Near-threshold pion production in diproton reactions with polarized beams and target at ANKE-COSY

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for the ANKE collaboration

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Contents

Introduction

<u>Two nucleon systems:</u>

Deuteron: bound (p+n) system, very well studied

Di-proton: free {pp}-pair in $^1S_0$ state, $E_{pp} < 3$ MeV

- Isotropy in {pp} - rest frame
- pp Final State Interaction (Migdal-Watson FSI factor)

New tool to study hadron interactions

<u>Di-proton program at ANKE-COSY</u>

- d-breakup $\vec{p}d \rightarrow \{pp\}_s(0^0)\,n$ at high momentum transfer
- $\vec{d}\vec{p} \rightarrow \{pp\}_s(0^0)\,n$ at low momentum transfer (pn CE amplitudes)
- $dp \rightarrow \{pp\}_s(0^0)\,\Delta^0$
- meson production in $pN \rightarrow \{pp\}_s X$
  - $X=\pi$
    - $\vec{p}p \rightarrow \{pp\}_s\pi^0$ at $T_p = 0.5$ -2.4 GeV
    - $\vec{p}N \rightarrow \{pp\}_s\pi$ near threshold
  - $X=(2\pi)$ (ABC effect in pp collisions)
  - $X=\eta, \omega$
- inverse diproton photodisintegration $pp \rightarrow \{pp\}_s\gamma$

Near-threshold pion production at ANKE (1)

- Theoretical description of $pN \rightarrow pp\,\pi$ process is considerably simplified if two final protons are detected at low excitation energy, i.e. such di-protons are predominantly in the $^1S_0$ state.
- Spin structure of the $pn \rightarrow \{pp\}_s \pi^-$ (or $pp \rightarrow \{pp\}_s \pi^0$) is $\frac{1}{2}^+ \frac{1}{2}^+ \rightarrow 0^+ 0^-$

→ only two spin amplitudes (compared to 6 for $pp \rightarrow d\pi^+$)

$$\left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{1}{4}(|A|^2 + |B|^2), \qquad A_y^p = A_y^Q = -\frac{2Im(A^*B)}{|A|^2 + |B|^2}$$

$$A_{xx} = -A_{zz} = \frac{|B|^2 - |A|^2}{|A|^2 + |B|^2}, \quad A_{yy} = 1, \quad A_{xz} = A_{zx} = -\frac{2Re(A^*B)}{|A|^2 + |B|^2}$$

From this it follows that the measurement of

- the differential cross section,
- the analyzing power and
- one spin correlation coefficient

is sufficient to extract magnitudes of the two amplitudes and their relative phase.

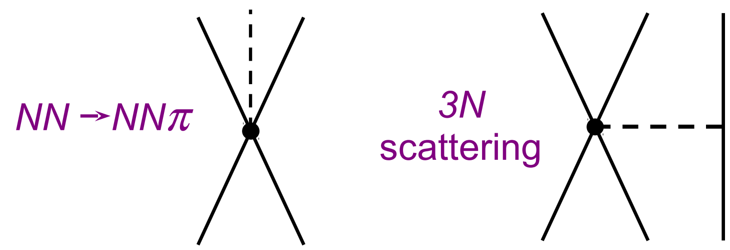
Near-threshold pion production at ANKE (2)

Extension of ChPT to the NN→NNπ process

- A full data set of all observables in $pp \to \{pp\}_s\pi^0$ and $np \to \{pp\}_s\pi^-$ would allow us to determine the *partial wave amplitudes* and test the ChPT predictions.

$pp \to \{pp\}_s\pi^0$ includes $^3P_0 \to {}^1S_0 s$, $^3P_2 \to {}^1S_0 d$ *and* $^3F_2 \to {}^1S_0 d$ *(Ps, Pd and Fd)*
$np \to \{pp\}_s\pi^-$ adds $^3S_1 \to {}^1S_0 p$ *and* $^3D_1 \to {}^1S_0 p$ *(Sp and Dp)*

- The p-wave amplitudes give access to the 4Nπ contact operator, controlled by the *low energy constant d*.



LEC d *connects different low-energy reactions*: $pp \to de^+\nu$, $pd \to pd$, $\gamma d \to nn\pi^+$

Our goal is to establish that the same LEC controls NN→NNπ

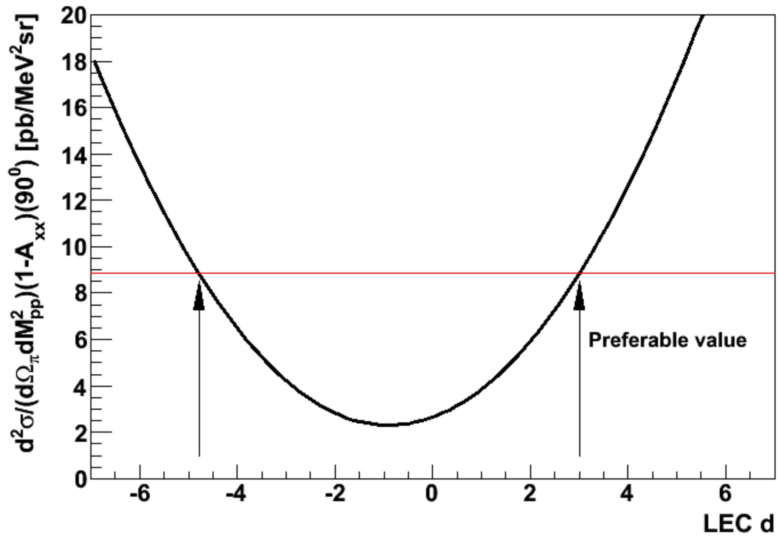
Accessing LEC *d* via $A_{x,x}$ and dσ/dΩ

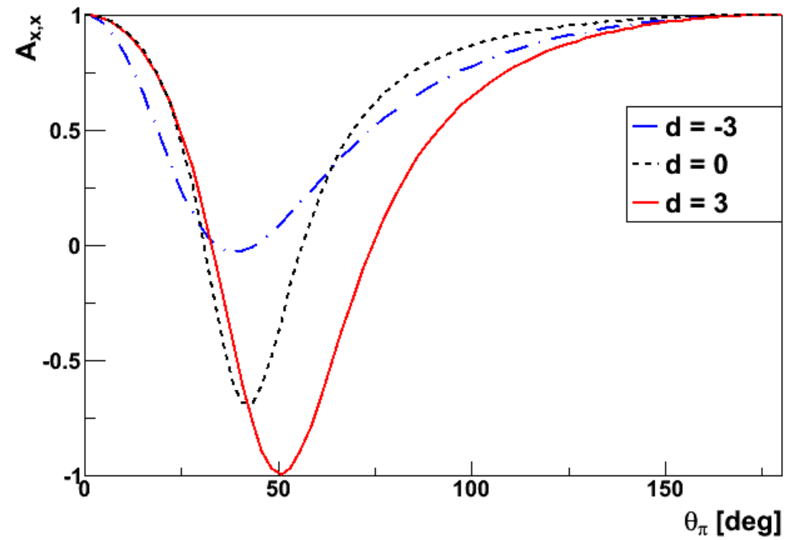
The <u>*direct and most clean*</u> way to access the *LEC d* is to measure *the cross section* and *the spin correlation coefficient* $A_{x,x}$ in $np \to \{pp\}_s\pi^-$:

$$(1-A_{x,x})d\sigma/d\Omega \sim |\delta|^2 k^2 \sin^2\theta, \qquad A_{y,y}=1$$

where δ is one of the p-wave amplitudes, containing the 4Nπ contact term

Only one factor $(1-A_{x,x})d\sigma/d\Omega(90^0)$ has to be extracted from the measurement.



