Three-nucleon system experimental overview

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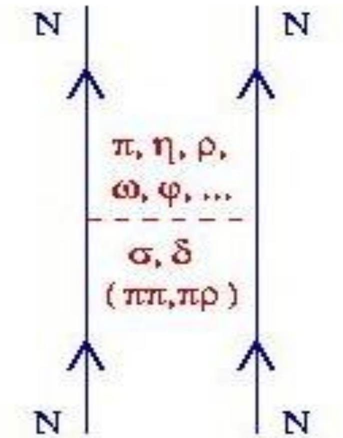
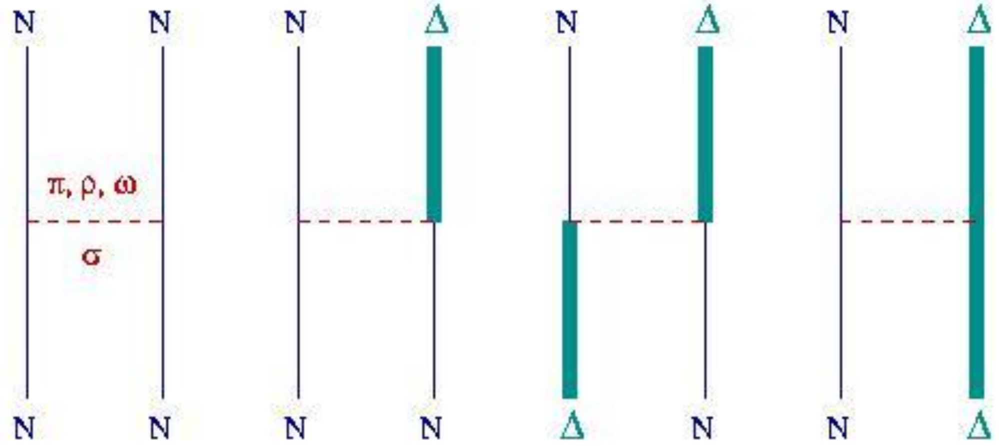
KVI-CART, University of Groningen, The Netherlands

Introduction - Two-nucleon standard interaction models

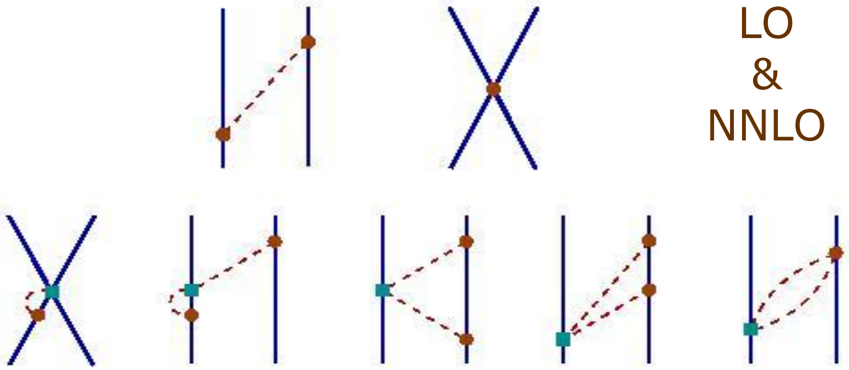
- Meson exchange theory of NN forces - nucleonic degrees of freedom (CD Bonn, Nijm I, Nijm II, AV18)
- CD Bonn/AV18 + explicit treatment of a single Δ-isobar degrees of freedom – **C**oupled barionic **C**hannels
- Effective Field Theory – **Ch**iral **P**erturbation **T**heory; expansion of potential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



Realistic
Potentials



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



LO
&
NNLO

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

Introduction - Two-nucleon standard interaction models

Modern NN potentials are in general able to:

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

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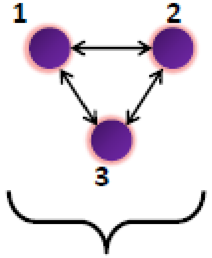
Three-nucleon system **is the simplest** **non-trivial** environment for testing predictions of observables, on the basis of the NN potential models.

Introduction - NN interaction

K. Ermisch et al., PRC 68, 051001(R) (2003)

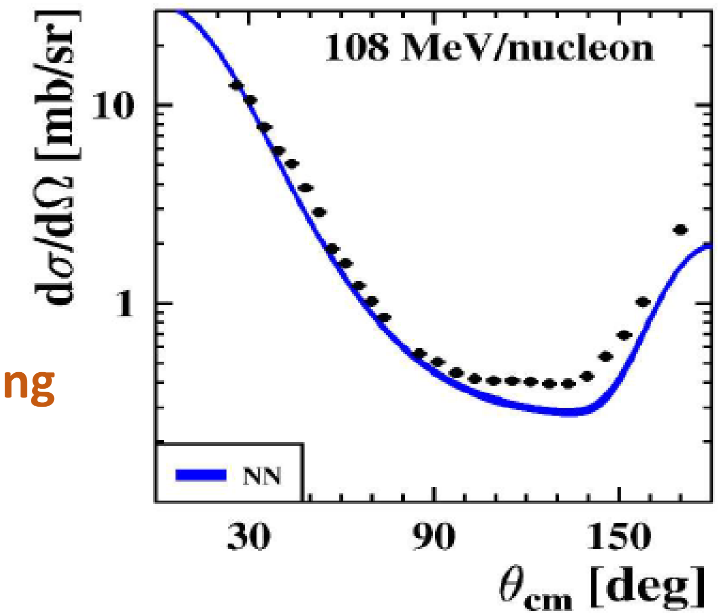
Predictions of **NN potentials alone**:

Binding energy [MeV]	^3H	^3He	^4He
Experimental value	**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**



$V_{12} + V_{23} + V_{31} = V_{th.}$

Elastic scattering
N + d



- **fail** to reproduce binding energies of 3N, 4N and heavier systems
- **fail** to reproduce minimum of the d(N,N)d elastic scattering cross section

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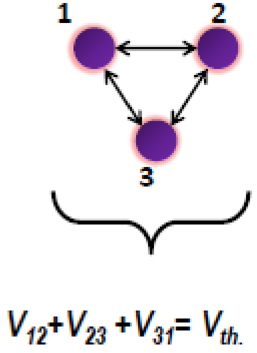
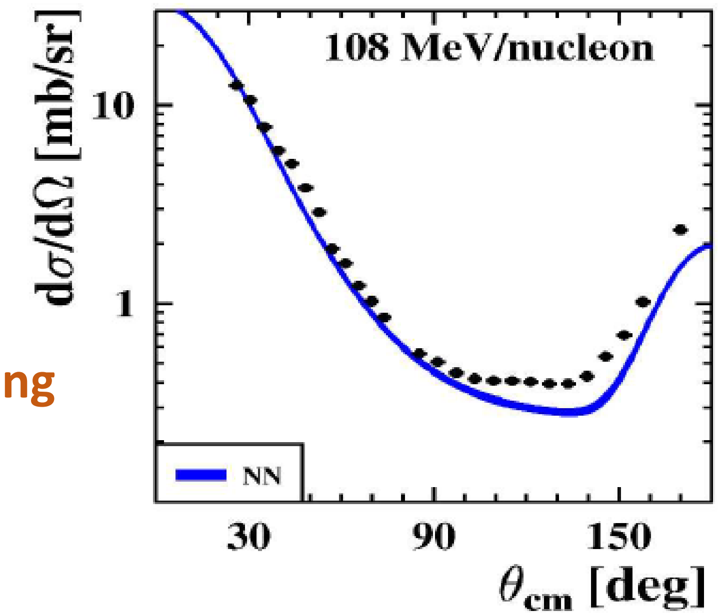


Elastic scattering N + d



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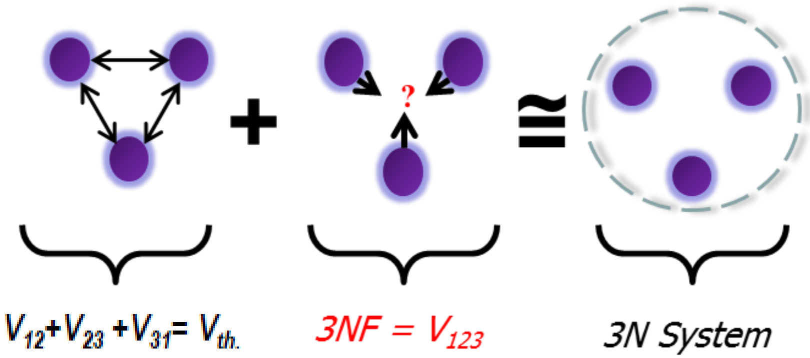
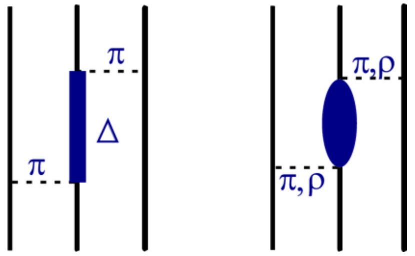
Introducing concept of **three-nucleon forces (3NF): a genuine (irreducible) interaction of three nucleons** (a consequence of internal nucleon structure)

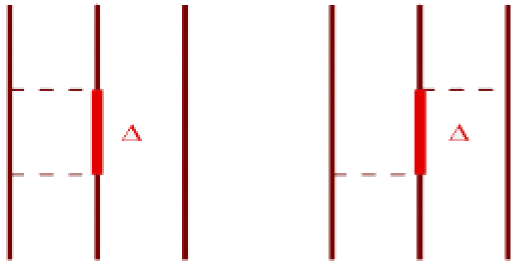


Introduction - 3N forces

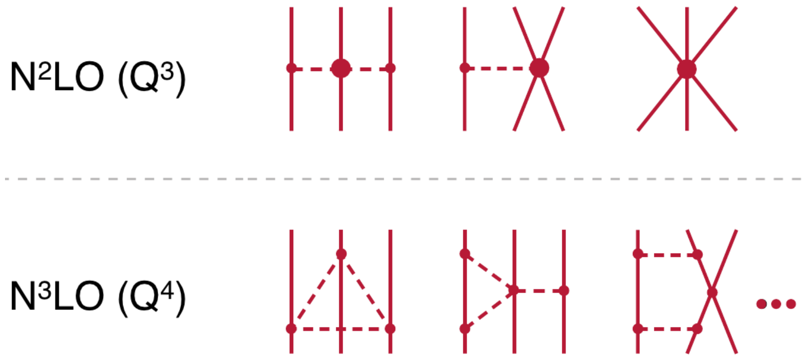
- Phenomenological three-nucleon forces: only weak connection to the NN potentials (e.g. TM99, Urbana IX, Brasil, Illinois);



- CC: Competing Δ-excitation effects (two nucleon dispersion and effective 3NF) – resulting net Δ influence is generally quite small;



- ChPT: three-nucleon forces appear naturally, fully consistent with the 2N graphs. (Under development, 3N system observables calculated up to N^{2}LO.)



Introduction – Interaction in the 3N system

Binding energy [MeV]	^{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

Predictions based on **NN potentials** combined with **3NF** models provide much better agreement with the experimental values of binding energies in 3N and 4N systems.

Further experimental verification of predictions obtained using different NN and 3N potential models is required.

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Extremes of the Nuclear Landscape

Experiments

The **Nd** system is **one of the simplest to study the dynamics of three nucleon systems**. Experiments with polarized beams (or targets) provide opportunities to study a number of observables (e.g. analyzing powers) sensitive to various dynamical components, which are hidden in the unpolarized case.

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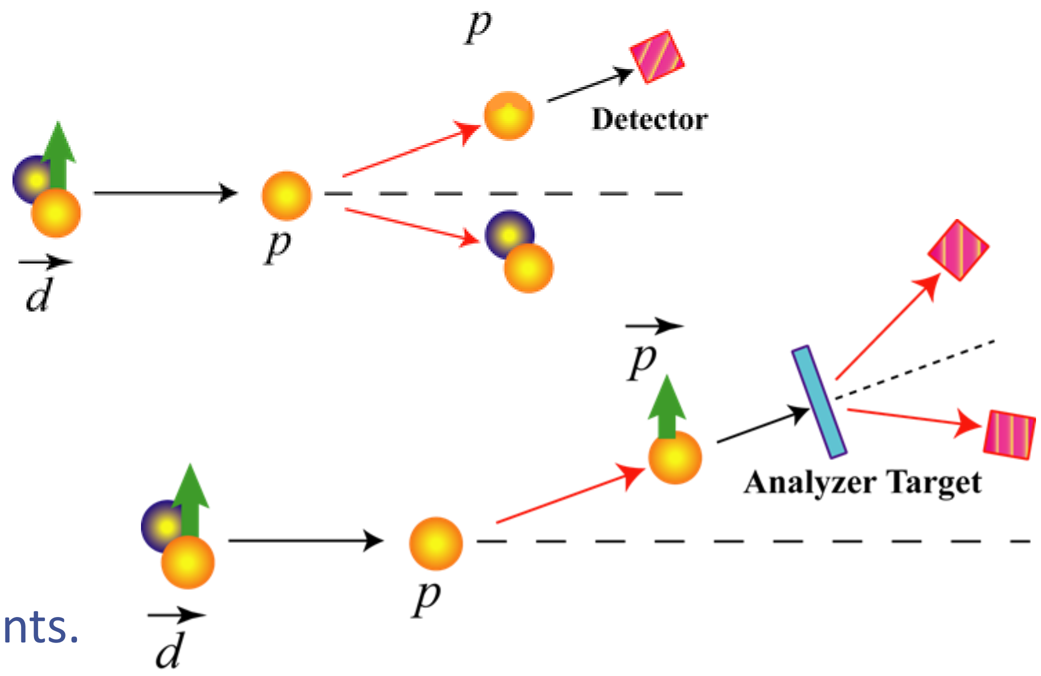
3N systems studied experimentally

Reaction mechanisms:

- elastic scattering N + d → N + d,
- breakup N + d → N + N + N,
- electromagnetic processes.



Observables:

- differential cross sections,
- vector and tensor analyzing powers,
- correlation, polarization transfer coefficients.

Various effects to be traced:

- comparisons between channels,
- influences of 3NF,
- Coulomb force action,
- relativistic effects.

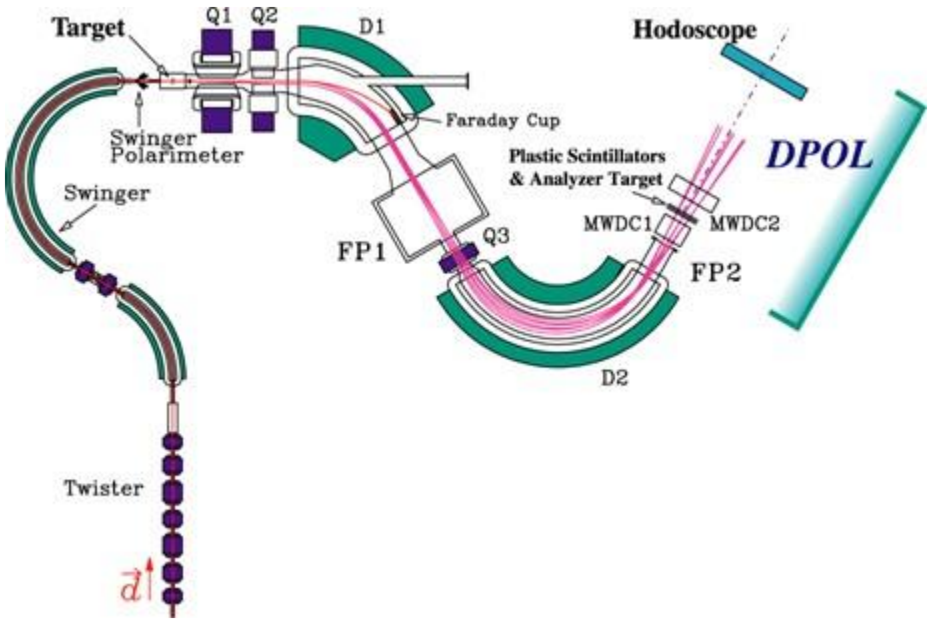
Techniques:

- spectrometers,
- large acceptance detectors.

