Investigating Three-Nucleon System Dynamics via the Deuteron-Proton Breakup

Experimental studies of few-body interactions in new-generation experiments

2026 A. N. Mitra Memorial Lecture Series

April 14th–15th, 2026

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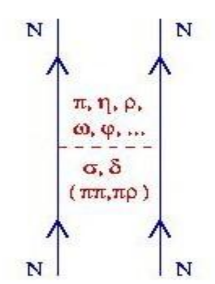
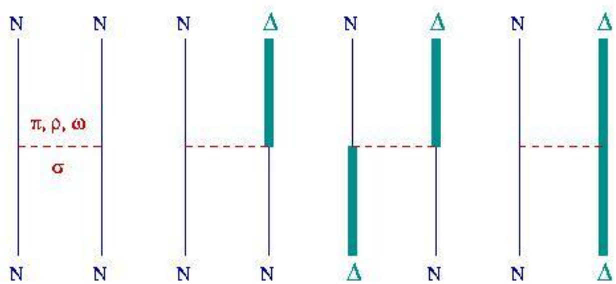
Two-Nucleon System
Standard Interaction Models

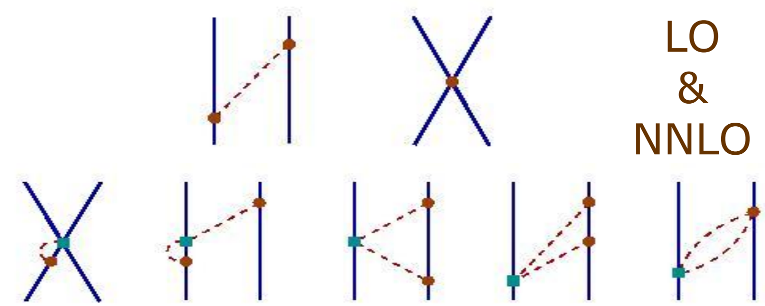
- *Meson exchange theory of NN forces - nucleonic degrees of freedom* (CD Bonn, Nijm I, Nijm II, AV18)
- CD Bonn + explicit treatment of a single Δ-isobar degrees of freedom – **C**oupled barion **C**hannels
- Effective Field Theory – **Ch**iral **P**erturbation **T**heory; expansion of potential in powers ν of small external momenta Q, $(Q/\Lambda_\chi)^\nu$, with $\Lambda_\chi \approx 1$ GeV



Realistic **P**otentials



Coupled-**C**hannels Potential (single Δ)



Chiral **P**erturbation **T**heory Potential (2π exchanges & contact terms)

Nucleon-Nucleon Interaction
Basis of Nuclear Physics

Modern NN potentials are in general able to

- reproduce properties of nuclear matter (eq. of state)
- reproduce (roughly) binding energies of light nuclei
- reproduce global features of the bulk of the scattering observables in 2N and (partly) in 3N systems

χ^2 / point

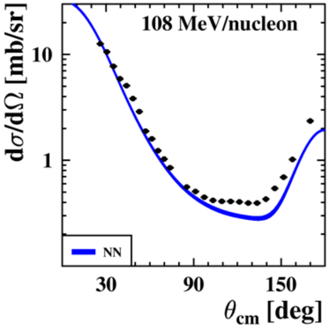
	CD Bonn	NijmI	NijmII	Av18	Coupl.Ch.
No. of parameters	45	41	47	40	~40
data pp	1.01	1.03	1.03	1.35	1.02
data np	1.02	1.03	1.03	1.07	1.03

From 2N to 3N System
Need of Additional Dynamics

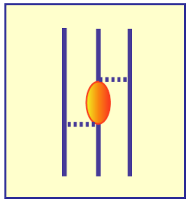
Modern NN potentials are in general able to

- reproduce properties of nuclear matter (eq. of state)
- reproduce (roughly) binding energies of light nuclei
- reproduce global features of the bulk of the scattering observables in 2N and (partly) in 3N systems

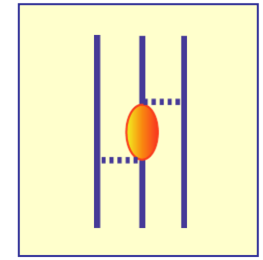
- Three-nucleon system is the simplest **non-trivial** environment to test predictions of observables obtained on the basis of the NN potential models



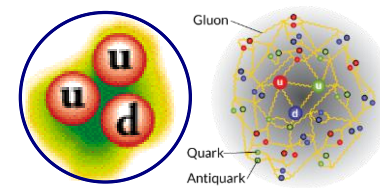
- Introducing concept of **three-nucleon forces**: genuine (irreducible) interaction of all three nucleons



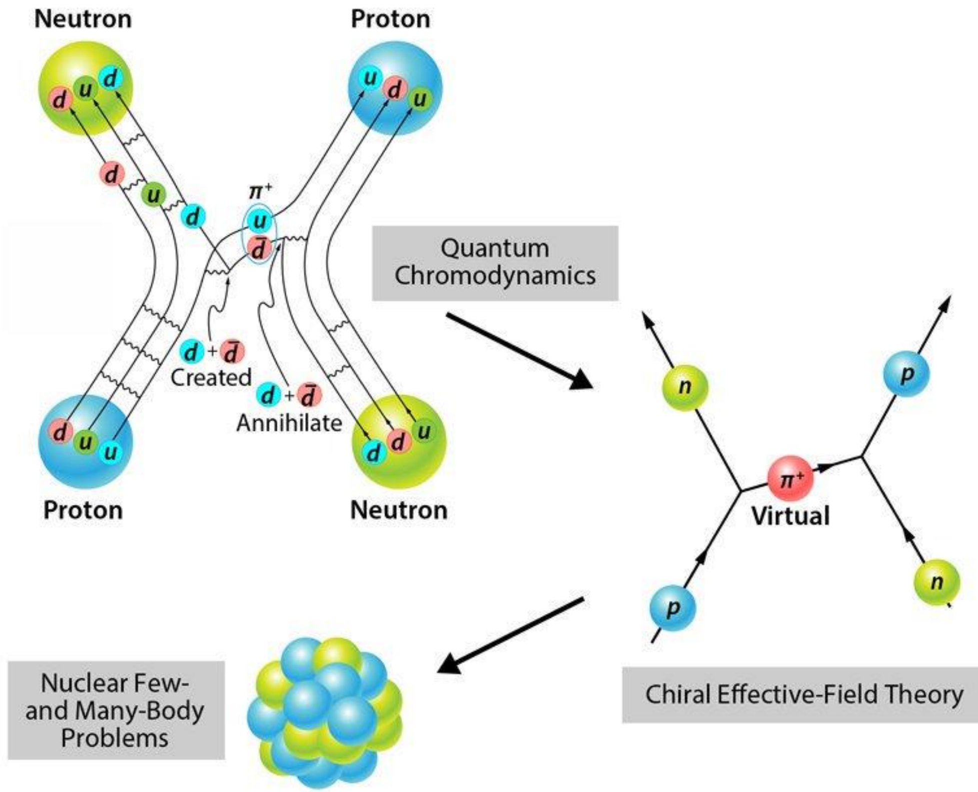
Origin of 3NF
Effective Forces in Few-Nucleon Systems



Nucleon is not an elementary particle, there are internal degrees of freedom



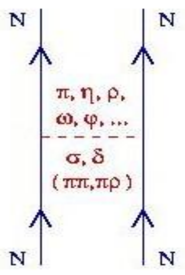
proton



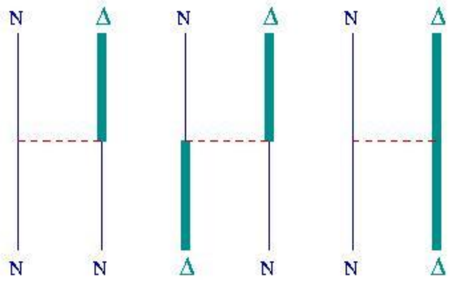
Nuclear forces, modelled by nucleon-meson exchanges, represent „rest" interaction of fundamental strong (colour) force.

Effecive 3NF is needed to account for the neglected internal d-o-f.

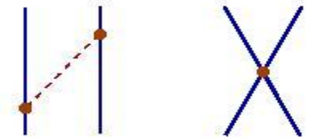
Three-Nucleon System
Standard Interaction Models



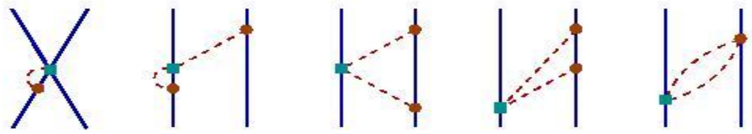
Realistic **P**otentials
CD Bonn, Nijm, AV



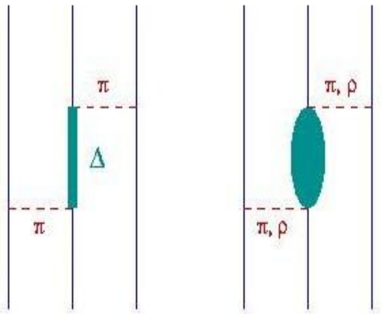
Coupled-**C**hannels
Potential (single Δ)



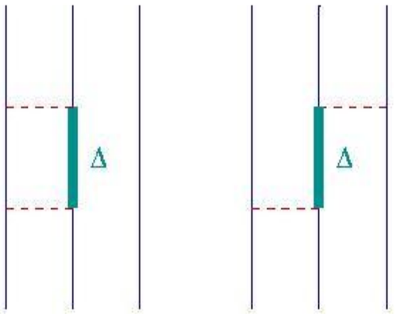
LO
&
NNLO

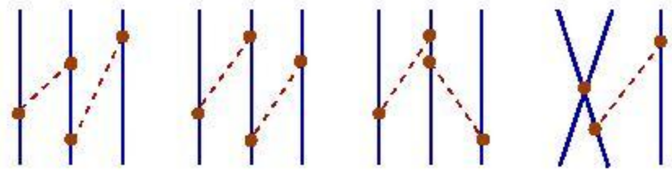


Chiral **P**erturbation **T**heory
(2π exchanges & contact terms)

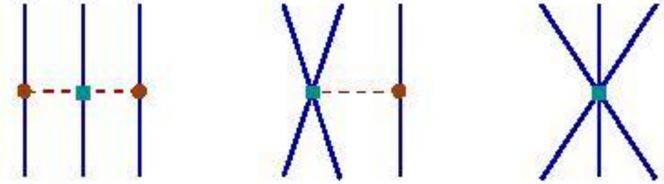


TM99 3NF





NLO: all contributions cancel out !



NNLO: three possible topologies

Three-Nucleon System
From Model to Observables

- Required experimental verification of predictions obtained with the use of different NN and 3N potential models
- Needed theoretical formalism which allows to conclude on **physical input** underlying the calculated observables; i.e. avoiding any approximations of the assumed dynamics (due to numerical complexity)

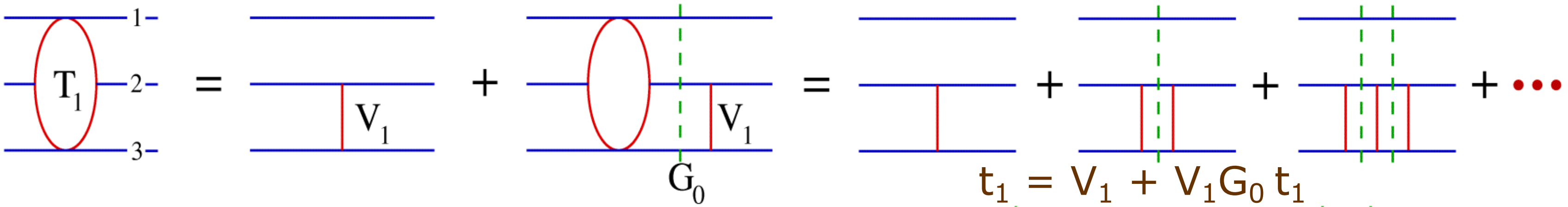
⬇

Numerical solutions of the Faddeev equations
(W.Glöckle, H.Witała et al.)

$T = tP + tPG_0T$ restricted to finite number of channels ($2N$ off-shell t operator from L-S eq. $t = V + VG_0t$) by including partial waves below certain limits j_{max} & J_{max}

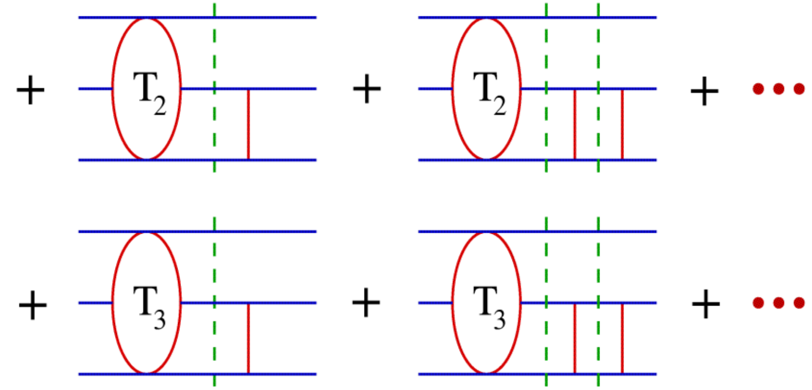
Three-Nucleon System
Faddeev Equations

Operators T_1, T_2, T_3, according to **the last** interacting pair of two nucleons



$t_1 = V_1 + V_1 G_0 t_1$

$$T_1 = t_1 + t_1 G_0 (T_2 + T_3)$$



$$\boxed{T = tP + tPG_0T}$$

E.g. breakup amplitude: $U_0 = (1+P)T \rightarrow$ obserwables

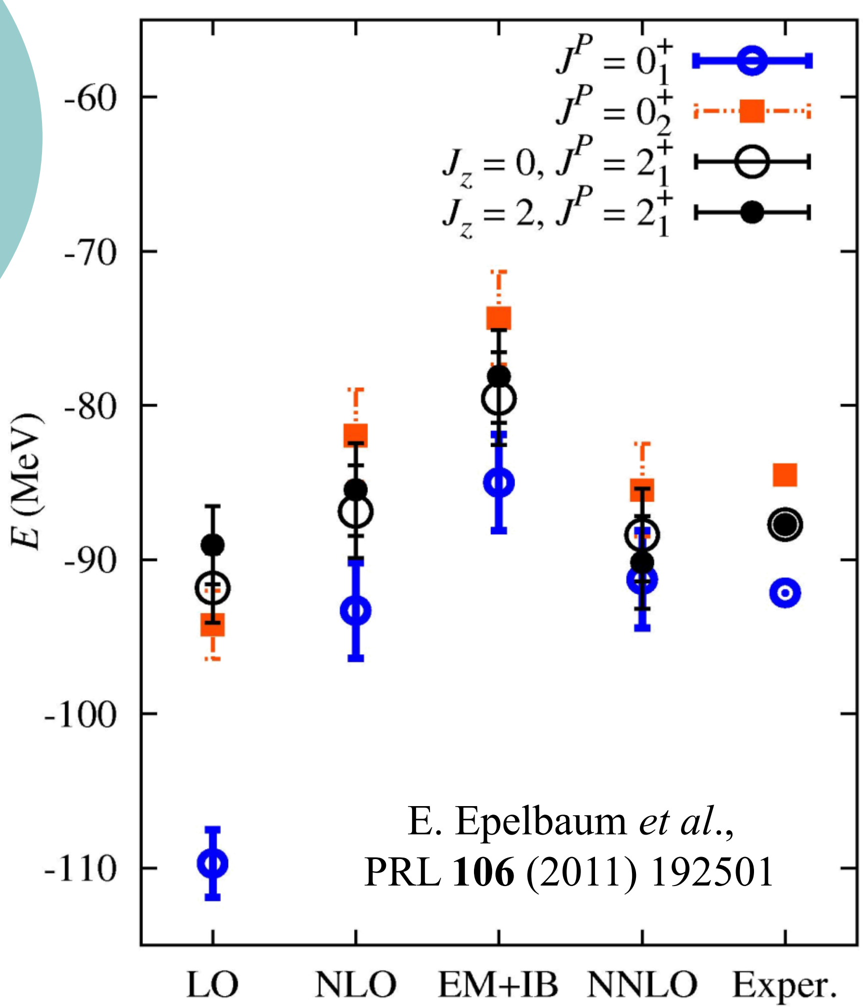
Influence of 3NF
Bound States of Few Nucleons

	^{3}H	^{3}He	^{4}He
Experimental	-8.48	-7.72	-28.3
CD Bonn	-8.01	-7.29	-26.3
NijmII	-7.66	-7.01	-24.6
Av18	-7.62	-6.92	-24.3
CD Bonn + TM99	-8.48	-7.73	-29.2
NijmII + TM99	-8.39	-7.72	-28.5
Av18 + TM99	-8.48	-7.76	-28.8
Av18 + UIX	-8.48	-7.76	-28.5
CC CD Bonn + Δ	-8.36	-7.64	-28.4

$E_B(^{3}H)$ used in 3NF fit (rows CD Bonn + TM99 to Av18 + UIX)

Predictions of NN potentials with 3NF models for 3N, 4N bounding energies (E_B [MeV]) do much better

