Two photon exchange and beam normal spin asymmetries in the A4 experiment

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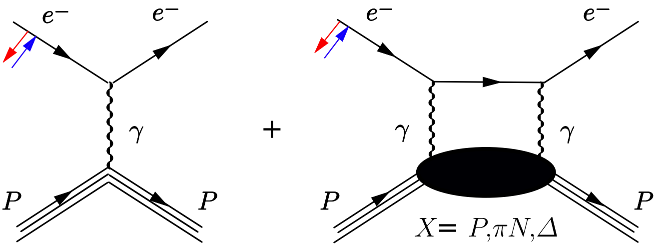
Outline

Two photon exchange

Two photon exchange

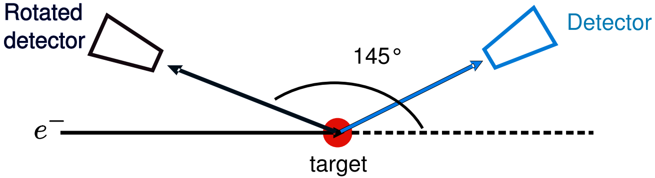


- $R = G_E^p/G_M^p$ discrepancy $\rightarrow$ 2γ exchange amplitude $A_{2\gamma}$
- Observable: Beam normal spin asymmetry BNSA
- BNSA sensitive to $Im(A_{2\gamma})$.
- Access to the intermediate states: $p, \pi^0 p, \pi^+ n, \Delta, ...$

Outline

A4 experimental setup

A4 experimental concept



Rotable detector at forward and backward angles

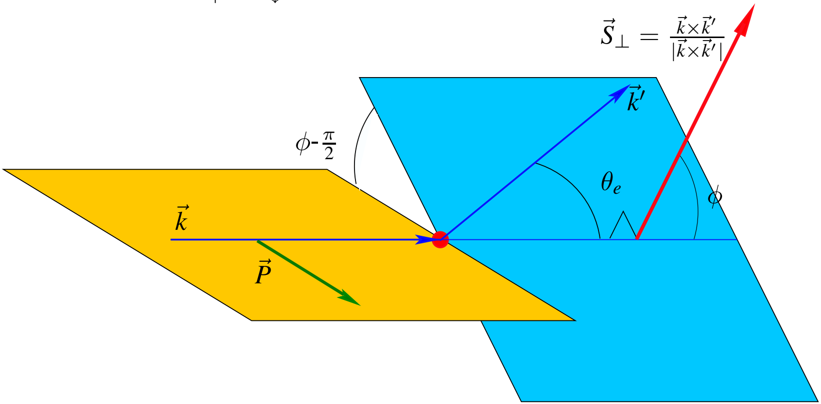
$$A_\perp = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{N^+ - N^-}{N^+ + N^-}$$

σ of (quasi)elastic scattered electrons on unpolarized nucleon

Asymmetry dependency on azimuthal angle

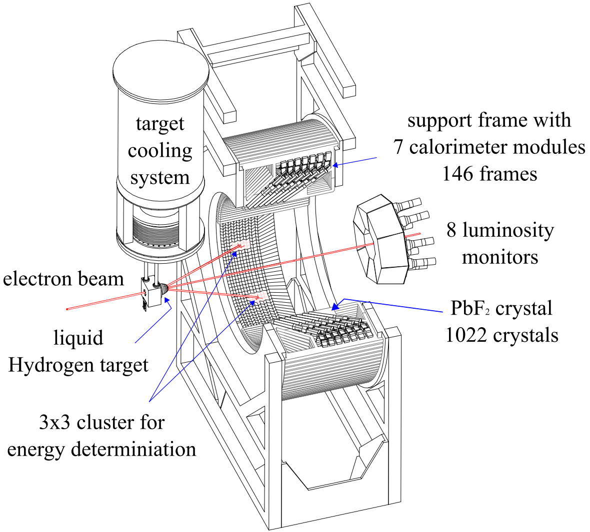
$$A_\perp^m = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = A_\perp(\theta)\vec{P}_e \cdot \vec{S} = A_\perp \cos\phi$$