Experimental tools

Spectrometers systems

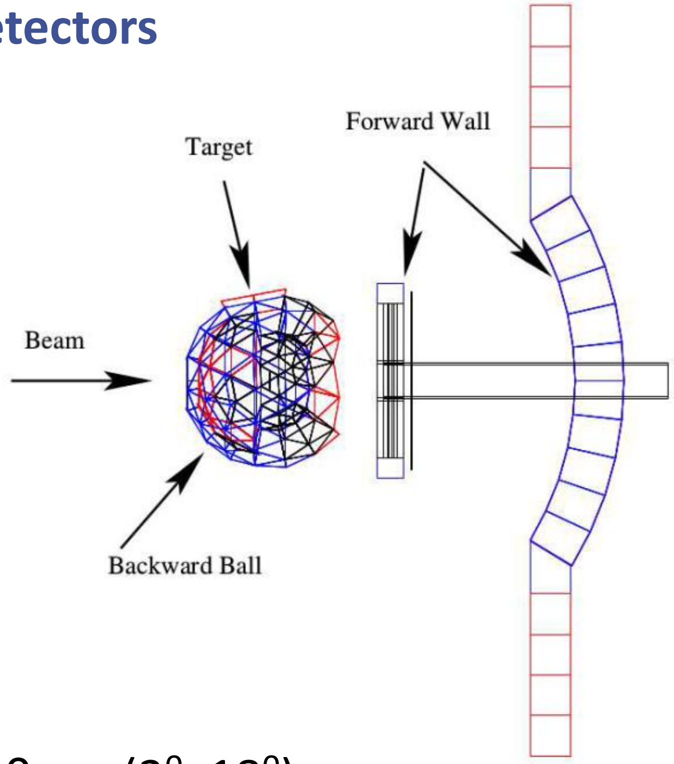
RIKEN RIBF



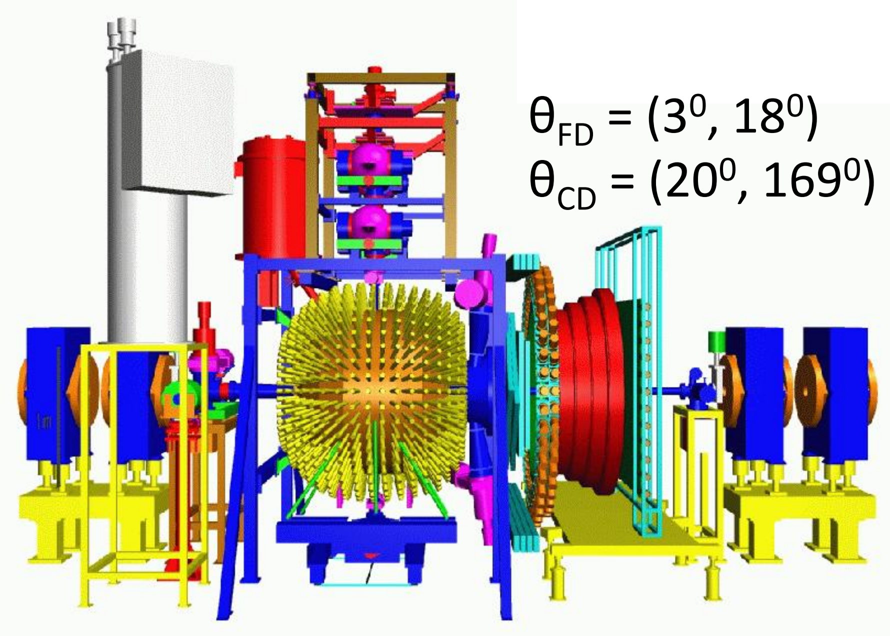
Large acceptance detectors

BINA

$\theta_{Wall} = (12^0, 35^0)$
$\theta_{Ball} = (40^0, 165^0)$



WASA



$\theta_{FD} = (3^0, 18^0)$
$\theta_{CD} = (20^0, 169^0)$

Also:

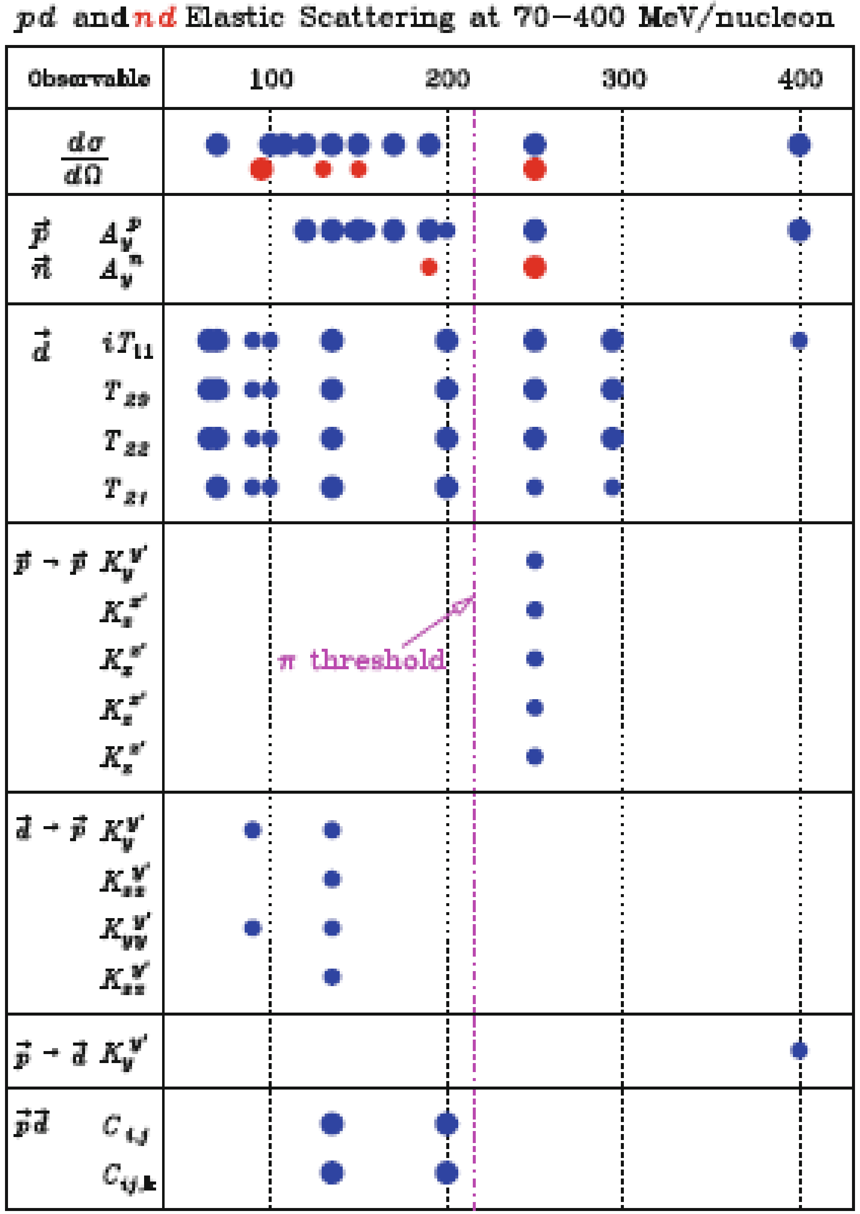
- Research Center of Nuclear Physics, Osaka University
- Indiana University - IUCF

Experiments – Nd elastic scattering studies

- High precision data for differential cross sections and spin observables (vector & tensor analyzing powers) have been collected;

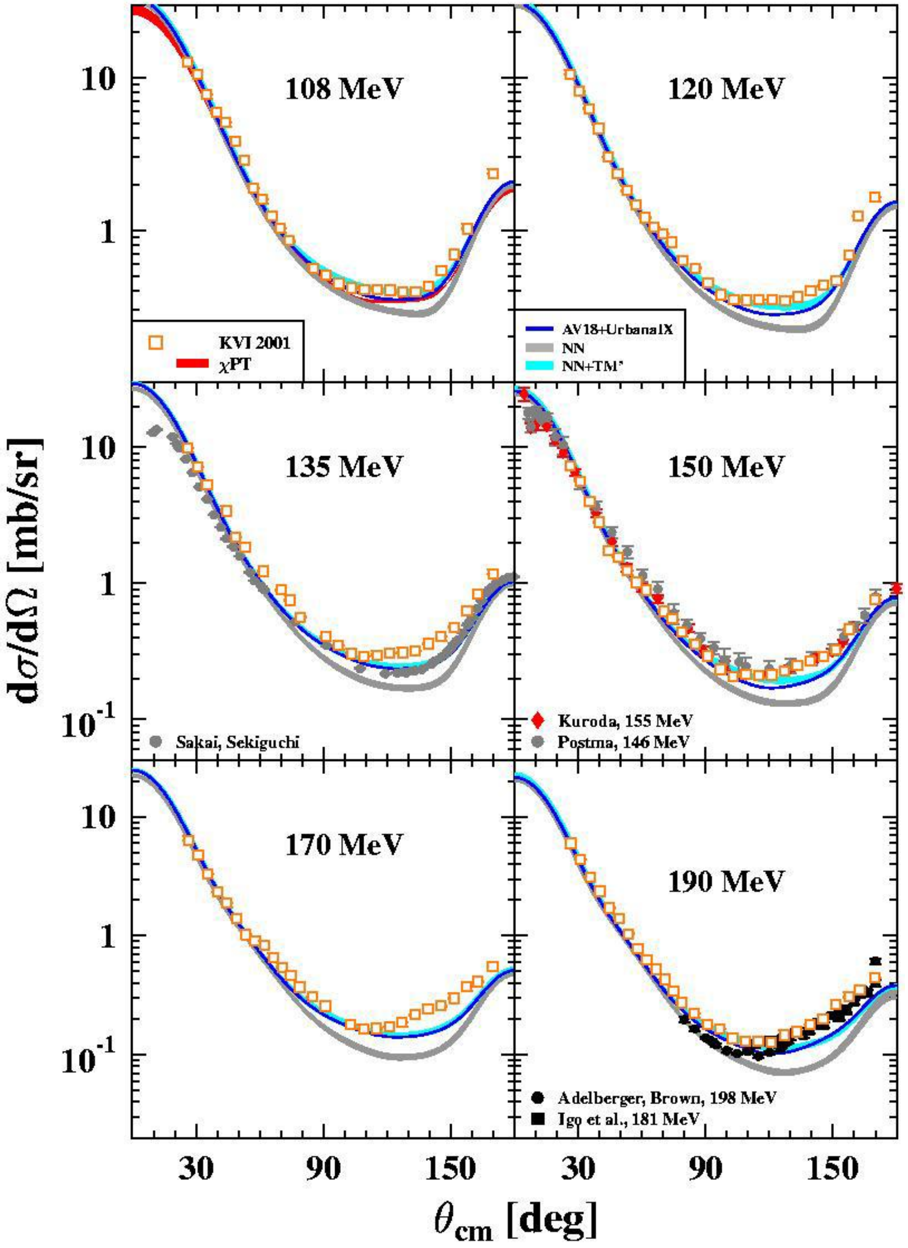
- only a fraction has been measured systematically with varying beam energy (KVI, RIKEN, RCNP and IUCF) - still much to explore;

- complete set of observables would provide rich dynamical information (at the given energy)
  new prospects e.g. at RIKEN, Y. Saito et al., Eur. Phys. J A62, 134 (2026).



K. Sekiguchi, FBS 54, 911 (2013)

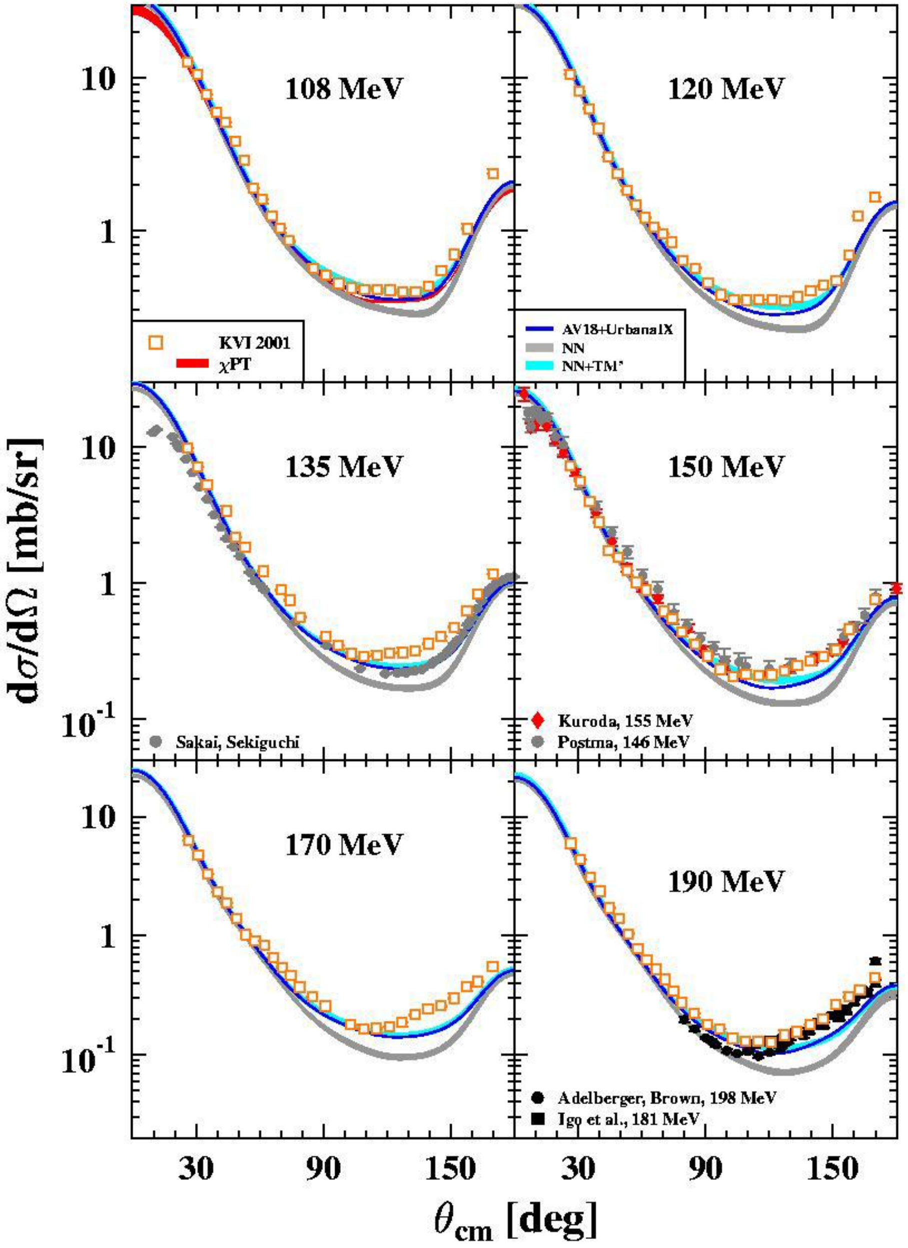
Experiments – Nd elastic scattering studies



K. Ermisch et al., PRC 71, 064004 (2005)

The inclusion of **3NF models** in theoretical calculations **significantly improves description of the differential cross section.**

