Polarization Observables in Few-Nucleon Scattering

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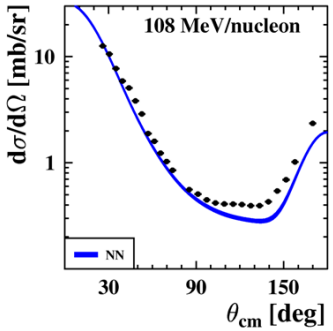
Nucleon-Nucleon Interaction
Basis of Nuclear Physics

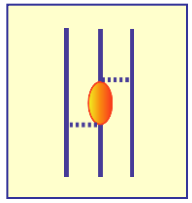
Modern NN potentials are in general able to

- 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

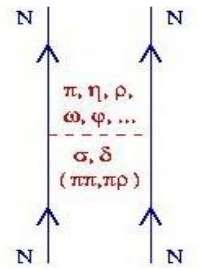
- Three-nucleon system is the simplest **non-trivial** environment to test predictions of observables obtained on the basis of NN potential models



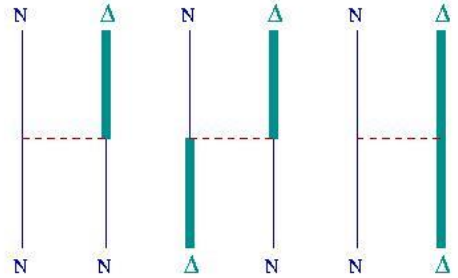
- Introducing concept of **three-nucleon forces**: genuine (irreducible) interaction of all three nucleons



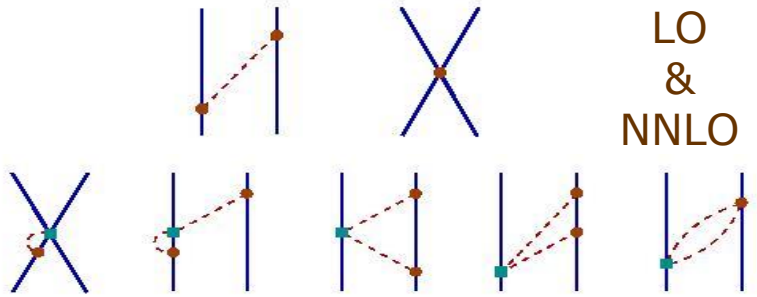
Three-Nucleon System
Standard Interaction Models



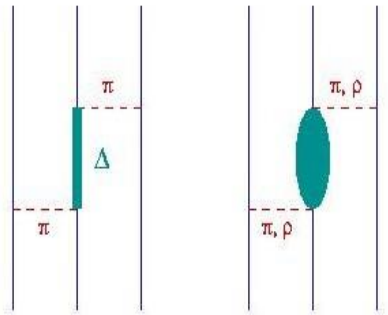
Realistic **P**otentials
CD Bonn, Nijm, AV



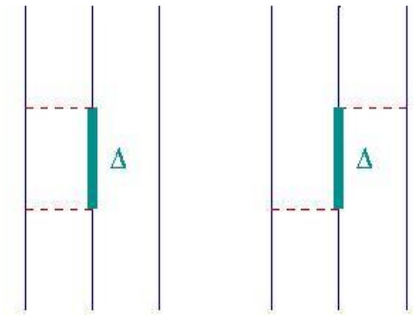
Coupled-**C**hannels
Potential (single Δ)

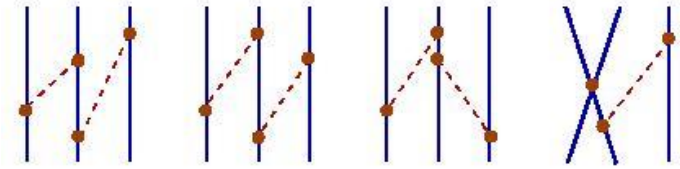


Chiral **P**erturbation **T**heory
(2π exchanges & contact terms)

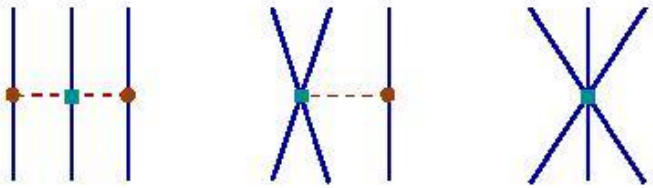


TM99 3NF





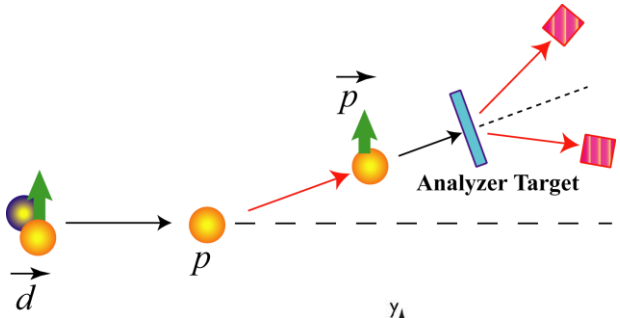
NLO: all contributions cancel out !

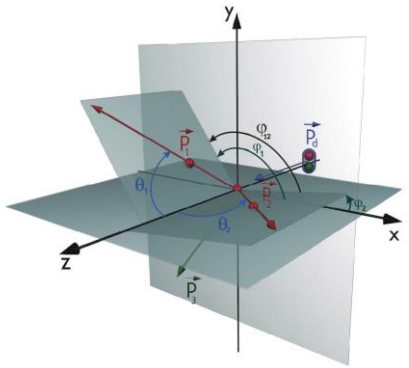


NNLO: three possible topologies

Three-Nucleon Scattering at Medium Energies

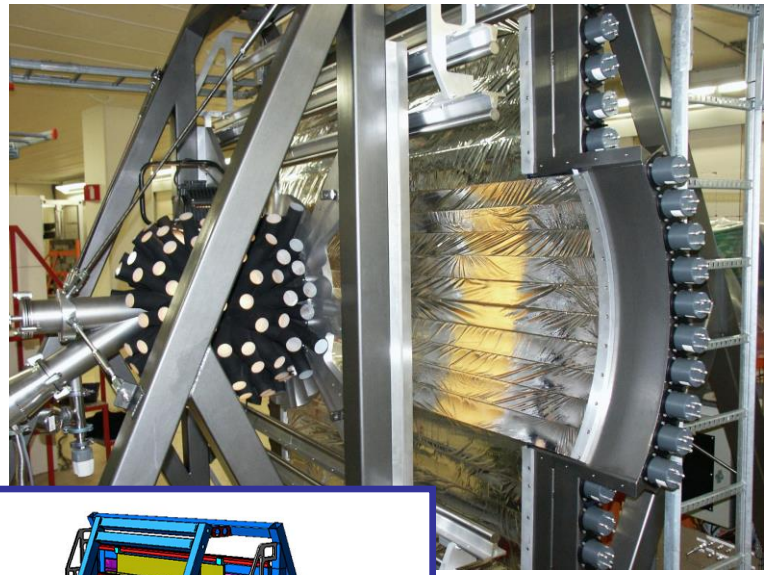
- Elastic: N + d → N + d
  - Beams of p or d
  - Various observables
- Breakup: N + d → N + N + N
  - Beams of p or d
  - Various observables
- Different effects to be traced
  - Comparisons between channels
  - Influences of 3NF
  - Coulomb force action
  - Relativistic effects

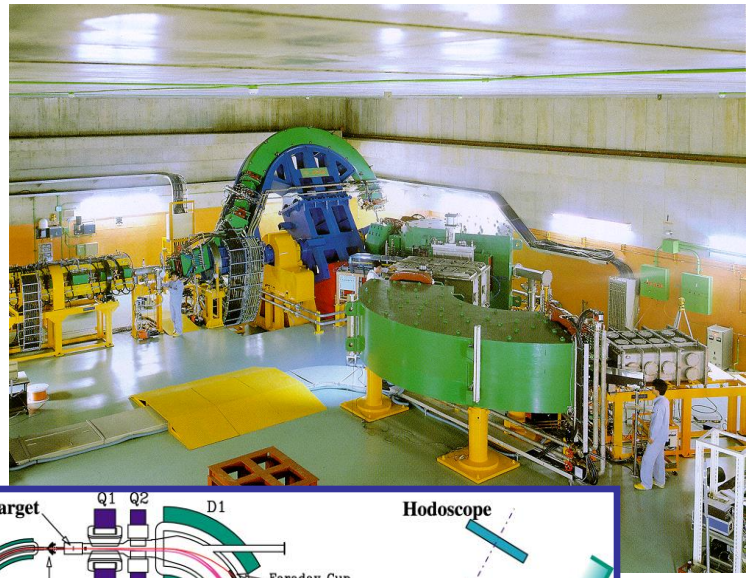


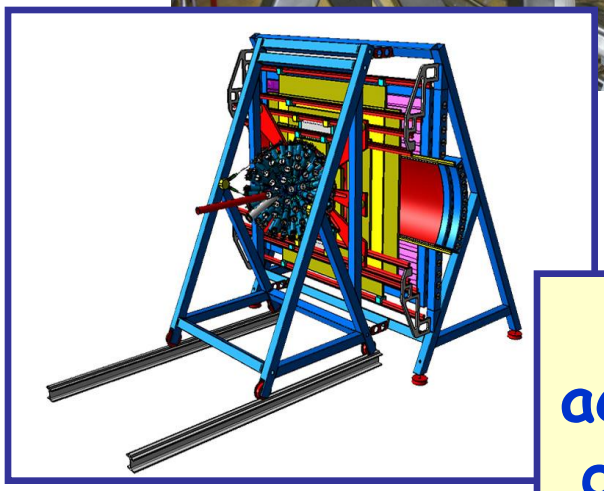


… and their interplay !

