CGSWHP
Caucasian-German School and Workshop on Hadron Physics
2014

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Deuteron breakup reactions at low energy

Testing the predictive power of chiral EFT N2LO:
2N-3N differences & Cut-off dependencies

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University of Ferrara and INFN
KTH Royal Institute of Technology

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Contents

- Motivation for a double polarized pd breakup experiment
- Experimental planned@COSY
- Analysis method: sampling of theoretical grids
- Simulation & Sampling
- Preliminary results from an experimental study
- Summary

- For introduction to PAX experiments: Talk by P. Lenisa
- For 3NF theory: Talk by A. Nogga
- For experimental details and overviews see talks by
  - Cassiti: PAX detector
  - Bertelli: Experiment 2011 (Ay in pd breakup)
  - Lenisa: Silicon detectors
  - Khoukaz: Internal targets

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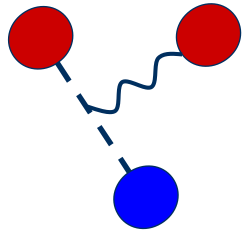
People

- **Theory: E. Epelbaum and A. Nogga**
- **PAX Collaboration**:S Barsov, Z Bagdasarian, S Bertelli, D Chiladze, A Kacharava, P Lenisa, N Lomidze, B Lorentz, G Macharashvili, K Marcks von Würtemberg, S Merzlyakov, S Mikirtytchiants, A Nass, D Oellers, F Rathmann, R Schleichert, H Ströher, PTE, M Tabidze, S Trusov, C Weidemann, M Zhabitsky and more …for PAX and ANKE Collaborations
- **COSY crew:** D. Prasuhn and B.Lorentz et al.

Motivation:
3Nucleon Force - What is it?



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

- 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):

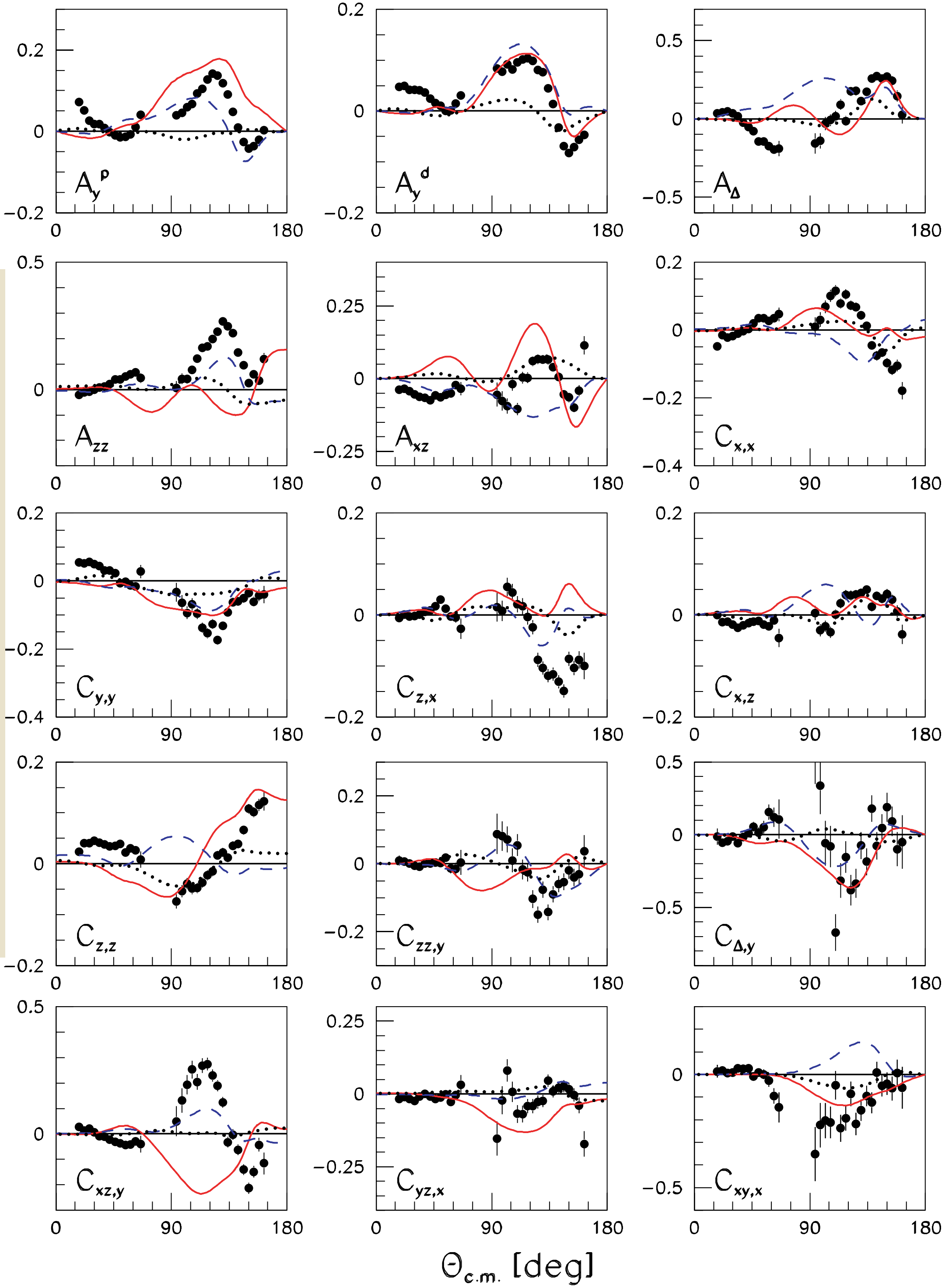
$$H = T + \sum V_{ij} + V_{1,2,3}$$

"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."

PINTEX@IUCF

pd elastic@135 MeV

B. v. Przewoski, *et. al*, PRC, 74, 064003 (2006)



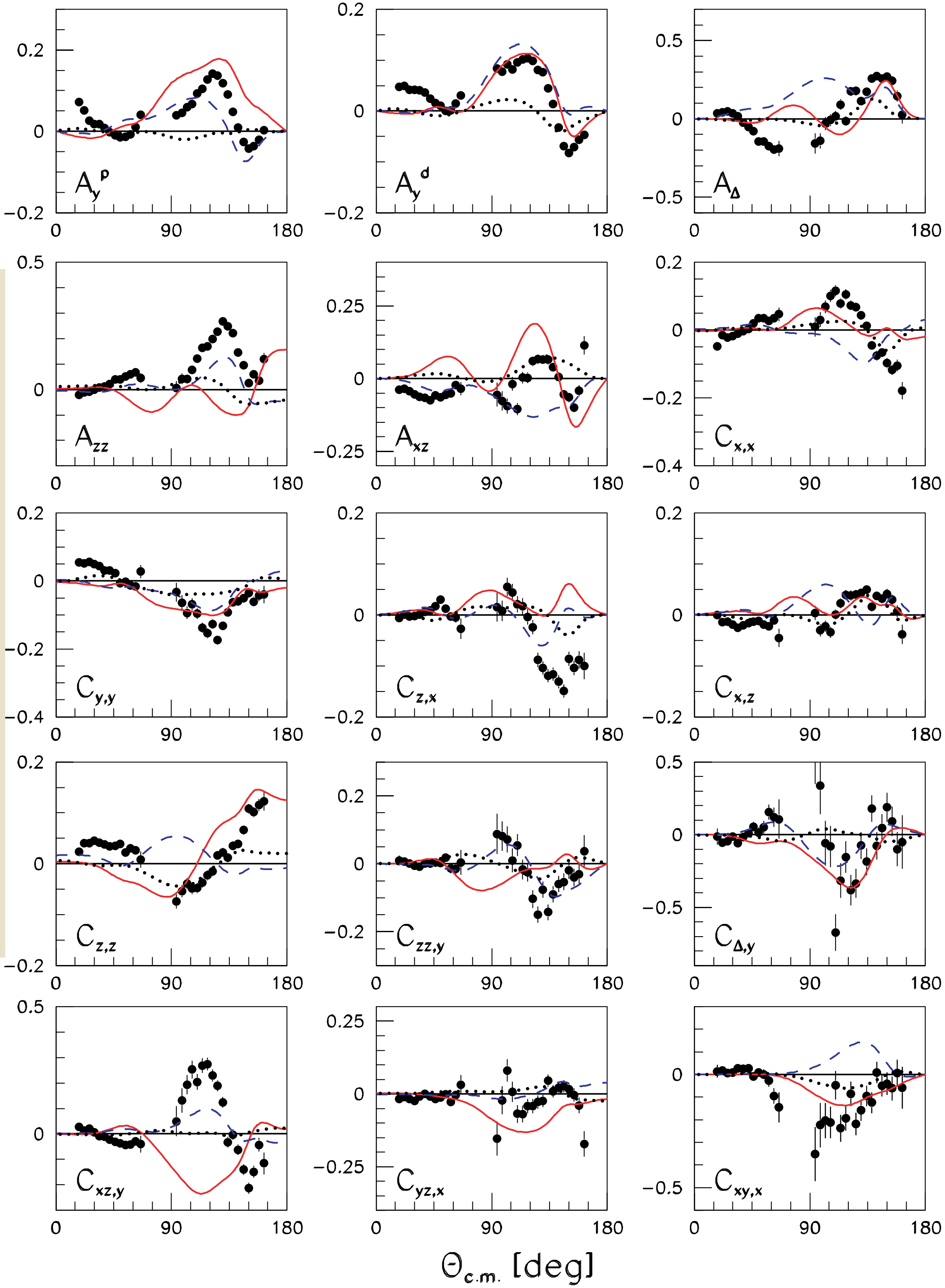
Difference **DATA-THEORY**

AV18 & CDBonn

CDBonn + TM

CDBonn+ TM'

B. v. Przewoski, *et. al*, PRC, 74, 064003 (2006)



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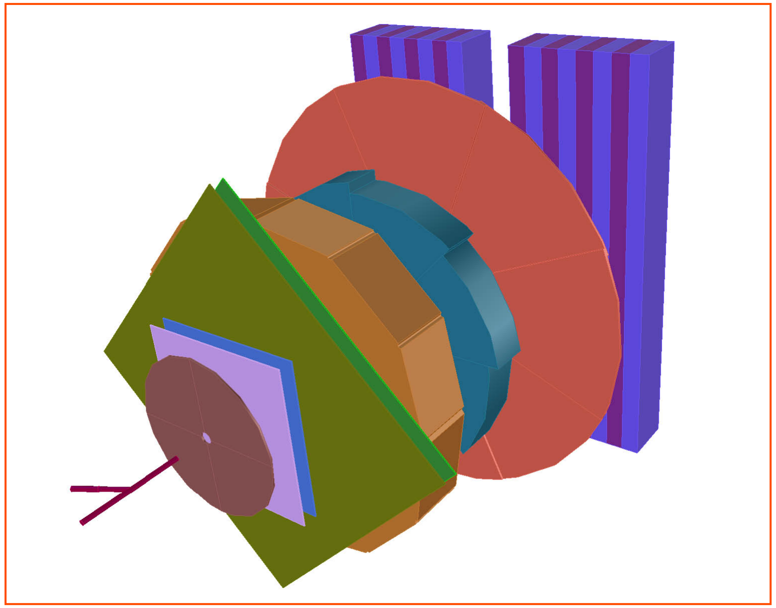
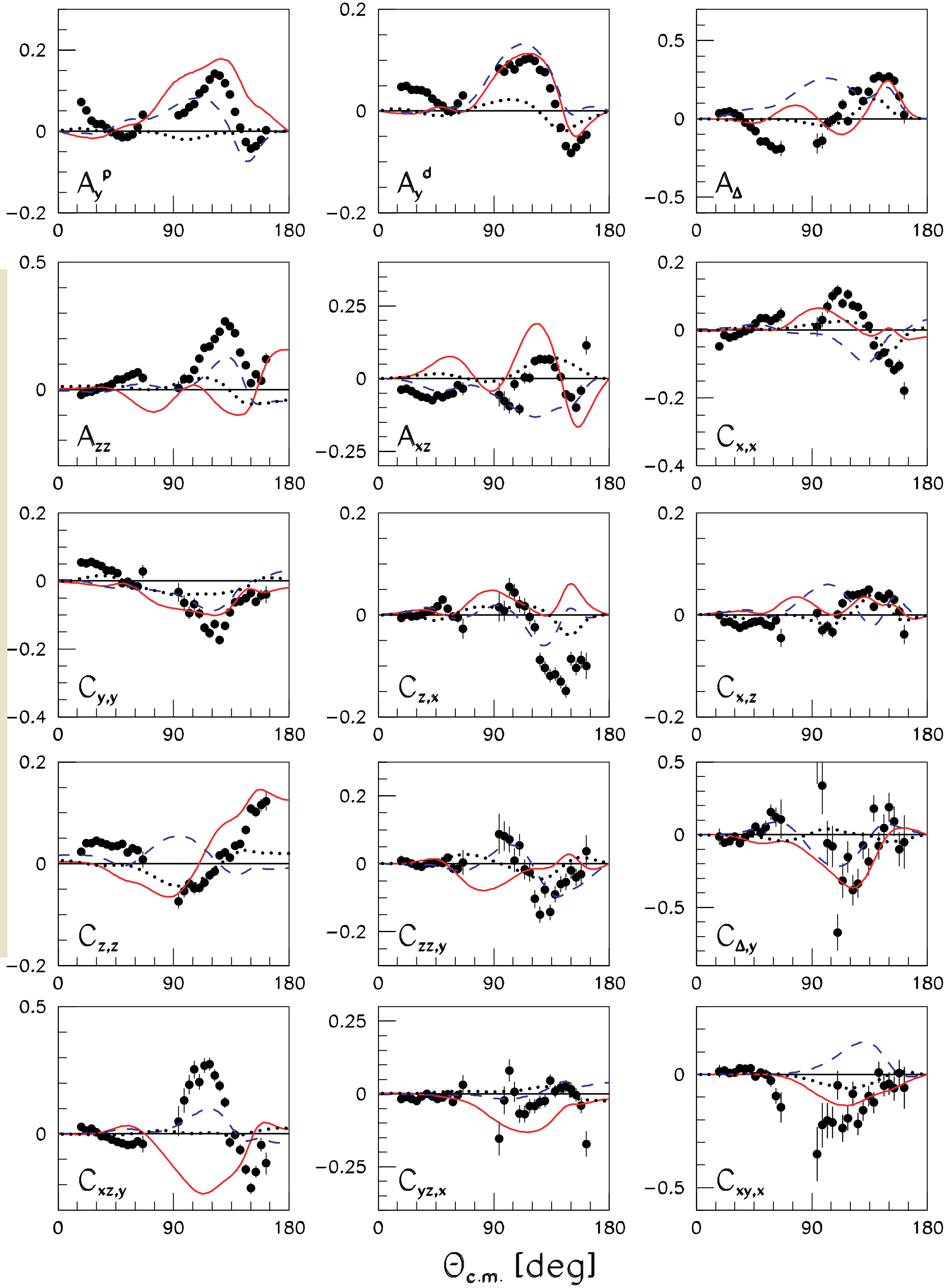


