The 11th International Workshop on Chiral Dynamics
26-30 August 2024

Dynamics of 3-nucleon systems studied in **proton-induced deuteron breakup** reaction.

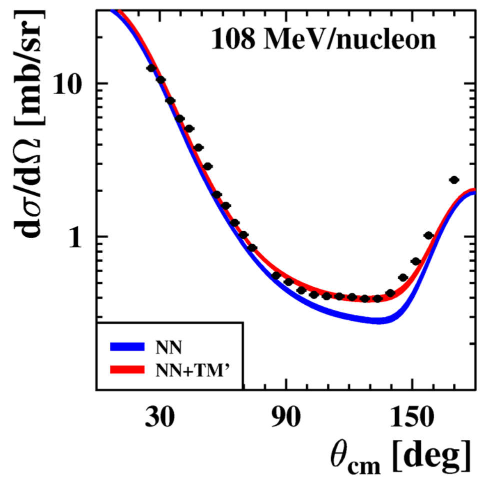
Elżbieta Stephan
University of Silesia, Poland

System of 3 Nucleons

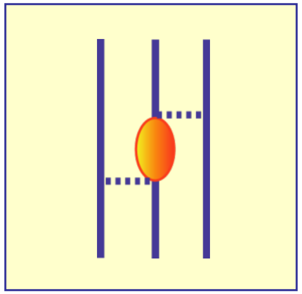
Predictions of NN potentials alone:

- 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

Binding energy [MeV]	^{3}H	^{3}He	^{4}He
Experimental value	8.48	7.72	28.3
CD Bonn	8.01	7.29	26.3
CD Bonn + TM99	8.48	7.73	29.2

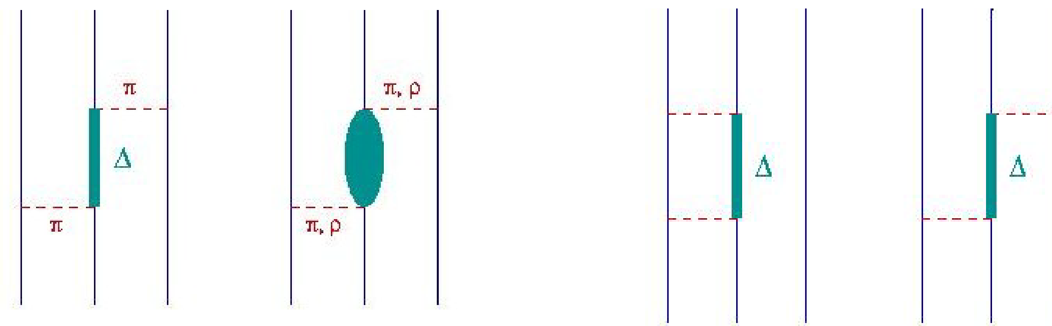


- Introducing concept of **three-nucleon forces**: genuine (irreducible) interaction of three nucleons
  - as a consequence of internal nucleon structure
- Systematic approach within ChEFT

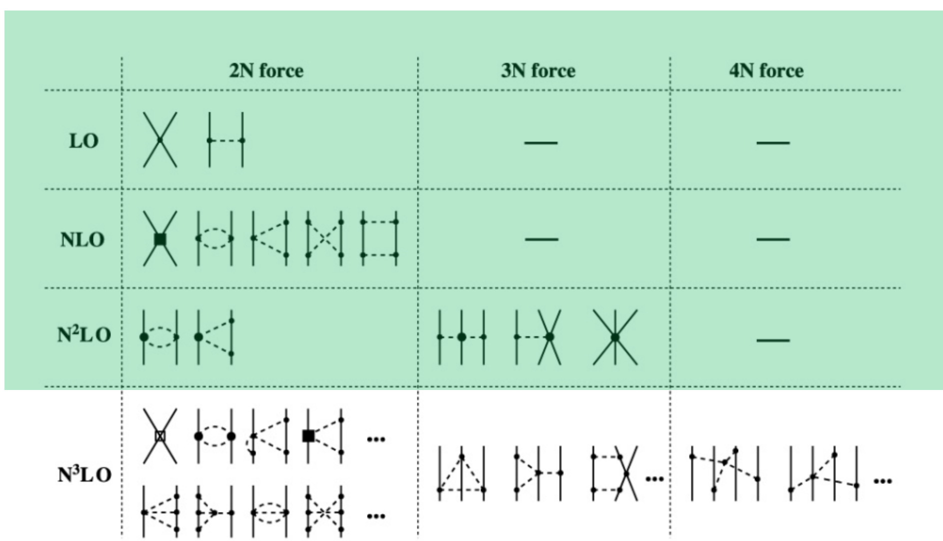


System of 3 Nucleons

- Models of 3NF:



- Naturally appearing in Chiral Effective Field Theory at N2LO:



$(Q/\Lambda_\chi)^0$

$(Q/\Lambda_\chi)^2$

$(Q/\Lambda_\chi)^3$

$(Q/\Lambda_\chi)^4$

3N Systems – Elastic Scattering

General picture

- 3NF significantly improves description of the differential cross section.
- At certain beam energy, predicted 3NF effects appear to be not large enough (?) to solve the discrepancy
- 3NF not always improves description of polarization observables, sometimes in contrary - a lot of examples at various energies.
- very low and local Coulomb and relativistic effects are predicted.

One should confront these important findings with measurements of observables in the deuteron breakup reaction

- 3 free nucleons in the final state .
- Variety of kinematic configurations lead to variable sensitivity to dynamical ingredients.

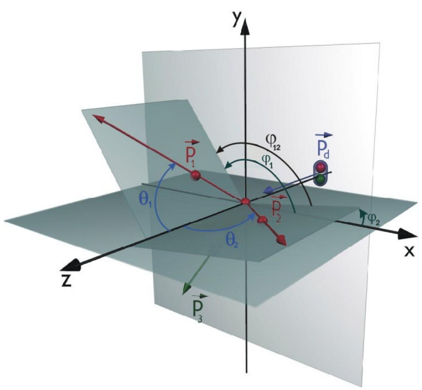
3N Systems – Scattering Experiments

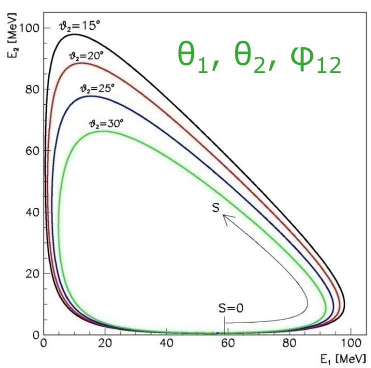
- Processes:
  - Elastic scattering: N + d → N + d
  - **Breakup: N + d → N + n + p**
  - and electromagnetic processes
- Observables
  - **differential cross section**
  - **vector&tensor analyzing powers, induced polarization**
  - polarization transfer, correlations
- Energy range - why "medium" and what does it mean?
  - measurable 3NF effects
  - below pion production threshold
- Technique:
  - spectrometers
  - **large acceptance detectors** – very usefull for studies of the final state continuum

Large Acceptance Detectors

for Studies of Deuteron Breakup in Collision with Proton

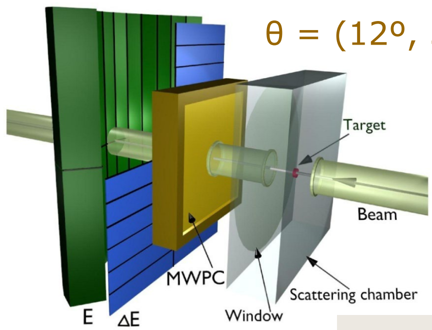
d+p **-> p+p**+n





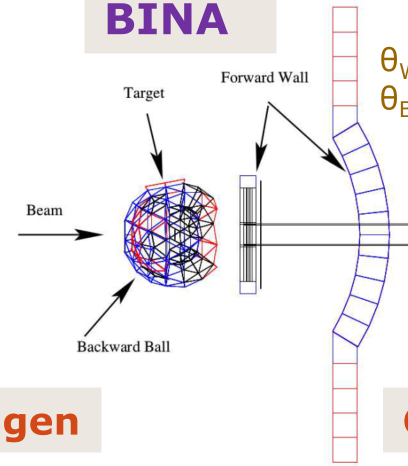
SALAD

θ = (12°, 35°)



KVI-Groningen

BINA

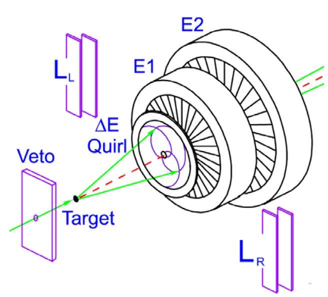


θ_{Wall} = (12°, 35°)
θ_{Ball} = (40°, 180°)

