SFB1044 workshop:
Electromagnetic observables for low-energy nuclear physics

Few-Nucleon Systems

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Hadronic Few Body Systems

Starting point: 2 Nucleons

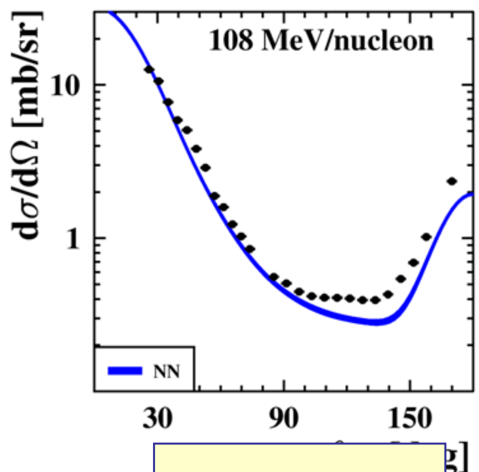
- very rich data base: ~3000 data points for pp below 350 MeV
- phase shift analysis by Nijmegen group (PWA93)
- quality of description: χ^2 close to 1

System of 3 Nucleons

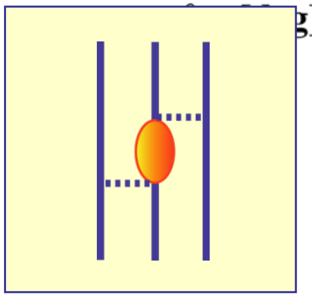
Predictions of NN potentials alone:

- 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



3N Systems

what can be studied experimentally?

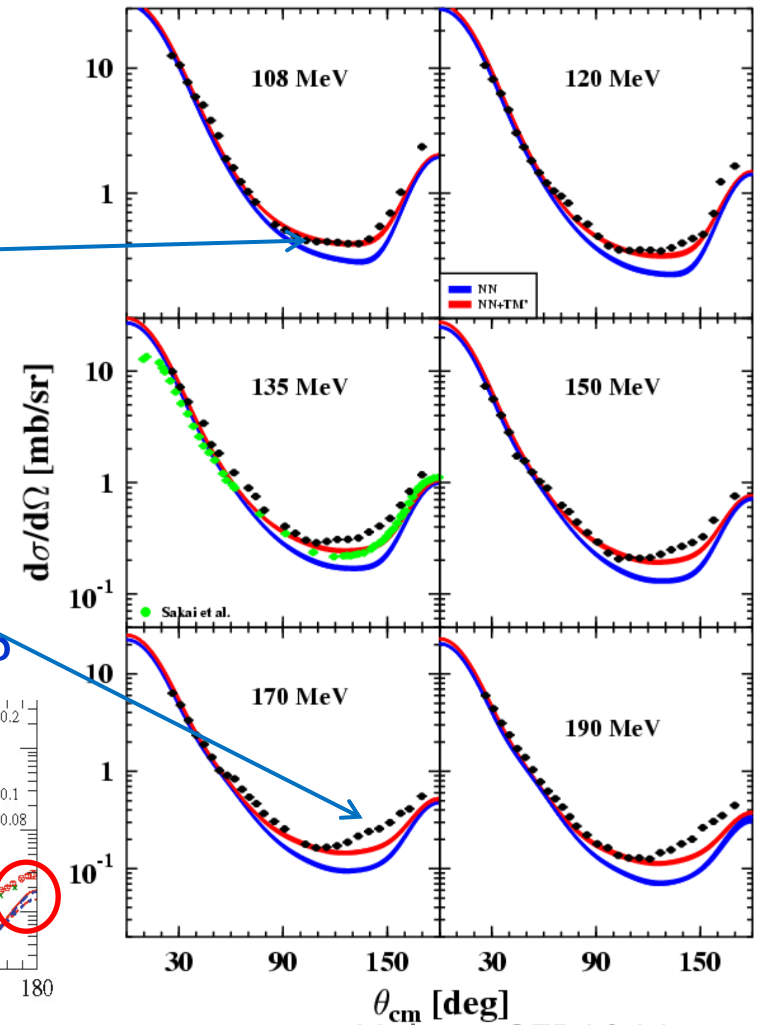
- **Processes:**
  - Elastic scattering: N + d → N + d
  - Breakup: N + d → N + N + N
  - and electromagnetic processes
- **Observables:**
  - differential cross section
  - vector&tensor analyzing powers
  - polarization transfer, correlations
- **Energy range - why "medium" and what does it mean?**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

3N Systems – Elastic Scattering

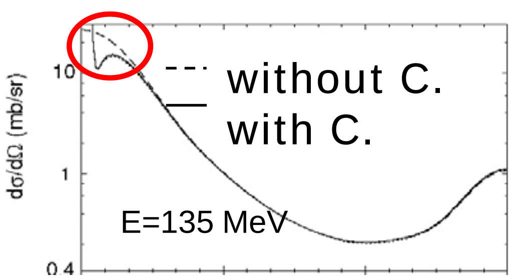
Differential Cross Section

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

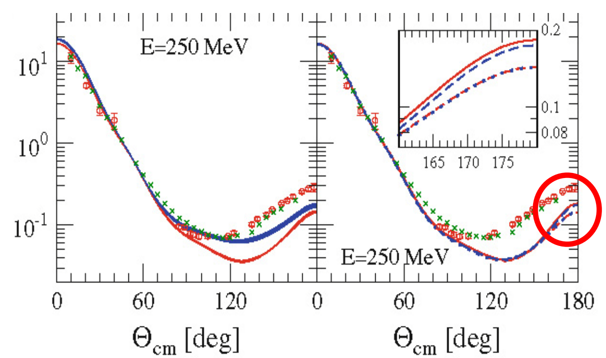
Effects small, located at extreme angles !



Coulomb interaction?



Relativistic effects?