PINTEX@IUCF



B. v. Przewoski, *et. al*, PRC, 74, 064003 (2006)

pd elastic@135 MeV

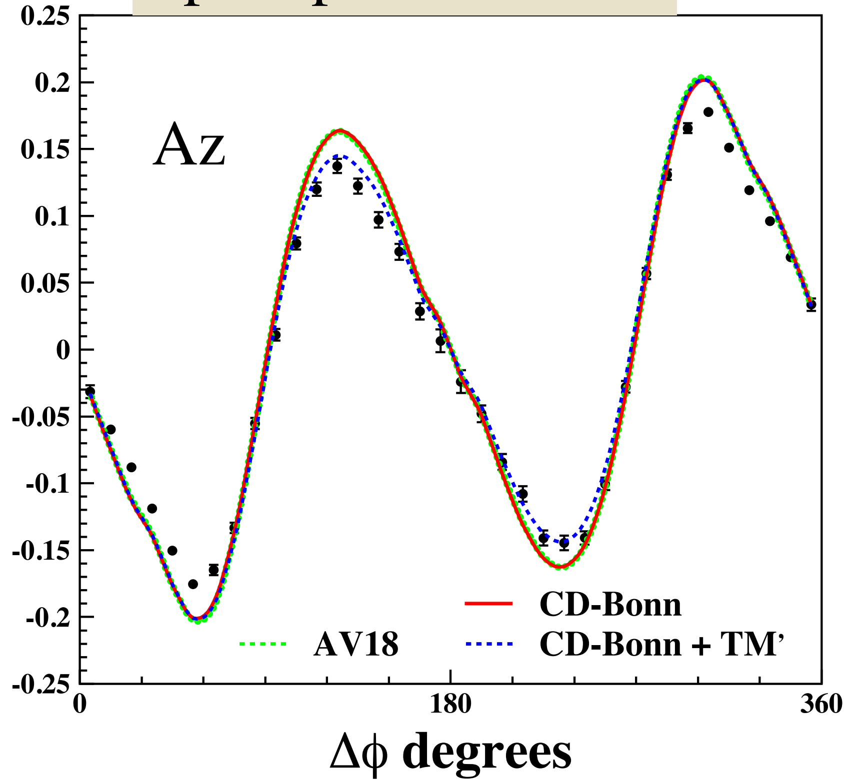
Difference **DATA-THEORY**

AV18 & CDBonn

CDBonn + TM

CDBonn+ TM'

dp bup@270 MeV

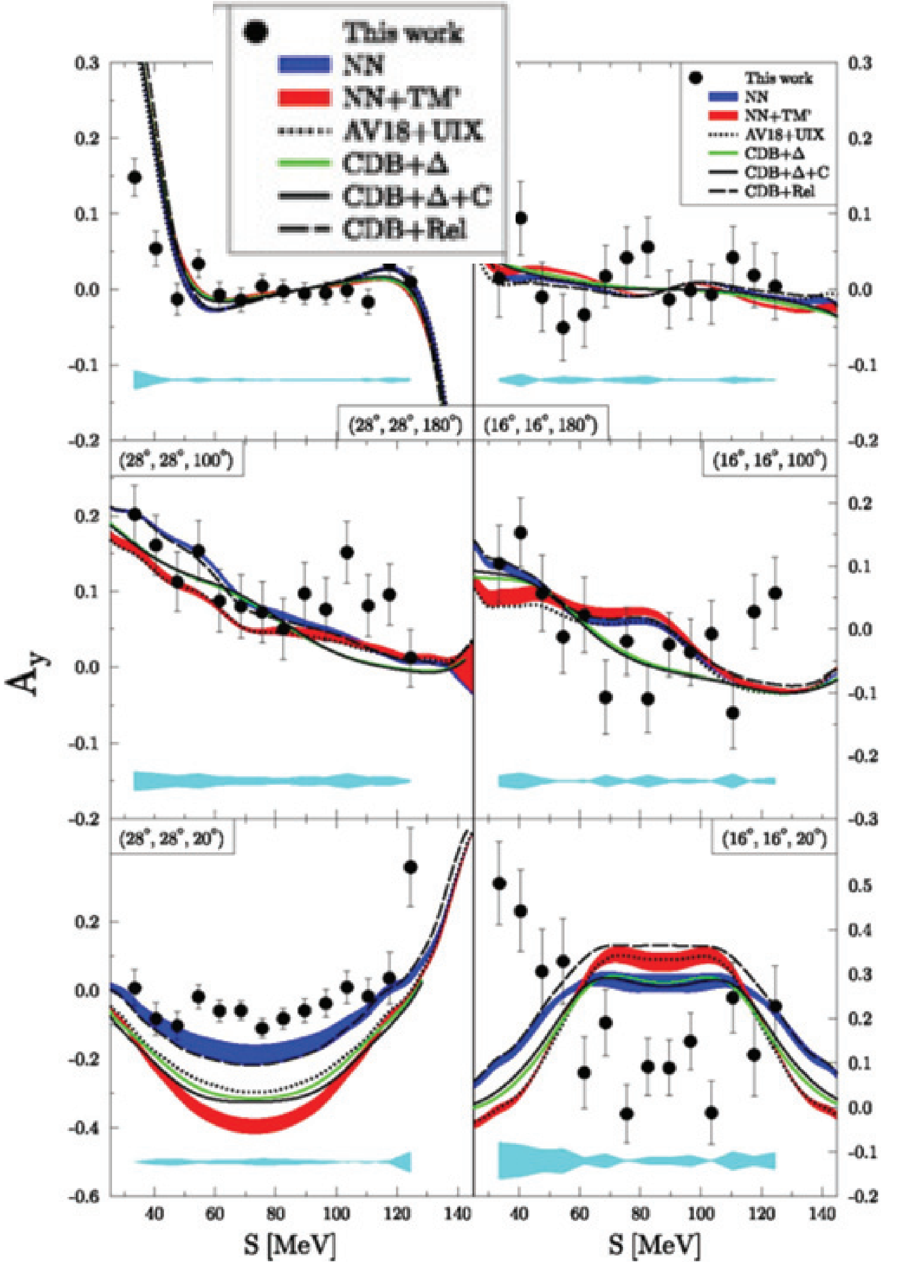


H.O. Meyer *et al.*, Phys. Rev. Lett. 93, 112502 (2004)
T.J. Whitaker IUCF PhD thesis

Ay pd bup@135 MeV

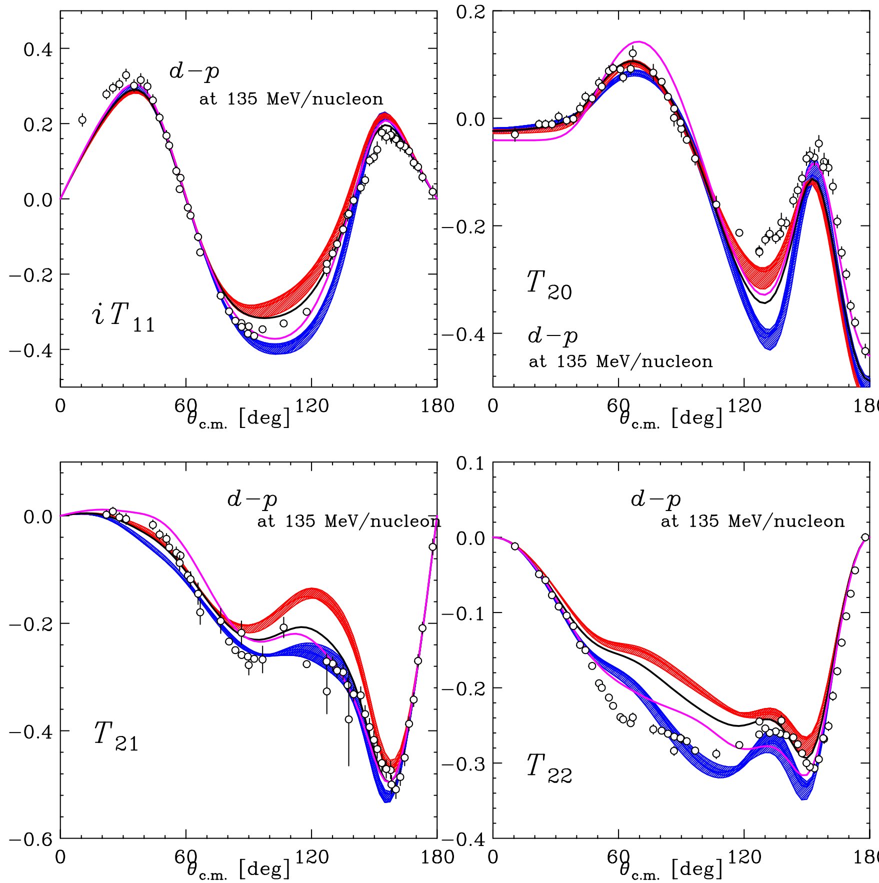
M. Eslamii-Kalantari *et al., @KVI*

Kistryn & Stephan J. Phys. G: Nucl. Part. Phys. **40** (2013) 063101



dp elastic at 135 MEV/nucleon

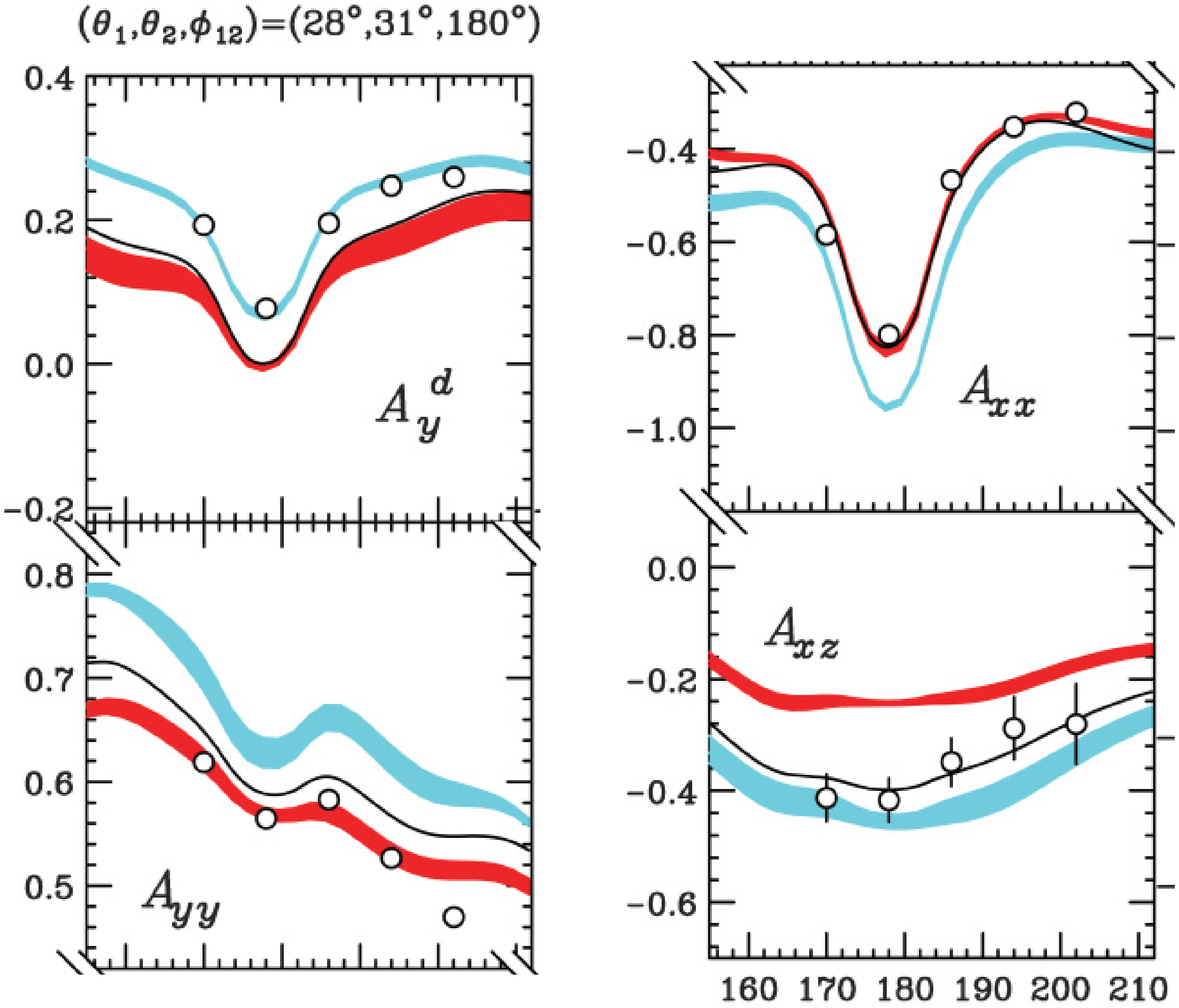
K. Sekiguchi et al. @ RIKEN



- NN(CDBonn, AV18, Nijmegen I,II)
- NN(CDBonn, AV18, Nijmegen I,II) + TM'99 3NF
- NN(AV18) + Urbana IX 3NF
- NN(CDBonn) + Delta-isobar
- NN(CDBonn) + Delta-isobar + Coulomb