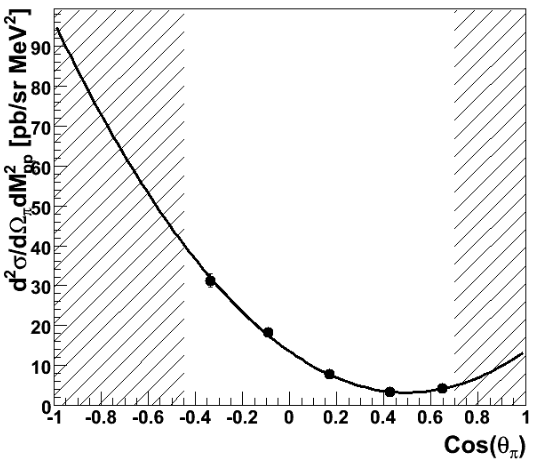


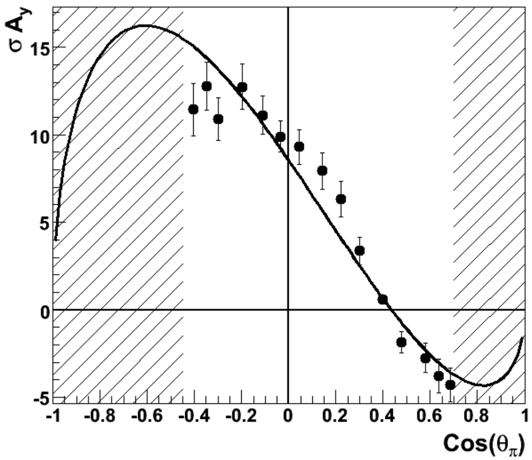
ChPT calculation by FZ-Juelich IKP theory, no d-waves included (V.Baru et al)

The method does not depend on assumptions about the d-waves or require subtraction of data with different systematic errors.

Available data on $d\sigma/d\Omega$ and A_y^p at 353 MeV

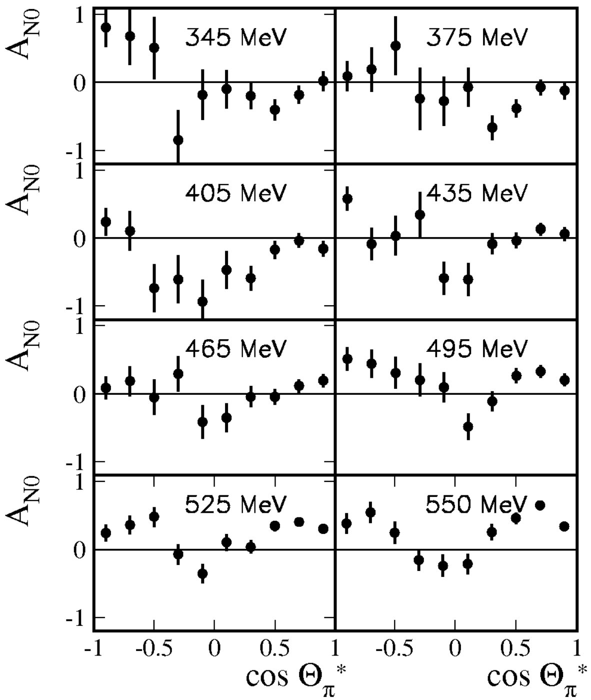
$pn \rightarrow \{pp\}_s \pi^-$





TRIUMF data

H. Hahn et al., Phys. Rev. Lett. 82 (1999) 2258,
F. Duncan et al., Phys. Rev. Lett. 80 (1998) 4390



PSI data

M. Daum et al., Eur. Phys. J. C 25 (2002) 55

Problems:

- Absence or poor precision of $pn \rightarrow \{pp\}_s \pi^-$ data at large and small angles.
- No $pp \rightarrow \{pp\}_s \pi^0$ A_y data at nearby energies.

Experimental program at ANKE

$pN \rightarrow \{pp\}_s \pi$ interactions at T=353 MeV:

- $d\sigma/d\Omega$ and A_y^p in $\vec{p}p \rightarrow \{pp\}_s \pi^0$ measured in 2009
- $d\sigma/d\Omega$ and A_y^p in $\vec{p}n \rightarrow \{pp\}_s \pi^-$ measured in 2009
- $A_{x,x,}$ $A_{y,y}$ in $\vec{n}\vec{p} \rightarrow \{pp\}_s \pi^-$ measured in 2011

- Next step: measurement of $A_{x,z}$ in $\vec{p}\vec{n} \rightarrow \{pp\}_s \pi^-$

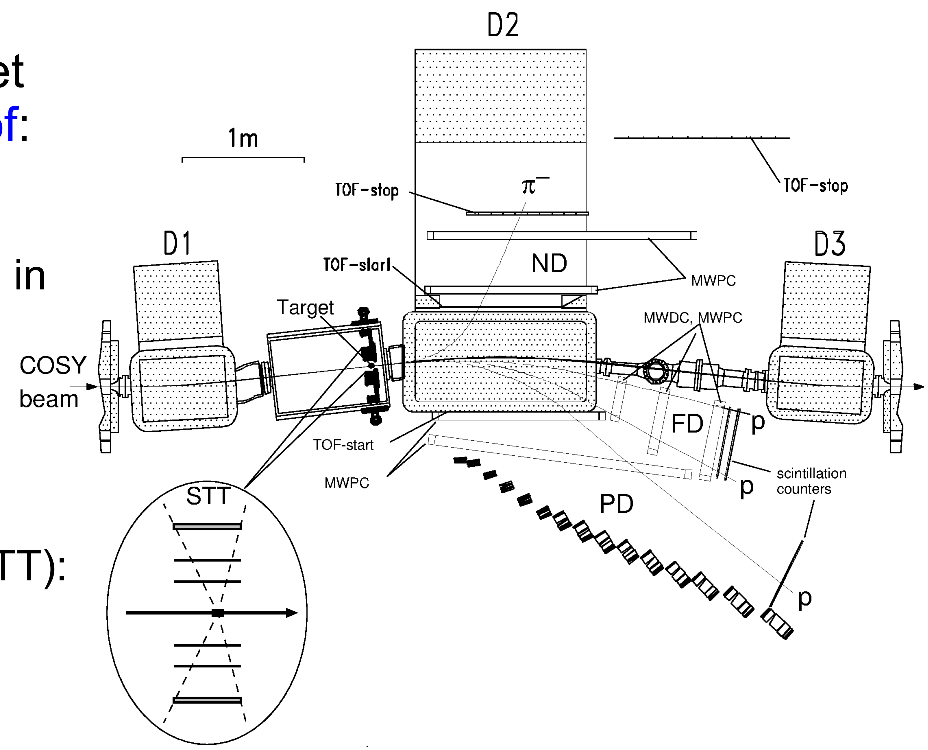
Experiment: ANKE@COSY

Cooler Synchrotron COSY at Juelich provides
polarized proton and *deuteron* beams of 600 – 3700 MeV/c momentum.