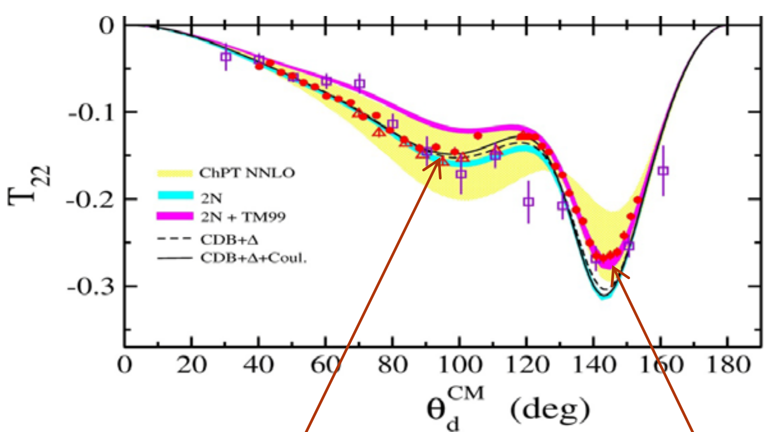


3N Systems – Elastic Scattering
Analyzing Powers

- 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.,

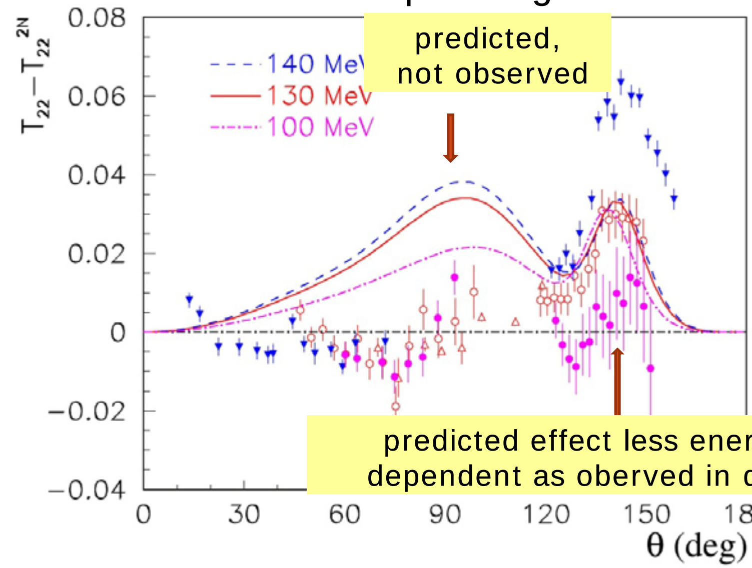
130 MeV (65 MeV/nucleon)



