The Caucasian-German School and Workshop on Hadron Physics 2004

Spin dependence in pd reactions at intermediate energies

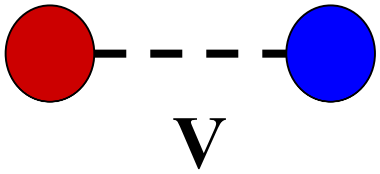
Pia Thörngren, Uppsala University

For the PINTEX collaboration

Outline

- Objective – Probing the spin dependence of the three-nucleon force (3NF)
  - PINTEX results from pd elastic scattering
- The PINTEX dp breakup experiment
  - Experimental set-up
  - Analysis tools – The sampling method
  - Recent results and present status
- Outlook

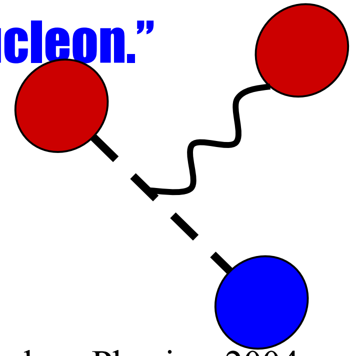
3NF - What is it ?



- **IUCF Workshop Sep 1998 - Working Session II:**
  - ***Question: What do we mean by 3NF, and where is the best place to look for experimental evidence?***
- **H. Witala (working session notes):**
  - **"In a pragmatic view, with nucleon DOF only**

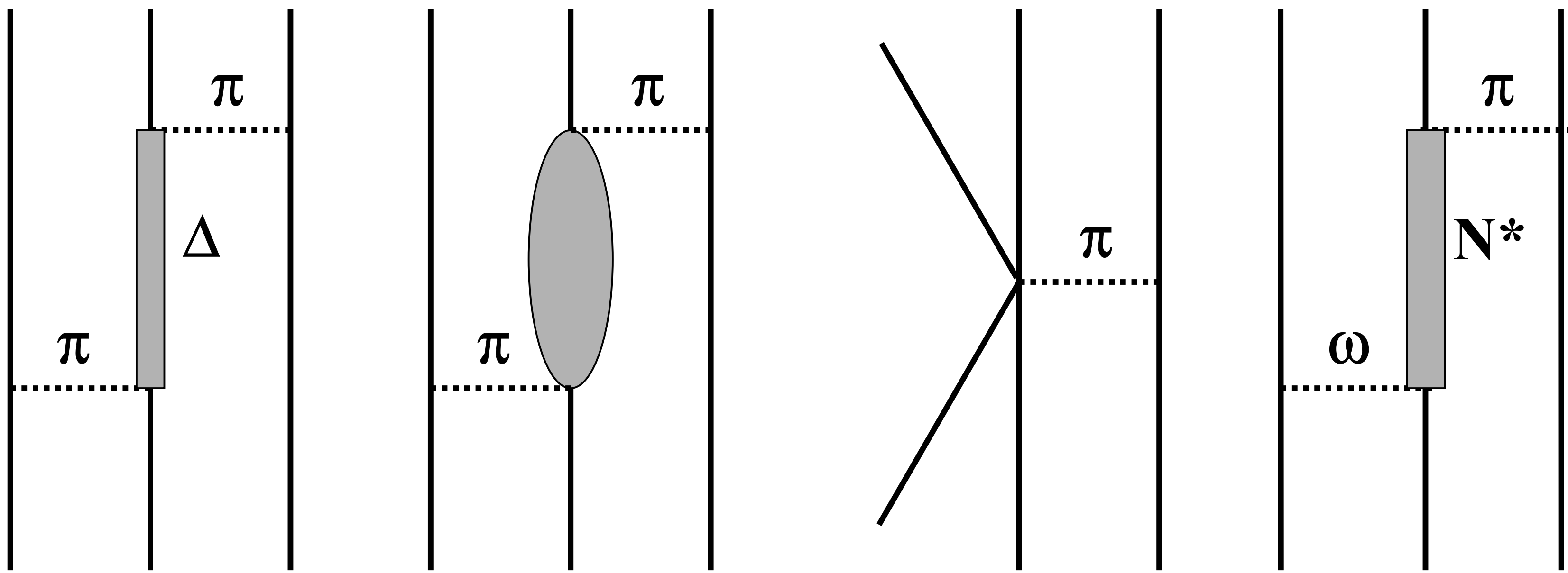
    $H = T + \sum V_{ij} + V_{1,2,3}$

    where the second term is all pairwise i.a. summed over the 3N. The rest is 3NF and takes into account any distorsion of NN potential energy caused by the presence of the third nucleon."



> **Size of the 3NF interaction:**
>
> **$\Delta V \approx V^2/Mc^2 \rightarrow 0.5 - 1$ MeV**

Three-Nucleon Interactions



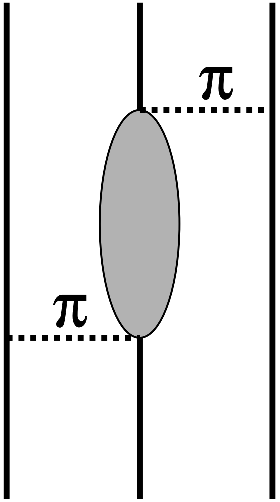
2 π-Xchange force **incl. short range i.a.**

Models for 3NF

❑ Tucson –Melbourne (TM)

S. Coon and W. Glöckle, PRC 23, 1790 (1981)

➢ 2π exchange process, full off-shell πN scattering amplitude



❑ TM modified (TM')

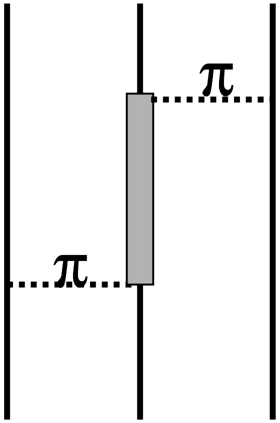
D. Hüber et al., Few-Body Syst. 30, 95 (2001)

➢ Drop one term and modify another to comply with chiral symmetry

❑ Urbana IX force

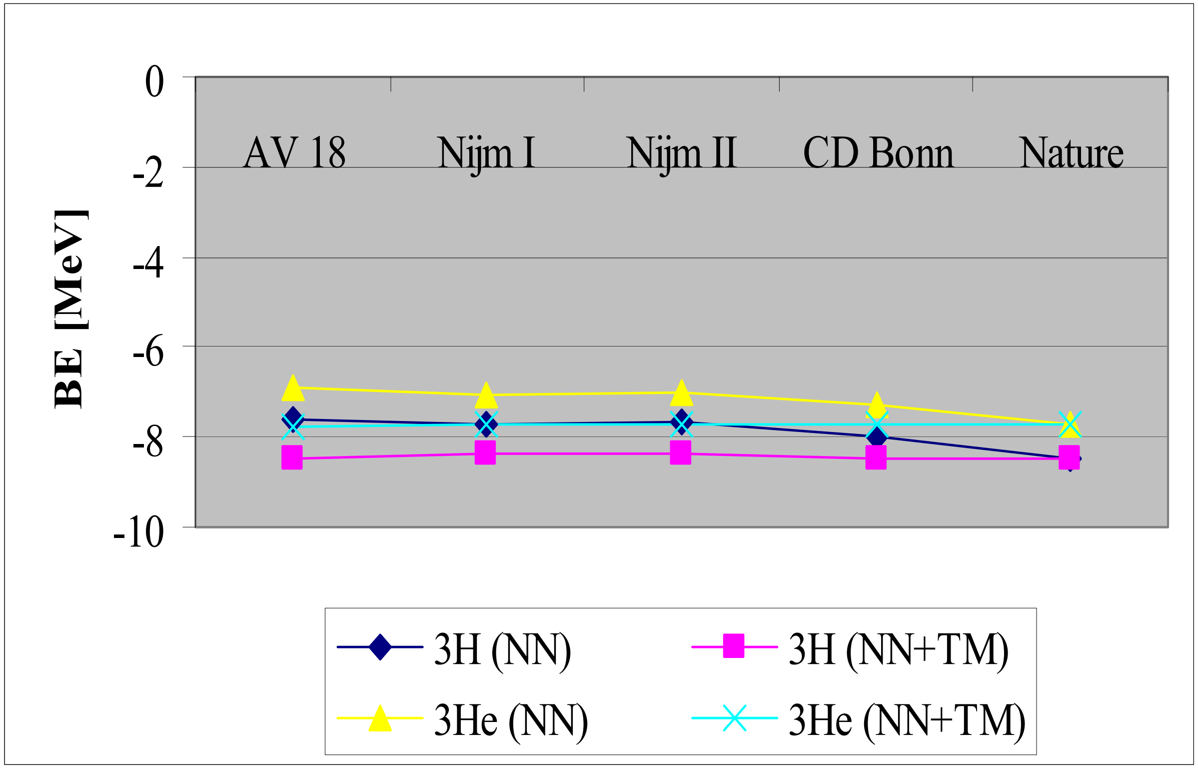
J. Carlson et al., Nucl. Phys. A401, 59 (1983)

➢ FM approach + phenomenological spin and isospin independent short-range part



Binding Energy of ^{3}He and ^{3}H

NN-potential	BE [MeV]			
	^{3}H(NN)	^{3}H(+TM)	^{3}He(NN)	^{3}He(+TM)
AV 18	-7.62	-8.48	-6.92	-7.76
Nijm I	-7.74	-8.39	-7.08	-7.72
Nijm II	-7.66	-8.39	-7.01	-7.72
CD Bonn	-8.01	-8.48	-7.27	-7.72
Nature	-8.48	-8.48	-7.72	-7.72



A.Nogga et al.,Phys. Rev. Lett. 85 (2000) 944

…so all is well….?

