Experimental Studies of Few-Body Interactions

Dynamics of few-body interactions studied in new-generation experiments

Stanisław Kistryn

Jagiellonian University

Kraków, Poland

COMEX5

The 5th International Conference on
"COLLECTIVE MOTION IN NUCLEI UNDER EXTREME CONDITIONS"

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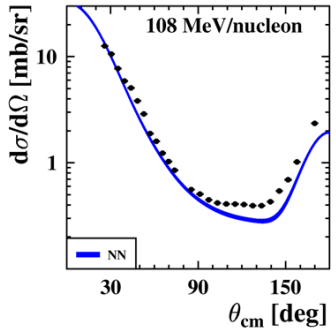
Nucleon-Nucleon Interaction
Basis of Nuclear Physics

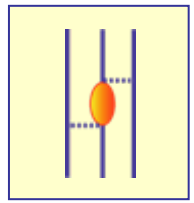
Modern NN potentials are in general able to

- 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

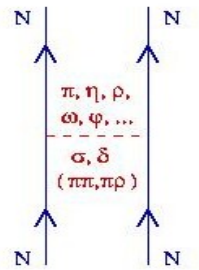
- Three-nucleon system is the simplest **non-trivial** environment to test predictions of observables obtained on the basis of NN potential models



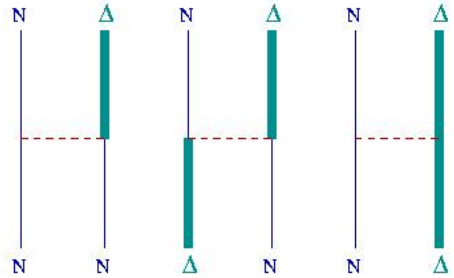
- Introducing concept of **three-nucleon forces**: genuine (irreducible) interaction of all three nucleons



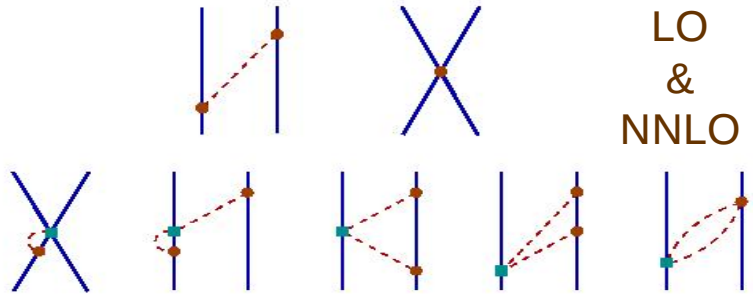
Three-Nucleon System
Standard Interaction Models



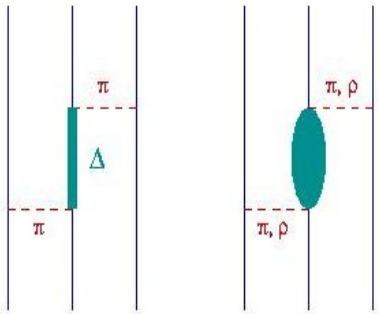
Realistic **P**otentials
CD Bonn, Nijm, AV



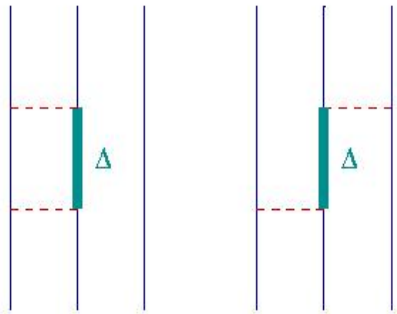
Coupled-**C**hannels
Potential (single Δ)

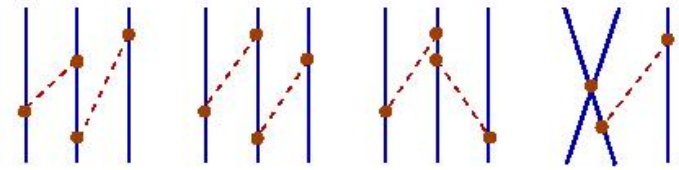


Chiral **P**erturbation **T**heory
(2π exchanges & contact terms)

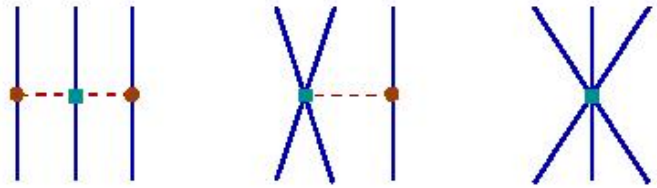


TM99 3NF





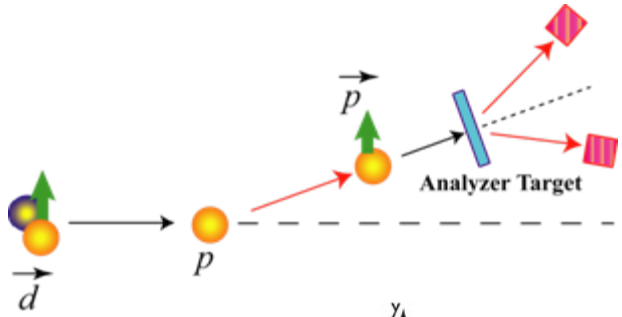
NLO: all contributions cancel out !

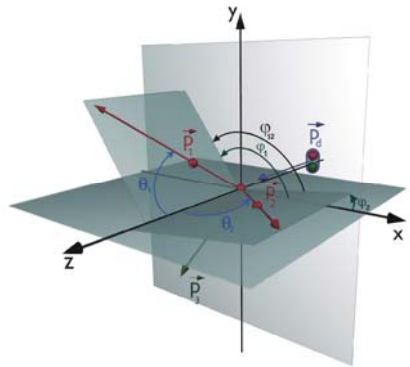


NNLO: three possible topologies

Three-Nucleon Scattering at Medium Energies

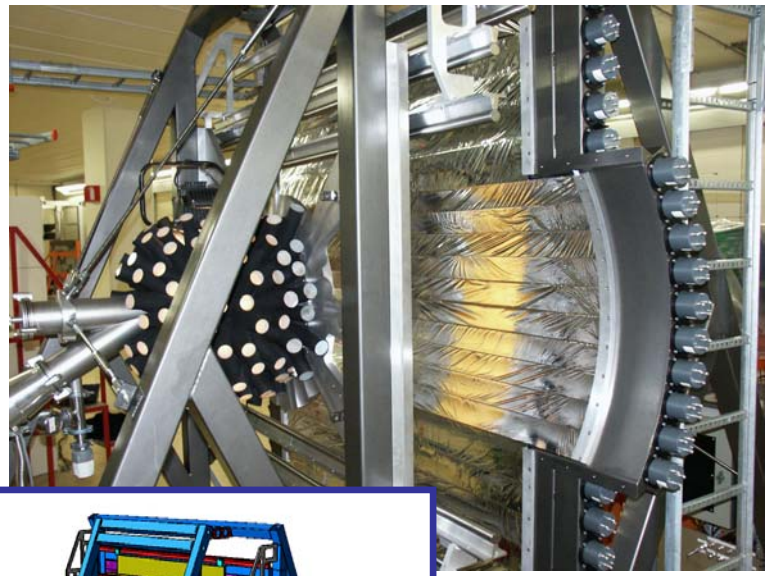
- Elastic: N + d → N + d
  - Beams of p or d
  - Various observables
- Breakup: N + d → N + N + N
  - Beams of p or d
  - Various observables
- Different effects to be traced
  - Comparisons between channels
  - Influences of 3NF
  - Coulomb force action
  - Relativistic effects

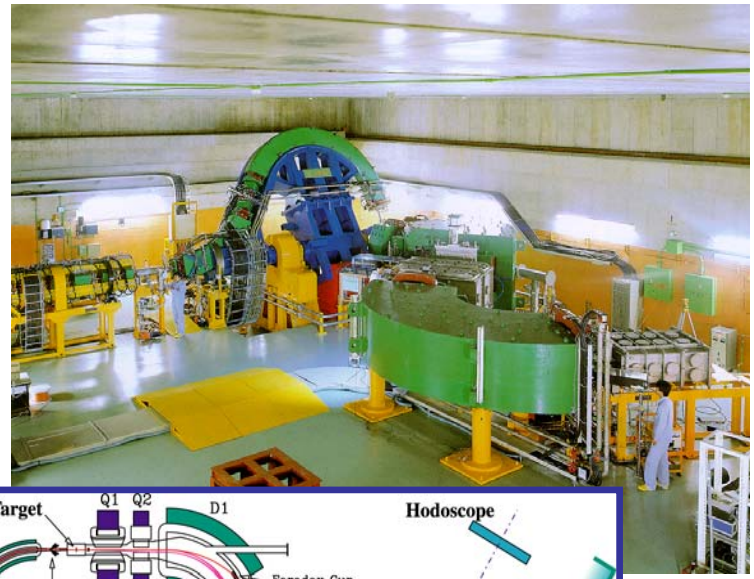


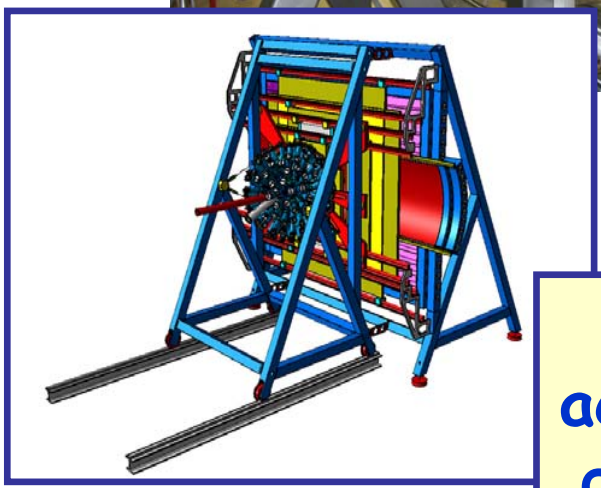


… and their interplay !

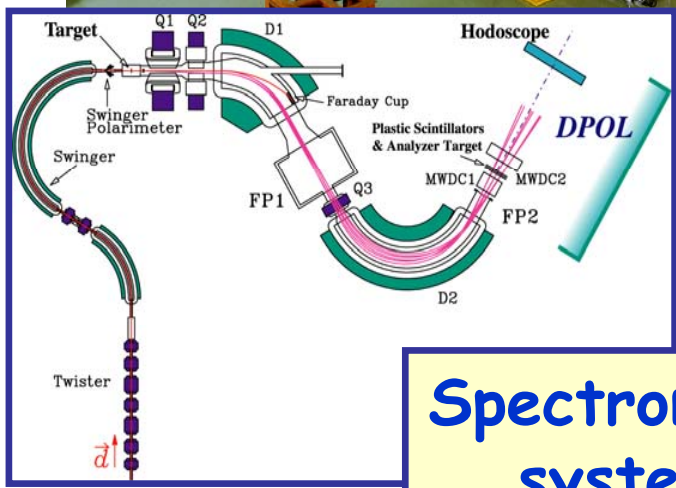
Experimental Tools of Few-Nucleon Physics







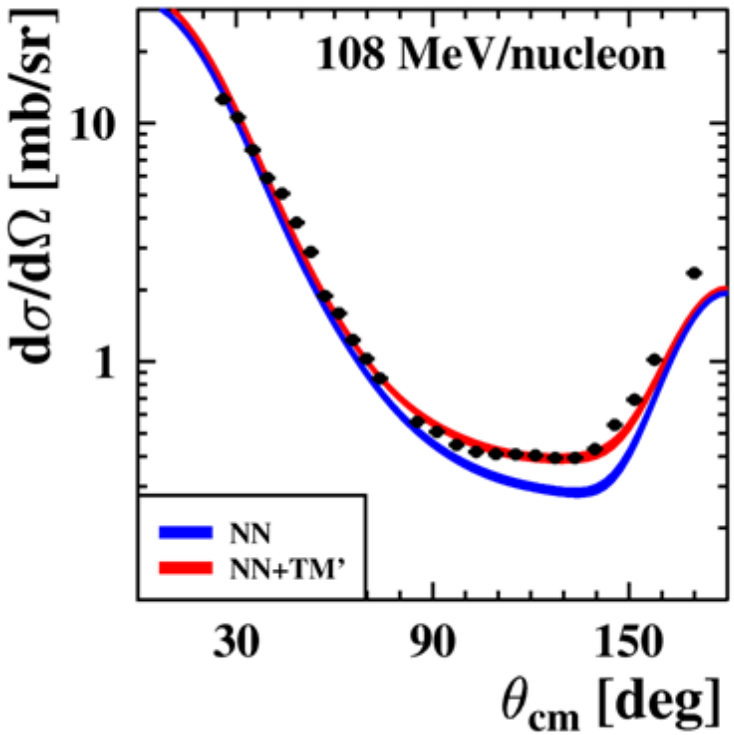
Large acceptance detectors

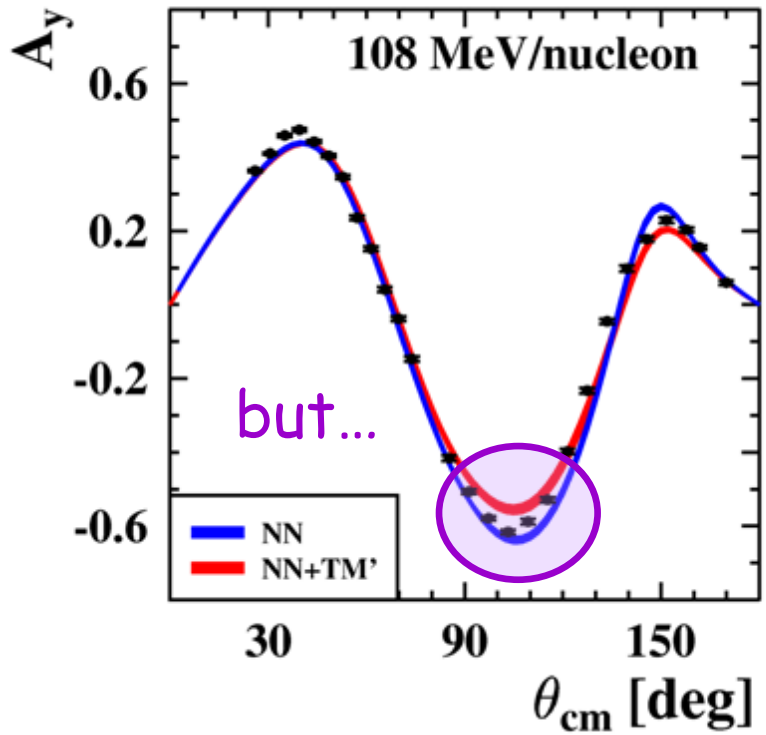


Spectrometer systems

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.



