton detection ($52^o < \theta_p < 76^o$)

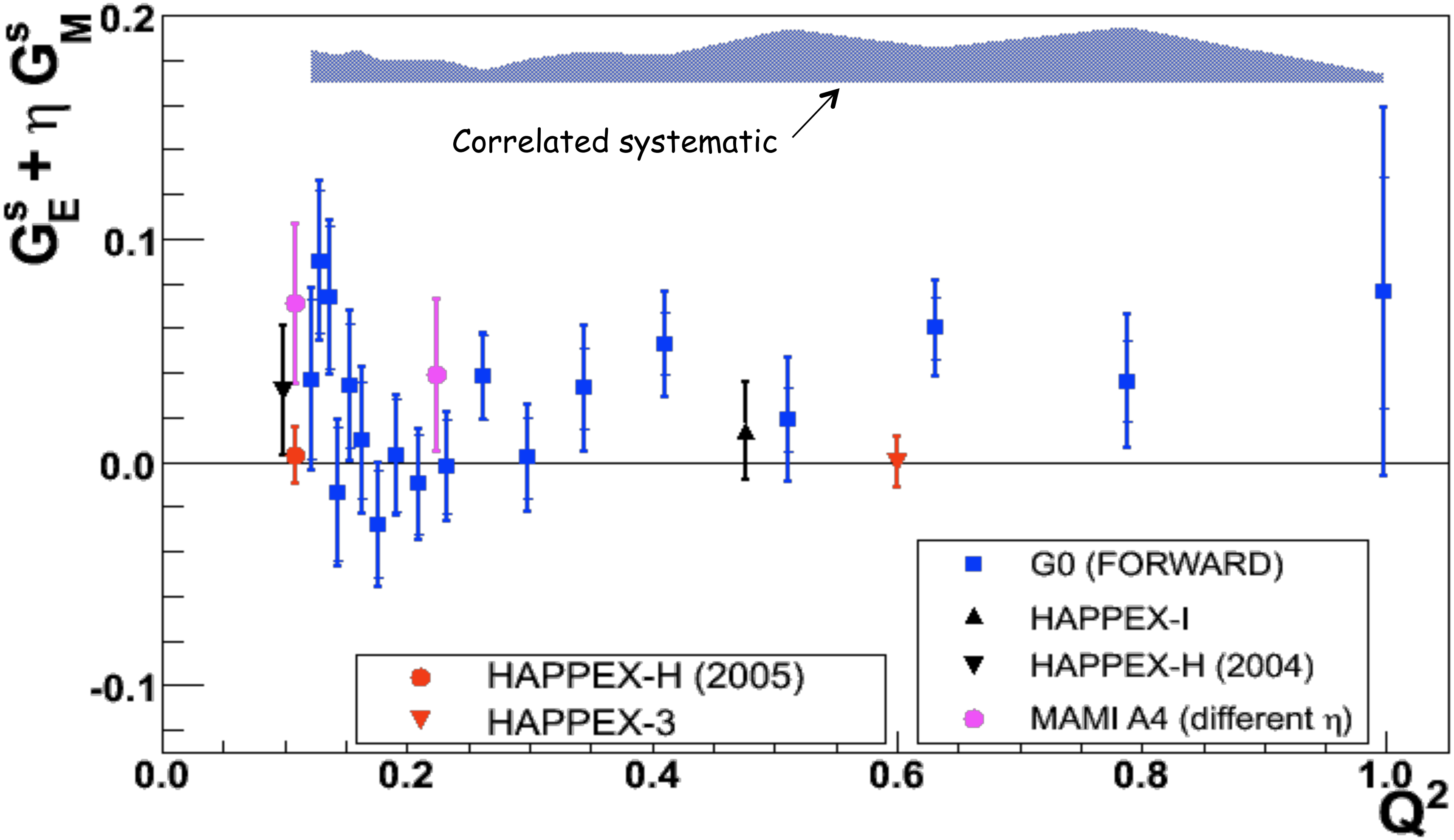
  ⇘ $0.12 \leq Q^2 \leq 1.0$ $(GeV/c)^2$

- Counting experiment – separate backgrounds via time-of-flight



G0: Forward-angle results

EM form factors:
J.J.Kelly, PRC **70**, 068202 (2004)



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

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

G0 Back Angle Apparatus: schematic

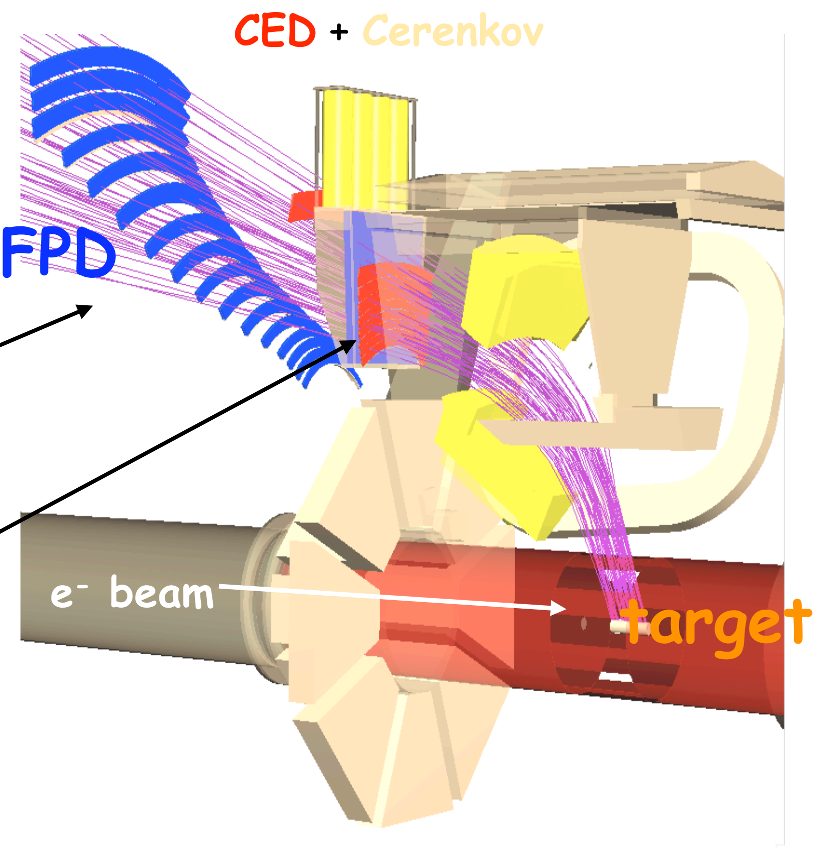
Single Octant Schematic

Shielding

FPD: Focal Plane Detector

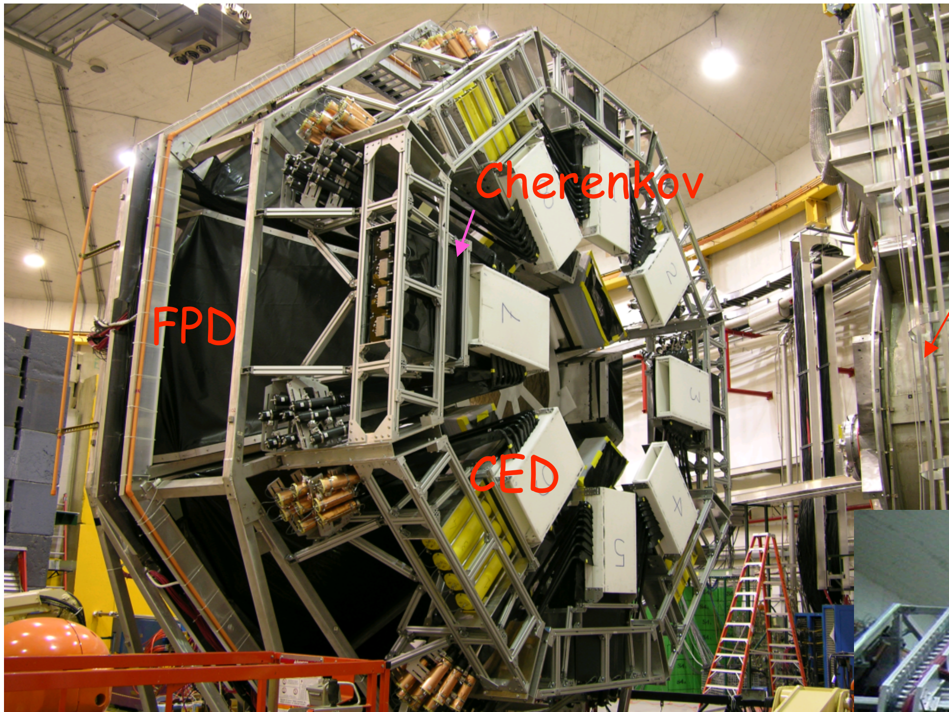
CED: Cryostat Exit Detector

Kinematic separation of elastic, inelastic



- Polarized electron beam at 362, 687 MeV, I ~ 20-60 μA
- Target: 20 cm LH_2, LD_2
- Elastic, inelastic scattering at ~108°, $\Delta\Omega \sim 0.5$ sr
- Electron/pion separation using aerogel Cerenkov

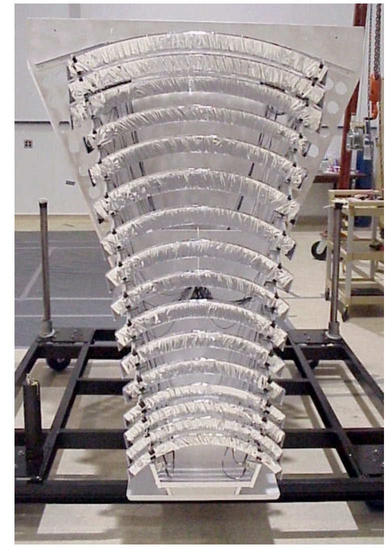
Back Angle Apparatus



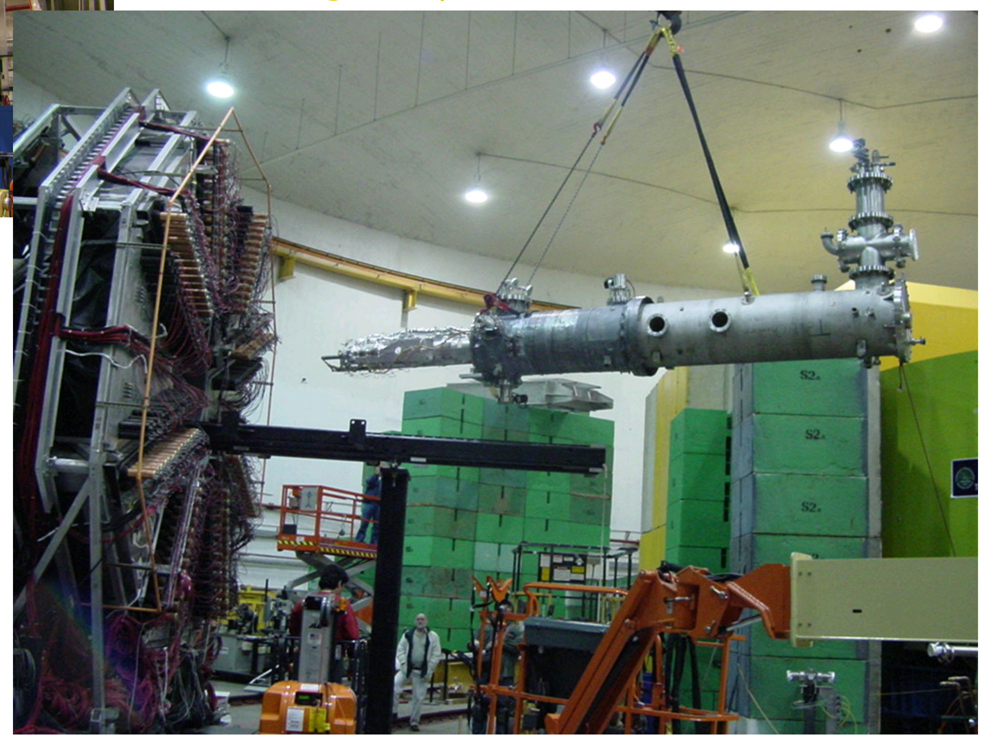
Detector package

Superconducting
Magnet

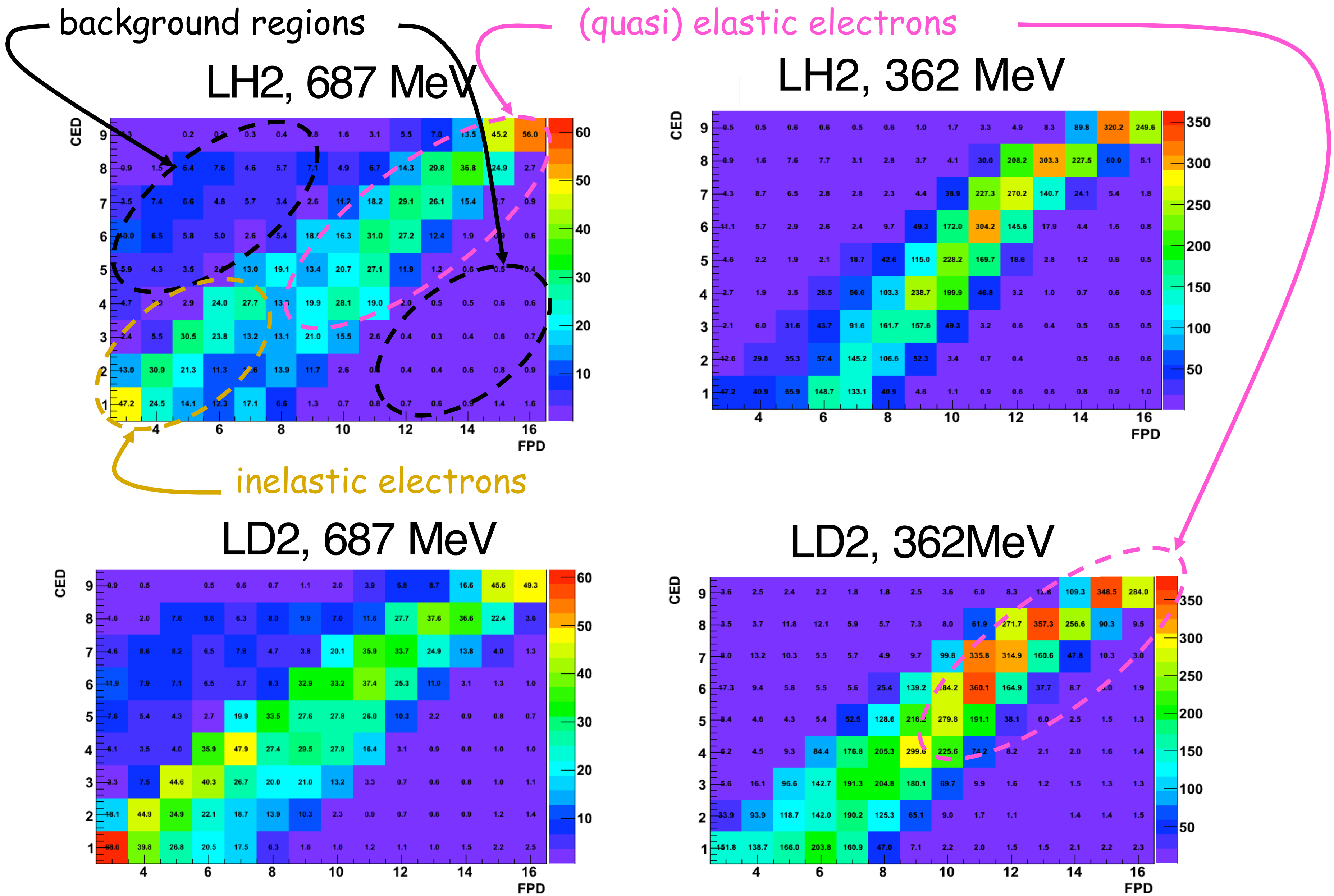
FPD (1 octant)



