Transverse Asymmetries in Elastic Electron Nucleon Scattering and the Imaginary Part of the Two-Photon Amplitude

Frank E.Maas

Institut de Physique Nucléaire de Orsay

Institut für Kernphysik

Workshop on Nucleon Form Factors

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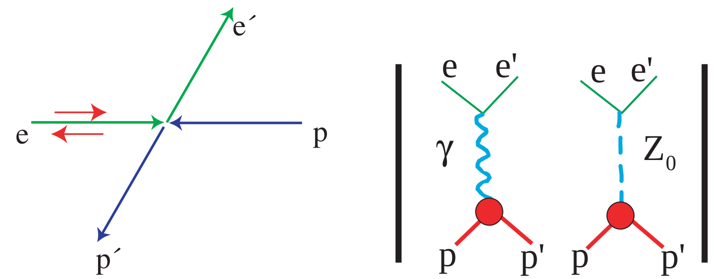
Imaginary Part of Two-Photon-Exchange

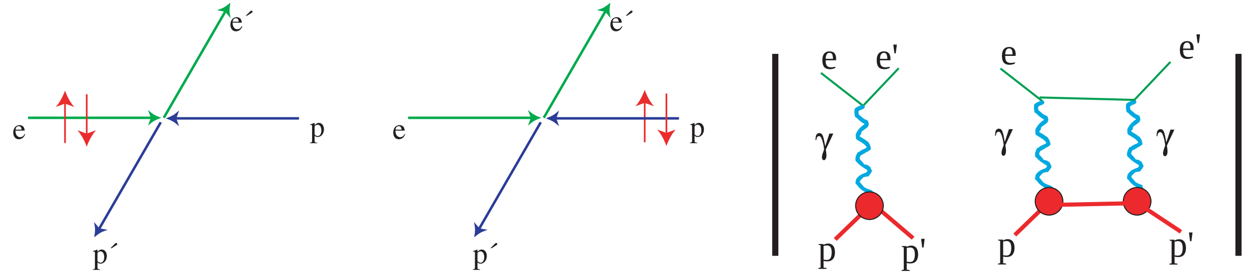
- Beam Spin Normal Asymmetries in elastic $\vec{e}\,p$ scattering
  - SAMPLE@MIT-Bates: backward
  - HAPPEX@JLab: forward
  - G0@JLab: forward
  - E158@SLAC: forward
  - A4@MAMI: forward
- Beam Spin Normal Asymmetries in Møller scattering
  - E158@SLAC: forward
- Future Measurements

Beam Spin Normal Asymmetries in Elastic Scattering

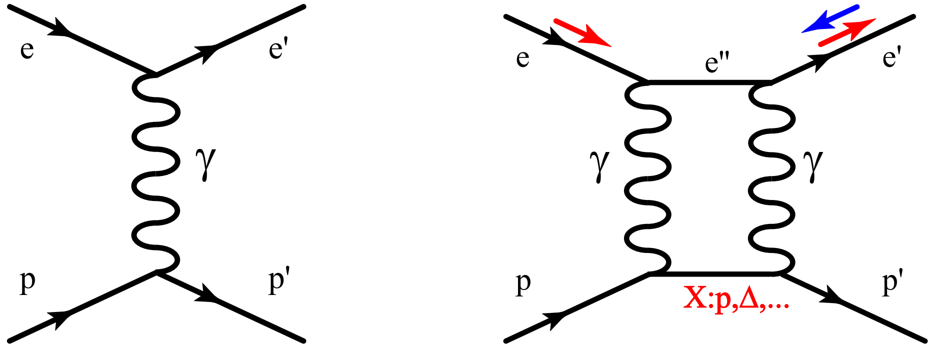
- Single-Spin-Asymmetries: e^- Spin longitudinal,
  Parity Violating, ϕ-symmetric
  $A_{PV} = 10^{-6}$



- Single-Spin-Asymmetries: e^- Spin transverse,
  Dependence on Azimuth Angle ϕ: $sin(\phi)$,
  $A_{\perp}^{beam} = 10^{-5}$,$A_{\perp}^{target} = 10^{-2}$



2-γ-Exchange



T_{nonflip} T_{flip}

Helicity Amplitudes

$$\bar{u}(k_2)\,\gamma\cdot P\,u(k_1)\cdot\bar{u}(p_2)\,\gamma\cdot K\,u(p_1) \qquad \bar{u}(k_2)\,u(k_1)\cdot\bar{u}(p_2)\,u(p_1)$$

$$\bar{u}(k_2)\,\gamma\cdot P\,u(k_1)\cdot\bar{u}(p_2)\,u(p_1) \qquad \bar{u}(k_2)\,u(k_1)\cdot\bar{u}(p_2)\,\gamma\cdot K\,u(p_1)$$

$$\bar{u}(k_2)\,\gamma_5\gamma\cdot P\,u(k_1)\cdot\bar{u}(p_2)\,\gamma_5\gamma\cdot K\,u(p_1) \qquad \bar{u}(k_2)\,\gamma_5\,u(k_1)\cdot\bar{u}(p_2)\,\gamma_5\,u(p_1)$$

Generalized Form Factors

$$\tilde{G}_M(s,Q^2),\ \tilde{G}_E(s,Q^2),\ \tilde{F}_3(s,Q^2) \qquad \tilde{F}_4(s,Q^2),\ \tilde{F}_5(s,Q^2),\ \tilde{F}_6(s,Q^2)$$

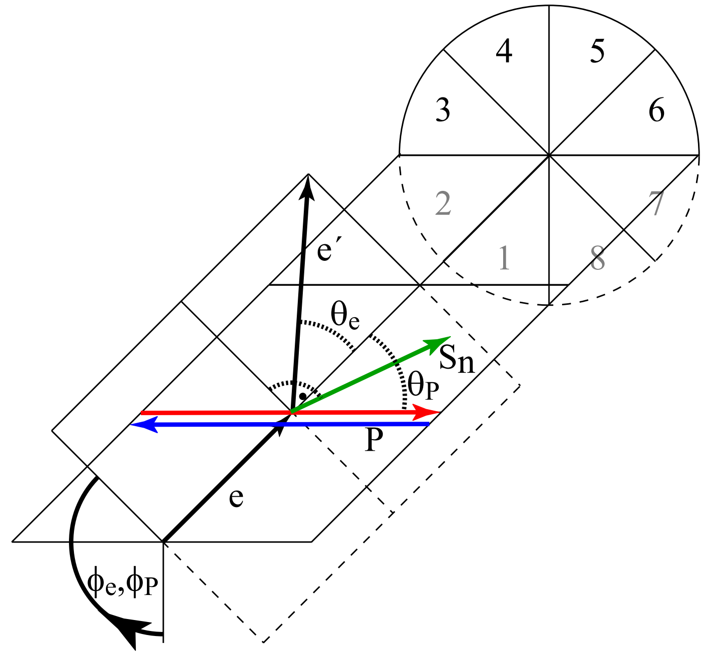
Two-Photon Exchange

$$
\begin{aligned}
M_{\text{non-flip}} &= \frac{e^2}{Q^2}\,\bar{u}(k_2)\,\gamma_\mu\, u(k_1)\;\bar{u}(p_2)\,[\hat{\mathrm{G}}_M(s,Q^2)\,\gamma_\mu\; - \\
&\quad \hat{\mathrm{F}}_2(s,Q^2)\,\frac{P^\mu}{M} + \hat{\mathrm{F}}_3(s,Q^2)\,\frac{\gamma\cdot K P^\mu}{M^2}\,]\,u(p_1) \\
M_{\text{flip}} &= \frac{m_e}{M}\,\frac{e^2}{Q^2}\,[\bar{u}(k_2)\,u(k_1)\;\bar{u}(p_2)\,[\hat{\mathrm{F}}_4(s,Q^2) \\
&\quad +\hat{\mathrm{F}}_5(s,Q^2)\frac{\gamma\cdot K}{M}]u(p_1) \\
&\quad +\hat{\mathrm{F}}_6(s,Q^2)\bar{u}(k_2)\,\gamma_5\,u(k_1)\;\bar{u}(p_2)\,\gamma_5\,u(p_1)]
\end{aligned}
$$

Observables

- 1-Photon forbidden Transitions in Nuclear States
- Elastic Cross Section Measurement (Real Part, Correction to 1-Photon)
- $\sigma_{e^- p}$ - $\sigma_{e^+ p}$ (Real Part, Correction to 1-Photon)
- ε-Dependence (at fixed Q^2) (Real Part, Correction to 1-Photon)
- Recoil Polarization P_x,P_y,P_z (Real Part,Imaginary Part)
- Transverse Target Spin Asymmetry (Imaginary Part, forbidden in 1-Photon)
- Transverse Beam Spin Asymmetry (Imaginary Part, only in 2-Photon)

Single Spin Asymmetry in Elast. Scattering



$$\vec{P} \qquad -\vec{P}$$

$$\vec{S}_n = (\vec{k}_1 \times \vec{k}_2)/|\vec{k}_1 \times \vec{k}_2|$$

$$A_\perp = \frac{\sigma_{\uparrow\uparrow} - \sigma_{\downarrow\uparrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\downarrow\uparrow}}$$

$$A(\phi_e, \theta_e) = A_\perp(\theta_e)\vec{S}_n \cdot \vec{P}$$

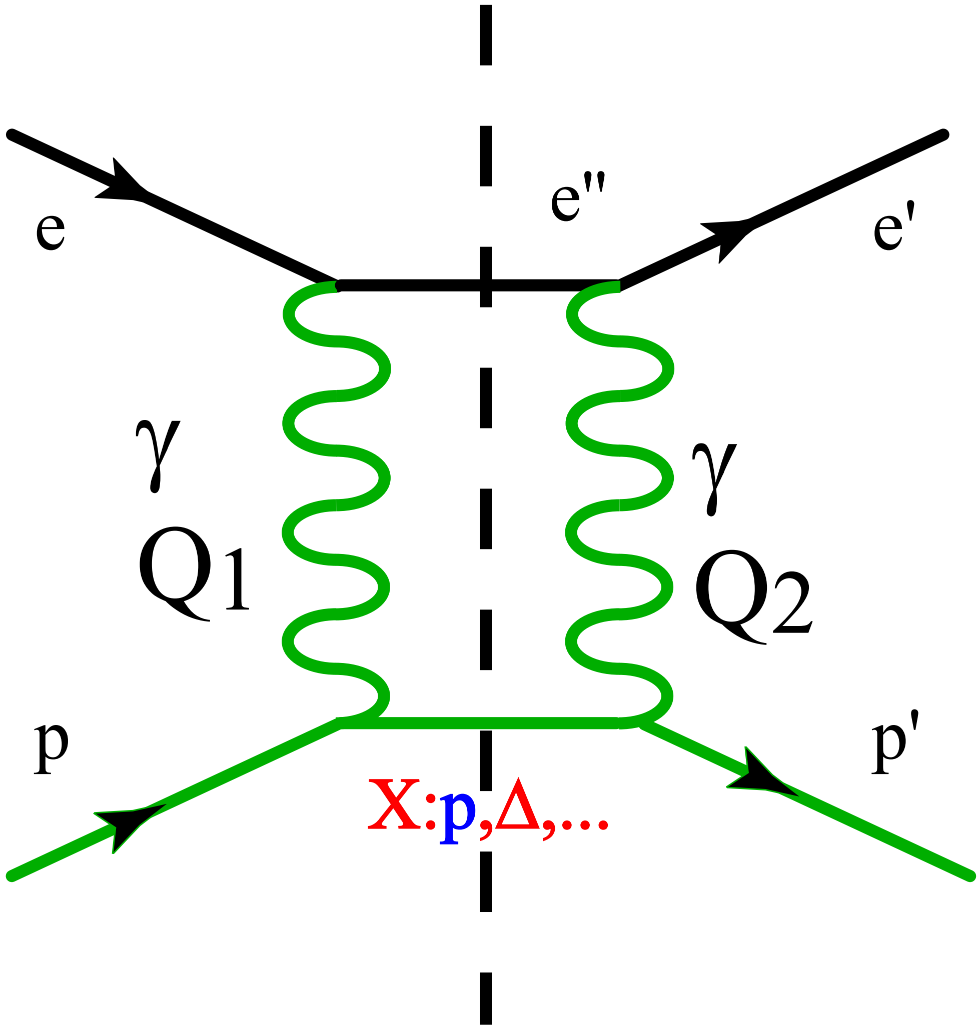
Single Spin Asymmetry in Elast. Scattering

$$A_\perp = \frac{\sigma_{\uparrow\uparrow} - \sigma_{\downarrow\uparrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\downarrow\uparrow}}$$

$$A_\perp = -\frac{m_e}{M}\sqrt{2\varepsilon(1-\varepsilon)}\frac{\sqrt{1+\tau}}{\tau}\left(1+\frac{\varepsilon}{\tau}\frac{|\tilde{G}_E|^2}{|\tilde{G}_M|^2}\right)^{-1}$$