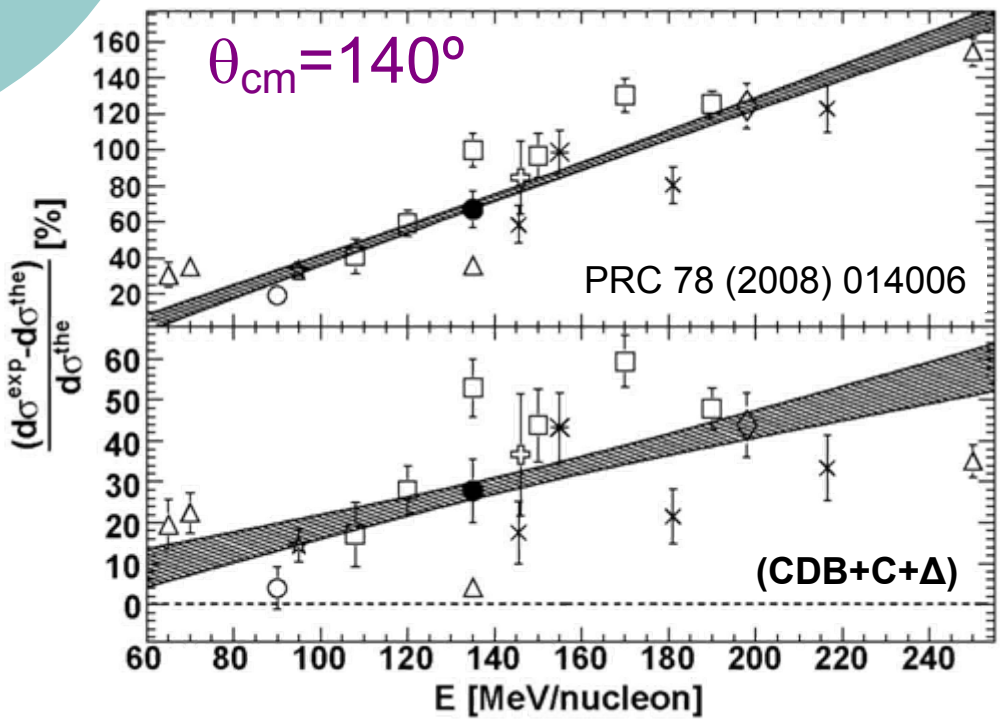


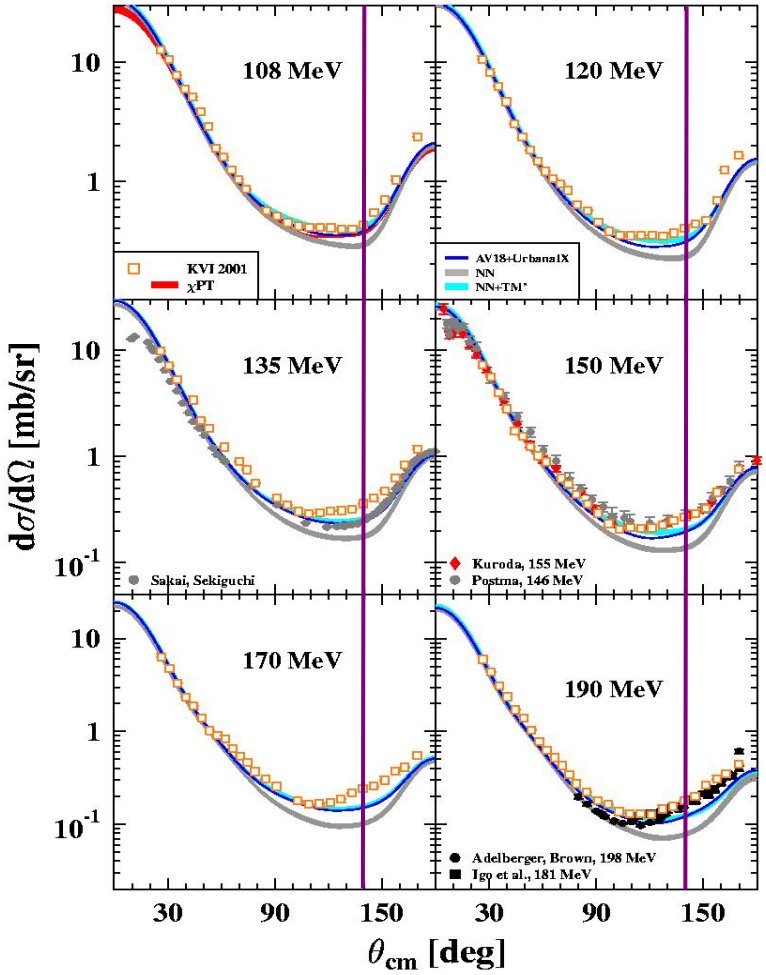
K. Ermisch *et al.*, Phys. Rev. C **71** (2005) 064004

3NF Effects
Elastic Nucleon-Deuteron Scattering

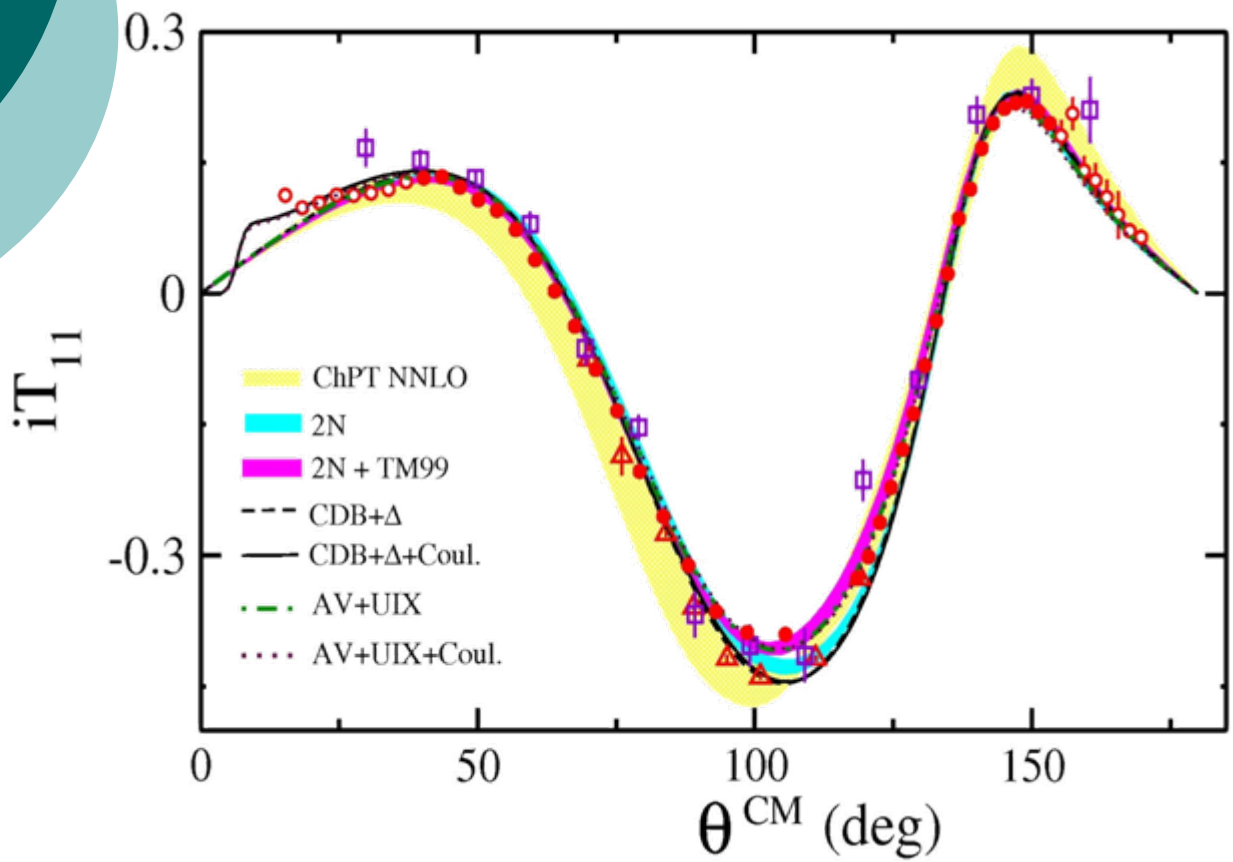
3NF help

alas, not completely



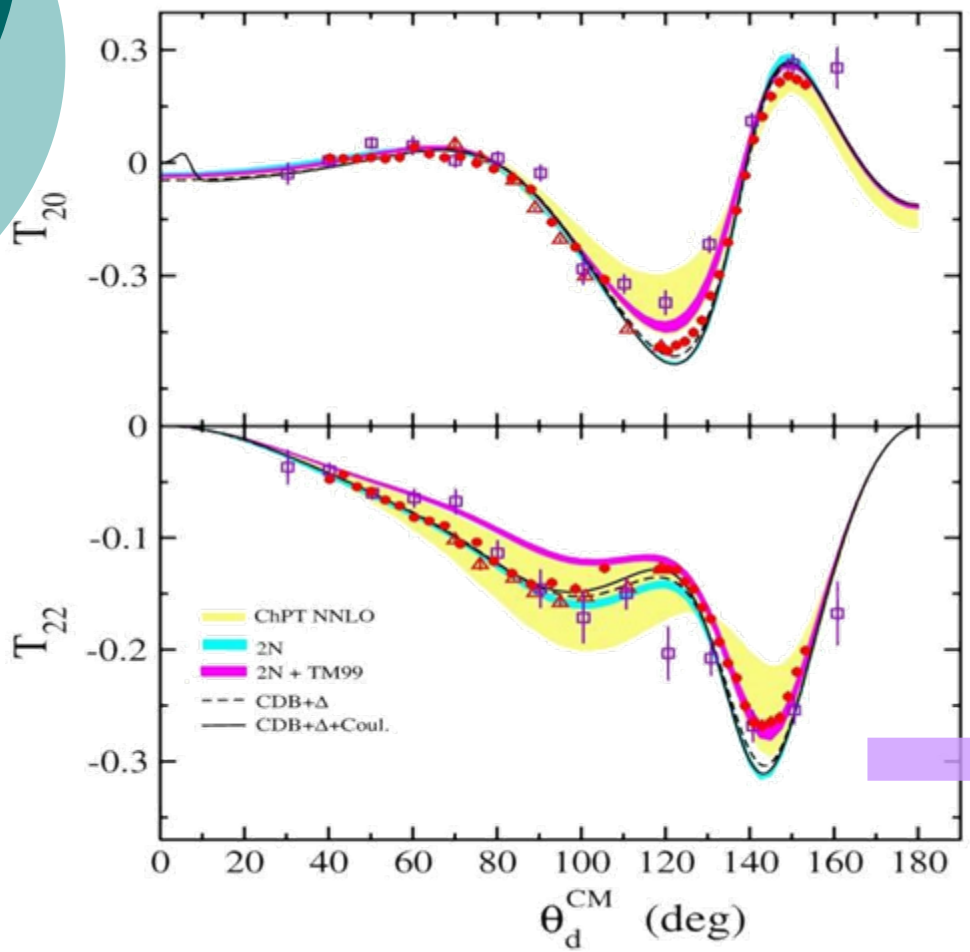


3NF Effects
Elastic Deuteron-Nucleon Scattering

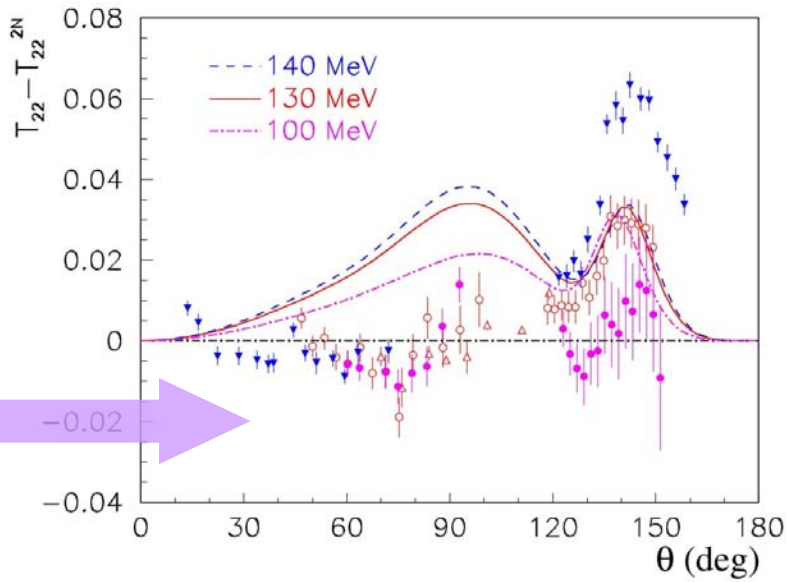


- E. Stephan et al., Phys. Rev. C 76, 057001 (2007)
- GeWall @ COSY
- H. Mardanpour et al., Eur. Phys. J. 31, 383 (2007)
- H. Witała et al., Few-Body Systems 15, 67-85 (1993)

3NF Effects
Elastic Deuteron-Nucleon Scattering



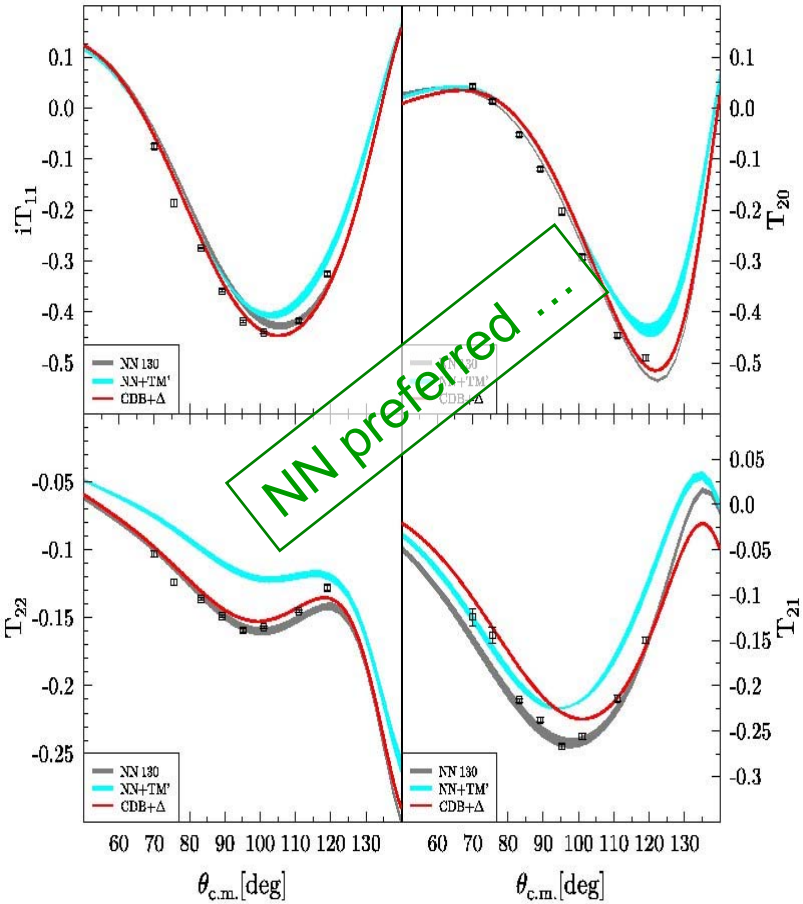
Different energy dependence of T_{22} data and theory in angular regions



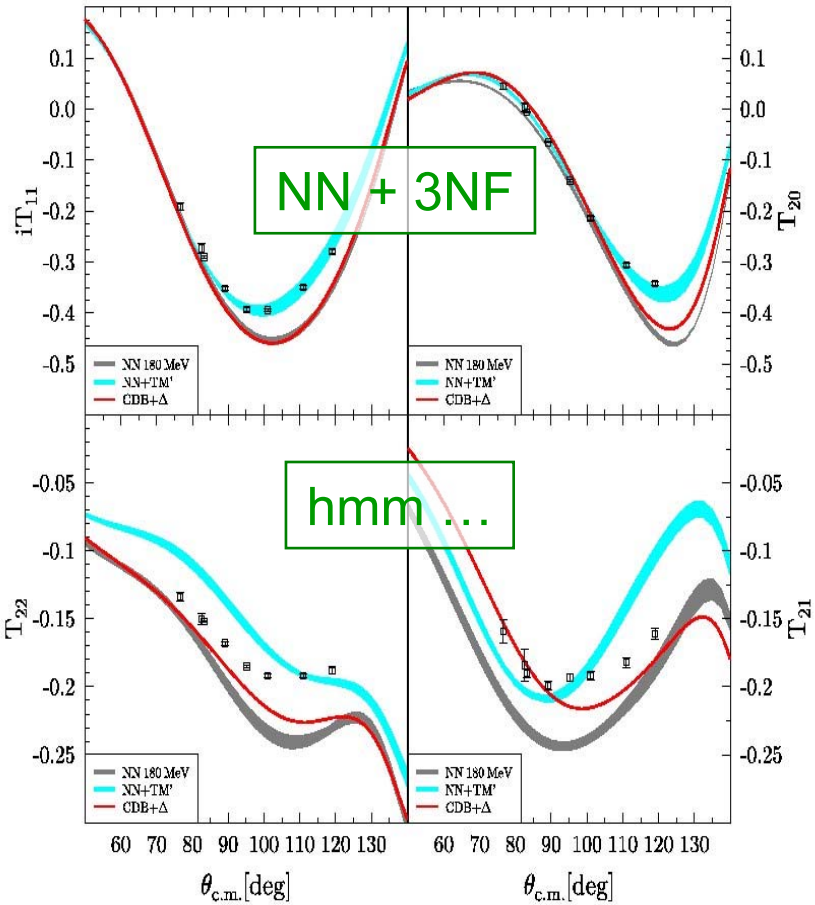
3NF Effects
Elastic Deuteron-Nucleon Scattering