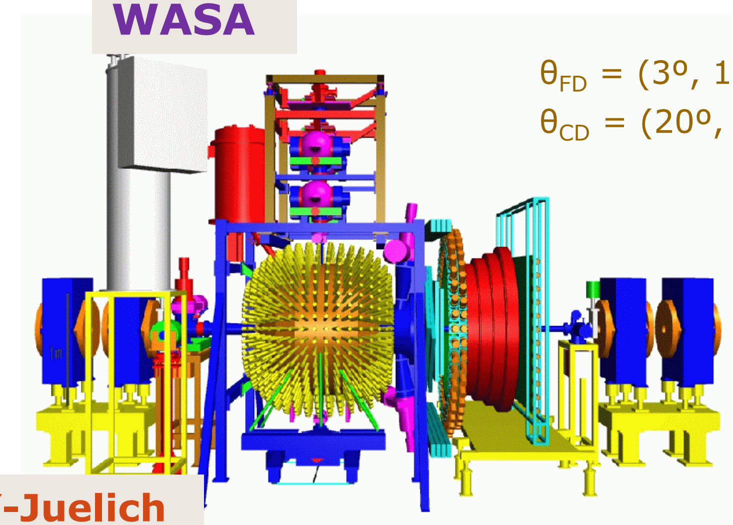
CCB Krakow

GeWall

θ = (3°, 15°)



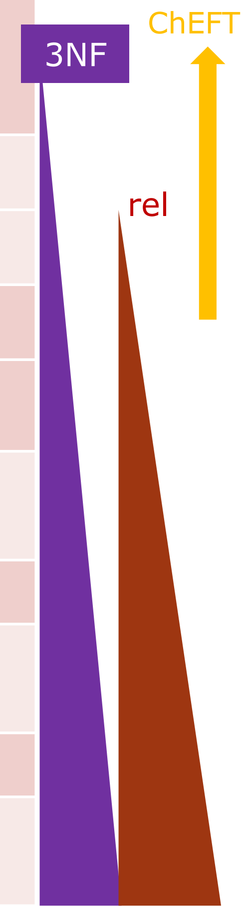
WASA



θ_{FD} = (3°, 18°)
θ_{CD} = (20°, 169°)

COSY-Juelich

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

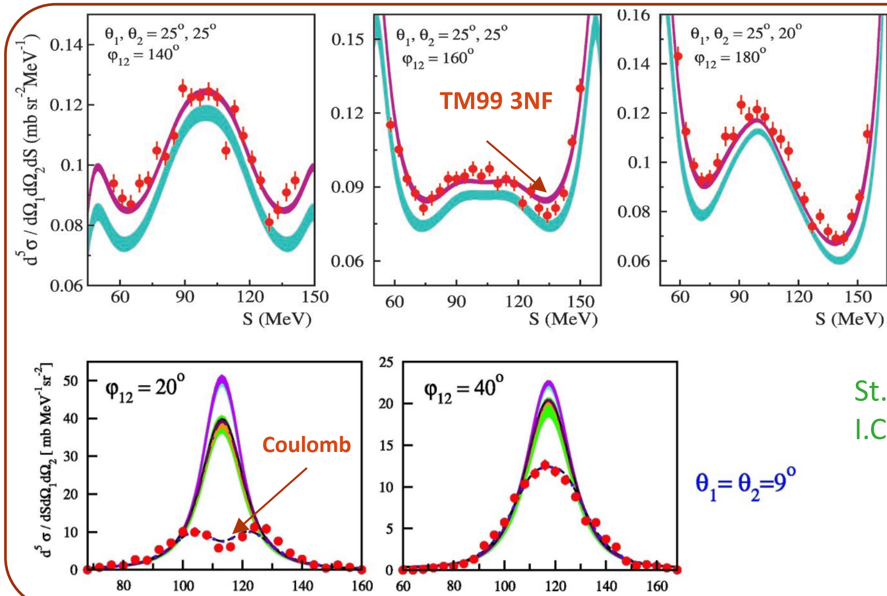


- So far no calculations including 3NF+Coulomb+relativistic approach
- Large phase space covered - one can profit from selectivity
- Systematic studies over energy may help to resolve various effects

CD2024

SALAD@KVI

GeWall@COSY



$\theta_1 = \theta_2 = 9^{\circ}$

St.Kistryn et al., Phys. Rev C 72 , 044006 (2005)
I.Ciepał et al., Few-Body Syst. 56, 665 (2015)

65 MeV/nucleon

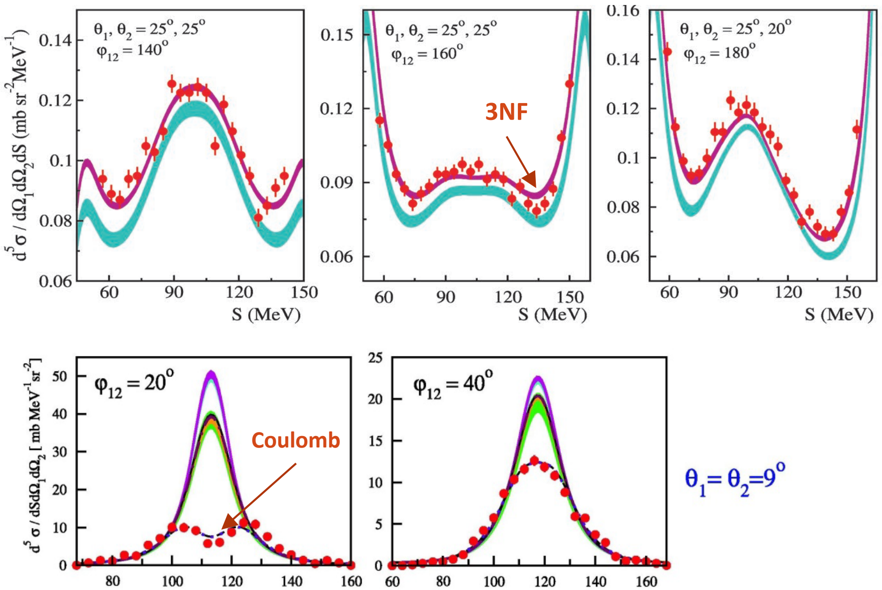
Differential cross section results

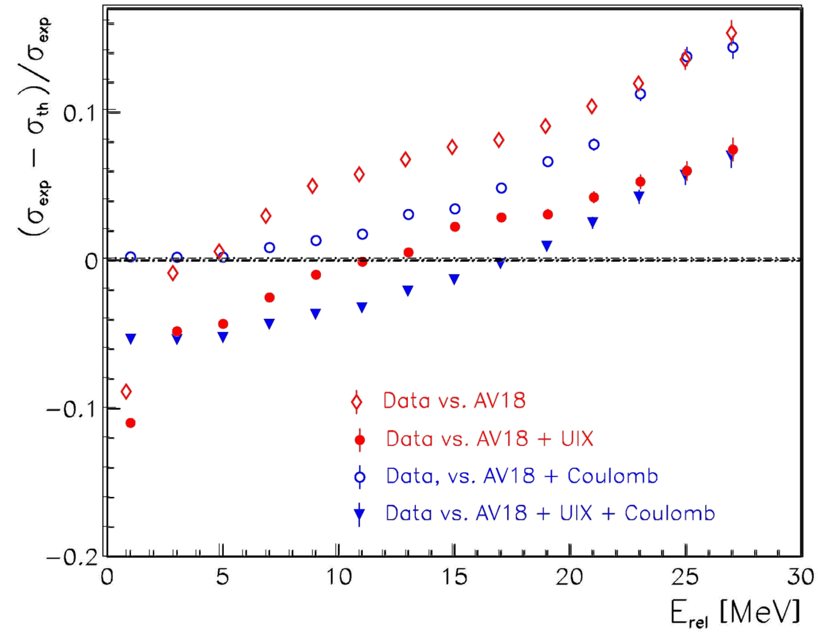
- $^{1}H(d,pp)n$ at 65 MeV/nucleon
- few hundreds data points (SALAD@KVI, GeWall@COSY)
- 3NF significantly improves description of the differential cross section, the effects are observed in particular kinematic configurations.
- significant Coulomb effects – locally very strong, in particular in pp FSI!