The ANKE spectrometer at internal target position of COSY allows measurement of:

- Fast forward positive and negative ejectiles in Forward, Positive and Negative detectors (FD, PD, ND):
  momentum, Id by TOF, dE/dX

- Slow positive ejectiles in Vertex detector (STT):
  energy, tracking, Id by dE/dX



Targets available:

- Cluster jet H_2 and D_2
- Internal polarized (H, D) target (PIT) with a storage cell

ANKE is well suited for the fast proton pairs with low excitation energy

Experiment: scheme of measurement

dσ/dΩ and A_y^p

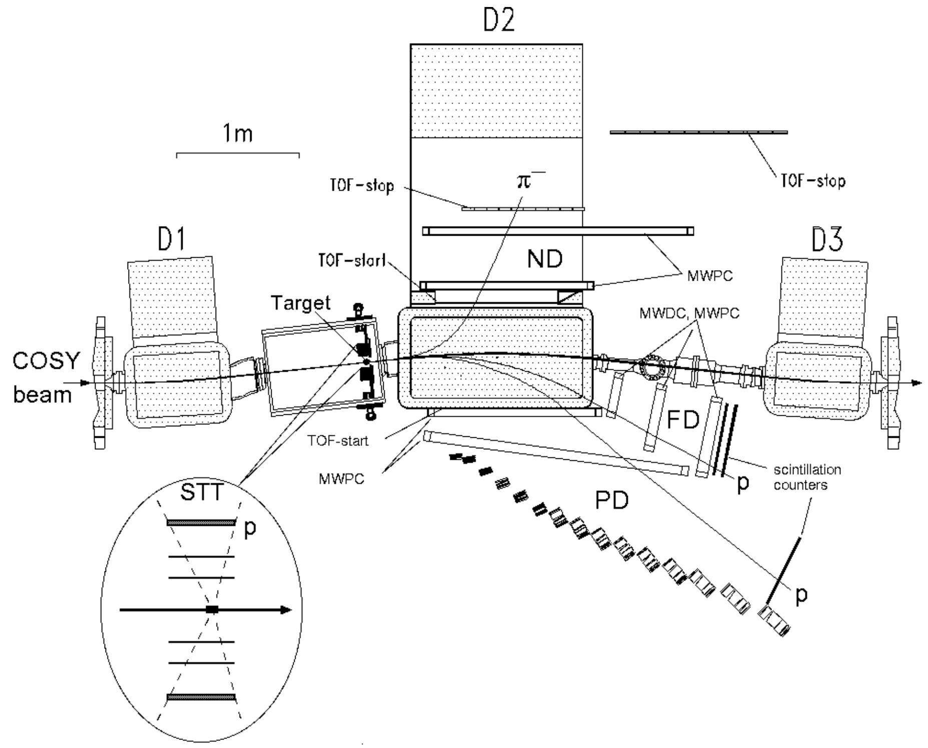
$\vec{p}d \to \{pp\}_s \pi^- + p_{spec}$ $\vec{p}p \to \{pp\}_s \pi^0$

Polarized proton beam: $P_y = 65\%$

H_2, D_2 *cluster jet target:* $d = 5 \cdot 10^{14}\ cm^{-2}$

Luminosity: $L = 1.5\ pb^{-1}$

Polarimetry, normalization: $pp \to d\pi^+$

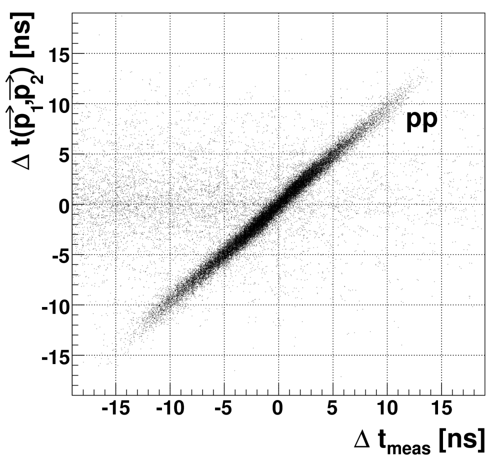


π^0 *case: {pp} detected*

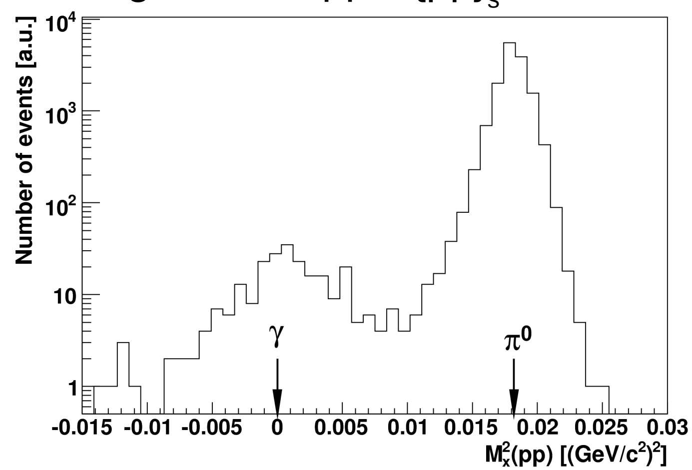
π^- case: + p_{spec} or π^-

Experiment:
Identification of pn → $\{pp\}_s\ \pi^-$ and pp → $\{pp\}_s\ \pi^0$

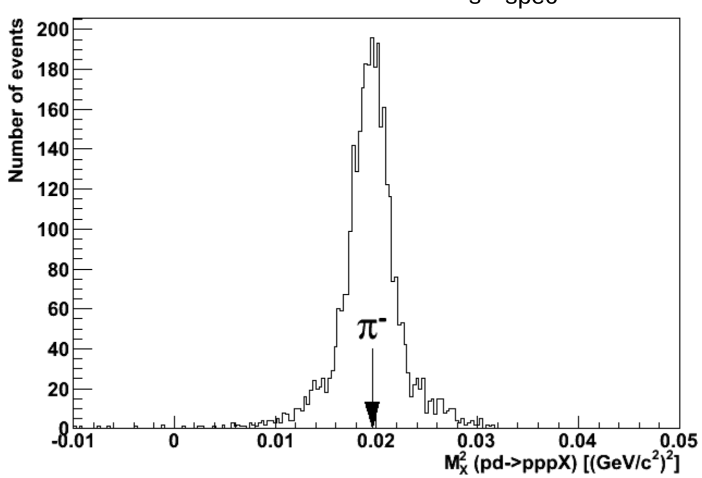
Diproton PID by TOF



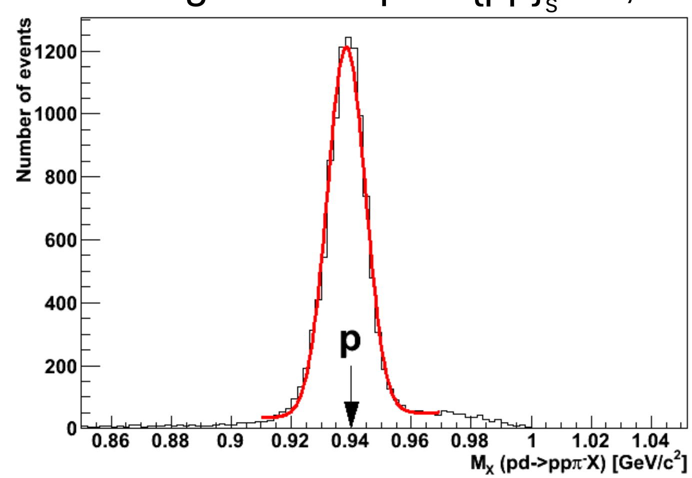
Missing mass in pp → $\{pp\}_s X$, $X=\pi^0$