H. Mardanpour *et al.*, *Eur. Phys. J. A* **31** (2007) 383

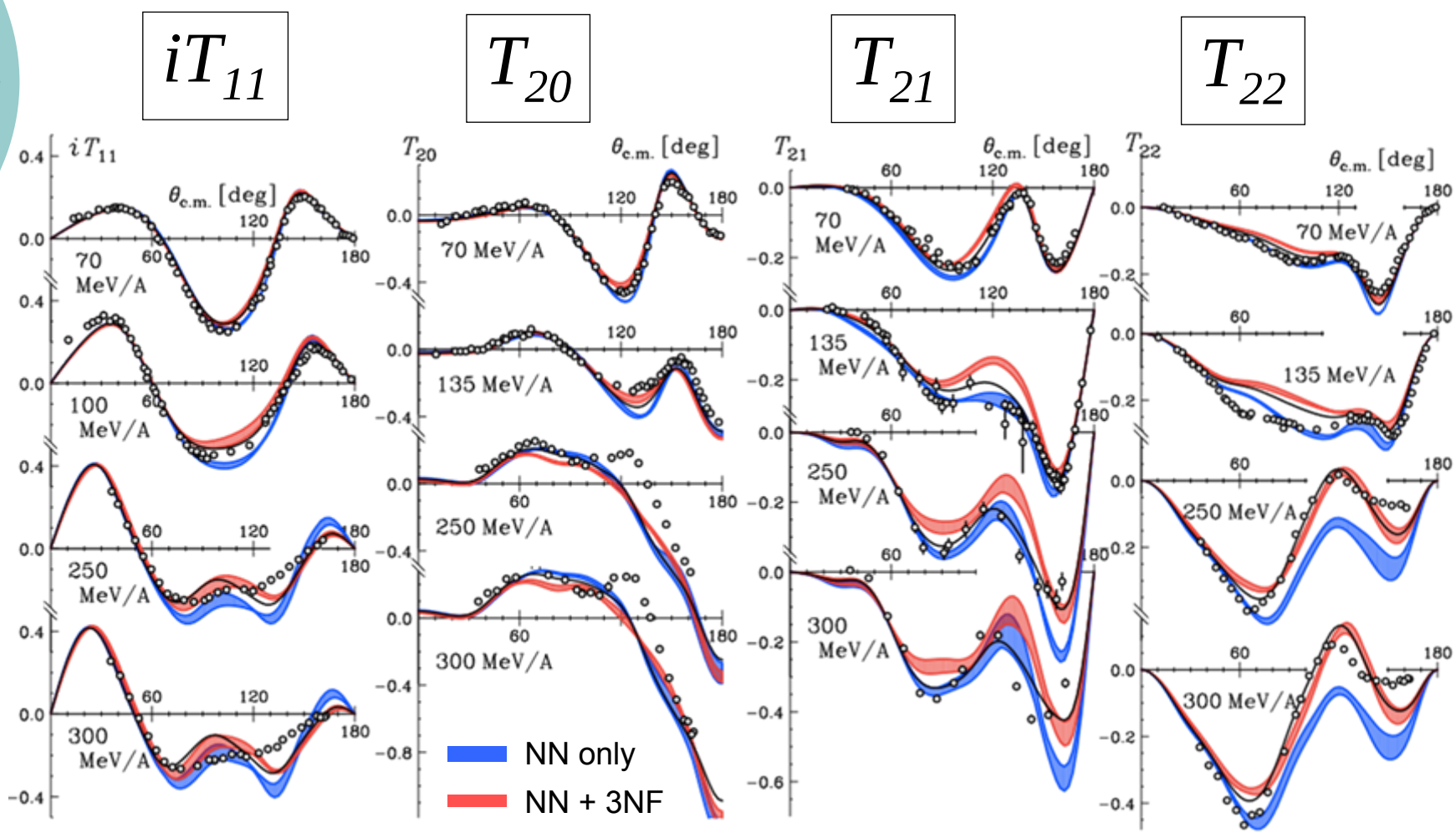
65 MeV/A



90 MeV/A



3NF Effects
Elastic Deuteron-Nucleon Scattering

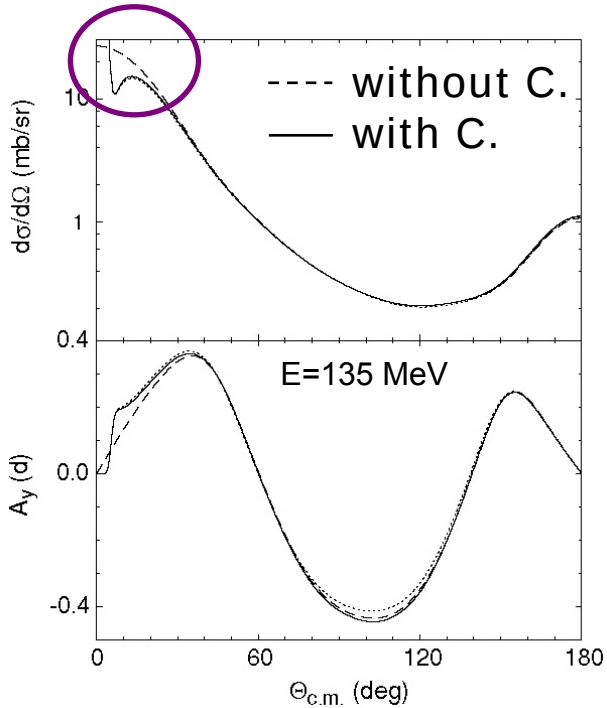


K. Sekiguchi *et al.*, *Phys. Rev. C* **83** (2011) 061001

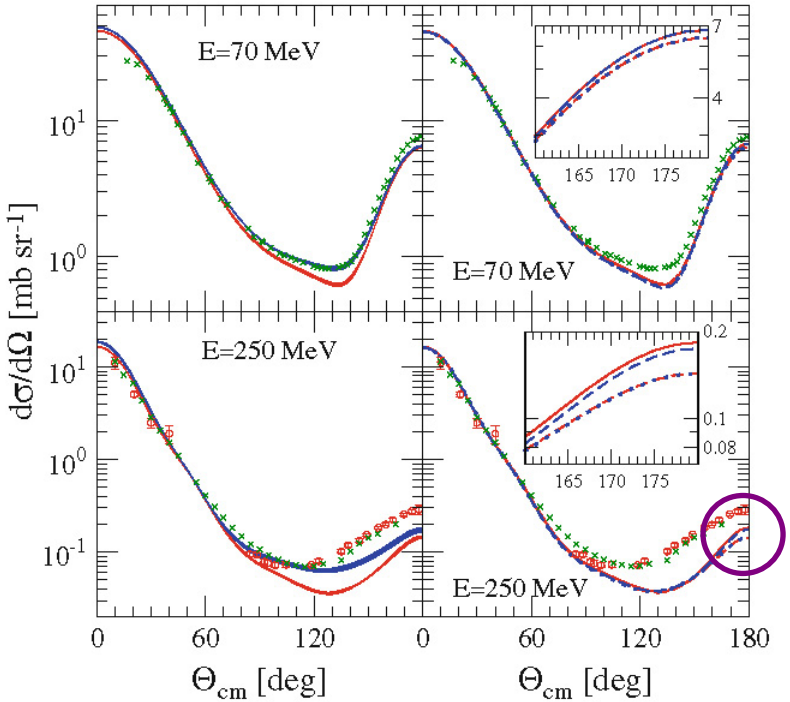
More Dynamical Effects ?
Coulomb force and relativity

Predictions for the N-d elastic scattering

Coulomb



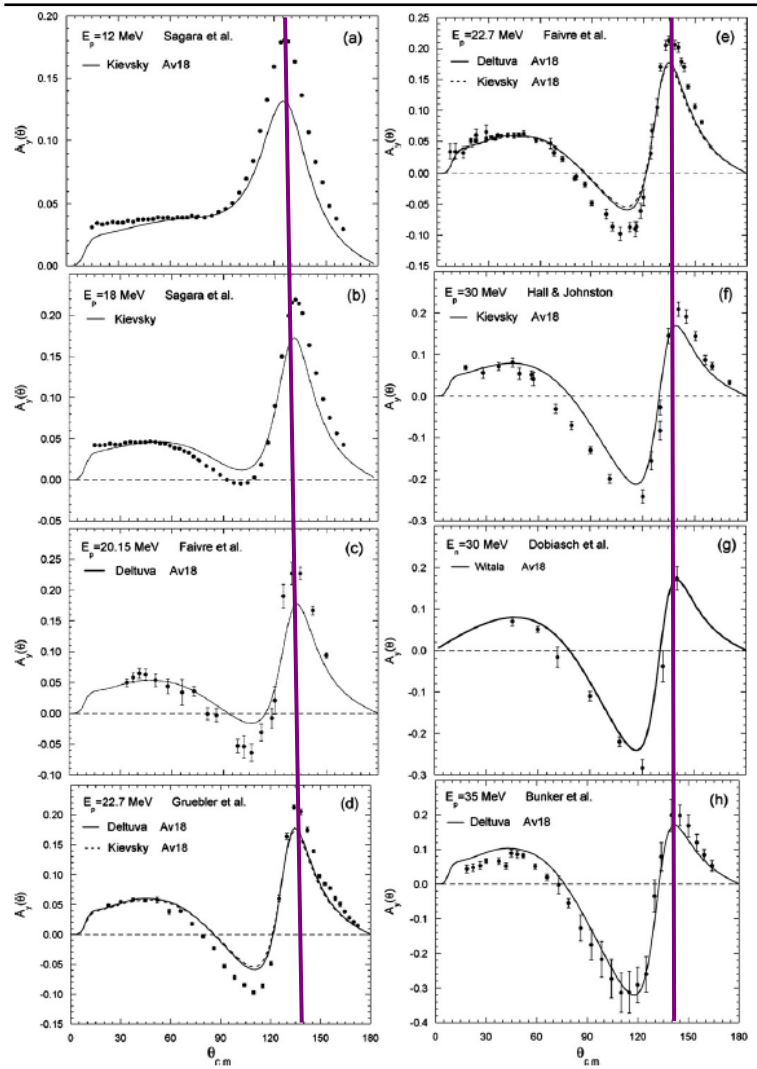
3NF relativity

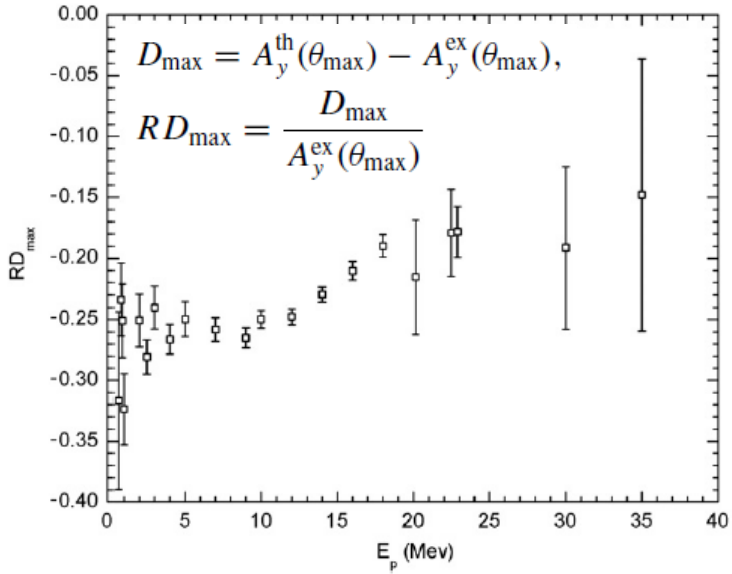


Effects small, located at extreme angles only !

Persistent A_y Puzzle at Low Energies Elastic Nucleon-Deuteron Scattering

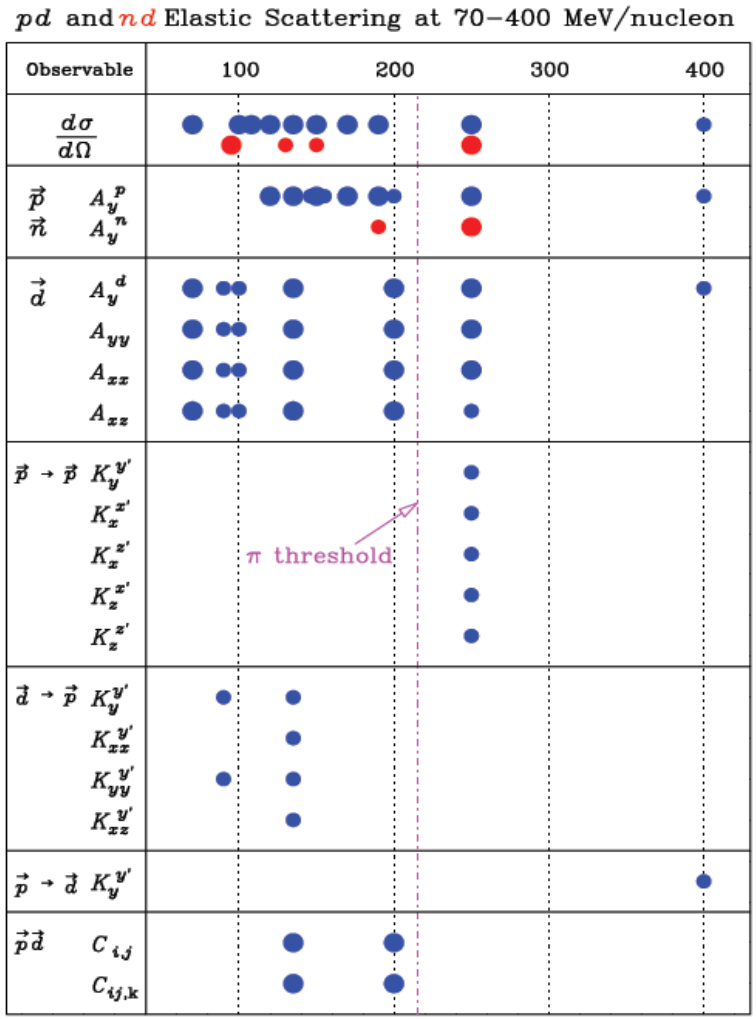
W. Tornow et al., J. Phys. G **35** *(2008) 125104*
G.J. Weisel et al., J. Phys. G **42** *(2015) 085106*





Energy-dependent discrepancy between measured and calculated analyzing power values (both p-d and n-d), not accounted by 3NF nor by P-waves modif.

