Acknowledgements: D. Armstrong, M. Dalton, K. Paschke, J. Mammei, M. Pitt, B. Waidyawansa and all my theory colleagues

A_n Experiments

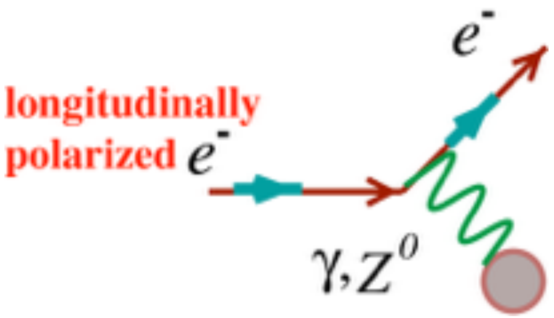
Krishna Kumar
Stony Brook University

The Electroweak Box
Workshop at ACFI, UMass, Amherst, September 28, 2017

Outline

- Brief motivation for A_n measurements
- Strange quark form factor experiments
- A_n in elastic electron-nuclear scattering
- A_n from electron-electron scattering
- Concluding remarks

Parity Violating Electron Scattering

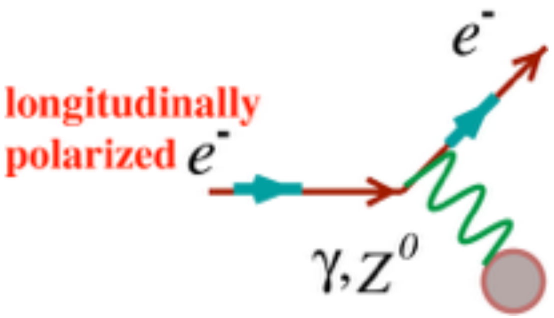


$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha}\left(g_A^e \boxed{g_V^T} + \beta\, g_V^e g_A^T\right)$$

Weak Charge Q_W

$\boxed{g_V \text{ is a function of } \sin^2\theta_W}$

Parity Violating Electron Scattering



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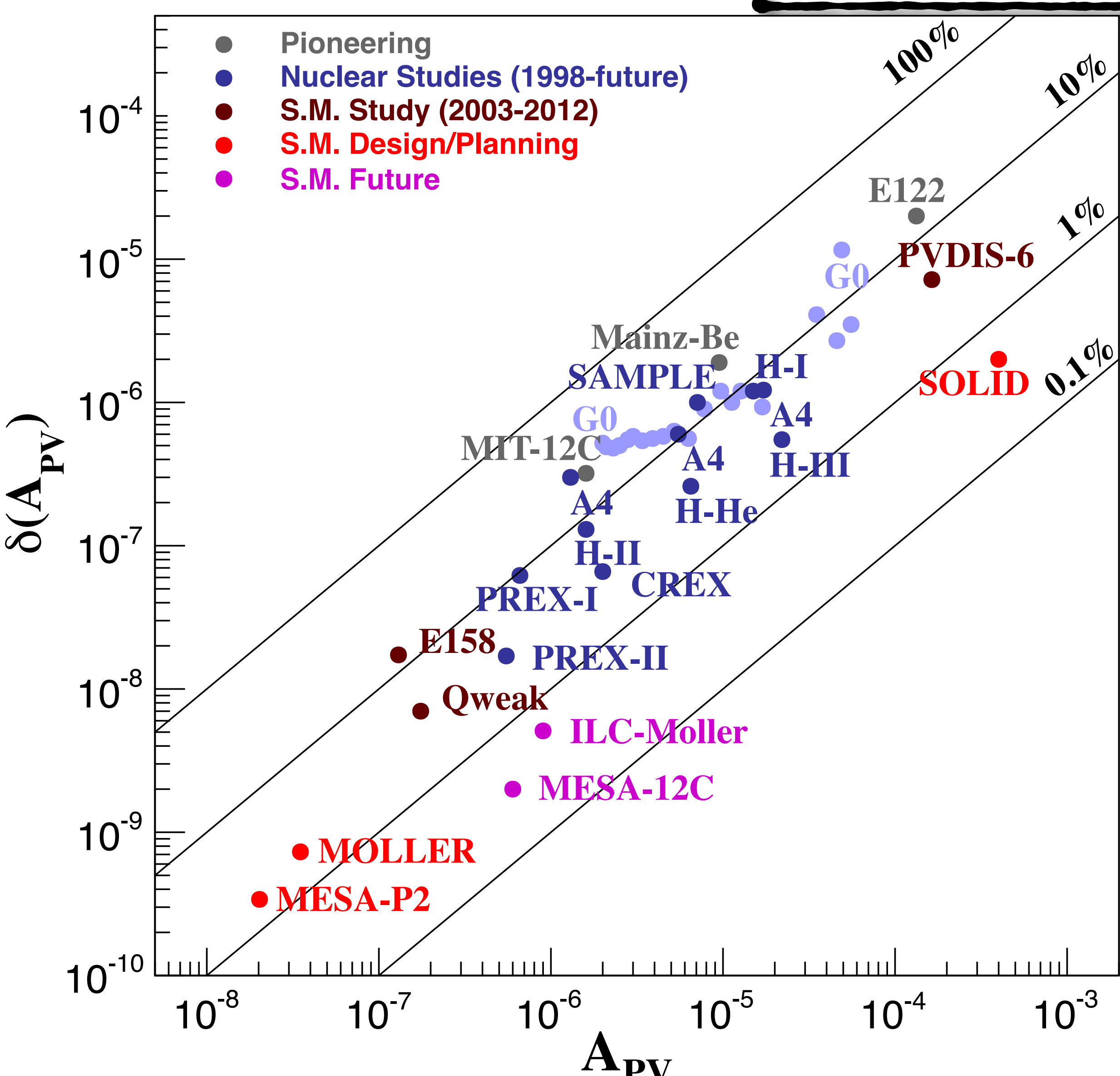


Variety of Physics Topics:

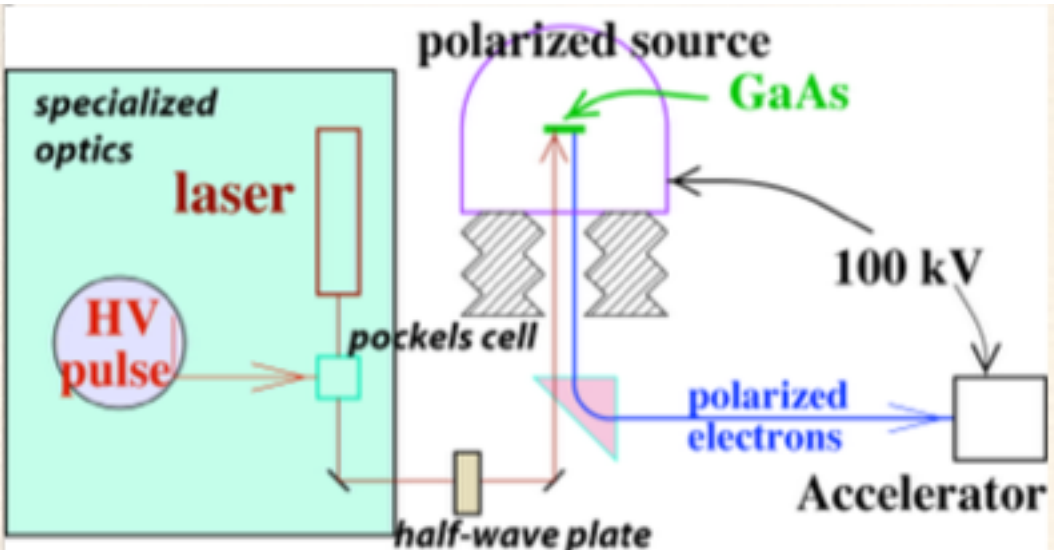
continuous interplay between hadron physics and electroweak physics

Steady improvements in accelerator and detector technology

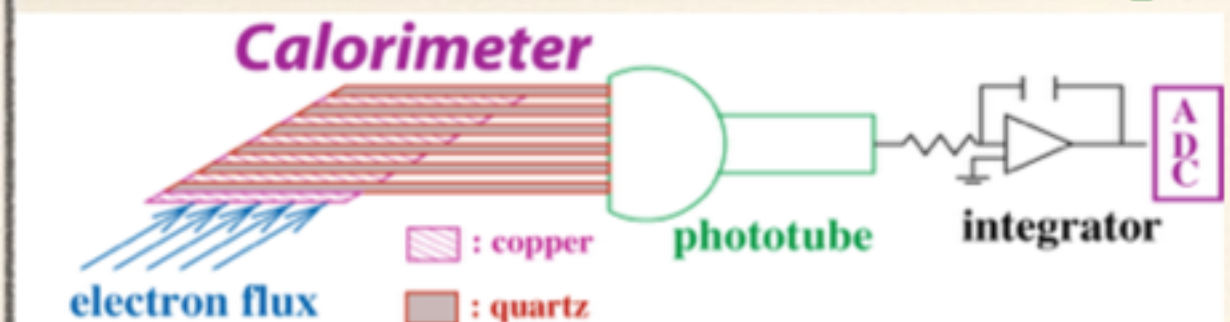
State of the Art

- sub-part per billion statistical reach and systematic control
- sub-1% normalization control

Experimental Technique



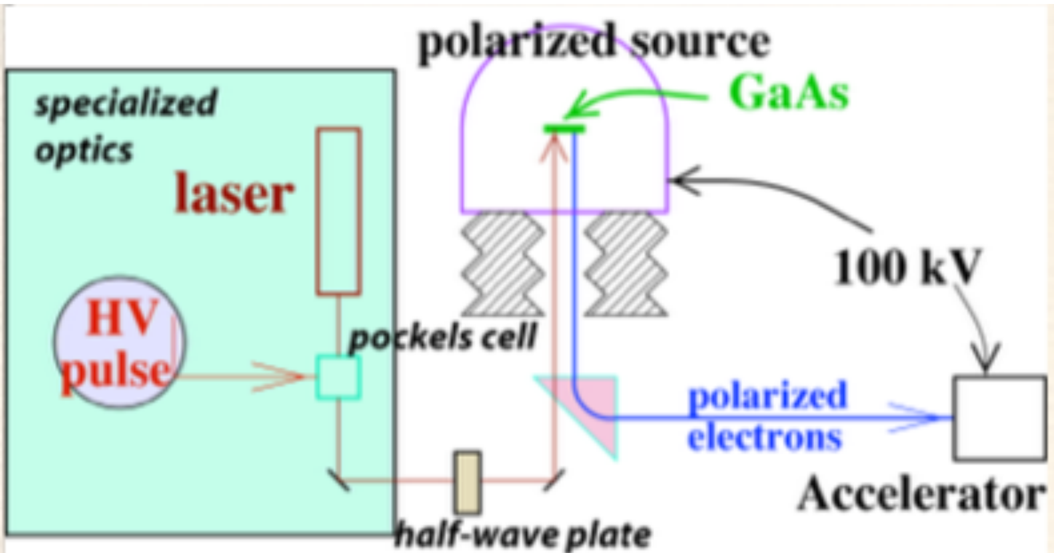
- Optical pumping of a GaAs wafer: "black magic" chemical treatment to boost quantum efficiency
- Rapid helicity reversal: polarization sign flips ~ 100 Hz to minimize the impact of drifts
- Helicity-correlated beam motion: under sign flip, beam stability at the micron level



"Flux Integration": very high rates

direct scattered flux to background-free region

Experimental Technique



- **Optical pumping of a GaAs wafer: "black magic" chemical treatment to boost quantum efficiency**
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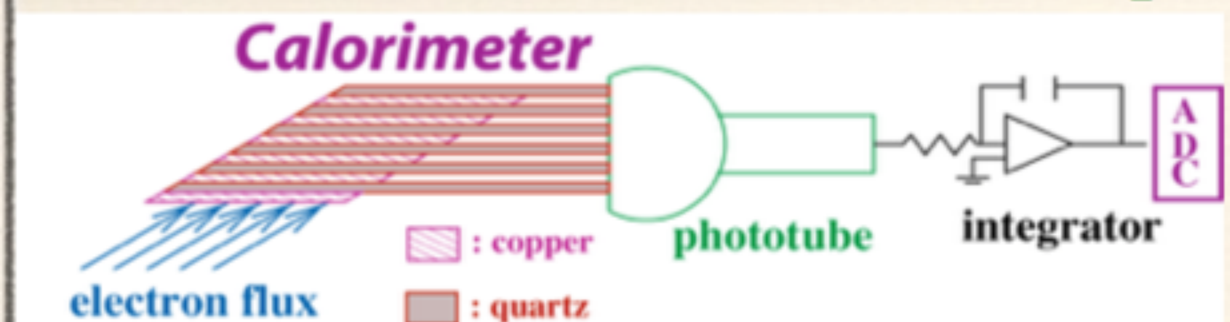


"Flux Integration": very high rates

direct scattered flux to background-free region

Symmetry of the apparatus helps systematic control:

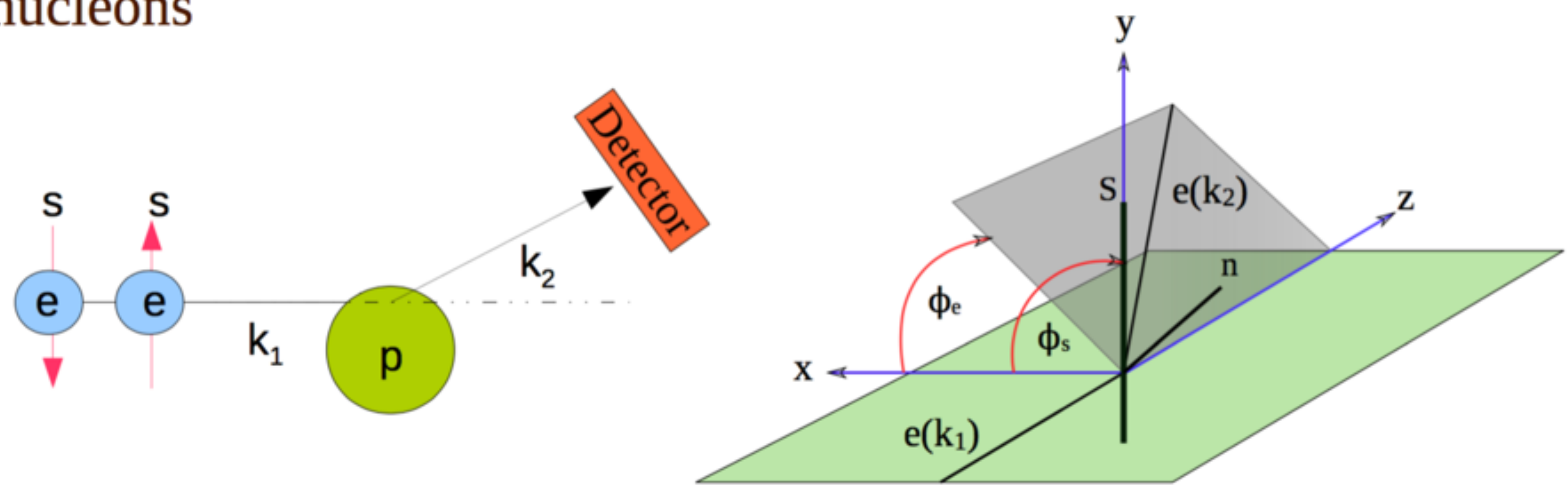
$$A_{corr} = A_{det} - A_Q + \alpha\, \Delta_E + \Sigma\beta_i\, \Delta x_i$$

