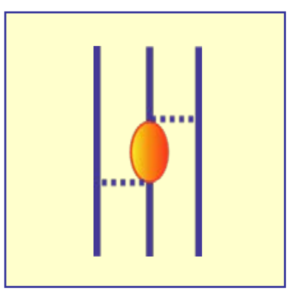
Deuteron Breakup in Collision with Proton

measurements at intermediate energies



Elżbieta Stephan

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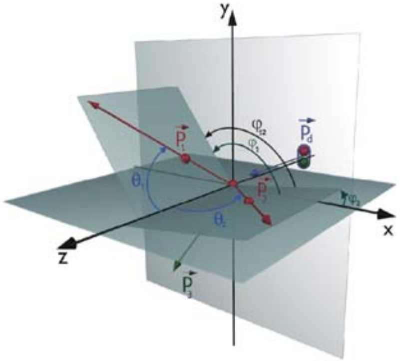
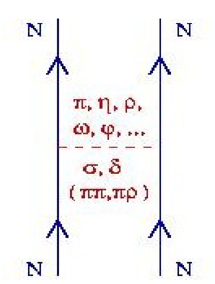
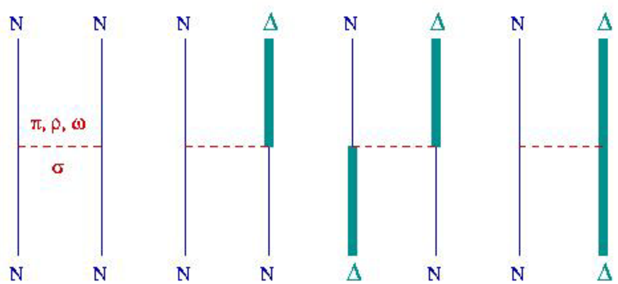


Starting point: 2 Nucleons

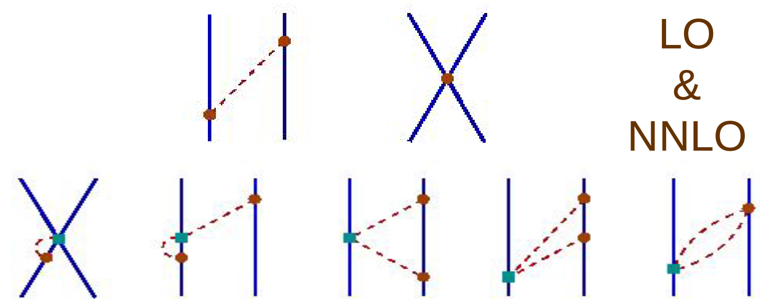
- Meson exchange theory of NN forces - *nucleonic degrees of freedom* (CD Bonn, Nijm I, Nijm II, AV18)
- CD Bonn + explicit treatment of a single Δ-isobar degrees of freedom – **C**oupled barion **C**hannels
- Effective Field Theory – **Ch**iral **P**erturbation **T**heory; expansion of potential in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



Realistic **P**otentials



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



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

Starting point: 2 Nucleons

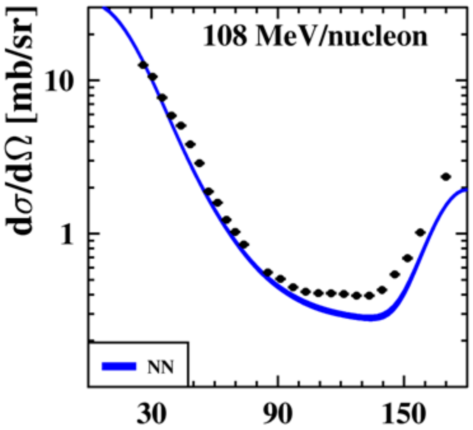
- very rich data base: ~3000 data points for pp below 350 MeV
- phase shift analysis by Nijmegen group (PWA93)
- quality of description: **χ^2 close to 1**

System of 3 Nucleons

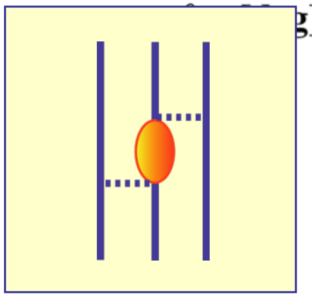
Predictions of NN potentials alone:

- 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

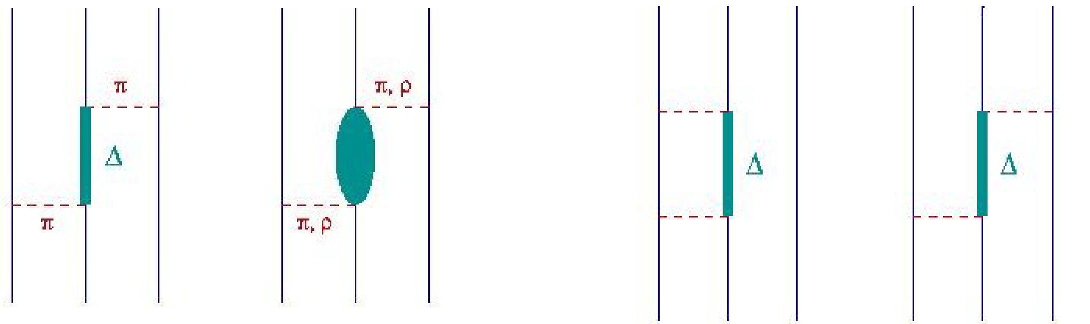


- Introducing concept of **three-nucleon forces**: genuine (irreducible) interaction of three nucleons
  - as a consequence of internal nucleon structure
- Systematic approach within ChPT

