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Study of coherent pion production in proton-deuteron collisions with polarized beams and target at ANKE-COSY

June 3th 2016,

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for the ANKE collaboration

MESON 2016, Cracow

Study of $pd \to {}^3He\pi^0$ at ANKE (1)

Simplest coherent π production process: $pp \to d\pi^+$

➔ Extensive database and accurate PSA
➔ But: symmetric initial state, no *S* and *P* interference in cross section

First more general process: $pd \to {}^3He\pi^0$/ ${}^3H\pi^+$

- *S-P* interference observed already at T_π^{cm}~1 MeV
- One isospin amplitude ➡ $\sigma({}^3H\pi^+) = 2 * \sigma({}^3He\ \pi^0)$, equal polarization observables
- But the spin structure is $\frac{1}{2}^+ 1^+ \to \frac{1}{2}^+ 0^-$
  ➡ six independent spin amplitudes, many observables required

Study of $pd \to {}^3He\pi^0$ at ANKE (2)

Only two spin amplitudes are left at 0, 180^0:

$$F(dp \to {}^3\mathrm{He}\pi^0) = \overline{u}_\tau \, \boldsymbol{p}\cdot(\mathrm{A}\boldsymbol{\epsilon} + \mathrm{iB}\boldsymbol{\epsilon}\times\boldsymbol{\sigma})u_\mathrm{p}.$$

Here $\boldsymbol{\epsilon}$ is the deuteron polarisation vector, $\boldsymbol{p}$ and $\boldsymbol{k}$ the proton and pion c.m. momenta, and u_p and u_τ are the initial and final fermion spinors.

Amplitudes **A, B** can be extracted from

- Cross section
- Tensor analyzing power
- Transverse spin correlation

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{kp}{3}(|A|^2 + 2|B|^2),$$

$$T_{20} = \sqrt{2}\frac{|B|^2 - |A|^2}{|A|^2 + 2|B|^2},$$

$$C_{y,y} = -\frac{2Re(A^*B)}{|A|^2 + 2|B|^2}.$$

Saclay data *C. Kerboul et al., Phys. Lett. B **181** (1986) 28*
Provide cross section and T_{20} at 0 and 180^0 at T_d=0.5 – 2.2 GeV

➡ Moduli of **A** and **B**

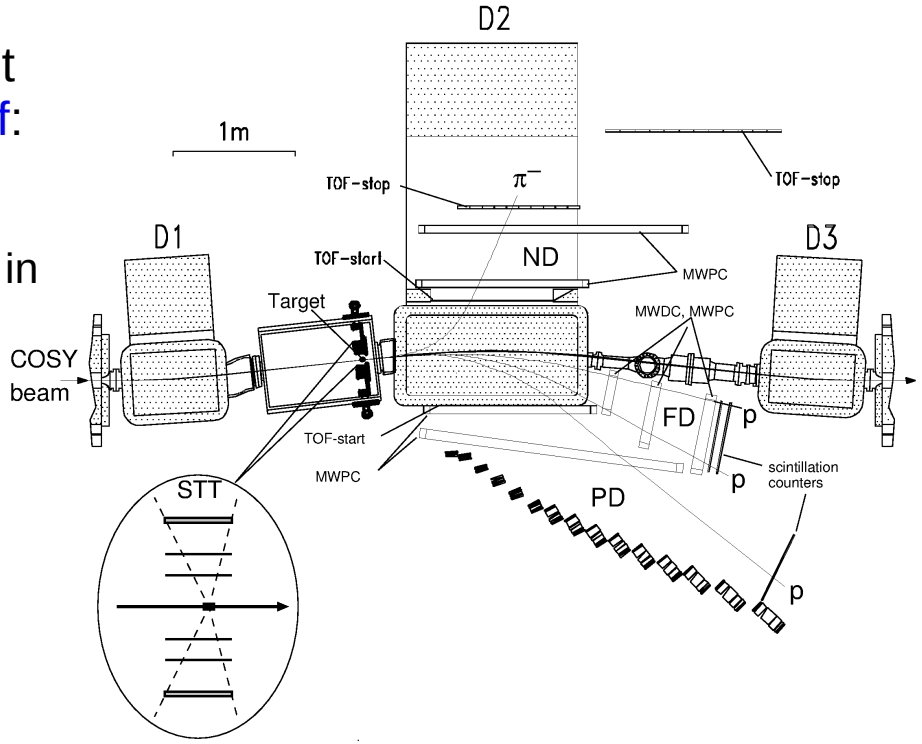
ANKE can measure spin correlations $C_{y,y}$ and $C_{x,x}$

➡ Relative phase

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 p/d in Silicon tracking telescope ***(STT)***:
  energy, tracking, Id by dE/dX

