JÜLICH FORSCHUNGSZENTRUM

Polarised nucleon-nucleon scattering experiments at ANKE/COSY

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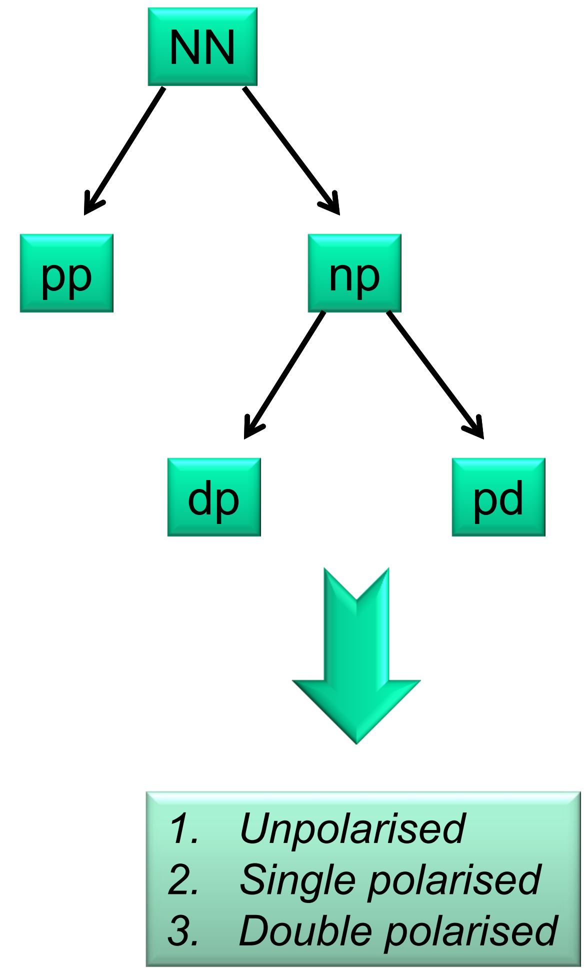
Outline:

- Experimental facility (COSY, ANKE)
- pp program
- np program
- Extension of the np program at ANKE
- Summary



Experimental facility: COSY storage ring

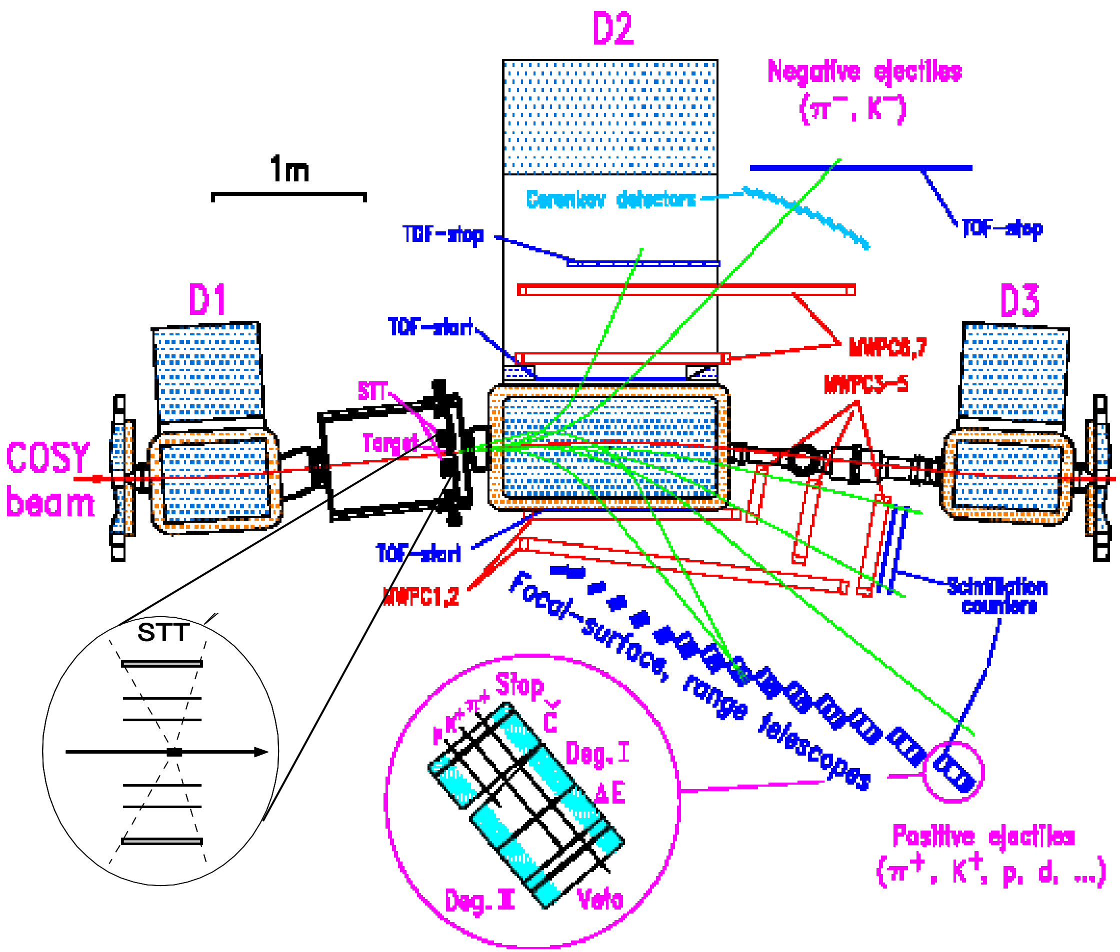
COSY (COoler SYnchrotron) at Jülich (Germany)

- Energy range:

  0.045 – 2.8 GeV (p)

  0.023 – 2.3 GeV (d)
- Max. momentum ~ 3.7 GeV/c
- Energy variation (ramping mode)
- Electron and Stochastic cooling
- Internal and external beams
- High polarisation (p,d)
- Spin manipulation

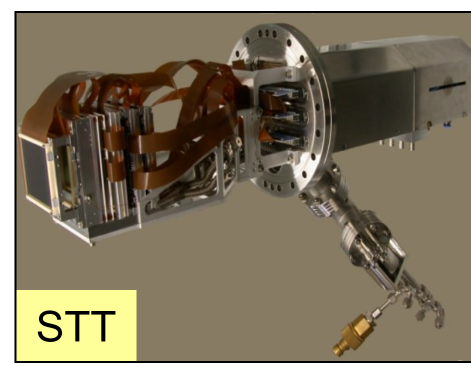
Apparatus: ANKE spectrometer



S. Barsov et al., NIM A 462, 364 (1997)

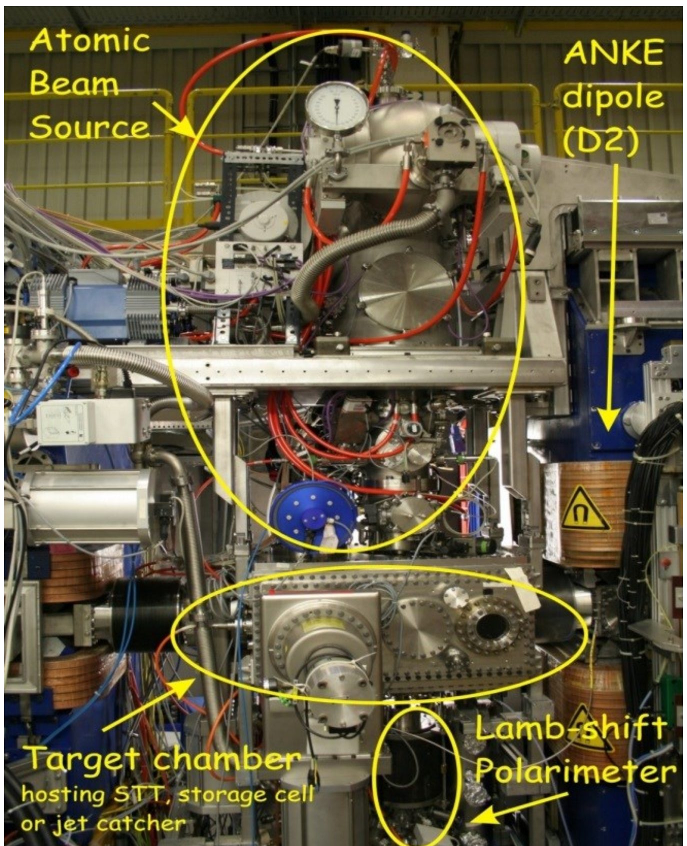
Main features:

- Excellent Kaon identification (Positive and Negative)
- Low energy proton (spectator) detection (STT)
- Di-proton ($\{pp\}_s$) selection (by FD)
- Polarized (unpolarized) dense targets

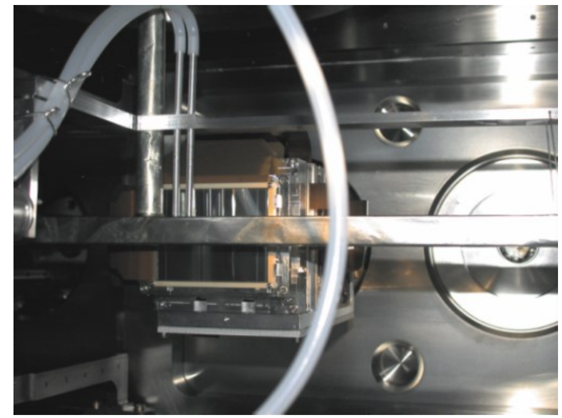


Polarised internal gas target at ANKE

1. Atomic Beam Source (ABS)
2. Lamb-shift Polarimetry
3. Cell: 20 x 15 x 370 mm^3



COSY beam



Benefit from cell:

I. Increased target density by factor of ≈100 (up to 10^{13} cm^{-2})

Drawback:

I. Dedicated beam development
II. Background handling
III. Vertex reconstruction in analyses

pp Scattering data

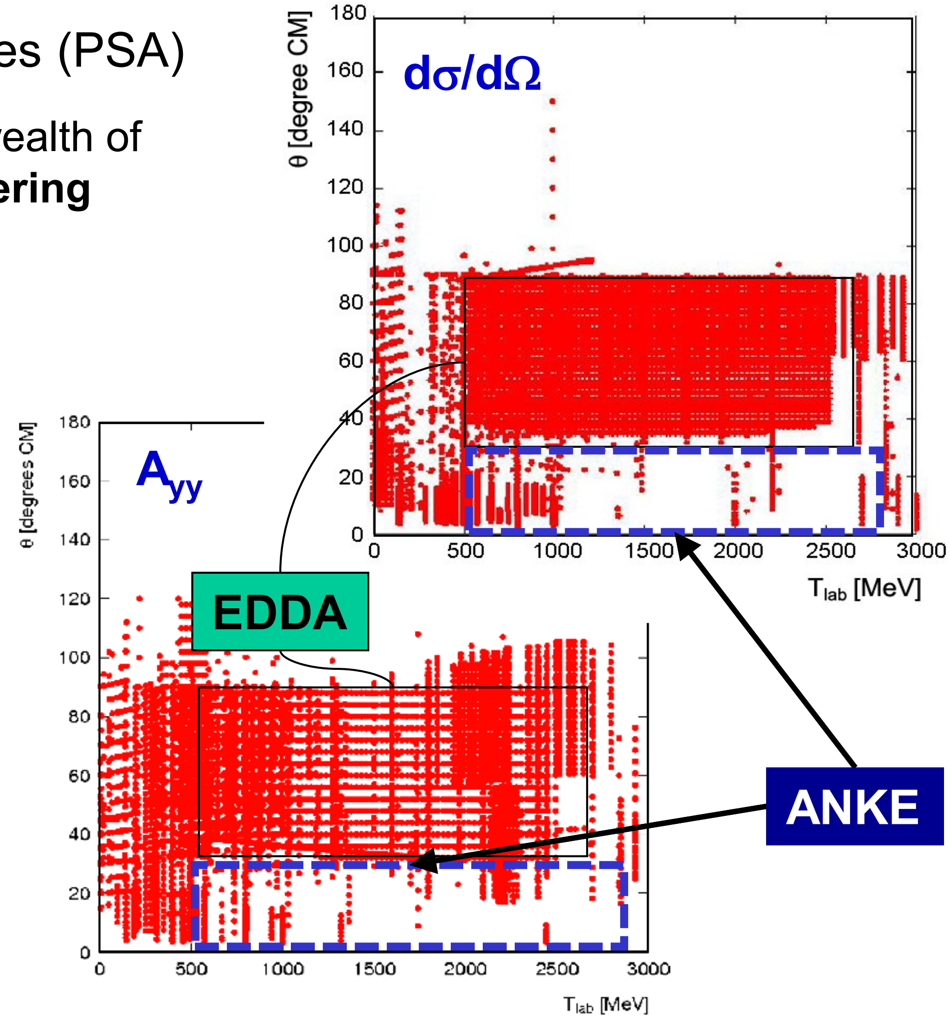
Available data for **P**hase **S**hift **A**nalyses (PSA)

- COSY-EDDA collaboration produced wealth of data ($35° < \theta_p < 90°$) for **pp elastic scattering**

- Large impact on PSA > 0.5 GeV: Significantly reduced ambiguities in I=1 phase shifts

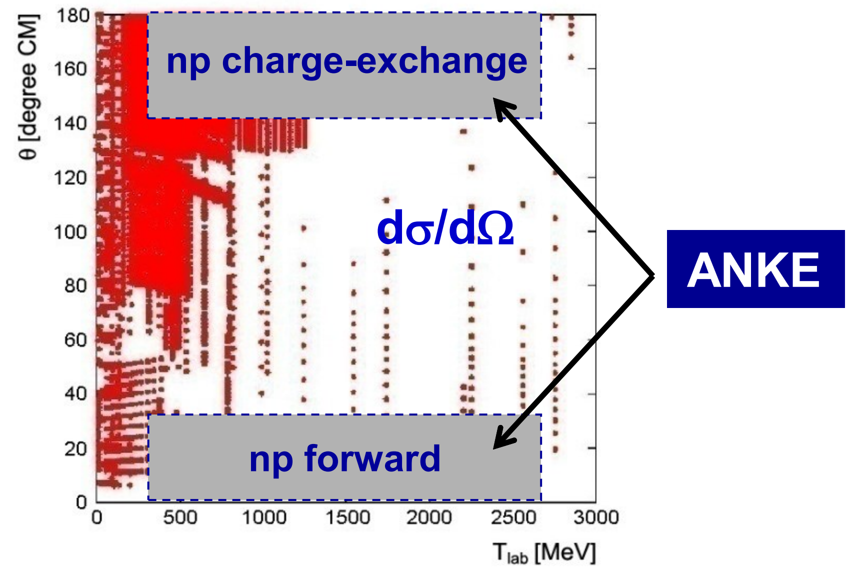
- No exp. data at smaller angles ($\theta_p < 35°$) above T_p=1.0 GeV

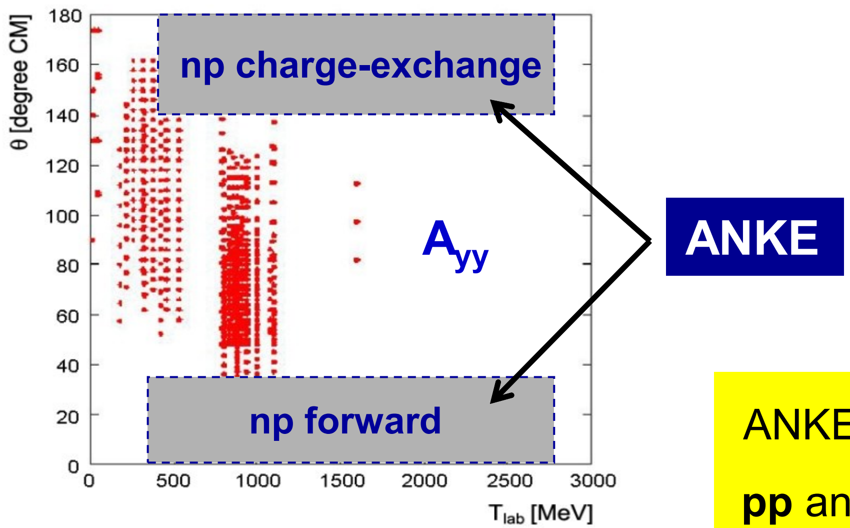
F. Bauer et al., PRL 90, 142301 (2003)
M. Altmeier et al., PRL 85, 1819 (2000)



np Scattering data

- Current experimental status of np data

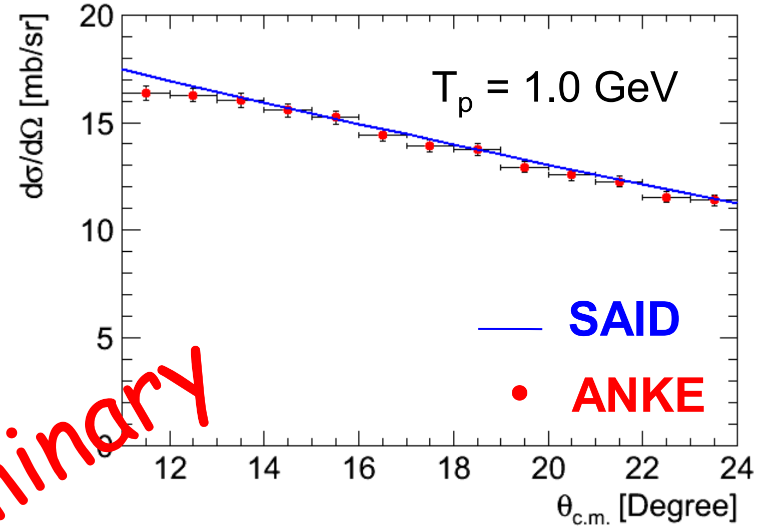




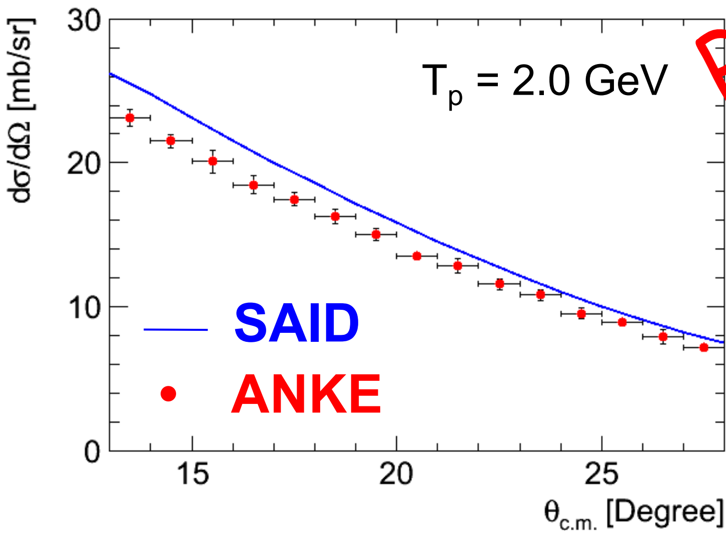
ANKE is able to provide the experimental data for **pp** and **np** systems at up to 2.8 GeV and improve our understanding of NN interaction