Influence of 3NF
Hoyle State of ^{12}C



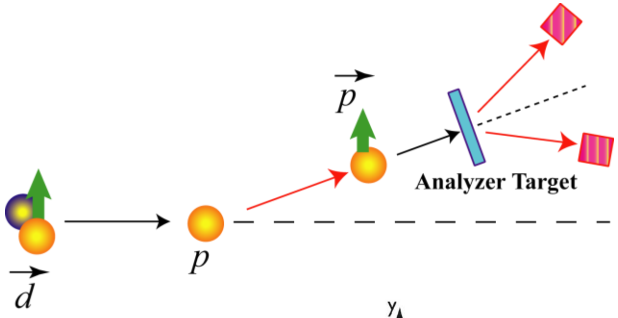
State of ^{12}C enabling the process of fusion $3\alpha \rightarrow {}^{12}C$ in star burning
(^{12}C catalyst in CNO cycle)

Nuclear Lattice Simulations

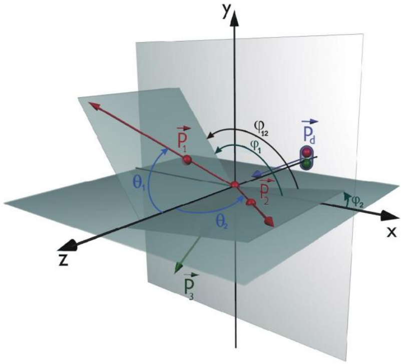
Only by taking into account effects of 3NF (at NNLO), it is possible <u>without fitting</u> (*ab initio*) to obtain the right sequence of states

Three-Nucleon Scattering at Medium Energies

- Elastic: N + d → N + d
  - Beams of p or d
  - Various observables



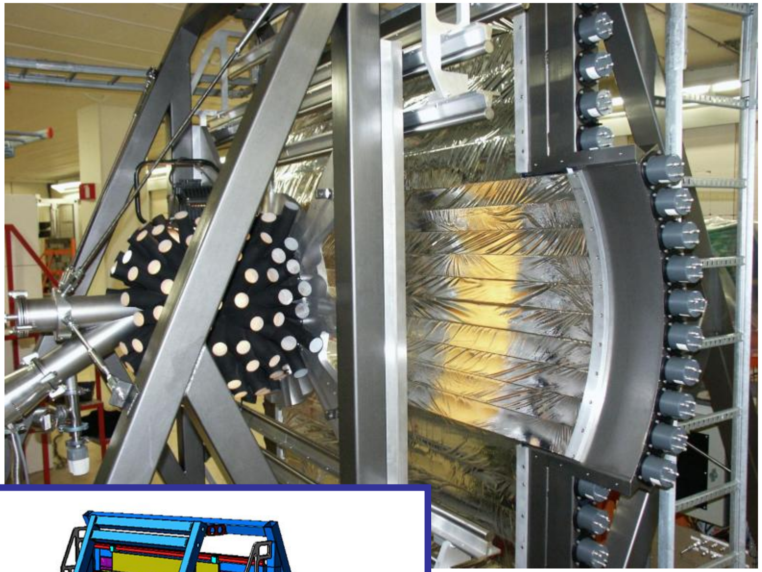
- Breakup: N + d → N + N + N
  - Beams of p or d
  - Various observables

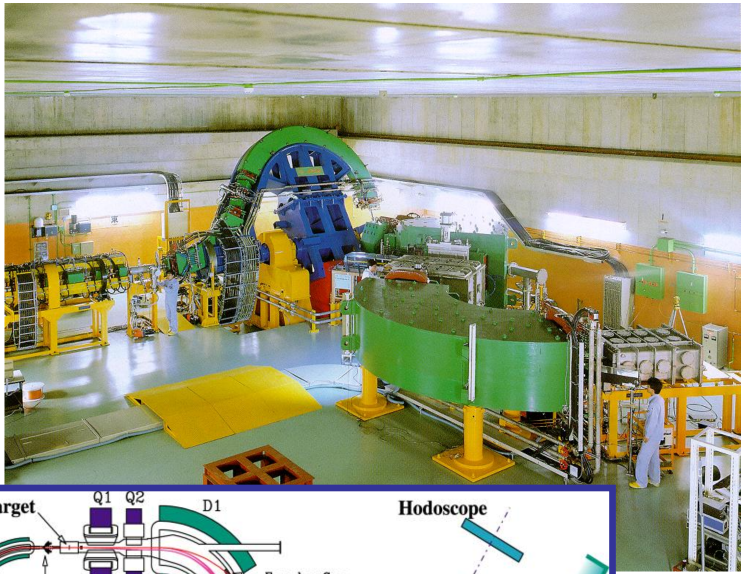


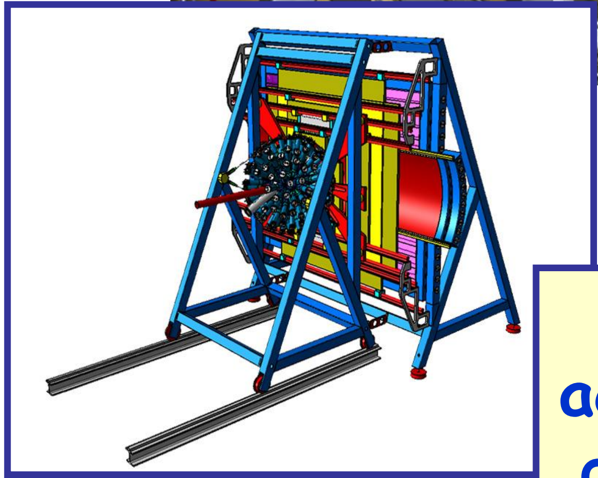
- Different effects to be traced
  - Comparisons between channels
  - Influences of 3NF
  - Coulomb force action
  - Relativistic effects

… and their interplay !

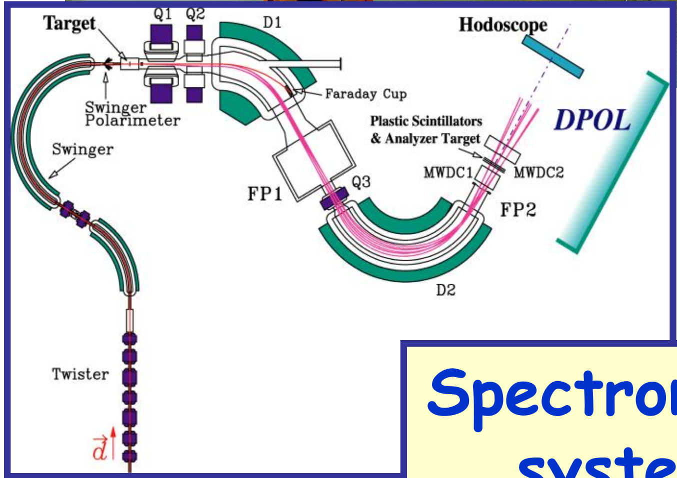
Experimental Tools of Few-Nucleon Physics







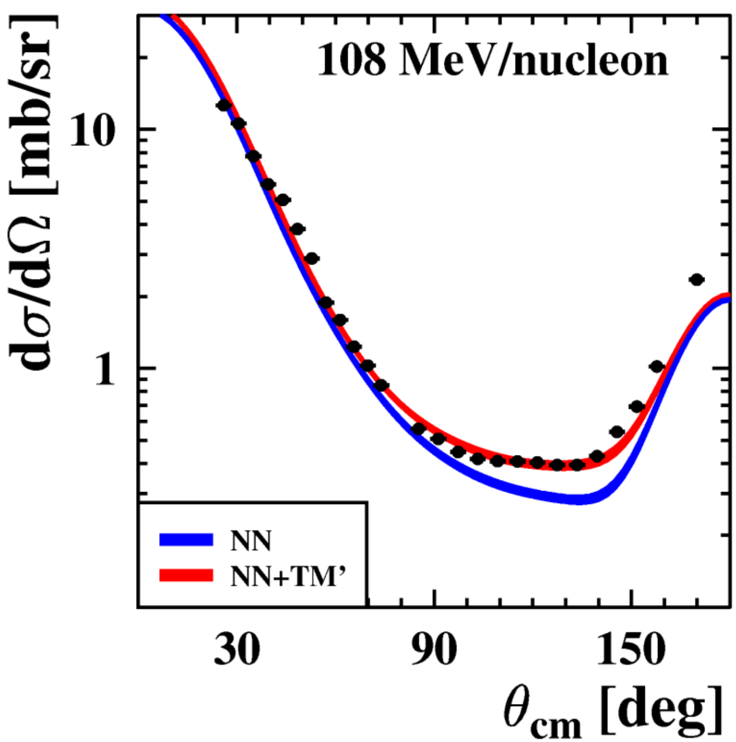
Large acceptance detectors

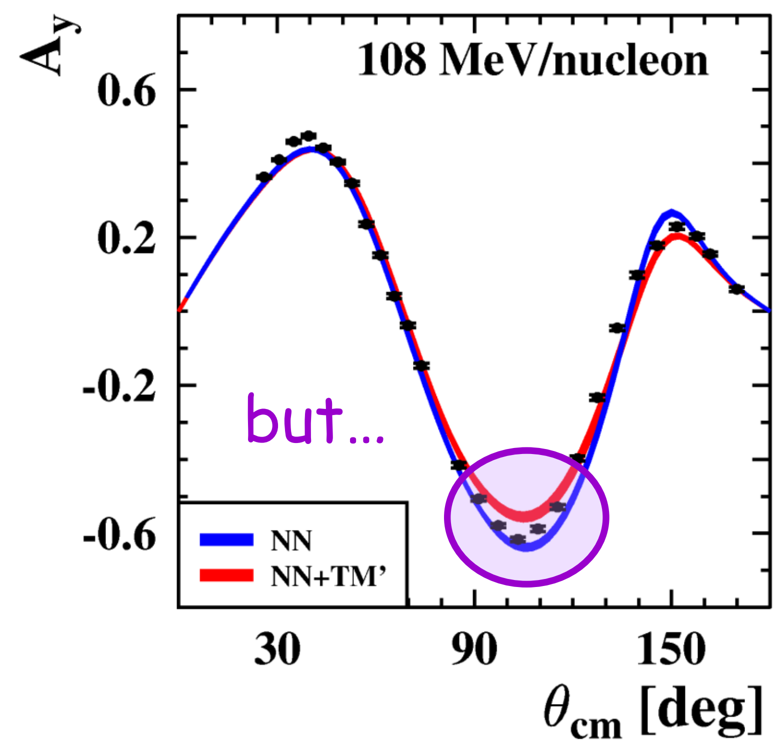


Spectrometer systems

3NF Effects
Elastic Nucleon-Deuteron Scattering

Predictions of NN potentials with 3NF models better reproduce minimum of the d(N,N)d scattering c.s.



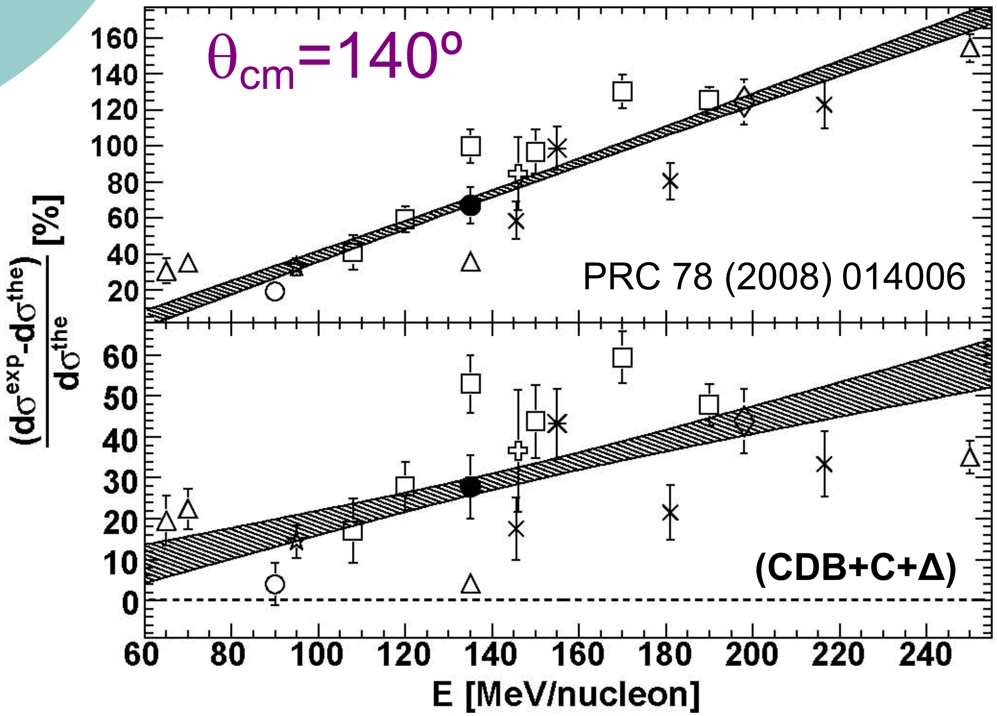


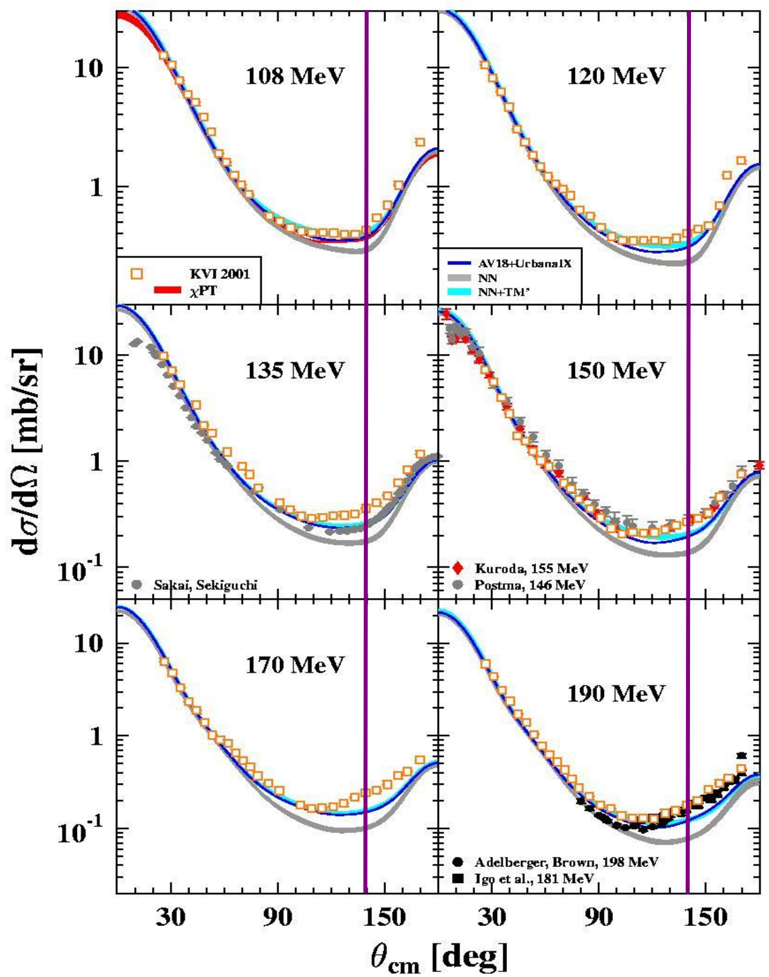
K. Ermisch *et al.*, Phys. Rev. C 71 (2005) 064004