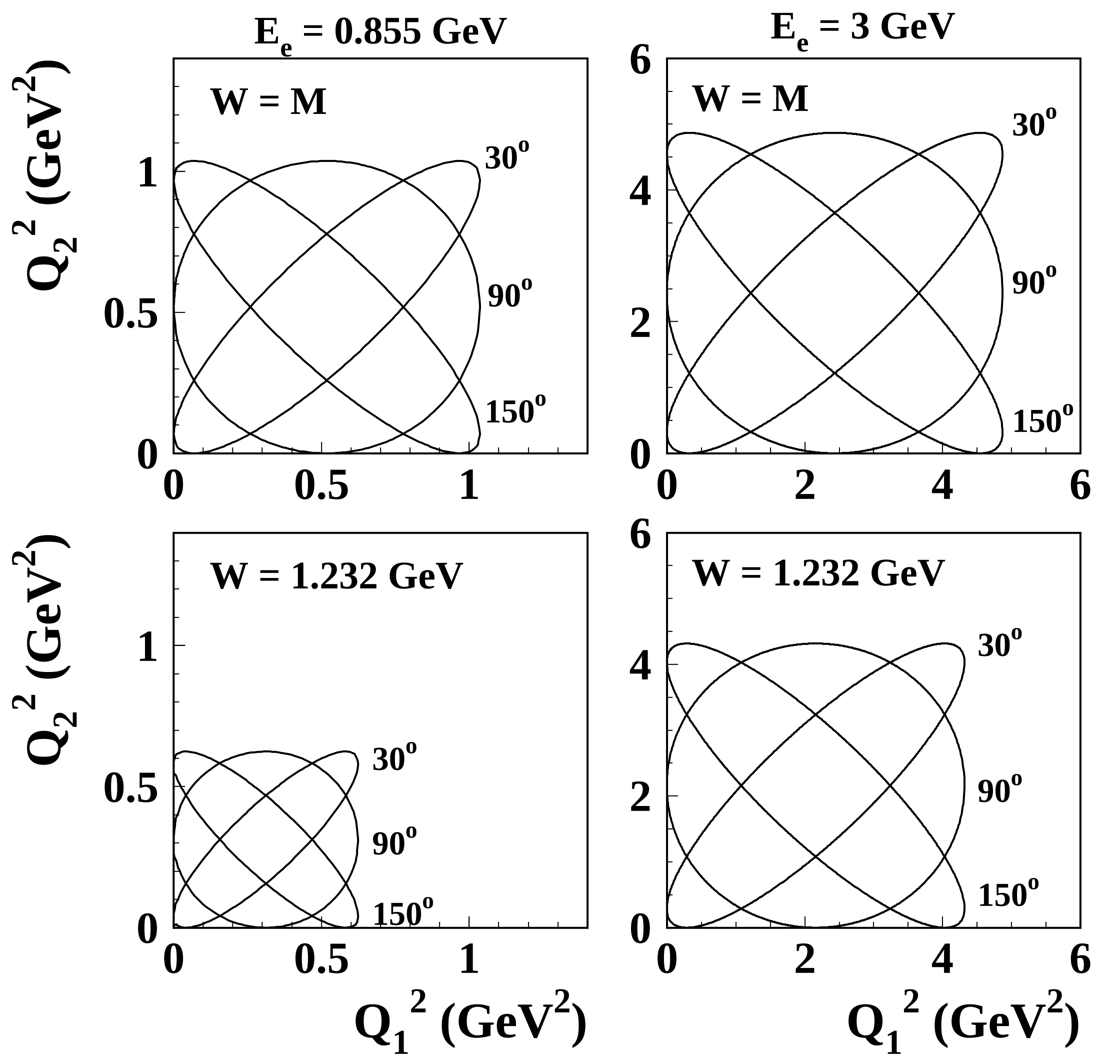
$$\times\left(-\tau\, I\left(\frac{\tilde{F}_3}{\tilde{G}_M}\right) - \frac{|\tilde{G}_E|}{|\tilde{G}_M|}\, I\left(\frac{\tilde{F}_4}{\tilde{G}_M}\right) - \frac{1}{1+\tau}\left(\tau + \frac{|\tilde{G}_E|}{|\tilde{G}_M|}\right) I\left(\frac{\nu\tilde{F}_5}{M^2|\tilde{G}_M|}\right)\right)$$

Imaginary Part: Study of Intermediate State Spectrum



Doubly Virtual Compton Scattering

integration over kinematics

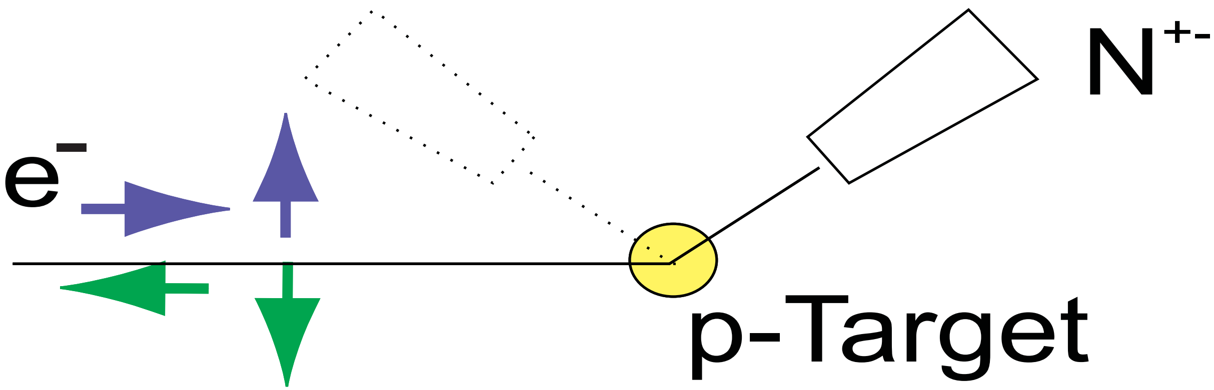


Transverse Asymmetry in Elastic Scattering

- Systematic Studies of the 2-Photon-Amplitude at low Energies
- $A_\perp$ proportional to Imaginary Part (Connect to Real Part via Dispersion Relations)
- “known”πN Amplitudes from π-Electro-Production for Calculation of $A_\perp$ (B.Pasquini MAID)
- Complementary Access to π-Electro-Production
- Electroweak Precision Experiments depend on $\gamma\, Z_0$ and $W^+\ W^-$ Box Graphs
  - Parity Violating Electron Scattering (A4, G0, Happex, SAMPLE, Q_{weak})
  - Parity Violation in Atomic Physics
  - V_{ud}
- Generalized Parton Distributions

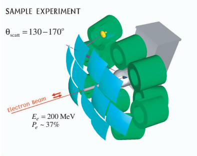
PV Experiments

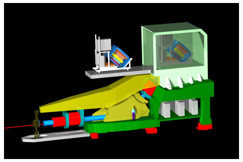
A4 Measurement Principle

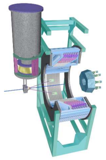


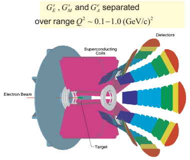
- Longitudinally or transversely polarized electrons
- Target: unpolarized protons
- Detector: scattering angle
- Counting experiment: $A = \frac{N^+ - N^-}{N^+ + N^-}$

Experimental Conditions for PV Experiments

SAMPLE: e^-,Air-Cherenkov(MIT-Bates) 

HAPPEX: e^-,magnetic Spectr., Integrating Det. 