$^1H(d, p1p2)n$ @135 MeV/Nucleon

K.Sekiguchi *et al.*, PRC **79**, 054008 (2009)



S [MeV]

AV18, CD-Bonn
Nijmegen I, Nijmegen II

+ TM′ (99) 3NF

AV18 + Urbana IX 3NF

Motivation

Comparison between data and theoretical predictions:

Combining 3N forces with NN-potentials sometimes lead to

→ improved agreement

→ worse agreement

→ no effect

B. v. Przewoski, *et. al,* PRC, 74, 064003 (2006), arXiv:nucl-ex/0411019

K. Sekiguchi *et al*., PRC 70, 014001 (2004), PRC 79, 054008 (2009)

Kalantar-Nayestanakir, Epelbaum, Messchendorp,Nogga; Rep.Prog.Phys 1108.1227 (2011)

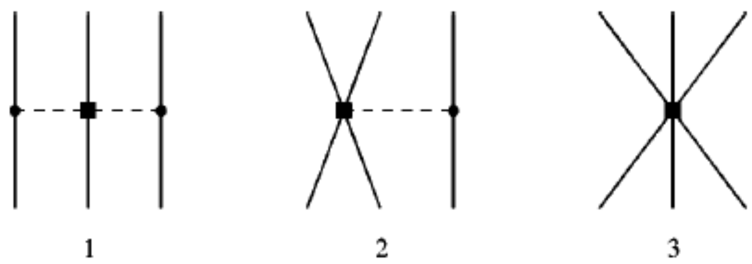
Kistryn & Stephan J. Phys. G: Nucl. Part. Phys. **40** (2013) 063101

….Progress require theoretical development & support →

Modern theory of nuclear forces

Epelbaum, Prog. Part. Nucl. Phys. 57 (2006) 57

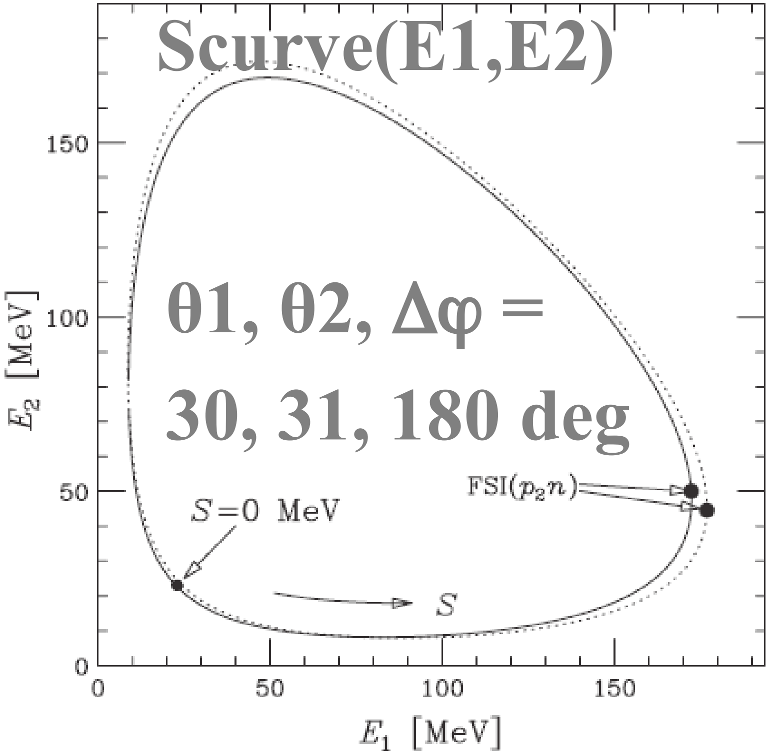
- Chiral effective field theory:
  - Systematic & model independent framework for low-energy few-nucleon physics
  - Few body forces enter naturally with increasing order
- At N2LO - first nonvanishing terms from the chiral Three-Nucleon Force (3NF)
  - Two-pion exchange
  - One-pion exchange
  - Contact interaction



Epelbaum et al., PRC 66, 064001 (2002)

E. Epelbaum, H.-W. Hammer, U.-G. Meißner, Rev. Mod. Phys. 81 (2009) 1773
R. Machleidt, D.R. Entem, Phys. Rep. 503 (2011) 1
E. Epelbaum, U.-G. Meißner, Ann. Rev. Nucl. Part. Sci. 62 (2012) 159-185

Why pd bup? 3 particles in the final state → 5 independent variables



G.G.Ohlsen, NIM 179 (1981) 283

Why pd bup? 3 particles in the final state → 5 independent variables

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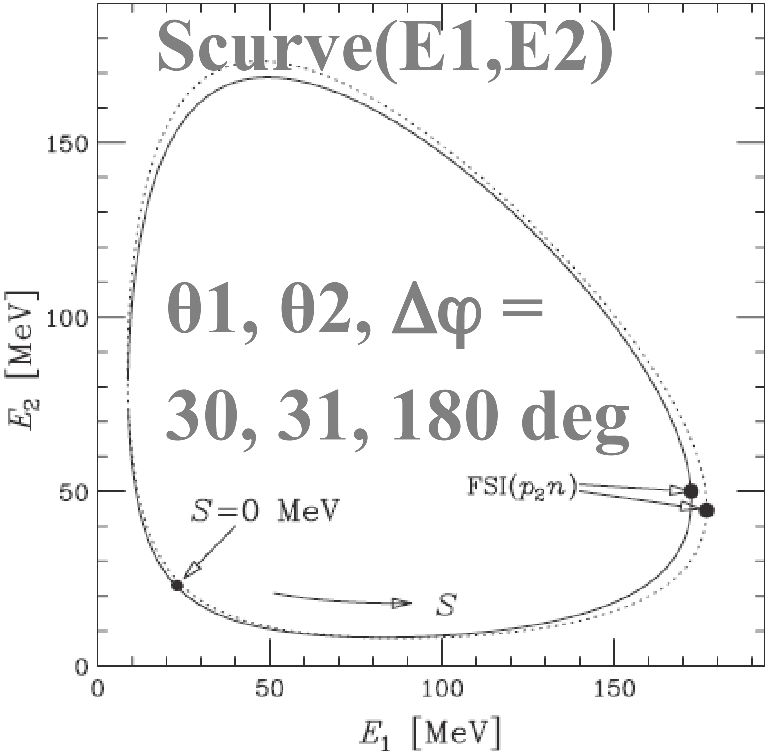
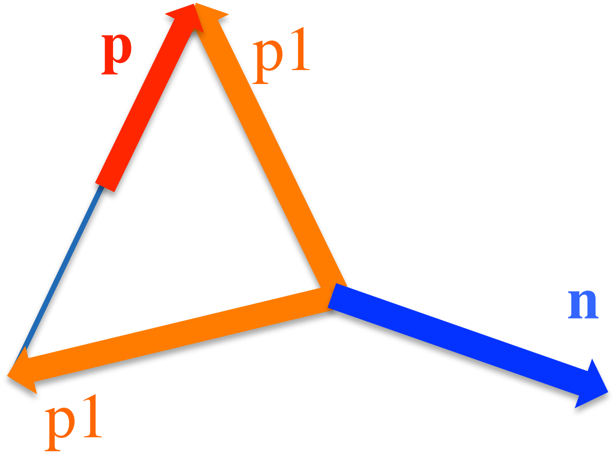


G.G.Ohlsen, NIM 179 (1981) 283

Exploit the rich kinematics



Jacobi momenta cm:

p = ½ (p1 - p2)

q = - (p1 + p2)

{ p, θp, ϕp, θq, ϕq }

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Why spin? & Why double polarized?

$$
\begin{aligned}
\sigma \quad = \quad & \sigma_0 (1 + p_y A_y(p) + p_z A_z(p) + \frac{3}{2} q_y A_y(d) + \frac{3}{2} q_z A_z(d) \\
& + \frac{3}{4}(q_x p_x + q_y p_y)(C_{x,x} + C_{y,y}) + \frac{3}{4}(q_x p_x - q_y p_y)(C_{x,x} - C_{y,y}) \\
& + \frac{3}{4}(q_y p_x - q_x p_y)(C_{y,x} - C_{x,y}) + \frac{3}{2} q_x p_z C_{x,z} + \frac{3}{2} q_z p_x \ C_{z,x} + \frac{3}{2} q_z p_z C_{z,z} \\
& + \frac{1}{6}(q_{xx} - q_{yy})(A_{xx} - A_{yy}) + \frac{1}{2} q_{zz} A_{zz} + \frac{2}{3} q_{xz} A_{xz} \\
& + \frac{1}{6}(q_{xx} - q_{yy}) p_y (C_{xx,y} - C_{yy,y}) + \frac{1}{2} q_{zz} p_z C_{zz,z} + \frac{1}{2} q_{zz} p_y C zz, y \\
& + \frac{2}{3} q_{xy} p_x C_{xy,x} + \frac{2}{3} q_{xz} p_y C_{xz,y} + \frac{2}{3} q_{yz} p_x C_{yz,x} \\
& + \frac{2}{3} q_{xy} p_z C_{xy,z} + \frac{2}{3} q_{yz} p_z C_{yz,z} + \frac{1}{3}(q_{xz} p_x + q_{yz} p_y)(C_{xz,x} + C_{yz,y}))
\end{aligned}
$$

PolObs	pU dU	pU dS	pU dA	pA dU	pA dS	pA dA	pU dAU	pU dAS
$A_y(p)$	X	X	X				X	X
$\mathbf{A_z(p)}$				X	X	X	pA dAU	pA dAS
$A_y(d)$	X	X		X	X		X	X
$\mathbf{A_z(d)}$			X			X	X	X
$A_{xx} - A_{yy}$	X	X		X	X		X	X
A_{zz}	X	X	X	X	X	X	X	X
A_{xz}							X	X
[illegible]	[illegible]						[illegible]	
$C_{x,x} + C_{y,y}$	X						X	
$C_{x,x} - C_{y,y}$	X	X					X	X
$\mathbf{C_{y,x} - C_{x,y}}$		X						X
$C_{x,z}$				X	X		pA dAU	pA dAS
$C_{z,x}$			X				X	X
$C_{z,z}$						X	pA dAU	pA dAS
[illegible]	[illegible]	[illegible]					[illegible]	[illegible]
$C_{xx,y} - C_{yy,y}$	X	X					X	X
$\mathbf{C_{xz,x} + C_{yz,y}}$						X	X	
$\mathbf{C_{zz,z}}$				X	X	X	pA dAU	pA dAS
$C_{zz,y}$	X	X	X				X	X
$C_{xy,x}$	X	X					X	X
$C_{xz,y}$							X	X
$C_{yz,x}$							X	X
$C_{xy,z}$				X	X		pA dAU	pA dAS
$C_{yz,z}$							pA dAU	pA dAS

