Strange Form Factors from the Sea: Parity-Violating Electron Scattering Results from the G^0 Experiment

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Fermi Lab - February 2, 2010

"The sea, once it casts its spell, holds one in its net of wonder forever."
-Jacques Yves Cousteau

Outline

- Strange quark contributions to the nucleon
- G^0 Backward angle measurement and analysis
- Strange and Axial Form Factor Results

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Strange Quark Contributions to Parity-Violating Asymmetries in the Backward Angle G0 Electron Scattering Experiment

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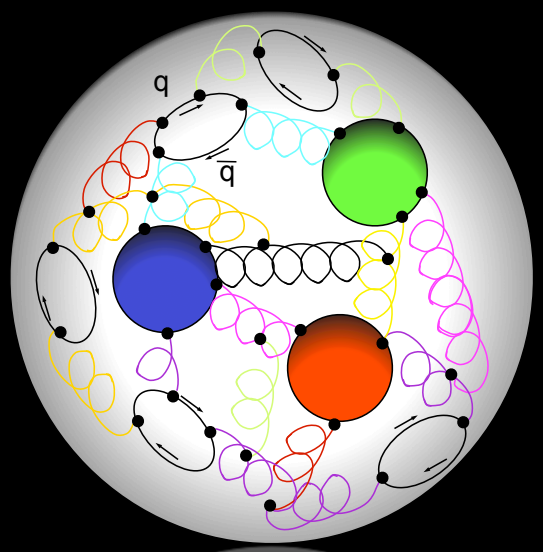
(G0 Collaboration)

Nucleon Structure



What's in a proton?

valence quarks carry baryon number and account for 1% of total mass (u, d)

sea of strongly coupled self interacting gluons and associated quark-antiquark pairs (u,d and ... s)

At the size scale of the bound state, ~1 fm, the QCD coupling constant is large and the effects of the color fields are a significant challenge, even in lattice QCD.

What do we know about the strange sea?

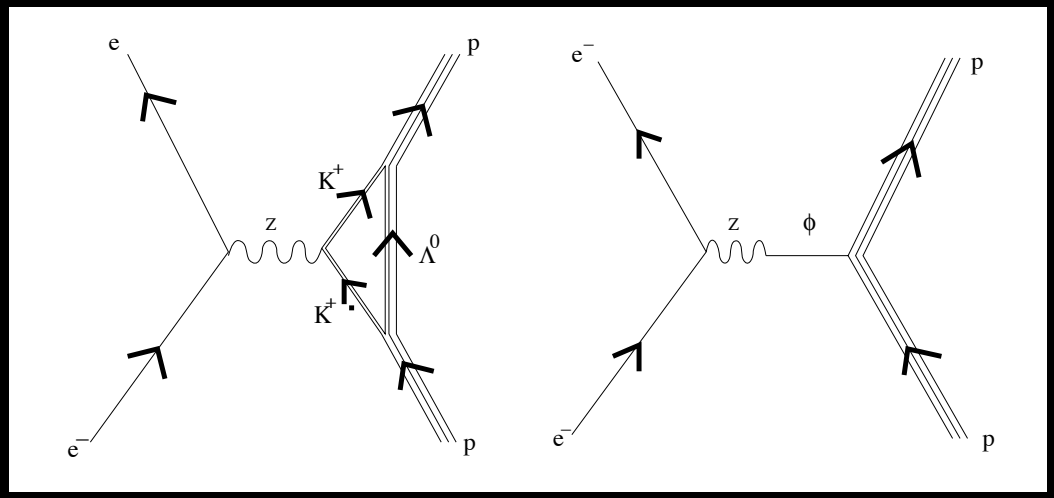
Mass / Scalar matrix element	$2\langle N\|s\bar{s}\|N\rangle / \langle N\|u\bar{u}+d\bar{d}\|N\rangle \sim 0.1-0.4$	
	πN Scattering	J. Gasser, H. Leutwyler, et.al.
Momentum	$2s/(\bar{u}+\bar{d}) = 0.42 \pm 0.07 \pm 0.06$	
	νN DIS	NUTEV
Spin	$\Delta s_{0.02} = 0.006 \pm 0.029 \pm 0.007$	
	(Semi-)Inclusive DIS	HERMES, COMPASS
Vector Matrix Elements / FF	$G \sim \langle N\|\sum_i e_i \bar{q}_i \Gamma_\mu q_i\|N\rangle$	

Predictions

Loops/Poles - Model the nucleon fluctuating into meson states.

Model	μ_s (n.m.)	$\langle r_s^2 \rangle_E$ (fm^2)
HBχPT	0.18	0.05
VMD	−0.25	0.02
Kaon Loop	−0.31	−0.03
Cloudy Bag	−0.026	−0.012
Hybrid	−0.28	−0.04
Chiral Quark	−0.05	0.02
Dispersion	−0.28	0.42
Skyrme	−0.13	−0.11
Chiral Soliton	0.12	−0.1
Lattice	0.05	−0.02

Beck/Holstein



Lattice QCD - Starts from the fundamental interaction of quarks/gluons to predict μ_s.

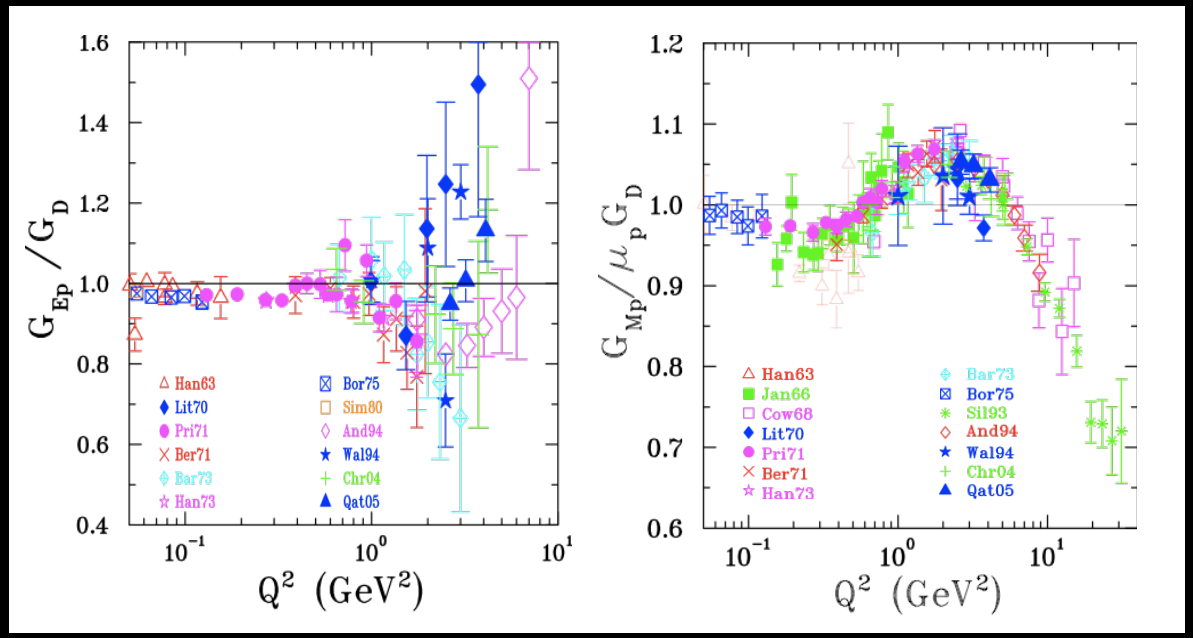
Form Factors

FFs characterize the extended nature of a particle

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_{Mott}}[G_E^2(Q^2) + \frac{\tau}{\epsilon}G_M^2(Q^2)]\frac{1}{1+\tau}$$

$$G_{M,E}(0) = \mu, q$$

Fourier Transform of
Electric and Magnetic Dist.
in specific frame



Rosenbluth Data

Flavored Form Factors

$$G_{E,M}^{\{\gamma,Z\},\{p,n\}} = q_u^{\gamma,Z} G_{E,M}^{u,\{p,n\}} + q_{d,s}^{\gamma,Z} (G_{E,M}^{d,\{p,n\}} + G_{E,M}^{s,\{p,n\}})$$

where

$$\{q_u^\gamma, q_{d,s}^\gamma, q_u^Z, q_{d,s}^Z\} = \{2, -1, 3 - 8\sin^2\theta_W, -3 + 4\sin^2\theta_W\}/3$$

plus charge symmetry

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

(see G.A. Miller PRC **57** (98) 1492.; B. Kubis and R. Lewis, PRC (74) , 015204)

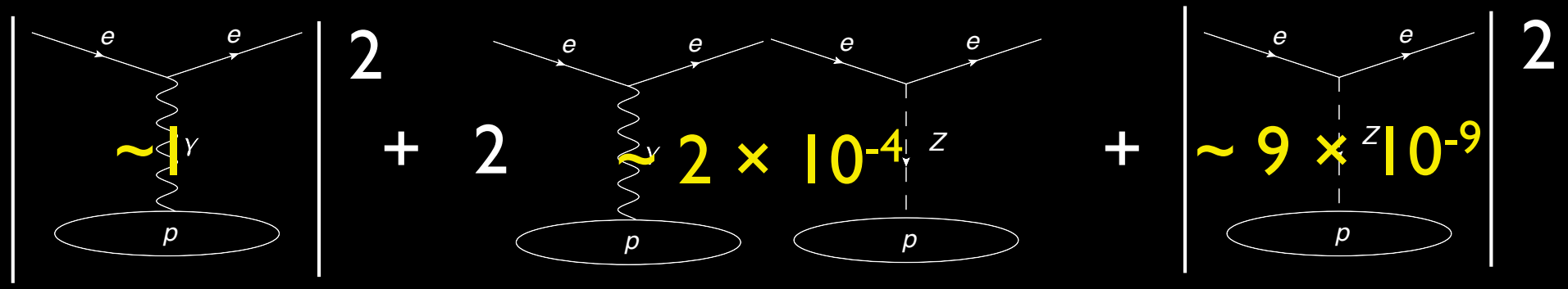
Note: Charge symmetry breaking effects are typically small (~1%) compared to the experimental precision

Flavored Form Factors

$$G^{s,p}_{E,M} = (1 - 4\sin^2\theta_w)G^{\gamma,p,}_{E,M} - G^{\gamma,n}_{E,M} - G^{Z,p}_{E,M}$$

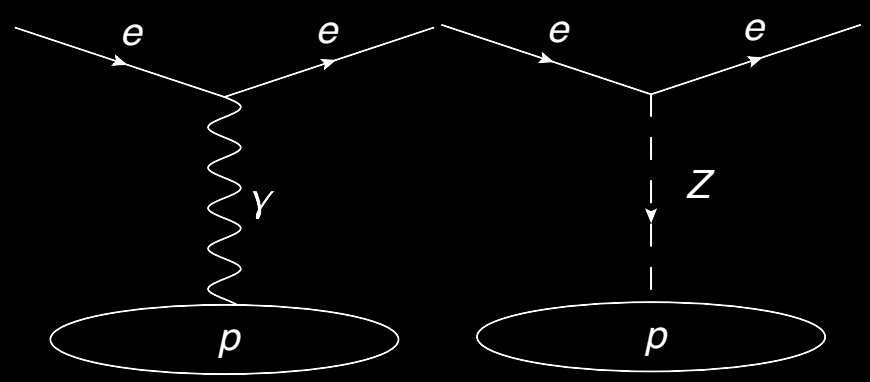
Electromagnetic form factors and the weak mixing angle are well measured quantities in this context.

Measurements of the neutral weak form factors are needed for flavor separation. Elastic e-p cross sections are sensitive to both Υ and Z exchange but .... Υ dominates!



Accessing Neutral Weak Currents

The parity violating cross term allows one to form an observable which is sensitive to G^Z:



$$A_{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} \sim \frac{2\mathcal{M}_\gamma^* \mathcal{M}_Z^{PV}}{|\mathcal{M}_\gamma|^2} \sim 10^{-5}$$

$$= -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \frac{\epsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - (1 - 4\sin^2\theta_W)\epsilon' G_M^\gamma G_A^e}{\epsilon (G_E^\gamma)^2 + \tau (G_M^\gamma)^2}$$

(D. H. Beck and R. D. McKeown, Ann. Rev. Nucl. Sci. 51, 189)

A_{PV} is sensitive to axial form factors at backward angles

Axial Current Contribution

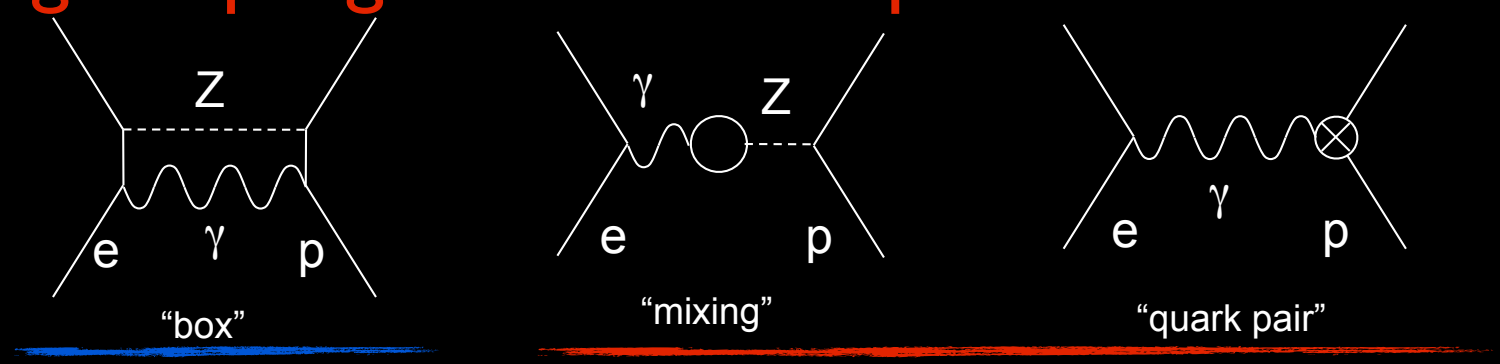
$$G_A^e = G_A\tau_3 + \eta F_A + R_e + \Delta s$$

G_A , from $\gamma_\mu\gamma_5$, probes the spin–isospin distribution of the nucleon and has been measured in neutrino scattering

s spin contribution suppressed and measured in DIS

Nucleon anapole form factor from the effective parity-violating coupling between real photons and nucleons

Ordinary Radiative Effects



PVES Measurements

3 measurements at a given Q^2 are needed to separate the form factors.

