Axial form factors of the nucleon and low Q^2 pion electroproduction

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- How we “see” the nucleon depends on the probe
- Vector current γ_μ:
  G_E, G_M Sachs form factors
  $\longrightarrow$ elastic electron scattering
- Axial current $\gamma_\mu\gamma_5$:
  G_A, G_P (isovector) axial form factors
  $\longrightarrow$ neutrino scattering
  $\longrightarrow$ pion electroproduction close to threshold
- Matrix element of axial current between two nucleons:

$$\left\langle N(P_f)|J^\alpha_{5\mu}|N(P_i)\right\rangle = \bar{u}_{P_f}\left[G_A(t)\gamma_\mu\gamma_5 + \frac{(P_f - P_i)_\mu}{2m} G_P(t)\gamma_5\right]\frac{\tau^\alpha}{2} u_{P_i}$$

where $t = (P_f - P_i)^2 = (q - k_\pi)^2$

Form factors G_A and G_P of the nucleon are not well known.

- **Axial form factor G_A**
  Coupling constant $G_A(Q^2 = 0) = g_A = 1.2601 \pm 0.0025$ known from neutron β decay.
  Form factor usually parametrized by dipole formula

$$G_A(Q^2) = \frac{G_A(0)}{(1 + Q^2/M_A^2)^2}$$

  "Axial mass" parameter M_A determined from:
  - Neutrino-nucleon scattering:
    $M_A = 1.017 \pm 0.023\,\mathrm{GeV}/c^2$ (world average)
  - Pion electroproduction:
    $M_A = 1.068 \pm 0.017\,\mathrm{GeV}/c^2$ (world average)

  The 2 σ discrepancy can be understood within ChPTh.
  [Bernard, Kaiser, Meißner: PRL *69* (1992) 1877, PRL *72* (1994) 2810]

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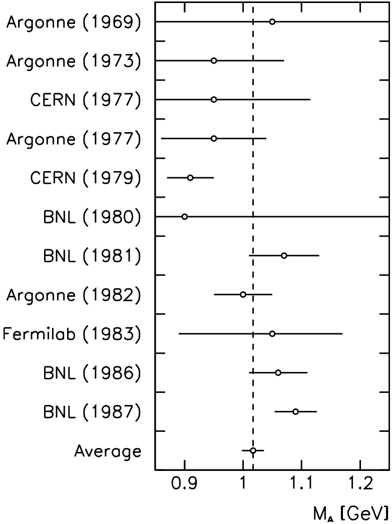
Axial mass M_A

from neutrino scattering experiments



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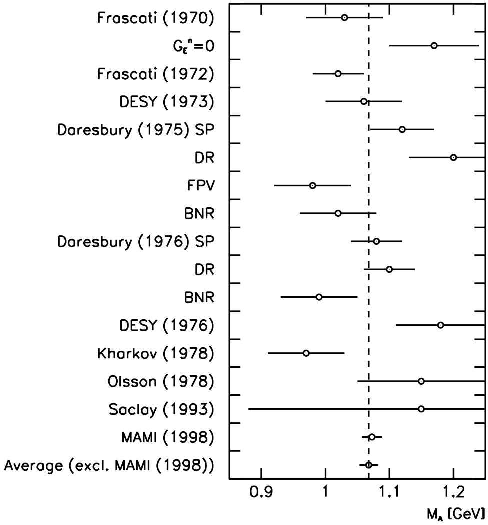

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Physics Motivation

Induced pseudoscalar form factor

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  Coupling constant $G_P(Q^2 = 0.88\, m_\mu^2) = g_p$ determined from:
  - Muon capture $\mu^- p \to \nu_\mu n$: $g_p = 8.7 \pm 1.9$.
    This is in agreement with theory (PCAC):
    $g_p = 8.21 \pm 0.09$.
  - However: Radiative muon capture (TRIUMF)
    $\mu^- p \to \nu_\mu n \gamma$ gives $g_p = 12.3 \pm 0.9$
    [Jonkmans et al.: PRL *77* (1996) 4512]
    New result: $g_p = 10.6 \pm 1.1$ by reanalysing TRIUMF data with new Λ_{op} value
    [Clark et al.: nucl-ex/0509025]

Form factor $G_P(Q^2)$:
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(However, no LT separation)