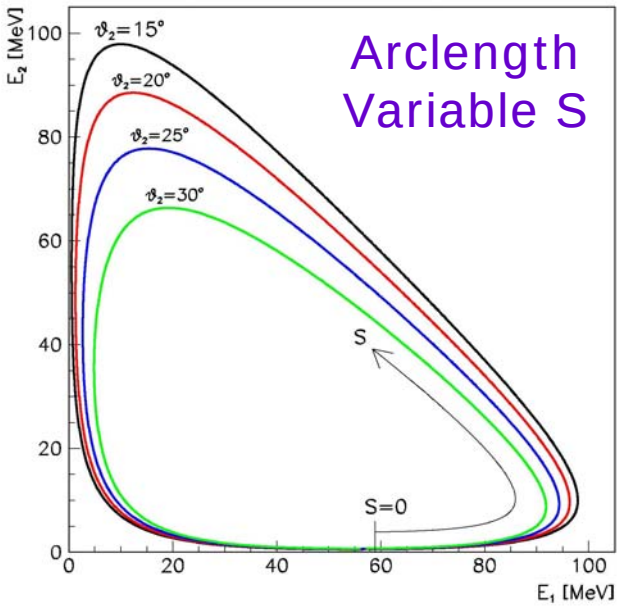
3N Systems
Elastic N-d Scattering

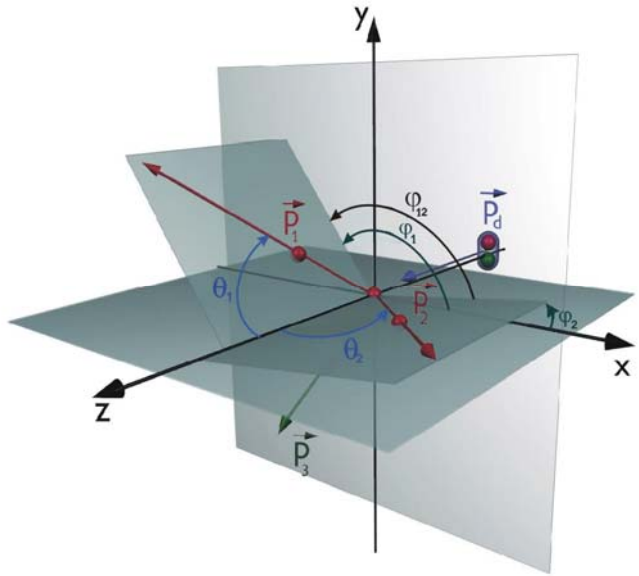


- Number of observables for the **elastic scattering channel**, allowing a multi-dimensional study of 3NF and other effects
- **Only fraction** has been measured accurately and systematically (RIKEN/RCNP/IUCF/KVI)
- Not completely clear picture - still much to explore !
- Complementary studies needed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

N-d Breakup Reaction

- 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





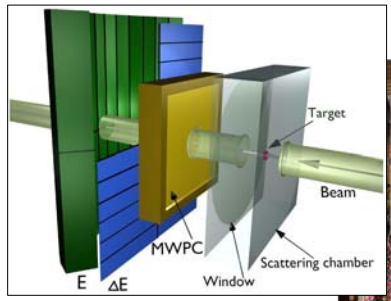
^{1}H(d,pp)n
measured:
directions and energies of two protons, i.e.
θ_1,φ_1,E_1
θ_2,φ_2,E_2

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

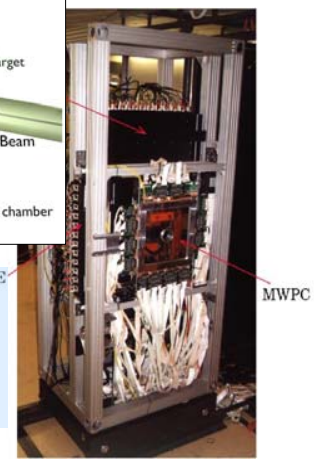
Cross Section and Analyzing Power Results

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

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

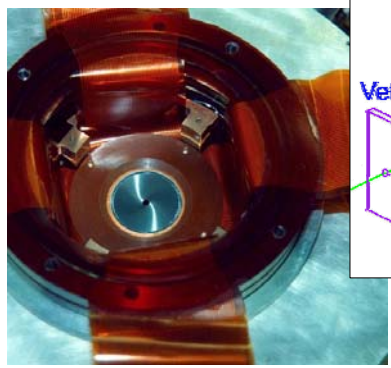


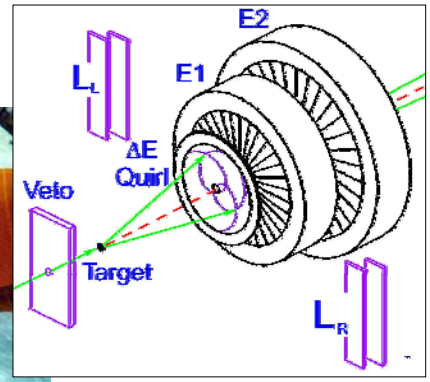
SALAD



KVI Groningen

FZ Jülich

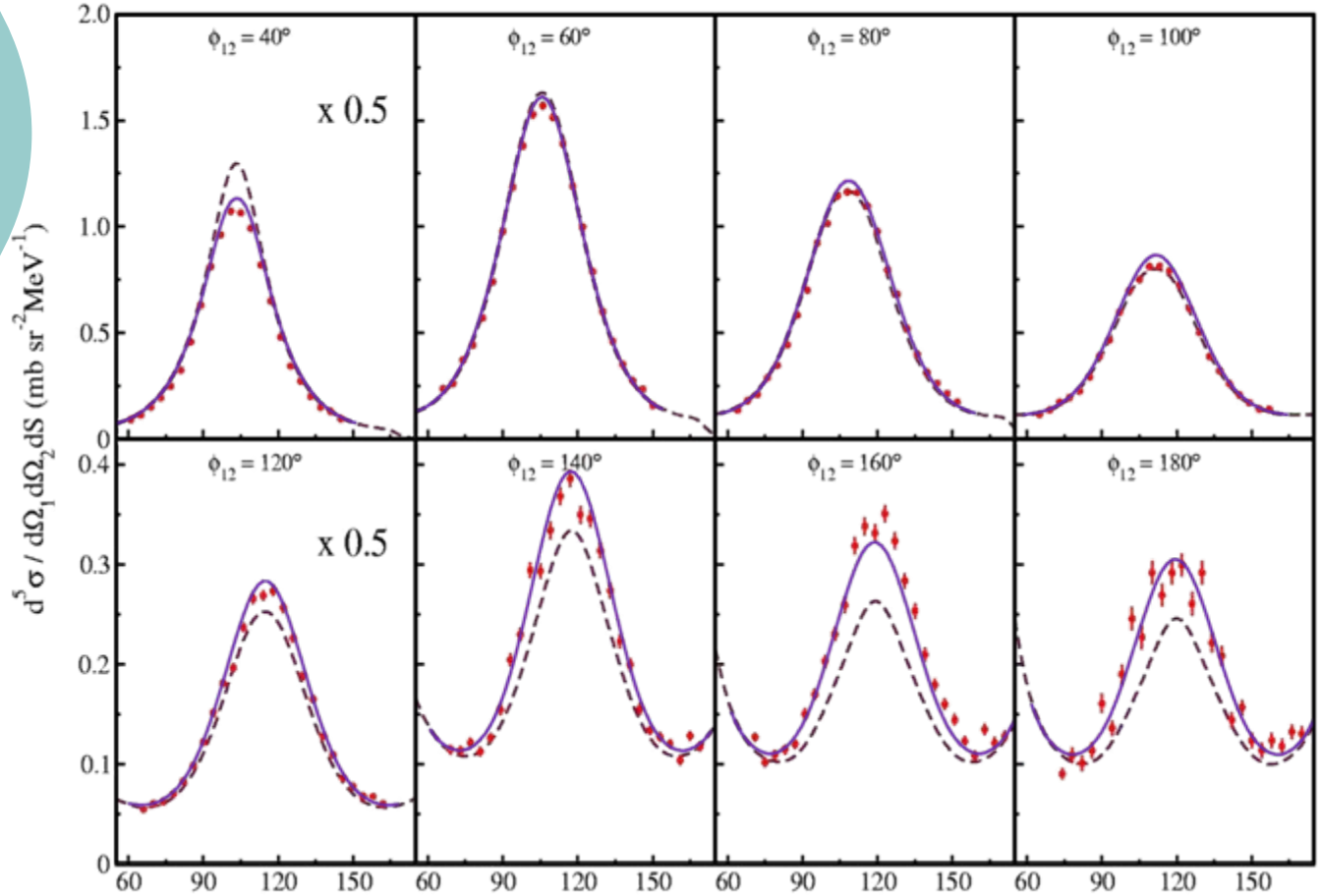




GeWall

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

Cross Section Results – Discrepancies Cured



$\theta_1, \theta_2 = 15°, 15°$

Coupled Channel calculations

CDB + Δ

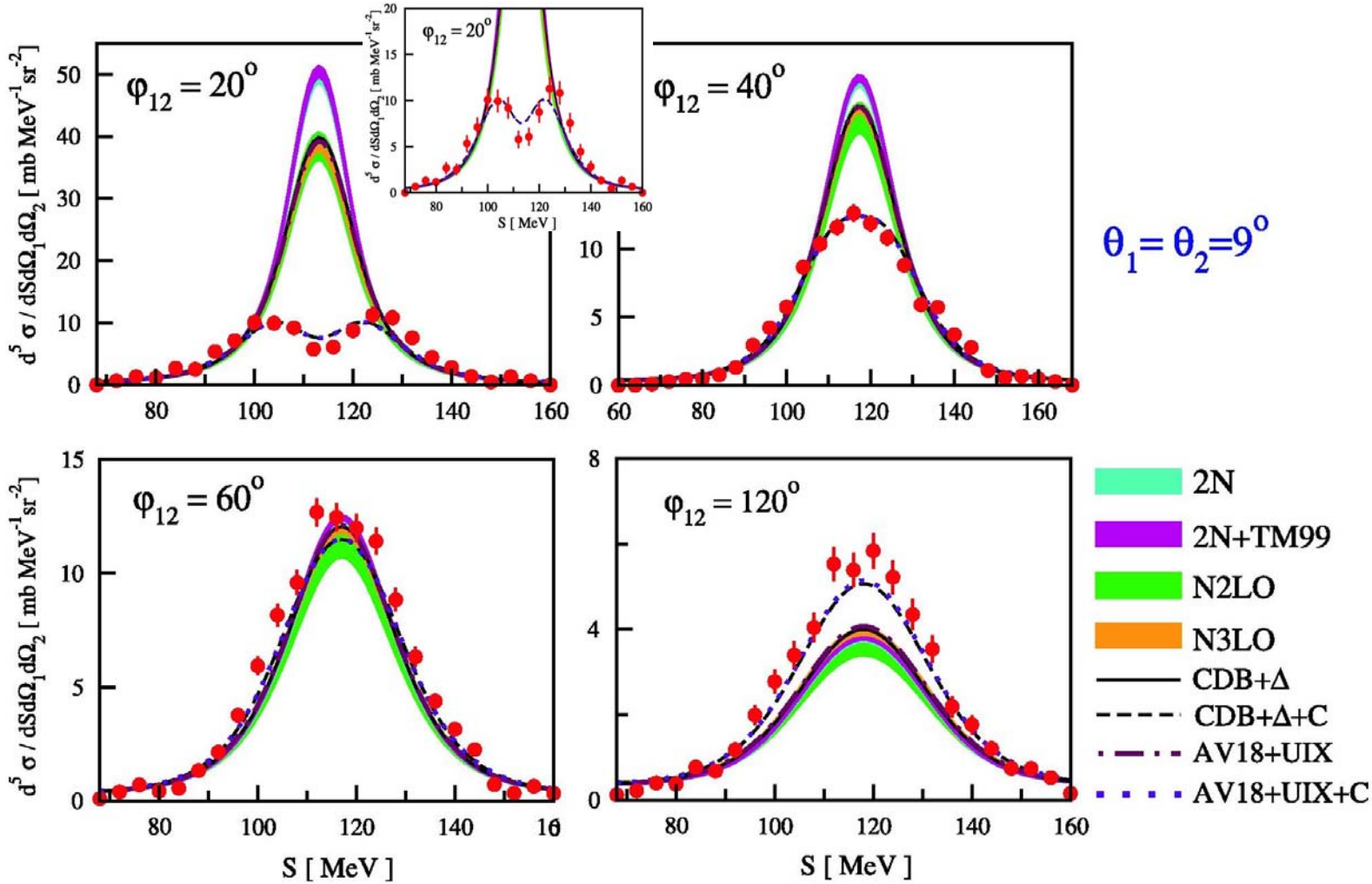
CDB + Δ + C

Coupled Channel calculations with Coulomb effects

Predictions with Coulomb reproduce data much better !

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

Cross Section Results – Examples



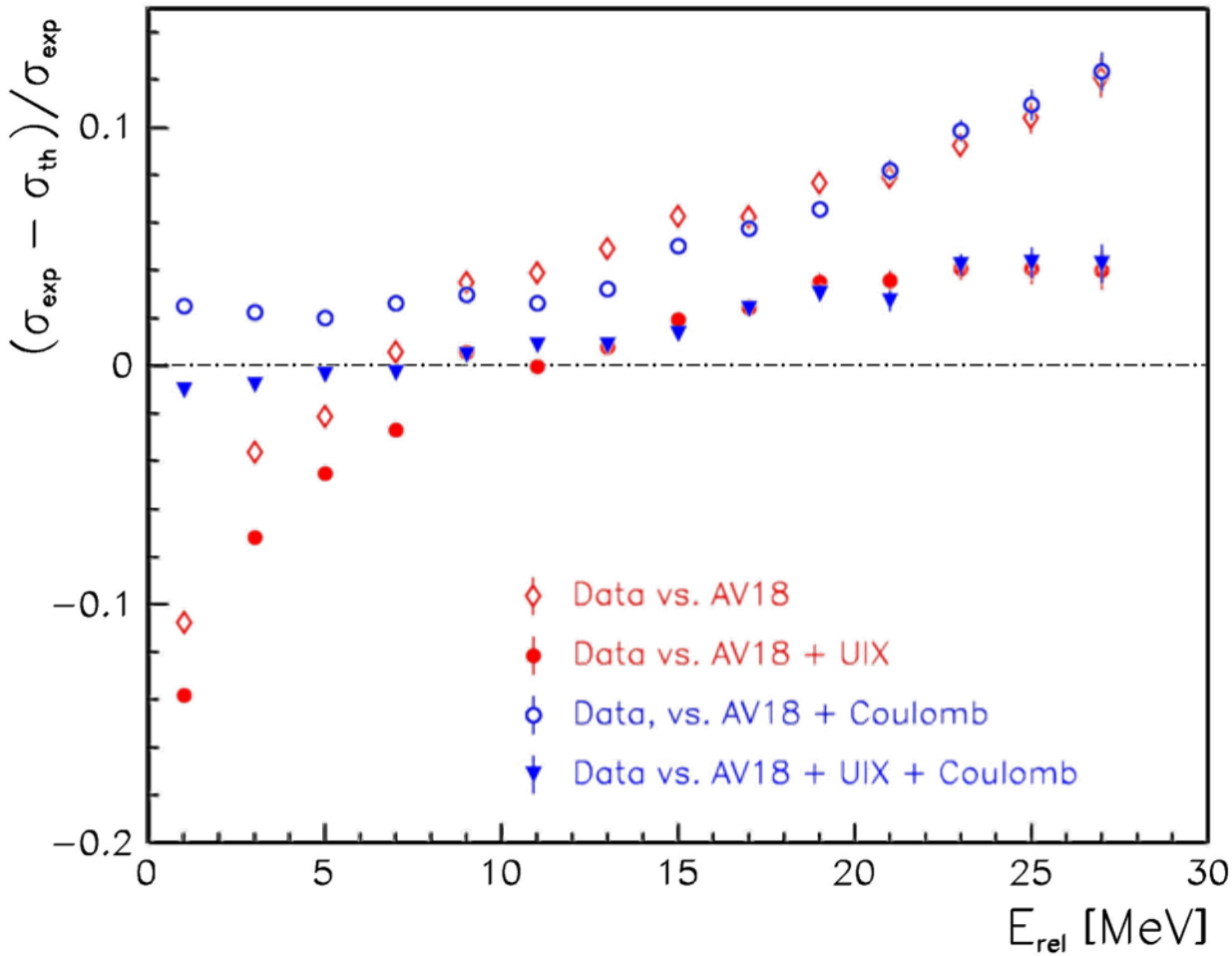
St. Kistryn *et al.*, *Phys. Proc.* **17** (2011) 126

$^1H(\vec{d},pp)n$ 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 !