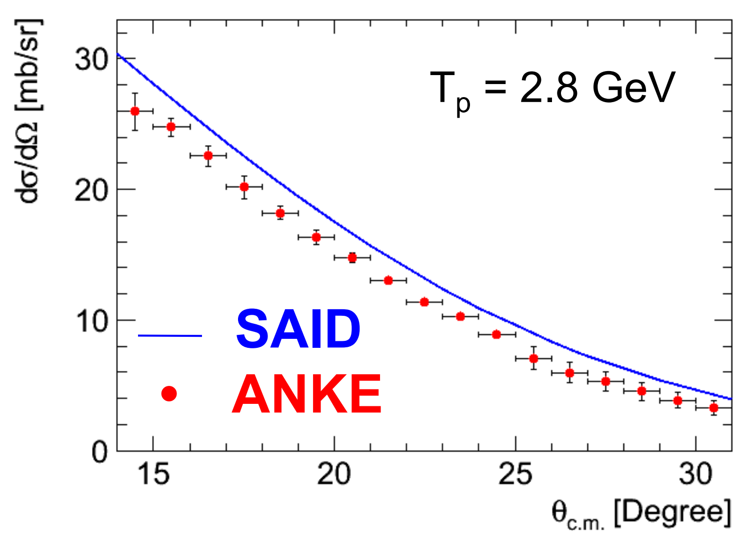
pp elastic scattering at ANKE: dσ/dΩ

- dσ/dΩ at 8 beam energies: T_p = **1.0**, 1.6, 1.8, **2.0**, 2.2, 2.4, 2.6, **2.8**
- Precision measurements:
  - Luminosity by Schottky technique ~ 2% *(Details: Stein et al., PR ST-AB 11, (2008))*
  - Absolute cross section ~ 5%



Preliminary





pp elastic scattering at ANKE: A_y

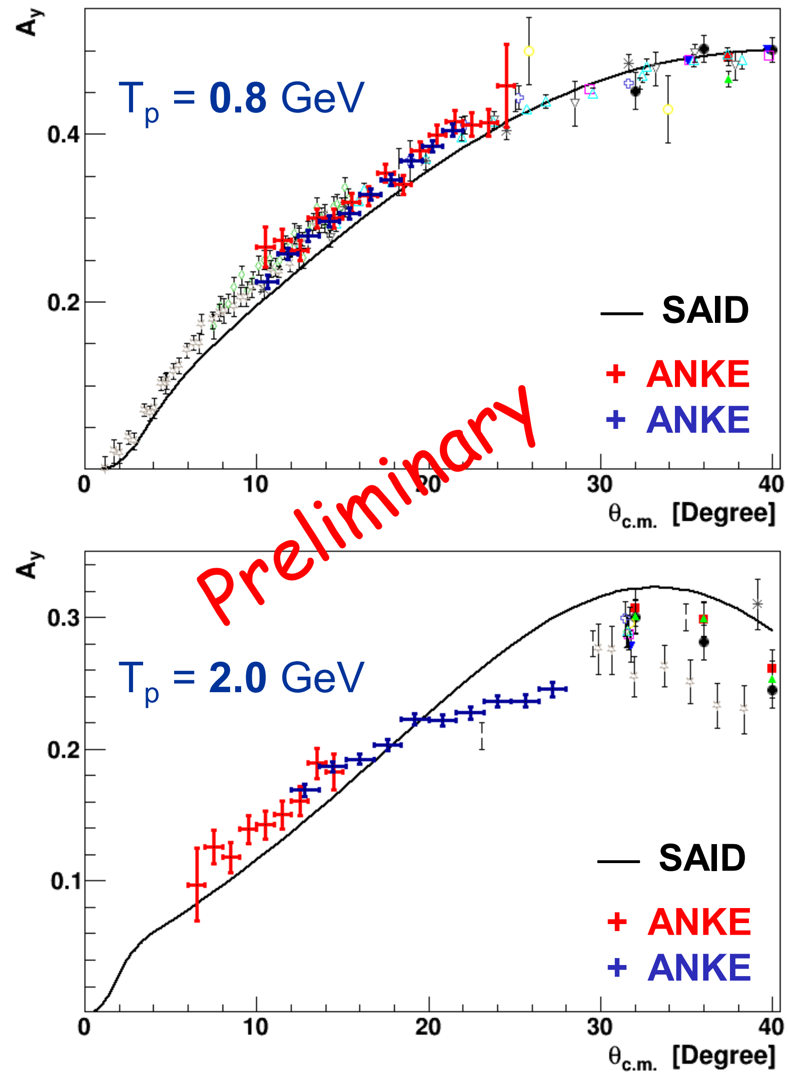
ANKE exp., April 2013, on-line (fast) analysis

- A_y for pp elastic (ANKE) at 6 beam energies: T_p = **0.8**, 1.6, 1.8, **2.0**, 2.2, 2.4
- FD and STT detection system is used

  Analysis in progress ...
- Beam polarization from EDDA

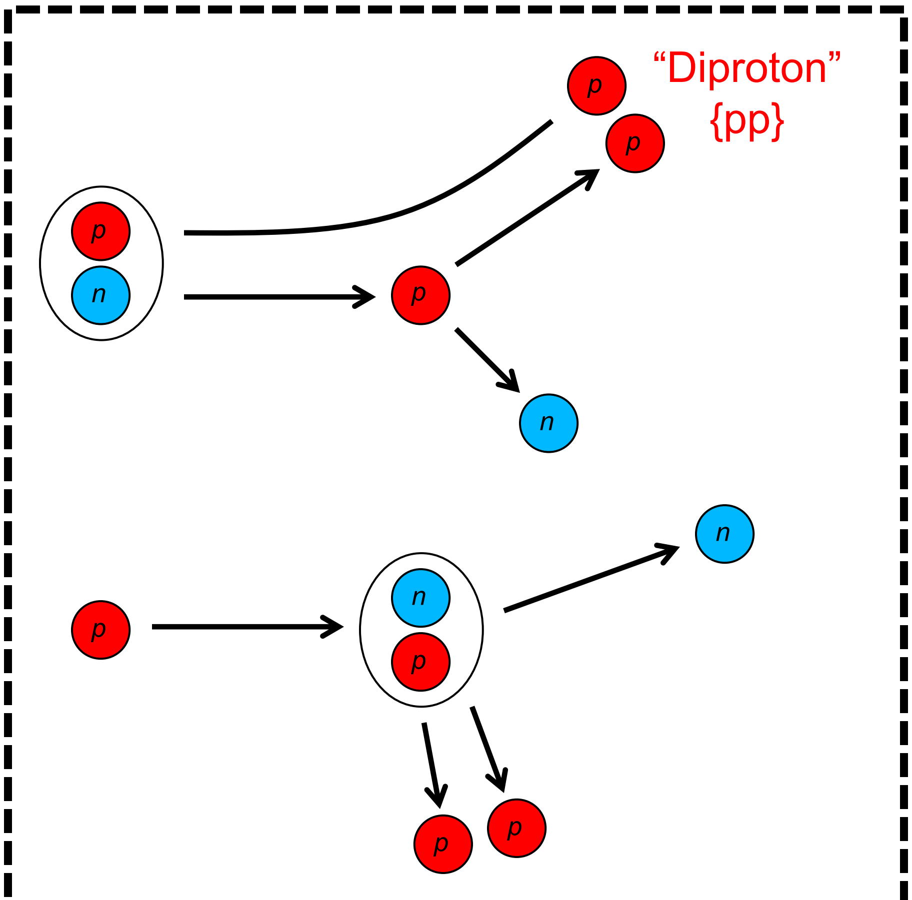
  $\langle P_y \rangle \approx$ 50 to 65% (Preliminary)

ANKE data shows different shape compared with **SAID** predictions at higher energies !

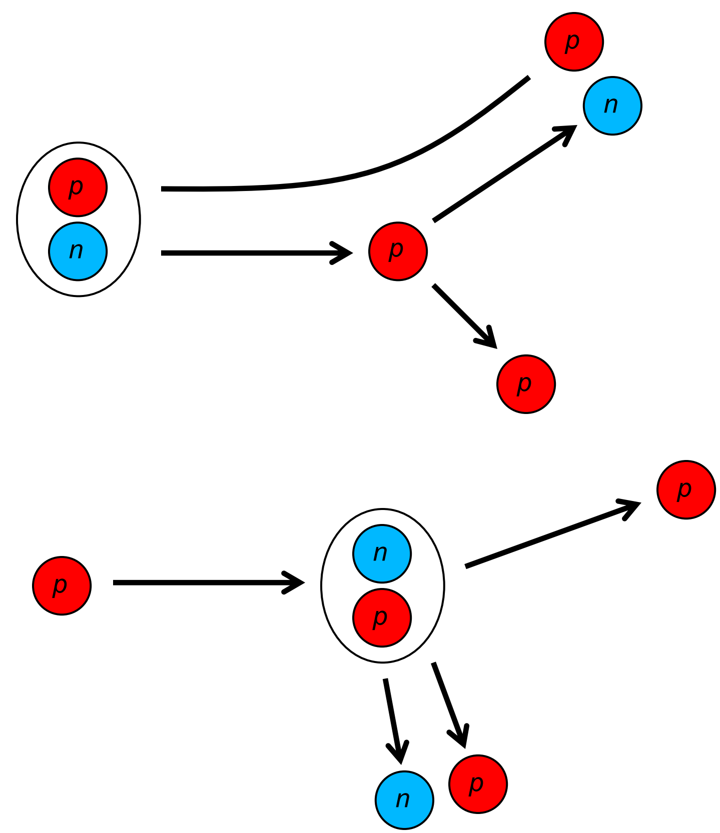


np Scattering at ANKE

Large cm scattering angles
(np charge-exchange)



Small cm scattering angles
(np forward)