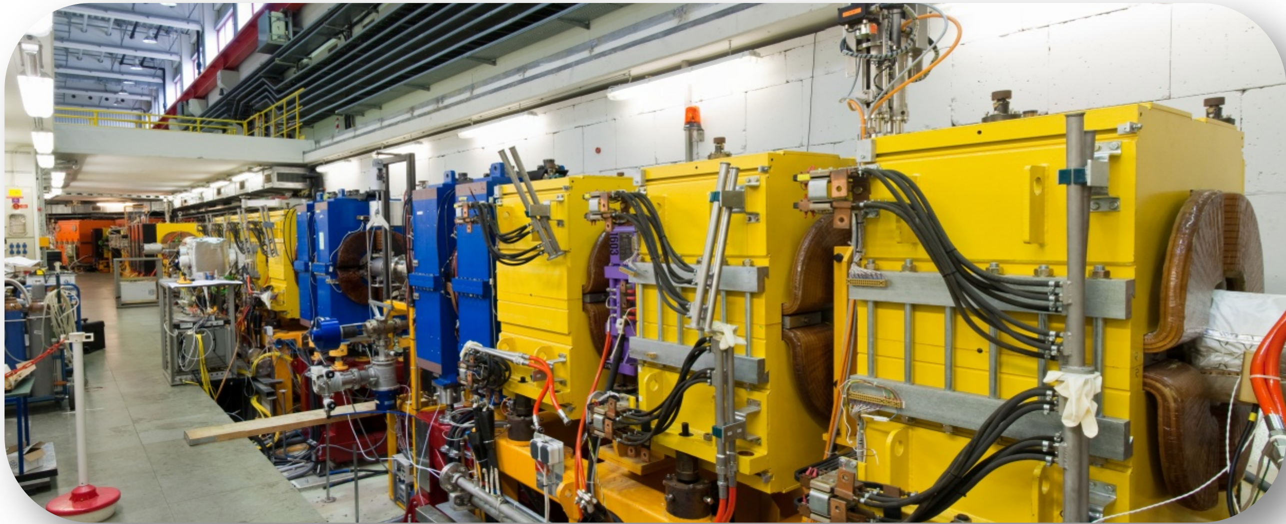
EXPERIMENTAL SETUP

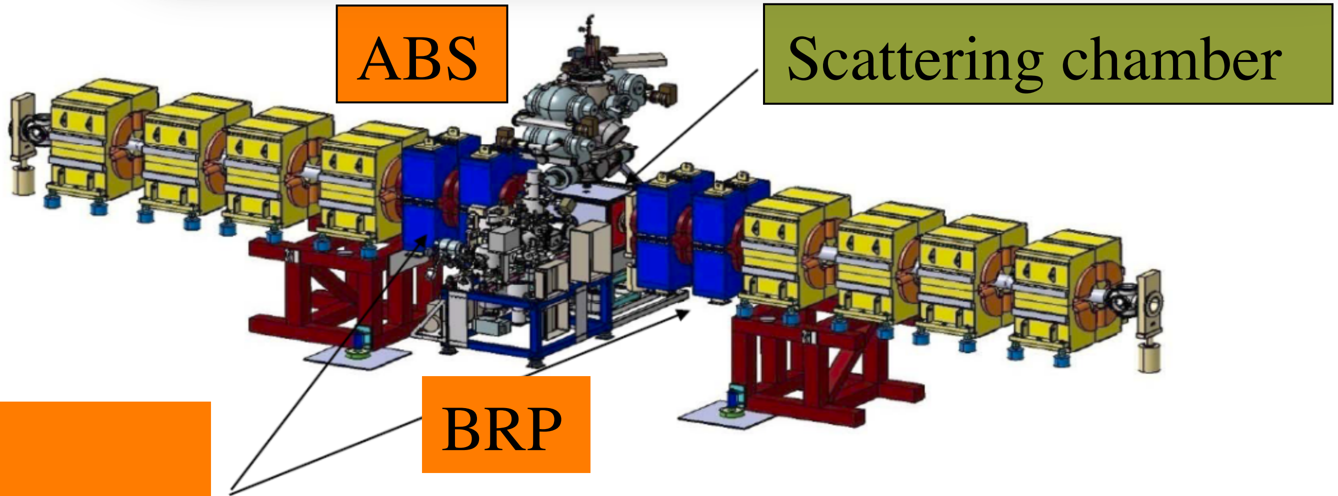
COSY Cooler synchrotron & storage ring

600 - 3700 MeV/c

Polarized proton & deuterons

PAX interaction point

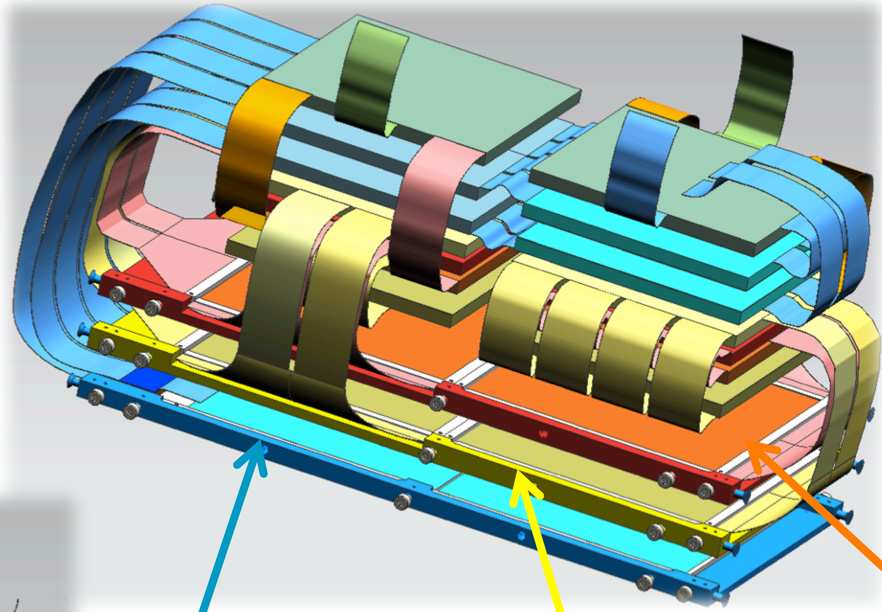




PAX detector development
COSY & AD

Talk by V. Carassiti

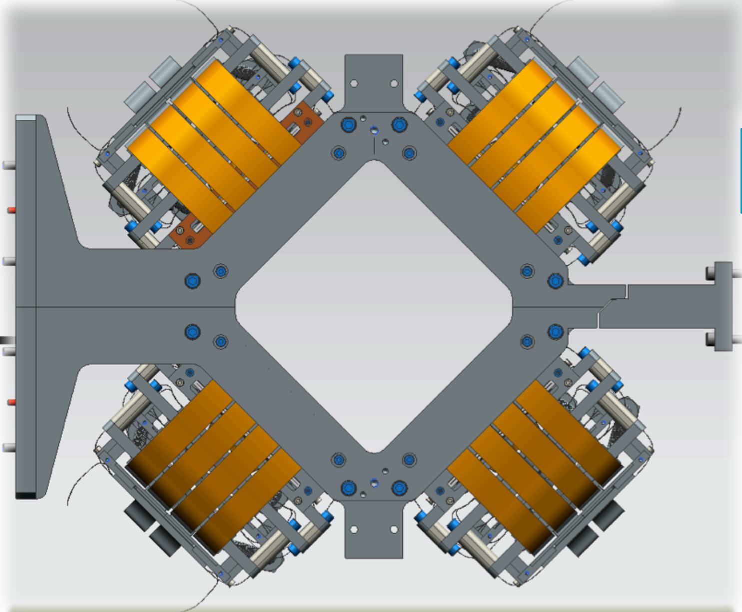
3 detector layers
φ−symmetric
4 quarters



Hermes 300 μm | PAX 300 μm | PAX 1.5 mm

Double-sided silicon strip sensors
Pitch 0.7 mm → vertex resolution ≤ 1mm

Inward ring



Detector setup front view

Experiment 2DO:
Double polarized pd bup @30-50 MeV @COSY

- **To test the predictive power of the Modern theory of nuclear forces (talk by Nogga)**
  - ➢ Validity of chiral EFT – N2LO ---→

'Low' energy ~30-50 MeV proton beam energy

- **Proton deuteron breakup → 3 nucleon interactions**
  - Rich variety of kinematical configurations
    - Five independent kinematical parameters
  - Using polarized beam & vector-tensor polarized target

---→22 independent spin observables

- 7 analyzing powers
- 6 vector-tensor correlation
- 9 tensor-tensor correlation parameters

More information:
COSY Proposal 202, PTE et al., ***Measurement of Spin Observables in the pd Breakup Reaction***,
http://www2.fz-juelich.de/ikp/publications/PAC39/PAX_proposal202.1_202.pdf

Preamble

3 particles in the final state: Comparison of theory to experimental data

- **Problem 1:**
  - Complexity of 3-particle final states
    - five independent kinematic variables (3 x dof – 4)
    - what part of phase space to integrate over
    - …acceptance + efficiency + systematics…
- **Solution 1:**
  - **Expose theory to the experiment**
    - Analysis → event list of accepted events
    - Calculate the theoretical prediction for each event
- **Problem 2:**
  - Time consuming & cumbersome (complexity of theory)
- **Solution 2:**
  - **Use pre-calculated grids covering phase space**
- **Examples: Azz@135 MeV/A**
- **Ay(N)@49.3 MeV proton beam energy**

Kuros-Zolnierczuk *et al.*, Few-BodySyst. **34**, 259 (2004)
PTE *et al.*, AIP Conf. Proc. **768**, 65 (2005), nucl-ex/0410006
H.O. Meyer *et. al*, PRL 93, 112502 (2004)

The sampling method – a shortcut

J. Kuros´-Żołnierczuk, P. Thörngren-Engblom, H.O. Meyer, T.J. Whitaker, H. Witała, J. Golak, H. Kamada, A. Nogga and R. Skibiński, Few-Body Systems **34**, 259 (2004)

◆ **Applicable to kinematically complete measurements**

1) Determine the theoretical O^{th} for each analyzed event
2) Sum these values and divide by the number of events

NOTE: This can be done for any chosen observable as fcn of any independent parameter of interest

In simple terms:

$$O^{\mathrm{th}}(\gamma) = \langle O^{\mathrm{th}} \rangle = \frac{\sum O^{\mathrm{th}}(x_k)}{N(\gamma)}$$

◆ **In other words:**

- expose the theory to the experiment

3 particles in the final state: Comparison of theory to experimental data

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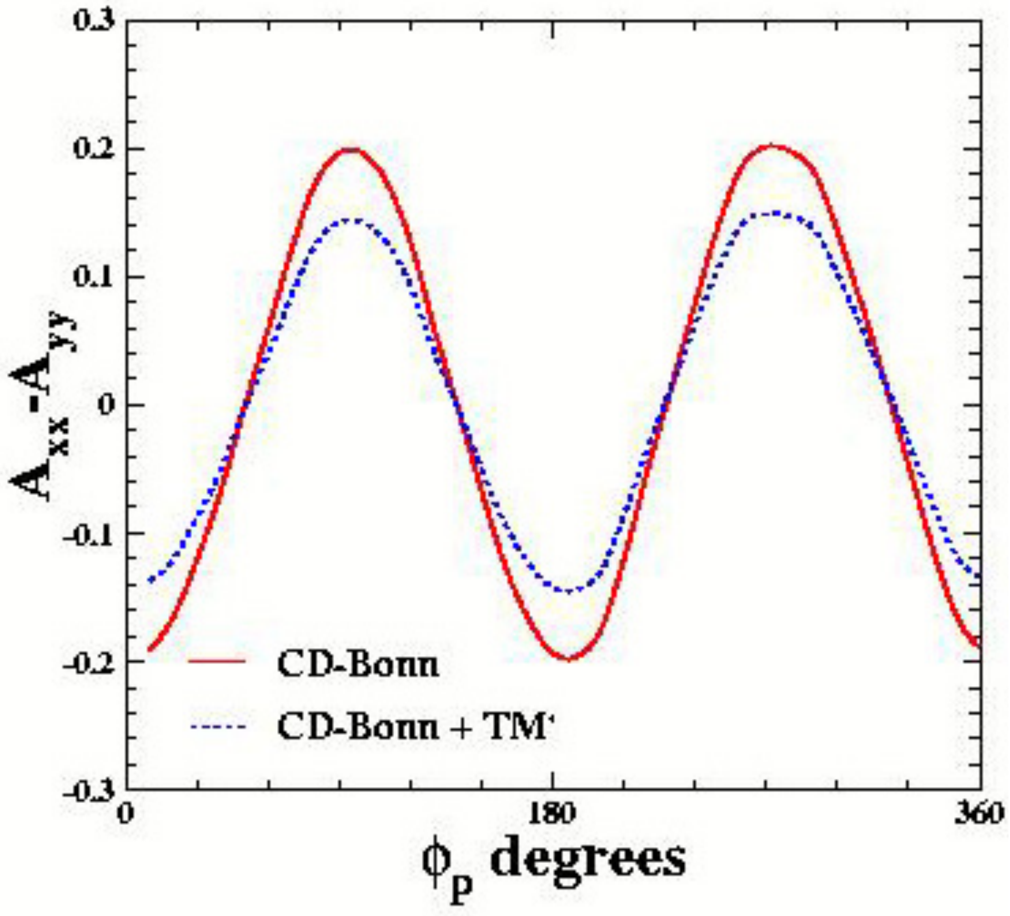
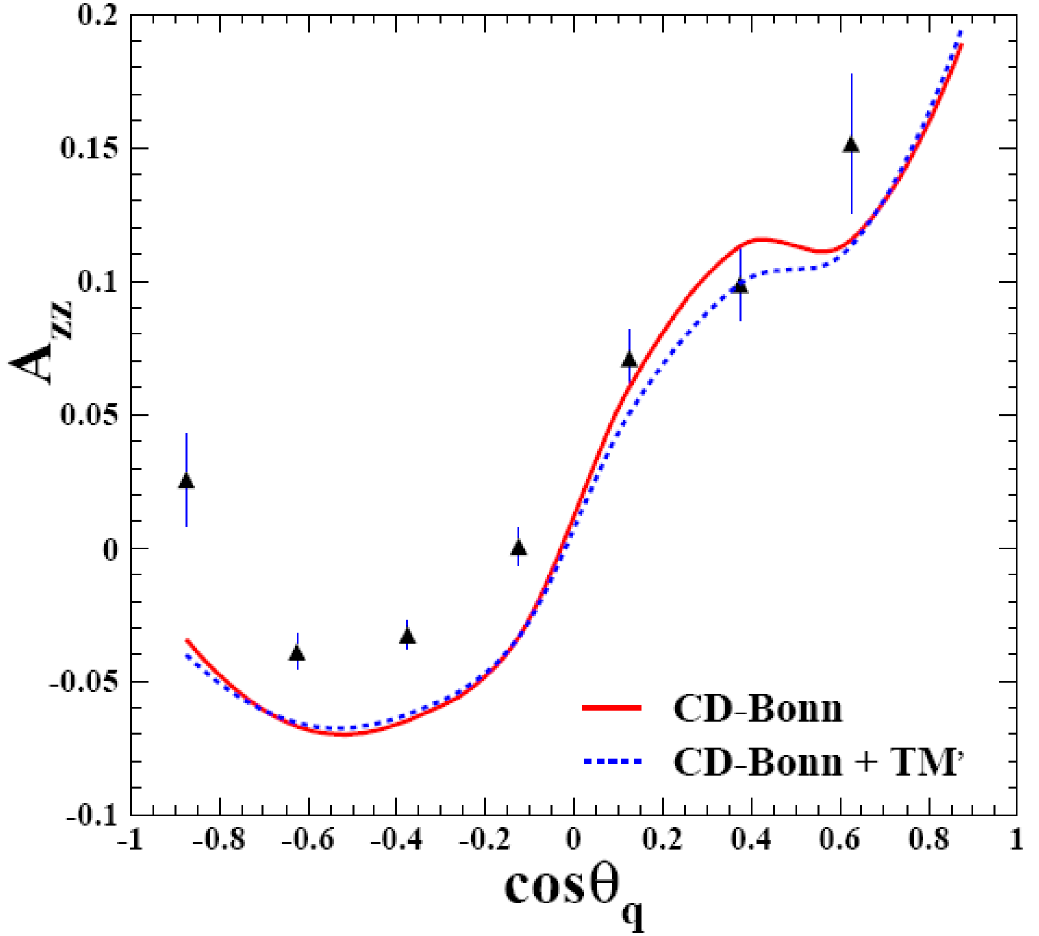
H.O. Meyer *et. al*, PRL 93, 112502 (2004)