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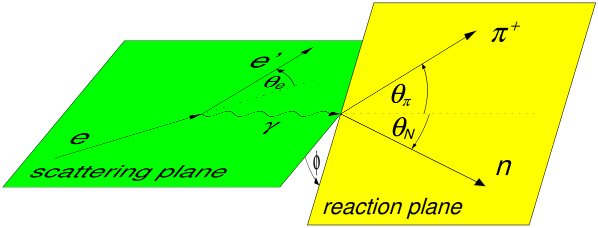

Differential cross section (unpolarized):

$$\frac{d\sigma}{d\Omega dE' d\Omega_\pi^*} = \Gamma \frac{d\sigma_v}{d\Omega_\pi^*}$$

where

$$\frac{d\sigma_v}{d\Omega_\pi^*} = \frac{d\sigma_T}{d\Omega_\pi^*} + \epsilon_L \frac{d\sigma_L}{d\Omega_\pi^*} + \sqrt{2\epsilon_L(1+\epsilon)} \frac{d\sigma_{LT}}{d\Omega_\pi^*} \cos\phi_\pi^* + \epsilon \frac{d\sigma_{TT}}{d\Omega_\pi^*} \cos(2\phi_\pi^*)$$

Experimental Method
Kinematics and cross section

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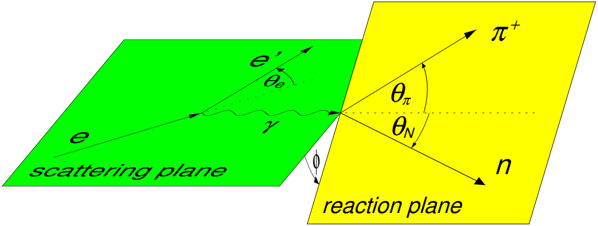

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Parallel kinematics ($\theta^*_\pi = 0$): Interference terms σ_{LT} and σ_{TT} vanish.
Rosenbluth separation of σ_L and σ_T by variation of virtual photon polarization ϵ_L.
(σ_{LT} accessible by additional measurement in non-parallel kinematics, $\theta^*_\pi \neq 0$.)

Threshold limit:
s-wave multipoles E_{0+} and L_{0+}:

$$\frac{d\sigma_T}{d\Omega^*_\pi} = \frac{|\mathbf{q}|}{k^*_\gamma}|E_{0+}|^2 \quad \text{and} \quad \frac{d\sigma_L}{d\Omega^*_\pi} = \frac{|\mathbf{q}|}{k^*_\gamma}|L_{0+}|^2$$

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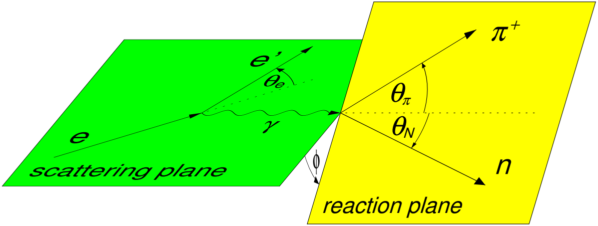

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A1

Multipoles

E_{0+} and L_{0+} in terms of electromagnetic and axial form factors

$$E_{0+}(k^2) = \sqrt{1-\frac{k^2}{4m_N^2}}\frac{1}{\sqrt{2}f_\pi}\left\{G_A(k^2)+\frac{k^2}{4m_N^2}G_A(0)G_M^V(k^2)+\delta(k^2)\right\}$$

$$L_{0+}(k^2) = \sqrt{1-\frac{k^2}{4m_N^2}}[D(t)-2m_N G_A(0)]\frac{\omega F_\pi(k_\pi^2)}{\sqrt{2}m_\pi f_\pi(2m_N+m_\pi)} + \frac{\omega}{m_\pi}E_{0+}(m_\pi^2)$$

with

$$D(t) = 2m_N G_A(t) + tG_P(t) = \frac{2f_\pi g_{\pi N} m_\pi^2}{m_\pi^2 - t} + 2(m_N G_A(0) - f_\pi g_{\pi N})\frac{\lambda^2}{\lambda^2 - t}$$

$D(t)$ contains free parameter λ to be determined by experiment, providing the connection between L_{0+} and $G_P(t)$.