e-p scattering at forward angles

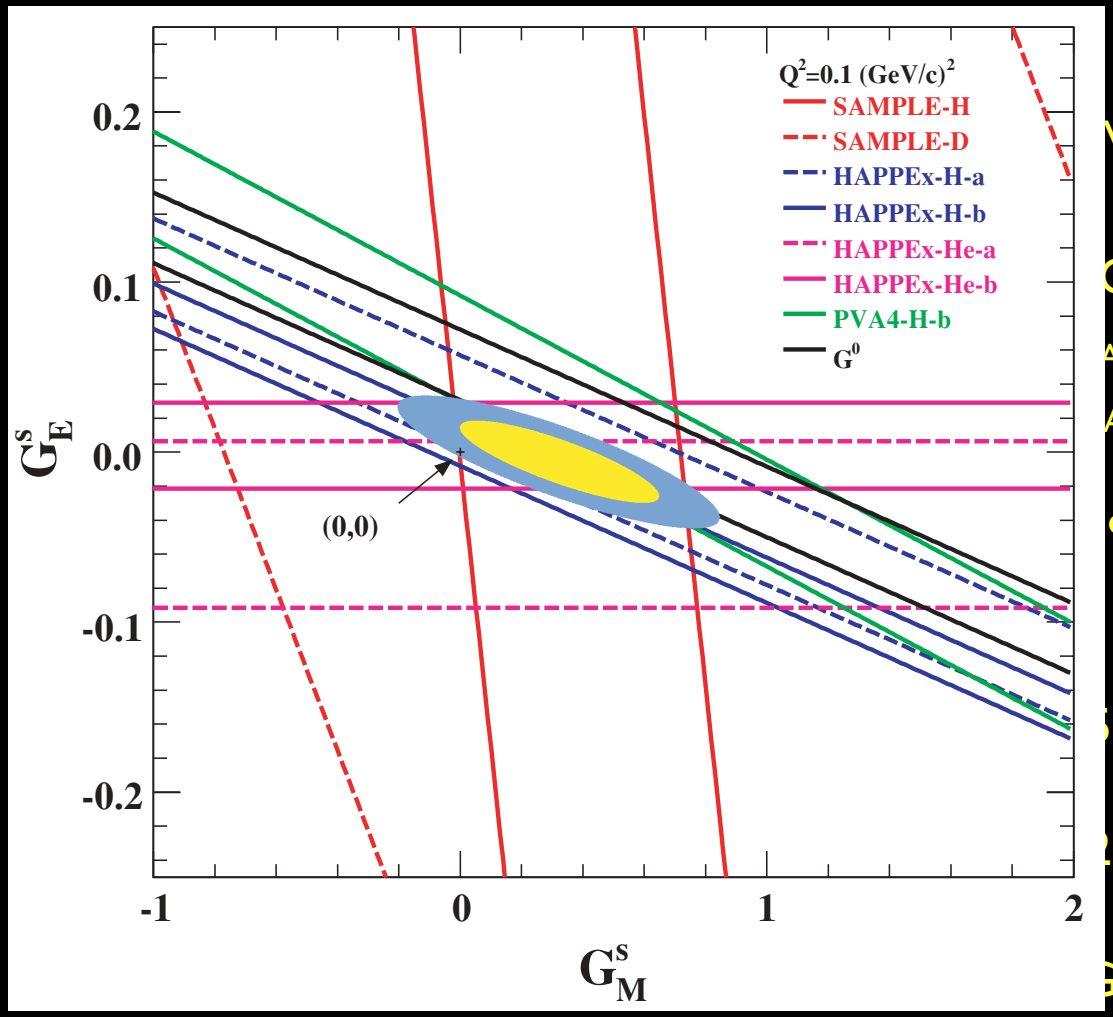
e-p scattering at backward angles

and e-d scattering at backward angles

$$A_D = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \times \frac{Num_n + Num_p}{Denom_n + Denom_p}$$

Sensitive to the axial form factor

PVES Measurements



Expt/Lab				vity	Status
SAMPLE/Bates					
SAMPLE I				G_A	2000
SAMPLE II				A	2004
SAMPLE III				A	2004
HAPPEx/JLab					
HAPPEx				$9G_M$	2001
HAPPEx II, III				G_M	2006, 2007
HAPPEx He					2006, 2007
HAPPEx				$5G_M$	(2009)
A4/Mainz					
				$2G_M$	2004
				G_M	2005
				$G_M + \eta' G_A$	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

G0 probes Q^2 larger than 0.1 GeV^2

G^0 Collaboration

Graduate Students:

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J. Mammei (VaTech), M. Muether (Illinois), J. Schaub (NMSU)
M. Versteegen (Ph.D. Oct. 09 Grenoble); S. Bailey (Ph.D. Jan. 07 W&M)

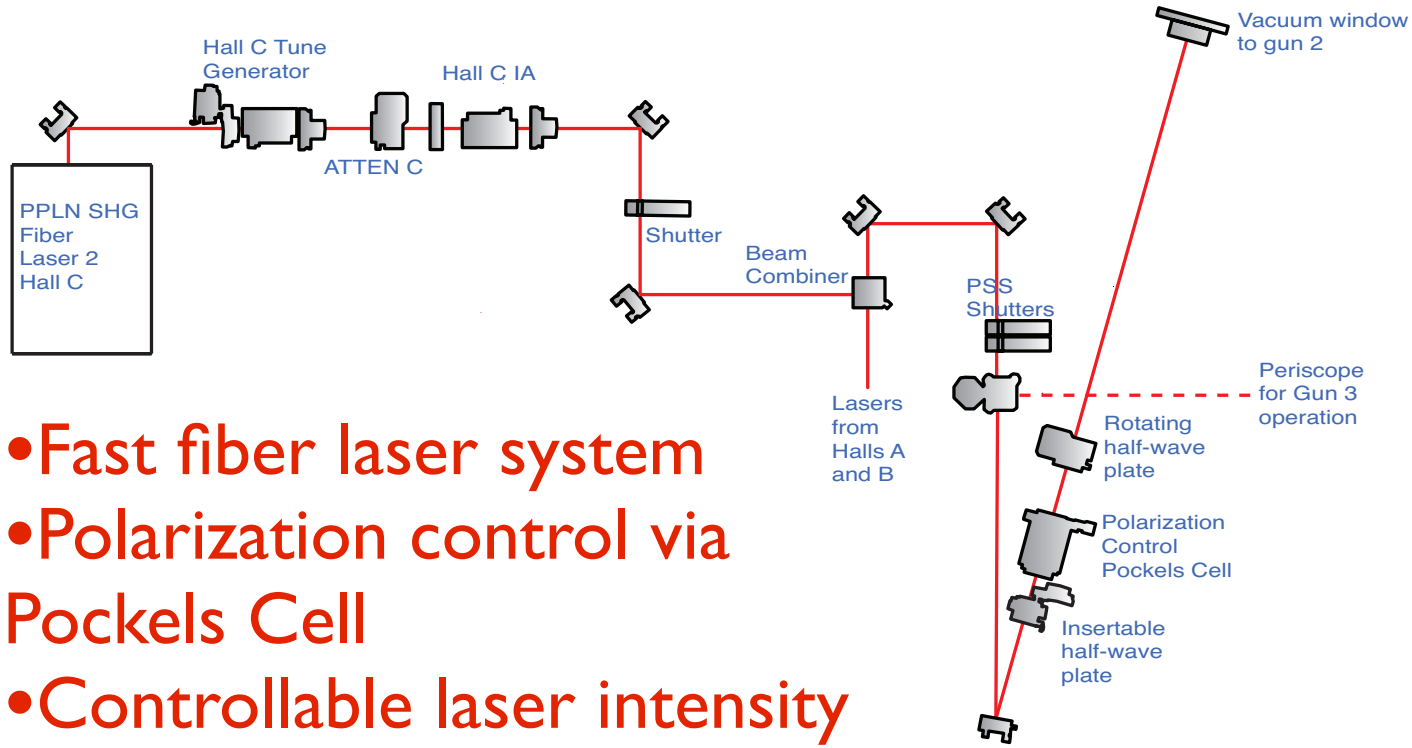
Analysis Coordinator:

F. Benmokhtar - Carnegie Mellon (Maryland)

Caltech, Hendricks College, Orsay, LA Tech, Ohio, JLab, TRIUMF, Kentucky, Manitoba, Winnipeg, Zagreb, Yerevan Physics Institute

CEBAF at JLab

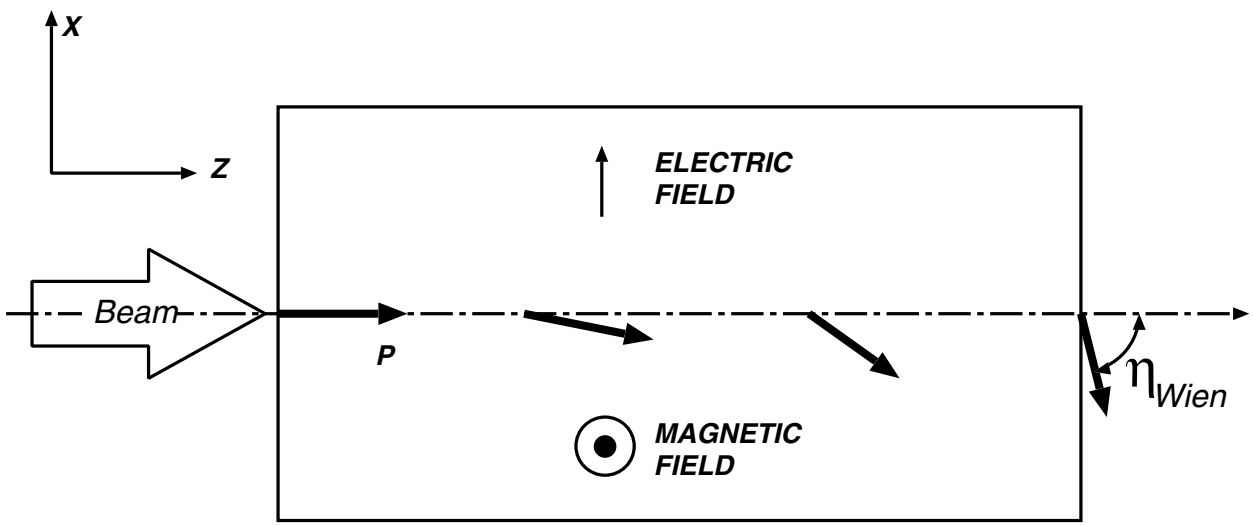
Polarized Source



- Fast fiber laser system
- Polarization control via Pockels Cell
- Controllable laser intensity via IA
- Slow Helicity control via IHWP
- Lattice Ga-As cathode provides >80% pol.

CEBAF at JLab

Injector



- Wien filter aligns the electron spin longitudinally within 2° in 100 keV beamline
- The polarization of the beam is monitored with a Mott polarimeter in the injector and a Moeller polarimeter in the hall

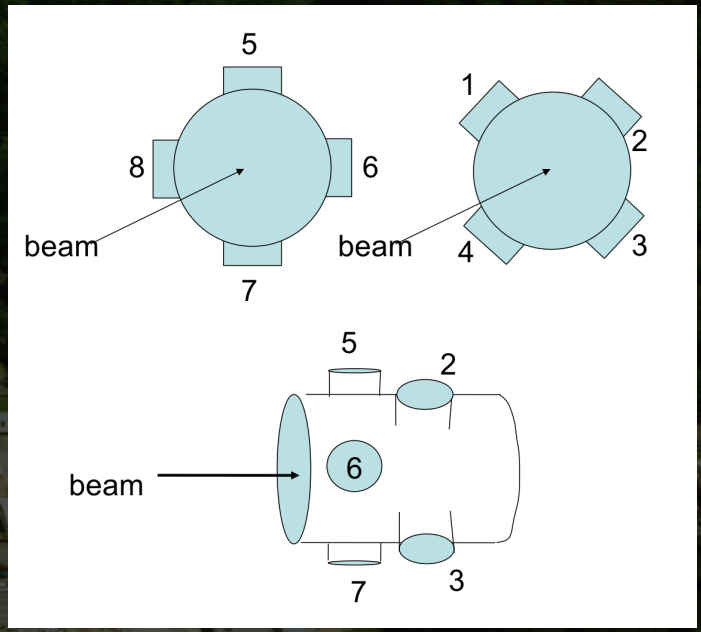
CEBAF at JLab

Electrons are accelerated to 362 and 687 MeV in the tandem recirculating LINACs before being steered into Hall C

CEBAF at JLab

- Beam charge and position monitors (BCMs/BPMs) measure charge, x and y position, and angle

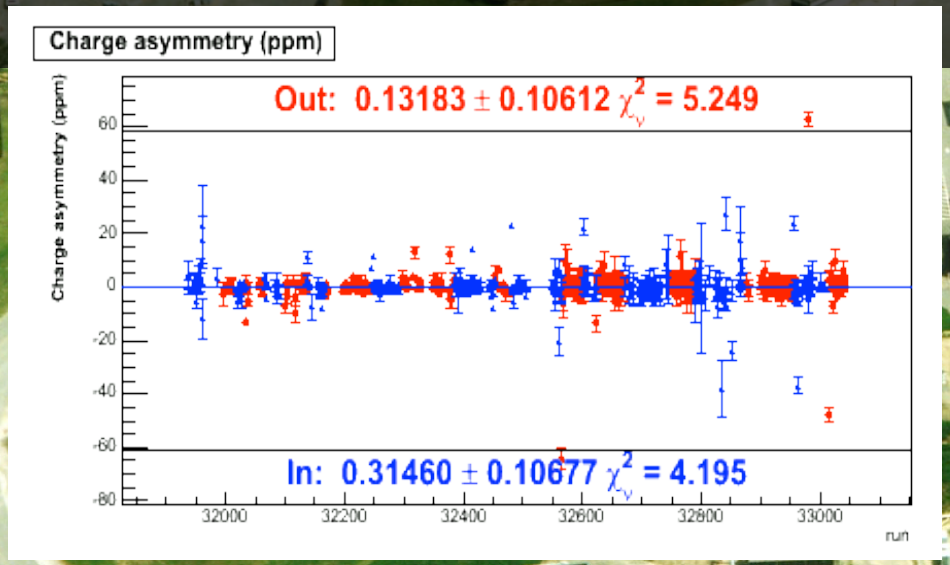
- A set of 8 azimuthally placed luminosity monitors provide additional spin and target density information from ~4° Moeller electrons