Missing mass in pd → $\{pp\}_s p_{spec} X$, $X=\pi^-$



Missing mass in pd → $\{pp\}_s \pi^- X$, $X=p_{spec}$



Results on dσ/dΩ and A_y (1)

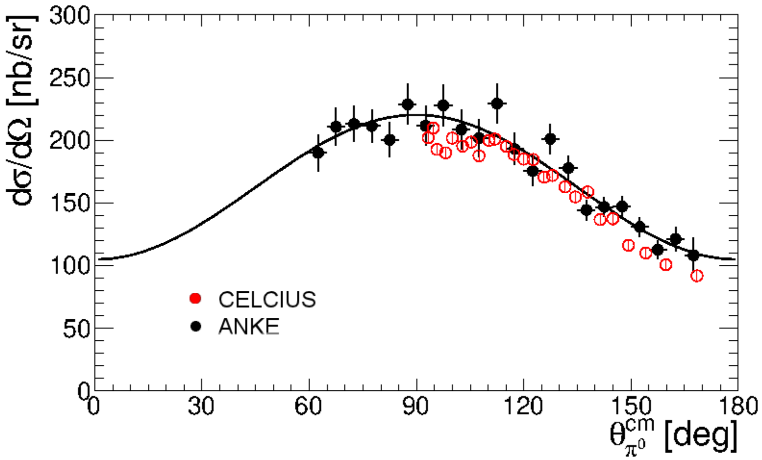
$pp \rightarrow \{pp\}_s \pi^0$

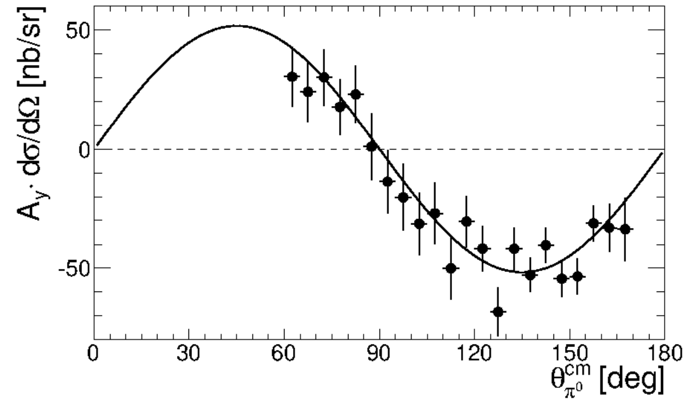
$$\left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{k}{4p}\left(a_0 + a_2\cos^2\theta_\pi + a_4\cos^4\theta_\pi + \cdots\right)$$

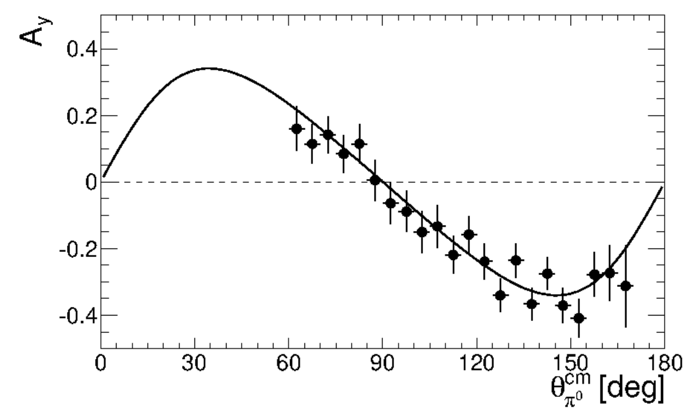
$$A_y\left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{k}{4p}\sin\theta_\pi\cos\theta_\pi\left(b_2 + b_4\cos^2\theta_\pi + \cdots\right)$$

$$a_0 = \quad 4.05 \pm 0.08\ \mu\mathrm{b/sr}, \qquad b_2 = 1.82 \pm 0.10\ \mu\mathrm{b/sr}$$

$$a_2 = -2.31 \pm 0.14\ \mu\mathrm{b/sr},$$







ANKE (black) compared to CELCIUS (red) at 360 MeV
(R. Bilger et al, NPA 663 (2001) 633)

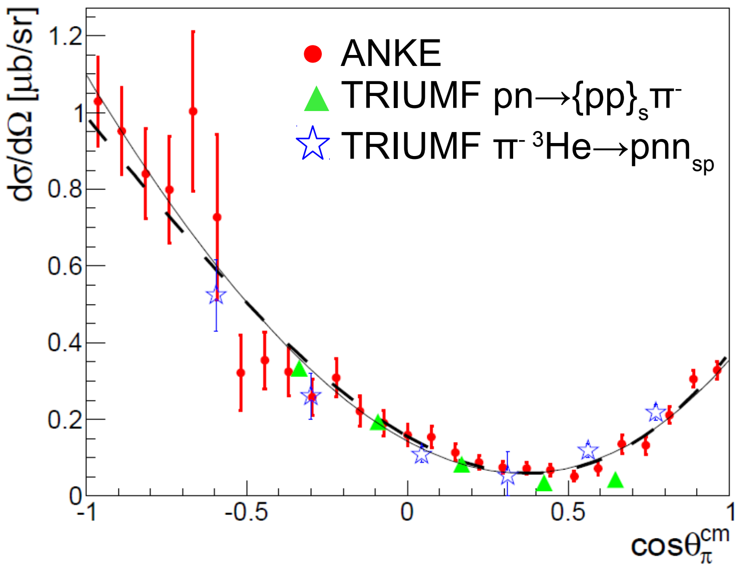
D.Tsirkov et al., Phys. Lett. B 712, 370 (2012)

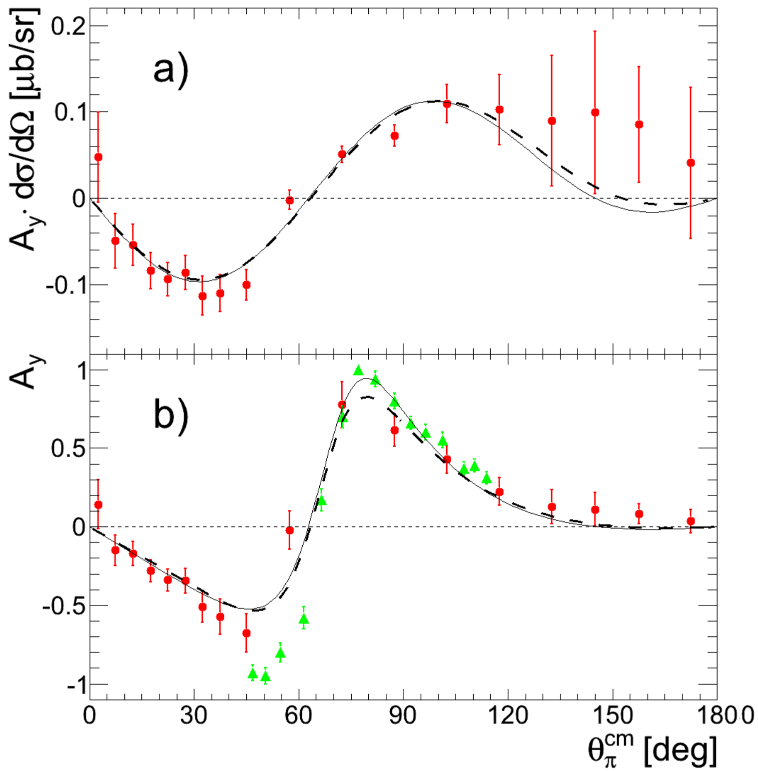
Results on dσ/dΩ and A_y (2)

pn→{pp}$_s$π$^-$

$$\left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{k}{4p}\sum_{n=0} a_n \cos^n\theta_\pi,$$

$$A_y\left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{k}{4p}\sin\theta_\pi\sum_{n=0} b_{n+1}\cos^n\theta_\pi$$





