SINGLE SPIN ASYMMETRIES FROM THE MAINZ A4 EXPERIMENT

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BARYONS04
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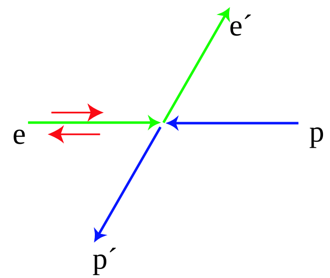
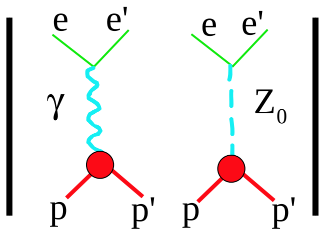
Outline

- Single Spin Asymmetries
- A4 Experimental setup
- Longitudinal spin: PV asymmetry
  Measurements at $Q^2 = 0.23 (GeV/c)^2$
  and $Q^2 = 0.11 (GeV/c)^2$
- Transverse spin - 2γ exchange
  Measurements at $Q^2 = 0.23 (GeV/c)^2$
  and $Q^2 = 0.11 (GeV/c)^2$

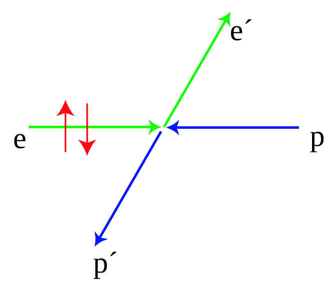
Single spin asymmetries in elastic scattering

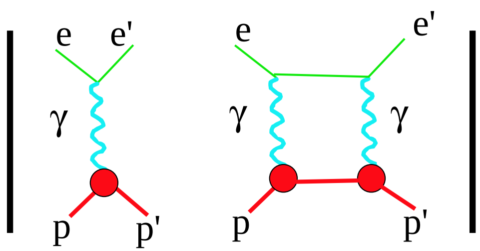
- Single Spin Asymmetries: e^- spin longitudinal,
  parity violating, ϕ-symmetric
  $A_{PV} = 10^{-6}$



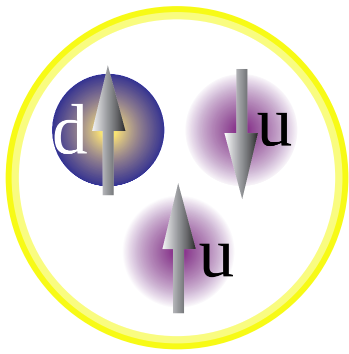


- Single-Spin-Asymmetries: e^- spin transverse,
  Azimuthal dependency: $\sin(\phi)$,
  $A_{\perp}^{beam} = 10^{-5}$





Strange quarks in the proton



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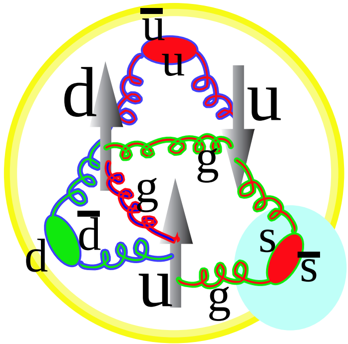


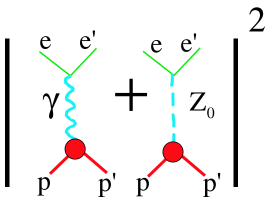
Simple quarks model

Full QCD

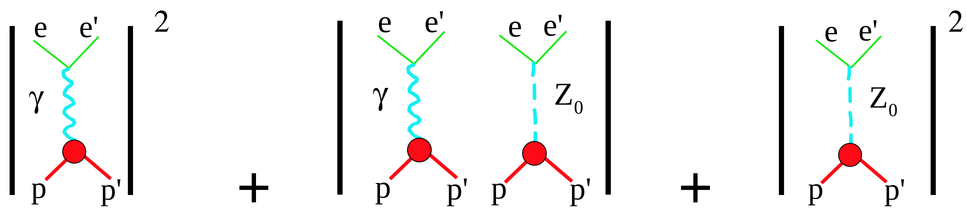
πN scattering $\langle p\vert\bar{s}s\vert p\rangle$	contribution to proton mass
DIS $\langle p\vert\bar{s}\gamma_\mu\gamma^5 s\vert p\rangle$	contribution to spin
PV e^- scattering $\langle p\vert\bar{s}\gamma_\mu s\vert p\rangle$	contribution to form factors

Electroweak interaction and parity violation

$\sigma \sim$



$\sim$



$$\sigma \sim 1 + 10^{-5} + 10^{-10}$$

PV asymmetry $A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$

Extraction of strange quark form factor contribution

Flavour decomposition:

$$G_E^p = \frac{2}{3} G_E^{p,u} - \frac{1}{3} G_E^{p,d} - \frac{1}{3} G_E^{p,s}$$

$$G_M^p = \frac{2}{3} G_M^{p,u} - \frac{1}{3} G_M^{p,d} - \frac{1}{3} G_M^{p,s}$$

Strange quark form factors

Goal:

A_{PV} in terms of G_E^s, G_M^s and the known electromagnetic form factors

- Weak interaction
- Isospin symmetry

Extraction of strange quark form factor contribution

$$A_{PV} = A_V + A_A + A_S = A_0 + A_S$$

Asymmetry without strangeness (A_0)

Strange quark contribution to asymmetry (A_S)

$$A_V = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left((1-4\sin^2\hat{\Theta}_W) - \frac{\varepsilon G_E^p G_E^n + \tau G_M^p G_M^n}{\varepsilon (G_E^p)^2 + \tau (G_M^p)^2}\right)$$

$$A_A = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{(1-4\sin^2\hat{\Theta}_W)\sqrt{1-\varepsilon^2}\sqrt{\tau(1+\tau)}G_M^p \tilde{G}_A^p}{\varepsilon (G_E^p)^2 + \tau (G_M^p)^2}$$

$$A_S = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{\varepsilon G_E^p G_E^s + \tau G_M^p G_M^s}{\varepsilon (G_E^p)^2 + \tau (G_M^p)^2}$$

with $\tau = \frac{Q^2}{4M_p^2}$ and $\varepsilon = [1 + 2(1+\tau) tan^2 \frac{\Theta}{2}]^{-1}$

Extraction of strange quark form factor contribution

Put in all known quantities... =>

- E=854.3 MeV, Q^2=0.23 $(GeV/c)^2$:

  $A_0 = (-6.30 \pm 0.43) \cdot 10^{-6}$

  $A_V = -5.61 \cdot 10^{-6}$, $A_A = -0.69 \cdot 10^{-6}$

- E5=70.4 MeV, Q^2=0.11 $(GeV/c)^2$:

  $A_0 = (-2.10 \pm 0.14) \cdot 10^{-6}$

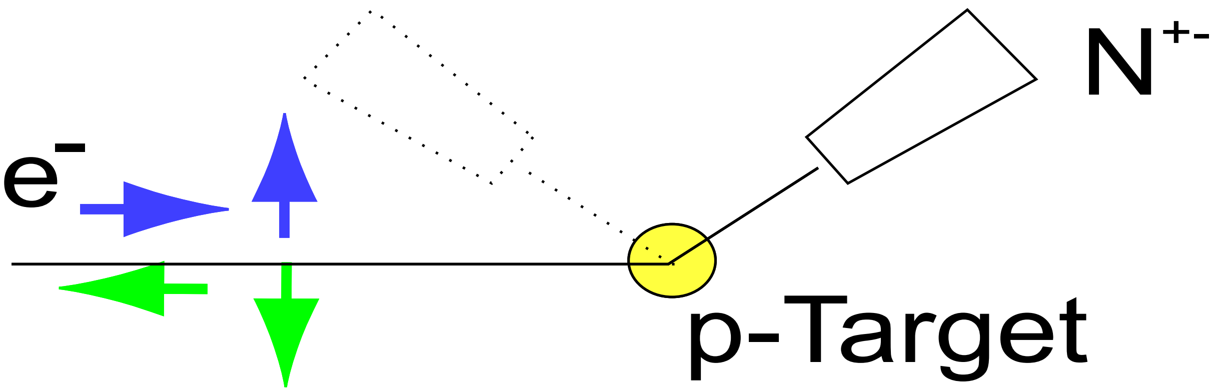
  $A_V = -1.85 \cdot 10^{-6}$, $A_A = -0.25 \cdot 10^{-6}$

Experimental requirements:

- Large statistics: $\frac{\Delta A}{A} \approx \frac{1}{A\sqrt{N}} = 5\%$ => $N \approx 10^{14}$ elastic counts
- Small systematics (beam fluctuations etc.)

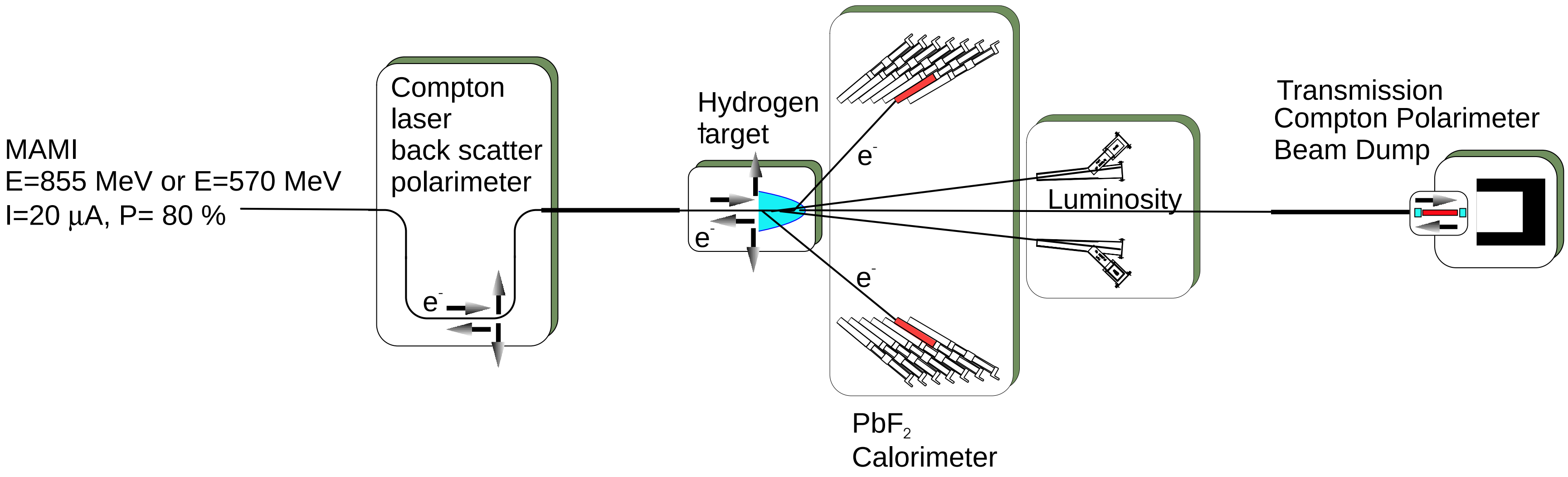
A4 Experiment

A4 Measurement Principle



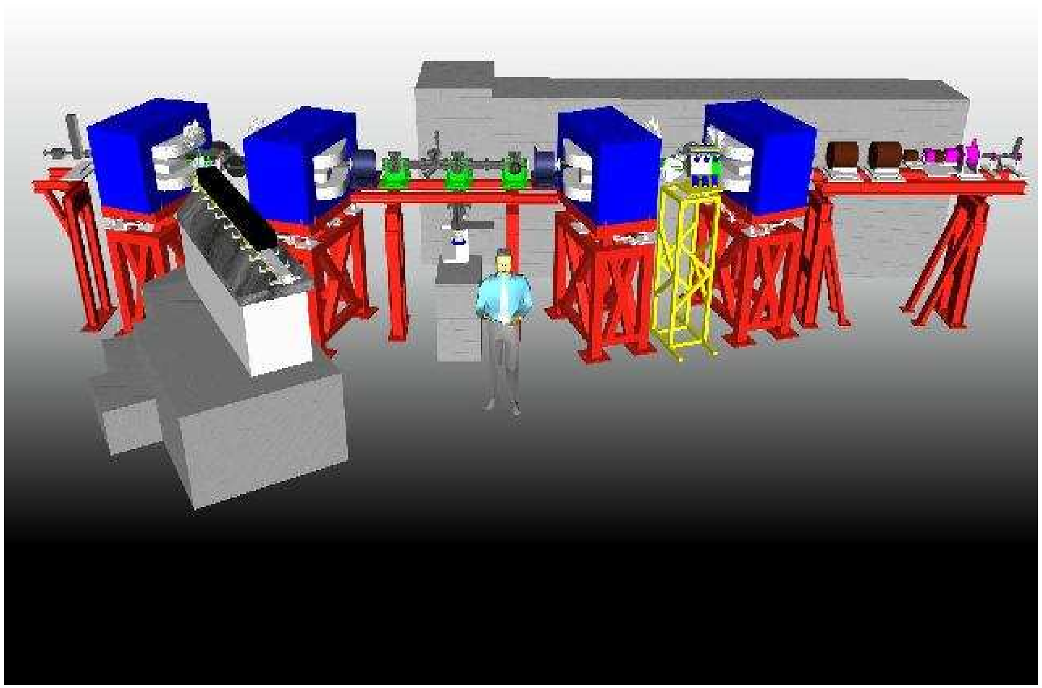
- Longitudinally or transversely polarised electrons
- Target: unpolarised protons
- Detector: scattering angle $35^\circ \pm 5^\circ$ or (in preparation) $145^\circ \pm 5^\circ$
- Counting experiment: $A = \frac{N^+ - N^-}{N^+ + N^-}$