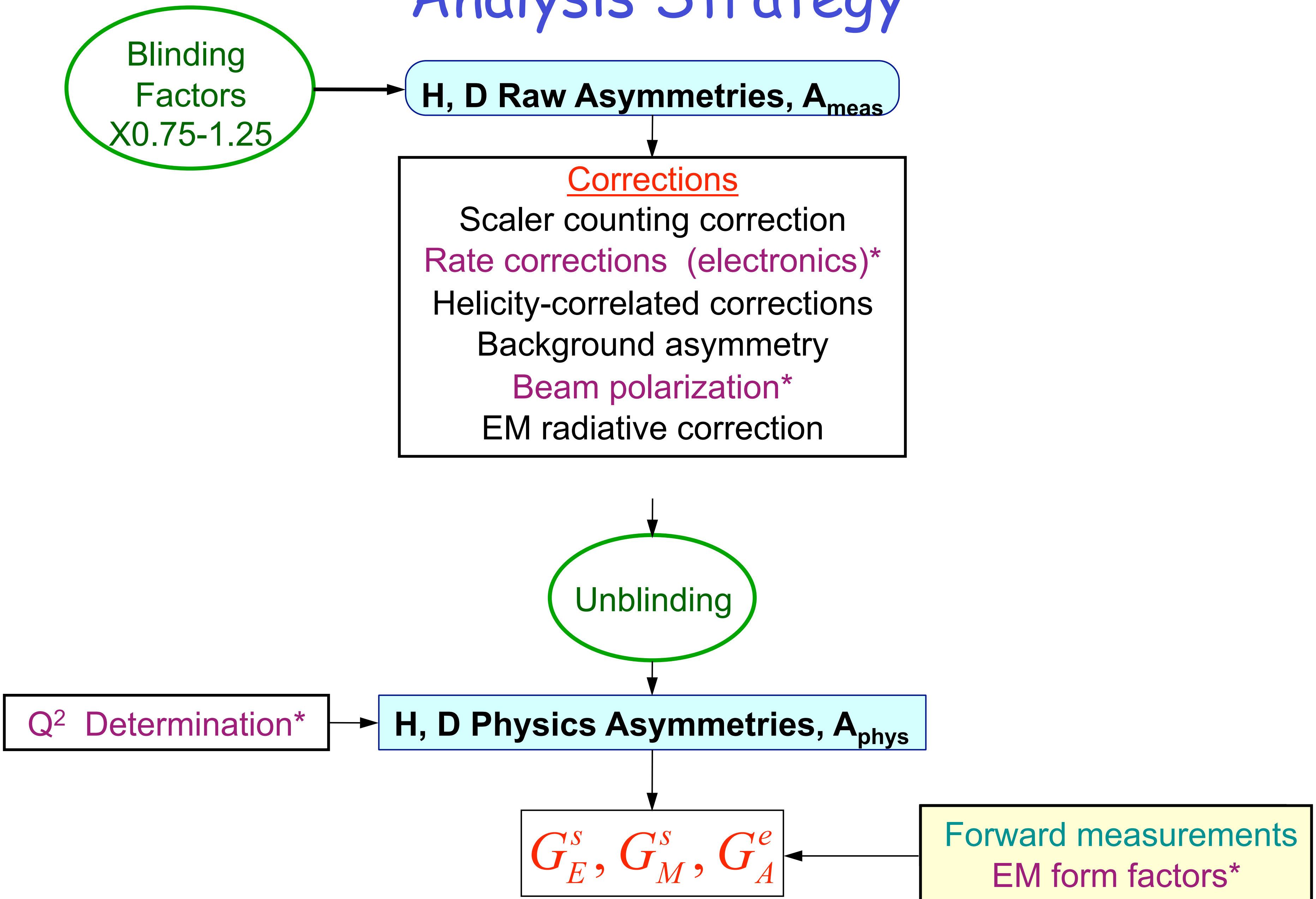
Target system installation



Electron Yields



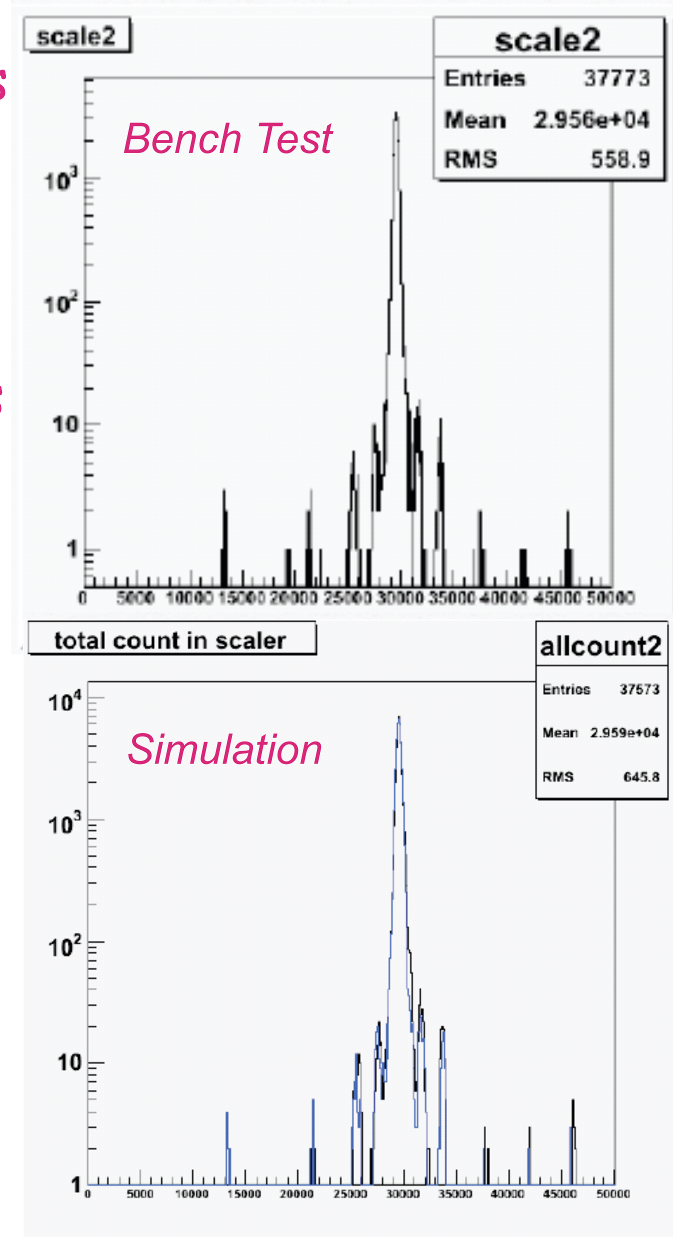
Analysis Strategy



*See talk by F. Benmokhtar

Scaler Counting Problem

- Electronics sorts detector coincidences (CED_i and FPD_j) into separate scaler channels
  - FPGA-based system in North American electronics (4 octants)
- Error in FPGA programming, two short (~3 ns) pulses could be sent to scaler in < 7 ns
  - ~ 1% of events have such pulse pairs (worst case)
- Such pulse pairs sometimes cause scaler to drop or add bits
  - Detailed simulation of ASIC with propagation delays between (flip flop) elements
- Effect on asymmetry is <0.01 A_{phys}
  - Test by cutting data
  - compare with French octants, and with data after FPGA fixed



Polarized Beam Properties

- 85.8% Polarization*

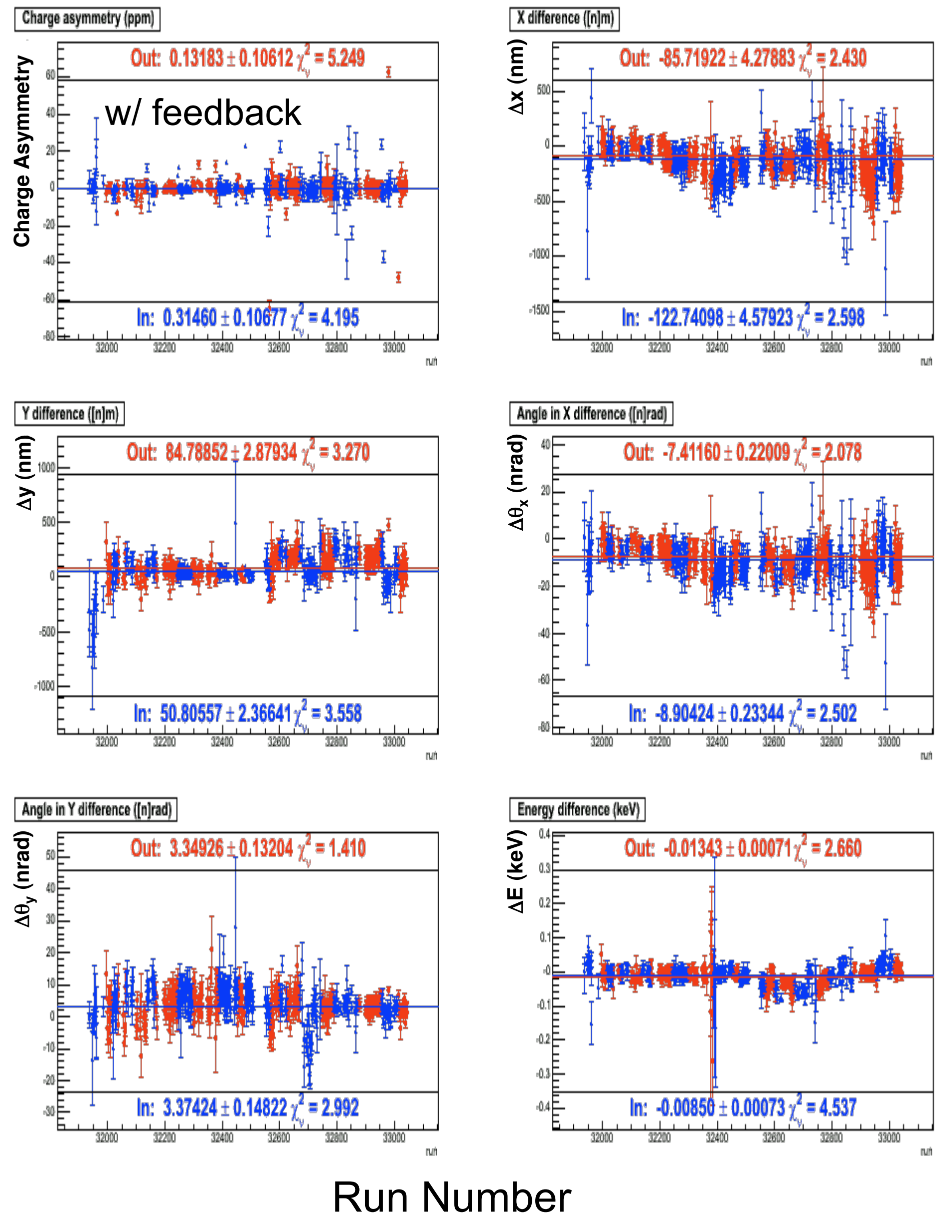
  *(see F. Benmokhtar's talk)

- Polarization reversal: 30 Hz, random quartets (+--+, -++-)

- Slow helicity reversal:
  λ/2 wave plate IN and OUT

- Helicity-correlated properties:

Beam Parameter	Achieved (OUT-IN)/2
charge asymmetry	0.09 +/- 0.08 ppm
x position difference	-19 +/- 3 nm
y position difference	-17 +/- 2 nm
x angle difference	-0.8 +/- 0.2 nrad
y angle difference	0.0 +/- 0.1 nrad
energy difference	2.5 +/- 0.5 eV
Beam halo (out 6 mm)	$< 0.3 \times 10^{-6}$



Correcting Beam Asymmetries

$$A_{raw} = A_{det} - A_Q + \Sigma_{i=1,5}\beta_i \Delta x_i$$

Determine Slopes from

- **natural beam jitter (regression)**
- **beam modulation (coil pulsing)**

Independent methods provide a cross-check.
Each subject to different systematic errors.

Regression:

- Natural beam motion, measure yield vs. beam parameter
- Simultaneous fit establishes independent sensitivities

Coil Pulsing:

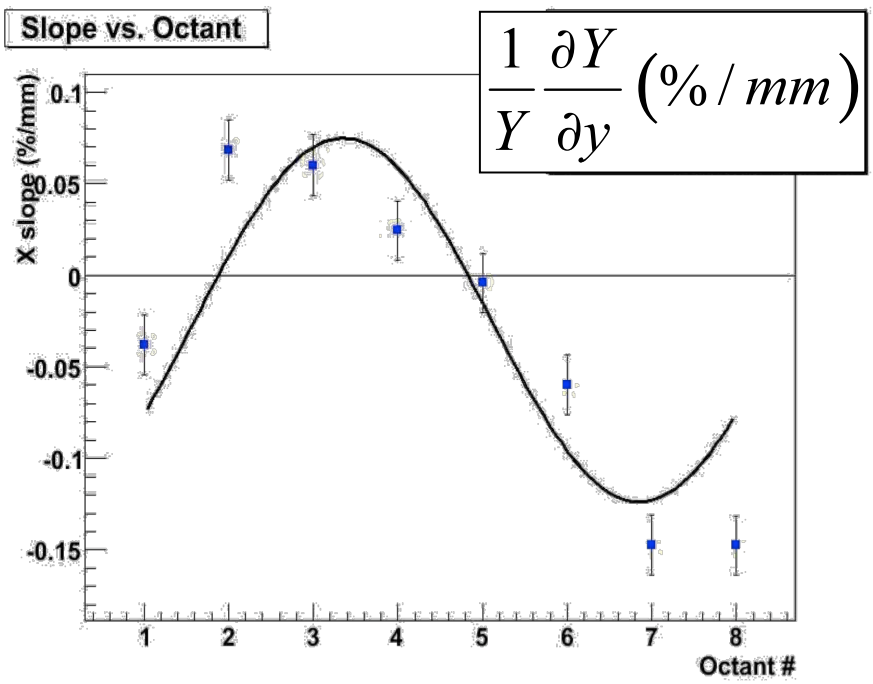
- Induce non-HC beam motion with coils, measure dS/dC_i, dx_i/dC_i
- Relate slopes to dS/dx_i

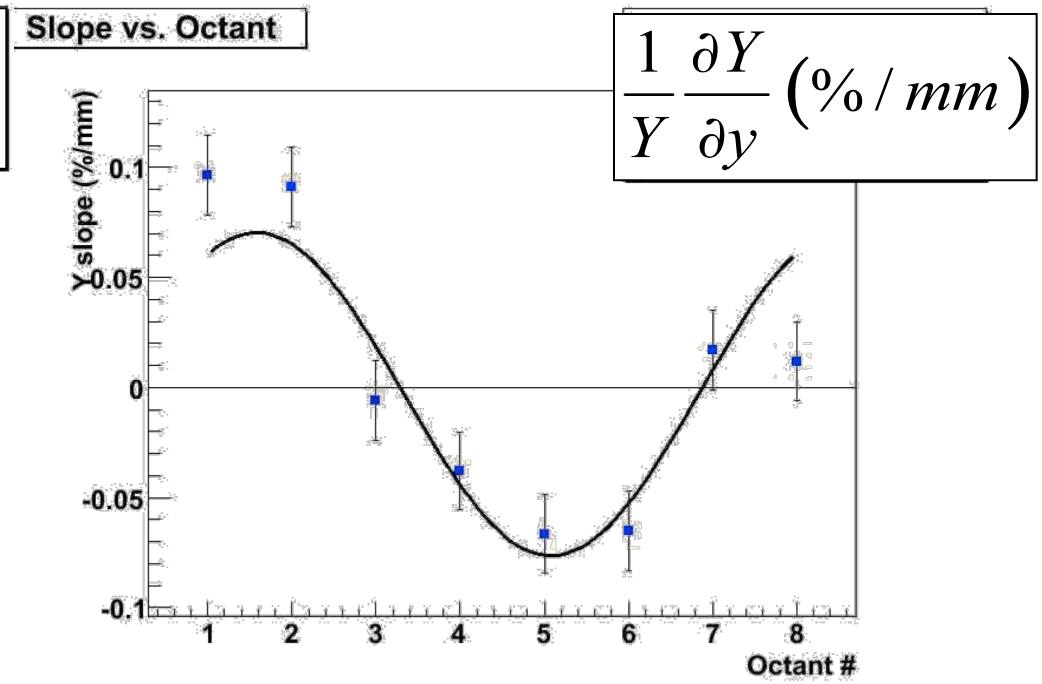
Sensitivities ~5x smaller than at forward angle