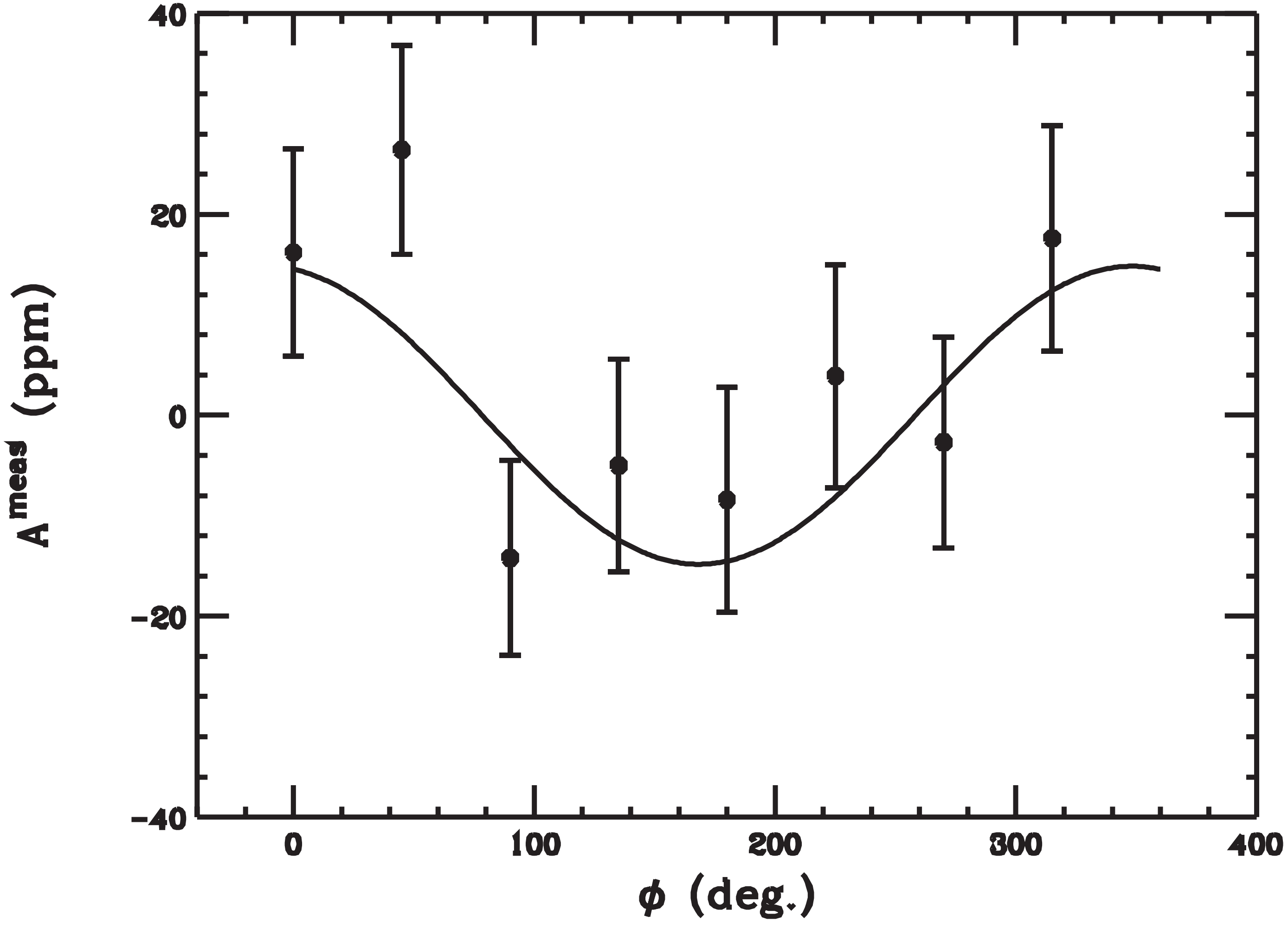
A4: e^-,EM-Calorimeter 

G0:p^+,Time of Flight, Toroidal Magnetic field 

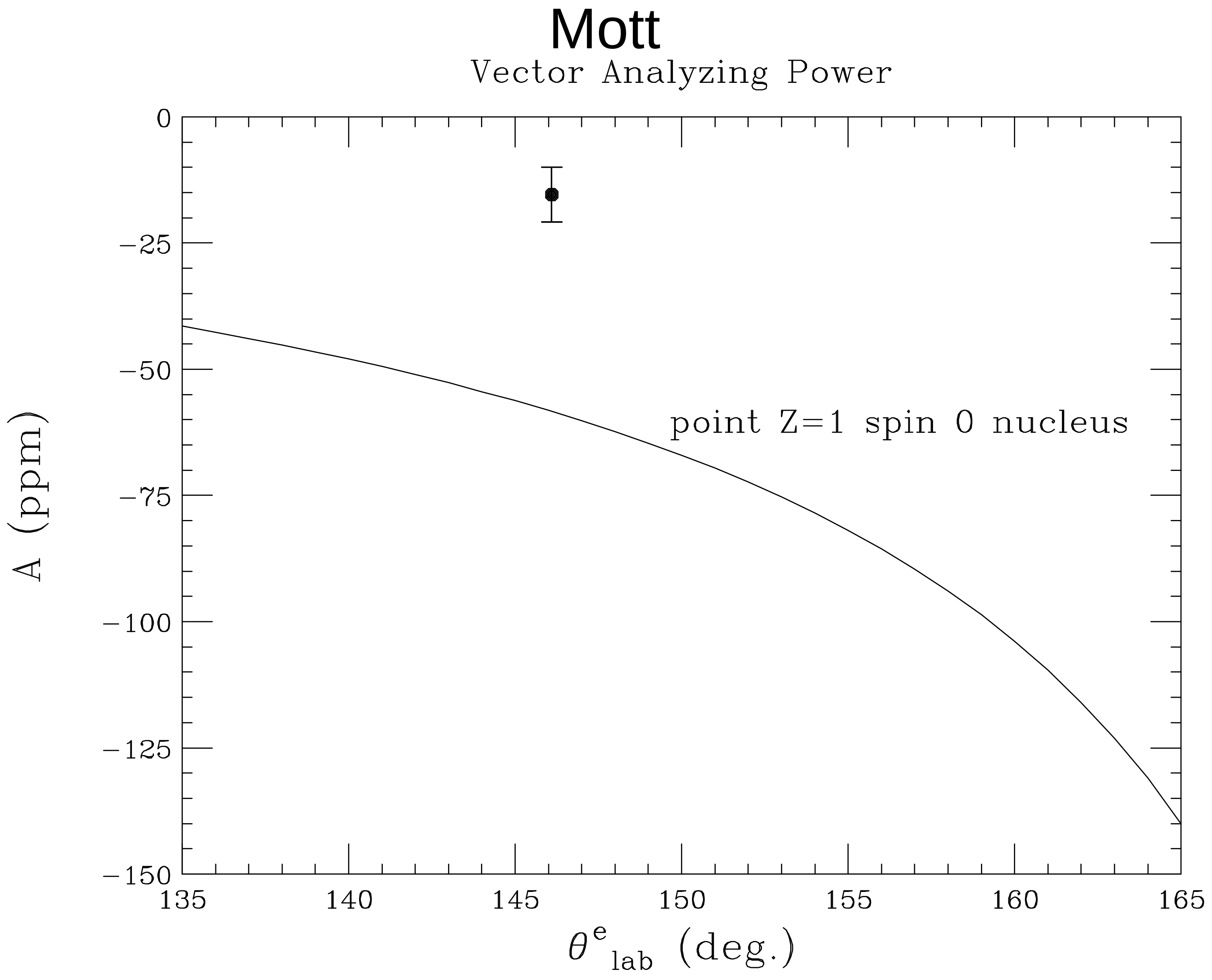
SAMPLE at MIT/Bates

Two Photon Physics: SAMPLE measurements

SAMPLE transverse beam asymmetry

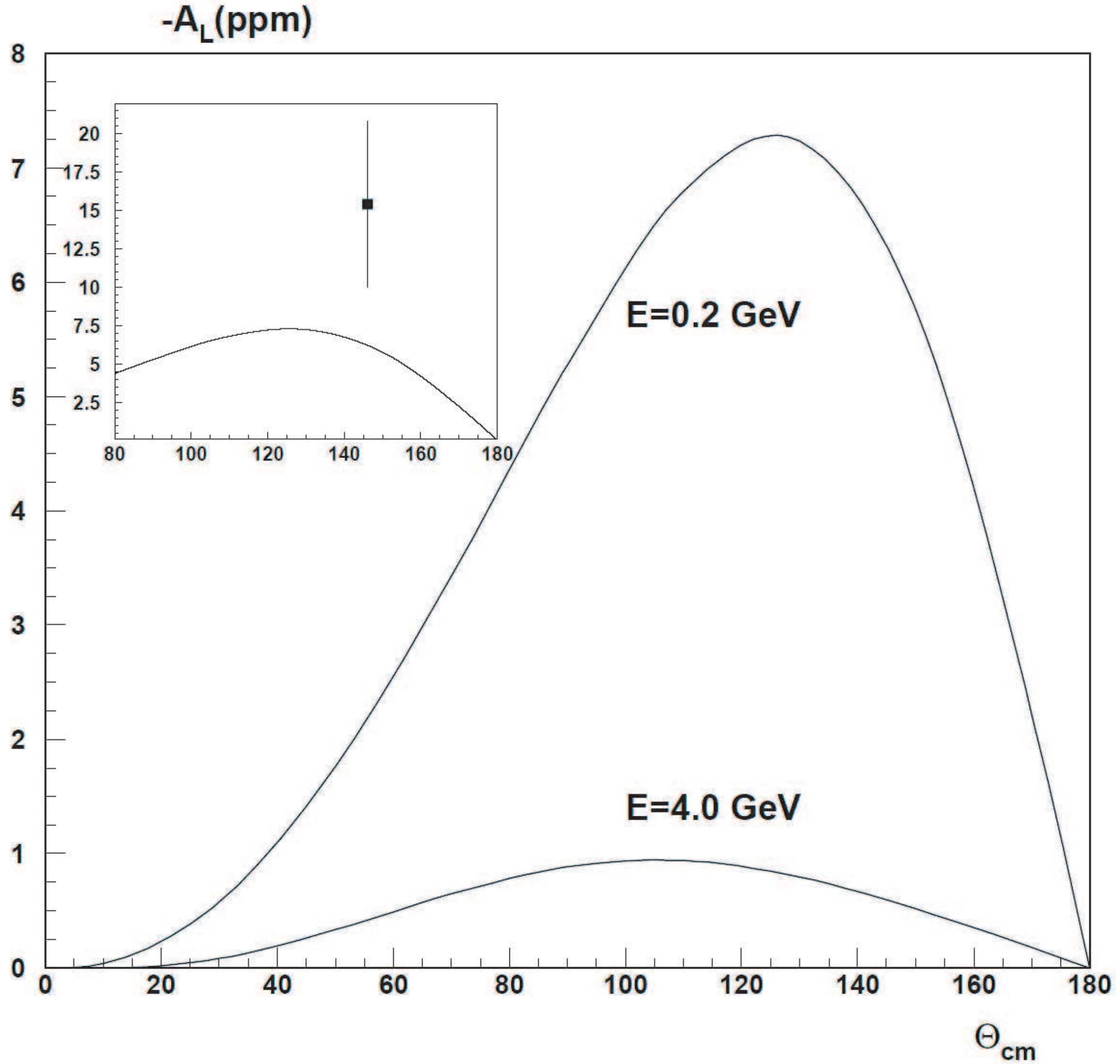


Two Photon Physics: SAMPLE measurements



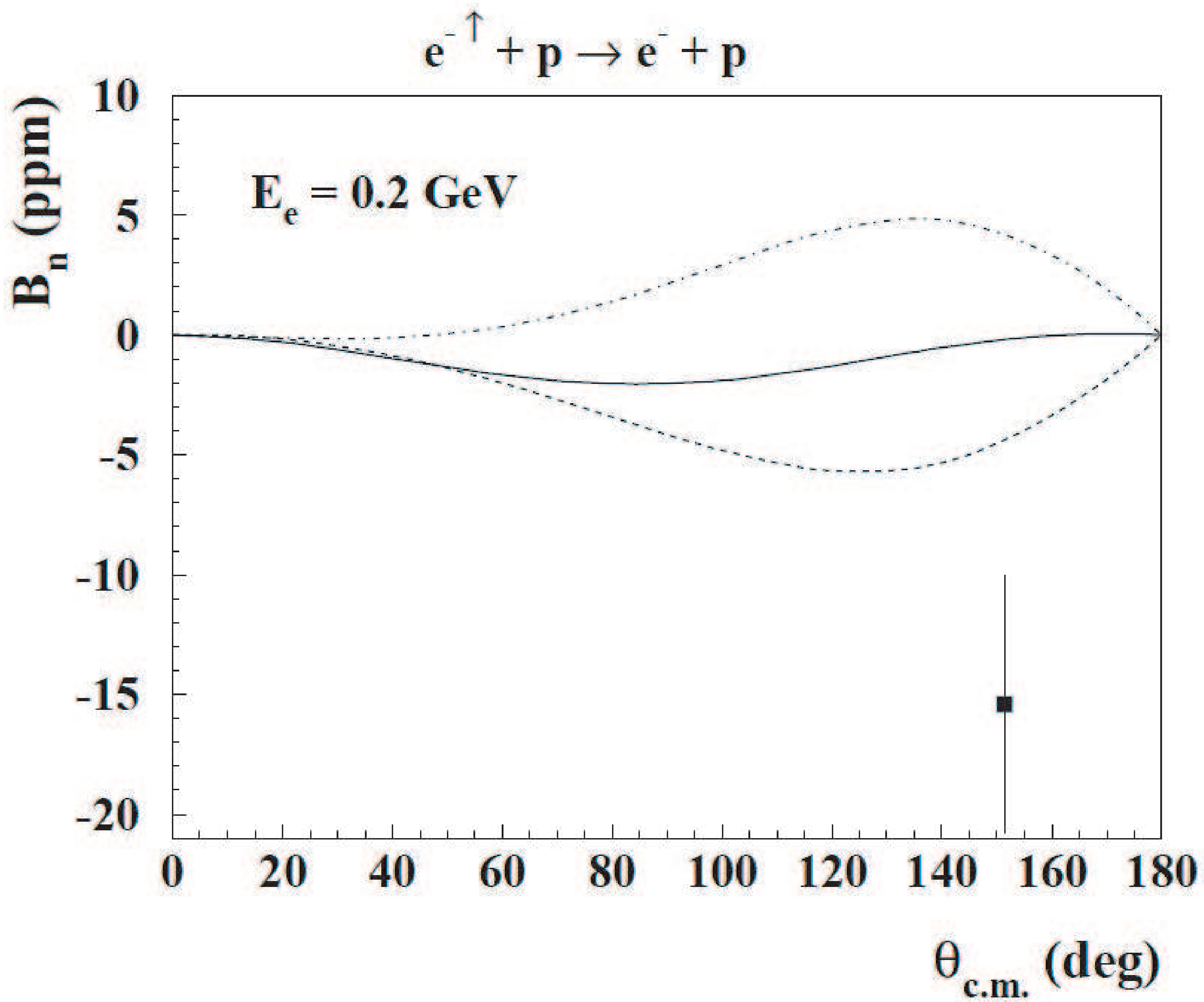
Two Photon Physics: SAMPLE measurements

Afanasev

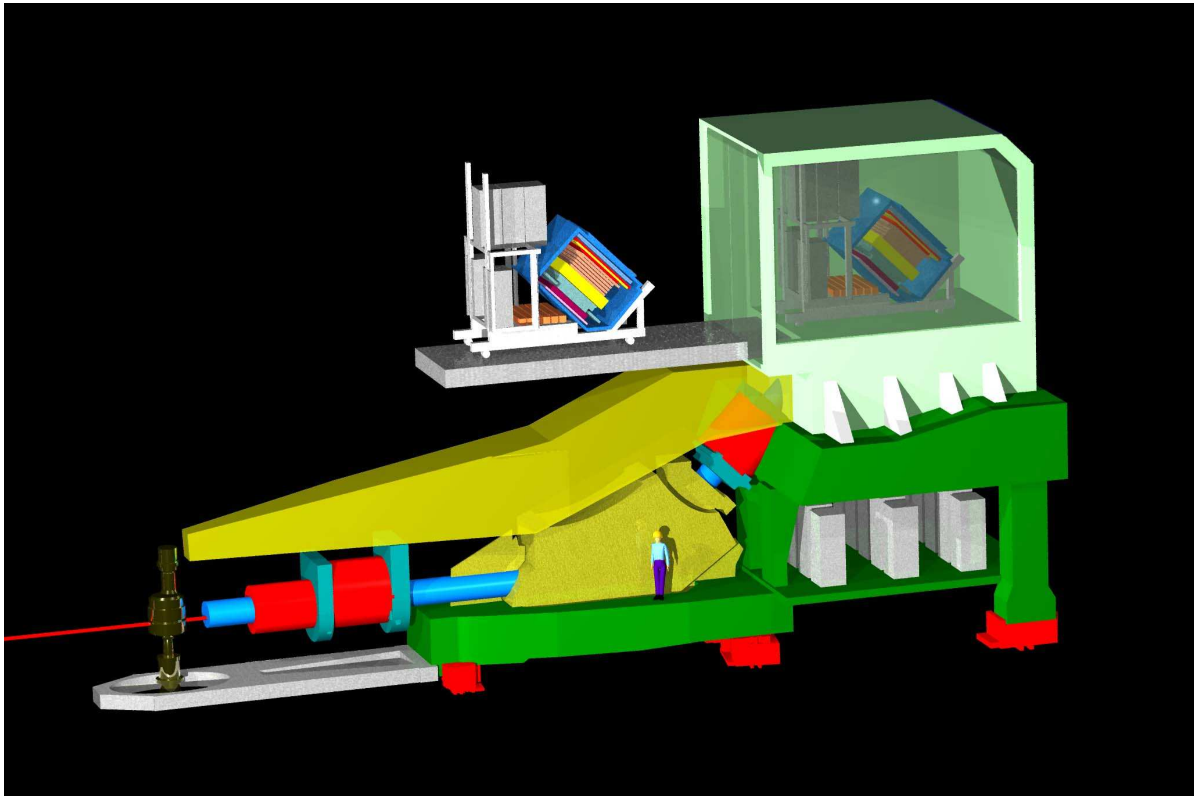


Two Photon Physics: SAMPLE measurements

Pasquini



Two Photon Physics: HAPPEX