$$\vec{S}_\perp = \frac{\vec{k}\times\vec{k}'}{|\vec{k}\times\vec{k}'|}$$



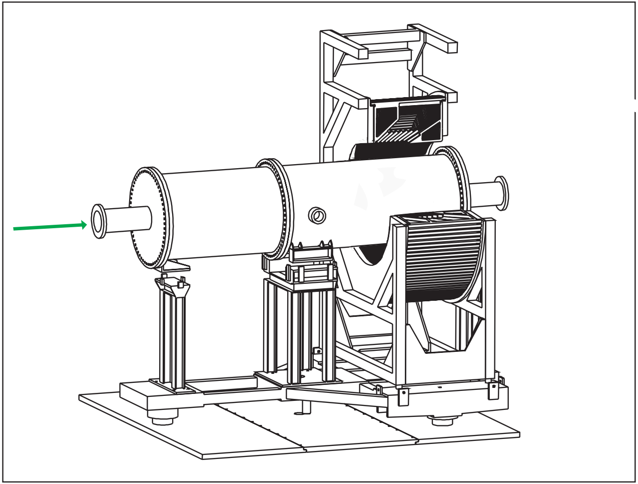
$A_\perp \sim 10^{-5}$

Target and detectors at forward angles

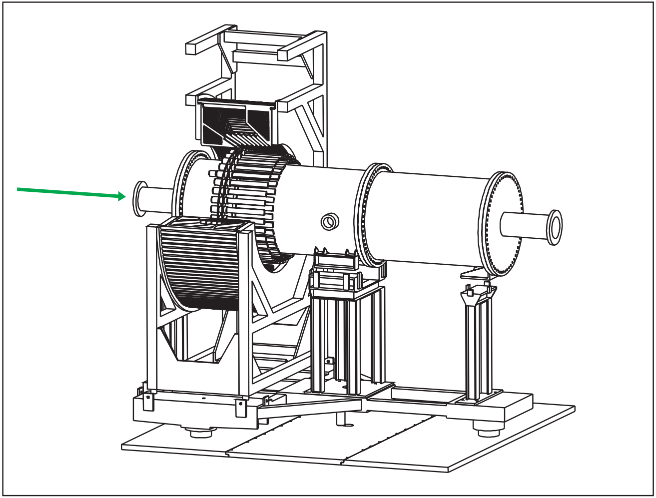


- Detector covers 2π ϕ.
- Counts single events and measures energy.
- Target of liquid H_2 and D_2.

Detector at forward angles

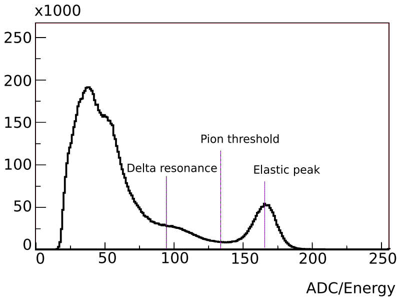


Rotated detector at backward angles

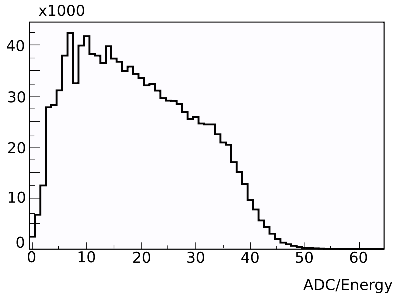


PbF_2 energy spectrum

Forwards, E = 854.3 MeV



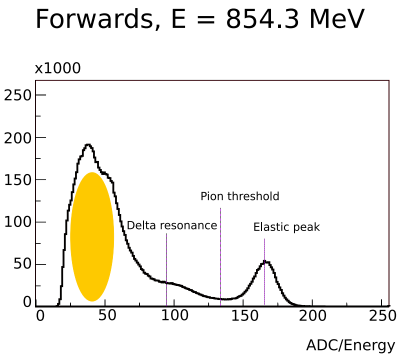
Backwards, E = 315.1 MeV

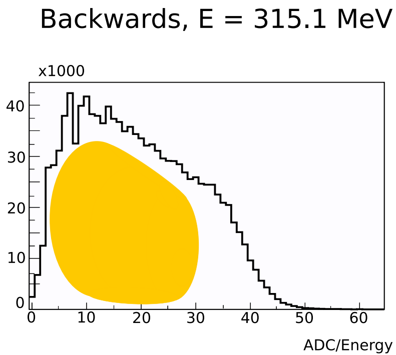


- Elastic peak clearly separated
- Background of $\pi^0 \to 2\gamma$ energetically separated.

- Elastic peak not separated
- Background of γs and elastic peak: same energy range

PbF_2 energy spectrum



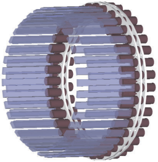


- Elastic peak clearly separated
- Background of $\pi^0 \rightarrow 2\gamma$ energetically separated.

- Elastic peak not separated
- Background of γs and elastic peak: same energy range

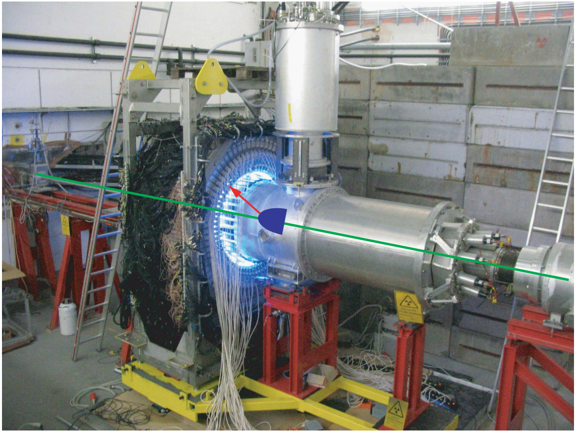
Plastic scintillators

- Plastic scintillators detect charged particles. Neutral particles not detected.



- 72 plastic scintillators: two rings of 36 with overlap.