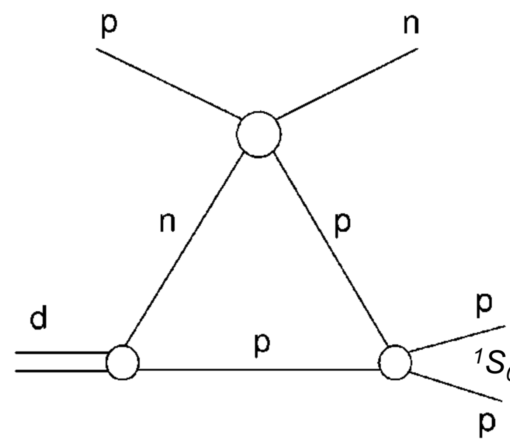


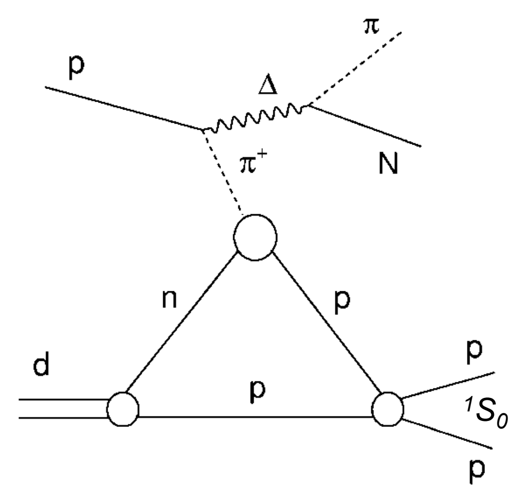
Deuteron break-up charge-exchange reaction

$$dp \to \{pp\}_{^1S_0} X$$

- $X = n$ ⇒ $np \to pn$

- $X = \Delta^0$ ⇒ $np \to p\Delta^0$



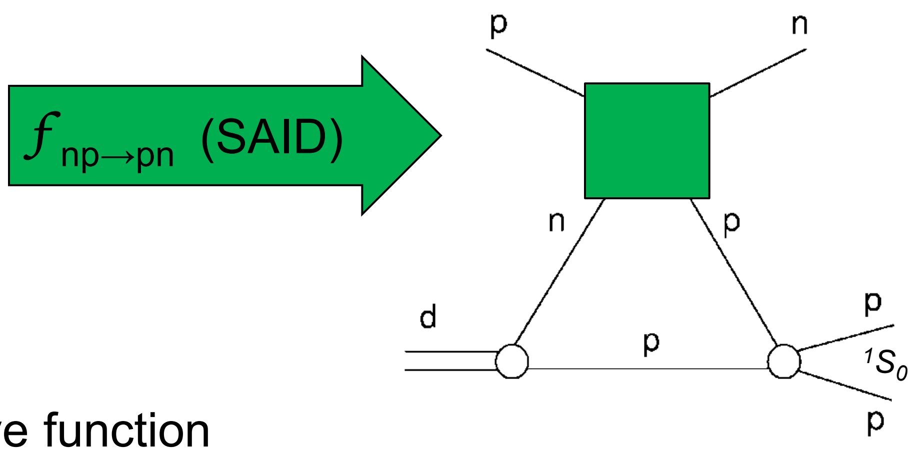


Impulse approximation

$dp \rightarrow \{pp\}_{^1S_0} n$

Transition F.F. ~

$$\langle \psi_d | \vec{\sigma} \cdot e^{i\vec{q}\vec{r}} | \psi_{pp} \rangle$$



F.F. is evaluated with PARIS wave function

np charge-exchange amplitudes in cm:

$$f_{np} = \alpha + i\gamma(\boldsymbol{\sigma}_\mathrm{n} + \boldsymbol{\sigma}_\mathrm{p}) \cdot \mathbf{n} + \beta(\boldsymbol{\sigma}_\mathrm{n} \cdot \mathbf{n})(\boldsymbol{\sigma}_\mathrm{p} \cdot \mathbf{n}) + \delta(\boldsymbol{\sigma}_\mathrm{n} \cdot \mathbf{m})(\boldsymbol{\sigma}_\mathrm{p} \cdot \mathbf{m}) + \varepsilon(\boldsymbol{\sigma}_\mathrm{n} \cdot \mathbf{l})(\boldsymbol{\sigma}_\mathrm{p} \cdot \mathbf{l})$$

with basis vectors in terms of initial and final cm momenta ***p*** and ***p***':

$$\mathbf{n} = \frac{\mathbf{p} \times \mathbf{p}'}{|\mathbf{p} \times \mathbf{p}'|}, \quad \mathbf{m} = \frac{\mathbf{p}' - \mathbf{p}}{|\mathbf{p}' - \mathbf{p}|}, \quad \mathbf{l} = \frac{\mathbf{p}' + \mathbf{p}}{|\mathbf{p}' + \mathbf{p}|}$$

$dp \to \{pp\}_{^1S_0} n$: Spin observables

Unpolarised intensity depends only upon spin-flip amplitudes:

$$I = |\beta|^2 + |\gamma|^2 + |\varepsilon|^2 + |\delta|^2 R^2$$

Define a ratio of form factors by

$$R = S^+\left(k, \tfrac{1}{2}q\right) / S^-\left(k, \tfrac{1}{2}q\right)$$

Terms can be separated by measuring with polarized beams/targets:

Unpolarised cross section

$$\frac{d^4\sigma}{dt d^3k} = \tfrac{1}{3} I \left\{S^-\left(k, \tfrac{1}{2}q\right)\right\}^2$$

d and *p* vector analysing powers

$$I A_y^d = 0$$
$$I A_y^p = -2\Im\left(\beta^* \gamma\right)$$

d tensor analysing powers

$$I A_{xx} = |\beta|^2 + |\gamma|^2 + |\varepsilon|^2 - 2|\delta|^2 R^2$$
$$I A_{yy} = |\delta|^2 R^2 + |\varepsilon|^2 - 2|\beta|^2 - 2|\gamma|^2$$

d-p vector spin correlations

$$I C_{y,y} = -2\Re\left(\varepsilon^* \delta\right) R$$
$$I C_{x,x} = -2\Re\left(\varepsilon^* \beta\right)$$

d-p tensor spin correlation

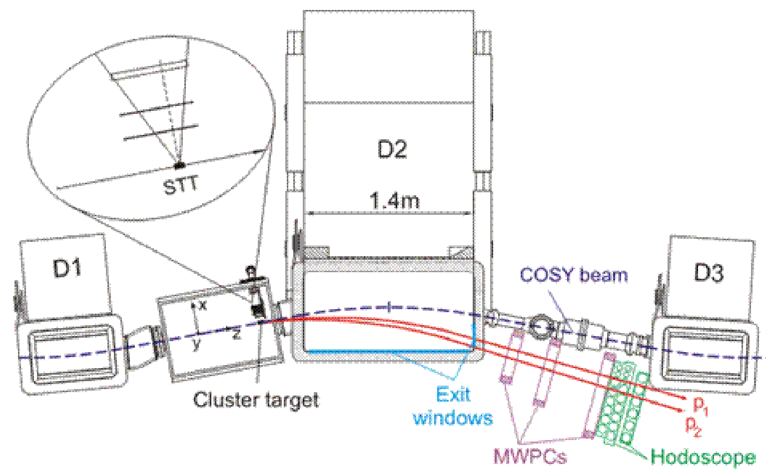
$$I C_{yy,y} = -2 A_y^p$$

*D.V.Bugg & C.W., Nucl.Phys.A**467** (1987) 575*

dp experiments

Single polarised:

- Beam: Polarised deuterons at T_d=1.2, 1.6, 1.8, 2.27 GeV
- Target: Unpolarised hydrogen cluster target
- Objectives: $d\sigma/dq$, A_{xx}, A_{yy}



Double polarised:

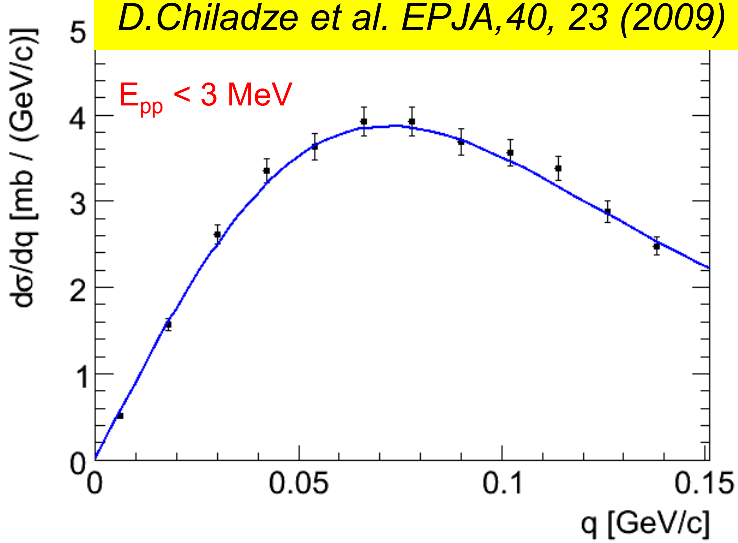
- Beam: Polarised deuterons at T_d=1.2, 2.27 GeV
- Target: Polarised hydrogen from ABS
- Objectives: A_y^p, $C_{x,x}$, $C_{y,y}$

Proof of principle at 1.17 GeV

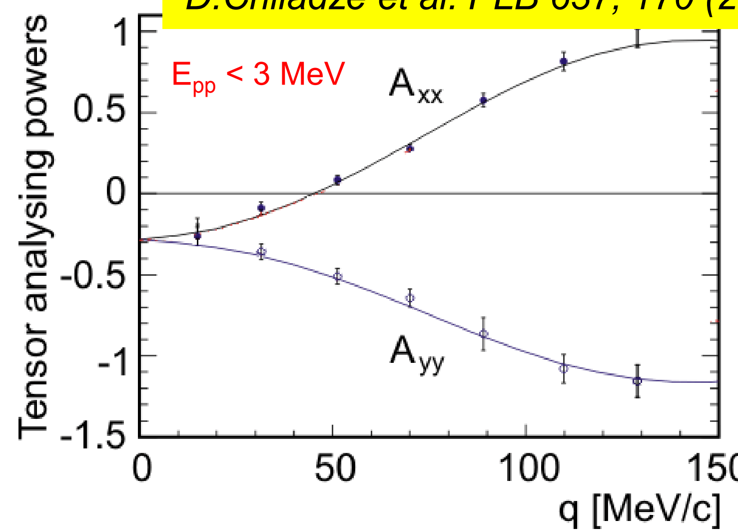
$$\vec{d}p \rightarrow \{pp\}_s n$$

- Methodology is valid at T_d = 1.17 GeV
- Application to higher energies T_d=1.6, 1.8, 2.27 GeV

D.Chiladze et al. EPJA,40, 23 (2009)