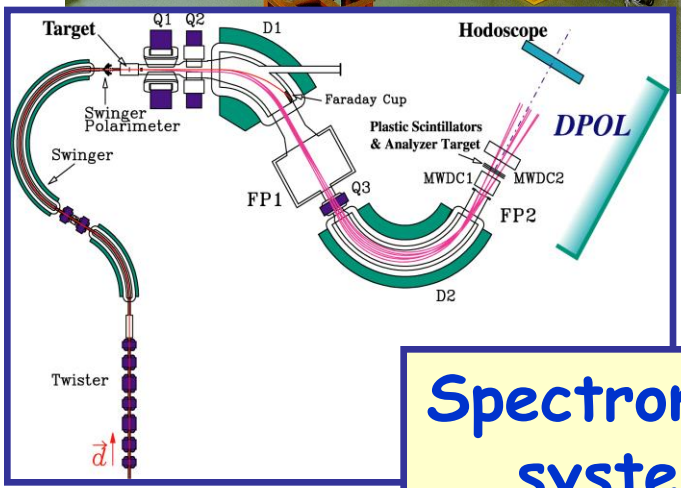
Experimental Tools of Few-Nucleon Physics







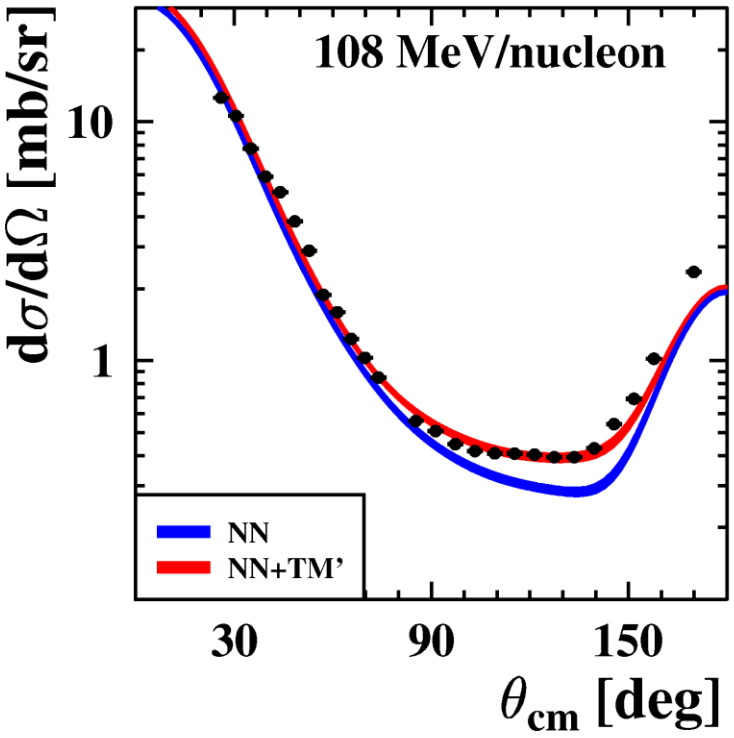
Large acceptance detectors

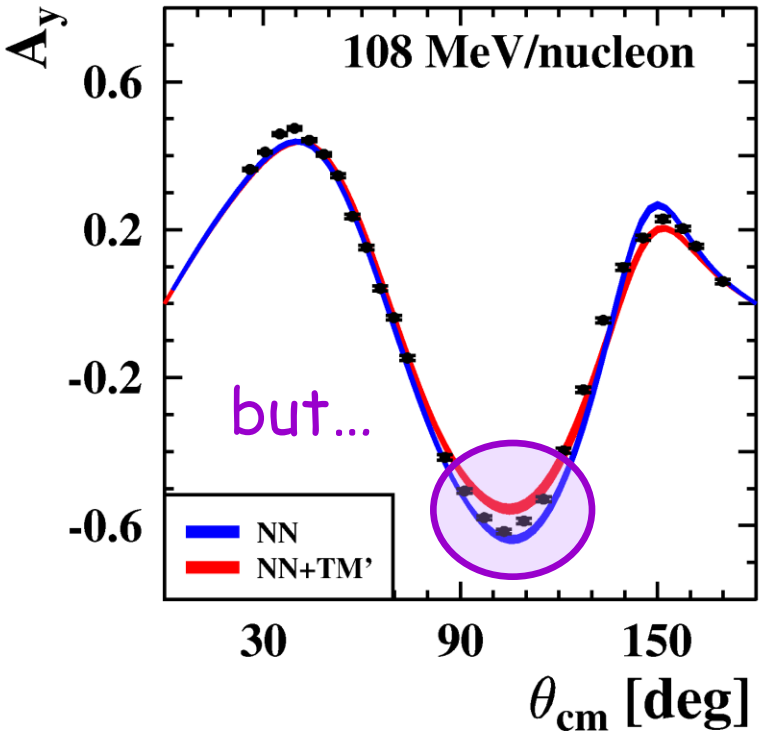


Spectrometer systems

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.



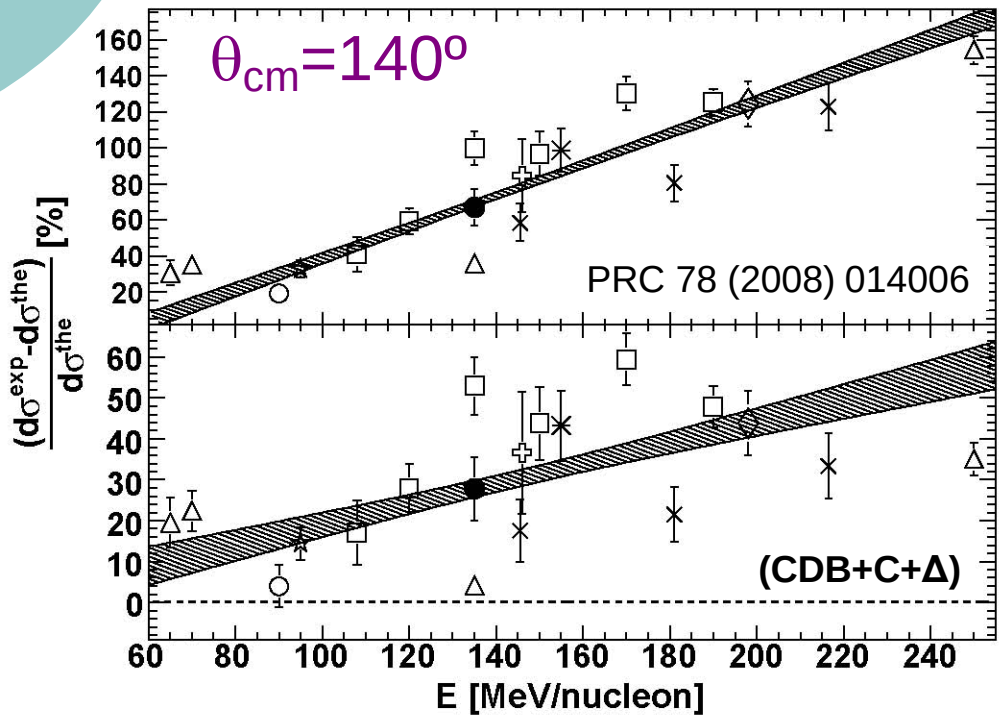


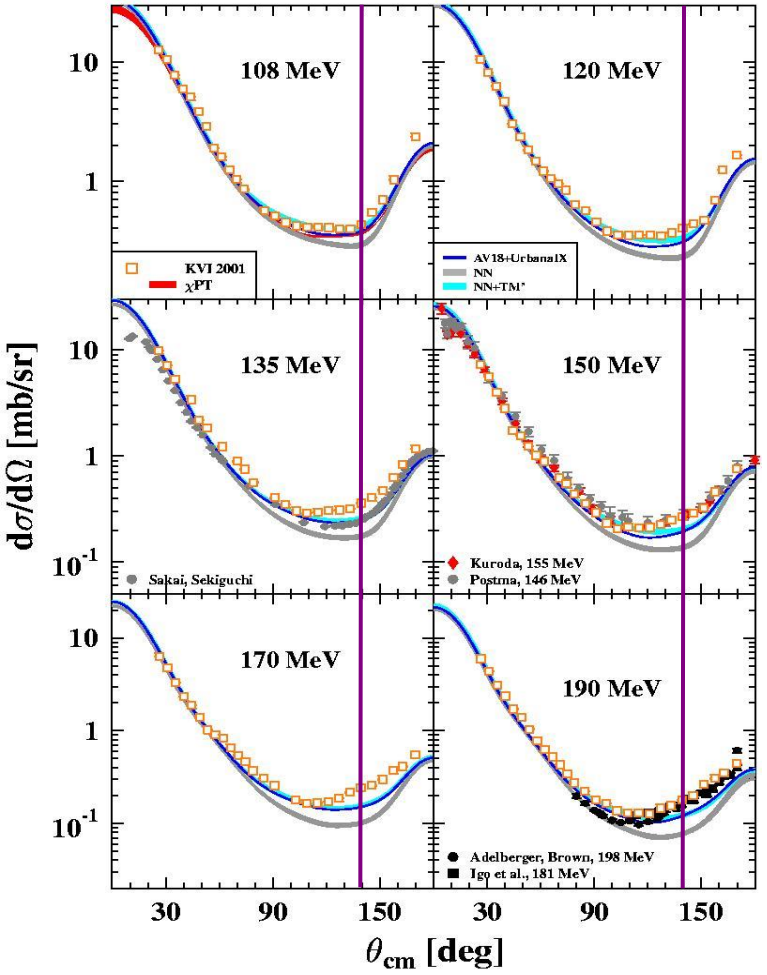
K. Ermisch *et al.*, Phys. Rev. C **71** (2005) 064004

3NF Effects
Elastic Nucleon-Deuteron Scattering

3NF help

alas, not completely

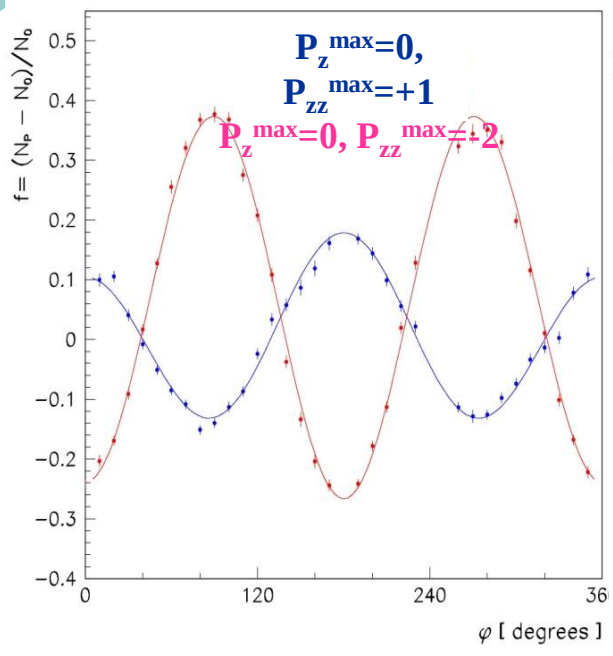




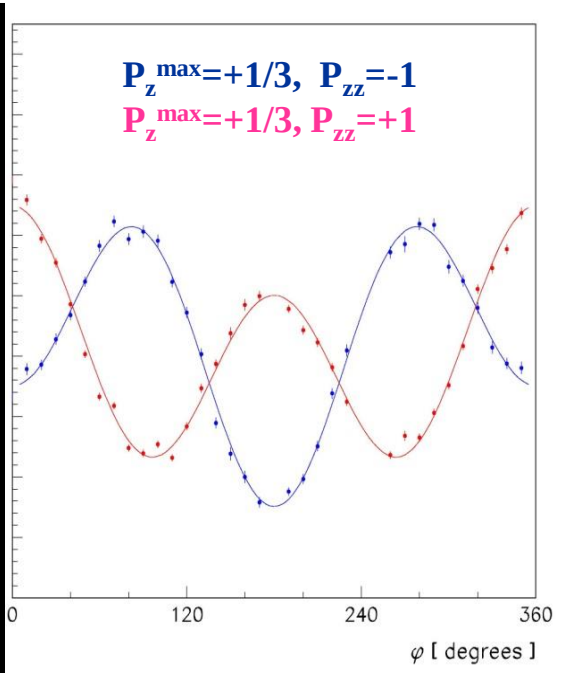
Elastic Deuteron-Nucleon Scattering
Beam Polarization