Experiments – Nd elastic scattering studies



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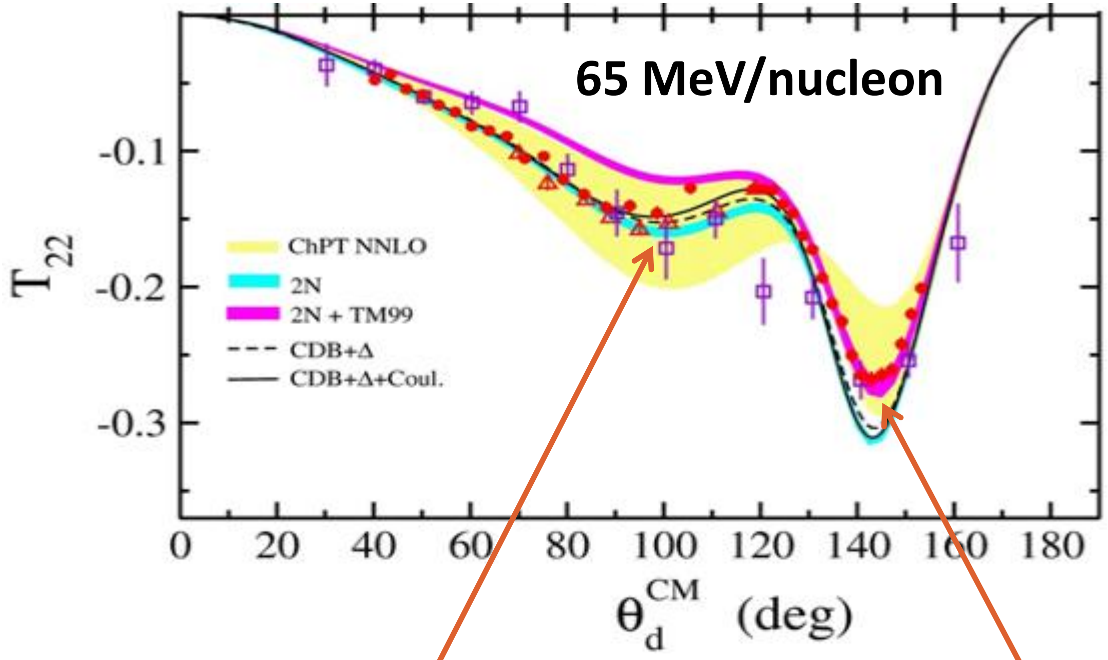
The inclusion of **3NF models** in theoretical calculations **significantly improves description of the differential cross section.**

BUT

E. Stephan et al., PRC 76, 057001 (2007)



data agree with NN calculations

data agree with NN+3NF

3NF not always improves description of polarization observables - a lot of examples at various energies

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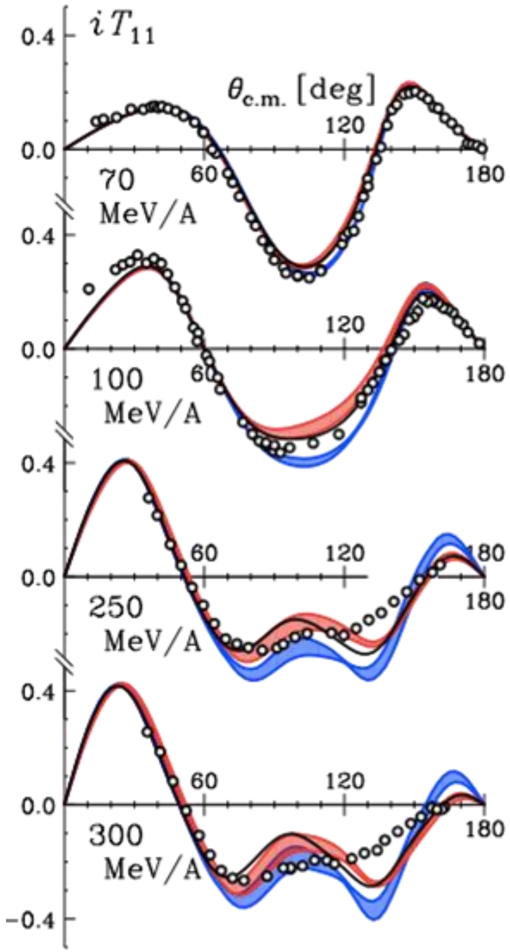
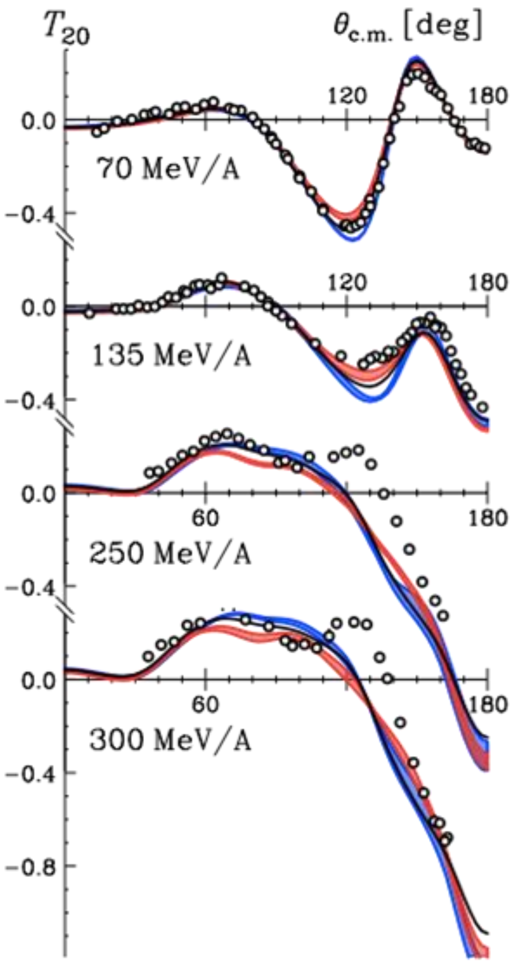
Experiments – Nd elastic scattering studies

K. Sekiguchi et al., PRC 83, 061001 (2011)

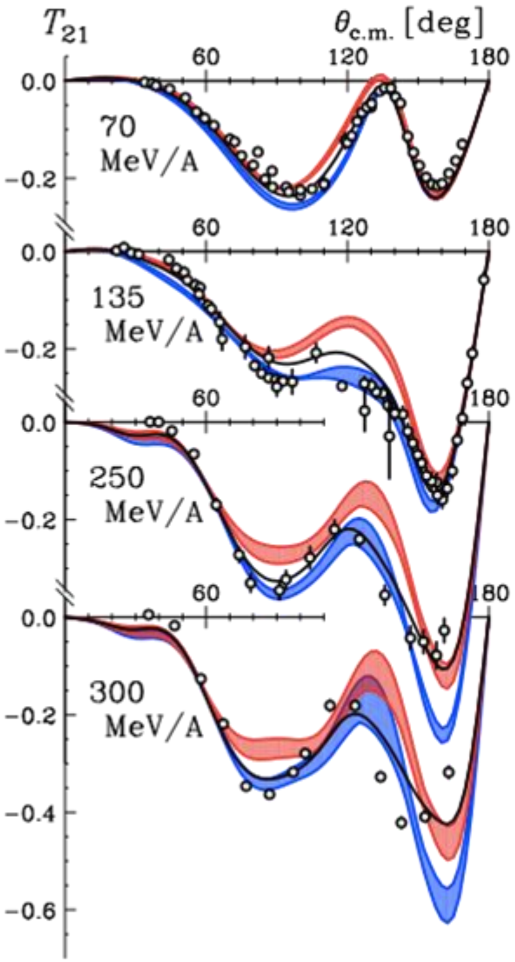
iT_{11}



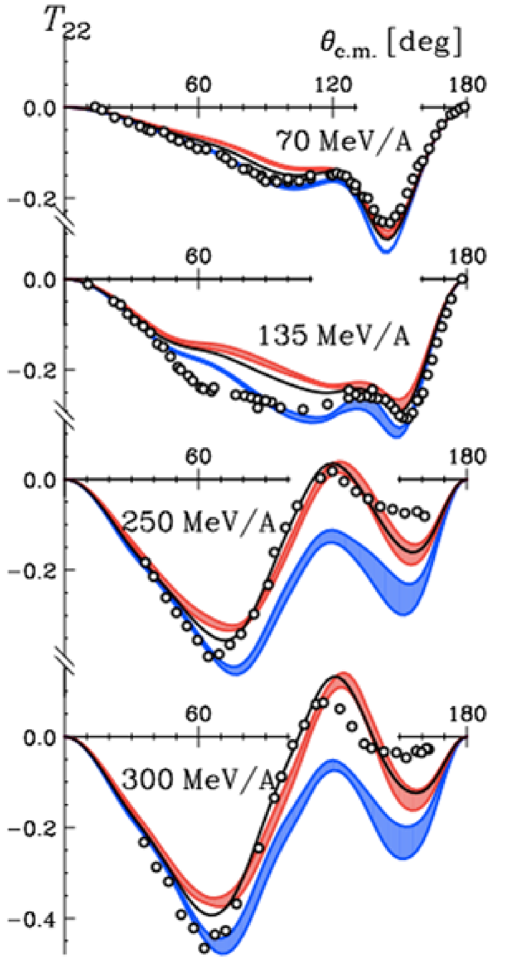
T_{20}



T_{21}



T_{22}



3NFs do not explain discrepancies at forward and backward angles

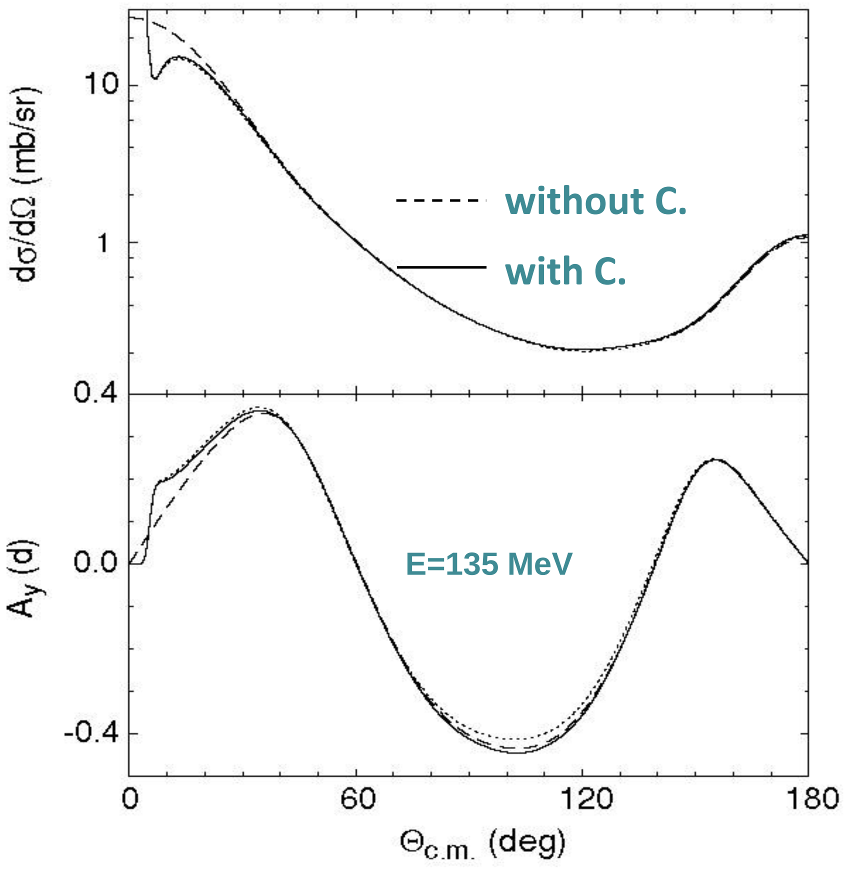
Experiments – Nd elastic scattering studies

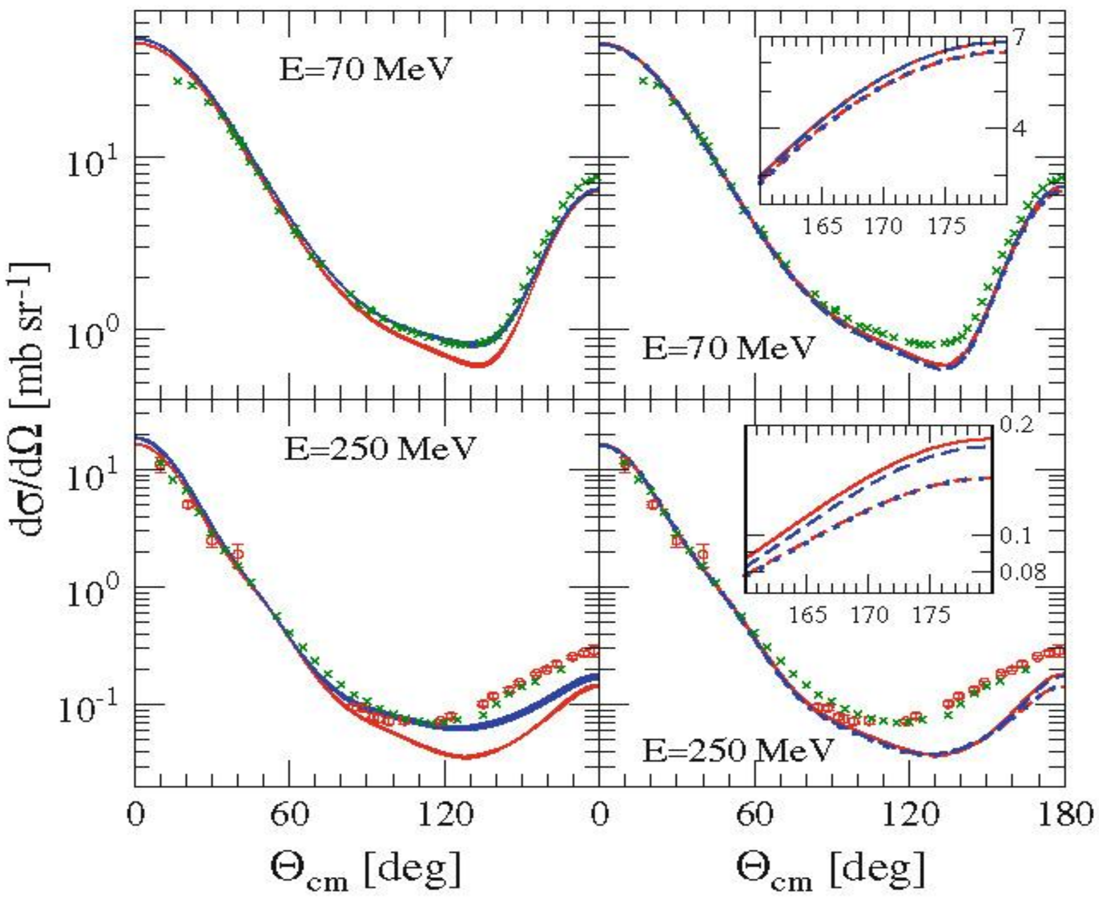
Effects small, located at extreme angles only !

More dynamical effects ? Coulomb force and relativity

Coulomb

3NF relativity





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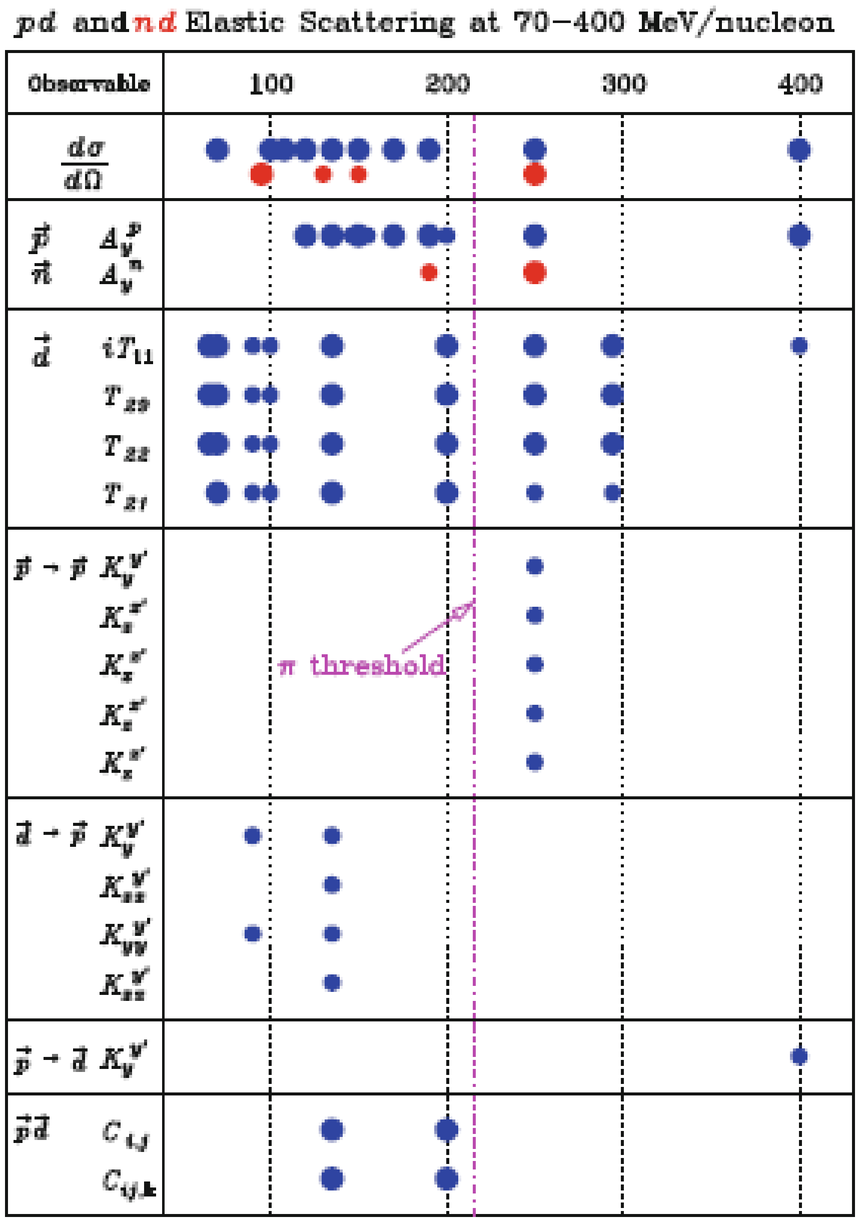
- complete set of observables would provide rich dynamical information (at the given energy)
  new prospects e.g. at RIKEN, Y. Saito et al., Eur. Phys. J A62, 134 (2026).