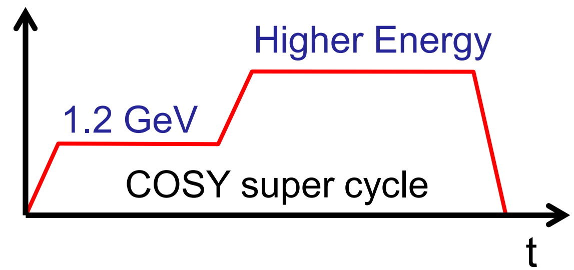
D.Chiladze et al. PLB 637, 170 (2006)



Input for impulse approximation predictions:
np charge-exchange amplitudes from current **SAID** solution at T_n = 585 MeV

Beam-target polarimetry

Beam polarisation is measured at $T_d = 1.2\ GeV$ and "polarisation export" technique is applied at *higher energies*



- $\vec{n}p \to d\pi^0$ ➡ P_y, Q_y (SAID A_y for $pp \to d\pi^+$)
- $\vec{d}p \to \{pp\}_s n$ ➡ P_{yy} (A_{xx}, A_{yy} from previous ANKE measurements)

Normalised count ratio of $\vec{d}p \to \{pp\}_s n$ events for low excited *pp* pairs ($E_{pp} < 3\ MeV$):

$$\frac{N_{pol}(q,\varphi)}{N_0(q)} = 1 + \frac{1}{4} P_{yy}\left(A_{xx}(q)(1-\cos 2\varphi) + A_{yy}(q)(1+\cos 2\varphi)\right)$$

Normalised count ratio of $np \to d\pi^0$ events:

- $\vec{d}p$ – $$\frac{N_{pol}(\vartheta,\varphi)}{N_0(\vartheta)} = 1 + P_y A_y^b(\vartheta)\cos\varphi$$
- $d\vec{p}$ – $$\frac{N_{pol}(\vartheta,\varphi)}{N_0(\vartheta)} = 1 + Q_y A_y^t(\vartheta)\cos\varphi$$

P_z up to 70%

P_{zz} up to 85%

Q_y up to 79%

Luminosity

dp→dp$_{sp}$π^0 (quasi free ***np→dπ^0***) reaction is used for the luminosity determination

$$L = \frac{R}{\sigma}$$ where $R,\ \sigma$ – count rate and cross section of the ***np→dπ^0*** reaction

$$\frac{\sigma(pp \to d\pi^+)}{\sigma(np \to d\pi^0)} \approx 2$$

Cross section for the ***pp→dπ$^+$*** reaction is well known from SAID

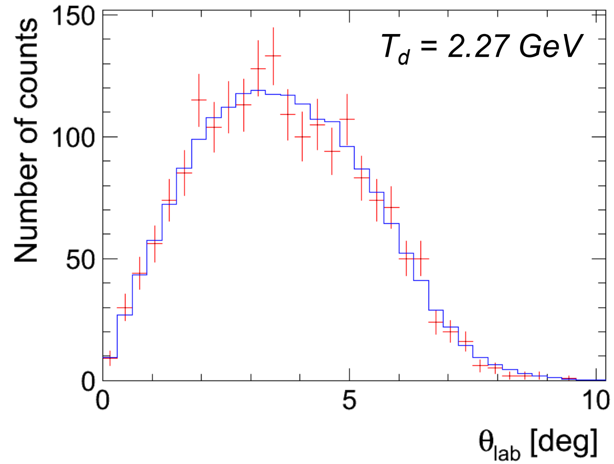
Count rate corrections factors:

- DAQ dead time
- Trigger prescaling
- Track reconstruction and MWPC efficiency
- ANKE geometric acceptance

Monte Carlo simulation

vs

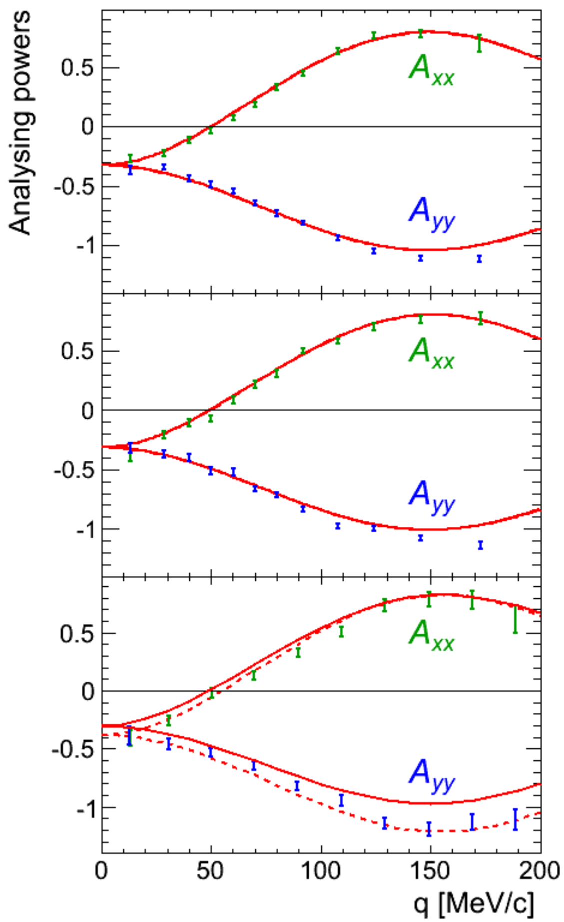
Experiment



Single polarised data: *dσ/dq*, A_{xx}, A_{yy}

$\vec{d}p \to \{pp\}_s n$ $(E_{pp}<3\,\mathrm{MeV})$

D.Mchedlishvili et al. EPJA, 49, 49 (2013)

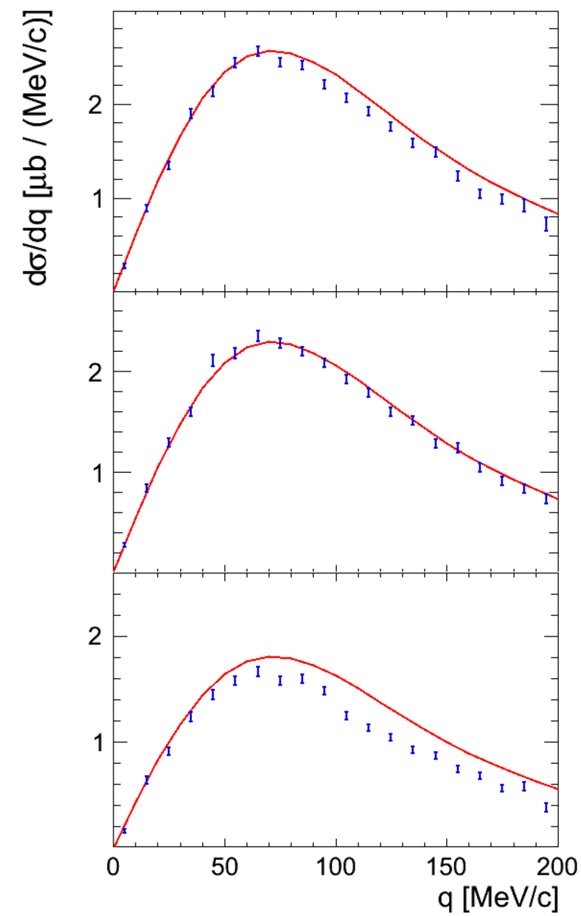


T_d = 1.6 GeV
(800 MeV/A)

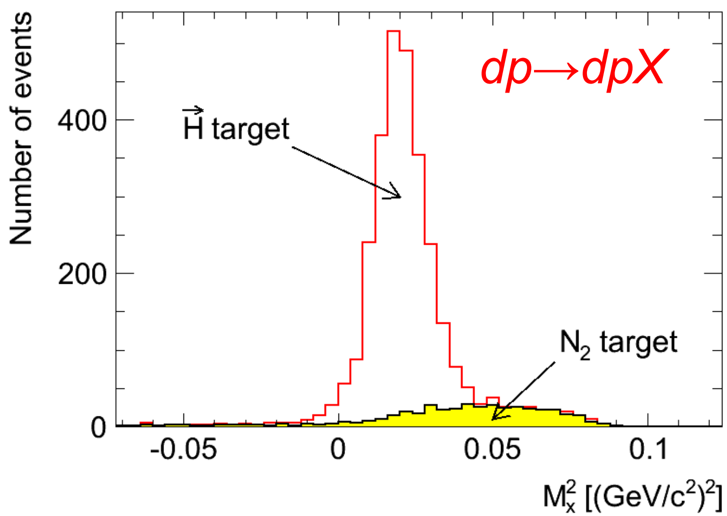
T_d = 1.8 GeV
(900 MeV/A)

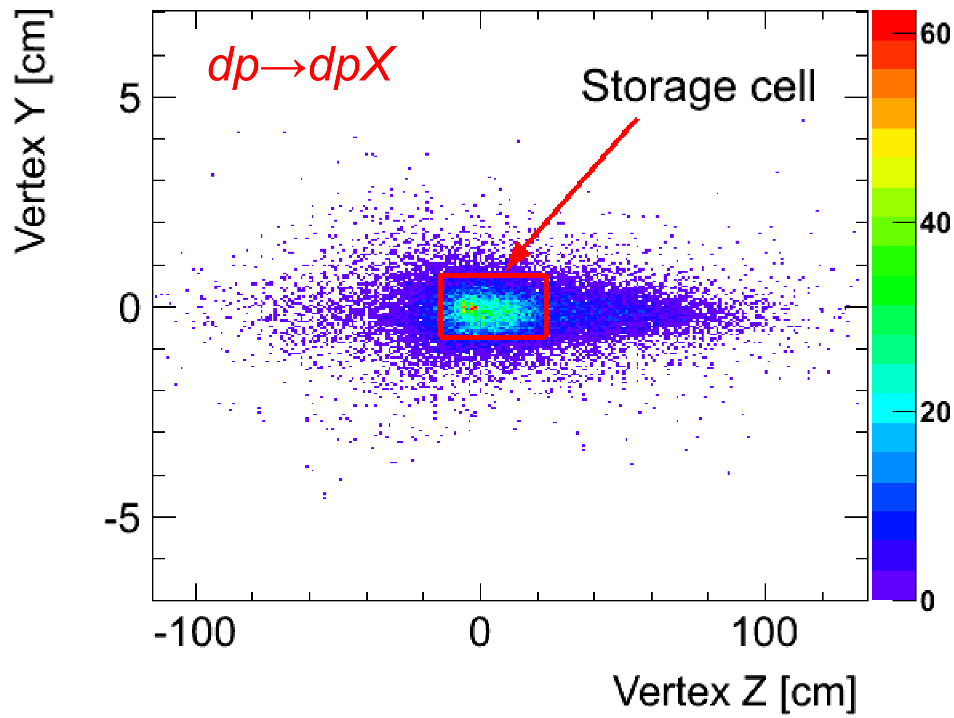
T_d = 2.27 GeV
(1135 MeV/A)