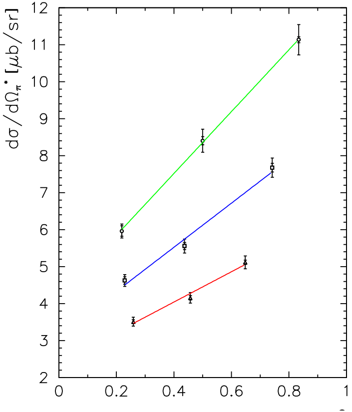
Experiment

The method of LT separation was applied in our previous measurement:

Liesenfeld, Richter, Širca et al., PLB ***468*** *(1999) 20*

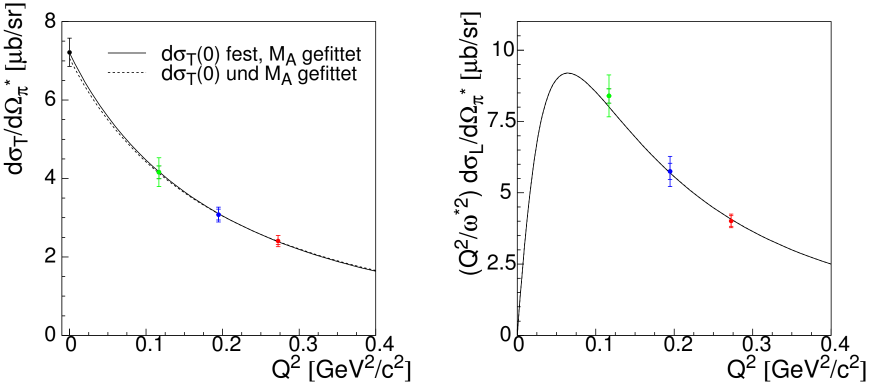
which aimed at a precise extraction of the axial mass parameter M_A from the transverse cross section.

$$G_A(Q^2) = \frac{G_A(0)}{(1 + Q^2/M_A^2)^2}$$



LT separation

Separated transverse and longitudinal cross sections for H$(e, e'\pi^+)n$ from that measurement:



- Solid line: "Theoretical" fit.

$$M_A = 1.077 \pm 0.039\,\text{GeV}$$

To pin down the low-Q^2 end of the transverse cross section, a rather imprecise value of $d\sigma_T$ at $Q^2 = 0$ had to be adopted from (scarce) low-energy photo-production data [SAID, MAID].

- Dotted line: Unconstrained fit.

$$M_A = 1.089 \pm 0.106\,\text{GeV}$$

$\rightarrow$ Proposal A1/1-99 for an additional measurement at low Q^2:
"From the viewpoint of the axial mass parameter, an additional data point in the vicinity of the photon point would significantly improve the reliability of the extraction since the theoretical fit is most sensitive to data points at lower values of Q^2."

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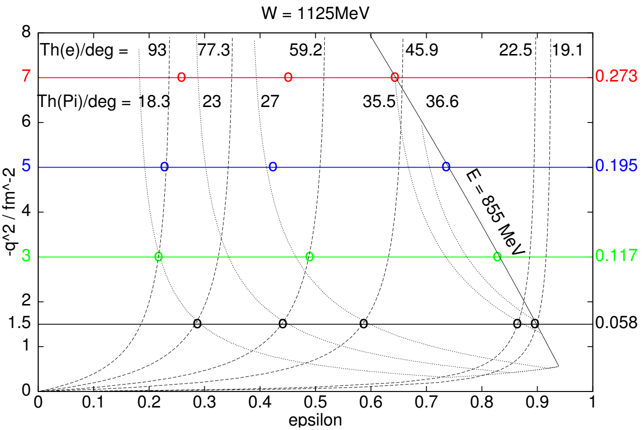
Measurements at $W = 1125\,\mathrm{MeV}$

- Aim: Low four-momentum transfer $Q^2 = 0.058\,(\mathrm{GeV}/c)^2$
- Reaction $^1\mathrm{H}(e, e'\pi^+)n$
- Measurement with the A1 standard setup
- Electron beam from MAMI accelerator, up to 20 μA beam current
- Liquid Hydrogen target, 5 cm long
- For LT separation, the lever arm in ϵ should be as large as possible.
- Data taking in 2000 and 2002

Dagmar Baumann, doctoral thesis (2005), to be published

Kinematic parameters



Control of systematic errors:

- Measurement with spectrometers exchanged
- Elastic reaction $^1H(e, e')$
- Spek. C as luminosity monitor