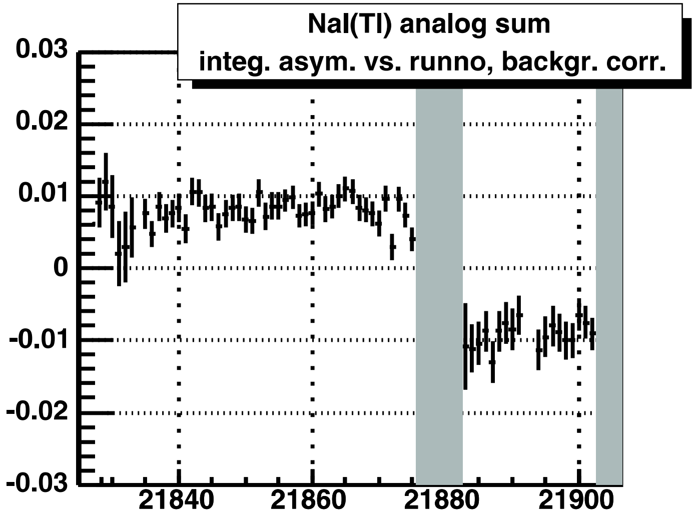
A4 Experimental setup



A4 Experimental setup

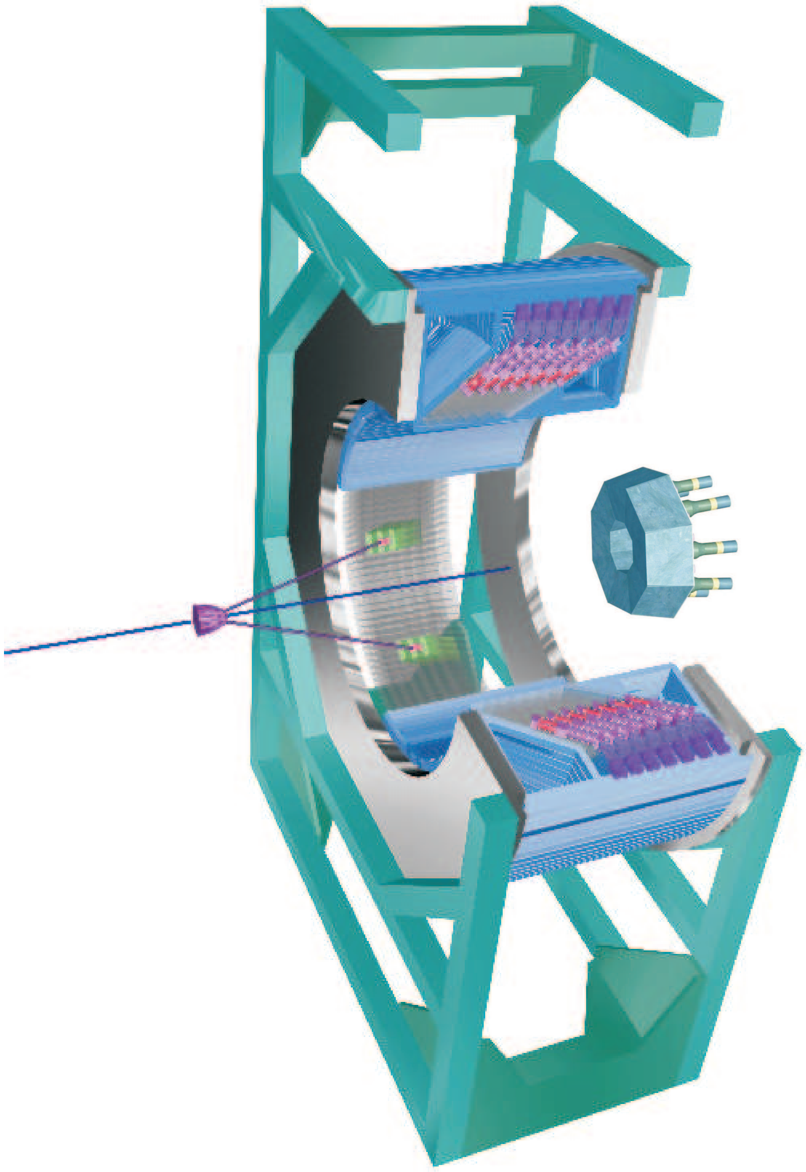
Compton backscatter polarimeter





- Magnetic chicane
- Intracavity $e^{-}\gamma$ - scattering
- First asymmetries in june 2004

A4 Calorimeter and Luminosity Monitors



Calorimeter:

1022 PbF_2 crystals

146 frames, 7 rings

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

Luminosity monitors:

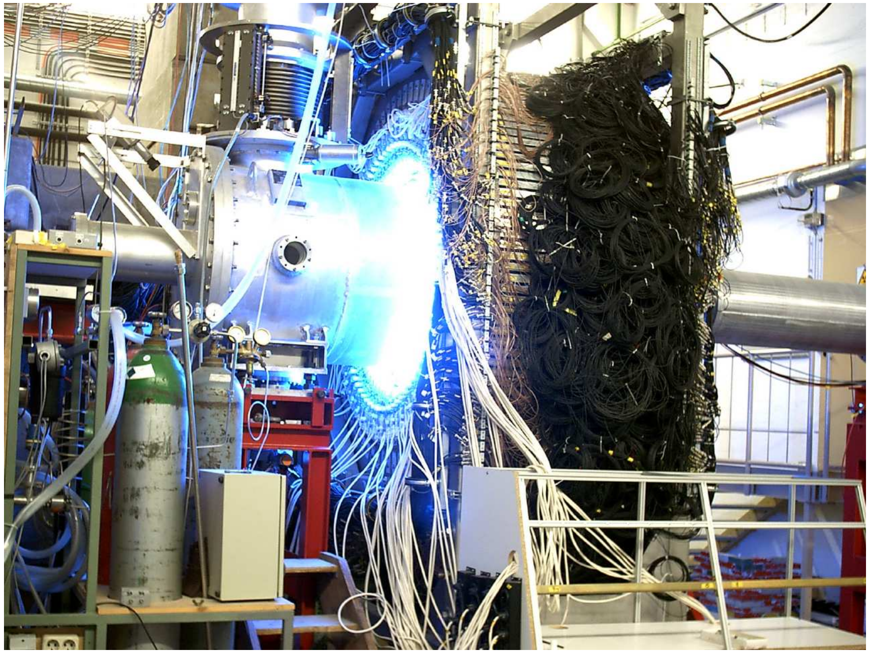
8 water cherenkov monitors

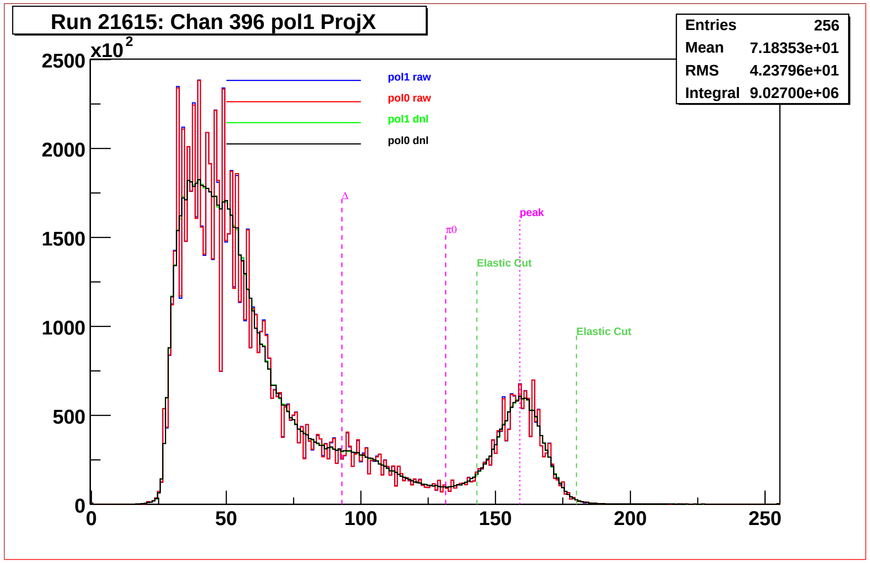
$\Theta = 4.4^\circ..10^\circ$, $\Phi = 0..2\pi$

Full coverage of azimuthal range

A4 Experimental setup

The Calorimeter





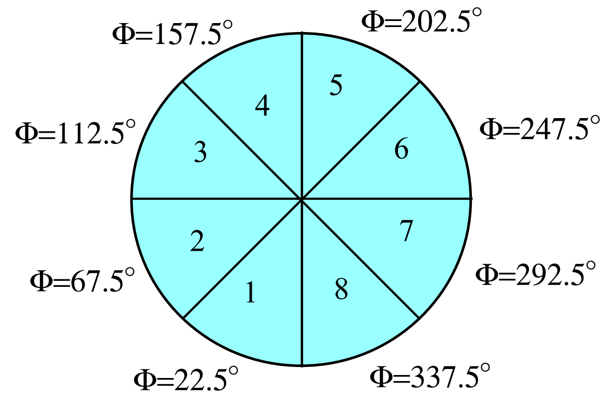
$d\Omega = 0.64\,sr$, rates: 100 MHz total, 10 MHz elastic (@855 MeV)

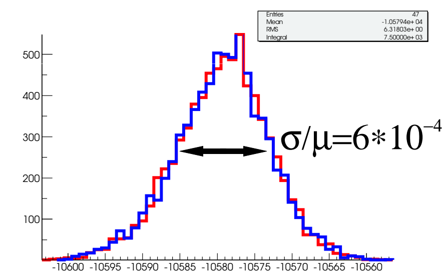
Count Single events, separation of elastic from inelastic events

2044 energy histograms (+-) every 5 minutes

Extract N^+ and N^-

The luminosity monitors





histogrammed

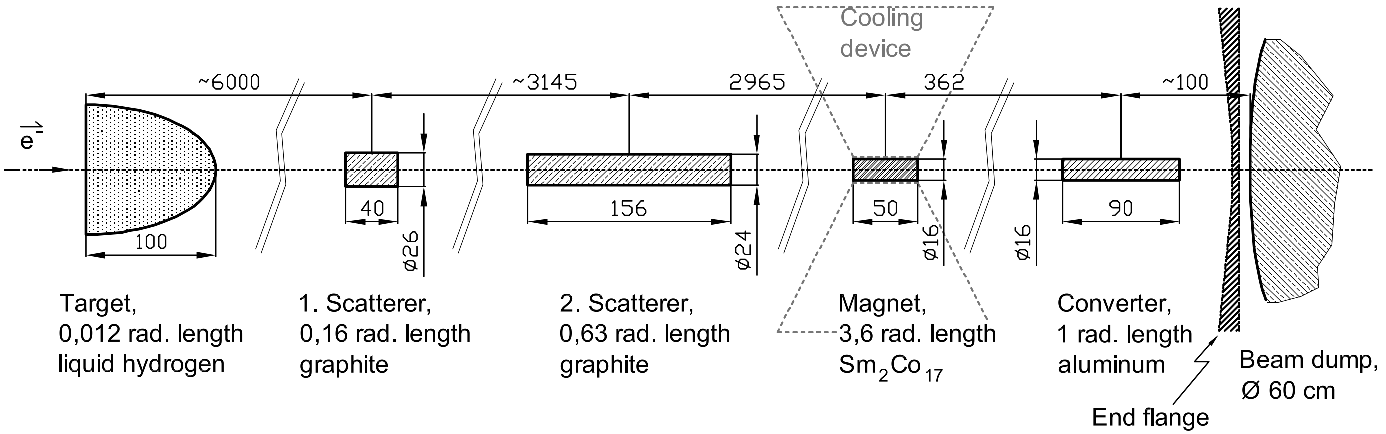
$d\Omega\ =\ 80\ msr$, rates: 2.6 GHz elastic, 350 GHz Møller

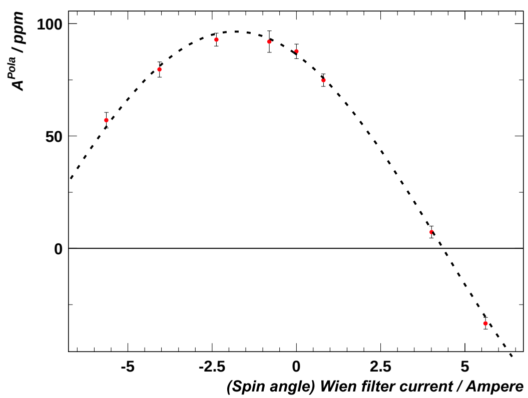
Integrating water cherenkov detectors, measurements every 20ms

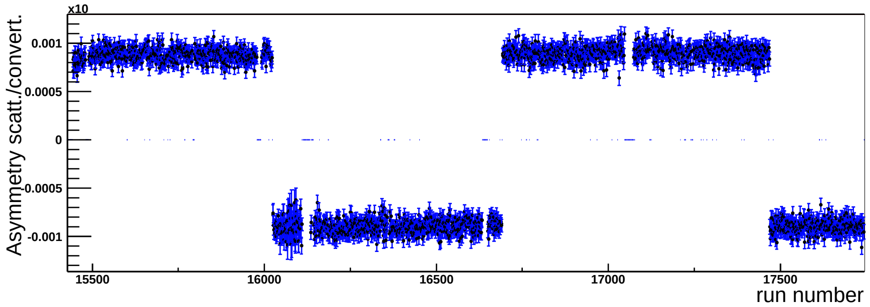
Design optimised for Møller electrons

Experimental setup

Dump polarimeter



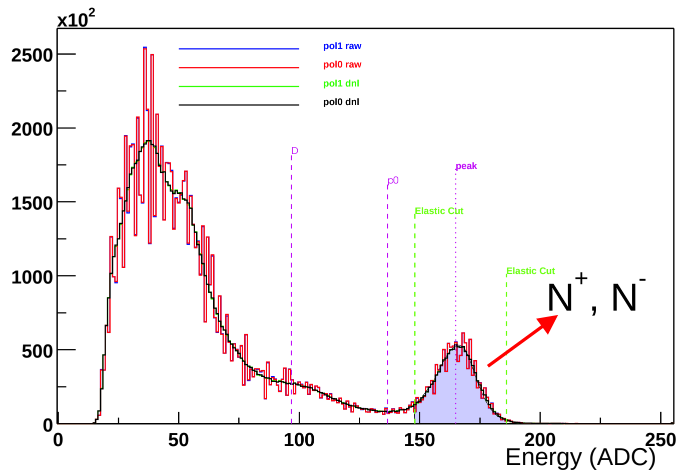




- Relative Measurement of polarization degree, sensitive to longitudinal spin
- Determination of spin angle
- Control of λ/2-plate status