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

SALAD@KVI

GeWall@COSY





A.Deltuva et al., Phys. Rev. C80, 064002, (2009)

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SALAD@KVI

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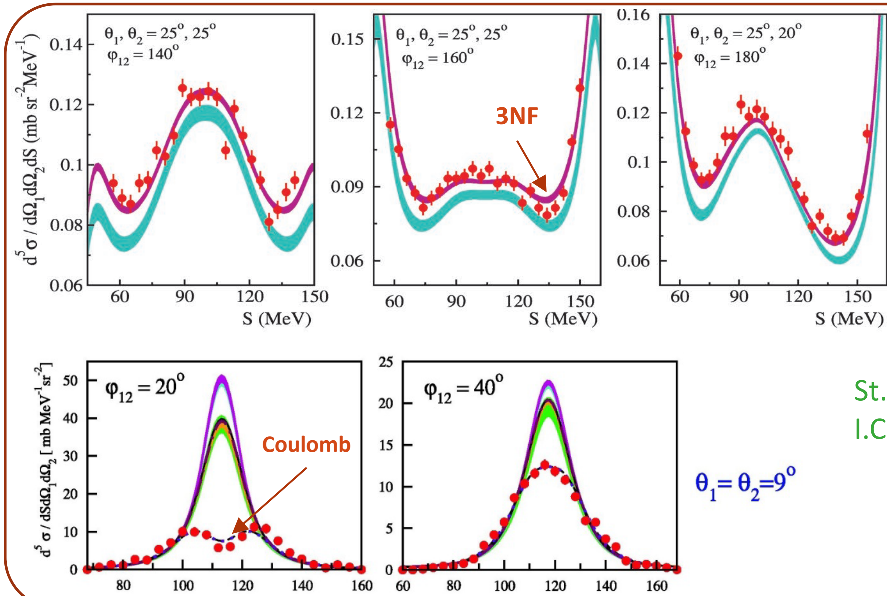
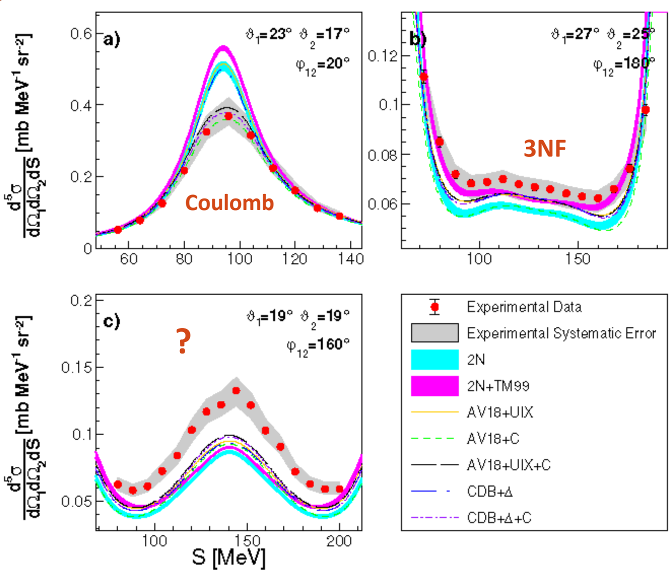


St.Kistryn et al., Phys. Rev C 72 , 044006 (2005)
I.Ciepał et al., Few-Body Syst. 56, 665 (2015)

$\theta_1 = \theta_2 = 9^o$

65 MeV/nucleon

BINA@KVI

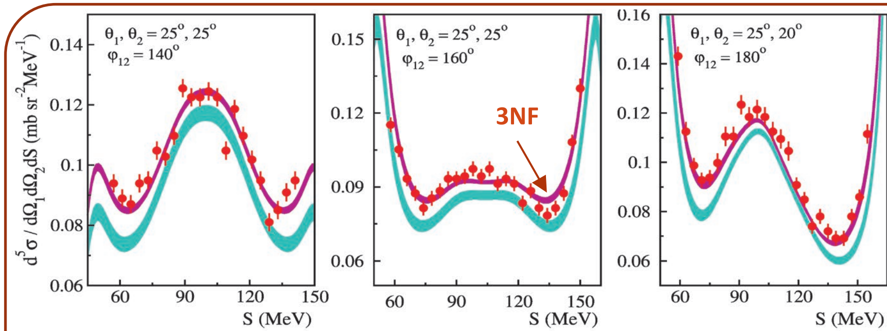


W. Parol et al., Phys. Rev C 102 , 054002 (2020)

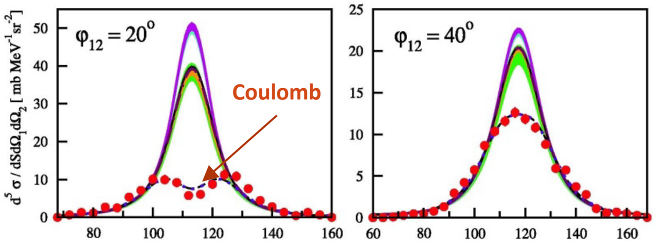
80 MeV/nucleon

- ^{1}H(d,pp)n at 80 MeV/nucl.,
- Polar angles <30^o (BINA@KVI)
- 3NF & Coulomb effects confirmed, general success of description
- Very local discrepancy between data and theories

SALAD@KVI



GeWall@COSY



$\theta_1 = \theta_2 = 9^o$

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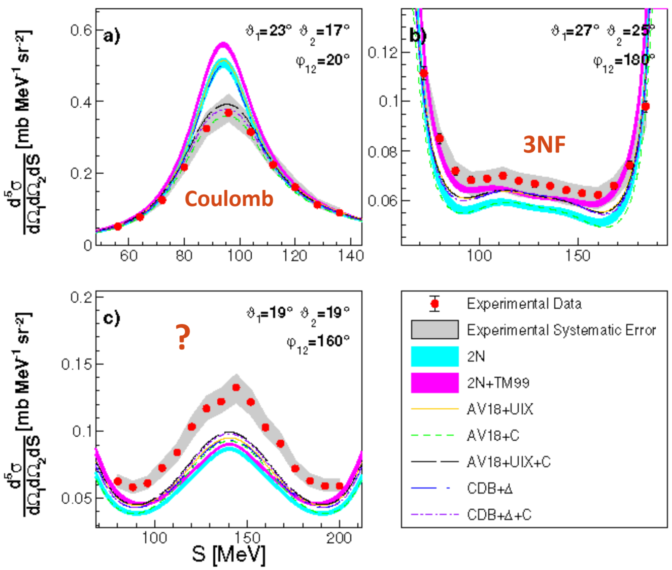
65 MeV/nucleon

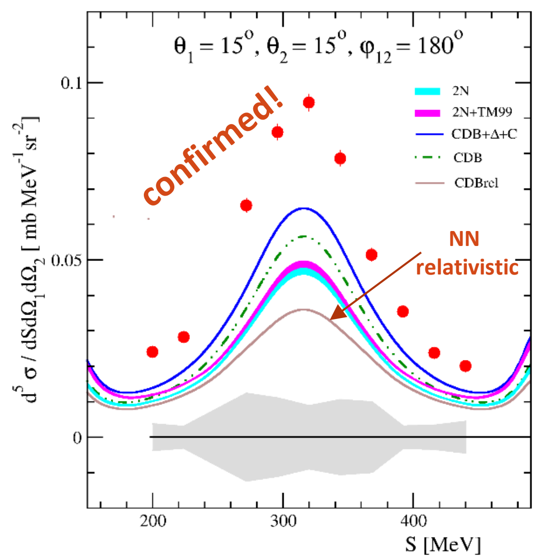
BINA@KVI



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

80 MeV/nucleon

WASA@COSY

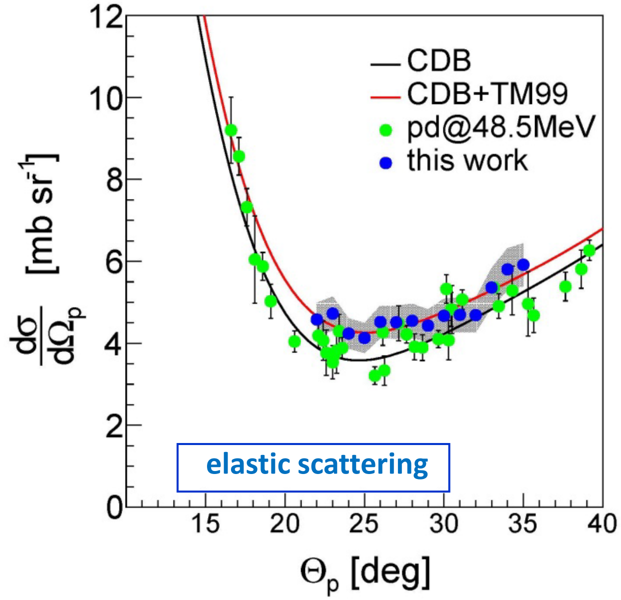


B.Kłos WASA@COSY, Phys. Rev C 101 , 044001 (2020)