TRIUMF data

H. Hahn et al., Phys. Rev. Lett. 82 (1999) 2258,
F. Duncan et al., Phys. Rev. Lett. 80 (1998) 4390

S.Dymov et al., , Phys. Lett. B 712, 375 (2012)

Results on $d\sigma/d\Omega$ and A_y (3)

The “direct” and PWA fit results

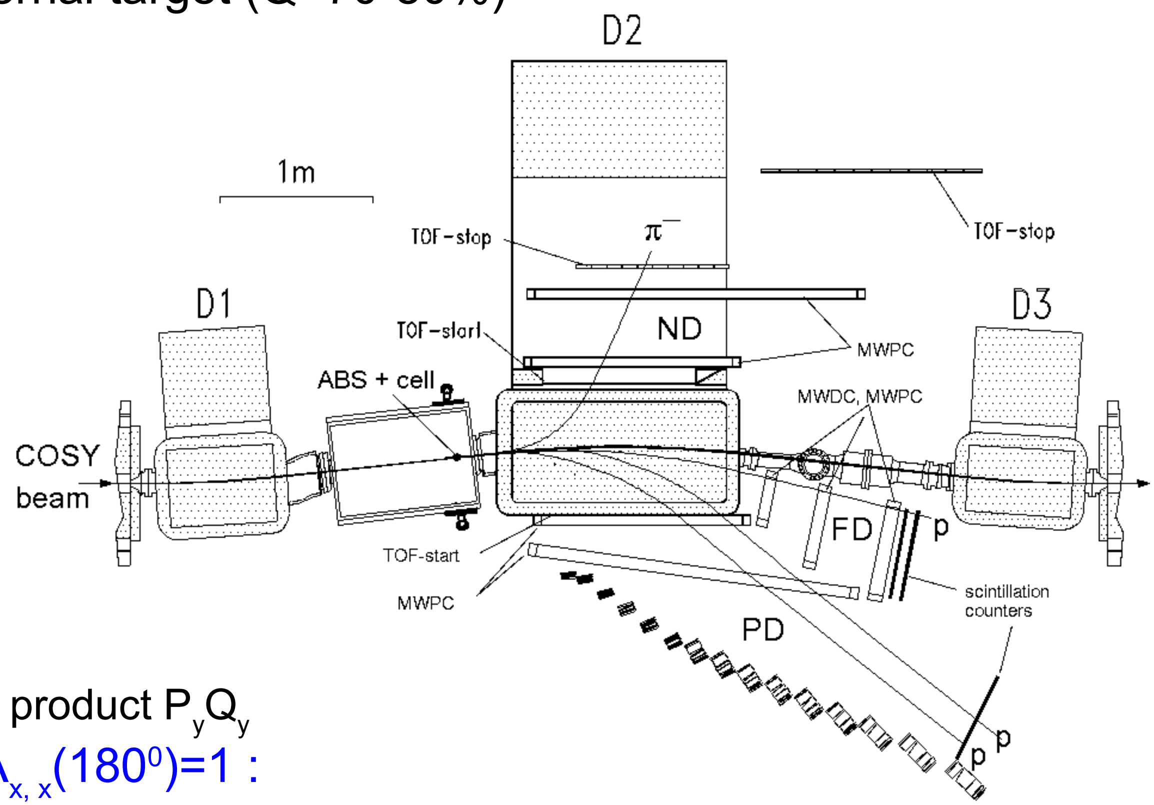
Observable	Direct fit	Global fit
$a_0(pp)$	4.05 ± 0.08	4.05 ± 0.08
$a_2(pp)$	-2.31 ± 0.14	-2.34 ± 0.14
$b_2(pp)$	1.82 ± 0.10	1.80 ± 0.10
$a_0(pn)$	2.69 ± 0.18	2.47 ± 0.08
$a_1(pn)$	-8.24 ± 0.51	-7.83 ± 0.45
$a_2(pn)$	9.11 ± 0.70	10.12 ± 0.41
$a_3(pn)$	2.89 ± 0.90	1.38 ± 0.27
$b_1(pn)$	1.77 ± 0.14	1.82 ± 0.13
$b_2(pn)$	-1.95 ± 0.50	-1.75 ± 0.36
$b_3(pn)$	-4.43 ± 0.70	-4.83 ± 0.27

- Phase of M_s^P fixed by Watson theorem
- Neglect initial $^3P_2$-$^3F_2$ coupling,
  phases of M_d^P, M_d^F fixed by Watson theorem
- Neglect squares of d-waves and their interference

$$
\begin{aligned}
M_s^P &= \quad (55.3 \pm 0.4) - (14.7 \pm 0.1)i \ \sqrt{\mathrm{nb/sr}},\\
M_d^P &= -(26.6 \pm 1.1) - (8.6 \pm 0.4)i \ \sqrt{\mathrm{nb/sr}},\\
M_d^F &= \quad 5.3 \pm 2.3 \ \sqrt{\mathrm{nb/sr}},\\
M_p^S &= -(32.4 \pm 2.2) + (17.3 \pm 2.7)i \ \sqrt{\mathrm{nb/sr}},\\
M_p^D &= -(109.6 \pm 9.6) + (140.7 \pm 4.0)i \ \sqrt{\mathrm{nb/sr}}.
\end{aligned}
$$

Measurement of $A_{x,x}$ in $\vec{d}\vec{p} \to p_{sp}\{pp\}_s\pi^-$

Vector polarized deuteron beam (P=50-60%)
+ hydrogen polarized internal target (Q=70-80%)
(lower target density)



Particle detection:

- The $\{pp\}_s$ proton pair in PD
- Spectator proton in FD
- π^- in ND at small θ_π

Beam and target polarization product P_yQ_y

from $A_{y,y}=1$, $A_{x,x}(0^0)=A_{x,x}(180^0)=1$:

$A_{x,x} \sim P_yQ_y$, $A_{y,y} \sim P_yQ_y$

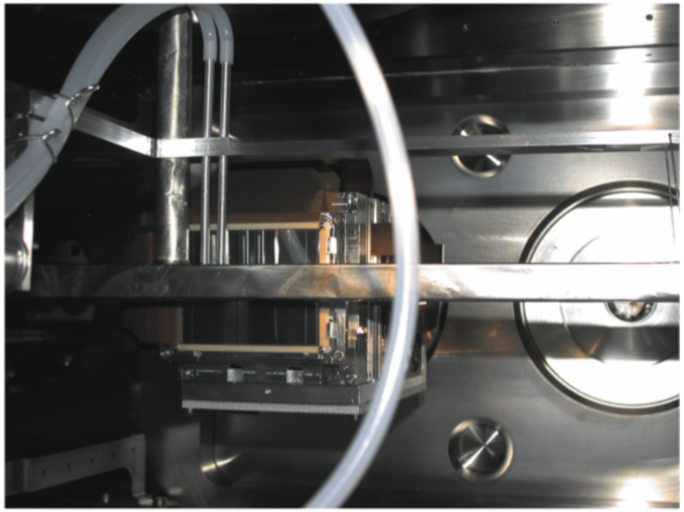
Measurements with a storage cell (1)

Polarized internal target:
atomic beam source (ABS) + storage cell + Lamb shift polarimeter

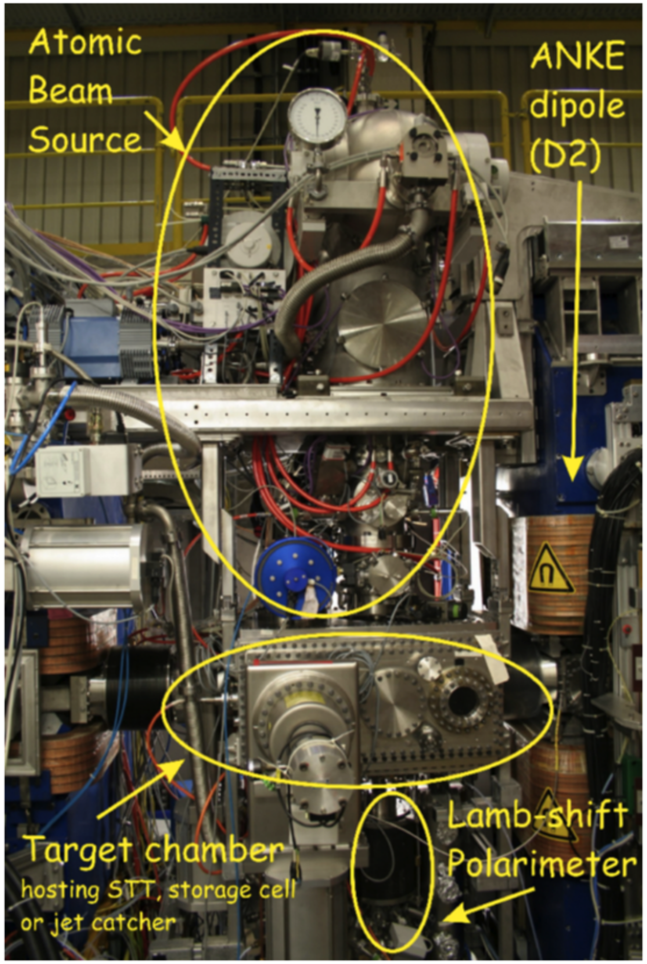
- Target thickness with the cell $d_t = 1.34 \times 10^{13}$ cm^{-2}
- Cell material: 25 μm of Al + 5 μm of teflon *is the main source of background*
- Shape of background obtained from dedicated measurement with N_2 in the cell and with empty cell

ABS feeding tube

COSY beam



ANKE D2

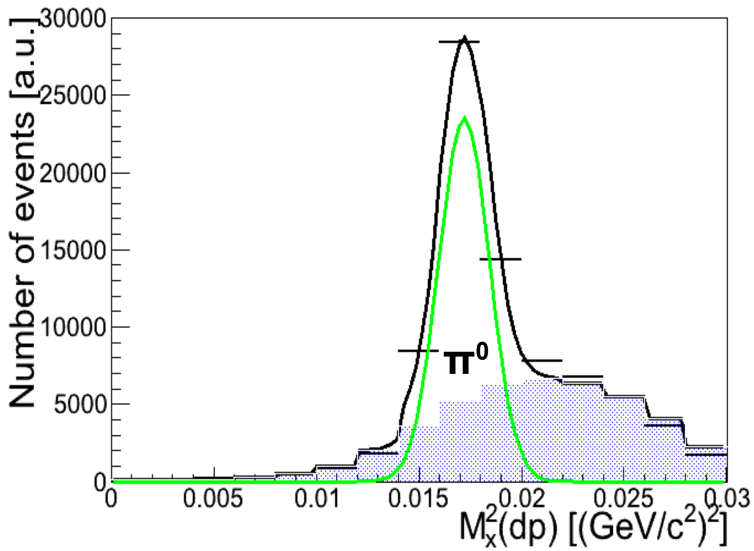


Measurements with a storage cell (2)

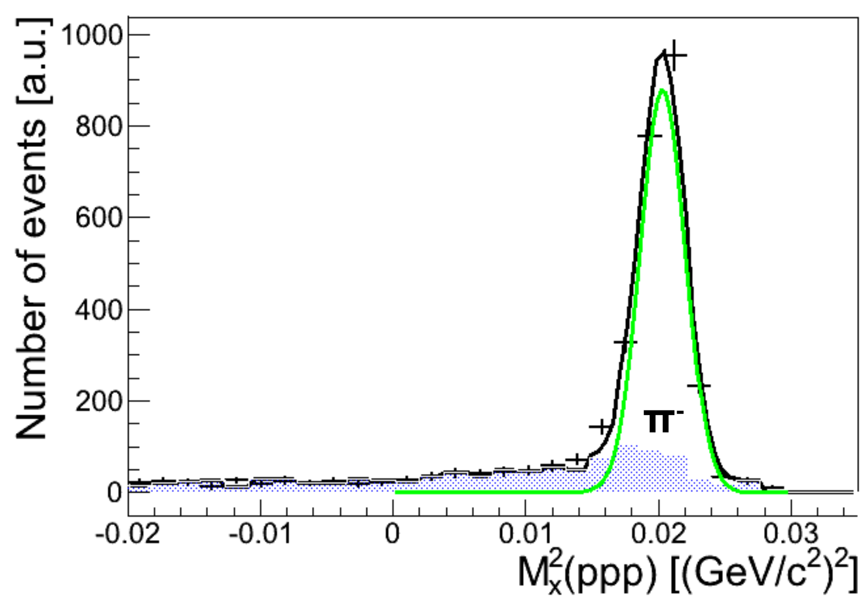
- Particles identified by TOF, dE/dX
- Process identified by missing mass
- Shape of background obtained from measurements with N_2

The polarimetry process

$np \to d\pi^0$ ($dp \to d\pi^0 + p_{sp}$)



The $pn \to \{pp\}_s\pi^-$ process



Results on $A_{x,x}$ in $pn \rightarrow \{pp\}_s \pi^-$ (1)

Observed experimental asymmetry:

$$\xi = \frac{\Sigma_1 - \Sigma_2}{\Sigma_1 + \Sigma_2}$$

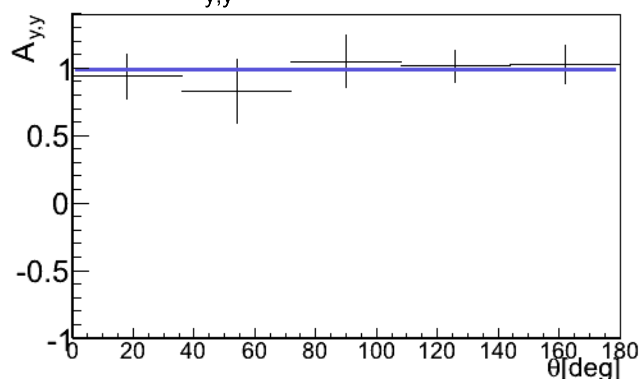
$$\xi / PQ = \left(A_{x,x} \sin^2\varphi + A_{y,y} \cos^2\varphi \right),$$

where $\Sigma_1 = N\uparrow\uparrow + N\downarrow\downarrow, \Sigma_2 = N\uparrow\downarrow + N\downarrow\uparrow$

1) $A_{y,y}$ from the 2-parameter fit

2) From the theory $A_{y,y}$ = 1, consistent with data.