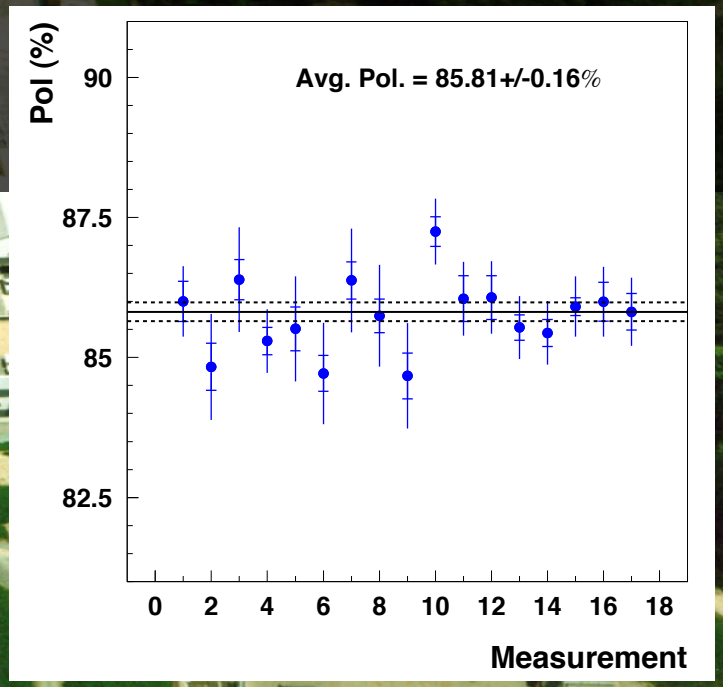


CEBAF at JLab

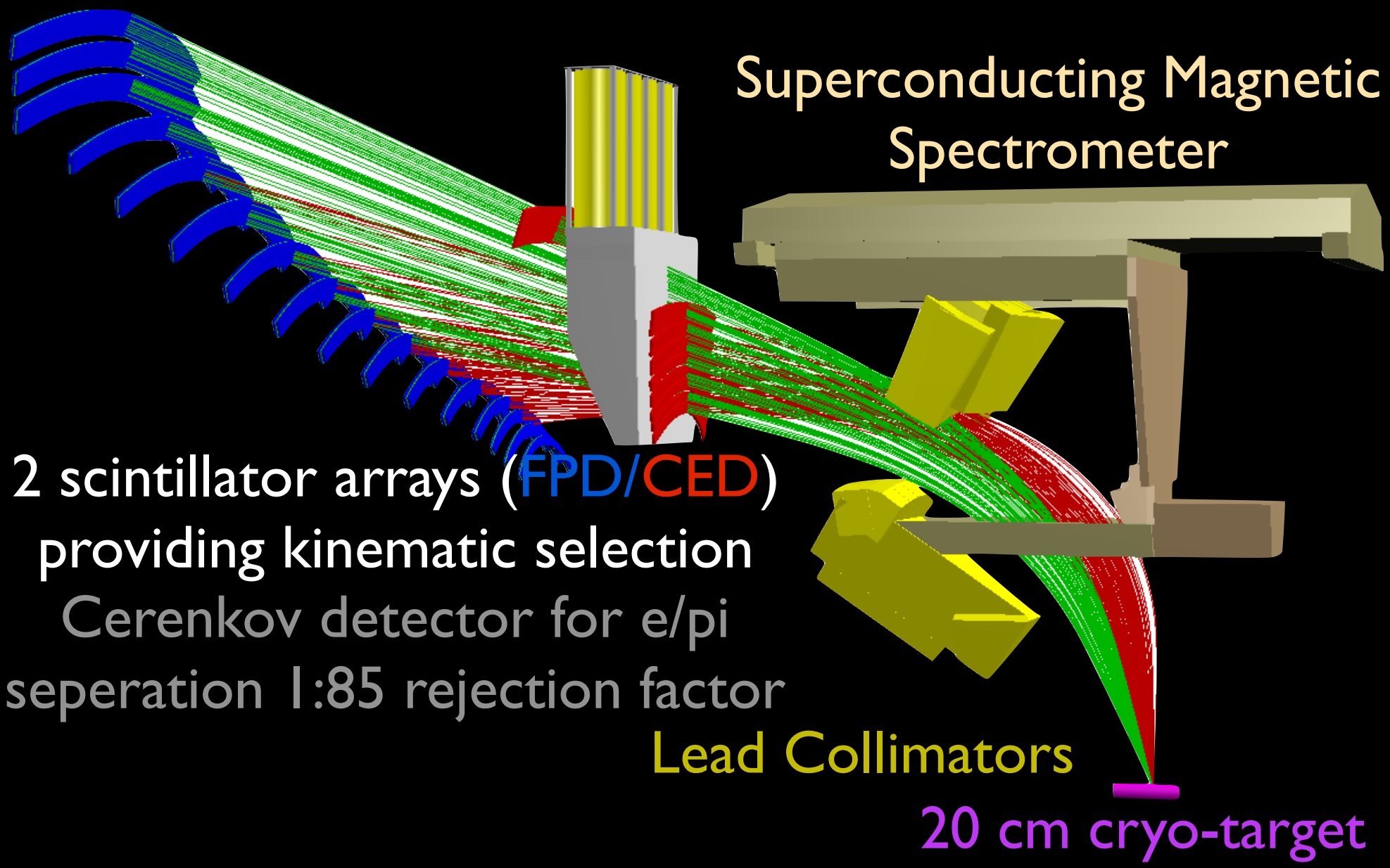
- Helicity changed every 1/30 sec (MPS).
- Form a pseudo-random quartet structure in helicity (+--+ or -++-).
- Excellent "parity quality" with active charge and position feedback:

  $A_q < 0.3$ ppm, $\Delta(x,y) < 20$ nm, $\Delta\Theta_{(x,y)} < 1$ nrad, $\Delta E < 3$ eV
- Beam Polarization 85.8%