data agree with NN calculations

data agree with NN+3NF

Net 3NF effects in T22 depending on beam energy



predicted, not observed

predicted effect less energy dependent as observed in data

3N Systems

Elastic Nucleon-Deuteron Scattering

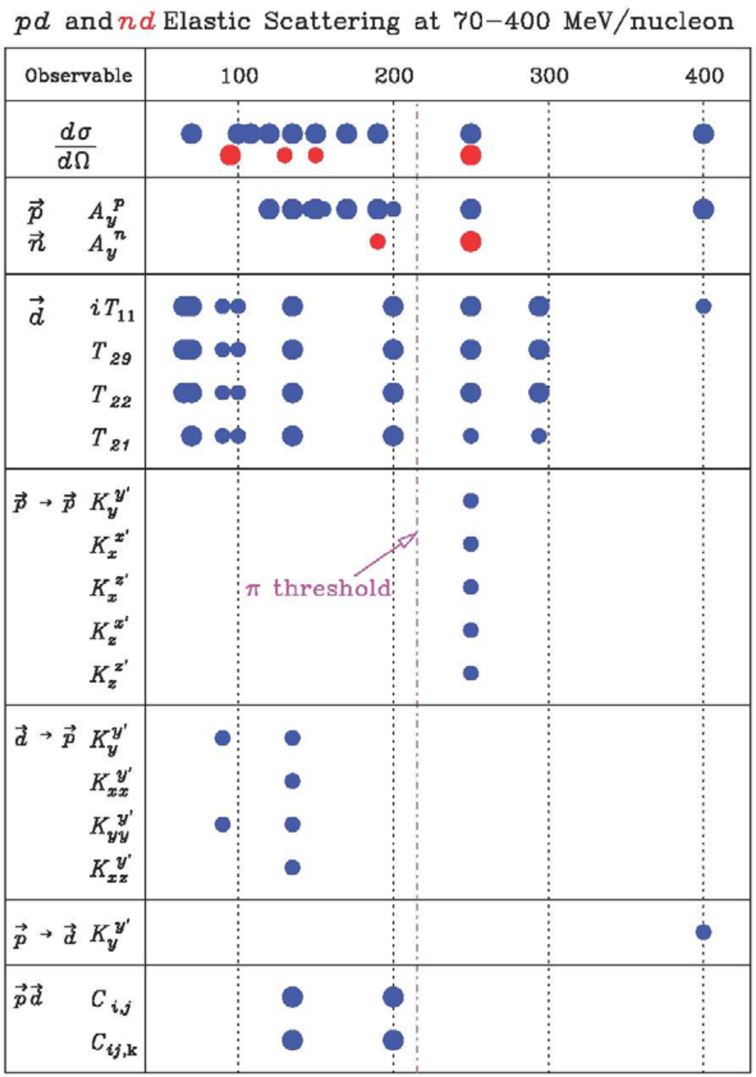


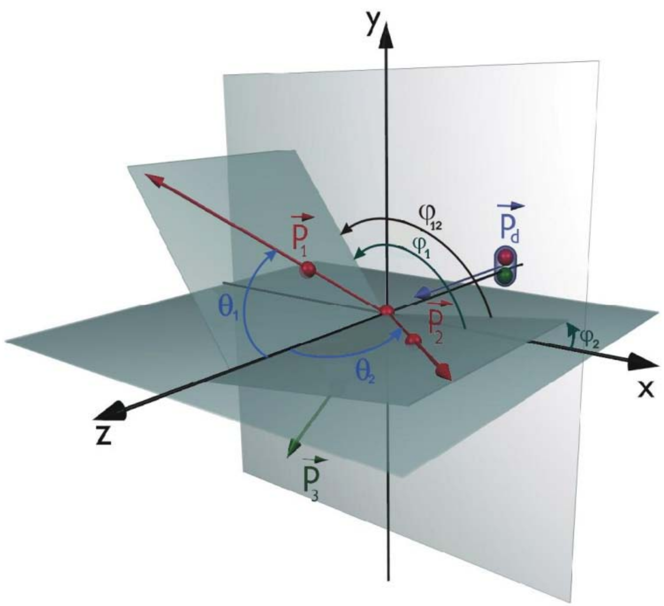
Diagram: K. Sekiguchi, FB20

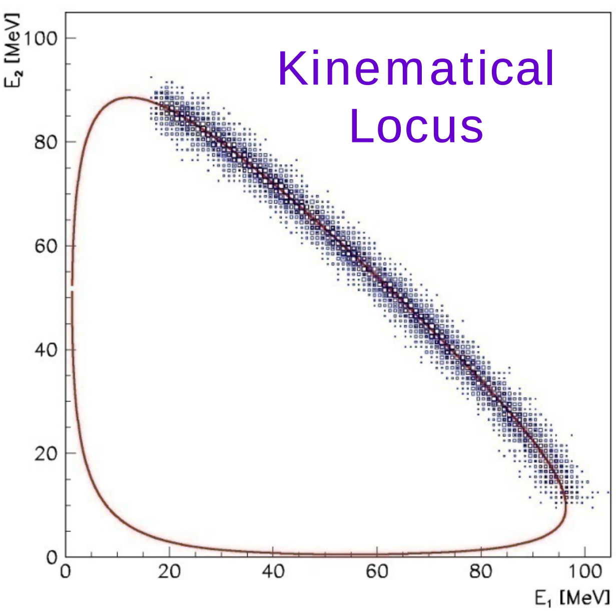
- Number of observables for the **elastic scatterng channel** - complete set would provide full dynamical information (at the given energy)
- **Only fraction** has been measured accurately and systematically (RIKEN/RCNP/IUCF/KVI)
- Not completely clear picture - still much to explore !
- Complementary studies needed: **Nucleon-Deuteron Breakup**

3N Systems-^{1}H(d,pp)n 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

^{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



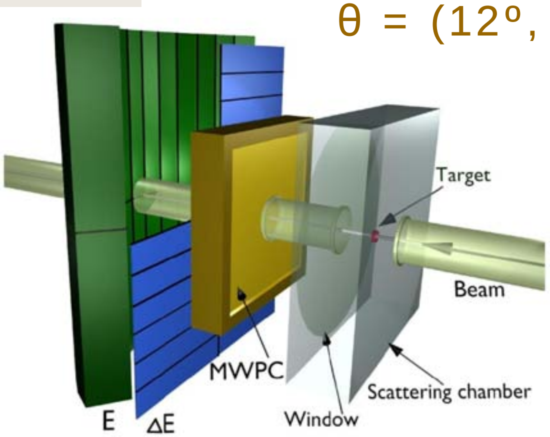


Large Acceptance Detectors for Few Nucleon System Studies

(50-200 MeV/nucleon)