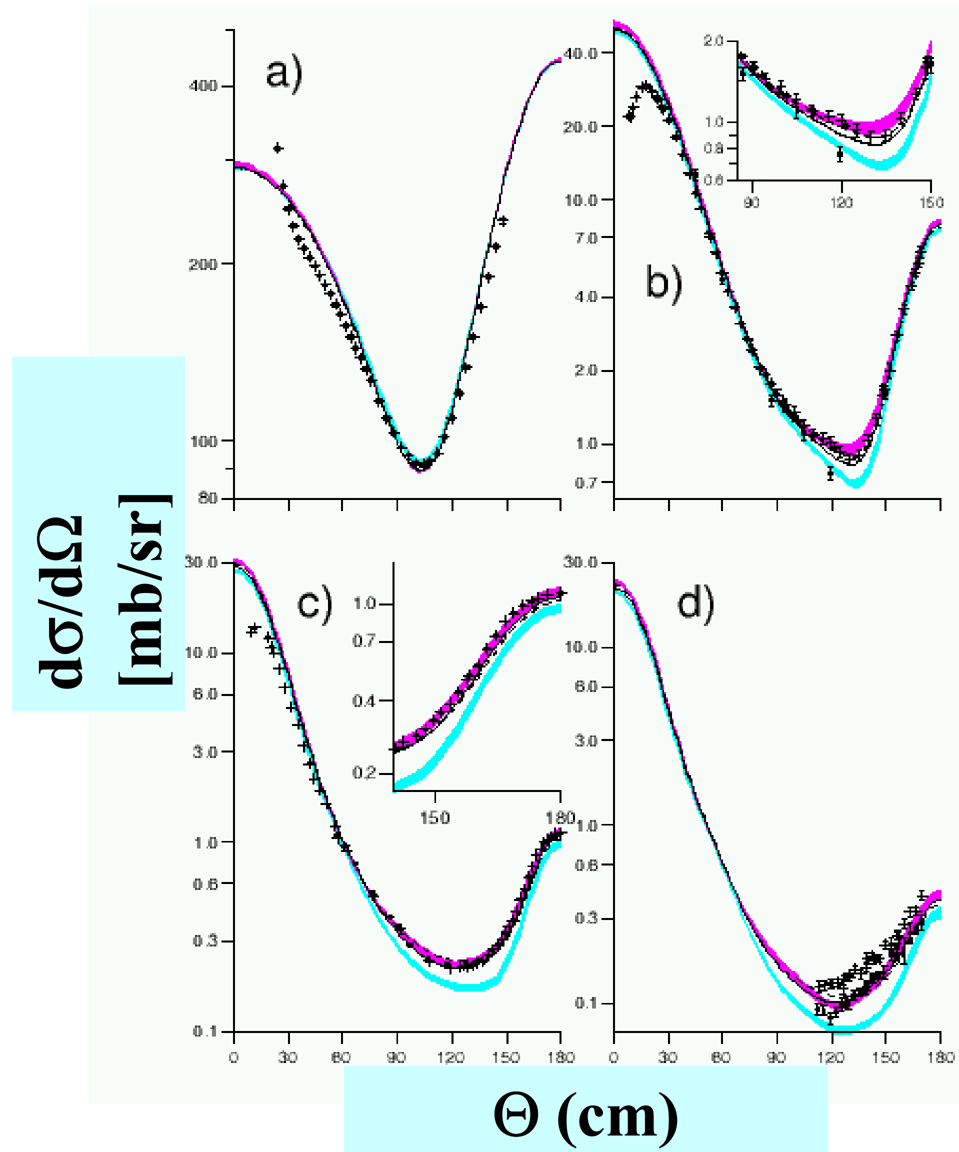
3NF in the continuum?

a) 3

b) 65

c) 135 MeV

d) 190 MeV



NN forces

NN+TM3NF

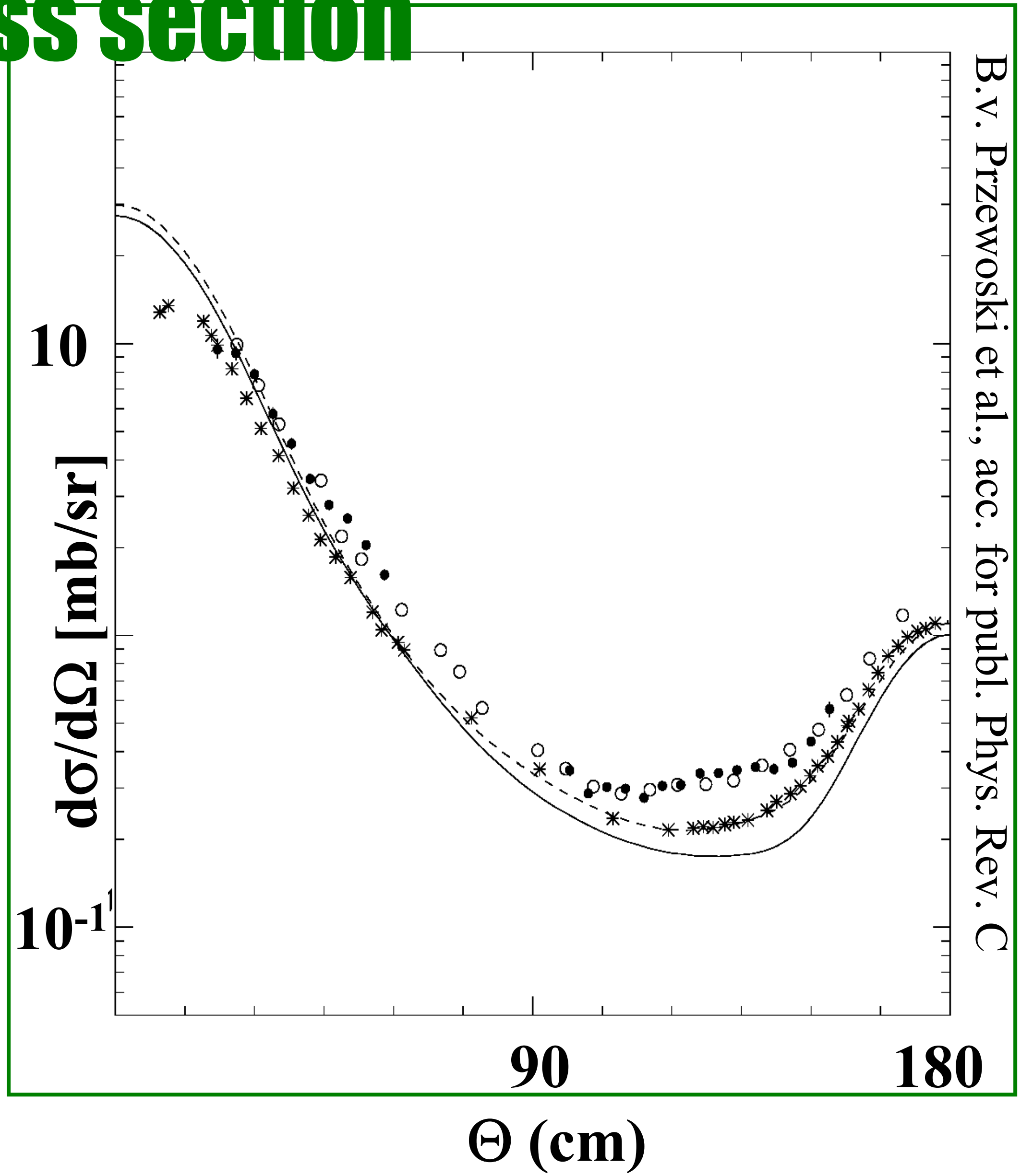
AV18+UIX

CDBonn+TM’

Differential cross section

p+d elastic scattering at 135 MeV

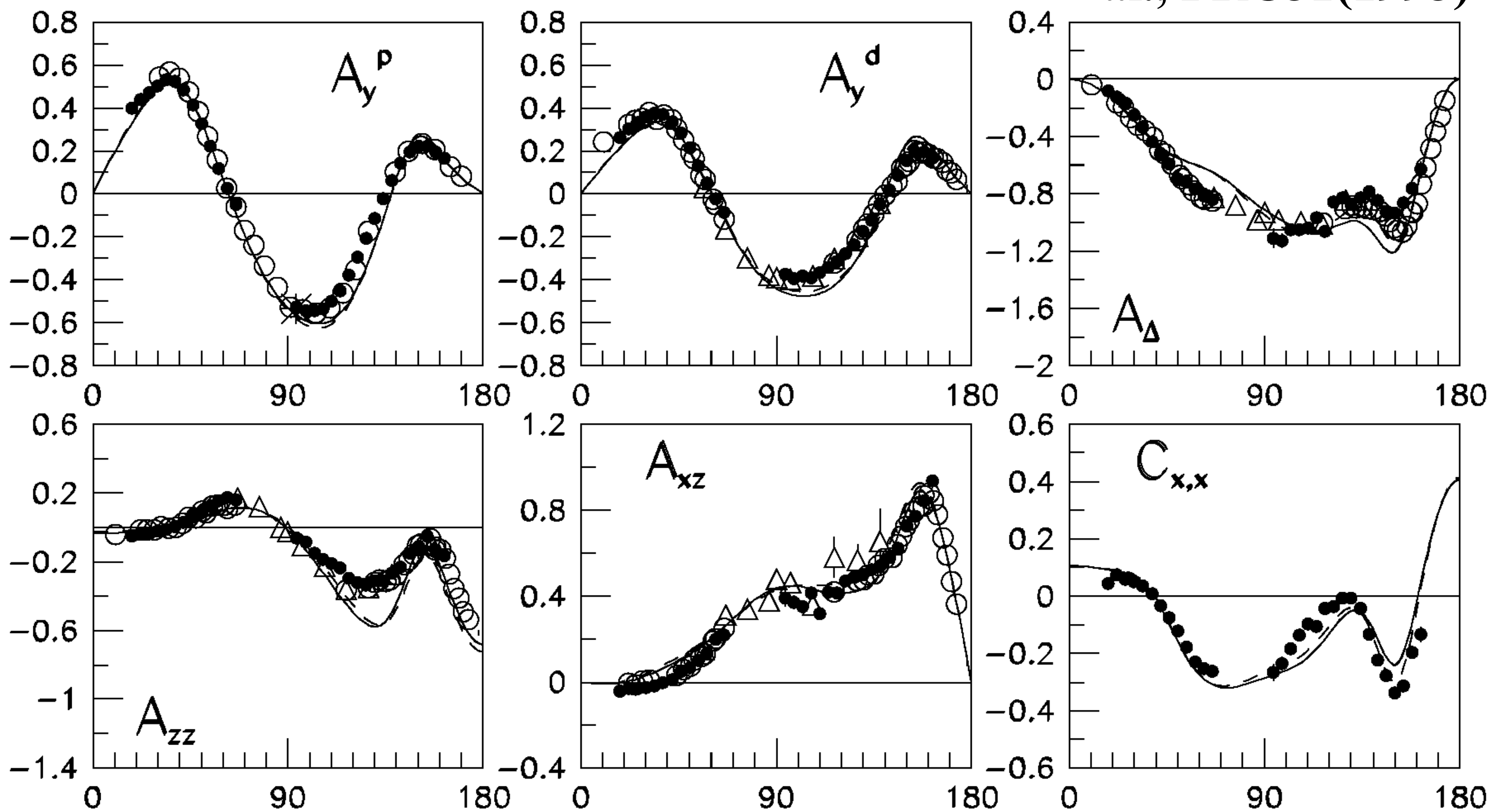
- o K. Ermisch et al., arXiv:nucl-ex/0308012, PhD thesis, KVI Groningen, ISBN:90-9016528-2
- • PINTEX-IUCF present data (normalized to Ermisch et al.)
- * K. Sekiguchi et al., Phys. Rev. C65 (2002) 034003
- — CD Bonn, R. Machleidt, PRC63, 024001 (2001)
- --- CDBonn + TM 3NF