Symmetric azimuthal coverage:
Up cancels down, right cancels left…

Assumption on previous page: perfect longitudinal polarization

The A_n Systematic

- Transversely polarized electrons scattering from unpolarized nucleons

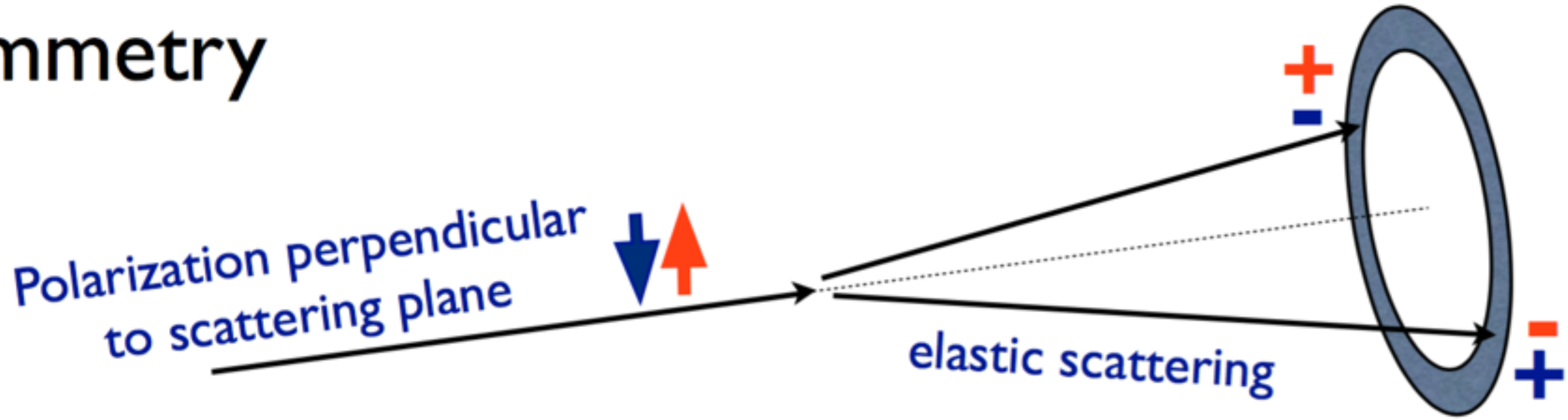


- Measured asymmetry has an azimuthal dependence

$$A_T(\phi_e) = \frac{N\uparrow - N\downarrow}{N\uparrow + N\downarrow} = B_n . S \sin(\phi_e - \phi_s) = B_n (P^V \cos\phi_e - P^H \sin\phi_e)$$

$$P^V = S \sin\phi_s \text{ and } P^H = S \cos\phi_s$$

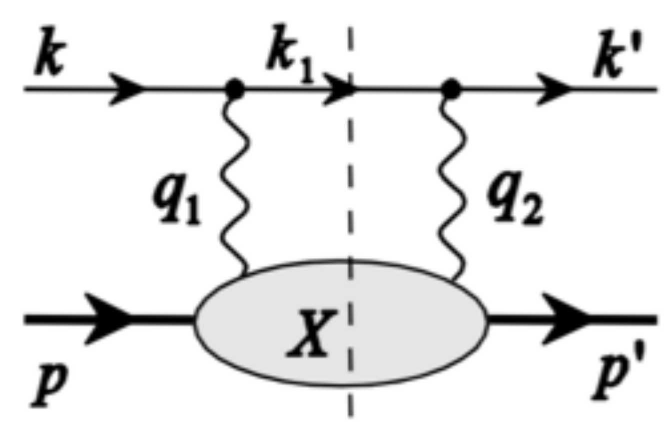
B_n asymmetry



time-reversal invariance forces this SSA to vanish for one-photon exchange

arises from an interference between the one-photon exchange (Born) amplitude and the imaginary part of the two-photon exchange amplitude

$$B_n = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = \frac{2\mathrm{Im}(T_{2\gamma} \cdot T^*_{1\gamma})}{|T_{1\gamma}|}$$



intermediate states on-shell

Asymmetry is very small

$$B_n \sim \alpha_{\mathrm{em}} \frac{m_e}{E_e} \sim 10^{-6} - 10^{-5}$$

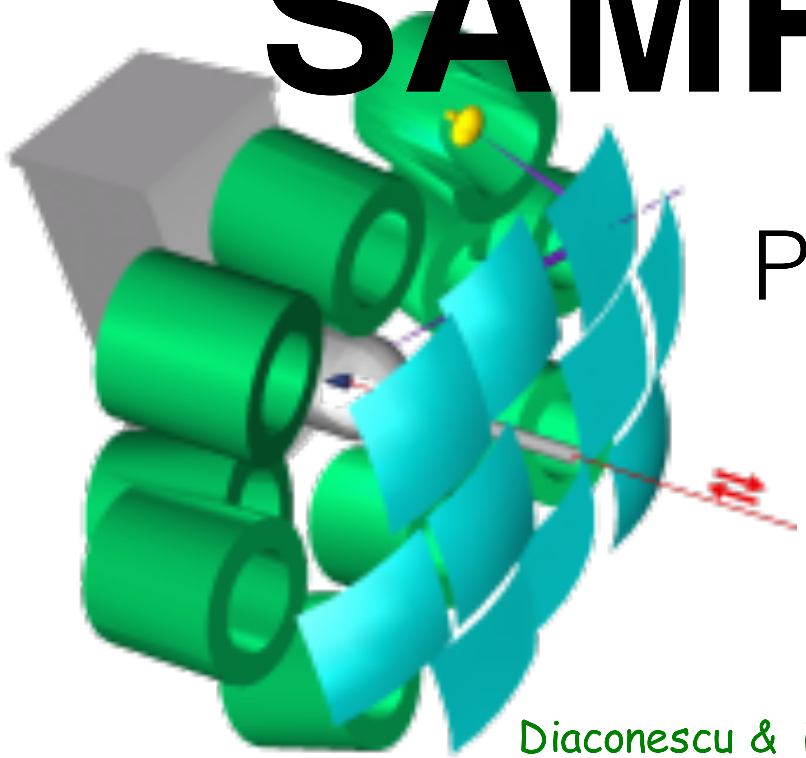
2-photon

ultra-relativistic

PV Experiments

Experiment	Magnets	Detector	Count	e^- angles($^\circ$)
SLAC E122	DQD	Pb Glass	No	4
Mainz	None	Air C	No	130
MIT-Bates	Q	Lucite C	No	35
SAMPLE	None	Air C	No	146
HAPPEX-I	QQDQ	Pb-Lucite	No	15
G0	Toroid	Scintillator	Yes	6–20; 110
A4	None	PbF_2	Yes	35; 145
SLAC E158	QQQQ	Cu-Quartz	No	2
HAPPEX-II	DQQDQ	Cu-Quartz	No	5
PREx -I	DQQDQ	Quartz	No	5
HAPPEX-III	QQDQ	Pb-Lucite	No	15
PVDIS	QQDQ	Pb Glass	Yes	19
PREx -II	DQQDQ	Quartz	No	5
CREx	DQQDQ	Quartz	No	4
Qweak	Toroid	Pb-Quartz	No	5
Møller	Toroid	Quartz	No	0.3–1
SoLID	Solenoid	Package	Yes	22–35
P2	Solenoid	Quartz	No	20
Mainz C	Solenoid	Quartz	No	40