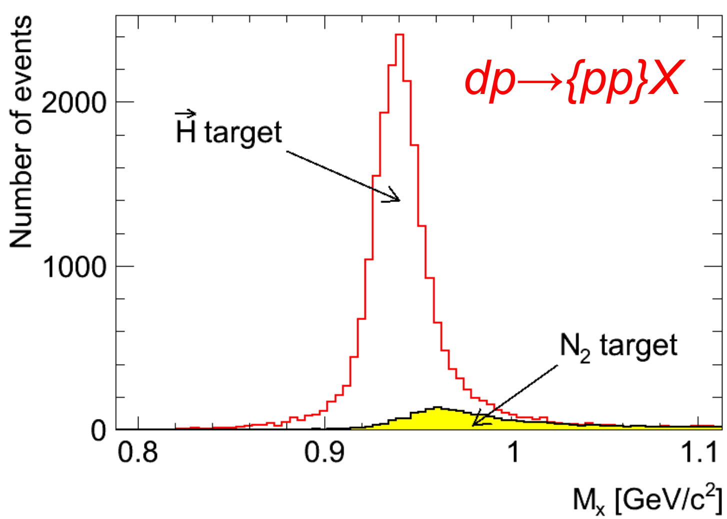
$\varepsilon(q)$ reduced by 25%



Background handling in double-polarised data





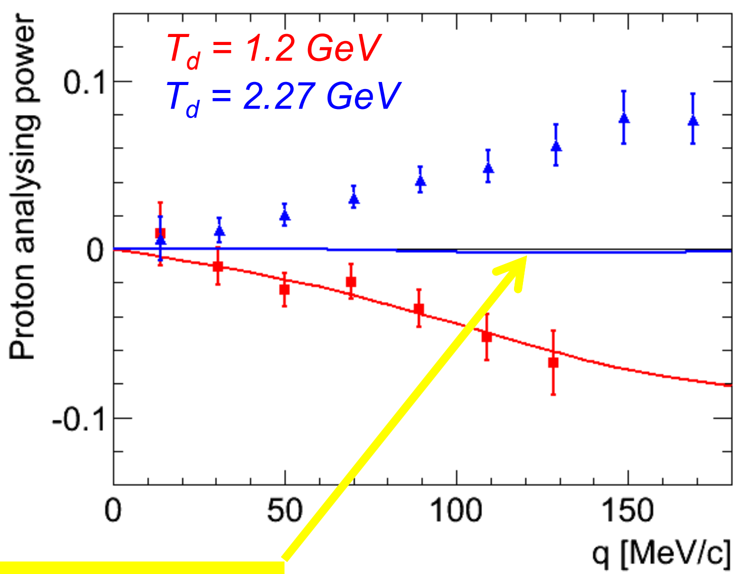


Background runs were recorded with N_2 in the cell

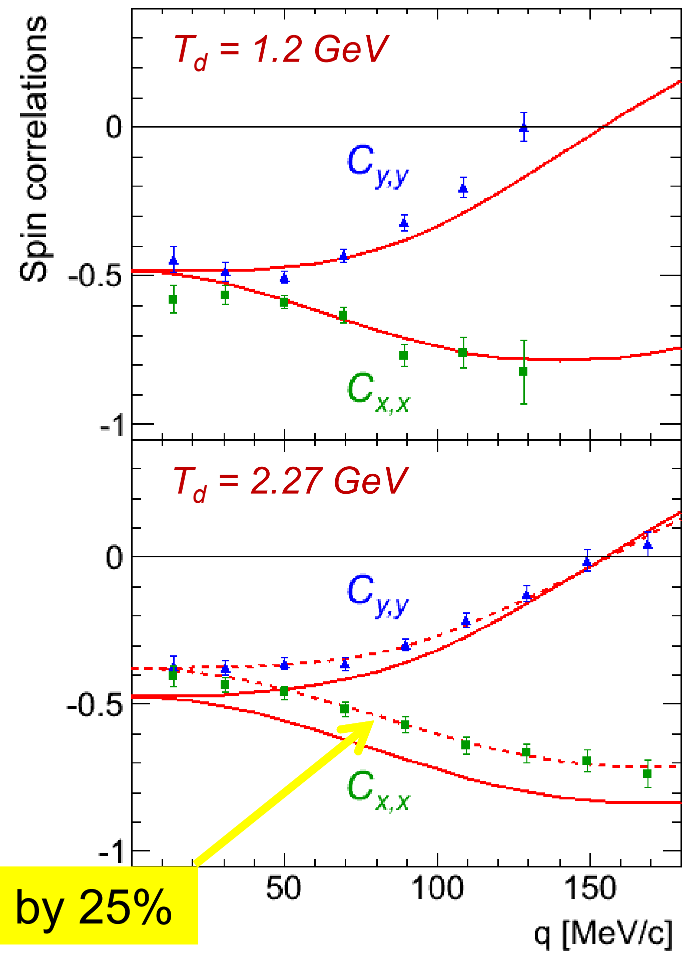
Double polarised data: A_y^p, $C_{y,y}$, $C_{x,x}$

- $\vec{d}\vec{p} \to \{pp\}_s n$
- $E_{pp} < 3$ MeV

D.Mchedlishvili et al. EPJA, 49, 49 (2013)

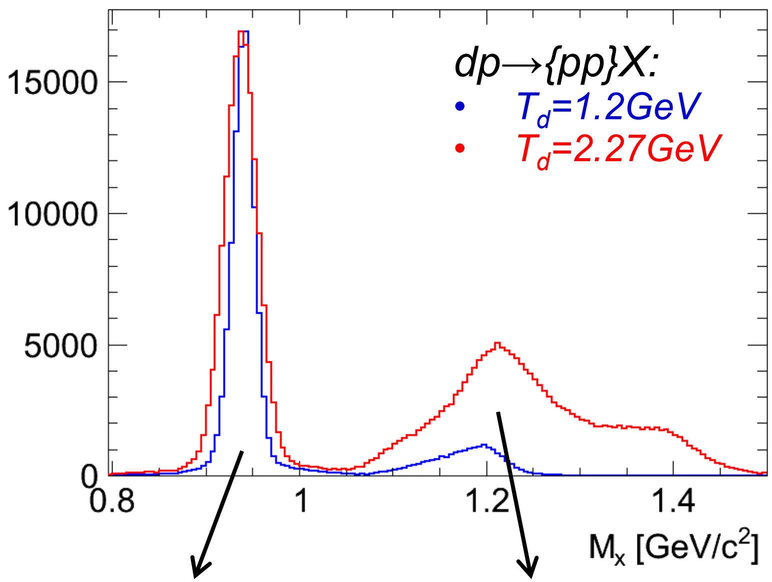


Problem with $\gamma(q)$



$\varepsilon(q)$ reduced by 25%

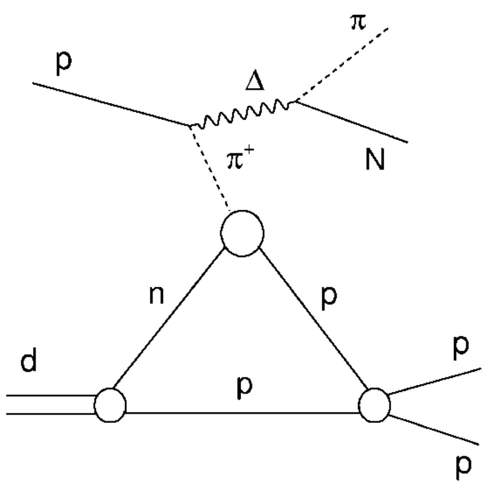
Δ^0 production in $dp \to \{pp\}_s \Delta^0$ reaction



$dp \to \{pp\}n$

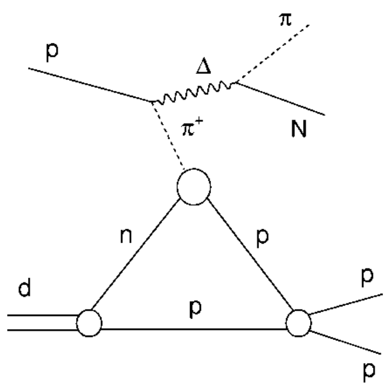
$dp \to \{pp\}\Delta^0$ + ???