170 MeV/nucleon

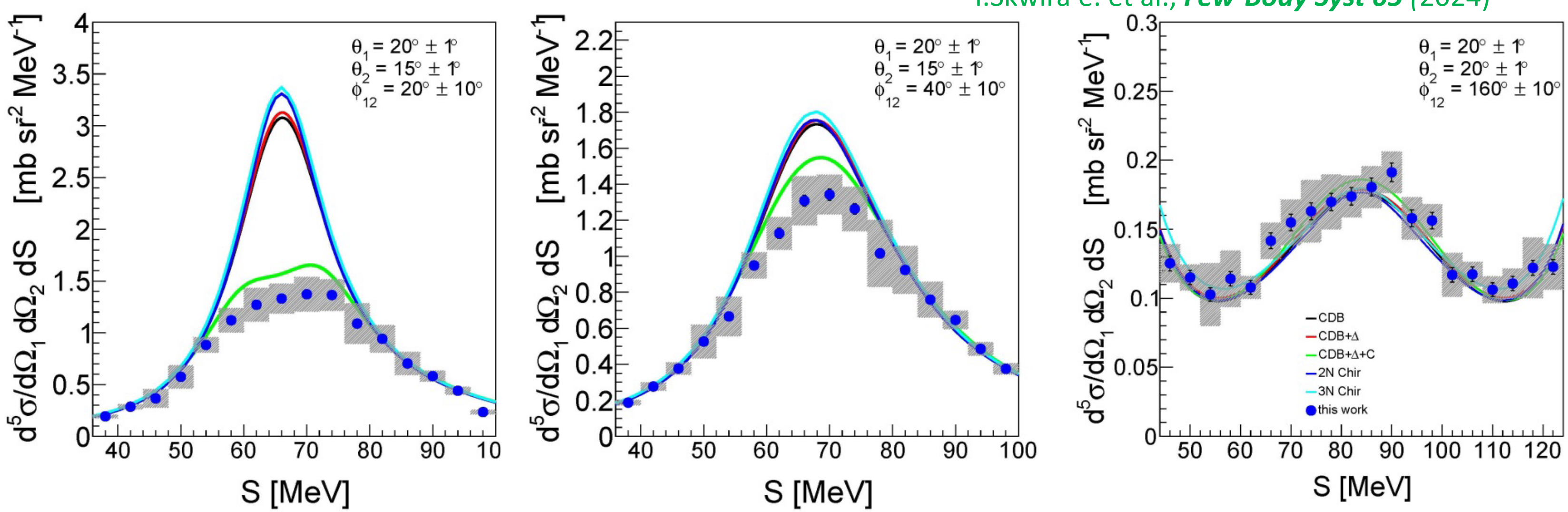
H. Witała et al.: 2N, 2N+TM99, CDBrel
A.Deltuva et al.: CBD+Δ+C, CBD+Δ+C,AV18, AV18+C, AV18+UIX, AV18+UIX+C, AV18+UIX+C

^{1}H(d,pp)n at 50 MeV/nucleon (BINA@KVI)



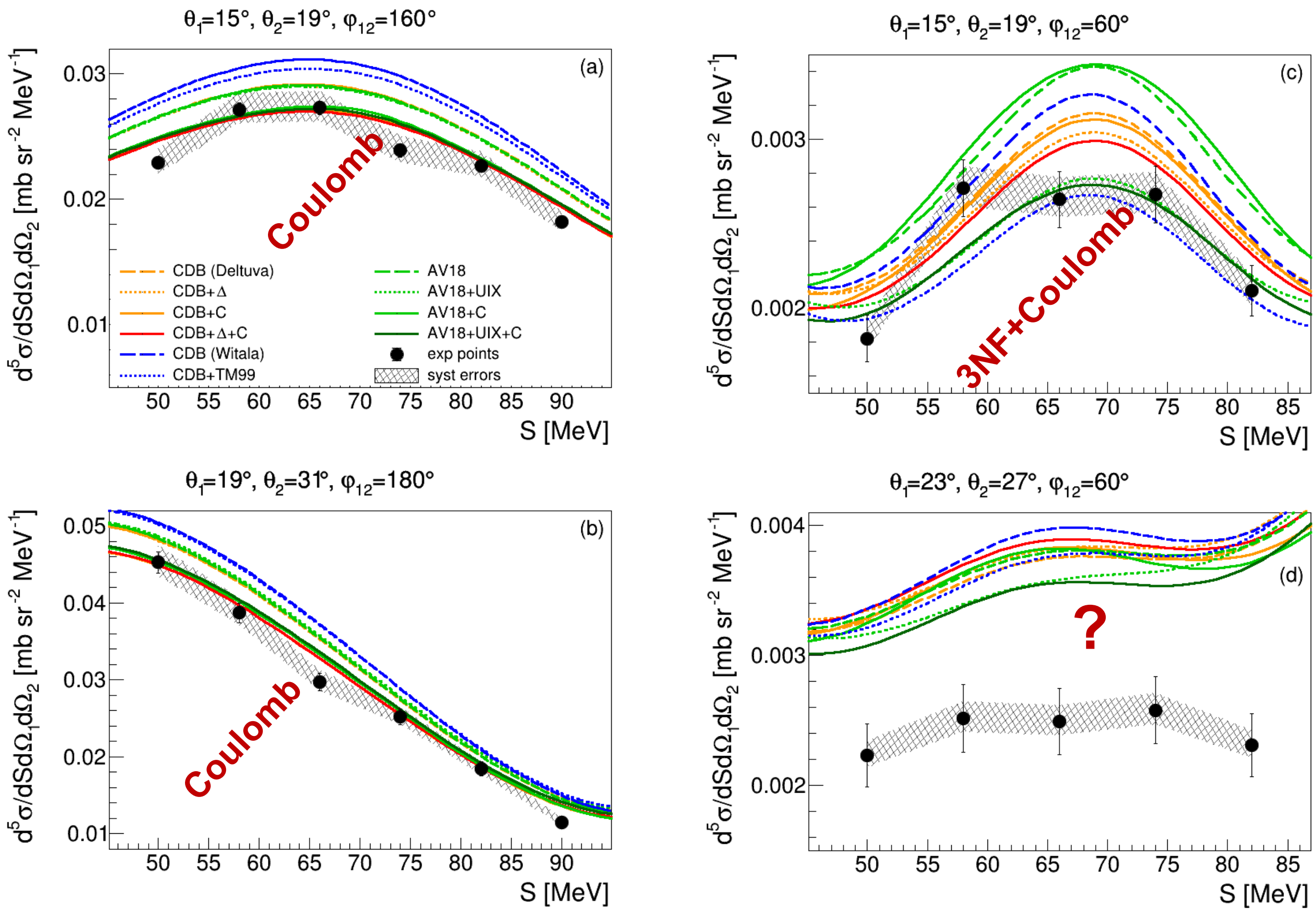
- ^{1}H(d,dp) elastic scattering– a small 3NF effect confirmed
- ^{1}H(d,pp)n breakup (θ<25^{o}):
  - Coulomb effects present
  - In the regions of negligible Coulomb effects, the description given by „realistic potentials” and ChEFT (SMS N4LO^{+} +N2LO 3NF), is very good

I.Skwira e. et al., ***Few-Body Syst 65*** *(2024)*



Results for $^{2}H(p,pp)n$ at 108 MeV BINA@CCB

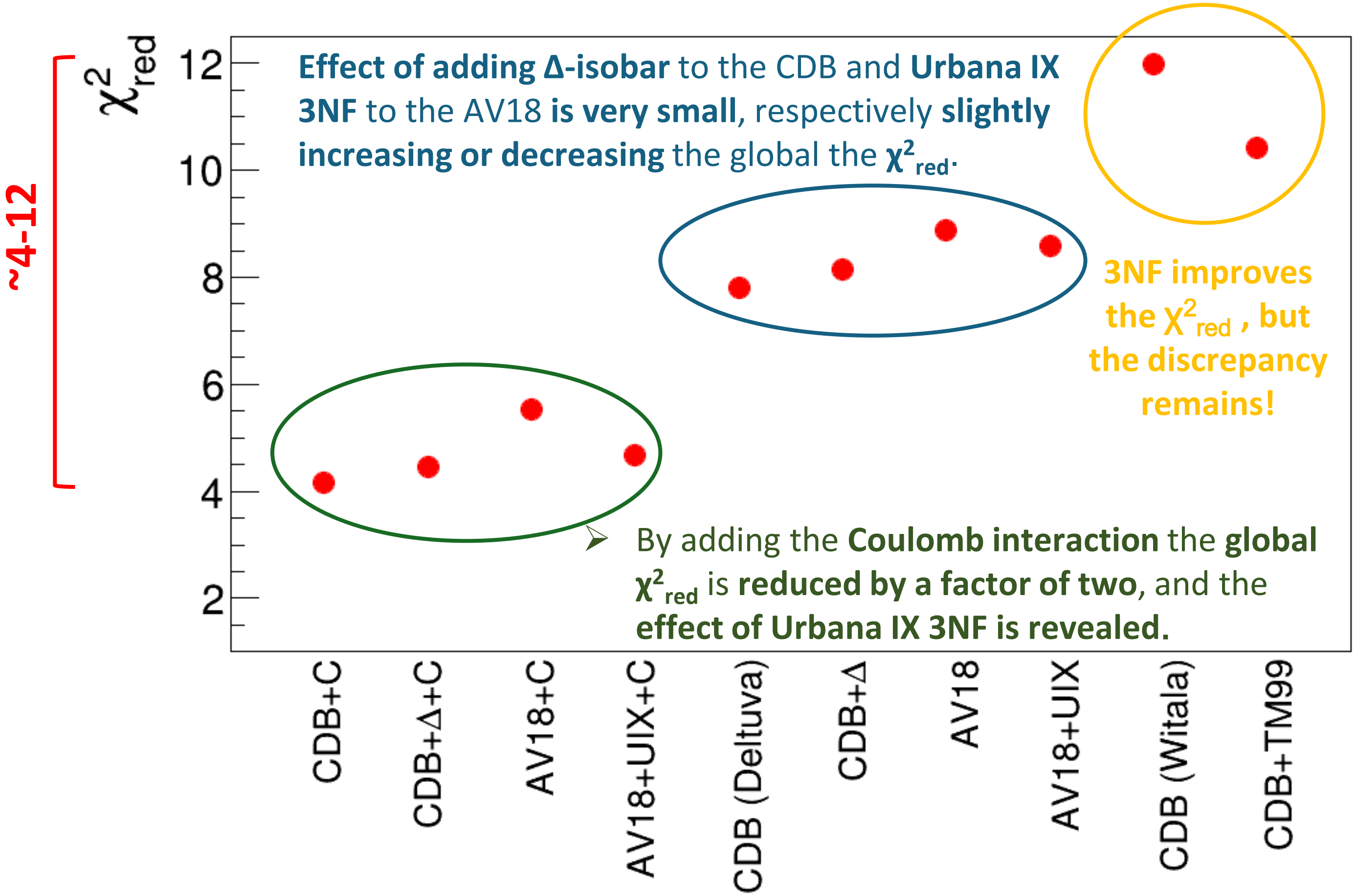
- The differential cross section obtained for a set of **84 angular configurations**; polar angles **θ from 13° to 33°,** and azimuthal angle **φ_{12} from 50° to 180°** (about 500 data points)