3NF Effects
Elastic Nucleon-Deuteron Scattering

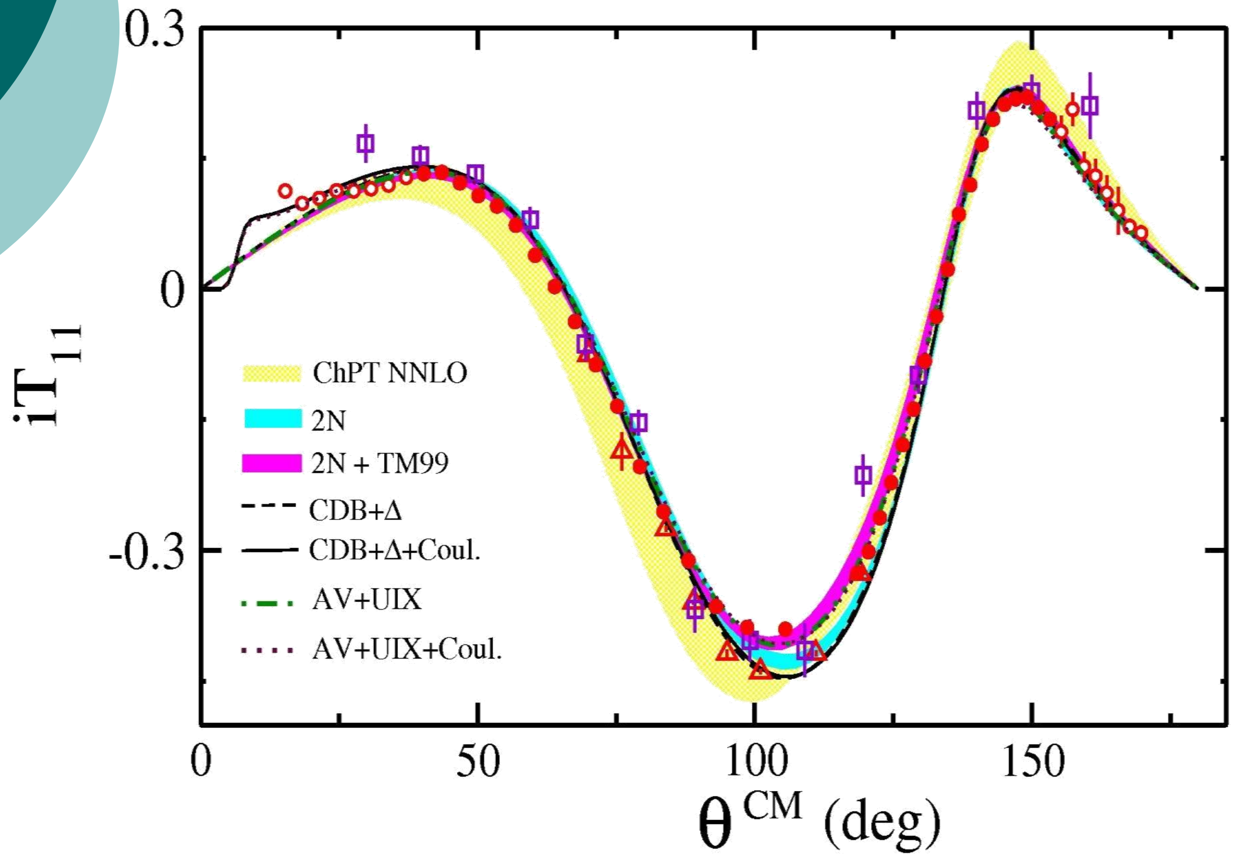
3NF help

alas, not completely



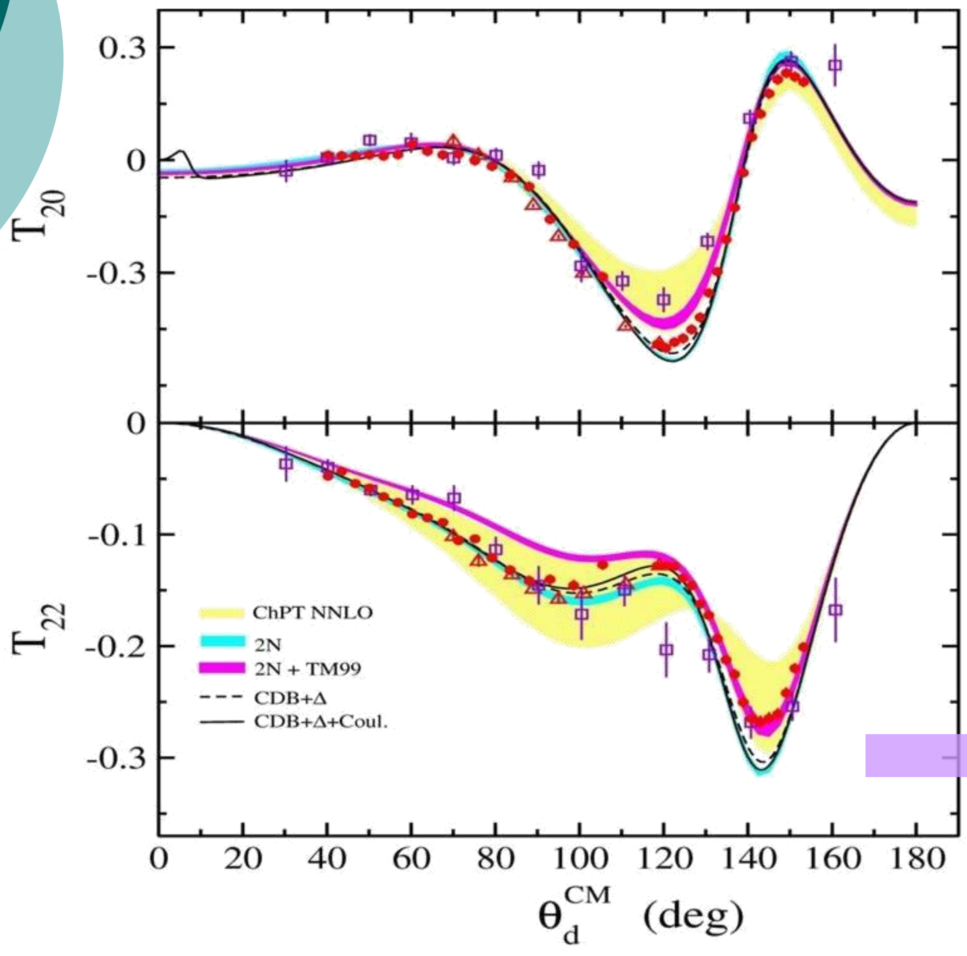


3NF Effects
Elastic Deuteron-Nucleon Scattering

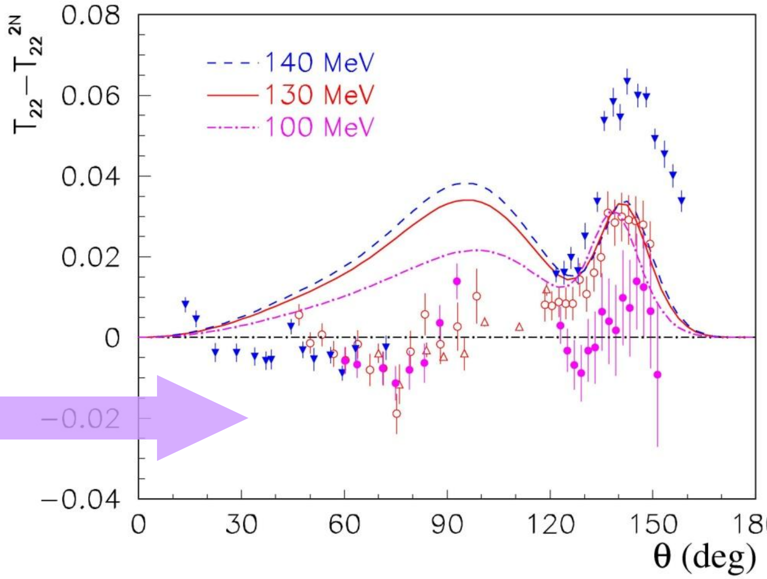


- E. Stephan et al., Phys. Rev. C 76, 057001 (2007)
- GeWall @ COSY
- H. Mardanpour et al., Eur. Phys. J. 31, 383 (2007)
- H. Witała et al., Few-Body Systems 15, 67-85 (1993)

3NF Effects
Elastic Deuteron-Nucleon Scattering

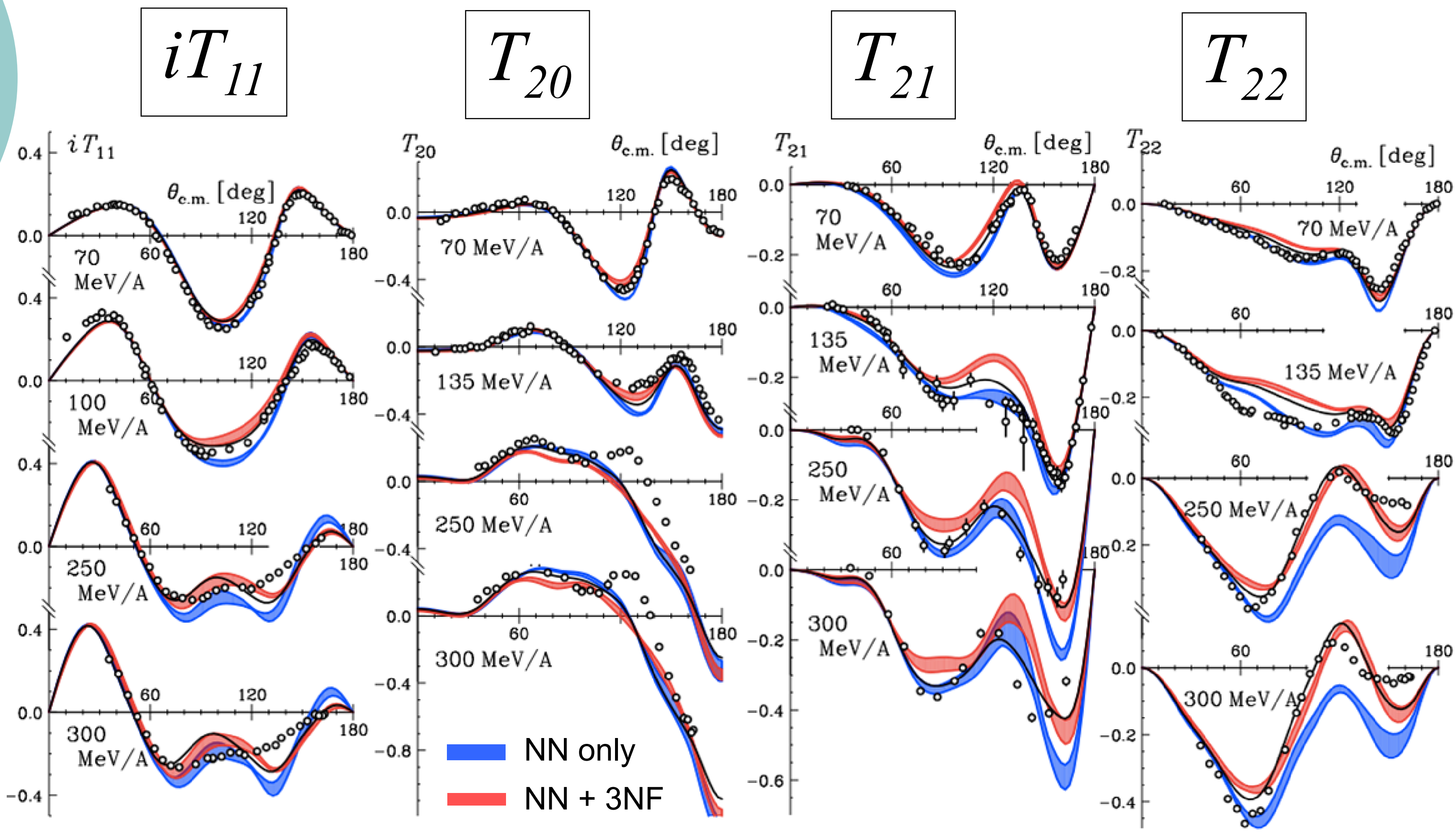


Different energy dependence of T_{22} data and theory in angular regions



3NF Effects
Elastic Deuteron-Nucleon Scattering

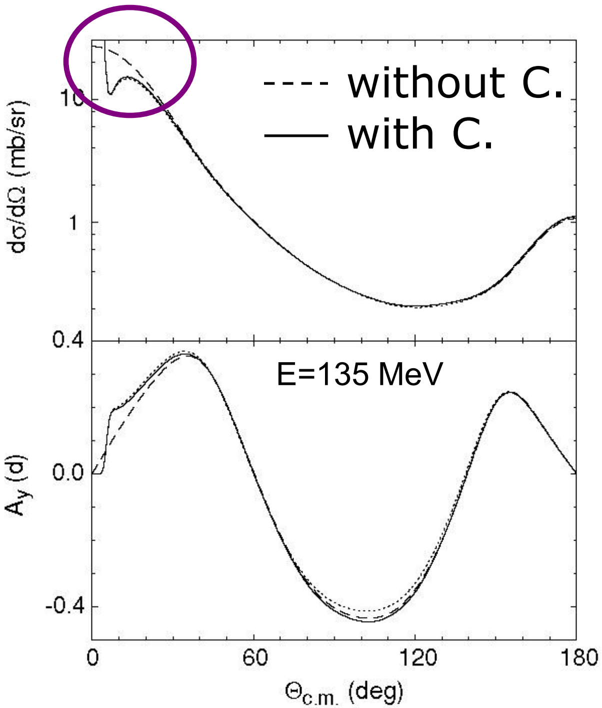
K. Sekiguchi *et al.*, Phys. Rev. C **83** (2011) 061001



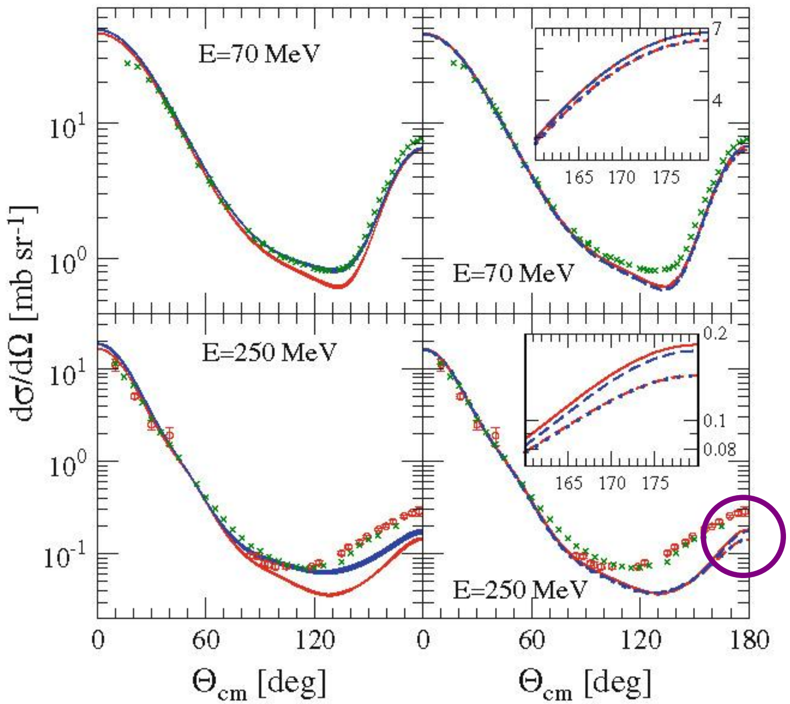
More Dynamical Effects ?
Coulomb force and relativity

Predictions for the N-d elastic scattering

Coulomb

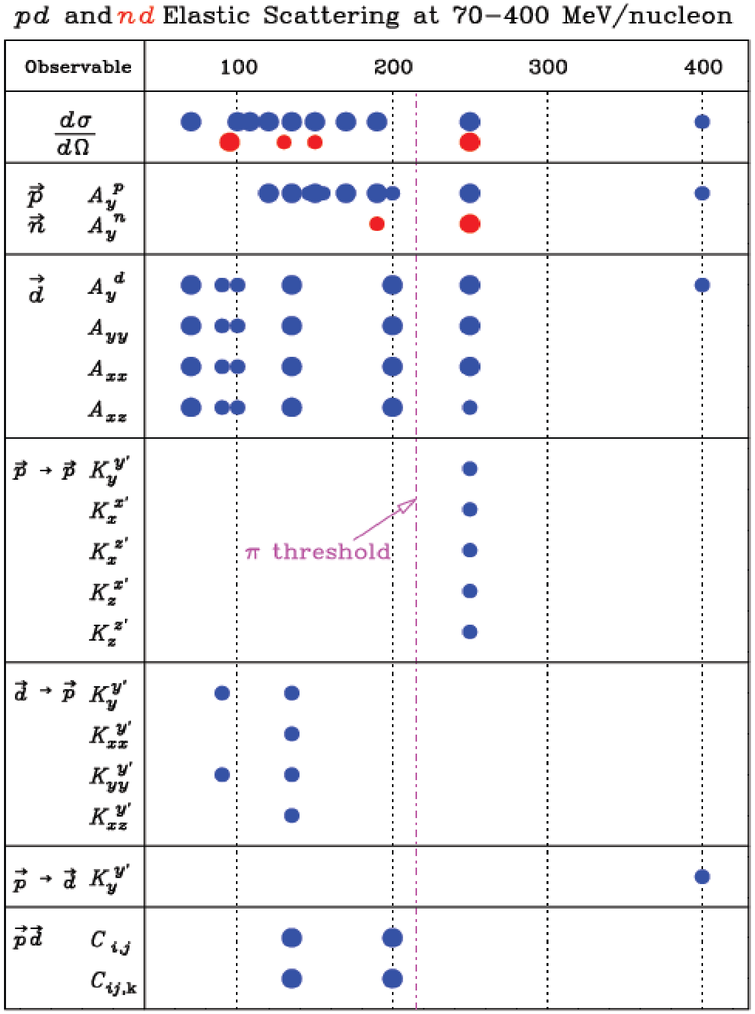


3NF relativity



Effects small, located at extreme angles only !