Not completely clear picture

Complementary studies needed at much richer field:
Nucleon-Deuteron Breakup

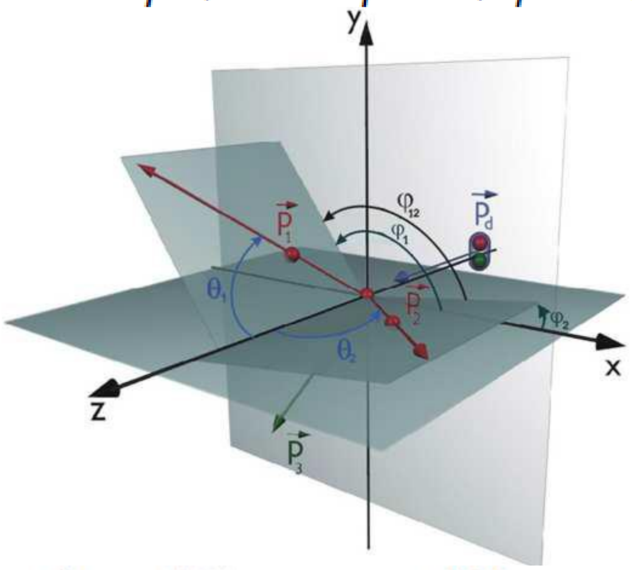


K. Sekiguchi, FBS 54, 911 (2013)

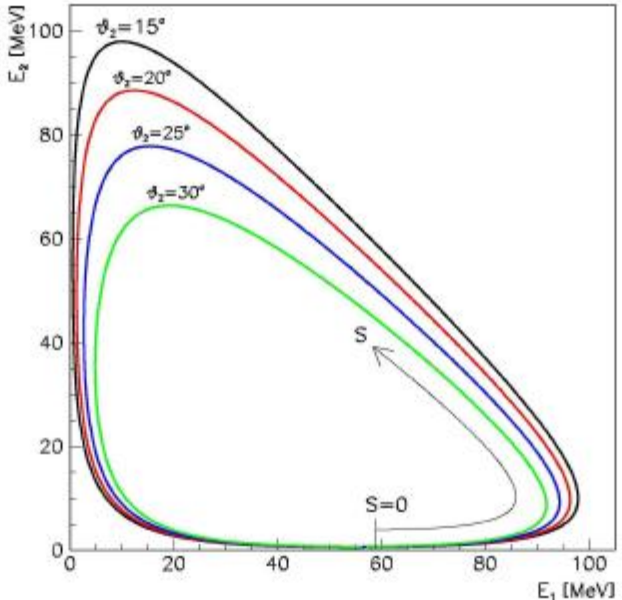
Experiments – Nd breakup studies

Energy [MeV/nucl]	Detector @ Laboratory	Angular range	Reaction	Observables about 1000 data points per observable	
50	BINA @ KVI	4π Wall: 12°-35°	^{1}H(d,pp)n	σ	A_x^d, A_y^d, A_{xy}, A_{xx}, A_{yy}
65	SALAD @ KVI	12°-35°	^{1}H(d,pp)n	σ	A_x^d, A_y^d, A_{xy}, A_{xx}, A_{yy}
	GeWall @ FZ-Juelich	5°-13°	^{1}H(d,pp)n	σ	A_x^d, A_y^d
80	BINA @ KVI	4π Wall: 12°-35°	^{1}H(d,pp)n	σ	
			^{1}H(d,pn)p	σ	
108	BINA @ CCB	4π Wall: 12°-35°	^{2}H(p,pp)n	σ	
135, 195	BINA @ KVI	4π	^{2}H(p,pp)n	σ	A_x, A_y
150	WASA @ FZ-Juelich	4π	^{1}H(d,pp)n	σ	
160	BINA @ CCB	4π	^{2}H(p,pp)n	σ	
170, 190, 200	WASA @ FZ-Juelich	4π FD: 5°-13°	^{1}H(d,pp)n	σ	

$$p + d \rightarrow p^{(1)} + p^{(2)} + n$$

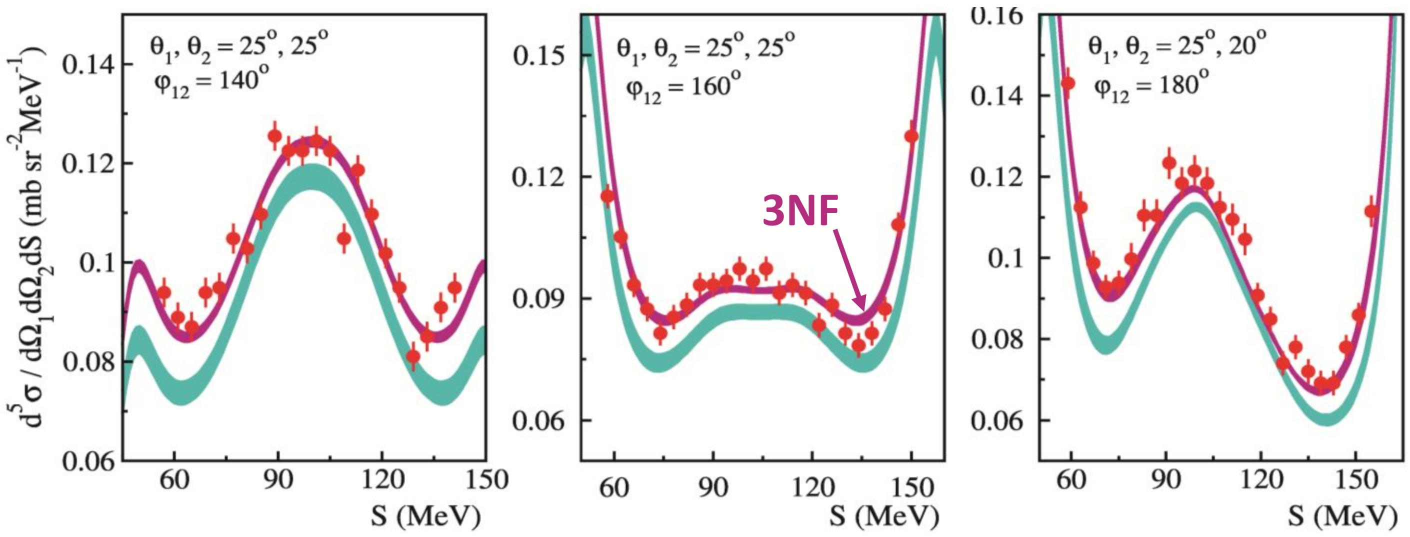


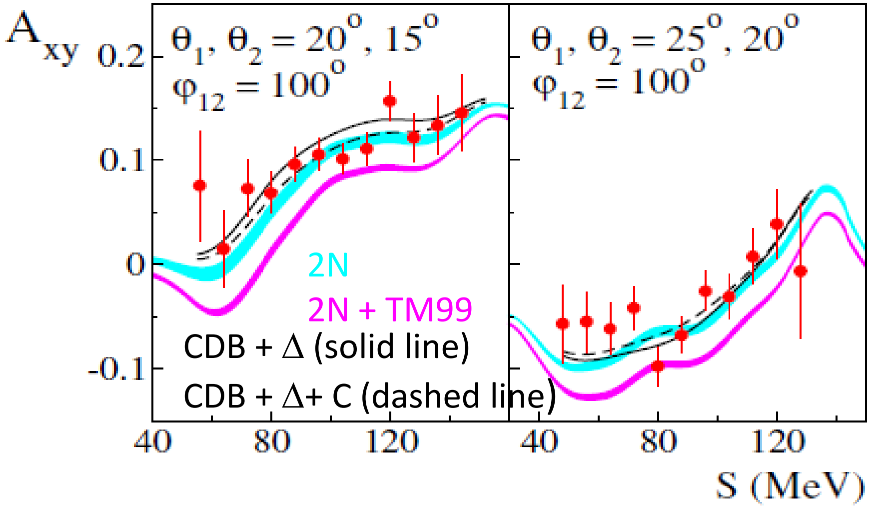
$$\theta_1 = 15^\circ, \quad \varphi_{12} = 90^\circ$$

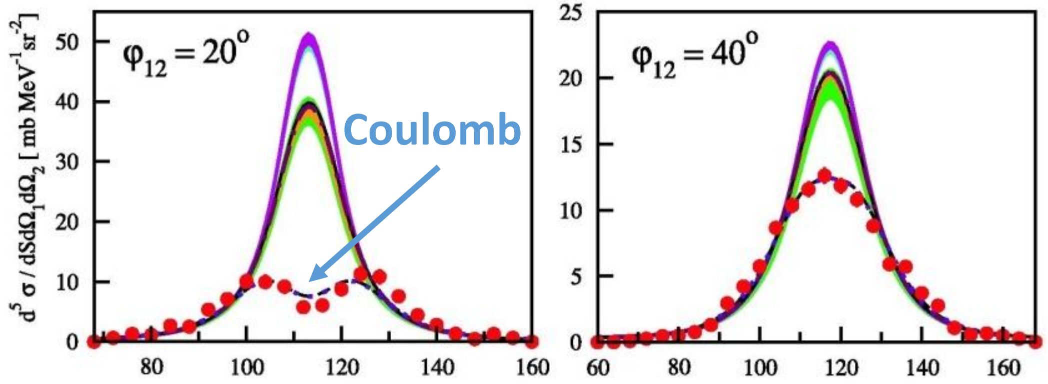


Experiments – 3N systems: 3NF & Coulomb

65 MeV/nucleon







$\theta_1 = \theta_2 = 9^o$

First ever experimental evidence:

- 3NF significantly improves description of the differential cross section (in specific kinematic configurations).
- 3NF not always improves description of polarization observables.
- Significant Coulomb effects – locally very strong.

St. Kistryn et al., PRC 72, 044006 (2005)
E. Stephan et al., PRC 82, 014003 (2010)
I. Ciepał et al., FBS 56, 665 (2015)

H. Witała et al.: 2N, 2N+TM99
A. Deltuva et al.: CBD+Δ+C, CBD+Δ+C, AV18, AV18+UIX, AV18+C, AV18+UIX+C

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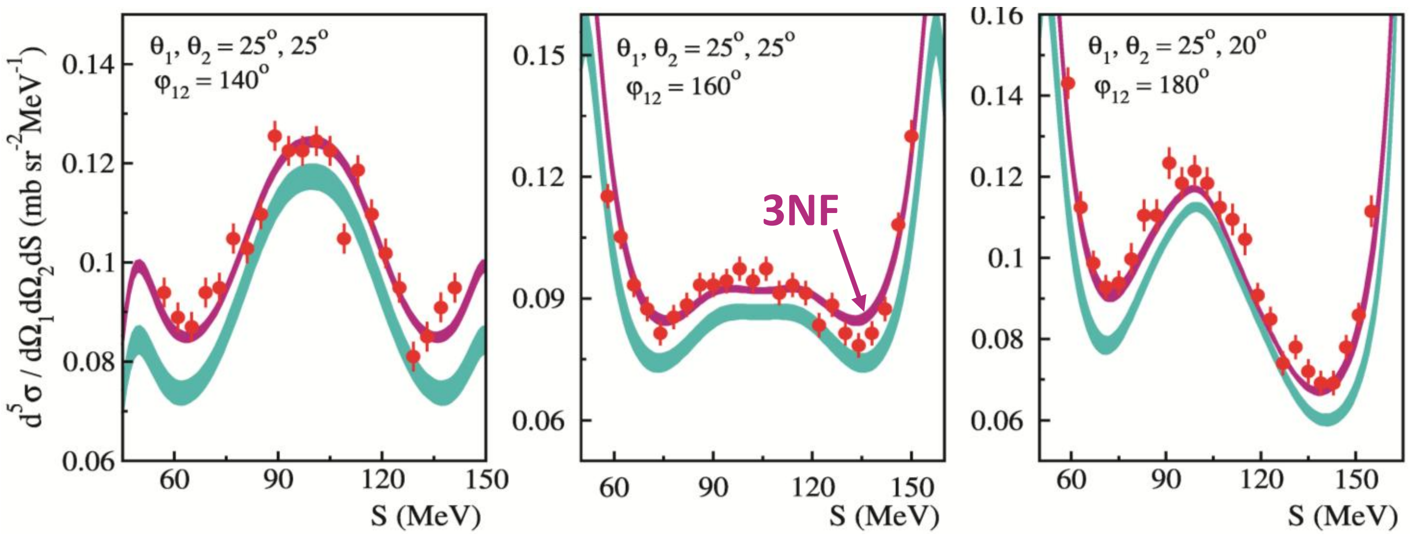
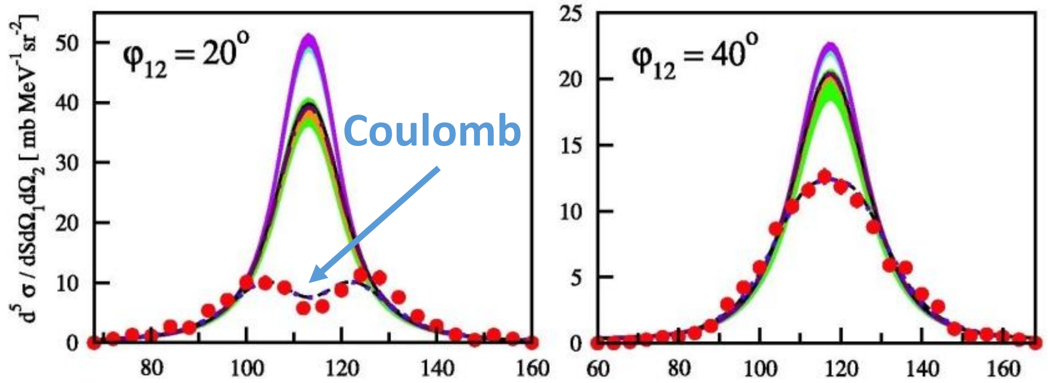
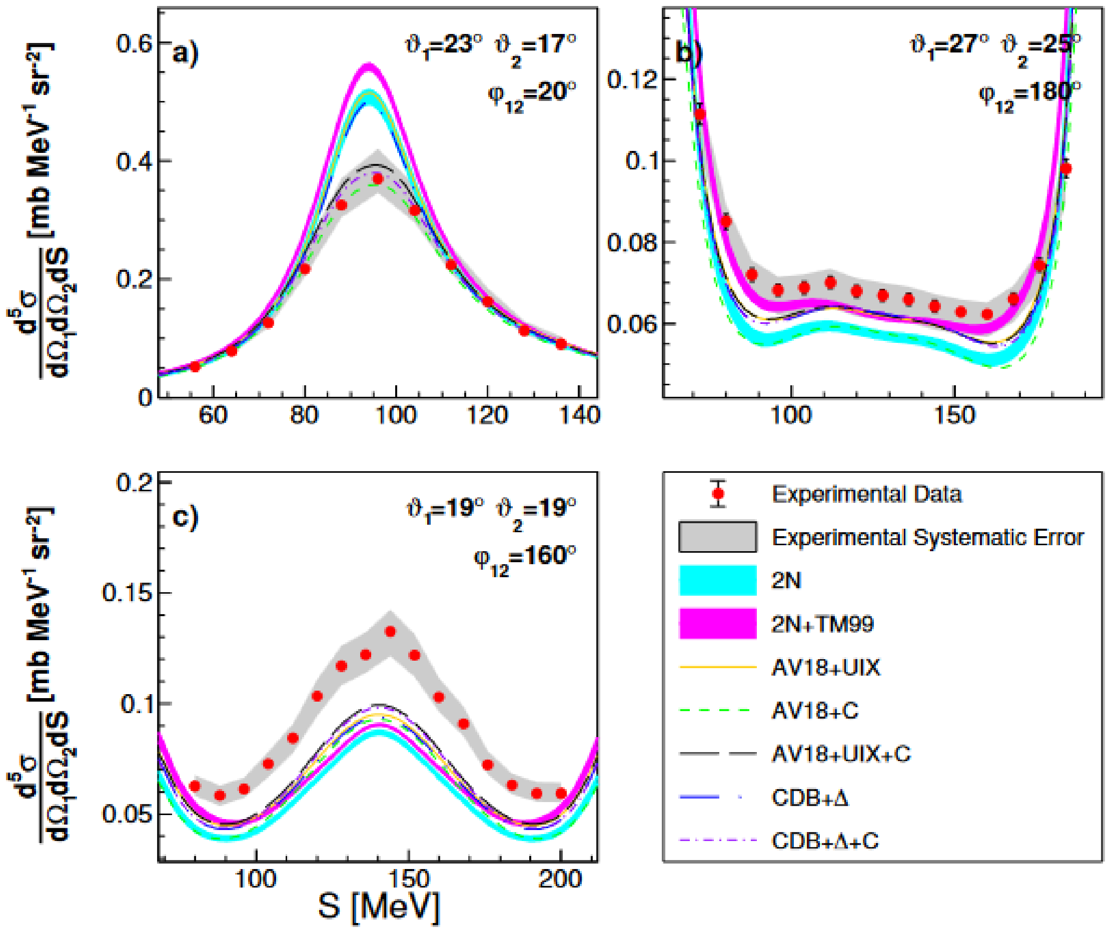