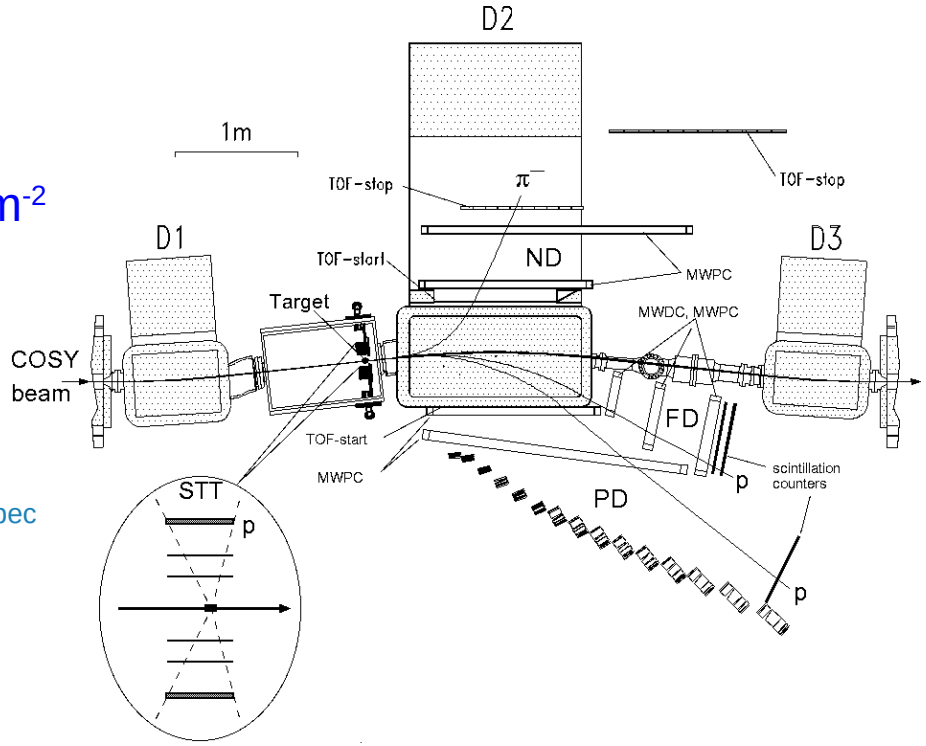
Targets available:

- Cluster jet H_2 and $\boldsymbol{D_2}$
- Internal polarized (***H***, D) target (PIT) with a storage cell

Measurement of A_y^p in $\vec{p}d \to {}^3He\,\pi^0$ @ 353 MeV

Byproduct of a study of $\vec{p}d \to \{pp\}_s\pi^- + p_{spec}$ (*PLB 712 (2012) 375*)

- Vert. polarized proton beam: P_y=65%
  spin flipped every 5 min
- D_2 cluster jet target: $d=5\cdot10^{14}$ cm^{-2}
- ^{3}He, ^{3}H detected in Fd

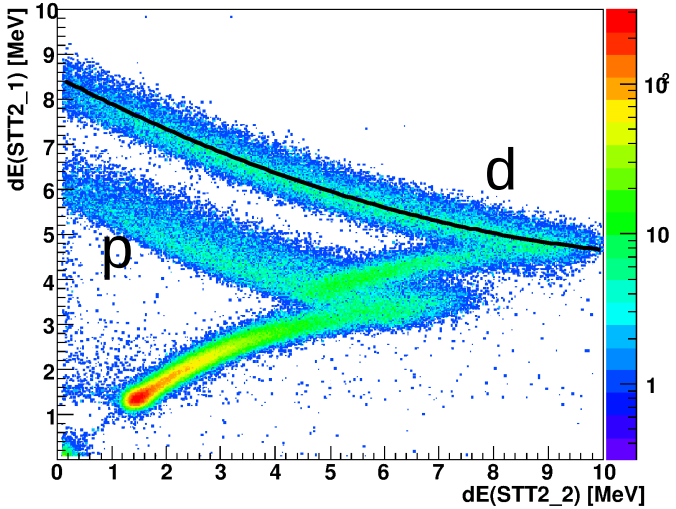


Polarimetry, normalization:
with quasi-free $pn \to d\pi^0$ via $pd \to d\pi^0 + p_{spec}$

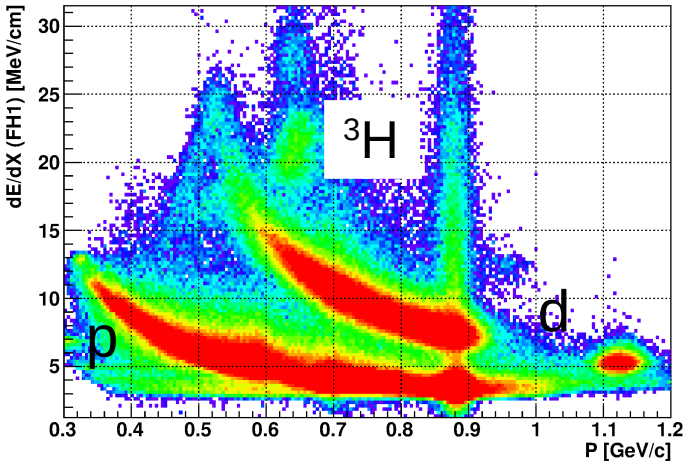
- Cross section, A_y from SAID database
- spectator proton in STT
- deuteron in Fd