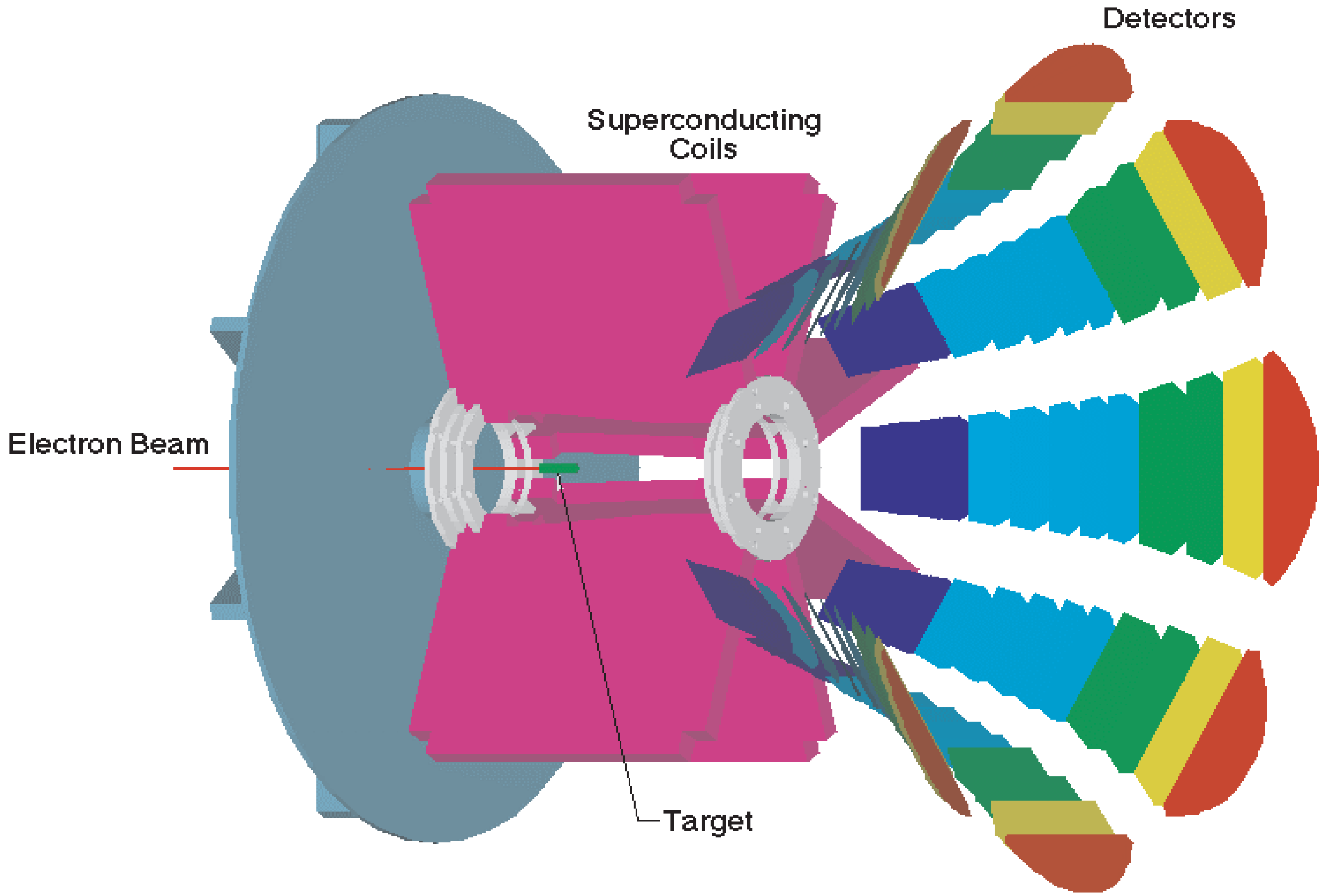
θ_e=6°, $Q^2 = 0.1$(GeV/c)^2, E$_e$ = 3 GeV A$_\perp$ = - 6.6 ppm $\pm$ 1.5 ppm (stat) $\pm$ 0.2 ppm (syst) (Kent Paschke)

Afanasev: A$_\perp$ = - 7.2 ppm (no cut in W of inelastic state)

G0 at JLab

G_E^s , G_M^s and G_A^e separated

over range $Q^2 \sim 0.1 - 1.0\ (\mathrm{GeV/c})^2$



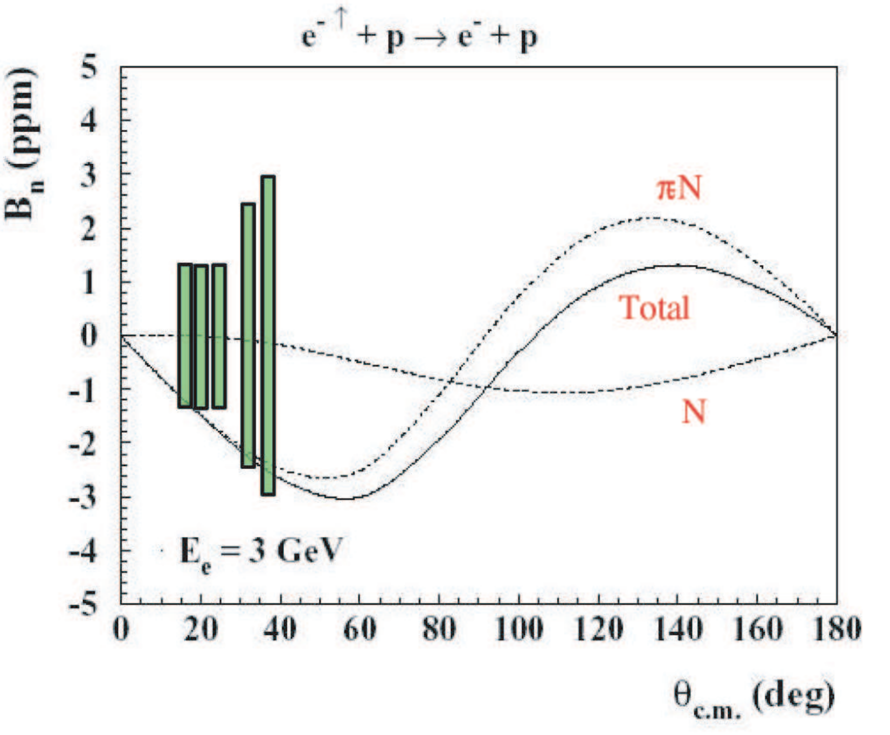
G0 at JLab

Expected precision on A_n for forward angle G^0

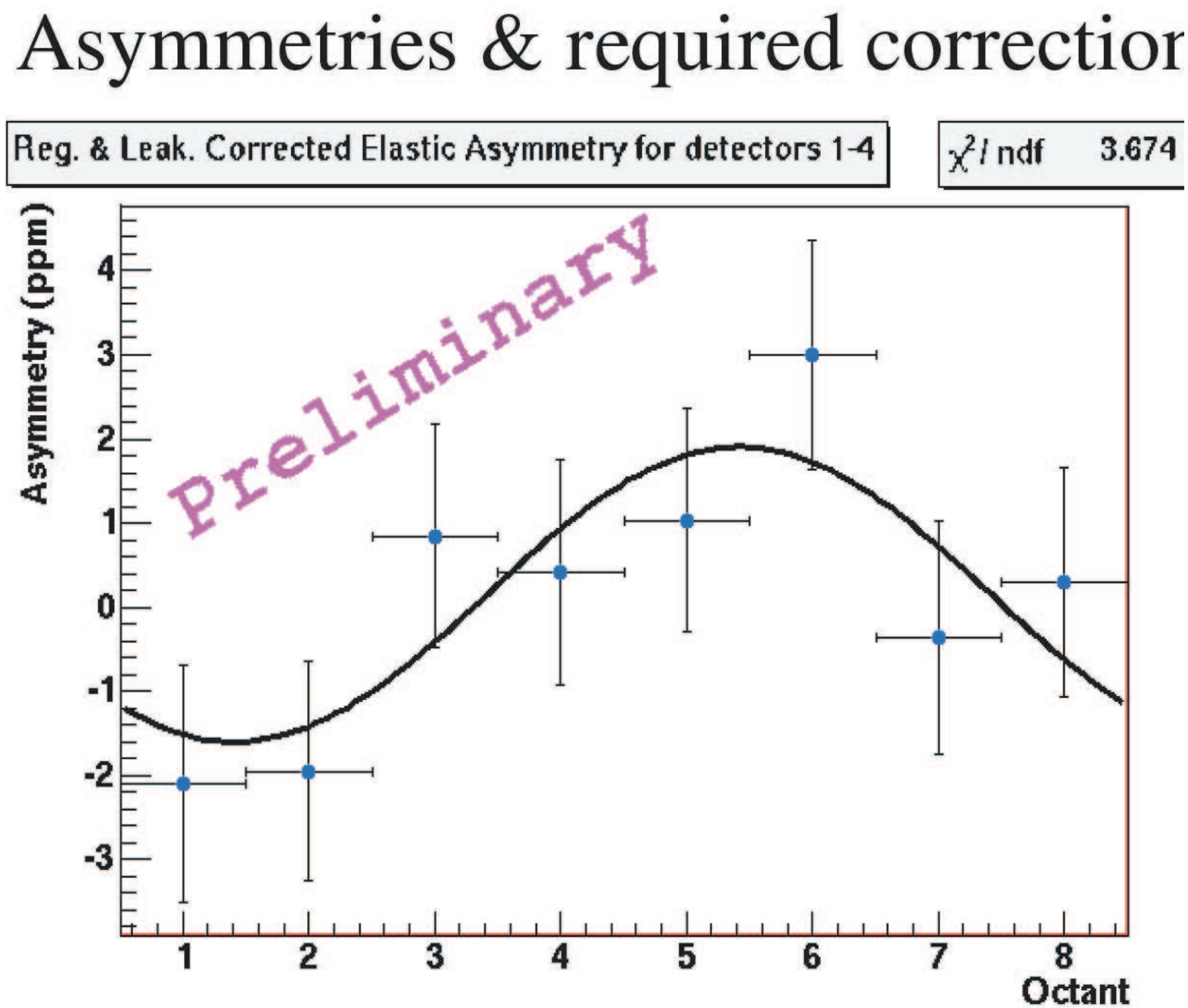
- Data collection took place over 22-26 March 2004:
  39 hrs (30 parity hrs) on LH2; 5.8 hrs (3.8 parity hrs) on Al.