$\theta_1 = \theta_2 = 9^o$

80 MeV/nucleon



W. Parol et al., PRC 102, 054002 (2020)

St. Kistryn et al., PRC 72, 044006 (2005)
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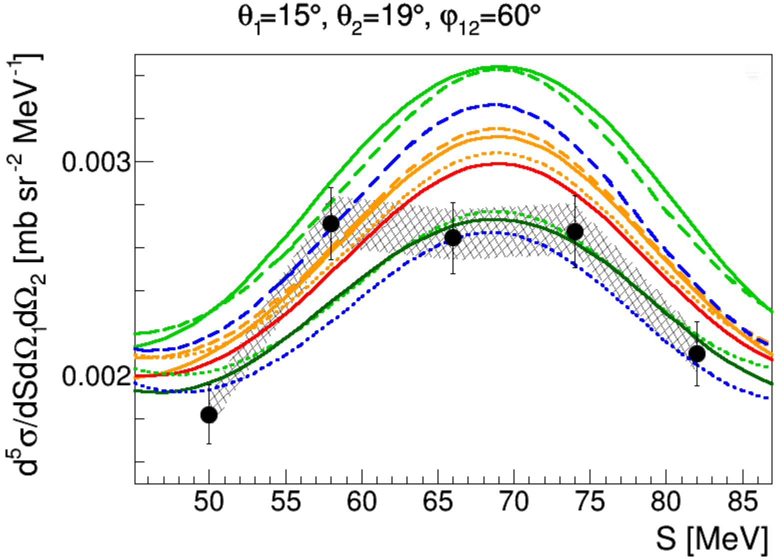
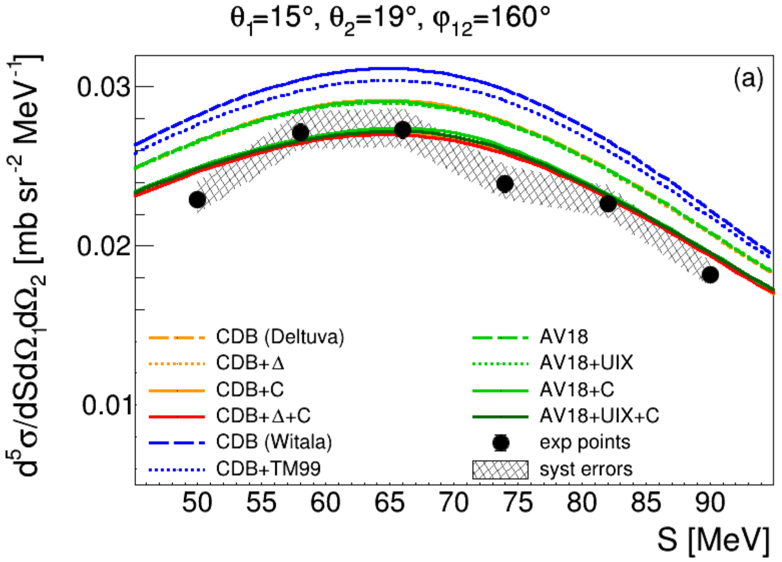
Experiments – 3N systems: 3NF & Coulomb

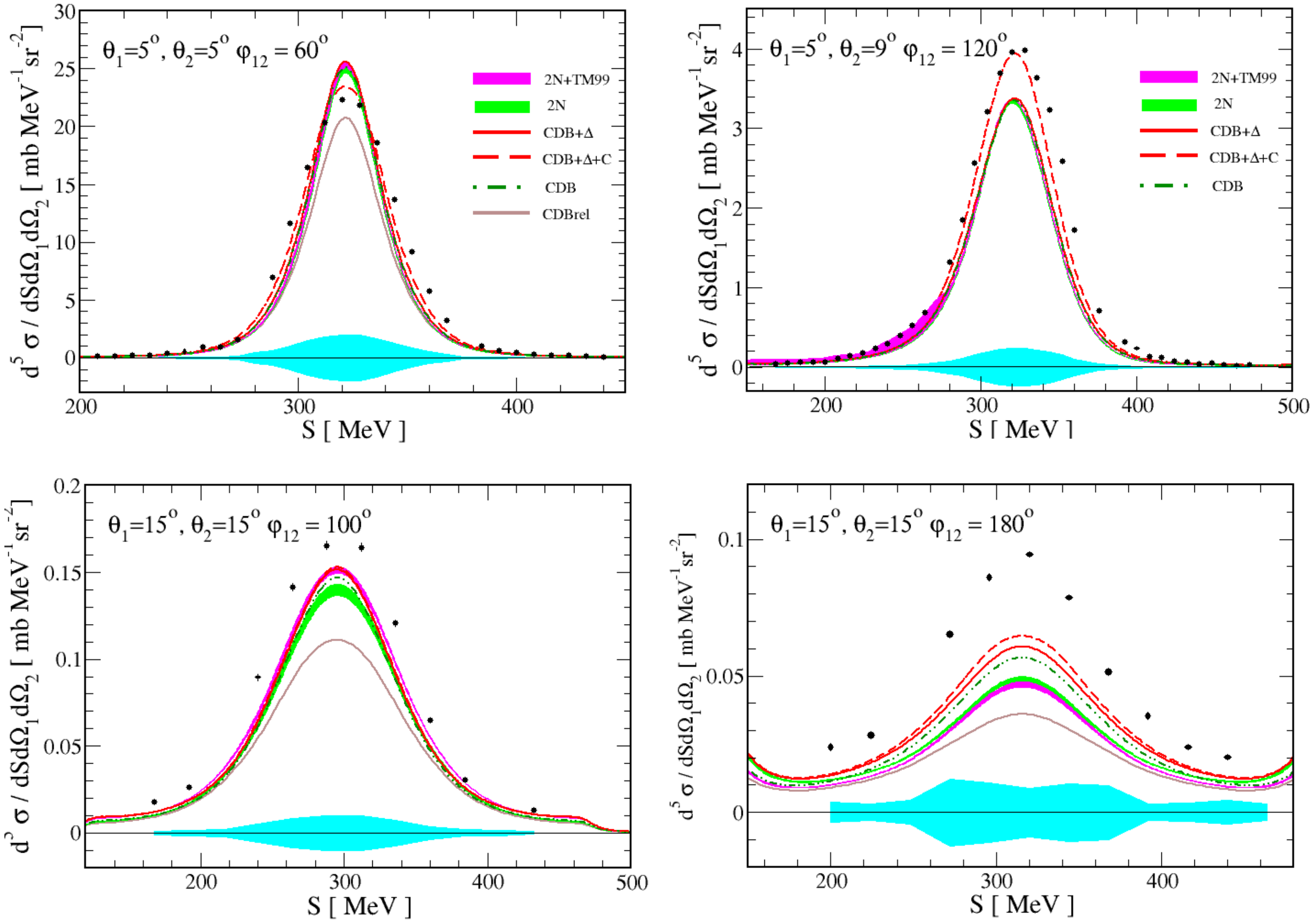
108 MeV/nucleon





A. Łobejko et al., FBS 65, 36 (2024)

170 MeV/nucleon



B. Kłos WASA@COSY, PRC 101 , 044001 (2020)

H. Witała et al.: 2N, 2N+TM99, CDBrel

A. Deltuva et al.: CBD+Δ+C, CBD+Δ+C, AV18, AV18+UIX, AV18+C, AV18+UIX+C

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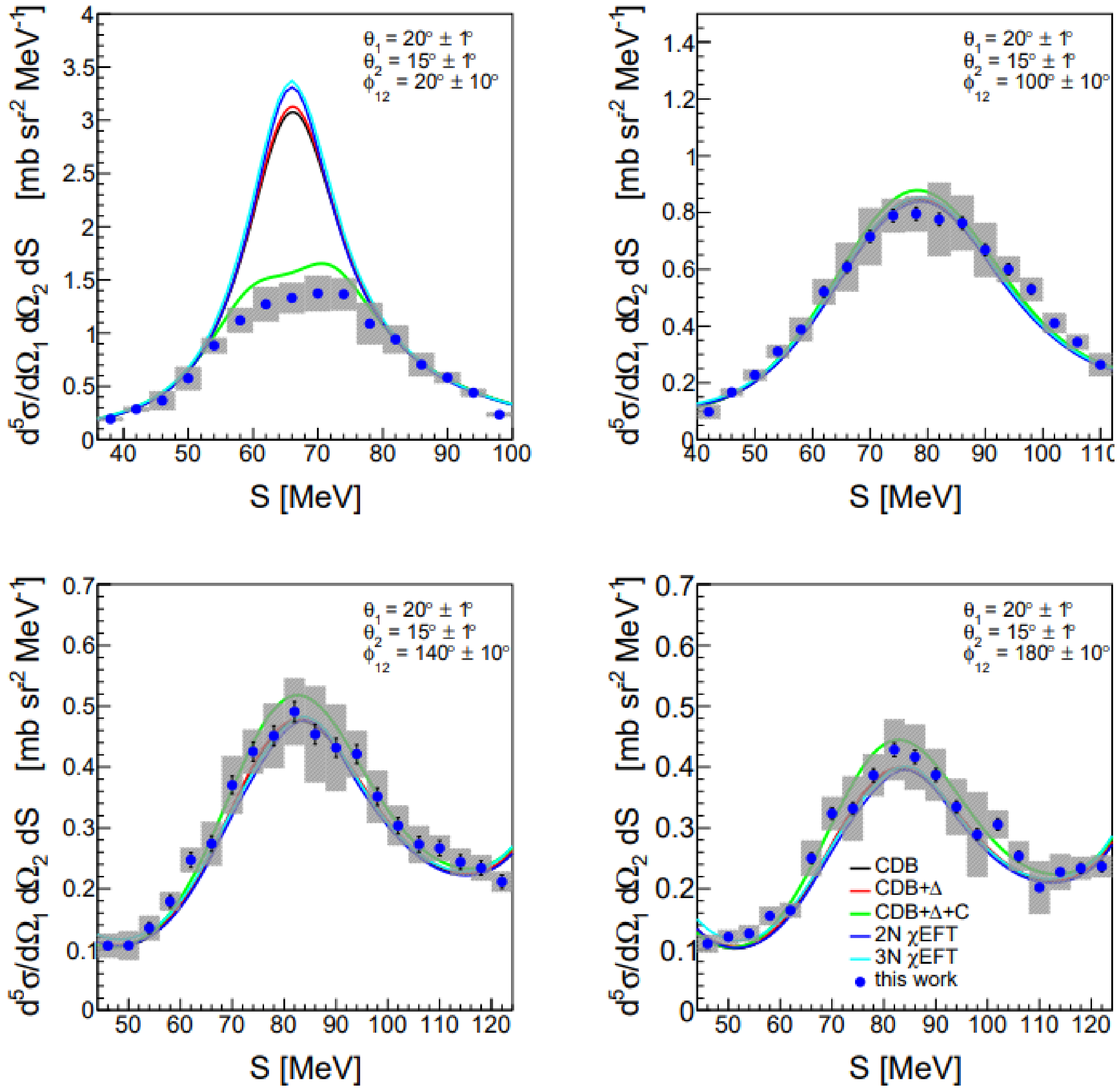
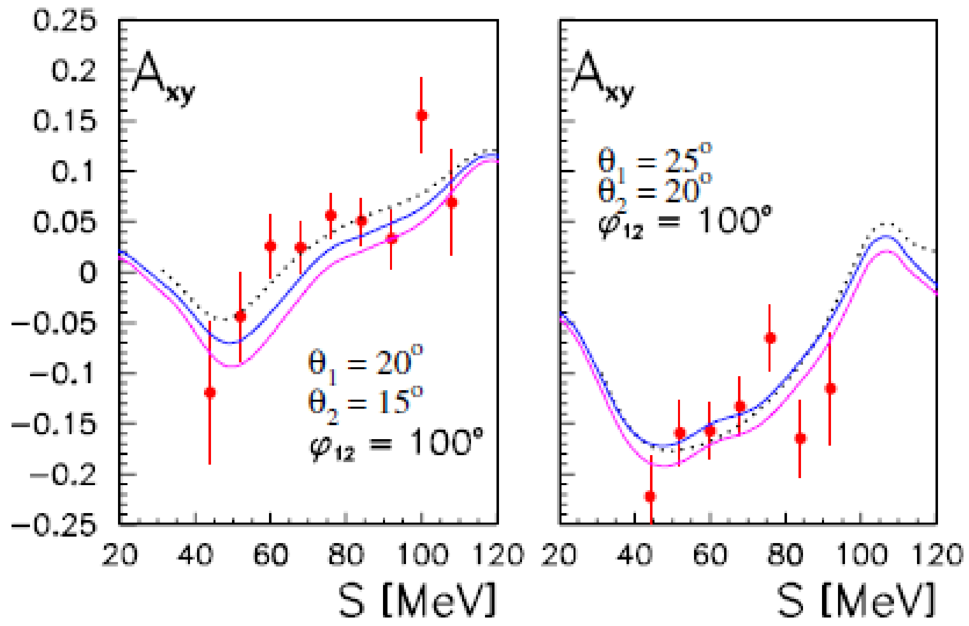
Extremes of the Nuclear Landscape

Experiments – 3N systems: 3NF & Coulomb

50 MeV/nucleon



CD Bonn   CD Bonn + TM99   CD Bonn + Δ+ C (dotted line)



- Predicted influence of the 3NF is small.
- The Coulomb force effect cannot be neglected.
- In the regions of negligible Coulomb effects the description given by realistic potentials and ChEFT (SMS N4LO$^+$+N2LO 3NF), is very good.

