The G0 Backward Angle Experiment

D. Beck
May 2009

- Parity-violating electron scattering from the nucleon
  - Longitudinal beam polarization
    - Strange quark contribution to elastic form factors
    - Axial-vector N-Δ transition
    - Weak interaction contribution to pion photoproduction
- Single-spin asymmetries
  - Transverse beam polarization
    - 2γ contribution to elastic scattering
    - (Single spin asymmetry in pion photoproduction)

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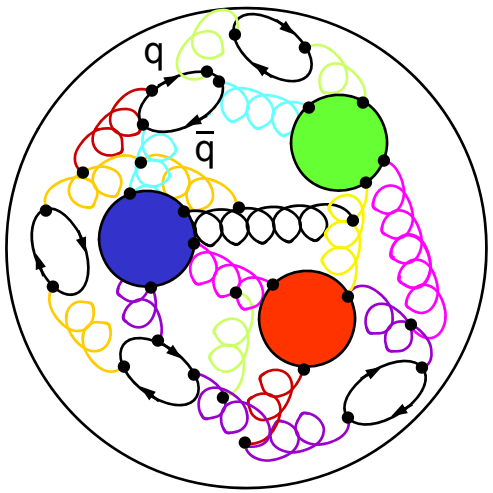
Hadron Structure

- Proton is both ordinary and extraordinary object
  - 50% of mass of visible universe
  - masses of constituents ~ 1% of total mass

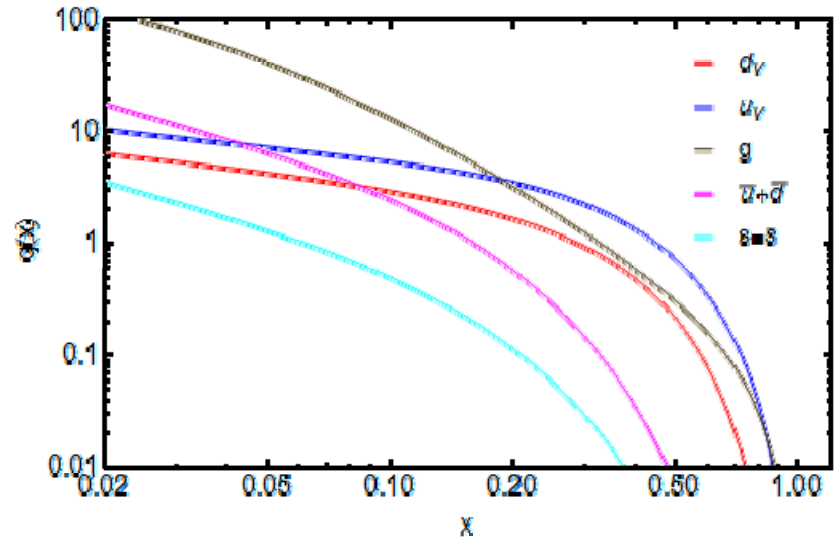


- What is it made of?
  - valence quarks carry baryon number
  - sea of gluons
  - and associated quark-antiquark pairs
    - analog of Lamb shift physics
  - very complicated because
    - strong coupling ●
    - gluons interact with each other

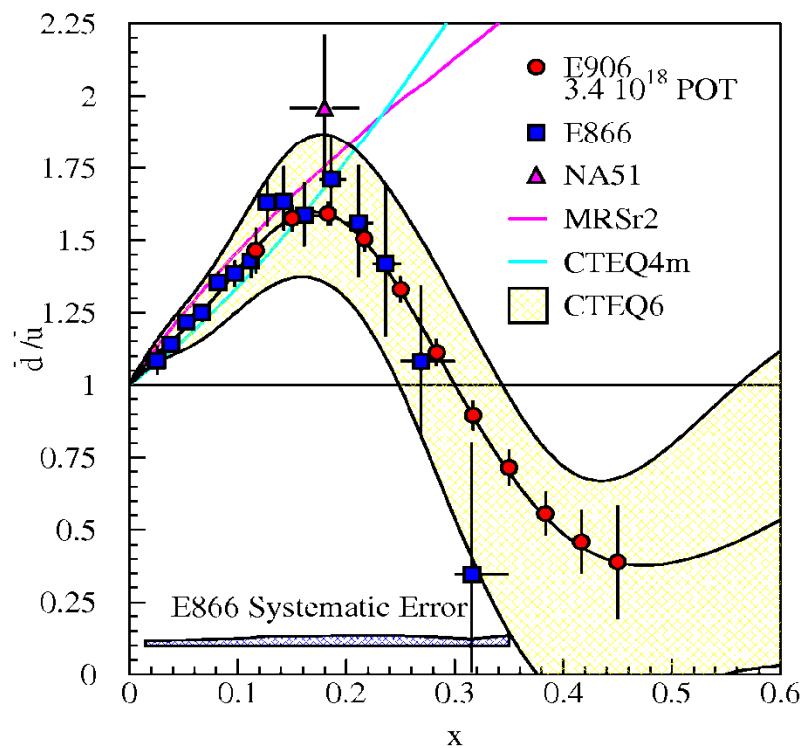
  → many-body physics with virtual particles

What Do We Know About the Sea?

- sea partons dominate in low-x region
  - CTEQ6m



- u and d quarks in sea have non-trivial structure

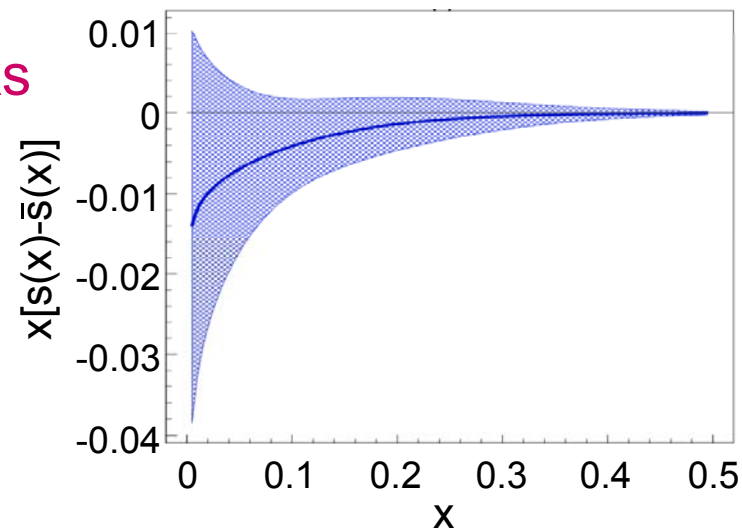


Strange Quark Observables

- scalar matrix element
  - $2\langle N|s\bar{s}|N\rangle / \langle N|u\bar{u}+d\bar{d}|N\rangle \sim 0.1-0.4$
- momentum carried by strange quarks
  - $2s/(\bar{u}+\bar{d}) = 0.42 \pm 0.07 \pm 0.06$

    NuTEV hep-ex/9906037
  - $s(x) \cong \bar{s}(x)$
- spin carried by strange quarks
  - as determined in sum rule
    - $\Delta s \sim -0.1 - 0$
  - as determined in semi-inclusive $\Delta s(x)$

$$\Delta s_{0.02} = 0.006 \pm 0.029 \pm 0.007$$



CTEQ6M, NLO
NuTEV hep-ex/0405037

- vector matrix elements

Quark Currents in the Nucleon

- Measure $G^{\gamma,p}, G^{Z,p}, G^{\gamma,n}$: $\quad G \sim \left\langle N \left| \sum_i e_i \bar{q}_i \Gamma_\mu q_i \right| N \right\rangle$
  - e.g.

$$G_{E,M}^{\gamma,p} = \frac{2}{3} G_{E,M}^{u,p} - \frac{1}{3}\left(G_{E,M}^{d,p} + G_{E,M}^{s,p}\right)$$

  - note

$$\left.\begin{aligned} G^{u,p} &= G^{d,n} \\ G^{d,p} &= G^{u,n} \\ G^{s,p} &= G^{s,n} \end{aligned}\right\}$$

charge symmetry

(see G. A. Miller PRC **57** (98) 1492.)

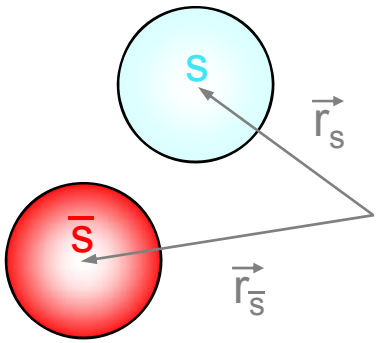
then

$$\boxed{\begin{aligned} G_{E,M}^{u} &= \left(3 - 4\sin^2\theta_W\right) G_{E,M}^{\gamma,p} - G_{E,M}^{Z,p} \\ G_{E,M}^{d} &= \left(2 - 4\sin^2\theta_W\right) G_{E,M}^{\gamma,p} + G_{E,M}^{\gamma,n} - G_{E,M}^{Z,p} \\ G_{E,M}^{s} &= \left(1 - 4\sin^2\theta_W\right) G_{E,M}^{\gamma,p} - G_{E,M}^{\gamma,n} - G_{E,M}^{Z,p} \end{aligned}}$$

dropping the *p* superscripts on the left

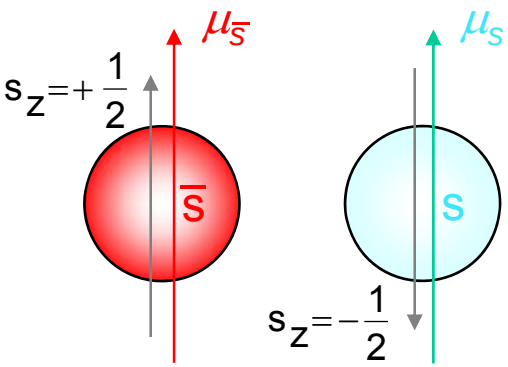
G_E^s, G_M^s Non-Zero?

- charge distribution
  - if s, $\bar{s}$ are separated, non-zero net contribution



- convection current
  - if s, $\bar{s}$ are separated, non-zero net contribution

- spin current
  - spin triplet: moments cancel
  - spin singlet: zero net moment
  - *also requires separation*

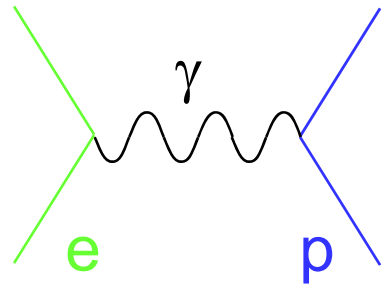


Parity-Violating Electron Scattering

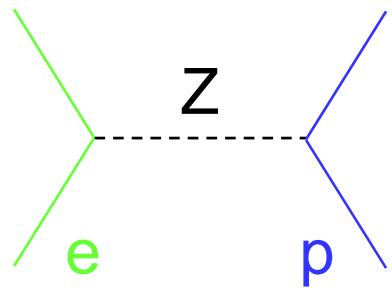
- $G^{Z,p}$ contributes to electron scattering

$$\sigma \propto \left| M^{\gamma} + M^{Z} \right|^2$$

- interference term: **large** M^{γ} x small M^{Z}



- Interference term violates parity: use $(\vec{e},e')$



$$A^{PV} \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim 10^{-5}$$

$$= -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \frac{A_E + A_M + A_A}{\varepsilon\left(G_E^{\gamma}\right)^2 + \tau\left(G_M^{\gamma}\right)^2}$$