Identification of $pd \to {}^3He\pi^0$/ $^3H\pi^+$ and $pn \to d\pi^0$

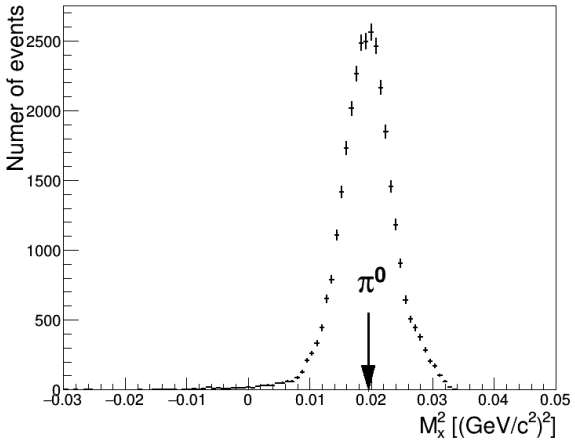
Spectator proton in STT by dE vs. E



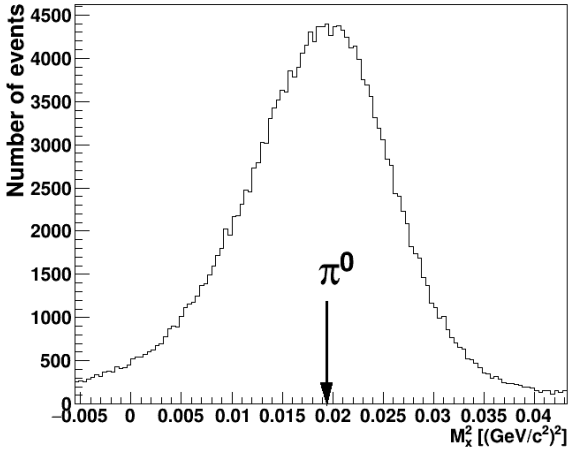
Deuterons, ^3He, ^3H in Fd by dE/dX



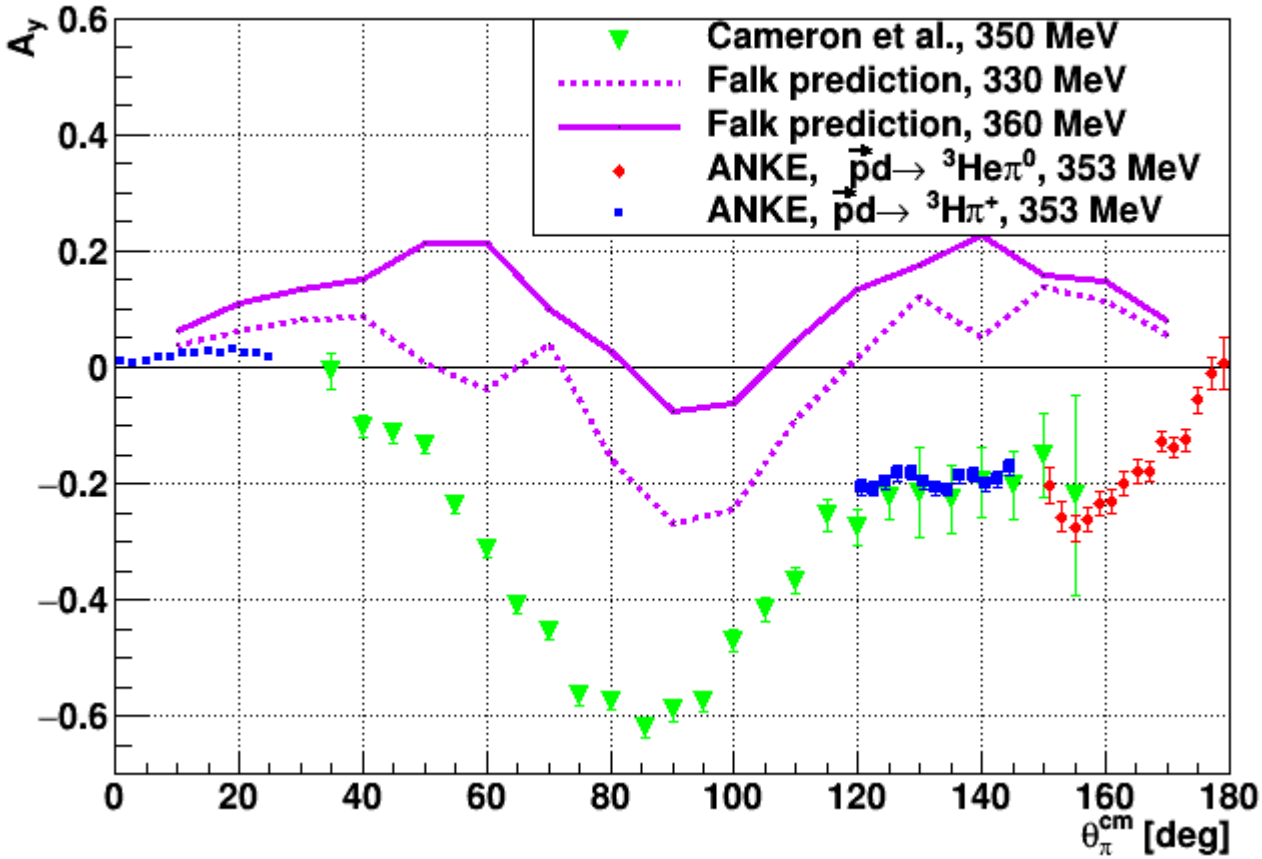
Missing mass in $pd \to dX + p_{spec}$, $X=\pi^-$