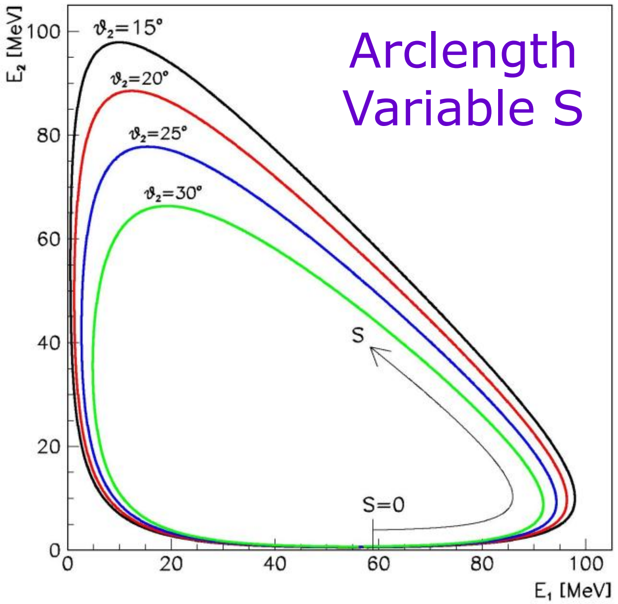
3N Systems
Elastic N-d Scattering

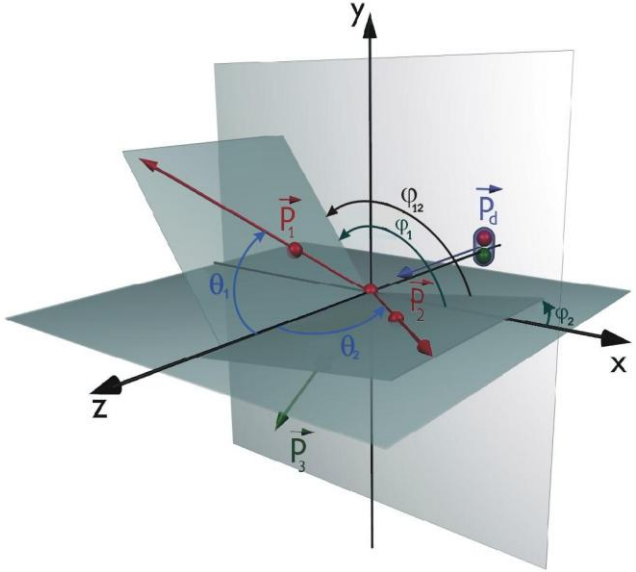


- Number of observables for the **elastic scattering channel**, allowing a multi-dimensional study of 3NF and other effects
- **Only fraction** has been measured accurately and systematically (RIKEN/RCNP/IUCF/KVI)
- Not completely clear picture - still much to explore !
- Complementary studies needed at much richer field: **Nucleon-Deuteron Breakup**

N-d Breakup Reaction
New Generation Experiments

- Coverage of large phase-space regions
- Precise, rich sets of data needed for **systematic studies** of various effects
  - Specific configurations sensitive to different dynamical effects



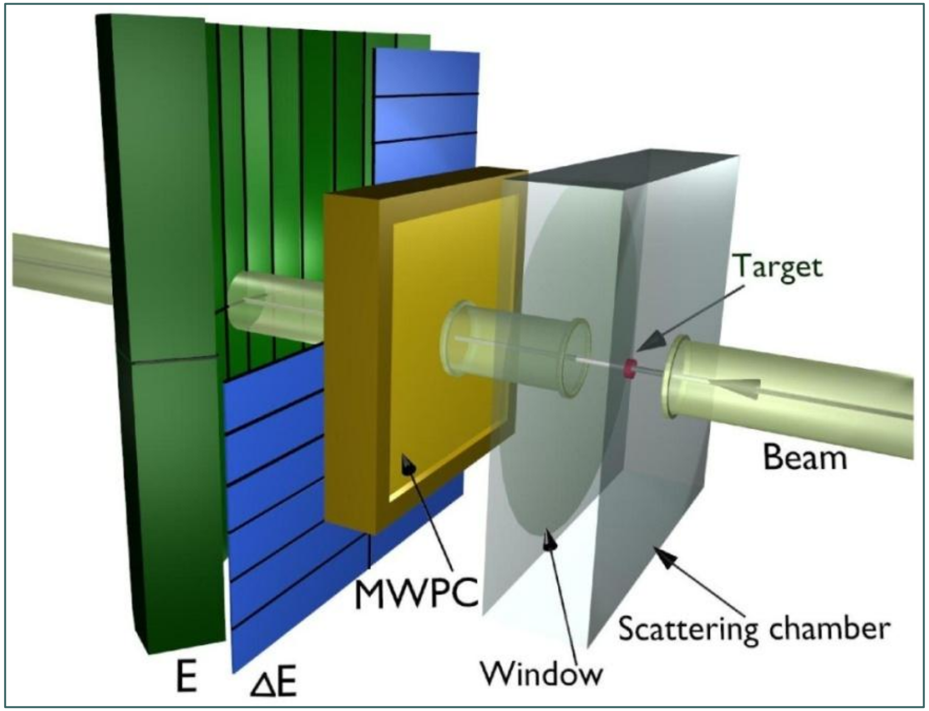


$^1H(d,pp)n$ measured: directions and energies of two protons, i.e.

θ_1, φ_1, E_1

θ_2, φ_2, E_2

N-d Breakup Reaction
Experimental Setups #1



N. Kalantar-Nayestanaki *et al.*, Nucl. Instrum. Methods Phys. Res. A **444** (2000) 591

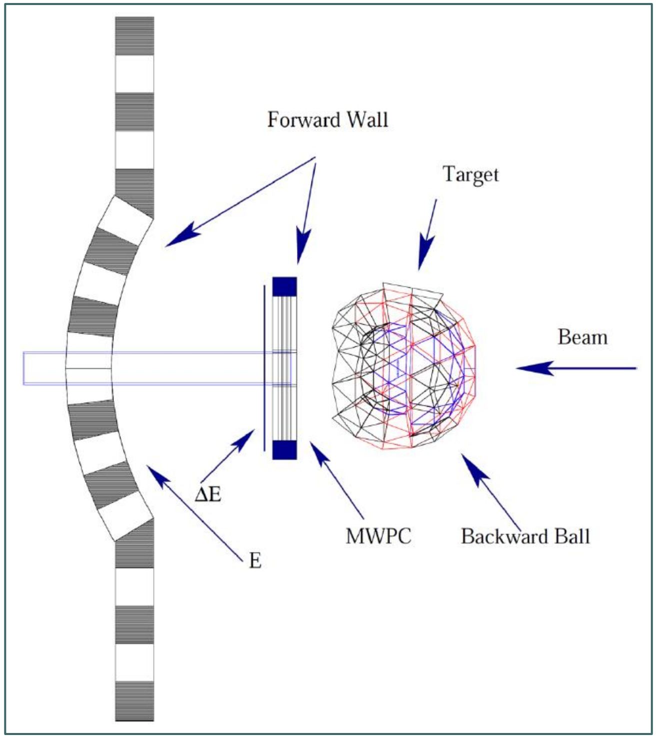
- 140 ΔE-E telescopes
- 3 plane MWPC
- $\theta = (12°, 38°), \varphi = (0°, 360°)$

SALAD
KVI Groningen, NL

- Liquid Hydrogen or Deuterium target ca. 4.5 mm thick
- MWPC: active area of $380 \times 380\ \mathrm{mm}^2$; central hole of 97.2 mm of diameter
- 24 ΔE detectors, 2 mm thick
- 24 E detectors 112.5 mm thick

N-d Breakup Reaction
Experimental Setups #2

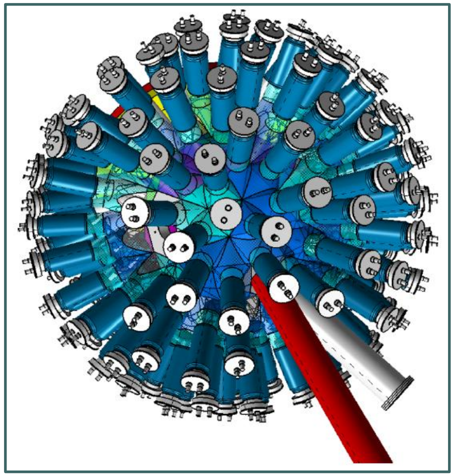
I. Ciepał *et al.*, Phys. Rev. C **99** (2019) 014620

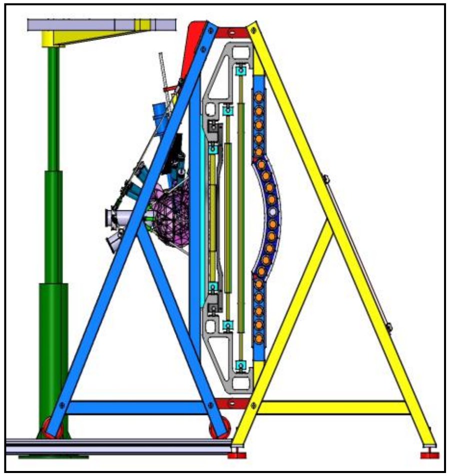


BINA

KVI Groningen, NL

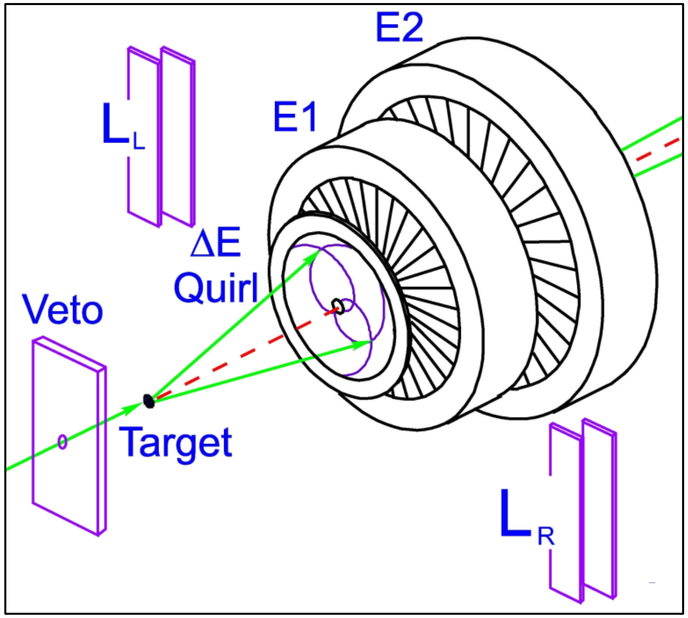
CCB PAS, Kraków, PL



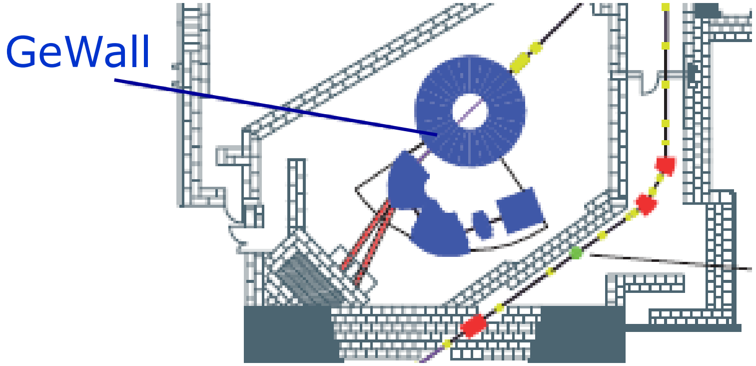


- Wall – very similar to SALAD
- Ball – arrangement of 149 phoswiches, acts as vacuum chamber
- $\theta_{Wall} = (12°, 35°), \theta_{Ball} = (40°, 180°)$

N-d Breakup Reaction
Experimental Setups #3



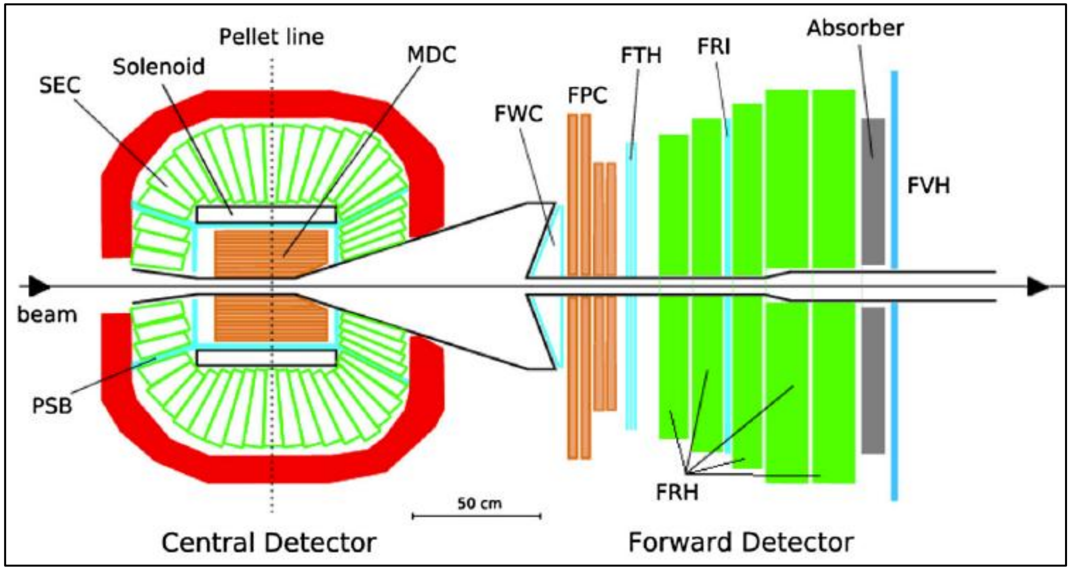
GeWall @ BigKarl
FZ Jülich, D



I. Ciepał *et al.*, *Few-Body Syst.* **56** (2015) 665

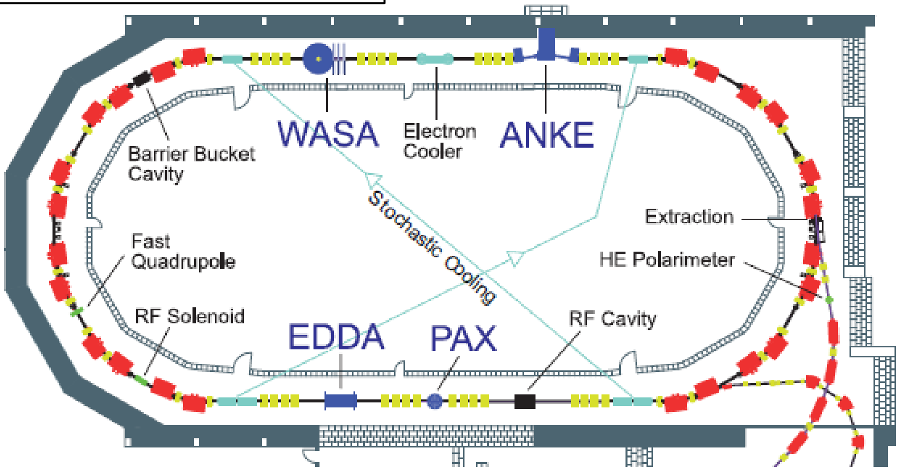
- Quirl – 2 mm thick, 2*200 spirals, Φ36 mm
- Pizza 1/2 – 15 mm thick, 32 sectors, Φ53/77 mm
- HPGe, central holes for beam passage Φ5/6/8 mm
- $\theta = (3°, 15°), \varphi = (0°, 360°)$

N-d Breakup Reaction
Experimental Setups #4



WASA @ COSY
FZ Jülich, D

- $\theta_{CD} = (20°, 169°)$
- $\theta_{FD} = (3°, 18°)$



B. Kłos *et al.*, Few-Body Syst. **55** (2014) 721

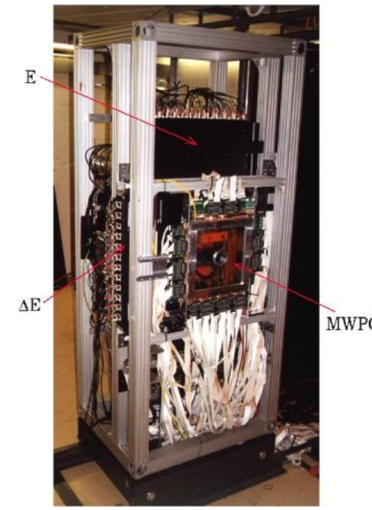
$^1H(\vec{d},pp)n$ Measurements at 130 MeV

Cross Section and Analyzing Power Results

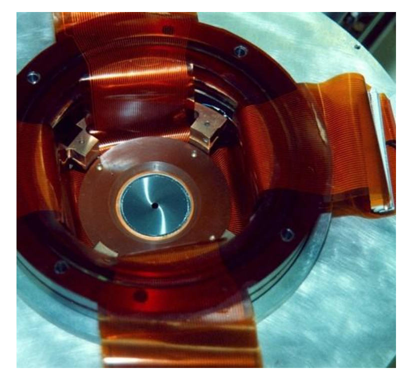
St. Kistryn & E. Stephan
J. Phys. G: Nucl. Part. Phys. **40** (2013) 063101

- ✓ 1800 cross section data points
  - θ_1, θ_2 = (13°) 15° – 30°; grid 5° ; $\Delta\theta$ = ±1°
  - φ_{12} = 40° – 180°; grid 10° – 20° ; $\Delta\varphi$ = ±5°
  - S [MeV] = 40 – 160; grid 4; ΔS = ±2
- ✓ 5*800 data points A_x, A_y, A_{xx}, A_{xy}, A_{yy}
  - θ_1, θ_2 = 15° – 30°; grid 5° ; $\Delta\theta$ = ±2°
  - φ_{12} = 40° – 180°; grid 20° ; $\Delta\varphi$ = ±10°
  - S [MeV] = 40 – 160; grid 8; ΔS = ±4
- ✓ 2700 cross section data points
  - θ_1, θ_2 = 5° – 13°; grid 2° ; $\Delta\theta$ = ±1°
  - φ_{12} = 20° – 180°; grid 20° ; $\Delta\varphi$ = ±5°
  - S [MeV] = 40 – 180; grid 8; ΔS = ±4
- ✓ 2*300 data points A_x, A_y
  - θ_1, θ_2 = 6° – 12°; grid 3° ; $\Delta\theta$ = ±1.5°
  - φ_{12} = 60° – 180°; grid 40° ; $\Delta\varphi$ = ±20°
  - S [MeV] = 40 – 160; grid 16; ΔS = ±8

SALAD



GeWall



3N Systems
Our Data Sets

Energy [MeV/nucleon]	Reaction	Detector@Lab	Observables ca 1000 data points per observable	
50	$^{1}H(d, pp)n$	BINA@KVI	σ	$A_x^d, A_y^d, A_{xy}, A_{xx}, A_{yy}$
65	$^{1}H(d, pp)n$	SALAD@KVI	σ	$A_x^d, A_y^d, A_{xy}, A_{xx}, A_{yy}$
		GeWall@FZ-Jülich	σ	A_x^d, A_y^d
80	$^{1}H(d, pp)n$	BINA@KVI	σ	
	$^{1}H(d, pn)p$			
108	$^{1}H(d, pp)n$	BINA@CCB	σ	
135, 195	$^{2}H(p, pp)n$	BINA@KVI	σ	A_x , A_y
150	$^{1}H(d, pp)n$	WASA@FZ-Jülich	σ	
160	$^{2}H(p, pp)n$	BINA@CCB	σ	
170, 190, 200	$^{1}H(d, pp)n$	WASA@FZ-Jülich	σ	
80	$^{2}H(d, dp)n$	BINA@KVI	σ	
80	$^{2}H(d, {}^{3}He)n$	BINA@KVI	σ	