- Projected statistical errors for the elastic scattering peak on LH2

Detectors	$<\theta_{CM}>$	Proj. Stat. Error
1-4	19.03	1.3 ppm
5-8	21.65	1.3 ppm
9-12	26.12	1.3 ppm
13-14	32.35	2.4 ppm
15	37.4	2.9 ppm

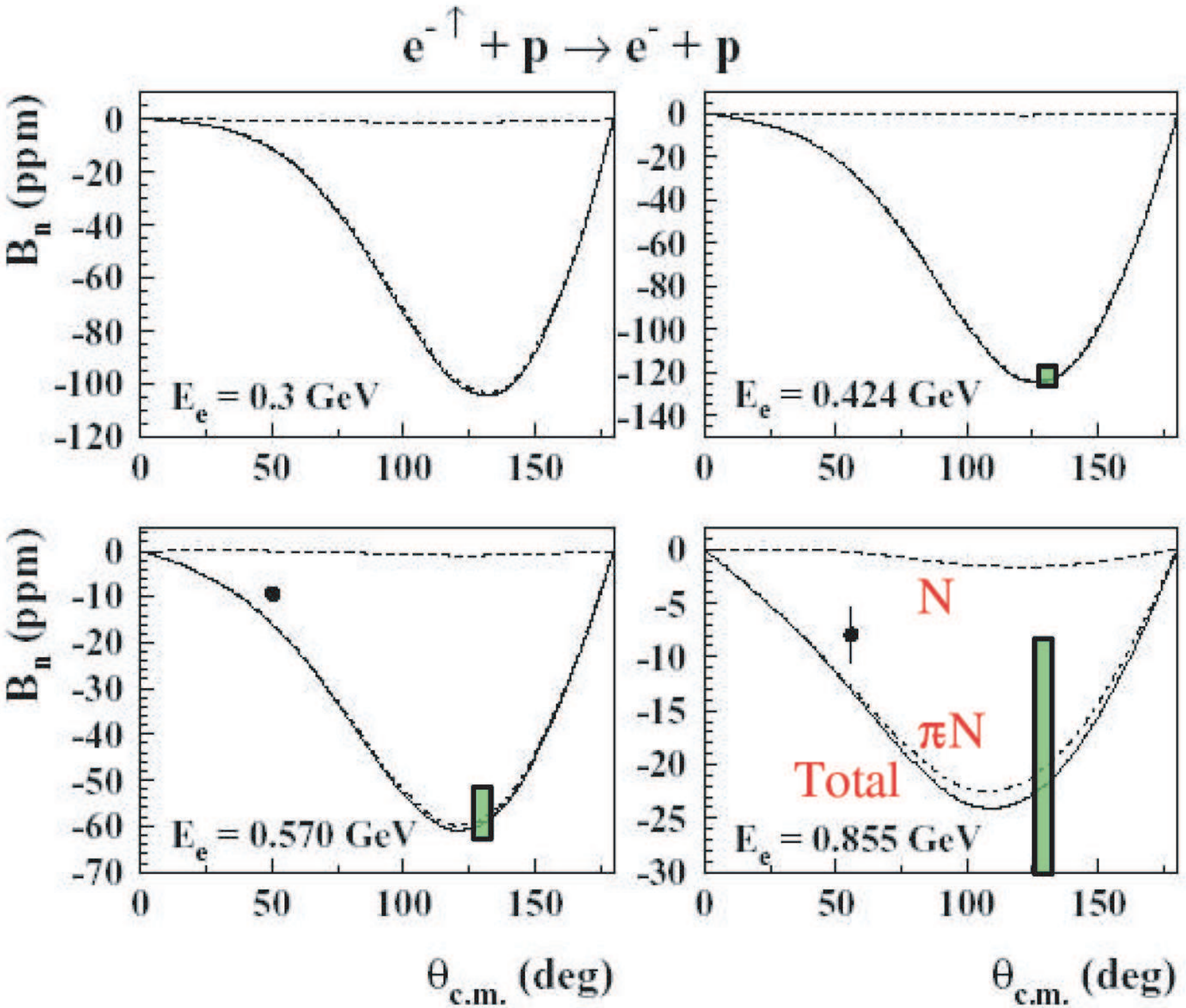


G0 at JLab



Asymmetries & required correctior
Reg. & Leak. Corrected Elastic Asymmetry for detectors 1-4
χ²/ ndf 3.674
Preliminary
Asymmetry (ppm)
4
3
2
1
0
-1
-2
-3
1
2
3
4
5
6
7
8
Octant

G0 at JLab



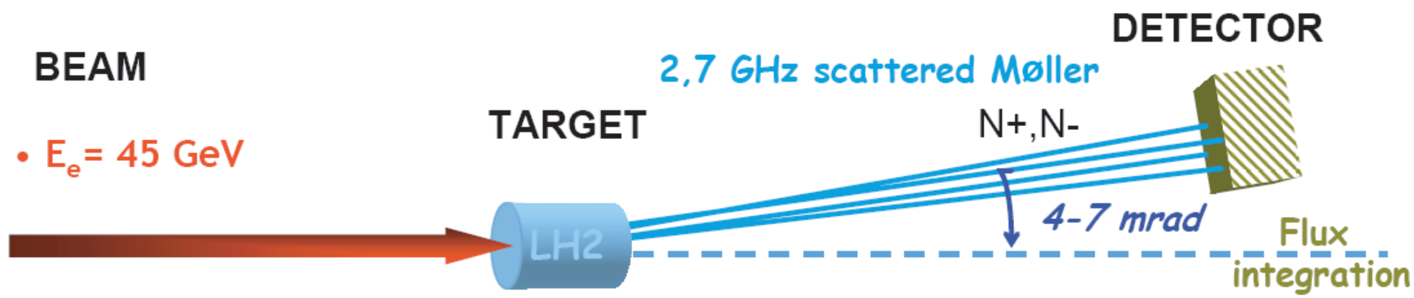
$e^{-\uparrow} + p \rightarrow e^{-} + p$
B_n (ppm)
$E_e = 0.3$ GeV
$E_e = 0.424$ GeV
$E_e = 0.570$ GeV
$E_e = 0.855$ GeV
N
πN
Total
$\theta_{c.m.}$ (deg)

E158 at SLAC: Møller Scattering

Experiment principle

Raw Asymmetry = 1.3×10^{-7} (130 ppb) $\Delta(A_{pv}) = 10^{-8}$ (10 ppb)

Need 10^{16} electrons



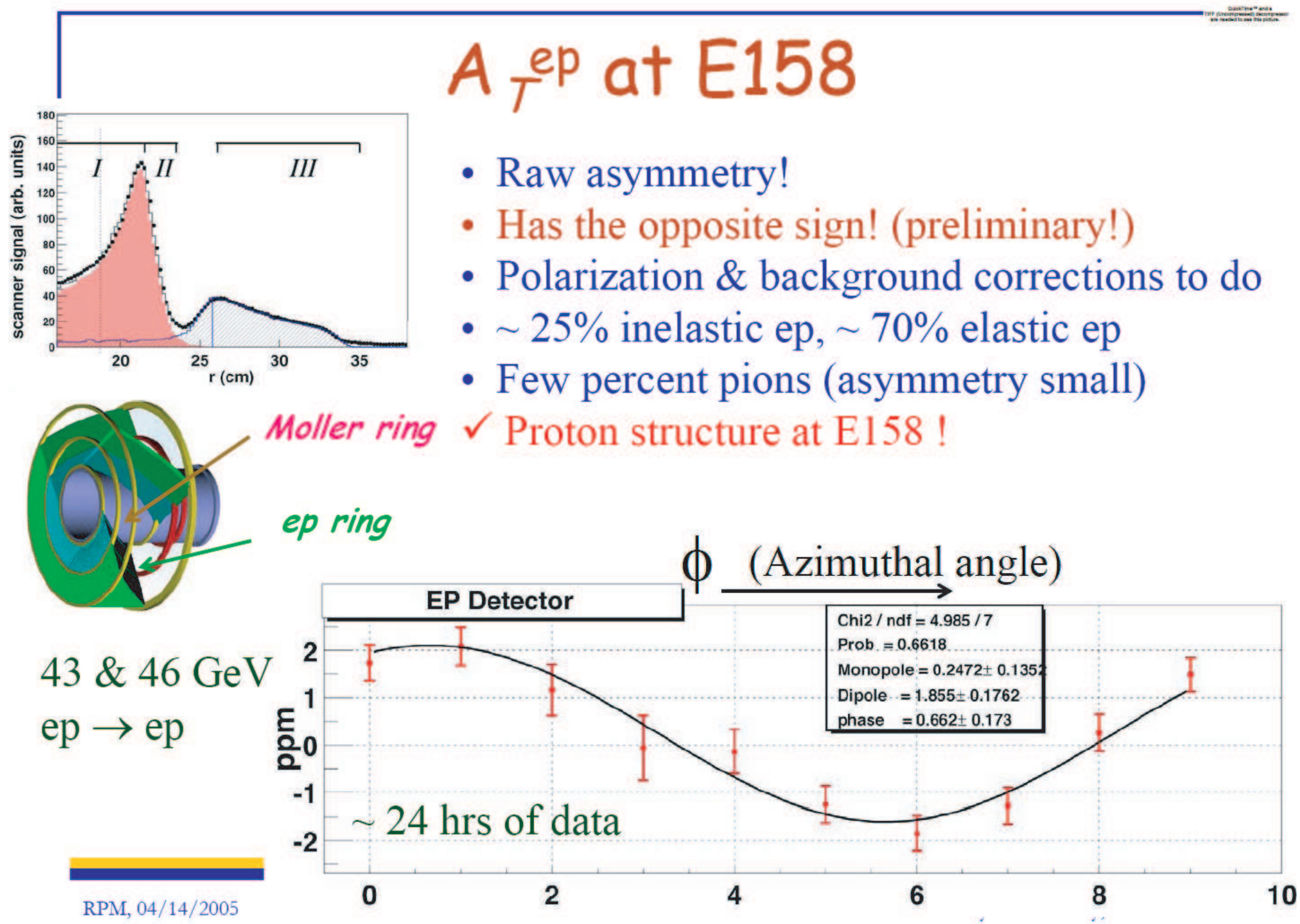
- $E_e = 45$ GeV
- High Polarization Pe=85%
  $A_{ee} = P_e A_{exp}$
- High intensity
  5×10^{11} e^-/pulse
- Fast polarization reversal
  120 Hz