Missing mass in $pd \to {}^3He\,X$, $X=\pi^0$



Results of A_y^p measurement



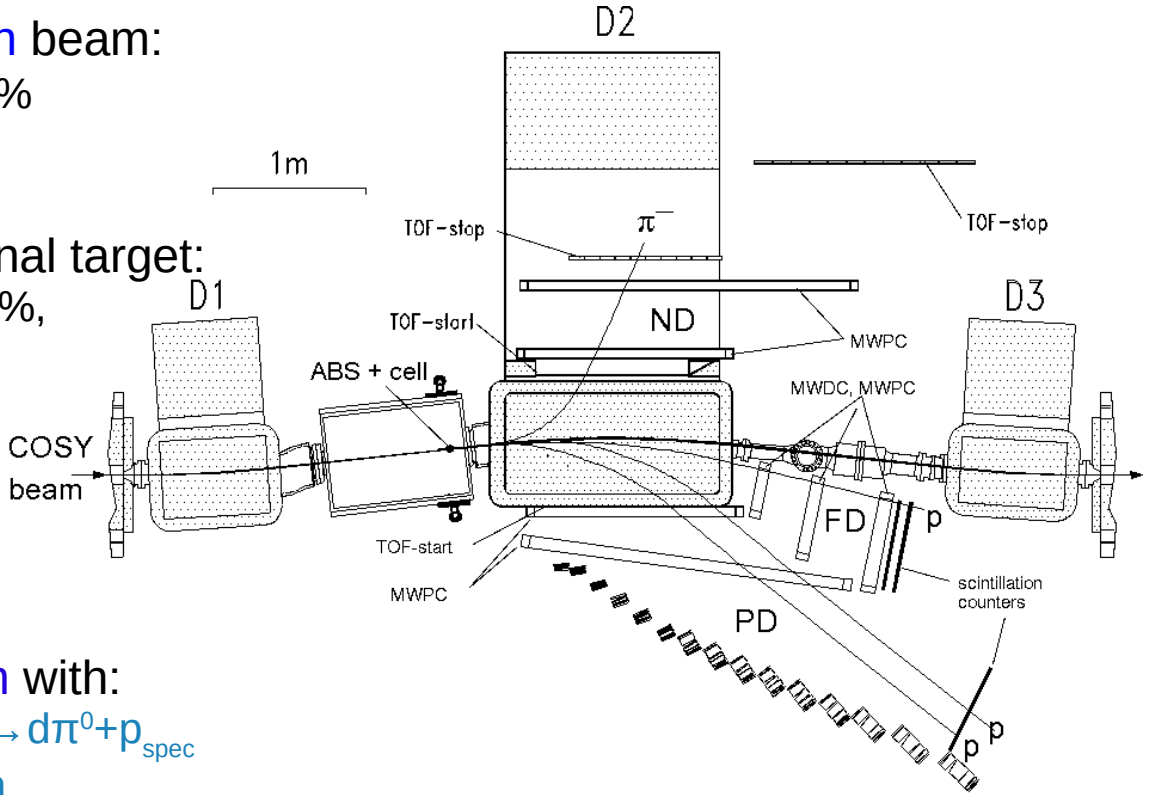
Data: J.M. Cameron et al., Nucl. Phys. A **472** (1987) 718
Cluster model: W.R. Falk Phys. Rev. C **50** (1994) 1574

Measurement of $C_{x,x}$ and $C_{y,y}$ in $\vec{d}\vec{p} \rightarrow {}^3He\pi^0$

Byproduct of study of $pd \rightarrow \{pp\}_s\pi^- + p_{spec}$ *at 363 MeV/A* (*PRC **88** (2013) 014001*)
and of $pd \rightarrow \{pp\}_s n$ *at 600 MeV/A* (*EPJ A **49** (2013) 49*)

- Vector polarized deuteron beam:
vertical polarization P_y=50-60%
spin flipped every injection