SALAD

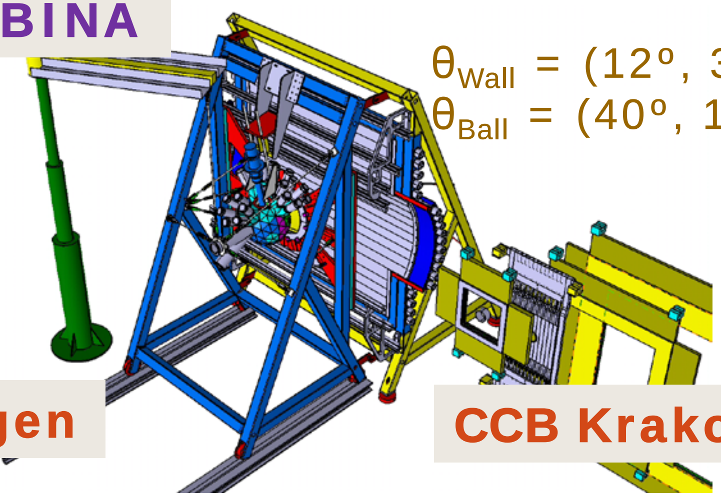
$\theta = (12^o, 35^o)$



BINA

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

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

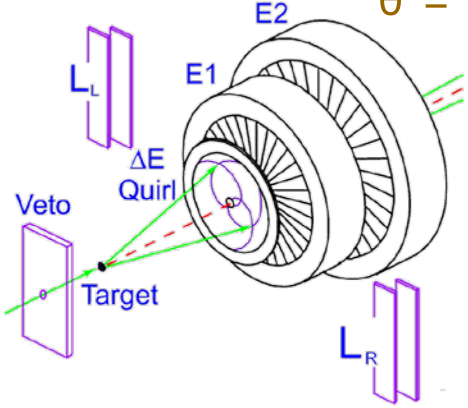


KVI-Groningen

CCB Krakow

GeWall

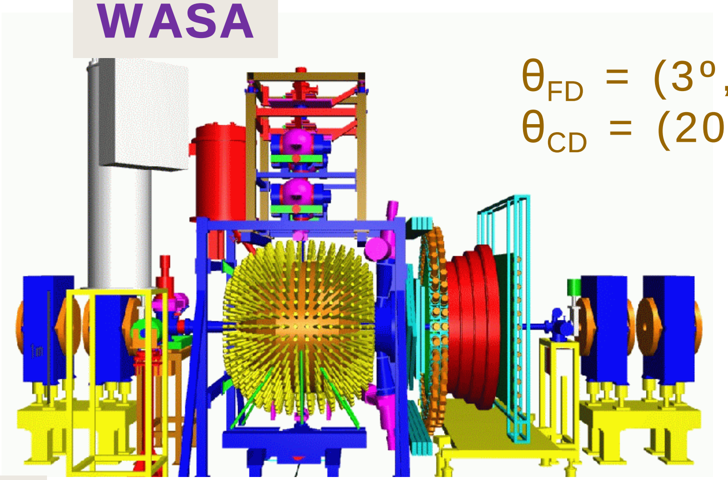
$\theta = (3^o, 15^o)$



WASA

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

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

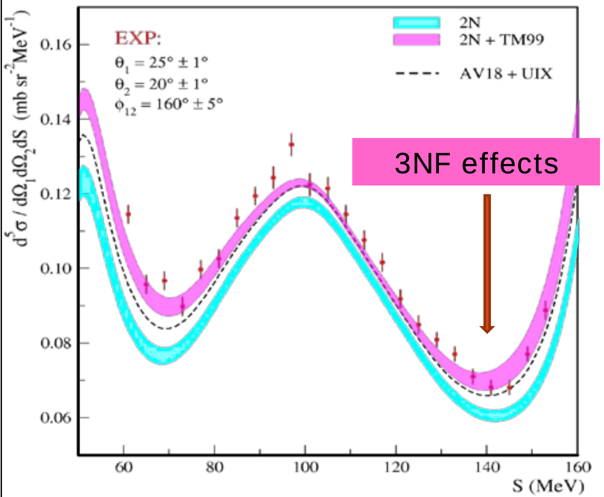


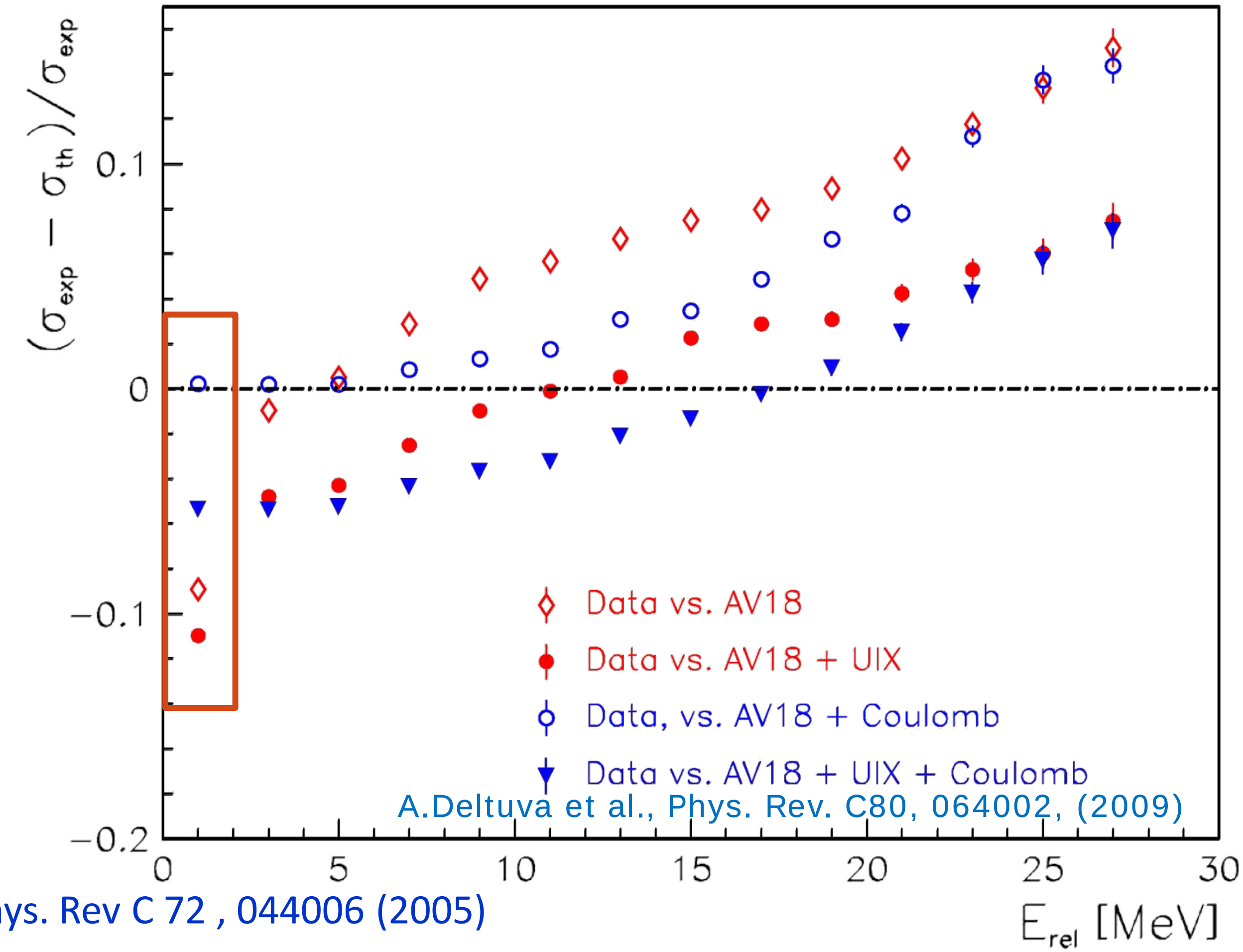
COSY-Juelich

[1]H(d,pp)n Measurement at 130 MeV (65 Mev/nucleon)

Cross Section Results – 3NF & Coulomb Effects

- few hundreds data points per observable



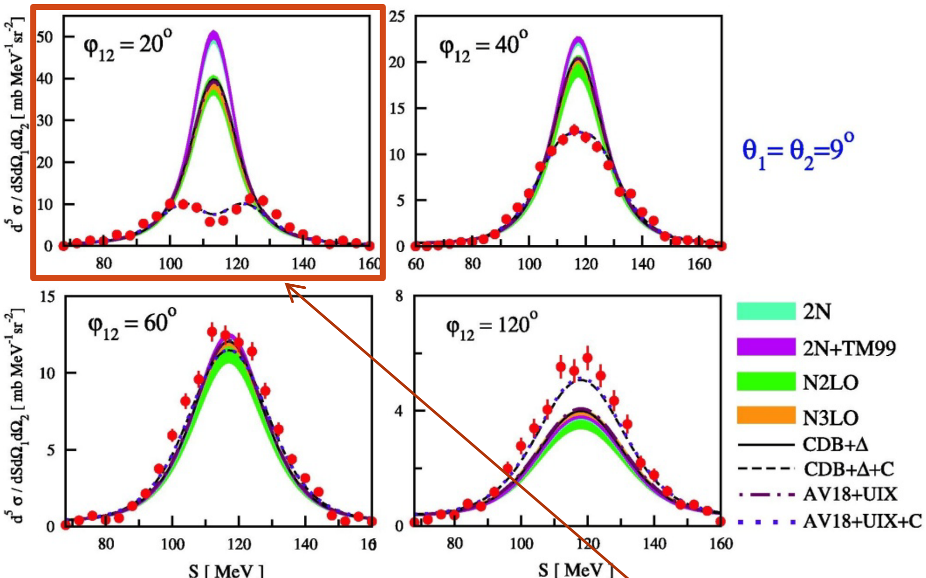


The best agreement is reached when both, the Coulomb force and the 3NF are taken into account !