Łobejko A. et al., ***Few-Body Syst 65,36*** *(2024)*

Łobejko A. et al., ***arXiv:2407.01582*** *(2024)*

Results for ^{2}H(p,pp)n at 108 MeV BINA@CCB

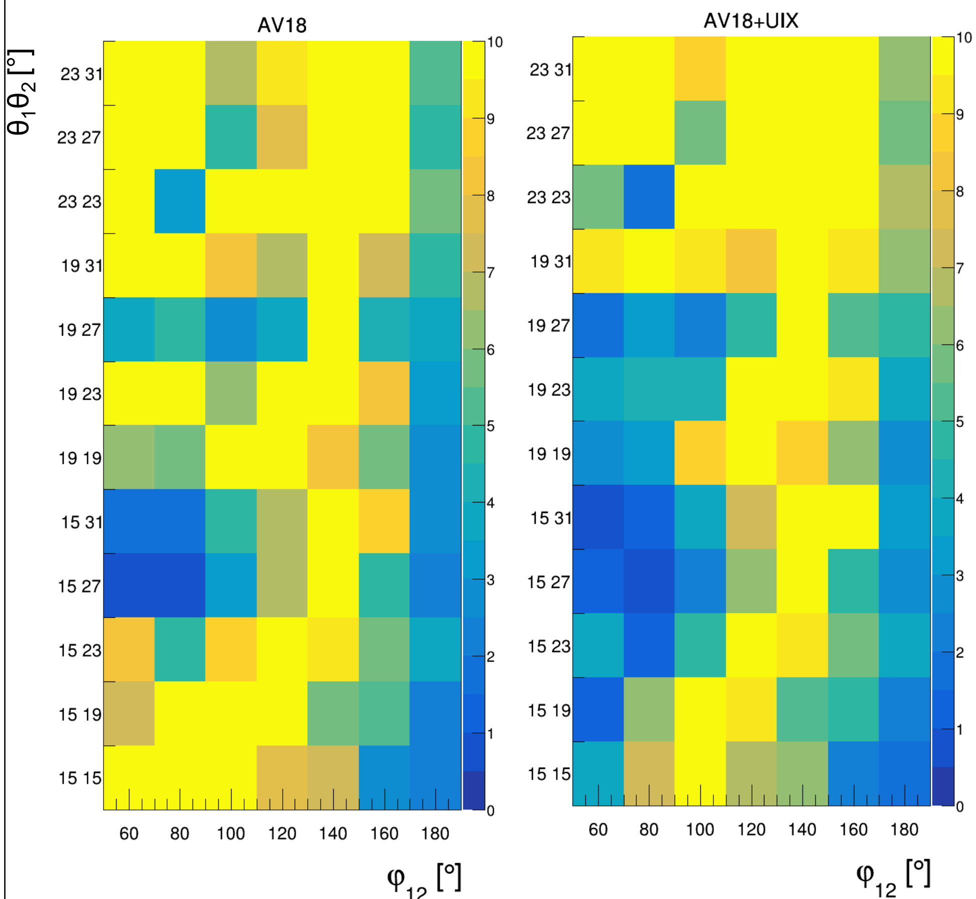


$$\chi^2_{red} = \frac{1}{N}\sum_{i=10}^{N}\left(\frac{\sigma_i^{exp} - \sigma_i^{th}}{\Delta\sigma_i^{tot}}\right)^2$$

- The **global χ^2_{red}** analysis clearly shows a **significant improvement** in the description when the **Coulomb force is taken into account**;

Cross section for $^2H(p,pp)n$ at 108 MeV BINA@CCB

- The χ^2_{red} **maps obtained** for theories **without Coulomb demonstrate deficiency** of the data description in **particular regions**;

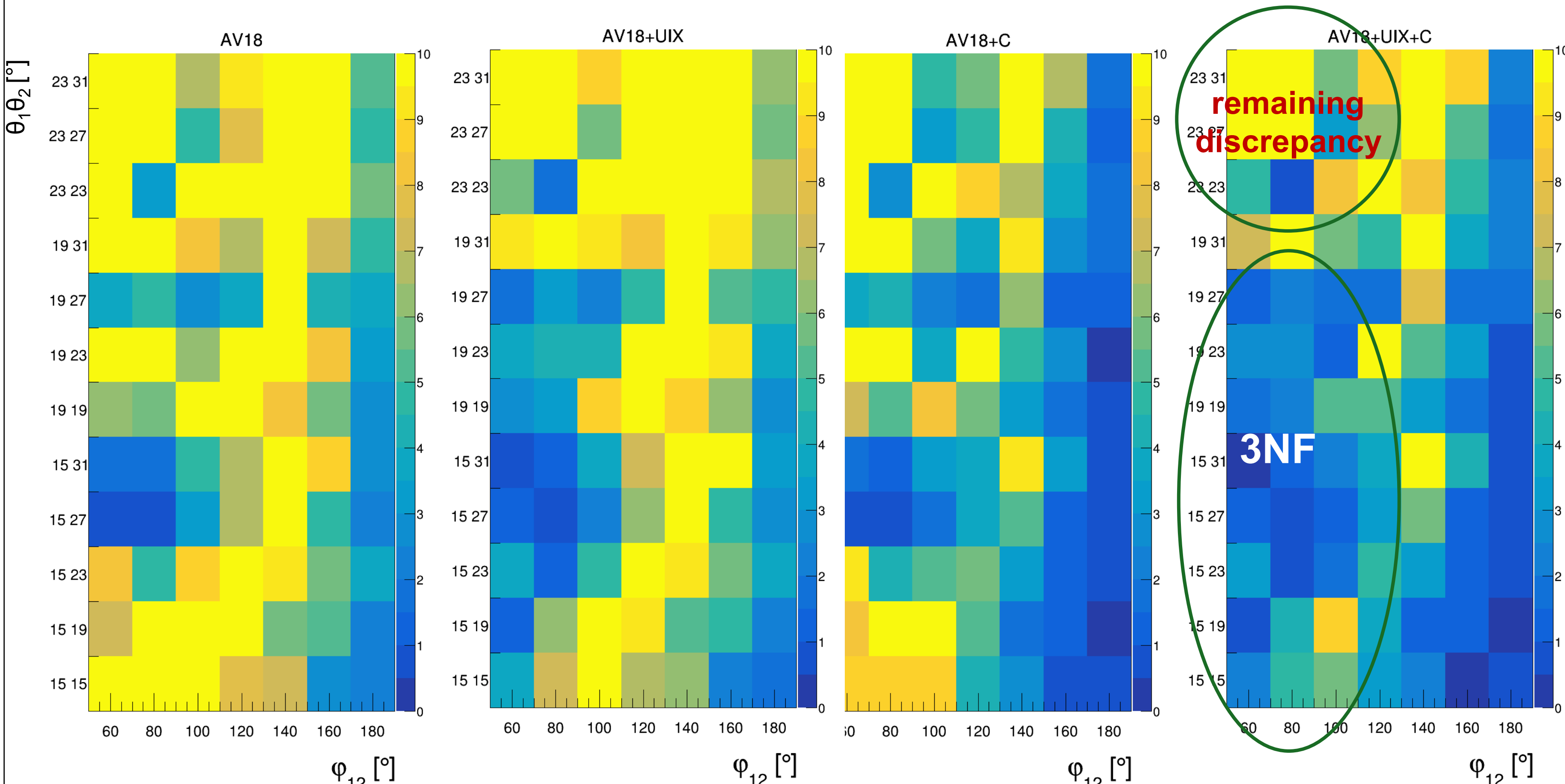


- **Max value of 10 for better visibility**

Cross section for ^{2}H(p,pp)n at 108 MeV BINA@CCB

- The χ^2_{red} **maps obtained** for theories **without Coulomb demonstrate deficiency** of the data description in **particular regions**;