- Hydrogen polarized internal target:
vertical polarization Q_y=70-80%,
Spin flipped every 5 sec



Particle detection:

- ^3He, ^3H detected in Fd
- π^+ from $dp \rightarrow {}^3H\pi^+$ in Pd

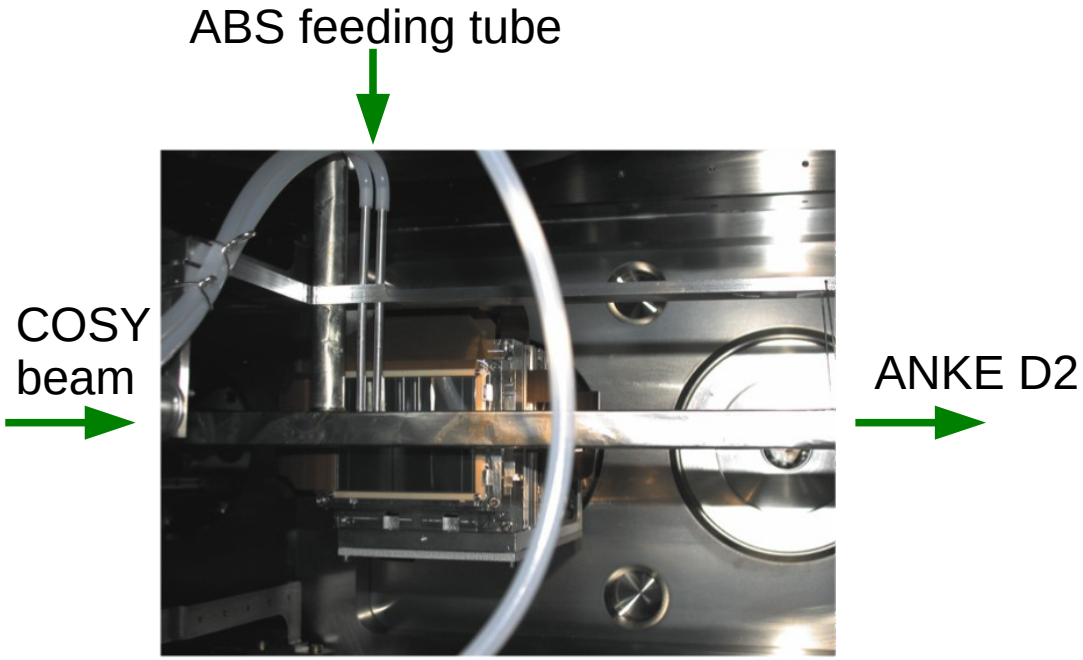
Polarimetry, normalization with:

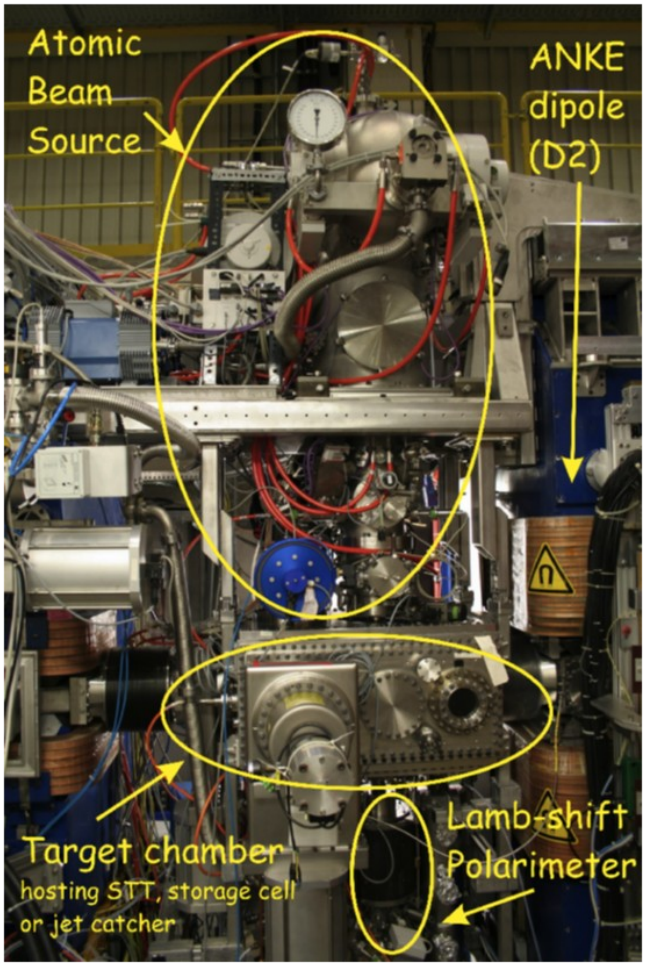
- quasi-free $pn \rightarrow d\pi^0$ via $pd \rightarrow d\pi^0 + p_{spec}$
- charge-exchage $pd \rightarrow \{pp\}_s n$
- inclusive $dp \rightarrow pX$ at small q < 60 MeV/c