Spin observables for pd elastic scattering

- • This experiment
- ○ △ Previous meas.
- —— CDBonn NN
- - - - - AV18 NN, Wiringa et al., PRC51(1995)

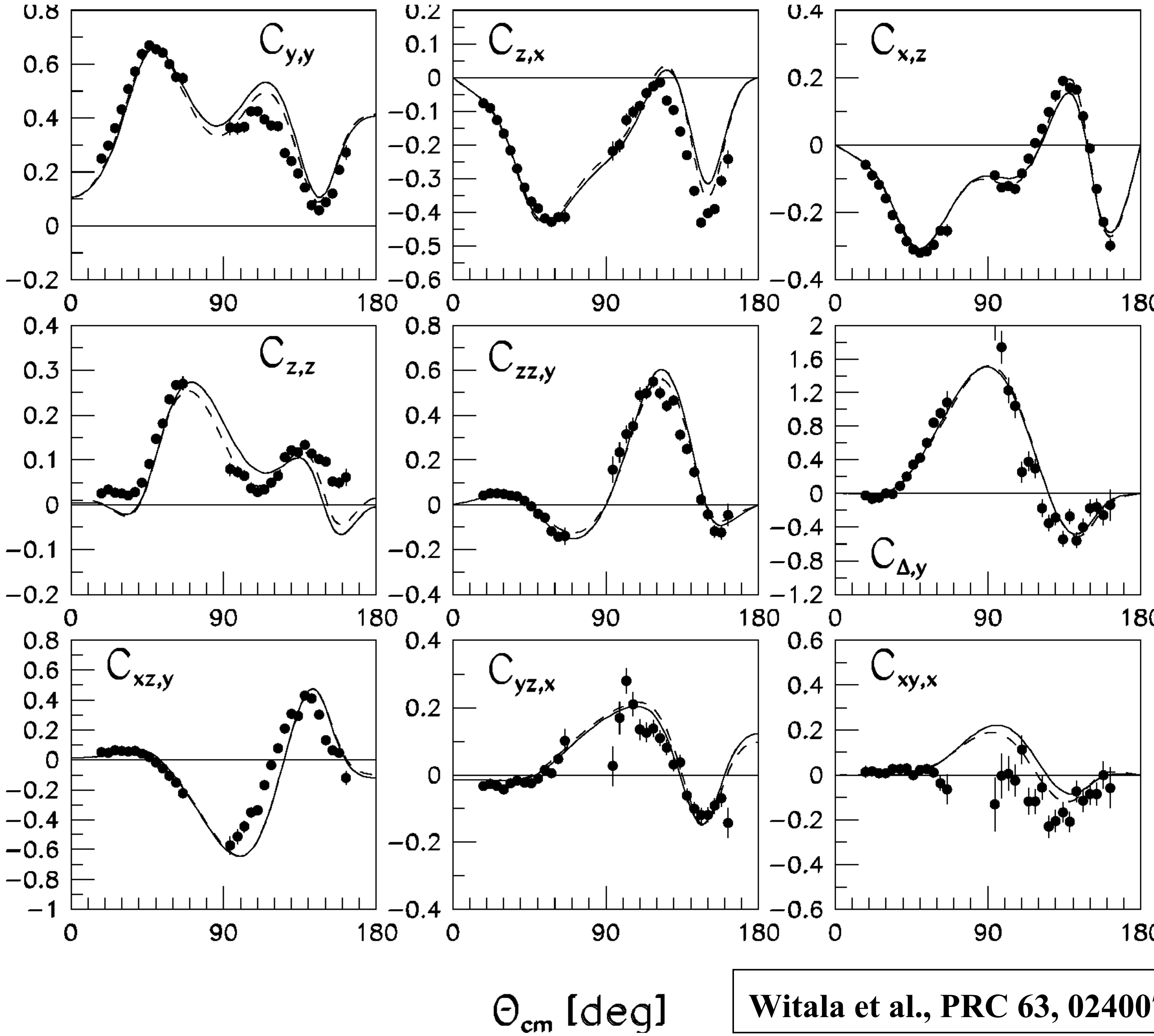
135 MeV



B.v. Przewoski et al., PRC, acc. July 04

Ermisch et al., PRL 86, 5862 (2001)
Adelberger&Brown, PRD5,2139 (1972)
Wells et al., NIM A325, 205 (1993

Stephenson PRC60, 061001 (1991) Bieber PRL 84, 606 (2000) Sakamoto PLB367, 60 (1996) Sakai PRL 84, 5288 (2000) Sekiguchi PRC65, 034003 (2002)



B.v. Przewoski et al., acc. for publ. Phys. Rev. C

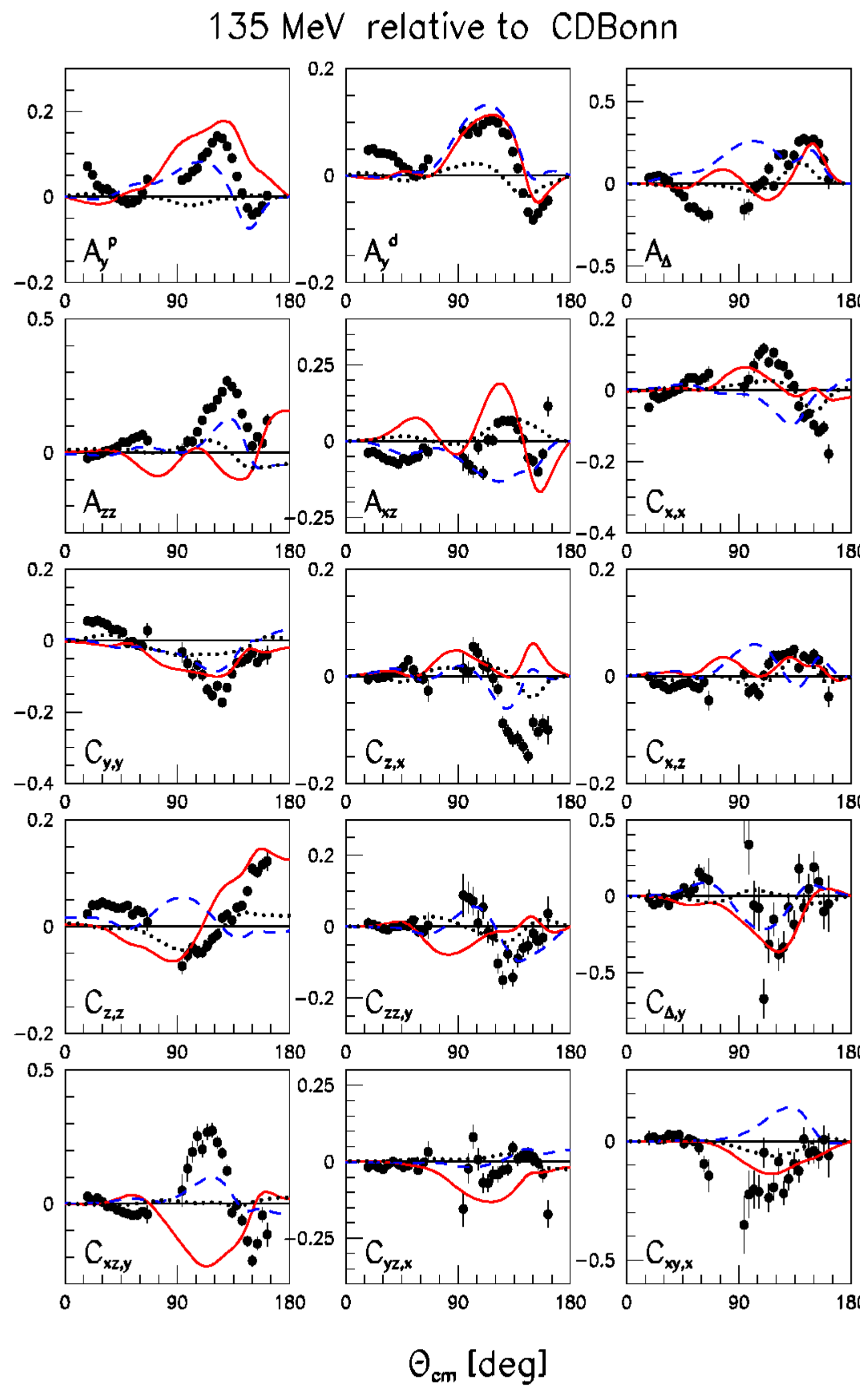
Witala et al., PRC 63, 024007 (2001)

Data – CDBonn

Spin observables for p+d elastic scattering at Tp=135 MeV

- **Data-CDBonn NN**
- **Including TM 3NF** (red solid line)
- **Including TM' 3NF** (blue dashed line)
- **AV18-CDBonn NN** (dotted line)