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

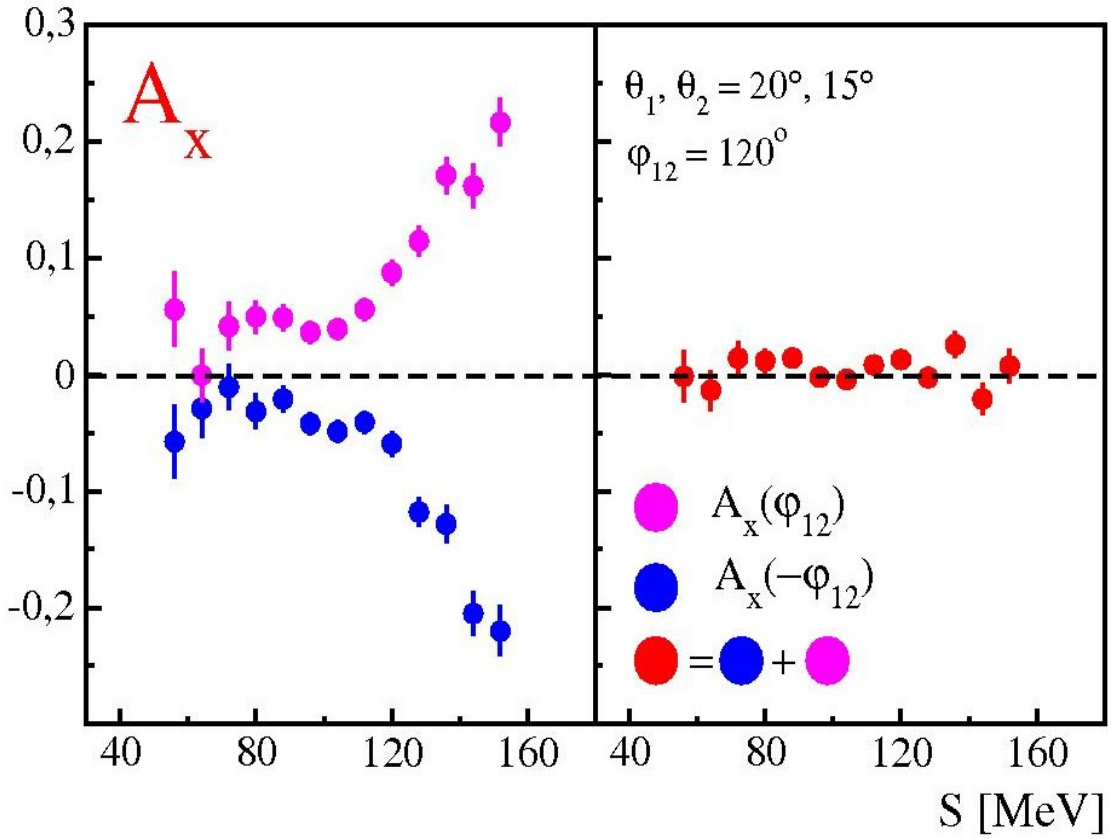
Analyzing Power Results – Parity Test of Data

Parity symmetry

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

$\mu = 1$ for $\beta = x, xy$

$\mu = 0$ for $\beta = y, xx, yy$



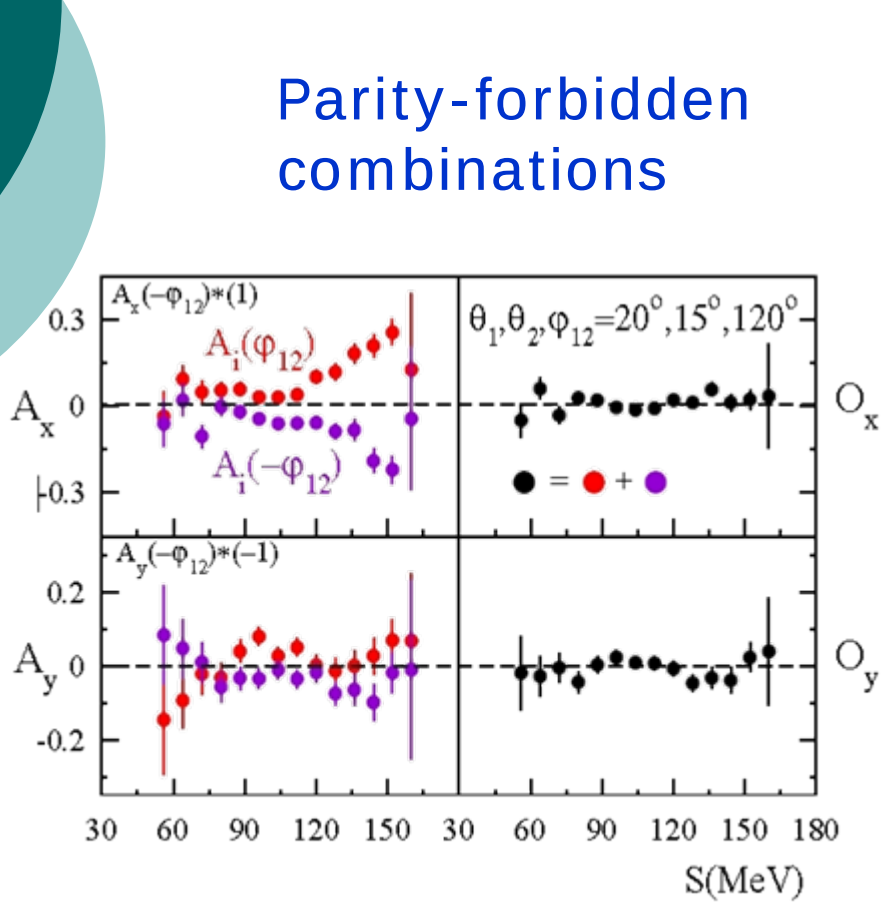
Parity-forbidden combinations

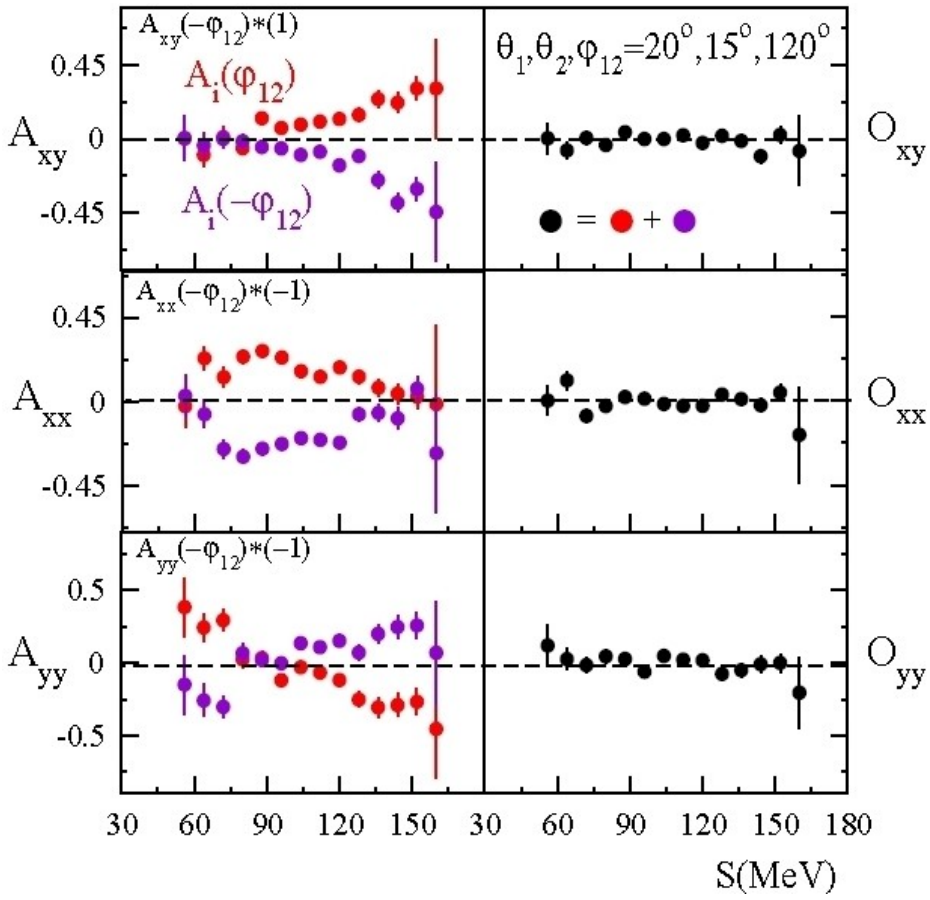
$$O_\beta(\varsigma',\varphi_{12}) = A_\beta(\varsigma',\varphi_{12}) + (-1)^{1-\mu} \bullet A_\beta(\varsigma',-\varphi_{12})$$

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

Analyzing Power Results – Parity Test of Data

Parity-forbidden combinations





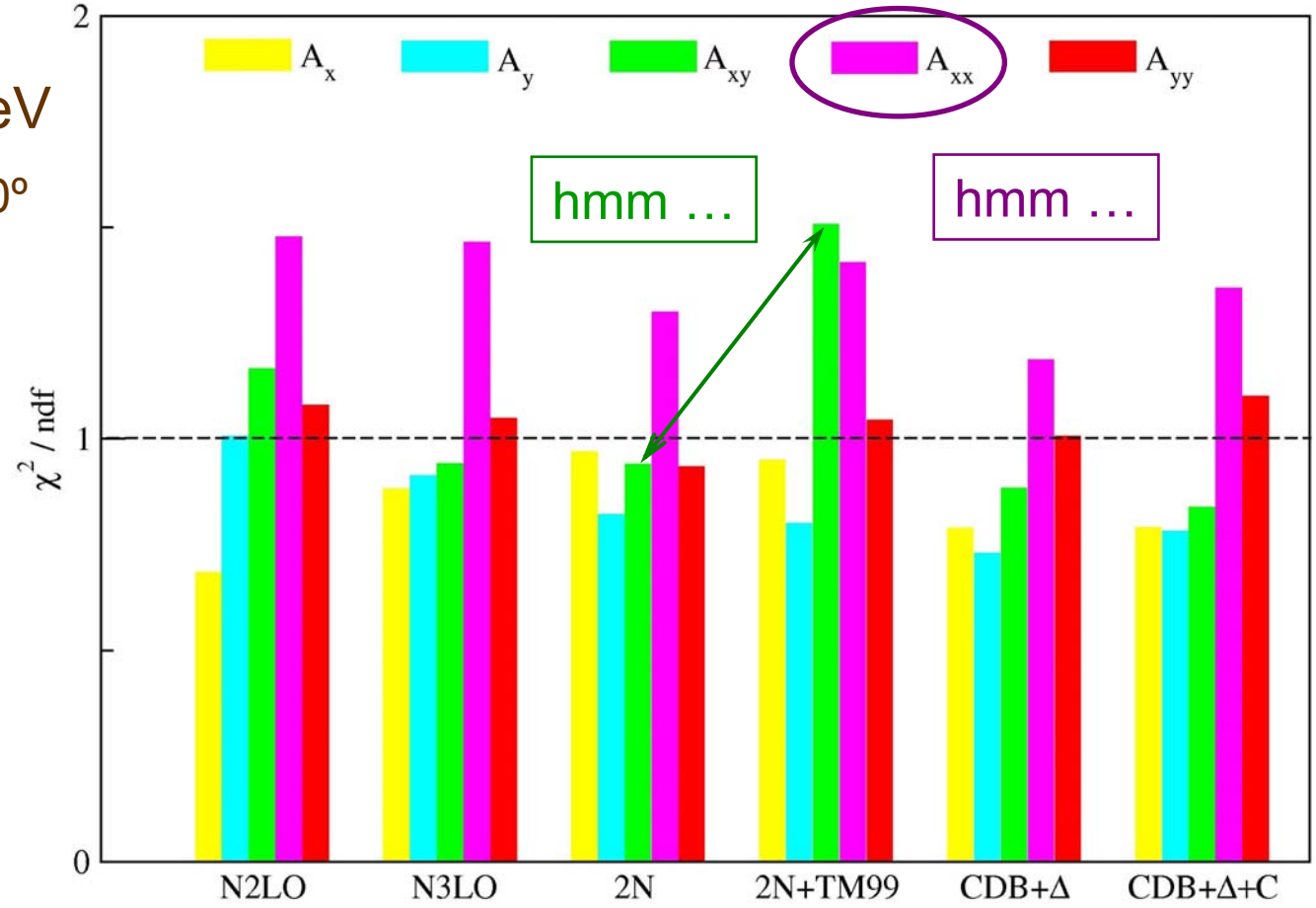
$$O_\beta(\varsigma',\varphi_{12}) = A_\beta(\varsigma',\varphi_{12}) + (-1)^{1-\mu} \bullet A_\beta(\varsigma',-\varphi_{12})$$

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

Analyzing Power Results

E_d = 130 MeV

θ_1,θ_2 = 15° - 30°



$$\frac{1}{N}\sum_{i=1}^{N\approx900}\frac{[A^{exp}(\varsigma_i)-A^{th}(\varsigma_i)]^2}{[\delta A^{exp}(\varsigma_i)]^2}$$

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

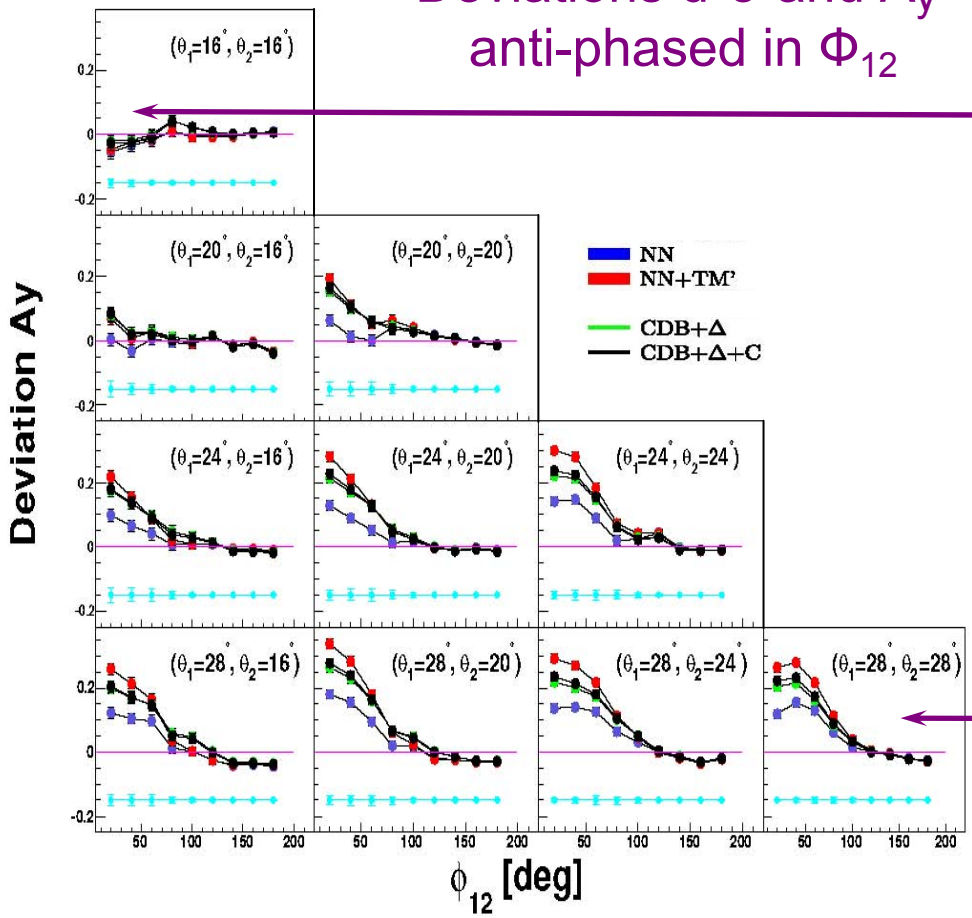
$^2H(\vec{p},pp)n$ Breakup Reaction
Analyzing Powers vs. Cross Sections