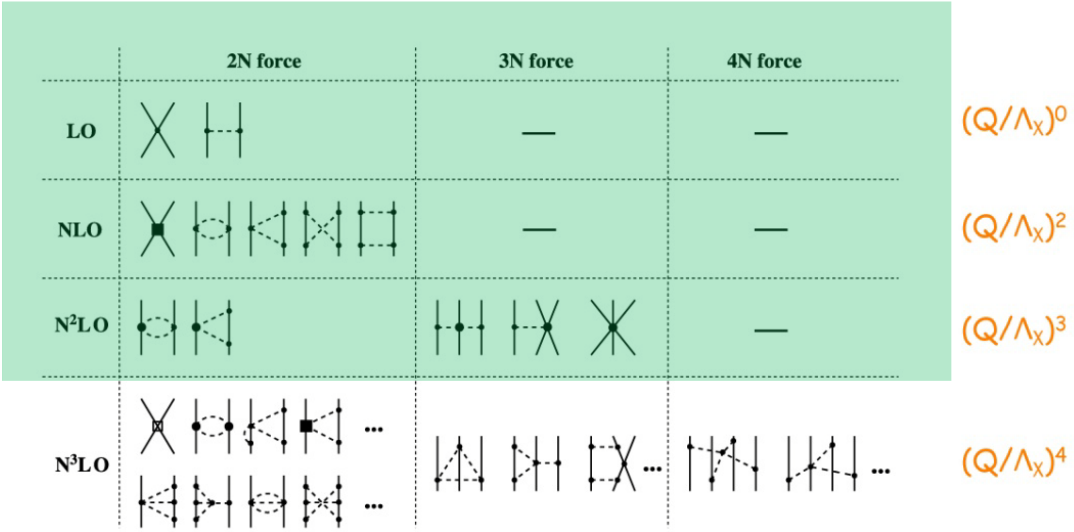


Next step: System of 3 Nucleons

- Models of 3NF:



- Naturally appearing in Chiral Perturbation Theory at N2LO:

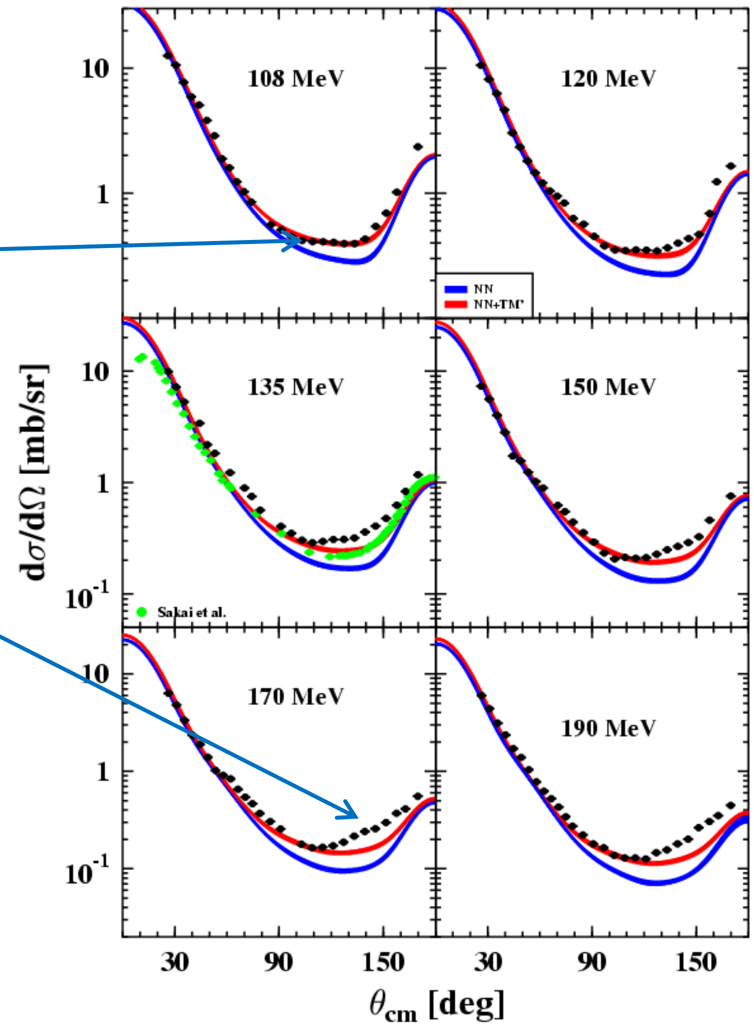


3N Systems - Reactions
what can be studied experimentally?

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

3N Systems – Elastic Scattering
Differential Cross Section

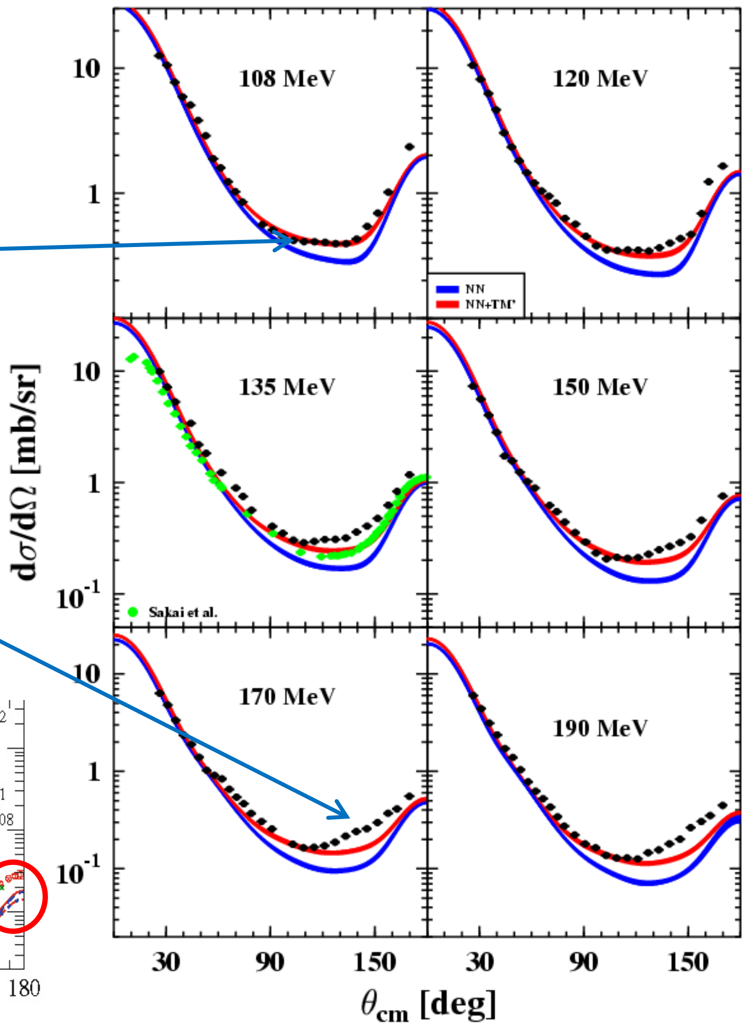
- ✓ rich data set (RIKEN/RCNP/IUCF/KVI)
- ✓ 3NF helps
- ➢ yet with rising energy discrepancy appears - problem with 3NF models?