Target and detectors at backward angles



Extra detector at backward angles: plastic scintillators

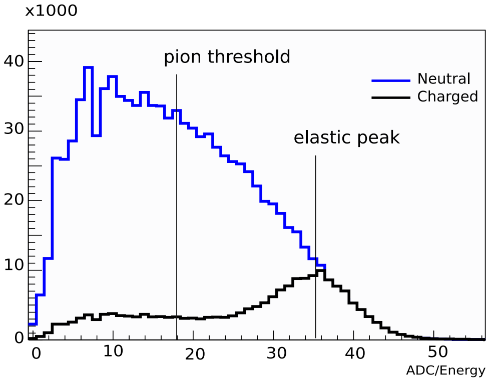
List of A4 measurements

θ	E [MeV]	Q^2 [GeV^2]	target	spin	process
$30^\circ - 40^\circ$	855	0.23	H_2	0°	PV
$30^\circ - 40^\circ$	570	0.11	H_2	0°	PV
$30^\circ - 40^\circ$	855	0.23	H_2	90°	2γ
$30^\circ - 40^\circ$	570	0.11	H_2	90°	2γ
$140^\circ - 150^\circ$	315	0.23	H_2	0°	PV
$140^\circ - 150^\circ$	315	0.23	D_2	0°	PV
$140^\circ - 150^\circ$	315	0.23	H_2	90°	2γ
$140^\circ - 150^\circ$	315	0.23	D_2	90°	2γ
$140^\circ - 150^\circ$	420	0.35	H_2	90°	2γ
$140^\circ - 150^\circ$	420	0.35	D_2	90°	2γ
$30^\circ - 40^\circ$	1508	0.62	H_2	0°	PV
$30^\circ - 40^\circ$	420	0.06	H_2	90°	2γ
$30^\circ - 40^\circ$	510	0.09	H_2	90°	2γ
$30^\circ - 40^\circ$	315	0.03	H_2	90°	2γ
$30^\circ - 40^\circ$	855	0.23	H_2	90°	2γ
$30^\circ - 40^\circ$	1508	0.62	H_2	90°	2γ
$140^\circ - 150^\circ$	200	0.10	H_2	0°	PV
$140^\circ - 150^\circ$	200	0.10	H_2	90°	2γ

Outline

Extraction of the beam normal spin asymmetry at E = 315 MeV

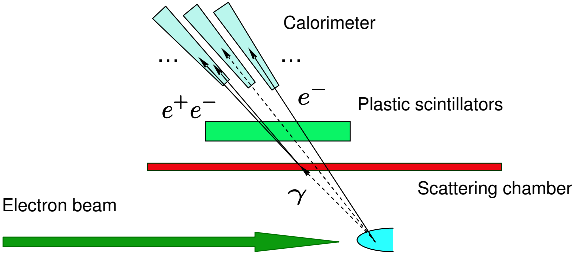
Energy spectra for l-H_2 target



- Two histograms: charged particles and neutral particles
- Separation of the elastic peak in the charged particles spectrum

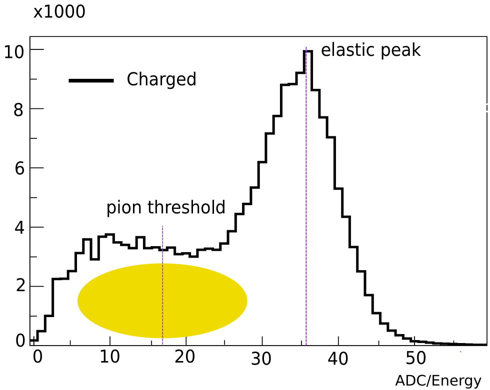
Background in the charged particles spectrum

- $\pi^0 \rightarrow 2\gamma$ and $\gamma \rightarrow e^+ + e^-$ in materials before calorimeter



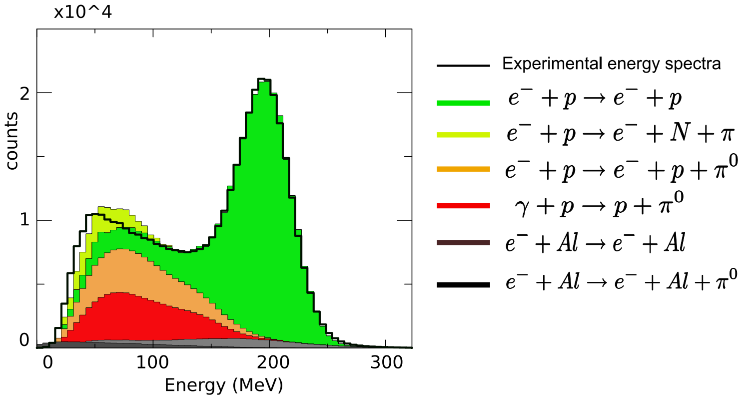
- γ background in the spectrum of charged particles
- Scattering on aluminium windows