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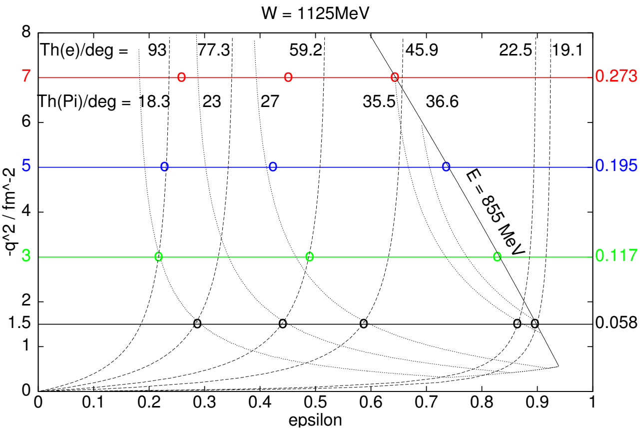

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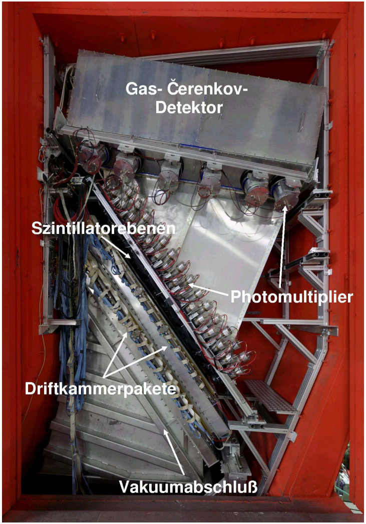
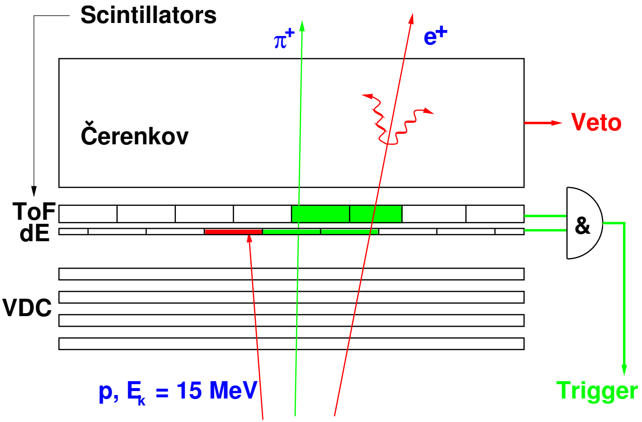
A1 Three-Spectrometer Setup



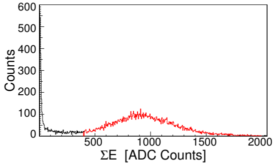
Protons ($E_{kin} = 15\,\mathrm{MeV}$) in trigger:



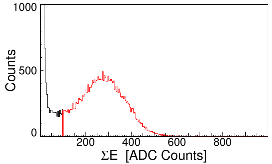
Trigger is “proton blind”

Čerenkov veto

$\epsilon = 0.866$, pion in A

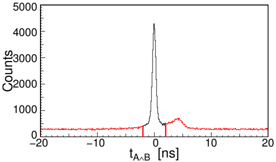


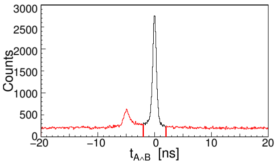
$\epsilon = 0.866$, pion in B



Muons

Cuts in coincidence time spectrum:



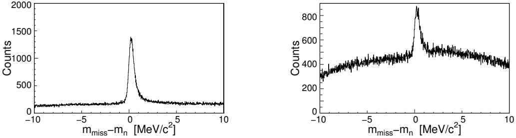


Pion decay losses and muon background are determined by simulation.

Background reduction in missing mass spectrum

$\epsilon = 0.9$, pion in A $\qquad$ $\epsilon = 0.286$, pion in B

Without any cuts:



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Additional Čerenkov cut:

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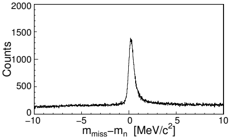

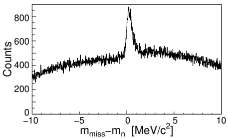

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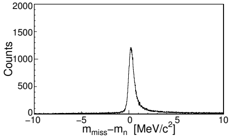

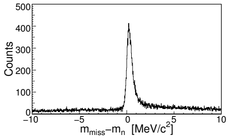

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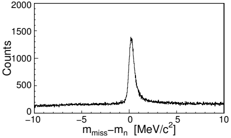

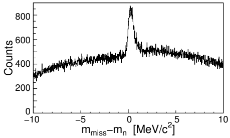

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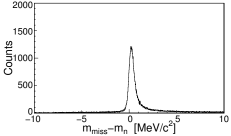