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

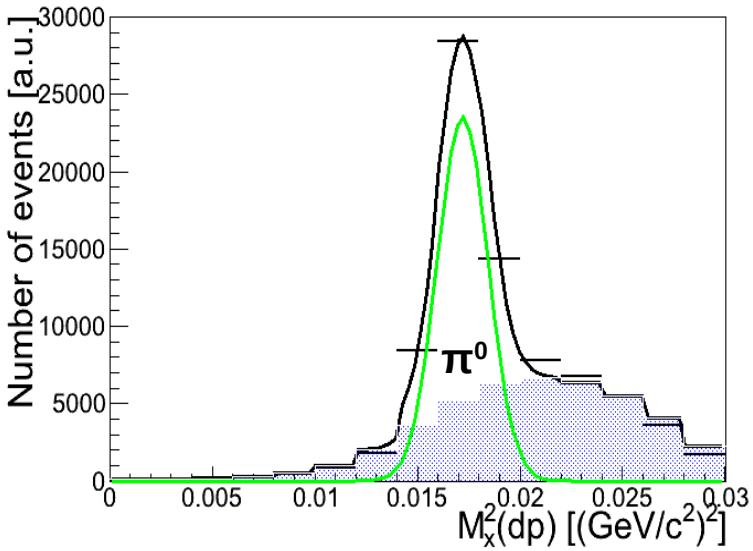




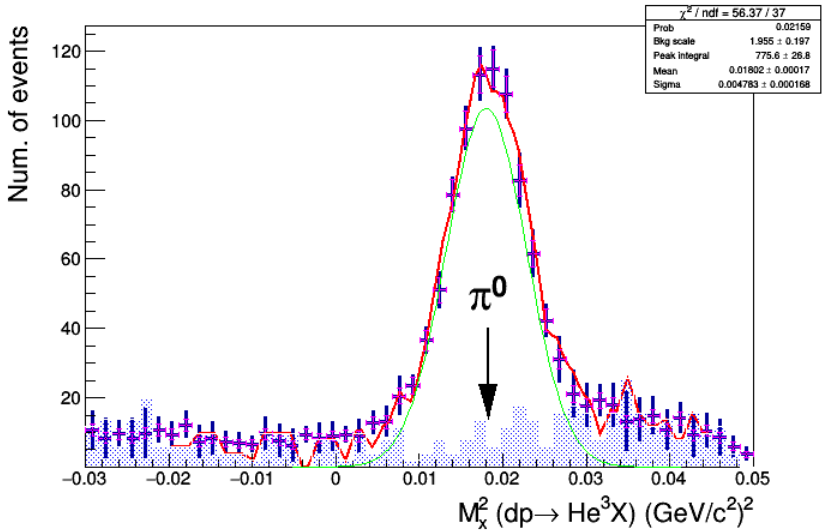
Measurements with a storage cell (2)

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

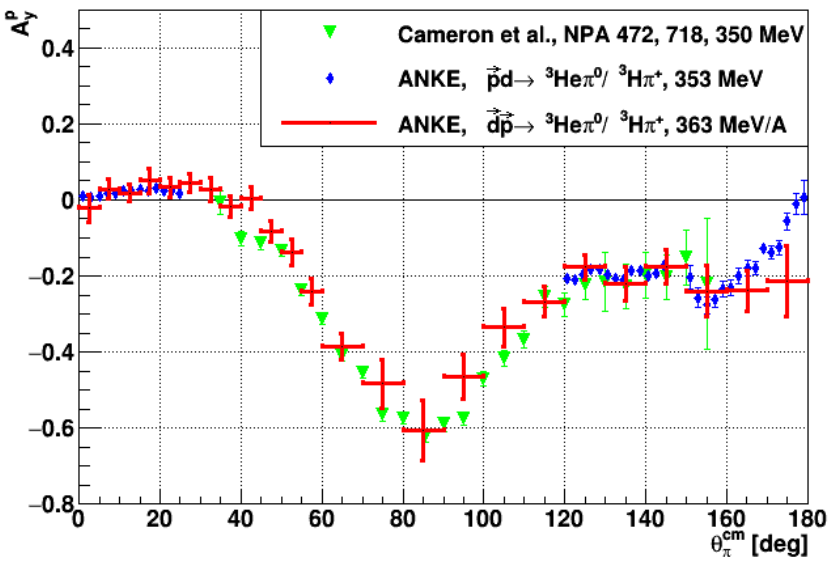
The polarimetry process
$np \rightarrow d\pi^0$ (via $dp \rightarrow d\pi^0 + p_{sp}$)