- **Adding the Coulomb interaction substantially improves the situation, allowing to examine the role of 3NF;**



Cross Section for d-p Breakup Reaction
Conclusions

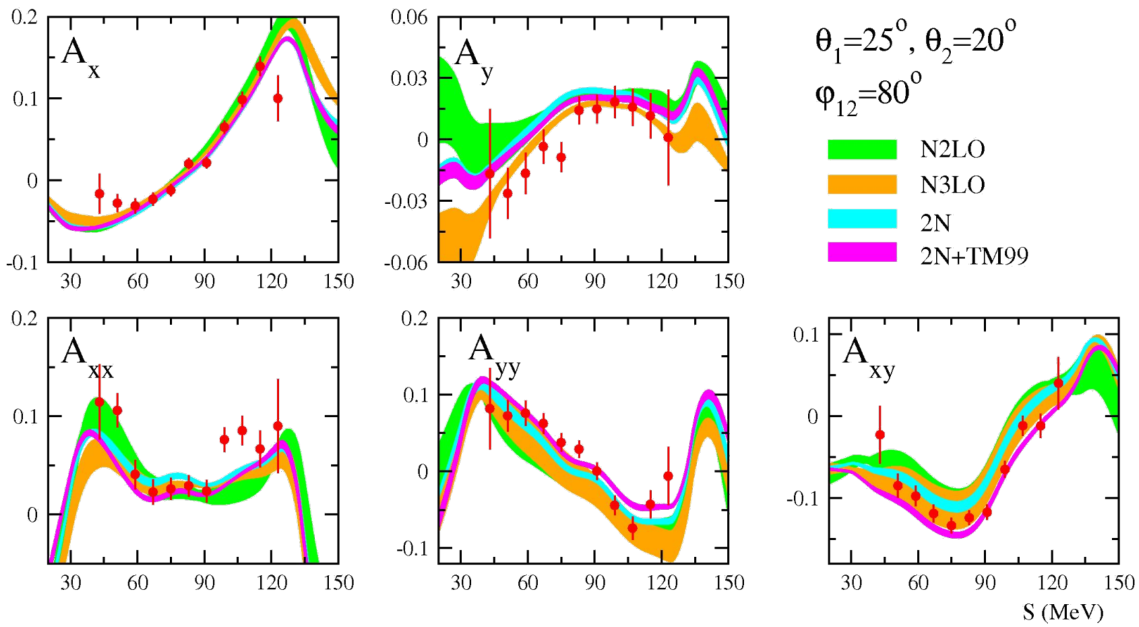
Large data set taken in a wide range of energies, from 50 to 200 MeV/nucl.

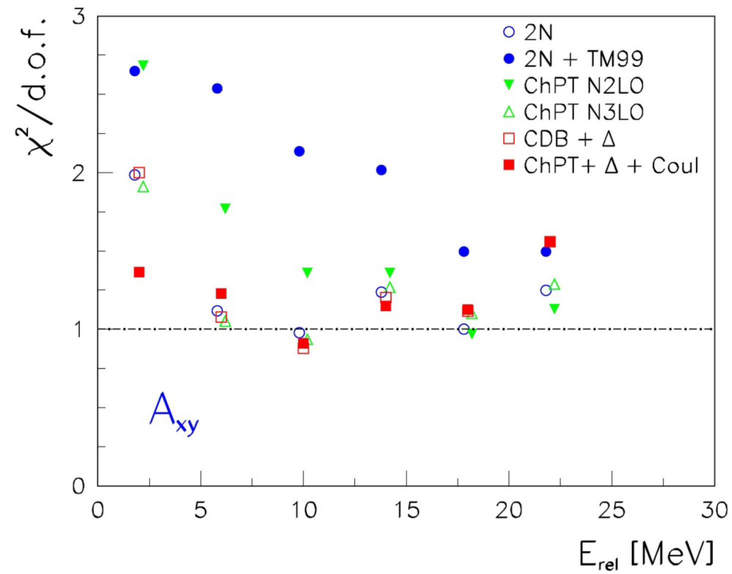
Sensitivity to a specific effect changes with kinematics – „selectivity" – but in many cases all dynamic contributions are important.

- **3NF effects** are significant, **confirmed**, rising with energy.
- **Coulomb** effects large, in particular **at pp FSI**, but spread over almost entire phase space. For the fair conclusions about quality of description, the Coulomb interaction has to be necessarily included into the theoretical calculations.
- General description by „3NF+Coulomb" calculations is very good, with a few exceptions. Especially at higher energies – **problem** with description of cross section data was found in particular configurations.
  - Relativistic effects?
  - Defficiencies of 3NF?

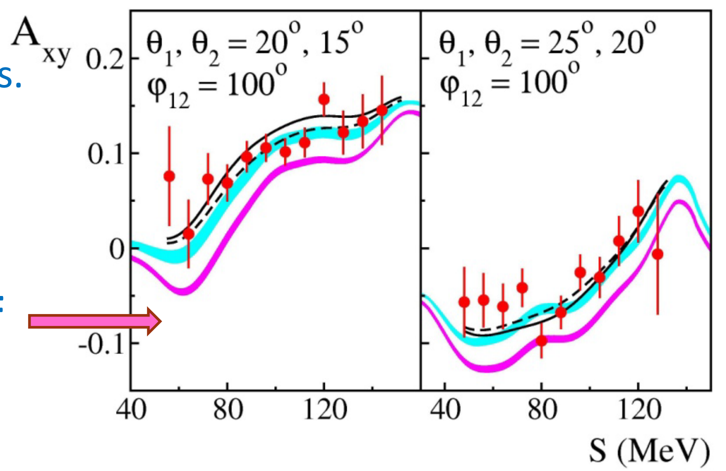
BINA@KVI: $^{1}H(\vec{d},pp)n$ breakup (65 and 50 MeV/nucleon)

Vector (Deuteron) and Tensor Analyzing powers



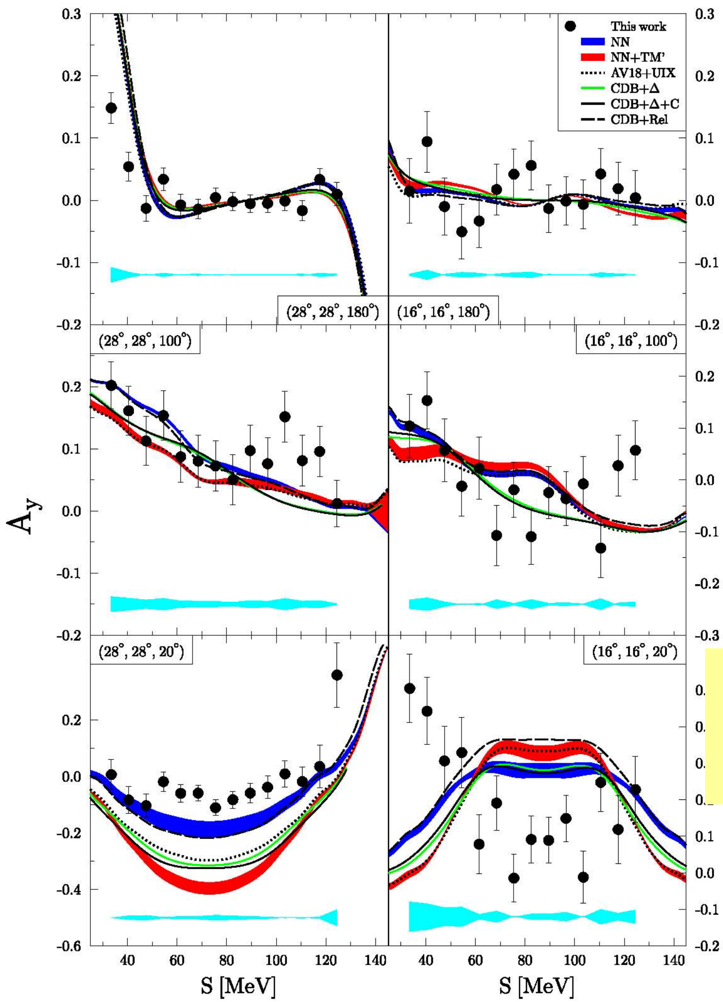


- 5 deuteron observables: vector and tensor analysing powers.
- Few hundreds data points per observable.
- Vector analyzing powers: 3NF effects negligible, good description of data.
- **Tensor analyzing powers: predicted but not confirmed 3NF effects.**