High density target, $\sigma_{ee} = 12\ \mu b$
→ $L \sim 10^{38}\ cm^{-2} s^{-1}$

4 Months to achieve 10% statistical precision

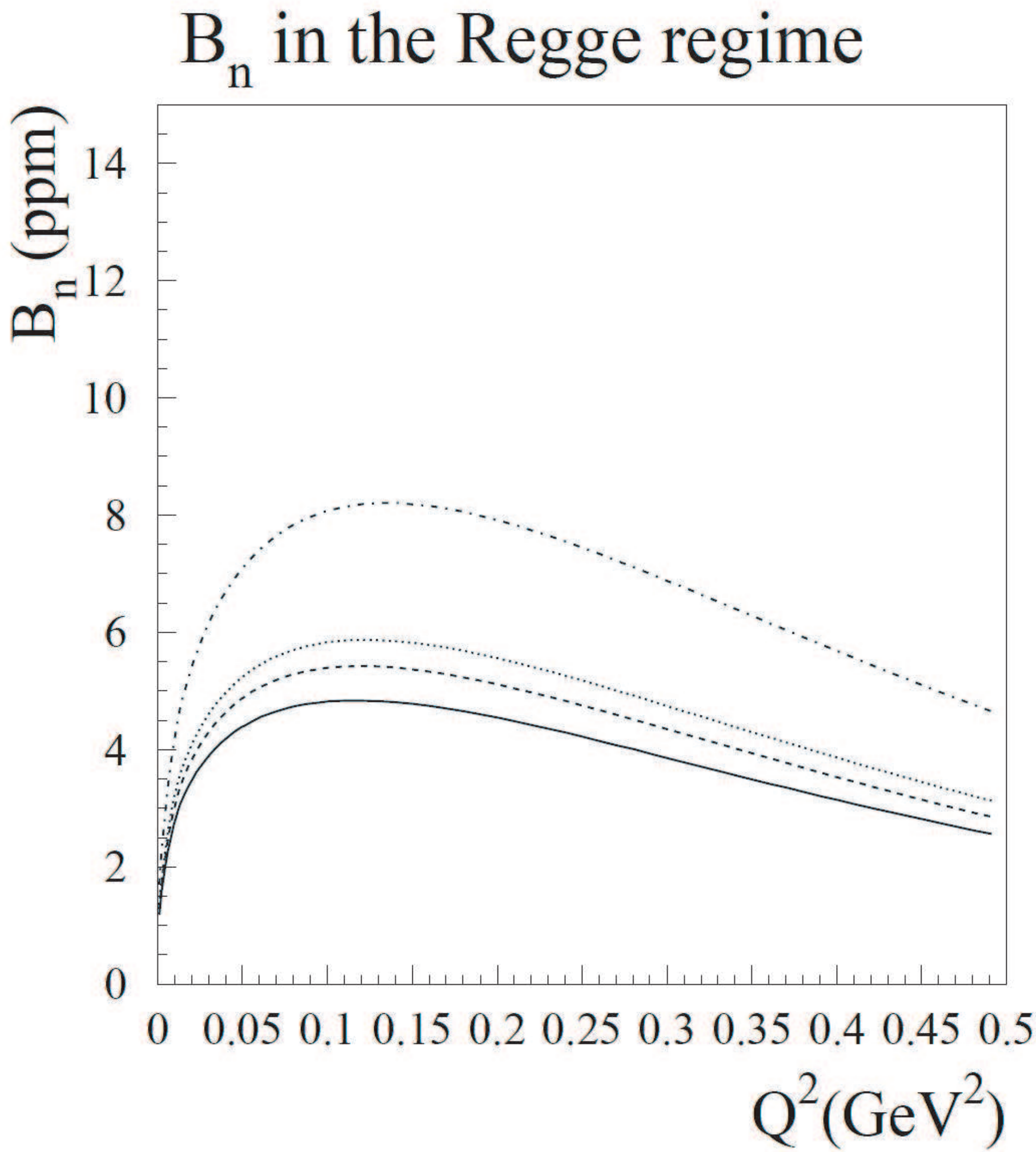
Antonin VACHERET, CEA-Saclay Dapnia/SPhN   SLAC E-158   PAVI 2004

E158 at SLAC: $\vec{e}$p Scattering



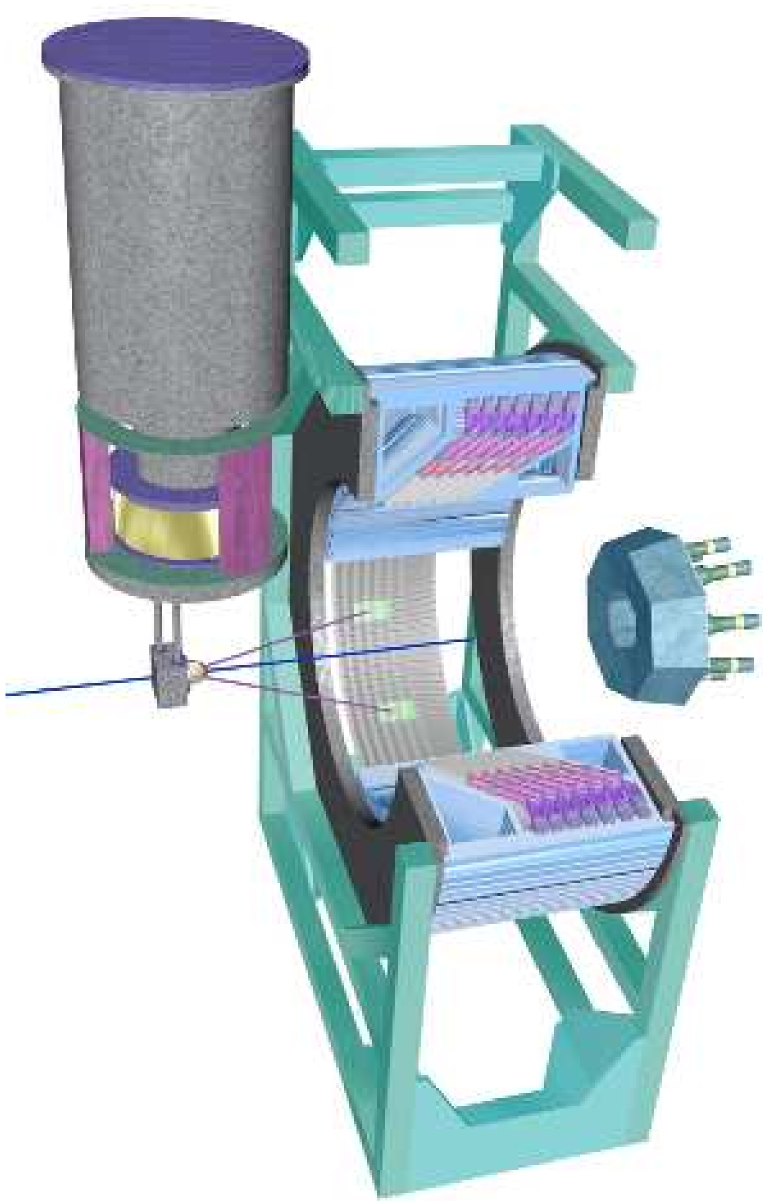
E158 at SLAC: $\vec{e}p$ Scattering

Gorchtein



A4 at MAMI/Mainz

A4 fast PbF_2 Calorimeter



Calorimeter:

1022 PbF_2 Crystal in 146 Frames

$\Theta = 30^\circ..40^\circ$, $\Phi = 0..2\pi$

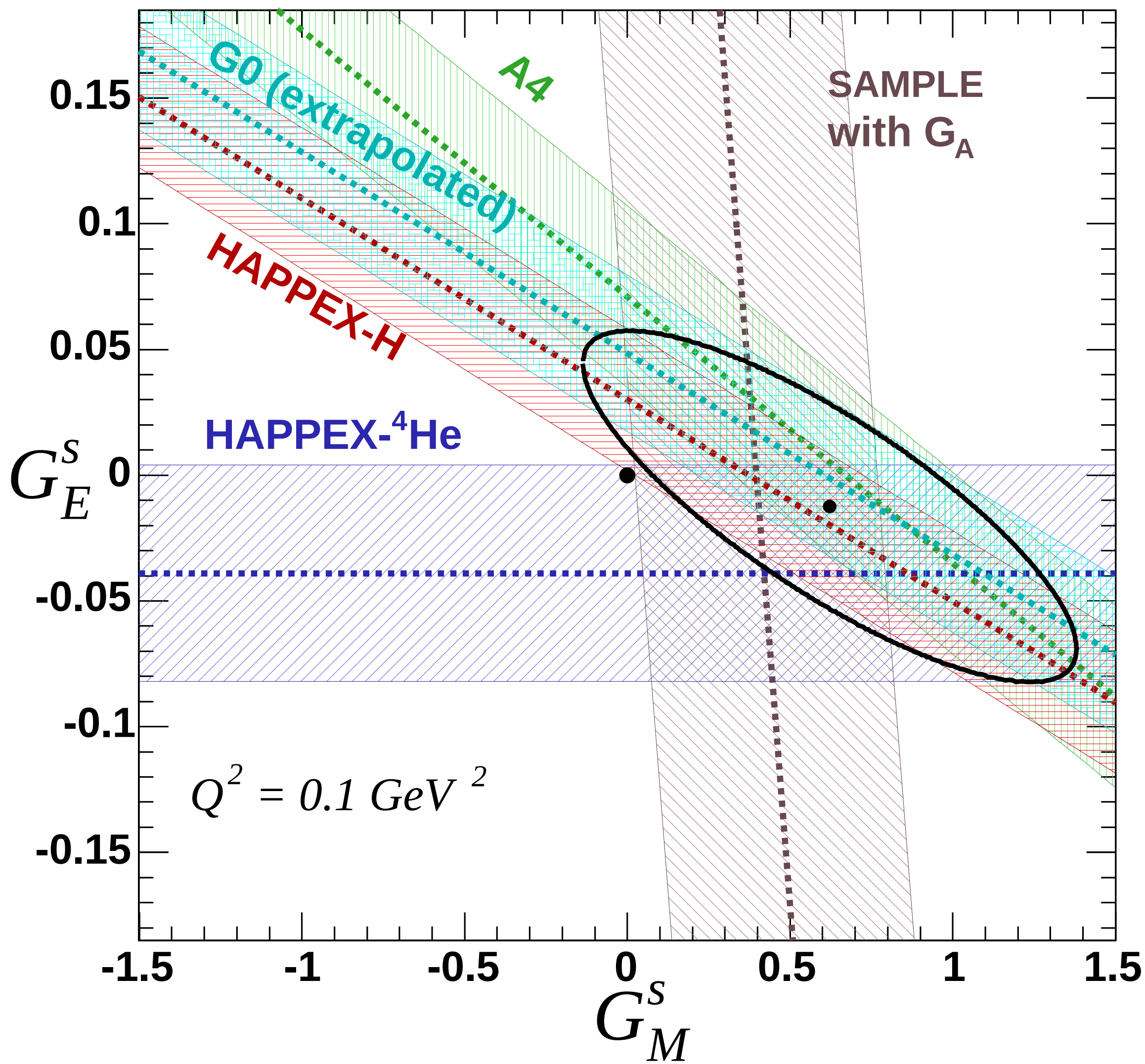
Luminosity Monitors:

8 Integrating Water-Cherenkov Detectors

$\Theta = 4.4^\circ..10^\circ$, $\Phi = 0..2\pi$

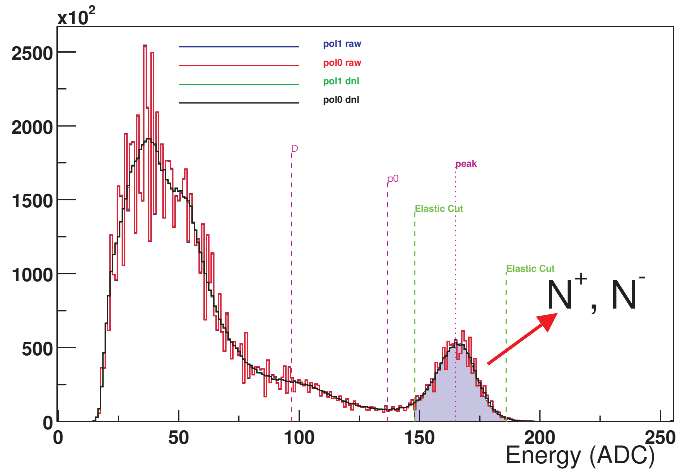
Full Coverage of the Azimuthal Angle ϕ

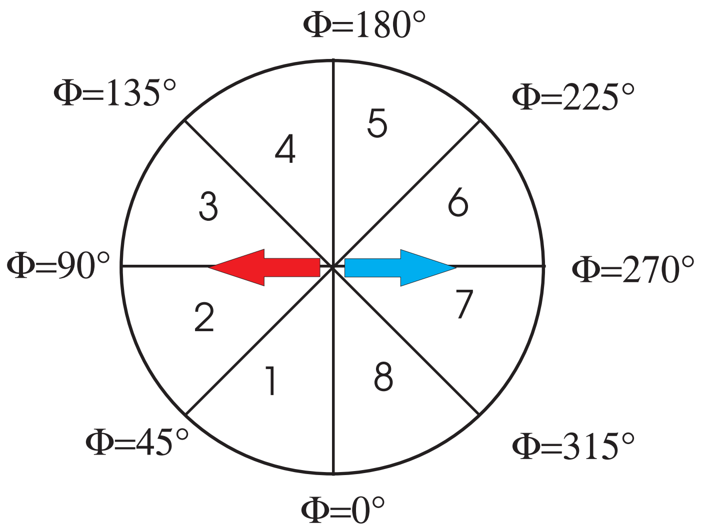
Strangeness Contribution



PRL 94, (2005) 152001, PRL 93 (2004) 022002

Extraction of physics asymmetry





Extract elastic counts N_i^+, N_i^- from channel $i = 1..1022$

Combine the 1022 channels to 8 sectors

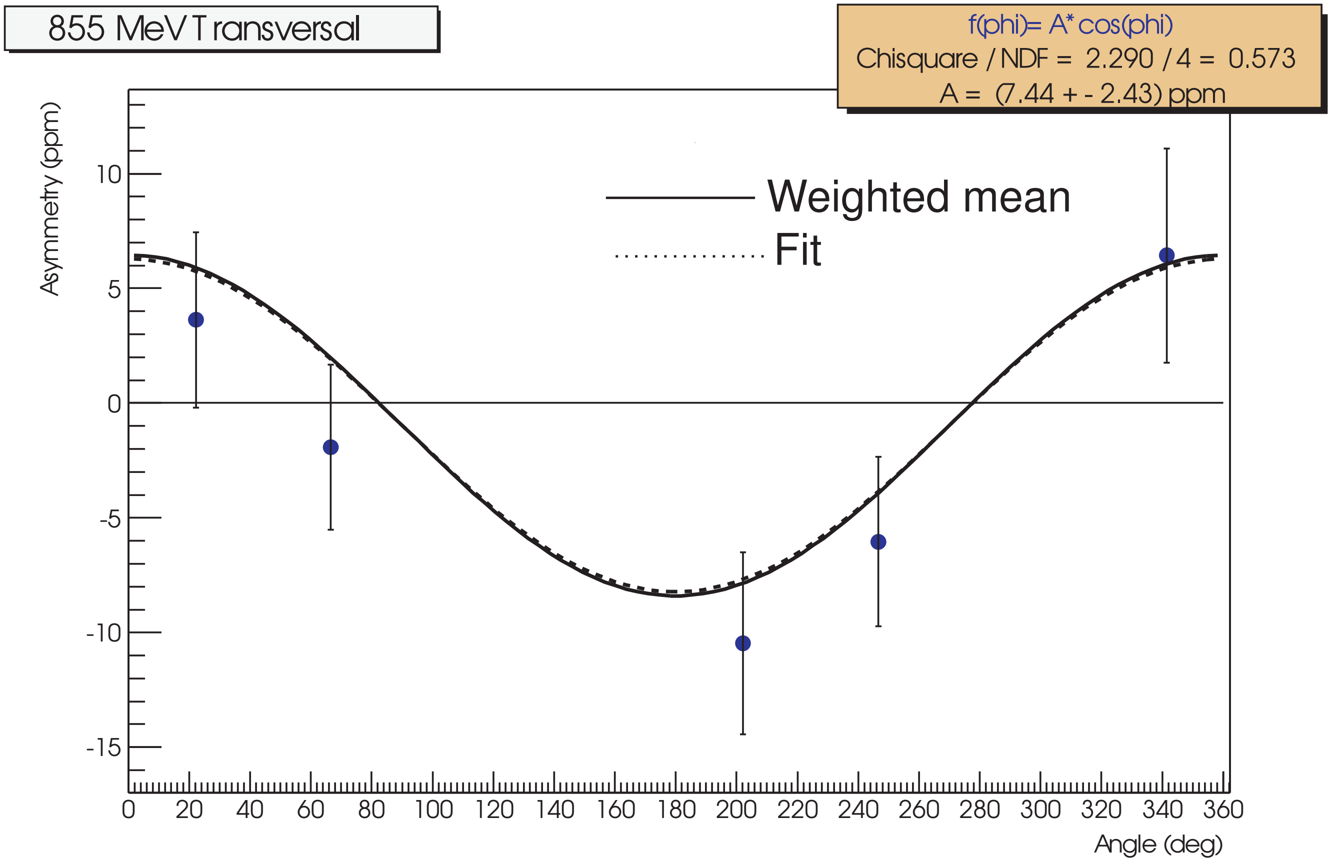
$N_{Sec}^+ = \Sigma N_i^+$, $N_{Sec}^- = \Sigma N_i^-$

Normalization to target density (L=luminosity, I=beam current)

$$A_{exp}^{Sec} \equiv A_{exp}(\Phi_i) = \frac{\frac{N_{Sec}^+}{\rho^-} - \frac{N_{Sec}^-}{\rho^-}}{\frac{N^+}{\rho^-} + \frac{N^-}{\rho^-}}, \quad \rho^\pm = \frac{L^\pm}{I^\pm}$$

Determination of $A_\perp$

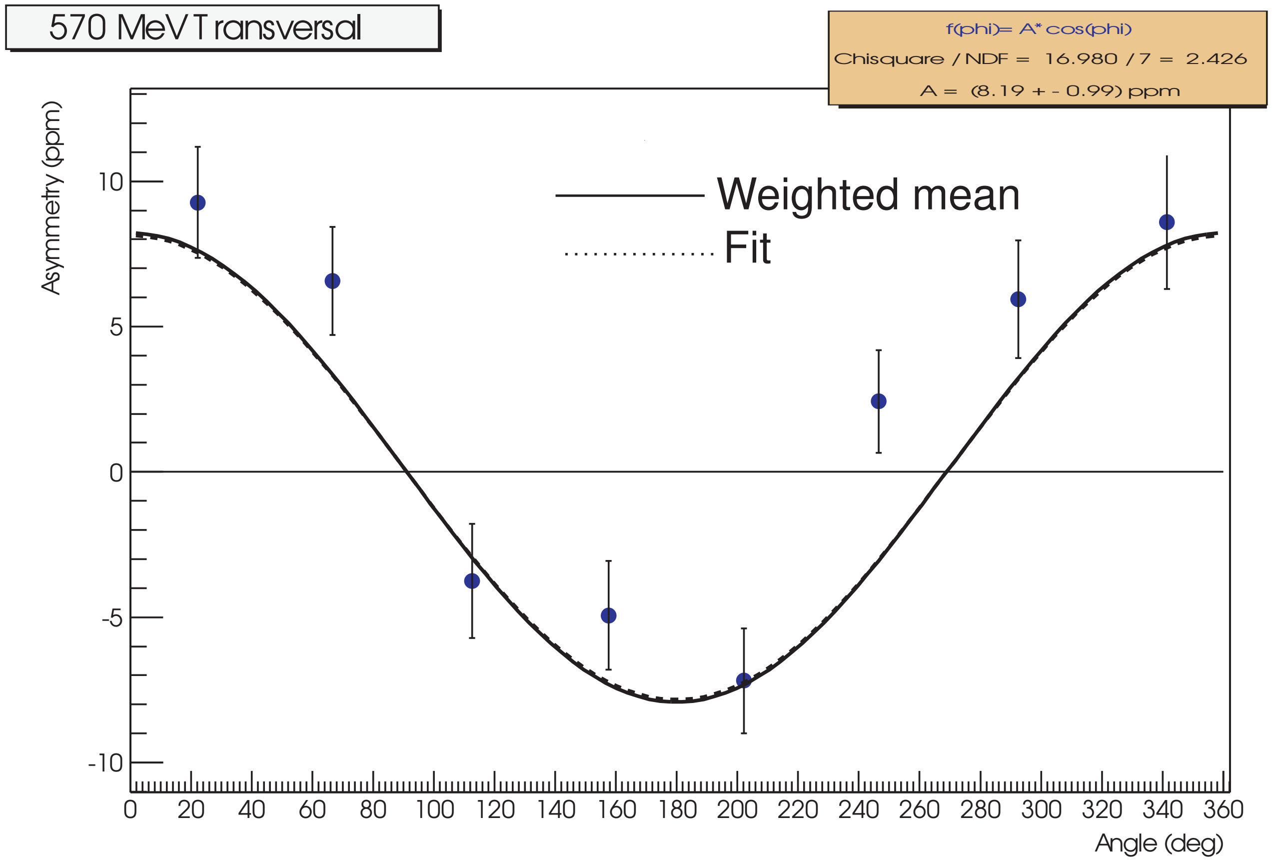
$E = 855.2 MeV$, $Q^2 = 0.23 (GeV/c)^2$, 50 h



$$A_\perp = (-7.62 \pm 2.34_{stat} \pm 0.80_{syst})\ ppm$$

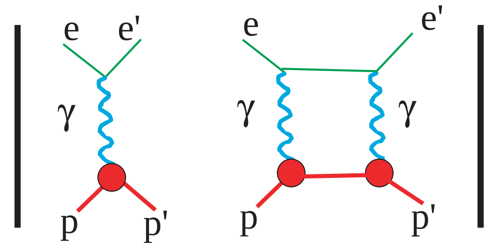
Determination of $A_\perp$

$E = 569.3 MeV$, $Q^2 = 0.11 (GeV/c)^2$, 50 h



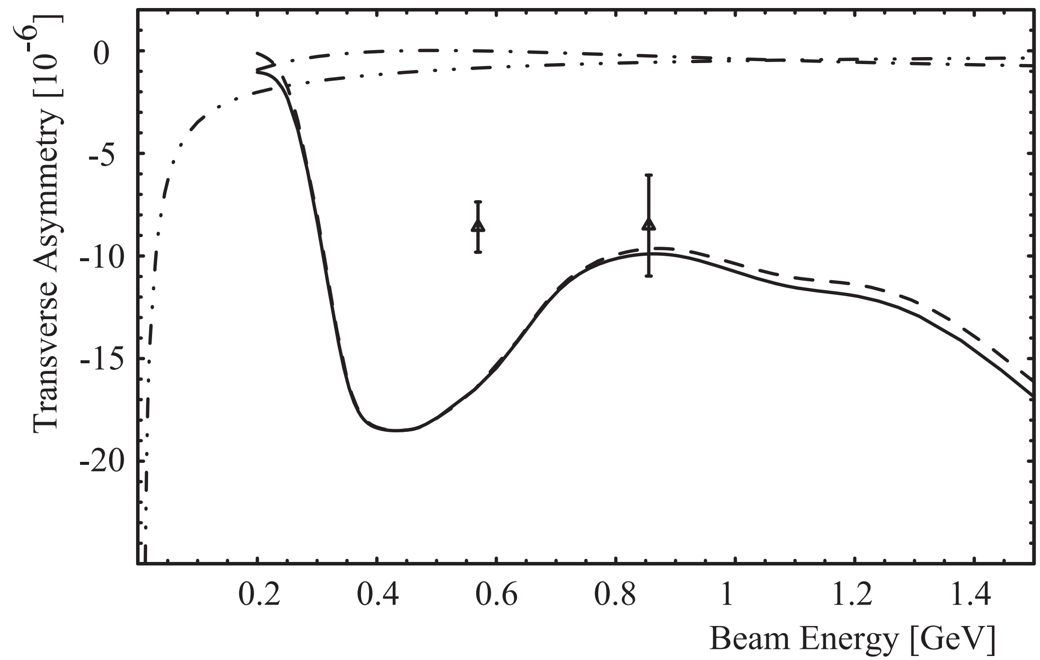
$$A_\perp = (-8.28 \pm 0.93_{stat} \pm 0.49_{syst})\ ppm$$