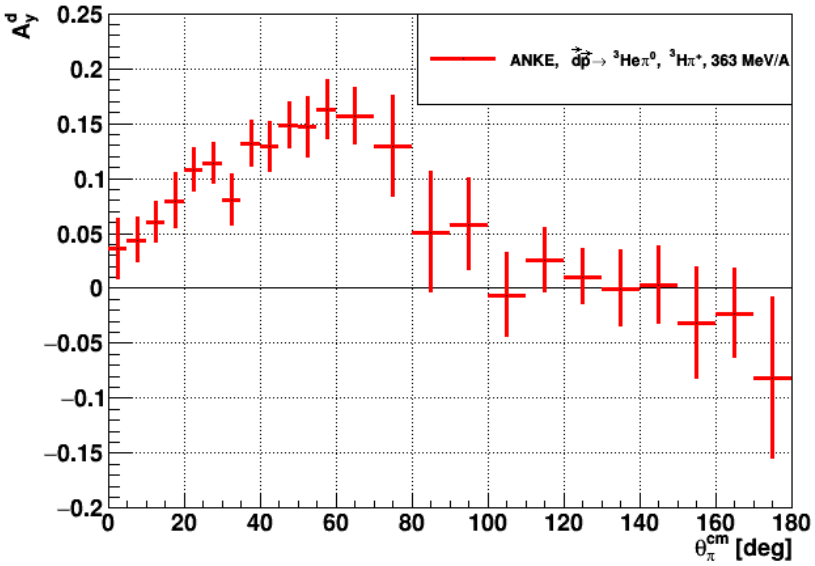


The $dp \rightarrow {}^3He\pi^0$ process



Results on A_y^p and A_y^d from $\vec{d}\vec{p}$ expt. (363 MeV/A)





- ➔ Central angular region covered
- ➔ Results consistent with both J.M. Cameron et al., Nucl. Phys. A **472** (1987) 718 and ANKE pd data
- ➔ New results on A_y^d: abrupt change at 80^0 related to minimum in A_y^p

Results on $C_{x,x}$ $C_{y,y}$ at 363 MeV/A

Observed experimental asymmetry:

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

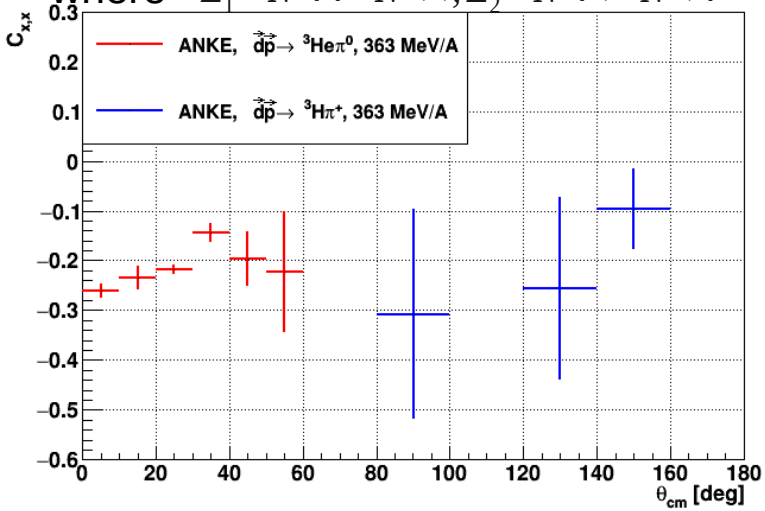
$$\xi / PQ = \left(C_{x,x} \sin^2\phi + C_{y,y} \cos^2\phi \right),$$

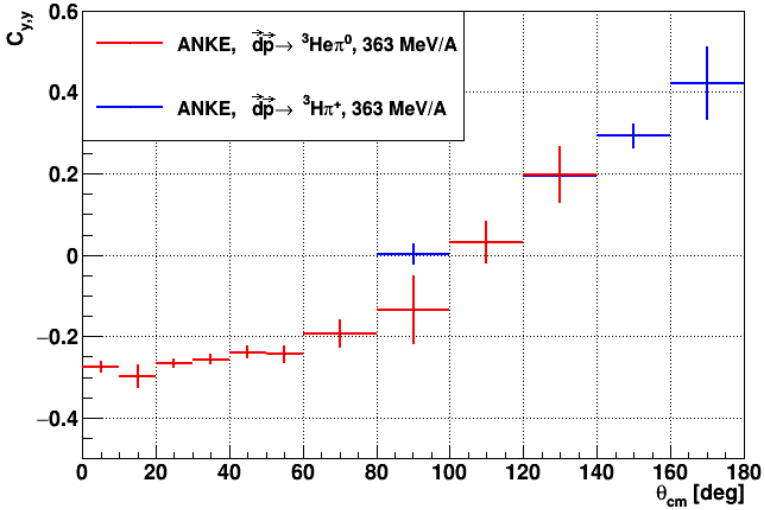
where $\Sigma_1 = N_{\uparrow\uparrow} + N_{\downarrow\downarrow}, \Sigma_2 = N_{\uparrow\downarrow} + N_{\downarrow\uparrow}$