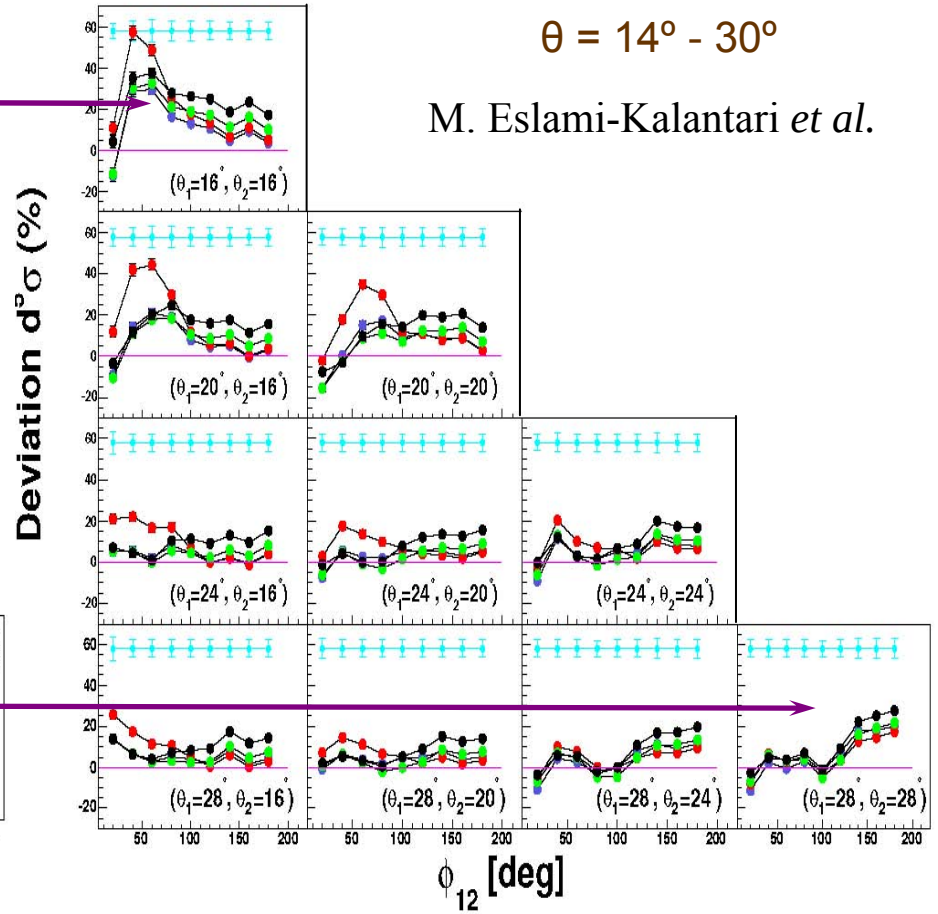
Deviations $d^5\sigma$ and A_y anti-phased in Φ_{12}

E_p = 135 MeV

θ = 14º - 30º

M. Eslami-Kalantari *et al.*

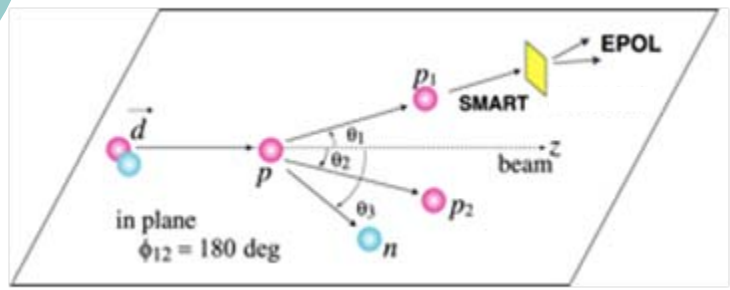




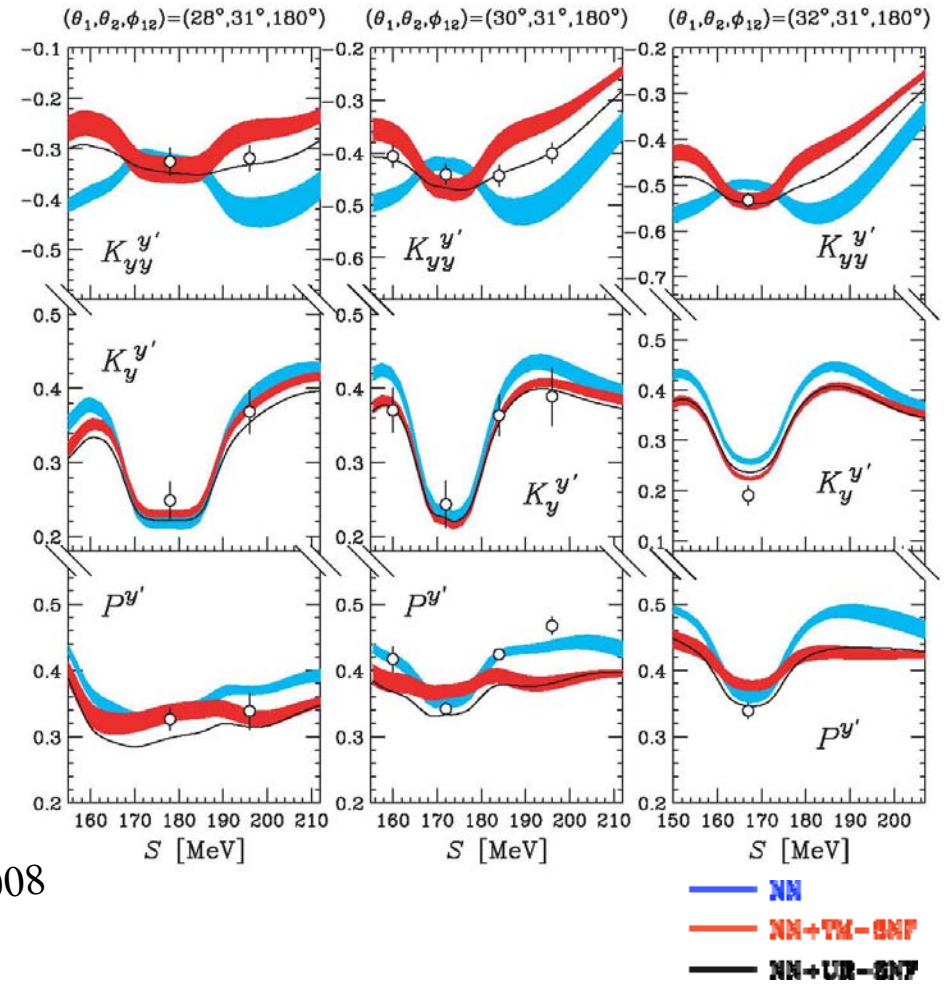
$^1H(\vec{d},pp)n$ Breakup Reaction
Polarization Transfer Coefficients

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

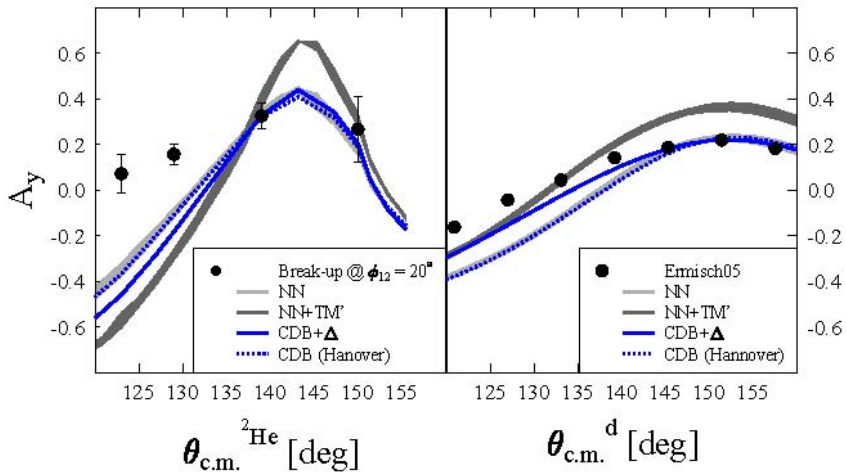
^{2}H(p,pp)n vs. ^{2}H(p,d)p
Spin-Isospin Selectivity

E_p = 190 MeV

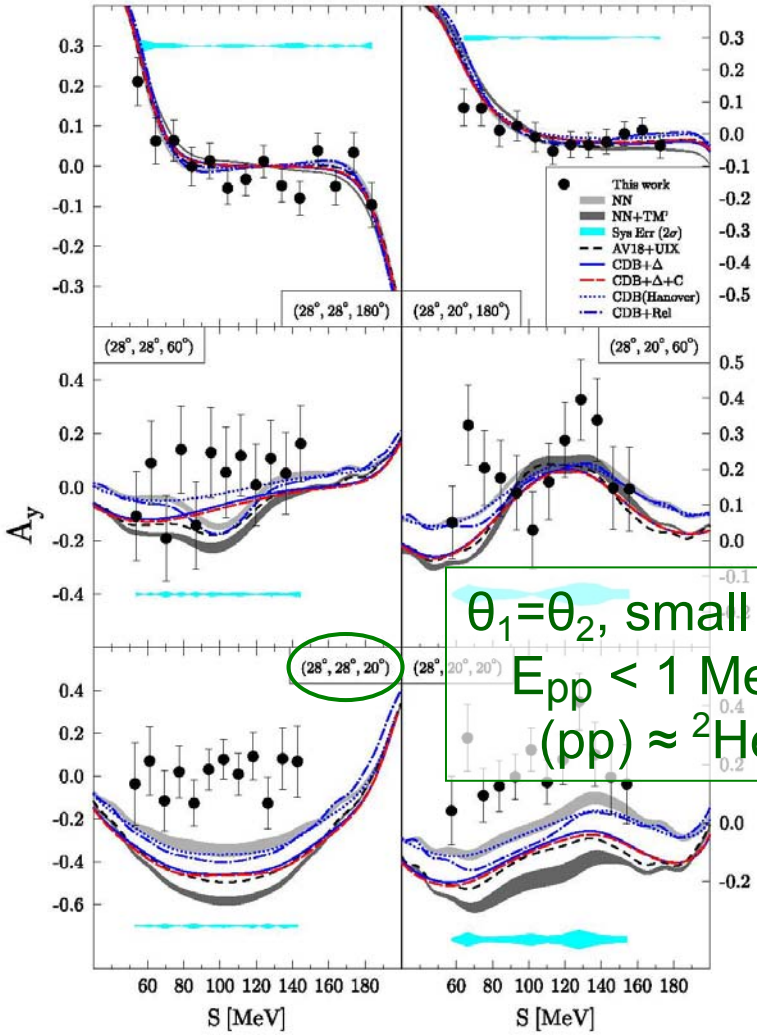
θ = 14° - 30°

H. Mardanpour *et al.*,
Phys. Lett. B **687** (2010) 149

$^2\vec{H}(\vec{p},^2He)n$ $^2\vec{H}(\vec{p},^2H)p$

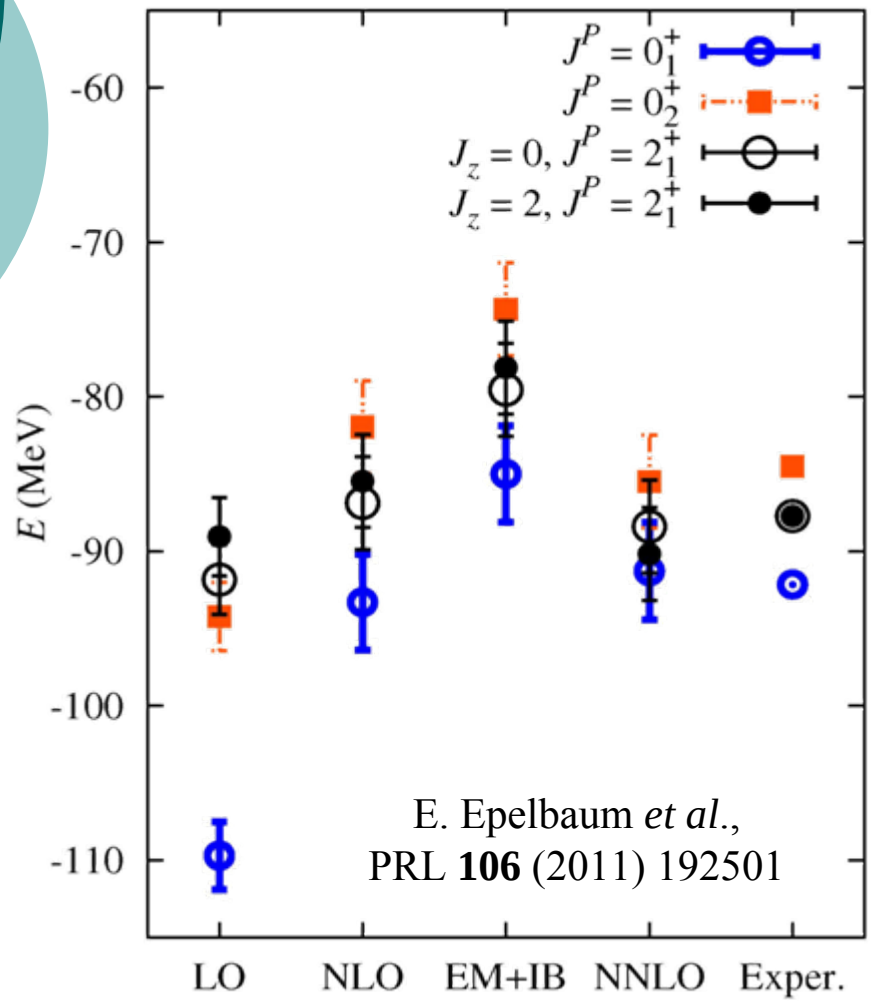


I_f = 1/2, 3/2 I_f = 1/2



$\theta_1=\theta_2$, small φ_{12}
E_{pp} < 1 MeV
(pp) ≈ ^{2}He

3NF + Coulomb Effects
Hoyle State of ^{12}C

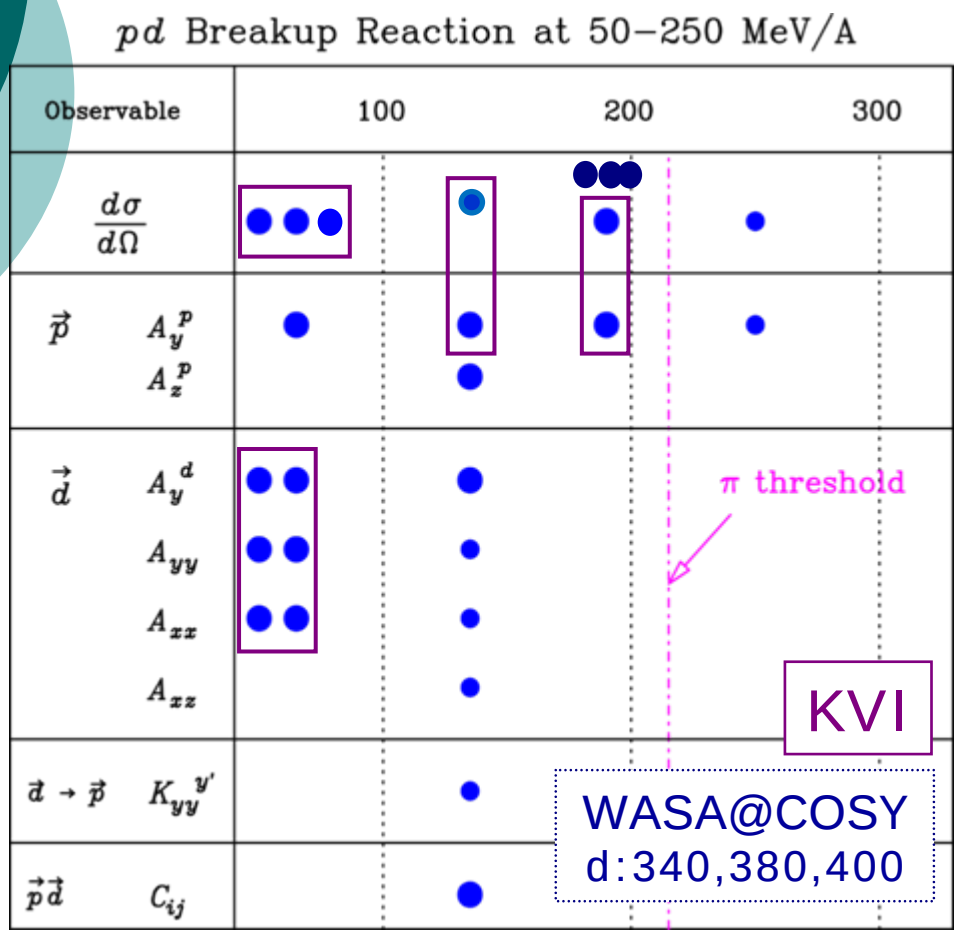


State of ^{12}C enabling the process of fusion $3\alpha \rightarrow {}^{12}C$ in star burning (^{12}C catalyst in CNO cycle)