Elastic $^1H(\vec{d},pd)$ scattering – azimuthal (φ) distribution at selected polar (θ) angle, where T_{ij}'s are known

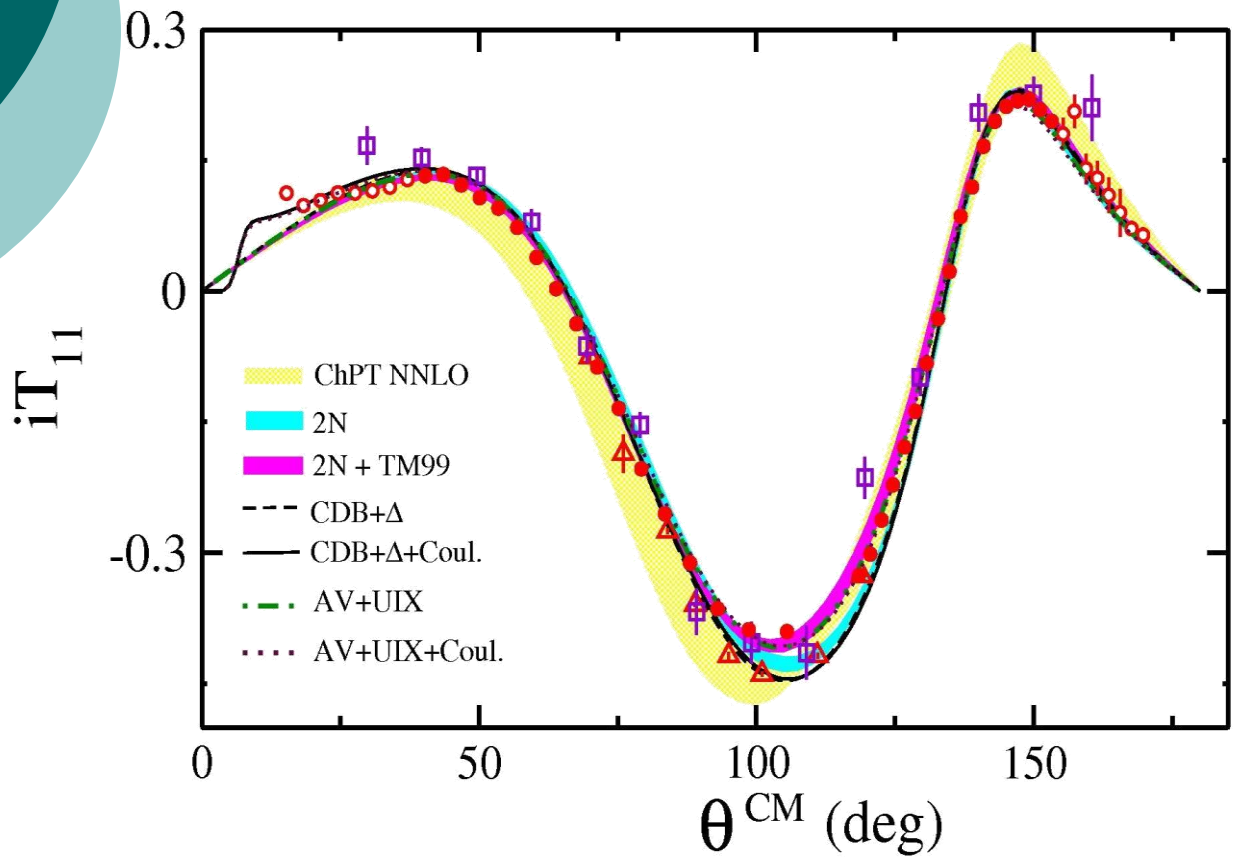
$$\sigma_P(\theta_p,\varphi_p)=\sigma_0(\theta_p)\cdot\left[1+\sqrt{3}\cdot iT_{11}(\theta_p)\cdot P_z\cdot\cos\varphi_p-\frac{\sqrt{3}}{2}\cdot T_{22}(\theta_p)\cdot P_{zz}\cdot\cos 2\varphi_p-\frac{\sqrt{2}}{4}\cdot T_{20}(\theta_p)\cdot P_{zz}\right]$$



7 states:		▯ P_z	▯ P_{zz}
		0.008	0.05
P_z^{max}	P_{zz}^{max}	P_z	P_{zz}
+1/3	-1	0.265	-0.73
+2/3	0	0.480	-0.08
-2/3	0	-0.469	0.06
0	+1	-0.058	0.52
0	-2	0.009	-1.37
+1/3	+1	0.219	0.61
0	0		

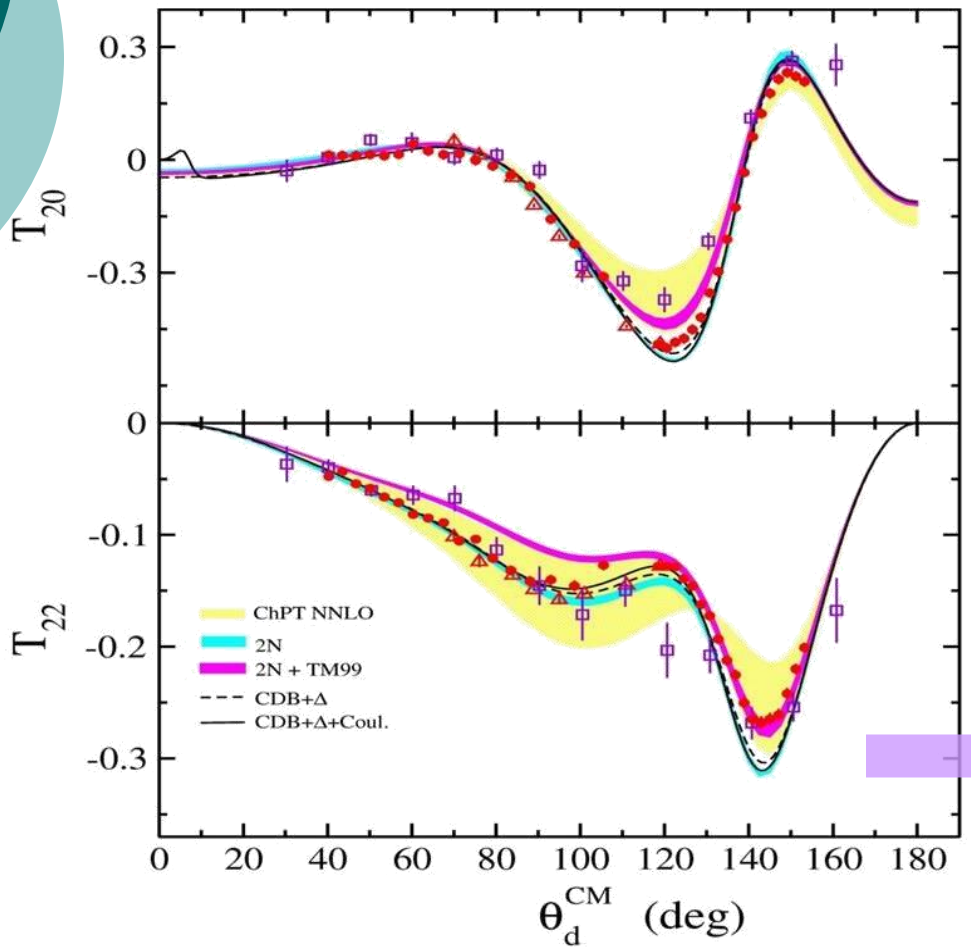


3NF Effects
Elastic Deuteron-Nucleon Scattering

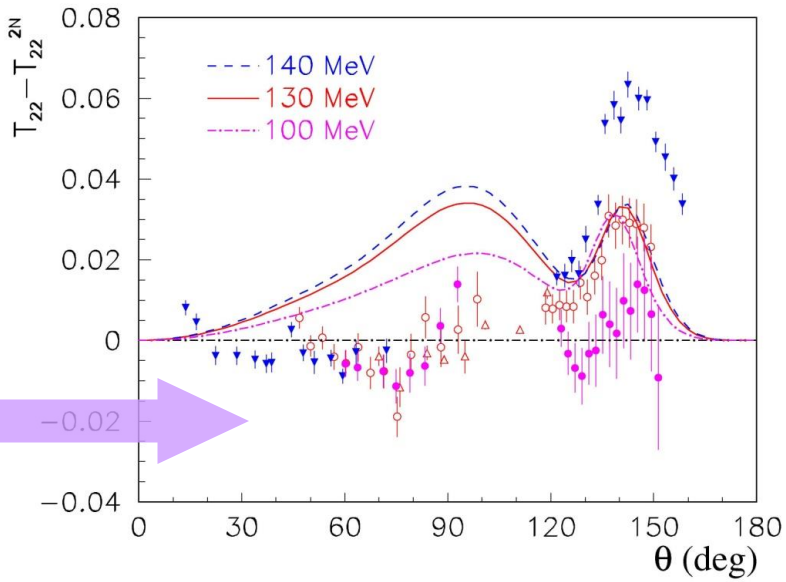


- E. Stephan et al., Phys. Rev. C 76, 057001 (2007)
- GeWall @ COSY
- H. Mardanpour et al., Eur. Phys. J. 31, 383 (2007)
- H. Witała et al., Few-Body Systems 15, 67-85 (1993)