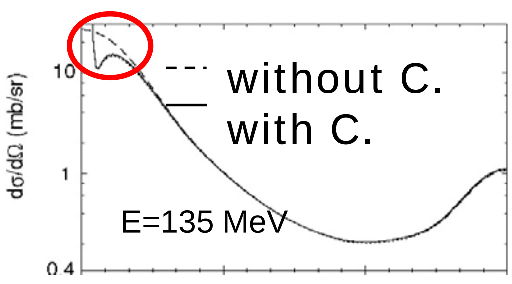
3N Systems – Elastic Scattering
Differential Cross Section

- ✓ rich data set (RIKEN/RCNP/IUCF/KVI)
- ✓ 3NF helps
- ➢ yet with rising energy discrepancy appears - problem with 3NF models?

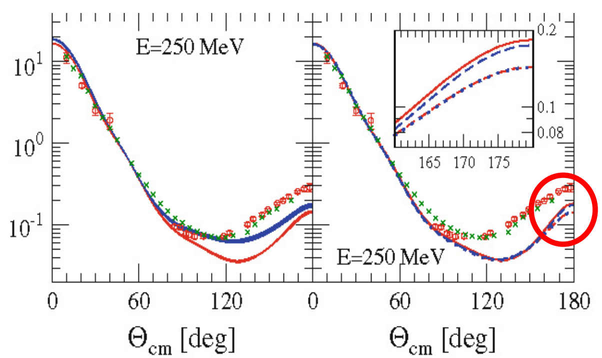
Effects small, located at extreme angles !



Coulomb interaction?



Relativistic effects?

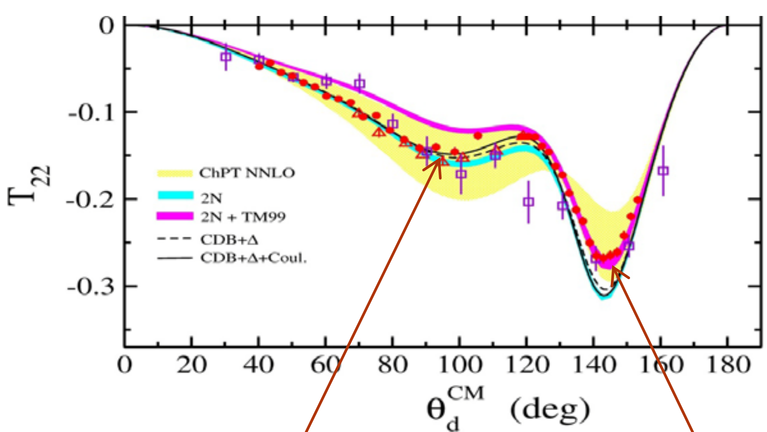


3N Systems – Elastic Scattering
Analyzing Powers

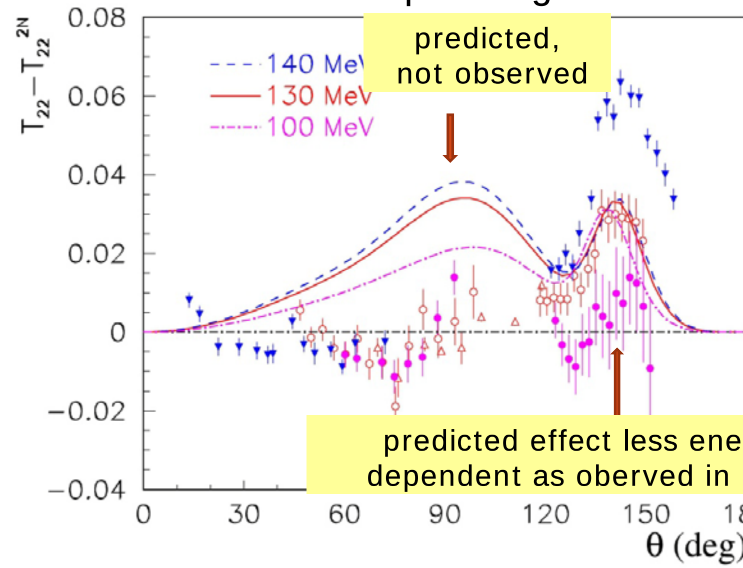
- 3NF not always improves description- a lot of examples at various energies
- problem with spin part of 3NF?

•**140 MeV** - K. Sekiguchi et al., Phys. Rev. C 70, 014001 (2004)
•**130 MeV** - H. Mardanpour et al., Eur. Phys. Jour. 31, 383 (2007), E.Stephan et al., Phys. Rev. 76 057001 (2007)
•**100 MeV** E.Stephan et al.,