Correcting Beam Asymmetries

$$A_{raw} = A_{det} - A_Q + \Sigma_{i=1,5}\beta_i \Delta x_i$$

Determine Slopes from
- natural beam jitter (regression)
- beam modulation (coil pulsing)





Consistent sensitivities from regression and coil pulsing

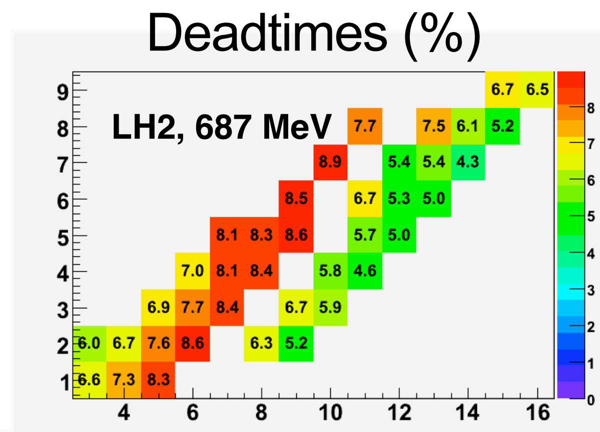
Net false asymmetry ~ 0.1 ppm

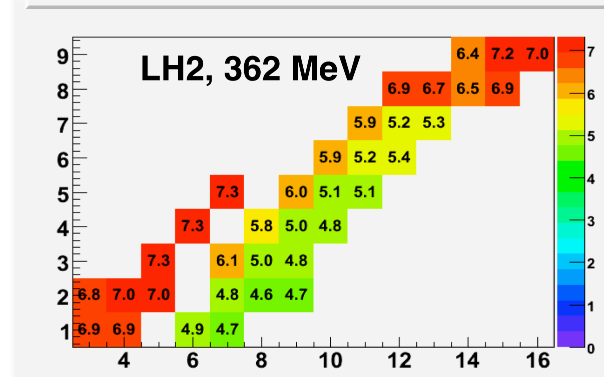
Rate Corrections*

- Counting experiment: must correct yields for Random Coincidences & Deadtime before calculating asymmetry

- Randoms: small except for 687 MeV LD2 (higher pion rate)
  - Direct (out-of-time) measurement

- Deadtime corrections: Simulated complete electronics chain using measured singles rates, *etc.*



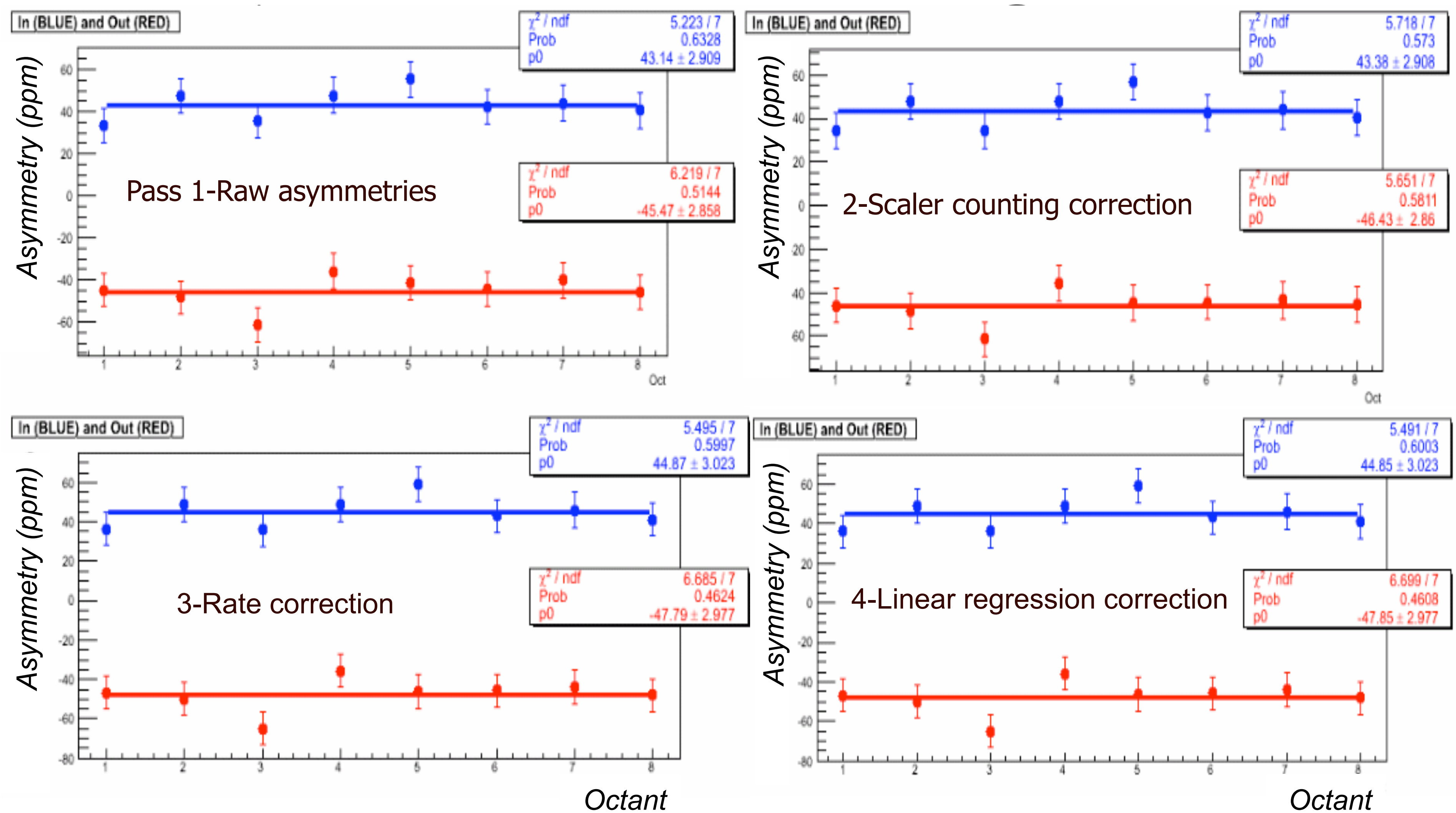


Data set	Correction to Yield (%)	Asymmetry Correction (ppm)	systematic error (ppm)
H 362	6	0.3	0.06
H 687	7	1.4	0.17
D 362	13	0.7	0.2
D 687	9	6	1.8

*more details: see F. Benmokhtar's talk

Elastic Asymmetries

- Hydrogen, 687 MeV (similar for all target/energy combos)
- Effect of rate, helicity-correlated corrections:



Backgrounds

- Primary background from aluminum target windows
  - about 12% of yield for all target/energy combinations
  - carries same asymmetry as deuterium (within ~ 2%)
- π^- contamination in D at 687 MeV
  - 5% contribution (measured), nearly zero asymmetry (measured)
- Hydrogen

$$A_{el} = \frac{A_{meas} - f_{Al}A_{Al} - f_{other}A_{other}}{1 - f_{Al} - f_{other}}$$

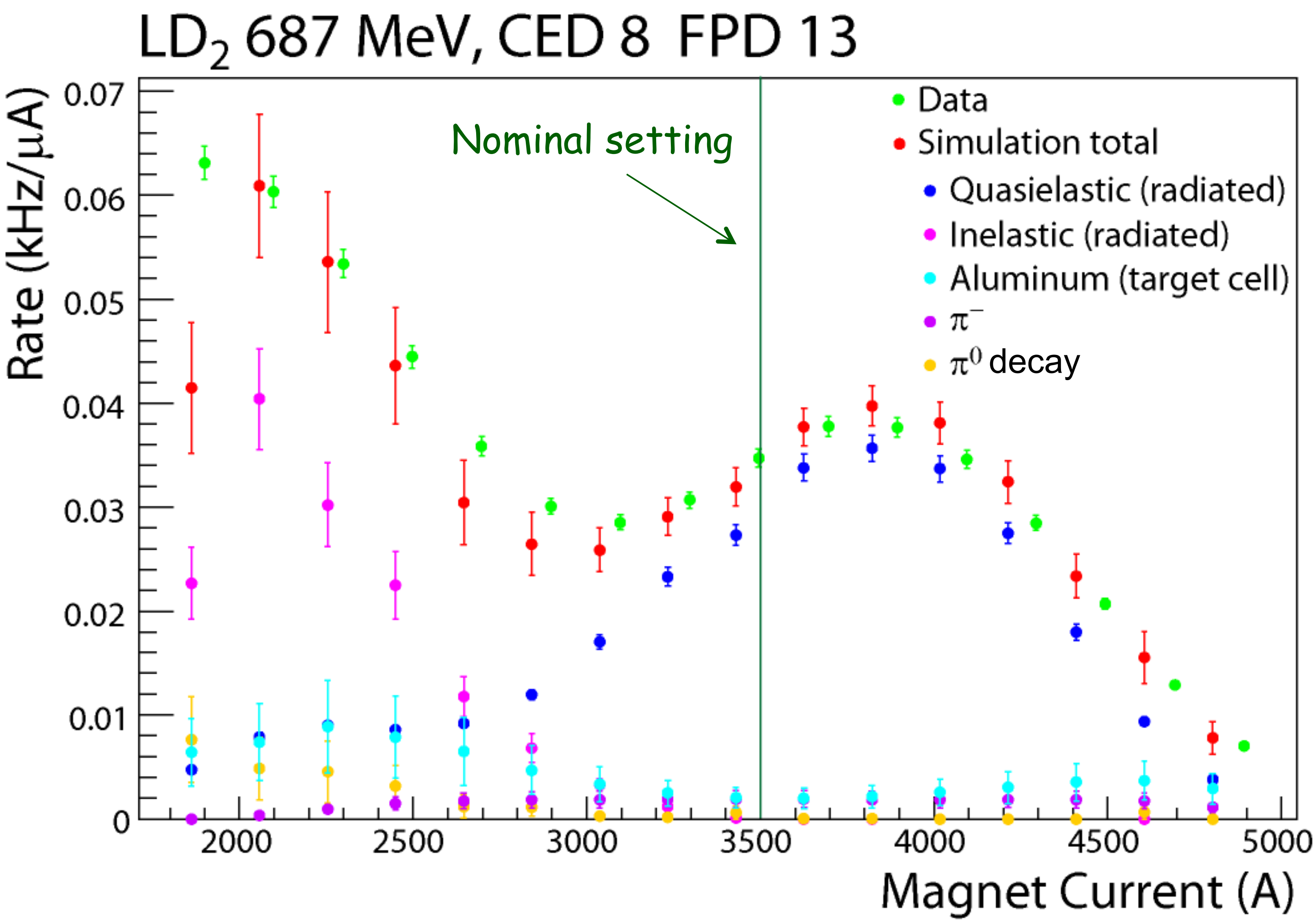
- Deuterium:

$$A_{el} = \frac{A_{meas} - f_{pion}A_{pion} - f_{other}A_{other}}{1 - f_{pion} - f_{other}},$$

with $f_{other} \sim 2 \pm 2\%,\ A_{other} = 0$

Backgrounds: Magnetic Field Scans

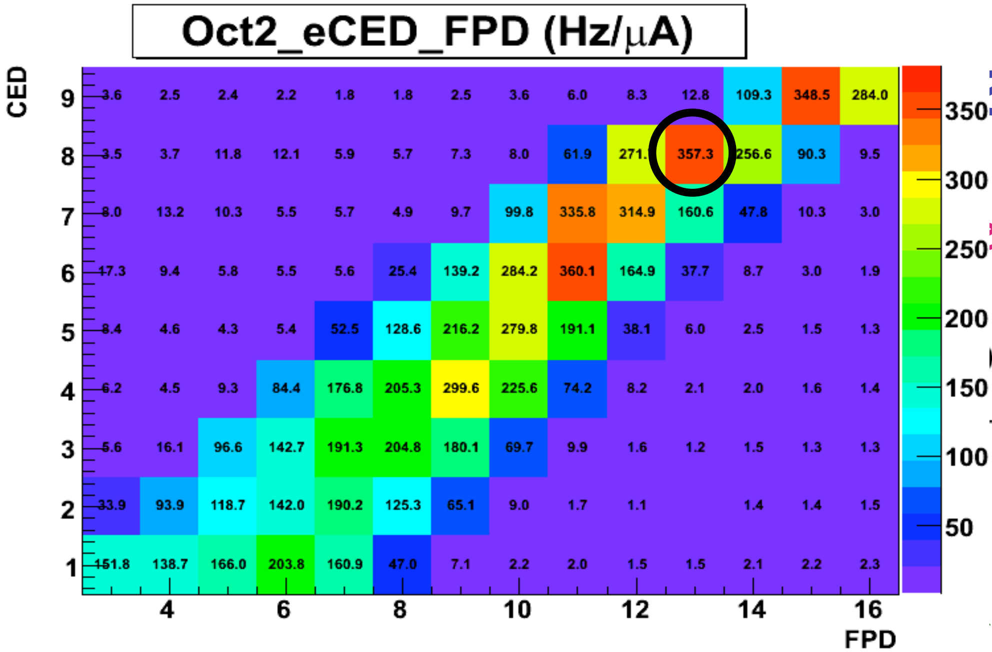
- Use simulation *shapes* to help determine dilution factors