St. Kistryn and E. Stephan, JPG: NPP 40, 063101 (2013)
I. Skwira-Chalot et al., FBS 65, 24 (2024)

H. Witała et al.: 2N, 2N+TM99
A. Deltuva et al.: CDB, CBD+Δ+C, CBD+Δ+C
R. Skibiński et al.: 2N χEFT, 3N χEFT

Invariant coordinates

Kinematics of the breakup reaction $\mathrm{p} + \mathrm{d} \rightarrow \mathrm{p}^{(1)} + \mathrm{p}^{(2)} + \mathrm{n}$ can be described in terms of invariant coordinates

Based on 4-momenta:

- in entrance channel: proton $\mathrm{p_p}$, deuteron $\mathrm{p_d}$
- in exit channel: protons $\mathrm{p_{p^{(1)}}}$, $\mathrm{p_{p^{(2)}}}$ and neutron $\mathrm{p_n}$.

For the pair of protons in the exit channel

$$\mathrm{s_{pp}} = (\mathrm{p_{p^{(1)}}} + \mathrm{p_{p^{(2)}}})^2$$

For the proton - neutron pair

$$\mathrm{s_{pn}} = (\mathrm{p_{p^{(1)}}} + \mathrm{p_n})^2$$

4-momentum transfer from the unbound proton to one of the two protons in the exit channel

$$\mathrm{t_p} = (\mathrm{p_p} - \mathrm{p_{p^{(2)}}})^2$$

4-momentum transfer from the bound neutron in the entrance channel to the free neutron in the exit channel

$$\mathrm{t_n} = (\frac{\mathrm{p_d}}{2} - \mathrm{p_n})^2$$

St. Kistryn and E. Stephan, JPG: NPP 40, 063101 (2013)

Invariant coordinates

ZAKOPANE CONFERENCE on Nuclear Physics 2026 Extremes of the Nuclear Landscape

Kinematics of the breakup reaction $\mathrm{p} + \mathrm{d} \rightarrow \mathrm{p}^{(1)} + \mathrm{p}^{(2)} + \mathrm{n}$ can be described in terms of invariant coordinates

Based on 4-momenta:

- in entrance channel: proton p_p, deuteron p_d
- in exit channel: protons $p_{p^{(1)}}$, $p_{p^{(2)}}$ and neutron p_n.

For the pair of protons in the exit channel

$$s_{pp} = (p_{p^{(1)}} + p_{p^{(2)}})^2$$

For the proton - neutron pair

$$s_{pn} = (p_{p^{(1)}} + p_n)^2$$

4-momentum transfer from the unbound proton to one of the two protons in the exit channel

$$t_p = (p_p - p_{p^{(2)}})^2$$

4-momentum transfer from the bound neutron in the entrance channel to the free neutron in the exit channel

$$t_n = \left(\frac{p_d}{2} - p_n\right)^2$$

Relative energy of two protons in the exit channel

$$E_{rel}^{pp} = \sqrt{s_{pp}} - m_p.$$

Relative energy of proton and neutron in the exit channel (a pair with the smallest value of s_{pn})

$$E_{rel}^{pn} = \sqrt{s_{pn}} - m_p - m_n.$$

Transfer of energy from the free proton to the one of the two protons in the exit channel which was not used in the calculation of E_{rel}^{pn}

$$E_{tr}^{p} = -\frac{t_p}{2m_p}.$$

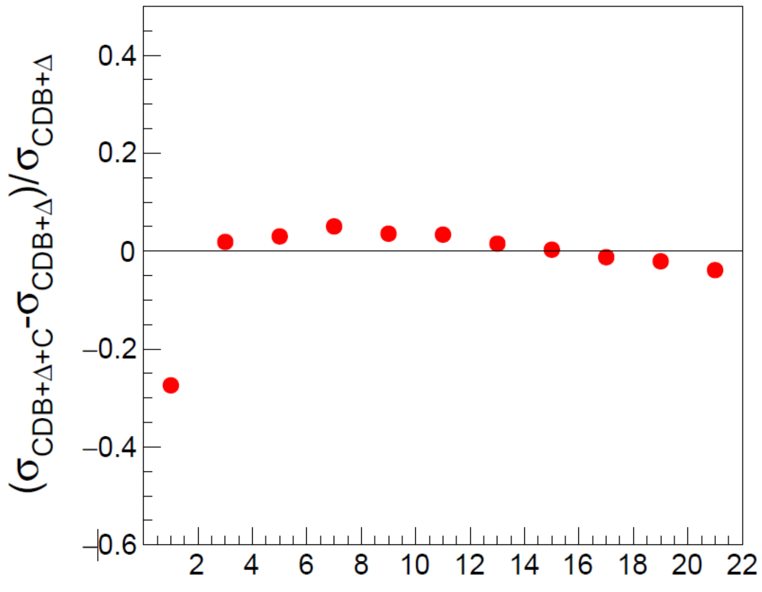
Transfer of energy from the bound neutron in the entrance channel to the free neutron in the exit channel

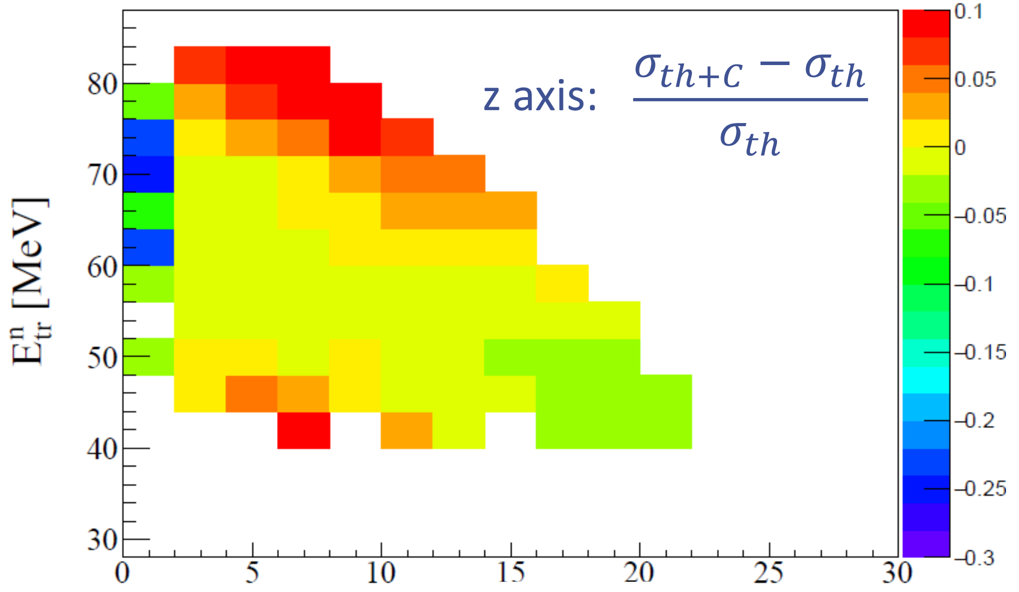
$$E_{tr}^{n} = -\frac{t_n}{2m_n}.$$

St. Kistryn and E. Stephan, JPG: NPP 40, 063101 (2013)

ZAKOPANE CONFERENCE on Nuclear Physics 2026 Extremes of the Nuclear Landscape

Coulomb effects at 50 MeV/nucleon studied in invariant coordinates

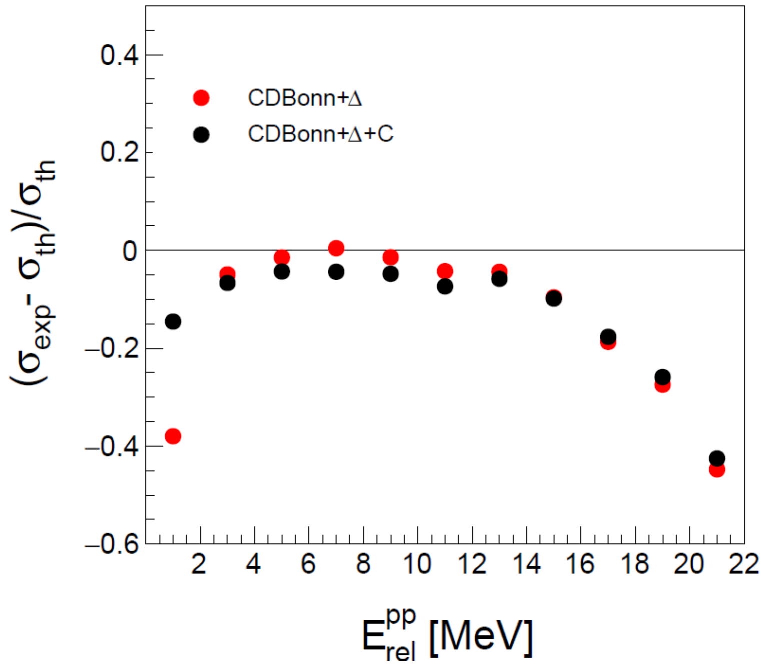


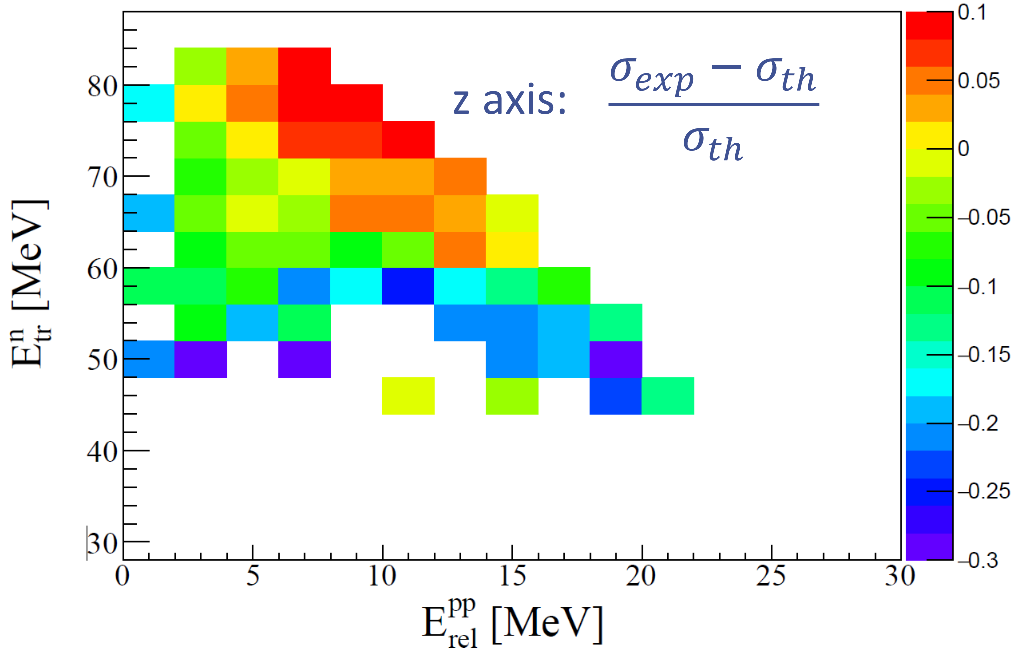


THEORY

VS

EXPERIMENT

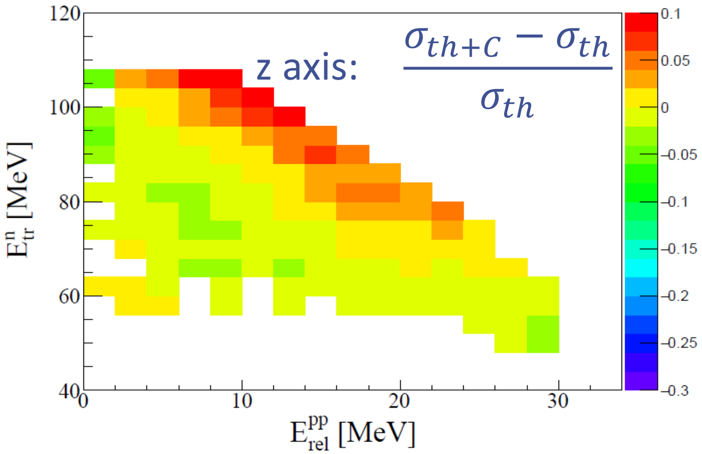


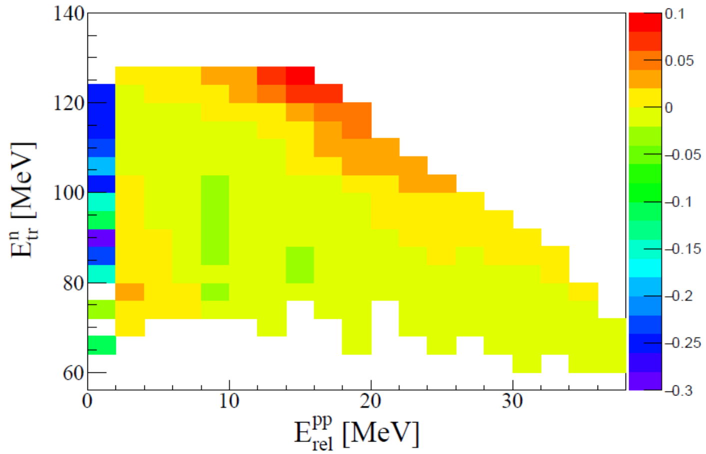


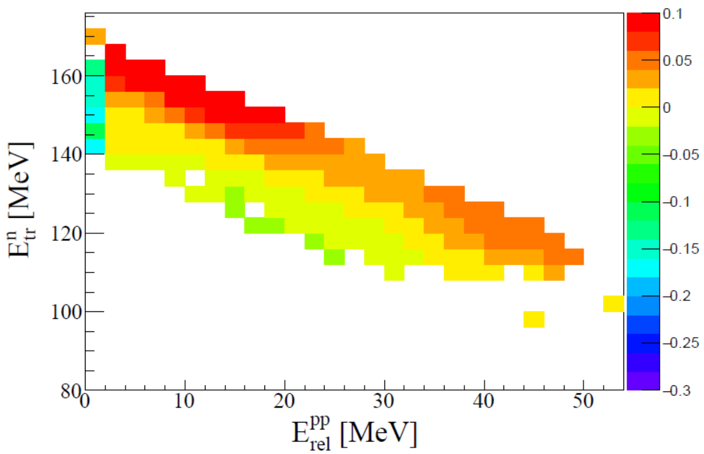
Coulomb effects at various energies studied in invariant coordinates