SAMPLE at MIT-Bates



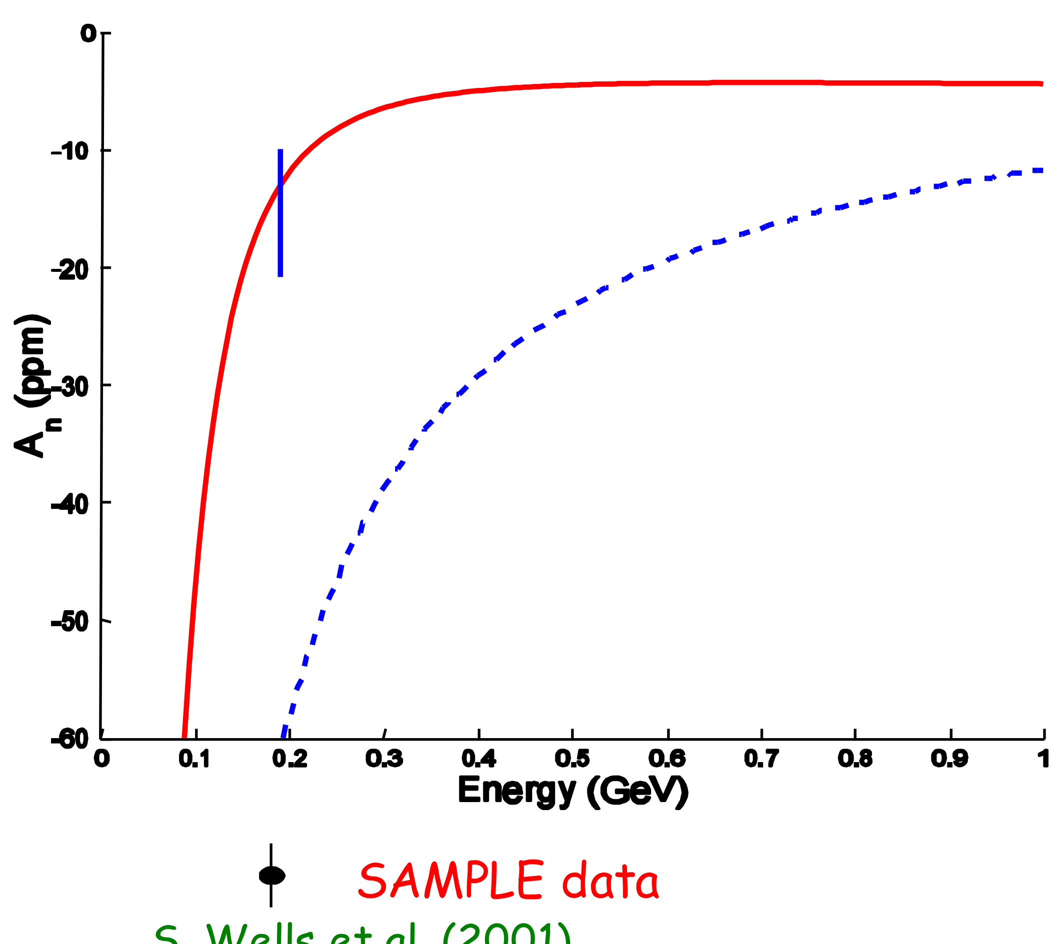
Proton Target
200 MeV

open geometry,
integrating

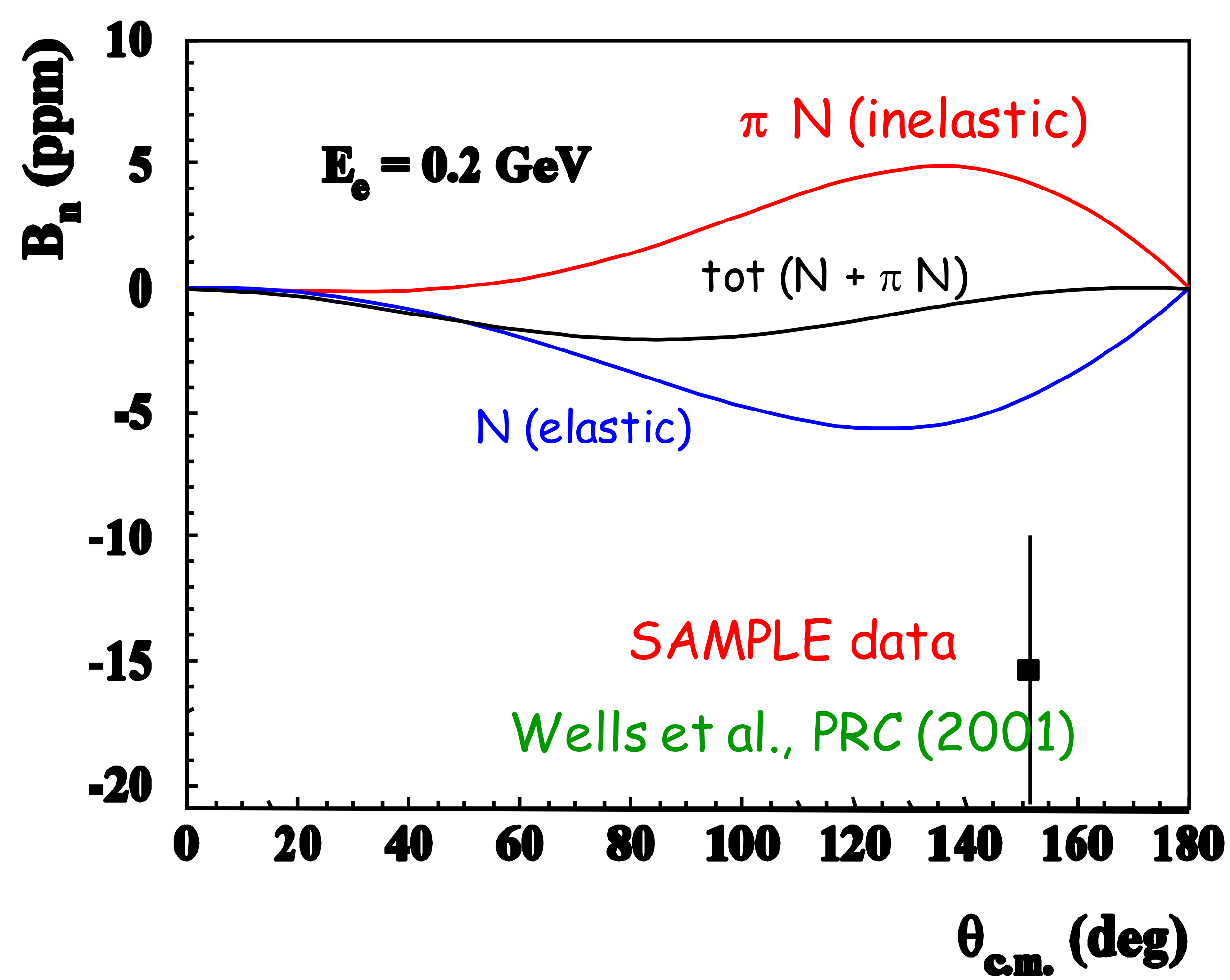
G_M^s, (G_A) at Q^2 = 0.1 GeV^2

Archival Plots

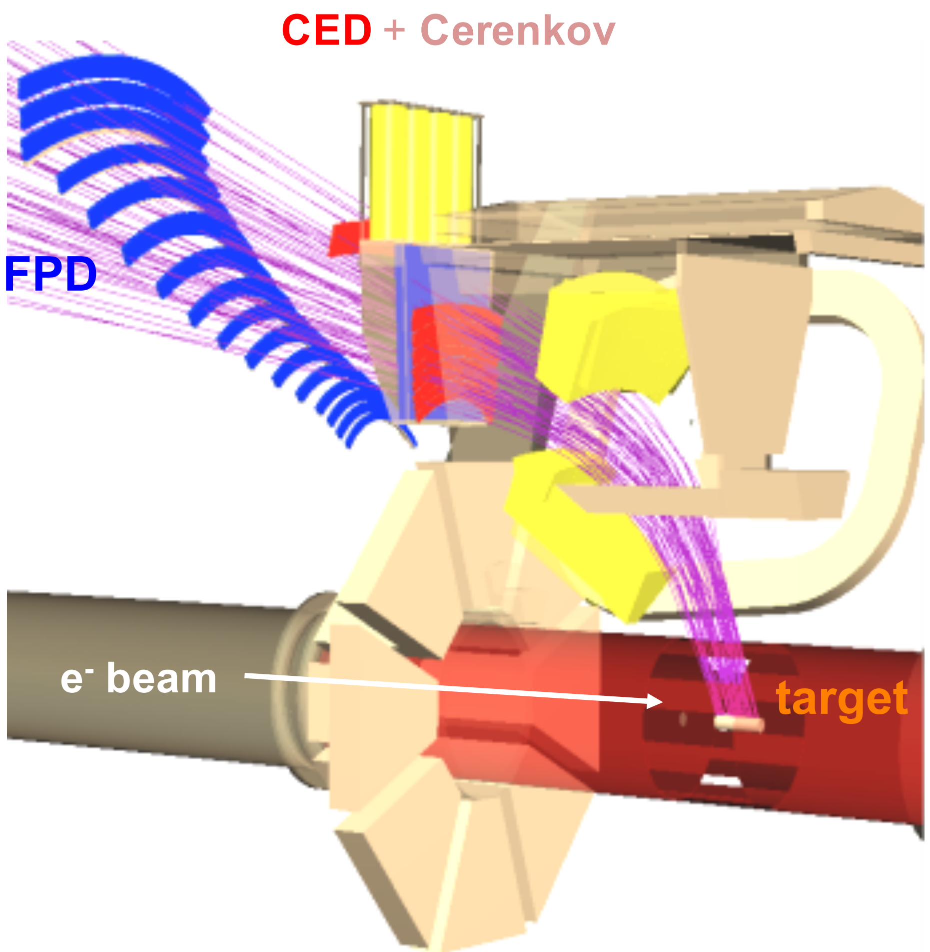
Diaconescu & Ramsey-Musolf (2004)



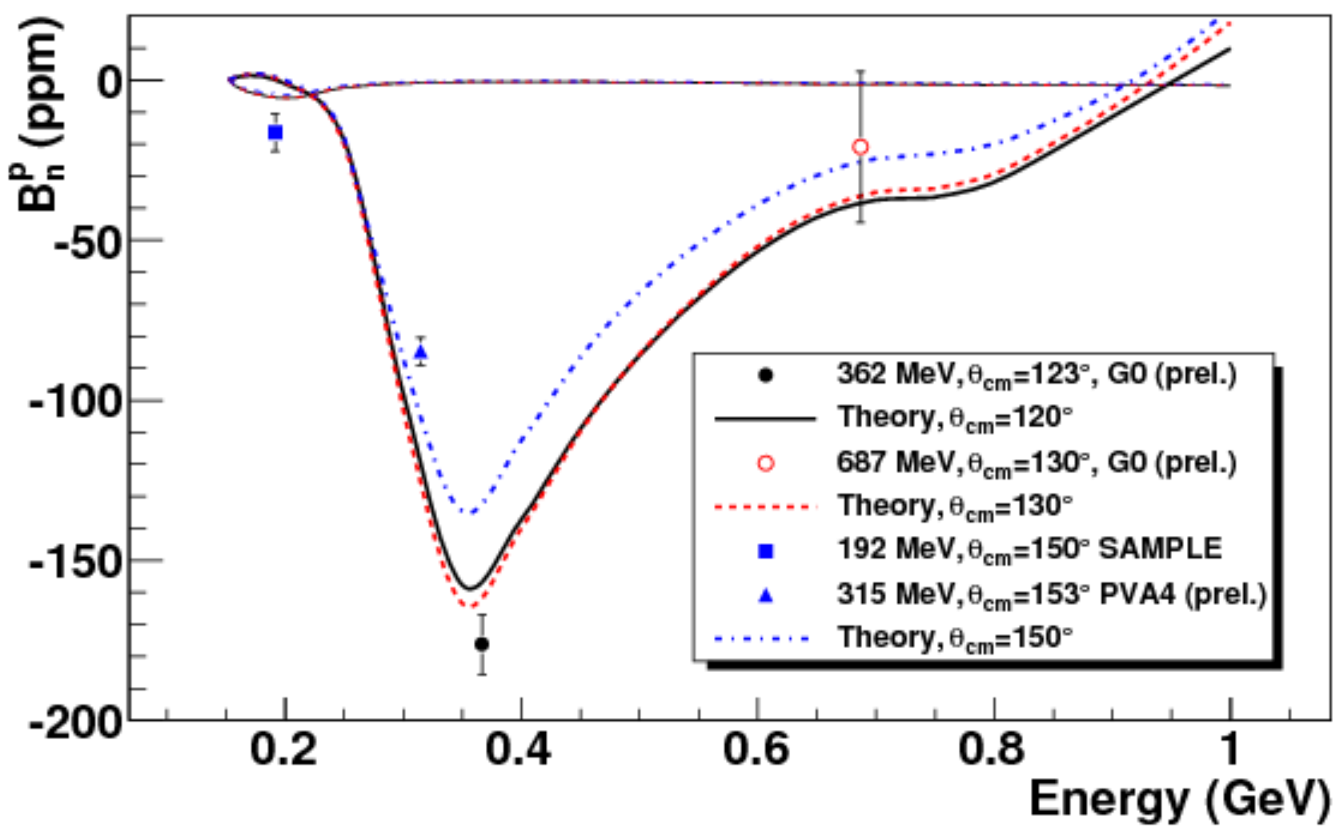
Pasquini & Vdh (2004)



G0 at JLab

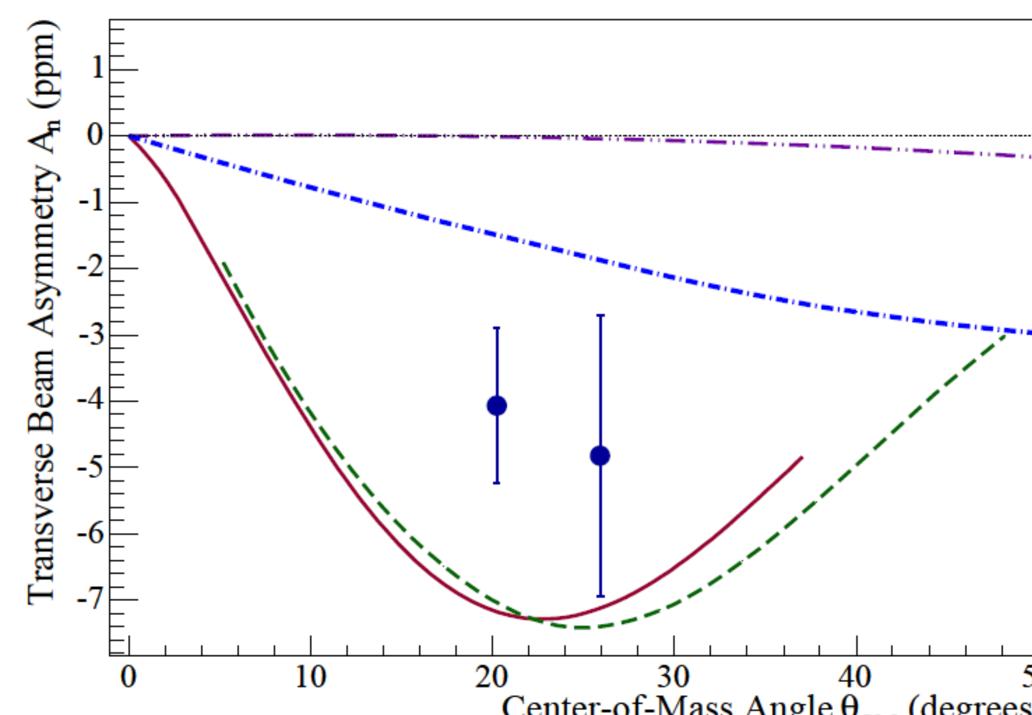


Proton Target



Forward angle: recoiling proton detected

Backward angle: Electrons and Pions detected



J. Mammei

G0 Neutron (from ^{2}H)

for the neutron

362 MeV:

σ_p = 23 µb/sr

σ_n = 8 µb/sr

687 MeV:

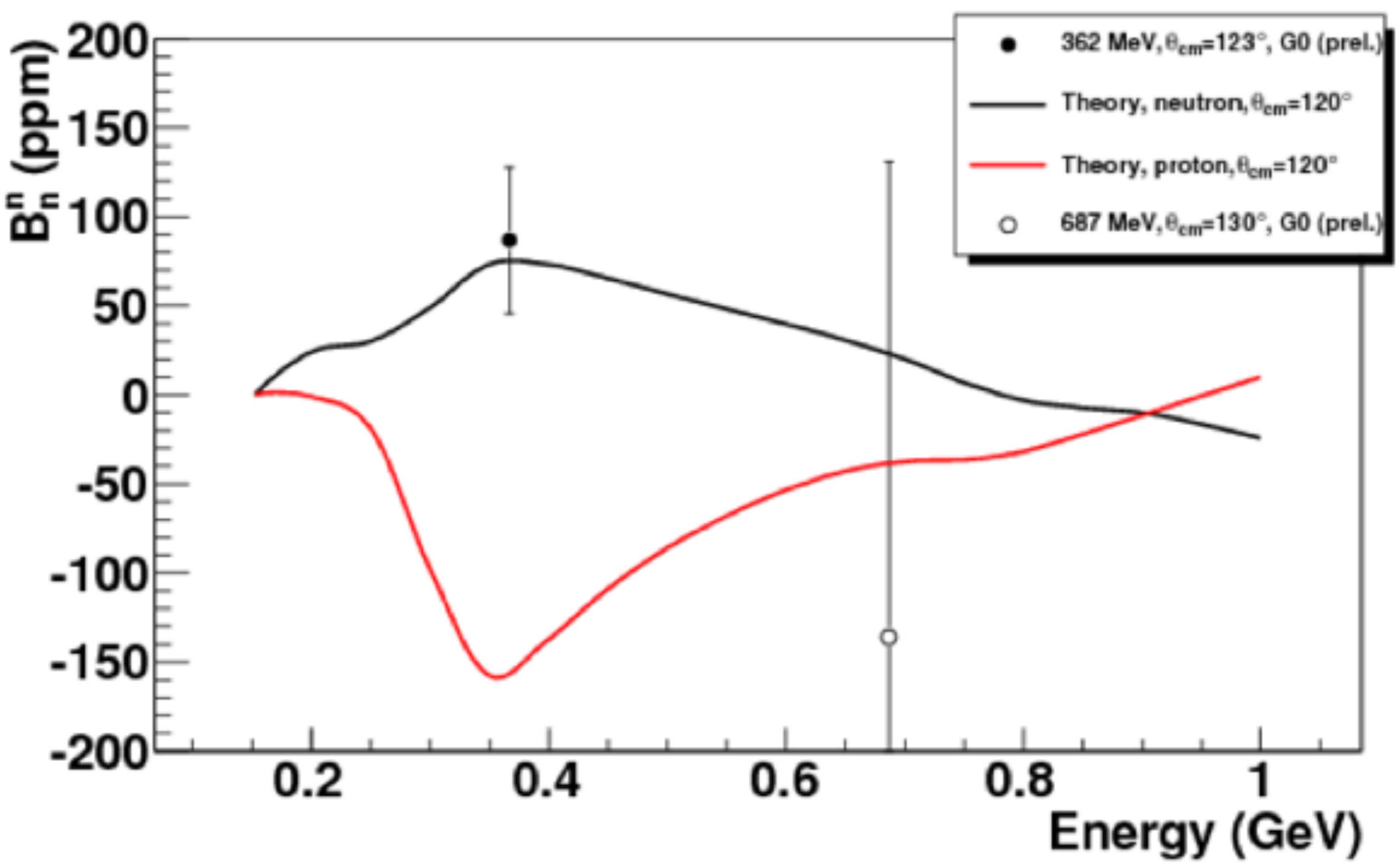
σ_p = 2.6 µb/sr

σ_n = 1.1 µb/sr

Assume 5% error on cross section

In the quasi-static approximation:

$$B_n^d = \frac{\sigma_p B_n^p + \sigma_n B_n^n}{\sigma_p + \sigma_n}$$



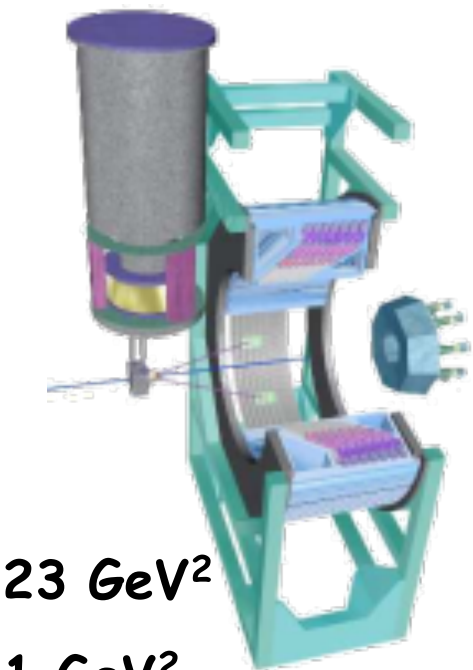
For 362MeV:

$$B_n^n = 86.7 \pm 41\, ppm$$

For 687MeV:

$$B_n^n = 136 \pm 267\, ppm$$

PVA4 at Mainz



Recent publication

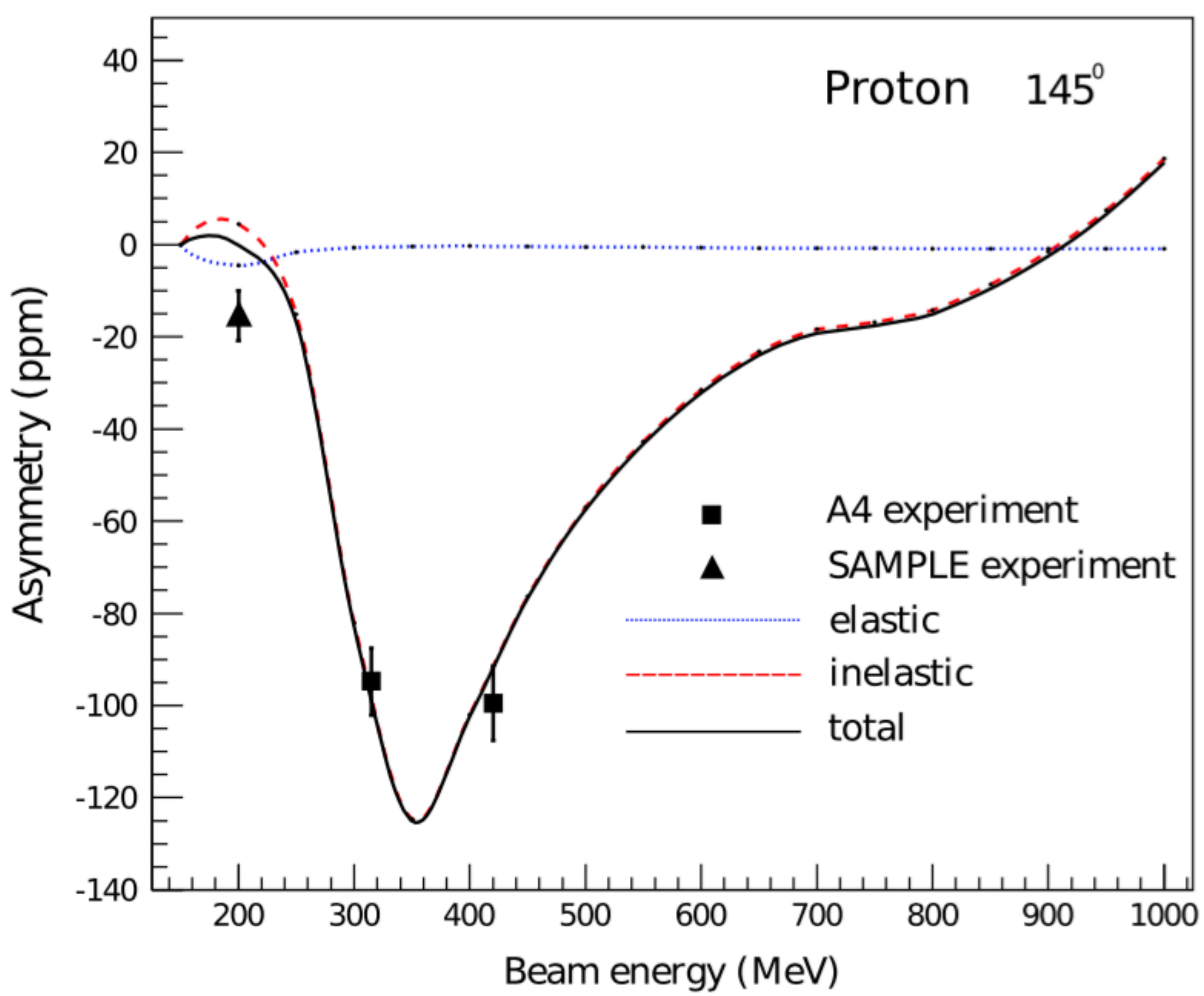
Precise backward angle measurements

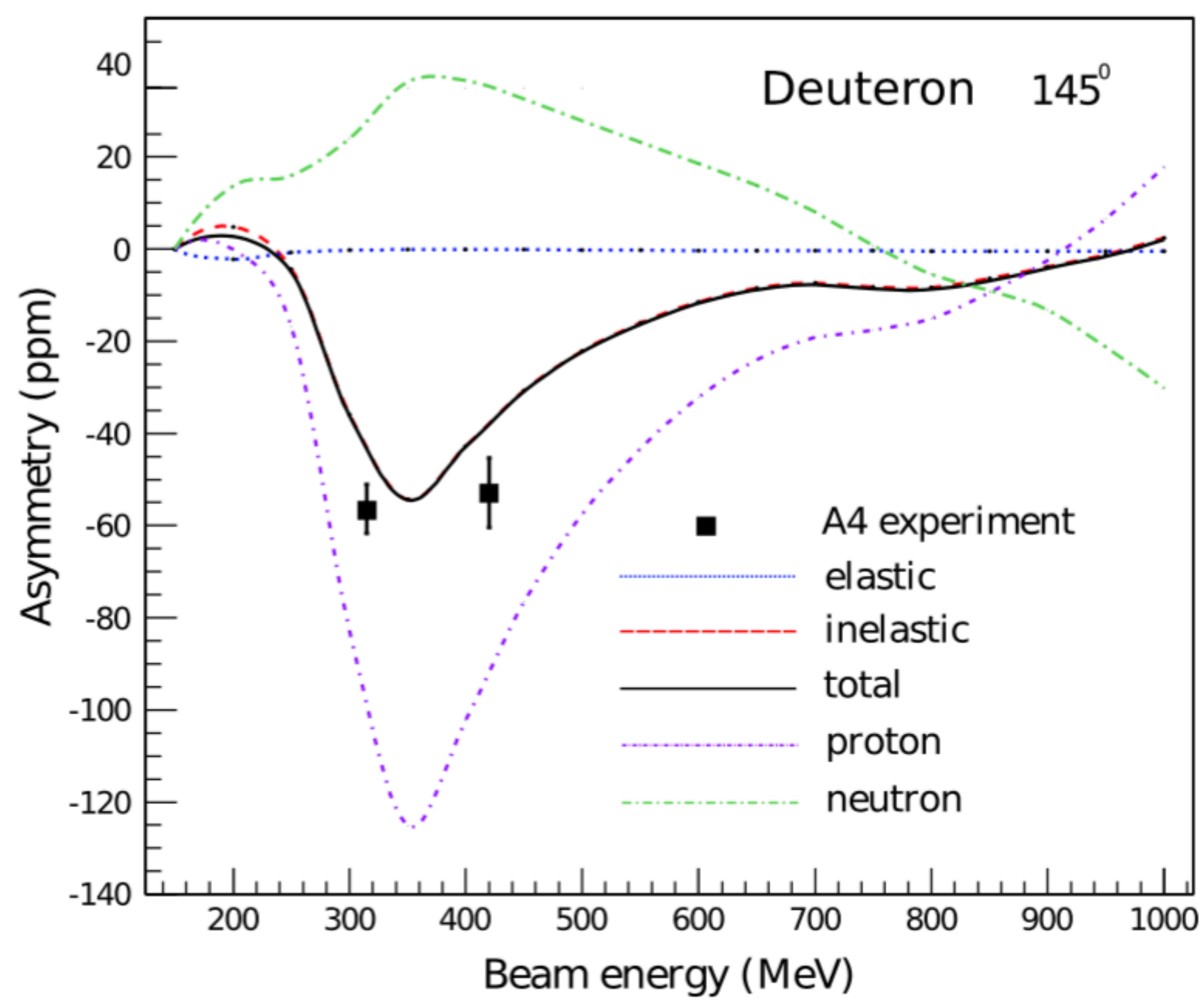
Both ^1H and ^2H

$G_E^s + 0.23\, G_M^s$ at $Q^2 = 0.23$ GeV^2

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

G_M^s, G_A^e at $Q^2 = 0.1, 0.23, 0.5$ GeV^2





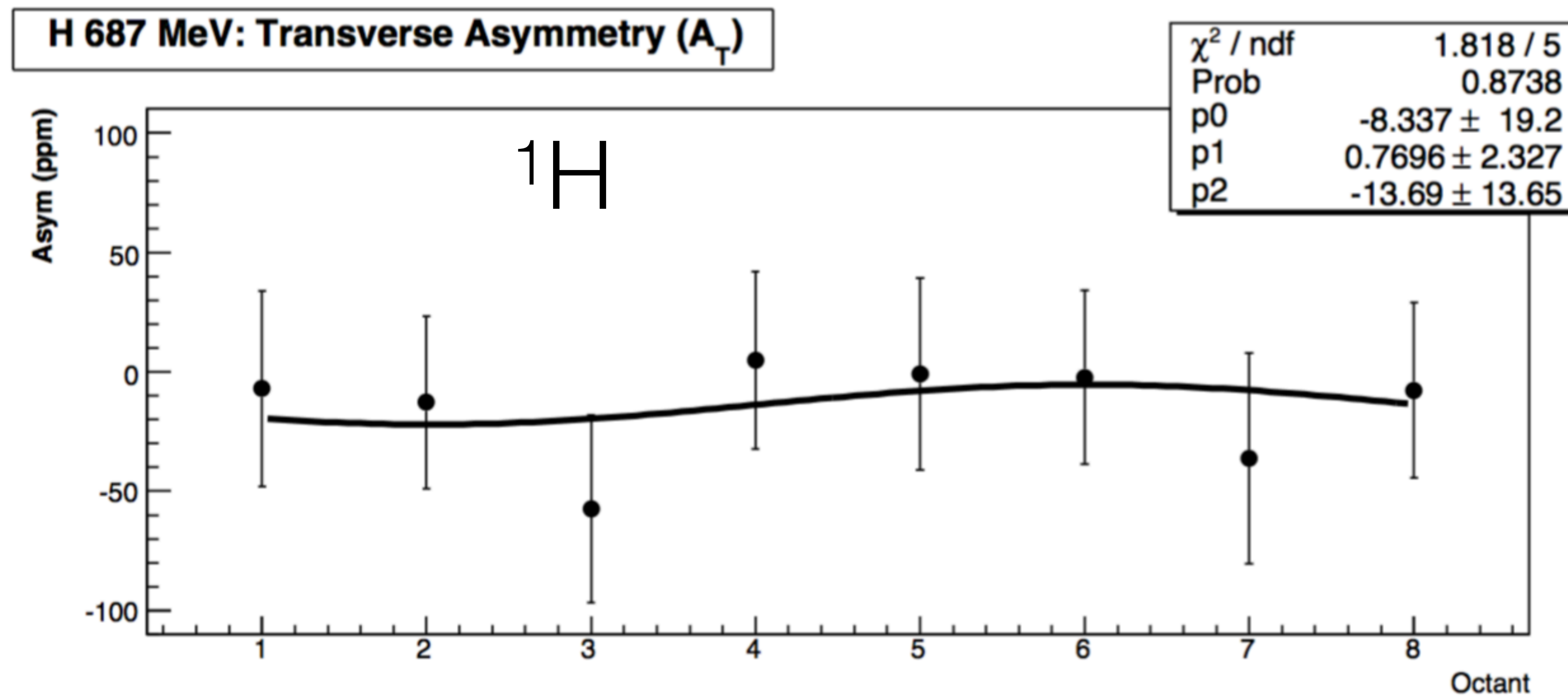
G0 Inelastic Scattering

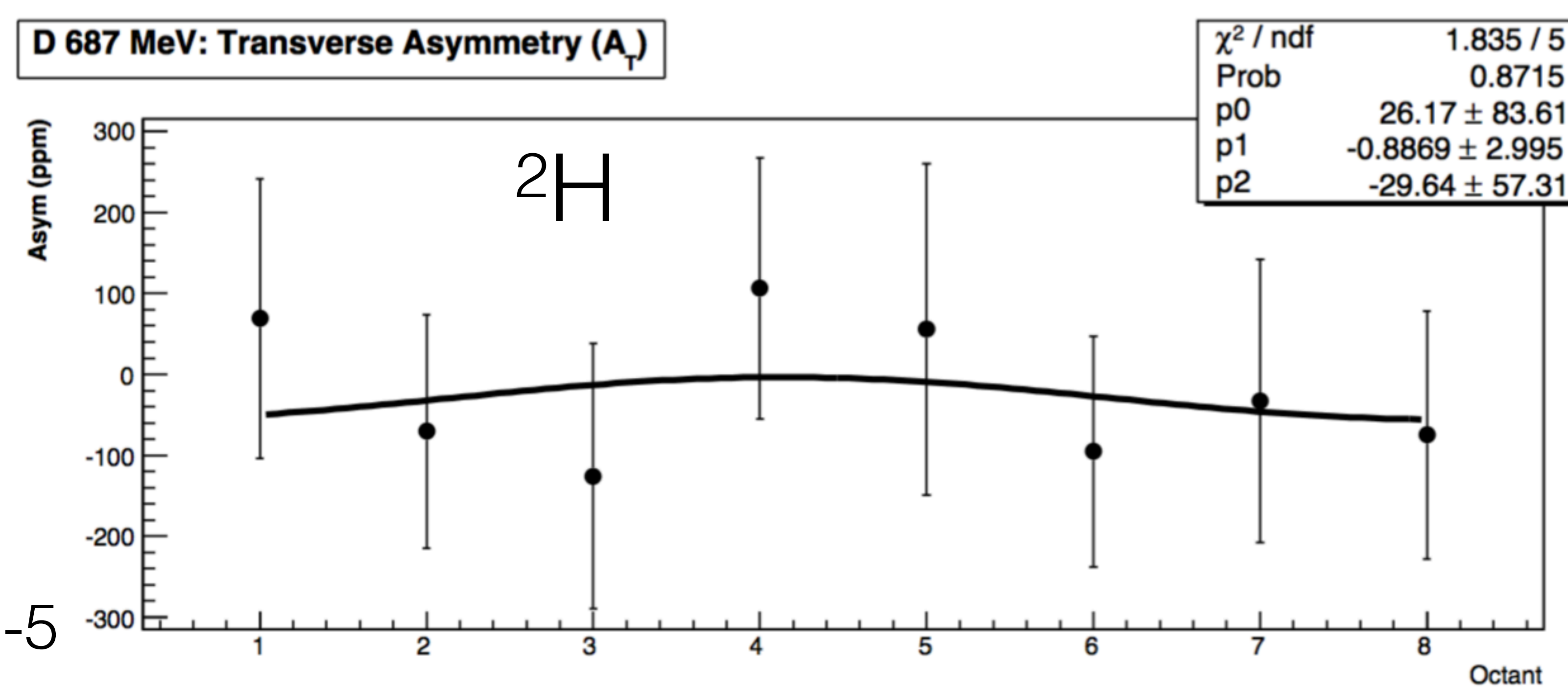
Backward angle measurements have the ability to tag electrons and pions, and there are bins dominated by inelastic electrons