The sampling method & dp @ 270 MeV

- Tensor analyzing powers in dp at 135 MeV/A
  - Theory CD-Bonn w. & w.o. 3N forces
  - Theoretical grids by: Kuros-Zolnierczuk

P. T.E. *et al.*, AIP Conf. Proc. **768**, 65 (2005), nucl-ex/0410006





A. Nogga: Theory grids

- Theoretical framework N2LO w. & w.o. 3NF**: Epelbaum & Nogga**

- Data or simulation:
(analyzed event list or
list of bup events isotropically generated)

- Multidimensional interpolation on a theory (n2lo) grid event by event

GRID SPACING	
p # of steps	20
θp # of steps	9
θp [deg]	5..90
θq # steps	18
θq [deg]	10..180
φp,q # steps	37
φp,q [deg]	0..360
# of grid points	4,435,560

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A. Nogga: Theory grids

Five versions w. different cutoffs and corresponding 3NF contact terms

- Integrations of the Lippman-Schwinger eq.
- Internal loops of the diagrams contributing to the potential

- c_D, c_E dimensionless parameters fixed from 3N low-energy observables

Λ	$\tilde{\Lambda}$	c_D	c_E
450	500	-0.14	-0.32
600	500	-4.71	-2.12
550	600	-0.45	-0.80
450	700	2.43	0.11
600	700	-2.00	-1.07

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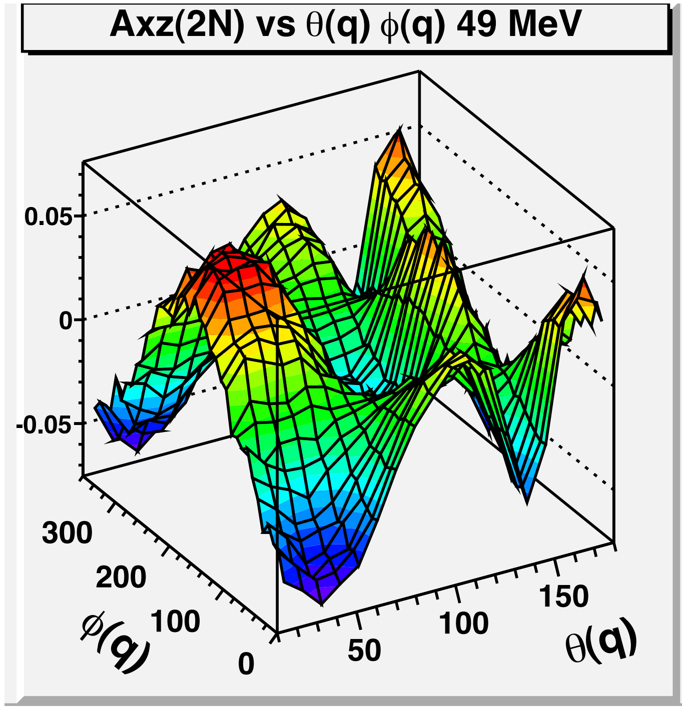
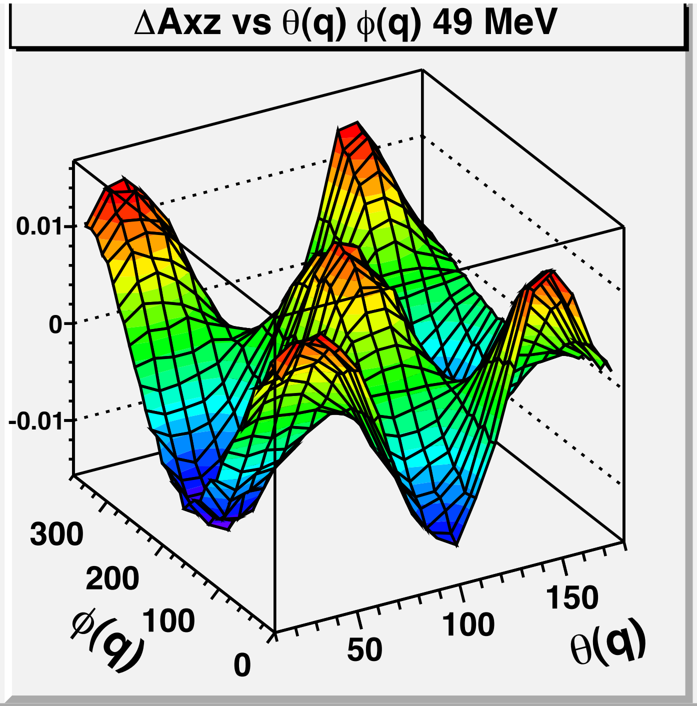
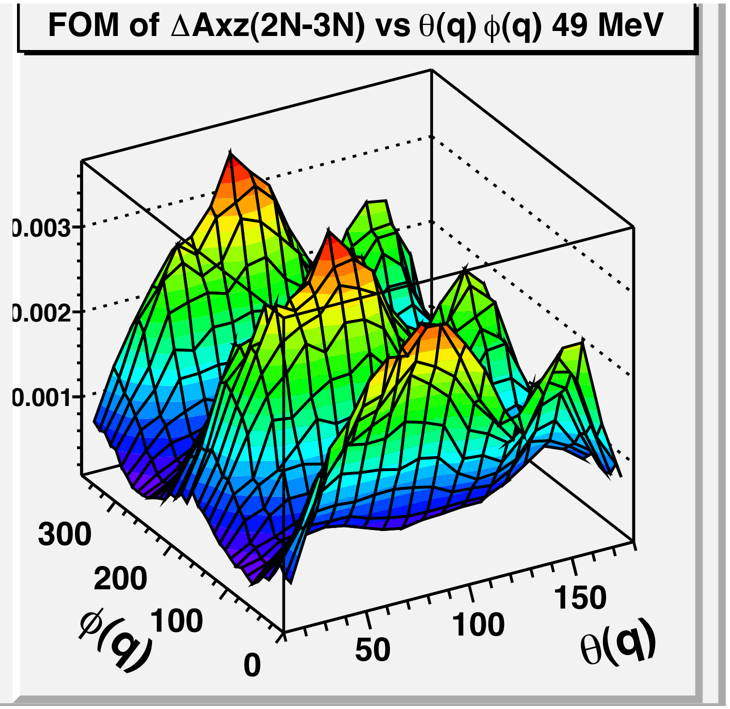
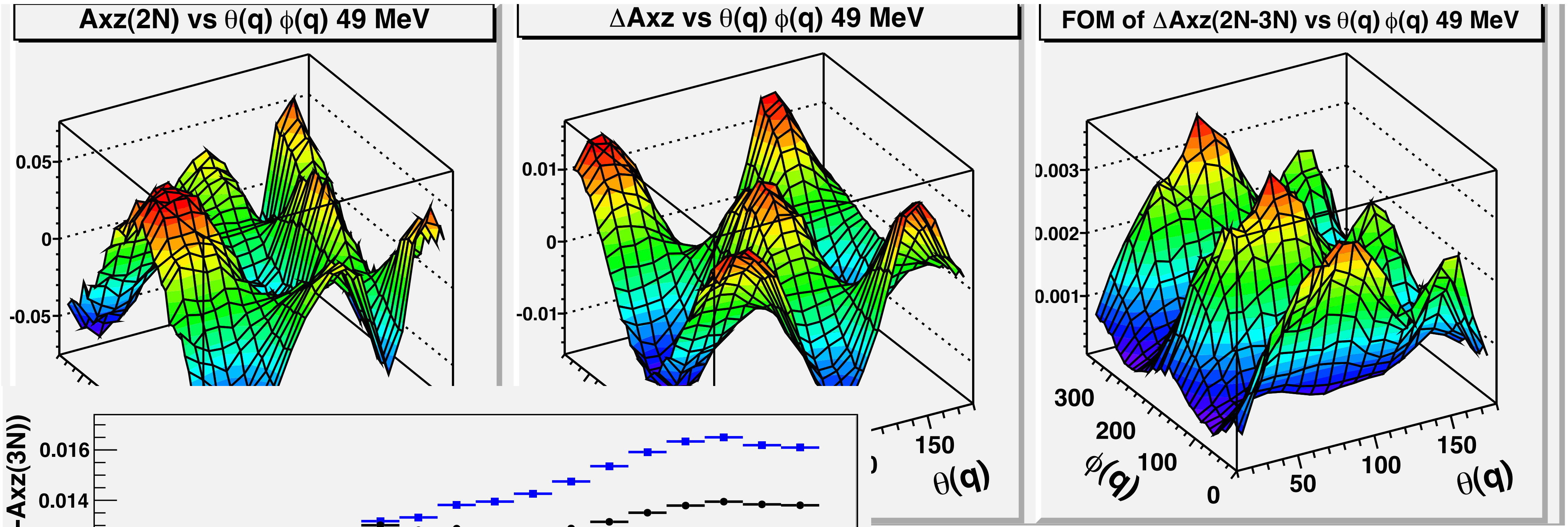
Example of sampling: Axz @49 MeV (phase space)