65 MeV/nucleon | **80 MeV/nucleon** | **170 MeV/nucleon**

THEORY

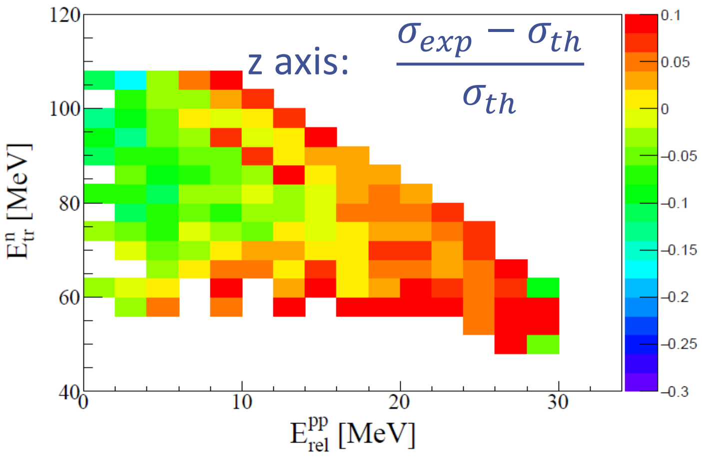


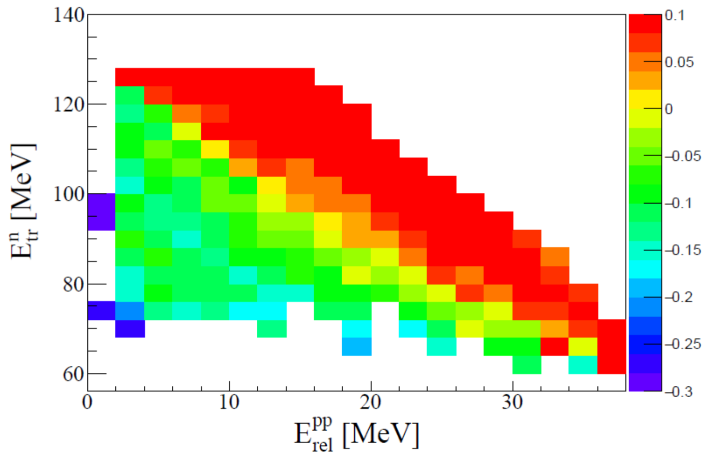


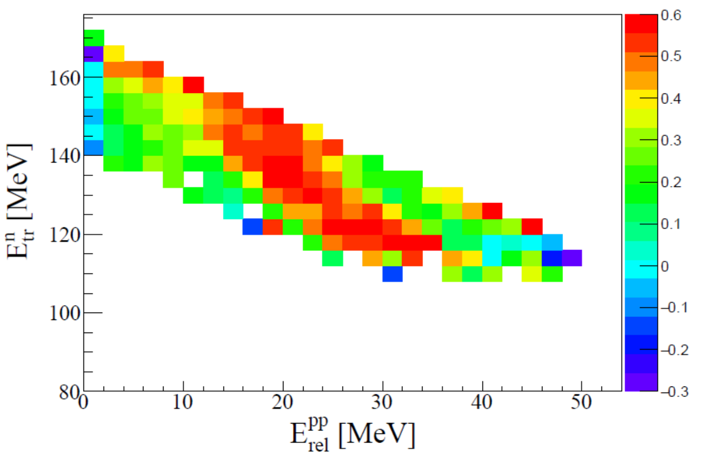


VS

EXPERIMENT







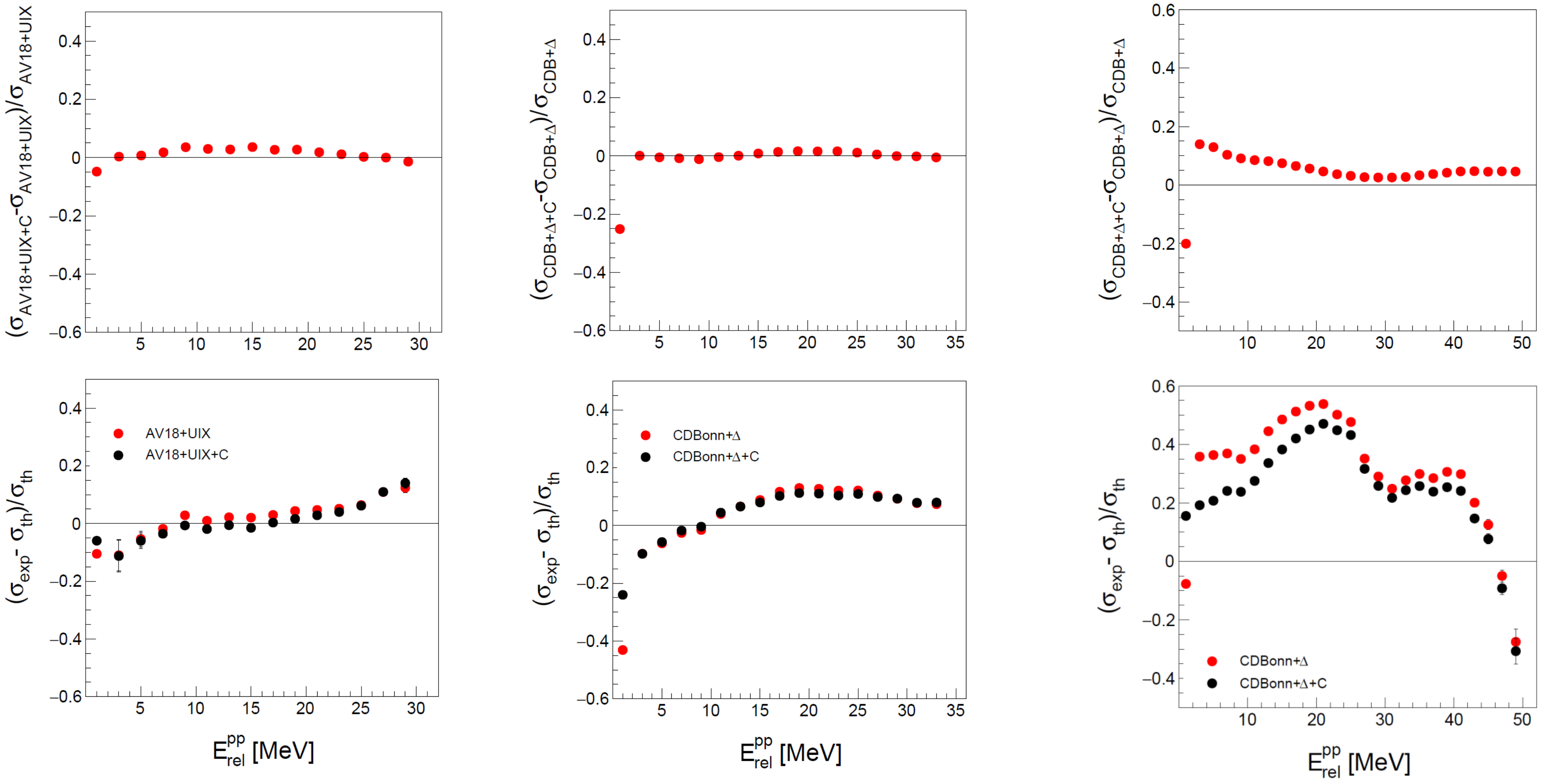
Coulomb effects at various energies studied in invariant coordinates

65 MeV/nucleon | 80 MeV/nucleon | 170 MeV/nucleon

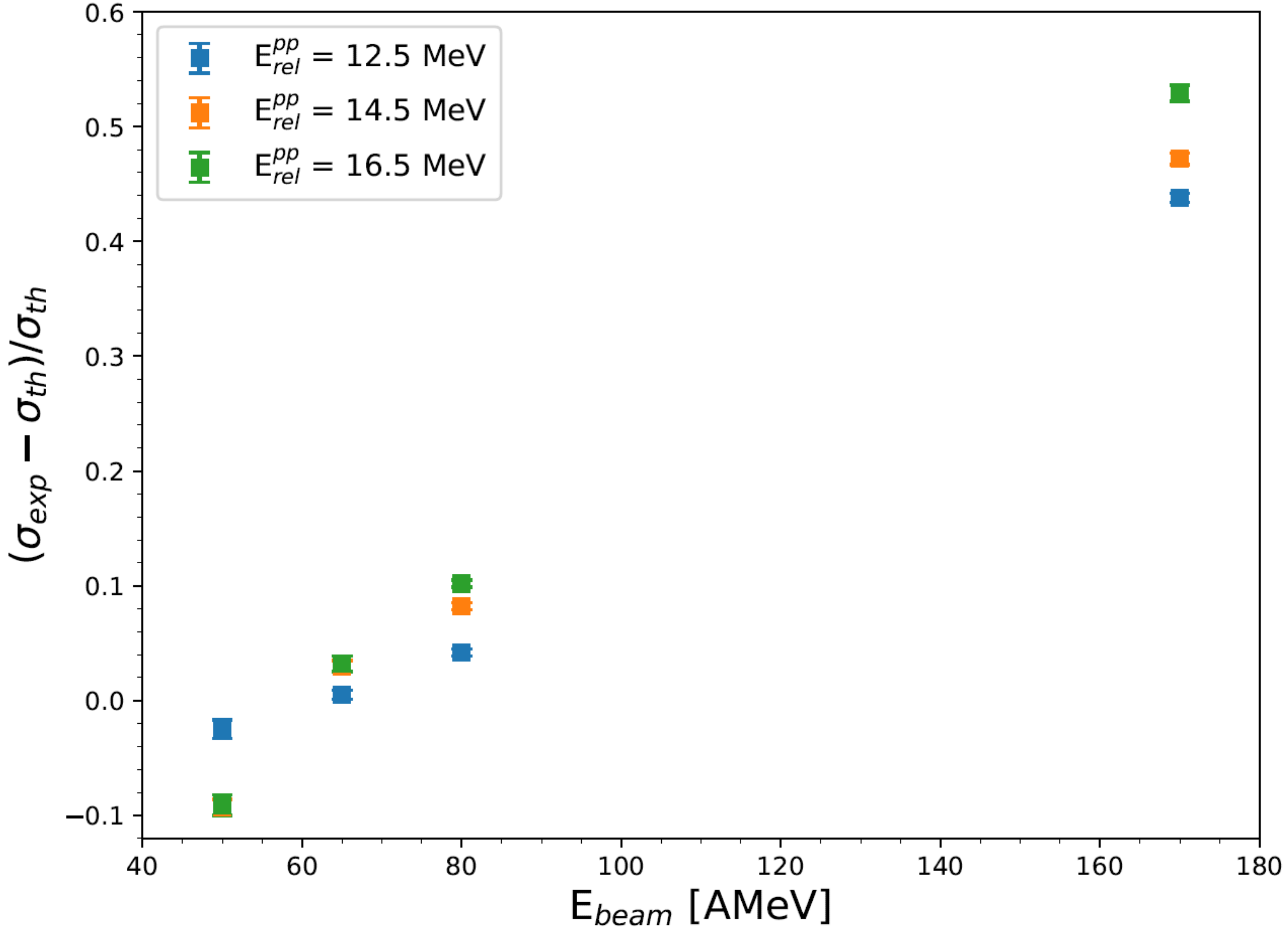
THEORY

VS

EXPERIMENT



Coulomb effects at various energies studied in invariant coordinates



Visible trend of discrepancy rising (linerary ?) with beam energy - further investigation (filling the gap and extending the range; trends in other invariant coordinates, …) needed.

ZAKOPANE CONFERENCE on Nuclear Physics 2026
Extremes of the Nuclear Landscape

Few-nucleon systems with BINA@CCB – research program

- Proton beam energy: 108 – 160 MeV – region of significant increase of 3NF and relativistic effects
- Studied reactions: ^{2}H(p,d)p elastic scattering and ^{2}H(p,pp)n breakup
- Existing ^{2}H(p,d)p elastic scattering data at 108 MeV – relative measurement of ^{2}H(p,pp)n breakup (run 2016)

Results for the ^{2}H(p,pp)n reaction at 108 MeV have been published, A. Łobejko et al., FBS 65, 36 (2024)

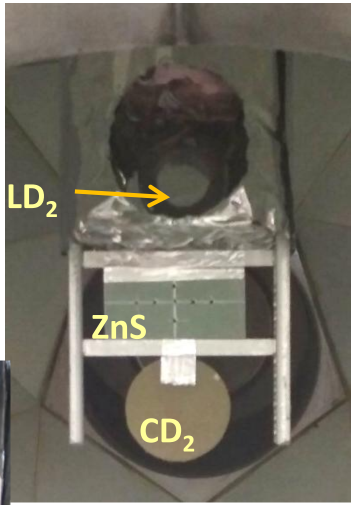
CD_2 measurement
pd elastic scattering

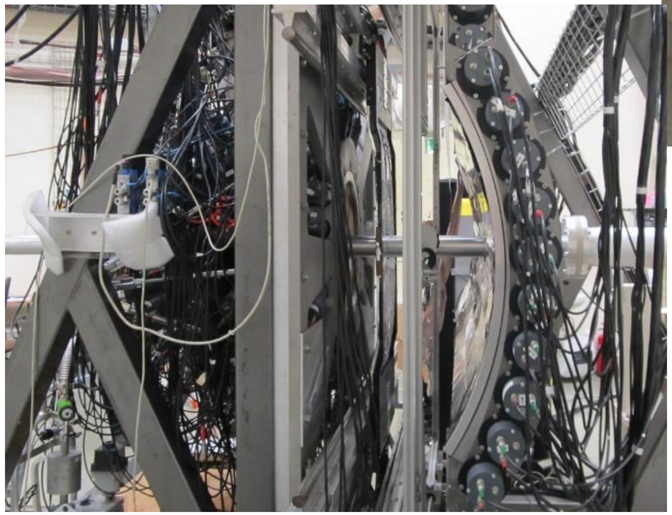
pd elastic scat. cross section

Liquid D_2 relative measurement:
^{2}H(p,pp)n breakup to ***pd*** elastic scattering

control over systematics

CH_2 measurement
pp elastic scattering





University of Silesia, Katowice, PL
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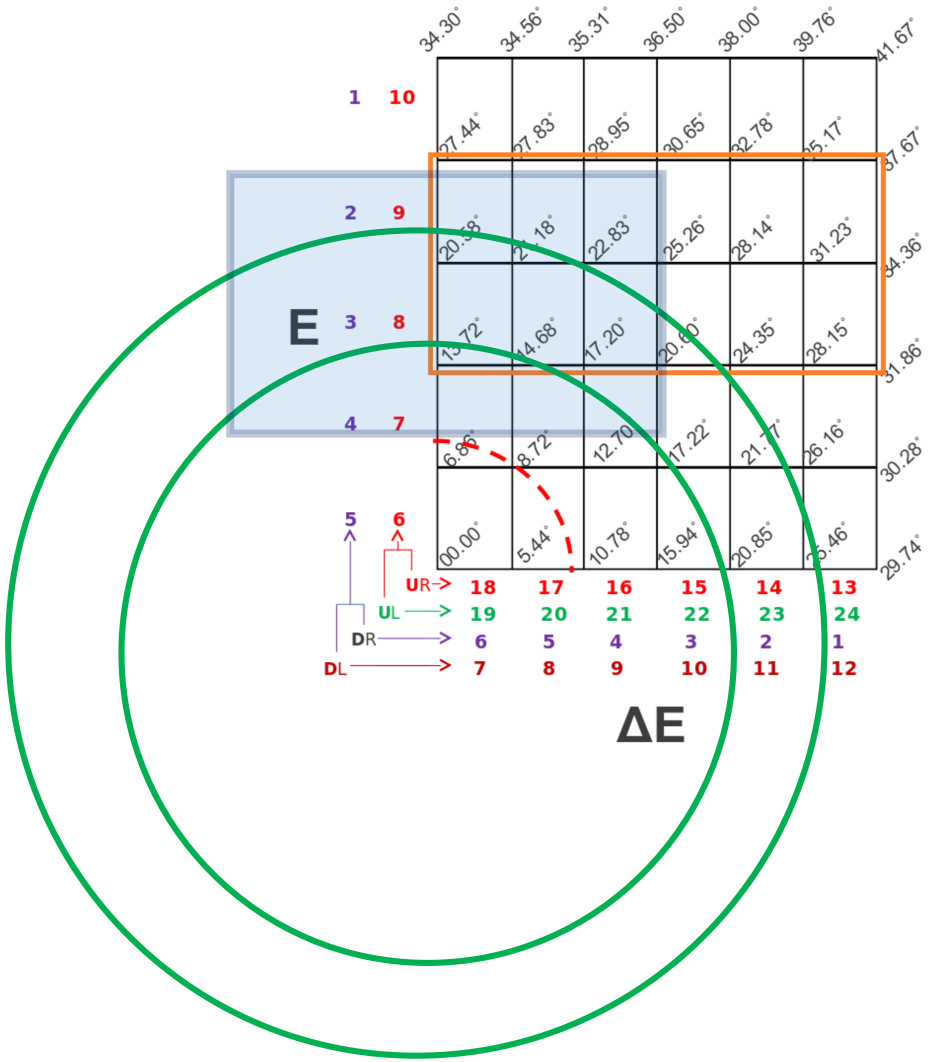
KVI-CART Groningen, NL
TIFR Mumbai, IN
Tokyo Institute of Technology, JP