Energy spectra for l-H_2 target



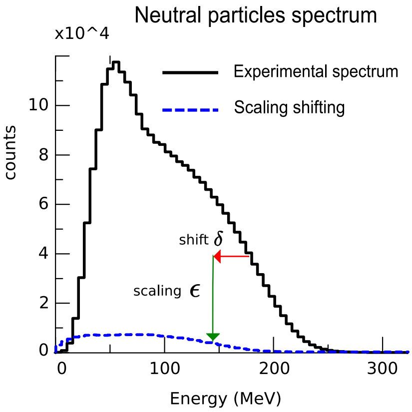
- Separation of the elastic peak in the charged particles spectrum
- Still neutral background from $\gamma \rightarrow e^- e^+$

Understanding the energy spectrum



- Monte Carlo Geant4 simulation: e^- processes and γs
- Background from Al walls: measurement with empty target
- Agreement above 125 MeV

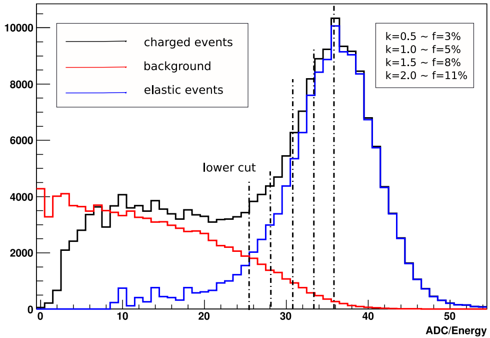
Background obtained from neutral spectrum



- γ background $A_\perp$?
- From experimental spectrum of neutral particles
- Method to obtain γ background
- Parameters
  - shift δ: energy loss of electrons
  - scaling factor ϵ: probability of γ conversion

Energy spectrum with H_2

target H_2, E$= 315$ MeV, $Q^2 = 0.23$ (Gev/c)^2, $\theta = 145°$

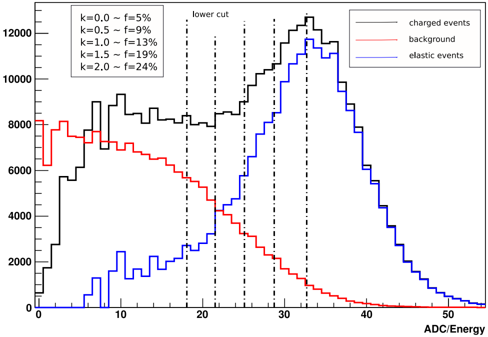


Elastic scattered electrons and background from $\gamma \rightarrow e^+e^-$

$$A_\perp = \frac{A_c - f \cdot A_\gamma}{1 - f}$$, dilution factor $f = \frac{N_\gamma}{N_c}$

Energy spectrum with D_2

target D_2, E$= 315$ MeV, $Q^2 = 0.23$ (Gev/c)^2, $\theta = 145°$



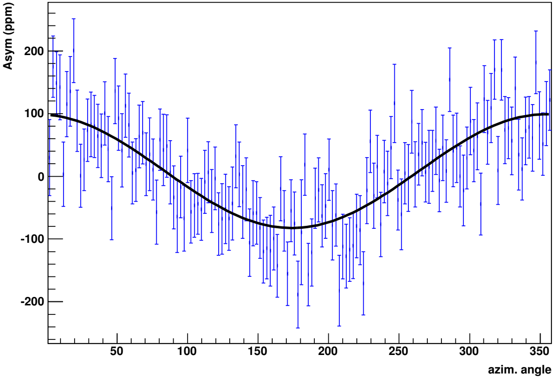
Quasi-elastic scattered electrons and background from $\gamma \to e^+e^-$

Static approximation $A_\perp^d = \dfrac{\sigma_p A_\perp^p + \sigma_n A_\perp^n}{\sigma_p + \sigma_n}$