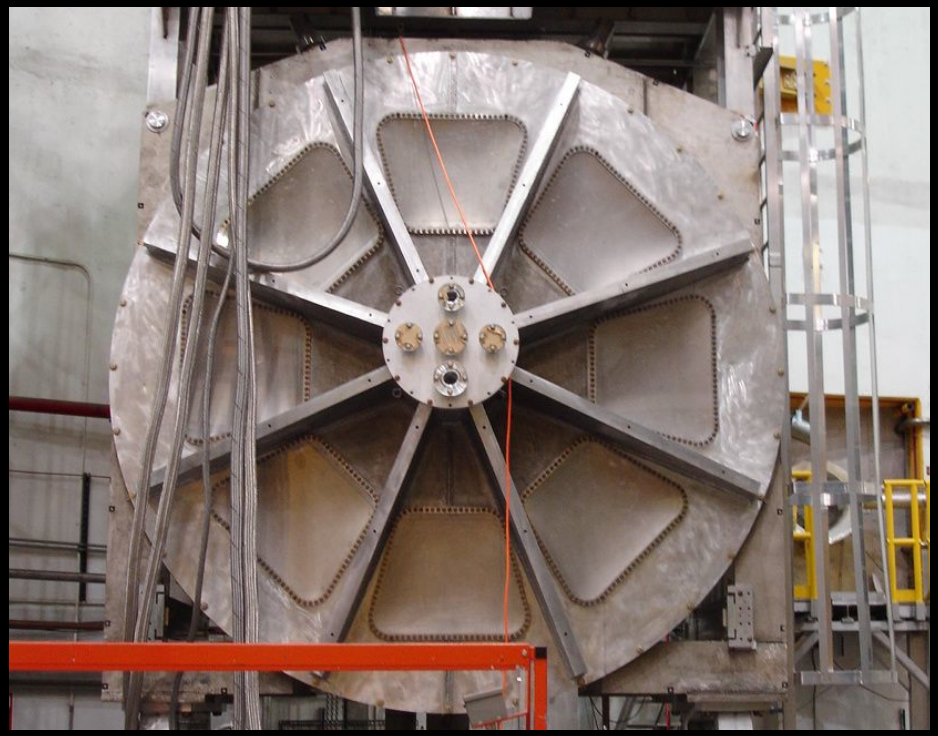


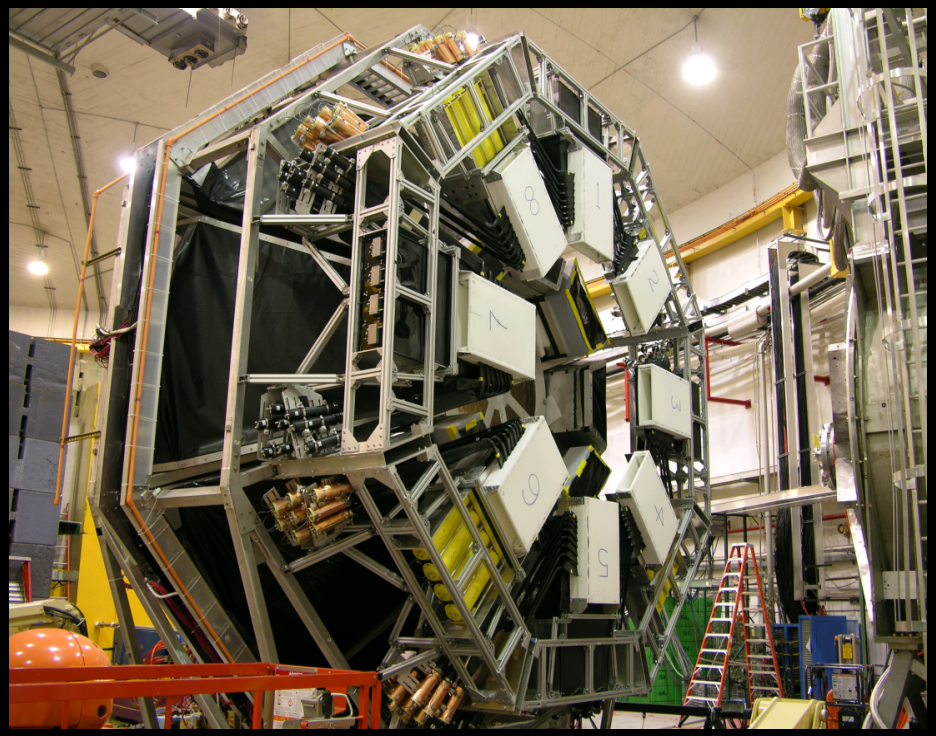
Detection scheme

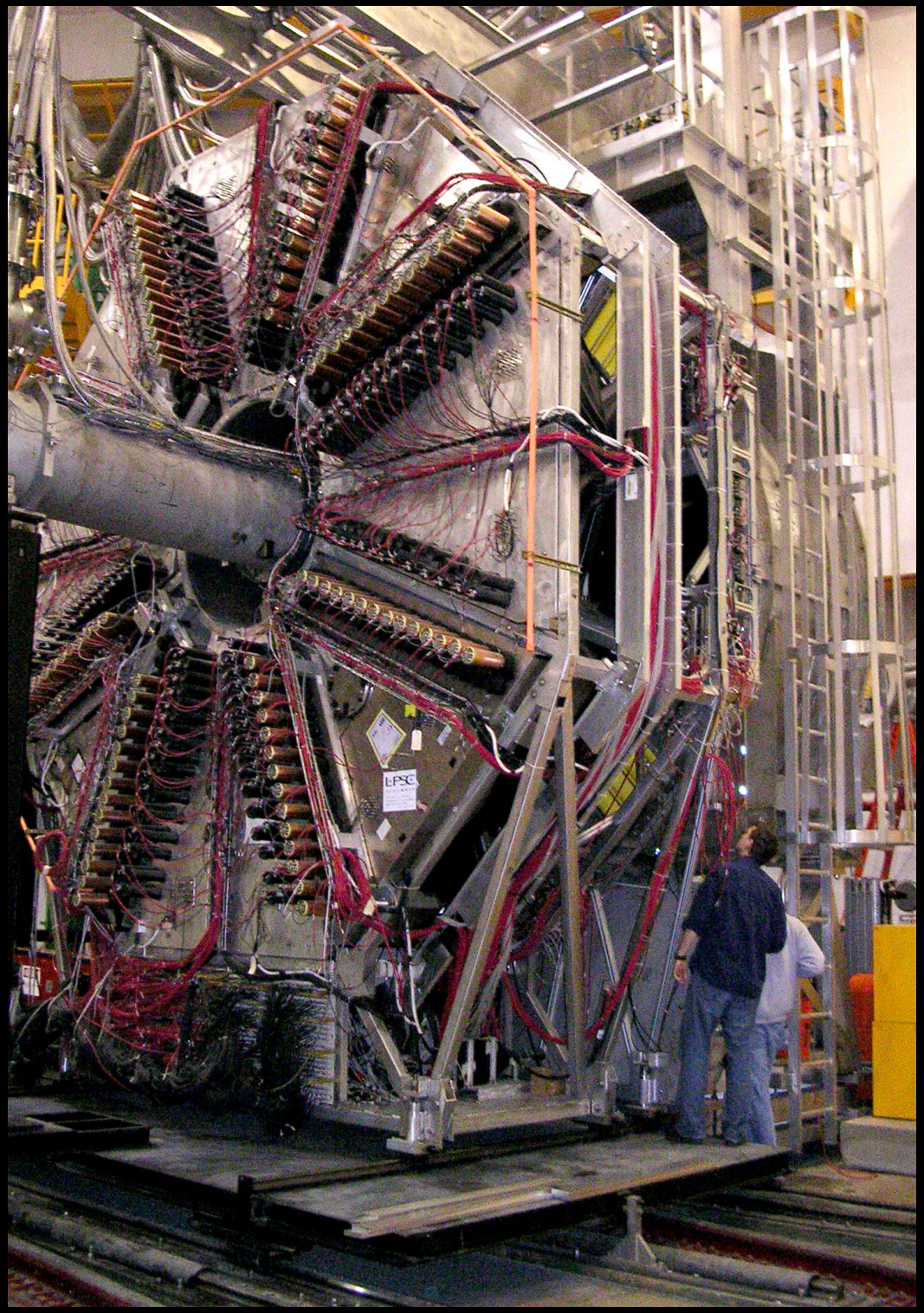


2 scintillator arrays (FPD/CED) providing kinematic selection

Cerenkov detector for e/pi seperation 1:85 rejection factor

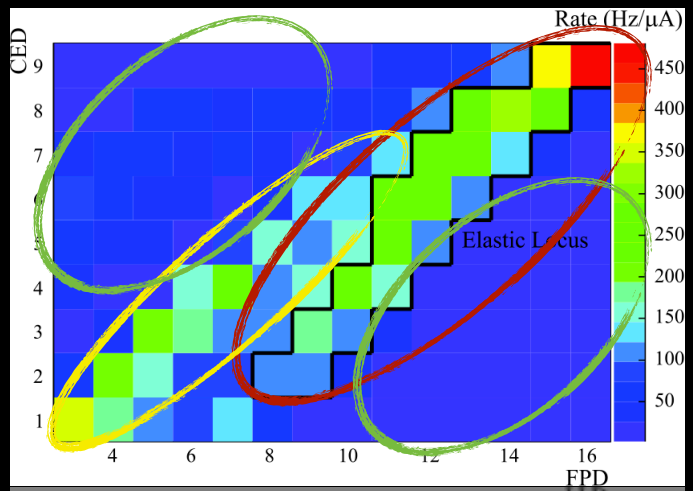




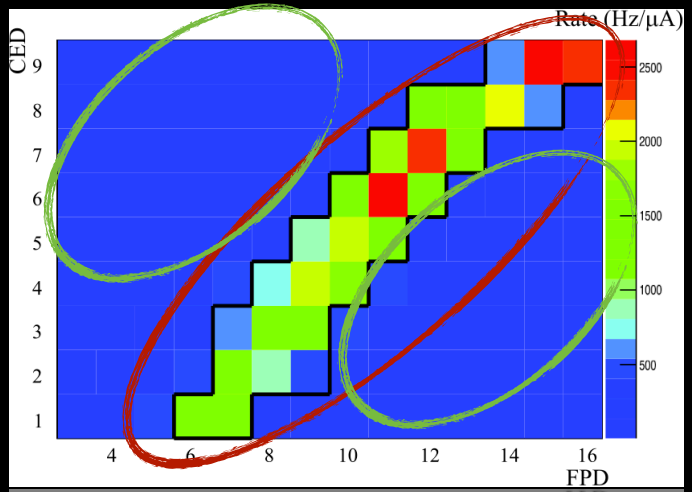

LPSC

Electron Yields

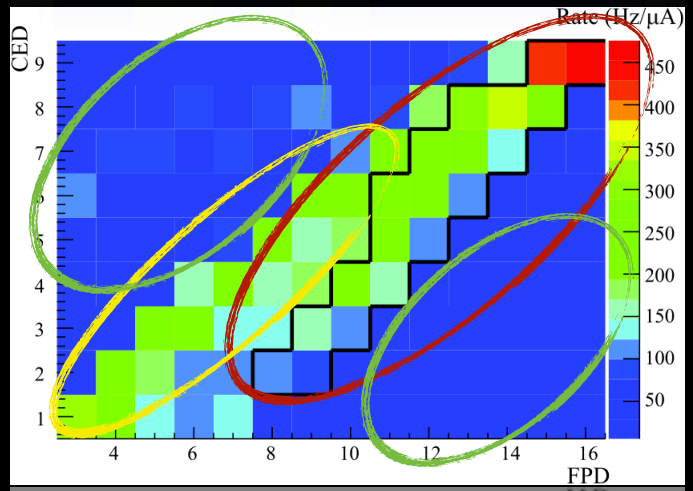
LH2, 687 MeV



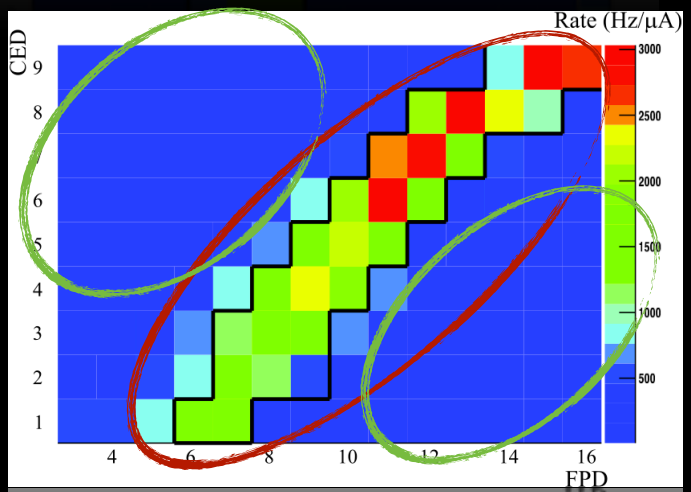
LH2, 362



LD2, 687 MeV



LD2, 362 MeV



Elastic

Inelastic

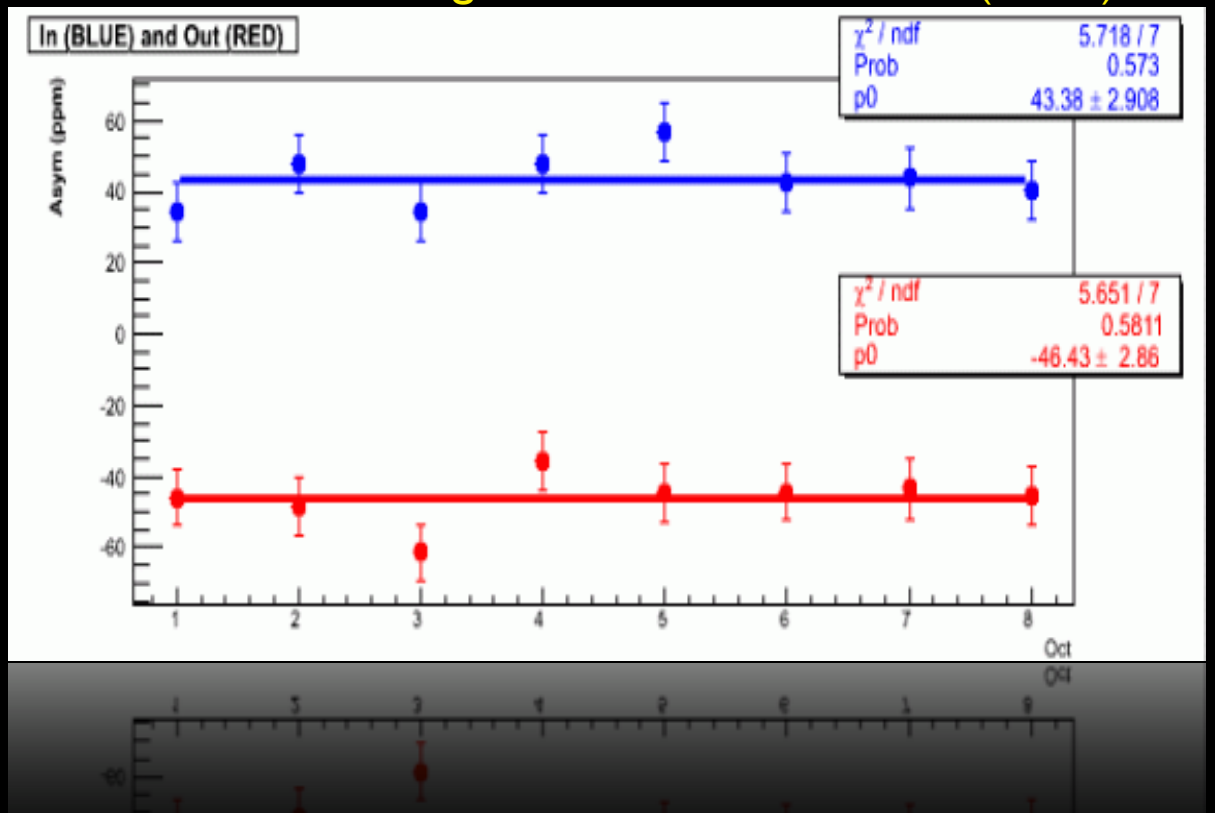
Background

Asymmetries

Each psuedo-random quartet in each cell in each octant,

$$A_{meas} = \frac{Y_+ - Y_- - Y_- + Y_+}{Y_+ + Y_- + Y_- + Y_+}$$

Elastic locus average for each octant, IHWP (H687)



Insertable half waveplate allows manual control of asymmetry sign for systematics control.

~100M quartets collected for each data set

Analysis Strategy

H, D Raw Asymmetries, A_{meas}

Instrumental & Beam corrections:
Helicity-correlated beam properties
Electronic Deadtime/Randoms
Beam polarization

Background corrections:
Dilution Factors
Backgrounds from target
Pion Contamination

Unblinding

LH2 A_{phys} | LD2 A_{phys}

→

Forward angle results
$G_E^s+\eta G_M^s$

Q^2 Determination

Radiative Corrections

Electromagnetic Form Factors

↓

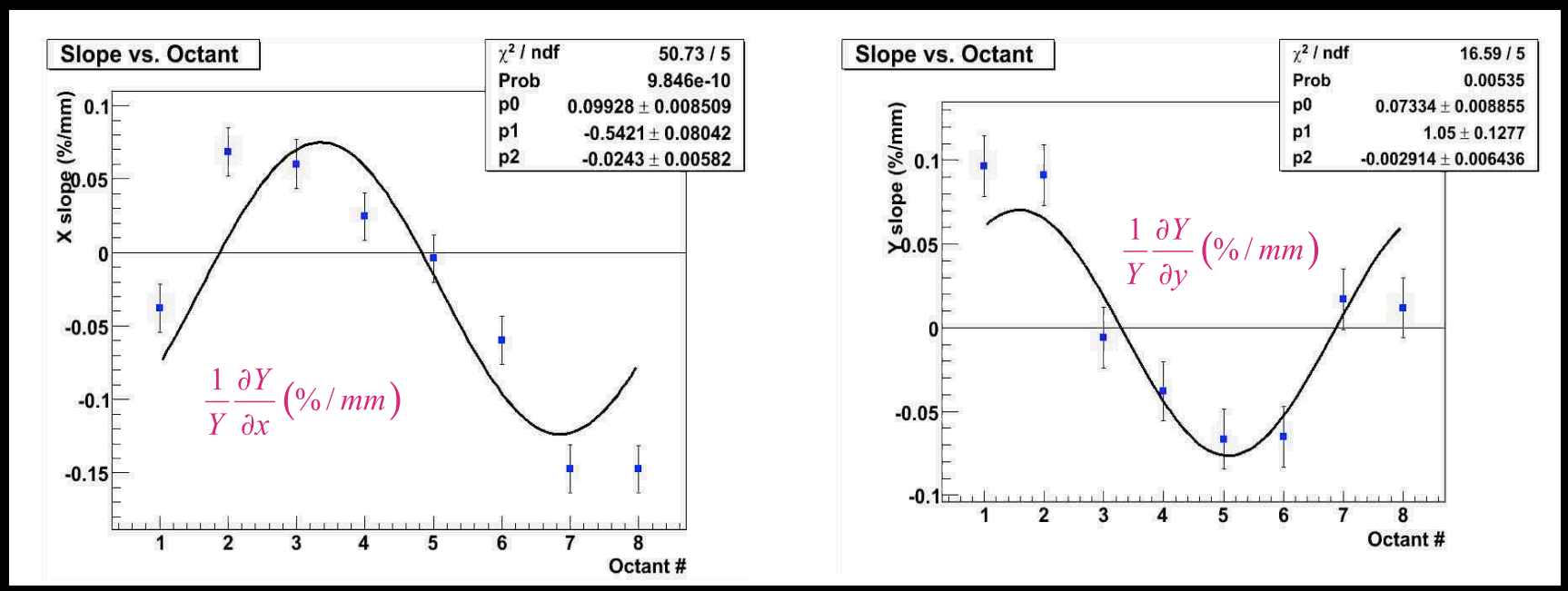
G_E^s G_M^s G_A^e

Instrumental Corrections

Helicity-correlated beam false asymmetries ~ 0.1 ppm

$$A_{corr} = A_{meas} + A_{false} \approx A_{meas} + \frac{1}{2 < Y >} \Sigma_i \frac{dY}{dP_i} \delta_{P_i}$$

Cross check with sensitivities determined from natural beam motion and from deliberate 'coil-pulsing' run



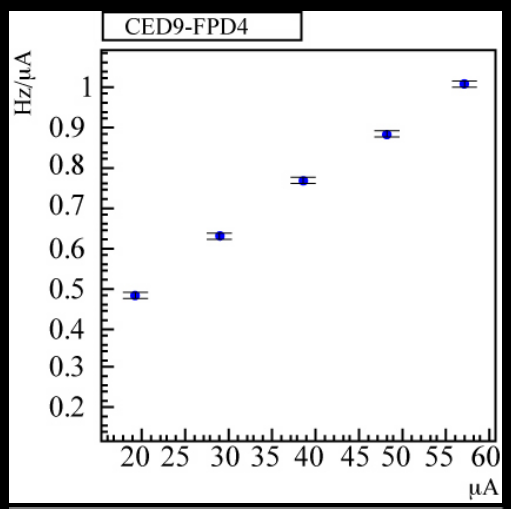
Instrumental Corrections

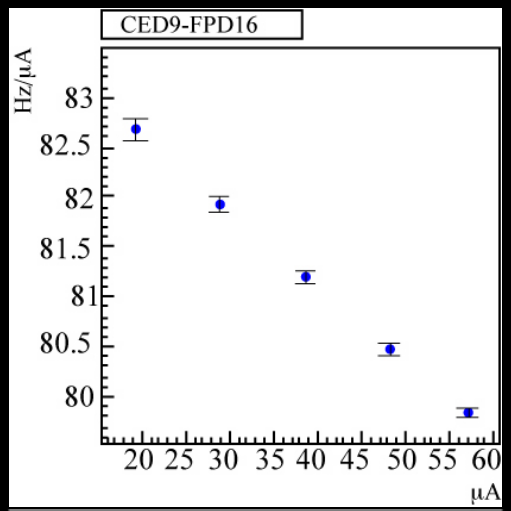
Electronic Deadtime/Randoms

- Direct (out-of-time) randoms measurement

- Deadtime determined through simulated electronics chain, measured singles asymmetries and studied via current scans

- Multi-hit effects are small





Simulated full electronics chain and studied via current scans

LH2, 687 MeV, 60 μA	~7%
LH2, 362 MeV, 60 μA	~6%
LD2, 687 MeV, 20 μA	~9%
LD2, 362 MeV, 35 μA	~13%

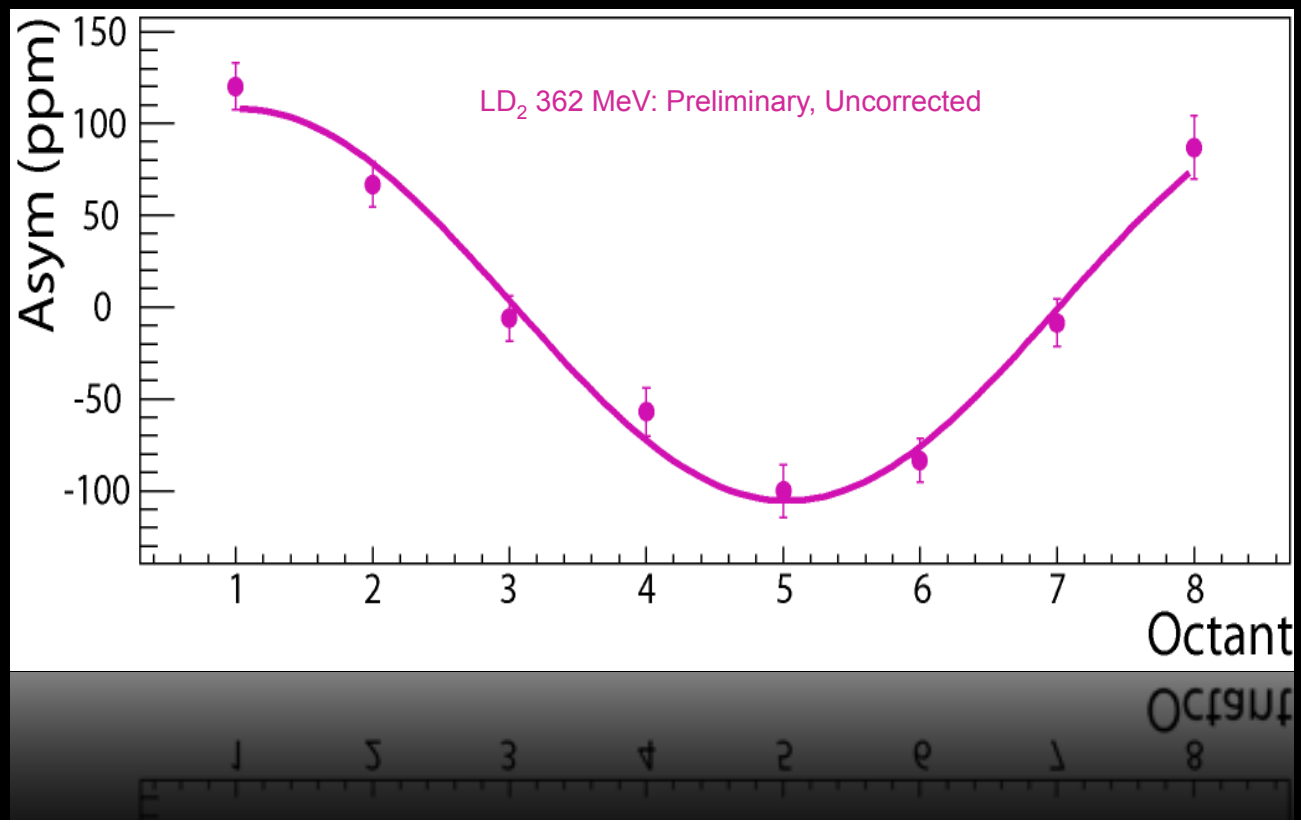
Instrumental Corrections

Beam polarization

$$A_{el} = \frac{1}{P} \times A_{meas} + K_s$$

1/P = 1/.858 +/- 0.02 (ppm)