C. Capuano

Ph.D. Thesis, William and Mary

B_n less than few x 10^{-5}



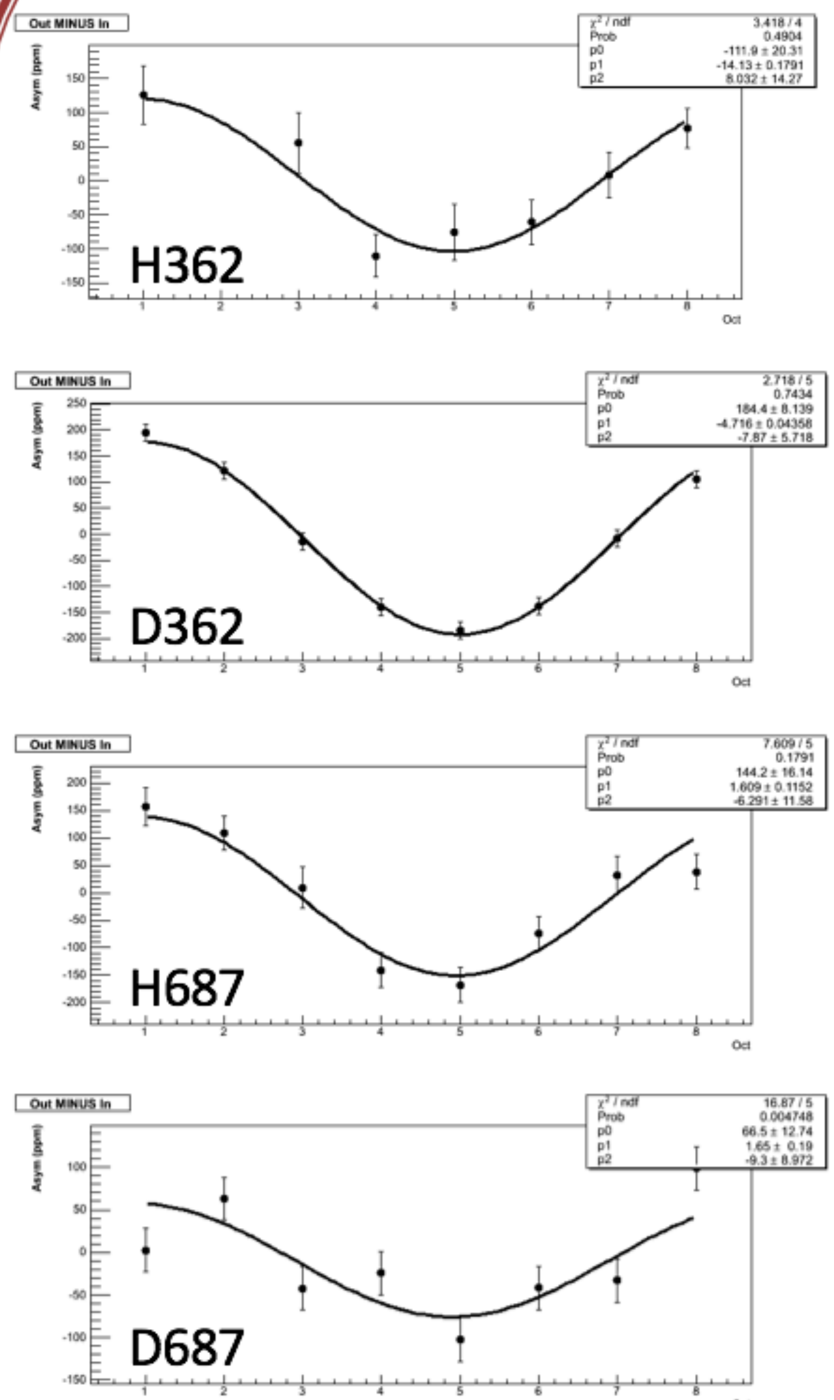


J. Mammei

G0 Pion Production

Pion Asymmetries

raw data



Dataset	Amplitude	ϕ_0
H362	-112 ± 20	-90° ± 2°
D362	-184 ± 8	-90° ± 2°
H687	-144± 16	-88° ± 7°
D687	-67 ± 13	-85° ± 11°

Note: there is no background asymmetry correction here; there may be very large electron contamination

errors are statistical

Trying to determine the theoretical implications – input is welcome!

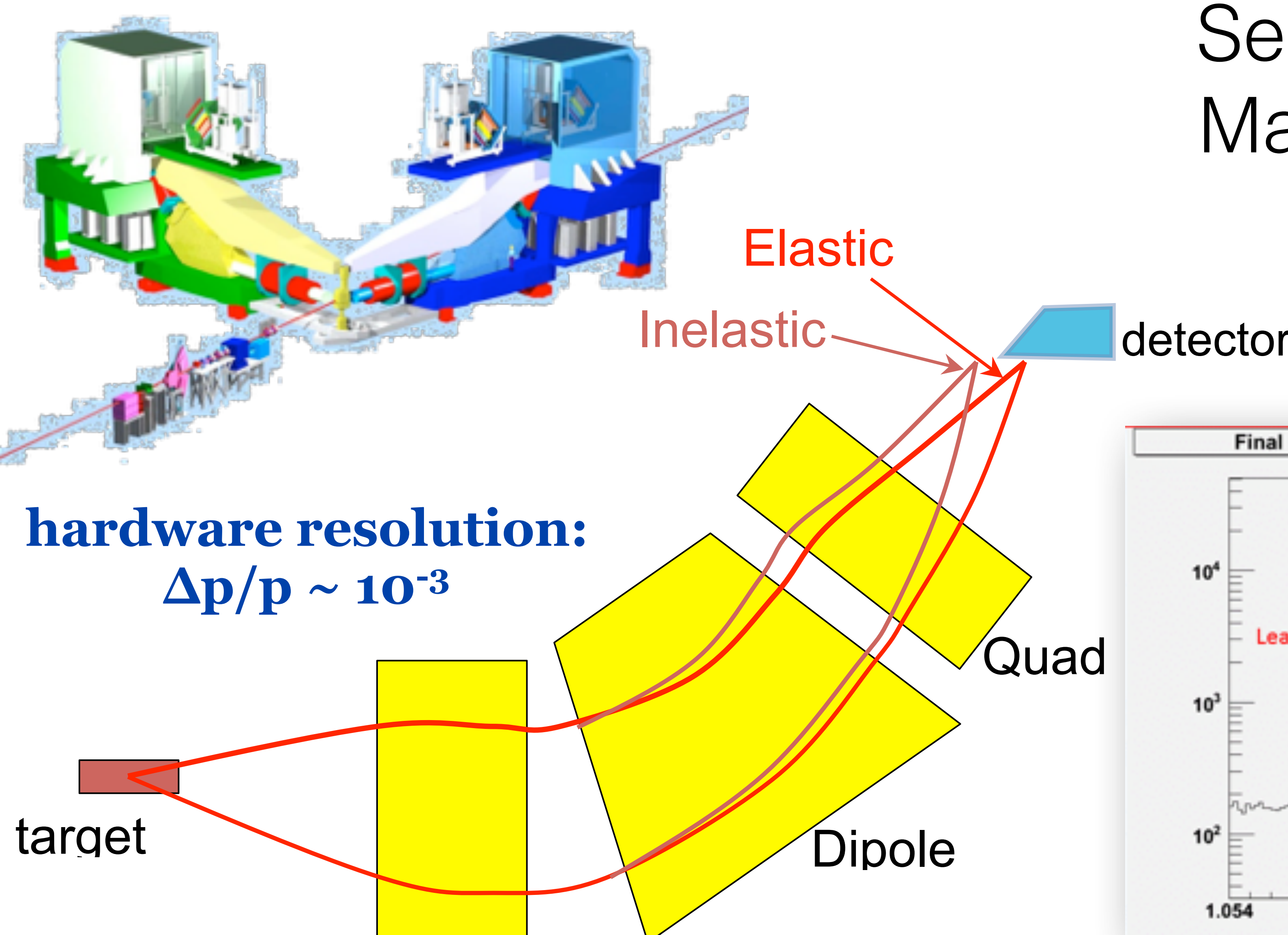
Hall C Users Meeting

30

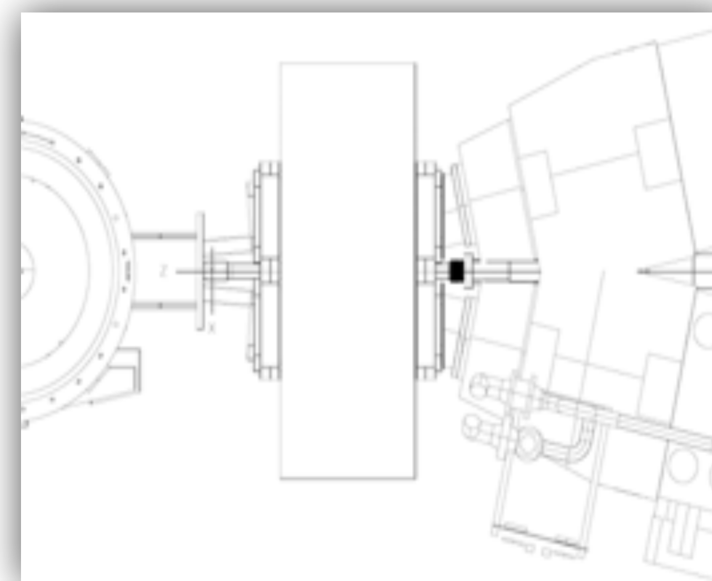
Very Forward Angle Measurements: HAPPEX/PREX (Hall A) and Qweak (Hall C)

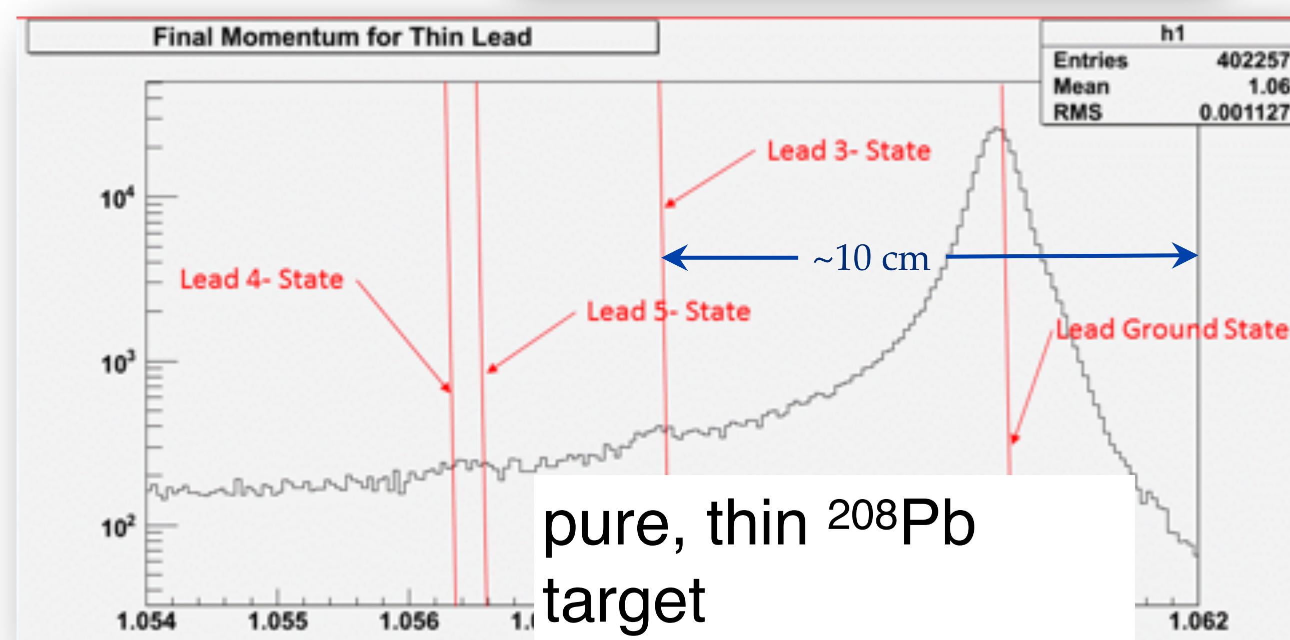
Relationship between photo production cross-section and forward scattering amplitude works well when $q/E \to 0$