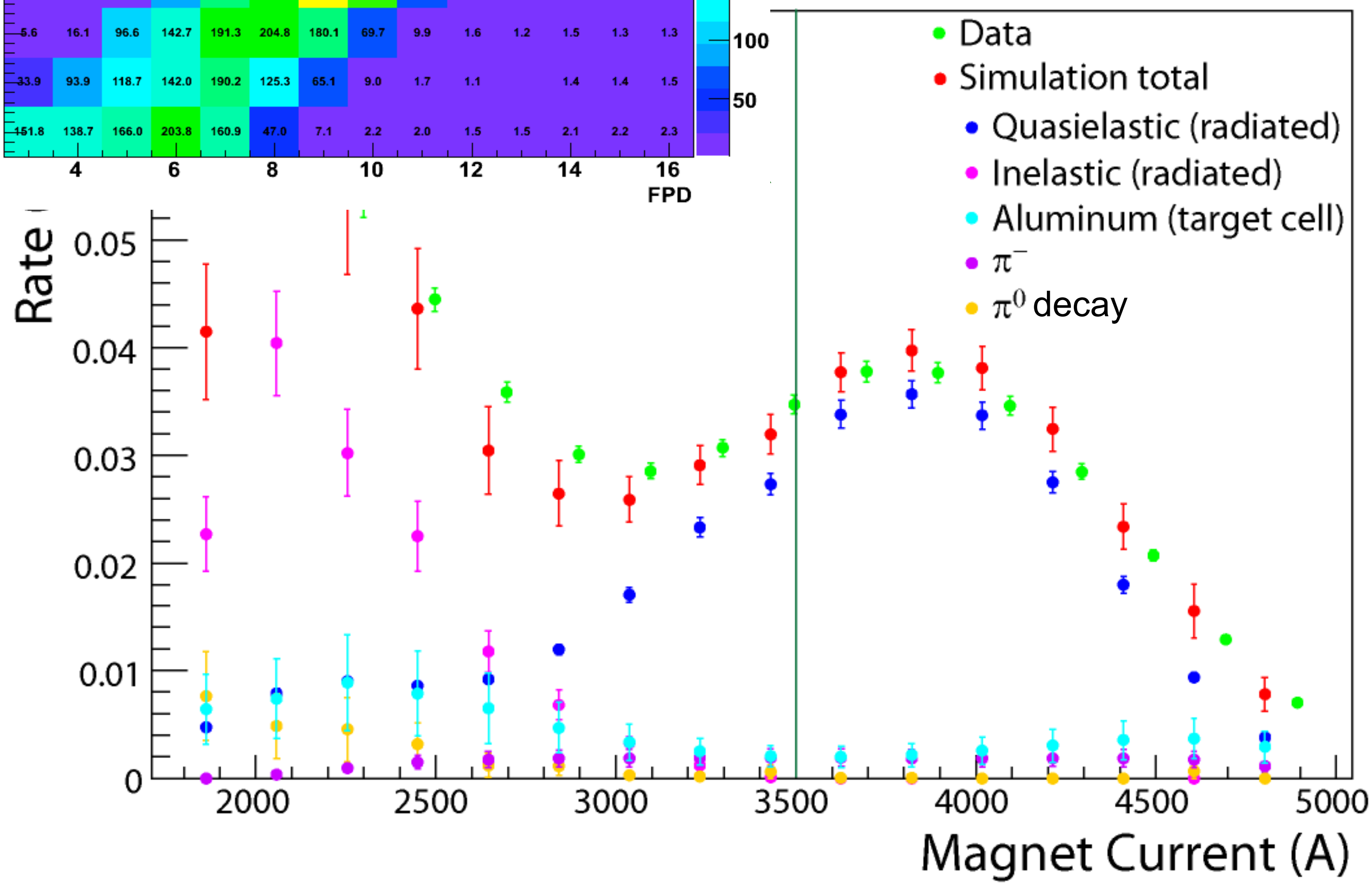


etic Field Scans

ermine dilution factors

D 13





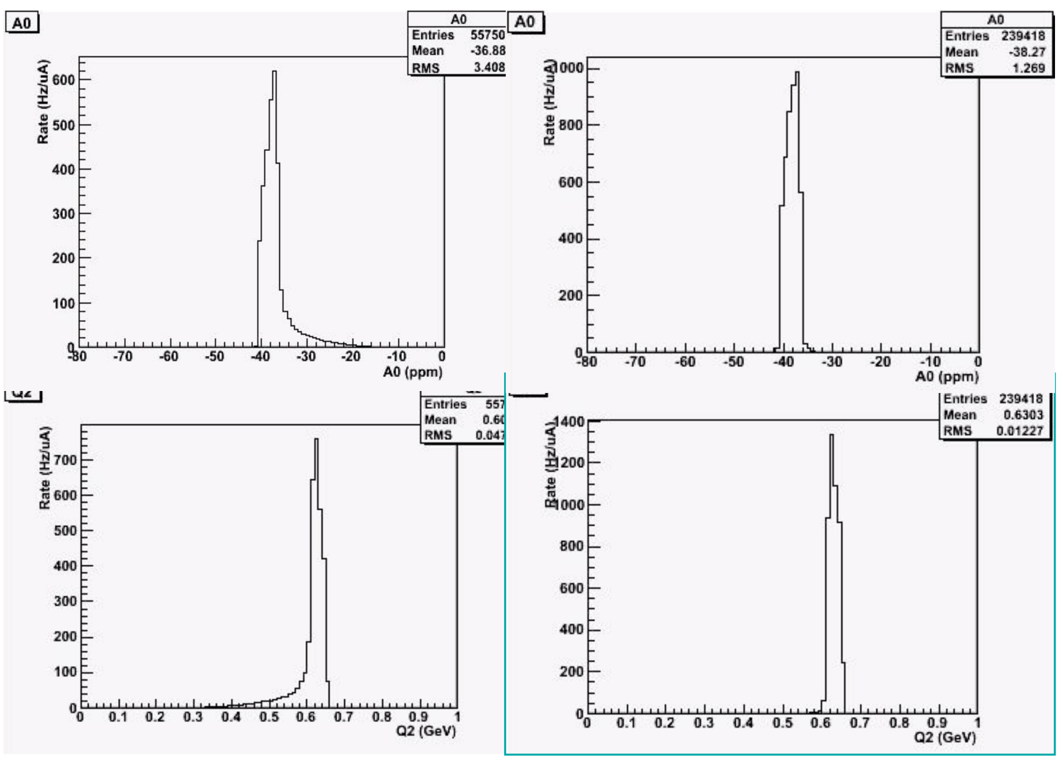
Other Corrections to Asymmetries

- Beam normal single-spin asymmetry (transverse asymmetry)
  - Any small transverse component in beam polarization + imperfect detector azimuthal symmetry + beam-normal spin asymmetry = false asymmetry
  - Measured asymmetry directly with transverse beam ➔ see J. Mammei's talk

Net correction < .01 ppm

- EM radiative corrections [Tsai (1971)]

LH2 687 with Radiation   LH2 687 no Radiation



GEANT: Calculate asymmetry based on kinematics at vertex after radiation, compare to tree level; both calculated after dE/dx in target

Tgt/Energy	$A_{0\ rc}$	$A_{0\ tree}$	$RC_{correction}$
LD2 687	-46.6	-48.43	3.7%
LD2 362	-13.64	-14.17	3.9%
LH2 687	-36.81	-38.22	3.8%
LH2 362	-10.1	-10.49	3.9%

Asymmetry Uncertainties (1)

- Hydrogen, 687 MeV

<table>
<tr><th></th><th>Value (ppm)</th><th>Stat (ppm)</th><th>Sys Pt (ppm)</th><th>Sys Gl (ppm)</th><th>Total (ppm)</th></tr>
<tr><td>Measured Asymmetry</td><td>-38.14</td><td>2.43</td><td></td><td></td><td></td></tr>
<tr><td>Background Asymmetry</td><td rowspan="2">-38.27</td><td></td><td>0.40</td><td></td><td></td></tr>
<tr><td>Dilution Correction</td><td></td><td>0.47</td><td>0.52</td><td></td></tr>
<tr><td>Transverse Correction</td><td></td><td></td><td></td><td>0.008</td><td></td></tr>
<tr><td>Rate Correction</td><td>-38.39</td><td></td><td>0.17</td><td></td><td></td></tr>
<tr><td>Beam Polarization</td><td>-44.76</td><td></td><td>0.52</td><td>0.53</td><td></td></tr>
<tr><td>EM Radiative Correction</td><td>-46.14</td><td></td><td>0.16</td><td></td><td></td></tr>
<tr><td>Physics Asymmetry</td><td>-46.14</td><td>2.43</td><td>0.84</td><td>0.75</td><td>2.68</td></tr>
</table>

Asymmetry Uncertainties (2)

- Deuterium, 687 MeV

	Value (ppm)	Stat (ppm)	Sys Pt (ppm)	Sys Gl (ppm)	Total (ppm)
Measured Asymmetry	-44.02	3.34			
Background Asymmetry	-46.05		0.050		
Dilution Correction			0.38		
Transverse Correction			0.009	0.008	
Rate Correction	-46.35		1.82		
Beam Polarization	-54.03		0.62	0.64	
EM Radiative Correction	-55.87		0.19		
Physics Asymmetry	-55.87	3.34	1.98	0.64	3.92

Asymmetry Uncertainties (3)

- Hydrogen, 362 MeV

<table>
<tr><th></th><th>Value (ppm)</th><th>Stat (ppm)</th><th>Sys Pt (ppm)</th><th>Sys Gl (ppm)</th><th>Total (ppm)</th></tr>
<tr><td>Measured Asymmetry</td><td>-9.941</td><td>0.872</td><td></td><td></td><td></td></tr>
<tr><td>Background Asymmetry</td><td rowspan="2">-9.441</td><td></td><td>0.034</td><td></td><td></td></tr>
<tr><td>Dilution Correction</td><td></td><td>0.109</td><td>0.362</td><td></td></tr>
<tr><td>Transverse Correction</td><td></td><td></td><td>0.025</td><td>0.008</td><td></td></tr>
<tr><td>Rate Correction</td><td>-9.444</td><td></td><td>0.090</td><td></td><td></td></tr>
<tr><td>Beam Polarization</td><td>-11.010</td><td></td><td>0.223</td><td>0.132</td><td></td></tr>
<tr><td>EM Radiative Correction</td><td>-11.416</td><td></td><td>0.022</td><td>0.000</td><td></td></tr>
<tr><td>Physics Asymmetry</td><td>-11.416</td><td>0.872</td><td>0.268</td><td>0.385</td><td>0.990</td></tr>
</table>

Asymmetry Uncertainties (4)

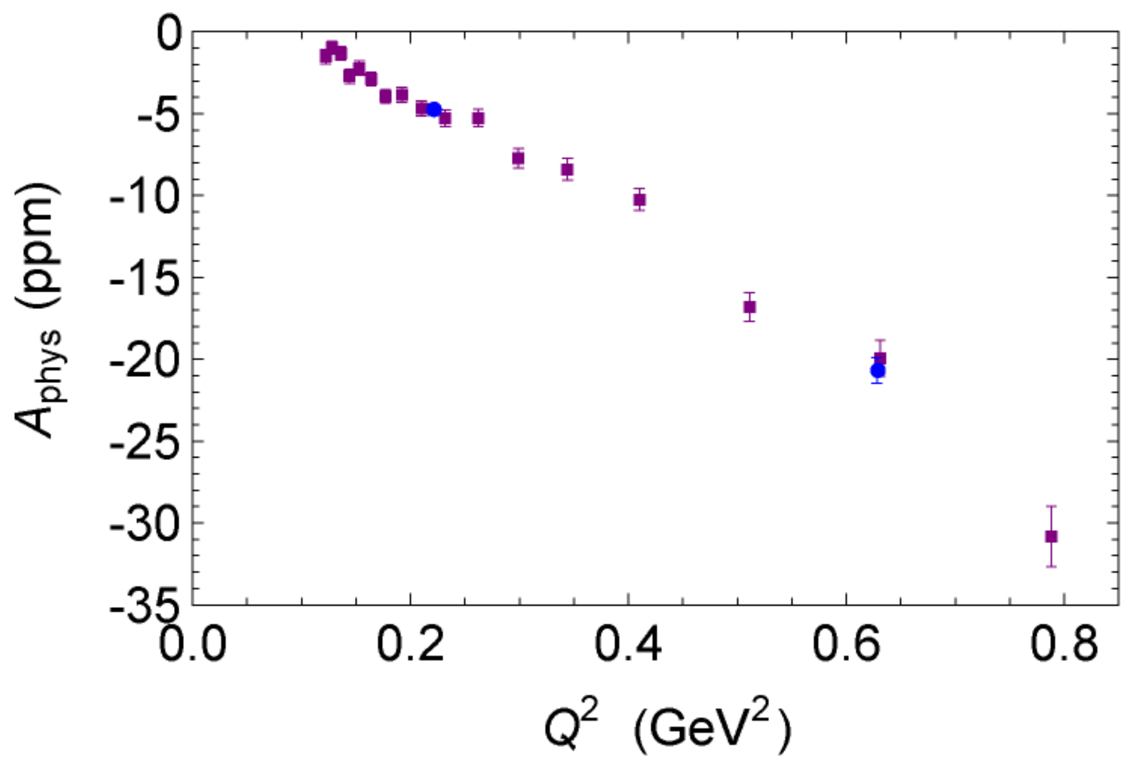
- Deuterium, 362 MeV

	Value (ppm)	Stat (ppm)	Sys Pt (ppm)	Sys Gl (ppm)	Total (ppm)
Measured Asymmetry	-14.047	0.813			
Background Asymmetry	-14.114				
Dilution Correction			0.020		
Transverse Correction			0.038	0.008	
Rate Correction	-14.152		0.232		
Beam Polarization	-16.498		0.331	0.197	
EM Radiative Correction	-17.018		0.059		
Physics Asymmetry	-17.018	0.813	0.411	0.197	0.932

Determining Form Factors

- Starting from asymmetries, need
  - Effective Q^2 determination* - simulation
  - Deuteron model (Schiavilla, priv. comm.)
  - Electromagnetic form factors* (Kelly PRC **70** (2004))
  - Electroweak Radiative corrections
  - check on 2-boson corrections*
    (Arrington, Blunden, Melnitchouk, et al.; Zhou, Kao & Yang, priv. comm.)

- Interpolation of G0 forward angle data:

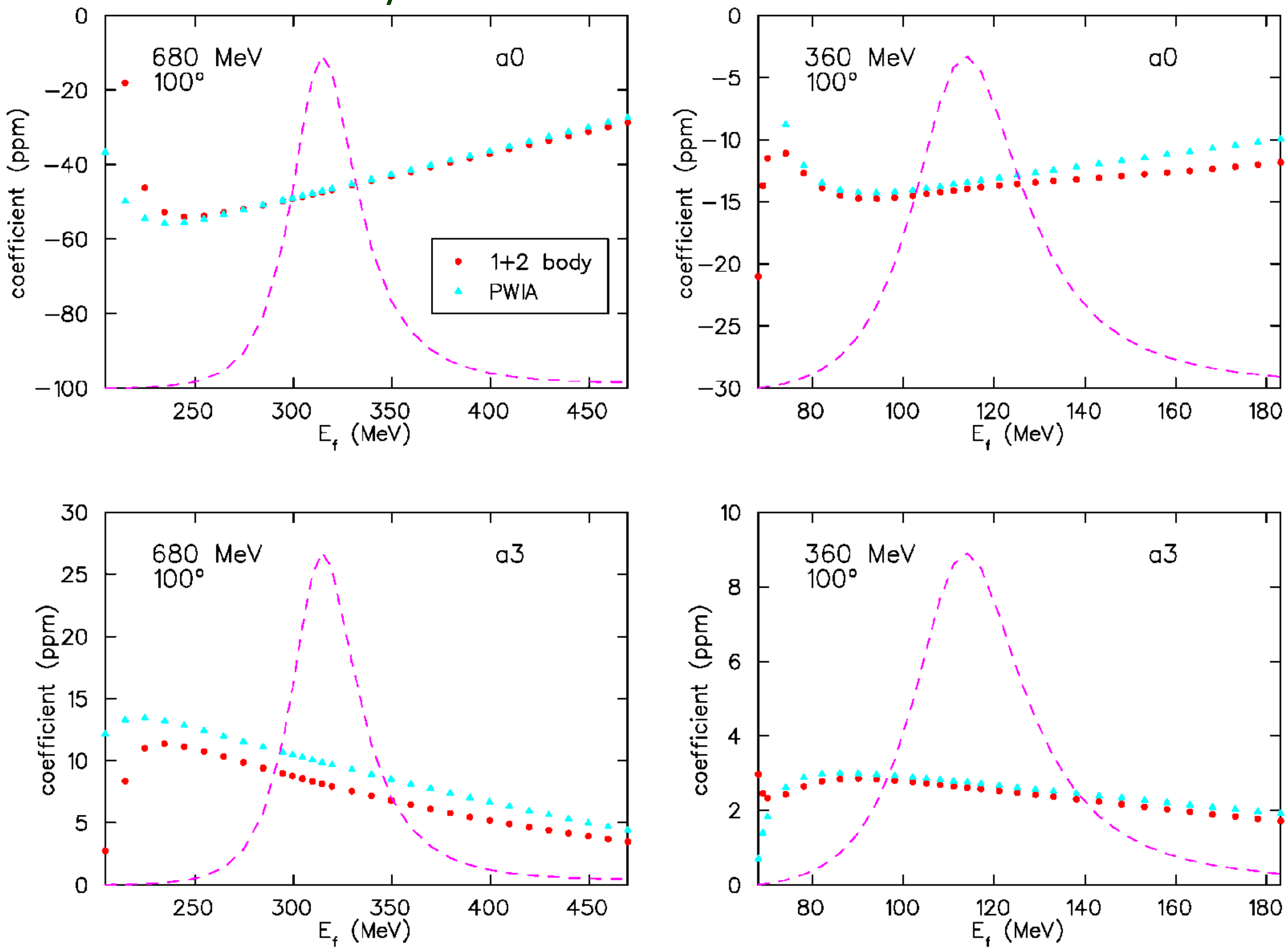


*see F. Benmokhtar's talk

Deuteron Model

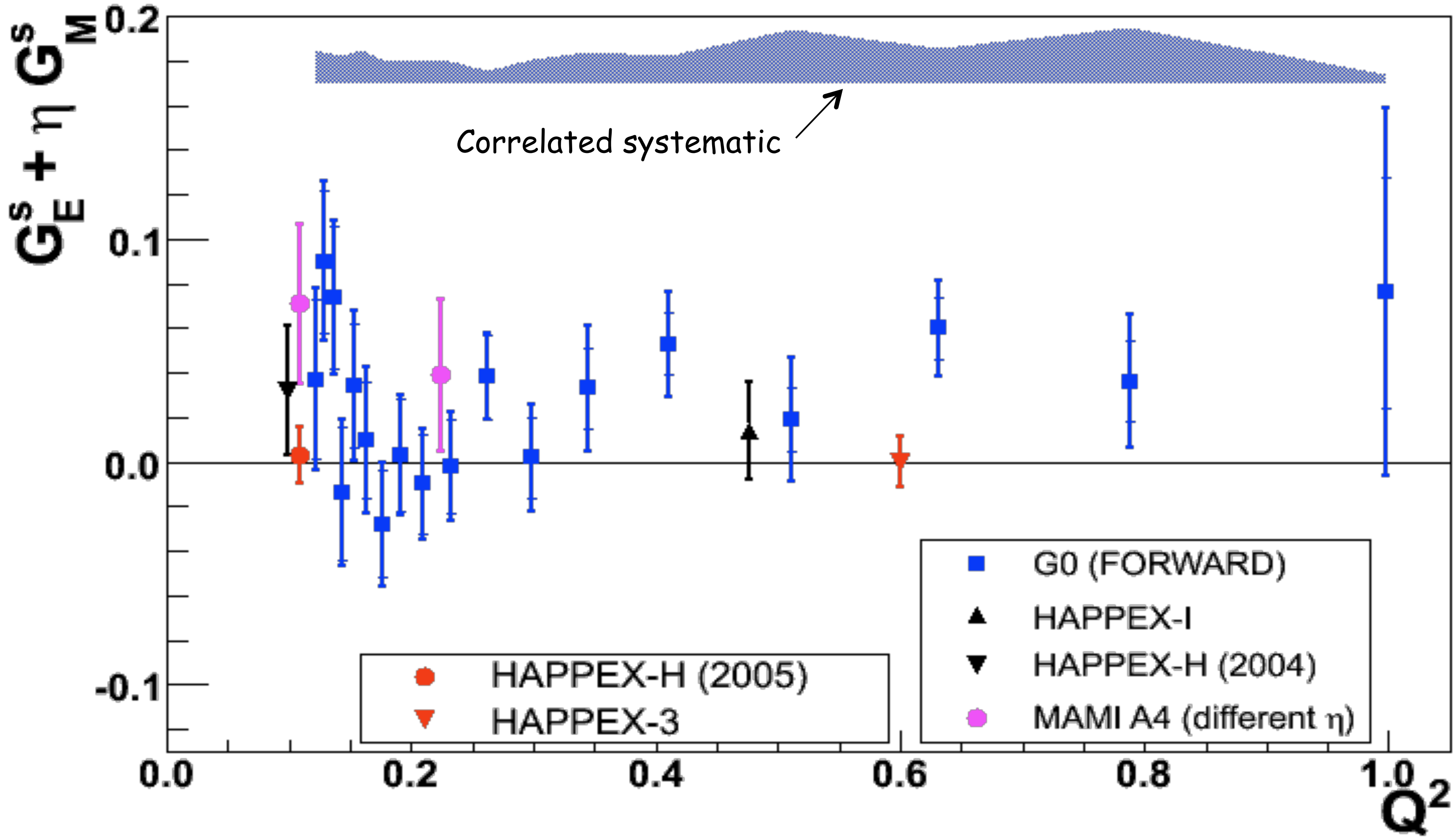
- Calculation from R. Schiavilla
  - includes FSI and 2-body effects

$$A_{phys} = a_0 + a_1 G_E^s + a_2 G_M^s + a_3 G_A^e$$



Forward Angle Results - reminder

EM form factors:
J.J.Kelly, PRC **70**, 068202 (2004)

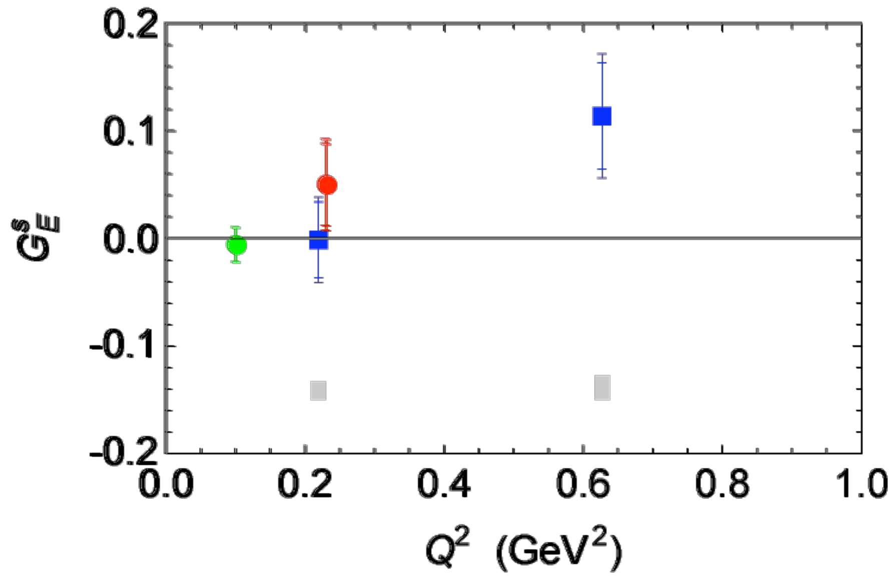


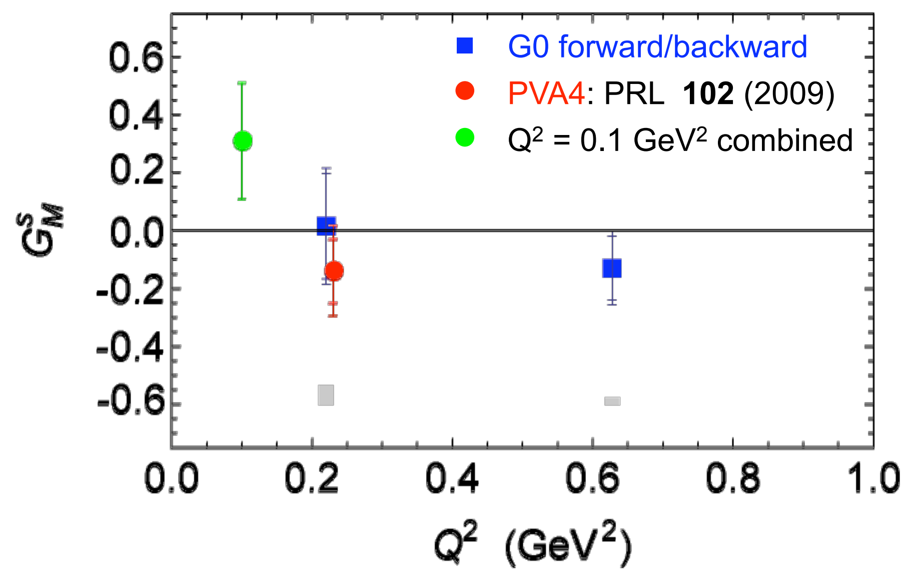
$G_E^s = G_M^s = 0$ Hypothesis excluded at 89% C.L.

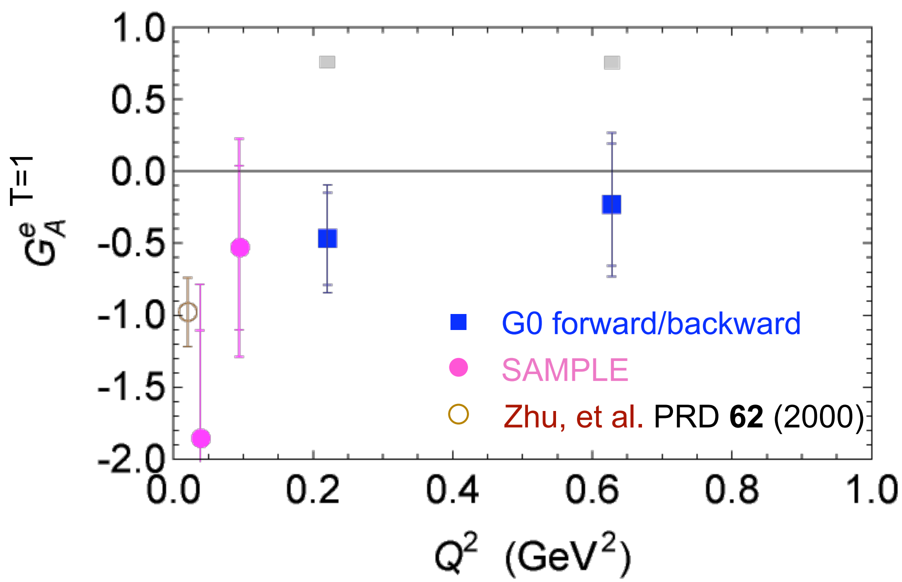
D.S. Armstrong *et al.*, PRL 95, 092001 (2005)

Backward Angle Results: *Preliminary*

- Using interpolation of G0 forward measurements







Global uncertainties

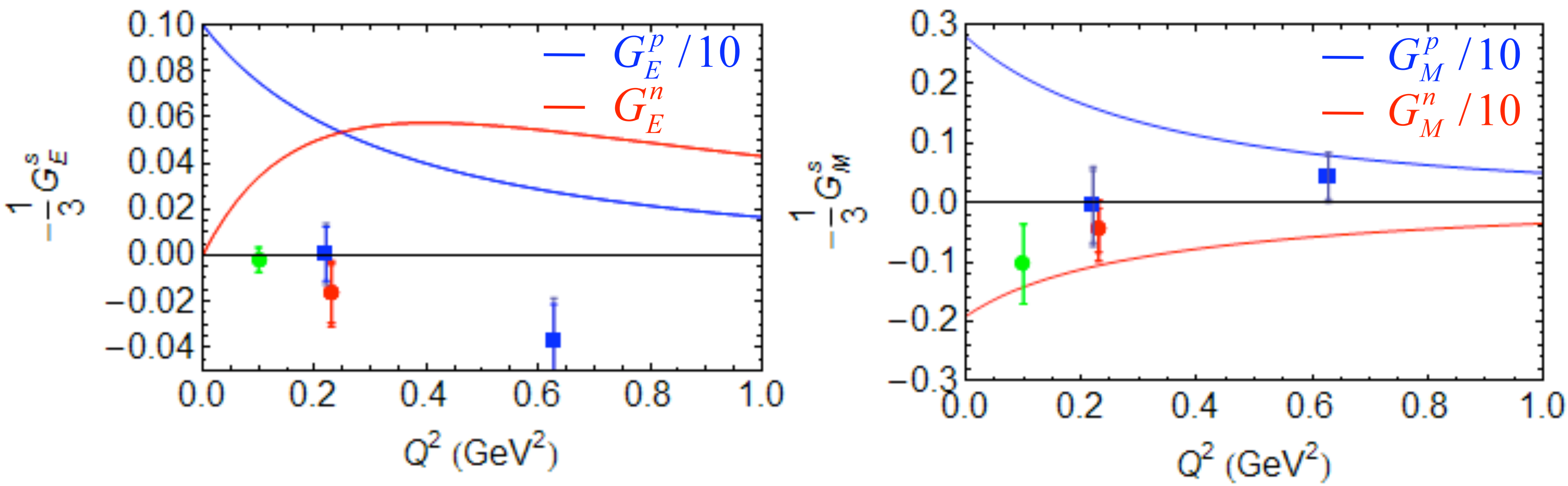
assumes:

$$G_{A,NS}^{T=0}\left(Q^2\right) = R_A^{T=0}\,\frac{3F-D}{2}\,G_A^{dipole}\left(Q^2\right)$$

$$G_{A,NS}^{T=0}\left(Q^2=0\right) = 0.070$$

Also assumes: no CSV

Contributions to Overall Form Factors

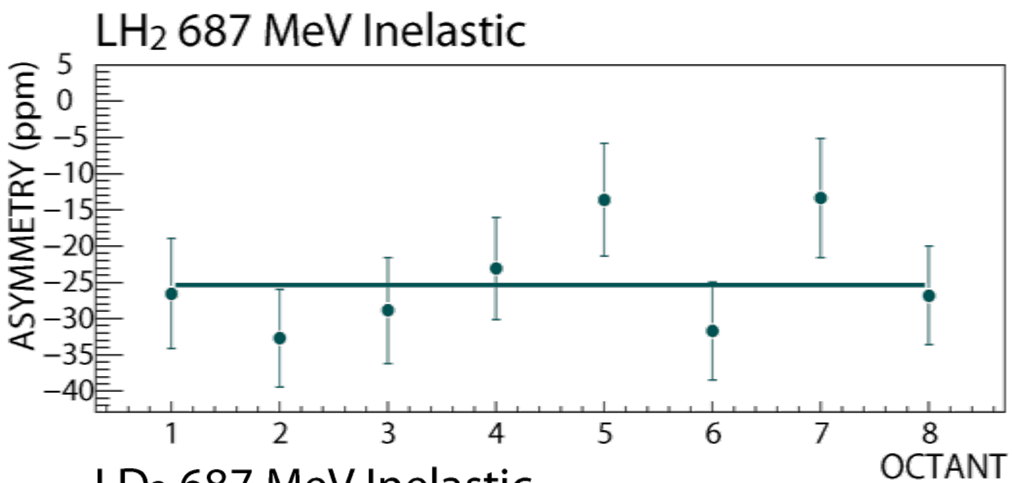


- NEXT STEP: fit 33 separate asymmetry measurements for H, D, He targets
  - at this point, not all data at quite the same level…

    consistent EM form factors, radiative corrections, CSV…

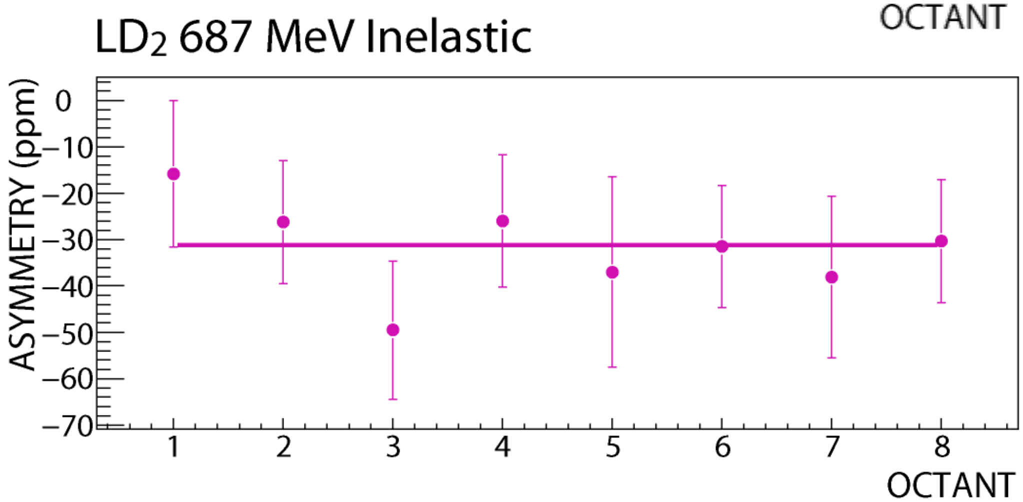
Preliminary Inelastic Asymmetries

$G_A^{N\Delta}(Q^2)$: Isovector ($\Delta I=1$), spin-flip form factor – encodes space/spin structure in transition to I=3/2 resonance, analogous to $G_A(Q^2)$



[OUT + IN = 0.07 ± 5.1 ppm]