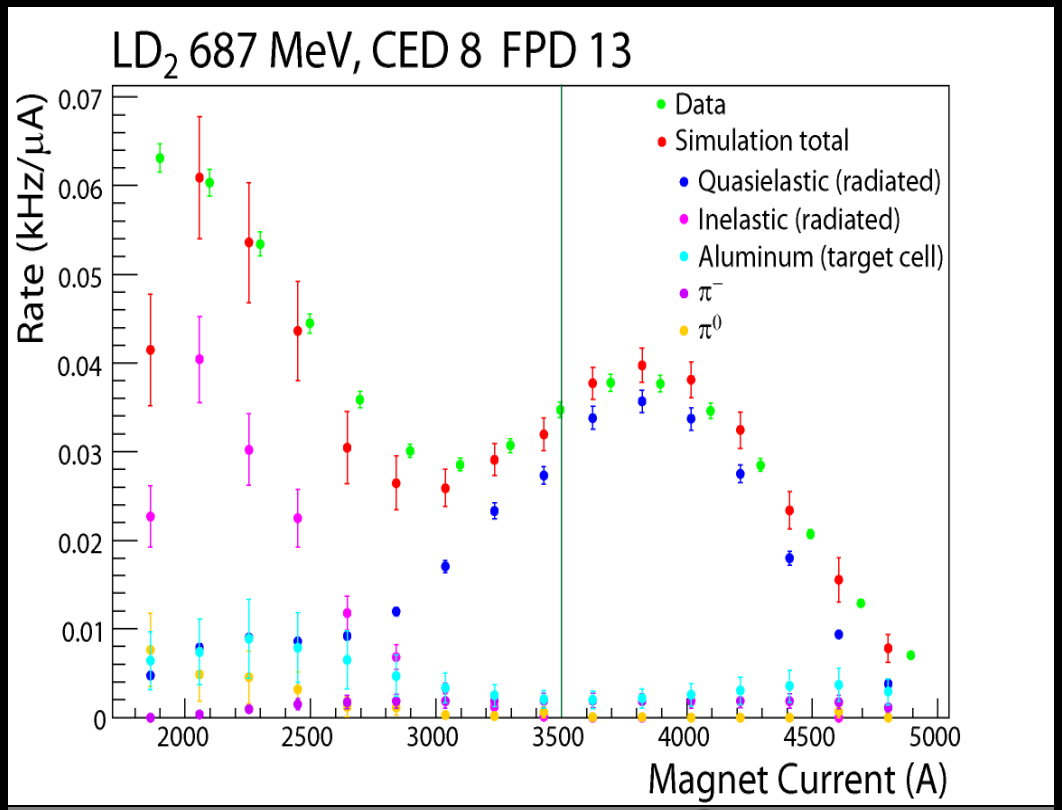
K_s: correction for transverse beam component <.04 ppm



Runs with transverse electron spin were take for all target/energy combinations.

Backgrounds: Field Scans

Use simulation *shapes* to help determine dilution factors



Tar	Q^2 GeV^2	f_{al}	f_{pi}	f_{other}	f_{total}
H	0.22	0.129 ± 0.064	0 ± 0.001	0.003	0.132 ± 0.064
D	0.22	0.099 ± 0.050	0 ± 0.002	0.005	0.104 ± 0.050
H	0.628	0.110 ± 0.055	0 ± 0.001	0.023	0.133 ± 0.060
D	0.628	0.061 ± 0.031	0.04 ± 0.015	0.029	0.13 ± 0.045

$A_{pi/other}$~0

A_{Al}~A_D with 15% uncer.

f_{pi-} from t.o.f./Cer. studies

f_{Al} from empty target

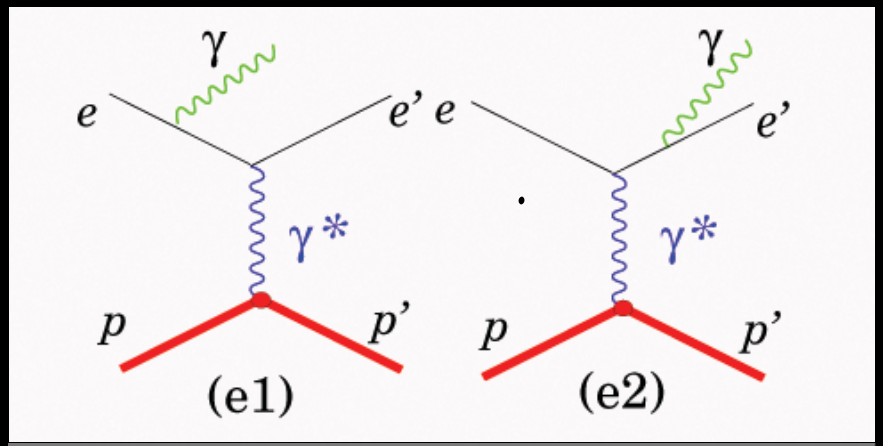
$$A_{el} = \frac{A_{meas} - f_{al}A_{Al} - f_{pi^-}A_{pi^-} - f_{other}A_{other}}{1 - f_{al} - f_{pi^-} - f_{other}}$$

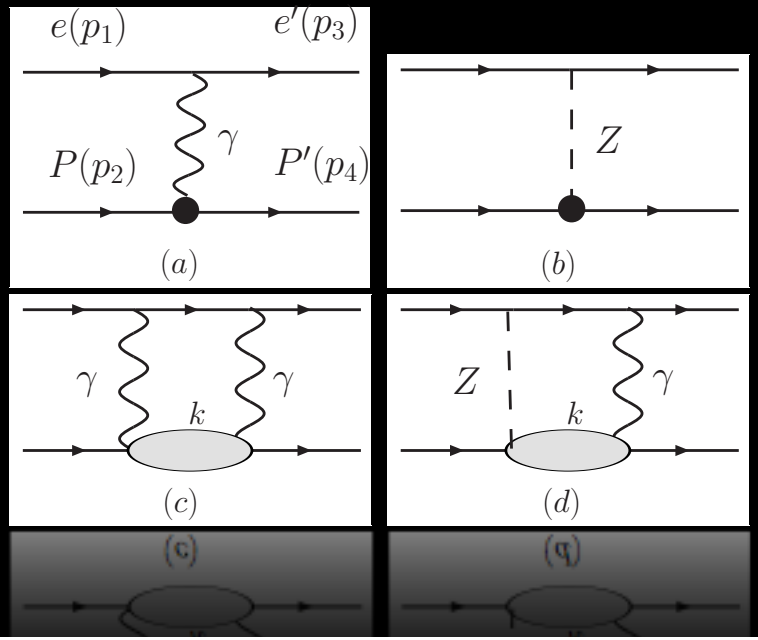
Ordinary Radiative effects

$$R_c = \frac{A_{tree}}{A_{RC}}$$

Found to be ~1.035 from simulation

Tsai 71





2-boson corrections (Arrington, Blunden, Melnitchouk, et al.; Zhou, Kao & Yang, priv. comm.) found to contribution less than .3 ppm

Systematics Summary

Background corrections

Point-to-point as well as global errors were determined for all asym. corrections

Target	Q^2 (GeV^2)	A_{meas} (ppm)	f	A_{el} (ppm)	ΔA_{corr} (ppm)
H	0.221	-9.72	0.13 ± 0.064	-9.22	$\pm 0.11 \pm 0.40$
D	0.221	-13.50	0.099 ± 0.050	-13.57	$\pm 0.02 \pm 0.08$
H	0.628	-36.9	0.11 ± 0.050	-37.0	$\pm 0.61 \pm 0.86$
D	0.628	-37.4	0.061 ± 0.031	-39.4	$\pm 0.48 \pm 0.23$

Additional Instrumentation corrections

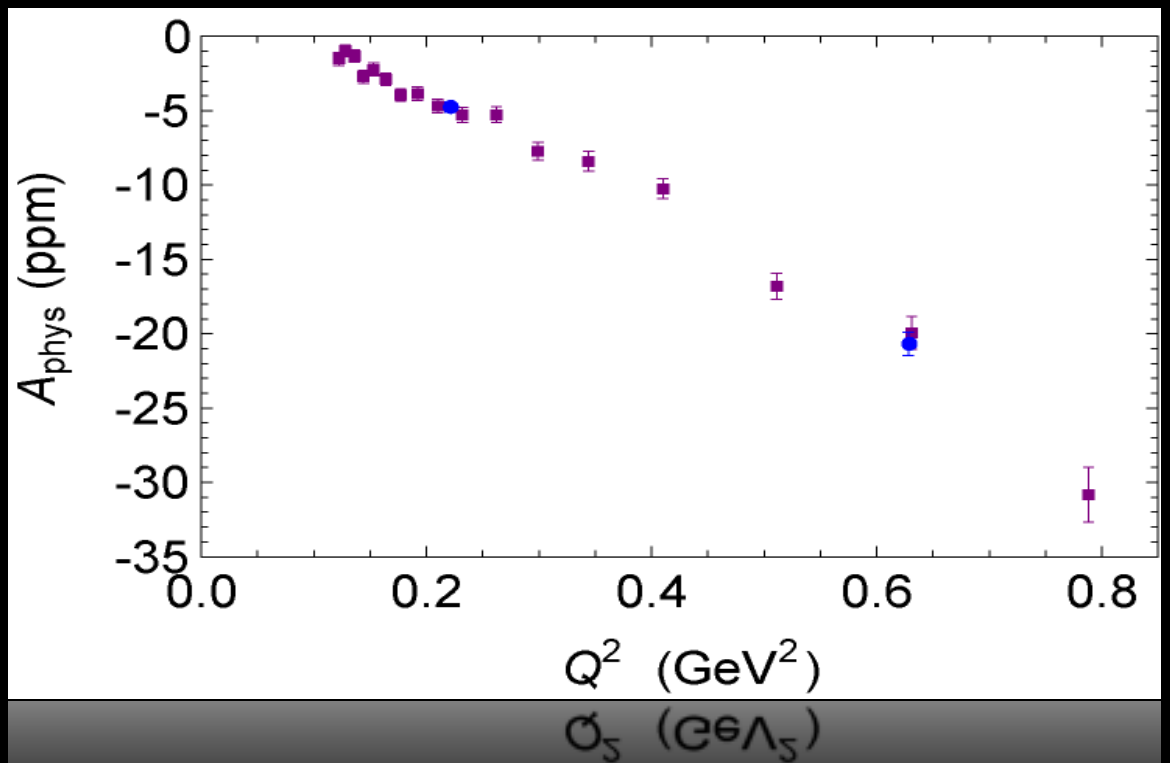
The final asymmetry includes statistical, pt-pt, and global error terms

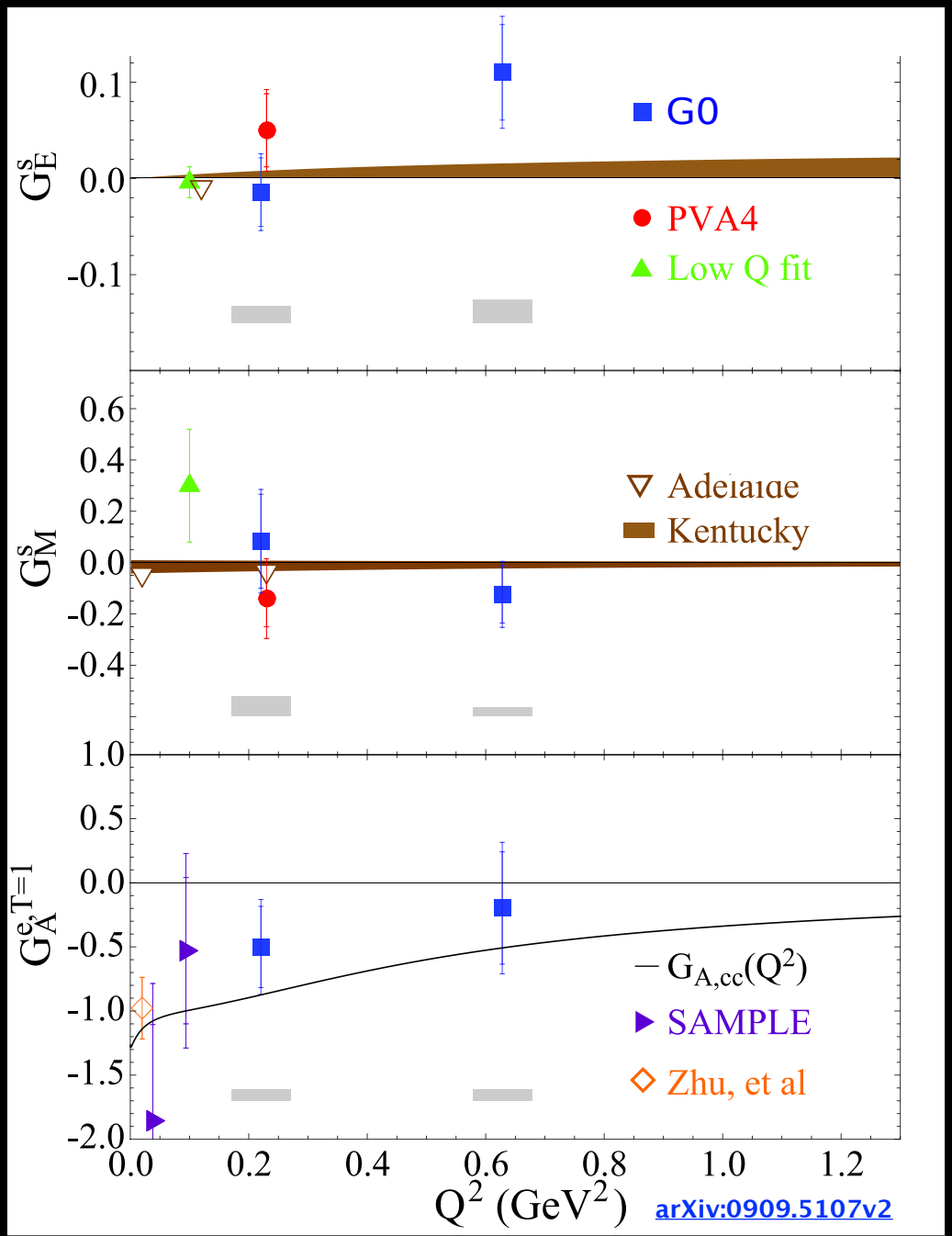
Rate (ppm)	Other (ppm)	Beam polarization	EM radiative	A_{phys} (ppm)
$-0.31 \pm 0.08 \pm 0$	$0.22 \pm 0.08 \pm 0.01$	$(1/0.858) \pm 0.02 \pm 0.01$	$1.037 \pm 0.002 \pm 0$	$-11.25 \pm 0.86 \pm 0.27 \pm 0.43$
$-0.58 \pm 0.21 \pm 0$	$0.06 \pm 0.10 \pm 0.01$	$(1/0.858) \pm 0.02 \pm 0.01$	$1.032 \pm 0.004 \pm 0$	$-16.93 \pm 0.81 \pm 0.41 \pm 0.21$
$-1.28 \pm 0.18 \pm 0$	$0.29 \pm 0.11 \pm 0.01$	$(1/0.858) \pm 0.01 \pm 0.01$	$1.037 \pm 0.002 \pm 0$	$-45.9 \pm 2.4 \pm 0.8 \pm 1.0$
$-7.0 \pm 1.8 \pm 0$	$0.34 \pm 0.21 \pm 0.01$	$(1/0.858) \pm 0.01 \pm 0.01$	$1.034 \pm 0.004 \pm 0$	$-55.5 \pm 3.3 \pm 2.0 \pm 0.7$