where

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

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

$$\varepsilon(\theta) = \left[1 + 2(1+\tau)\tan^2(\theta/2)\right]^{-1},$$

$$\tau = \frac{Q^2}{4M_p^2},$$

$$\varepsilon'(\theta) = \sqrt{\tau(1+\tau)(1-\varepsilon^2)}$$

The Axial Current Contribution

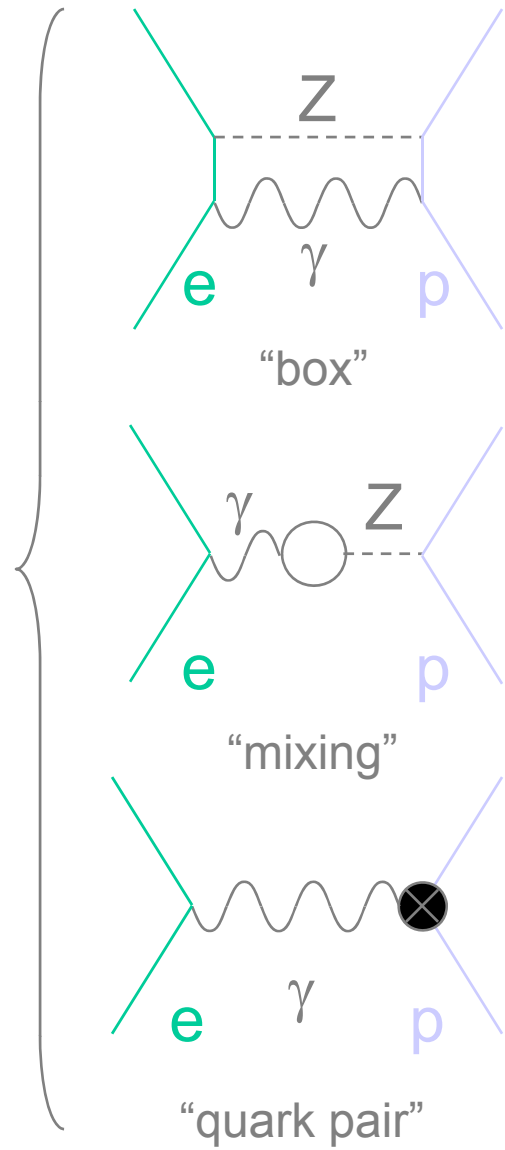
- Recall

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

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

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

  - "unknown 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



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

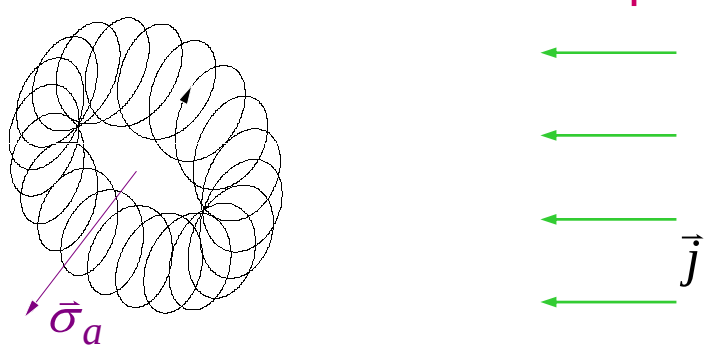
$$\langle p'|J_\mu^\gamma(Q^2)|p\rangle = \bar{u}(p')\left(F_1(Q^2)\gamma_\mu - i\frac{F_2(Q^2)}{2M}\sigma_{\mu\nu}q^\nu + \frac{F_A(Q^2)}{M^2}\left(q^2\gamma_\mu - \not{q}q_\mu\right)\gamma_5 - i\frac{F_E(Q^2)}{2M}\sigma_{\mu\nu}q^\nu\gamma_5\right)u(p)$$

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



$$U = -\vec{\sigma}_a\cdot\vec{j}$$

$$\vec{\Gamma} = \vec{\sigma}_a \, x \, \vec{j}$$

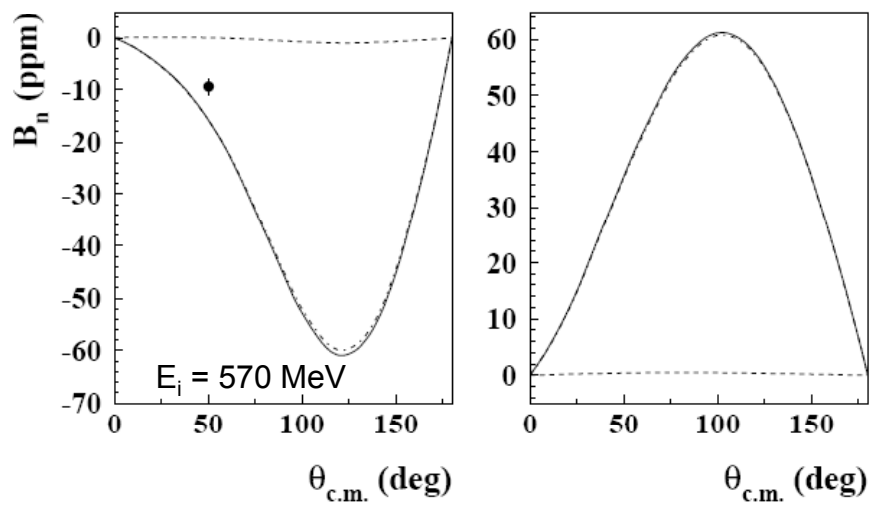
PV: Inelastic Scattering/Pion Production

- N-Δ transition
  - Dominant magnetic dipole (M1) transition in photoproduction
    - Coupling to vector current
    - Corresponds roughly to quark "spin flip" (via magnetic moment)
  - Also study spin flip in axial current
    - e.g. charged pion electroproduction $ep \rightarrow e\pi^{-}\Delta^{++}$
      A. Liesenfeld *et al* , Phys. Lett. **B468** (1999) 20.
    - "Pure" spin flip accompanied by flavor change
  - We measure neutral current coupling to nucleon axial transition current: A_{PV}(inel)
    - Like electroproduction, different flavor structure

- Pion production
  - Measure inclusive π^{-} from D target, dominated by photoproduction
  - Asymmetry at Q^2 =0 not zero (current conservation)
  - d_{Δ} related to the anomalous ΔS = 1 hyperon decays

Transverse Asymmetries

- Elastic scattering
  - Second order e.m. effects generate single-spin asymmetries
  - Easy to measure with PV apparatus



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

  - Interference of 1γ and 2γ amplitudes; time reversal invariance requires A_n to involve the imaginary part of $M_{2\gamma}$
  - Real part of $M_{2\gamma}$ related to important contribution to longitudinal scattering: G_E/G_M ratio

- Pion production
  - Inclusive pion yield also has azimuthal dependence
  - Involves longitudinal/transverse interference
  - Suppressed by $\sim m_e/E$

Parity-Violating Electron Scattering Expts

Expt/Lab	Target/ Angle	Q^2 (GeV^2)	A_{phys} (ppm)	s 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	^{4}He/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

G0 Collaboration

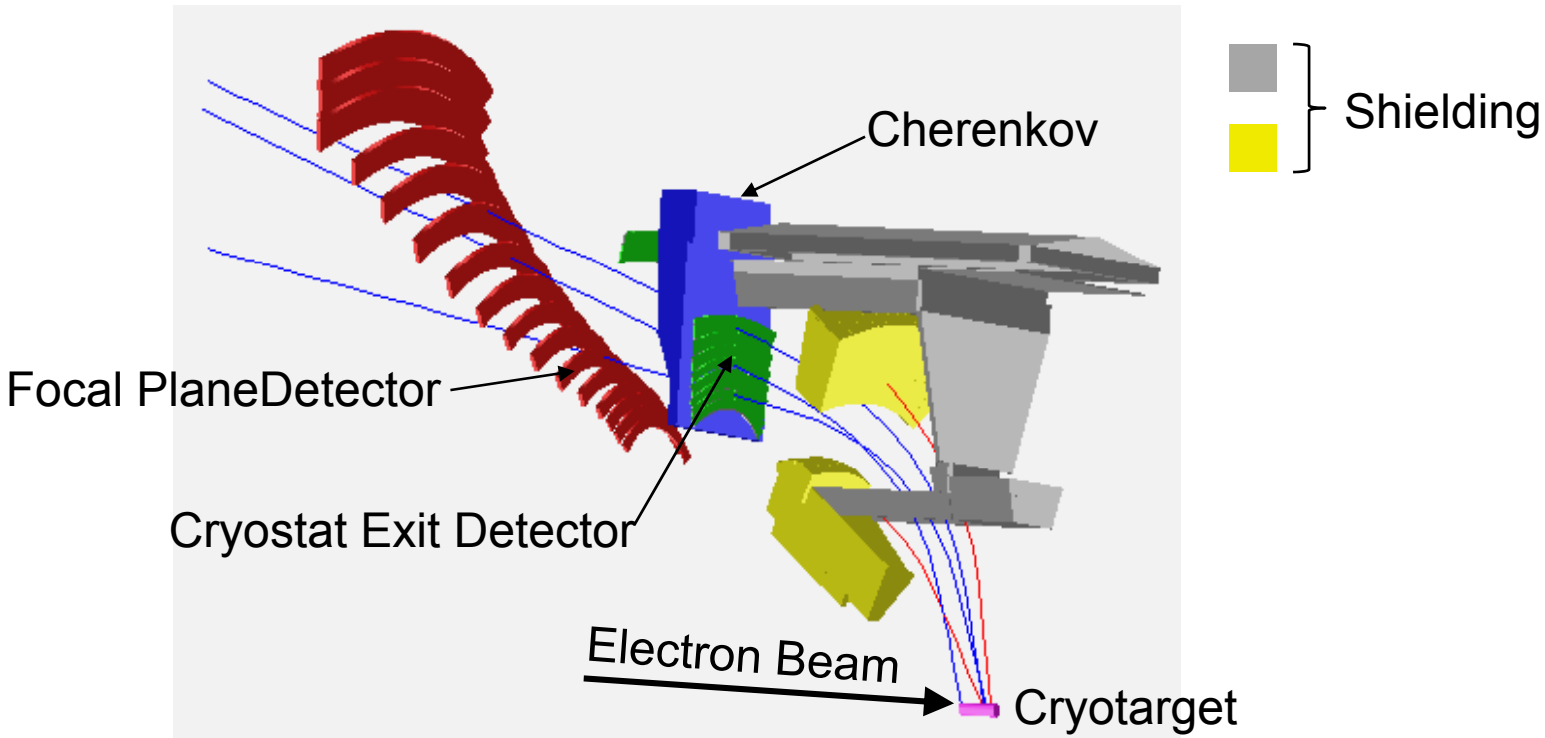
California Institute of Technology, Carnegie Mellon University,
College of William and Mary, Grinnell College,
Institut de Physique Nucléaire d'Orsay,
Laboratoire de Physique Subatomique et de Cosmologie-Grenoble,
Louisiana Tech University, New Mexico State University, Ohio University,
Thomas Jefferson 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 Stude
C. Cap (Maryland),
J. Mam (New Mexico
State), n. 07 W&M)

Analysis Coord
F. Benr

SU you!