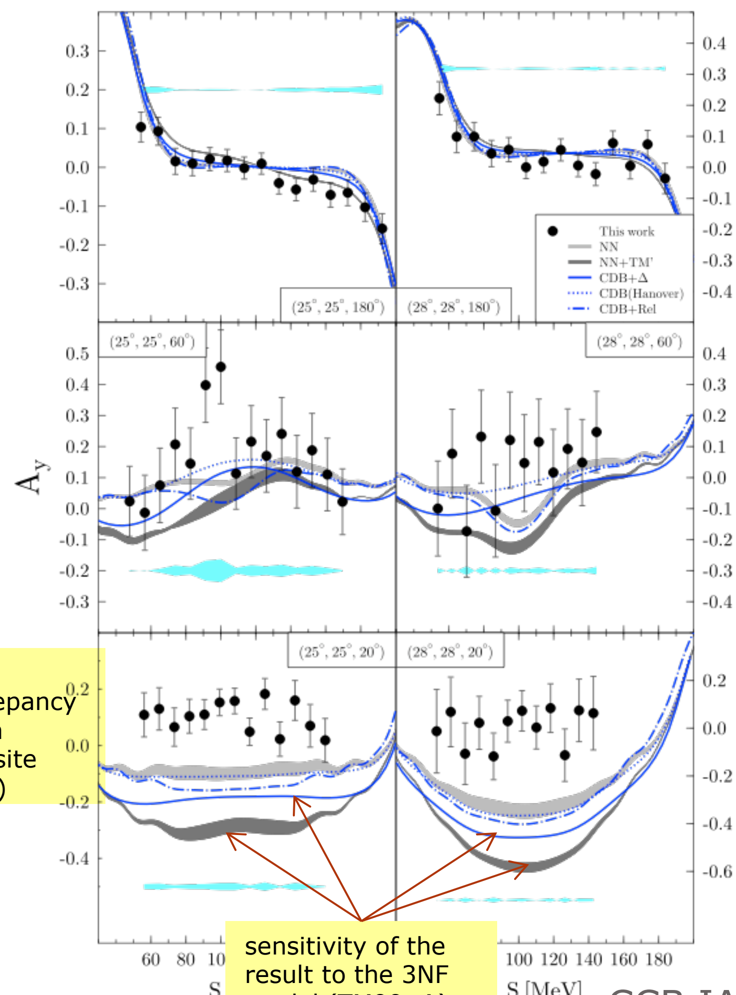
BINA@KVI: ^{2}H($\vec{p}$,pp)n breakup
Vector (Proton) Analyzing Powers

135 MeV, M. Eslami-Kalantari et al.



large discrepancy (even opposite signs)

190 MeV, H. Mardanpour et al.



sensitivity of the result to the 3NF model (TM99, Δ)

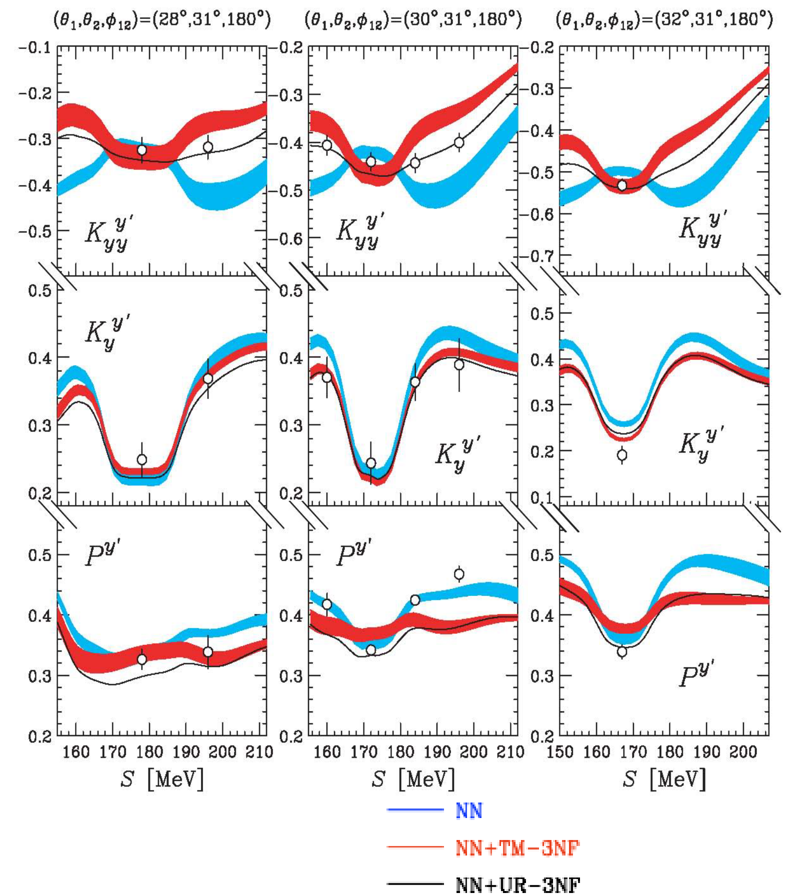
HOW TO ACCESS POLARIZATION OBSERVABLES WITHOUT POLARIZED BEAM/TARGET ?

- **Induced proton polarization can be measured ONLY in the double scattering experiment**
- Induced polarization, $\mathbf{P^y}$, was measured at RIKEN at 135 MeV/nucleon for several data points corresponding to pn FSI:

Double-scattering experiment for breakup

θ_1,θ_2 = 28º-32º, Φ_{12} = 180º

K. Sekiguchi *et al.*, PRC 78 (2009) 054008



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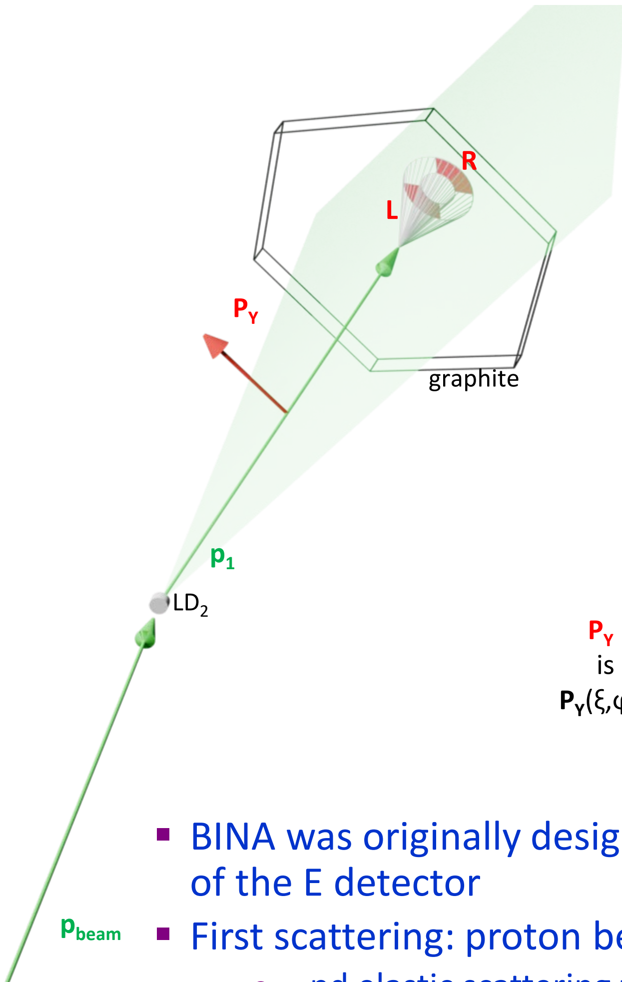
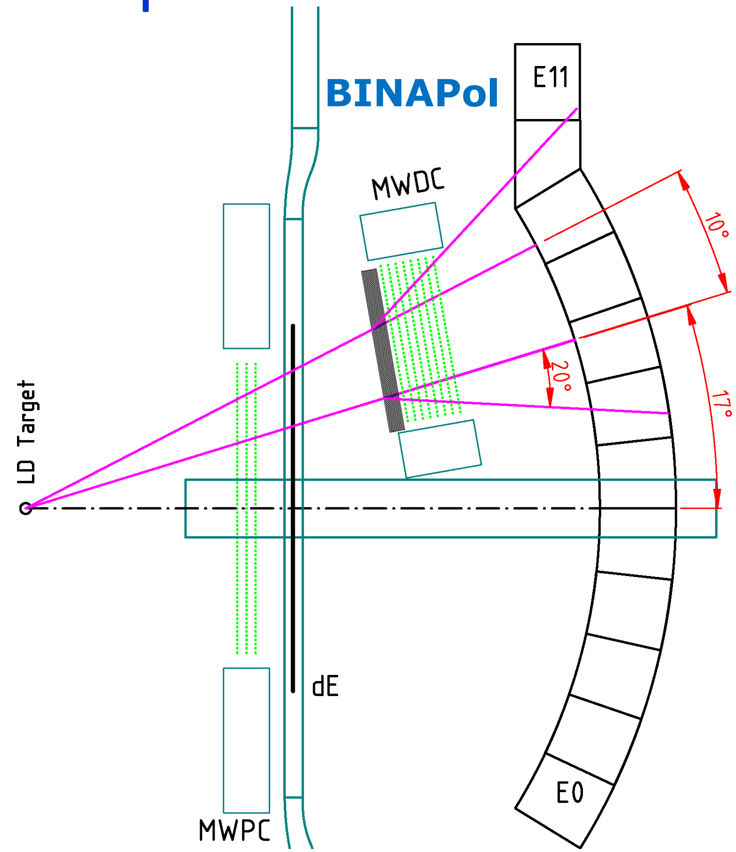
PROPOSAL: BINA equipped with polarimeter to measure the induced polarization