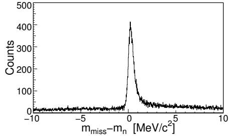

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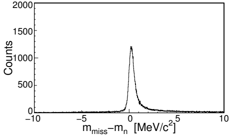

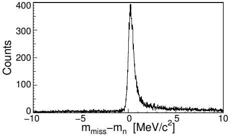

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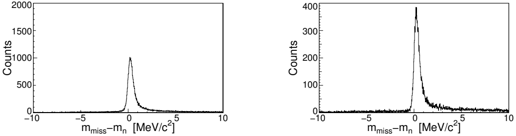
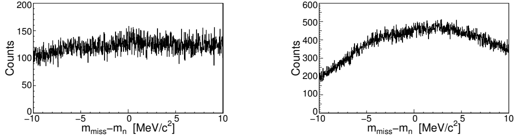
Additional cut on path length and acceptance:



Background:



Corrections and systematic errors

- Target density
  - Pressure and temperature $\rightarrow$ equation of state
- Pion decay
  - Determine decay factor for each accepted pion
  - Global correction by mean value of decay factor
- Cut in missing mass
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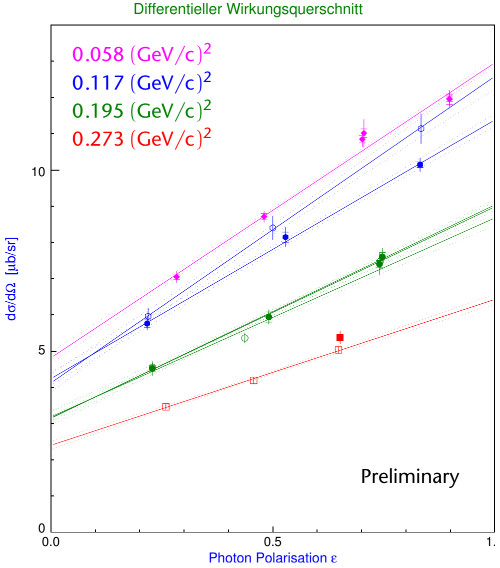
Results

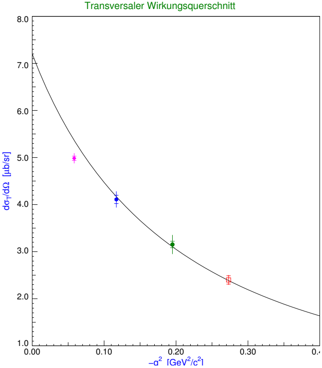
Differential cross sections from 2002 data taking

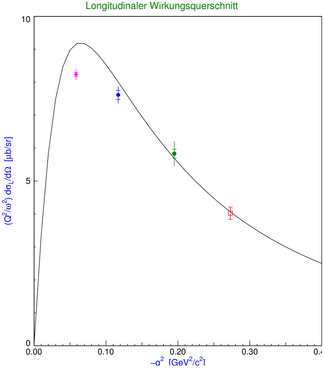


- open symbols: results from:
  Blomqvist et al.,
  ZPA *353* (1996) 415
  Liesenfeld et al.,
  PLB *468* (1999) 20
- solid symbols: new results

Results

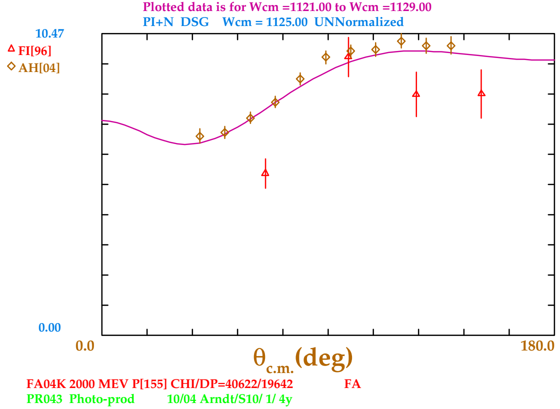
Separated transverse and longitudinal cross sections





- Cross sections at low Q^2 lower than expected from previous experiments
- At higher Q^2 consistent with Liesenfeld et al.
- Curves show "old" fit from previously published results

$\gamma p \to \pi^+ n$ at $W = 1125$ MeV ($E_\gamma = 205$ MeV)



Fissum et al., PRC *53* (1996) 1278 (Saskatoon)
Ahrens et al., EPJA *21* (2004) 323 (Mainz A2)

Short-Orbit Spectrometer

Why another spectrometer?