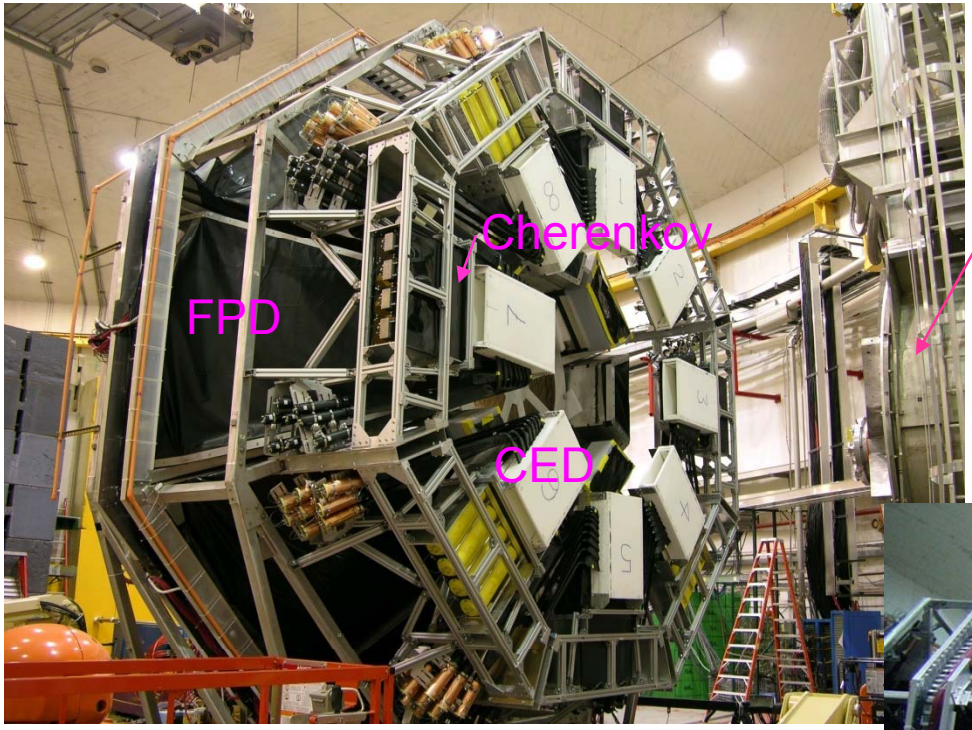
Back Angle Layout



Single Octant Schematic

- 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
- Elastic, inelastic electron separation using FPD, CED
- Electron/pion separation using aerogel Cherenkov

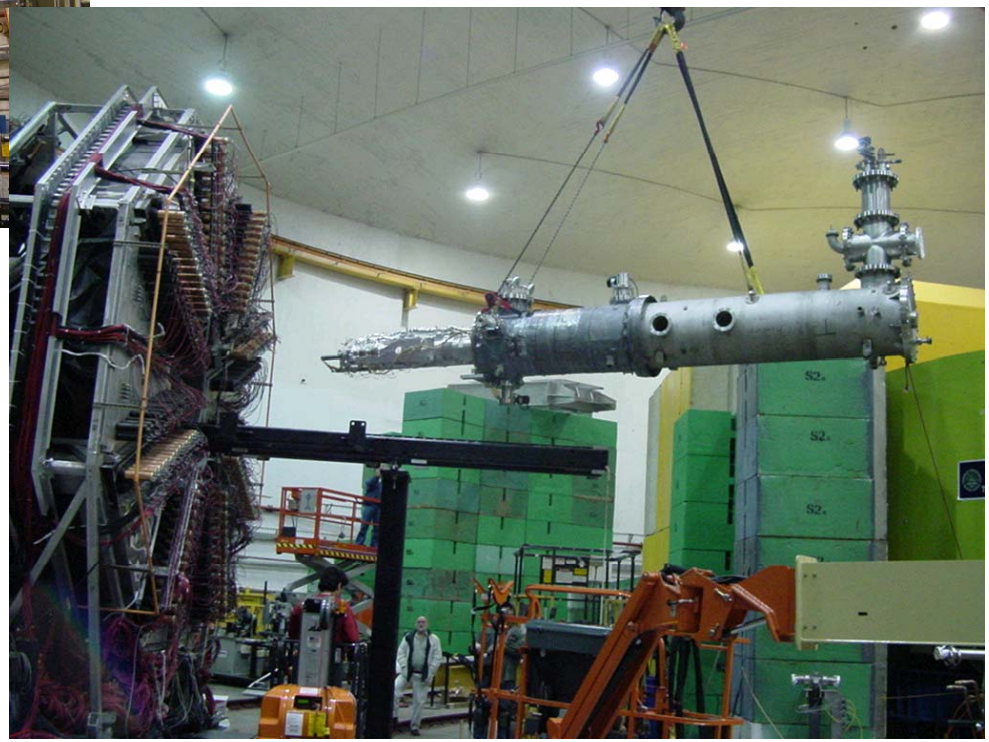
Back Angle Apparatus



Superconducting Magnet

Back angle detector package

Target system installation

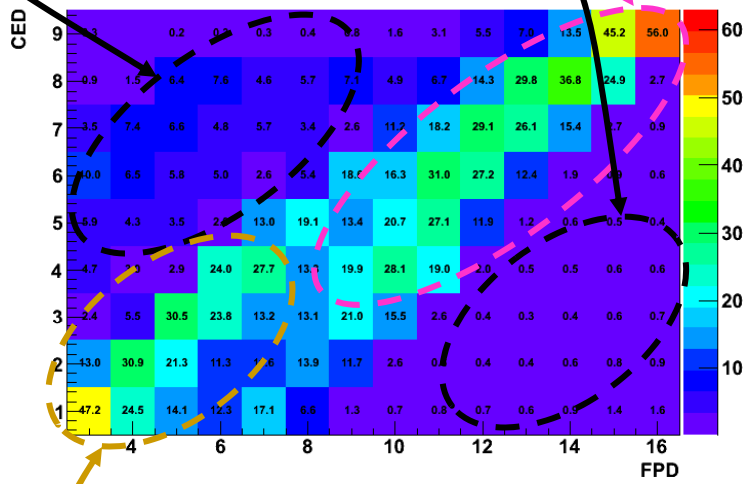


Electron Yields

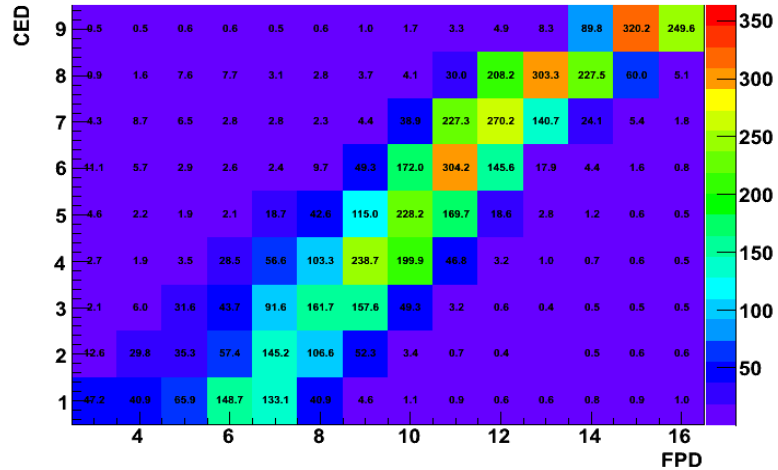
background regions

(quasi) elastic electrons

LH2, 687 MeV

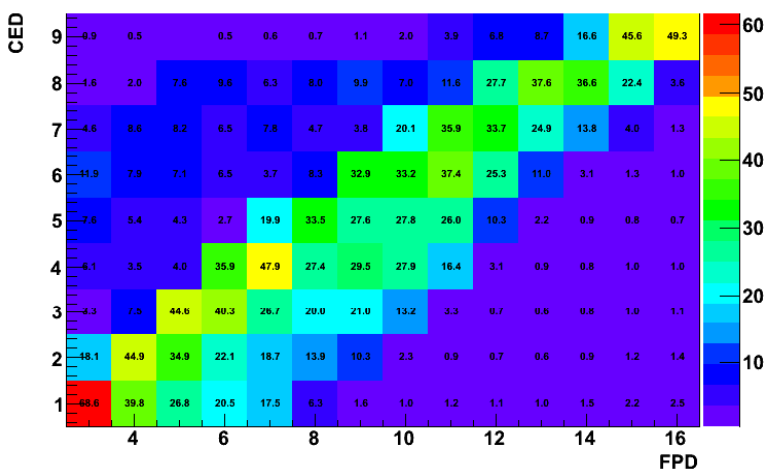


LH2, 362 MeV

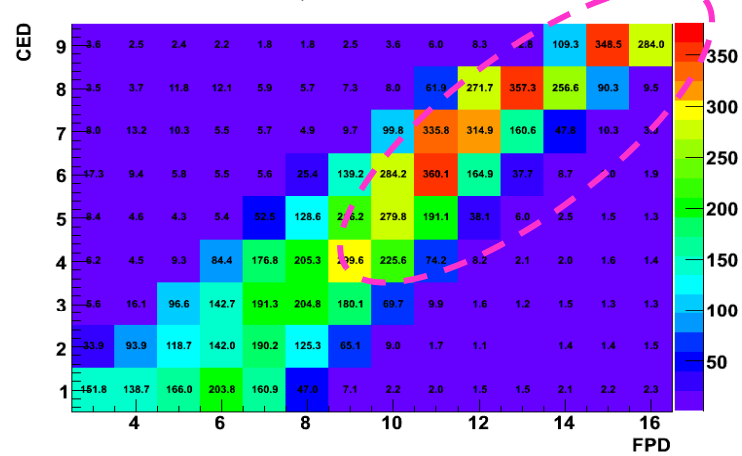


inelastic electrons

LD2, 687 MeV



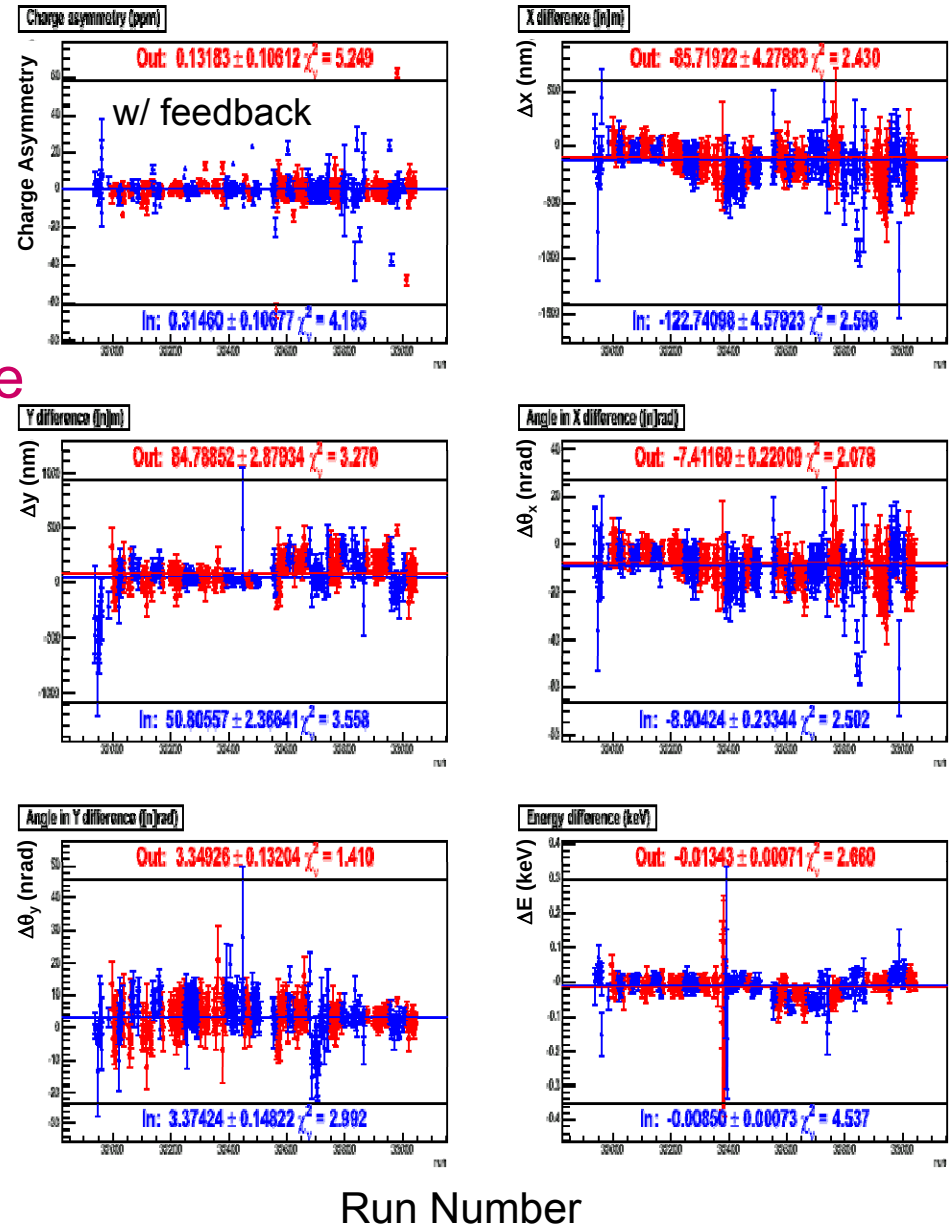
LD2, 362 MeV



Polarized Beam Properties

- 2 ns time structure
- Polarization reversal: 30 Hz, random quartets (+--+, -++-)
- Slow helicity reversal: $\lambda/2$ wave plate IN and OUT
- Helicity-correlation properties:

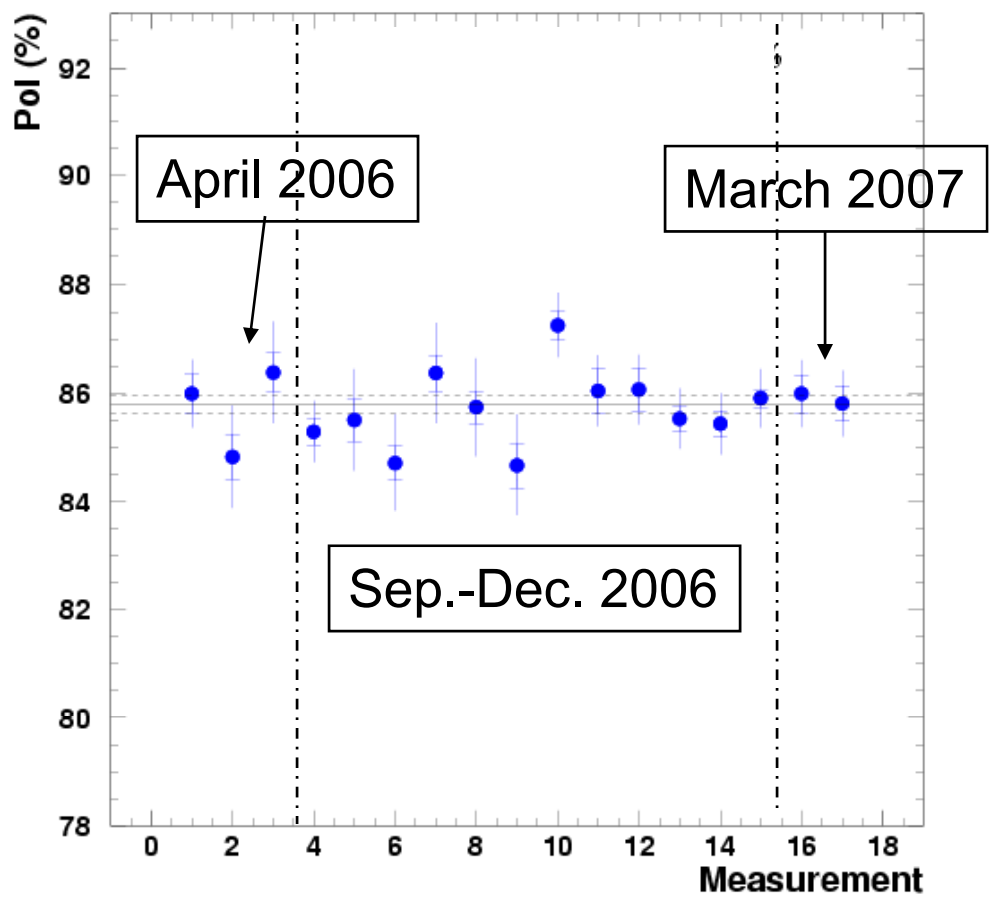
Beam Parameter	Achieved (OUT-IN)/2	"Specs"
charge asymmetry	0.09 +/- 0.08	2 ppm
x position difference	-19 +/- 3	40 nm
y position difference	-17 +/- 2	40 nm
x angle difference	-0.8 +/- 0.2	4 nrad
y angle difference	0.0 +/- 0.1	4 nrad
energy difference	2.5 +/- 0.5	34 eV
Beam halo (out 6 mm)	$< 0.3 \times 10^{-6}$	10^{-6}



Beam Polarization

- Measurements of Møller asymmetry at 687 MeV
  - Low energy tune of Møller spectrometer
- Use Mott scattering for 362 MeV measurements
  - Mott asymmetry measured at 5 MeV in injector
  - New work on effect of background improves agreement with Møller

687 MeV Møller Results

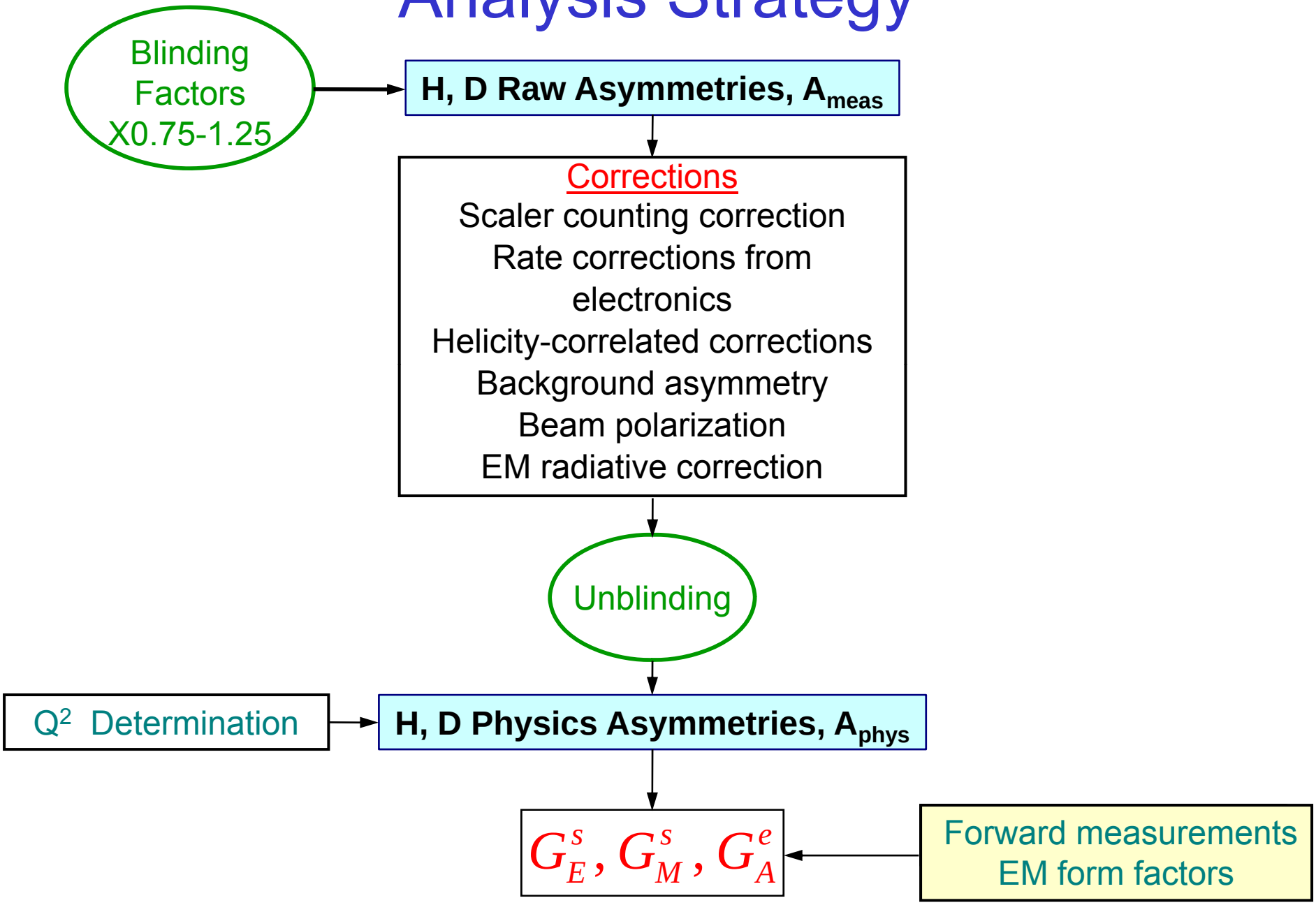


Bottom Lines:

P_e(687 MeV) = 85.78±0.07±1.38%

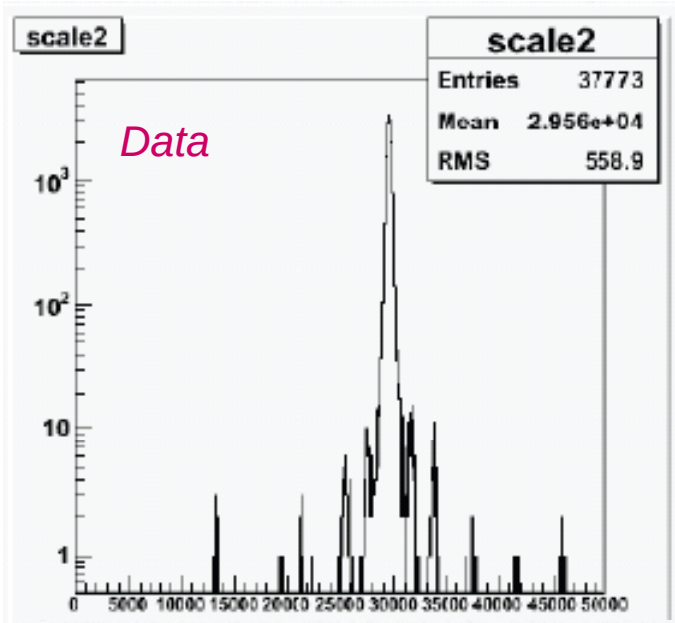
P_e(362 MeV) = ±2.05%

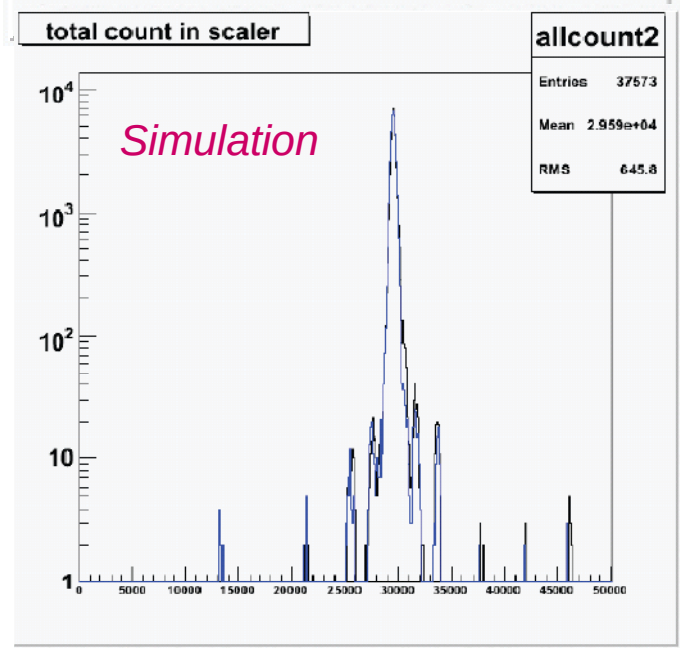
Analysis Strategy



Scaler Counting Problem

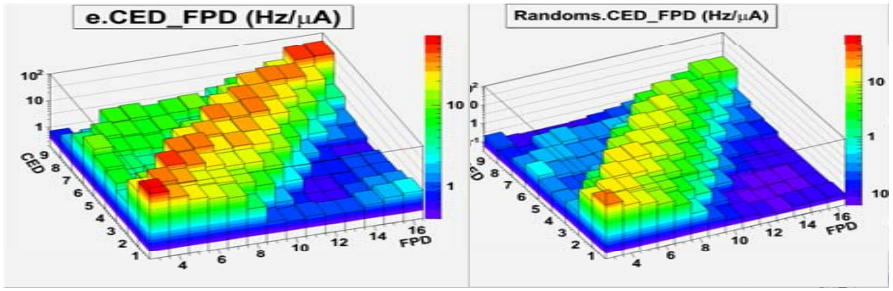
- Electronics sorts detector coincidences (CED_i and FPD_j) into separate scaler channels
  - FPGA-based system in North American electronics (4 octants)
- Because of error in FPGA programming, two short (~3 ns) pulses could be sent to scaler in < 7 ns
  - ~ 1% of events have such miscounts
- Such pulse pairs can 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