Nuclear Lattice Simulations

Only by taking into account both effects, Coulomb force and 3NF (at NNLO), it is possible without fitting (*ab initio*) to obtain the right sequence of states

3N Systems
N-d Breakup Reaction



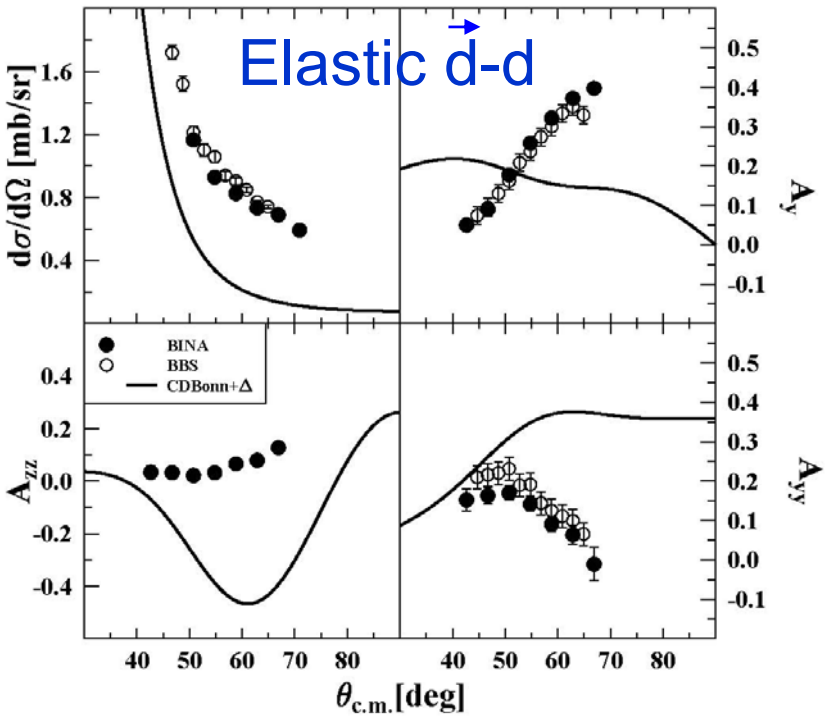
- Variety of observables and configurations (wide ph.sp.) for **the breakup reaction**, field of tests for different dynamic ingredients
- **Sets (a few only)** of rich, systematic and precise data are (at last) available
- Picture very ambiguous - still much to be learnt !
- Comparisons between beam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

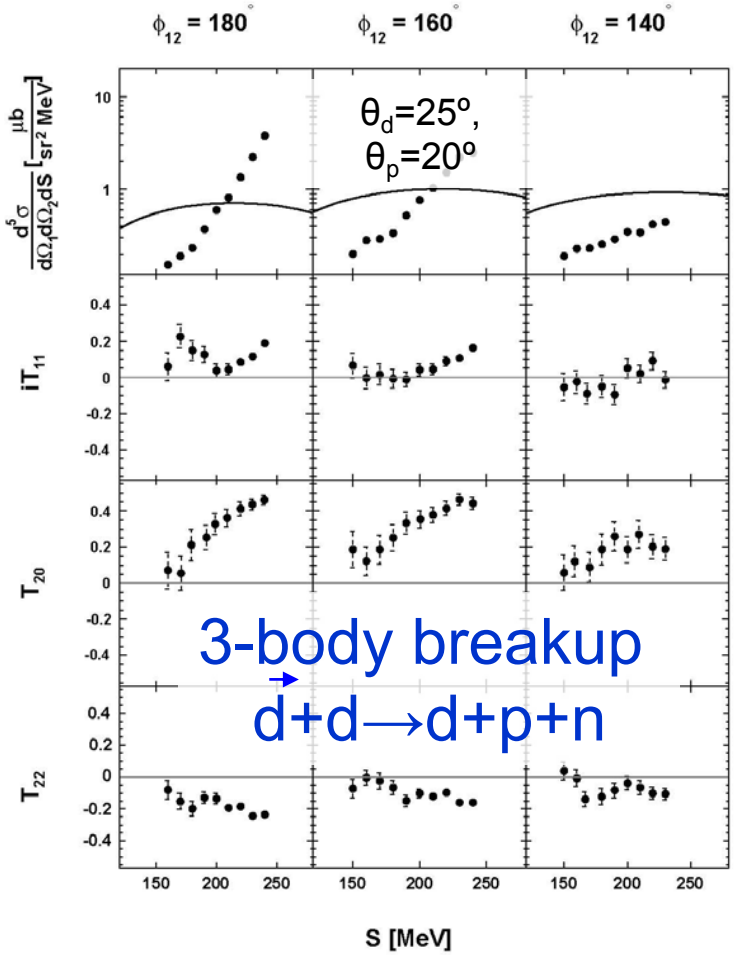
Four-Nucleon Systems

E_d = 130 MeV

θ = 15° - 30°

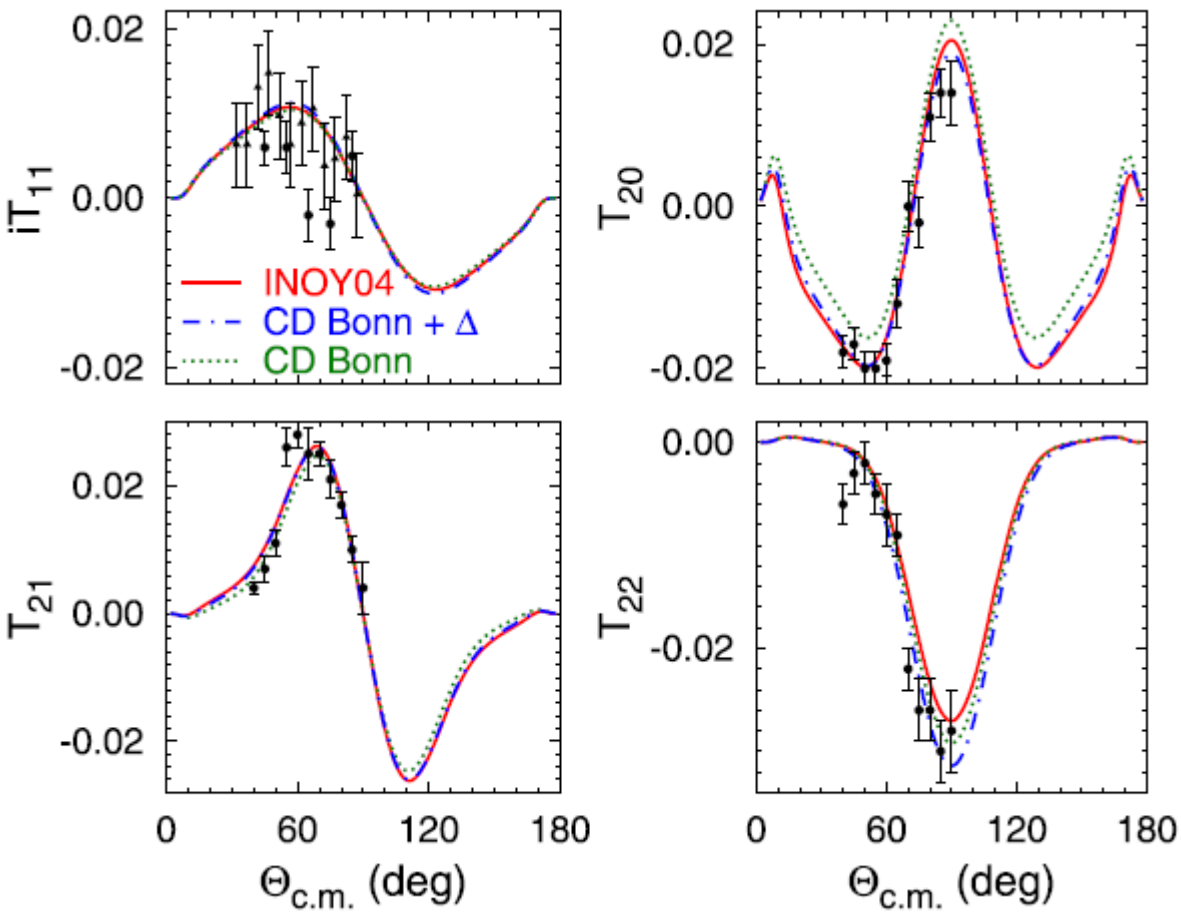
A. Ramazani-Moghaddam-Arani *et al.*
Phys. Rev. C **83** (2011) 024002





4N Systems : First Calculations above Breakup Threshold

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

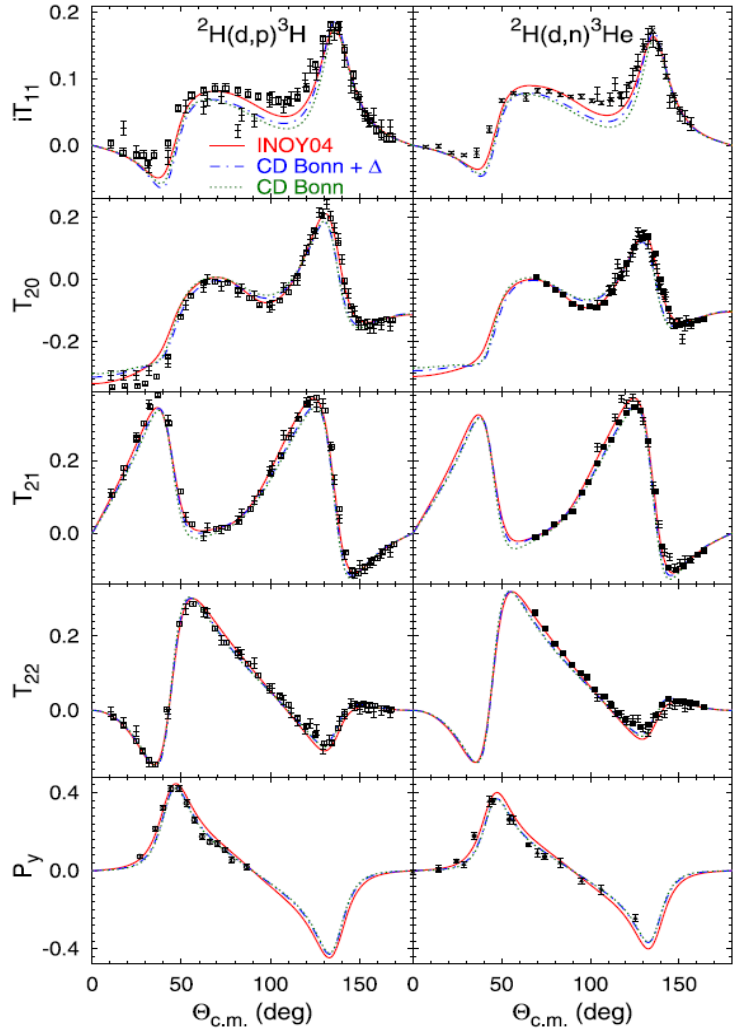


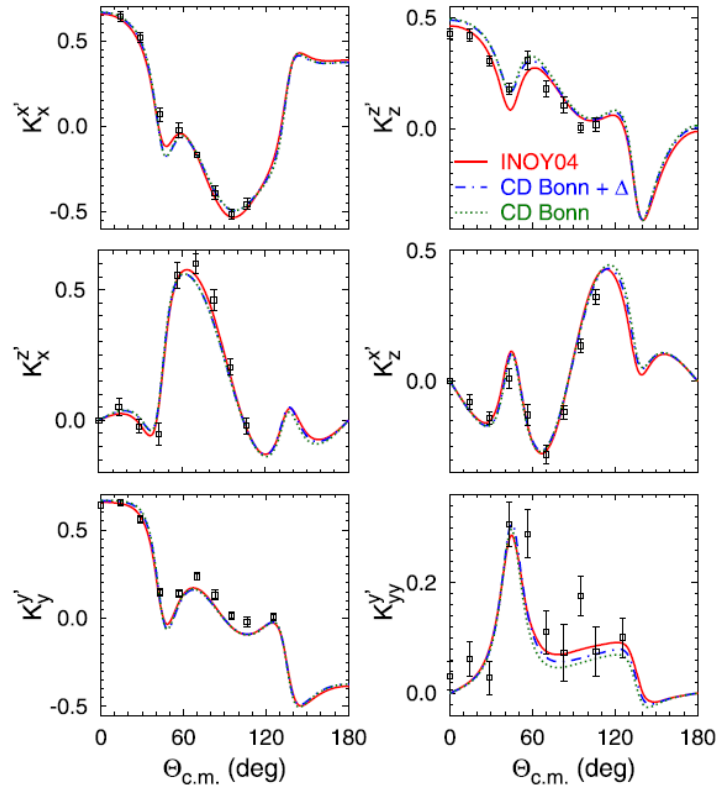
Elastic $\vec{d}$-d at 10 MeV

data:
W. Grüebler *et al*.
P. Guss *et al*.