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

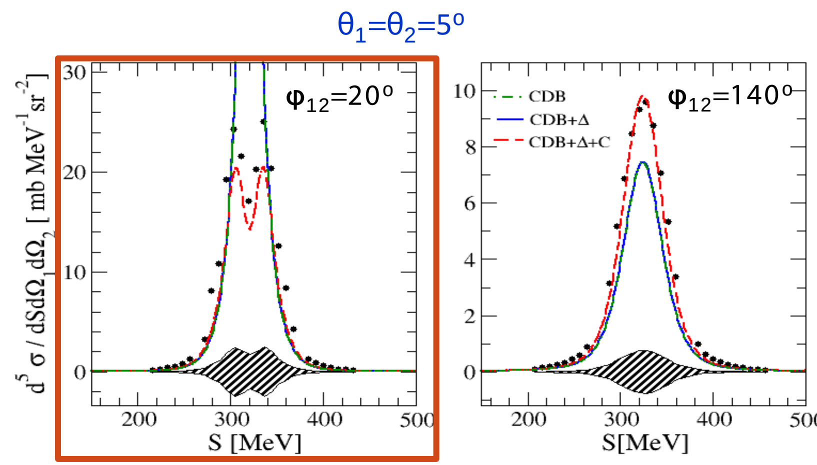
^{1}H(d,pp)n Breakup Cross Section
3NF+Coulomb

65 MeV/nucleon



GeWall@COSY, I.Ciepał et al.

170 MeV/nucleon



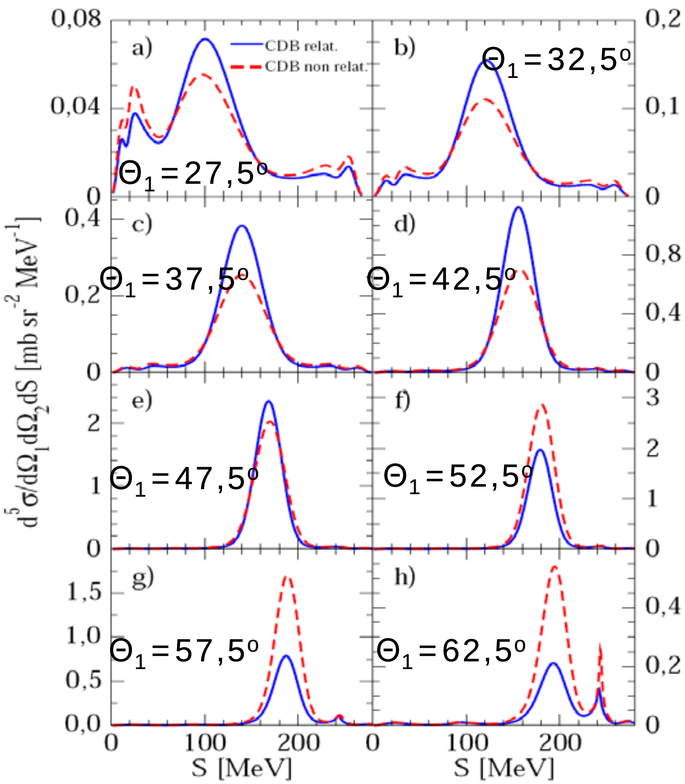
WASA@COSY, B. Kłos et al.