- Experiments completed at $\Delta W = 46\,\mathrm{MeV}$
- Contributions from p-wave multipoles

$\longrightarrow$ Measurement closer to threshold, $\Delta W = 5\,\mathrm{MeV}$

- Pion momentum decreases with CMS energy W
- Charged pion: lifetime 26 ns
- Path length in A1 spectrometers $\approx 10\,\mathrm{m}$
- At $\Delta W = 5\,\mathrm{MeV}$ about 90 % of pions decay
- Systematic errors due to muon contamination

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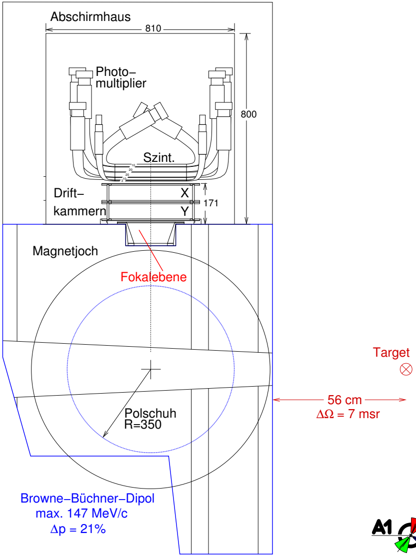
- At $\Delta W = 5\,\text{MeV}$ about 90 % of pions decay
- Systematic errors due to muon contamination

$\longrightarrow$ Additional "short-orbit" spectrometer (SOS) for low-energy charged pions

Short-Orbit Spectrometer

Schematic view

- Dipole magnet of Browne-Buechner type
- Short flight path of only 1.6 m minimizes pion decays
- Two focal planes (only one is equipped with detectors, for the time being)
- Momentum acceptance up to 147 MeV/c (at 1.4 T)
- Solid angle acceptance between 2 and 4 msr
- Minimal forward angle 15.4°

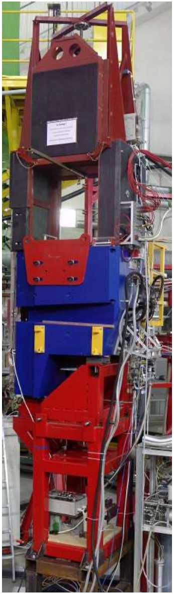


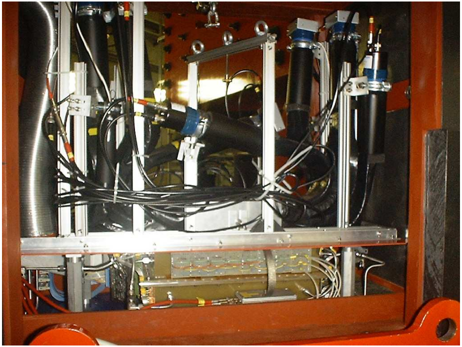
Detector System

Goal: Measure pions with kinetic energies of only 16–32 MeV with an angular resolution of a few mrad.

- Trigger and particle identification
  - Range telescope of five consecutive layers of scintillator (3, 10, 20, 20 and 10 mm thickness).
  - Online particle ID by stopping / energy thresholds.
  - Positron veto by last scintillator layer.
  - Offline particle ID by $\Delta E_i / \Delta E_j$ cuts.
- Drift chamber
  - "Volume type" chamber.
  - Optimized for small effective thickness.
  - Cathode wires: 80 μm aluminium, silver coated.
  - Operated with helium-hydrocarbon mixture.
- Shielding house of lead and borated polyethylene

Detector System

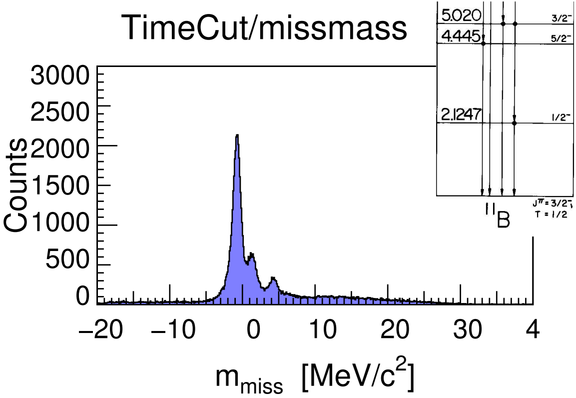




- Range telescope:
  Trigger and particle identification
- Drift chamber

Test measurement

- Calibration with quasi-elastic process $^{12}C(e, e'p)^{11}B$
- Electron detected in SOS
- Cut on ground state of residual ^{11}B nucleus
- Mass resolution 1.5 MeV/c^2 FWHM with first order transfer matrix