Statistical errors



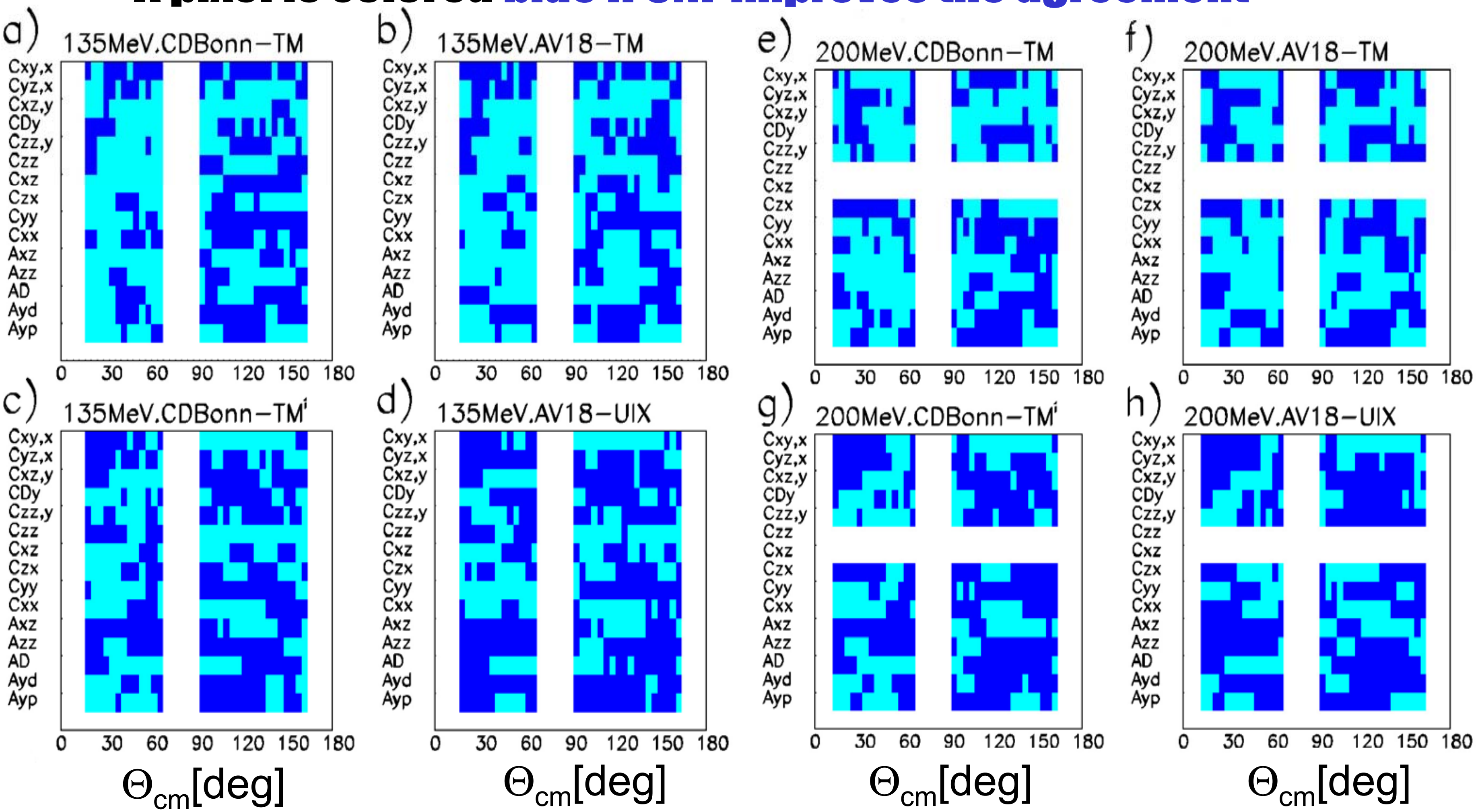
B.v. Przewoski et al., acc. for publ. Phys. Rev. C

B.v. Przewoski et al., accepted for publication Phys. Rev. C

Systematics of different 3NFs

Each pixel corresponds to one of the 868 data points

A pixel is colored blue if 3NF improves the agreement



Analyzing Powers & Spin Correlation in pd elastic at 135 and 200 MeV

- All analyzing powers, and 10 of 12 possible spin corrrelation coefficients in p+d elastic scattering were measured at 135 and 200 MeV beam energy. A discrepancy was resolved between two recent measurements of the differential cross section
- The Faddeev predictions based on modern NN potentials agree 'fairly' well with the data, the largest disagreements at backward angles
- Input of 3NF into the calculations did not improve the agreement with the data in any consistent way.

Spin dependence of dp breakup

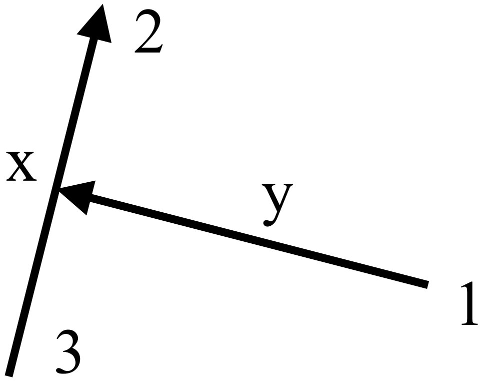
- The PINTEX dp breakup experiment
  - Motivation
  - Experimental set-up
  - Analysis tools – The grid method
  - Recent results and present status
    - Axial observables
    - Tensor analyzing powers

Axial observables in dp breakup

- Axial observables are required to be zero for coplanar events due to parity conservation. BUT - This is not the case in a breakup reaction.
- Axial observables: Azp, Cy,x-Cx,y, Czz,z, Azd, Cxz,x-Cyz,y)
- There are operators that are unique to axial observables that would vanish if there were no 3NFs. It is suggested that the axial operators might enhance the Axial observables.

$$O\,(2\pi - 3N) = (\sigma_2 \cdot x)(\sigma_3 \cdot y) - (\sigma_2 \cdot y)(\sigma_3 \cdot x)$$

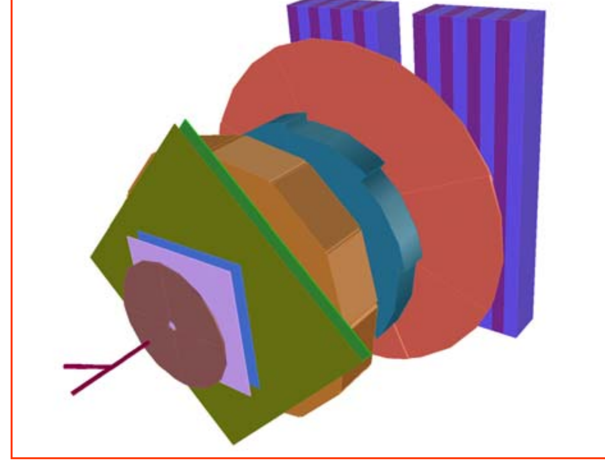
$$= (\sigma_2 \times \sigma_3) \cdot (x \times y)$$



L.D. Knutson PRL 73 (1994) 3062

IUCF

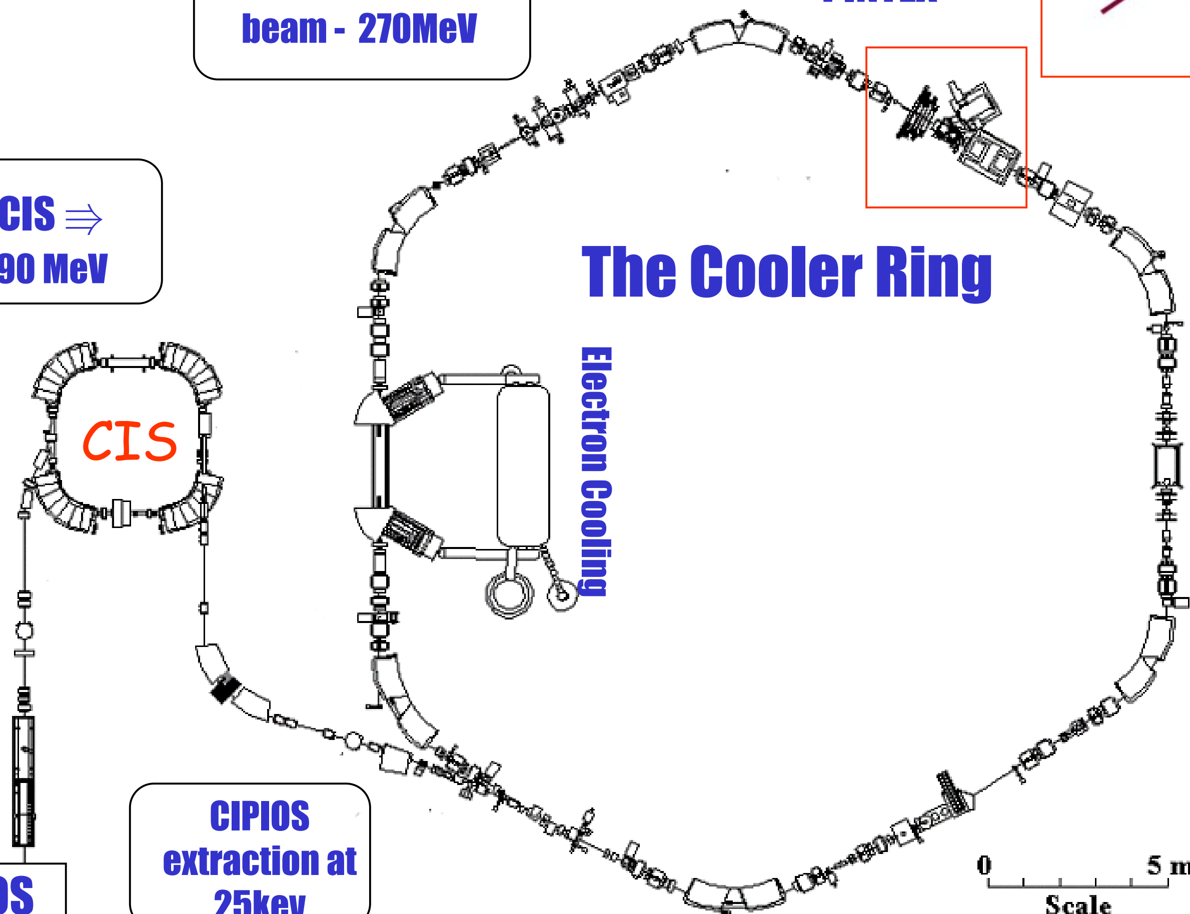
Indiana University Cyclotron Facility



Polarized deuteron beam - 270MeV

PINTEX

CIS ⇛ 90 MeV



RFQ: deuterons at 4 MeV

CIPIOS extraction at 25kev

CIPIOS

Polarized deuteron beam

Beam state	Sextu pole 1	MFT	Sextu pole 2	WFT	SFT	Hyper fine s.	$\sim Q_\zeta$	$\sim Q_{\zeta\zeta}$
1	1,2,3	$3\rightarrow4$	1,2		$2\rightarrow6$	1,6	**+0.8**	**+0.7**
2	1,2,3	$1\rightarrow4$	2,3	$2\rightarrow4$		3,4	**–0.6**	**+0.7**
3	1,2,3	$1\rightarrow4$	2,3		$2\rightarrow6$	3,6		**+0.8**
4	1,2,3	$1\rightarrow4$	2,3		$3\rightarrow5$	2,5		**–1.6**