Raw data: Backgrounds, radiative corrections *not yet included*

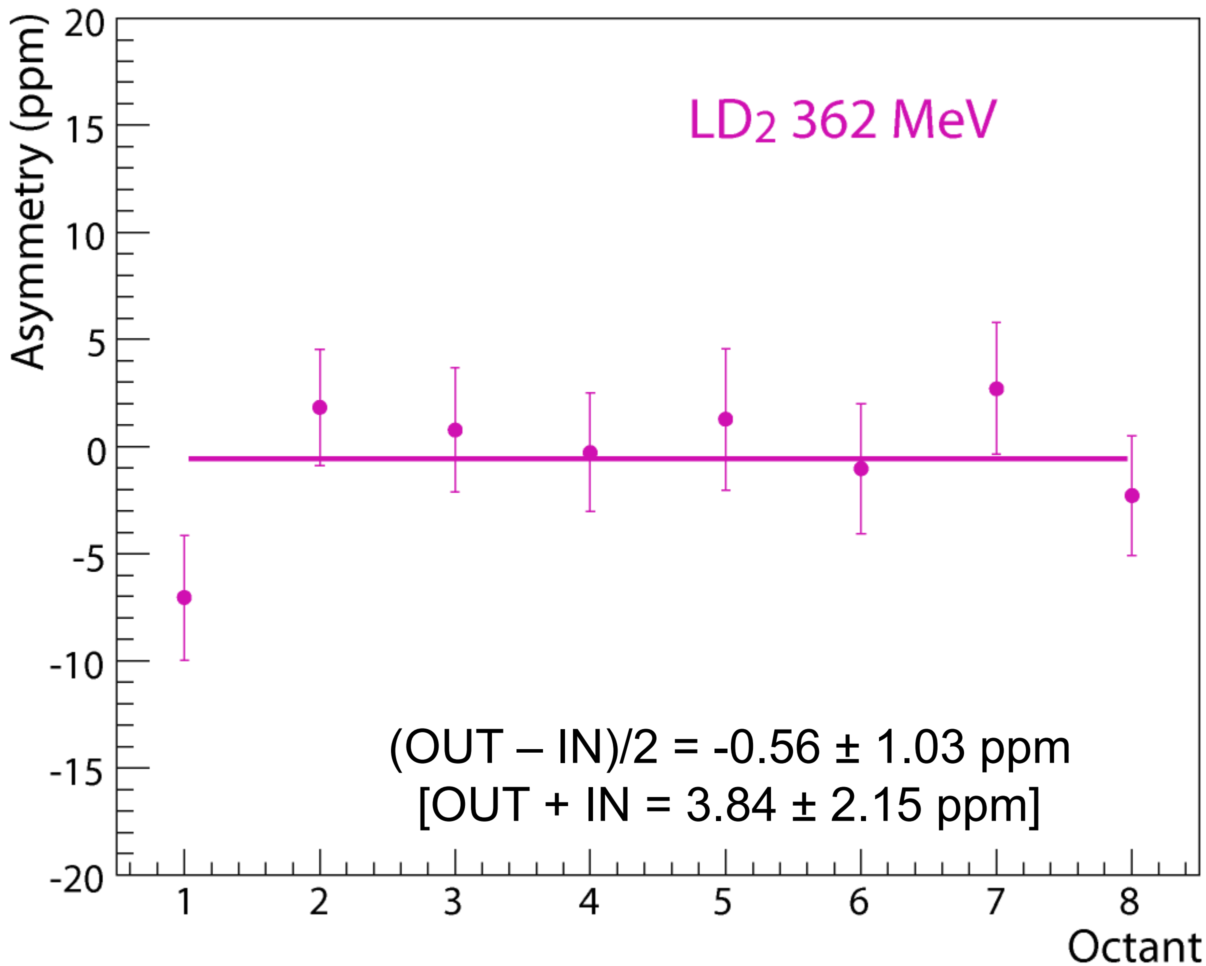


[OUT + IN = -9.9 ± 10.5 ppm]

We seek theory guidance for the deuteron case

Preliminary Pion Asymmetries

- Measure inclusive π^- from D target, dominated by photoproduction
- Asymmetry at $Q^2 = 0$ not zero ➔ constrain small asymmetry "d_Δ"
- d_Δ related to the anomalous $\Delta S = 1$ hyperon decays



working on systematic uncertainties (~ 0.5 ppm):

Summary

- Comparison of electromagnetic and weak neutral elastic form factors allows determination of strange quark contribution
  - large distance scale dynamics of the sea
- Small positive G_E^s at higher Q^2, G_M^s consistent with zero, small quenching of G_A^e, consistent with theory
  - next step: global fit to all 33 asymmetries

- First measurement of neutral current $N\Delta$ transition around $Q^2 = 0.3$ GeV^2
- First measurement of PV asymmetry in inclusive π^- production at low Q^2

- see J. Mammei's talk: First measurements of transverse asymmetries in
  - back angle elastic scattering from H, D targets
  - Inclusive π^- production

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

Backup Slides

Form Factor Uncertainties (1)

- Pt-pt systematics

	$Q^2 = 0.22\ GeV^2$			$Q^2 = 0.63\ GeV^2$		
	G_E^s	G_M^s	G_A^e	G_E^s	G_M^s	G_A^e
Backward H Energy	7.11×10^{-4}	$4. \times 10^{-3}$	6.72×10^{-4}	8.46×10^{-4}	1.59×10^{-3}	3.61×10^{-4}
Backward D Energy	6.04×10^{-4}	3.9×10^{-3}	1.04×10^{-2}	$5. \times 10^{-4}$	1.25×10^{-3}	5.56×10^{-3}
Forward Q^2	3.71×10^{-3}	1.68×10^{-3}	8.69×10^{-3}	5.61×10^{-3}	6.73×10^{-4}	6.65×10^{-3}
Backward H Q^2	3.4×10^{-3}	1.91×10^{-2}	3.22×10^{-3}	4.45×10^{-3}	8.35×10^{-3}	1.9×10^{-3}
Backward D Q^2	2.92×10^{-3}	1.89×10^{-2}	5.05×10^{-2}	3.19×10^{-3}	7.94×10^{-3}	3.55×10^{-2}
G_E^p	1.17×10^{-3}	5.22×10^{-4}	9.55×10^{-3}	2.94×10^{-3}	2.54×10^{-4}	3.88×10^{-3}
G_M^p	1.58×10^{-3}	4.13×10^{-3}	7.18×10^{-3}	3.76×10^{-3}	4.73×10^{-3}	7.21×10^{-3}
G_E^n	3.31×10^{-3}	2.75×10^{-3}	7.36×10^{-3}	4.53×10^{-3}	1.52×10^{-3}	6.78×10^{-3}
G_M^n	2.14×10^{-3}	7.69×10^{-3}	3.71×10^{-2}	1.26×10^{-3}	7.97×10^{-3}	1.4×10^{-2}
a_0^D	4.08×10^{-3}	2.63×10^{-2}	7.05×10^{-2}	1.3×10^{-3}	3.23×10^{-3}	1.44×10^{-2}
a_E^D	5.57×10^{-5}	3.59×10^{-4}	9.62×10^{-4}	1.75×10^{-4}	4.37×10^{-4}	1.95×10^{-3}
a_M^D	3.11×10^{-4}	2.01×10^{-3}	5.38×10^{-3}	1.04×10^{-4}	2.59×10^{-4}	1.16×10^{-3}
a_A^D	1.81×10^{-3}	1.17×10^{-2}	3.13×10^{-2}	9.74×10^{-4}	2.43×10^{-3}	1.08×10^{-2}
Total	8.62×10^{-3}	4.09×10^{-2}	1.01×10^{-1}	1.05×10^{-2}	1.56×10^{-2}	4.45×10^{-2}

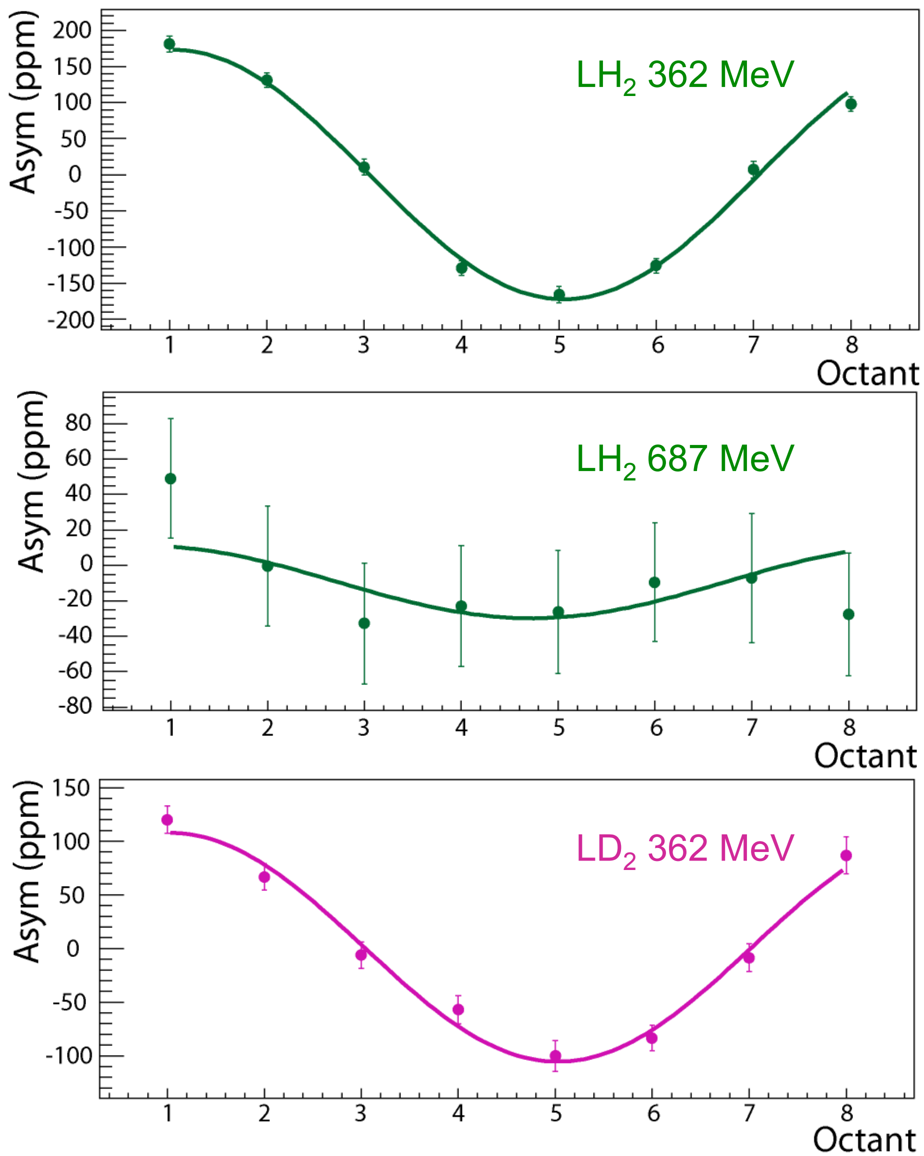
Form Factor Uncertainties (2)

- Global systematics

	$Q^2 = 0.22\ \mathrm{GeV}^2$			$Q^2 = 0.63\ \mathrm{GeV}^2$		
	G_E^s	G_M^s	G_A^e	G_E^s	G_M^s	G_A^e
Forward H Energy	4.26×10^{-6}	1.93×10^{-6}	9.98×10^{-6}	1.39×10^{-5}	1.66×10^{-6}	1.64×10^{-5}
G_A^s	6.13×10^{-4}	3.96×10^{-3}	1.44×10^{-3}	5.5×10^{-4}	1.37×10^{-3}	6.48×10^{-4}
EW Rad. Corr.	2.52×10^{-3}	1.63×10^{-2}	5.93×10^{-3}	2.26×10^{-3}	5.63×10^{-3}	2.66×10^{-3}
Total	2.59×10^{-3}	1.67×10^{-2}	6.1×10^{-3}	2.33×10^{-3}	5.79×10^{-3}	2.74×10^{-3}

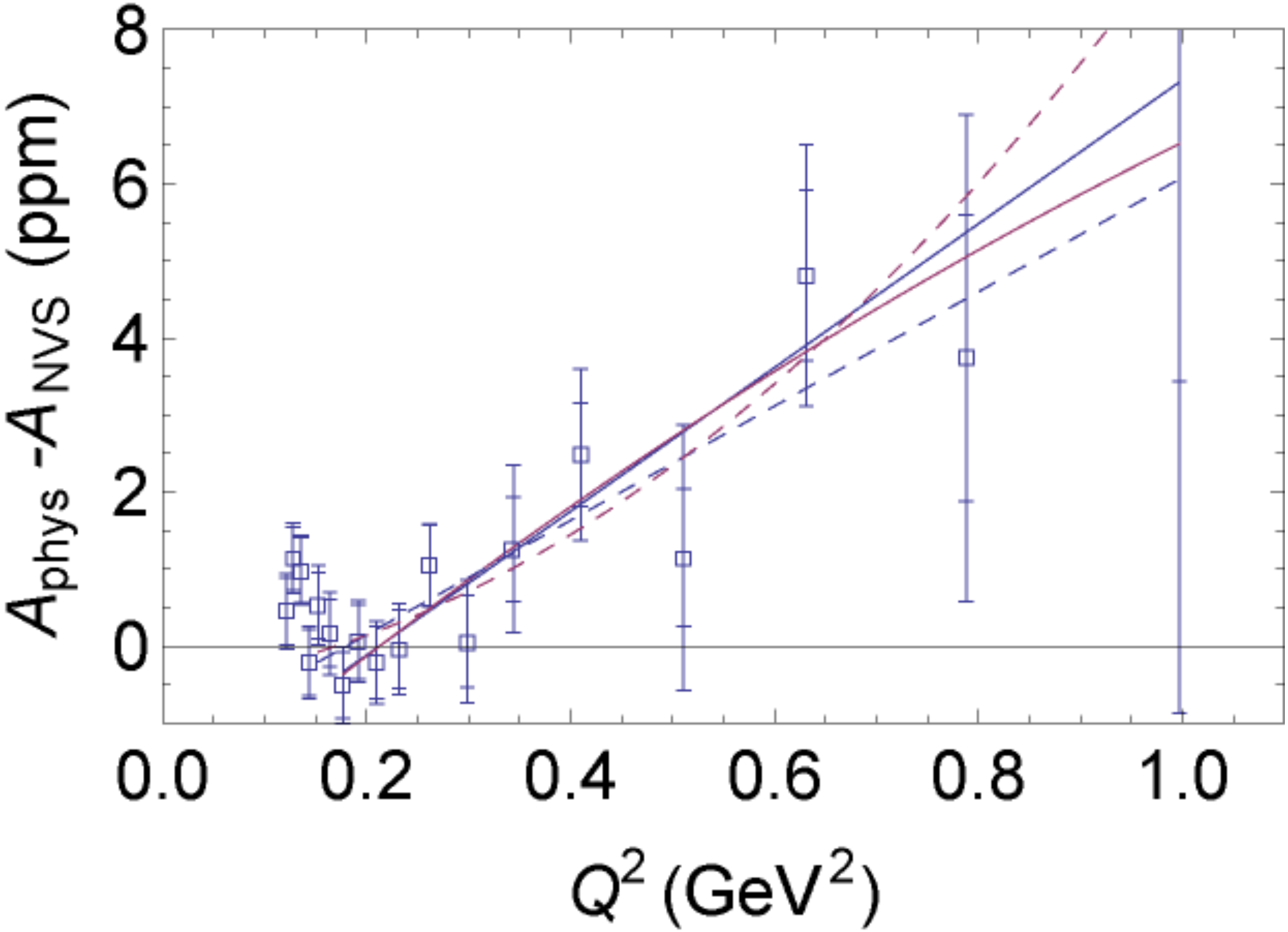
Preliminary Transverse Asymmetries

- Background, radiative corrections *not included*



– need theory for em radiative corrections

Forward Angle Data



What is the Anapole Moment?