3NF Effects
Elastic Deuteron-Nucleon Scattering



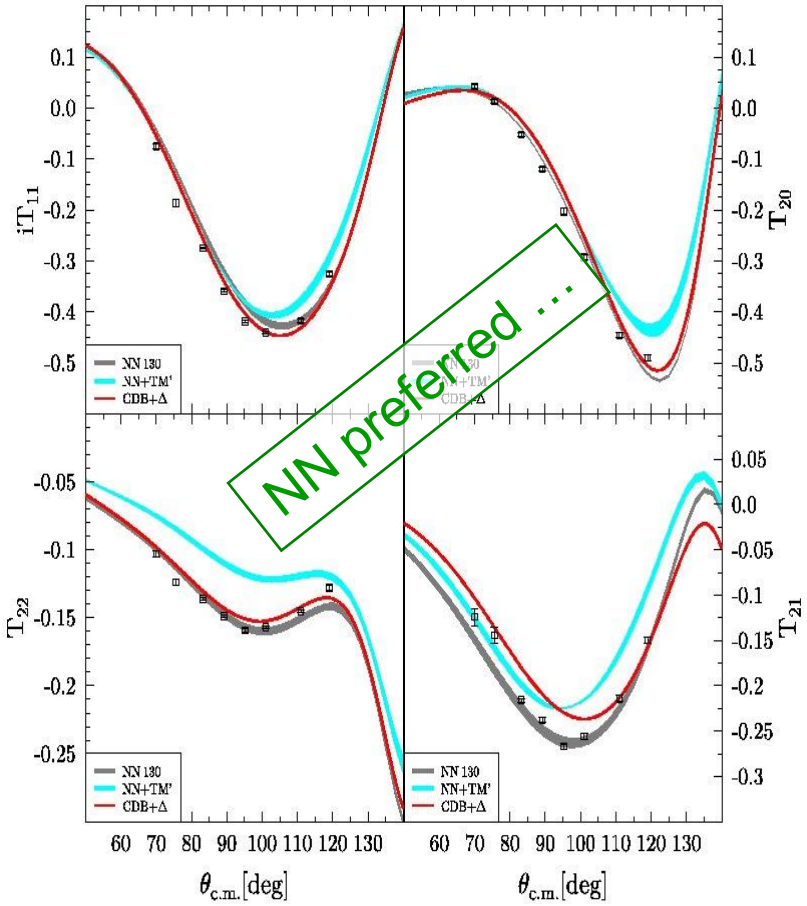
Different energy dependence of T_{22} data and theory in angular regions



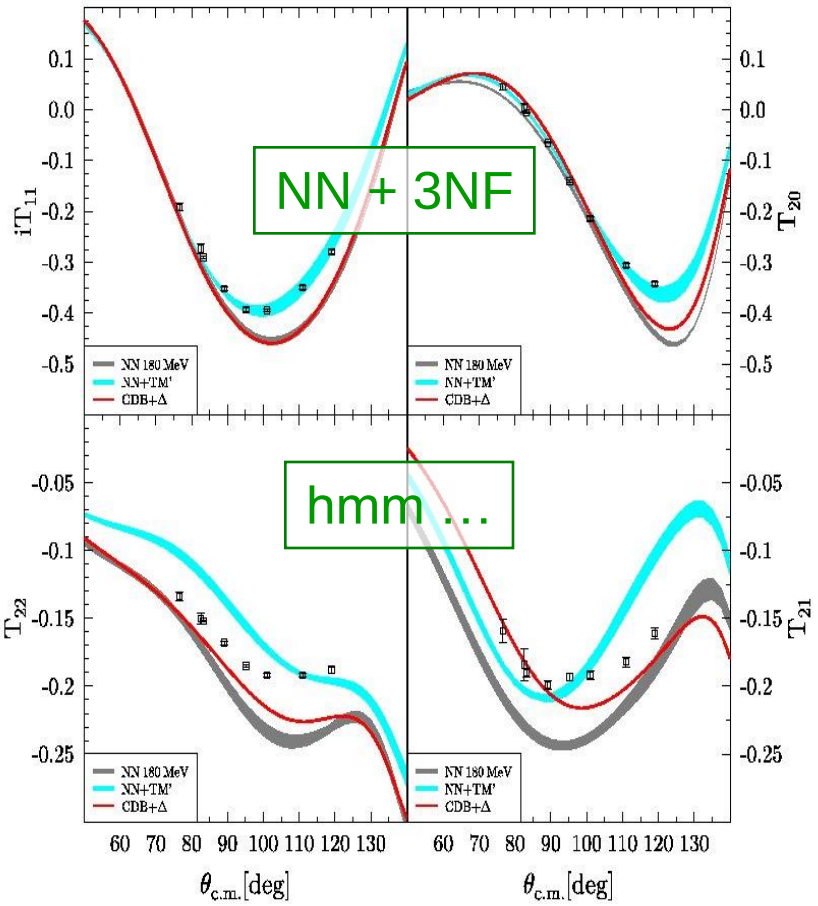
3NF Effects
Elastic Deuteron-Nucleon Scattering