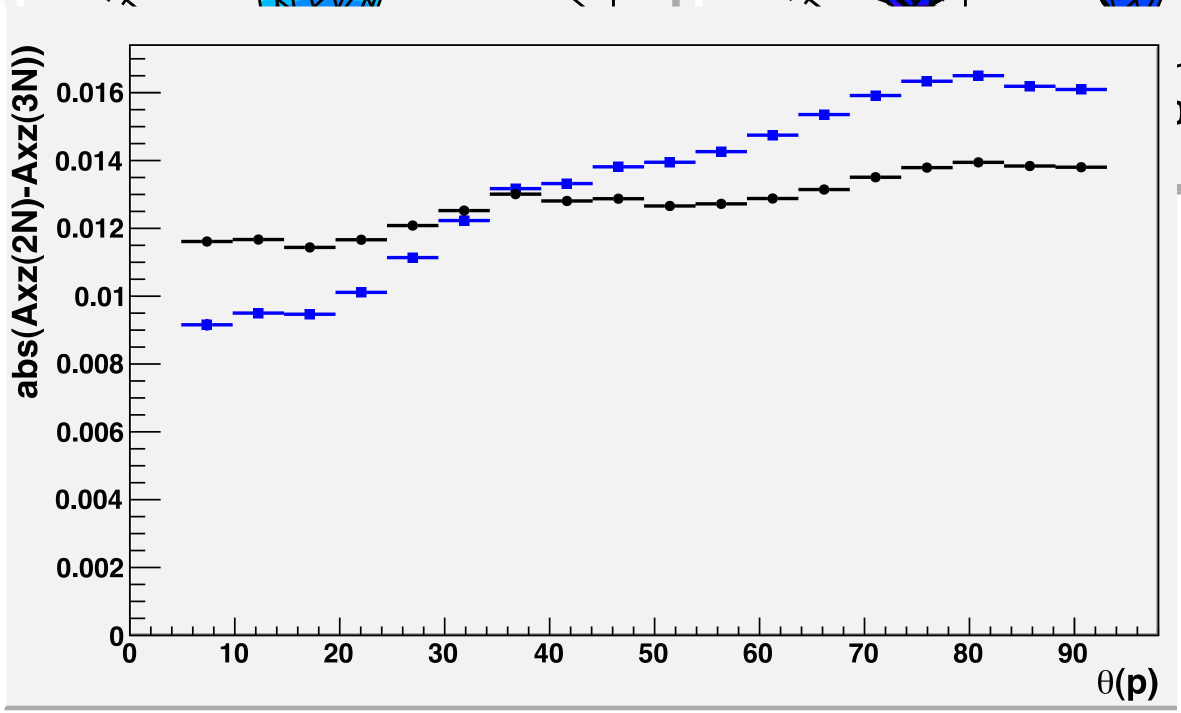






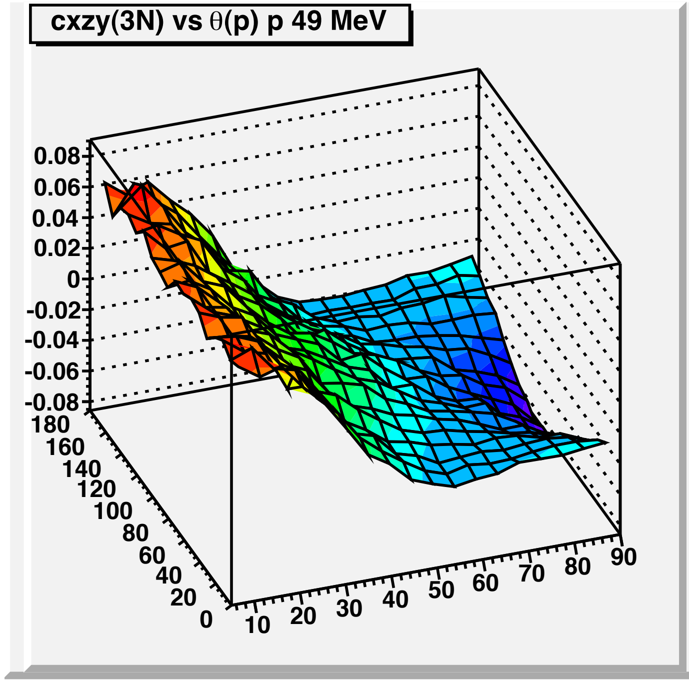
Example of sampling: Axz @49 MeV (phase space)

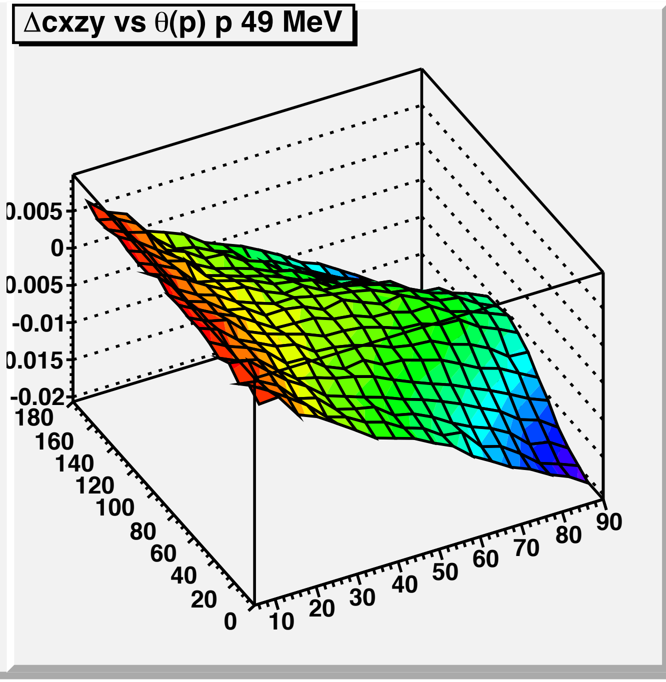


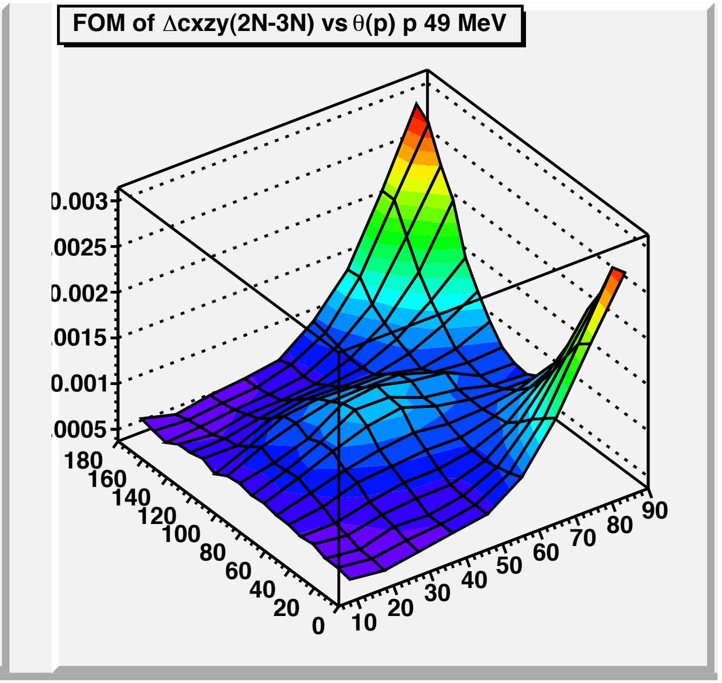


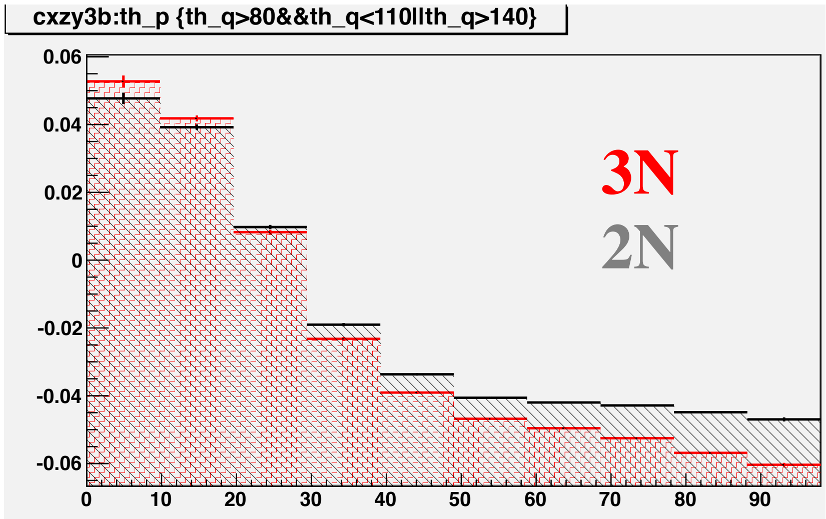
Using cuts in phase space for sensitivity studies comparing 3N & 2N calculations at n2lo

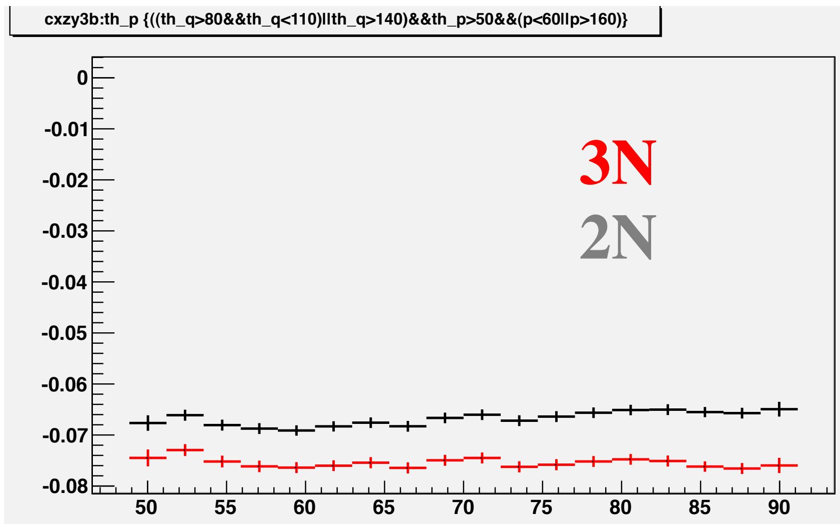
Example of sampling: Cxz,y @49 MeV (phase space) Observable of interest for TRIC experiment (Eversheim)





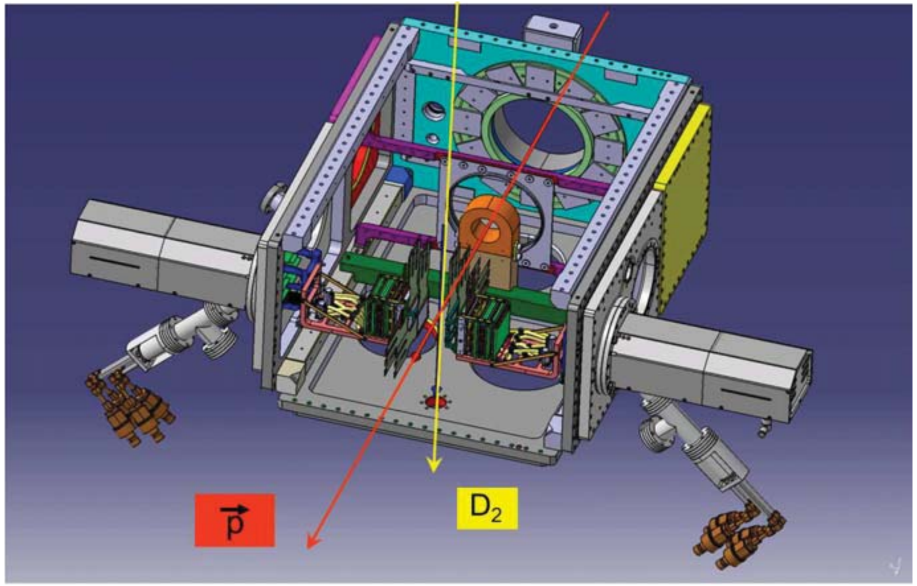


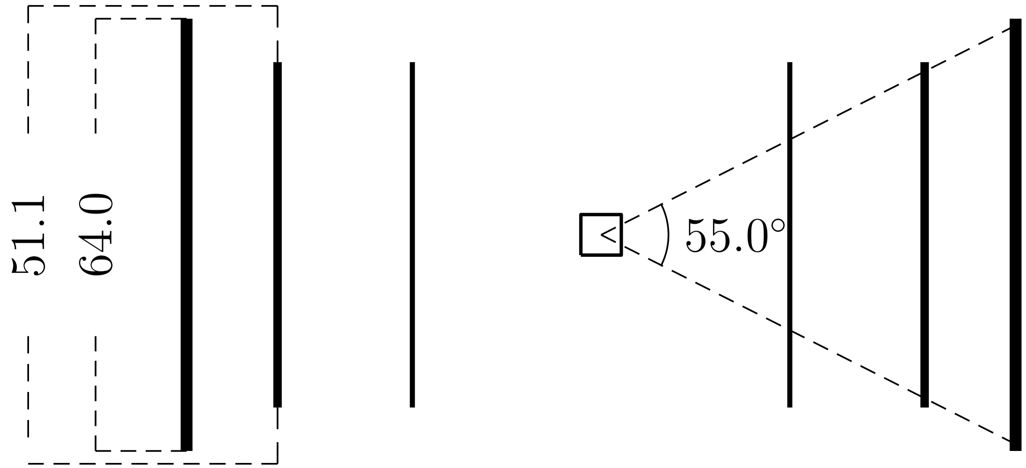




Ay (N)@50 MeV

- Vertically polarized proton beam 49.3 MeV
- Deuterium cluster gas target
- Left-Right Silicon Detector Telescopes
  - **Experimental & analysis details → Talk by Bertelli**