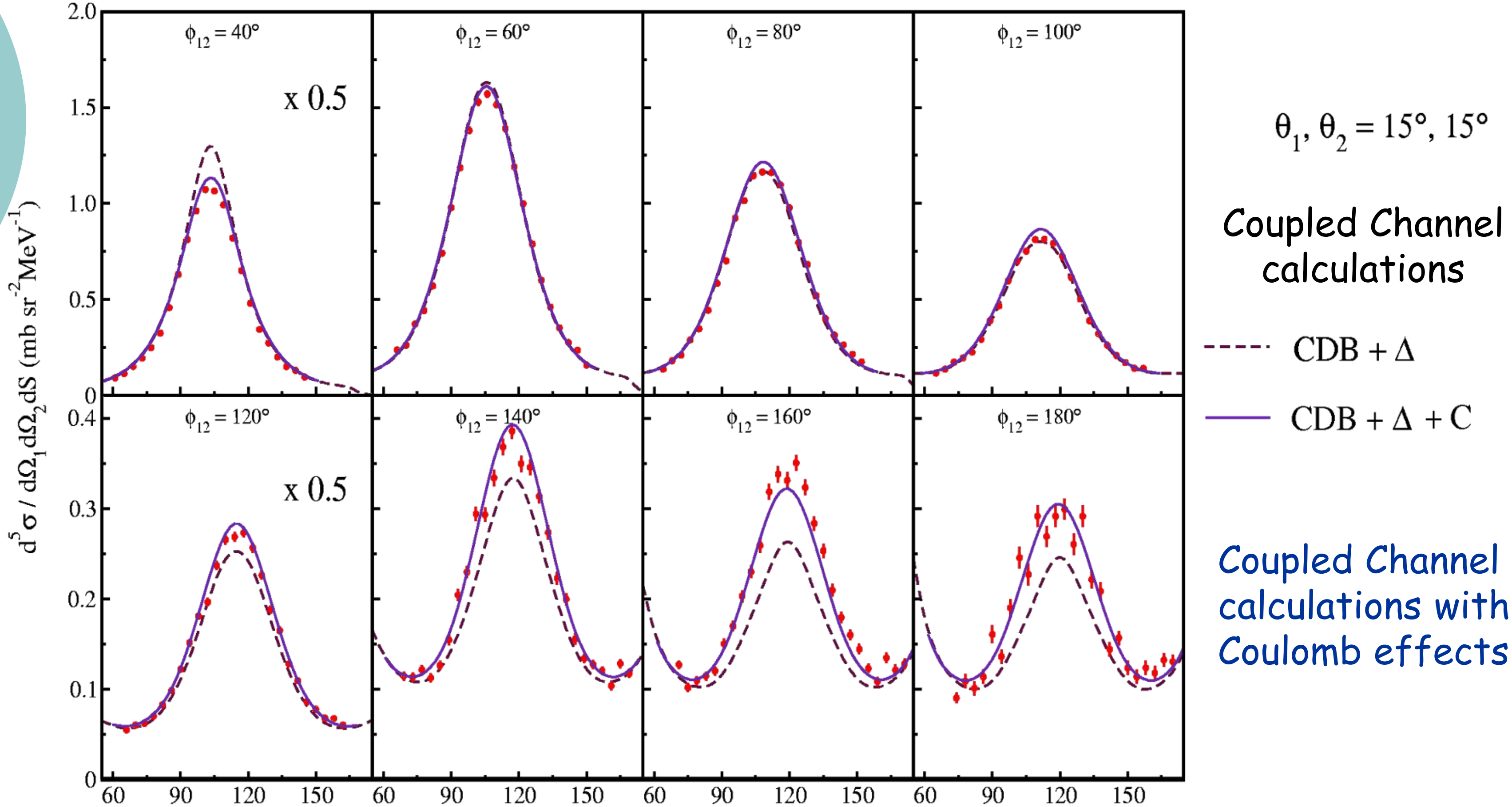
KVI-CART

UNIWERSYTET ŚLĄSKI W KATOWICACH

WASA@COSY

^{1}H($\vec{d}$,pp)n Measurement at 130 MeV

Cross Section Results – Discrepancies Cured

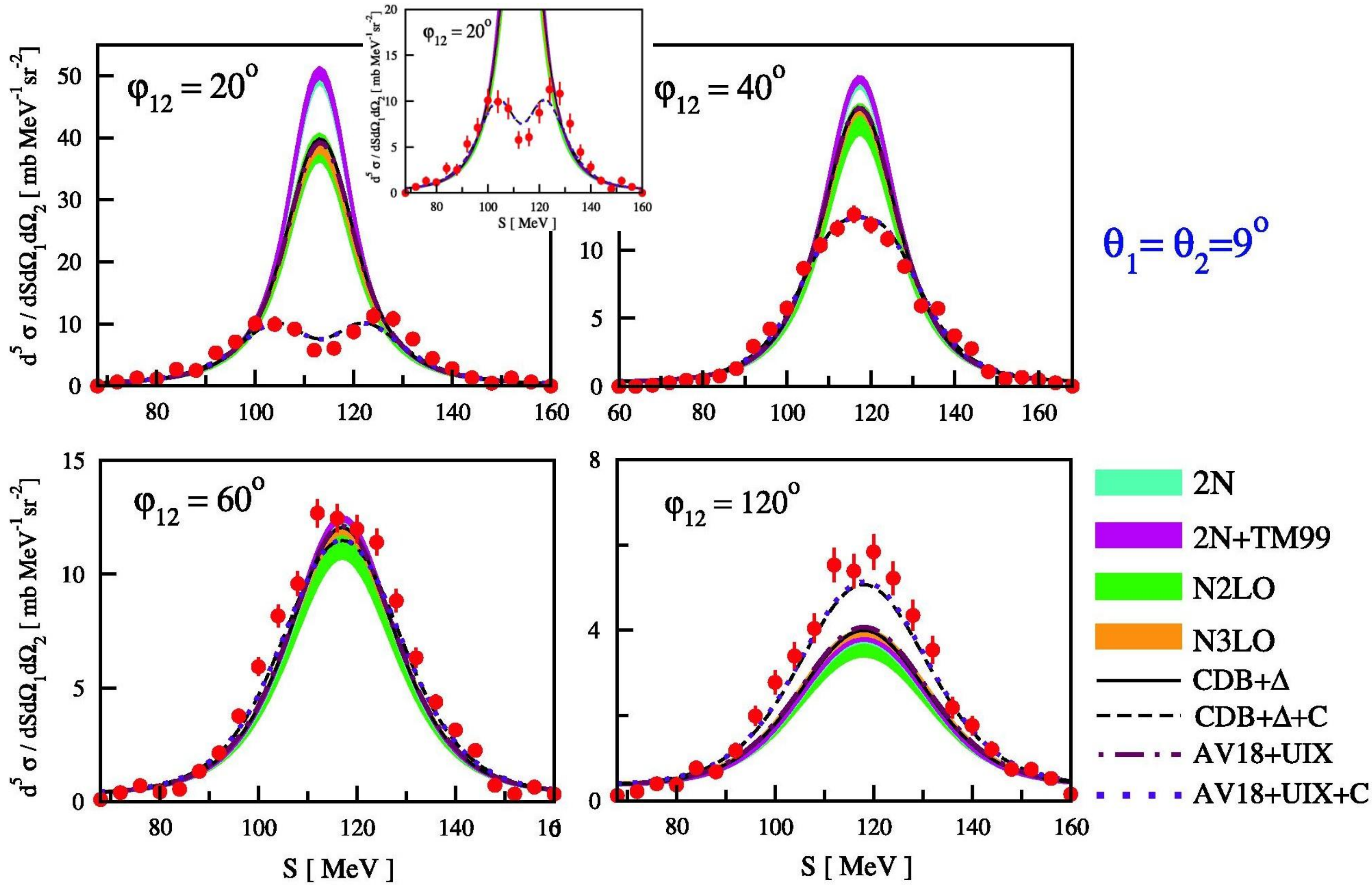


Predictions with Coulomb reproduce data much better !

^{1}H($\vec{d}$,pp)n Measurement at 130 MeV

Cross Section Results – Examples

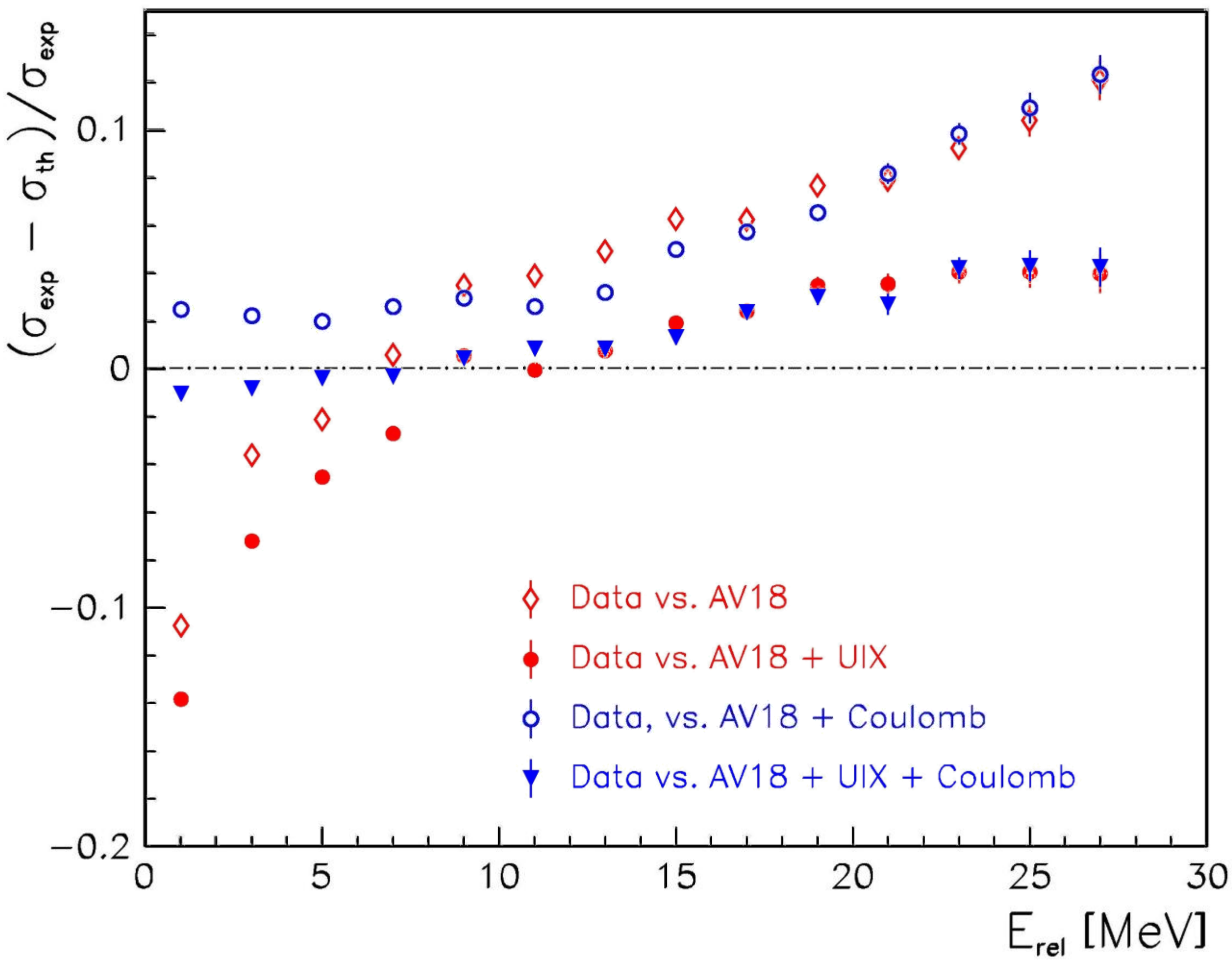
St. Kistryn *et al.*, Phys. Proc. **17** (2011) 126



$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Cross Section Results – 3NF & Coulomb Effects

Including Coulomb force effects improves the agreement with the data at low E_{rel} values

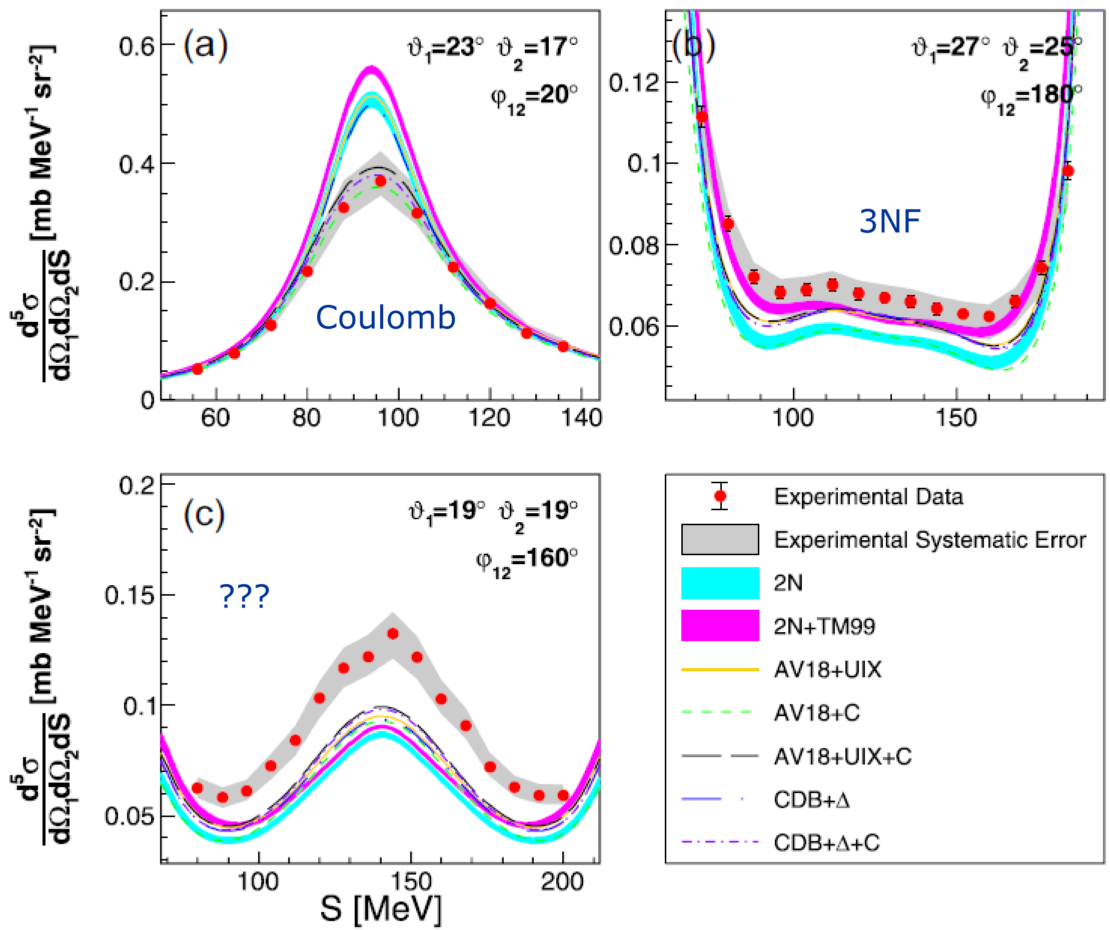


The best agreement is reached when both, the Coulomb force and the 3NF are taken into account !