Rate Corrections

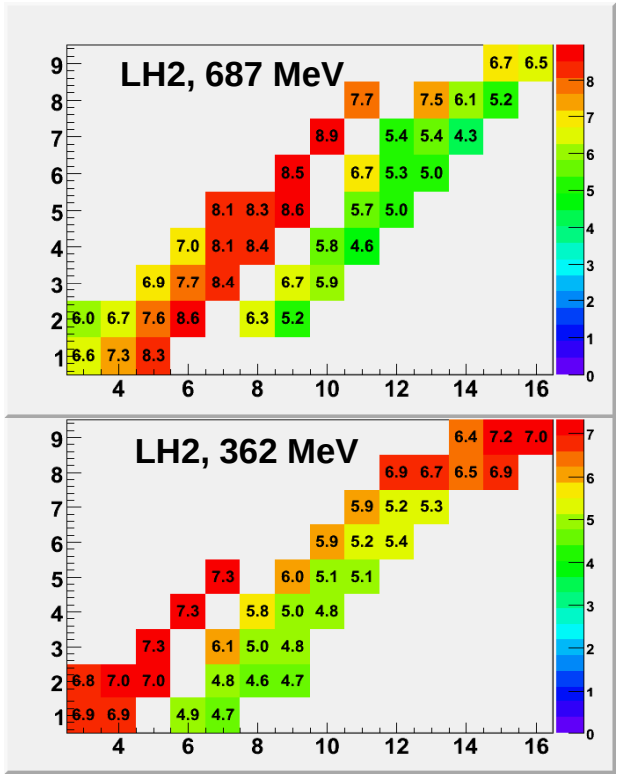
- Randoms corrections (yield)
  - LH2 randoms small
  - LD2 randoms significant
    - higher pion rate
  - Direct (out-of-time) measurement



- Deadtime corrections (yield)
  - Simulated the complete electronics chain

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

Deadtimes (%)



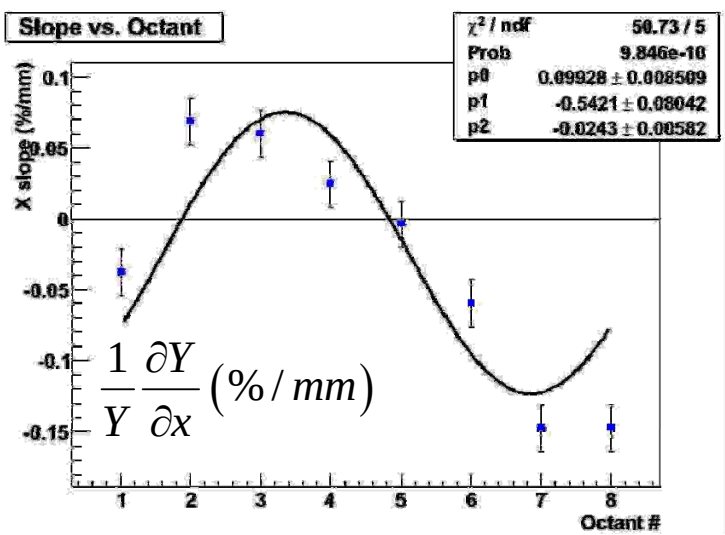
- Multihit corrections smaller (yield)
  - Arise because of trigger: (any CED) and (any FPD)

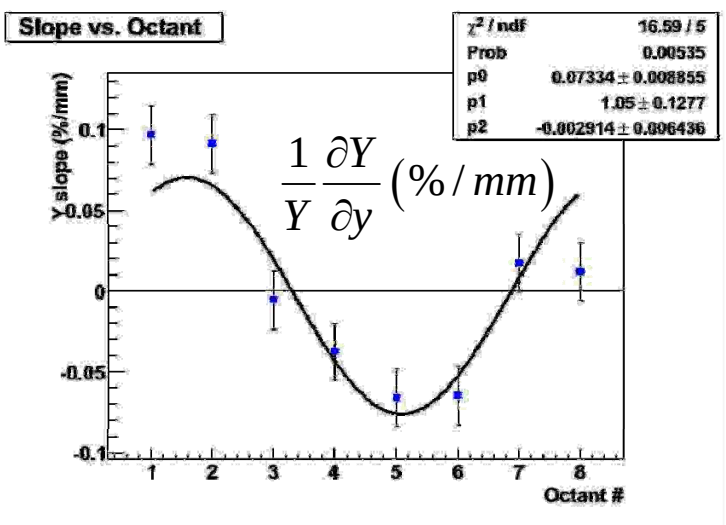
- Use measured singles *asymmetries* for correction

Helicity-correlated Beam Properties: Linear Regression

- Cross check with sensitivities determined from natural beam motion and from deliberate 'coil-pulsing' runs
- Sensitivities smaller at backward angles
  - ~ 1/5 of slopes at forward angles
  - Kinematic correlation (momentum/angle) combined with spectrometer acceptance

Simulation

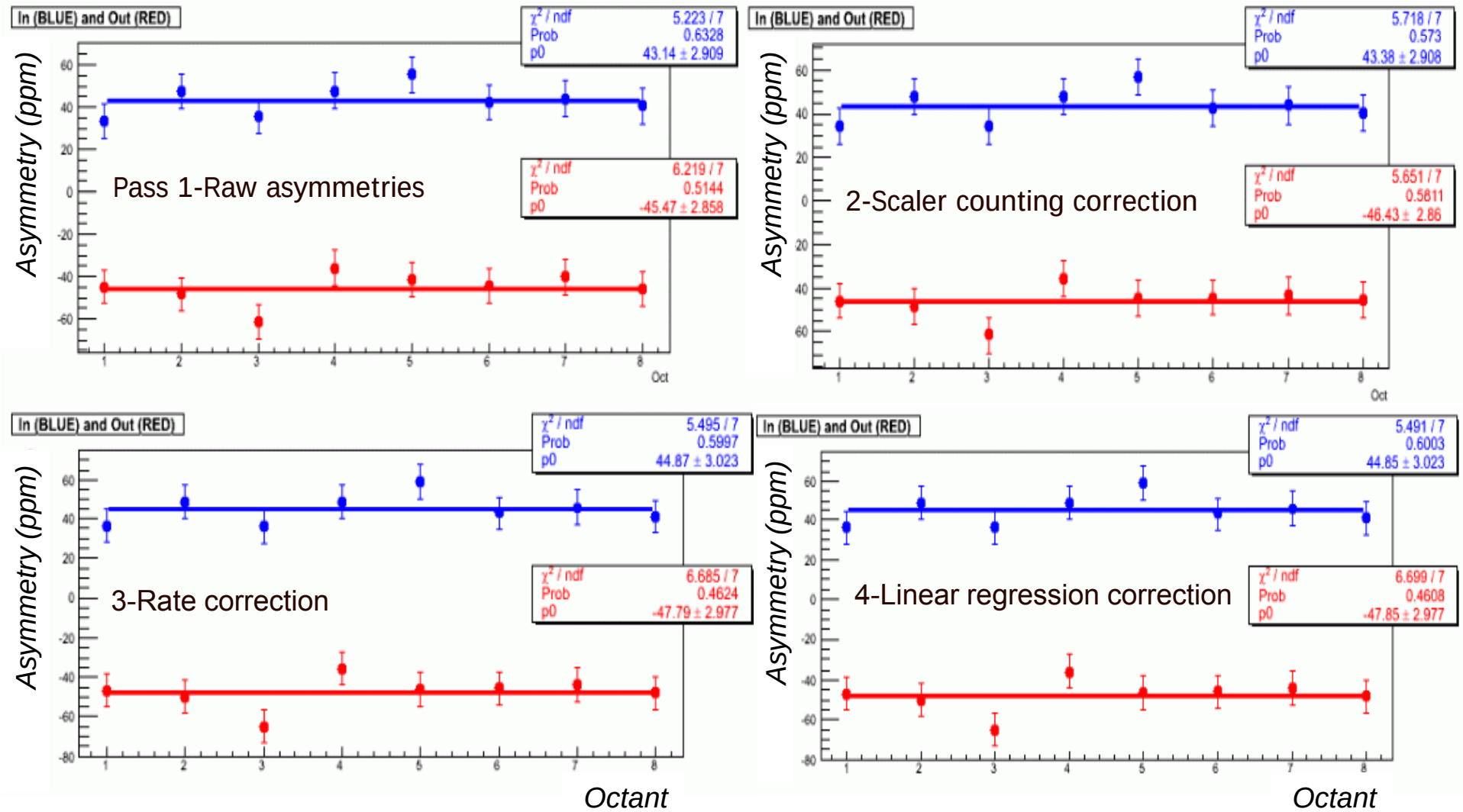




- Bottom line: false asymmetry ~ 0.1 ppm

Elastic Asymmetries

- Hydrogen, 687 MeV, BLINDED
- Including 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, 687 MeV
  - 5% contribution (measured), nearly 0 asymmetry (measured)

- Hydrogen

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

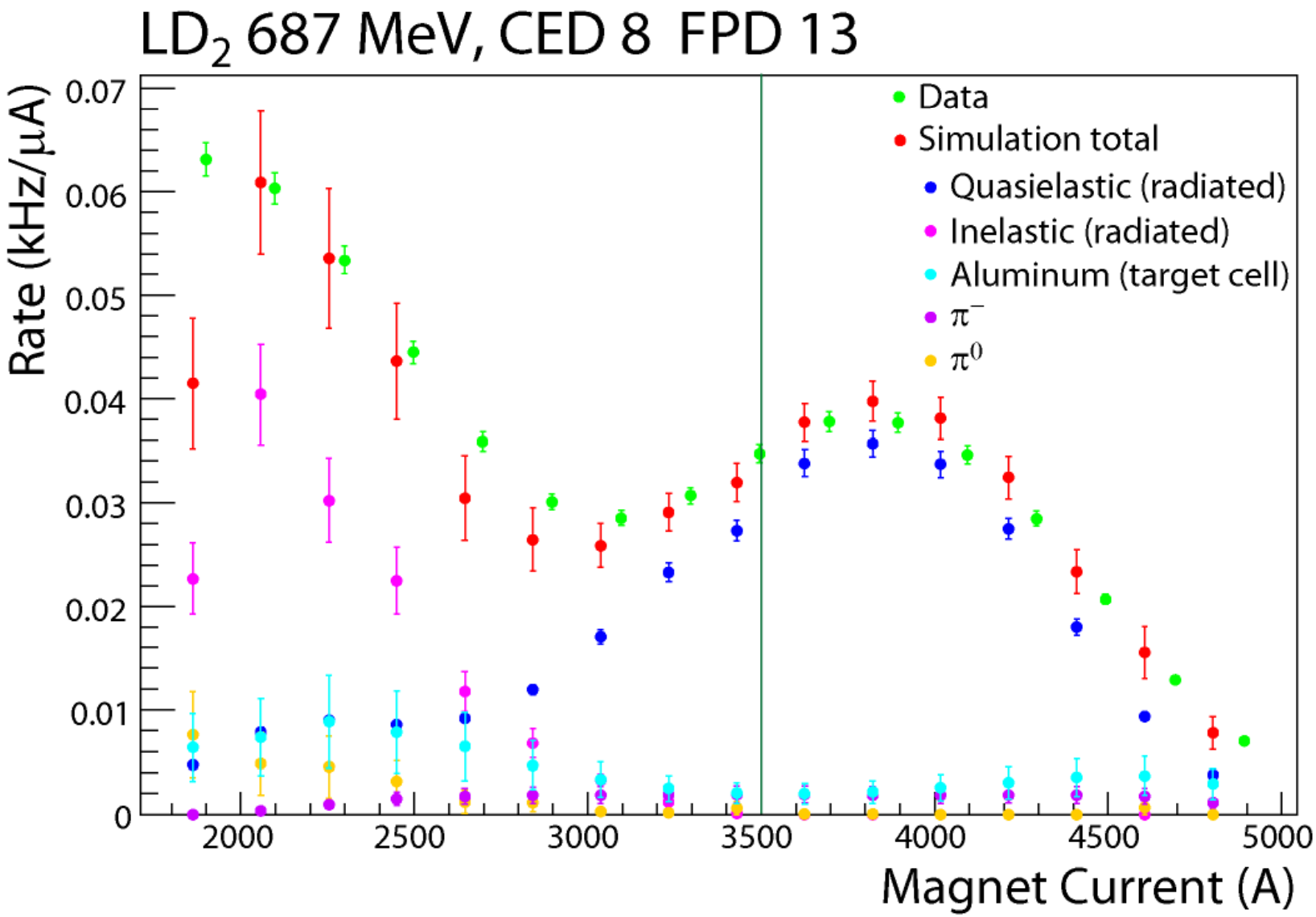
- Deuterium:

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

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

Backgrounds: Field Scans

- Use simulation *shapes* to help determine dilution factors



Asymmetry Uncertainties (1)

- 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

Do Not Quote

Asymmetry Uncertainties (2)

- Deuterium, 687 MeV

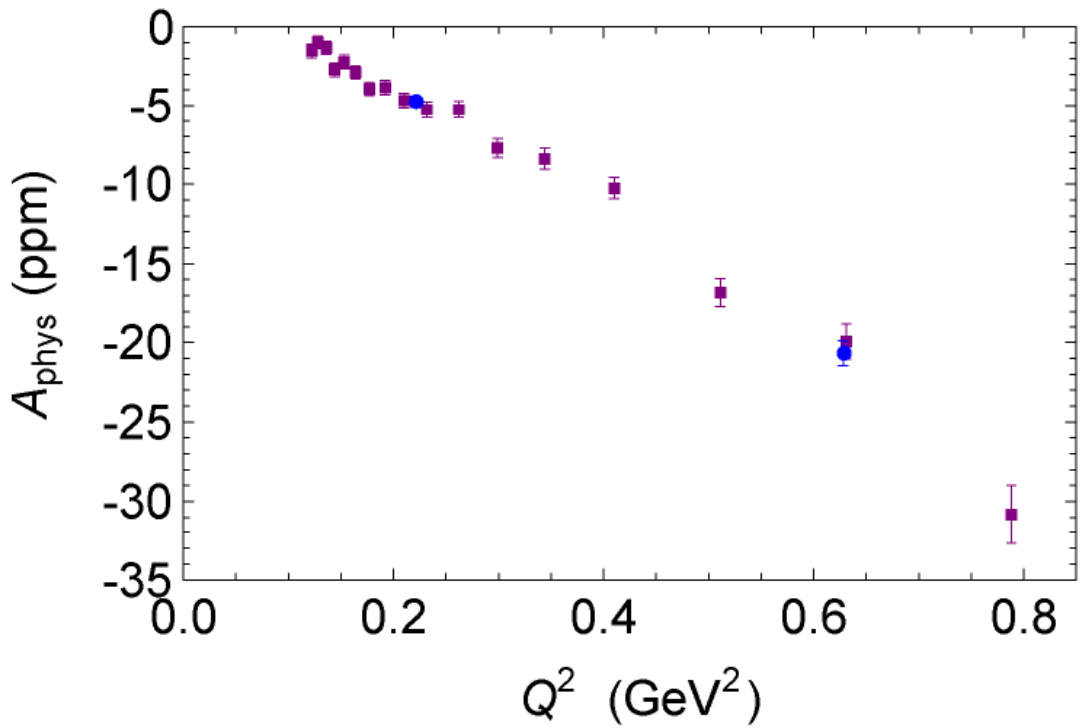
	Value (ppm)	Stat (ppm)	Sys Pt (ppm)	Sys Gl (ppm)	Total (ppm)
Measured Asymmetry	-44.02	3.34			
Background Asymmetry	-46.05		0.050		
Dilution Correction			0.38		
Transverse Correction			0.009	0.008	
Rate Correction	-46.35		1.82		
Beam Polarization	-54.03		0.62	0.64	
EM Radiative Correction	-55.87		0.19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

Do Not Quote

Determining Form Factors

- Starting from asymmetries, need
  - deuterium model (Schiavilla, priv. comm.)
  - electromagnetic form factors (Kelly PRC **70** (2004))
  - check on 2-boson corrections (Arrington, Blunden, Melnitchouk, et al.; Zhou, Kao & Yang, priv. comm.)

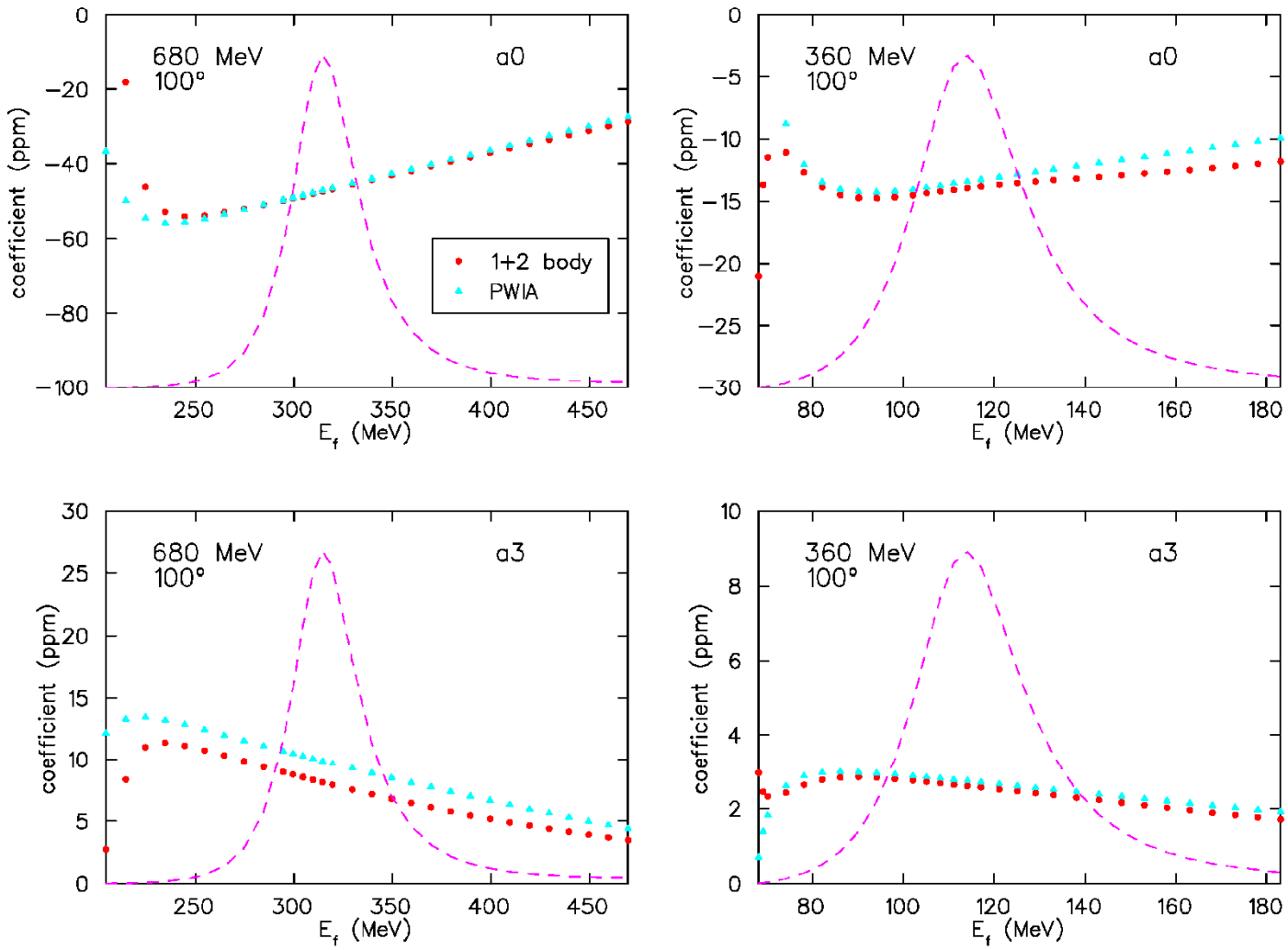
- Interpolation of G0 forward angle measurement



Deuterium Model

- Calculation from R. Schiavilla

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



Electromagnetic Form Factors

- These results: Kelly form factors from (PRC **70** (2004))
  - used in Schiavilla deuterium calculation

- Including new low Q^2 data
  - Arrington and Melnitchouk for proton (PRC **76** (2007))
  - perhaps Arrington and Sick for the neutron (PRC **76** (2007))

- Use prescription of Tjon, Blunden & Melnitchouk for applying 2 boson corrections (arXiv:0903.2759v1)

$$A_{meas} = (1+\delta)\, A_{Born} = \left(\frac{1+\delta_{Z(\gamma\gamma)} + \delta_{\gamma(\gamma Z)}}{1+\delta_{\gamma(\gamma\gamma)}} \right) A_{Born}$$

- Need values for *p* and *n* (prelim: Melnitchouk, priv. comm.)

	H forward	H backward	D backward
Low Q^2	-0.52%	1.17%	
High Q^2	-0.11	1.20	

Form Factor Uncertainties (1)

- Pt-pt systematics

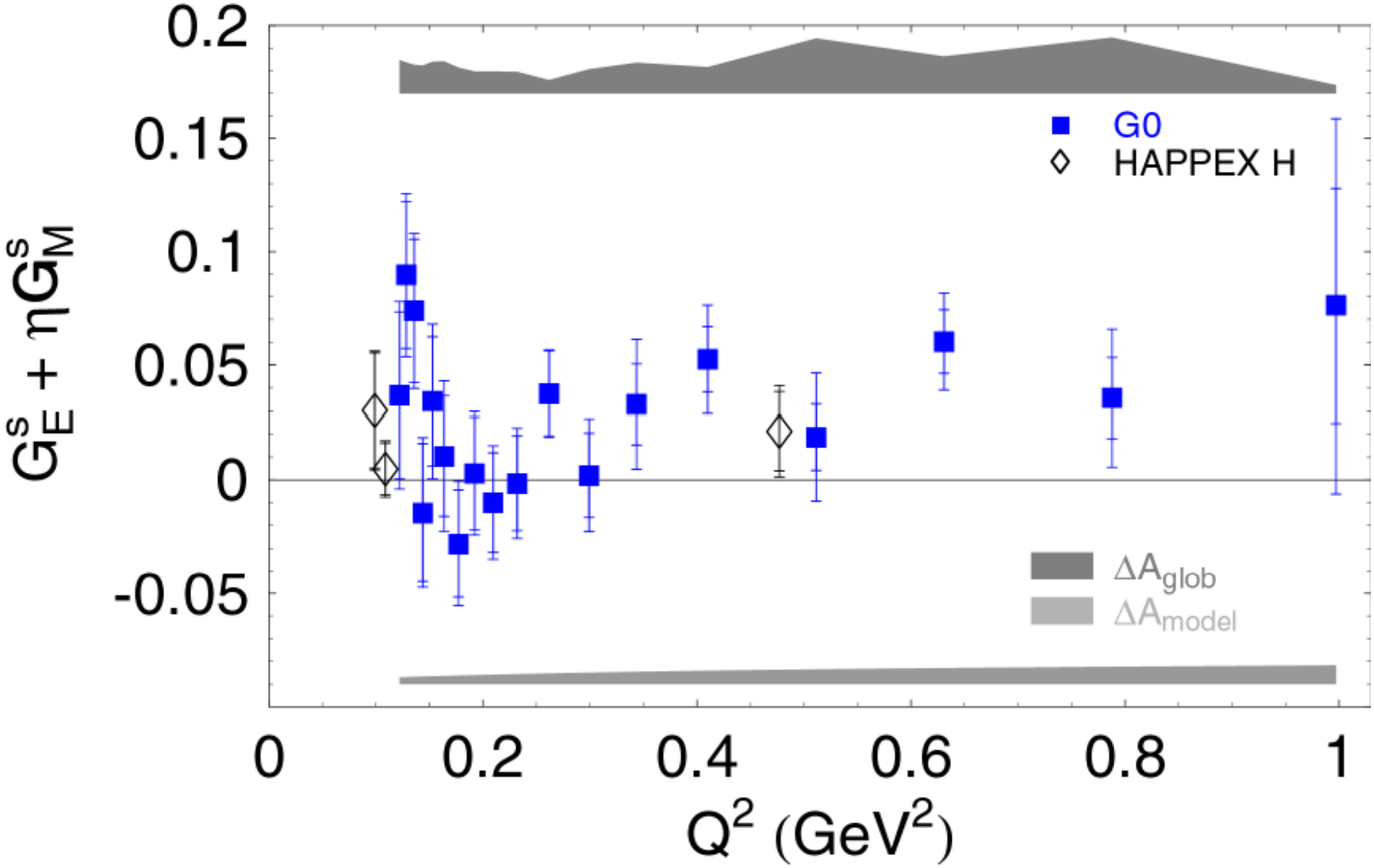
	$Q^2 = 0.22\ GeV^2$			$Q^2 = 0.63\ GeV^2$		
	G_E^s	G_M^s	G_A^e	G_E^s	G_M^s	G_A^e
Backward H Energy	7.11×10^{-4}	$4. \times 10^{-3}$	6.72×10^{-4}	8.46×10^{-4}	1.59×10^{-3}	3.61×10^{-4}
Backward D Energy	6.04×10^{-4}	3.9×10^{-3}	1.04×10^{-2}	$5. \times 10^{-4}$	1.25×10^{-3}	5.56×10^{-3}
Forward Q^2	3.71×10^{-3}	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