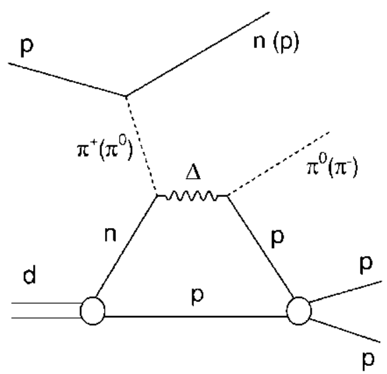
One pion exchange model:



Valuable information on the modelling of the $np \to p\Delta^0$ amplitudes

$dp \rightarrow \{pp\}_s \Delta^0$: cross section





Direct mechanism:

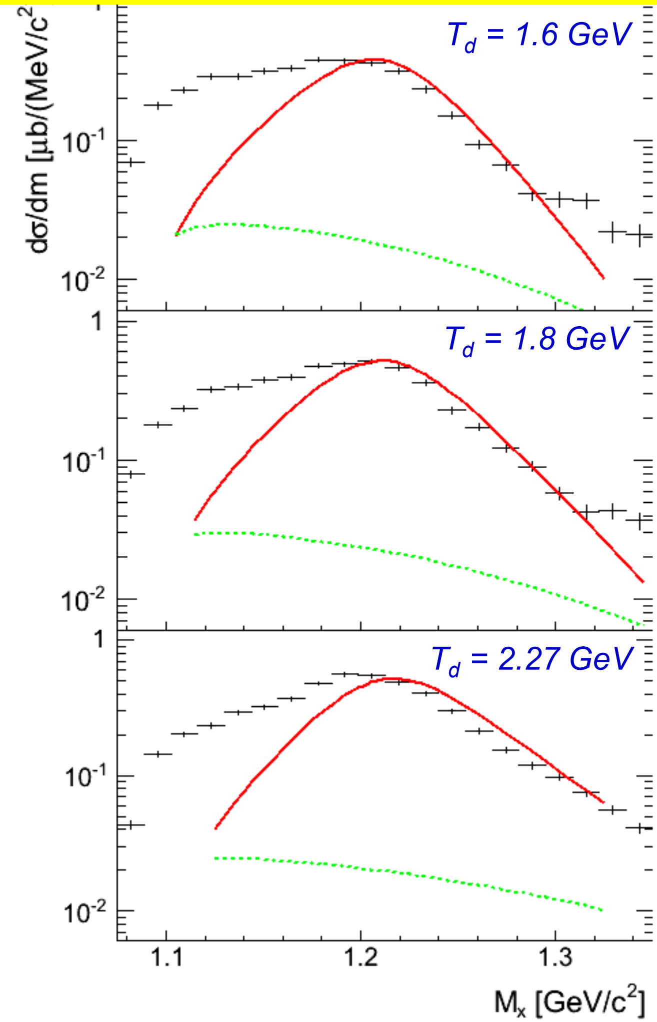
Δ isobar direct production by the one pion exchange

Exchange mechanism:

Δ isobar excites inside the projectile deuteron

1. Pion-nucleon are from different vertices
2. I=1/2 and I=3/2 both are allowed

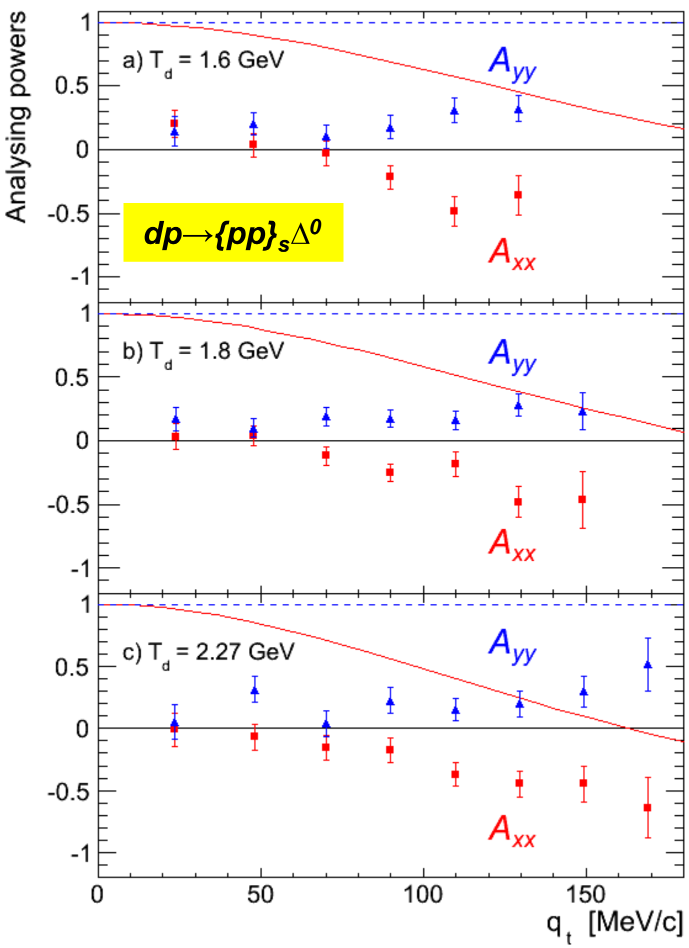
Accepted in PLB (arXiv:1305.5475)



- ➢ Direct one-pion-exchange works fine at high M_x
- ➢ Other mechanisms dominate near πN threshold

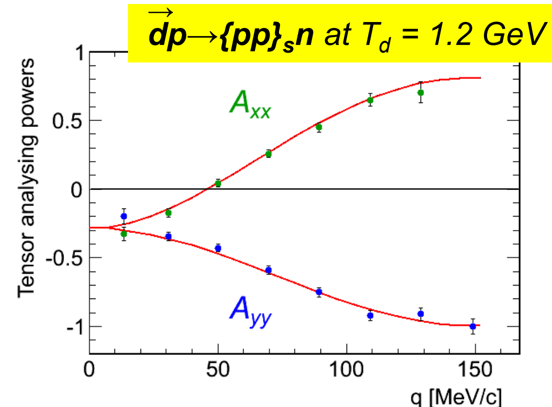
Further theory work is needed !

Tensor analysing powers



High mass region: $1.19 < M_X < 1.35$ GeV/c^2

COMPARE!



Differences from neutron channel:

- Signs are flipped
- A_{xx} and A_{yy} are small at q_t=0

Valuable constraints on the modeling of the $np \to p\Delta^0$ amplitudes

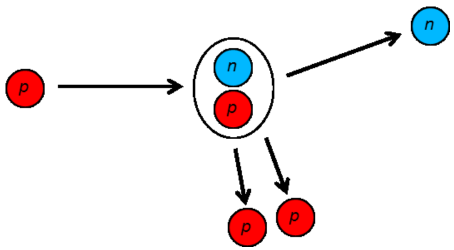
More theory details: see talk by Yuriy Uzikov

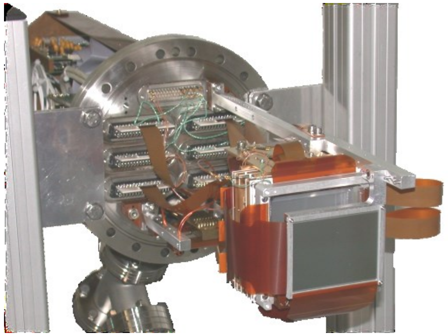
Extension of np program in inverse kinematics (dp $\Rightarrow$ pd)

Maximum COSY energy:

T_d = 2.3 GeV (1.15 GeV per nucleon) vs T_p = 2.8 GeV

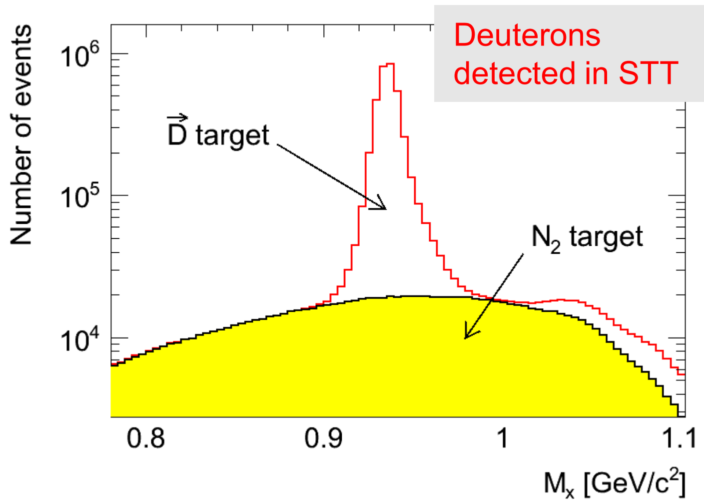
- Polarised deuteron target commissioning ($p\vec{d}$) in 2012 (10 days of data taking)
  - Unpolarised proton beam T_p = 600 MeV
  - Polarised deuteron cell target, with vector and tensor polarisations.
- Solid state spectator detectors were involved to extend the ANKE capabilities.



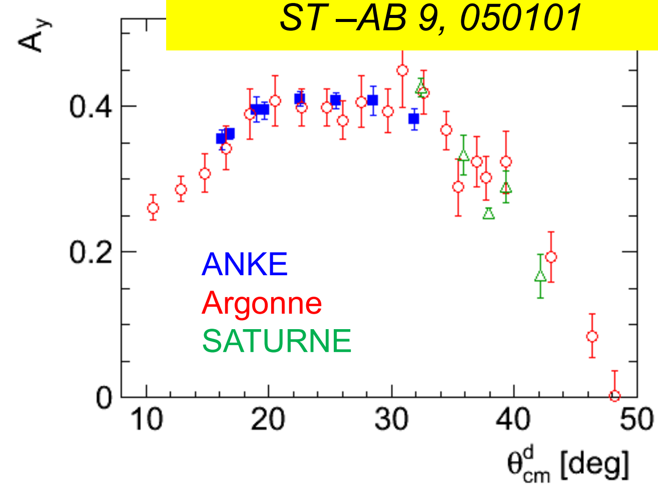


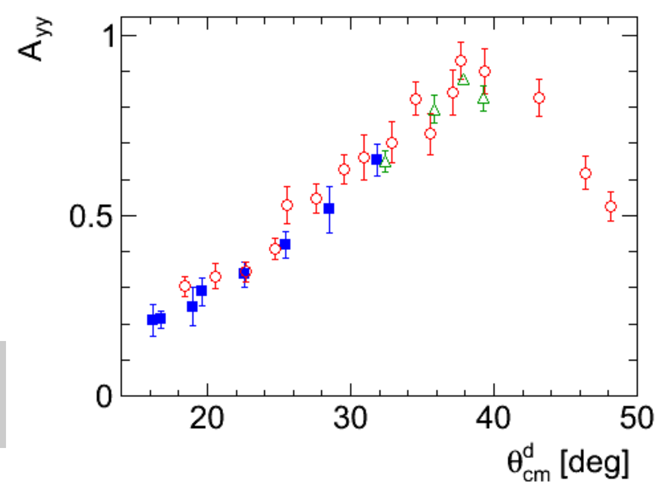
Deuterium target polarimetry with *pd* → *pd*