Extracting experimental asymmetry A_{exp}

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



$$N^+ = \Sigma N_i^+,\ N^- = \Sigma N_i^-$$

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

$$A_{exp} = \frac{\frac{N^+}{\rho^+} - \frac{N^-}{\rho^-}}{\frac{N^+}{\rho^+} + \frac{N^-}{\rho^-}}, \quad \rho^\pm = \frac{L^\pm}{I^\pm}$$

Extraction of physical asymmetry A_{phys}

- Correction for helicity correlated false asymmetries and polarization

  $$A_{exp} = P \cdot A_{phys} + \sum_{i=1}^{6} a_i X_i$$

  P: Beam polarisation

  X_1: A_I, Current asymmetry

  X_2: ΔX, Horizontal position difference

  X_3: ΔY, Vertical position difference

  X_4: $\Delta X'$, Horizontal angle difference

  X_5: $\Delta Y'$, Vertical angle difference

  X_6: ΔE, Energy difference

  Determination of a_i via multiple linear regression

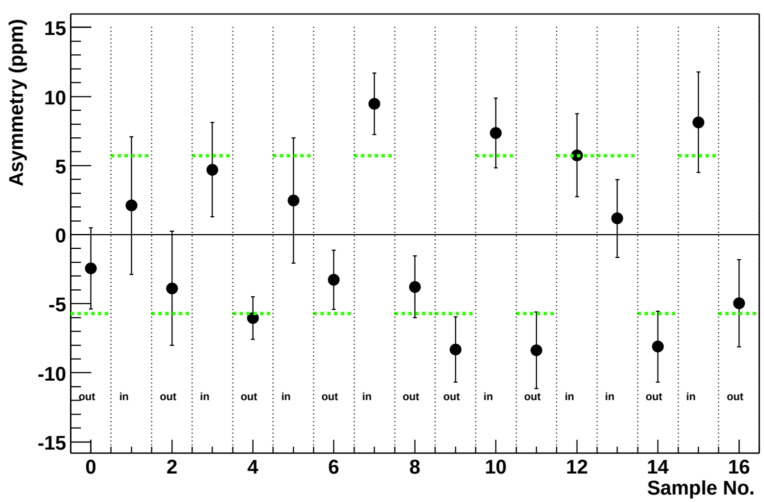
- Correction for dilution from quasielastic scattering off aluminium (target entrance/exit windows)

- Systematic check with $\lambda/2$-plate flip

Physical asymmetries

$$Q^2 = 0.23(GeV/c)^2$$

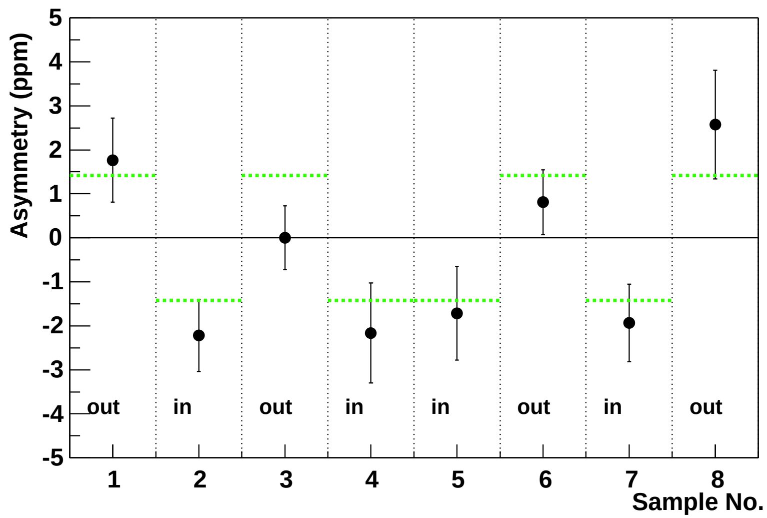
550 hours beam data



$$A_{phys} = (-5.44 \pm 0.54_{stat} \pm 0.26_{syst}) \cdot 10^{-6}$$

$$Q^2 = 0.11(GeV/c)^2$$

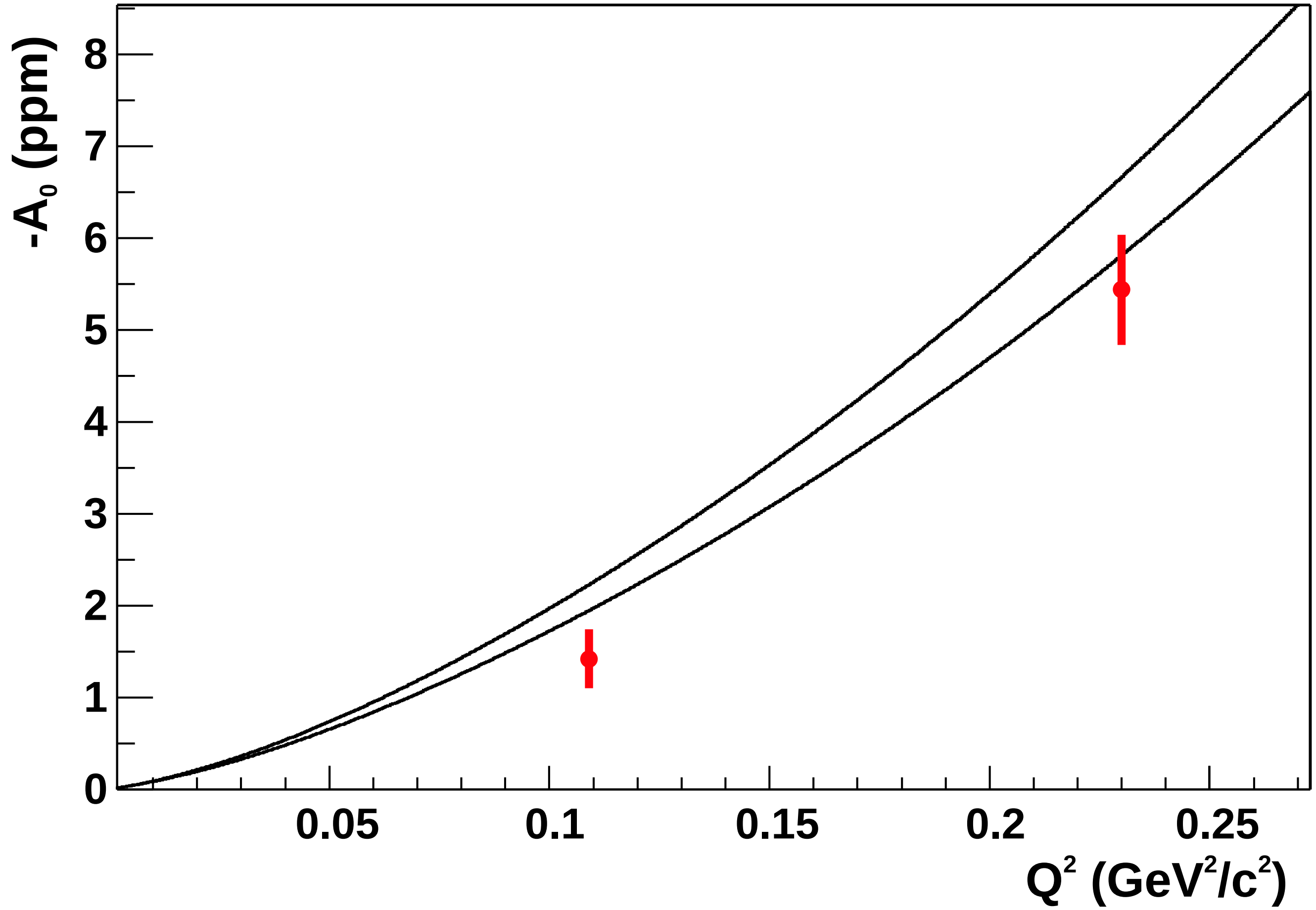
350 hours beam data



$$A_{phys} = (-1.42 \pm 0.29_{stat} \pm 0.12_{syst}) \cdot 10^{-6}$$

Physical asymmetries

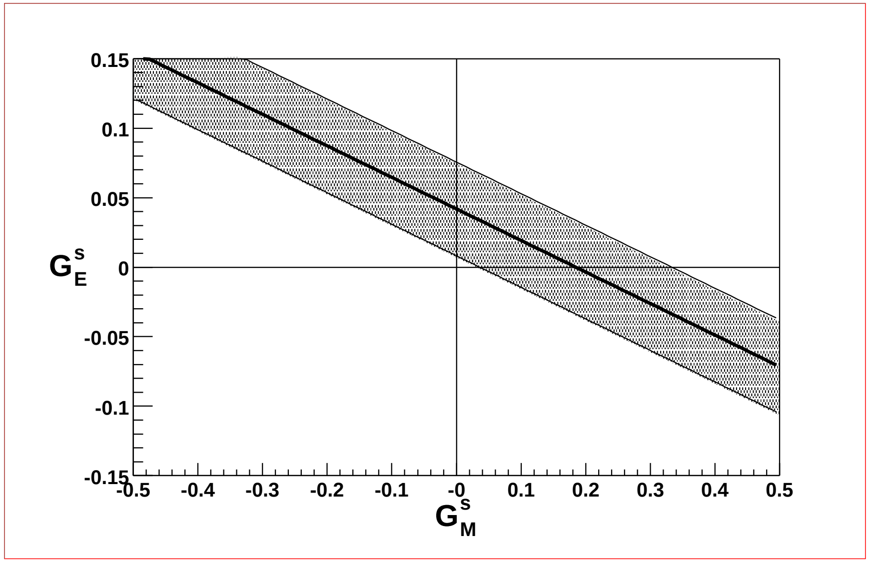
Comparison of measured asymmetries with A_0



Strange form factors

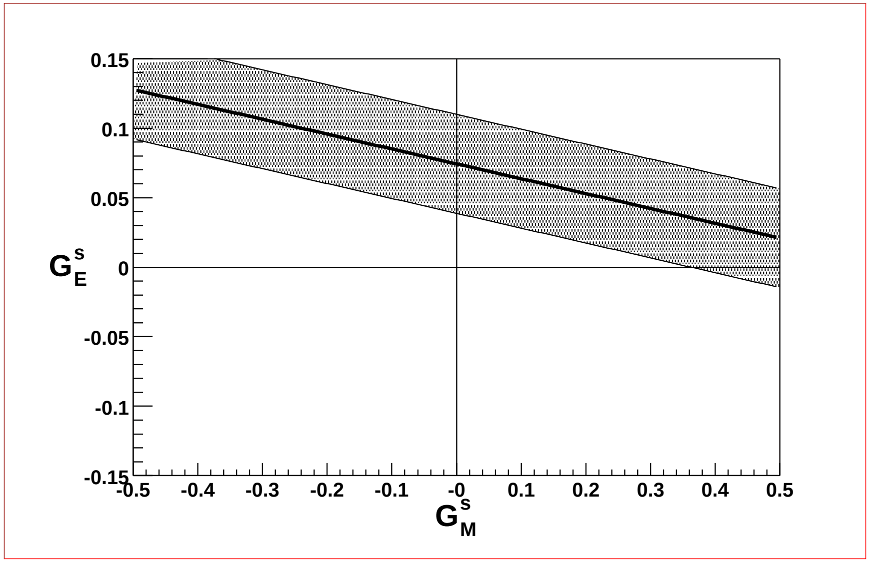
$Q^2 = 0.23 (GeV/c)^2$

$G_E^s + 0.225 G_M^s = 0.039 \pm 0.034$



$Q^2 = 0.11 (GeV/c)^2$

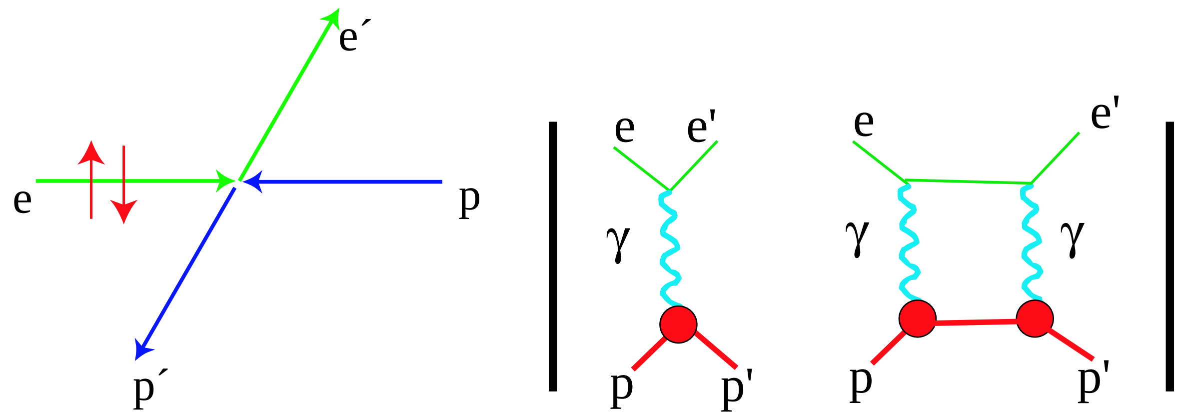
$G_E^s + 0.107 G_M^s = 0.069 \pm 0.036$



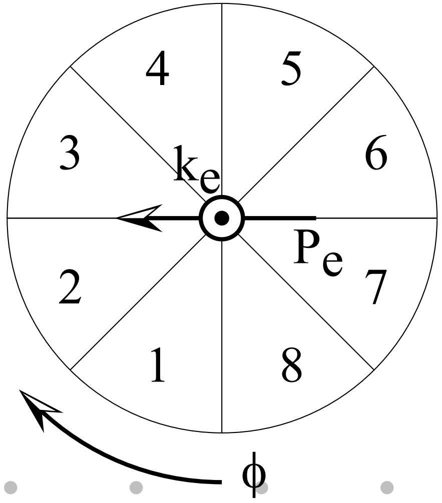
- Determination of G_E^s, G_M^s separately: Preparation of measurements under backward angle in preparation
- $Q^2 = 0.11 (GeV/c)^2$: Combination with SAMPLE and HAPPEX results