Additive Multiplicative

In addition

- Starting from asymmetries, need
  deuterium model (Schiavilla, priv. comm.)
  electromagnetic form factors (Kelly PRC **70** (2004))
- Interpolation of G0 forward angle measurement (D. S. Armstrong et al., PRL **95**, 092001)





Results

Error bars: statistical and statistical plus point-to-point systematic; shaded bars show global systematic uncertainties (for G^0 points).

For G_E^s and G_M^s, an extraction at $Q^2 = 0.1$ GeV^2 from Liu as well as the results of the PVA4 (Mainz) experiment are shown.

Note: PVA4 assumes GeA value based on Zhu and dipole

Lattice calculations from Adelaide and Kentucky groups are shown.

For G_A^e, results from the SAMPLE experiment are shown together with the calculation of Zhu, et al.

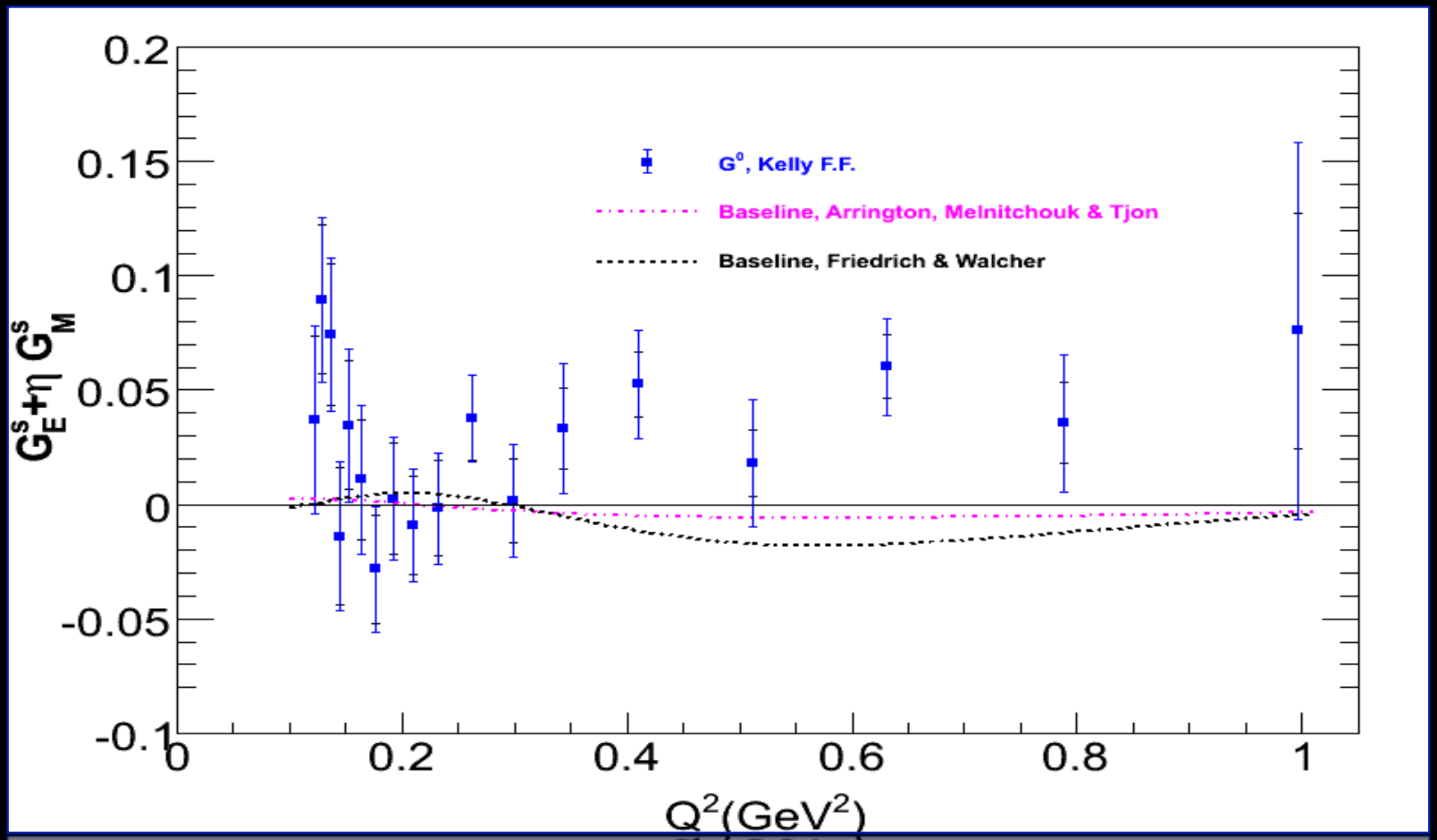
Conclusions

- We have measured backward angle parity-violating asymmetries in elastic electron-proton and quasi-elastic electron-deuteron scattering at $Q^2 = 0.221$ and 0.628 GeV^2.
- From the asymmetries we have determined G_E^s , G_M^s and G_A^e which indicate that the strange quark contributions to the nucleon form factors are <10%, and provide the first information on the Q^2 dependence of G_A^e.
- Additional forward angle experiments at $Q^2 = 0.63$ GeV^2 are planned at Jefferson Lab and Mainz to further improve the precision of these determinations.

-Thank you

Backup Slides

Forward Angle Result

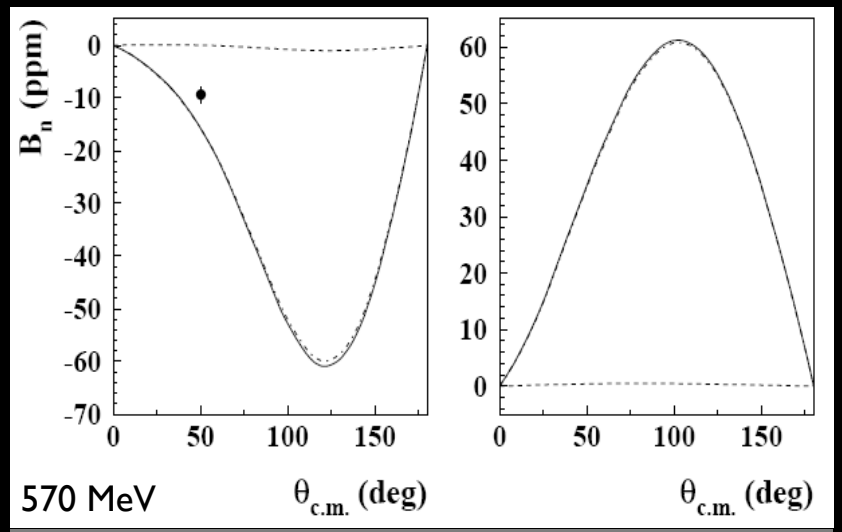


Transverse Asymmetries

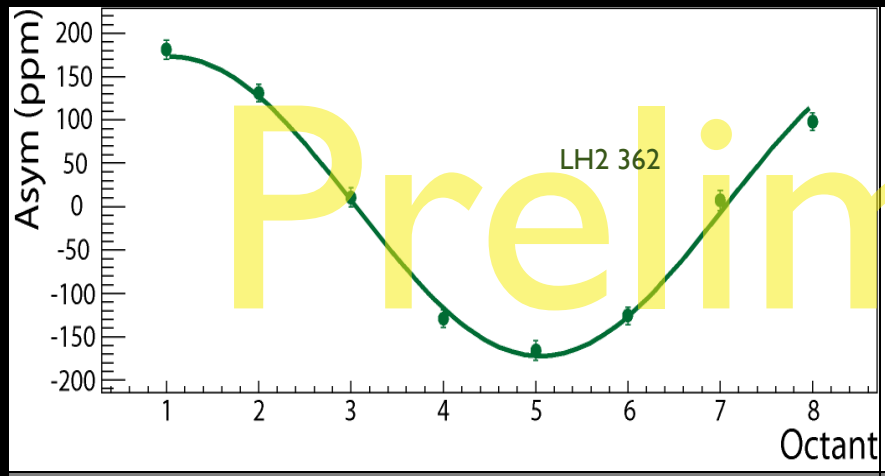
Pasquini & Vanderhaeghen PRC **70** (2004) 045206

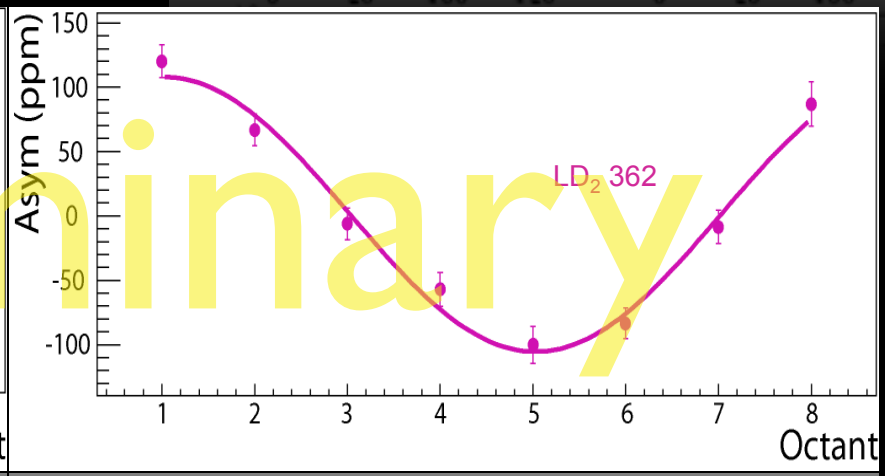
- Elastic scattering:
  Second order e.m. effects generate single-spin asymmetries

$$A_n \propto \frac{M_\gamma \; Im M_{\gamma\gamma}}{|M_\gamma|^2}$$



•Real part of $M_{2\gamma}$ related to important contribution to longitudinal scattering: G_E/G_M ratio