One beam state was unpolarized

Target storage cell

- Front view

25 cm long, Ø 12 mm

0.025 mm aluminum

Teflon coated

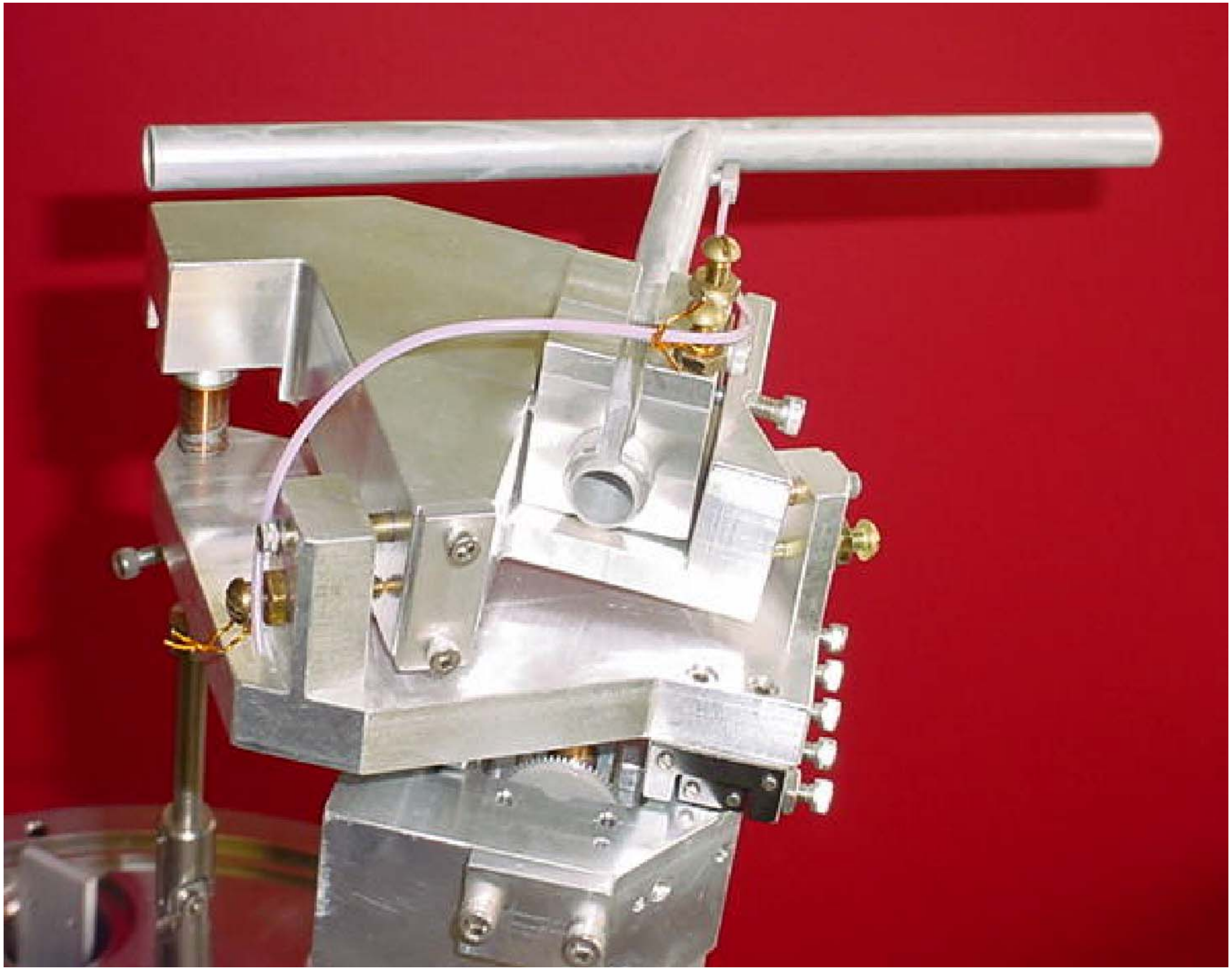
Target thickness

$\sim 10^{13}$ atoms/cm^2

Polarization ~0.6

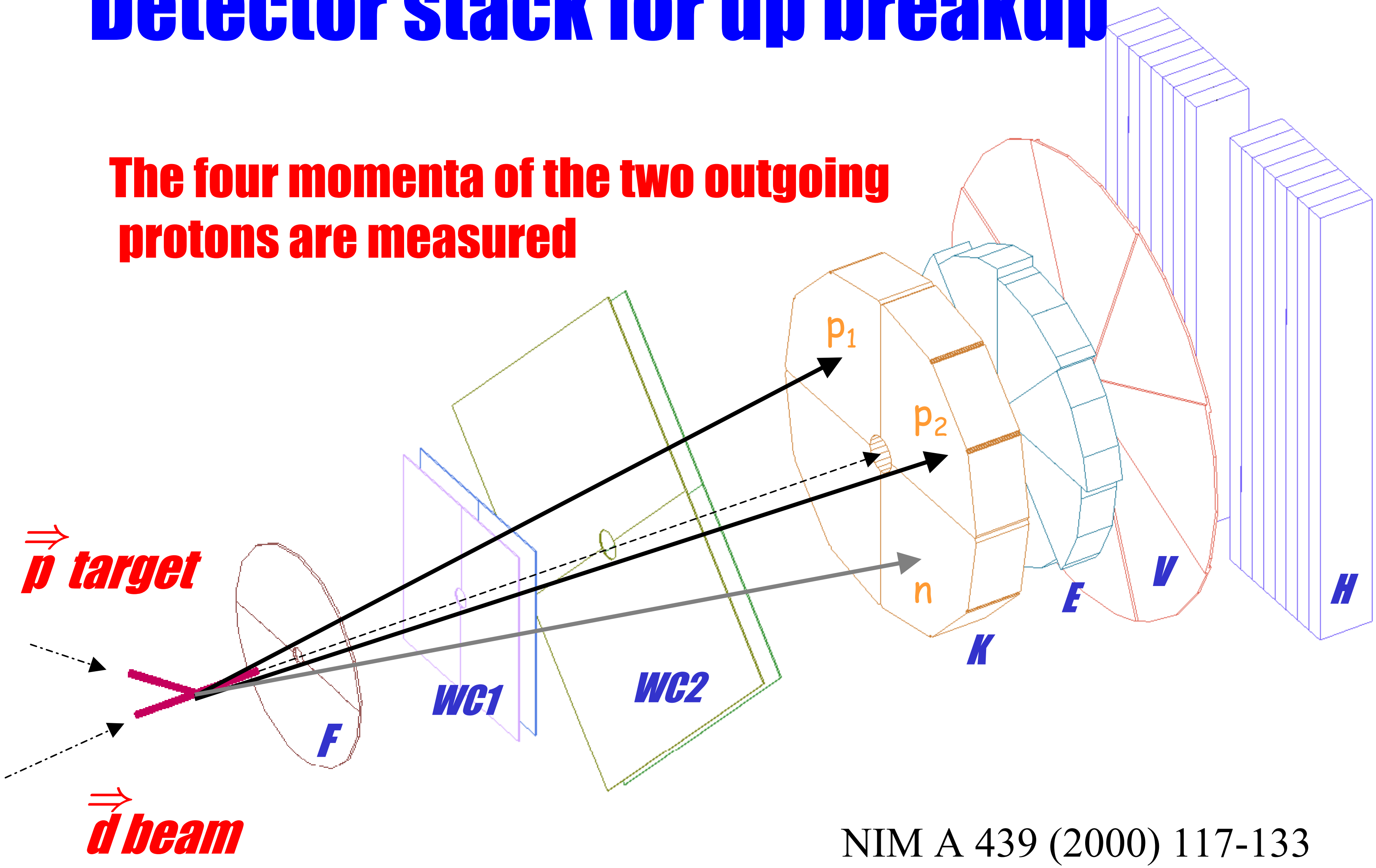
$\pm x$, $\pm y$, $\pm z$ directions

Target storage cell – side view



Detector stack for dp breakup

The four momenta of the two outgoing protons are measured

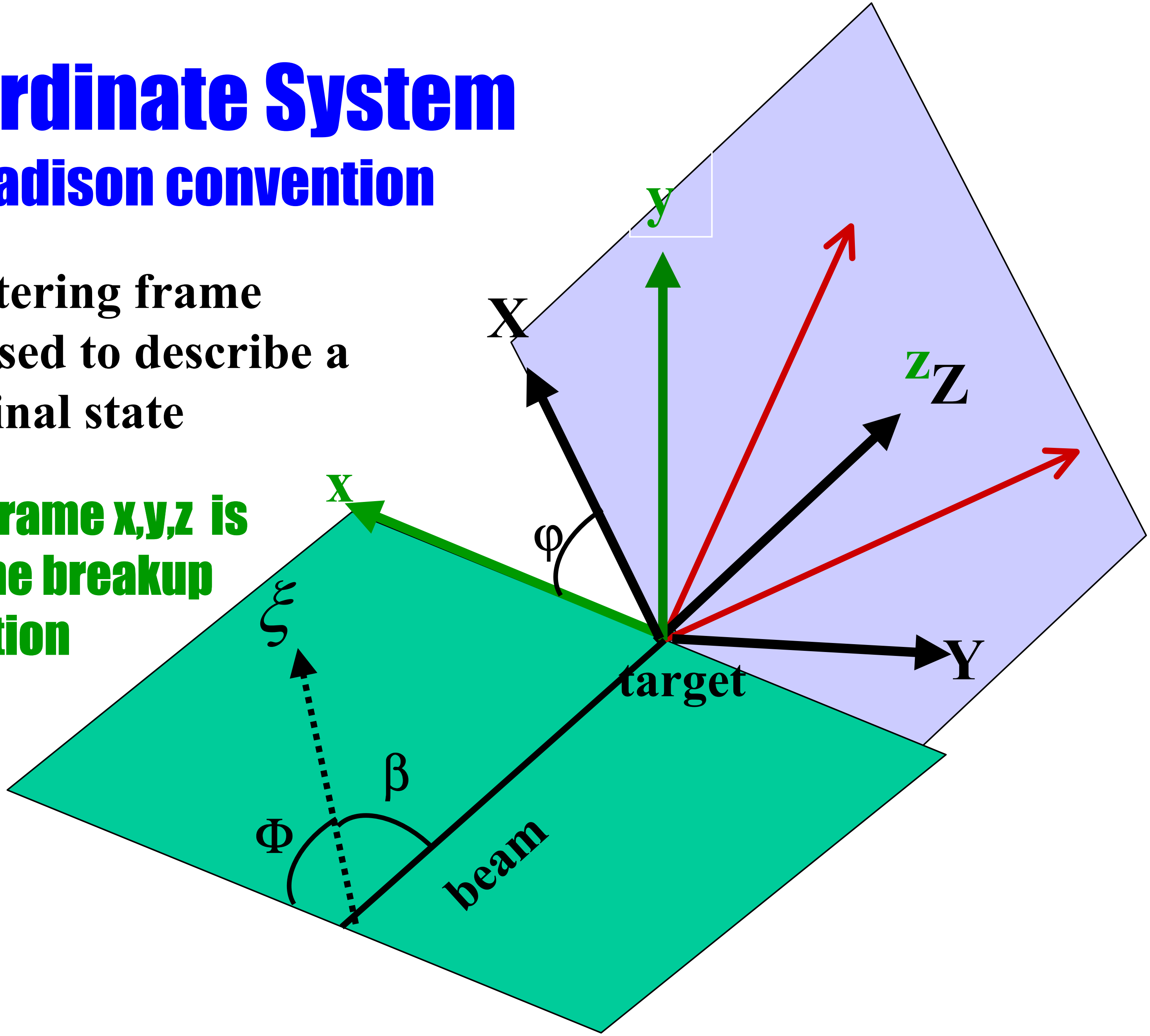


NIM A 439 (2000) 117-133

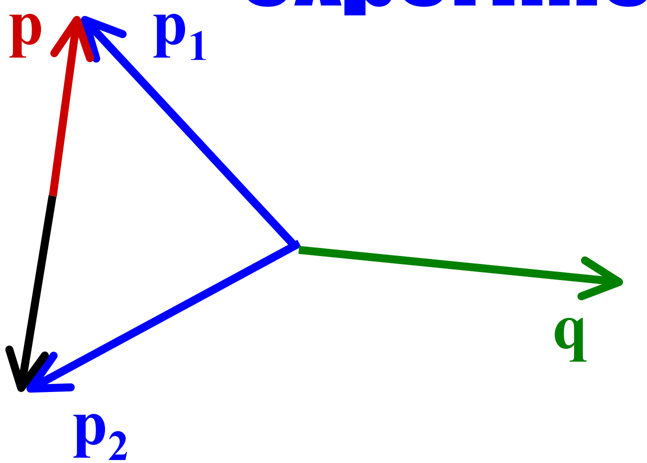
Coordinate System
Madison convention

The scattering frame X,Y,Z used to describe a 2-body final state

The fixed frame x,y,z is used for the breakup configuration



Comparison of theory and experiment for 3N final states



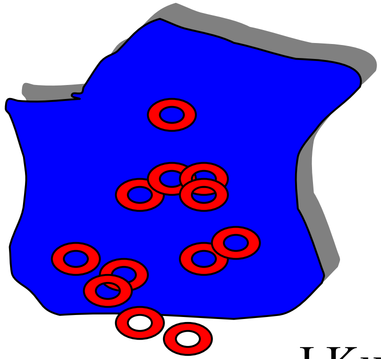
Jacobi momenta

$\mathbf{p} = ½ (\mathbf{p}_1 - \mathbf{p}_2)$

$\mathbf{q} = -(\mathbf{p}_1 + \mathbf{p}_2)$

$\Delta\varphi = \varphi(\mathbf{p}) - \varphi(\mathbf{q})$

- **Problem: How do we compare data to theory in a consistent way?**
  - **True experimental acceptance/efficieny?**