Transverse Spin

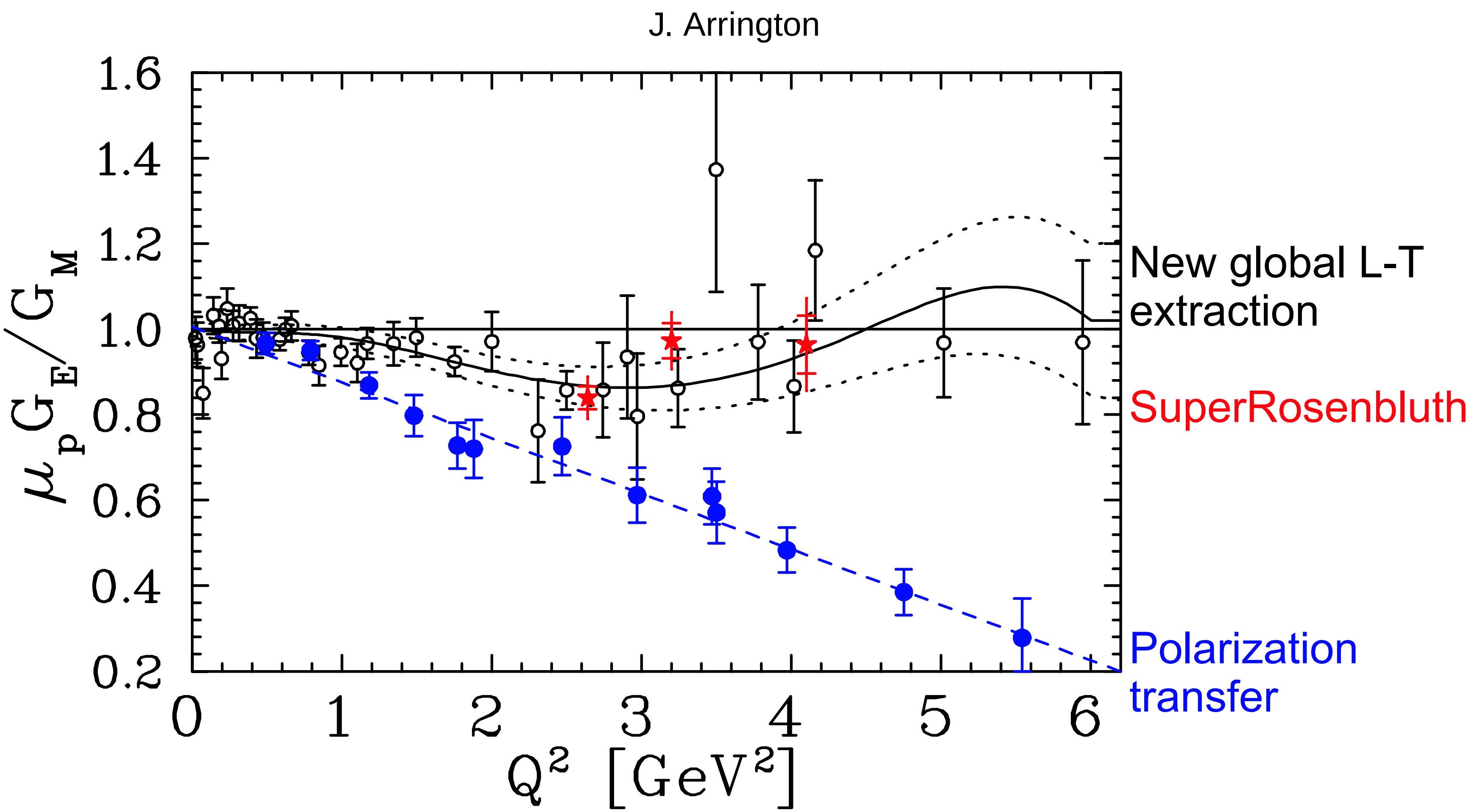
Single-Spin-Asymmetries: e^- spin transverse



- Imaginary part of 2γ exchange amplitude
- πN intermediate states
- Azimuthal dependency: $A(\phi) = A_\perp \cos(\phi)$

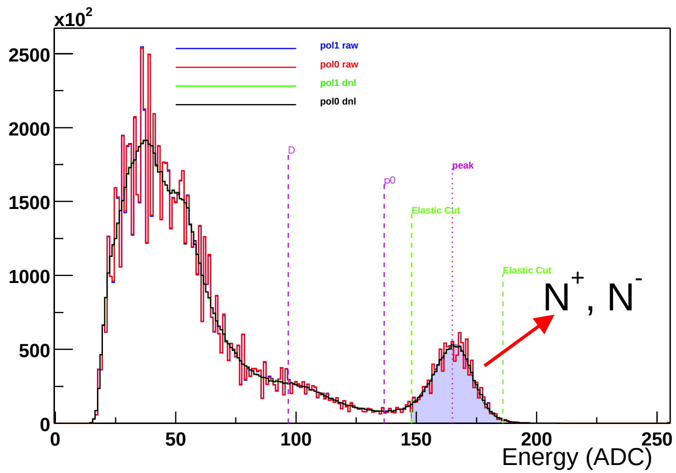


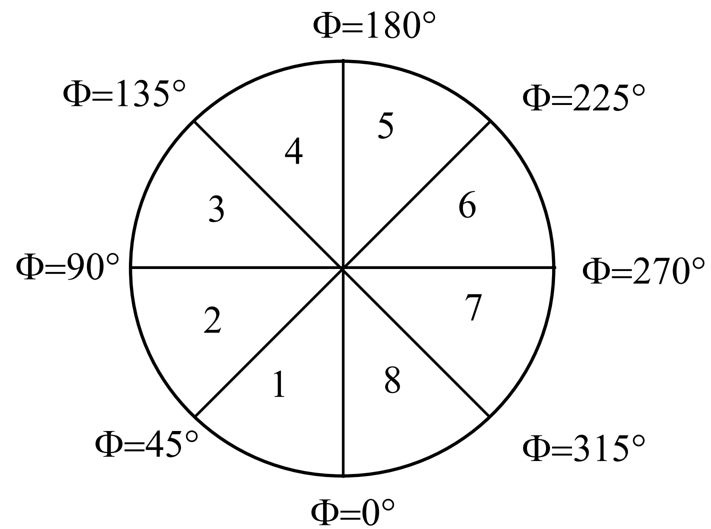
Transverse Asymmetry: Why is it interesting?



$\mu_p G_E^p / G_M^p$ different in different experiments

Extraction of physical asymmetry





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

Combine the 1022 channels to 8 sectors

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

Normalisation to target density (L=luminosity, I=beam current

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

Analysis

Normalisation to target density

$$A_{exp} = \frac{\frac{N^+}{\rho^-} - \frac{N^-}{\rho^-}}{\frac{N^+}{\rho^-} + \frac{N^-}{\rho^-}}, \quad \rho^\pm = \frac{L^\pm}{I^\pm}$$

with N = Elastic counts, L = Luminosity, I = Beam current

Normalisation to target density

$$A_{exp} = \frac{\frac{N^+}{\rho^-} - \frac{N^-}{\rho^-}}{\frac{N^+}{\rho^-} + \frac{N^-}{\rho^-}}, \quad \rho^\pm = \frac{L^\pm}{I^\pm}$$

with N = Elastic counts, L = Luminosity, I = Beam current

$$A_{exp} \approx \frac{N^+ - N^-}{N^+ + N^-} - \frac{L^+ - L^-}{L^+ + L^-} + \frac{I^+ - I^-}{I^+ + I^-}$$

Analysis

Normalisation to target density

$$A_{exp} = \frac{\frac{N^+}{\rho^-} - \frac{N^-}{\rho^-}}{\frac{N^+}{\rho^-} + \frac{N^-}{\rho^-}}, \quad \rho^{\pm} = \frac{L^{\pm}}{I^{\pm}}$$

with N = Elastic counts, L = Luminosity, I = Beam current

$$A_{exp} \approx \frac{N^+ - N^-}{N^+ + N^-} - \frac{L^+ - L^-}{L^+ + L^-} + \frac{I^+ - I^-}{I^+ + I^-}$$

=> Requirement: $A_L \ll A_{phys}$

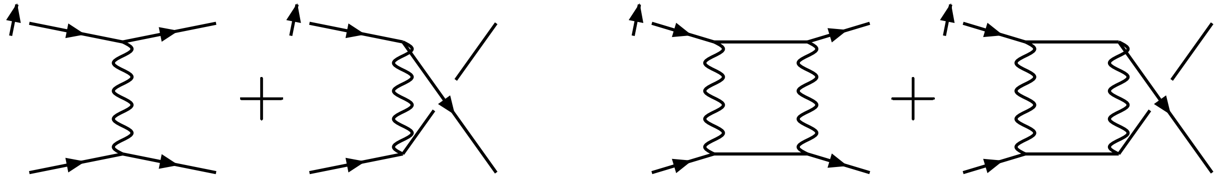
=> In PV case A_L an order of magnitude smaller than PV asymmetry

=> But with transverse spin: Two photon exchange...

Møller Scattering

Single Spin Asymmetry in Møller Scattering

Dixon, Schreiber, hep-ph/0402221: *Azimuthal Asymmetry in Transversely Polarized Møller Scattering*



(a) (b)

- (a) Tree diagrams
- (b) Box diagrams
- => Leading term in cross section containing azimuthal asymmetry arises at order α^3 from interference of diagrams in (a) and (b)

Leading Order Single Spin Asymmetry in Møller Scattering

$$\frac{d\sigma^{Born}}{d\Omega} = \frac{\alpha^2}{2s}[\frac{t^2+tu+u^2}{tu}]^2$$

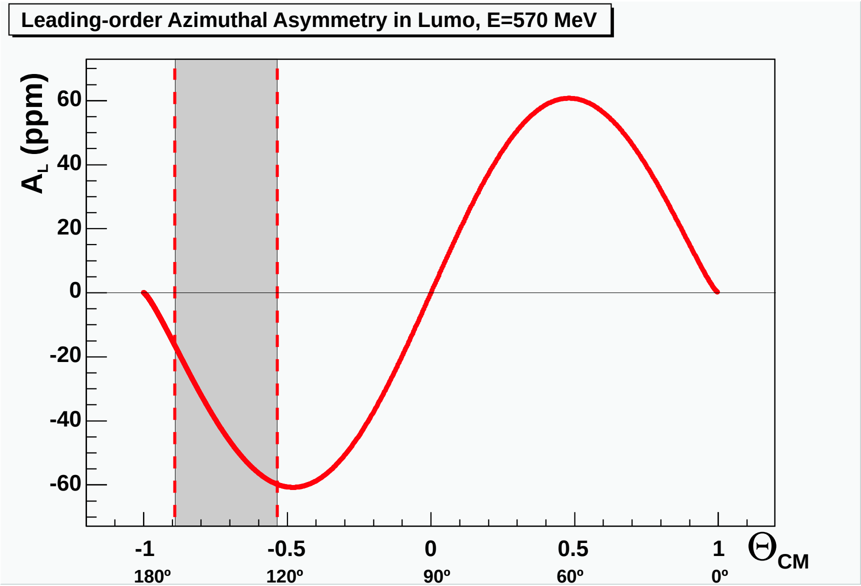
$$\frac{d\sigma^{\Phi}}{d\Omega} = -\frac{\alpha^3}{8}\frac{m_e}{\sqrt{s}}\sin\Theta_{CM}\ \sin\Phi\ \frac{1}{t^2u^2}\cdot$$
$$[3s[t(u-s)\ln(\frac{-t}{s}) - u(t-s)\ln(\frac{-u}{s})] - 2(t-u)tu]$$

with

$$s = 2m_eE\,, t = -\frac{s}{2}(1-\cos\Theta_{CM}), u = -\frac{s}{2}(1+\cos\Theta_{CM})$$
$$E' = \frac{E}{2}(1+\cos\Theta_{CM}), \cos\Theta_{lab} = 1 - \frac{m_e}{E}\frac{1-\cos\Theta_{CM}}{1+\cos\Theta_{CM}}$$