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

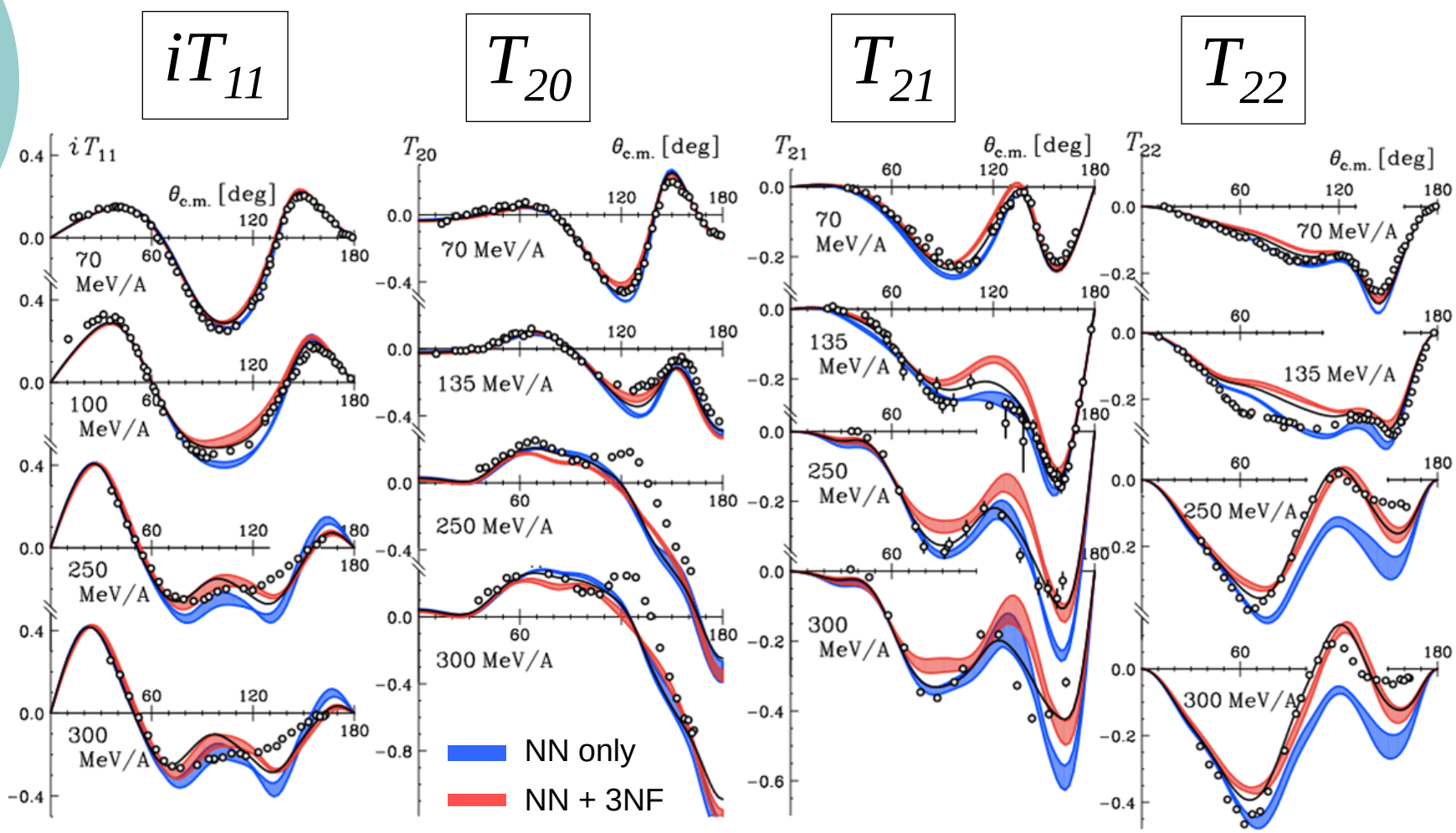
65 MeV/A



90 MeV/A



3NF Effects
Elastic Deuteron-Nucleon Scattering

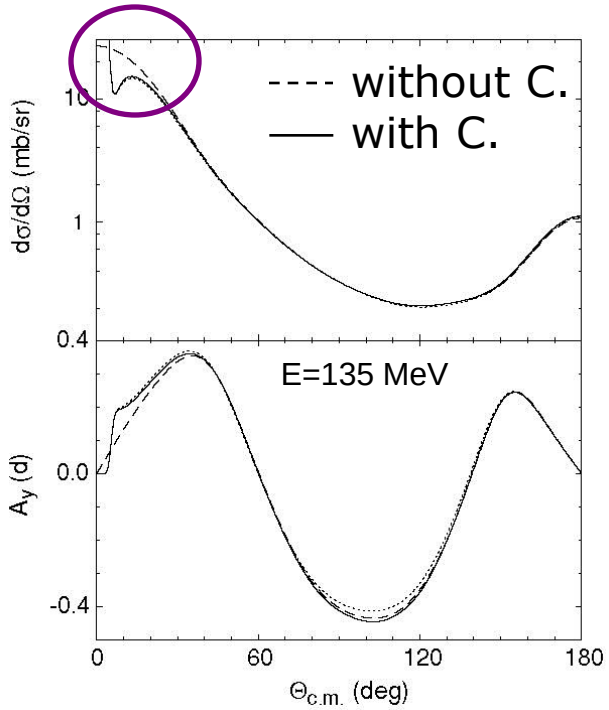


K. Sekiguchi *et al.*, Phys. Rev. C **83** (2011) 061001

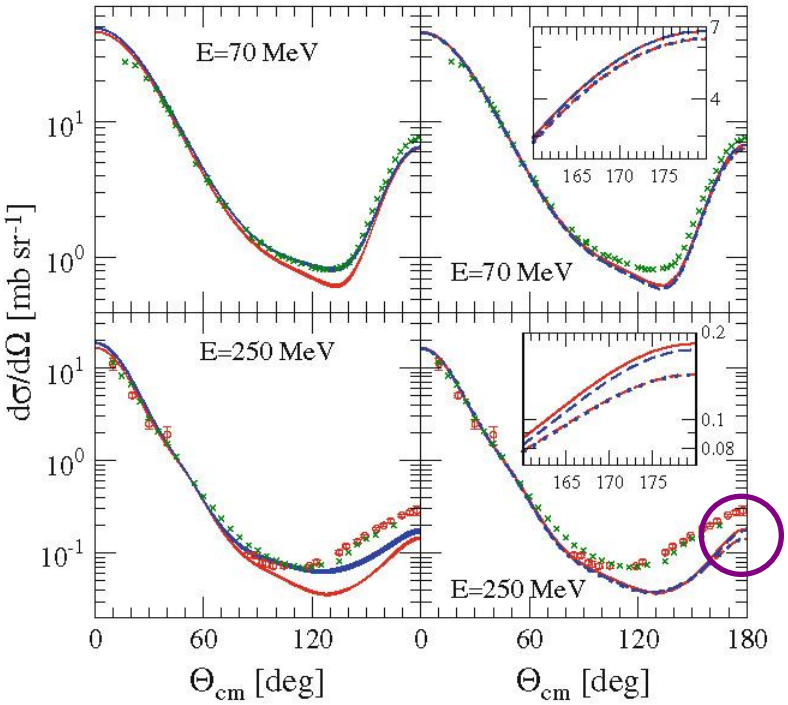
More Dynamical Effects ?
Coulomb force and relativity

Predictions for the N-d elastic scattering

Coulomb



3NF relativity



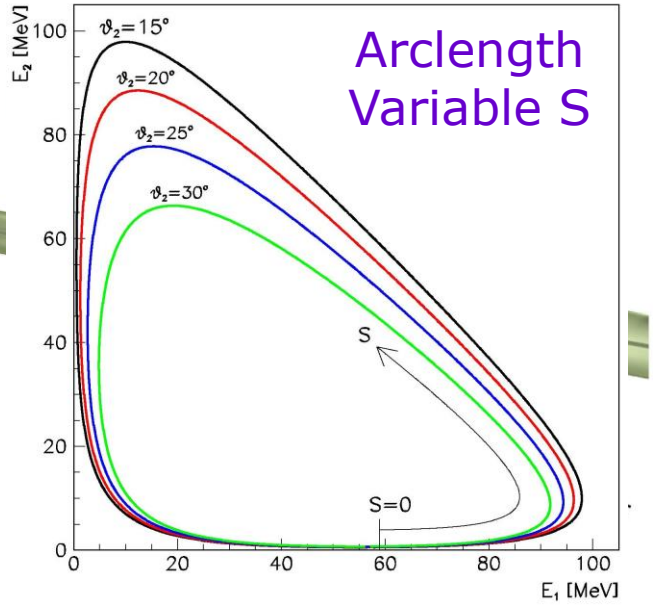
Effects small, located at extreme angles only !

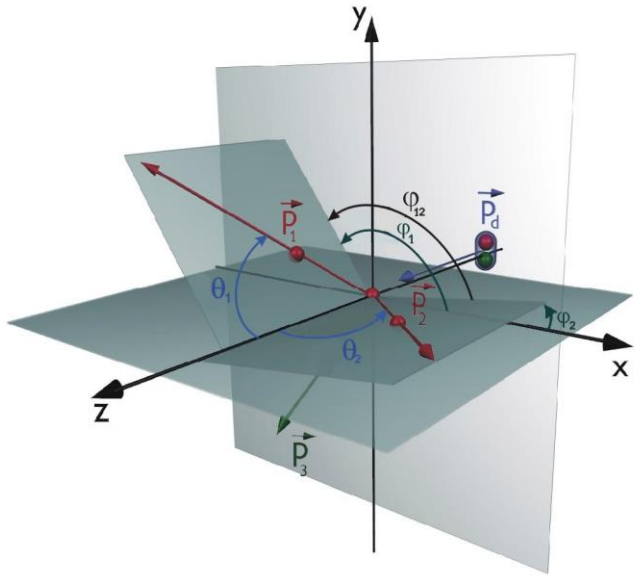
3N Systems
Elastic N-d Scattering

- Substantial number of observables for the **elastic scattering channel**, allowing multi-dimensional studies of 3NF and other effects
- **Only fraction** has been measured really 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

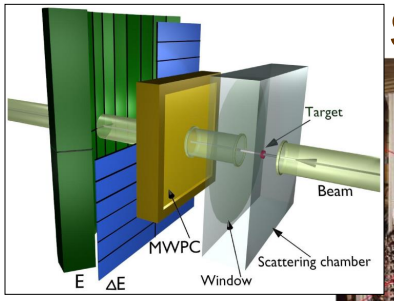




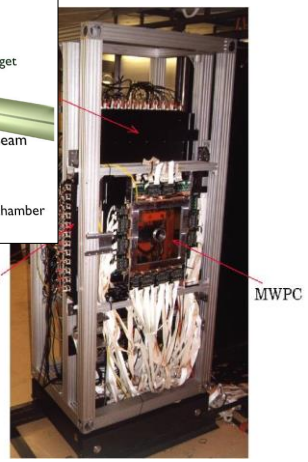
^{1}H(d,pp)n
measured:
directions and energies of two protons, i.e.
θ_1,φ_1,E_1
θ_2,φ_2,E_2

$^1H(\vec{d},pp)n$ Measurements at 130 MeV
Cross Section and Analyzing Power Results

- ✓ 1800 cross section data points
  - θ_1, θ_2 = (13°) 15° – 30°; grid 5° ; $\Delta\theta$ = ±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