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

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

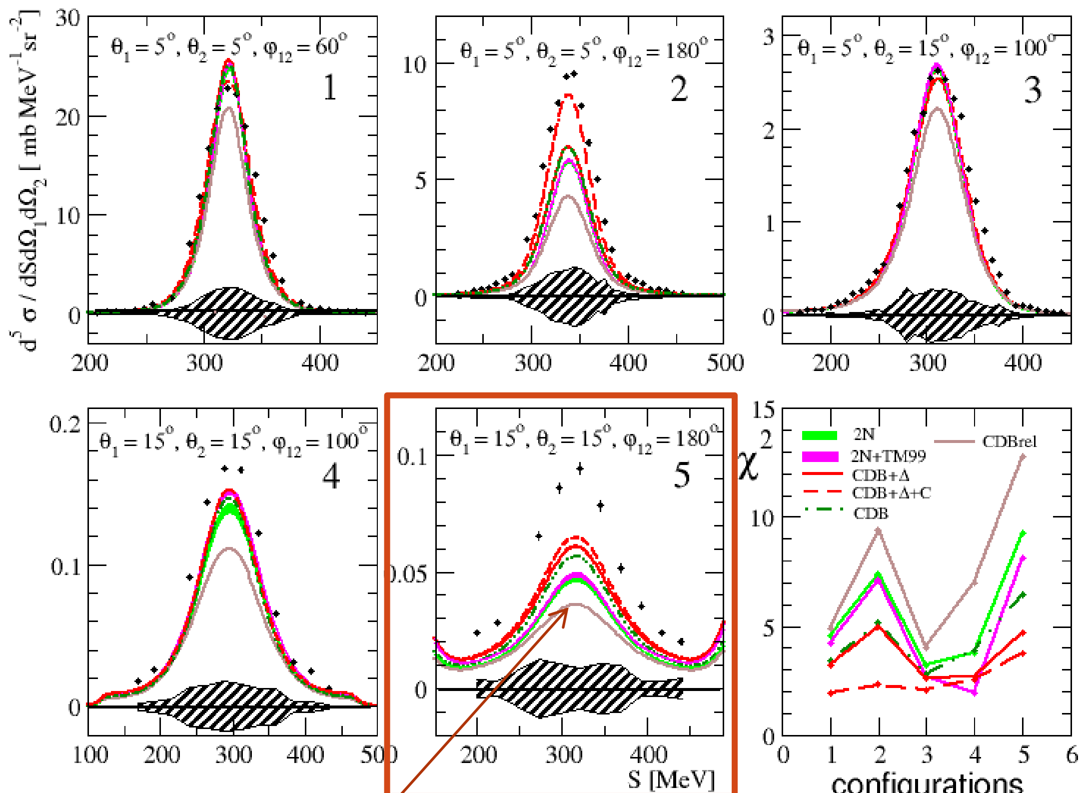
^{2}H(n,pn)n 200 MeV

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



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

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



CDBonn relativistic

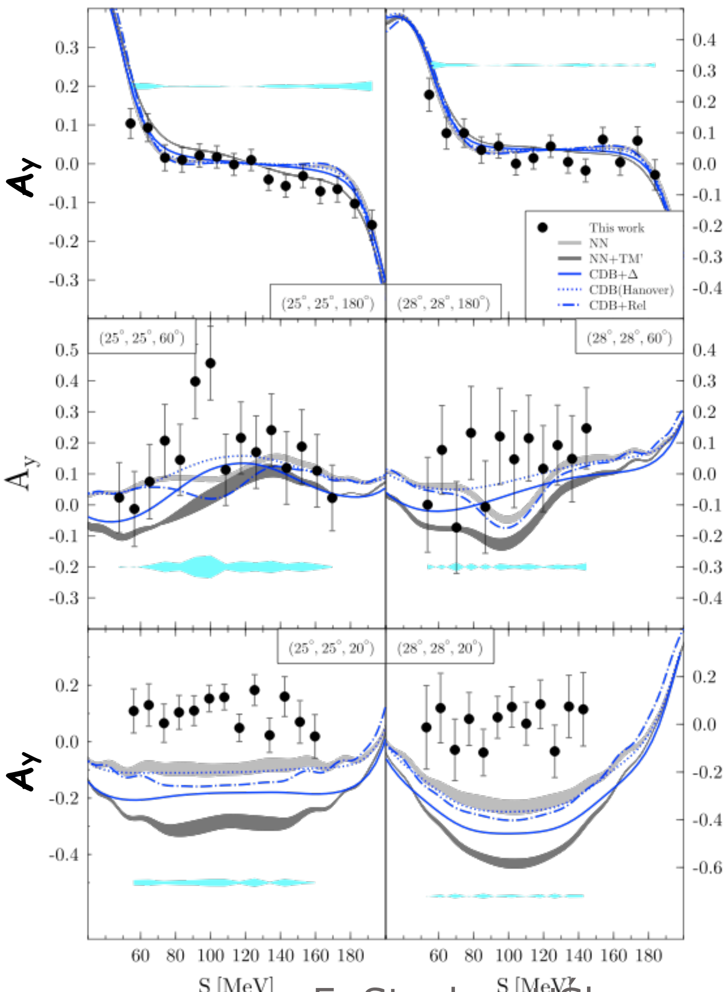
Nucleon-Deuteron Breakup
Recent achievements in theoretical calculations

- ChPT
  - awaited **new ChPT** calculations, at N3LO with 3NF
- Realistic potentials
  - calculations including each ingredient separately: 3NF, Coulomb, relativistic approach - all the effects are important at medium energies !
  - calculations including Coulomb interaction and 3NF *(A.Deluva et al. 2009)*
  - calculations in relativistic approach including 3NF *(H.Witała et al. 2011)*