Møller Scattering

Single Spin Asymmetry in Møller Scattering

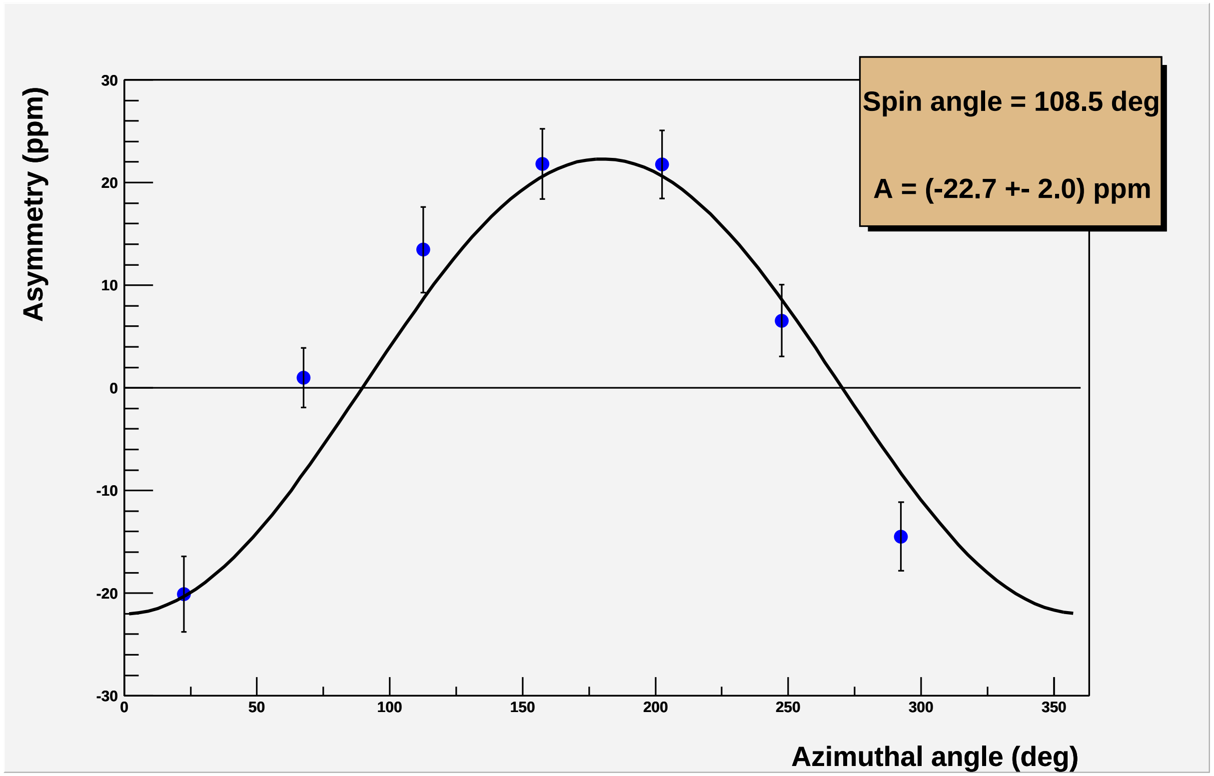


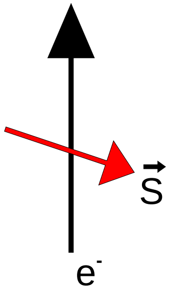
- Asymmetry seen by a detector is sensitive to the acceptance
- Symmetric acceptance in Θ_{CM} would lead to zero asymmetry
- Luminosity monitors A4: backward angles in CM frame
- => Nonvanishing azimuthal asymmetry in luminosity monitors