Fit of *cos² dependence:*

cos²(φ) = 1 ➡ *get* $C_{y,y}$

cos²(φ) = 0 ➡ *get* $C_{x,x}$





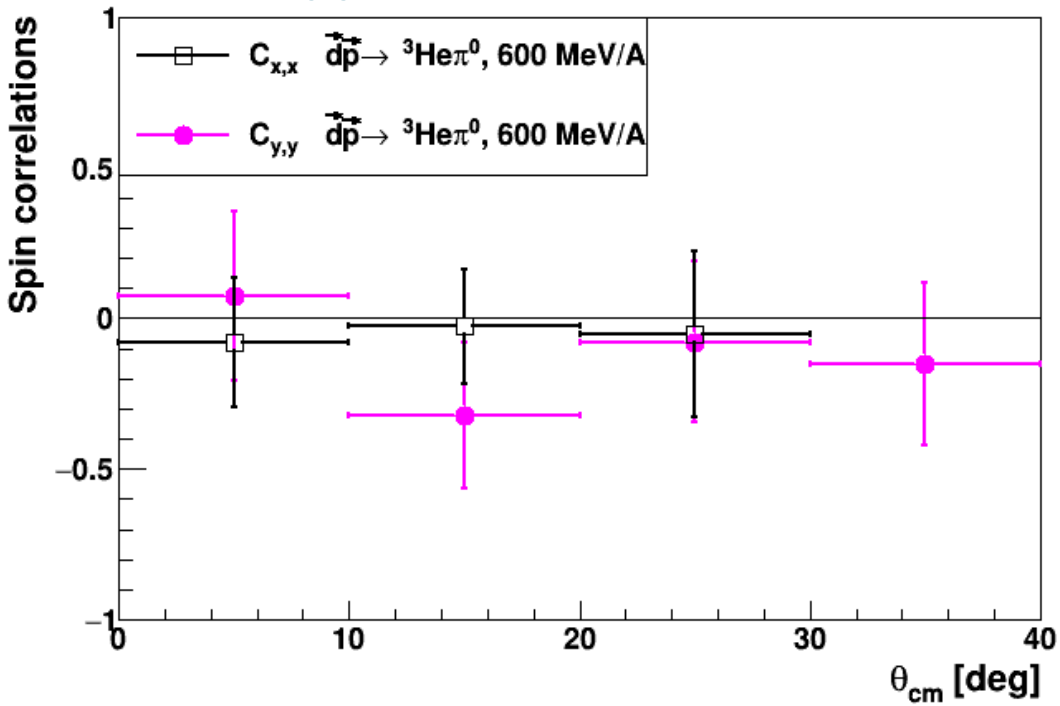
- ANKE acceptance is best at 0^0, 180^0 ➡ smaller errors of $C_{y,y}$
- $C_{y,y}$ changes sign at ~90^0
- $C_{y,y}(0) = -0.28 \pm 0.02$ + $T_{20}(0) = -1.01 \pm 0.01$ (Saclay)

  ➡ cos(φ=arg(B/A)) = 0.50 ± 0.04, **φ= 59.7⁰ ± 2.4⁰**

  $C_{y,y}(180) = 0.454 \pm 0.005$ + $T_{20}(180) = -1.10 \pm 0.06$ (Saclay)

  ➡ cos(φ=arg(B/A)) = -0.904 ± 0.072, **φ= 154.6⁰ ± 9.6⁰**

Results on $C_{x,x}$ $C_{y,y}$ at 600 MeV/A



- High background in $dp \to {}^3H\pi^+$ channel
  - ➡ only $dp \to {}^3He\pi^0$ is used
    - ➡ limited forward angles
- Lower statistics and beam polarization ➡ large error bars
- $C_{y,y}(0) = -0.07 \pm 0.28$ + $T_{20}(0) = -0.66 \pm 0.02$ (Saclay)
  - ➡ cos(φ=arg(B/A)) = 0.099 ± 0.41, **φ= 84⁰ ± 24⁰**

Summary

- Proton analyzing power A_y^p obtained for $pd \rightarrow {}^3He\pi^0$ at 353 MeV, extending the angular range of existing data

- Spin correlation coefficients $C_{x,x}$ and $C_{y,y}$ for $pd \rightarrow {}^3He\pi^0$ measured at 363 MeV/A in full range of angle
- Relative phase of spin amplitudes in the forward **$\varphi = 59.7^0 \pm 2.4^0$** and backward **$\varphi = 154.6^0 \pm 9.6^0$** directions calculated from ANKE $C_{y,y}$ and Saclay T_{20} values

- $C_{x,x}$ and $C_{y,y}$ were measured at 600 MeV/A in the range $\Theta_\pi^{CM} = 0\text{-}40^0$, relative phase of spin amplitudes at 0^0 is **$\varphi = 84^0 \pm 24^0$**

Additional slides

Beam polarisation and luminosity at T_n = 353 MeV

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

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

Example:

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