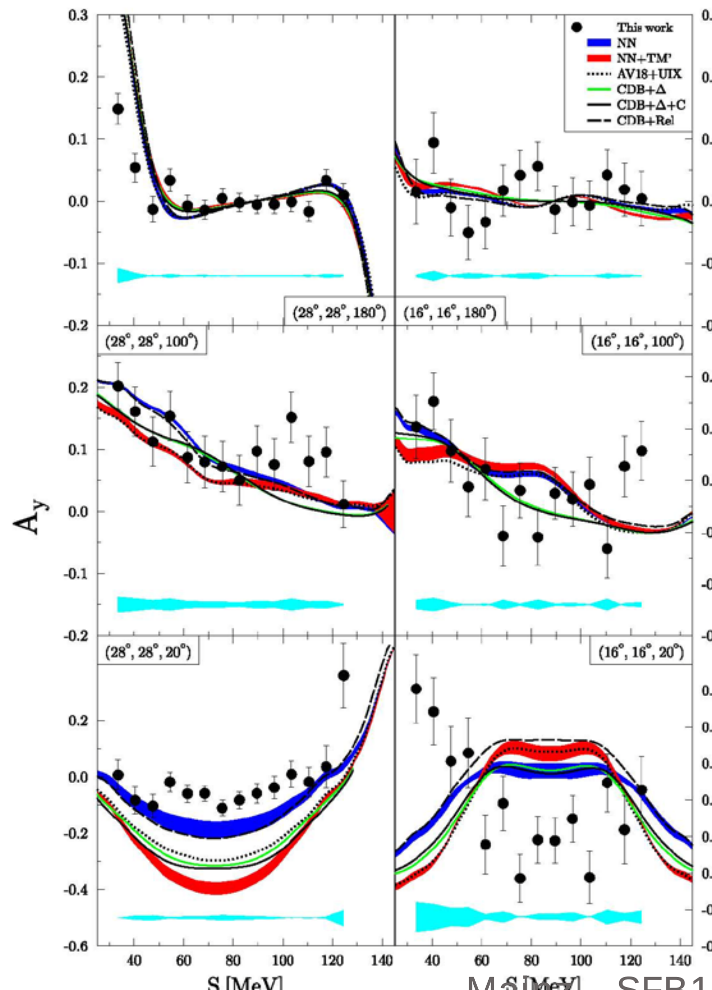
3N system - $^2H(\vec{p},pp)n$ Breakup

Vector (proton) Analyzing Power

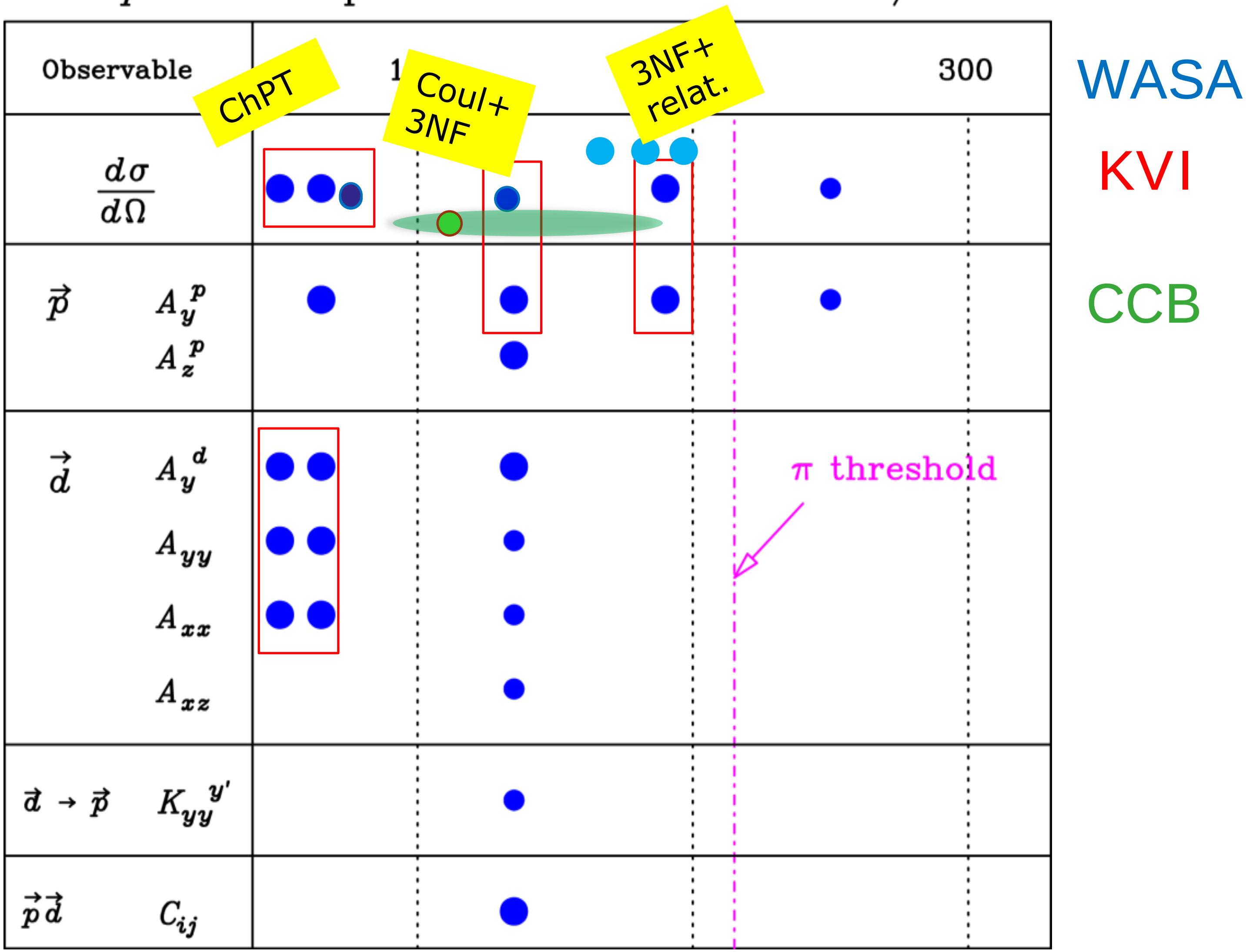
190 MeV, H. Mardanpour et al.



135 MeV, M. Eslami-Kalantari et al.



pd Breakup Reaction at 50–250 MeV/A



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 in progress

Electron scattering for Few Body Physics
Basic questions.

- What can be calculated?
- **What is interesting?**
  - on the basis of calculations, i.e. sensitivity to dynamics
  - on the basis of existing data (discrepancies)
- What can be measured? At what accuracy?
  - statistical accuracy - luminosity, detector acceptance
  - systematic accuracy

Beams vs Targets

- Beam MESA
  - external: 155 MeV, 0.1mA, polarization 80%
  - internal (recovery mode): 105 MeV, >**1 mA**, polarization 80% ?
  - if polarization - polarimeter (Moller, Mott)
- Target (d, ^{3}He, ^{4}He, ...)
  - internal gas (jet) target
    - no windows
    - low density
    - well defined interaction point (beam - target intersection)
  - open tube target -
    - walls - threshold for outgoing particles (p,d)
    - polarization

electron scattering

what can be studied experimentally?

- **Processes:**
  - Inclusive (dominated with quasielastic?)
  - Semi-exclusive
  - Exclusive
- **Observables:**
  - differential cross section I
  - polarized beam (analysing power) II
  - polarized target (analysing power) II
  - polarized beam x polarized target (correlations) III
  - polarized beam x polarization analysis in final state (polarization transfer) III

Kinematics

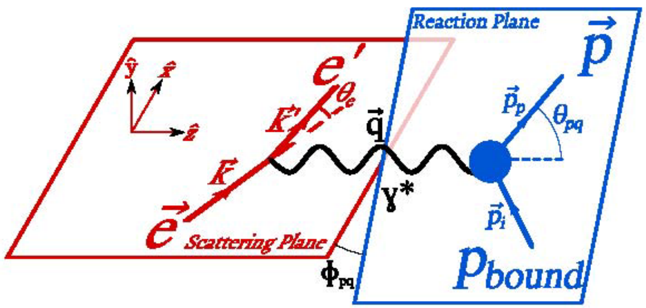


Fig. 1. The kinematics for quasi-elastic scattering of a bound proton in a nucleus, defining scattering and reaction planes.

Dytman et al.

θ = 60^o , 134.5^o

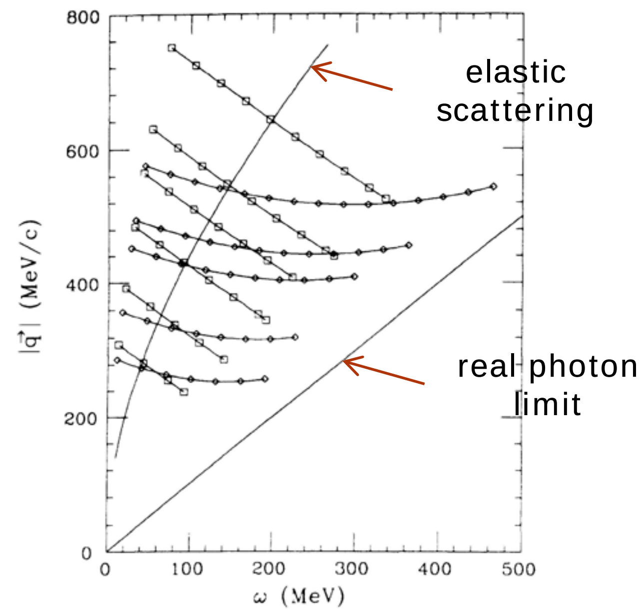


FIG. 2. Kinematics for this experiment. The locus of points covered at the various beam energies and scattering angles is shown in terms of the energy loss (ω) and momentum transfer (q). Forward-angle kinematics (60°) are shown as diamonds and back-angle kinematics (134.5°) are shown as boxes joined by solid lines. The solid line cutting across these lines shows the kinematics for elastic electron-nucleon scattering. The diagonal line shows the real photon limit, $q=\omega$.

Reactions to study

Number of particles & level of exclusivity...