130 MeV (65 MeV/nucleon)



Net 3NF effects in T22 depending on beam energy



predicted, not observed

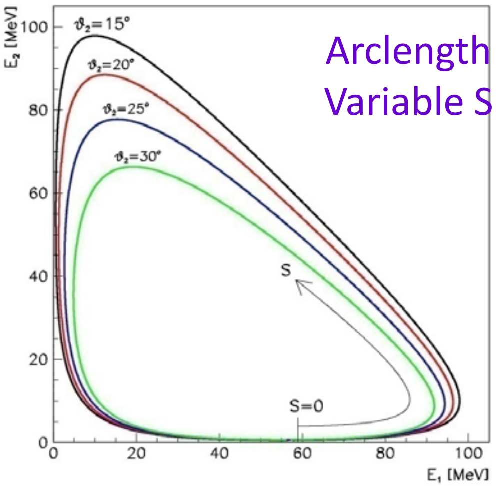
predicted effect less energy dependent as oberved in data

data agree with NN calculations

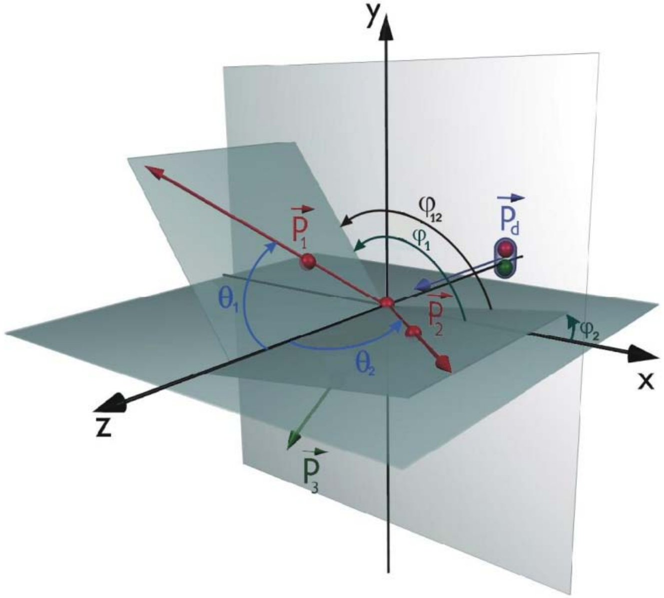
data agree with NN+3NF

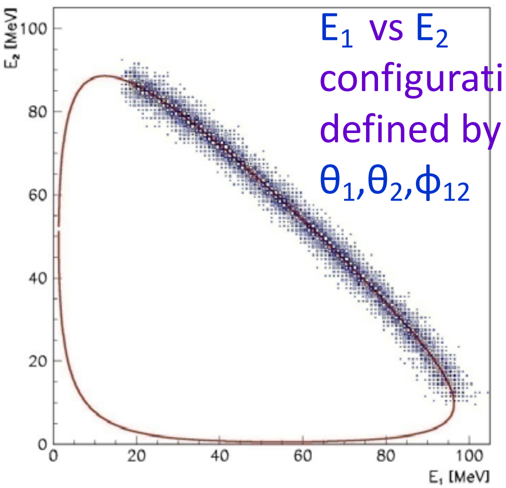
3N Systems-Breakup Reaction

- **Three nucleons** in the final state - 9 variables
- Energy-momentum conservation – 4 equations
- Five independent kinematical variables
  - ✓ Complete (exclusive) exp. – measured ≥ 5
  - ✓ Inclusive exp. – measured ≤ 4 parameters