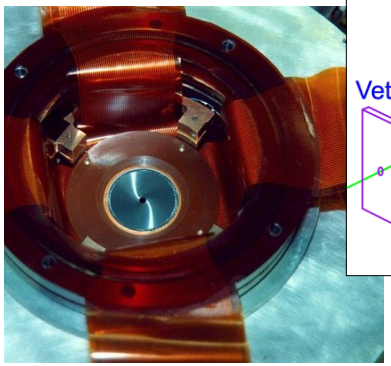


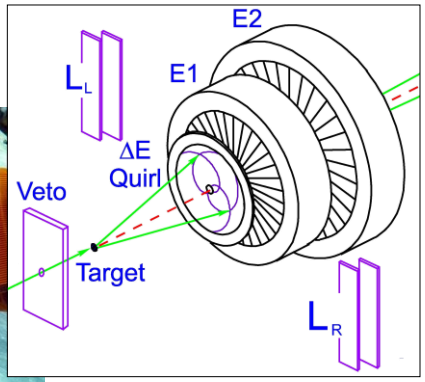
SALAD



KVI Groningen

FZ Jülich



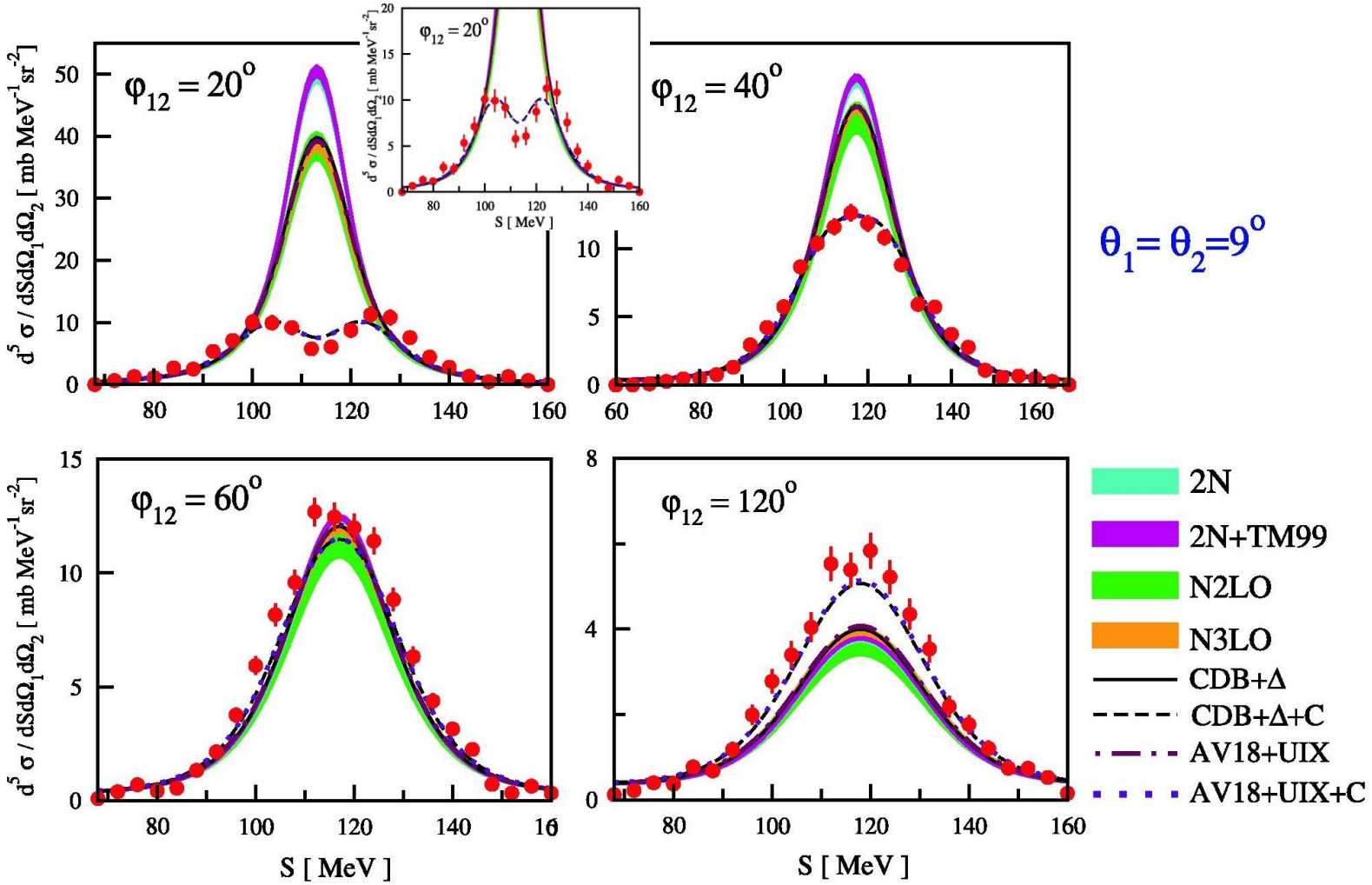


GeWall

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

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

Cross Section Results – Examples



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

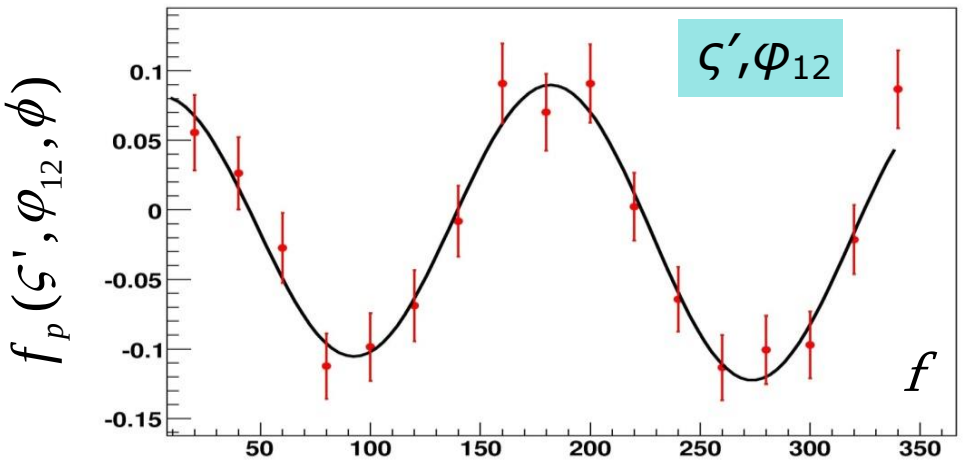
$^1H(\vec{d},pp)n$ Measurement at 130 MeV

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

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

$$\left. + P_{zz} \cdot \left(\frac{1}{2}\sin^2\phi \cdot A_{xx} + \frac{1}{2}\cos^2\phi \cdot A_{yy} \right) \right]$$



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

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

Analyzing Power Results – Parity Test of Data

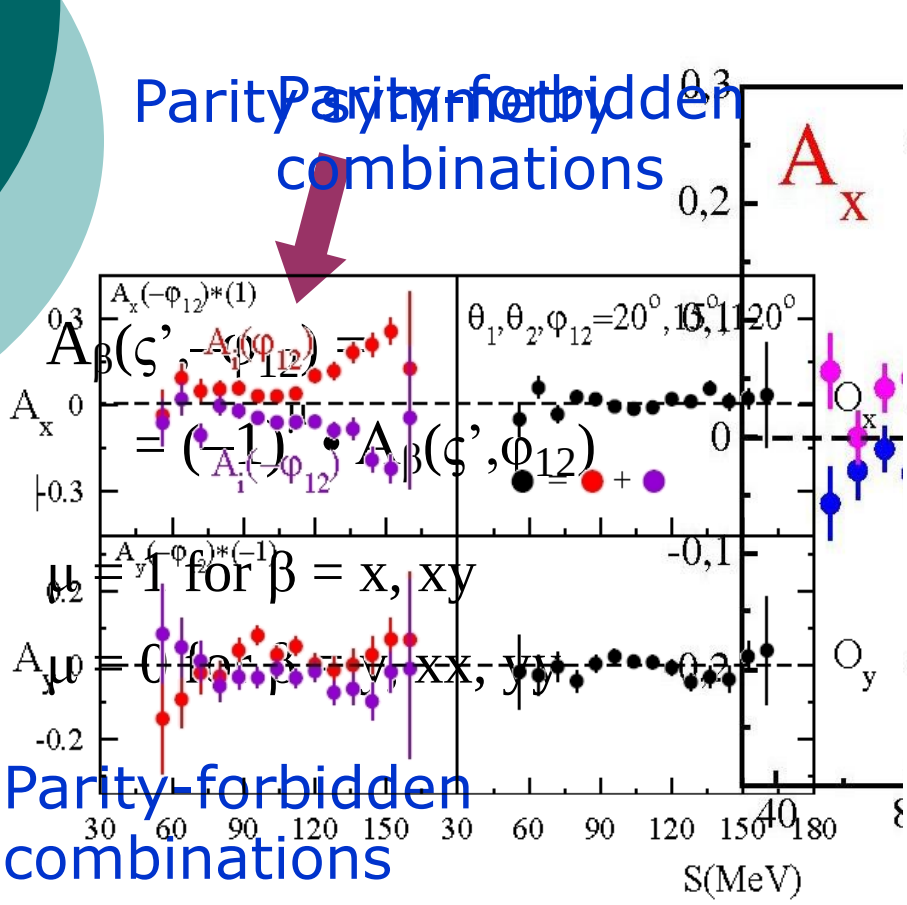
Parity-forbidden combinations

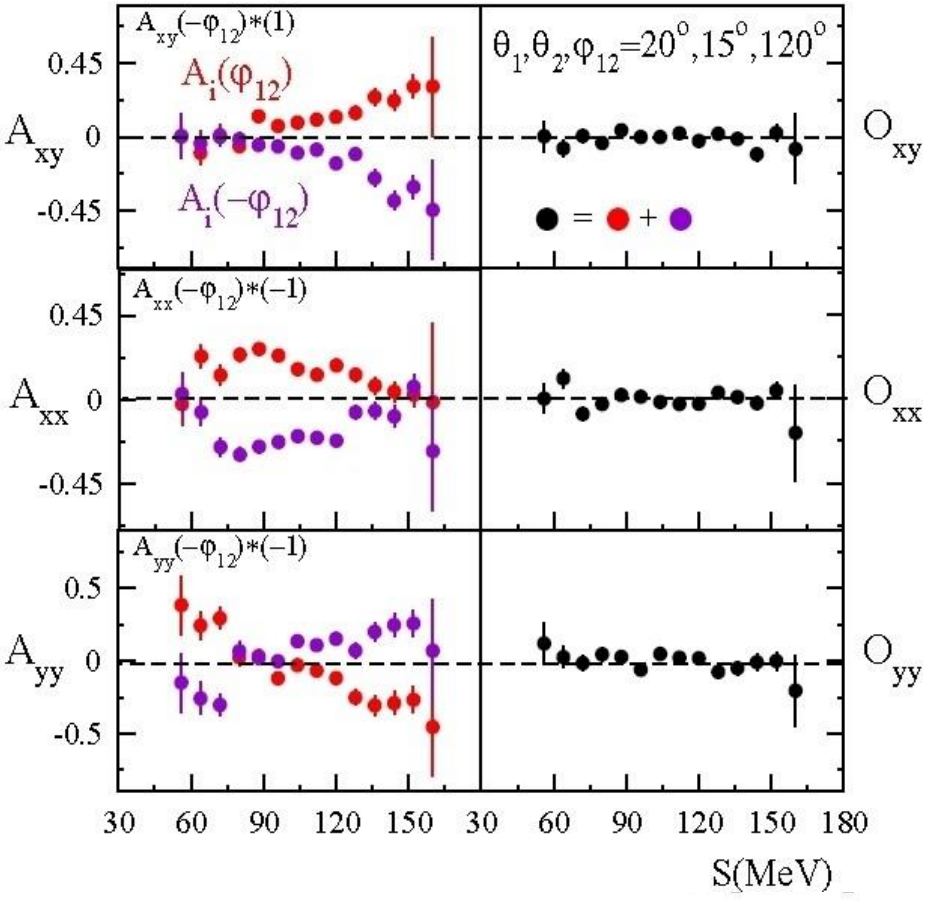
Parity-forbidden combinations

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

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

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





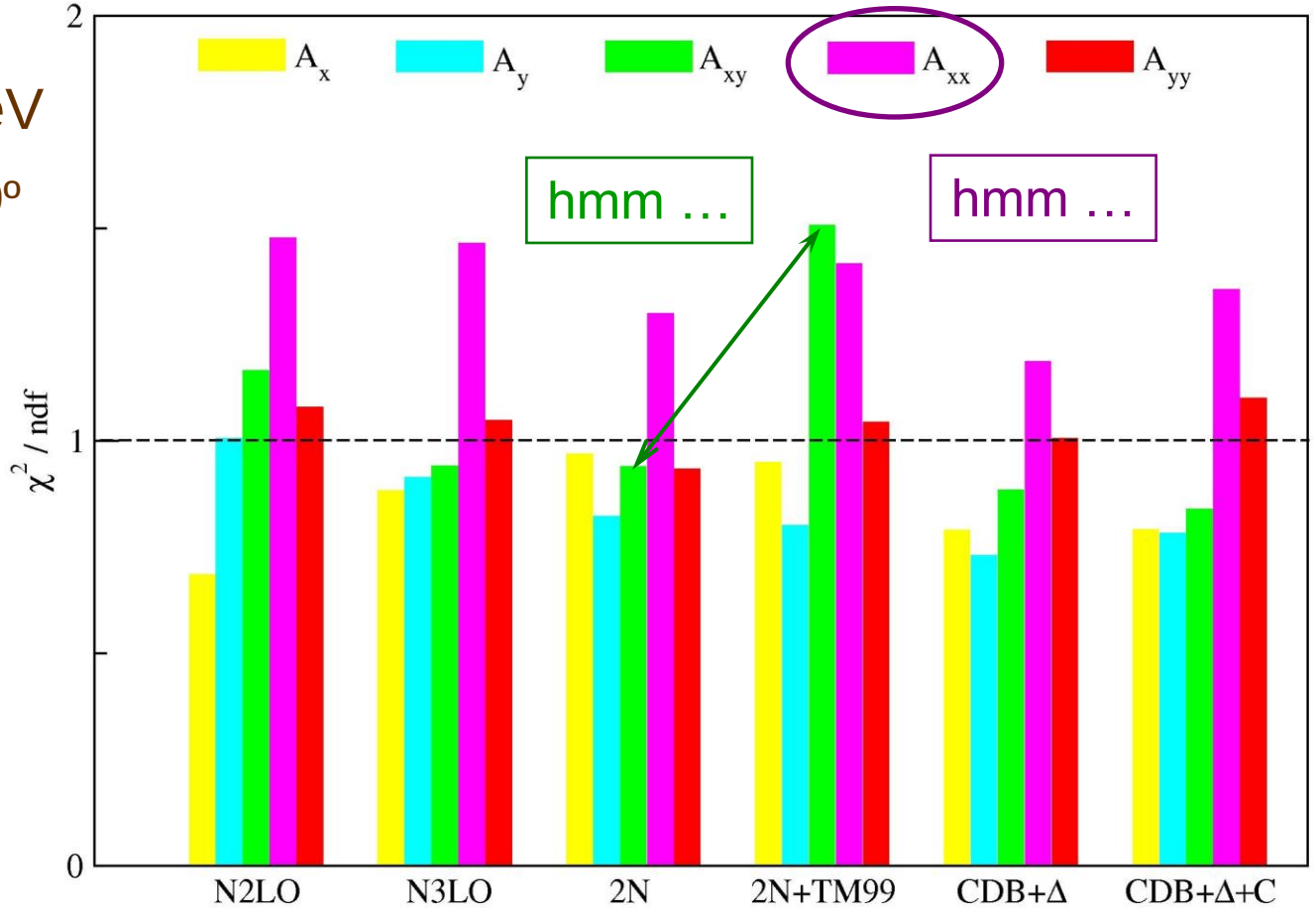
$$O_\beta(\varsigma', \varphi_{12}) = A_\beta(\varsigma', \varphi_{12}) + (-1)^{1-\mu} \cdot A_\beta(\varsigma', -\varphi_{12})$$