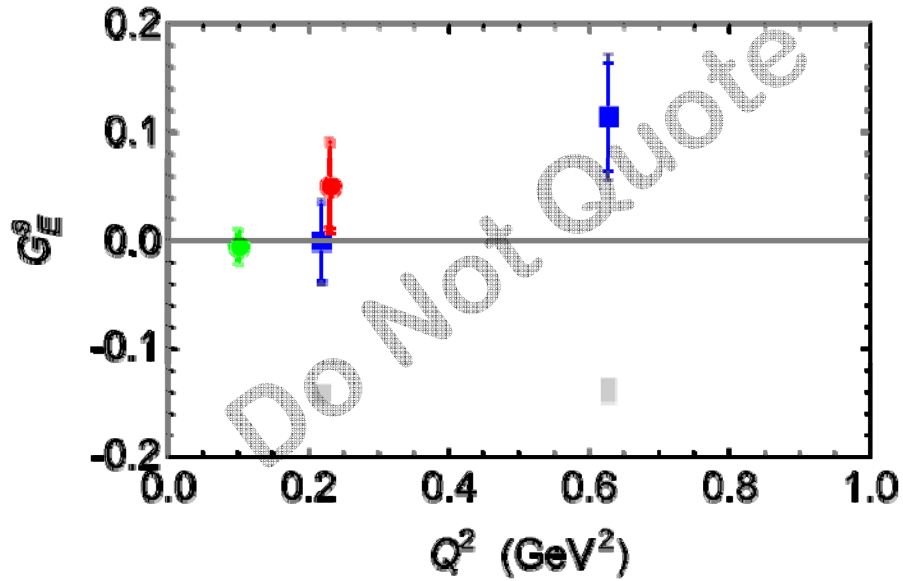
	$Q^2 = 0.22\ \mathrm{GeV}^2$			$Q^2 = 0.63\ \mathrm{GeV}^2$		
	G_E^s	G_M^s	G_A^e	G_E^s	G_M^s	G_A^e
Forward H Energy	4.26×10^{-6}	1.93×10^{-6}	9.98×10^{-6}	1.39×10^{-5}	1.66×10^{-6}	1.64×10^{-5}
G_A^s	6.13×10^{-4}	3.96×10^{-3}	1.44×10^{-3}	5.5×10^{-4}	1.37×10^{-3}	6.48×10^{-4}
EW Rad. Corr.	2.52×10^{-3}	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}

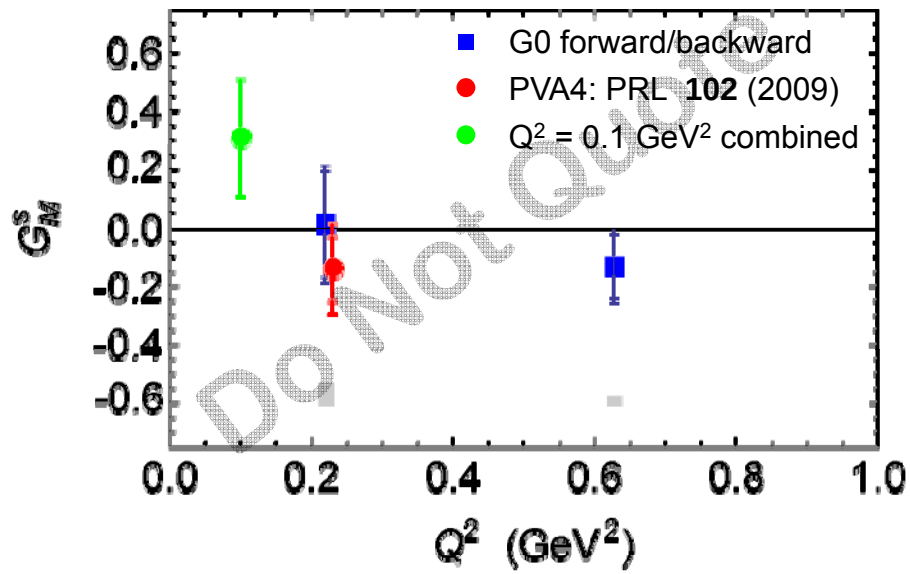
Forward Angle Results

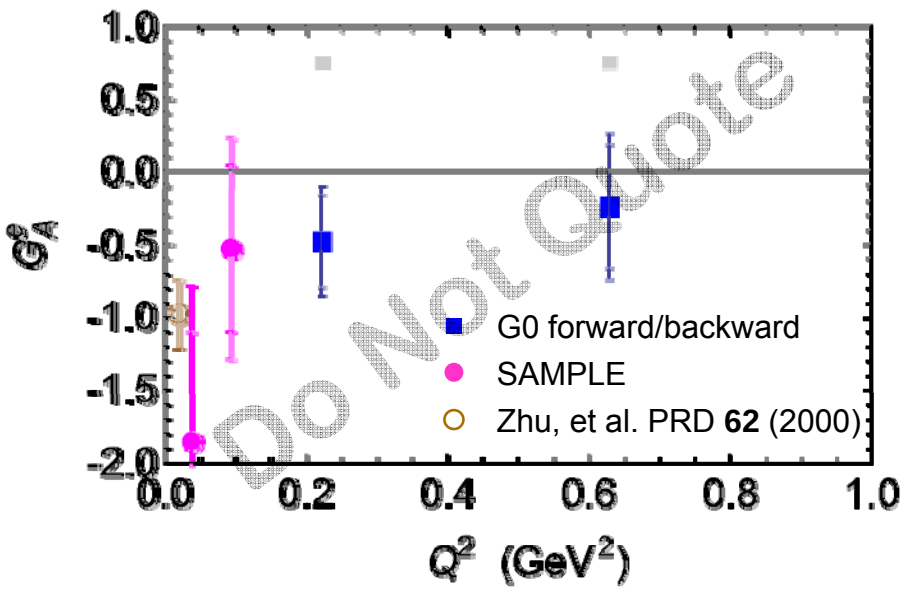


New: Backward Angle Results

- Using interpolation of G0 forward measurements







Global uncertainties

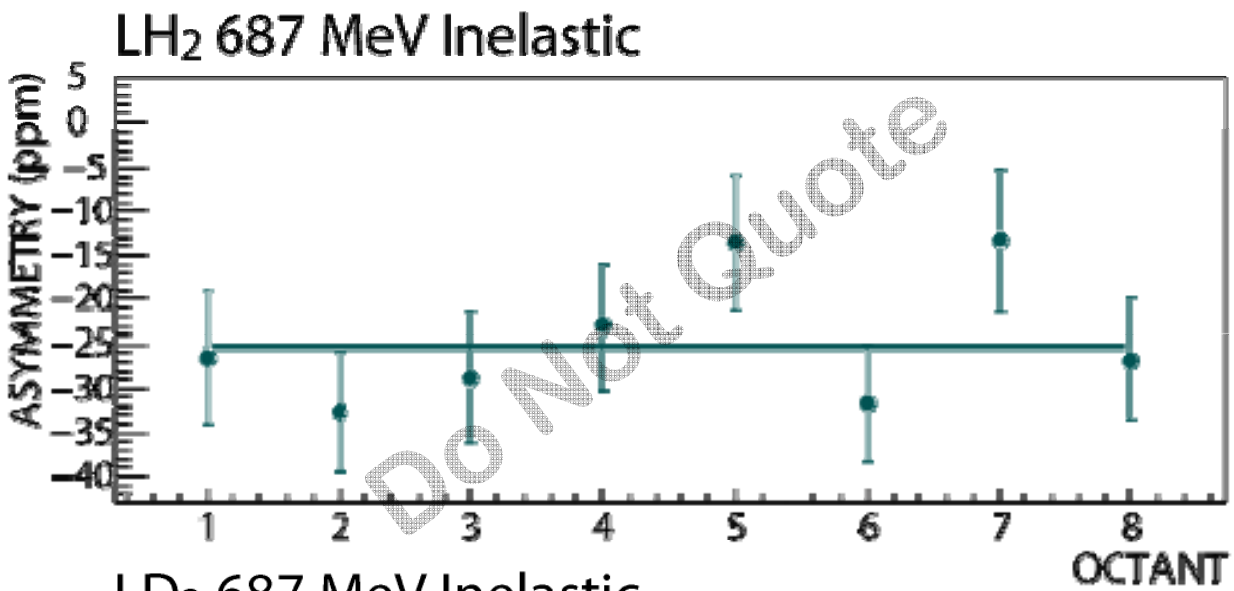
- also assuming

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

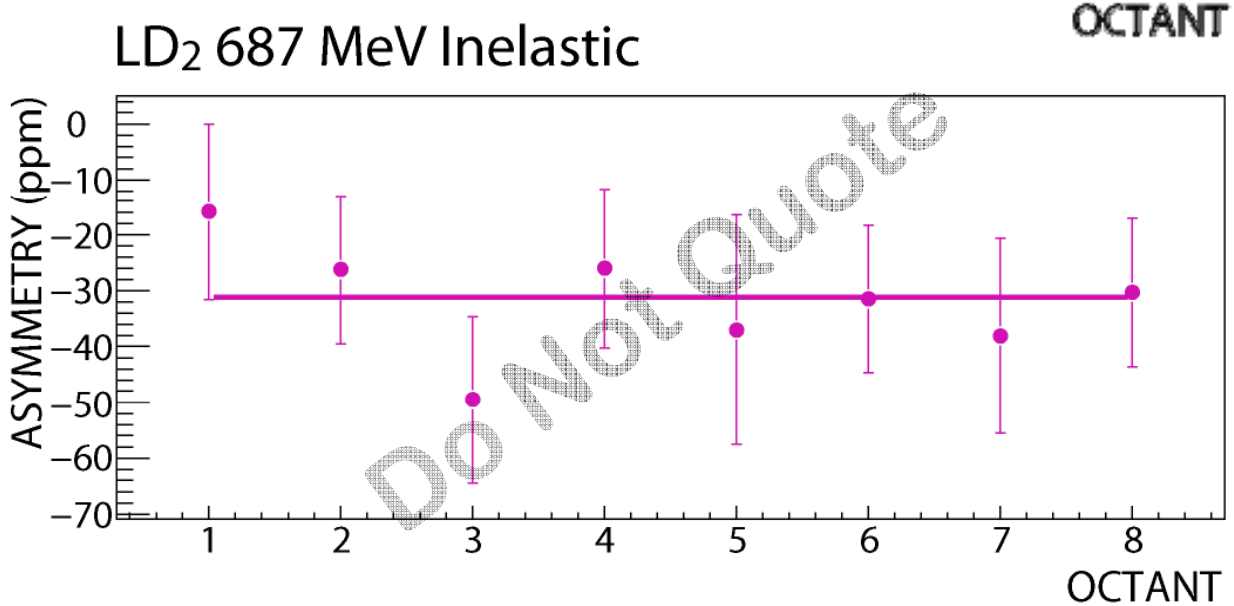
$$G_{A,NS}^{T=0}\left(Q^2=0\right) = 0.070$$