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

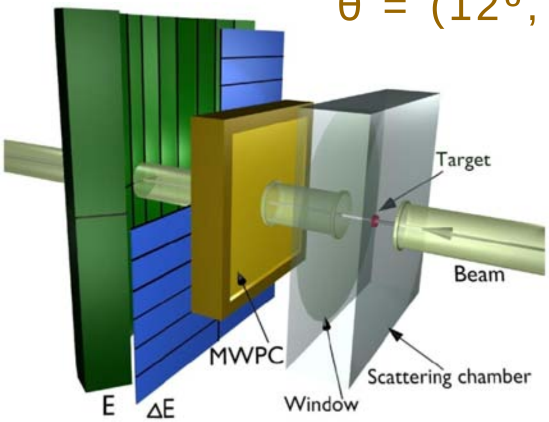




Large Acceptance Detectors for Few Nucleon System Studies

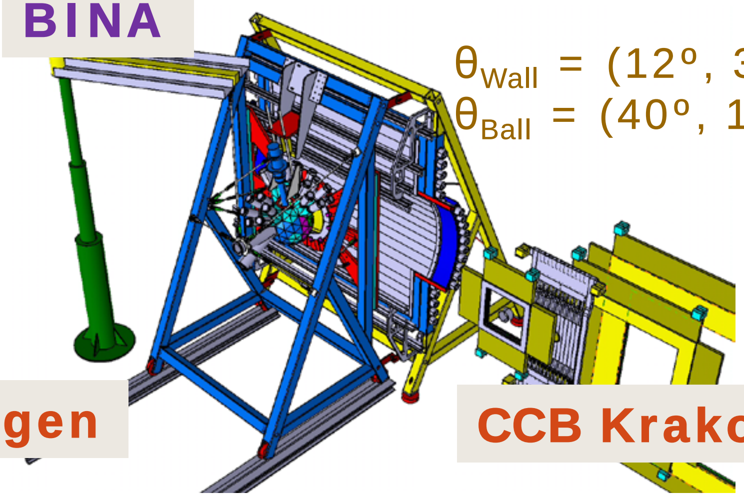
SALAD

$\theta = (12^o, 35^o)$



BINA

$\theta_{Wall} = (12^o, 35^o)$
$\theta_{Ball} = (40^o, 180^o)$

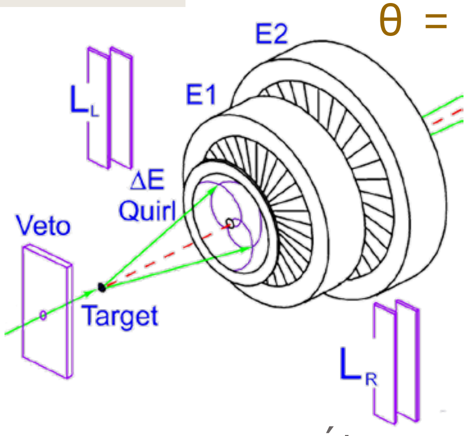


KVI-Groningen

CCB Krakow

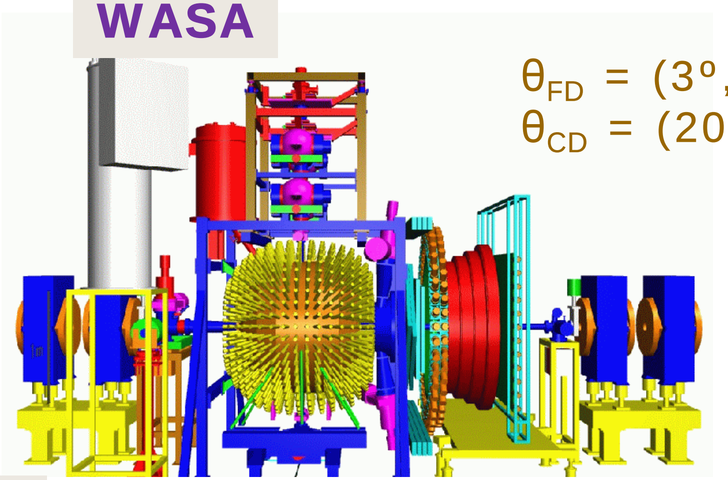
GeWall

$\theta = (3^o, 15^o)$



WASA

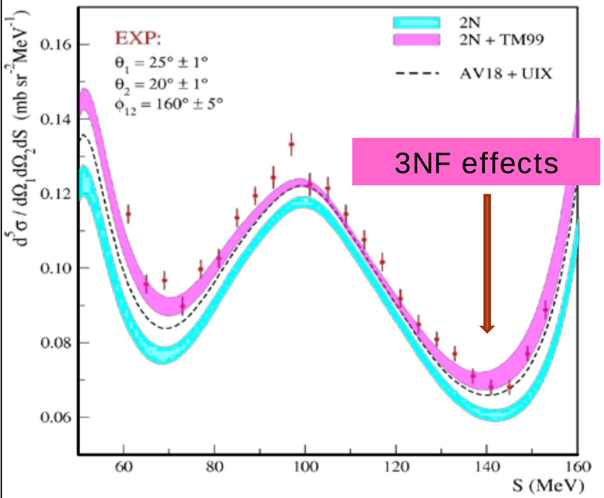
$\theta_{FD} = (3^o, 18^o)$
$\theta_{CD} = (20^o, 169^o)$



COSY-Juelich

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

Cross Section Results – 3NF & Coulomb Effects

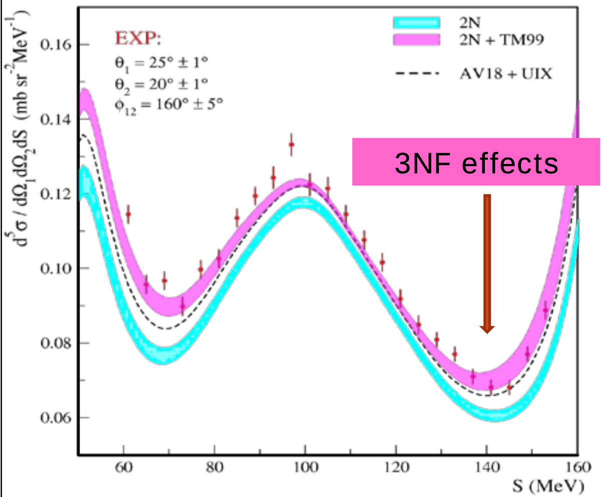


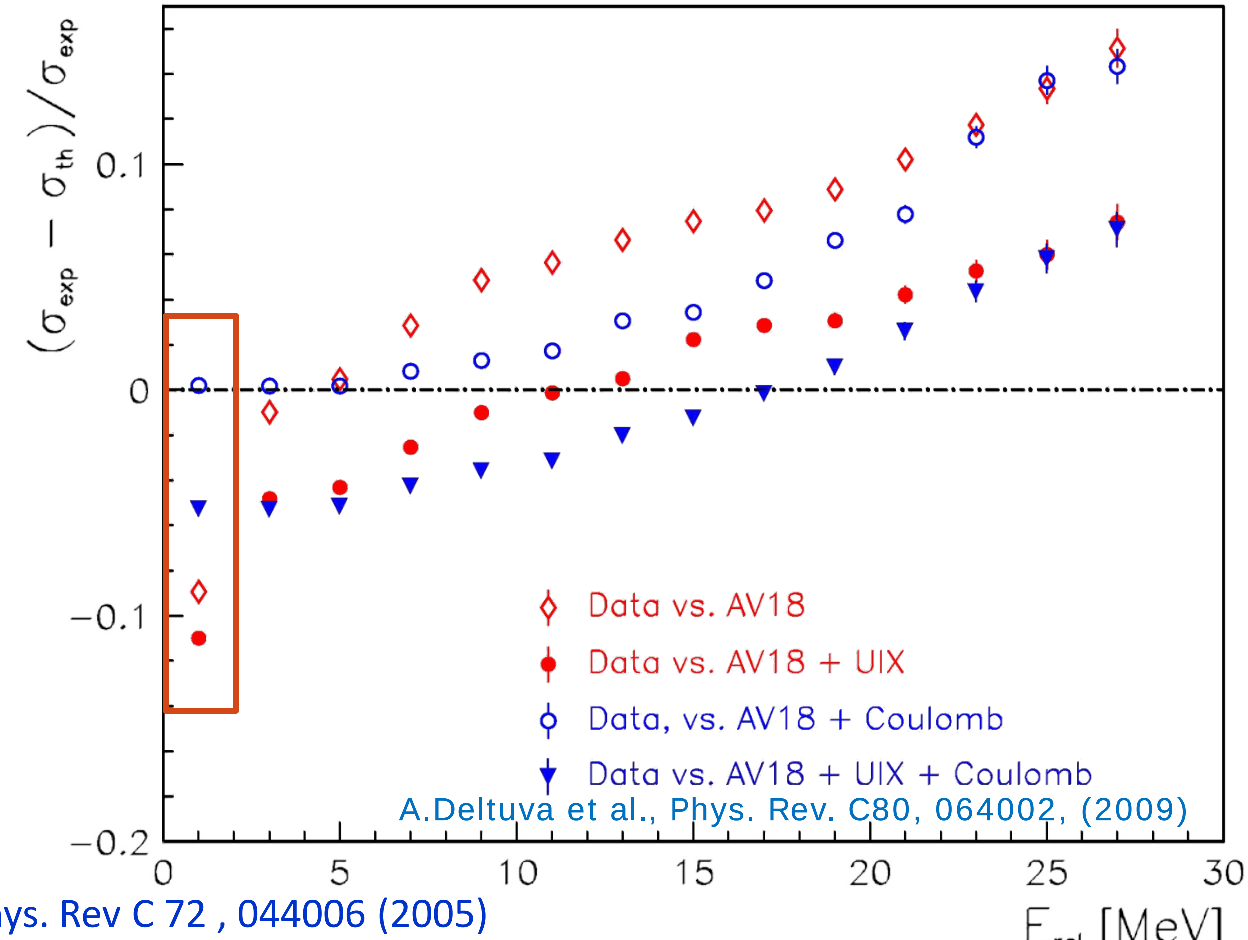
SALAD@KVI, St. Kistryn et al., Phys. Rev C 72 , 044006 (2005)