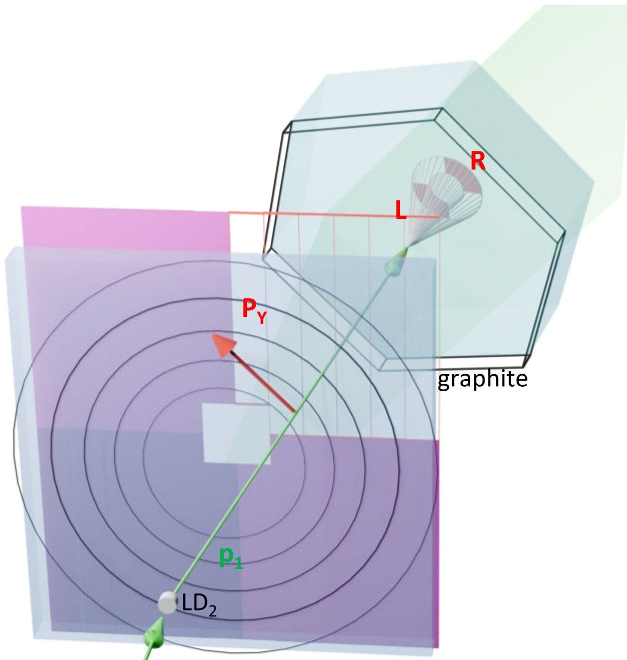


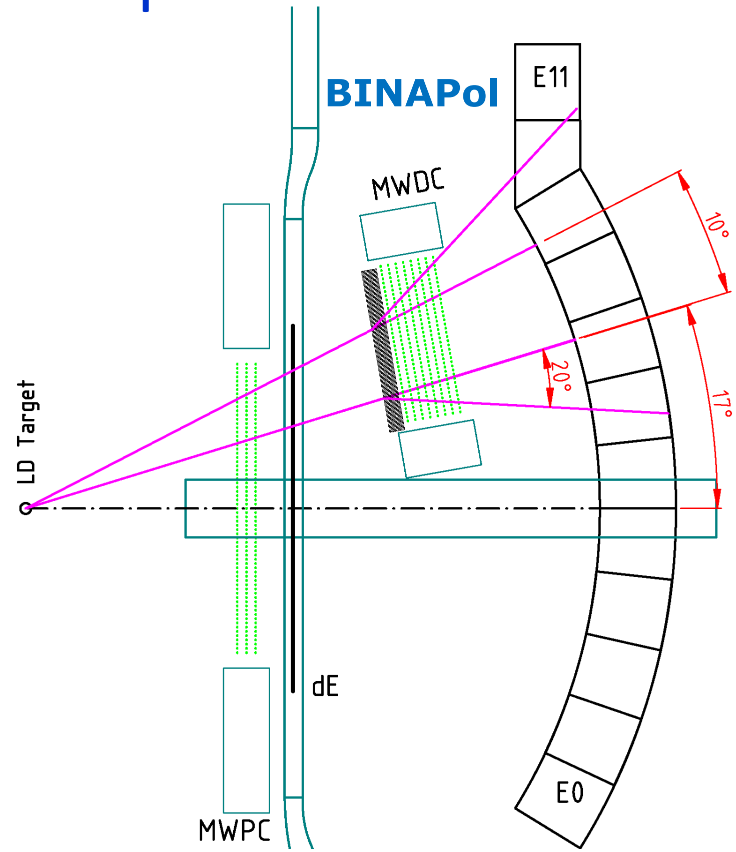
$P_Y \parallel (p_{beam} \times p_1)$
is parity even:
$P_Y(\xi,\varphi_{12}) = P_Y(\xi,-\varphi_{12})$



- BINA was originally designed for polarymetry - with adequate place and acceptance of the E detector
- First scattering: proton beam on deuteron, outgoing proton tracked in MWPC
  - pd elastic scattering for polarimeter calibration (single proton in Wall)
  - pd breakup (coincidence of two protons, polarization of one proton analysed)
- Second scattering: proton on Carbon, track of the scattered proton in MWDC

PROPOSAL: BINA equipped with polarimeter to measure the induced polarization





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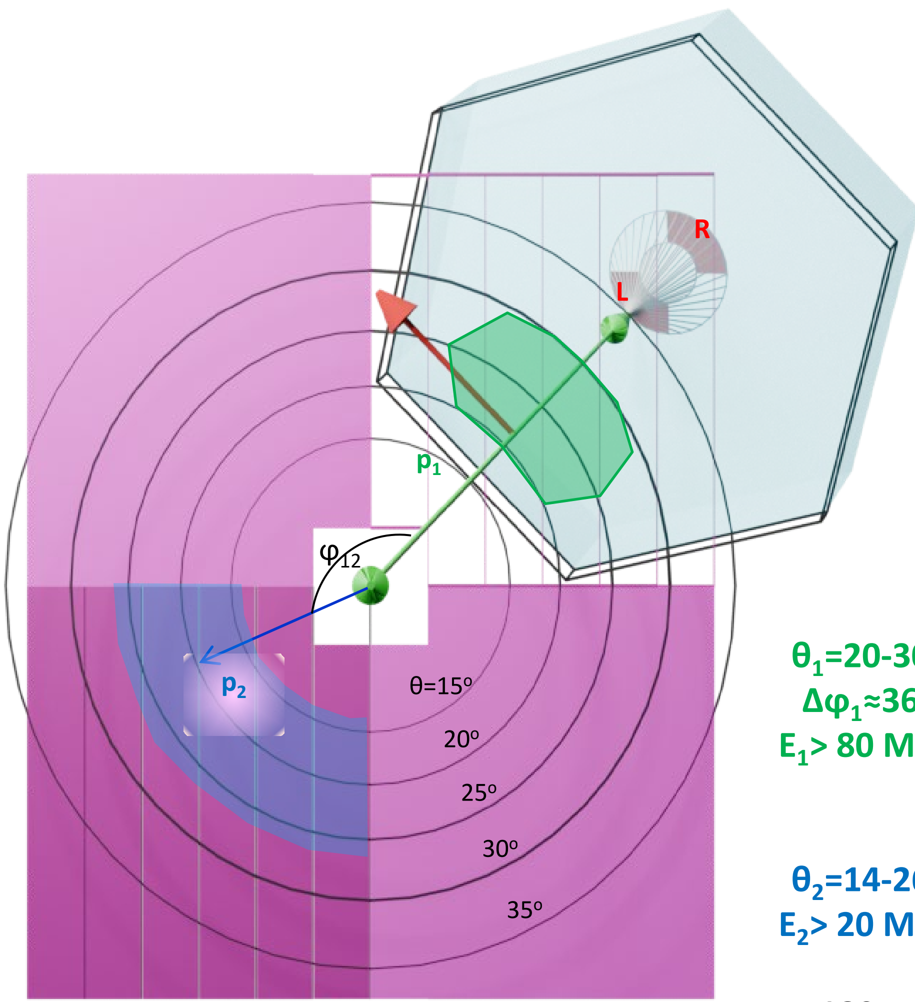
Measurement of P^y in $^2H(p,\vec{p}p)n$ breakup reaction in nearly coplanar configurations

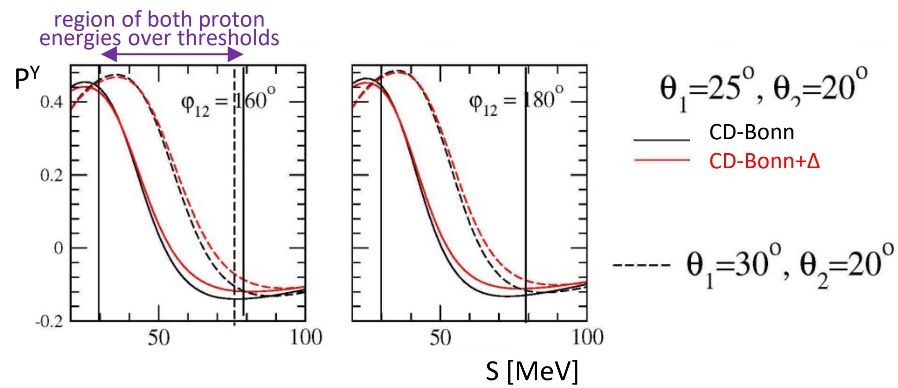


θ_1=20-30°
$\Delta\varphi_1$≈36°
E_1> 80 MeV

θ_2=14-26°
E_2> 20 MeV

φ_{12}=180°+/-20°

Theoretical calculations by A.Deltuva (150 MeV)



Coincidence of two protons registered in diagonal sectors of the BINA Wall:

first proton in the BINAPol
(after pC scattering, both L and R segments are within the BINAPol acceptance)

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

second proton – in the left-bottom sector

Thank you for your attention !

UNIWERSYTET JAGIELLOŃSKI W KRAKOWIE

UNIWERSYTET ŚLĄSKI W KATOWICACH

UNIWERSYTET WARSZAWSKI

KVI-CART

WASA@COSY