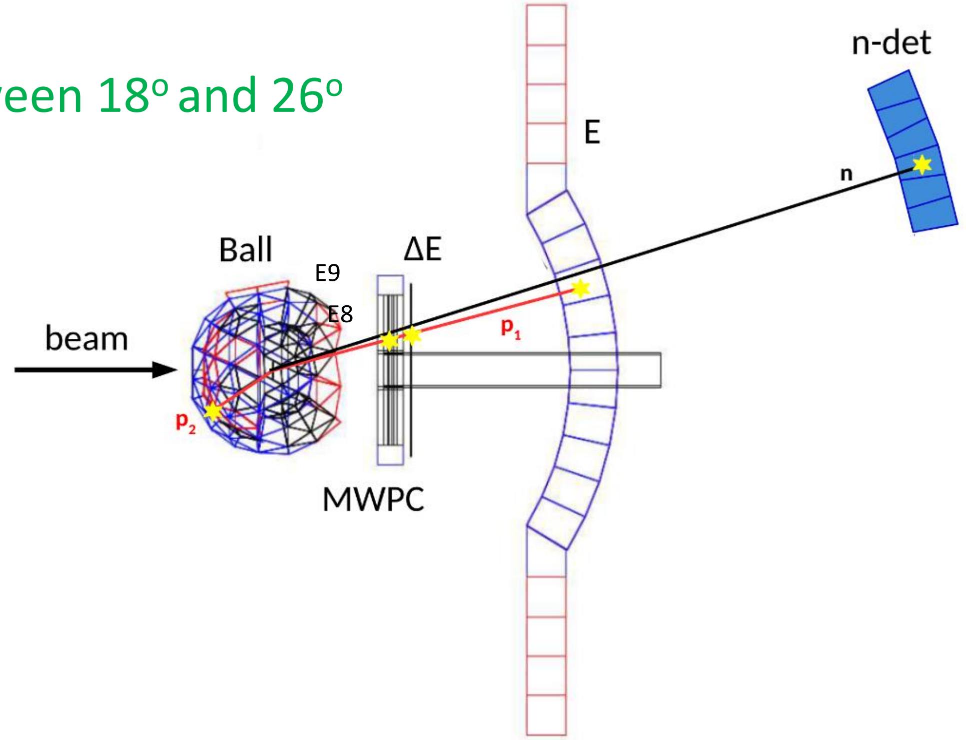
Few-nucleon systems with BINA@CCB – research program

Measuremet of ***pn* FSI**

Neutron detection with a dedicated n-det(ector)

Coverage of ~ ¼ of azimuthal angle in the region of interest θ between 18º and 26º





particle	E	θ, ϕ
p_1	deposited	MWPC
n	TOF	n-det
p_2	deposited	Ball element

ZAKOPANE CONFERENCE on Nuclear Physics 2026 Extremes of the Nuclear Landscape

Few-nucleon systems with BINA@CCB – research program

Energy [MeV/nucl]	Angular range	Reaction	Observables about 1000 data points per observable	
50	4π Wall: 12°-35°	$^{1}H(d,pp)n$	σ	A_x^d, A_y^d, A_{xy}, A_{xx}, A_{yy}
65	12°-35°	$^{1}H(d,pp)n$	σ	A_x^d, A_y^d, A_{xy}, A_{xx}, A_{yy}
	5°-13°	$^{1}H(d,pp)n$	σ	A_x^d, A_y^d
80	4π Wall: 12°-35°	$^{1}H(d,pp)n$	σ	
		$^{1}H(d,pn)p$	σ	
108	4π Wall: 12°-35°	$^{2}H(p,pp)n$	σ	
135, 195	4π	$^{2}H(p,pp)n$	σ	A_x, A_y
150	4π	$^{1}H(d,pp)n$	σ	
160	4π	$^{2}H(p,pp)n$	σ	
170, 190, 200	4π FD: 5°-13°	$^{1}H(d,pp)n$	σ	

Few-nucleon systems with BINA@CCB – research program

Energy [MeV/nucl]	Angular range	Reaction	Observables about 1000 data points per observable	
50	4π Wall: 12°-35°	^{1}H(d,pp)n	σ	A_x^d , A_y^d, A_{xy} , A_{xx} , A_{yy}
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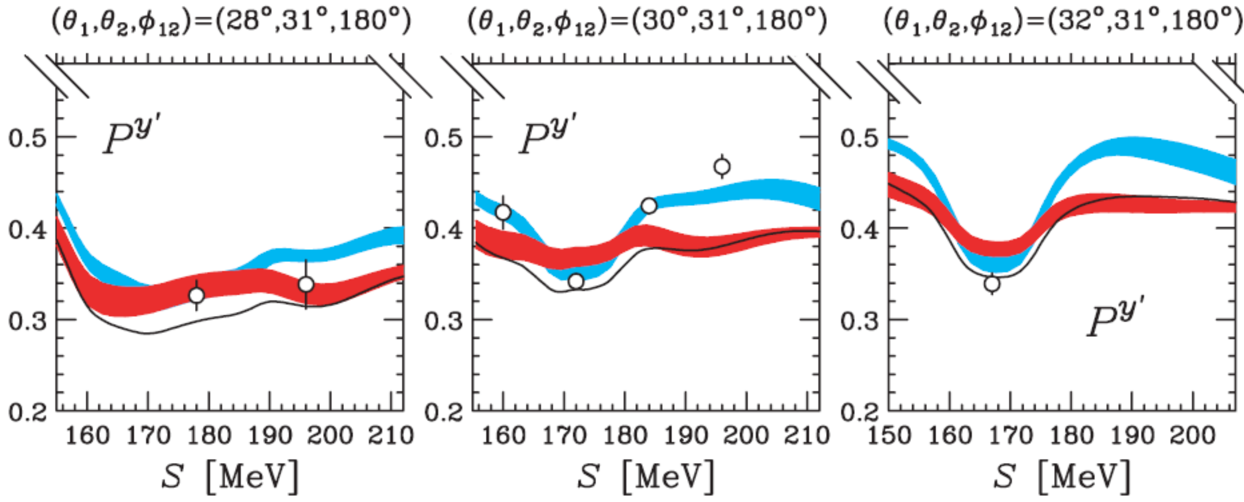
	5°-13°	^{1}H(d,pp)n	σ	A_x^d , A_y^d
80	4π Wall: 12°-35°	^{1}H(d,pp)n	σ	
		^{1}H(d,pn)p	σ	
108	4π Wall: 12°-35°	^{2}H(p,pp)n	σ	
135, 195	4π	^{2}H(p,pp)n	σ	A_x , A_y
150	4π	^{1}H(d,pp)n	σ	
160	4π	^{2}H(p,pp)n	σ	
170, 190, 200	4π FD: 5°-13°	^{1}H(d,pp)n	σ	

How to access polarization observables without polarized beam/target?

- **Induced proton polarization can be measured ONLY in a double scattering experiment.**
- Induced polarization, P^y, was measured at RIKEN at **135 MeV/nucleon** for a few data points corresponding to pn FSI.



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

Few-nucleon systems with BINA@CCB – research program

Energy [MeV/nucl]	Angular range	Reaction	Observables about 1000 data points per observable	
50	4π Wall: 12°-35°	^{1}H(d,pp)n	σ	A_x^d , A_y^d, A_{xy} , A_{xx} , A_{yy}
65	12°-35°	^{1}H(d,pp)n	σ	A_x^d , A_y^d, A_{xy} , A_{xx} , A_{yy}
	5°-13°	^{1}H(d,pp)n	σ	A_x^d , A_y^d
80	4π Wall: 12°-35°	^{1}H(d,pp)n	σ	
		^{1}H(d,pn)p	σ	
108	4π Wall: 12°-35°	^{2}H(p,pp)n	σ	
135, 195	4π	^{2}H(p,pp)n	σ	A_x , A_y
150	4π	^{1}H(d,pp)n	σ	
160	4π	^{2}H(p,pp)n	σ	
170, 190, 200	4π FD: 5°-13°	^{1}H(d,pp)n	σ	

How to access polarization observables without polarized beam/target?

- **Induced proton polarization can be measured ONLY in a double scattering experiment.**

Measurement of **induced polarization of one of the two protons** originating from the ^{2}H(p,pp)n breakup reaction.

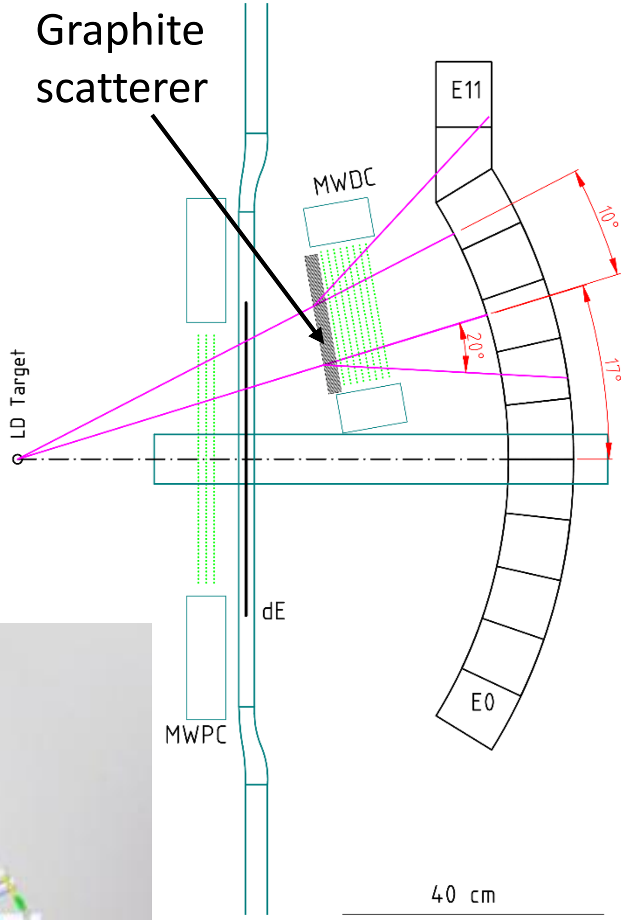
Beam energy: 160 MeV

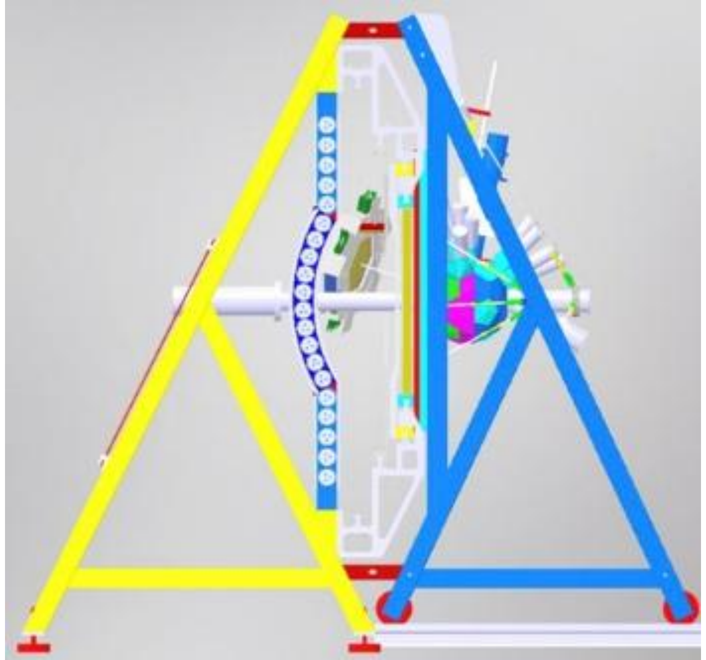
With the use of the **dedicated polarimeter** installed within **the Wall part of the BINA detector**.

BINA was originally designed for polarimetry - with adequate place and acceptance of the E detector for double scattering experiments.

Few-nucleon systems with BINA@CCB – research program

Measurement of **induced polarization of a proton** for a set of kinematic configurations of the ^{2}H(p,$\vec{p}$p)n breakup reaction at the beam energy of 160 MeV.



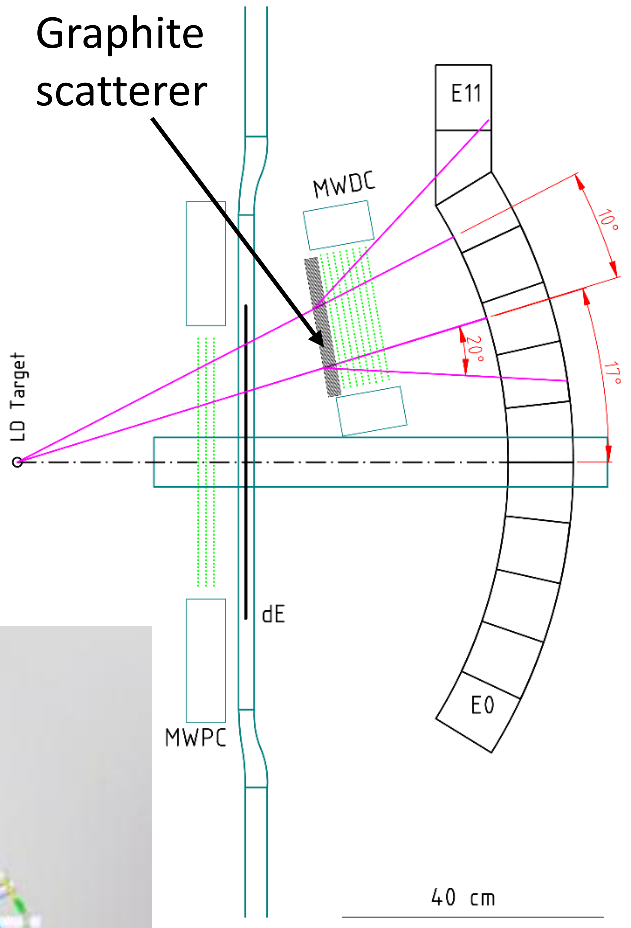


Few-nucleon systems with BINA@CCB – research program

Measurement of **induced polarization of a proton** for a set of kinematic configurations of the $^{2}H(p,\vec{p}p)n$ breakup reaction at the beam energy of 160 MeV.

Two protons emitted forward, within the acceptance of Wall:

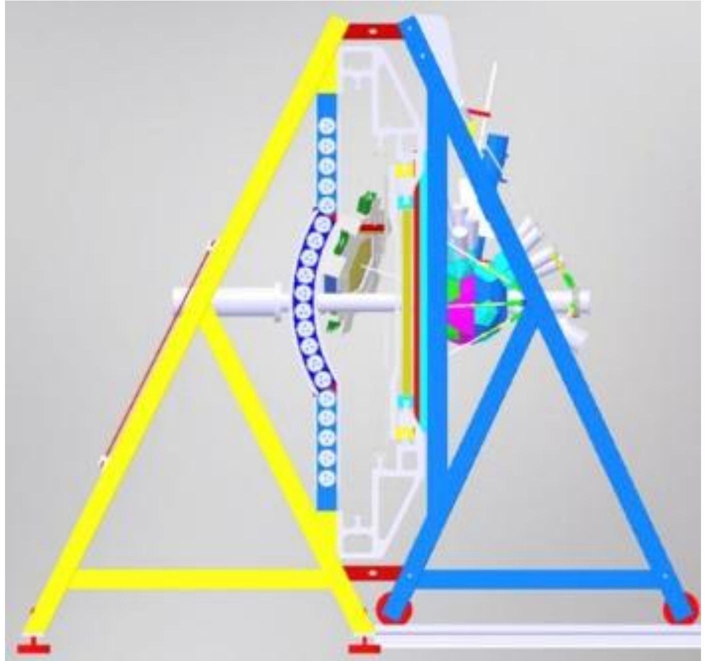
- the **proton of higher energy**, at least 80 MeV, is **emitted towards the polarimeter and scattered off graphite,**
- the **proton of lower energy** is **registered in the part of Wall** which is free of polarimeter.



First stage:

$\Delta\theta_1, \Delta\theta_2 = 4^0, \Delta\varphi_{12} = 20^0$, the setup allows measurement at:

- **two θ_1 values** (limited by the polarimeter acceptance),
- **three θ_2 values** (limited by the Wall acceptance),
- **two φ_{12}** values 160^0 and 180^0 („first" proton in the polarimeter, "second" proton outside the polarimeter).



This corresponds to **12 coplanar configurations** for P^y.

Conclusions

A large amount of precise experimental data for 3N systems is available (many for the Nd elastic scattering and fewer for the Nd breakup reaction), providing a basis for comparing different theoretical approaches that are used to predict 3N observables.

Sensitivity to a specific effect changes with the kinematics – „selectivity" – but in many cases all dynamic contributions are important.

- **3NF effects** are significant, **confirmed**, rising with beam energy.
- **Coulomb** effects are locally large**.**
- At higher energies – a **problem** with description of the cross section data.
  - **Relativistic effects**?
  - Defficiencies of 3NF models?

Systematic studies using **invariant coordinates** for extensive datasets of the breakup reactions at various energies are currently ongoing.

Experimental studies of the breakup reaction in a wide range of energies are continued at **CCB** with the **BINA** detector, addressing further important aspects e.g. induced polarization.