hardware resolution: $\Delta p/p \sim 10^{-3}$

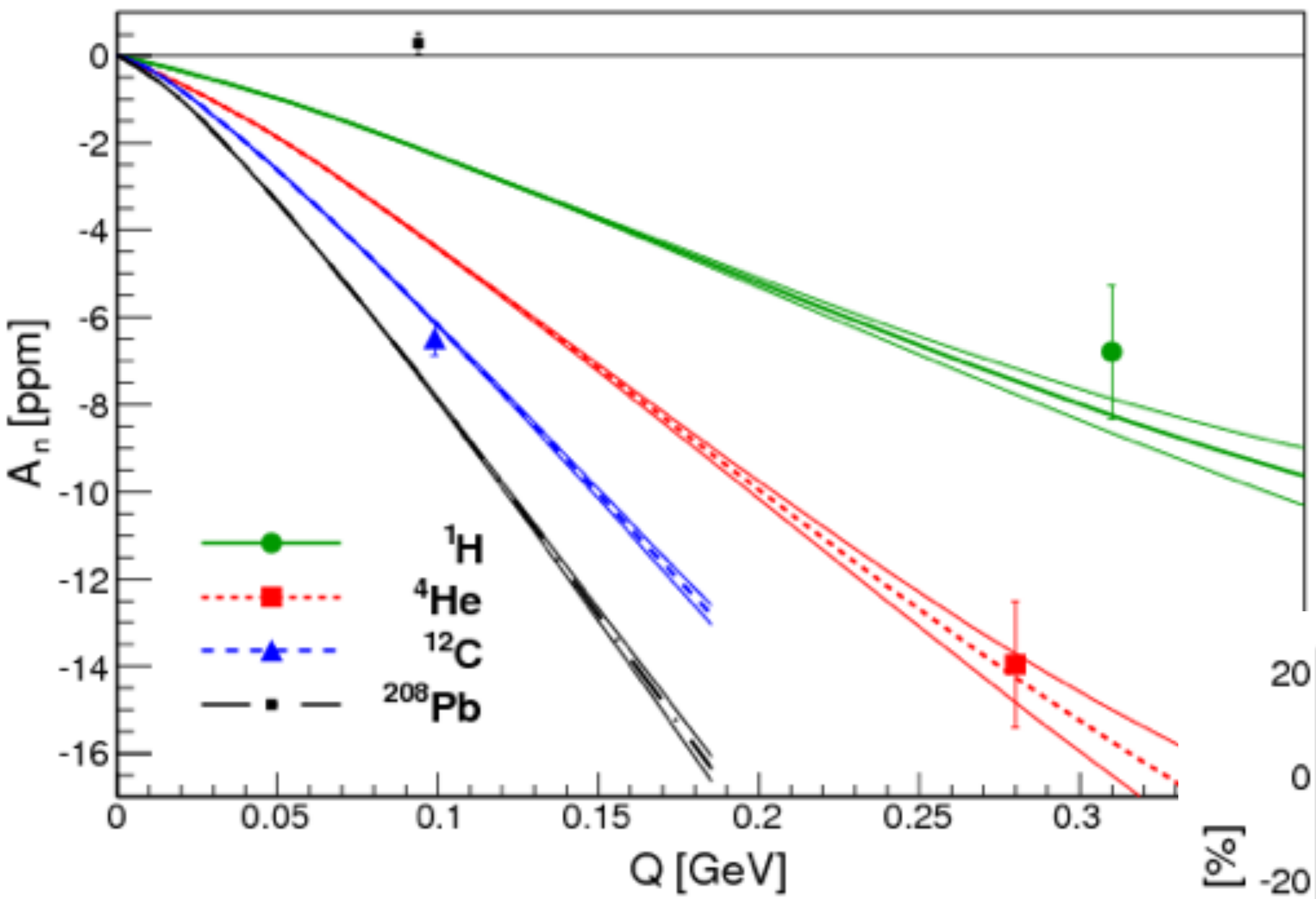


Septum Magnet



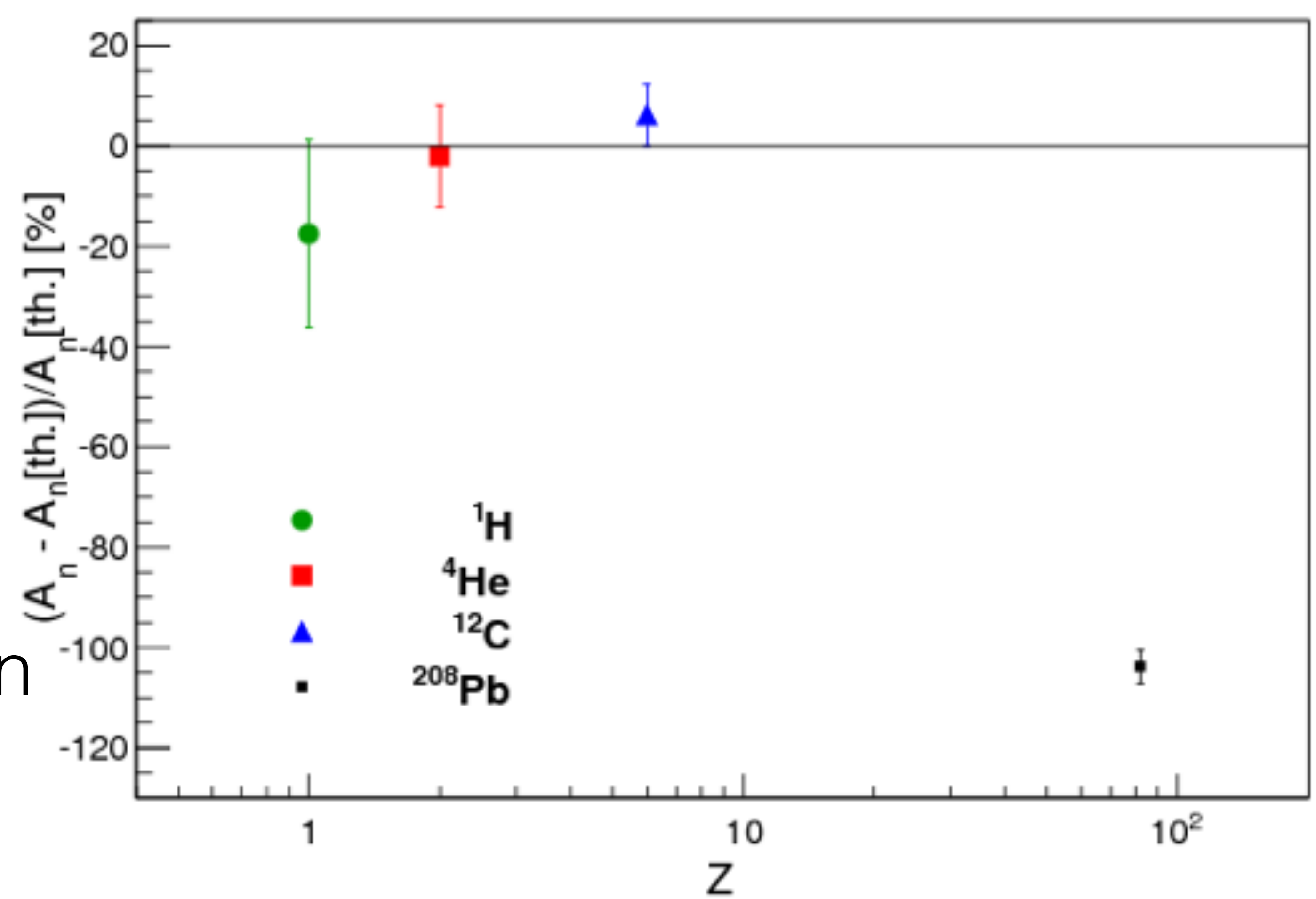


HAPPEX/PREX Data



Prediction fails dramatically for ^{208}Pb

Any relevance for precision calculations of gamma-Z boxes for e-N scattering predictions?



theory prediction works remarkably well for light nuclei

work by A. Afanasev, M. Gorchstein and collaborators

Talks by W. Deconinck and J. Dowd

B. Waidyawansa

QWeak

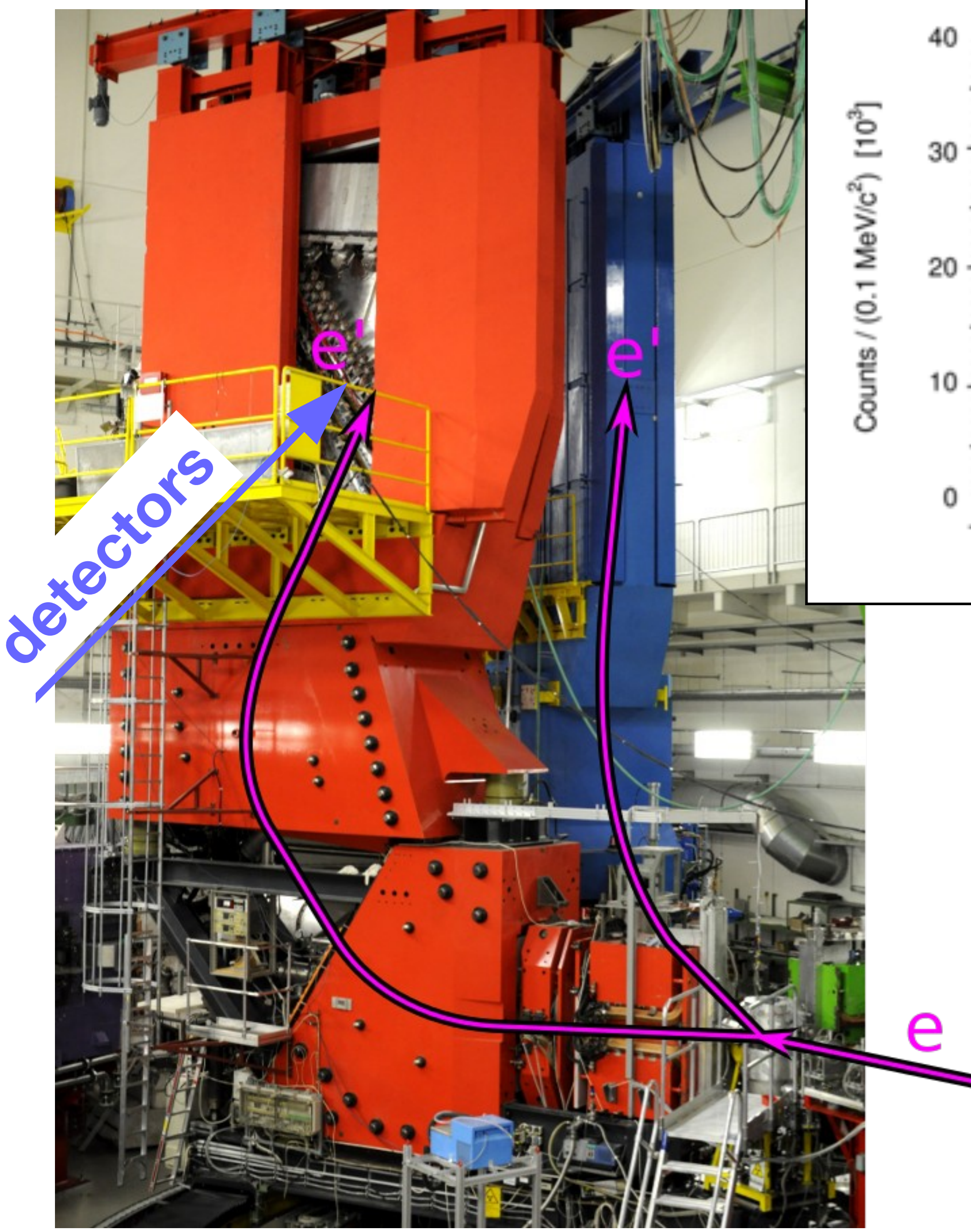
right column obsolete

Lots of new BNSSA measurements!

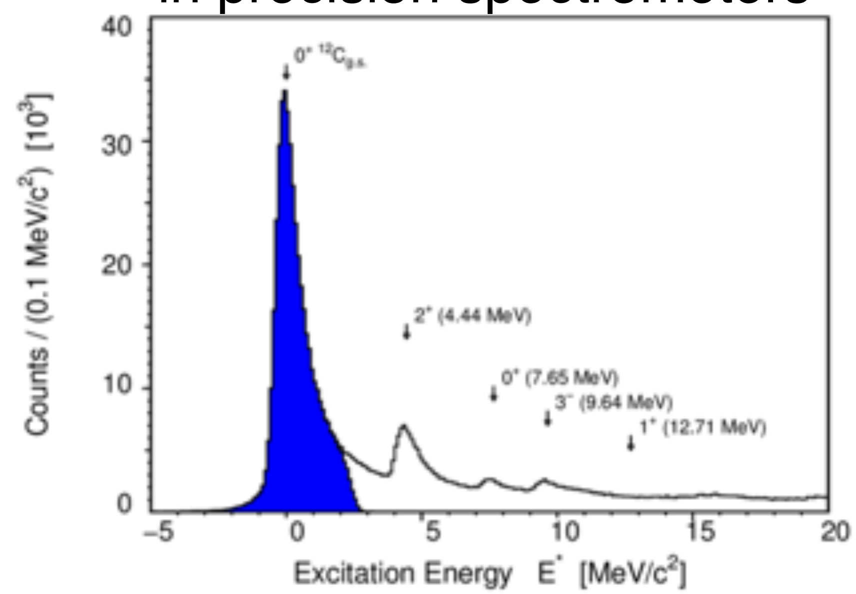
Interaction	Target	Analysis Status
Elastic e+p at E = 1.165 GeV	Hydrogen	Ready for publication
	Aluminum	Ongoing
	Carbon	Ongoing
Inelastic e+p with a Δ in the final state E=0.877 GeV and 1.165 GeV	Hydrogen, Al, C	Ongoing
Elastic e+e at E=0.877 GeV	Hydrogen	Ongoing
Deep inelastic e+p at W=2.5GeV	Hydrogen	Ongoing
Pion electro-production at E=3.3GeV	Hydrogen	Ongoing

Measuring A_n from ^{12}C at Mainz-A1

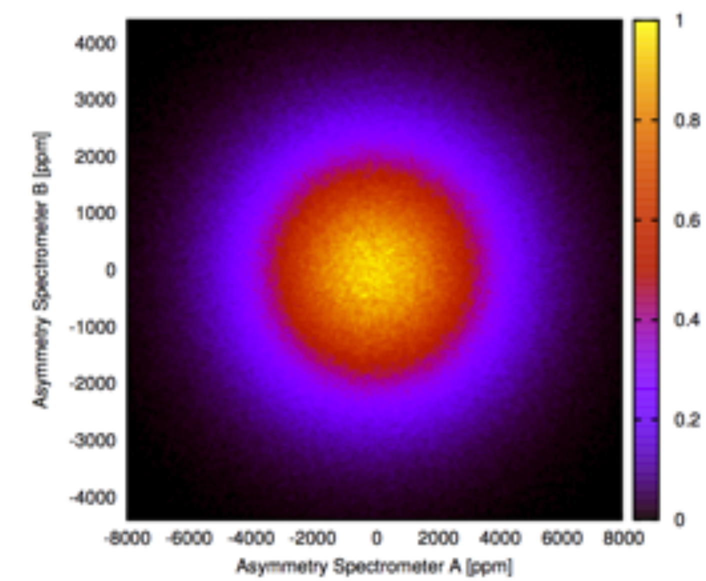
Michaela Thiel, Anselm Esser, A1 collaboration K. Paschke

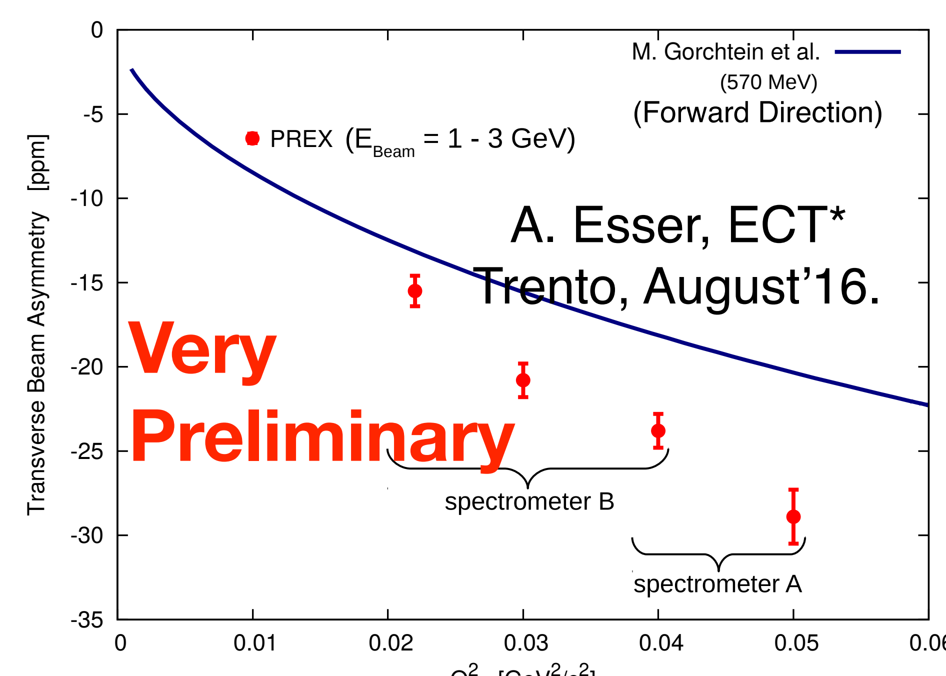


elastic peak is well-separated in precision spectrometers



raw data is uncorrelated between left/right spectrometers: very quiet beam!