$p\vec{d}$ at T_p = 600 MeV



D.Childadze et al. Phys. Rev. ST –AB 9, 050101





- ✓ Deuterons are clearly identified in the STT, with almost no background
- ✓ Vector and tensor analysing powers are known

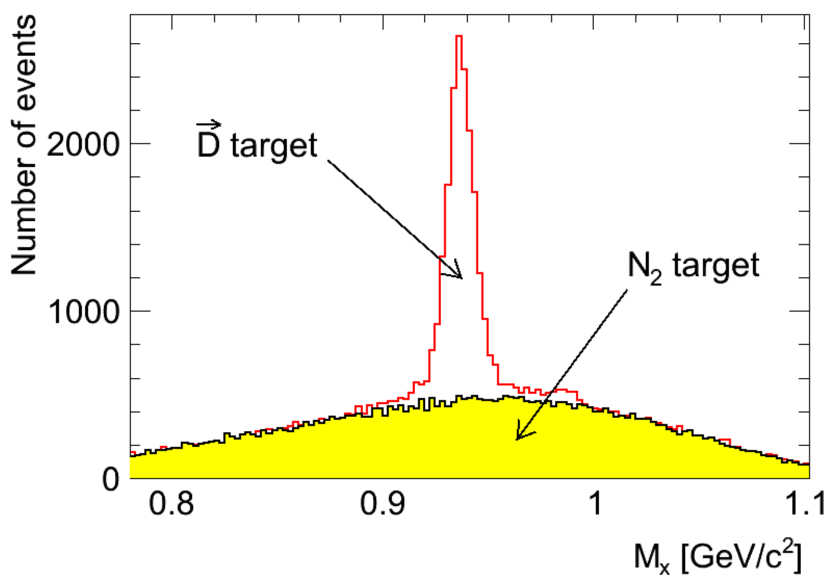
Achieved: ***Q_y*, *Q_{yy}*** up to 70% from the nominal

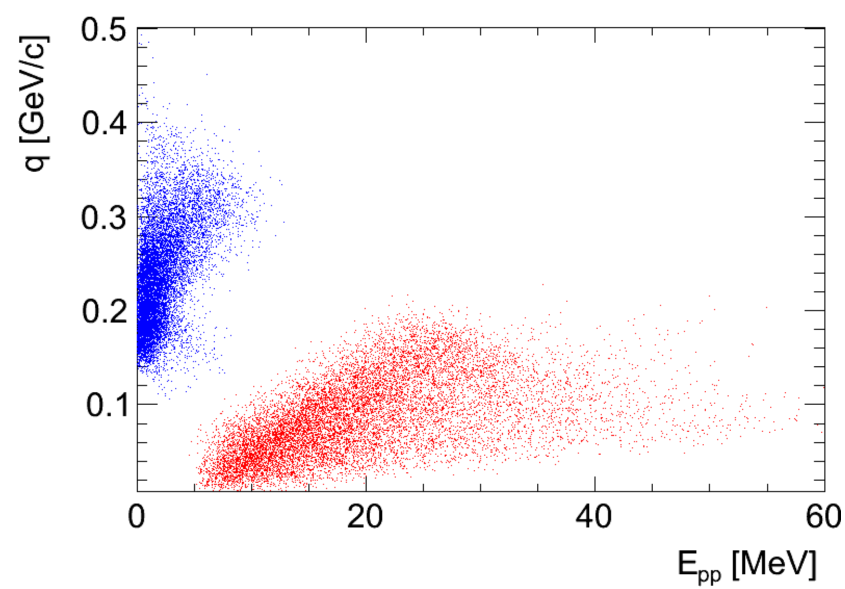
Deuteron breakup in inverse kinematics

$p\vec{d} \rightarrow \{pp\}n$ at T_p = 600 MeV

Two different region:

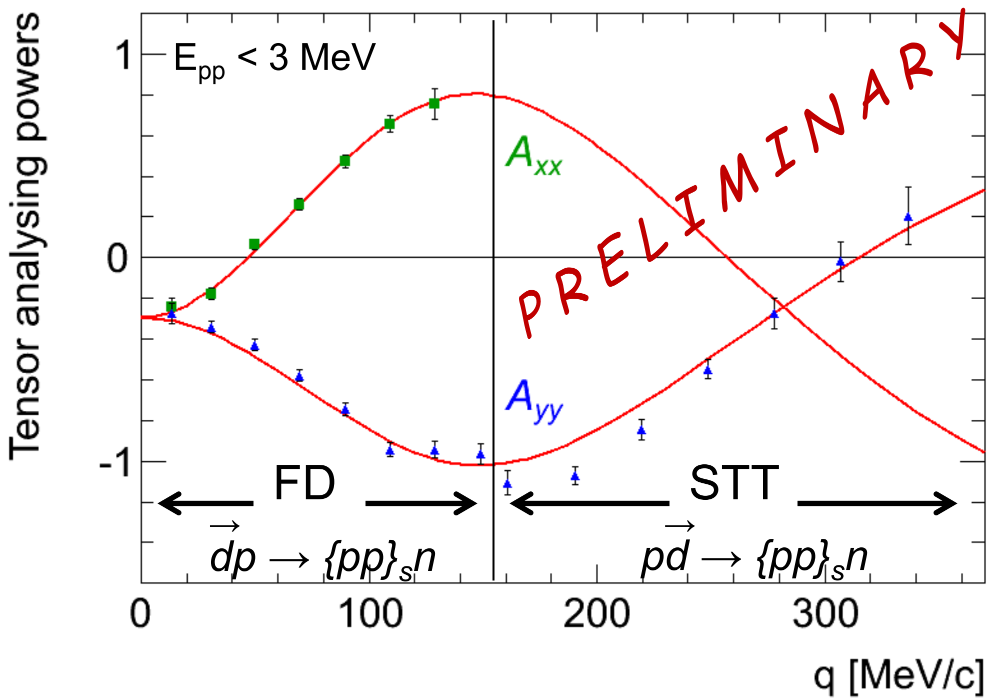
1. pp in same side of STT ⇒ small E_{pp}, large q
2. pp in oposite side of STT ⇒ large E_{pp}, small q

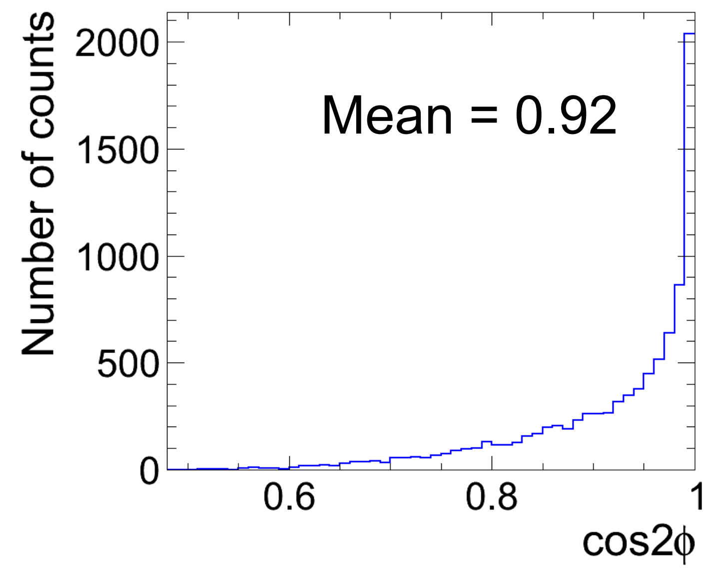




Tensor analysing powers in the *pd* → *{pp}$_s$n*

$p\vec{d}$ at T_p = 600 MeV





$$\frac{N_{pol}(q,\varphi)}{N_0(q)} = 1 + \frac{1}{4} Q_{yy} (\cancel{A_{xx}(q)(1-\cos 2\varphi)} + A_{yy}(q)(1+\cos 2\varphi))$$

Future studies

$\vec{p}\vec{d}$ experiment at ANKE:

- Polarised proton beam at 0.6, 1.135, 1.3 and 1.8 GeV
- Polarised deuterium target from the ABS

Primary aims:

1. Tensor analysing powers (A_{xx}, A_{yy}) and spin correlation parameters ($C_{x,x}$, $C_{y,y}$) in the $pd \to \{pp\}_s X$ reaction (X=n, X=Δ^0).
   - *Opportunity to study the Δ polarisation by detecting the decay products in ANKE*
2. Spin correlation parameters ($A_{x,x}$, $A_{y,y}$) for quasi-free pn elastic. Due to the Fermi motion, several energy intervals will be produced at given beam energy in the angular range $5° < \theta_{cm} < 40°$.

List of reactions fall in ANKE acceptance

- $pd \to \{pp\}_s n$: pp detected in the STT or in the ANKE FD
- $pd \to pd$: d detected in the STT (*small angles*) or in ANKE (*large angles*)
- $pd \to \{pp\}_s \Delta^0$: pp detected in the STT and Δ^0 decay products in ANKE
- $pd \to p_{sp}\{pp\}_s \pi^-$: pp detected in ANKE
- $pd \to n_{sp} d \pi^+$ and $pd \to p_{sp} d \pi^0$
- $pd \to p_{sp} dX$ (quasi free $pn \to dX$ including the isoscalar $\pi\pi$ system in the final state): fast d detected in ANKE

Summary

✓ *pp* elastic:

- $d\sigma/d\Omega$ at T_p = 1.0, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6, 2.8 GeV
- A_y at T_p = 0.8, 1.6, 1.8, 2.0, 2.2, 2.4 GeV

Analysis in progress…

✓ $dp \to \{pp\}_s n$ observables:

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- $d\sigma/dq$, A_{xx}, A_{yy} at T_d = 1.2, 1.6, 1.8, 2.27 GeV
- A_y^p, $C_{x,x}$, $C_{y,y}$ at T_d = 1.2, 2.27 GeV
- Corrections are needed for $\varepsilon(q)$ and $\gamma(q)$

✓ $dp \to \{pp\}_s \Delta^0$ observables:

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- $d\sigma/dm$, A_{xx}, A_{yy} at T_d = 1.6, 1.8, 2.27 GeV
- More theoretical work is needed to explain differences from neutron channel

THANK YOU