Comparison of $A_\perp$ with Model Calculations



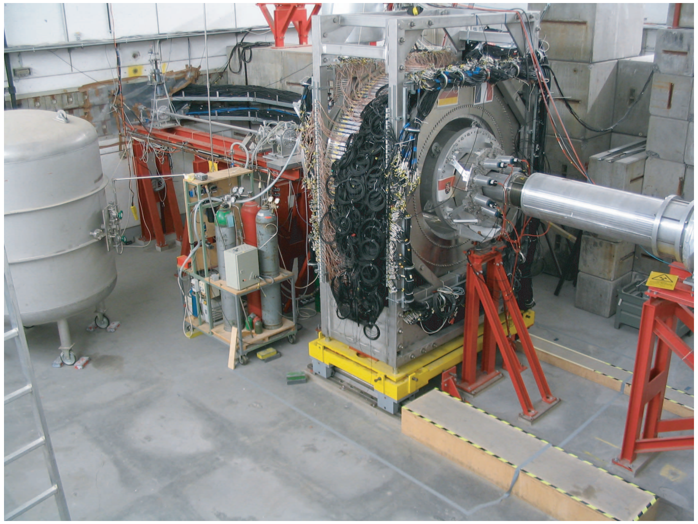
Intermediate State: Proton, πN States (MAID)

(B. Pasquini)



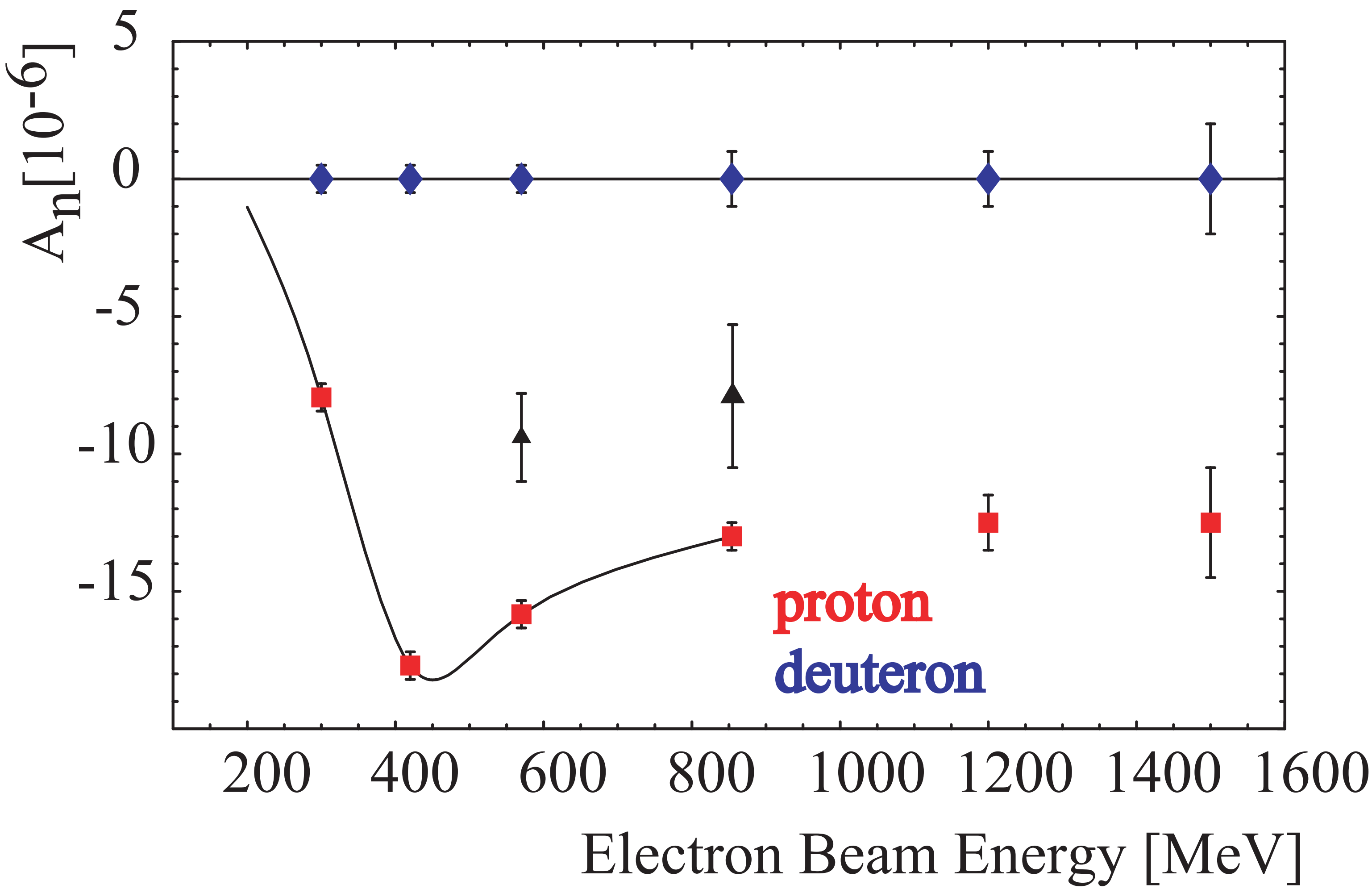
PRL **94, 082001 (2005)**

Elastic Scattering at Forward Angles

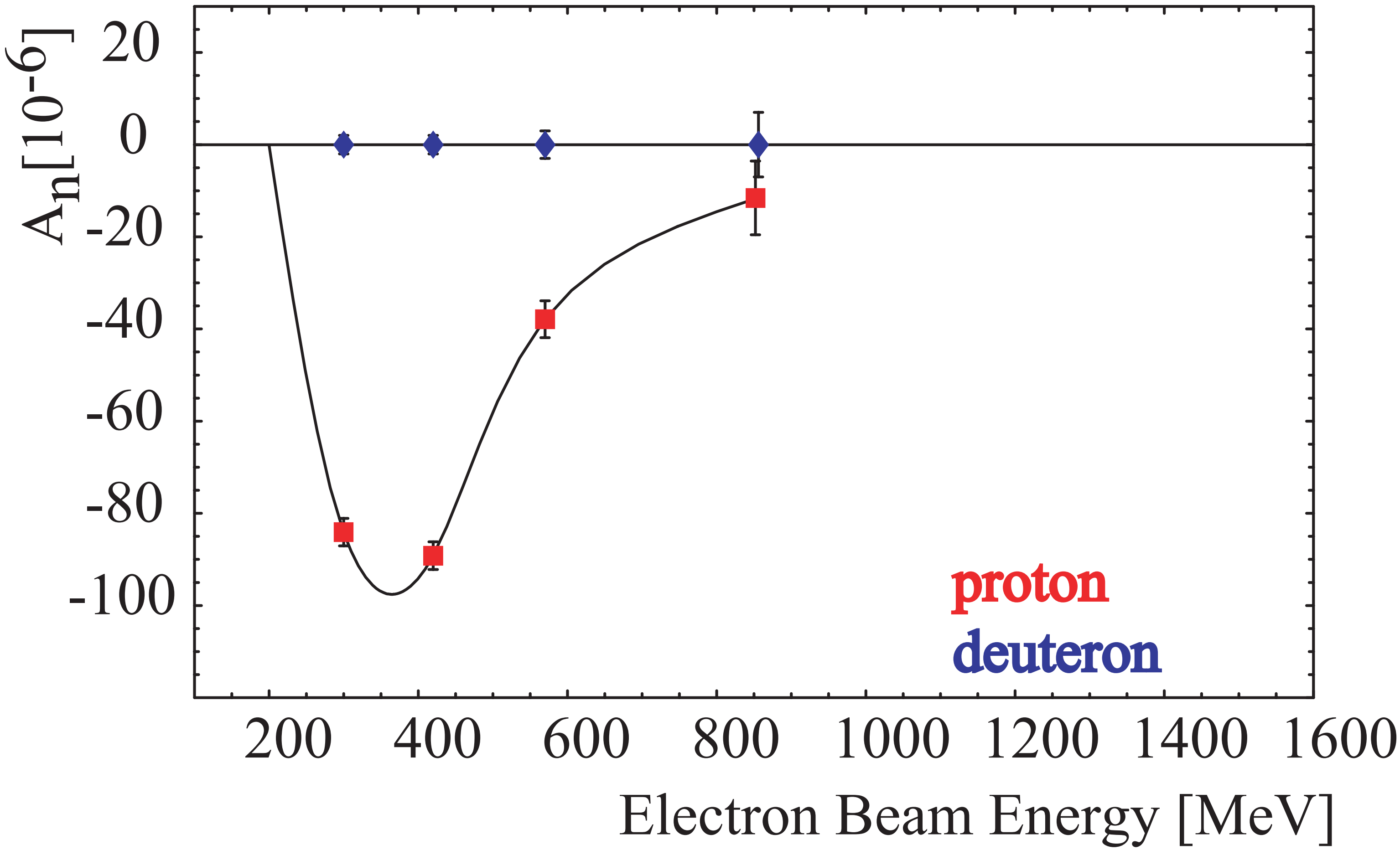
Program at $\theta = 35^\circ$

Hydrogen and Deuterium



Program at $\theta = 145°$

Hydrogen and Deuterium



A4 transverse Programm

E_e [MeV]	θ_e [degrees]	$\delta A_\perp^p$ [ppm]	hours proton	$\delta A_\perp^D$ [ppm]	hours deuteron	$\delta A_\perp^n$ [ppm] (extracted)
315	$(35\pm5)\circ$	0.5	20	0.5	20	20
420	$(35\pm5)\circ$	0.5	40	0.5	35	11
510	$(35\pm5)\circ$	0.5	90	0.5	70	7
570	$(35\pm5)\circ$	0.5	90	0.5	70	7
854	$(35\pm5)\circ$	0.5	300	0.5	220	4
1200	$(35\pm5)\circ$	1	260	1	180	6
1500	$(35\pm5)\circ$	2	180	2	120	11
315	$(145\pm5)\circ$	3	90	2	130	10
420	$(145\pm5)\circ$	3	(230)	2	(320)	10
510	$(145\pm5)\circ$	4	(300)	3	(390)	13
570	$(145\pm5)\circ$	4	(370)	3	(390)	13
854	$(145\pm5)\circ$	8	(490)	7	(380)	28

Summary

- Transverse Single-Spin-Asymmetries SAMPLE, A4, G0, HAPPEX, E158
- Imaginary Part of the 2-Photon-Amplitude
  precision tool $\longrightarrow$ inelastic πN intermediate States
- Intermediate Inelastic States Dominate
- Systematic Study of 2-Photon-Amplitude
- Experiments at Forward- and Backward angles