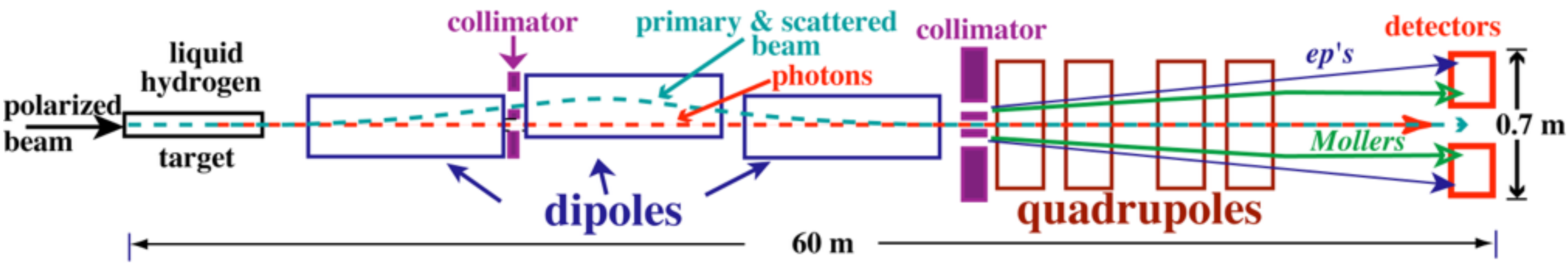


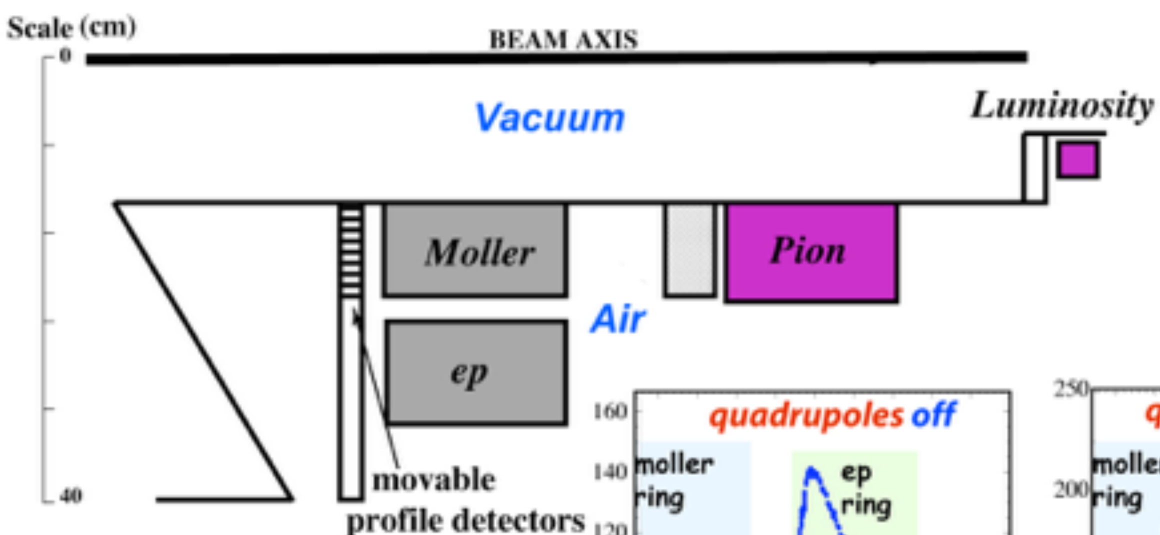


Future: could use other targets (^{28}Si, ^{40}Ca, ^{208}Pb)
210-570 MeV beam energies, 15°-25° scattering angles

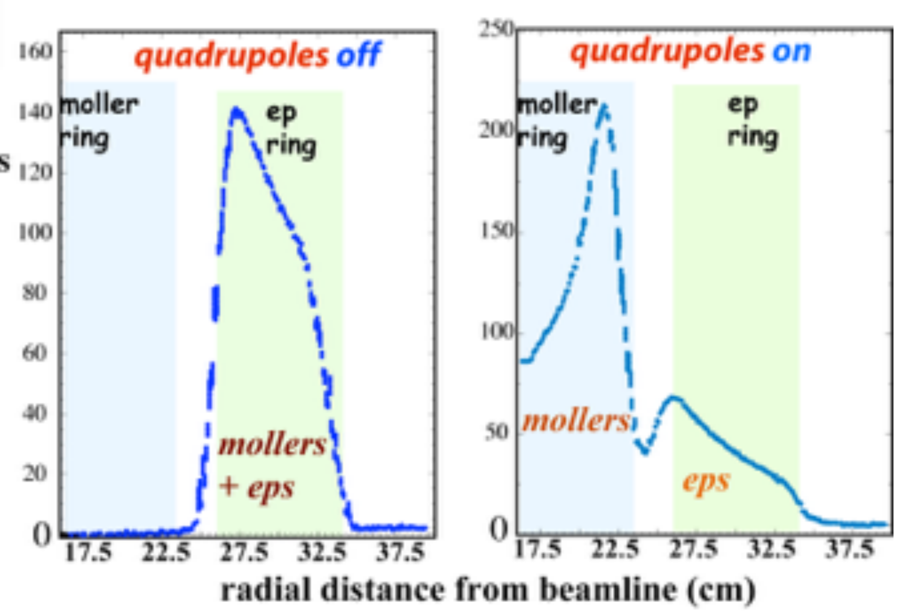
E158: Electron-Electron (Møller) Scattering

~ 11 ppb raw statistical error at highest E_{beam}, ~ 0.4% error on weak mixing angle





Hydrogen Target



* 4 integrating detectors
* profile detectors for calibration

Apart from longitudinal running, transversely polarized electron beam data was collected

A_n must vanish at 90 degrees in the COM for Møller scattering

E158 Transverse Data

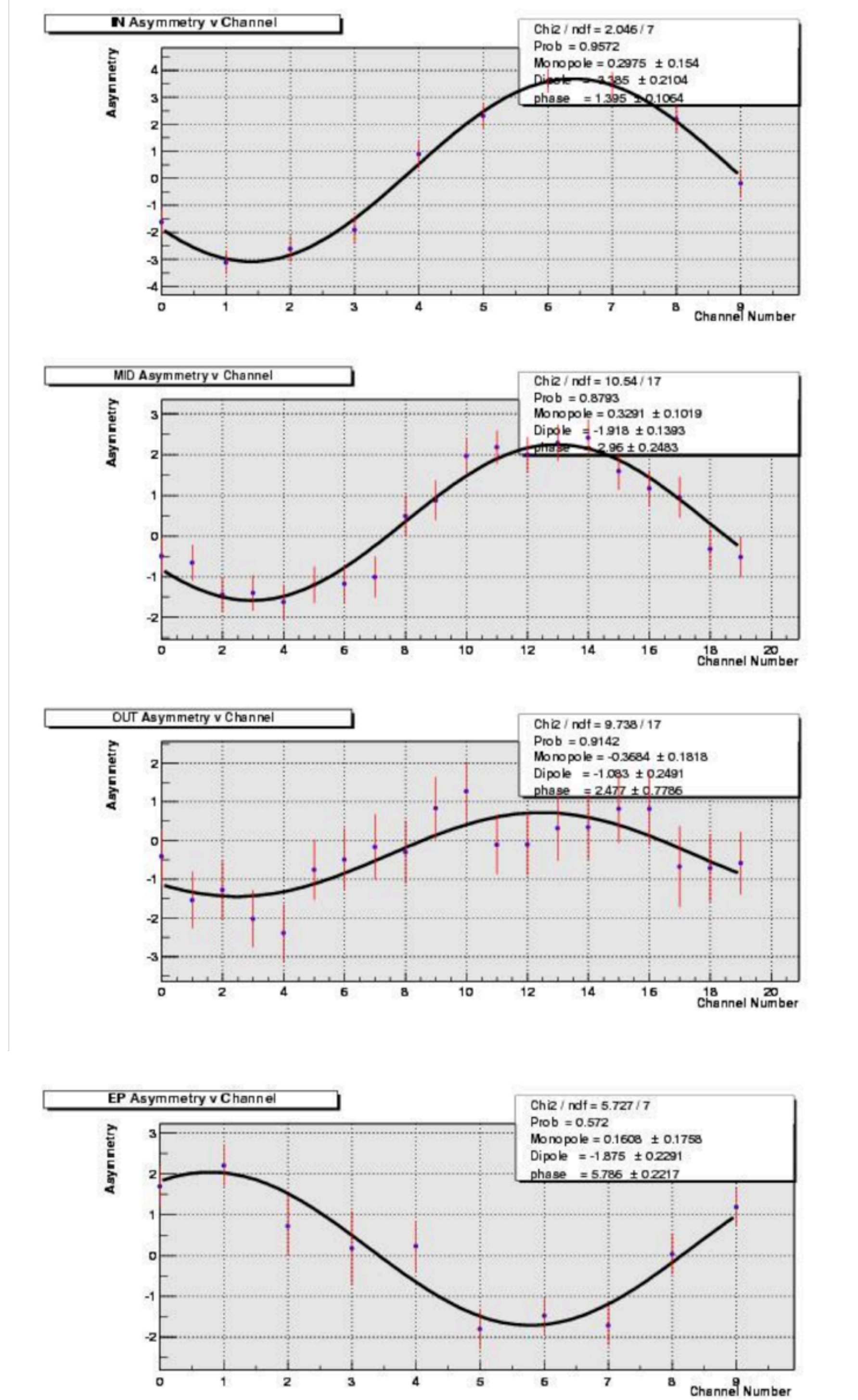
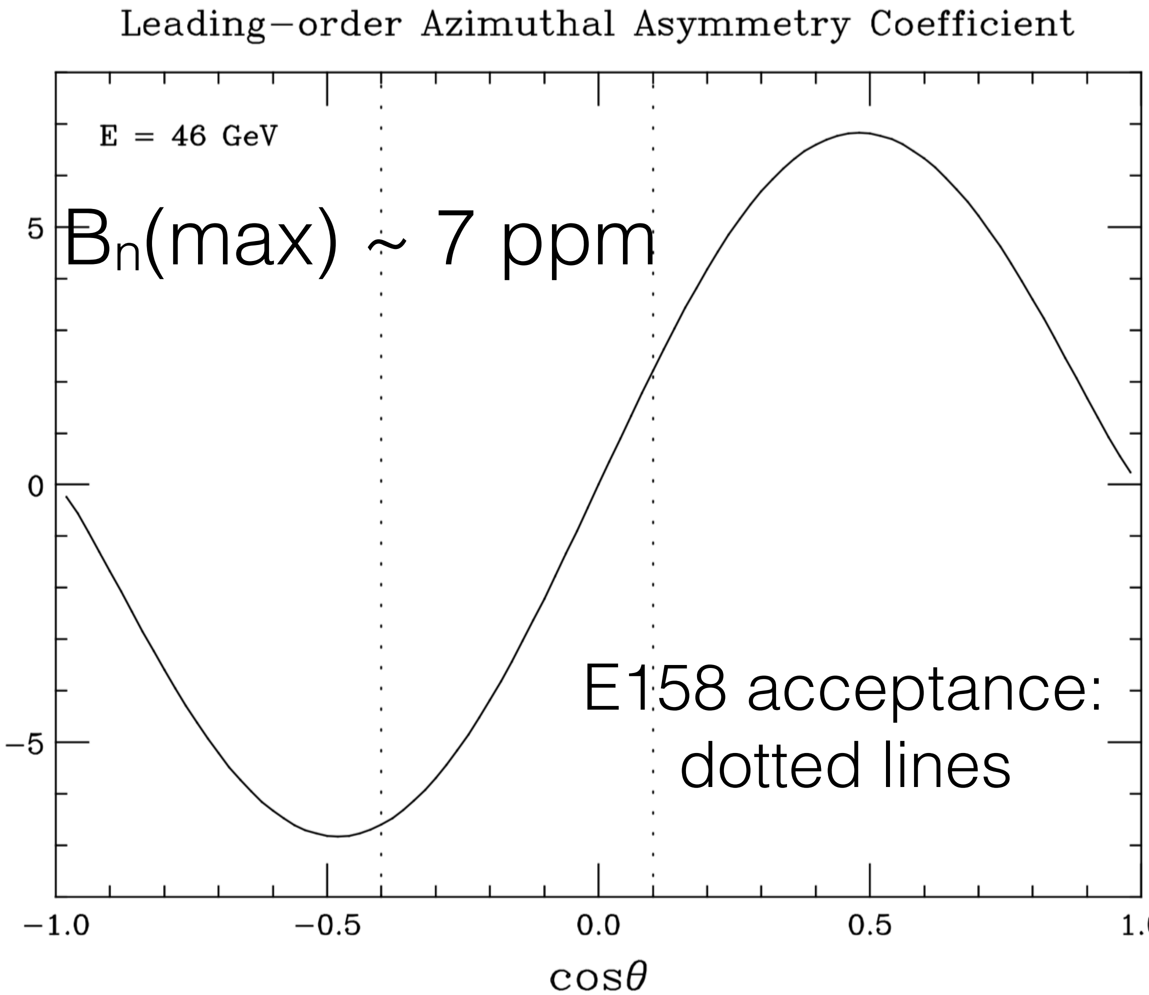


Fig 2: Run2 46GeV Asymmetries vs Channel [6]

Dixon and Schreiber (2004)



Result: -7.03 ± 0.25 ± 0.36 ppm

Theory: -6.91 ppm

E158 unpublished data might be interesting for phenomenology

- The e-p vector analyzing power is found to be consistent with a dispersive approach prediction assuming that the asymmetry of the 30% inelastic background is zero

- A_{PV} for e-p scattering is found to be consistent with what is expected from the dominant inelastic scattering amplitude (similar to the inelastic scattering measurements done by G0, PVDIS and Qweak at JLab)

MOLLER proposed to do factor of 5 better than E158

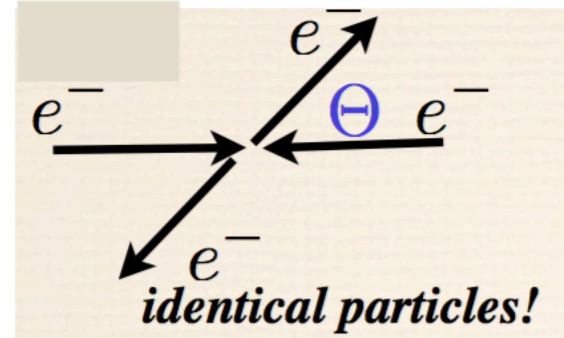
“Odd” MOLLER Acceptance

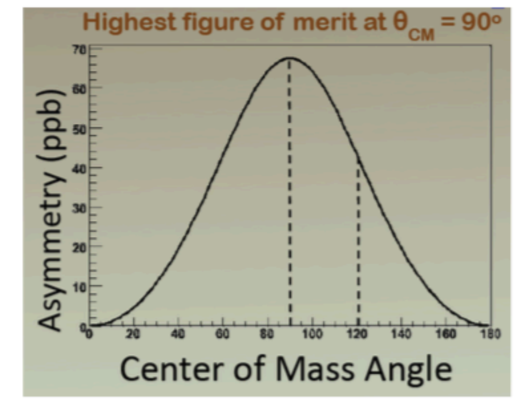
Spectrometer – Kinematics and Azimuthal Acceptance