Rear view of the geometry

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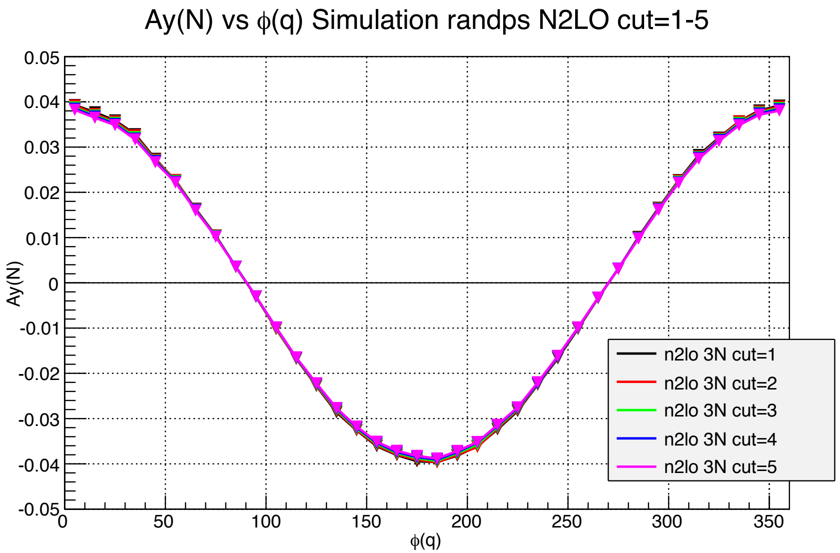
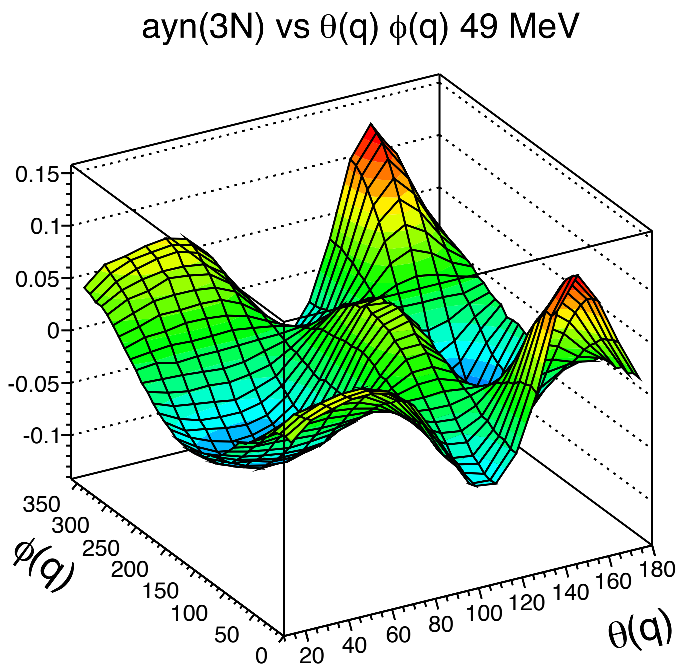
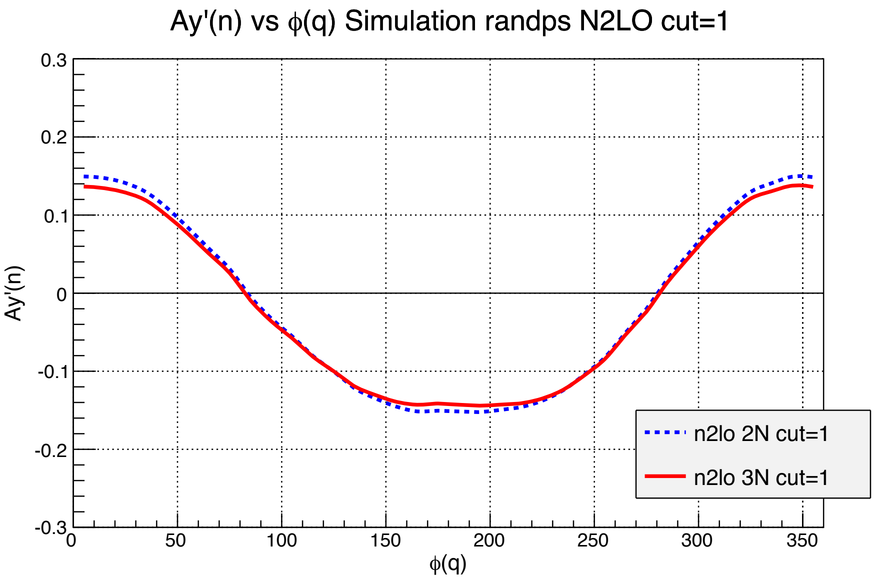
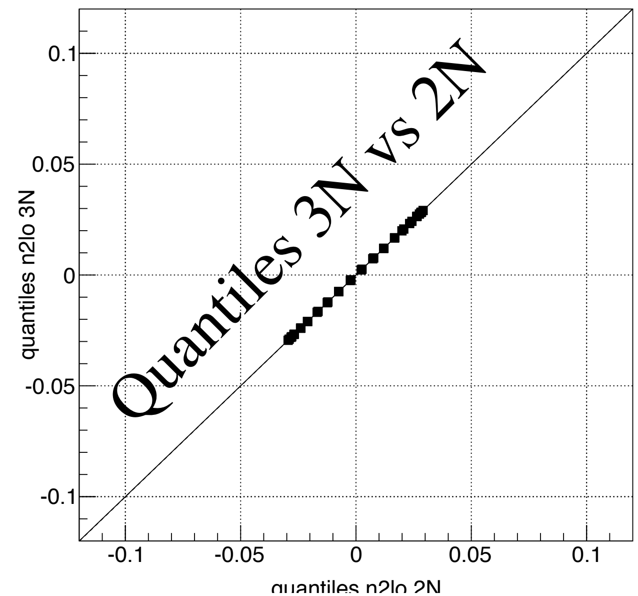
Ay (N)@50 MeV & Phase space & Sampling n2lo(3N)

Theoretical grids by A. Nogga
Five versions of n2lo-grids at different cutoffs





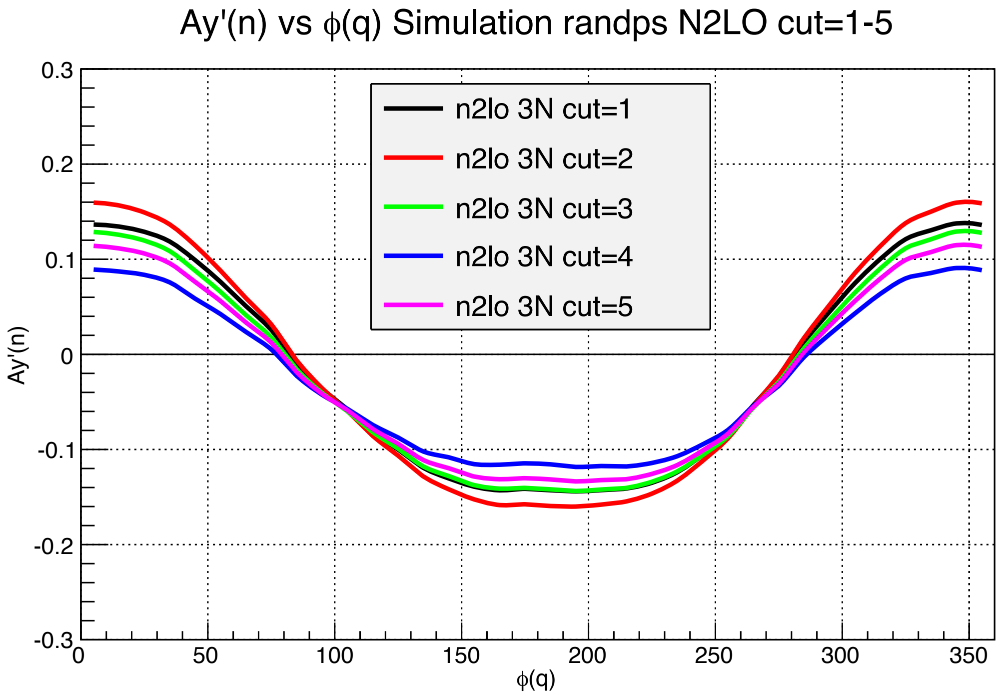


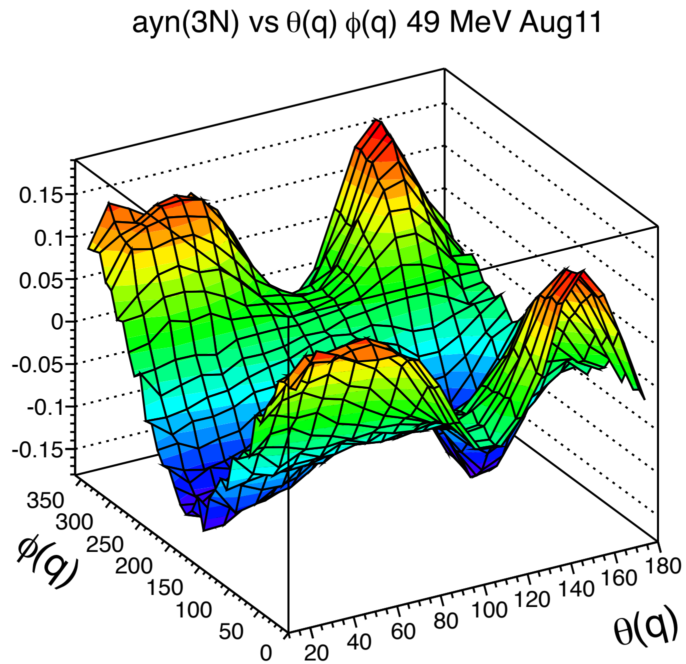


Ay(N)@50 MeV & Limited phase space & Sampling n2lo(3N)

- Five versions of n2lo(3N) grids at different cutoffs
- Phase space isotropic distributed events
  - Geometry as using Left-Right Si telescopes →
  - Limited acceptance in *p, θp, θq, φp*

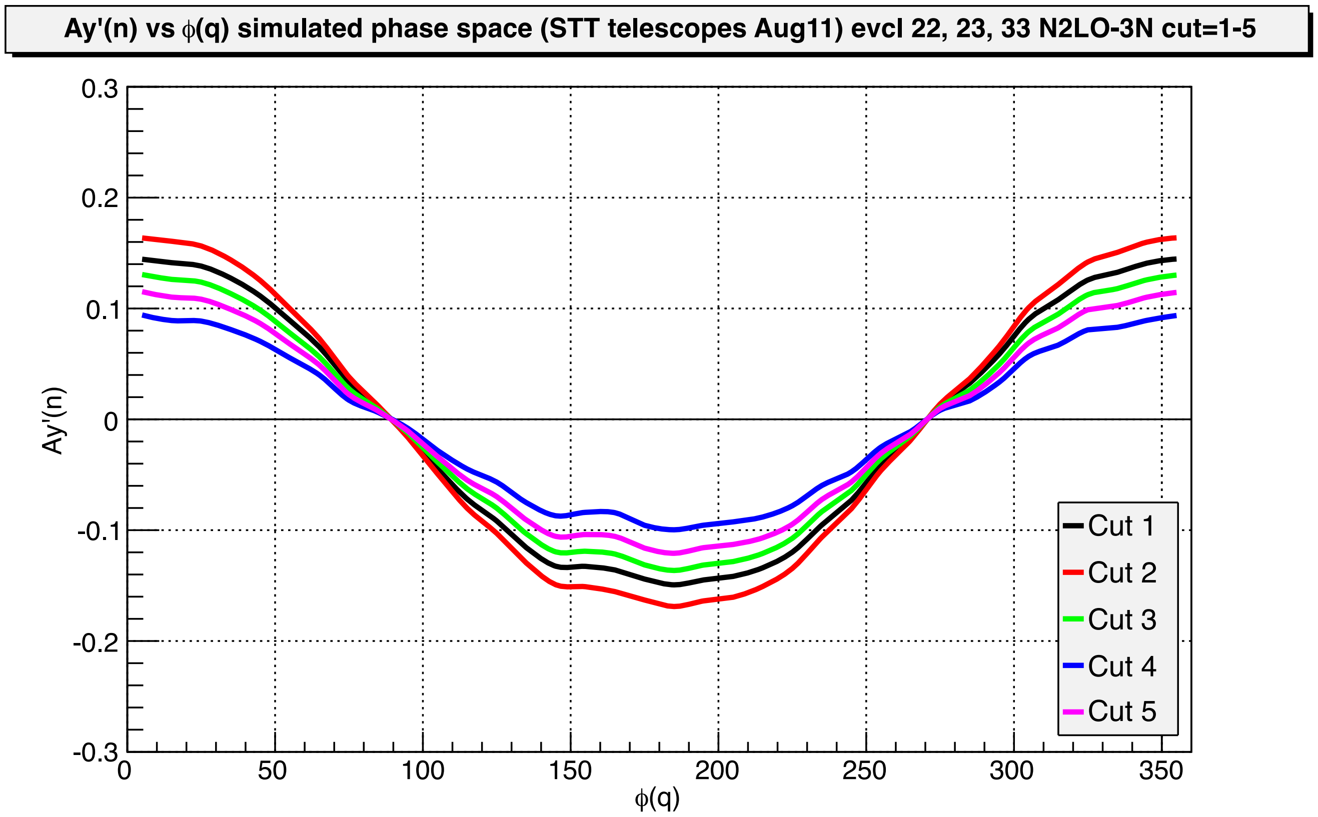
p [100,170] MeV/c
θp [65,90] deg
θq [10,80] deg
φp ~ ±30 deg
(left right detectors)





Ay(N)@50 MeV & Geant phase space & Sampling n2lo(3N)