  - **Which is the most interesting observable and which independent variable to plot against, which to integrate over?**



The Sampling Method

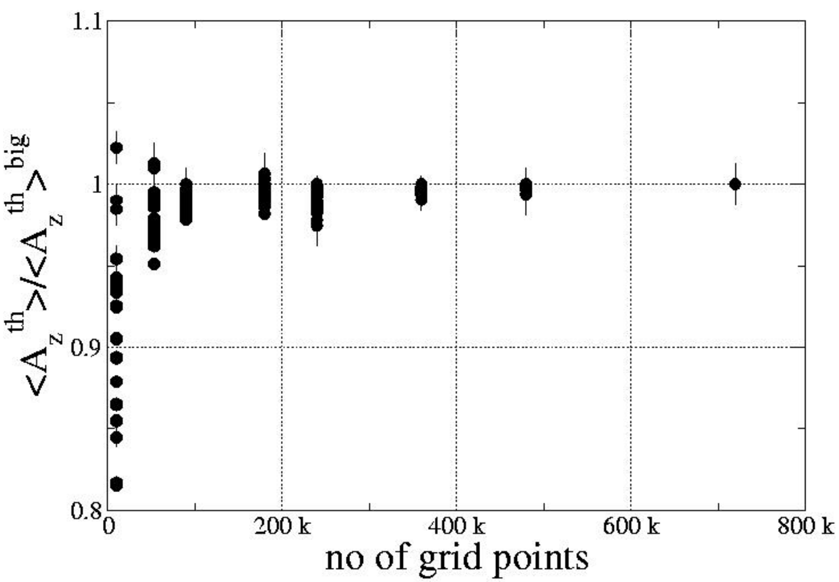
J.Kuros-Zolnierczuk, P.Thörngren, H.O. Meyer et al., FBS 34, 259 (2004)

- **For any 3b final state known with complete kinematics – 'sample' the theoretical value for each event in γ = (detected) region of phase space**

$$O_{th}(\gamma) = \frac{\int \sigma_0(x)\, \varepsilon(x)\, O_{th}(x)\, dx}{\int \sigma_0(x)\, \varepsilon(x)\, dx} = \frac{\sum_x N(x_i)\, O_{th}(x_i)}{\sum_x N(x_i)}$$

The Sampling Method Using a Grid

Few Body Syst. 34, 259 (2004)



- **Requirement:**
  - **Calculate a theoretical value for each event**

  Drawback: X time consuming
- **Solution:**
  - **Construct a grid covering phase space**
  - **Use multidimensional interpolation**

Four-dimensional

2^4=16 corners / grid cell

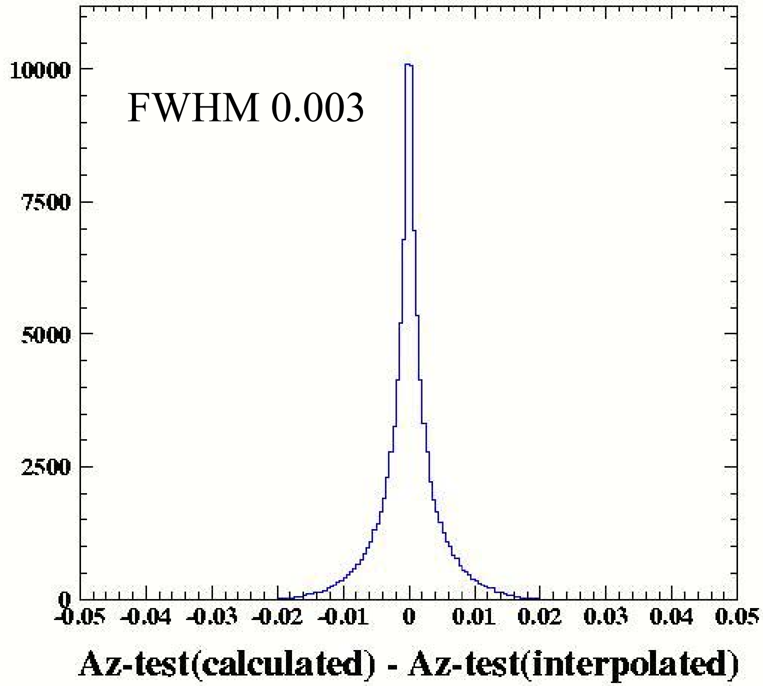
Five-dimensional:

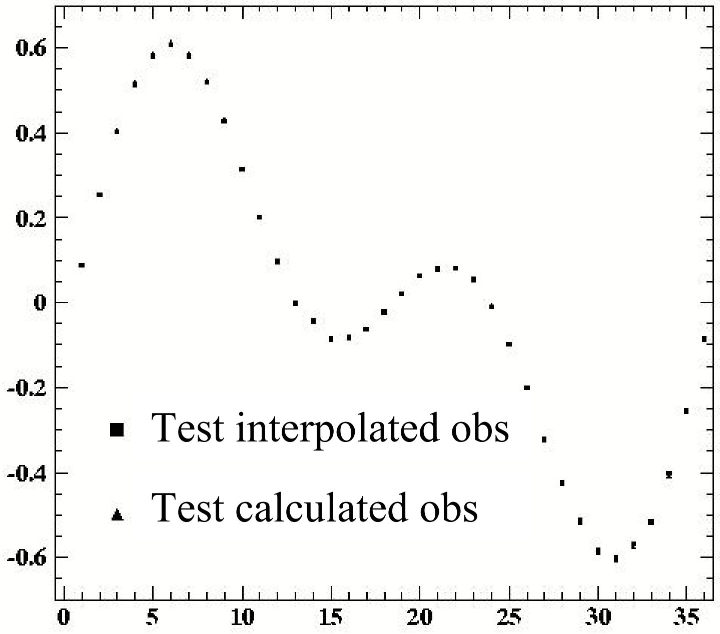
2^5=32 corners / grid cell

Grid behaviour

Few Body Syst. 34, 259 (2004)