BNSA of the elastic events on H_2

target H_2, E$= 315$ MeV, $Q^2 = 0.23$ (Gev/c)^2, $\theta = 145°$

$A_\perp = A_0 \cos(\phi + \delta) + p$



$\chi^2/\nu = 0.94$

$P = 0.68$

$A_\perp = (-91.58 \pm 4.28)$ ppm

$\alpha = (5.62 \pm 3.81)°$

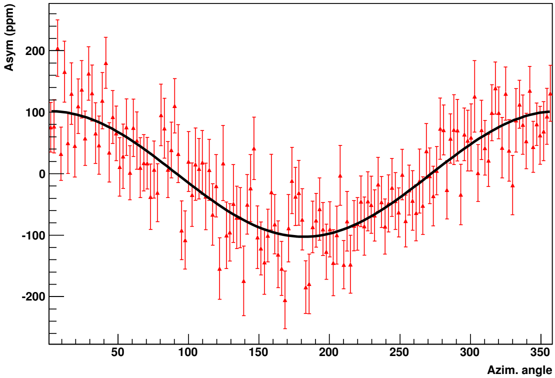
$p = (6.76 \pm 4.25)$ ppm

Dependence on the azimuthal angle

BNSA of the background

target H_2, E$= 315$ MeV, $Q^2 = 0.23$ (Gev/c)^2, $\theta = 145°$

$A_\perp = A_0 \cos(\phi + \delta) + p$



$\chi^2/\nu = 1.01$

$P = 0.47$

A = (-90.48 ± 3.98) ppm

$\alpha = -2.60 \pm 3.10$

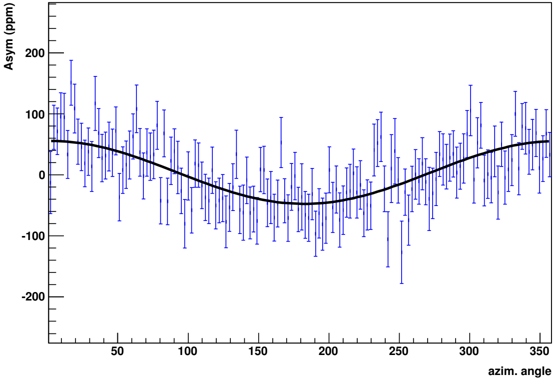
$p = (-1.50 \pm 2.97)$ ppm

Dependence on the azimuthal angle

BNSA of the quasielastic events on D_2

target D_2, E$=315$ MeV, $Q^2=0.23$ (Gev/c)^2, $\theta=145°$

$A_\perp = A_0 \cos(\phi+\delta)+p$



$\chi^2/\nu = 0.90$

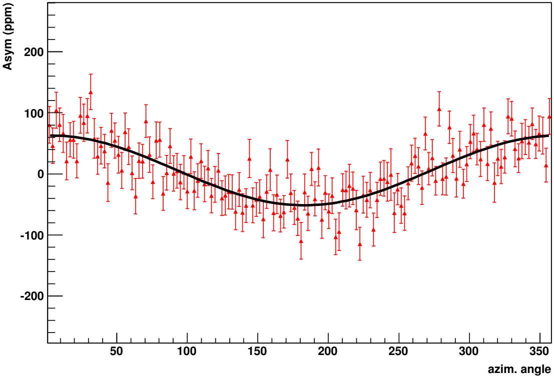
$P = 0.81$
A = (-51.32 ± 3.30) ppm
$\alpha = (-2.30 \pm 4.86)°$
$p = (4.36 \pm 3.19)$ ppm

Dependence on the azimuthal angle

BNSA of the background

target D_2, E$= 315$ MeV, $Q^2 = 0.23$ (Gev/c)^2, $\theta = 145^\circ$

$A_\perp = A_0 \cos(\phi + \delta) + p$



χ^2/ν = 1.01

$P = 0.47$

A = (-54.06 ± 2.82) ppm

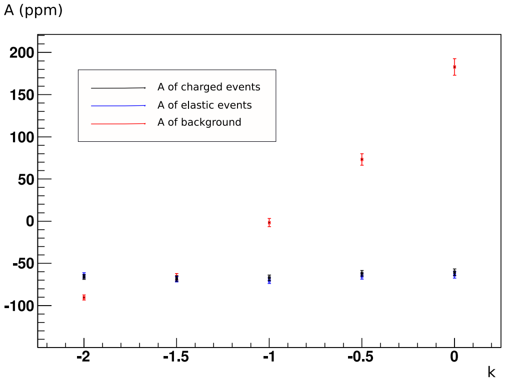
$\alpha = (-2.60 \pm 3.10)^\circ$

$p = (-1.50 \pm 2.97)$ ppm

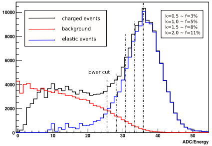
Dependence on the azimuthal angle

Extracted BNSA

target H_2, E$=315$ MeV, $Q^2=0.23$ (Gev/c)^2, $\theta=145°$

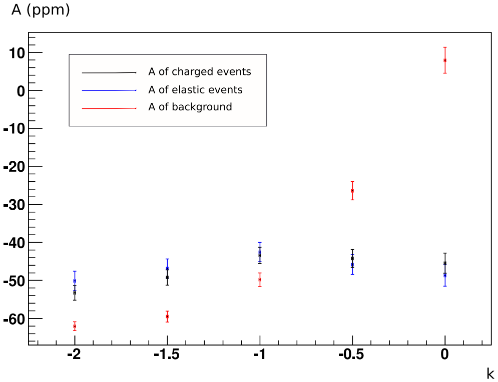


Dependence on the lower cut $(=\mu-k\cdot\sigma)$
BNSA of background depends strongly on energy

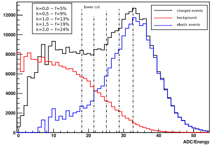


Extracted BNSA

target D_2, E$=315$ MeV, $Q^2=0.23$ (Gev/c)^2, $\theta=145°$

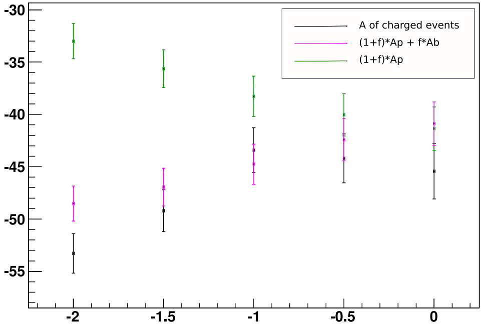


Dependence on the lower cut ($=\mu - k\cdot\sigma$)
BNSA of background depends strongly on energy