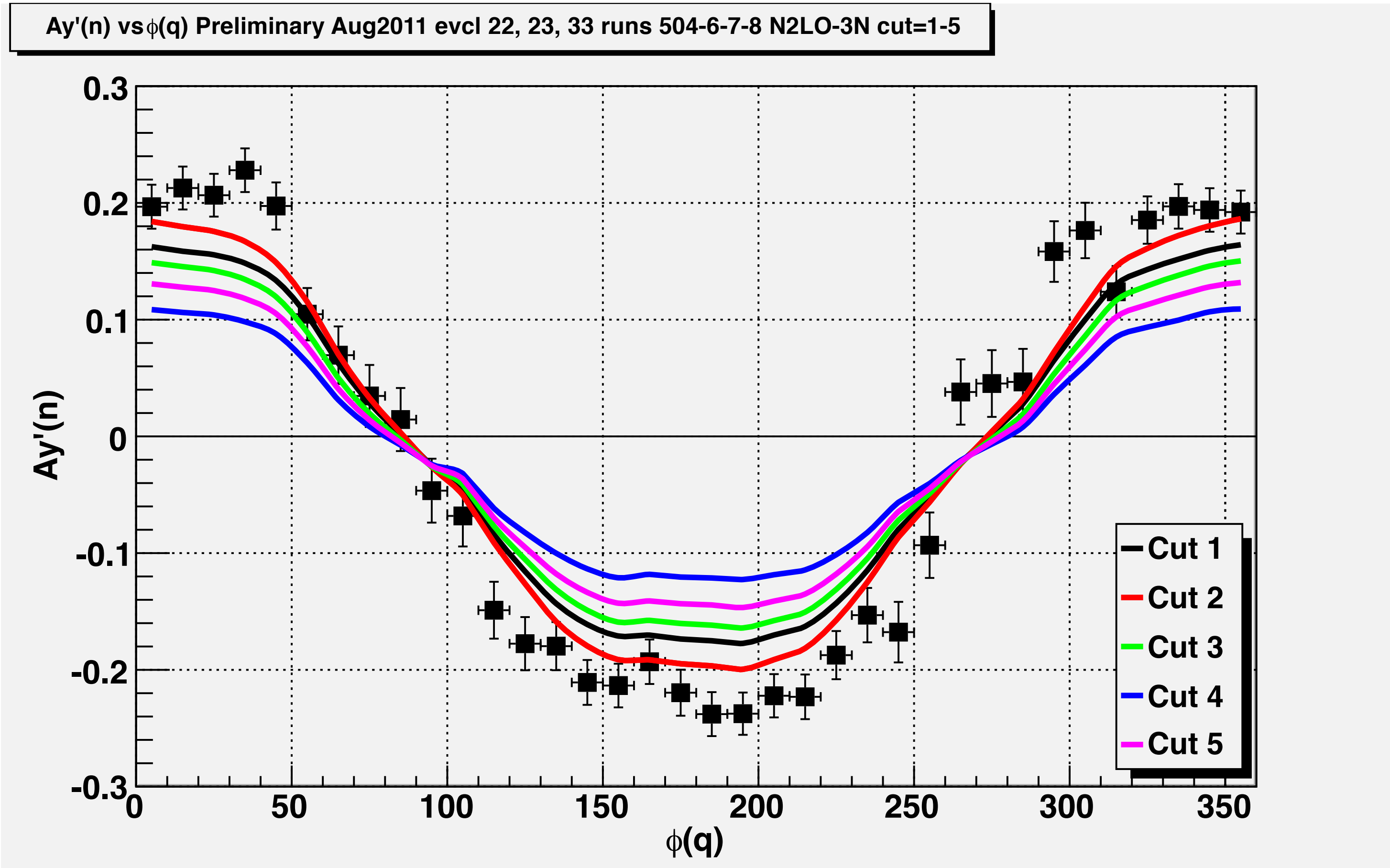
- Five versions of n2lo grids at different cutoffs
- Geant simulation:
  - Phase space isotropically distributed events + geant4
  - Left-Right Si detector telescopes → **limited acceptance**



Λ	$\tilde{\Lambda}$	c_D	c_E
450	500	-0.14	-0.32
600	500	-4.71	-2.12
550	600	-0.45	-0.80
450	700	2.43	0.11
600	700	-2.00	-1.07

Ay(N)@50MeV & Experimental data & Sampling n2lo(3N)

Data analysis: PhD thesis by K. Marcks von Würtemberg



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Ay(N)@50MeV & Experimental data & Sampling n2lo(3N)

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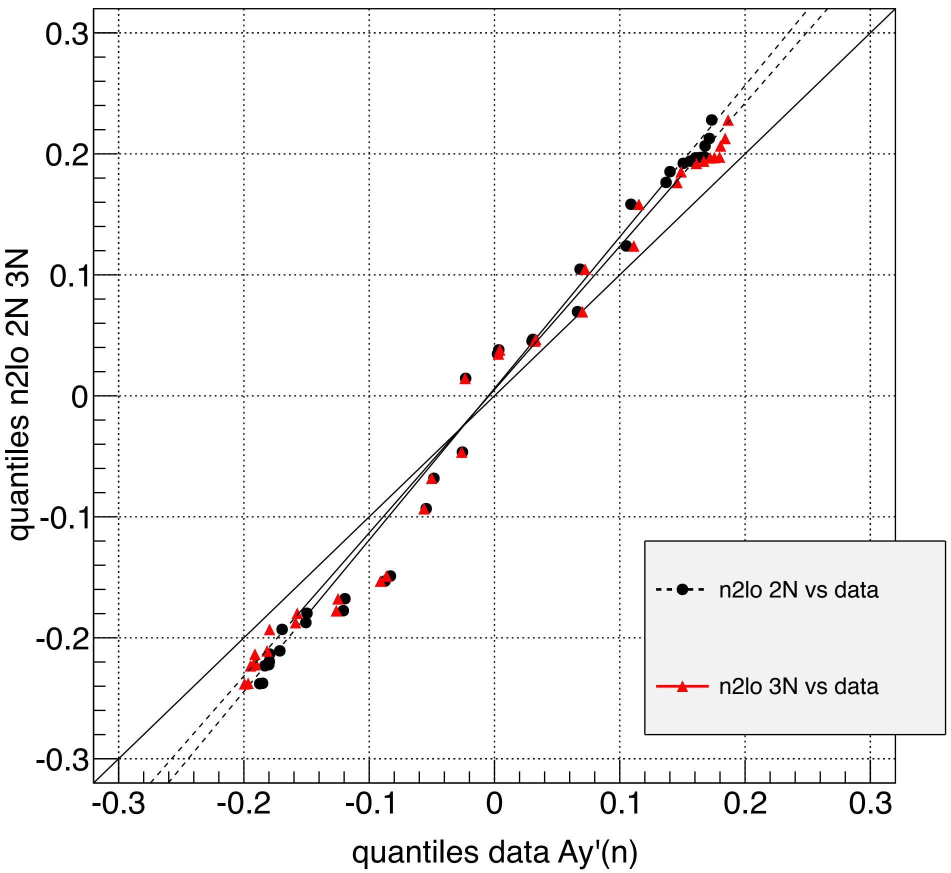
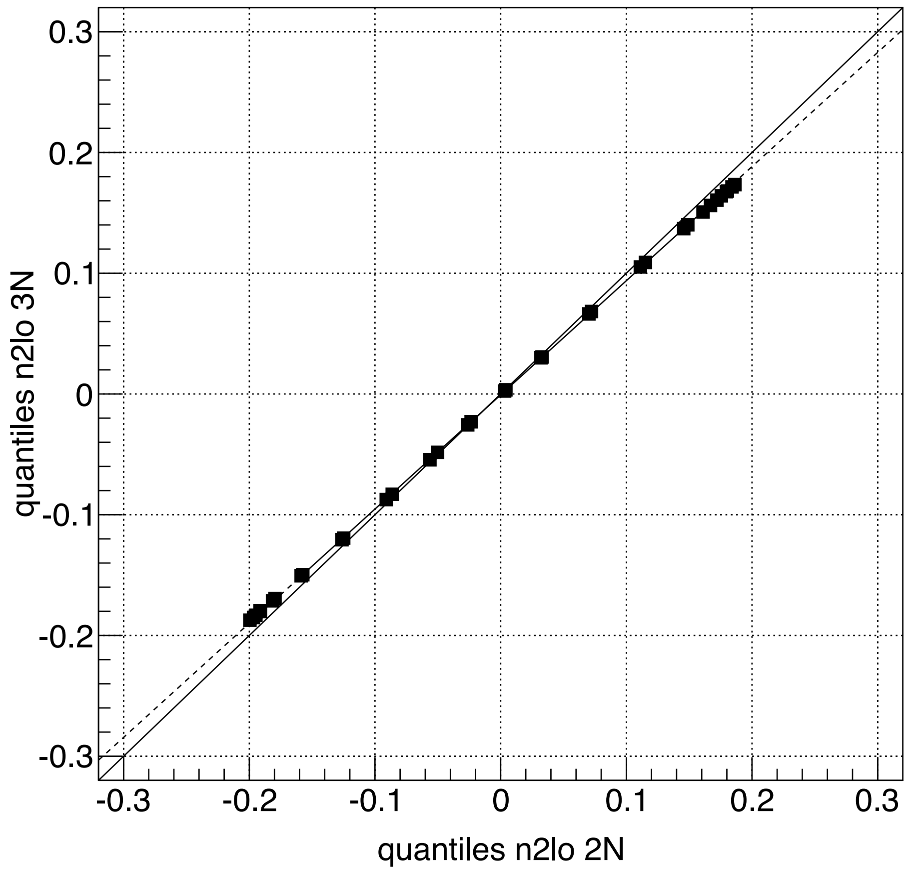
Quantiles n2lo vs data



Quantiles n2lo(3N) vs n2lo(2N)



Summary

- Experimental study show large cut-off dependencies in parts of phase space for n2lo chiral EFT

- Planned experiment @ COSY using the new PAX facility:

- Double polarized pd breakup at 30 – 50 MeV
  - Few previous measurement exist
  - Measure most observables with large phasespace coverage – Direct comparison of experiment & theory

  ➨ **Would provide precise data for constraints of chiral EFT in a relevant energy range 30-50 MeV**
    - New effects of 3NF that appear at N3LO can be accessed
    - Cut-off dependencies can be studied in detail

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Tomonaga's "The Story of Spin"

- "[Spin] It is a mysterious beast, and yet its practical effect prevails over the whole of science. The existence of spin, and the statistics associated with it, is the most subtle and ingenious design of Nature
- without it the whole universe would collapse."

  - *Foreword by Takeshi Oka*

Thank you for your attention!

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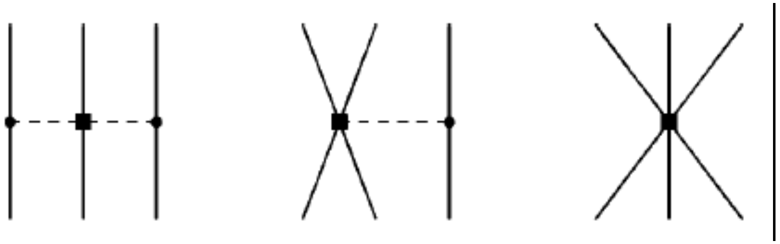
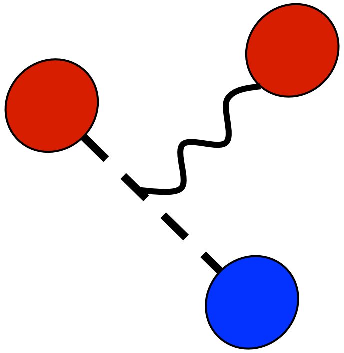
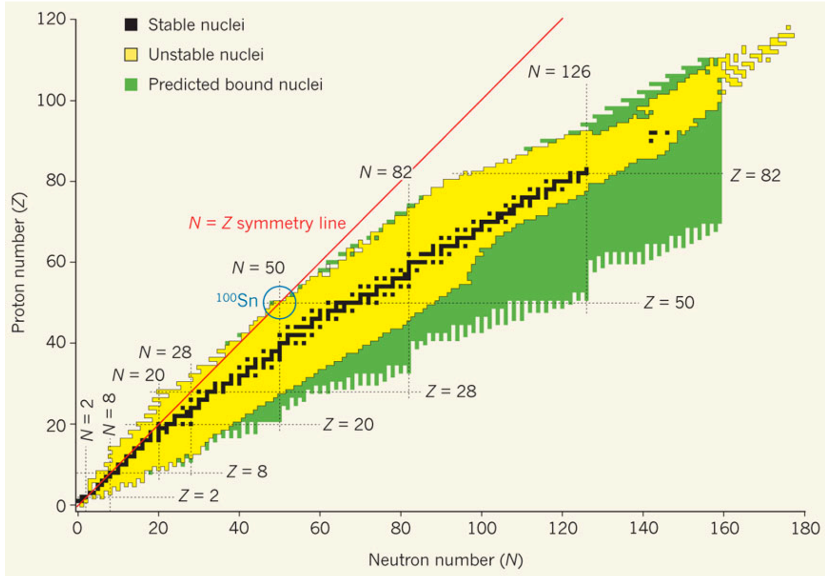
Thank you for your attention!

Motivation II

$$H = H_0 + V_{2N} + V_{3N} + V_{4N} + \ldots..$$







Low-energy antiproton-proton scattering – long range part chEFT

Zhou, Timmermans, PRC 86, 044003 (2012)