$^2H(p,pp)n$ Measurement at 135 MeV

Cross Section Results – local discrepancies

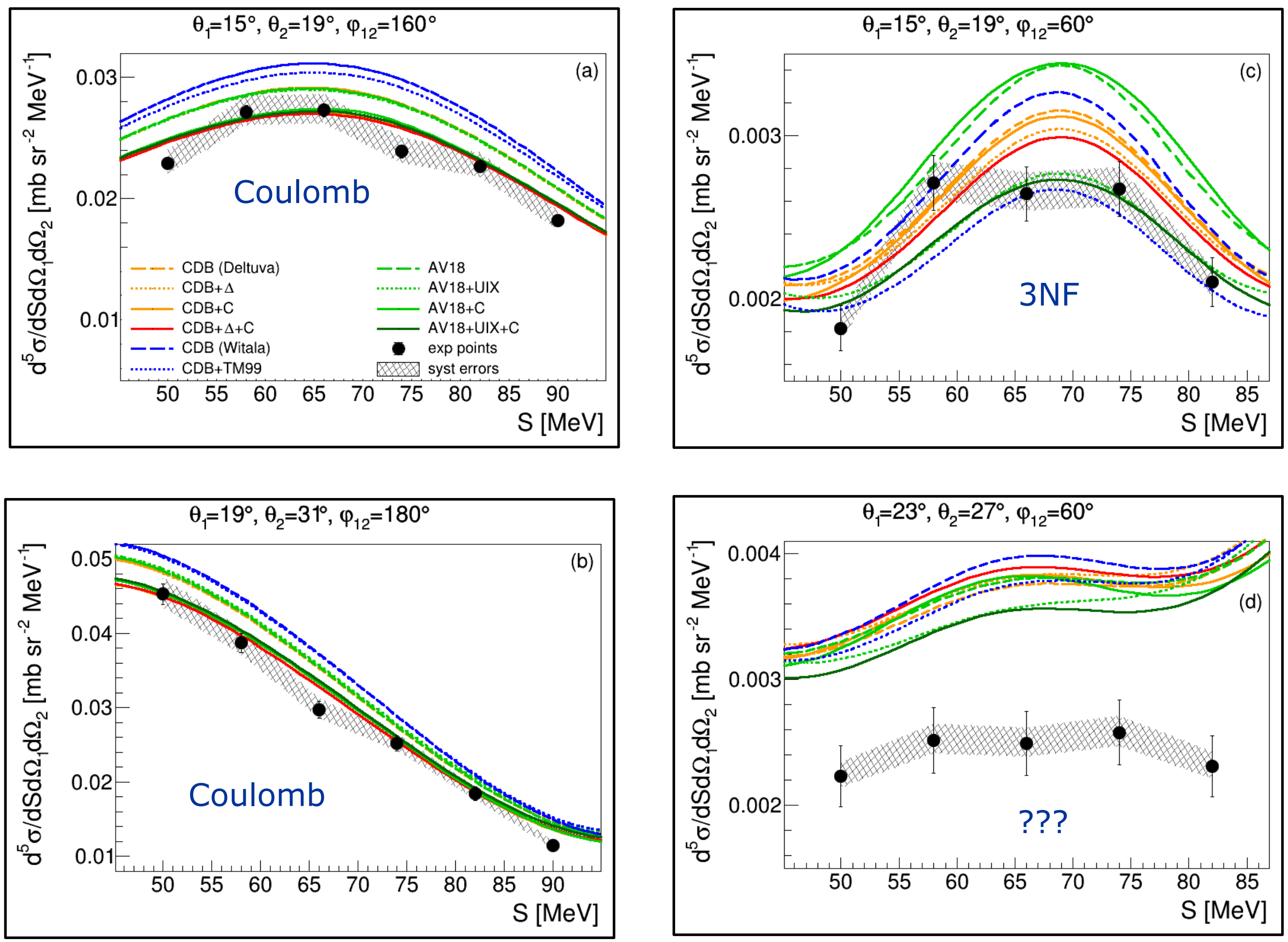
W. Parol *et al.*, *Phys. Rev.* C **102** (2020) 054002



In general, including 3NF or/and Coulomb effects improves agreement of data and theory, but local dicrepancies persist

^{2}H(p,pp)n Measurement at 135 MeV

Cross Section Results – local discrepancies



A. Łobejko *et al.*, *Phys. Rev. C* **111** (2025) 054001

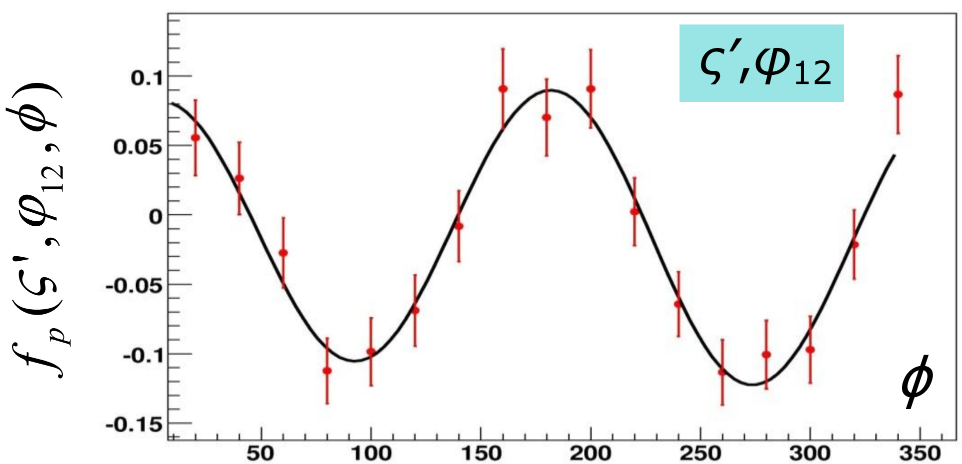
BINA @ CCB

$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

Breakup Analyzing Powers – Extraction

Azimuthal (Φ) distribution at every kinematical point $(\theta_1,\theta_2,\varphi_{12},S) \equiv (\varsigma',\varphi_{12})$, with known P_z and P_{zz} of rate asymmetry $f_P(\varsigma',\varphi_{12},\Phi)$ for pol. and unpol. states

$$f_p(\varsigma',\varphi_{12},\phi) = \left[P_z \cdot \left(-\frac{3}{2}\sin\phi \cdot A_x + \frac{3}{2}\cos\phi \cdot A_y \right) + P_{zz} \cdot \left(-\frac{1}{2}\sin 2\phi \cdot A_{xy} \right) + P_{zz} \cdot \left(\frac{1}{2}\sin^2\phi \cdot A_{xx} + \frac{1}{2}\cos^2\phi \cdot A_{yy} \right) \right]$$



$$A \equiv A(\varsigma',\varphi_{12})$$

$^{1}H(\vec{d},pp)n$ Measurement at 130 MeV

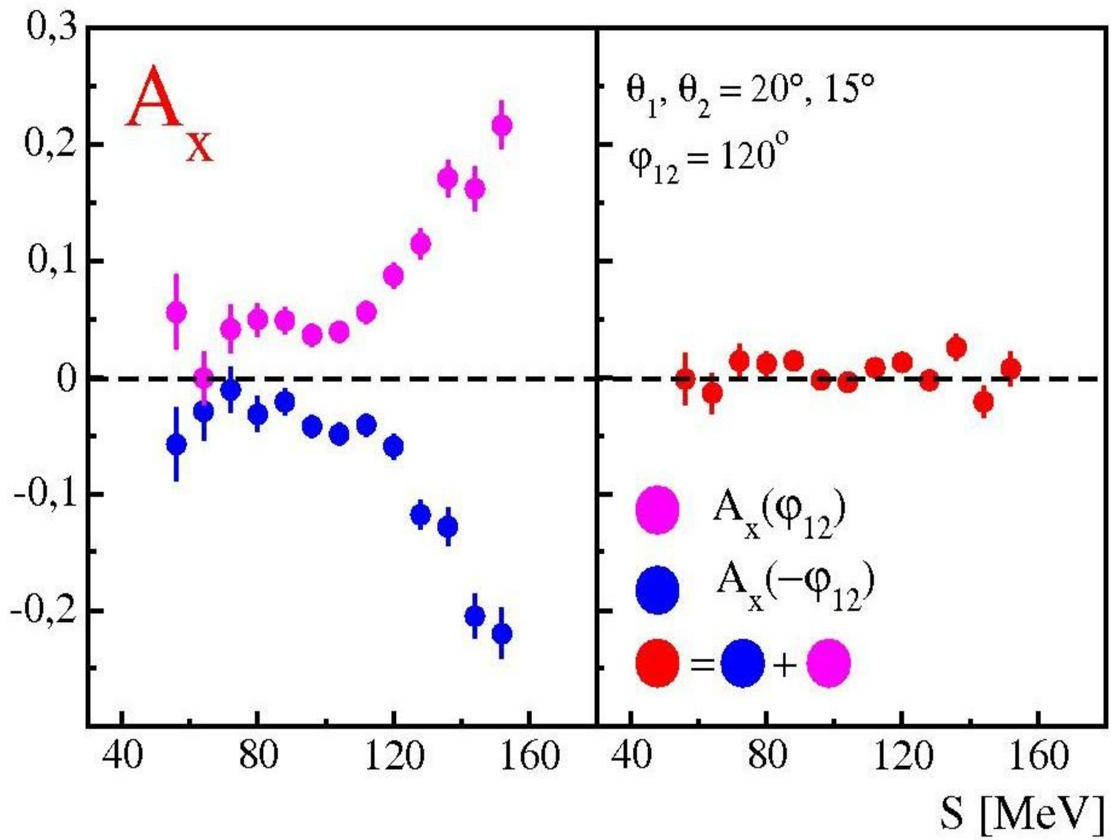
Analyzing Power Results – Parity Test of Data

Parity symmetry

$$A_\beta(\varsigma',-\varphi_{12}) = \\ = (-1)^{\mu} \bullet A_\beta(\varsigma',\varphi_{12})$$

$\mu = 1$ for β = x, xy

$\mu = 0$ for β = y, xx, yy



Parity-forbidden combinations

$$O_\beta(\varsigma',\varphi_{12}) = A_\beta(\varsigma',\varphi_{12}) + (-1)^{1-\mu} \bullet A_\beta(\varsigma',-\varphi_{12})$$

^{1}H($\vec{d}$,pp)n Measurement at 130 MeV

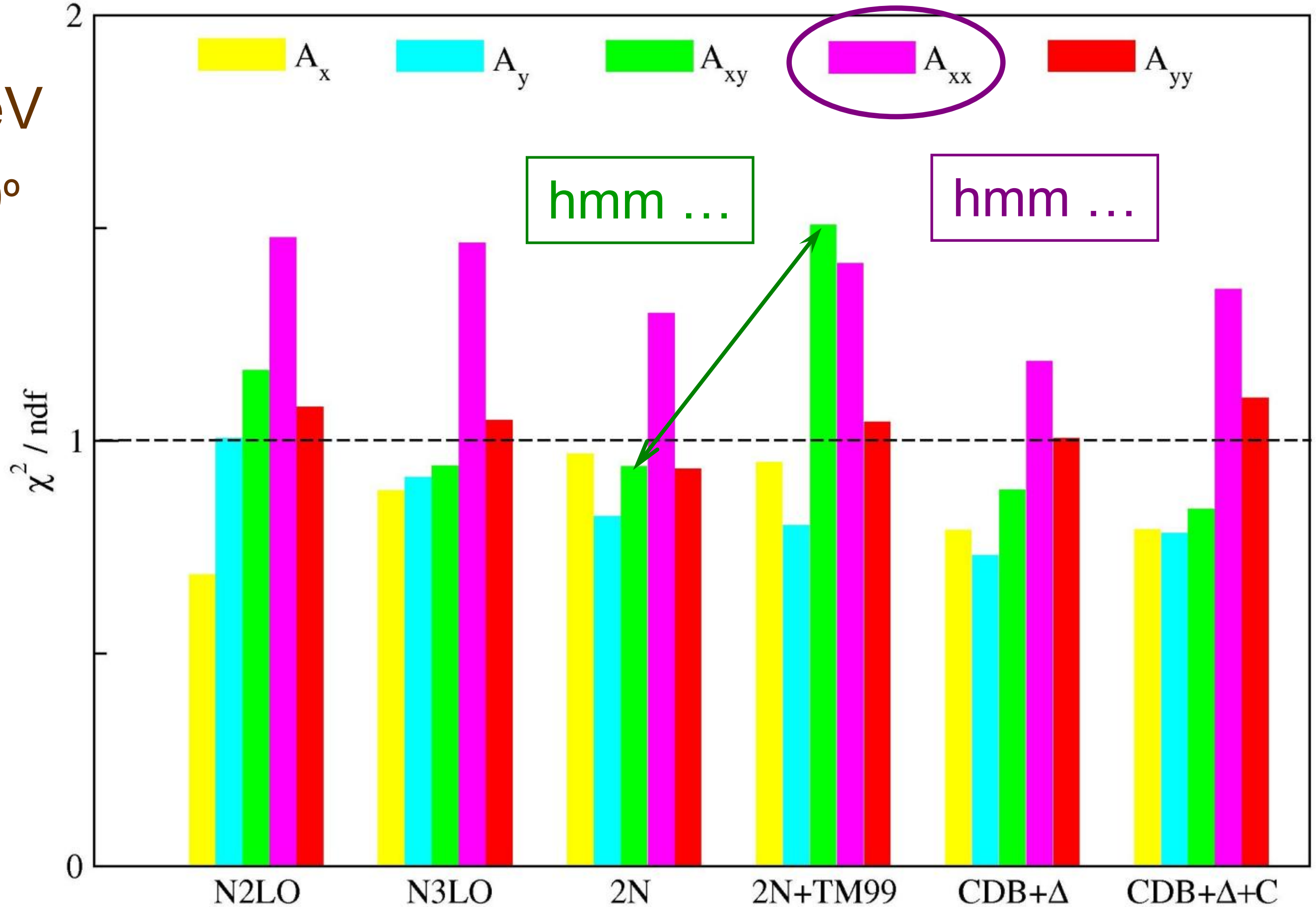
Analyzing Power Results

E_d = 130 MeV

θ_1,θ_2 = 15° - 30°

E. Stephan *et al.*,
Phys. Rev. C **82** (2010) 014003

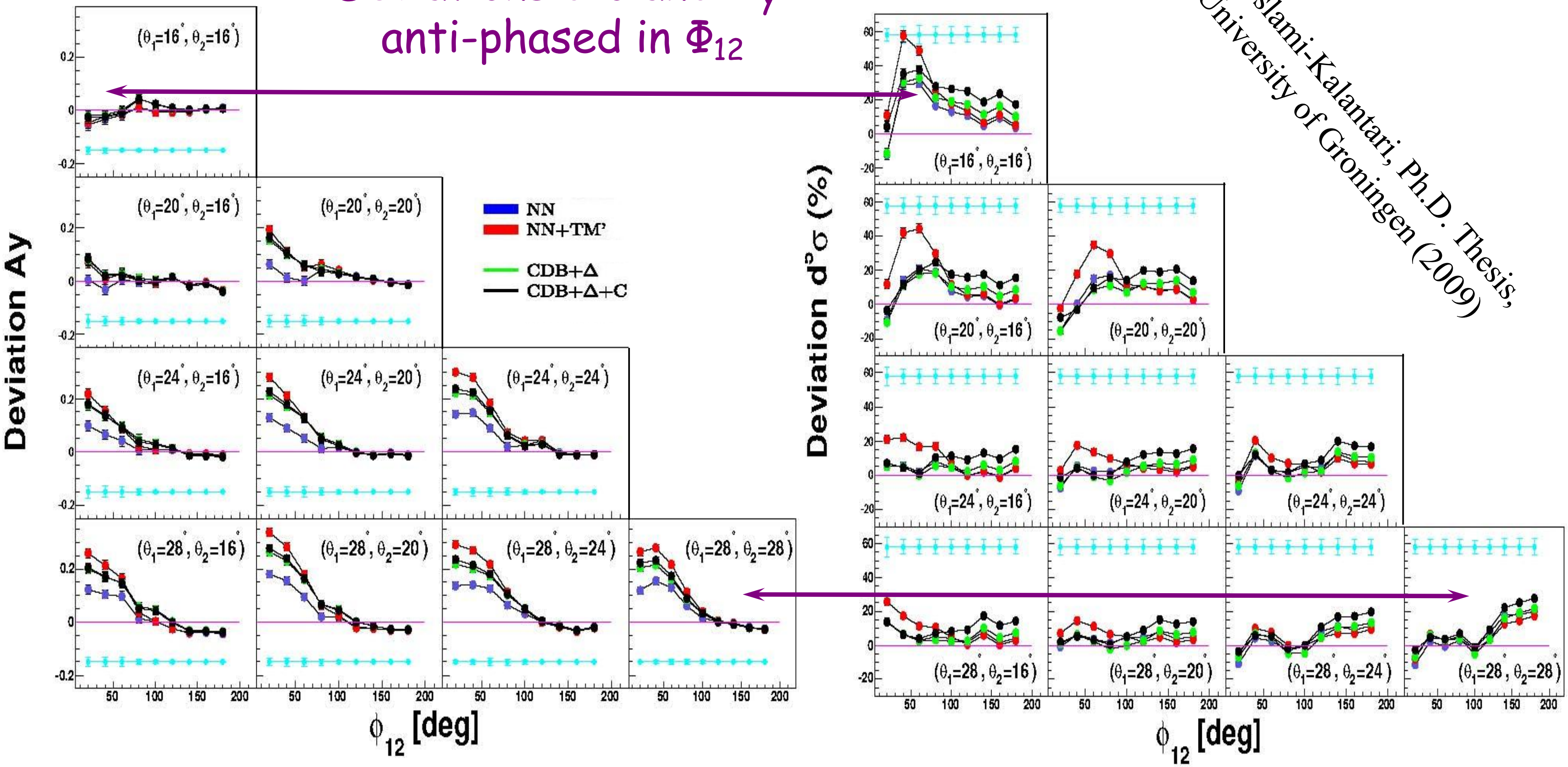
$$\frac{1}{N}\sum_{i=1}^{N\approx 900}\frac{[A^{\rm exp}(\varsigma_i)-A^{\rm th}(\varsigma_i)]^2}{[\delta A^{\rm exp}(\varsigma_i)]^2}$$



^{2}H($\vec{p}$,pp)n Breakup Reaction at 135 MeV
Analyzing Powers vs. Cross Sections