Extracted BNSA

target D_2, E$=315$ MeV, $Q^2 = 0.23$ (Gev/c)^2, $\theta = 145°$



Dependence on the lower cut

BNSA of background depends strongly on energy

Data analysis plan

- Asymmetry is extracted for every module and every run.

$$\mathsf{A}_{\perp} = \frac{\mathsf{A}_c - f\mathsf{A}_{\gamma}}{1 - f}$$

- Average of asymmetries over all runs for each frame (azimuthal angle)
- Correction of systematics and evaluation of systematic errors
- Normalization to the electron beam polarization $A_{\text{phys}} = \frac{A_{\text{exp}}}{P_e}$

Outline

Measurements at E = 315 MeV

statistics

target H_2, E$= 315$ MeV, $Q^2 = 0.23$ (Gev/c)^2, $\theta = 145°$

- Low cut k = 1.5σ, dilution factor f$= 8\%$

- 5 inner rings of the calorimeter: 730 crystals
- 50 hours of data taking
- Altogether 10^{11} elastic events

- Effective $P_e = 77.0\%$, error $\Delta(P_e) = 4\%$
- Statistical error: $\sigma(A) = \dfrac{1}{P_e\sqrt{N_{el}}} \Rightarrow \sigma(A) = 4.13$ ppm

Systematics and measurement

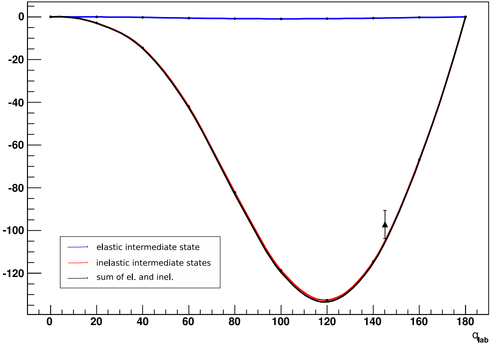
target H_2, E$= 315$ MeV, $Q^2 = 0.23$ (Gev/c)^2, $\theta = 145°$

	Scaling factor	Error(ppm)
Polarization	0.77	3.29
	Correction(ppm)	Error(ppm)
Dilution of γ backgr.	-1.10	1.16
ϵ, δ parameters	–	2.90
Helicity corr. beam diff.	-0.12	0.70
Non-helicity corr. beam fluc.	–	1.03
Al windows	-1.93	0.10
Random coinc. events	-1.25	0.07
Luminosity	-0.61	0.20
Nonlinearity of L	-0.47	0.17
spin angle deviation	-0.65	0.89
Sum syst. errors		4.79

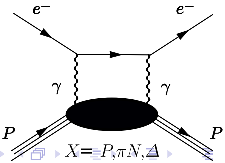
$$A_\perp = (-96.61 \pm 4.13 \pm 4.79)\ \text{ppm}$$

Model calculation of the BNSA for proton

target H_2, E$= 315$ MeV, $Q^2 = 0.23$ (Gev/c)^2, $\theta = 145°$



Inelastic intermediate states contribution to BNSA is dominant



statistics

target D_2, E$= 315$ MeV, $Q^2 = 0.23$ (Gev/c)^2, $\theta = 145°$

- Low cut k = 1.0σ, dilution factor f$= 13\%$
- 5 inner rings of the calorimeter: 730 crystals
- 60 hours of data taking
- Altogether $1.7 \cdot 10^{11}$ elastic events
- Effective $P_e = 79.0\%$, error $\Delta(P_e) = 4\%$
- Statistical error: $\sigma(A) = \dfrac{1}{P_e\sqrt{N_{el}}} \Rightarrow \sigma(A) = 3.04$ ppm

Systematics and measurement

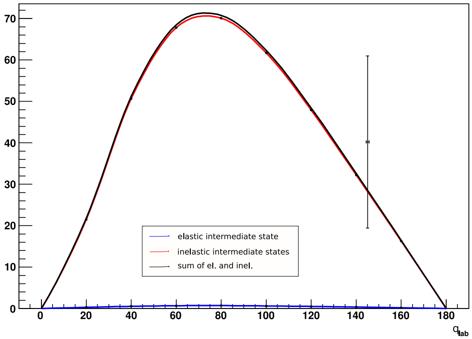
target D_2, E$= 315$ MeV, $Q^2 = 0.23$ (Gev/c)^2, $\theta = 145°$