- As first noted by Zel'dovich (Sov. Phys. JETP **6** (58) 1184), a parity-violating coupling of the photon can occur

$$\langle p'|J^{\gamma}_{\mu}(Q^2)|p\rangle = \bar{u}(p')\left(F_1(Q^2)\gamma_{\mu} - i\frac{F_2(Q^2)}{2M}\sigma_{\mu\nu}q^{\nu} + \frac{F_A(Q^2)}{M^2}\left(q^2\gamma_{\mu} - \not{q}q_{\mu}\right)\gamma_5 - i\frac{F_E(Q^2)}{2M}\sigma_{\mu\nu}q^{\nu}\gamma_5 \right)u(p)$$

where F_A and F_E are the anapole (parity-violating, time-reversal conserving) and electric dipole (parity- and time-reversal- violating) moments, respectively

- At low Q^2 the corresponding interaction energy is

(Musolf and Holstein, Phys. Rev. D **43** (91) 2956)

$$L_{anapole} = -e^2\frac{F_A}{M^2}\psi\gamma_{\mu}\gamma_5\psi\; j_{\mu} \sim -e^2\frac{F_A}{M^2}\vec{\sigma}\cdot\vec{j}$$

- The classical analog of the anapole moment is that property of a toroidal magnetic field that leads to a torque in an external current field

Validity of charge symmetry assumption

$$u \leftrightarrow d$$

$$G^{u,p}_{E,M} = G^{d,n}_{E,M} \qquad G^{d,p}_{E,M} = G^{u,n}_{E,M} \qquad G^{s,p}_{E,M} = G^{s,n}_{E,M}$$

Size of charge symmetry breaking effects in some n,p observables:

- n - p mass difference → $(m_n - m_p)/m_n \sim 0.14\%$
- polarized elastic scattering $\vec{n}$ + p, $\vec{p}$+n $\Delta A = A_n - A_p = (33 \pm 6) \times 10^{-4}$
  Vigdor et al, PRC 46, 410 (1992)
- Forward backward asymmetry n + p → d + π^0 $A_{fb} \sim (17 \pm 10) \times 10^{-4}$
  Opper et al., nucl-ex 0306027 (2003)

→ For vector FF: theoretical CSB estimates indicate < 1% violations -
Miller PRC **57**, 1492 (1998) Lewis & Mobed, PRD **59**, 073002(1999)

Recent : effects could be large as statistical error on
HAPPEx data! B. Kubis & R. Lewis Phys. Rev. C **74** (2006) 015204

Two Photon Exchange - recent work

H.Q. Zhou, C.W. Kao and S.N. Yang   arXiv:0708.4297   2-Sept 2007

Beyond single boson exchange in electroweak interference:

- $\gamma\gamma$ and γZ box (+crossing diagrams) → interfere with single γ & Z exchange
- Only elastic intermediate states adopted
  [as in Blunden, Melnitchouk & Tjon PRL **91**, 12304 (2003)]
- Find: for HAPPEx and PVA4 kinematics (Q2<0.5 GeV, ε>0.83)
  γZ box dominates the two boson effects

- All analyses to data used γZ at Q^2=0 [Marciano & Sirlin PRD 27, 27 (1983)]
  Find: *This grossly overestimates effect*
  - *Extracted* $G^s_E + \beta\, G^s_M$ ***tend to be reduced***

Recent global fits and theory

1. Global Fit: R.D. Young, et al. Phys.Rev.Lett. 97 (2006) 10200
   - all data $Q^2 < 0.30$, leading moments of G_M^s, G_E^s
   - float G_A^e separately for n, p

$$G_M^s = -0.01 \pm 0.25 \quad G_E^s = 0.002 \pm 0.018$$

2. Global Fit: J. Liu, R.D. McKeown, M. Ramsey-Musolf arXiv:0706.0226
   - all data $Q^2 < 0.164$, leading moments of G_M^s, G_E^s
   - constrain G_A^e to data and radiative corrections (χPT theory of Zhu et al.)

$$G_M^s = 0.29 \pm 0.21 \quad G_E^s = -0.008 \pm 0.016$$

3. Two Boson exchange: H.Q. Zhou, C.W. Kao and S.N. Yang arXiv:0708.4297

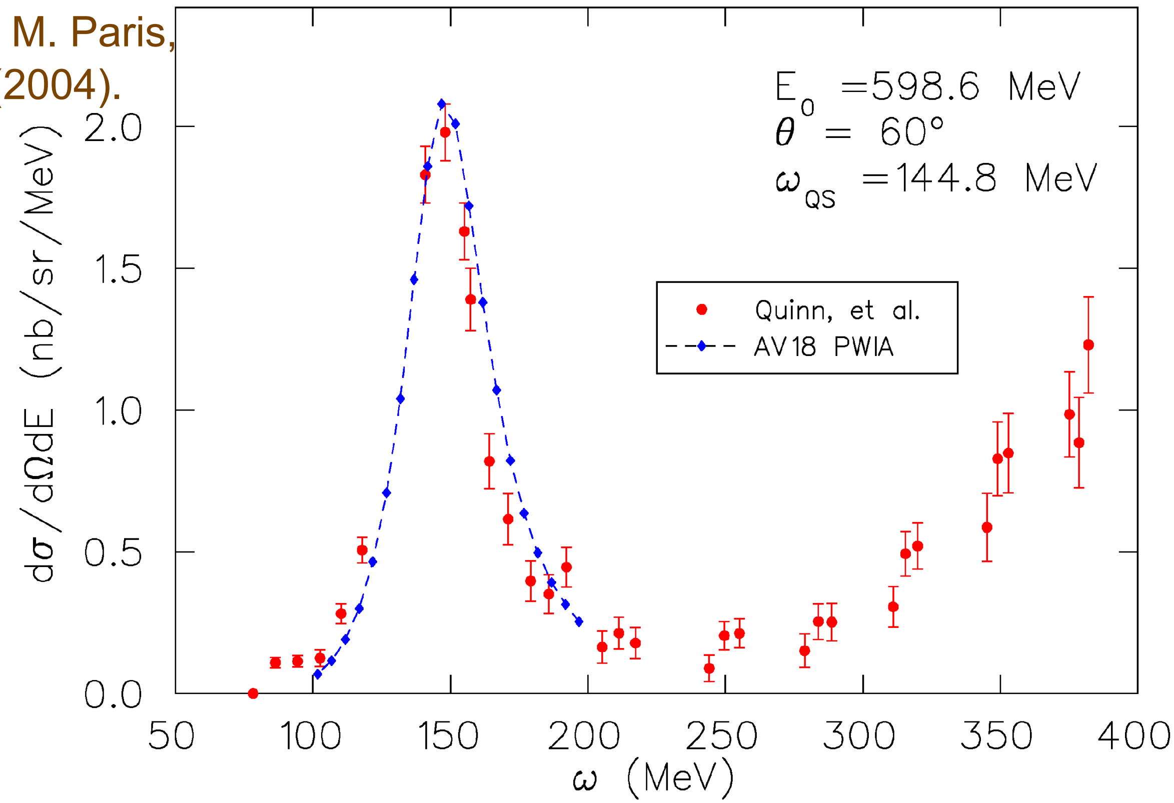
   γZ box dominates the two boson effects at HAPPex, PVA4 kinematics

   $\rightarrow$ reduces extracted $\boldsymbol{G^s_E + \beta\, G^s_M}$ ***(not yet put into global fits)***

Deuterium model comparison to cross section data

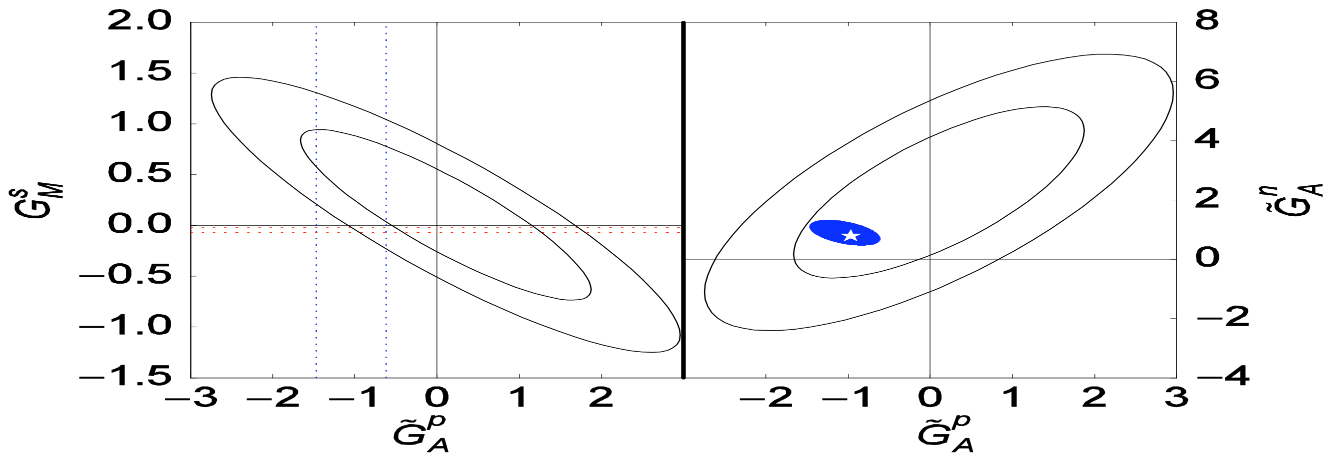
calculation from R. Schiavilla
see also
R.S., J. Carlson, and M. Paris,
PRC70, 044007 (2004).

- AV18 NN potential
- relativistic kinematics
- J.J. Kelly fit to nucleon form factors



data from:
S. Dytman, et al., Phys. Rev. C **38**, 800 (1988)
B. Quinn, et al., Phys. Rev. C **37**, 1609 (1988)

Effect of "floating" axial radiative corrections

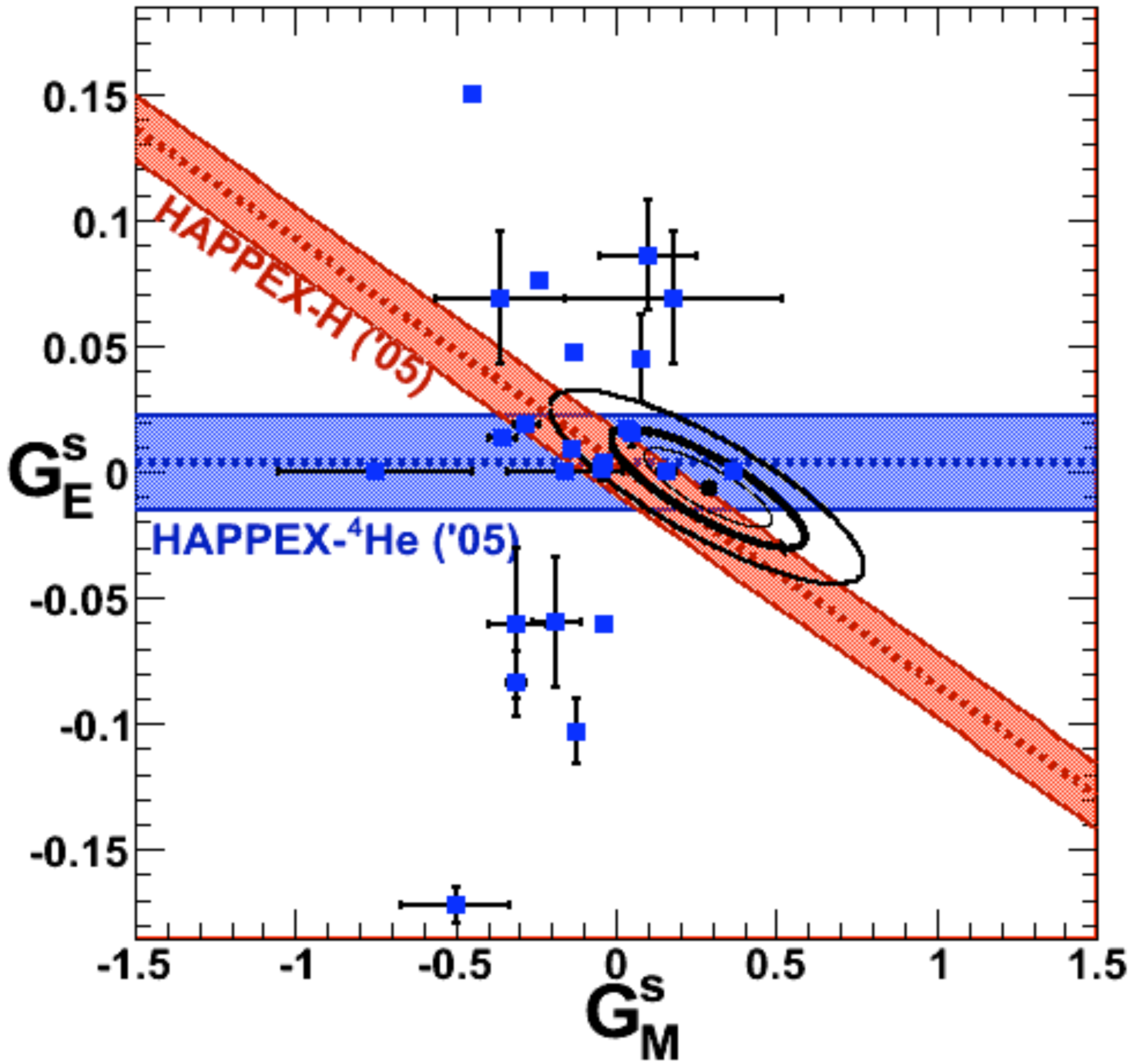


$$\tilde{G}_A^{p,n} = G_A^e = -\tau_3(1+R_A^{T=1})G_A + \sqrt{3}R_A^{T=0}G_A^8 + \Delta s$$

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

Data from $Q^2 < 0.3$, (pre-HAPPEx 2005),

World Data near Q^2 ~0.1 GeV^2



$G_M^s = 0.28 \pm 0.20$

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

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

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

Lattice: Leinweber et al.

$G_M^s = -0.046 \pm 0.022$

$G_E^s = +0.001 \pm 0.006$

$G_A^{N\Delta}$ and its relevance

- $G_A^{N\Delta}(Q^2)$: Isovector (ΔI=1), spin-flip form factor – encodes space/spin structure in the transition to the I=3/2 resonance, analogous to $G_A(Q^2)$
  - Filters away isoscalar s-sbar currents (i.e. strange quark effects)
    - Complementary to Electromagnetic $N \rightarrow \Delta$ form factors
- Axial currents dominates ν scattering cross section at moderate energies
  - eg. ν_e appearance experiments such as NOvA
  - Alvarez-Ruso *et al.* PRC 76, 068501 (2007)
    " $G_A^{N\Delta}$ ... largest source of uncertainty in neutral current pion production"

Axial Matrix element in $N \rightarrow \Delta$ determined by 4 transition form factors:

$C_3^A(Q^2)$, $C_4^A(Q^2)$, $C_5^A(Q^2)$, and $C_6^A(Q^2)$

$G_A^{N\Delta}(Q^2) = \sqrt{6}\, C_5^A(Q^2)$ in SU(6) limit $G_A^{N\Delta}(Q^2) = (6\sqrt{2}/5)\, G_A(Q^2)$

G_A digression

- $G_A(Q^2)$: "elastic" axial form factor

1. $G_A(0) = g_a = 1.2695 \pm 0.0029$ neutron beta decay
2. Quasi-elastic anti-neutrino charged-current scattering
   $G_A(Q^2) = g_a/(1-Q^2/M_A^2)^2$ $m_A = 1.001 \pm 0.020$ GeV
3. Pion electroproduction + Adler-Gilman relation $m_A = 1.068 \pm 0.017$ GeV

reconciled in HBχPT Bernard, Kaiser, Meissner PRL 69, 1877 (1992)

pion loop corrections change pion electroproduction result to $m_A = 1.012 \pm 0.017$ GeV

Connecting A_{PV}^{inel} to $G_A^{N\Delta}$

- Consider single pion electroproduction (below 2π threshold):

  $\rightarrow$ multipole and isospin expansion

- A_{PV}^{inel} arises, as usual, from γ-Z interference

$$A_{PV}^{inel} = -\tfrac{1}{2} A_0 \left(A^{\pi}_{(1)} + A^{\pi}_{(2)} + A^{\pi}_{(3)} \right)$$

where

$A^{\pi}_{(1)}$ = axial vector electron x vector/isovector (I=1/2, 3/2) ⟸ EM FF data

(resonant and non-resonant pieces)

$A^{\pi}_{(2)}$ = axial vector electron x vector/isovector (I=1/2) ⟸ EM FF data

(non-resonant pieces)

$A^{\pi}_{(3)}$ = vector electron x axial hadronic matrix element

(resonant and non-resonant pieces)

⇑

The resonant part of this axial hadronic matrix element depends on $G_A^{N\Delta}$

<u>*Note:*</u> for inclusive scattering, the non-resonant and resonant parts can interfere !