- ❑ Test: Construct a 'fake' observable with similar angular dependencies

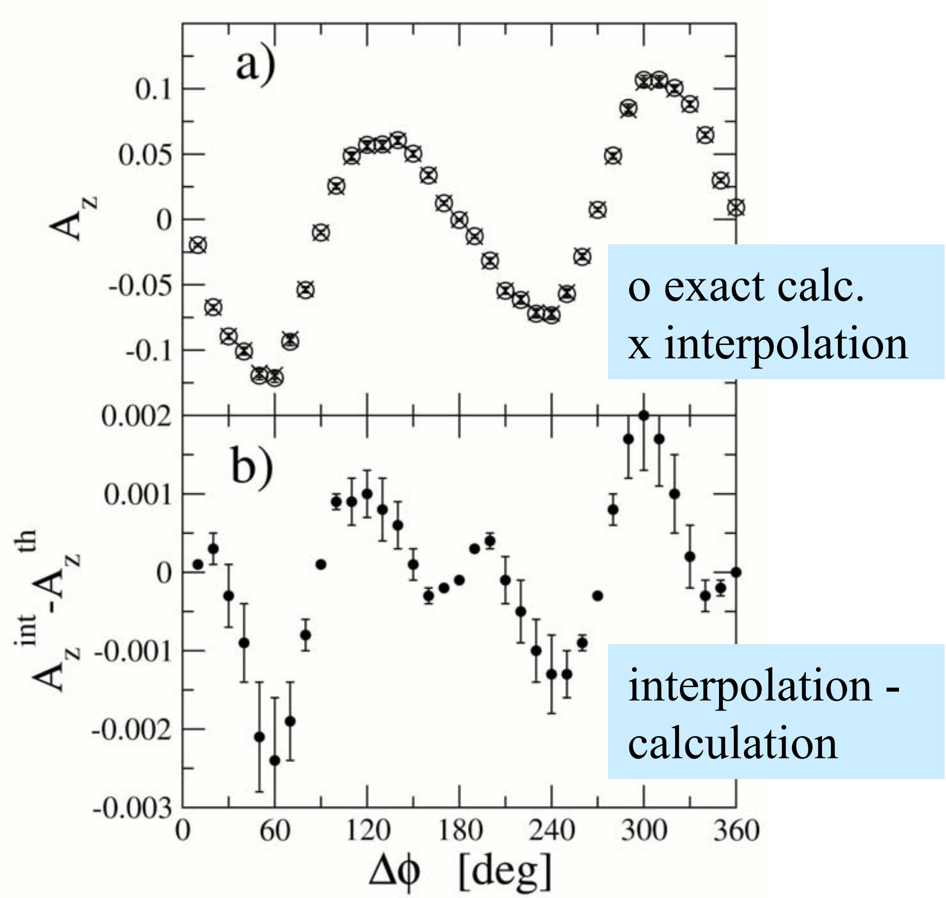




The Sampling Method Using a Grid

Few Body Syst. 34, 259 (2004)

- **Test of accuracy:**
  - **Compare single-shot exact calculation and interpolation**
- **Conclusion**
  - **The sampling method eliminates the necessity of monte carlo simulations and reflects the true detector acceptance and efficiency. Using a theoretical grid and interpolation reduces the computing time.**

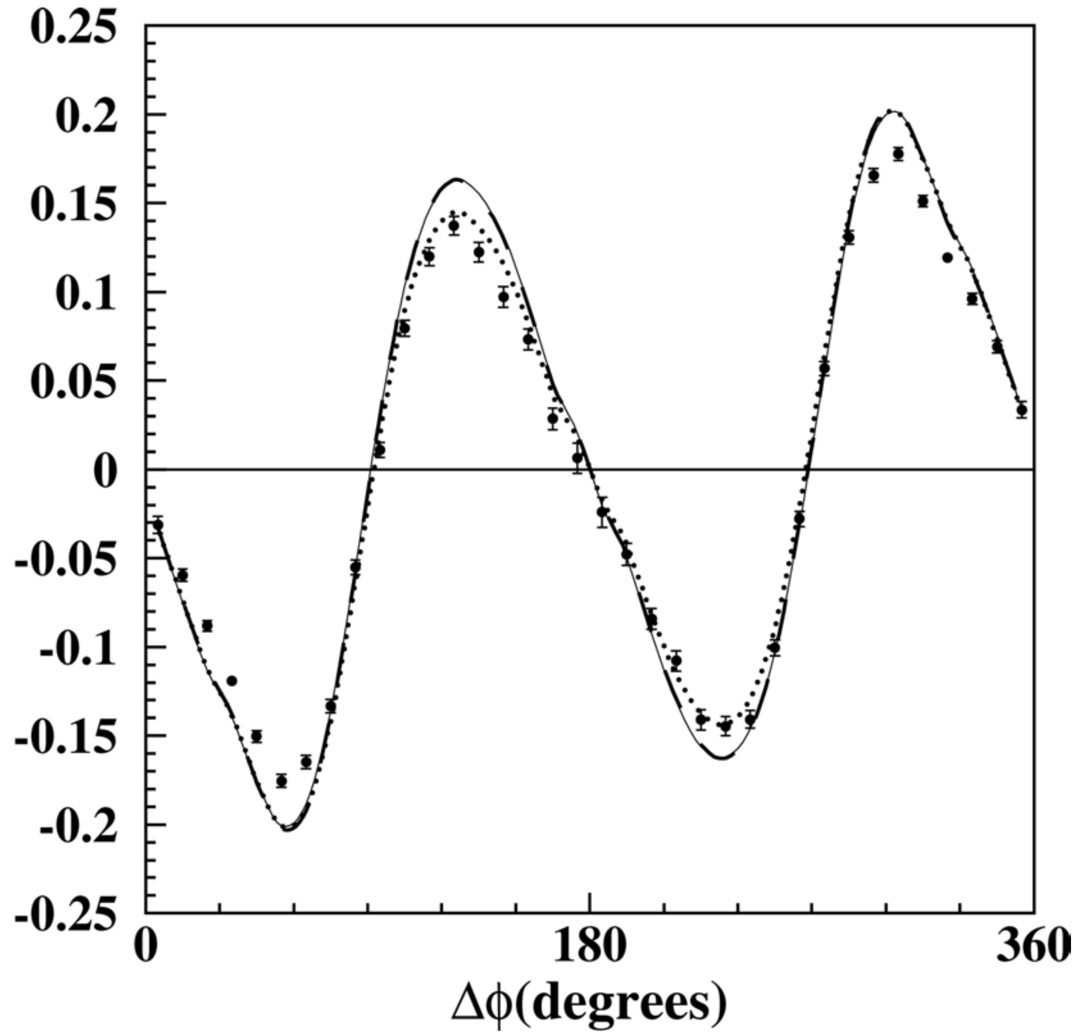


H.O. Meyer et al., accepted for publication PRL,
T.J. Whitaker PhD thesis, IUCF

A_z vs $\Delta\phi$

Data using all five beam states and $\pm z$ target

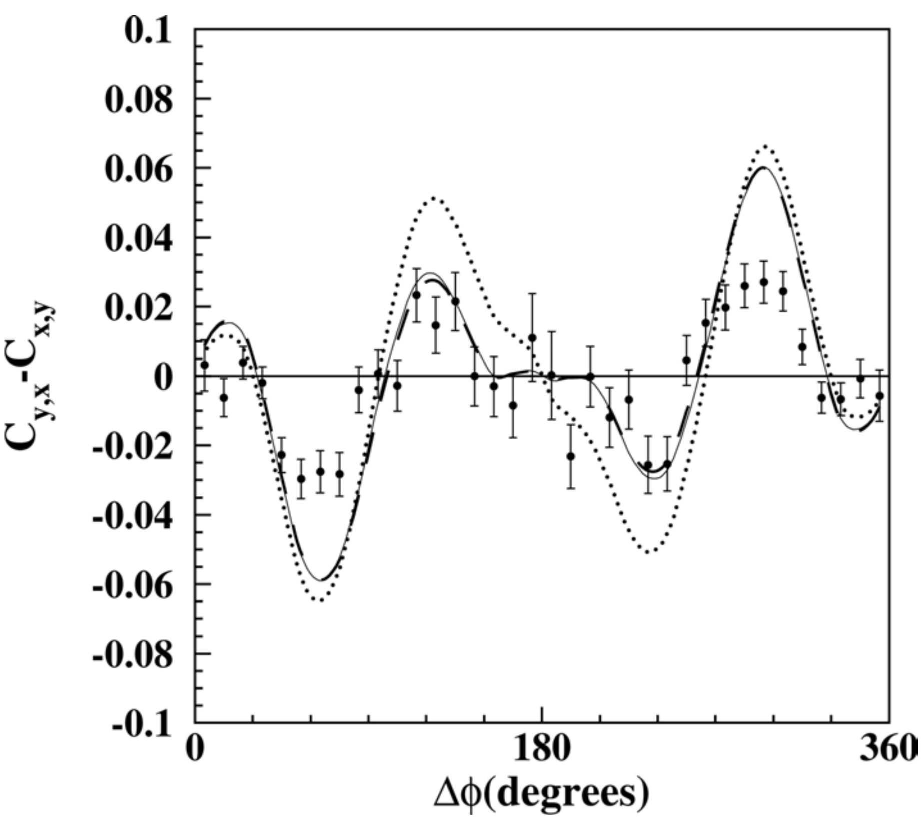
solid line: CD-Bonn
dashed: AV18
dotted: CD-Bonn+TM′