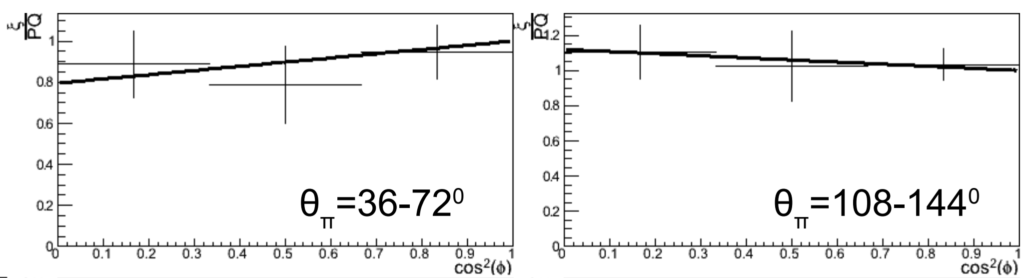
$\Rightarrow$ $A_{y,y}$ can be fixed

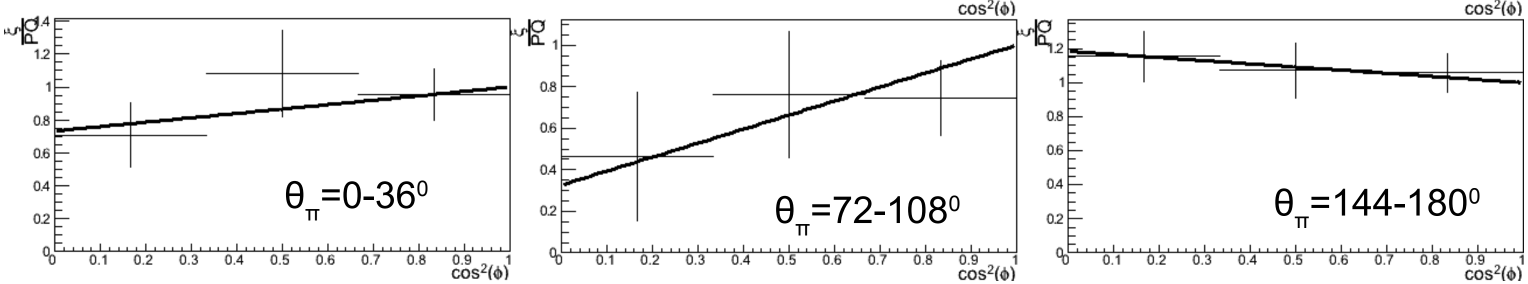


3) $A_{x,x}$ from 1-parameter fit

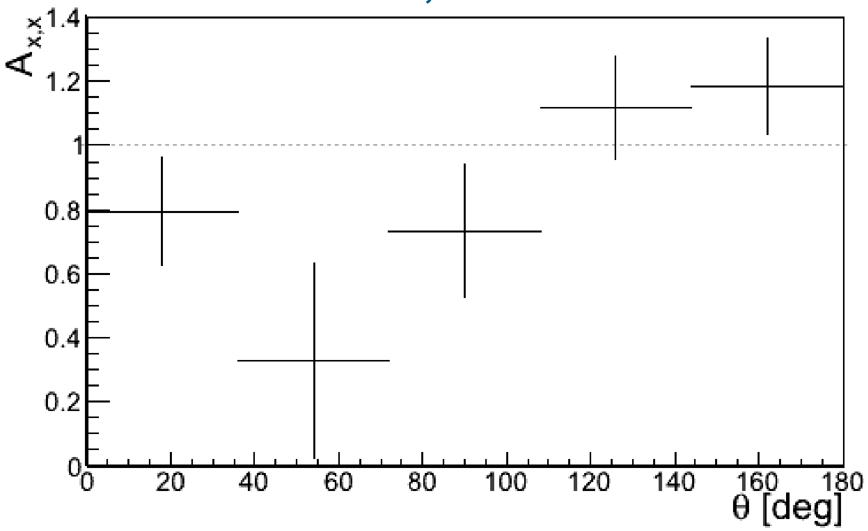
$\cos^2(\varphi)$ = 1 $\Rightarrow$ *get $A_{y,y}$*

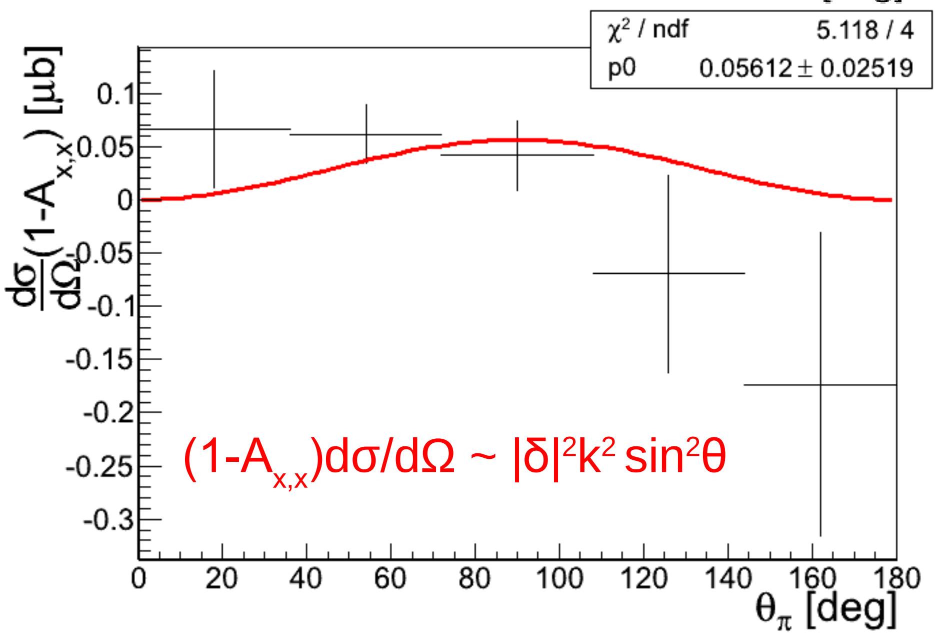
$\cos^2(\varphi)$ = 0 $\Rightarrow$ *get $A_{x,x}$*





Results on $A_{x,x}$ in $pn \to \{pp\}_s \pi^-$ (2)





PWA prediction:

$(1-A_{x,x})\ d\sigma/d\Omega(90^0) \approx 52$ nb

Preliminary result from the $A_{x,x}$ measurement:

$(1-A_{x,x})d\sigma/d\Omega(90^0) = (56 \pm 25)$ nb
(analysis is in progress)