	Scaling factor	Error(ppm)
Polarization	0.79	2.23
	Correction(ppm)	Error(ppm)
Dilution of γ backgr.	2.73	1.28
ϵ, δ parameters	–	0.97
Helicity corr. beam diff.	−0.40	0.32
Non-helicity corr. bean fluc.	–	1.14
Al windows	0.50	0.05
Random coinc. events	−1.55	0.10
Luminosity	−0.97	0.41
Nonlinearity of L	−0.82	0.25
spin angle deviation	−0.90	1.30
Sum syst. errors		3.29

$$A_\perp = (-55.46 \pm 3.04 \pm 3.29) \text{ ppm}$$

Model calculation of the BNSA for neutron

target D_2, E$=315$ MeV, $Q^2 = 0.23$ (Gev/c)^2, $\theta = 145°$



$$A_\perp^d = \frac{\sigma_p A_\perp^p + \sigma_n A_\perp^n}{\sigma_p + \sigma_n} \quad \Rightarrow \quad A_\perp^n = (40.00 \pm 20.79) \cdot 10^{-6}$$

Barbara Pasquini et al. Phys. Rev. C 70, 045206 (2004)

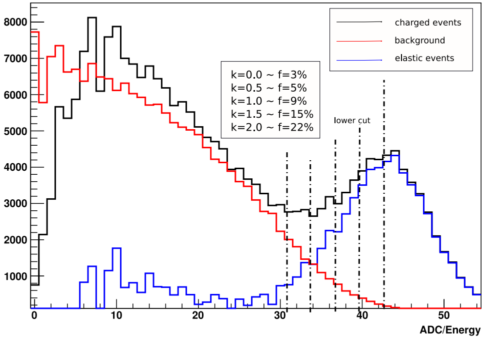
Outline

Extraction of the beam normal spin asymmetry at $E = 420$ MeV

Energy spectrum with H_2

target H_2, E$= 420$ MeV, $Q^2 = 0.35$ (Gev/c)^2, $\theta = 145°$

$$A_\perp = A_0 \cos(\phi + \delta) + p$$

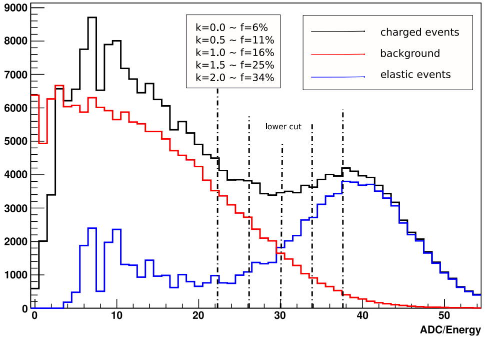


Elastic scattered electrons and background

$$A_\perp = \frac{A_c - f \cdot A_\gamma}{1 - f}$$, dilution factor $f = \frac{N_\gamma}{N_c}$

Energy spectrum with D_2

target D_2, E$= 420$ MeV, $Q^2 = 0.35$ (Gev/c)^2, $\theta = 145°$

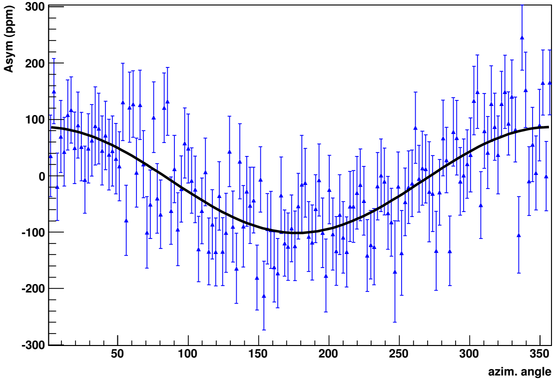


Quasielastic scattered electrons and background

Static approximation $A_\perp^d = \dfrac{\sigma_p A_\perp^p + \sigma_n A_\perp^n}{\sigma_p + \sigma_n}$

BNSA of the elastic events on H_2

target H_2, E$= 420$ MeV, $Q^2 = 0.35$ (Gev/c)^2, $\theta = 145°$



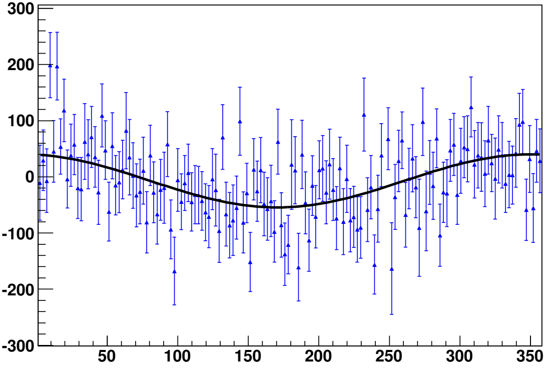
$\chi^2/\nu = 1.12$

$P = 0.14$
$A_\perp = (-93.97 \pm 7.30)$ ppm
$\alpha = (2.66 \pm 4.44)°$
$p = (-7.34 \pm 5.17)$ ppm