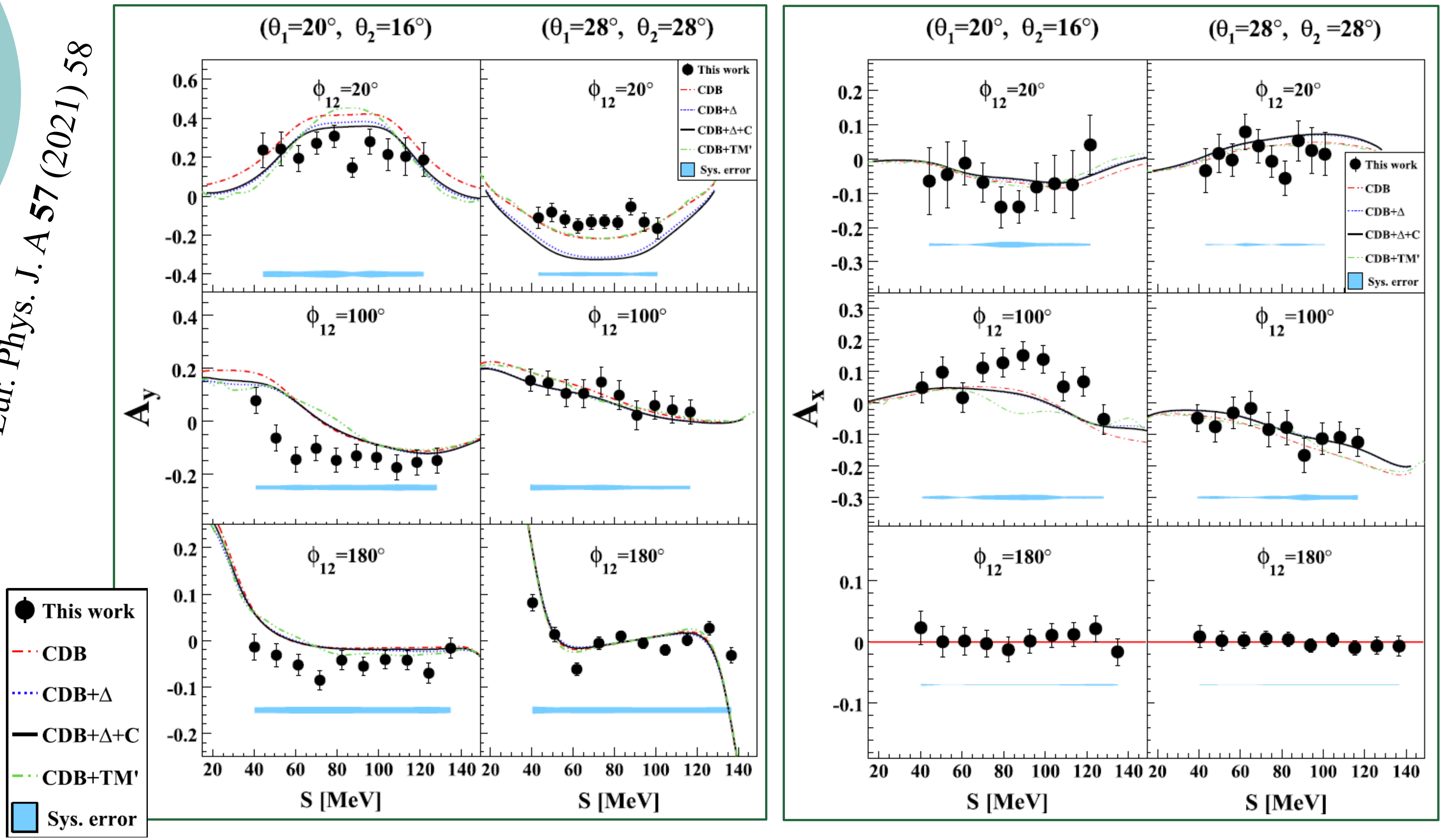
Deviations $d^5\sigma$ and A_y anti-phased in Φ_{12}

M. Eslami-Kalantari, Ph.D. Thesis, University of Groningen (2009)



^{2}H($\vec{p}$,pp)n Breakup Reaction at 135 MeV
Analyzing Powers – general agreement, but …

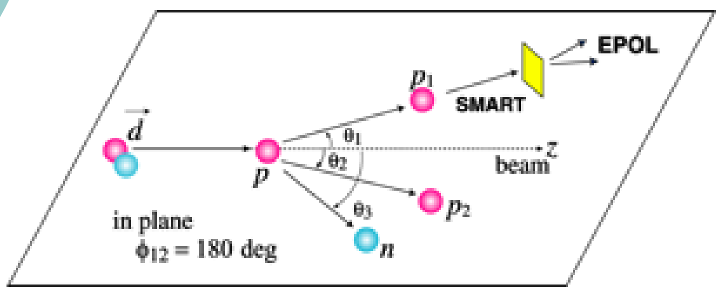
H. Tavakoli-Zaniani *et al.* Eur. Phys. J. A **57** (2021) 58

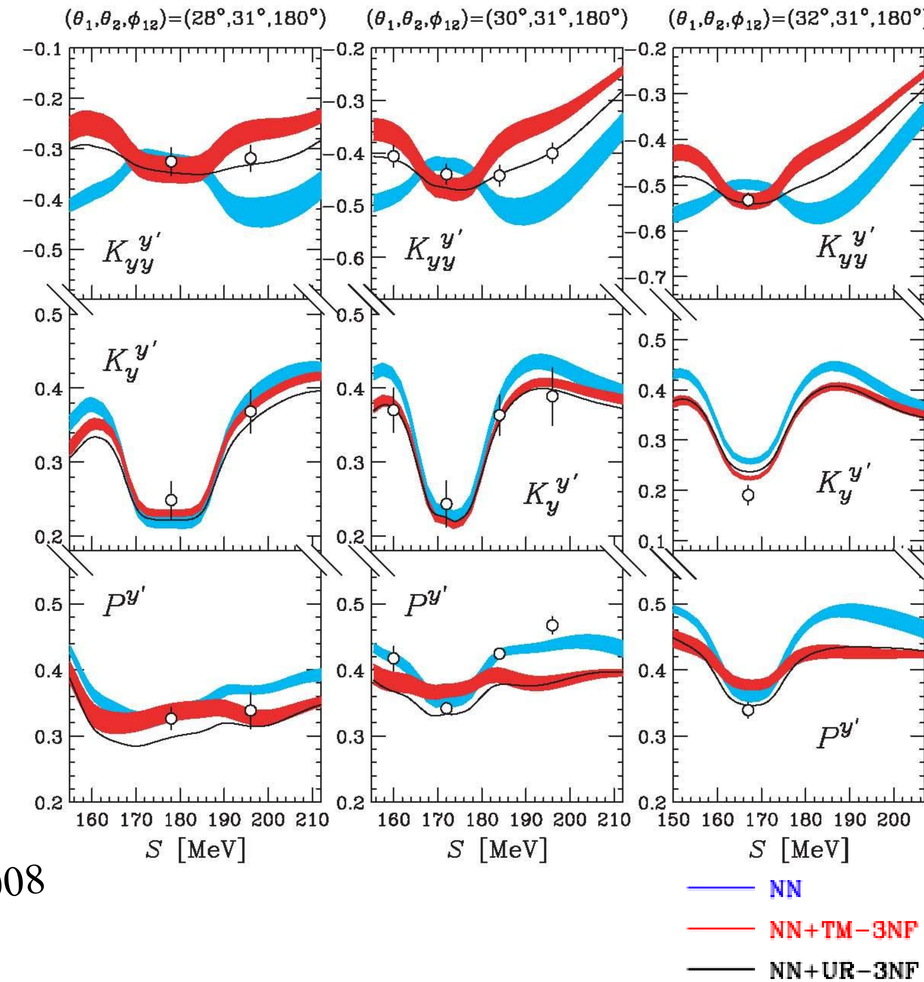


$^1H(\vec{d},pp)n$ Breakup Reaction
Polarization Transfer Coefficients

E_d = 270 MeV

θ_1,θ_2 = 28º-32º, Φ_{12} = 180º

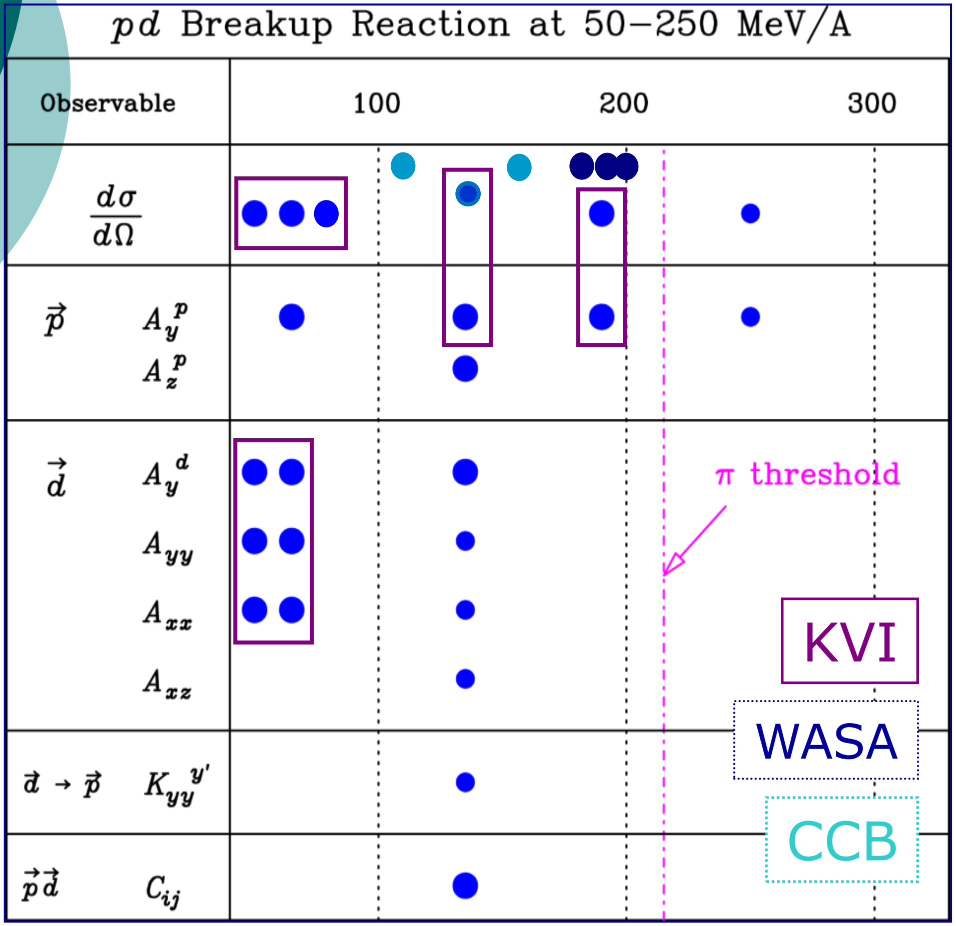




Double-scattering experiment for breakup !

K. Sekiguchi *et al.* Phys. Rev. C **78** (2009) 054008

3N Systems
N-d Breakup Reaction

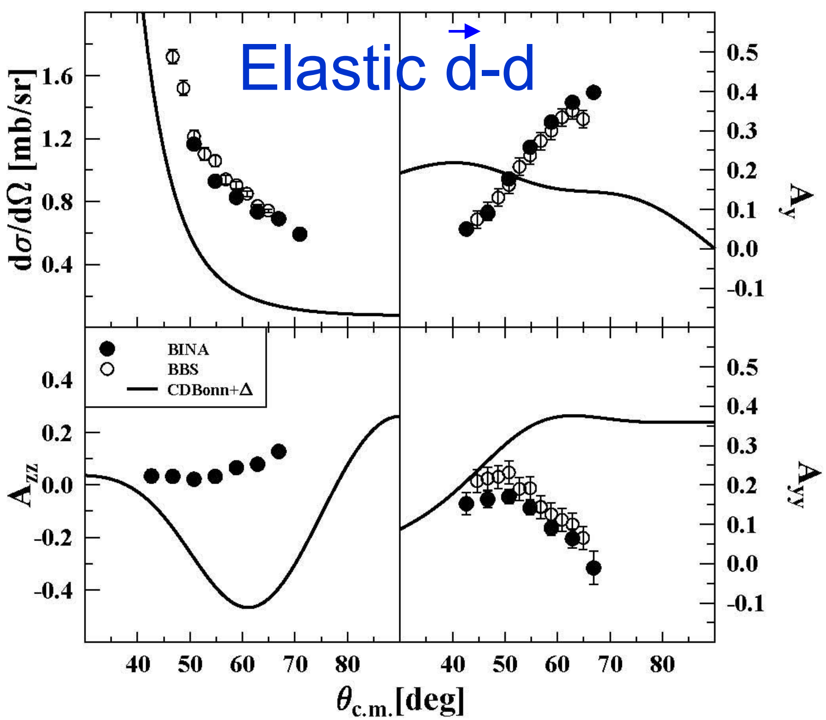


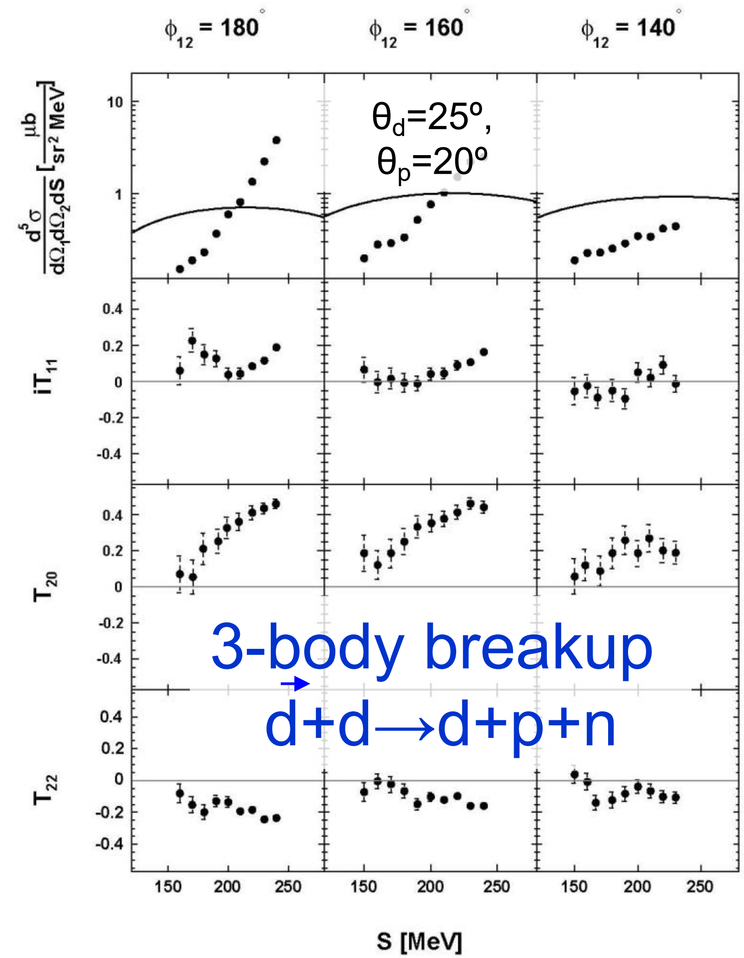
- Variety of observables and configurations (wide ph.sp.) for **the breakup reaction**, field of tests for different dynamic ingredients
- **Sets (a few only)** of rich, systematic and precise data are (at last) available
- Picture very ambiguous - still much to be learnt !
- Comparisons between beam energies – need of new (invariant) variables