Matthias Ding, doctoral thesis

Summary

- Experiments with 3-Spectrometer Setup
  - Charged pion electroproduction $^1\mathrm{H}(e, e'\pi^+)n$ at $W = 1125\,\mathrm{MeV}$
  - Three different Q^2 values (3 to 5 kinematical settings each) measured in one experiment
  - Results indicate that the cross section at low Q^2 is considerably lower than expected from previous experiments
- Future experiments with Short-Orbit Spectrometer
  - Measure $^1\mathrm{H}(e, e'\pi^+)n$ at $\Delta W = 5\,\mathrm{MeV}$
  - Access to $\mathrm{D}(e, e'\pi^\pm)$ also possible

The A1 Collaboration

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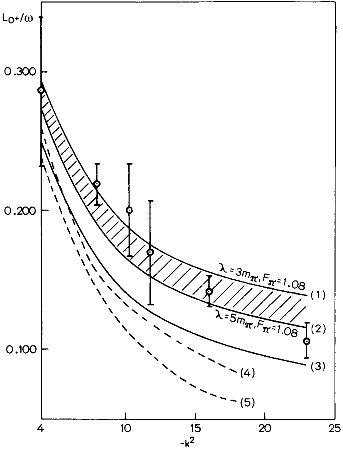
Multipoles

Data for $(L_{0+}/\omega)_{\text{thr}}$ at threshold from older π^+ electroproduction experiments (Frascati, DESY).
Theoretical fits for different values of λ are shown.



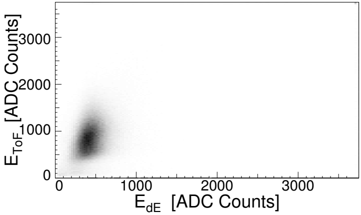
Kinematic parameters

Invariant mass $W = 1125$ MeV for all measurements

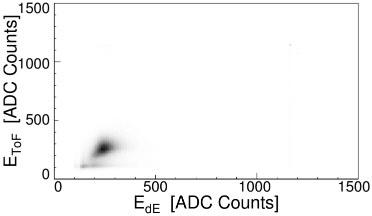
q^2	ϵ	E	E'	$\theta_{e'}$	p_{π^+}	θ_{π^+}	π^+
$(\text{GeV}/c)^2$		MeV	MeV	$^\circ$	MeV/c	$^\circ$	
0.058	0.900	855	618.6	19.1°	170.5	36.8°	A
0.058	0.705	525	288.6	36.2°	170.5	30.2°	A,B
0.058	0.484	405	168.6	55.1°	170.5	24.1°	A
0.058	0.286	345	108.6	77.3°	170.5	18.3°	B
0.117	0.834	855	587.4	27.9°	188.8	39.3°	A
0.117	0.529	525	257.3	55.5°	188.8	29.2°	B
0.117	0.219	405	137.3	93.0°	188.8	18.4°	B
0.195	0.742	855	545.8	37.7°	209.0	38.3°	A,B
0.195	0.489	615	305.8	61.2°	209.0	29.8°	B
0.195	0.229	495	185.8	93.5°	209.0	20.1°	B
0.273	0.648	855	504.6	46.8°	228.0	35.8°	B

- Identify positrons by energy loss?
  No, both are minimum ionising particles:

$\epsilon = 0.866$, pion in A



$\epsilon = 0.866$, pion in B



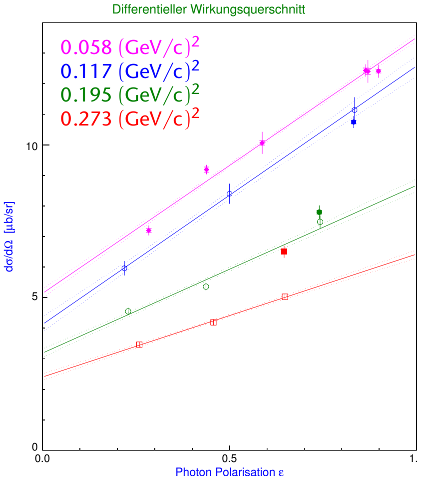
Elastic measurements $\mathbf{H}(e, e'p)$