Dependence on the azimuthal angle

BNSA of the elastic events on H_2

target D_2, E$= 420$ MeV, $Q^2 = 0.35$ (Gev/c)^2, $\theta = 145°$



$\chi^2/\nu = 1.12$

$P = 0.14$

$A_\perp = (-49.93 \pm 5.27)$ ppm

$\alpha = (7.39 \pm 6.05)°$

$p = (-4.33 \pm 3.73)$ ppm

Dependence on the azimuthal angle

Outline

Measurements at E = 420 MeV

statistics

target H_2, E$= 420$ MeV, $Q^2 = 0.35$ (Gev/c)^2, $\theta = 145°$

- Low cut k = 1.5σ, dilution factor f$= 15\%$

- 5 inner rings of the calorimeter: 730 crystals
- 85 hours of data taking
- Altogether $8.2 \cdot 10^{10}$ elastic events

- Effective $P_e = 74\%$, error $\Delta(P_e) = 4\%$
- Statistical error: $\sigma(A) = \dfrac{1}{P_e\sqrt{N_{el}}} \Rightarrow \sigma(A) = 4.73$ ppm

Systematics and measurement

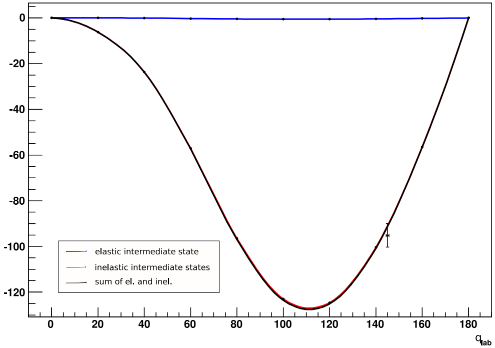
target H_2, E$=315$ MeV, $Q^2=0.23$ (Gev/c)^2, $\theta=145^\circ$

	Scaling factor	Error(ppm)
Polarization	0.74	4.19
	Correction(ppm)	Error(ppm)
Dilution of γ backgr.	-1.37	2.09
ϵ, δ parameters	–	-0
Helicity corr. beam diff.	0.10	0.92
Non-helicity corr. beam fluc.	–	1.62
Al windows	-4.79	0.24
Random coinc. events	3.63	0.19
Luminosity	-1.59	0.52
Nonlinearity of L	-1.30	0.64
spin angle deviation	–	–
Sum syst. errors		5.11

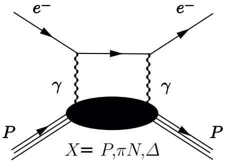
$$A_\perp = (-97.42 \pm 4.73 \pm 5.11)\ \text{ppm}$$

Model calculation of the BNSA for proton

target H_2, E$= 420$ MeV, $Q^2 = 0.35$ (Gev/c)^2, $\theta = 145°$



Inelastic intermediate states contribution to BNSA is dominant



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statistics

target D_2, E$= 420$ MeV, $Q^2 = 0.35$ (Gev/c)^2, $\theta = 145°$

- Low cut k = 1.0σ, dilution factor f$= 16\%$

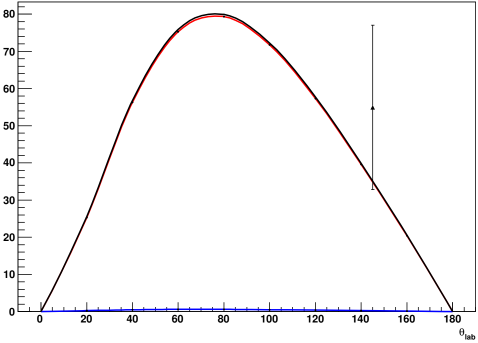
- 5 inner rings of the calorimeter: 730 crystals
- 83 hours of data taking
- Altogether $6.2 \cdot 10^{10}$ elastic events

- Effective $P_e = 85\%$, error $\Delta(P_e) = 4\%$
- Statistical error: $\sigma(A) = \dfrac{1}{P_e\sqrt{N_{el}}} \Rightarrow \sigma(A) = 4.73$ ppm

$$\boxed{A_\perp = (-49.97 \pm 4.20 \pm 2.18)\ \text{ppm}}$$

Model calculation of the BNSA for neutron

target D_2, E$= 315$ MeV, Q$^2 = 0.23$ (Gev/c)^2, $\theta = 145^\circ$



$$A^d_\perp = \frac{\sigma_p A^p_\perp + \sigma_n A^n_\perp}{\sigma_p + \sigma_n} \quad \Rightarrow \quad \boxed{A^n_\perp = (54.94 \pm 22.11) \cdot 10^{-6}}$$

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Outline

Summary and outlook

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- Measurement of the beam normal spin asymmetry with H_2 and D_2 at $Q^2 = 0.23$ (GeV/c)^2
- Preliminary analysis of the beam normal spin asymmetry with H_2 and D_2 at $Q^2 = 0.35$ (GeV/c)^2
- Comparison of the measurements with the model calculation of the BNSA
- Analysis of the new data with beam normal spin polarization at forward angles
- New measurement of the BNSA at backward angles with 200 MeV and $Q^2 = 0.10$ (GeV/c)^2