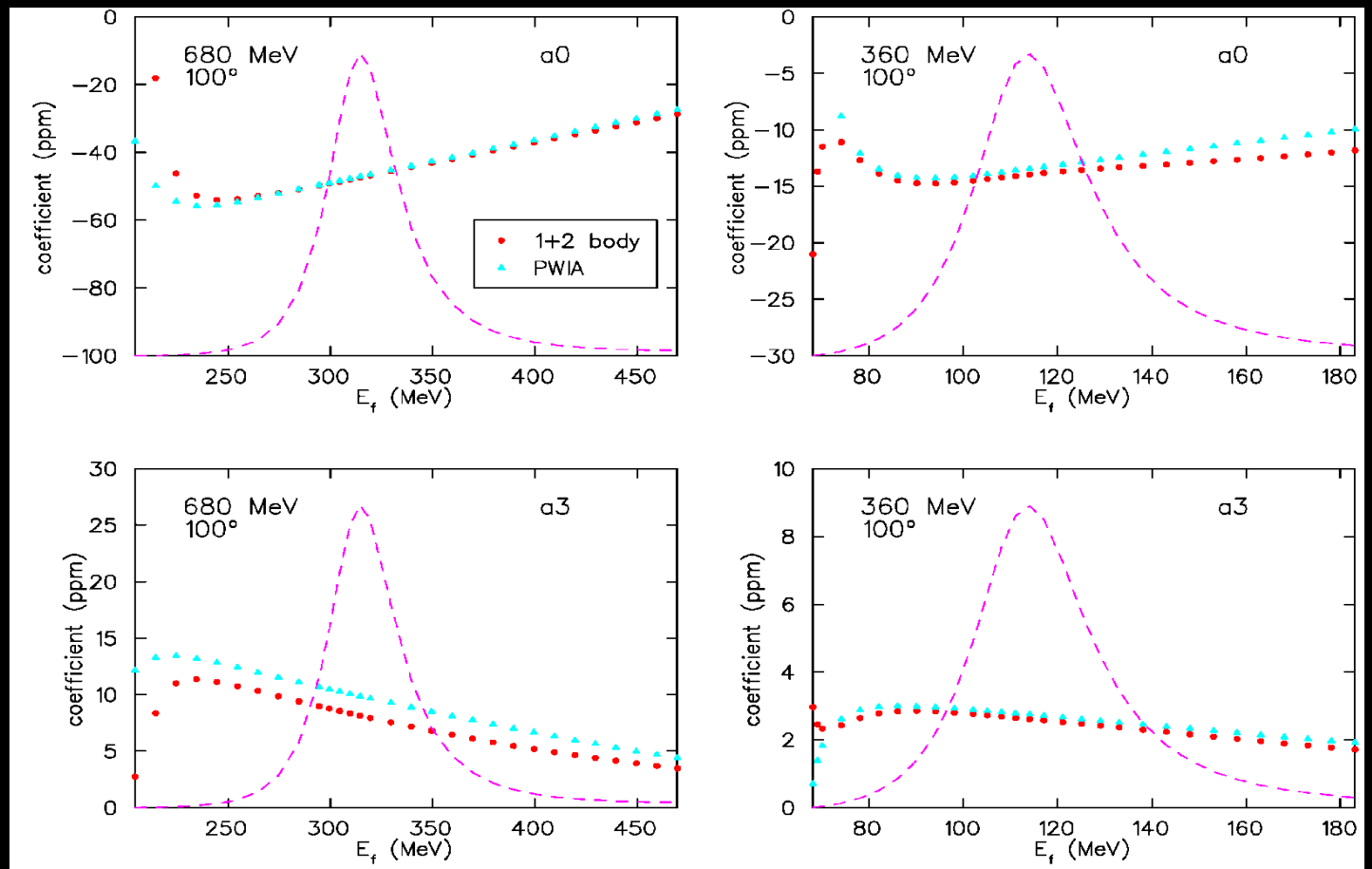


Preliminary

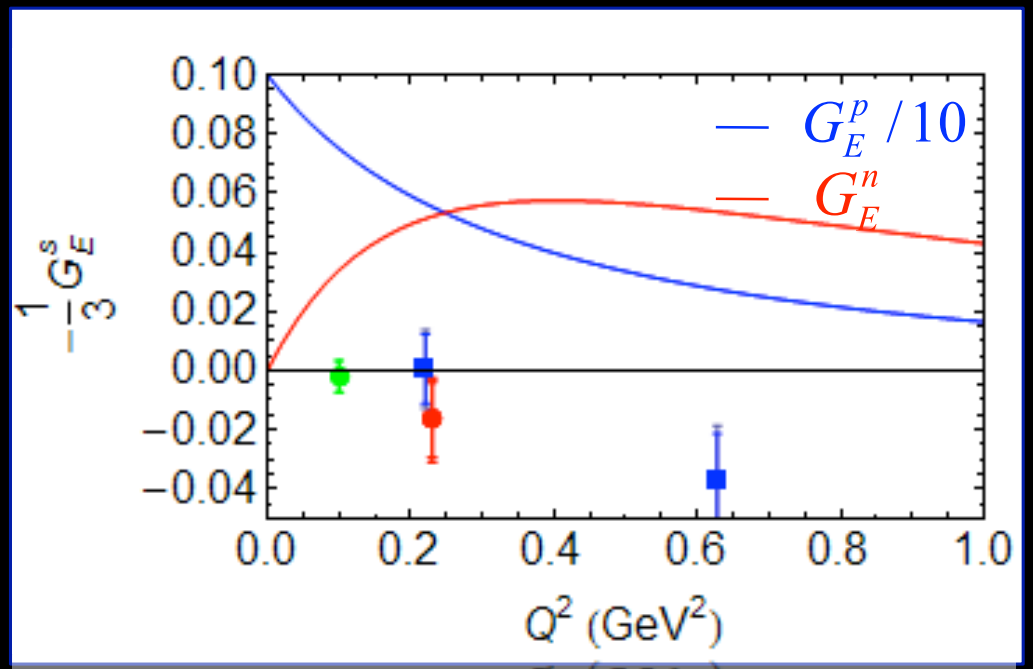
Deuterium Model

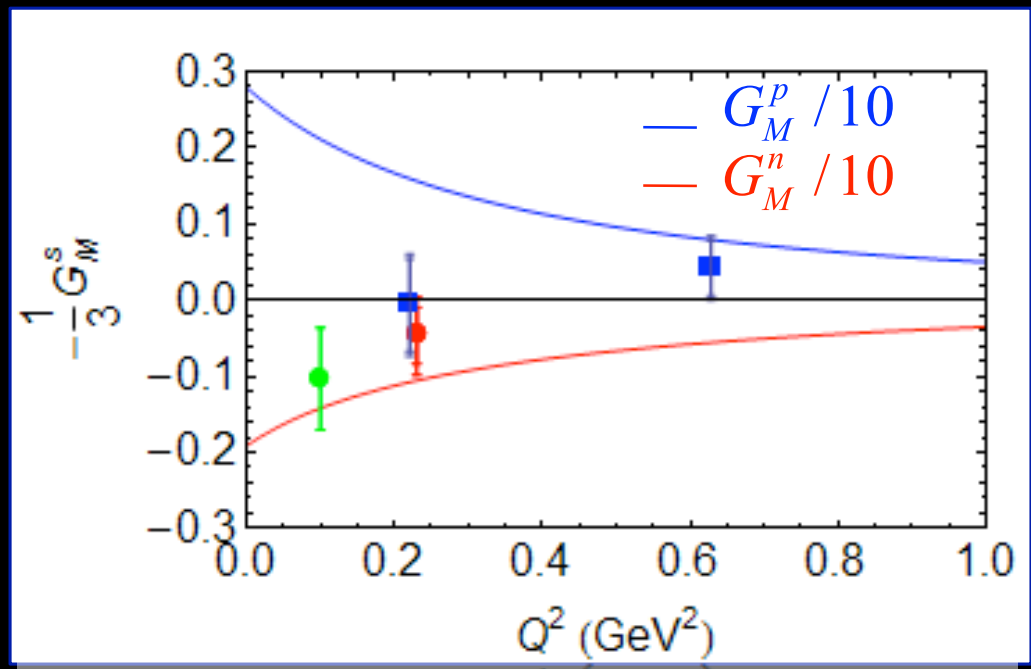
$$A_{phys} = a_0 + a_1 G_E^s + a_2 G_M^s + a_3 G_A^e$$

- Calculation from R. Schiavilla

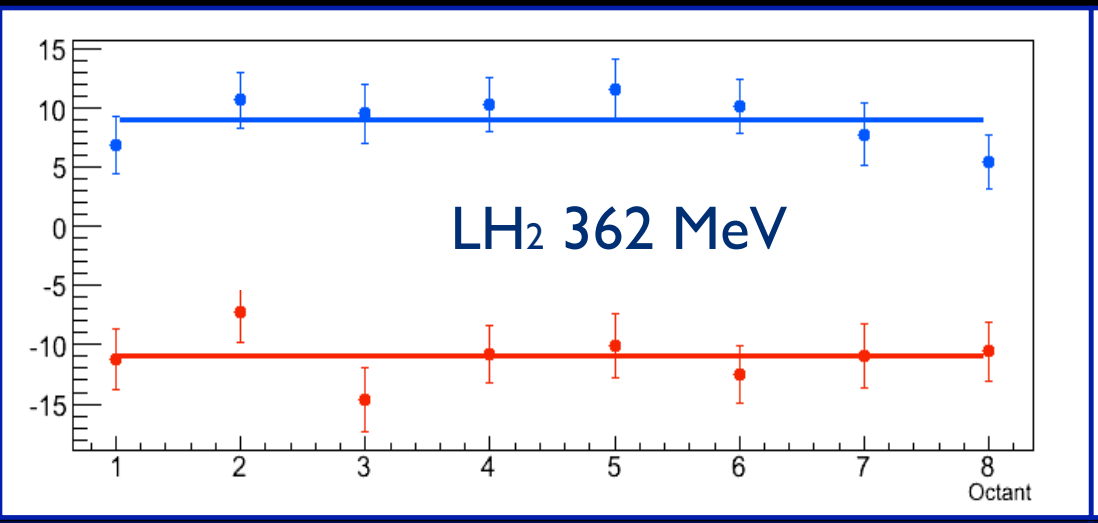


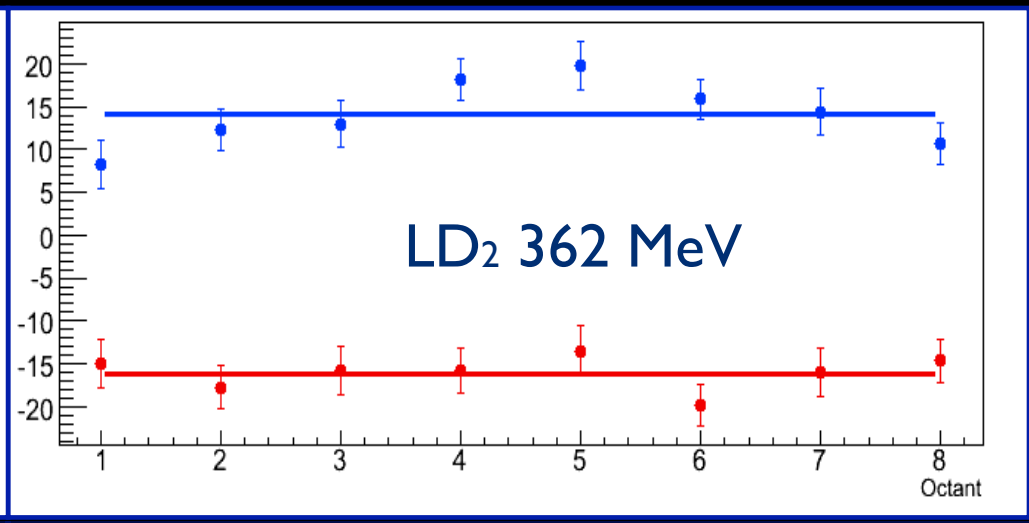
Contributions to Overall Form Factors

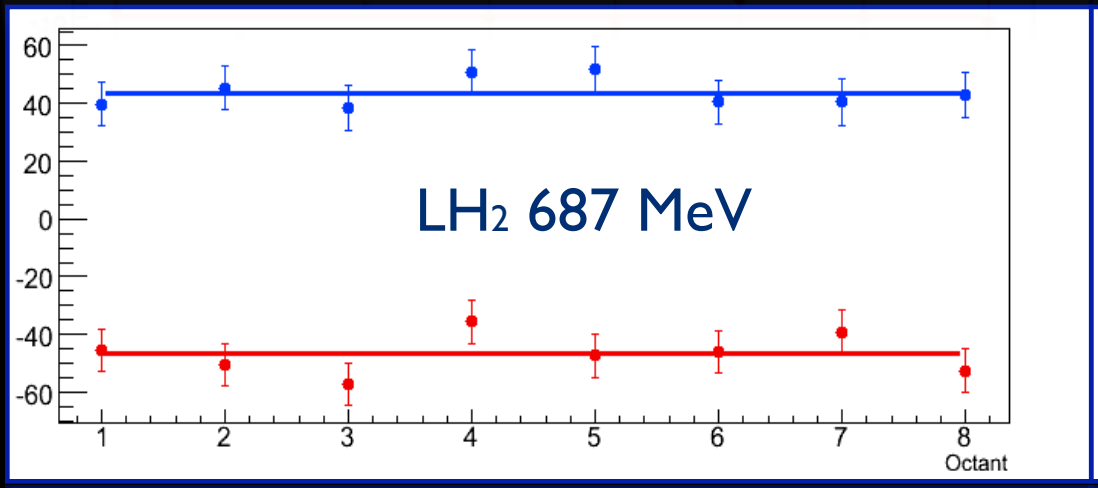


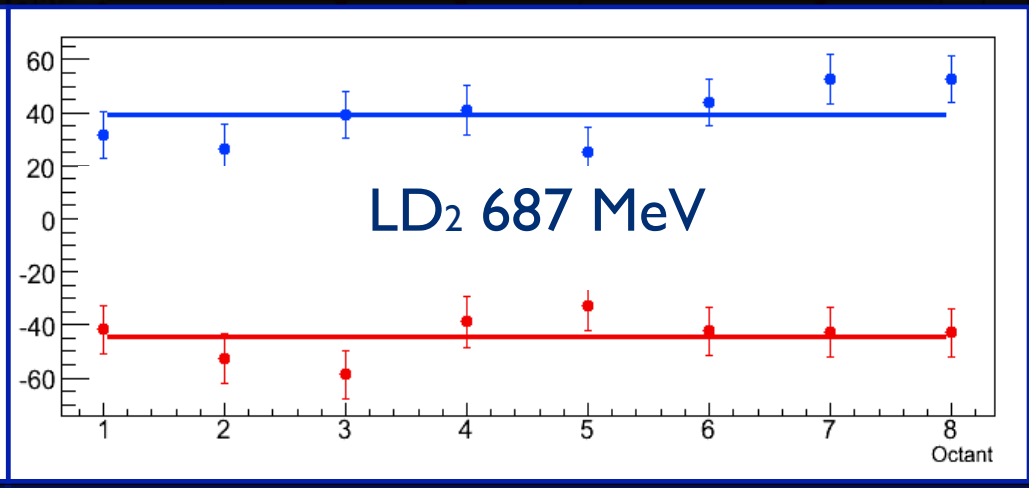


Measured Asymmetries









Asymmetry Uncertainties

• Hydrogen, 687 MeV	Value (ppm)	Stat (ppm)	Sys Pt (ppm)	Sys Gl (ppm)	Total (ppm)
Measured Asymmetry	-38.14	2.43			
Background Asymmetry	-38.27		0.40		
Dilution Correction			0.47	0.52	
Transverse Correction				0.008	
Rate Correction	-38.39		0.17		
Beam Polarization	-44.76		0.52	0.53	
EM Radiative Correction	-46.14		0.16		
Physics Asymmetry	-46.14	2.43	0.84	0.75	2.68

Asymmetry Uncertainties

• 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

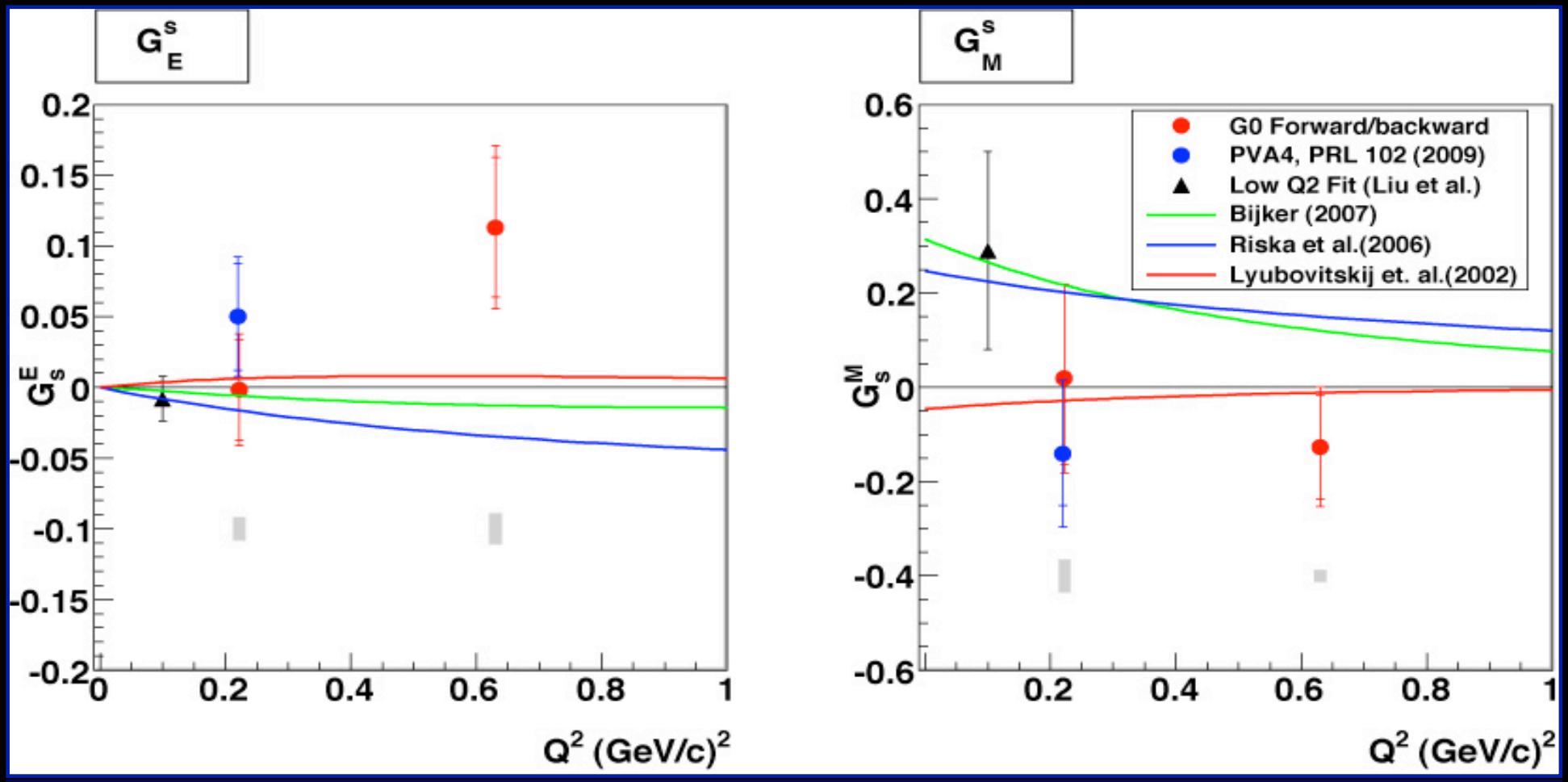
Asymmetry Uncertainties

• Hydrogen, 362 MeV	Value (ppm)	Stat (ppm)	Sys Pt (ppm)	Sys Gl (ppm)	Total (ppm)
Measured Asymmetry	-9.941	0.872			
Background Asymmetry	-9.441		0.034		
Dilution Correction			0.109	0.362	
Transverse Correction			0.025	0.008	
Rate Correction	-9.444		0.090		
Beam Polarization	-11.010		0.223	0.132	
EM Radiative Correction	-11.416		0.022	0.000	
Physics Asymmetry	-11.416	0.872	0.268	0.385	0.990