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

Cross Section Results – 3NF & Coulomb Effects

- few hundreds data points per observable



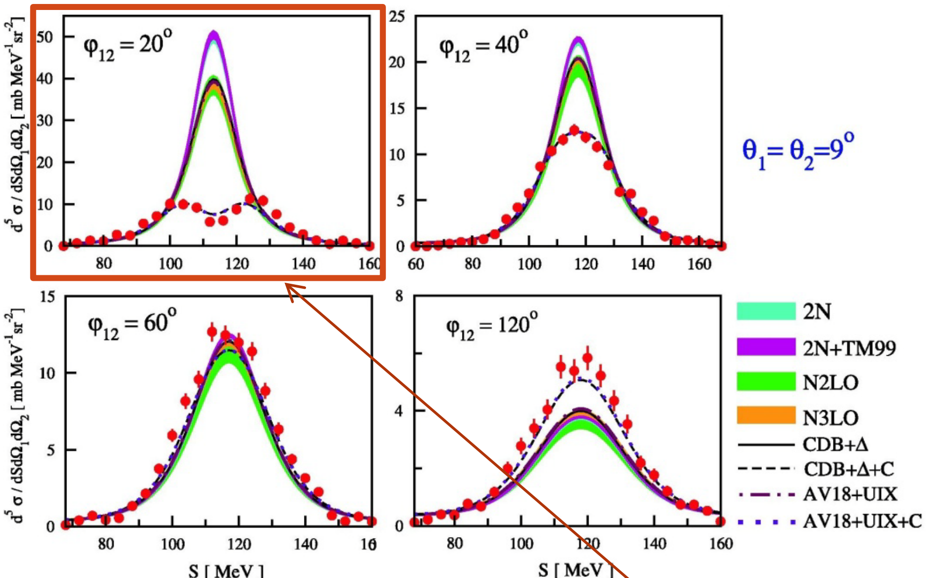


The best agreement is reached when both, the Coulomb force and the 3NF are taken into account !

SALAD@KVI, St. Kistryn et al., Phys. Rev C 72 , 044006 (2005)

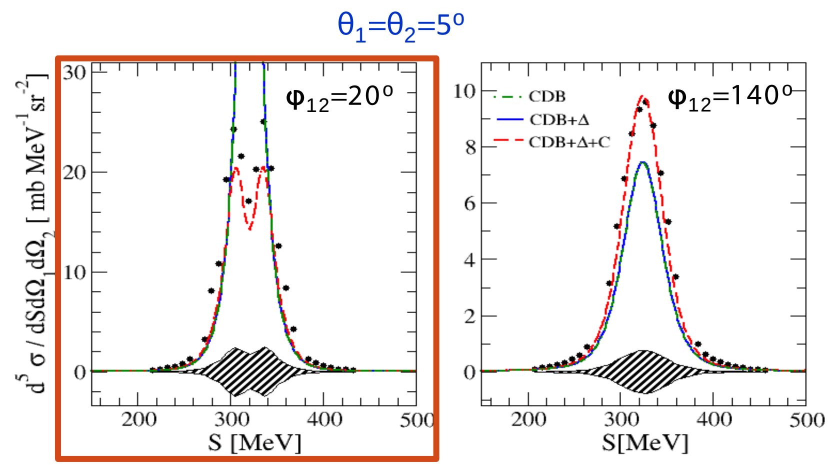
^{1}H(d,pp)n Breakup Cross Section
3NF+Coulomb

65 MeV/nucleon



GeWall@COSY, I.Ciepał et al.

170 MeV/nucleon



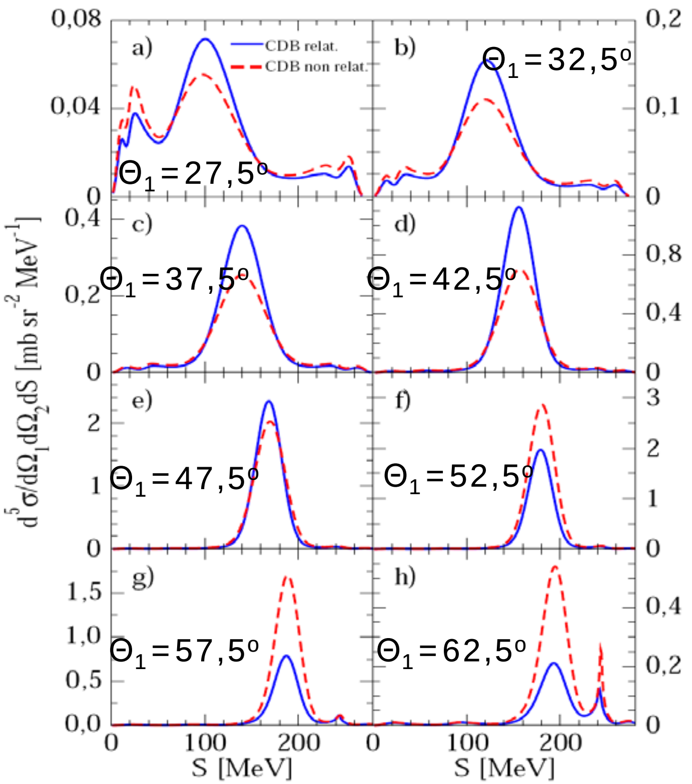
WASA@COSY, B. Kłos et al.