$$A_{Lumi}(\Phi_i) = A_L \cdot \sin\Phi_i$$

Luminosity Monitors

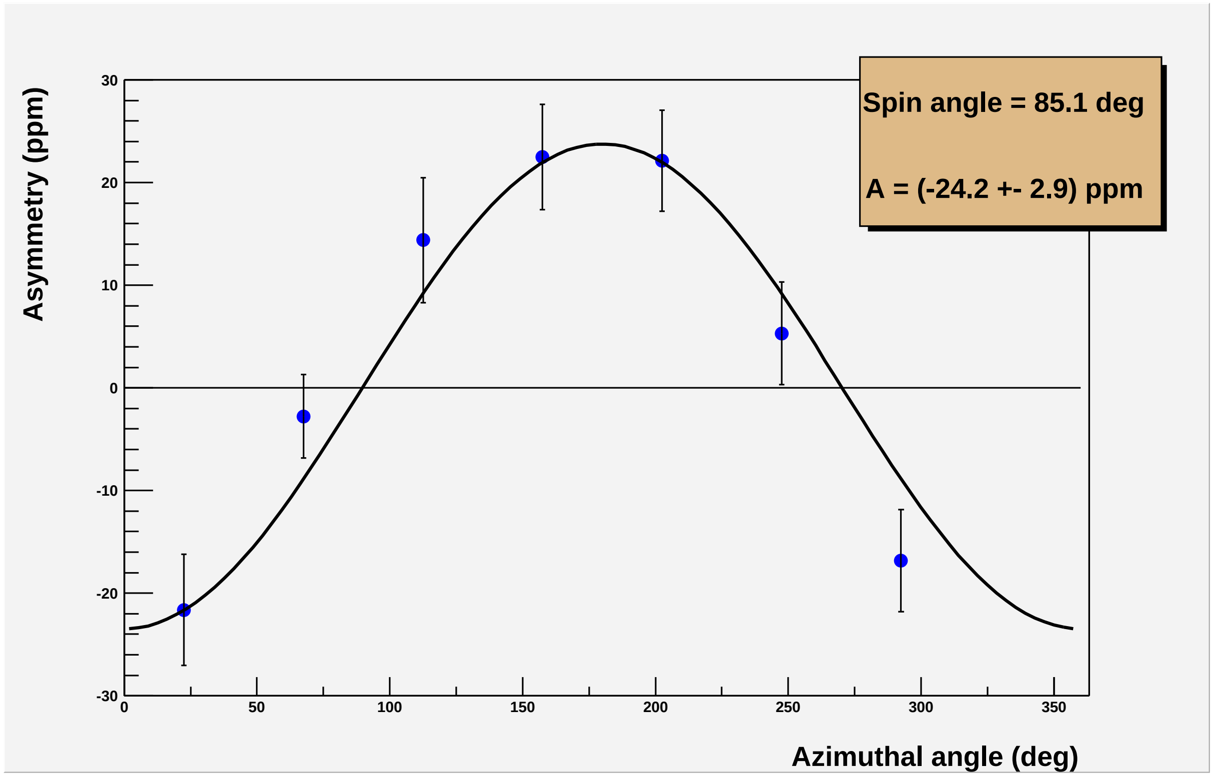
Spin Angle $\phi_s = 108.5^\circ$

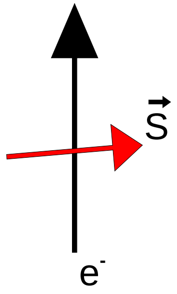




Luminosity Monitors

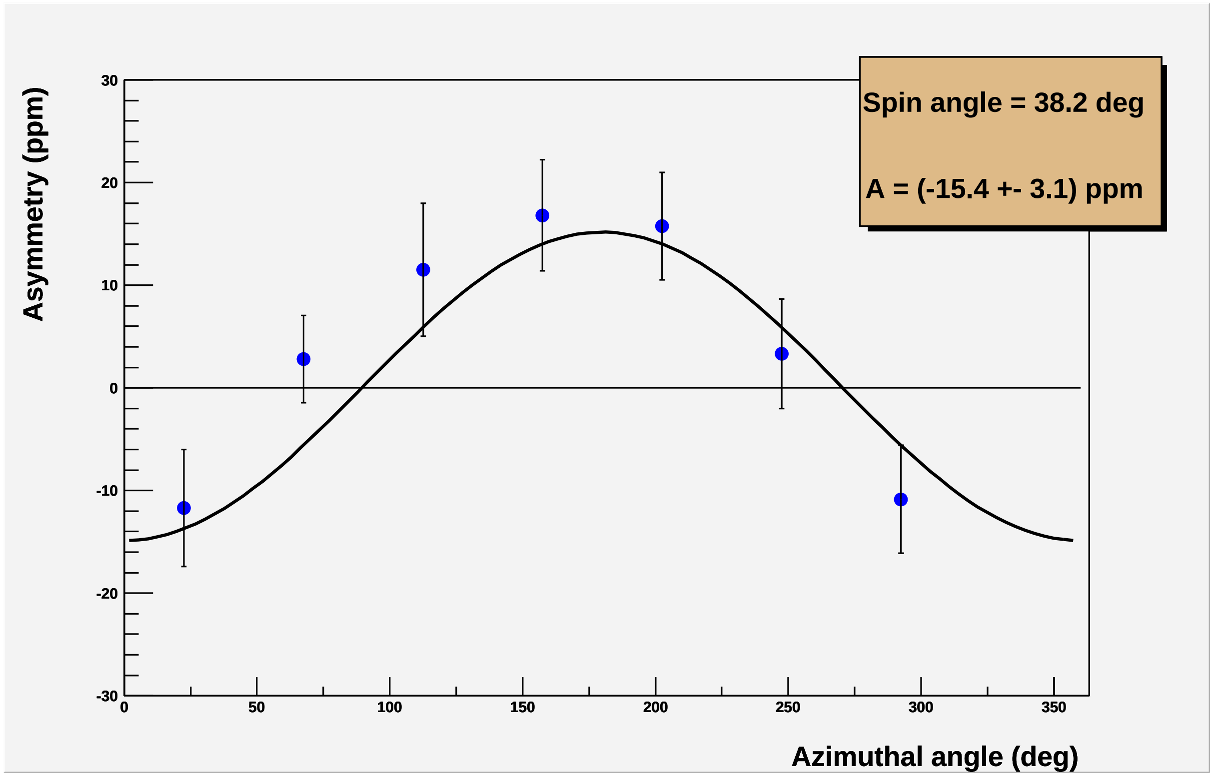
Spin Angle $\phi_s = 85.1^\circ$

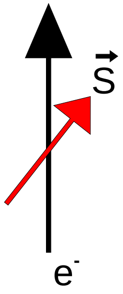




Luminosity Monitors

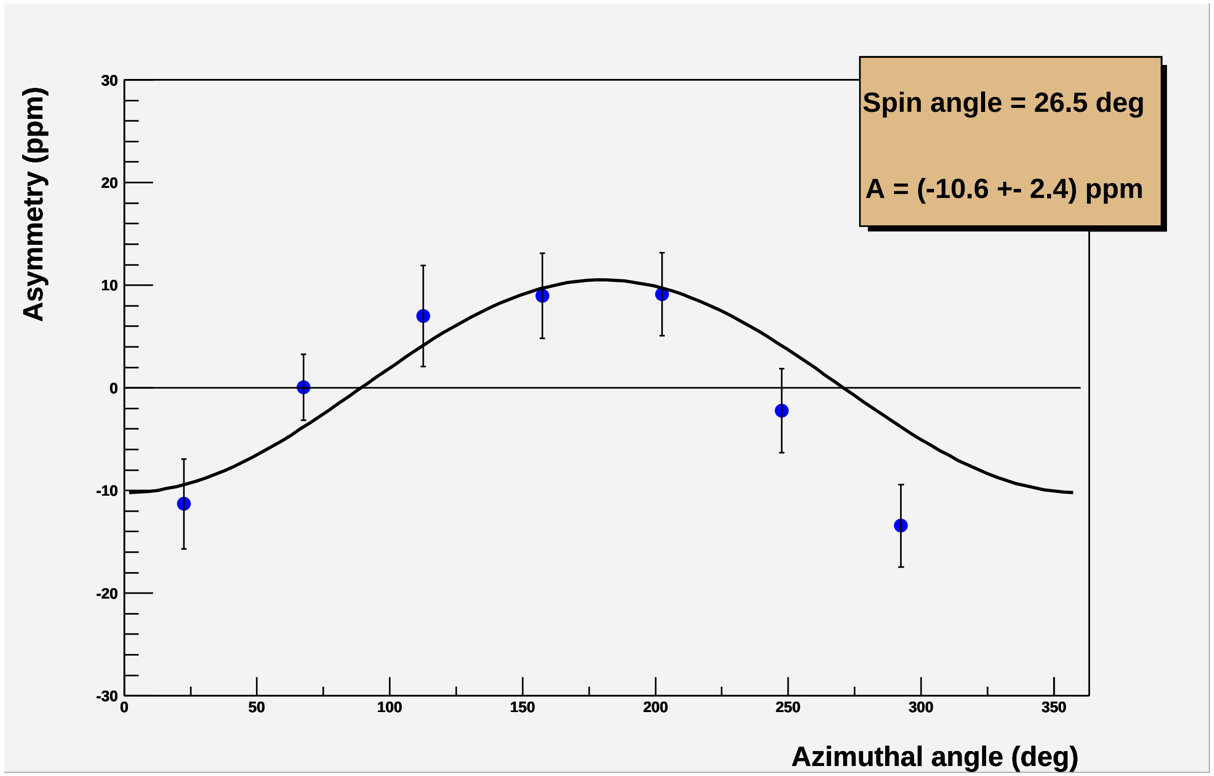
Spin Angle $\phi_s = 38.2^\circ$

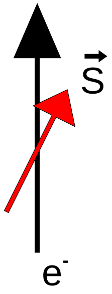




Luminosity Monitors

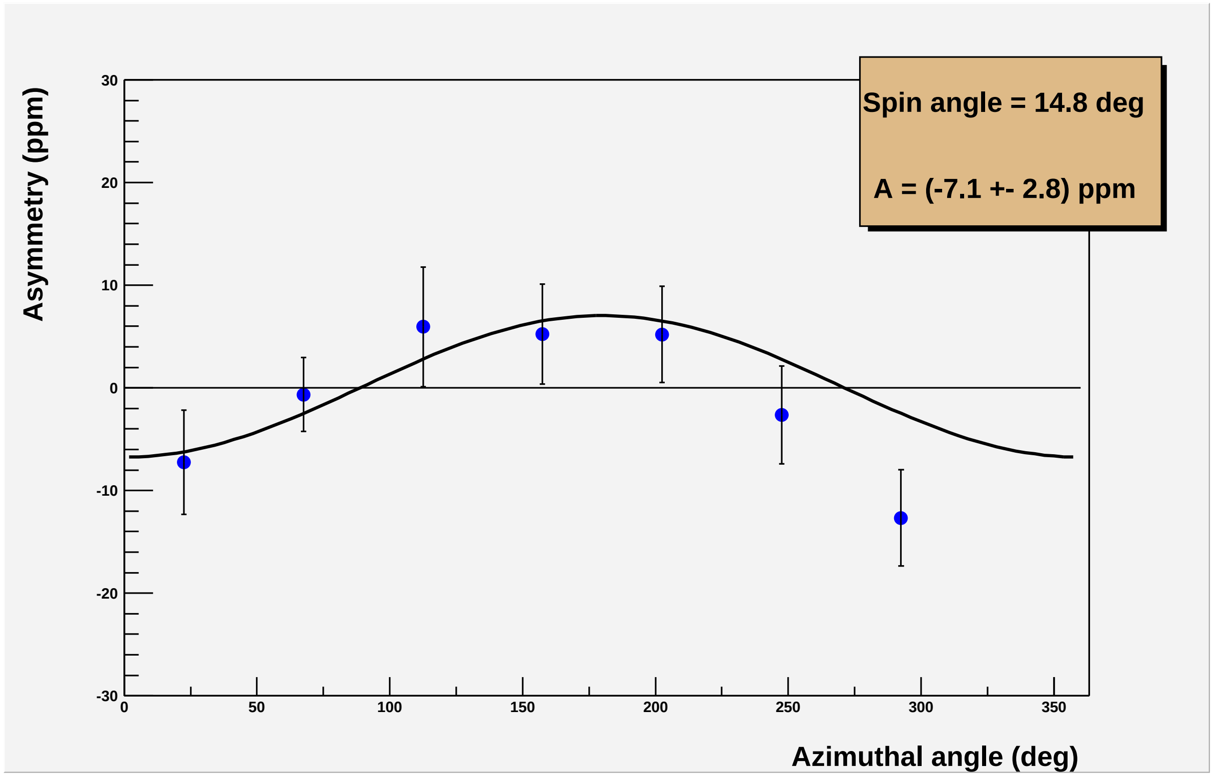
Spin Angle $\phi_s = 26.5^\circ$

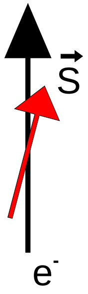




Luminosity Monitors

Spin Angle $\phi_s = 14.8^\circ$

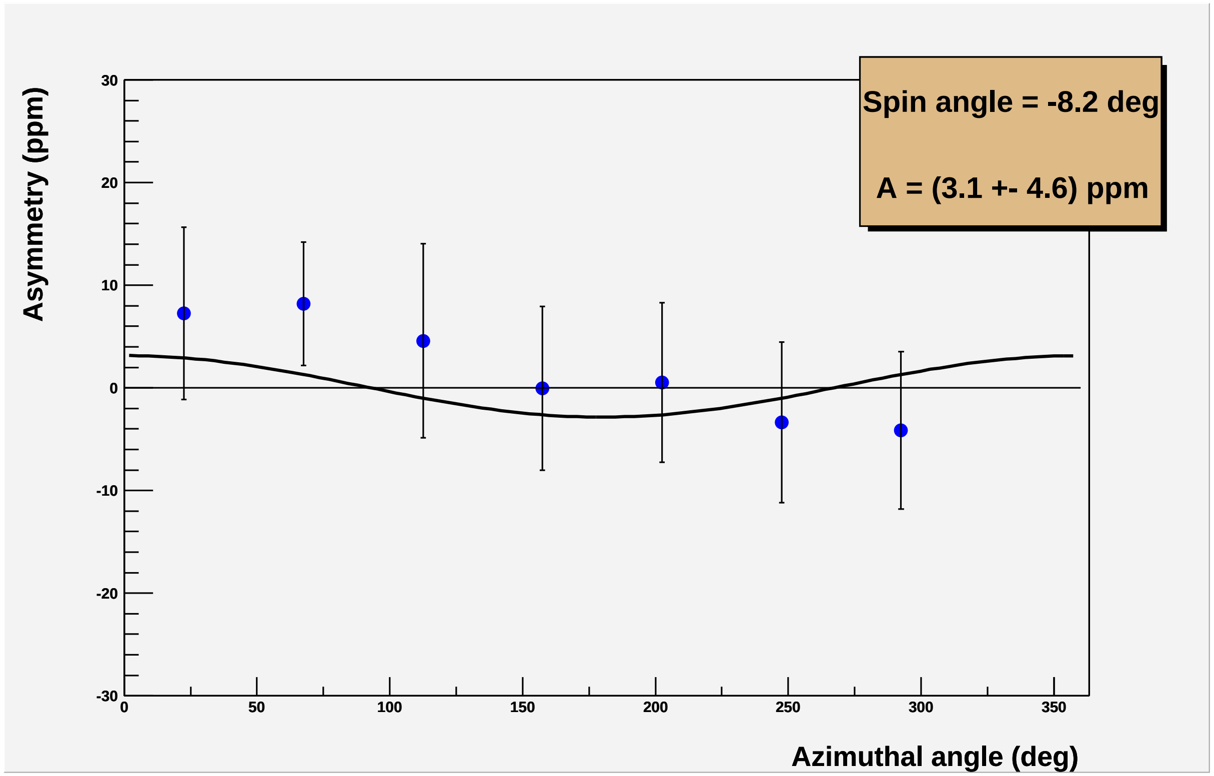


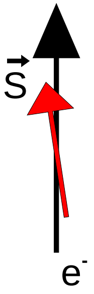


Møller Scattering

Luminosity Monitors

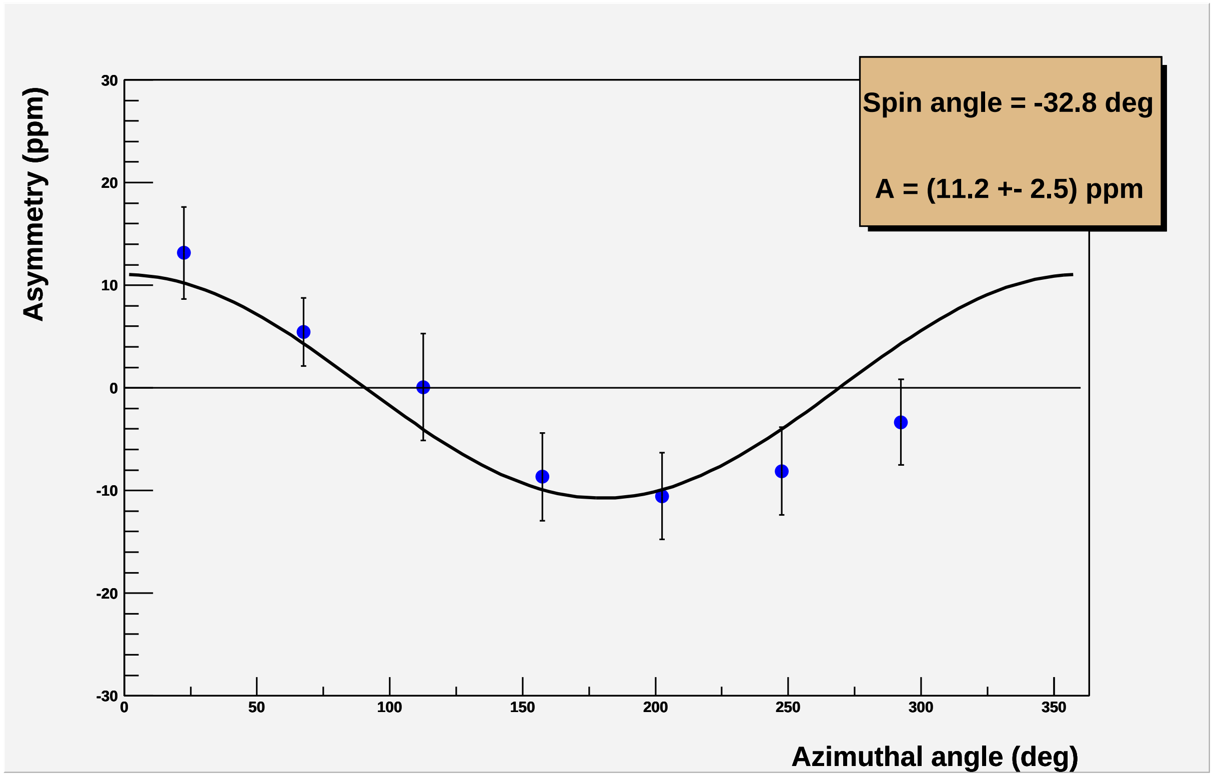
Spin Angle $\phi_s = -8.6^\circ$

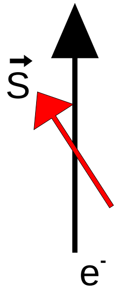




Luminosity Monitors

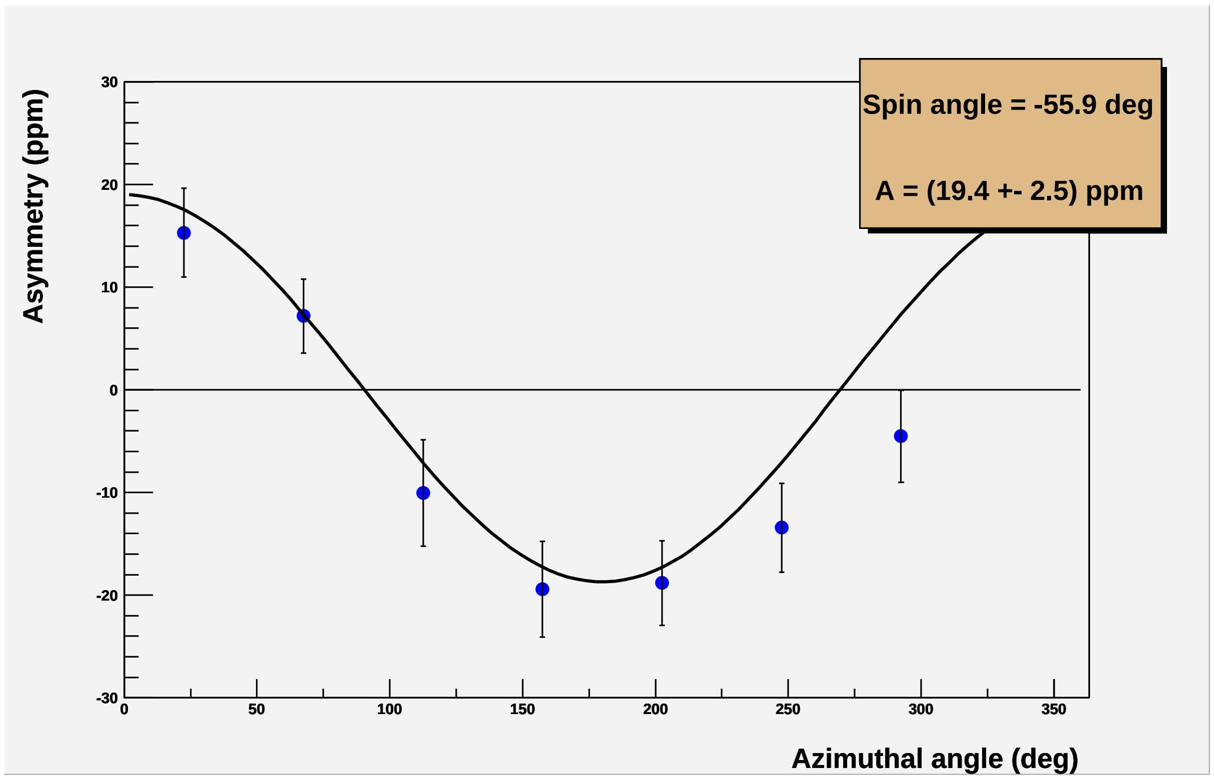
Spin Angle $\phi_s = -32.8^\circ$

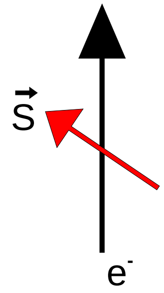




Luminosity Monitors

Spin Angle $\phi_s = -55.9^\circ$



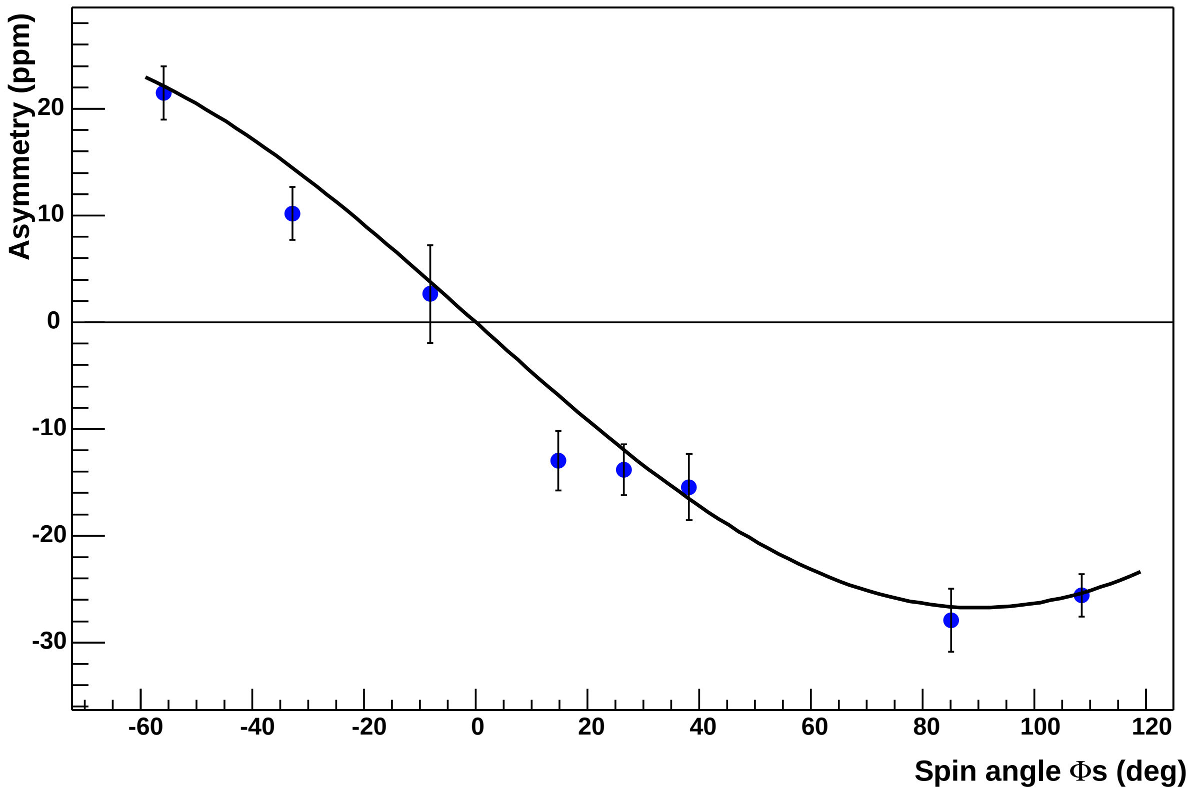


=> 8 Spin Angles ϕ_s, 8 Amplitudes $A_L(\phi_s)$

Møller Scattering

Spin angle dependency of A_L

$A_L(\phi_s)$ seen by luminosity monitors:



Sensitive to **transverse** spin

Møller Scattering

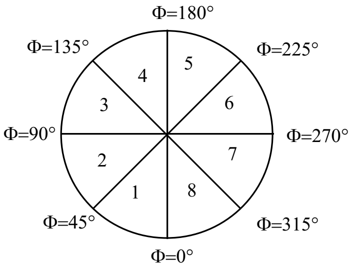
Single Spin Asymmetry in Møller Scattering, Results

Energy	A_{Lumi} Experiment (ppm)	A_{Lumi} NLO calculation (ppm)
570 MeV	-26.7 ± 1.3	-29.6
855 MeV	-23.3 ± 4.3	-16.6

- We agree in sign and magnitude with QED calculations
- Asymmetries in LuMos not negligible
- Φ-symmetric summation: cancellation of asymmetry

Geometrical aspects

Azimuthal range of each sector $d\Phi \approx \pi/4$



$$P \cdot A_{Phys}(\Phi) = \frac{\int_{Sec} A_\perp \cdot \cos\varphi \, d\varphi}{\int_{Sec} d\varphi} \equiv F^{Sec} \cdot A_\perp$$

Sec	Φ_0	Φ_{min}	Φ_{max}	F^{Sec}
1	22.19°	0°	44.38°	0.903
2	66.58°	44.38°	88.77°	0.388
3	112.19°	88.77°	135.62°	−0.367
4	157.81°	135.62°	180°	−0.903
5	202.19°	180°	224.38°	−0.903
6	246.58°	224.38°	268.77°	−0.388
7	292.19°	268.77°	315.62°	0.367
8	337.18°	315.62°	360°	0.903

Determination of $A_\perp$

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

$\approx 50h$ beam data

Data taking in January 03:

Sectors 1, 2, 5, 6, 8 of PbF_2 calorimeter equipped

Total number of elastic counts: $N_{total} = 6.3 \cdot 10^{11}$

$\Phi_S = 99.9^\circ \pm 1^\circ$

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

$\approx 50h$ beam data

Data taking in September 03:

Calorimeter fully equipped

Total number of elastic counts: $N_{total} = 3.9 \cdot 10^{12}$

$\Phi_S = 96.8^\circ \pm 0.5^\circ$

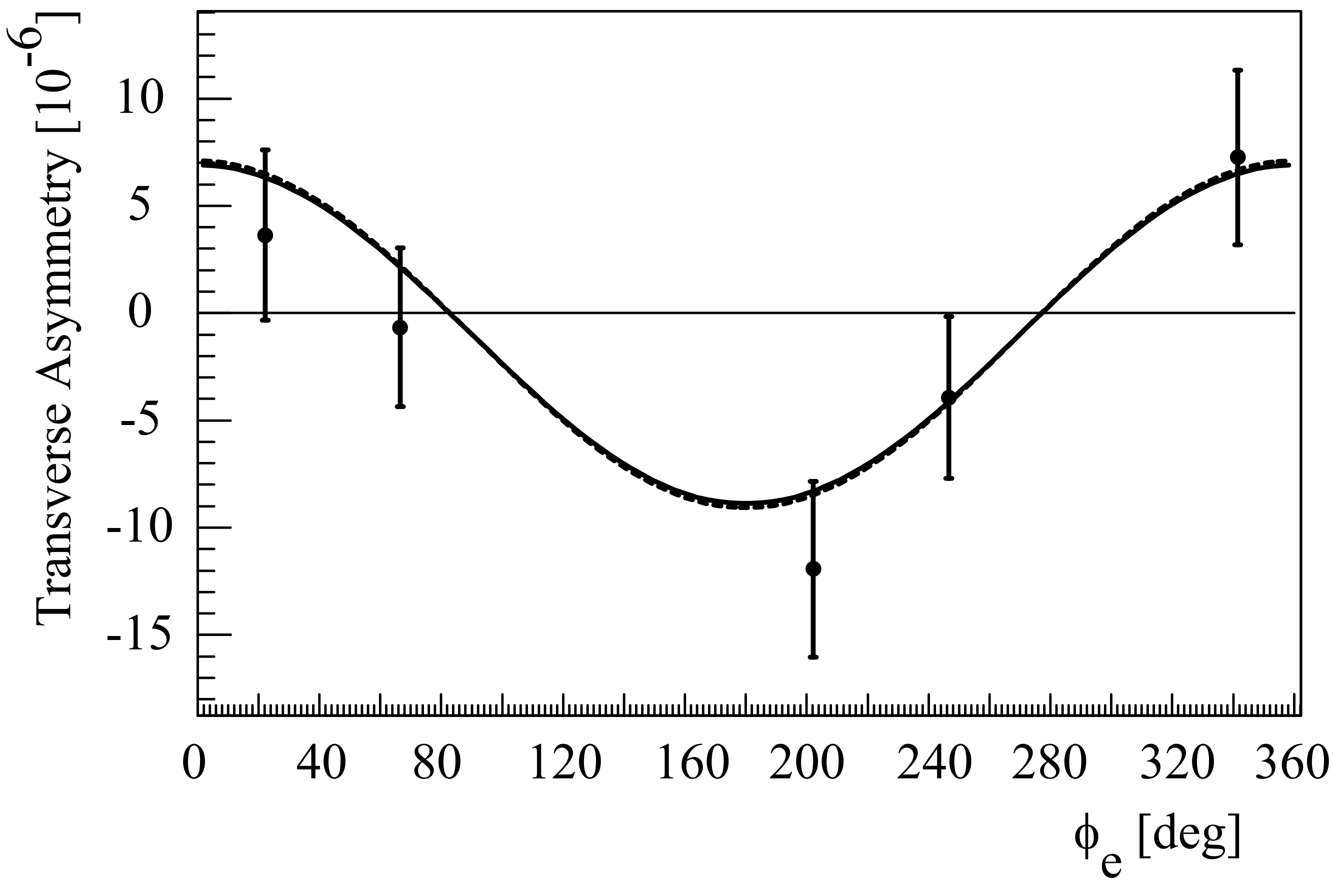
Determination of $A_\perp$

Beam parameter

Parameter	$0.23\ (GeV/c)^2$	$0.11\ (GeV/c)^2$
A_I	$(2.5 \pm 0.6)ppm$	$(0.4 \pm 1.4)ppm$
Δx	$(15.1 \pm 3.4)nm$	$(157.0 \pm 150.0)nm$
Δy	$(-126.7 \pm 18.0)nm$	$(-504.3 \pm 43.7)nm$
$\Delta x'$	$(5.4 \pm 0.8)nrad$	$(20.5 \pm 12.9)nrad$
$\Delta y'$	$(21.5 \pm 3.0)nrad$	$(45.4 \pm 3.9)nrad$
ΔE	$(0.2 \pm 0.3)eV$	$(41.4 \pm 2.6)eV$

Determination of $A_\perp$

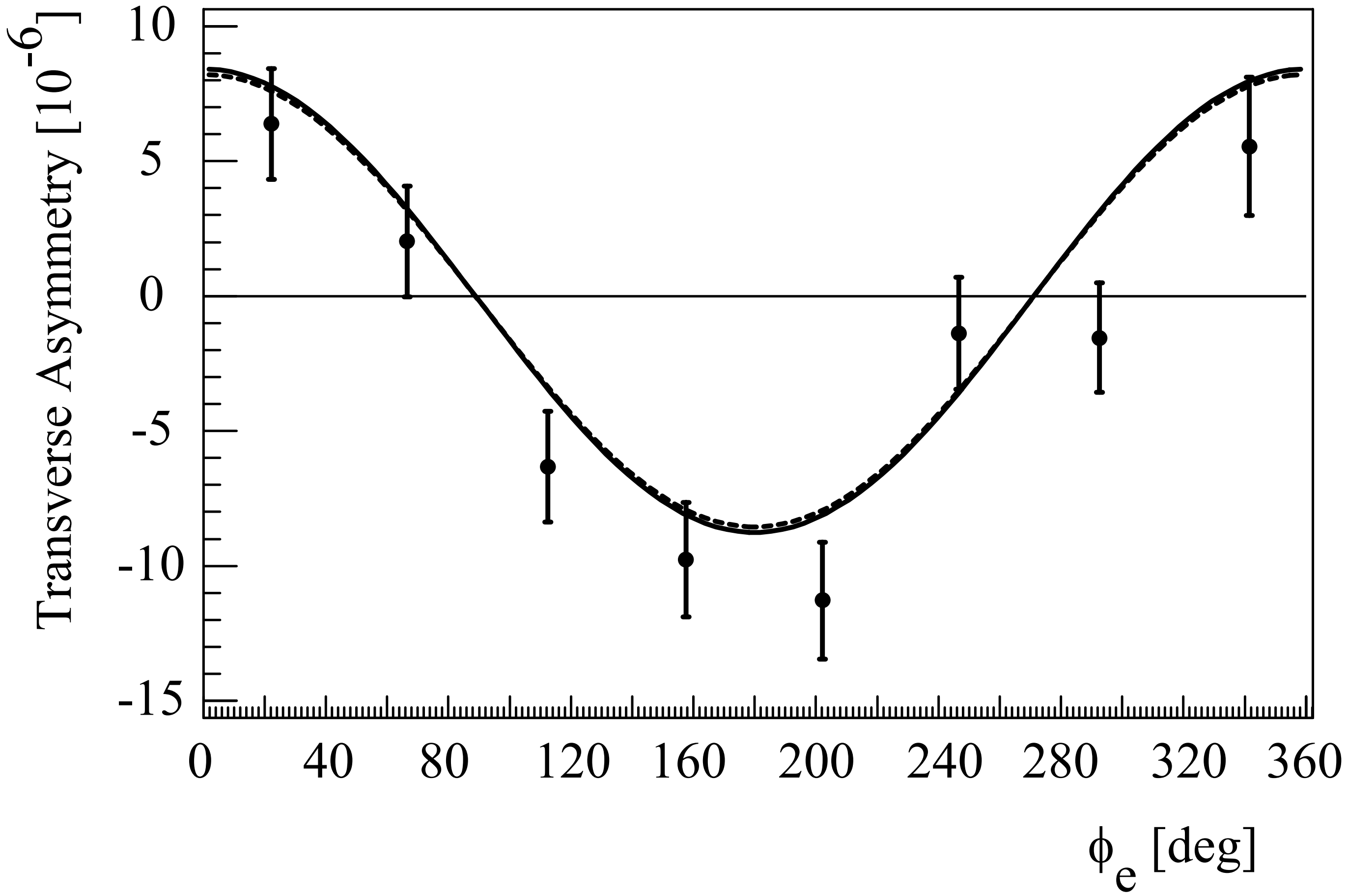
$$E = 855.2 MeV, \; Q^2 = 0.23 (GeV/c)^2$$



$$A_\perp = \left(-8.52 \pm 2.31_{stat} \pm 0.87_{syst}\right) ppm$$

Determination of $A_\perp$

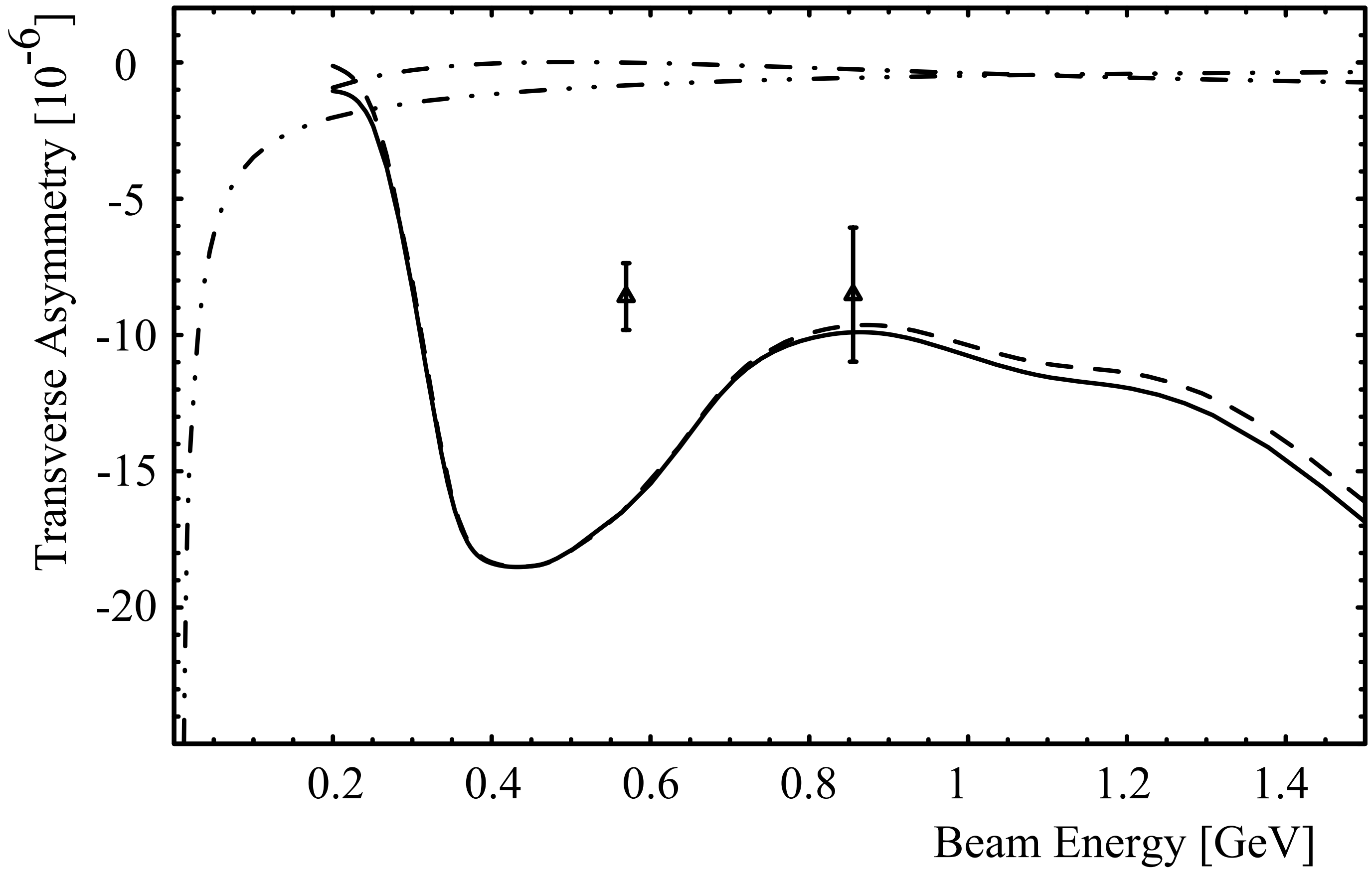
$$E = 569.3 MeV,\ Q^2 = 0.11 (GeV/c)^2$$