(aargh…)

^{4}He: Nuclear Effects – newer results

Vaviani, Schiavilla, Kubis, Lewis, *et al.*

- include isospin-breaking effects in nucleon

as/per Kubis & Lewis χPT (Phys. Rev. C 74 (2006) 015204)

- include nuclear isospin-breaking effects:

  - ^{4}He wavefunction from Hyperspherical Harmonic expansion

  - wide variety of modern NN potentials (include isospin breaking terms from both strong and Coulomb effects)

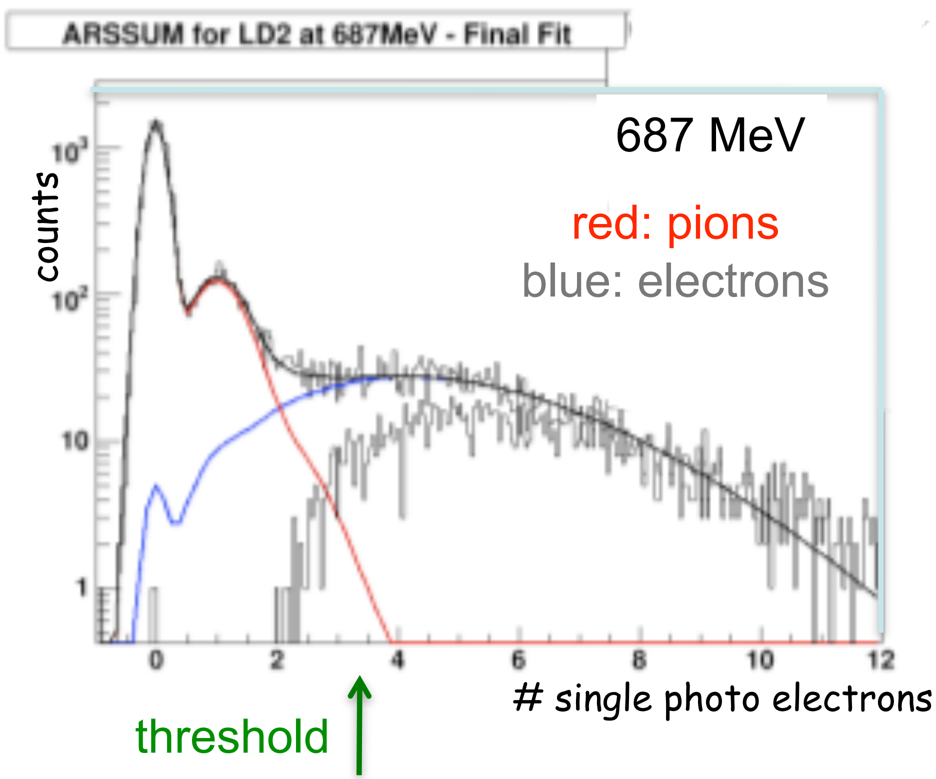
Results: isospin-breaking effects are ≈ 30% of experimental error on G_E^s

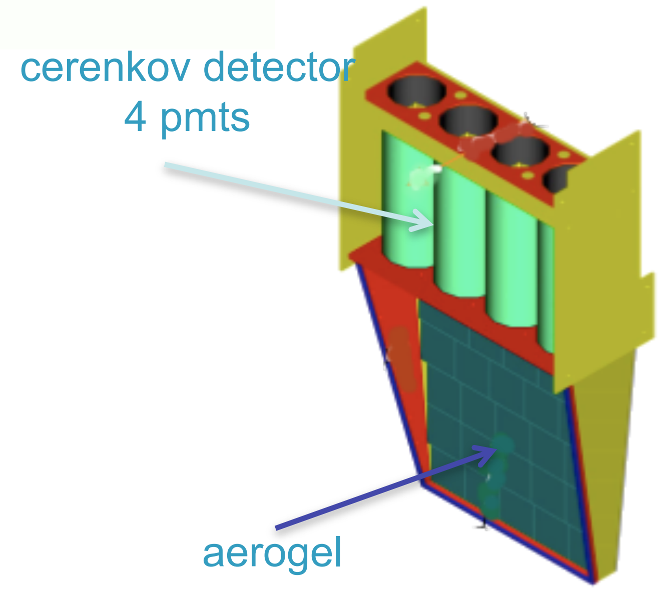
- verified that MEC effects are small at low Q^2

Correction due to misidentified pions

3 Ways to calculate

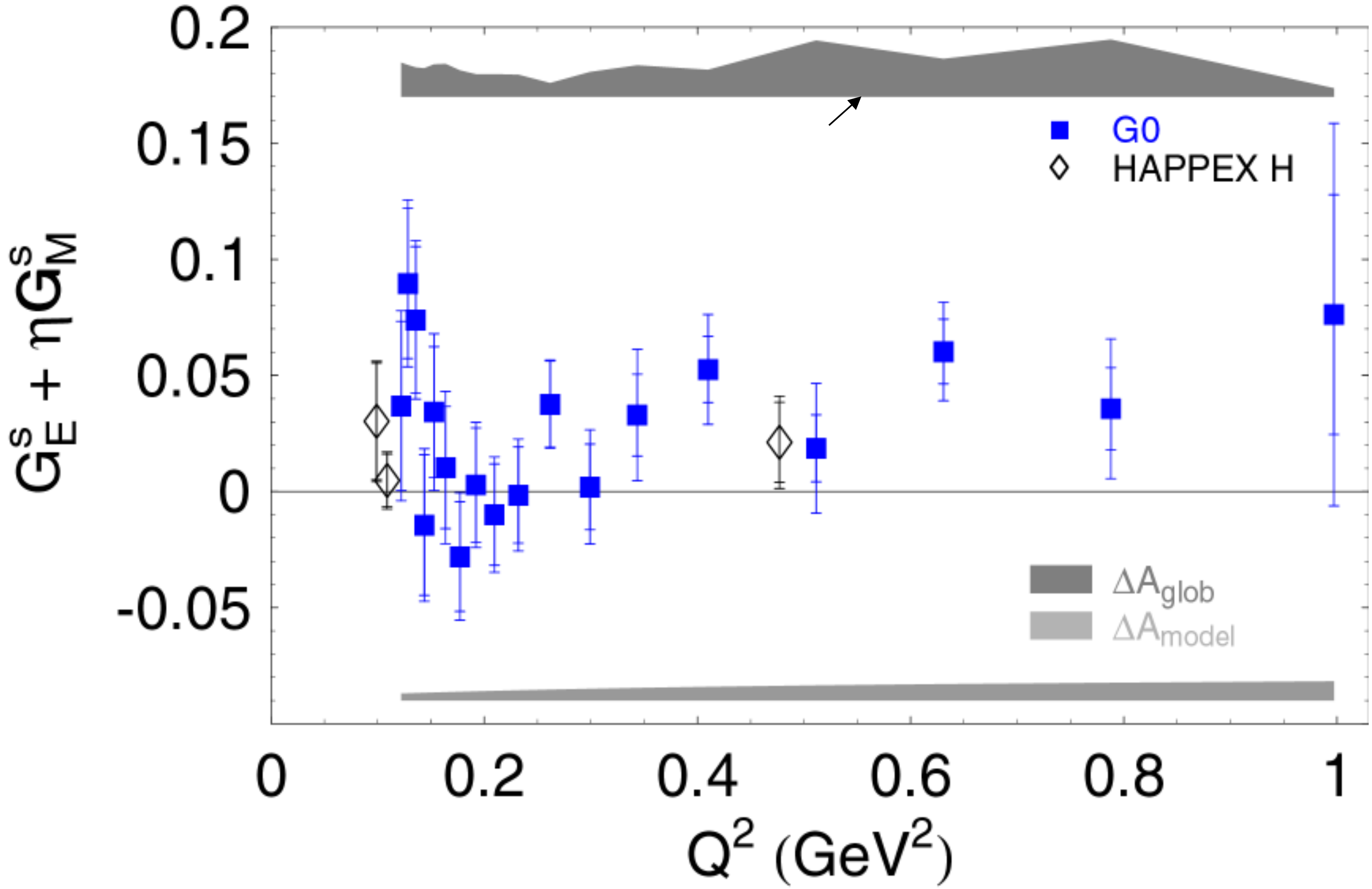
- runs with special beam structure providing timing reference allowing particle TOF
- PMT Multiplicity (two versus three of the cerenkov PMT's firing)
- Pulse heights (waveform digitized)





π^- contamination to electron yield ($A_\pi \sim 0$)
D 362: 0.5%
D 687: 4%

Correlated systematic



Anapole form factor $F^{\gamma}_{A}(Q^2)$

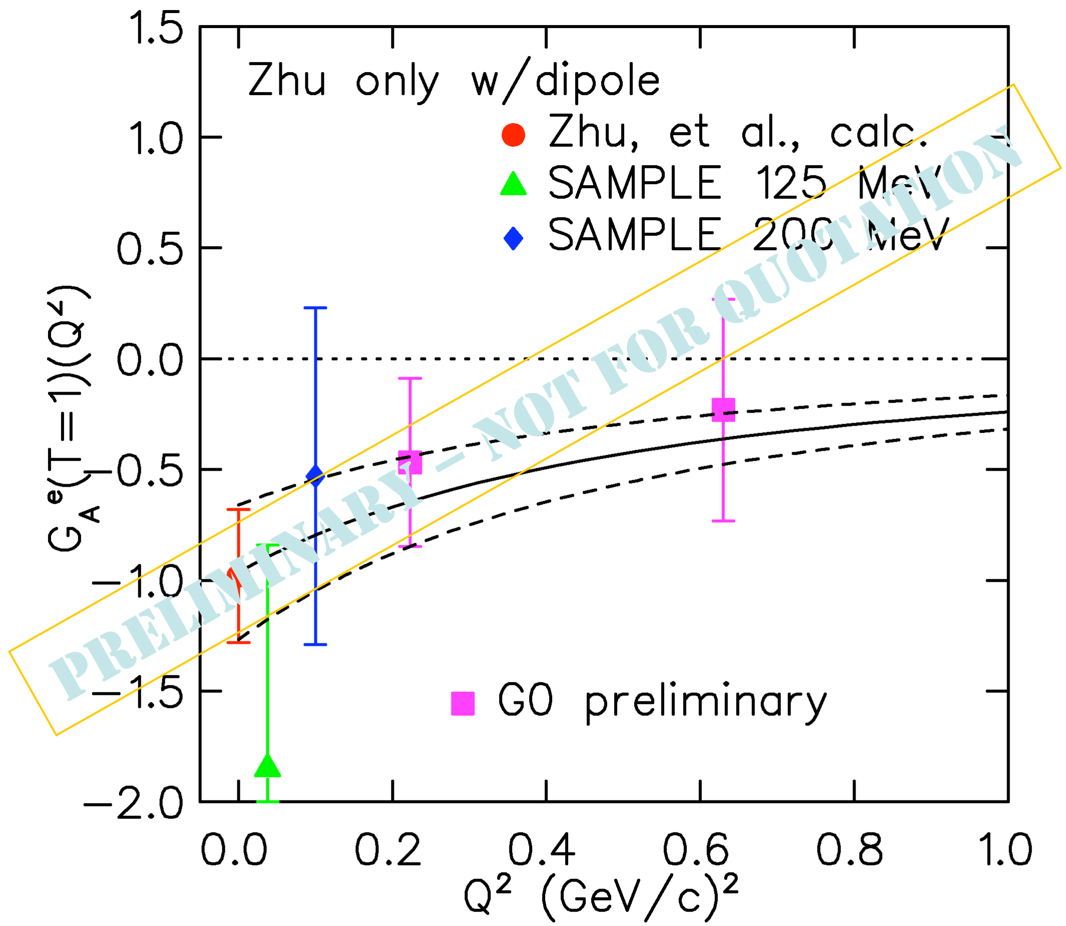
Three scenarios

1. $F_A(Q^2)$ is like $G_A(Q^2)$

2. $F_A(Q^2)$ is flat (Riska, NPA 678 (2000) 79)

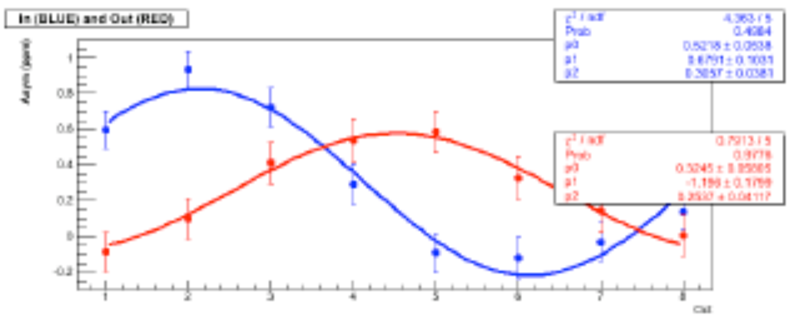
3. $F_A(Q^2) \sim 1 + Q^2$ (Maekawa, Viega, van Kolck, PLB 488 (2000) 167)

– (shown here are the most extreme set of model parameters)

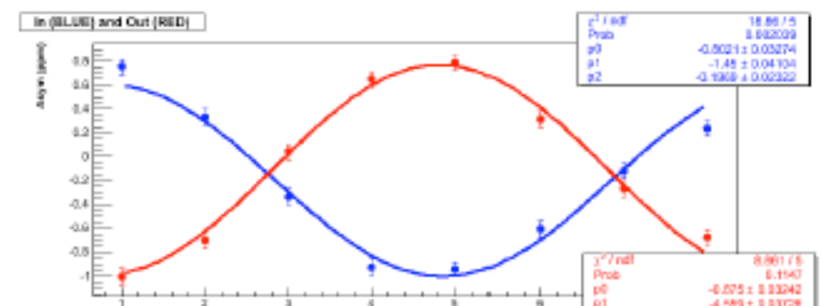


Lumi Asymmetries

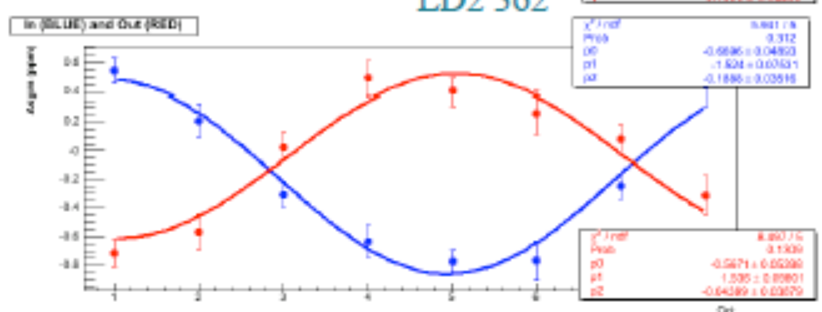
Small angle detectors – asymmetry expected to be ~0.1 ppm



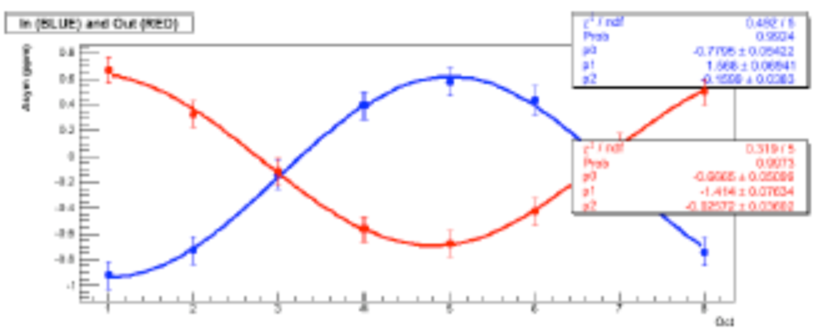
LH2 362



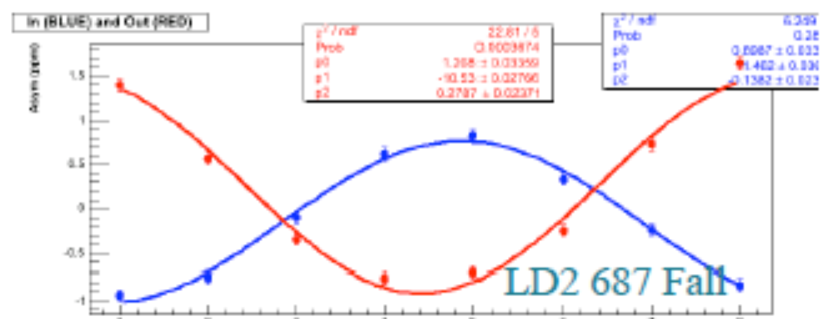
LD2 362



LD2 687 after 3/9/07



LH2 687



LD2 687 Fall