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

Analyzing Power Results

E_d = 130 MeV

θ_1,θ_2 = 15º - 30º



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

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

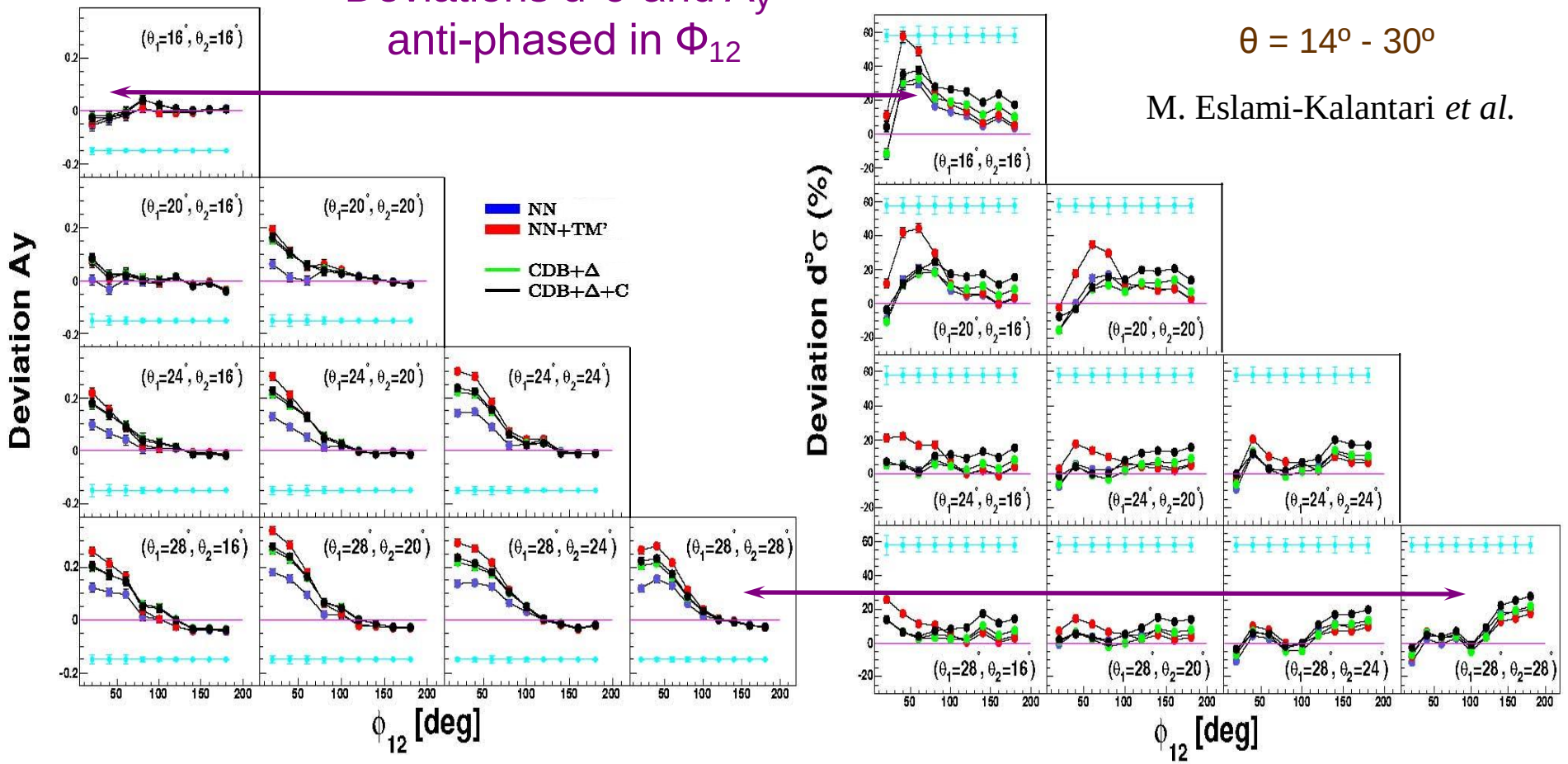
$^2\vec{H}(\vec{p},pp)n$ Breakup Reaction
Analyzing Powers vs. Cross Sections

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

E_p = 135 MeV

θ = 14º - 30º

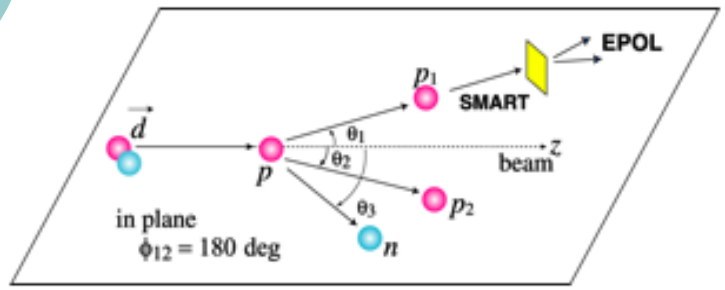
M. Eslami-Kalantari *et al.*



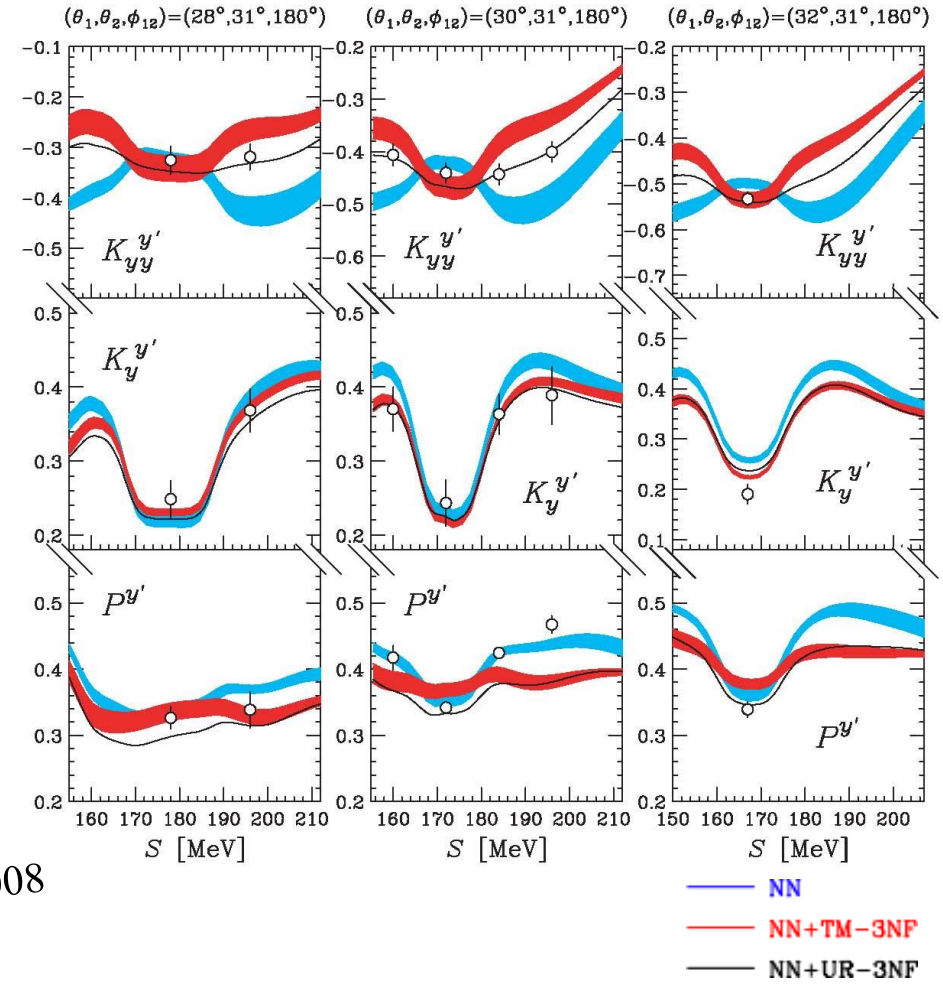
$^1H(\vec{d},pp)n$ Breakup Reaction
Polarization Transfer Coefficients

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

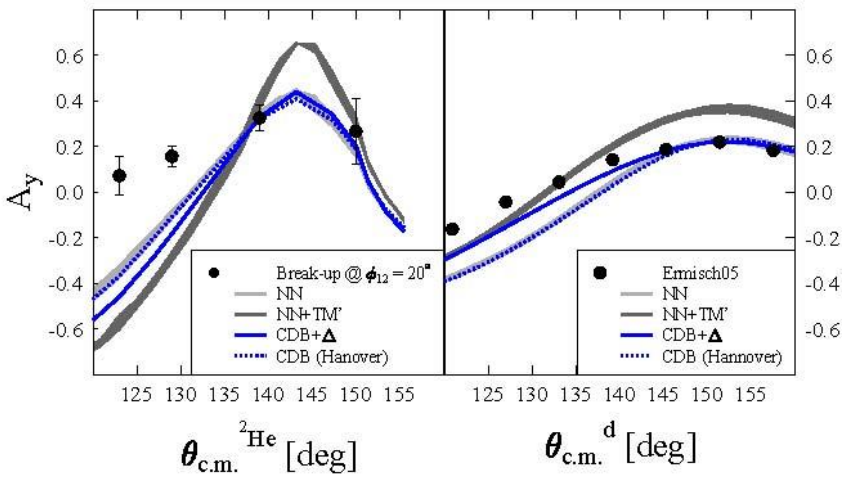
^{2}H(p,pp)n vs. ^{2}H(p,d)p
Spin-Isospin Selectivity