Asymmetry Uncertainties

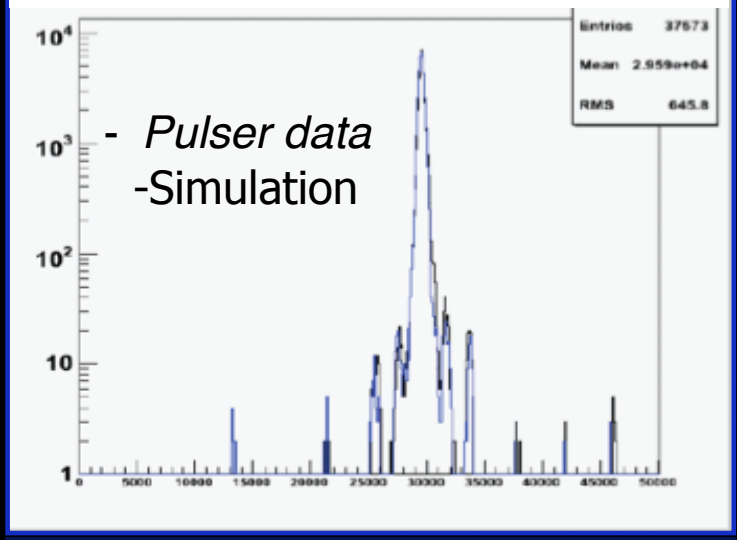
• Deuterium, 362 MeV	Value (ppm)	Stat (ppm)	Sys Pt (ppm)	Sys Gl (ppm)	Total (ppm)
Measured Asymmetry	-14.047	0.813			
Background Asymmetry	-14.114				
Dilution Correction			0.020		
Transverse Correction			0.038		
Rate Correction	-14.152		0.232		
Beam Polarization	-16.498		0.331	0.197	
EM Radiative Correction	-17.018		0.059		
Physics Asymmetry	-17.018	0.813	0.411	0.197	0.932

Comparison to theory

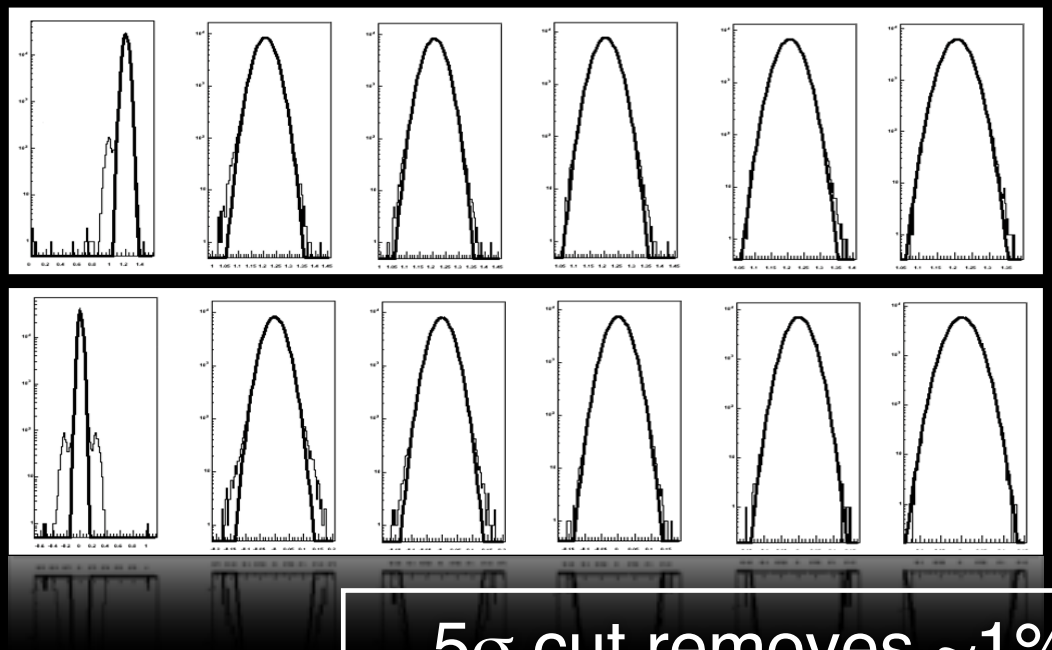


Scaler Counting issue

- An occasional bit drop in a North American scaler was traced down to trigger electronics. At high rates: LD2 target at 362 MeV. This was fixed during the run (Jan07)
- Problem blind to helicity.



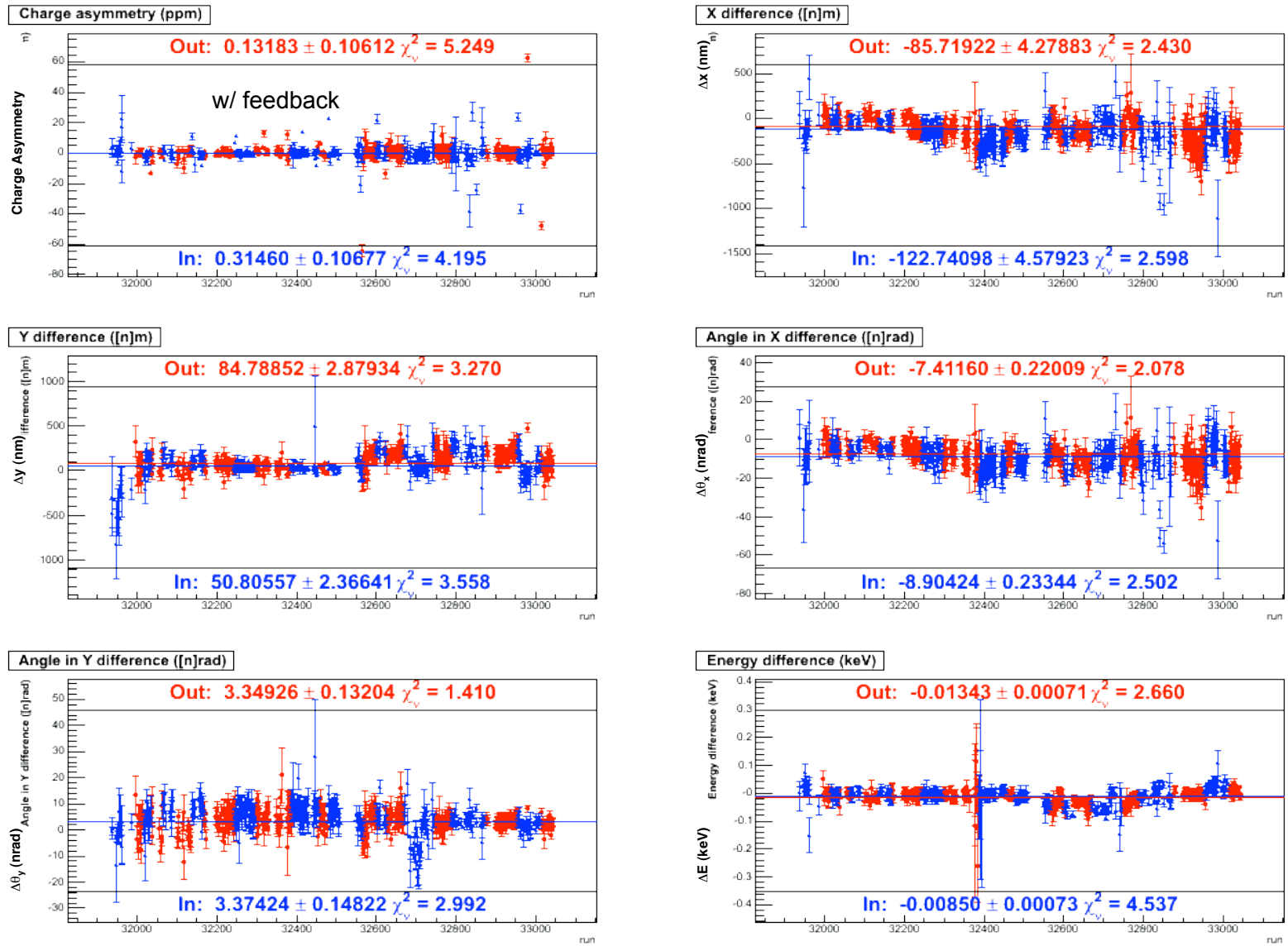
Uncut 7σ 6σ 5σ 4σ 3σ



- Test by cutting data; compare with French octants.
- Confirmed by unchanged asymmetry

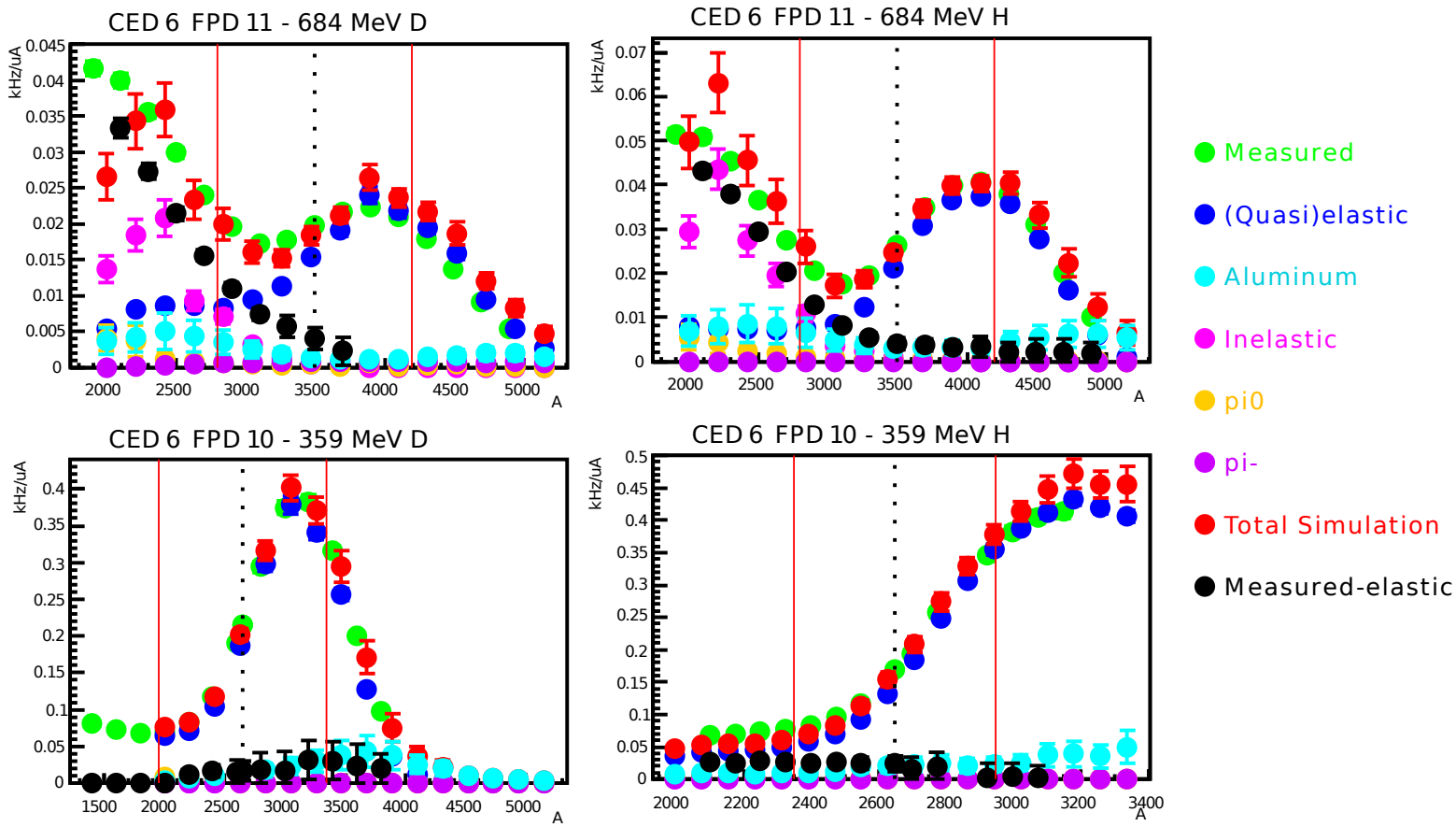
5σ cut removes ~1% of our data for 362MeV LD2,which is the worst case!

Beam Properties



$$A_{corr} = A_{meas} + A_{false} \approx A_{meas} + \frac{1}{2 < Y >} \Sigma_i \frac{dY}{dP_i} \delta_{P_i}$$

Field Scan


CED 6 FPD 11 - 684 MeV D
CED 6 FPD 11 - 684 MeV H
CED 6 FPD 10 - 359 MeV D
CED 6 FPD 10 - 359 MeV H
kHz/uA
A
Measured
(Quasi)elastic
Aluminum
Inelastic
pi0
pi-
Total Simulation
Measured-elastic