Four-Nucleon System
First Approaches

E_d = 130 MeV

θ = 15° - 30°

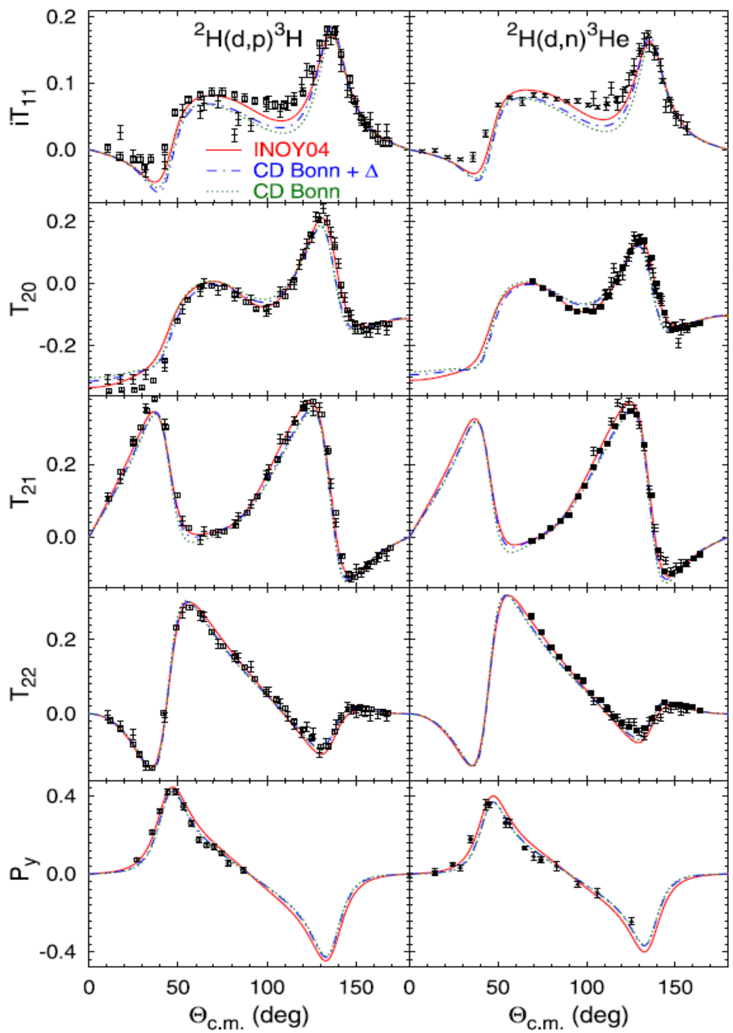


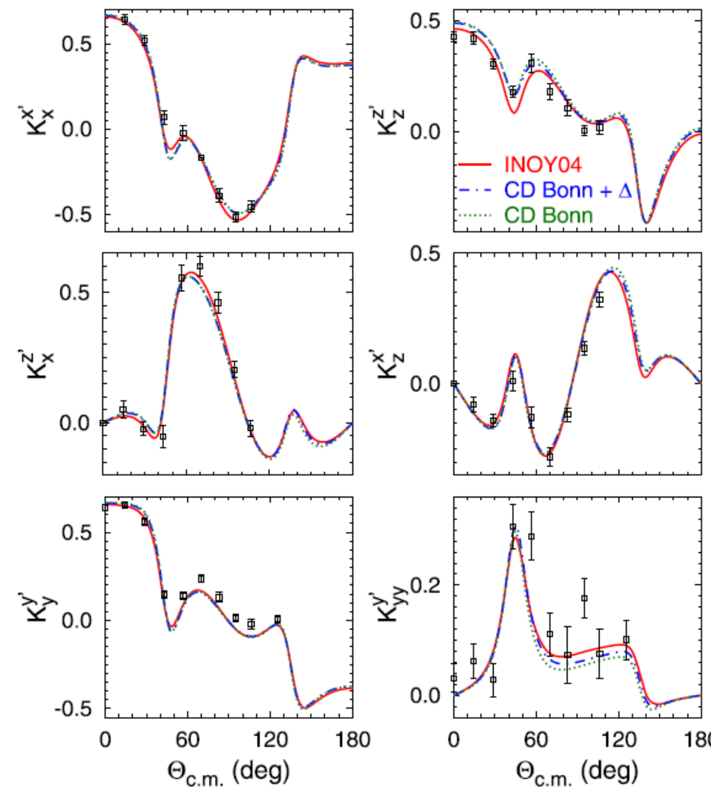


A. Ramazani-Moghaddam-Arani *et al.*,
Phys. Rev. C **83** (2011) 024002

4N System:
First Calculations for Reaction

A. Deltuva, A.C. Fonseca, Phys. Lett. B **742** (2015) 285

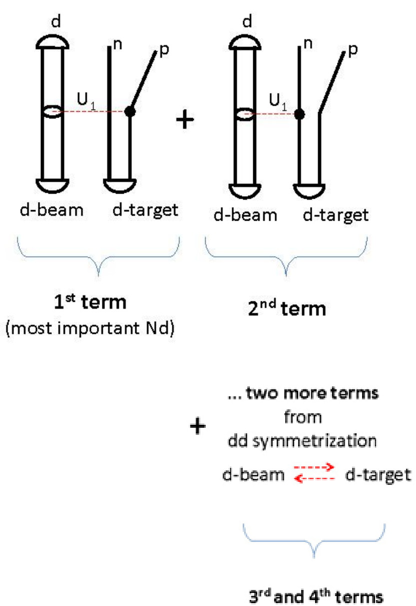


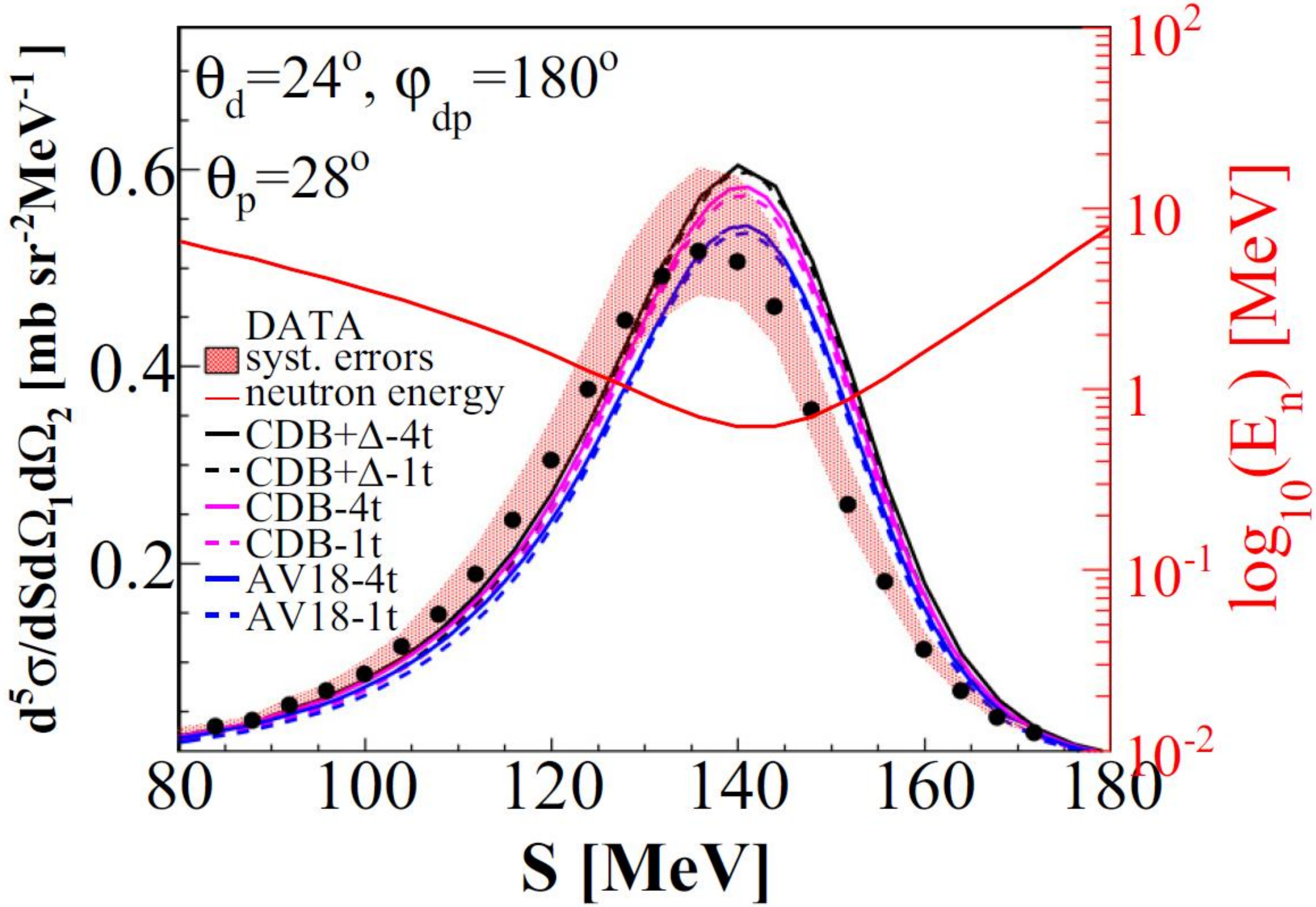


4N Systems

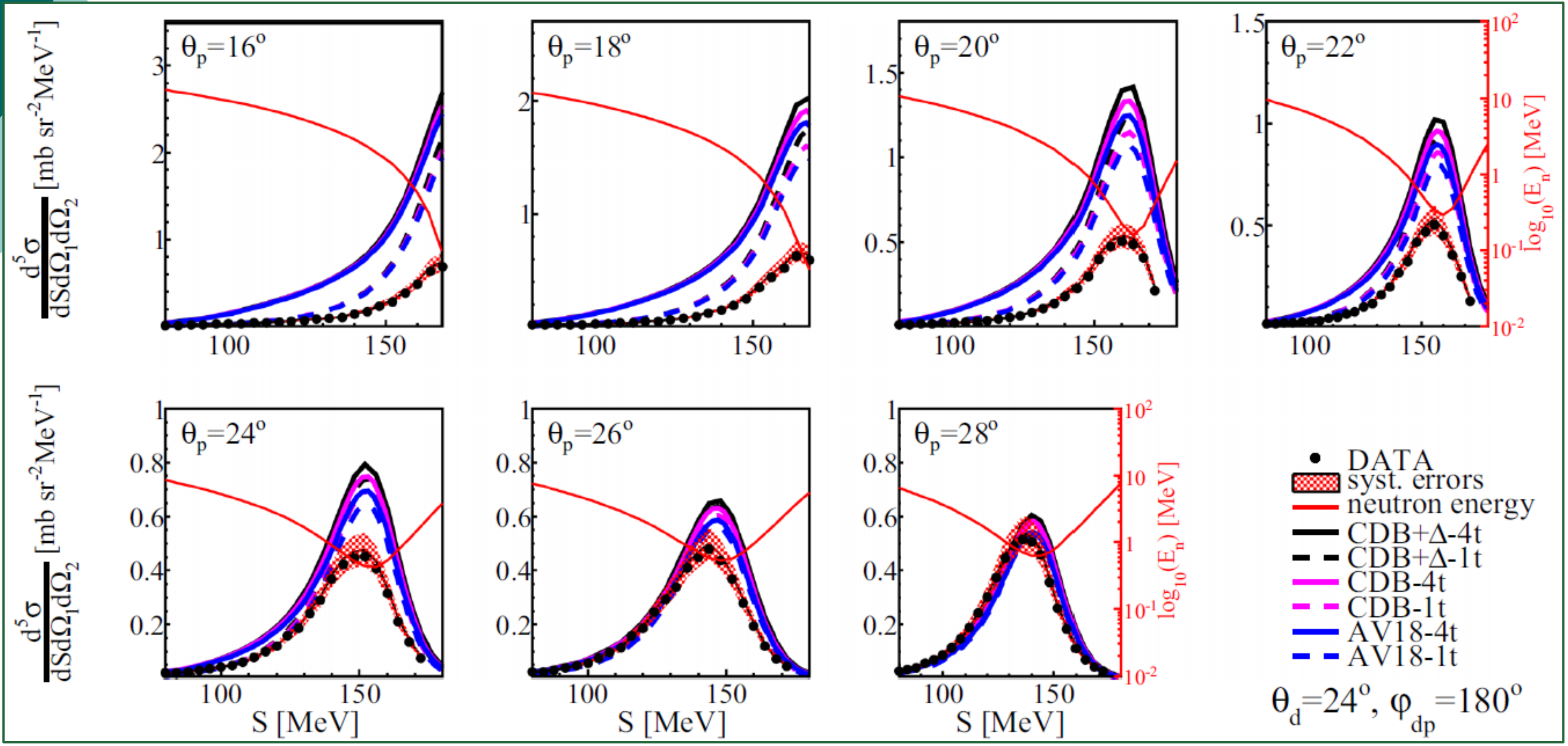
^{2}H(d,dp)n Reaction at 160 MeV

I. Ciepał *et al.*, Phys. Rev. C **100** (2019) 024003





4N Systems
^{2}H(d,dp)n Reaction at 160 MeV



I. Ciepał *et al*., Phys. Rev. C **100** (2019) 024003

Three-Nucleon Systems
Summary

- N. Kalantar *et al.*, Rep. Prog. Phys. **75** (2012) 016301
- St. Kistryn, E. Stephan, J. Phys. G **40** (2013) 063101
- S. Ishikawa, Few-Body Syst. **67** (2026) 19

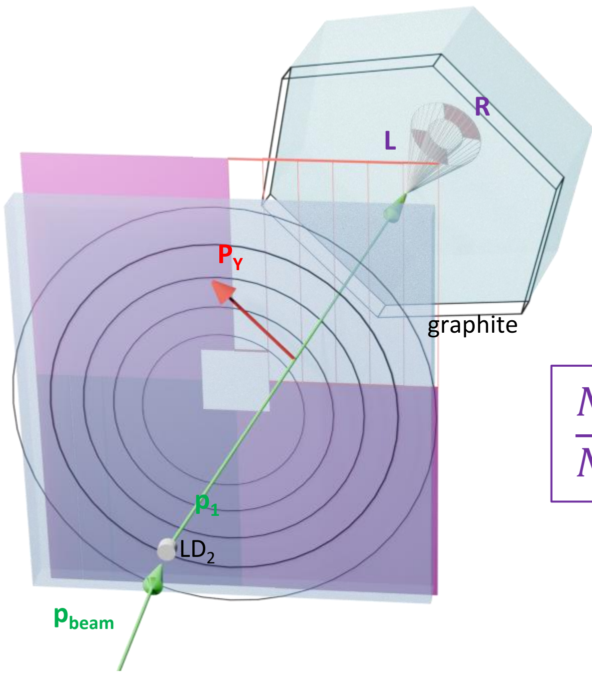
- Rich, systematic and precise sets of data available (elastic scattering – many, breakup – a few)
  ➡ basis for comparing different approaches which predict the 3N system observables
- Showed significant 3NF effects
- Found large influence of the Coulomb force on c.s.
- Relativistic effects to be studied in detail
- Interplay of different ingredients of 3N system dynamics – inspection under way !
  - Discrepancies → hints of imperfections in 3NF models
- General picture not quite clear – needed studies to provide evidences of trends in deficiencies

Few-Nucleon Studies
Outlook & Wishes

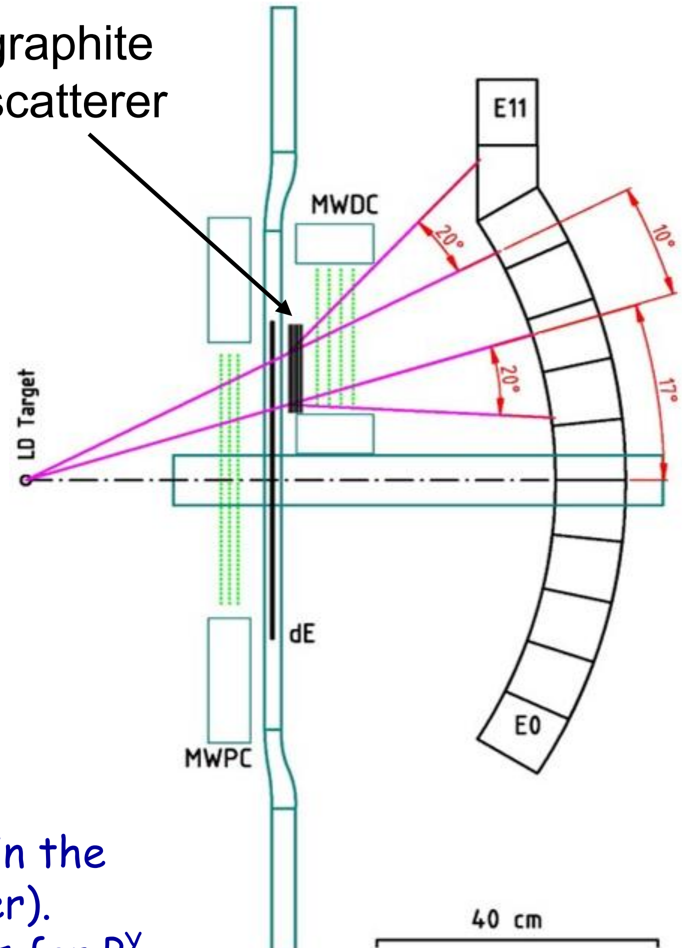
Personal, surely incomplete view

- Prospects for further results:
  - Completing evaluation of the data accumulated in several experiments at KVI and COSY
  - Analysis of the breakup data with new variables, studies of energy dependence of observables
  - More measurements:
    - RIKEN, RCNP, RIBF, ... (other labs ?)
    - **BINA @ INP PAS Cracow**
      - neutron-proton FSI studies
      - **induced polarization** in p-d breakup
      - transition to systematic 4N system investigation

Induced Polarization P^Y in Breakup
BINA @ Cyclotron Center Bronowice INP PAS



$$\frac{N_L - N_R}{N_L + N_R} = P^Y A_C$$



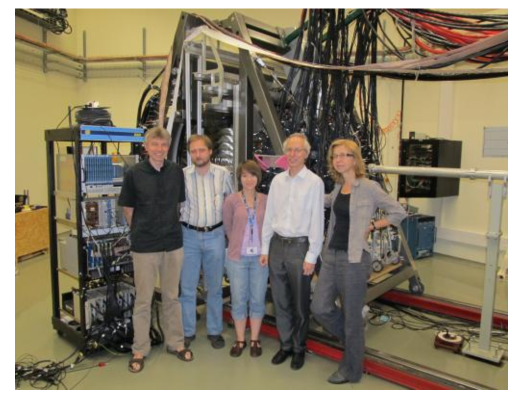
Assumed bins: $\Delta\theta_1$, $\Delta\theta_2$ = 2^0, $\Delta\varphi_{12}$ = 20^0

- four θ_1 values (polarimeter acceptance),
- eight θ_2 values (Wall acceptance),
- six φ_{12} values between 80^0 and 180^0 („first" proton in the polarimeter, "second" proton outside the polarimeter).

32 coplanar configurations, around 6*32*2 data points for P^Y.

Few-Nucleon Studies
Outlook & Wishes

- **Prospects for further results:**
  - Completing evaluation of the data accumulated in several experiments at KVI and COSY
  - Analysis of the breakup data with new variables
  - More measurements:
    - RIKEN, RCNP, RIBF, ... (?)
    - **BINA @ INP PAS Cracow**



- **Progress on theoretical side:**
  - 3NF at N^3LO and higher orders
  - ChPT with Δ (work in progress…)
  - ✓ Realistic potentials with Coulomb
  - ✓ Relativistic potentials with 3NF
  - Rigorous calculations for 4N system

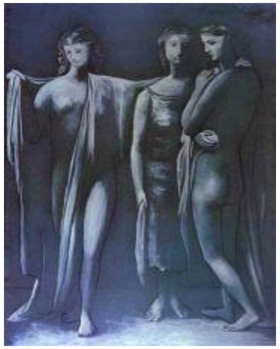
Personal, surely incomplete view

Few-Body Systems Remain Attractive

Thank You for attention








Nucleon-Nucleon Interaction
and
Nuclear Many-Body Problem
ICTS TIFR Mumbai
18-27 November 2010