E_p = 190 MeV

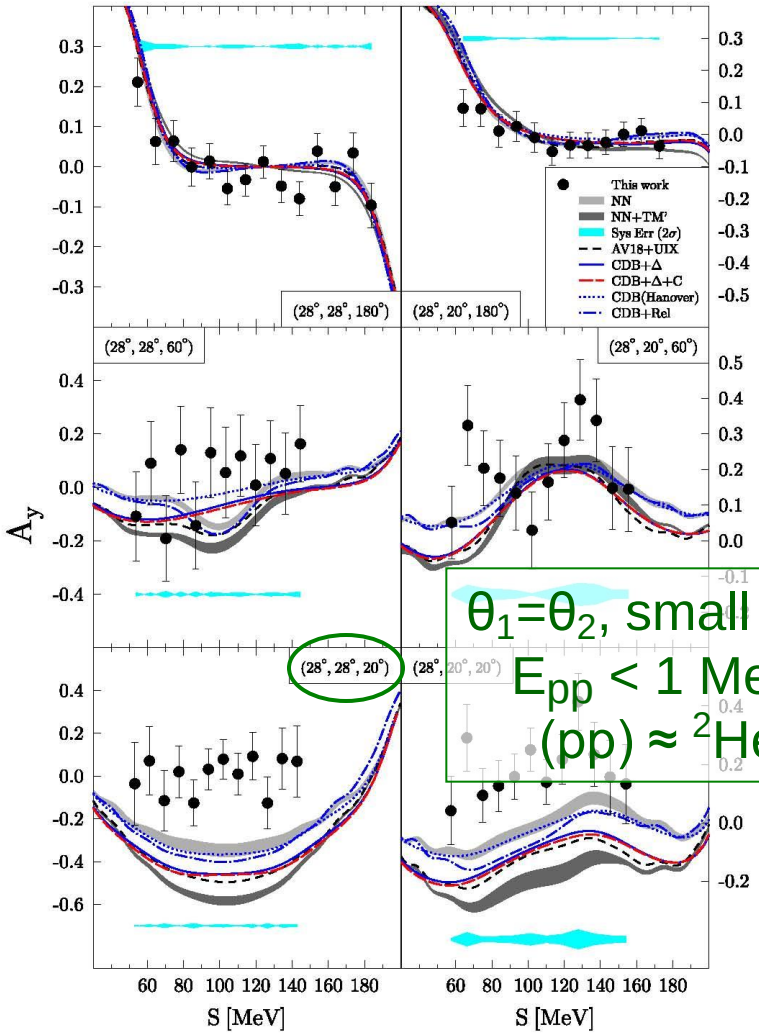
θ = 14º - 30º

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

3N Systems
N-d Breakup Reaction

- Variety of observables and configurations (wide phase space) 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

N-d Breakup Reaction Invariant Variables

Defining configurations in terms of angles and energies makes comparisons of experiments performed at different energies difficult.

Using 4-momenta we can define:

$$s_{pp} = (p_{p1} + p_{p2})^2$$
$$s_{pn} = (p_{p1} + p_n)^2$$
$$t_n = (p_d/2 - p_n)^2$$
$$t_p = (p_p - p_{p2})^2$$

More intuitively:

$$E_{rel}^{pp} = \sqrt{s_{pp}} - 2m_p$$
$$E_{rel}^{pn} = \sqrt{s_{pn}} - m_p - m_n$$
$$E_{tr}^{p} = \frac{-t_p}{2m_p}$$
$$E_{tr}^{n} = \frac{-t_n}{2m_n}$$

Then eg:

FSI: $E_{rel}^{pp} = 0$, $E_{rel}^{pn} = 0$

QFS: $E_{tr}^{p} = 0$, $E_{tr}^{n} = 0$

3N Systems
N-d Breakup Reaction

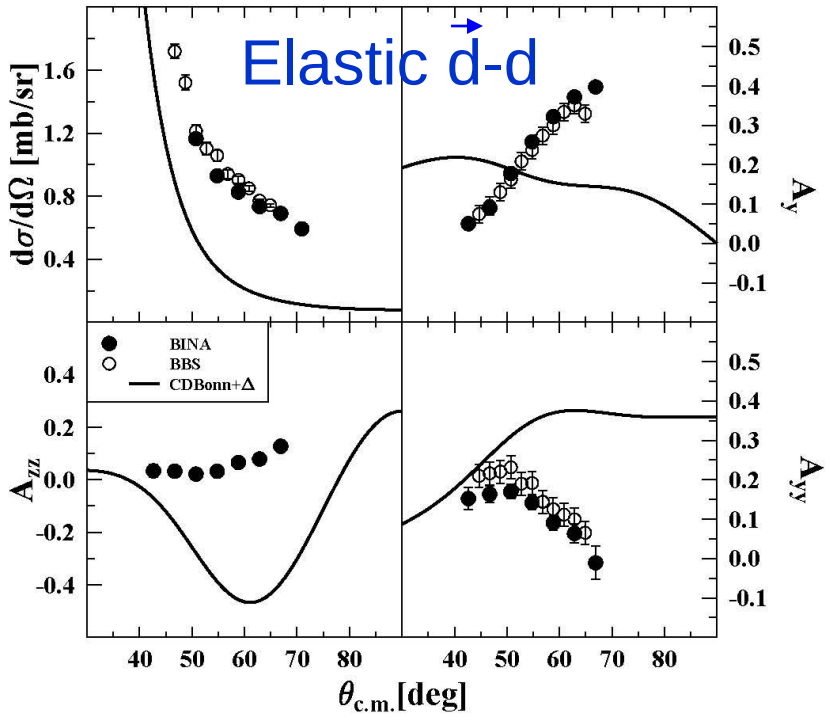
- Variety of observables and configurations (wide phase space) for **the breakup reaction**, field of tests for different dynamic ingredients
- **Sets (a few only)** of rich, systematic and precise data are (at last) available
- Picture very ambiguous - still much to be learnt !
- Comparisons between beam energies – need of new variables
- Are we ready for next step: **Four-Nucleon System** studies ?

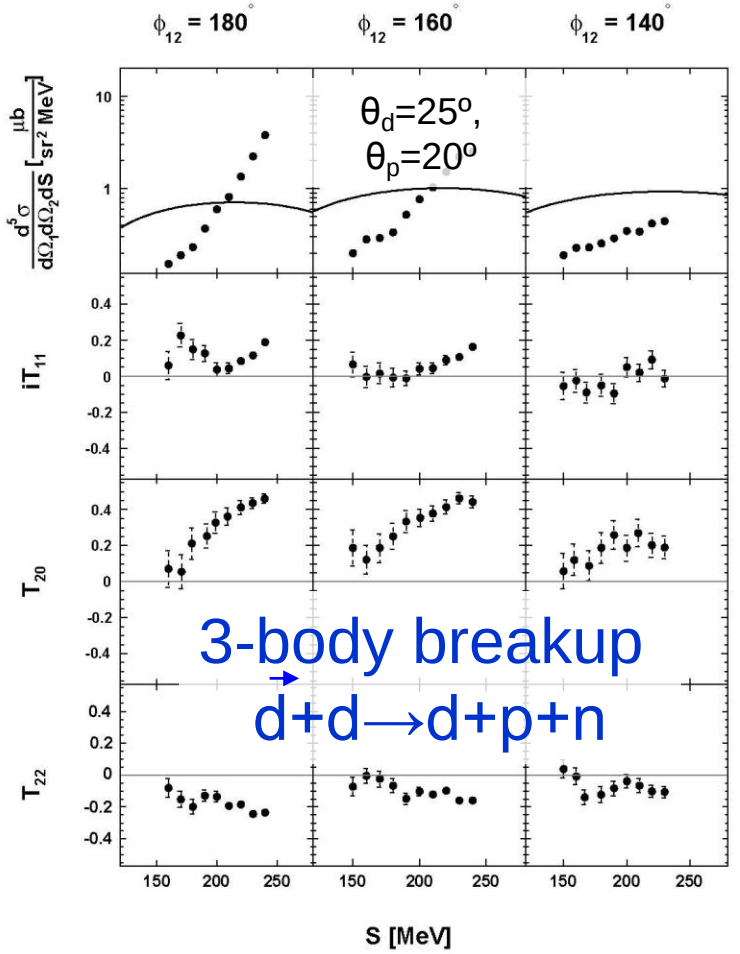
Four-Nucleon Systems

E_d = 130 MeV

θ = 15º - 30º

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





Few-Nucleon Systems
Summary

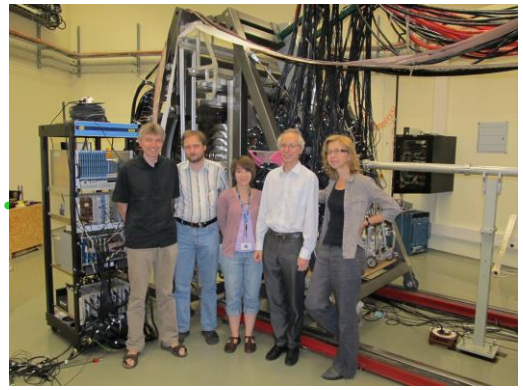
- Rich, systematic and precise sets of data available (elastic scattering – many, breakup – a few)
  - ➡ basis for comparing different approaches which predict the 3N system observables
- Showed significant 3NF effects
- Found large influence of the Coulomb force on c.s.
- Relativistic effects to be 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

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**

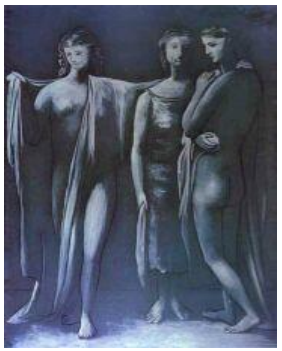


- Awaited theoretical achievements:
  - 3NF at N^{3}LO (close ahead...)
  - ChPT with Δ (work in progress...)
  - ✓ Realistic potentials with Coulomb
  - ✓ Relativistic potentials with 3NF
  - Rigorous calculations for 4N system (dreamed for !)

Few-Body Systems Remain Attractive !








Thank You for attention