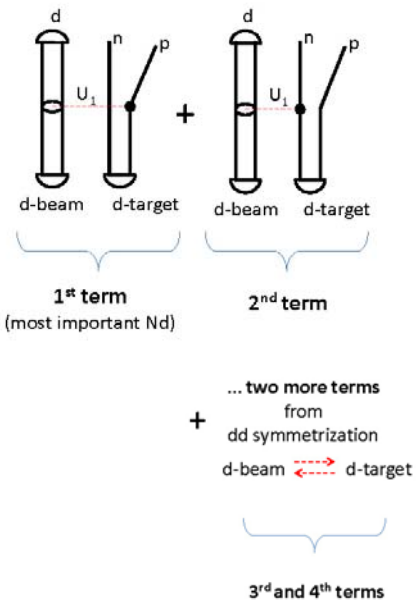
4N Systems : First Calculations above Breakup Threshold

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

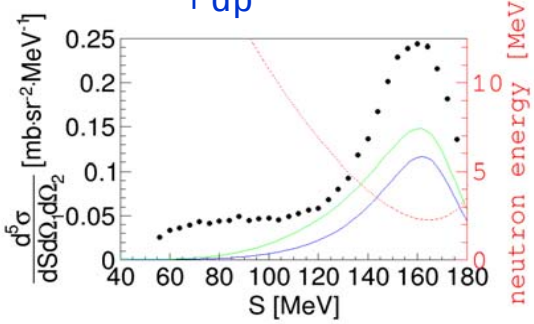


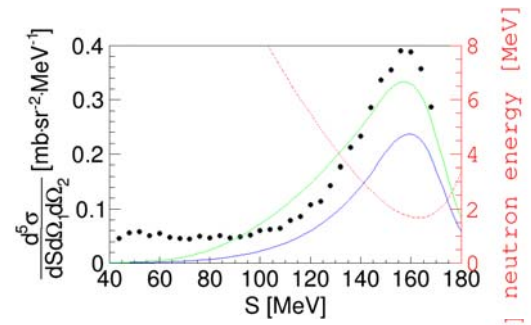


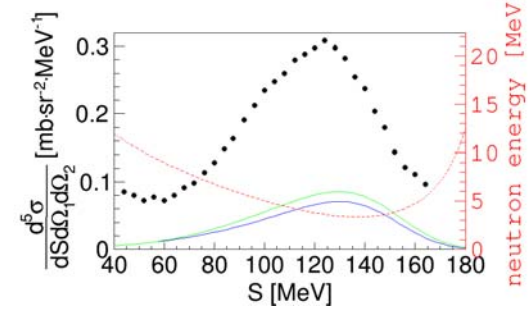
4N Systems : ^{2}H(d,dp)n Measurement at 160 MeV (preliminary)



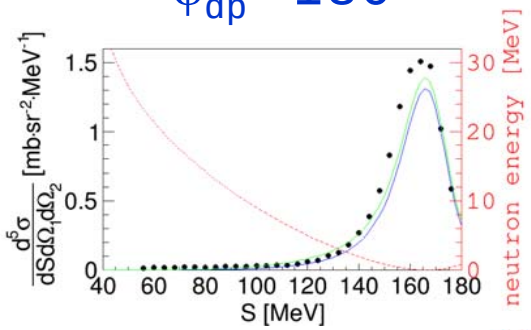
$\varphi_{dp} = 160^o$

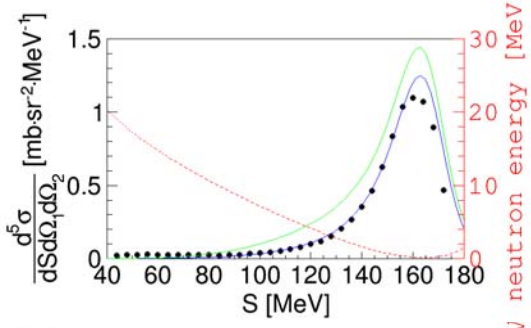


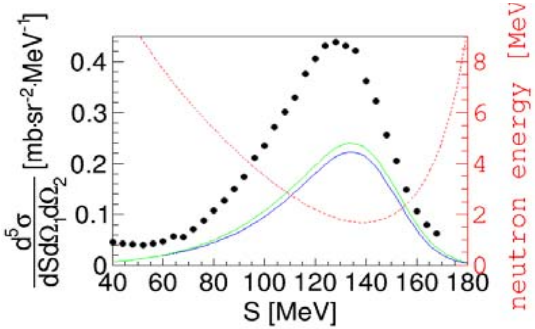




$\varphi_{dp} = 180^o$







$\theta_d = 28^o$
$\theta_p = 24^o$

$\theta_d = 24^o$
$\theta_p = 20^o$

$\theta_d = 20^o$
$\theta_p = 26^o$

Few-Nucleon Systems
Summary

- 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 started !
  - Discrepancies → hints of imperfections in 3NF models
- General picture not quite clear – needed studies to provide evidences of trends in deficiencies

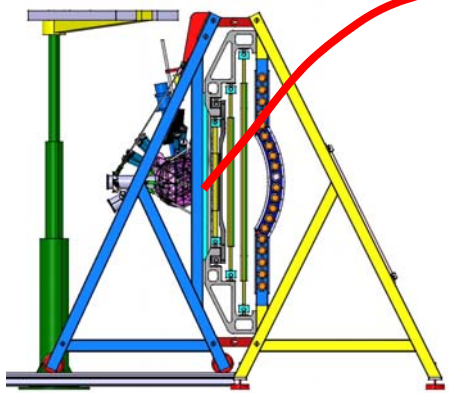
K. Sagara, *Few-Body Syst.* **48** (2010) 59; **55** (2014) 1073
N. Kalantar *et al.*, *Rep. Prog. Phys.* **75** (2012) 016301
St. Kistryn, E. Stephan, *J. Phys. G* **40** (2013) 063101

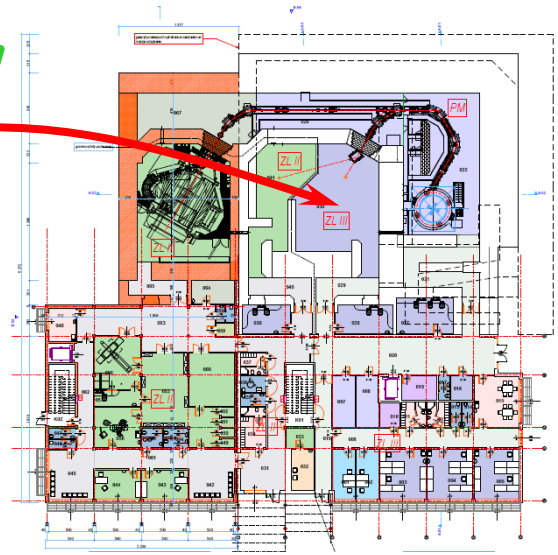
Few-Nucleon Studies
Outlook & Wishes

- Prospects for further results:
  - Evaluating the data accumulated in several experiments at KVI and COSY
  - More measurements:
    - Japan: RIKEN, RCNP, RIBF, ...
    - Projects @ COSY Jülich
    - **BINA @ IFJ PAN Cracow**

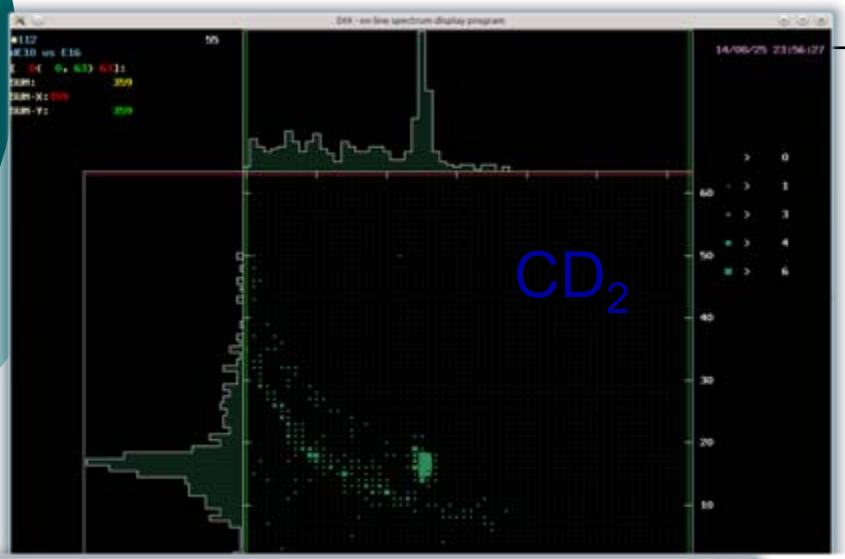
Personal, surely incomplete view

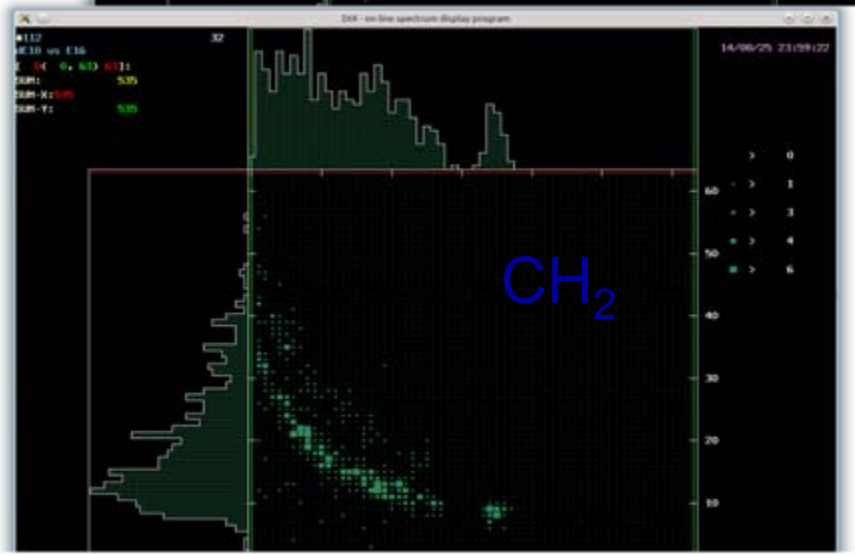
BINA detection system moved from KVI to CCB in 2012

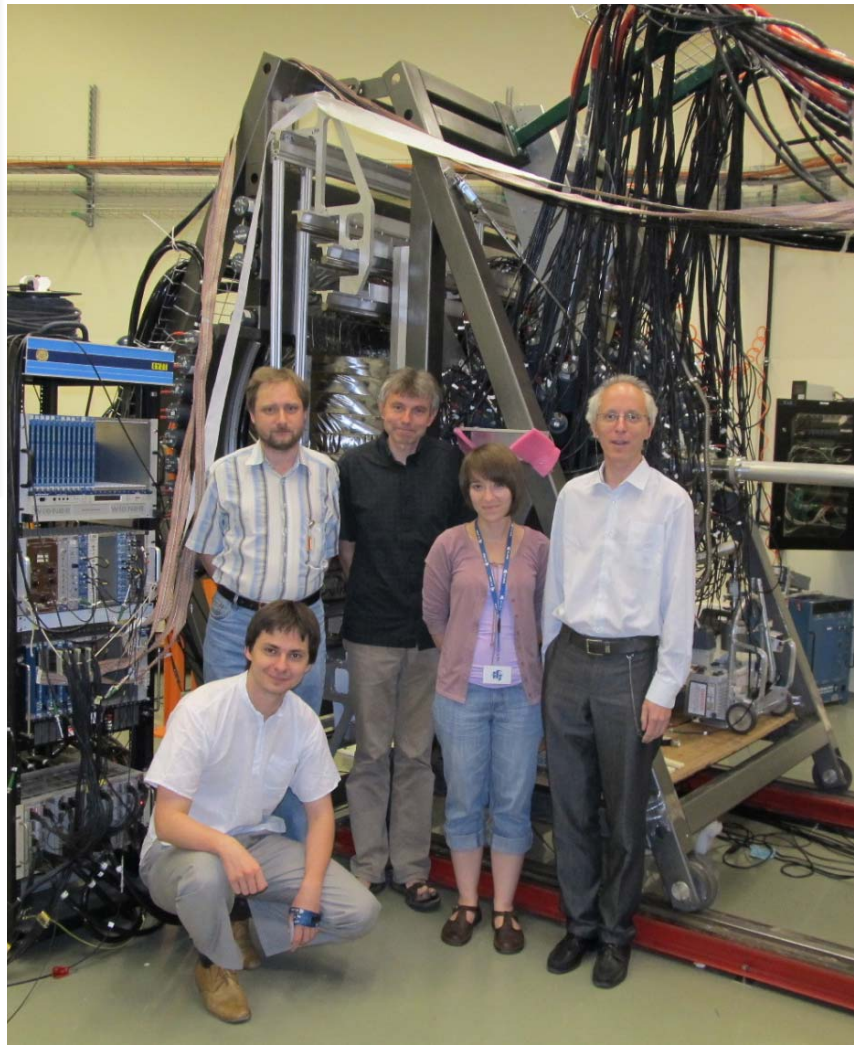




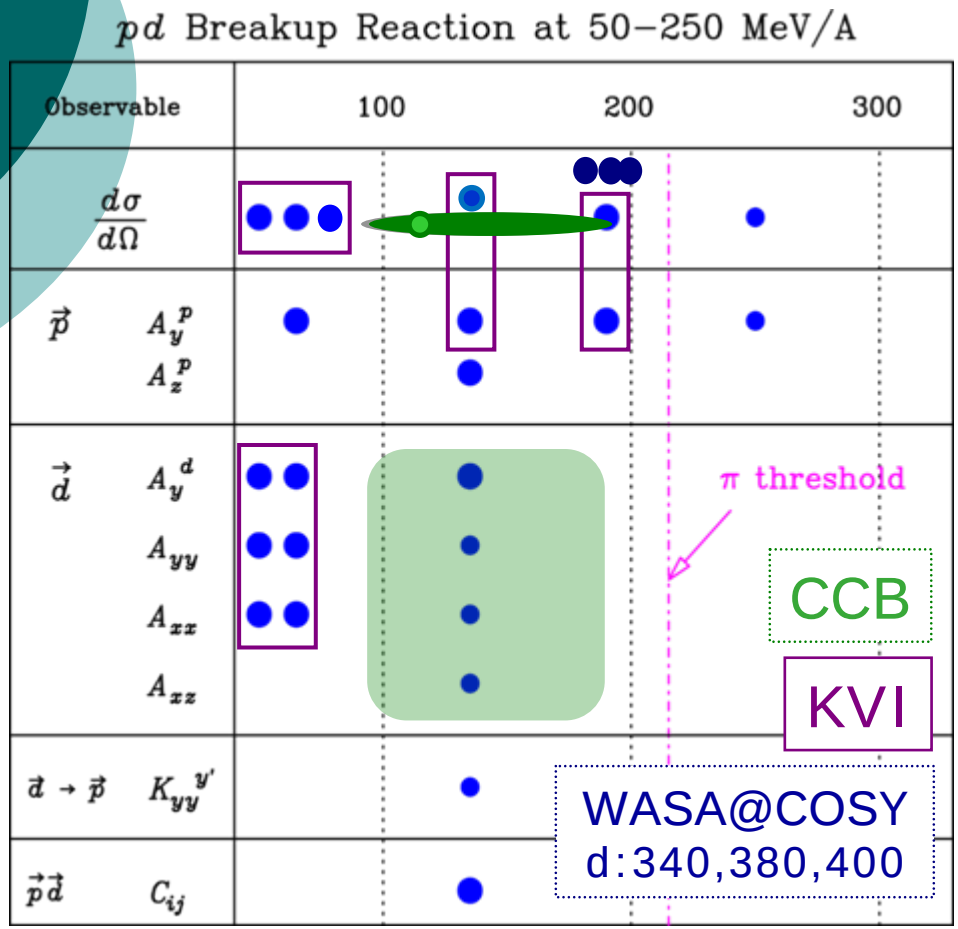
BINA at Cyclotron Center Bronowice







BINA at CCB – Expected Results



Measurement of dσ/dΩ(θ) of p + d elastic scattering at 108, 135 and 160 MeV

- 108 MeV - data exist (cross check)
- 135 MeV - discrepancy between data sets
- 160 MeV - no data

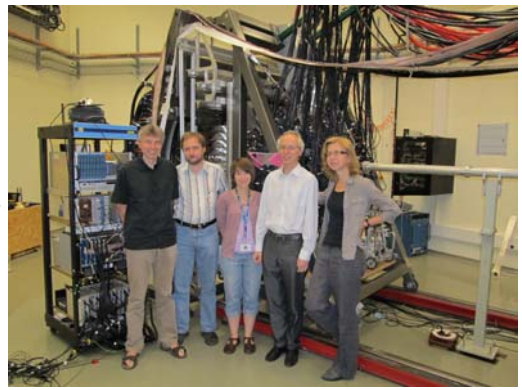
❖ all three energies in one experiment - good control over normalization to luminosity

- Further plans – polarized ^{2}H target

Few-Nucleon Studies
Outlook & Wishes

Personal, surely incomplete view

- Prospects for further results:
  - Evaluating the data accumulated in several experiments at KVI and COSY
  - More measurements:
    - Japan: RIKEN, RCNP, RIBF, ..
    - Projects @ COSY Jülich
    - **BINA @ IFJ PAN Cracow**

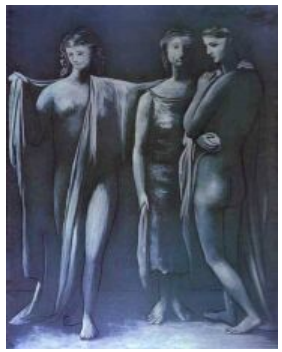


- Awaited theoretical achievements:
  - 3NF at N^3LO (close ahead...)
  - ChPT with Δ (work in progress...)
  - ✓ Realistic potentials with Coulomb
  - ✓ Relativistic potentials with 3NF
  - Rigorous calculations for 4N system (dream comes true ?)

Few-Body Systems Remain Attractive !








Thank You for attention