Cross-checks by elastic $H(e, e'p)$ measurements:

particles	E MeV	θ_A	p_A MeV/c	θ_B	p_B MeV/c
A: e′, B: p	345	100°	241, 231	31.5°	453, 435
A: e′, B: p	525	55.5°	439, 422	50.6°	468, 450
A: p, B: e′	525	50.6°	468, 450, 432	55.5°	439, 422, 405
A: p, B: e′	855	56.9°	545, 524, 503	37.7°	747, 719, 690
A: e′, B: p	495	93.5°	323, 311	31.6°	615, 591
A: e′, B: p	615	61.2°	468, 450	45.6°	573, 551
A: e′, B: p	855	67.1°	546	38.3°	810
A: e′, B: p	855	46.8°	665	50.4°	628

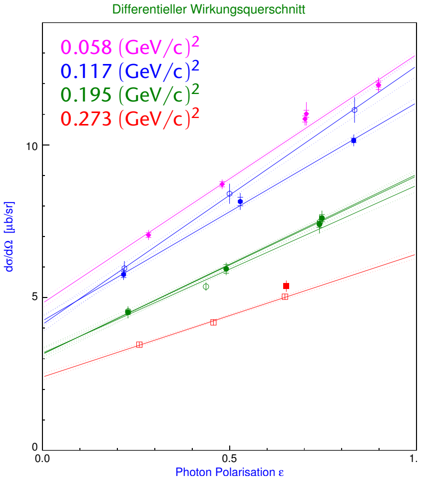
Results

Differential cross sections from 2000 data taking



Results

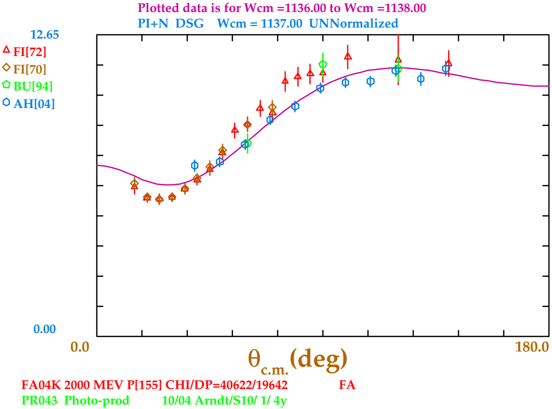
Differential cross sections from 2002 data taking



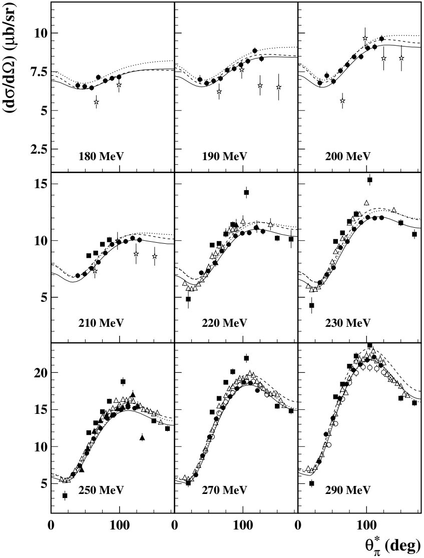
Results

Comparison with photoproduction

$\gamma p \to \pi^+ n$ at $W = 1137\,\text{MeV}$ ($E_\gamma = 220\,\text{MeV}$)



Results
Comparison with photoproduction



Kinematics

Kinematic parameters for $W = 1084$ MeV. Cross sections are calculated by the MAID program.

Q^2	ϵ	E	E'	$\theta_{e'}$	θ_π	p_π	$\exp(-\Delta t/\gamma\tau)$	$d\sigma/dE'd\Omega d\Omega$
GeV^2		MeV	MeV	$^\circ$	$^\circ$	MeV/c		pb/MeV sr^2
0.156	0.820	855	614.7	31.6	44.2	99.9	0.75	4.57
	0.535	540	299.7	58.8	33.7			1.21
	0.255	420	179.7	91.9	22.9			0.510
0.078	0.902	855	656.2	21.5	44.5	82.7	0.71	27.3
	0.614	450	251.2	49.0	33.6			4.46
	0.289	330	131.2	84.2	22.4			1.47
0.035	0.904	660	484.0	19.1	38.0	70.5	0.67	70.8
	0.666	375	199.0	40.0	29.9			13.5
	0.404	285	109.0	64.1	22.5			4.87