Theoretical interpretation is ongoing

Next step: $A_{x,z}$ in $pn \to \{pp\}_s \pi^-$

<u>Assumptions used in PWA:</u>

- Phase of M_S^P fixed by Watson theorem
  (relates the phase of initial interaction to that of pp-elastic scattering)

- Neglect initial $^3P_2$-$^3F_2$ coupling,
  phases of M_d^P, M_d^F fixed by Watson theorem

- Neglect squares of d-waves and their interference

Theoretical uncertainty inherent in the assumptions is hard to estimate

$A_{x,z}$ will test the assumptions and provide new constrains on PWA.
$np \to \{pp\}_s\pi^-$ is preferable since it contains information on the p-waves

Longitudinal beam polarization requires a Siberian snake @ COSY
(snake installation at PAX IP is foreseen in 2012)

Summary

- Di-proton final state provides a new tool to study hadron interactions

- Further development of ChPT requires new data on
  the $pp \to \{pp\}_s \pi^0$ and $pn \to \{pp\}_s \pi^-$ processes near the threshold:
  ⟶ unpolarized, single and double polarized measurements at ANKE

- $d\sigma/d\Omega$ and A_y in the two processes has been measured at 353 MeV.
  PWA analysis is done with use of Watson theorem (2 PLB)

- Double polarization measurement of $A_{x,x}$ in $pn \to \{pp\}_s \pi^-$, done
  in 2011, will provide new information on the 4Nπ contact term in ChPT

Outlook

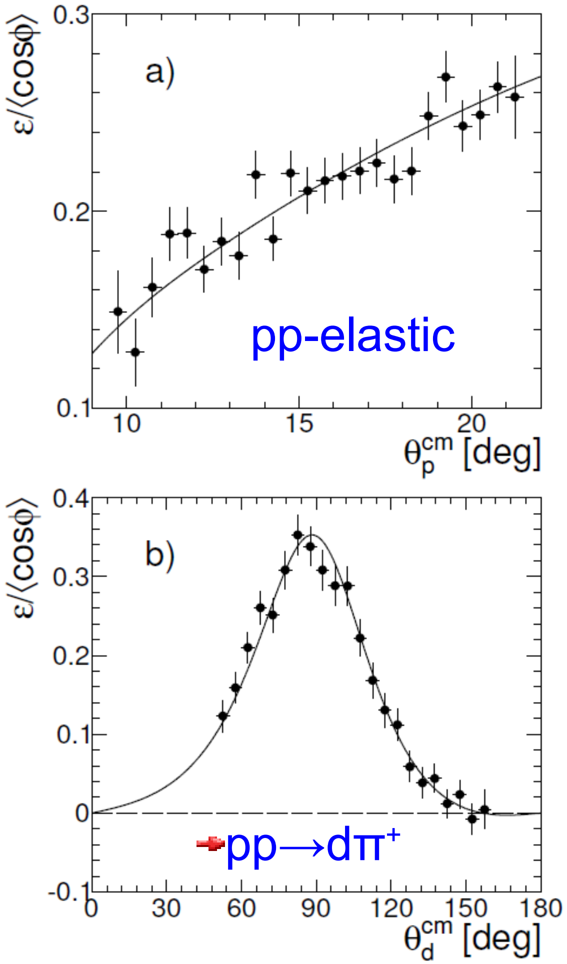
Next measurement: $A_{x,z}$ in $pn \to \{pp\}_s \pi^-$ – need Siberian snake at COSY

Additional slides

Beam polarisation and luminosity at T_n = 353 MeV

- Using (quasi-) free $pp \rightarrow d\pi^+$ and $np \rightarrow d\pi^0$

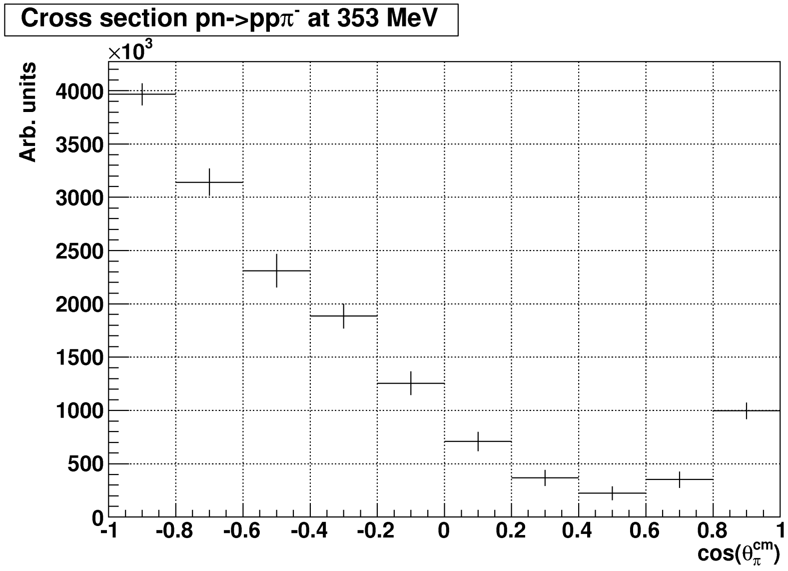
  $d\sigma/d\Omega$ and A_y^p available from the SAID database

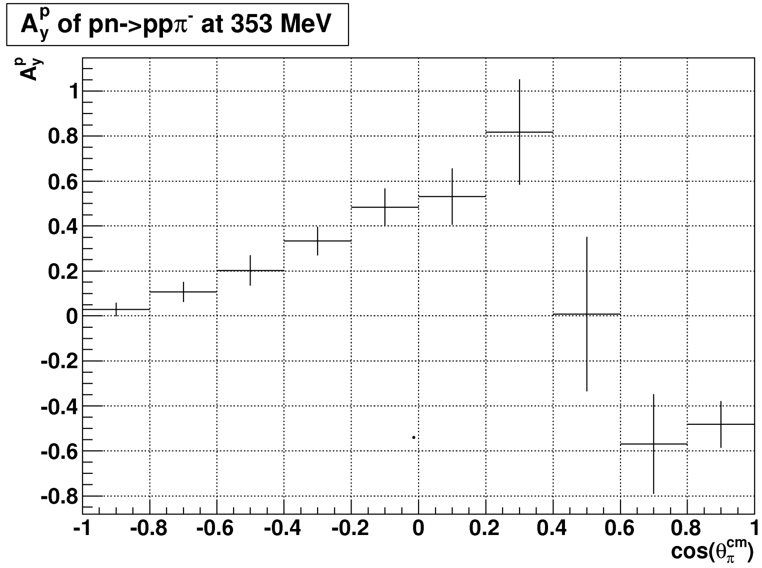


Example:

Determination of the beam polarization for
$pp \rightarrow pp\pi^0$ measurement:
Consistent results P=0.68 from elastic and $pp \rightarrow d\pi^+$

Cross section and Ay from the new data





ANKE detection system (3)

Polarized internal target:
atomic beam source (ABS) + storage cell + Lamb shift polarimeter

- Target thickness with the cell of 15x20 mm 1.34×10^{13} cm^{-2}
- Cell material: 25 μm of Al + 5 μm of teflon
  is the main source of background

The main beam losses with the cell happen at injection, when the beam is wide

The cell should open at injection and close after acceleration:

- *Small beam losses during acceleration (also important for STT!)*
- *Smaller cell size* → *Higher target density*