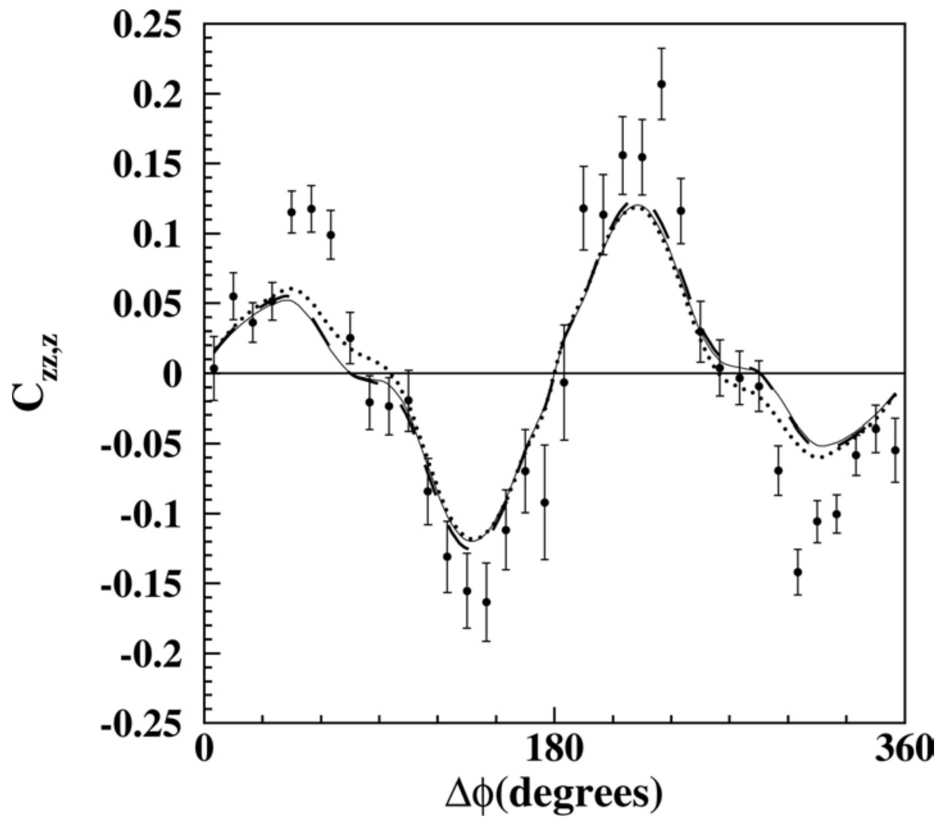


H.O. Meyer et al., accepted for publication PRL,
T.J. Whitaker PhD thesis, IUCF

solid line: CD-Bonn
dashed: AV18
dotted: CD-Bonn+TM´

$C_{y,x}$-$C_{x,y}$ and $C_{zz,z}$ as a function of $\Delta\phi$



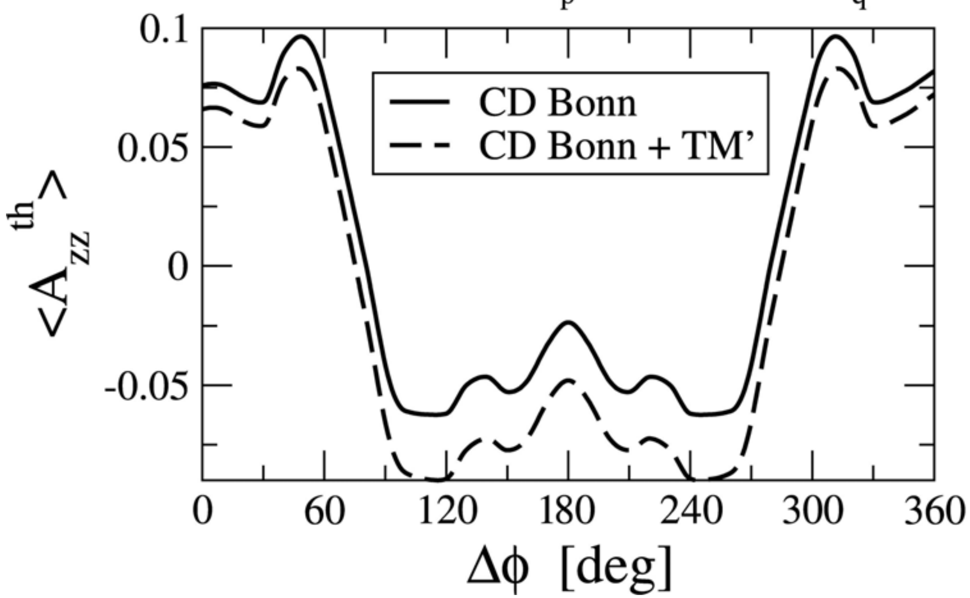


Tensor analyzing powers

- Using the tensor polarized beam states and summing over all target polarization: σ (tensor) =

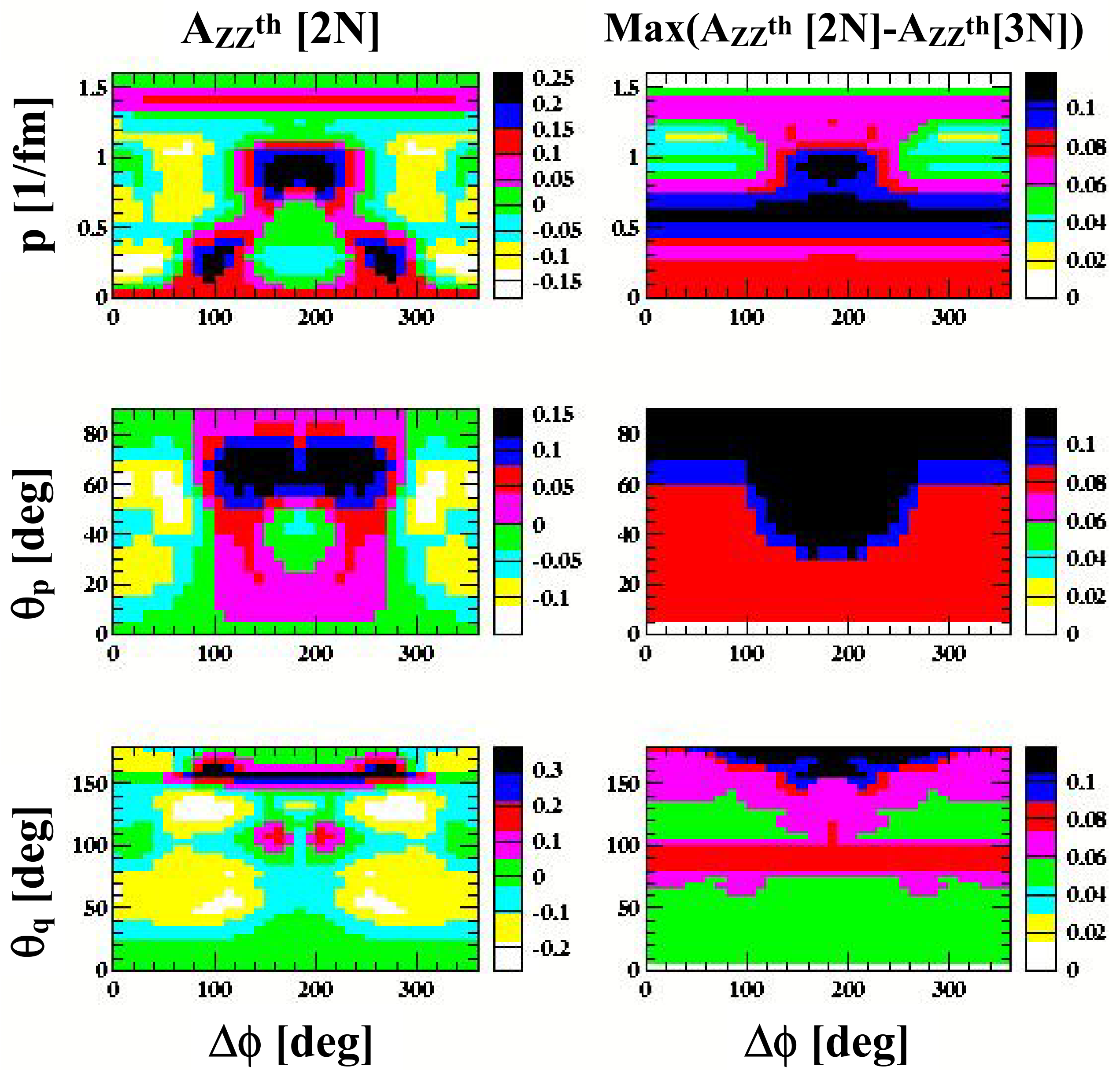
$$\sigma_0 \left(1 - \frac{1}{4} QQ \cos(2\,\phi)\,(Axx - Ayy) - \frac{1}{4} QQ\, Azz \right)$$

$0.05 \leq p \leq 1.45$, $5° \leq \theta_p \leq 90°$, $100° \leq \theta_q \leq 180°$



Using the grid -

To investigate theoretical predictions –



Joanna Kuros-Zolnierczuk

Krakow-Bochum group

Observables measured in dp breakup

- d+p breakup at T_d=270MeV
- Measured in this experiment:

(deuteron spin alignment +y)

- **Analyzing powers:** $A_y{}^p$, $A_z{}^p$, $A_y{}^d$, A_{zz} , $(A_{xx} - A_{yy})$
- **Vector-vector correlation coefficients:**

$(C_{x,x} - C_{y,y})$ $(C_{x,x} + C_{y,y})$ $C_{x,z}$ $(C_{y,x} - C_{x,y})$

- **Tensor-vector correlation coefficients**

$(C_{xx,y} - C_{yy,y})$ $C_{xy,x}$ $C_{xy,z}$ $C_{zz,y}$ $C_{zz,z}$

Summary and outlook

- A new method has been developed for the analysis of dp breakup reactions. It allows for quick searches for places in phase space that are sensitive for 3NF
- A_z , $(C_{y,x}$- $C_{x,y})$, $C_{zz,z}$ measured for the first time – they do not show enhanced sensitivity to TM´3NF

  Analysis of other observables is in progress, 3NF effects are predicted to be large in tensor analyzing powers
- The breakup data will together with the 15 measured spin observables in p+d elastic scattering, constrain any future 3NF model
  - Compare with predictions for 3N from chiral effective field theory

The tools are in place!

Acknowledgements

- The PINTEX collaboration:

  H.O. Meyer, J. Kuros-Zolnierscuk, B.v.Przewoski, P.Thörngren Engblom,T.J. Whitaker, J.T.Balewski, J.Doskow, W.W.Daehnick, W.Haeberli, R.Ibald, B.Lorentz, P.Pancella, F. Rathmann, Swapan K. Saha, A.Wellinghausen

Cross section for spin 1 on spin 1/2

- The most general case:

$$\sigma = \sigma_0 \Big(1 + py\, Ayp + pz\, Azp + \frac{3}{2} qy\, Ayd + \frac{3}{2} qz\, Azd + \frac{1}{6} (qxx - qyy)(Axx - Ayy) + \frac{1}{2} qzz\, Azz + \frac{2}{3} qxz\, Axz$$

$$+ \frac{3}{4} (qx\, px + qy\, py)(Cx\_x + Cy\_y) + \frac{3}{4} (qx\, px - qy\, py)(Cx\_x - Cy\_y) + \frac{3}{4} (qy\, px - qx\, py)(Cy\_x - Cx\_y)$$

$$+ \frac{3}{2} qx\, pz\, Cx\_z + \frac{3}{2} qz\, px\, Cz\_x + \frac{3}{2} qz\, pz\, Cz\_z + \frac{1}{6} (qxx - qyy)\, py\, (Cxx\_y - Cyy\_y) + \frac{1}{2} qzz\, pz\, Czz\_z + \frac{1}{2} qzz\, py\, Czz\_y$$

$$+ \frac{2}{3} qxy\, px\, Cxy\_x + \frac{2}{3} qxz\, py\, Cxz\_y + \frac{2}{3} qyz\, px\, Cyz\_x + \frac{2}{3} qxy\, pz\, Cxy\_z + \frac{2}{3} qyz\, pz\, Cyz\_z$$

$$+ \frac{1}{3} (qxz\, px + qyz\, py)(Cxz\_x + Cyz\_y) \Big)$$