Prominent Coulomb effects at p-p FSI
in wide range of beam energies

$^1H(d,pp)n$ and $^2H(p,pp)n$ Breakup Cross Section Relativistic Effects

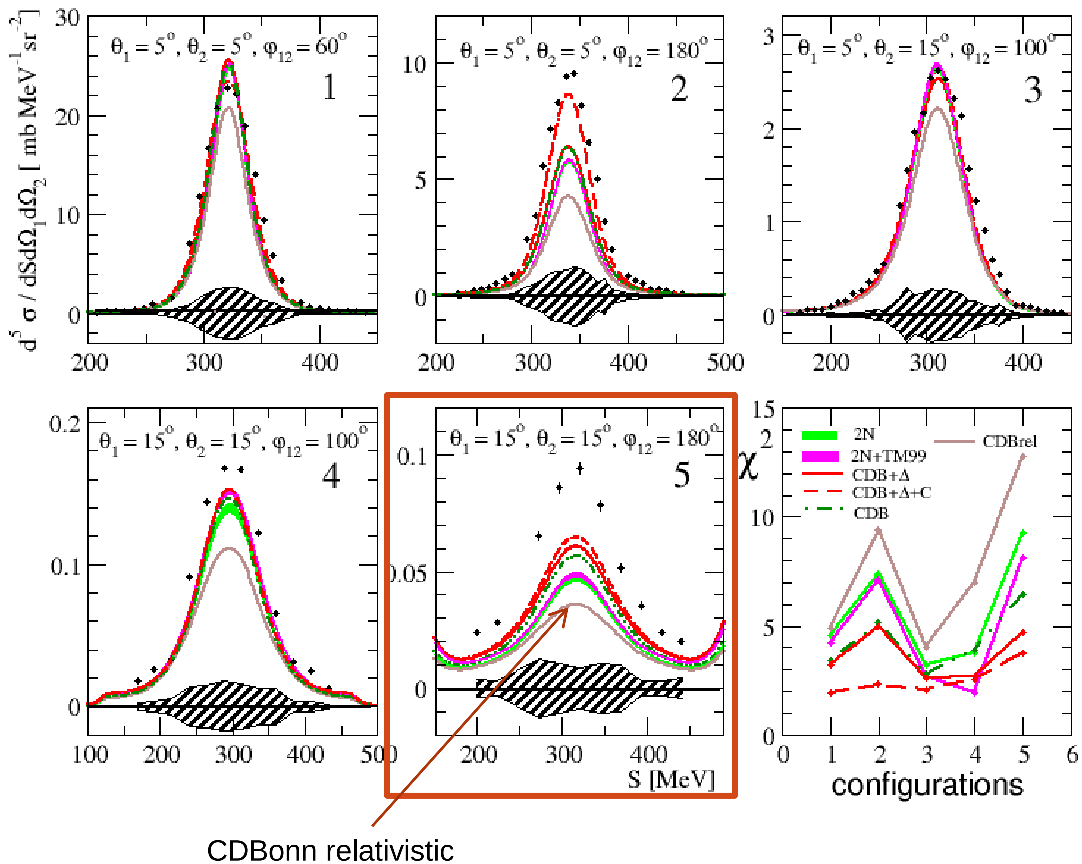
$^2H(n,pn)n$ 200 MeV

R. Skibiński, Eur. Phys. J. A 30, 369, (2006)



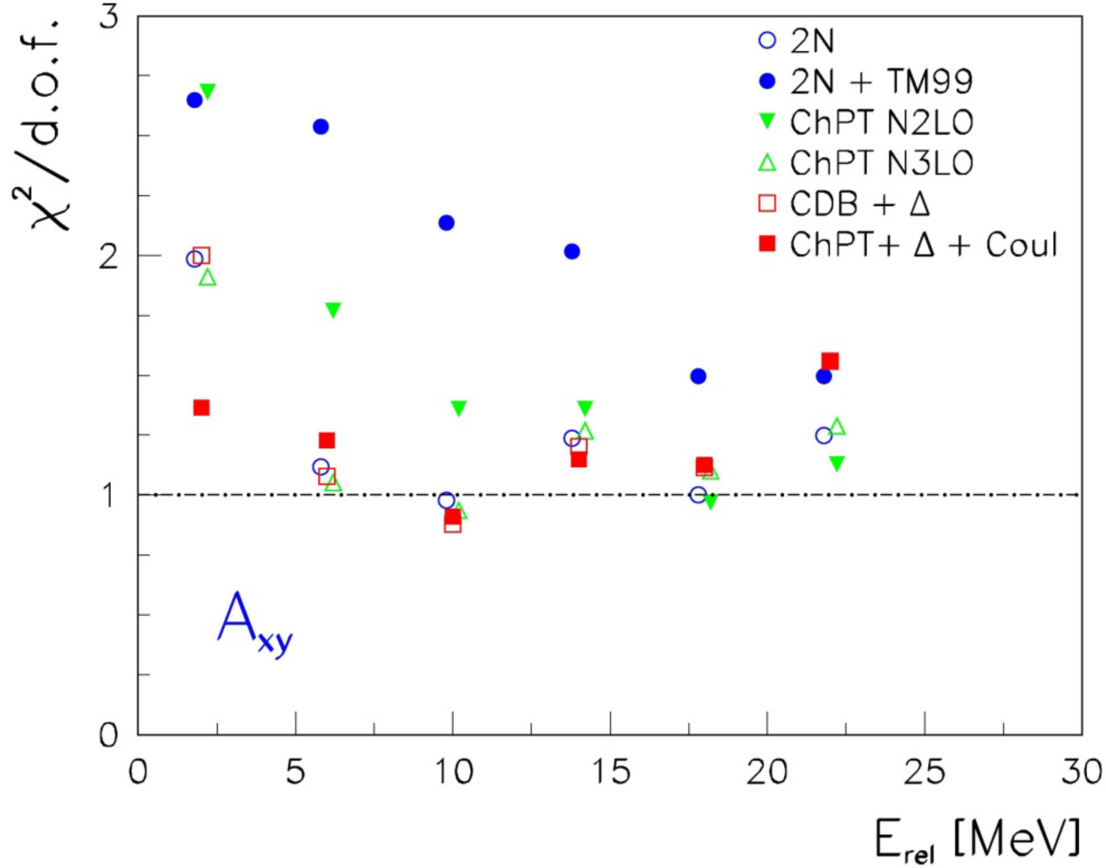
$\theta_2=37.5^0$, $\varphi_{12}=180^0$

$^1H(d,pp)n$ 170 MeV/nucleon

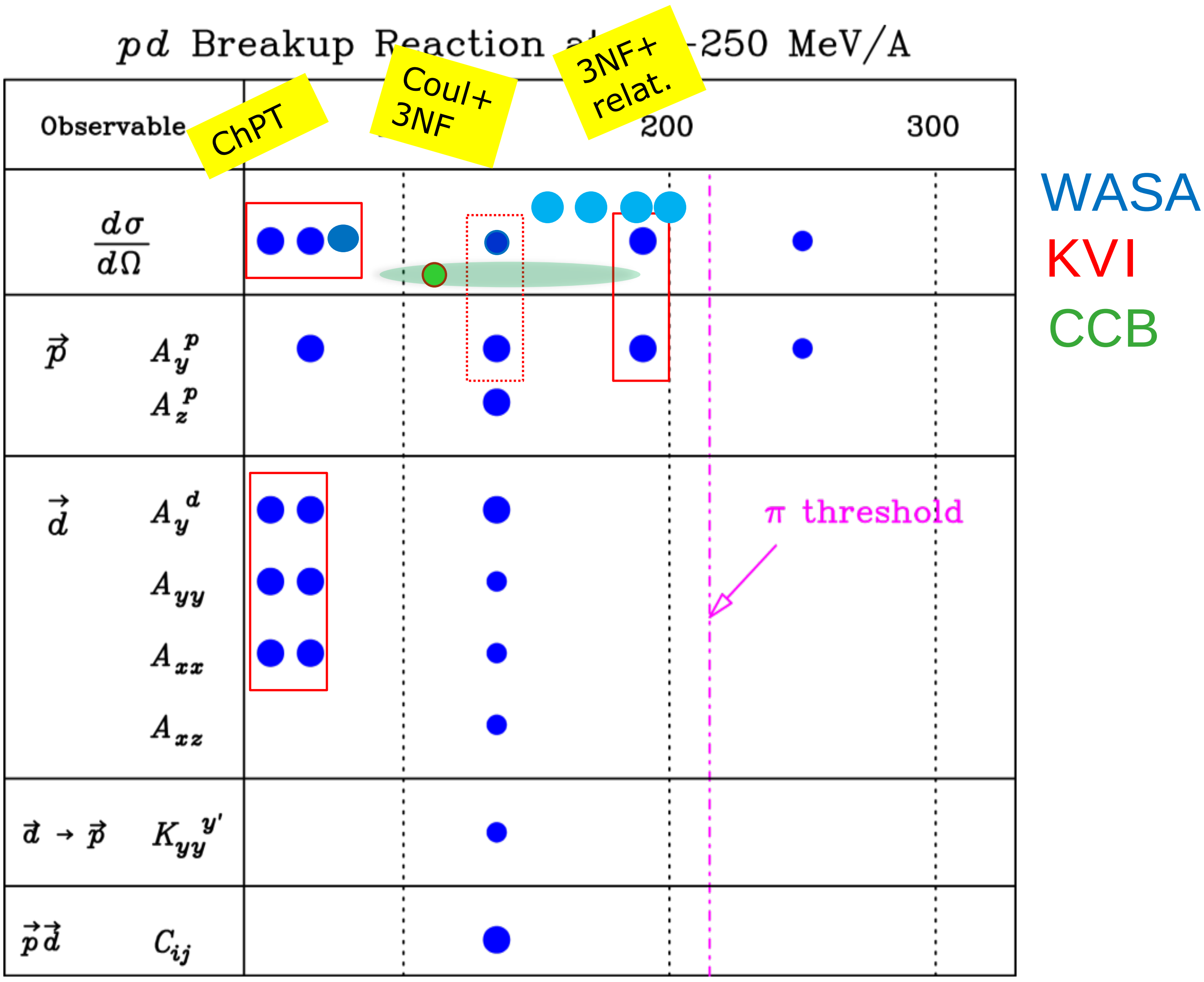


$^{1}H(\vec{d},pp)n$ breakup at 130 MeV

Tensor analyzing power



Problem with TM99 3NF



pd Breakup Reaction
-250 MeV/A
Observable
ChPT
Coul+ 3NF
3NF+ relat.
200
300
$\frac{d\sigma}{d\Omega}$
$\vec{p}$ A_y^p
A_z^p
$\vec{d}$ A_y^d
A_{yy}
A_{xx}
A_{xz}
$\vec{d} \rightarrow \vec{p}$ $K_{yy}^{y'}$
$\vec{p}\vec{d}$ C_{ij}
π threshold
WASA
KVI
CCB

Proton-Deuteron Collisions: role of 3NF

Elastic Scattering vs Breakup Reaction

	p-d Elastic Scattering	Deuteron Breakup in p-d
3NF - influence on the cross section	significant, confirmed problem at energies >100 MeV	significant, confirmed ? (relativistic effects)
3NF - polarization observables	inconclusive	inconclusive
Coulomb interaction-influence on the cross section	negligible	significant, dominating at pp FSI , confirmed
relativistic effects	negligible	large effects in calculations, experimental confirmation needed

Nucleon-Deuteron Breakup
Recent achievements in theoretical calculations

- ChPT
  - awaited **new ChPT** calculations, at N2LO / N3LO
- Realistic potentials
  - calculations including each ingredient separately:
    - 3NF *(Witała et al., Deltuva et al.),*
    - Coulomb *(Deltuva et al.),*
    - relativistic *(Witała et al.)* approach

    - all the effects are important at medium energies !
  - calculations including Coulomb interaction and 3NF *(A.Deluva et al.)*

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Warsaw University
KVI-CART Groningen
WASA@COSY Collaboration

Thank you for your attention !