Preliminary Inelastic Asymmetries

- Background, radiative corrections *not included*



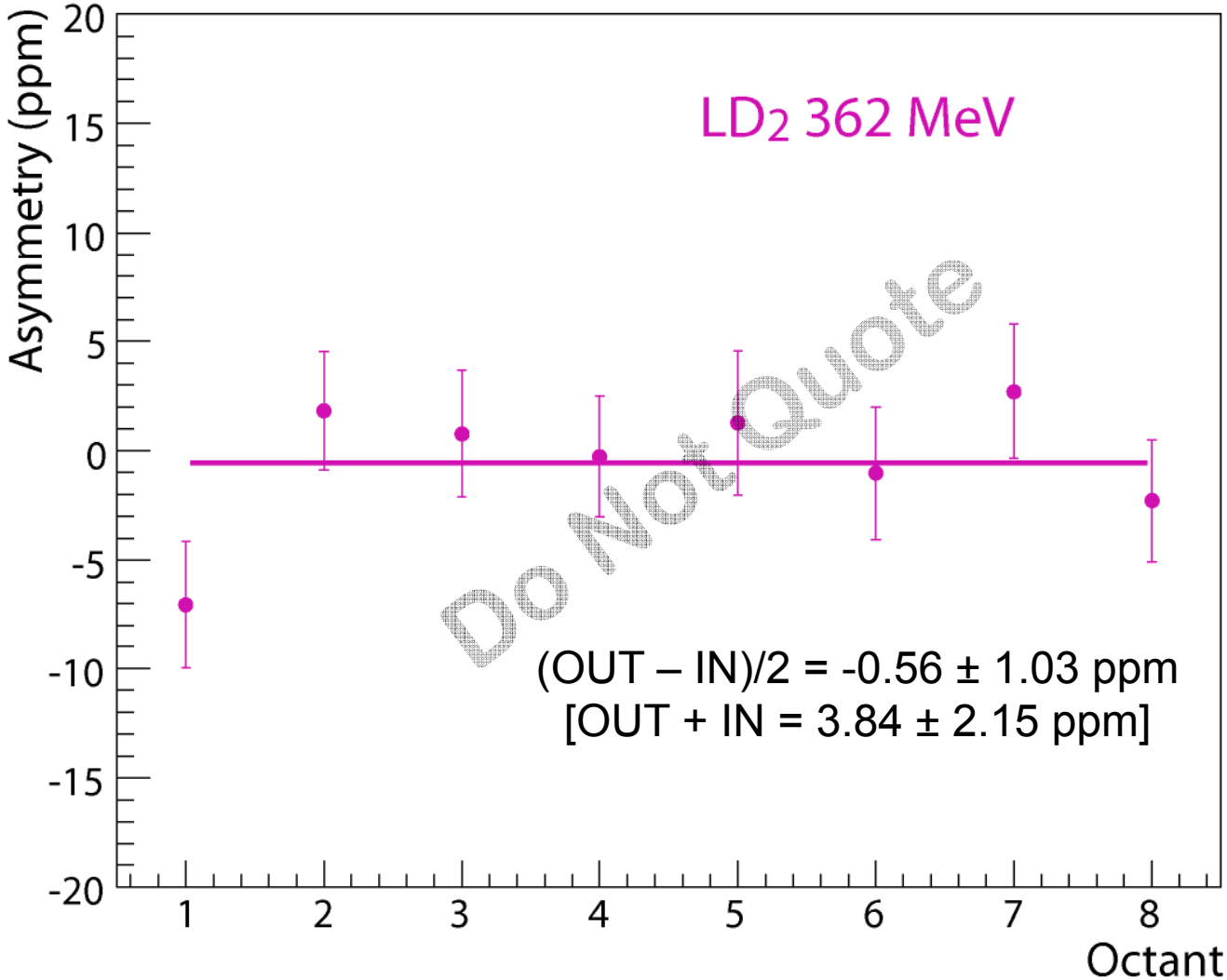
[OUT + IN = 0.07 ± 5.1 ppm]



[OUT + IN = -9.9 ± 10.5 ppm]

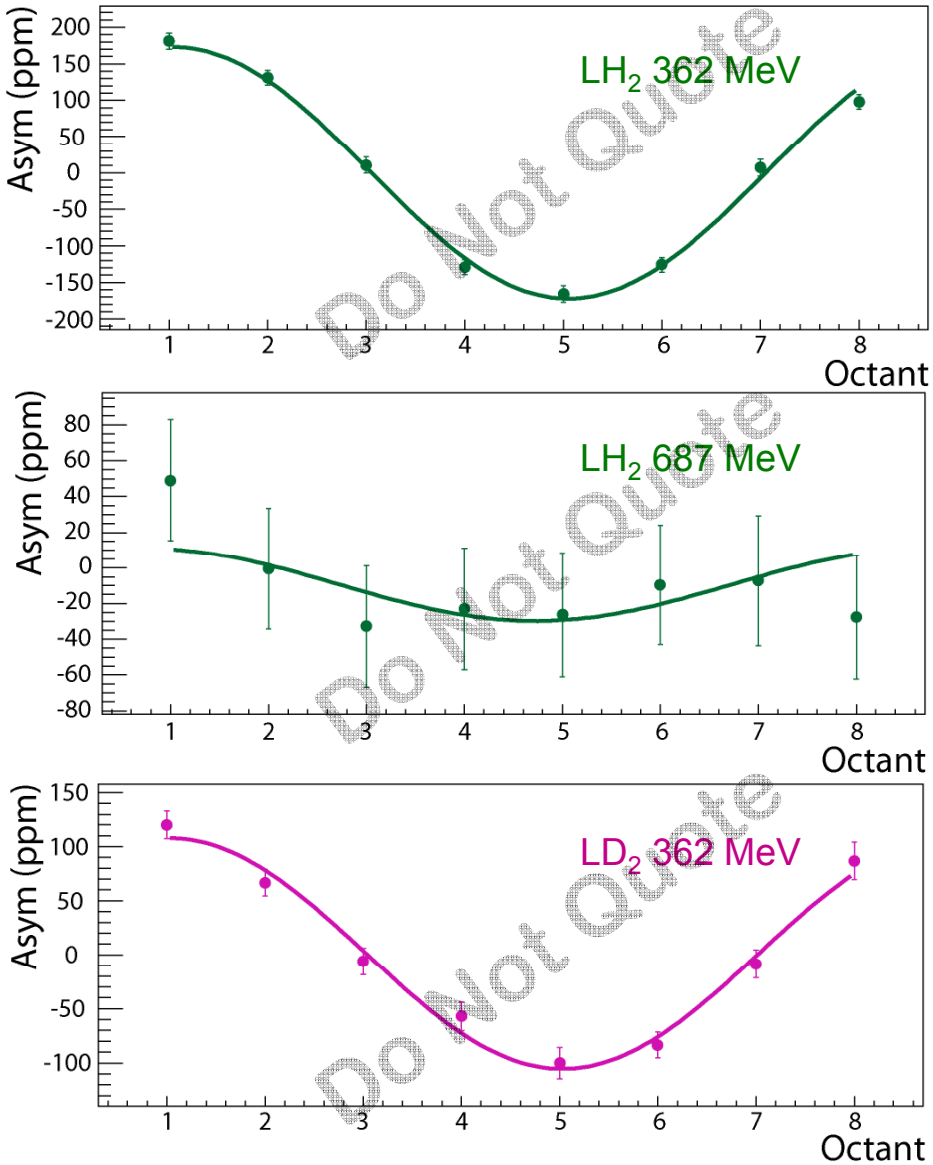
Preliminary Pion Asymmetries

- Constrain small photoproduction asymmetry "d_Δ"
  - working on systematic uncertainties (~ 0.5 ppm)



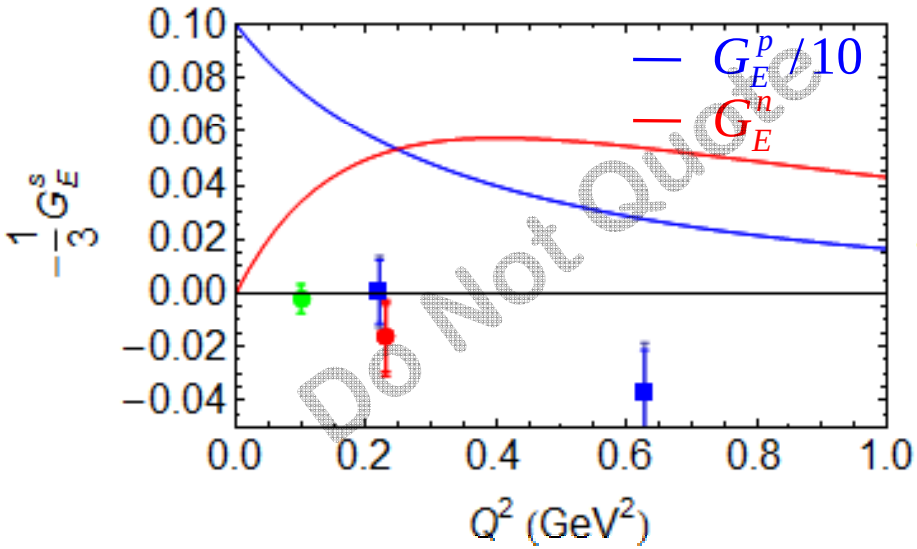
Preliminary Transverse Asymmetries

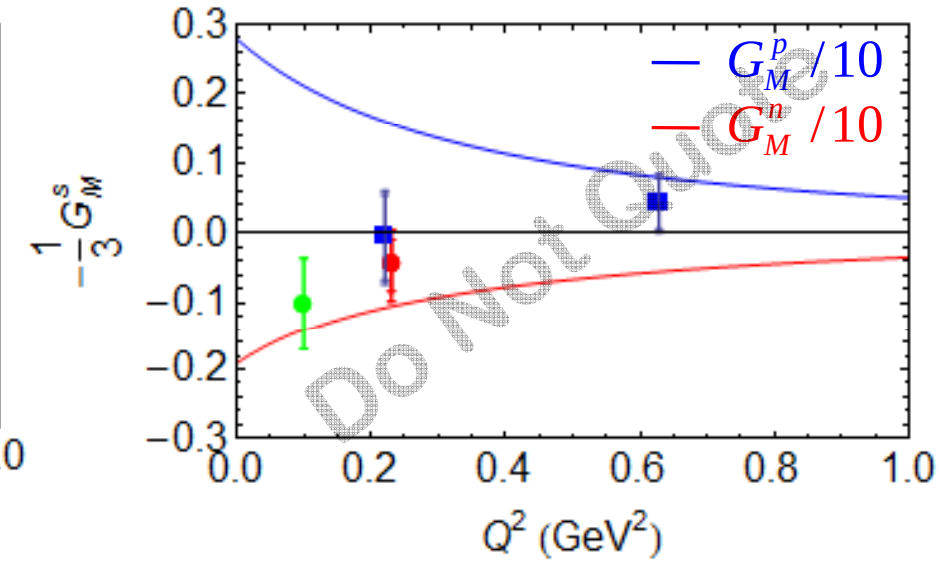
- Background, radiative corrections *not included*



– need theory for em radiative corrections

Contributions to Overall Form Factors





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

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 to fit all 33 asymmetries

- First measurements of neutral current NΔ transition around $Q^2 = 0.3$ GeV^2
- First measurements of PV asymmetry in inclusive π^- production at low Q^2
- First measurements of transverse asymmetries in
  - back angle elastic scattering from H, D targets: Im(2γ)
  - Inclusive π^- production: $R_{LT'}$