Target	Inclusive	Semi-exclusive	...	Exclusive
^{2}H	$^{2}H(e,e')$			$^{2}H(e,e'p)$
^{3}He	$^{3}He(e,e')$	$^{3}He(e,e'p)$ $^{3}He(e,e'd)$		$^{3}He(e,e'pp)$
^{4}He	$^{4}He(e,e')$	$^{4}He(e,e'p)$ $^{4}He(e,e'd)$	$^{4}He(e,e'pp)$	$^{4}He(e,e'pd)$

electron scattering

Detection Technique for Exclusive Measurements

- spectrometer - the only choice for electrons
- outgoing hadrons -
  - large (as compared to spectrometers) acceptance detector ,
  - position sensitive,
  - with PID and energy determination
- cross section normalization: elastic scattering?

Measurements at NIKHEF (C.M.Spaltro et al.)
in plane $^{3}He(e,e'd)$ and $^{3}He(e,e'p)$

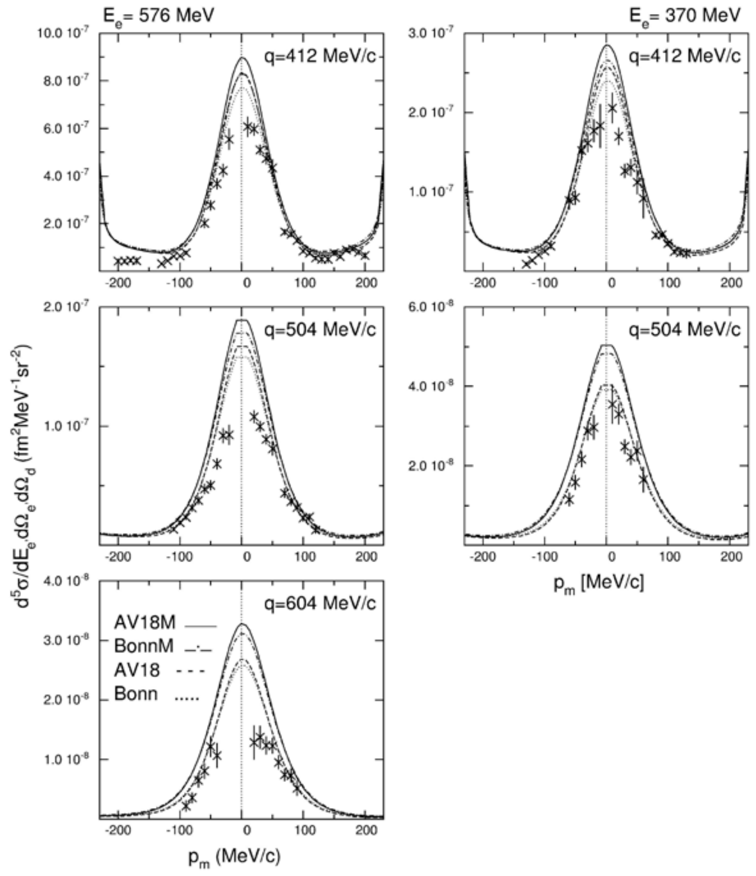
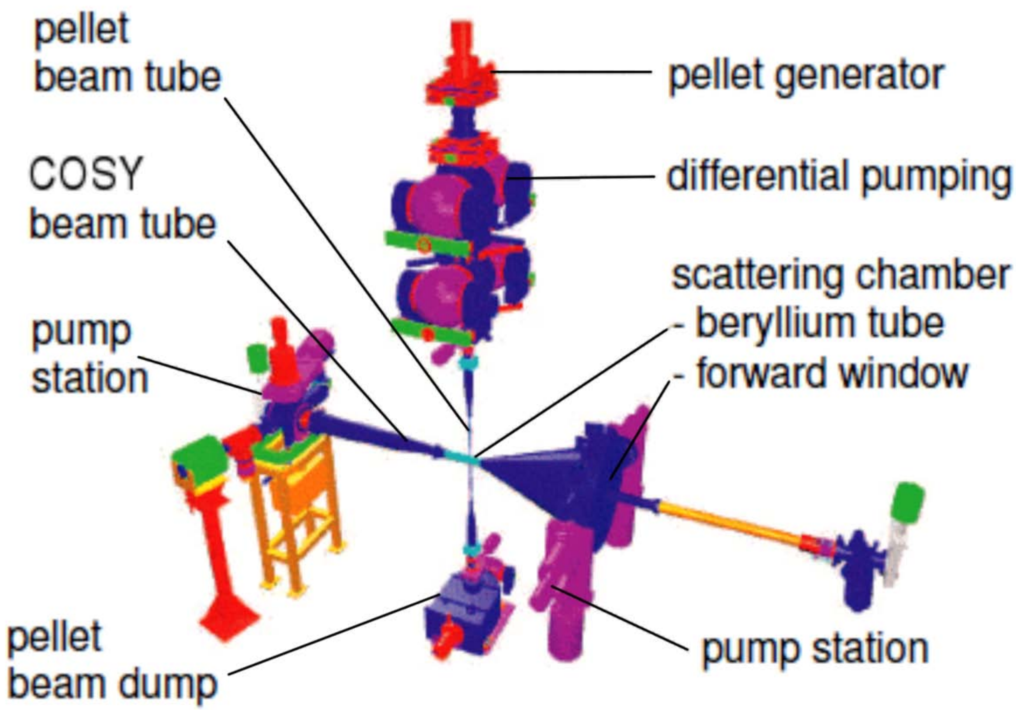


Fig. 3. Measured cross sections for different values of q at the two beam energies, compared to the results of the calculations by Golak et al. for the Bonn-B (dotted and dash-dotted curves) and AV18 potential (dashed and full curves), without and with the inclusion of MEC, respectively.

outlook

- basic checks for feasibility of ^{3}He(e,e'd) and ^{3}He(e,e'p) measurement at MESA energies:
- choice of kinematics - with respect to energy thresholds
- calculation of cross section - feasible measurement? with which ranges of averaging? interesting with respect of 3NF effects?

WASA@COSY Pellet Target



deuteron beam energy	300, 340, 380, 400 MeV
reaction channels	dp → dp dp → ppn dp → ^{3}He + γ dp → dp γ
luminosity	~10^{29}/s/cm^{2}
deuterons in flat top	(1.3-1.4)*10^{8}
total trigger rate	~6*10^{4} events/s (trigger in) ~3*10^{4} events/s (trigger out)
coincidence rate per bin	0.05-0.1 breakup events/s
Δσ /σ	~1%
collected data	22 TB (984 runs ,~22GB per run)