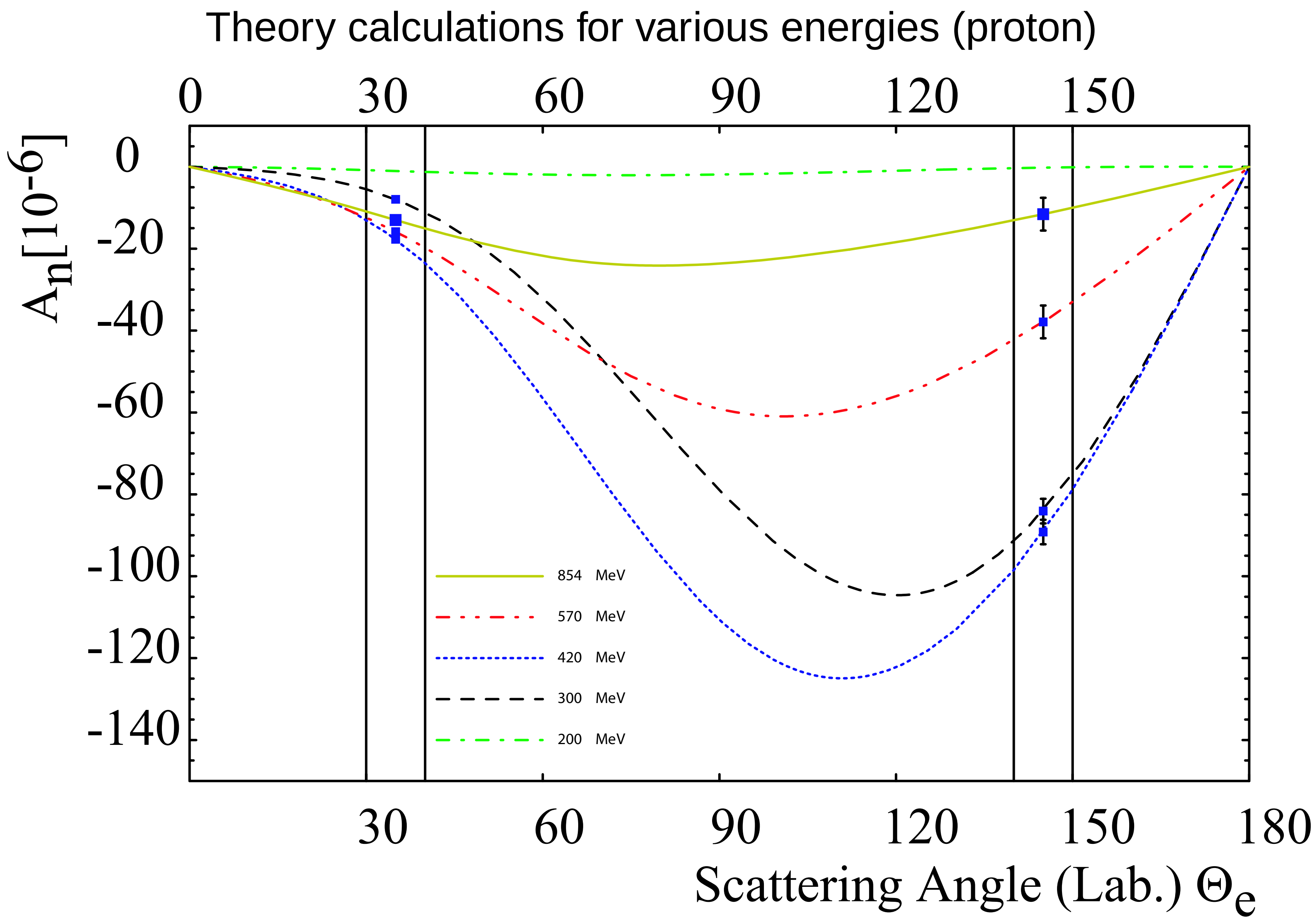
$$A_\perp = \left(-8.59\ \pm 0.93_{stat}\ \pm 0.75_{syst}\right)\ ppm$$

Comparison of $A_\perp$ with theory

Intermediate state: proton, πN states (MAID)
(B. Pasquini)



Outlook



Theory calculations for various energies (proton)
0
30
60
90
120
150
$A_n[10^{-6}]$
0
-20
-40
-60
-80
-100
-120
-140
854 MeV
570 MeV
420 MeV
300 MeV
200 MeV
30
60
90
120
150
180
Scattering Angle (Lab.) Θ_e

Outlook

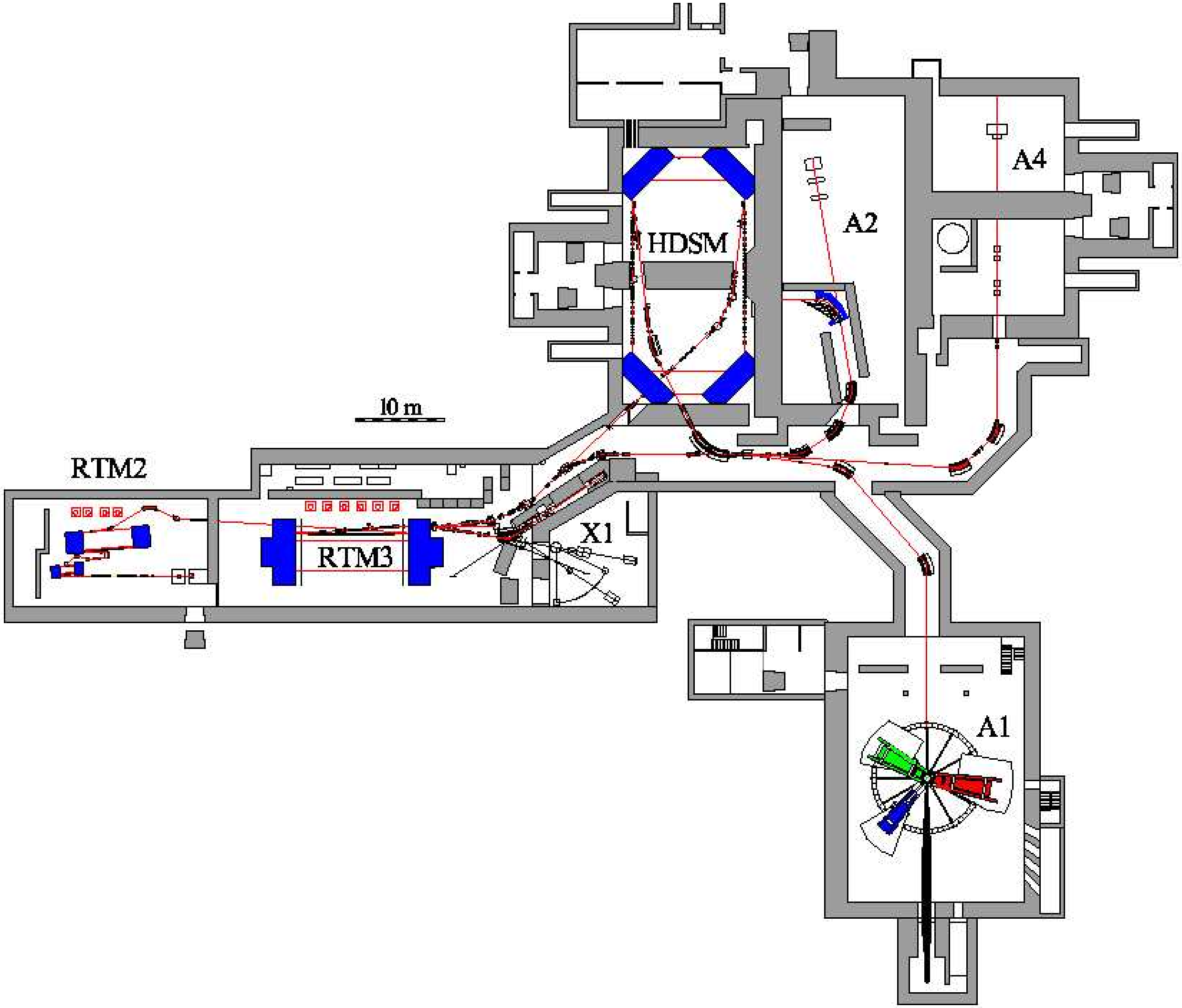
Projected future measurements

E_e [MeV]	θ_e [$\circ$]	$\delta A_\perp^p$ [ppm]	hours proton	$\delta A_\perp^D$ [ppm]	hours deuteron	$\delta A_\perp^n$ [ppm] (extracted)
300	$(35 \pm 5)\circ$	0.5	20	0.5	20	20
420	$(35 \pm 5)\circ$	0.5	40	0.5	35	11
570	$(35 \pm 5)\circ$	0.5	90	0.5	70	7
854	$(35 \pm 5)\circ$	0.5	300	0.5	220	4
1200	$(35 \pm 5)\circ$	1	260	1	180	6
1500	$(35 \pm 5)\circ$	2	180	2	120	11
300	$(145 \pm 5)\circ$	3	90	2	130	10
420	$(145 \pm 5)\circ$	3	230	2	320	10
570	$(145 \pm 5)\circ$	4	370	3	390	13
854	$(145 \pm 5)\circ$	8	490	7	380	28

Summary

- Single spin asymmetries in elastic ep scattering
- Longitudinal spin: Contribution of strange quarks to form factors
- Determination of $G_E^s + xG_M^s$ for two momentum transfers
- Measurements with backward kinematics in preparation
- Transverse spin: Imaginary part of 2γ exchange amplitude
- Substantial contribution of πN intermediate states
- Measurements at various energies at forward and backward angles, proton and deuteron projected

MAMI Accelerator



Analysis

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

Contributions to corrections and systematic error

Quantitity	Correction (ppm)	Systematic Error (ppm)
Current asymmetry A_I	-1.14	0.30
Horizontal pos. diff. Δx	-0.47	0.43
Vertical pos. diff. Δy	0.02	0.14
Horizontal angle diff. $\Delta x'$	-0.09	0.39
Vertical angle diff. $\Delta y'$	0.02	0.18
Energy diff. ΔE	0.09	0.07
Pile-Up correction	-0.11	0.26
LuMo Nonlinearity	0.39	0.01
Target density (current)	0.00	0.12
Target density (LuMo)	0.18	0.03
Spin angle deviation δ	0.46	0.06
Polarisation	1.90	0.30

Analysis

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

Contributions to corrections and systematic error

Quantitity	Correction (ppm)	Systematic Error (ppm)
Current asymmetry A_I	-0.16	0.11
Horizontal pos. diff. Δx	-0.55	0.14
Vertical pos. diff. Δy	0.29	0.17
Horizontal angle diff. $\Delta x'$	-0.52	0.14
Vertical angle diff. $\Delta y'$	0.42	0.17
Energy diff. ΔE	-0.39	0.04
Pile-Up correction	-1.31	0.29
LuMo Nonlinearity	-0.30	0.00
Target density (current)	0.12	0.05
Target density (LuMo)	-0.91	0.03
Spin angle deviation δ	-0.44	0.01
Polarisation	1.49	0.33

Linear Regression

Covariance matrix:

$$\mathbf{S} = \begin{pmatrix} s_{00} & s_{01} & s_{02} & \dots & s_{06} \\ s_{10} & s_{11} & s_{12} & \dots & s_{16} \\ \dots & \dots & \dots & \dots & \dots \\ s_{60} & s_{61} & s_{62} & \dots & s_{66} \end{pmatrix}$$

with

$$s_{jk}^2 = \frac{\frac{1}{N-1}\sum_{i=1}^{N}\left[\frac{1}{\delta(X_i^0)^2}(X_i^j - \overline{X^j})(X_i^k - \overline{X^k})\right]}{\frac{1}{N}\sum_{i=1}^{N}\frac{1}{\delta(X_i^0)^2}}$$

and

$$\overline{X^j} = \frac{1}{N}\sum_{i=1}^{N} X_i^j$$

Linear Regression

Correlation matrix:

$$\mathbf{R} = \begin{pmatrix} r_{00} & r_{01} & r_{02} & \dots & r_{06} \\ r_{10} & r_{11} & r_{12} & \dots & r_{16} \\ \dots & \dots & \dots & \dots & \dots \\ r_{60} & r_{61} & r_{62} & \dots & r_{66} \end{pmatrix}$$

with

$$r_{jk}^2 = \frac{s_{jk}^2}{s_{jj} s_{kk}}$$

Correlation coefficients:

$$a^j = \frac{s_{00}}{s_{jj}} \sum_{k=1}^{6} r_{k0} r_{j0}^{-1}$$

Linear Regression

Error estimation:

$$\delta a^j = \sqrt{\frac{\frac{1}{N-1}\frac{1}{s_{jj}^2} r_{jj}^{-1}}{\frac{1}{N}\sum_{i=1}^{N}\frac{1}{(\delta X_i^0)^2}}}$$

$$\delta A^{phys} = \sqrt{\frac{\frac{1}{N} + \frac{1}{N-1}\sum_{j=1}^{6}\sum_{k=1}^{6}(\overline{X^j}\,\overline{X^k}\frac{1}{s_{jj}}\frac{1}{s_{kk}} r_{jk}^{-1})}{\frac{1}{N}\sum_{i=1}^{N}\frac{1}{(\delta X_i^0)^2}}}$$