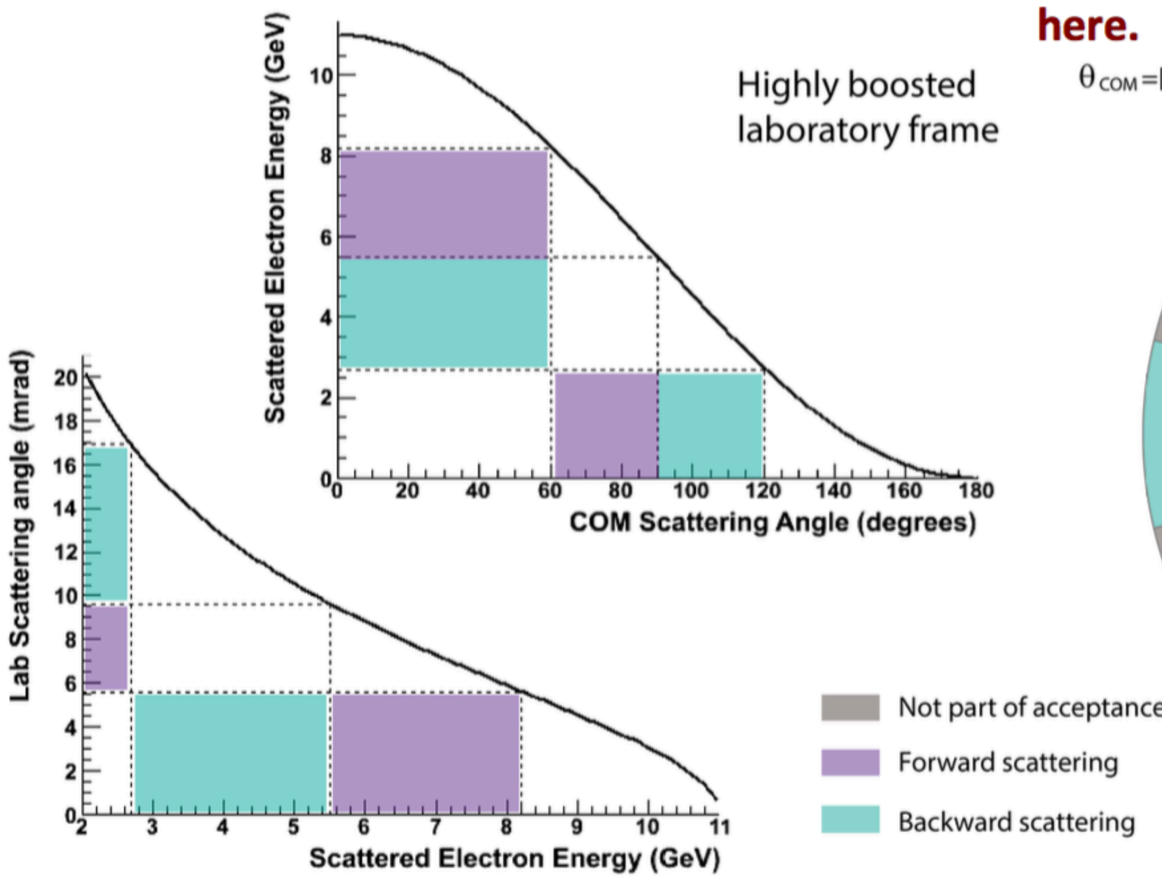
Optimized spectrometer:

50% azimuth, 100% acceptance

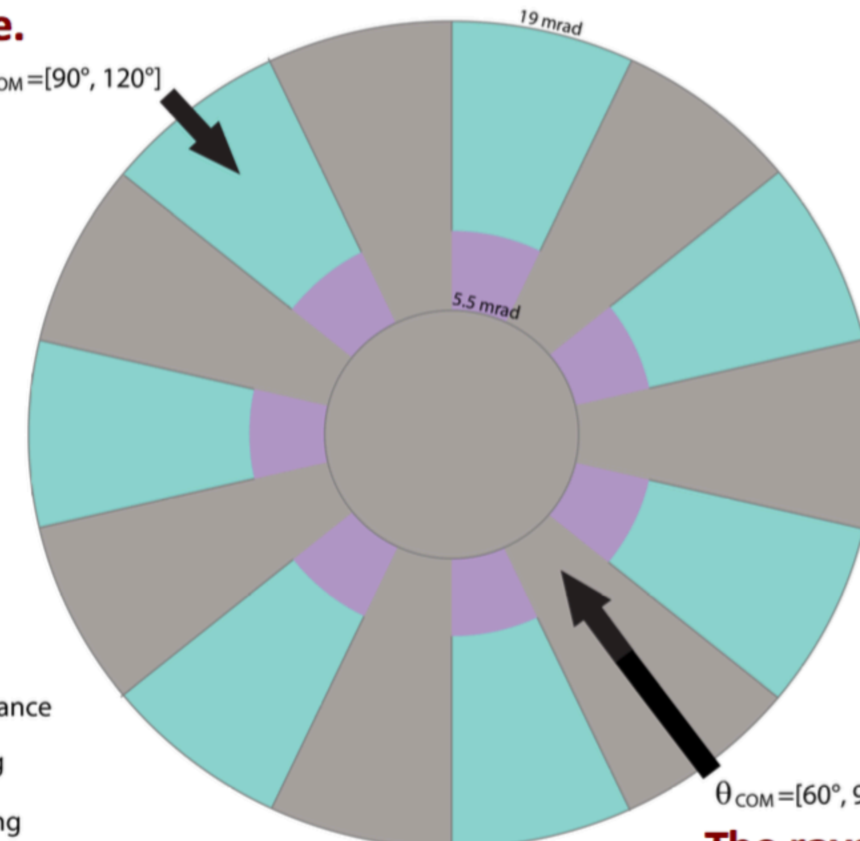
FOM optimized at 90º in COM







...are collected over here.



The rays that are blocked here...

- Accept all Møller scattered electrons in range Θ_{CM} = 60º – 120º
- Exploit identical particle nature for 100% acceptance; needs odd number of coils

Why Interesting Here?

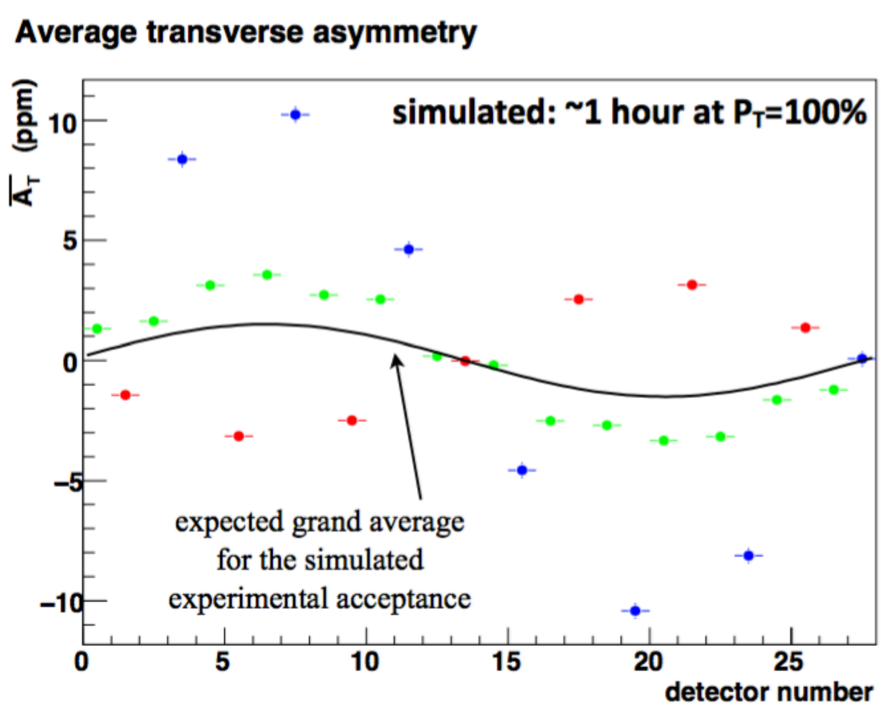
Transverse asymmety (parity-conserving):

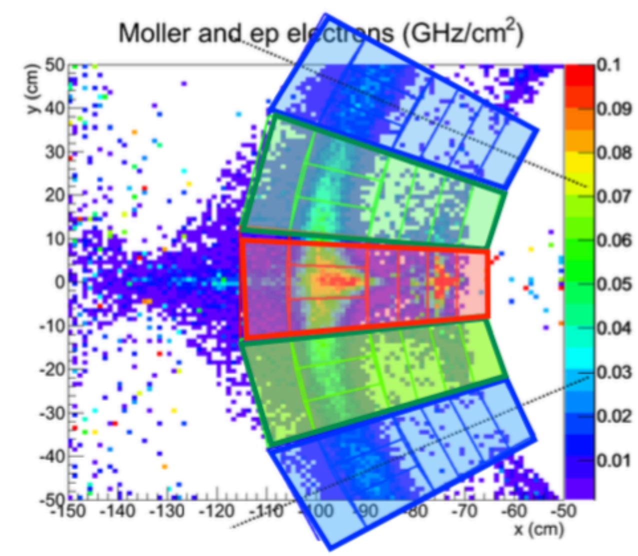
electron beam polarized
transverse to beam direction

$$A_T \equiv \frac{2\pi}{\sigma^{\uparrow}+\sigma^{\downarrow}} \frac{d(\sigma^{\uparrow}-\sigma^{\downarrow})}{d\phi} \propto \vec{S}_e \bullet (\vec{k}_e \times \vec{k}'_e)$$

Potential systematic error in A_{PV}.
Suppressed by
- small transverse polarization
- azimuthal acceptance symmetry
- acceptance symmetry in c.m.s. polar angle

Strategy: measure and minimize via feedback





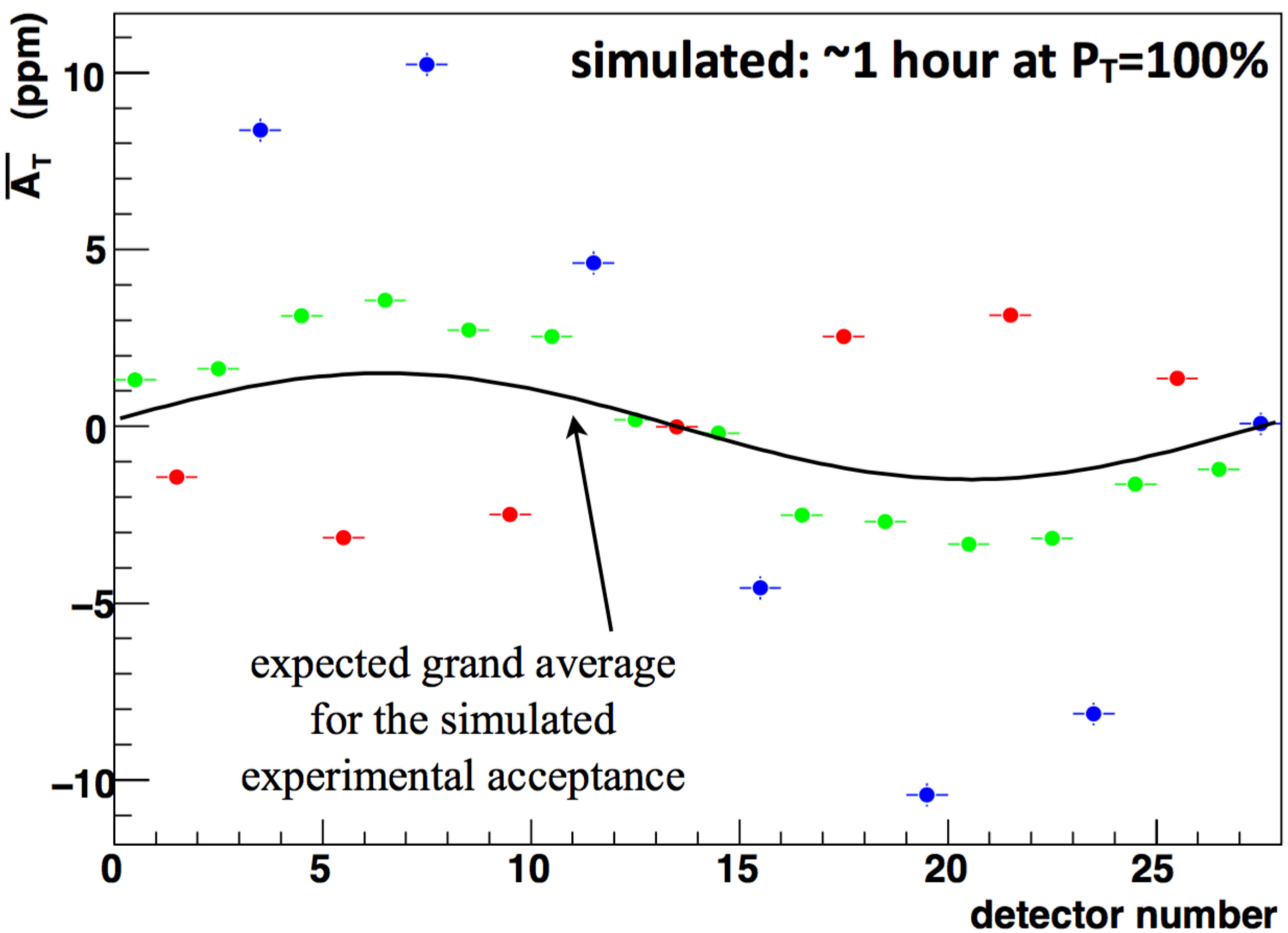
- Initial beam setup ~ 1-2 degrees
- Unique signature of transverse beam polarization
- 50 ppb error on A_T*P_b in 4 hours: 1 degree precision
- Over entire run: feedback will hold transverse polarization small (<<1 degree)

Run Phase 1:
- A_T measurement
- Feedback technique tested

Run Phases 2 and 3:
- Routine feedback

Precision Test Planned for MOLLER

Average transverse asymmetry



- set up for physics running
- convert to vertical polarization at polarized source
- run a few hours
- back to longitudinal polarization
- back off beam energy by 50 MeV: horizontal polarization on target
- extract vector analyzing power to precision and accuracy of around or better than 0.5%

*demonstrate complete understanding of apparatus: **simultaneous test of beam polarization, radiative corrections, detector acceptance, backgrounds***

Is theory good to 0.1% with Dixon/Schreiber work?

Concluding Remarks

- There is a wealth of A_n measurements from the parity violation experiments on forward and backward angle elastic electron-proton scattering
- Some additional A_n measurements of electron-proton inelastic scattering might be of interest; new data forthcoming from Qweak
- A_n measurements on heavier nuclei provides an interesting theoretical challenge: any new insights relevant to electroweak boxes on light nuclei/proton? New data will soon become available both at 1 GeV (Qweak) and lower energies (Mainz A1)
- There are already some interesting constraints on the neutral current amplitude in inelastic electron proton scattering: have all the available data been used to reduce gamma-Z box uncertainties?
- The future holds many possibilities for providing precision measurements of A_{PV} in inelastic electron proton scattering at a variety of kinematic points: MOLLER, SOLID and P2. How useful will they be? These experiments are all capable of making new A_n measurements: what's interesting?

Continued dialog is necessary to make best use of existing results and optimizing the future program of auxiliary measurements