Deuteron-Deuteron Collision at 160 MeV

by

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Outline

- Introduction
- Experimental tools
- 4N System – a step forward
- **Data analysis for d+d @ 160 MeV**
  - Raw-analysis & Event selection
  - Kinematics and BINA acceptance
- Results of QFS in *dd->dpn* : Comparison with first theories
- Summary

Nuclear Force

- ✓ **1935**: **Yukawa** presented a Theory
- ✓ **1947**: **Powell** proved the theory by experiments

➢ Today , many different Theoretical models are available to exactly describe the nuclear force between **any two nucleons**.

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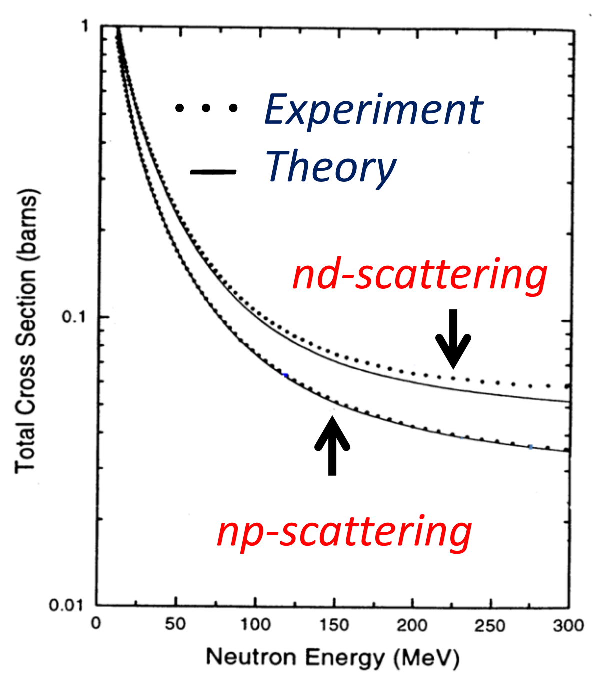
***...but** FAILS to describe Interaction between more than two nucleons!*

➢ even for the simplest Atomic Nucleus
e.g. ^{3}**H** and ^{3}**He**

Model	[MeV]
Nijm I	7.72
Nijm II	7.62
AV18	7.62
Reid-93	7.63
Exp.	8.48

Binding Energy of Triton



High precision data from Los Alamos
W. P. Abfalterer et al., PRL 81, 57 (1998)

Introduction

Adding Thee Nuclear Force (3NF) helps

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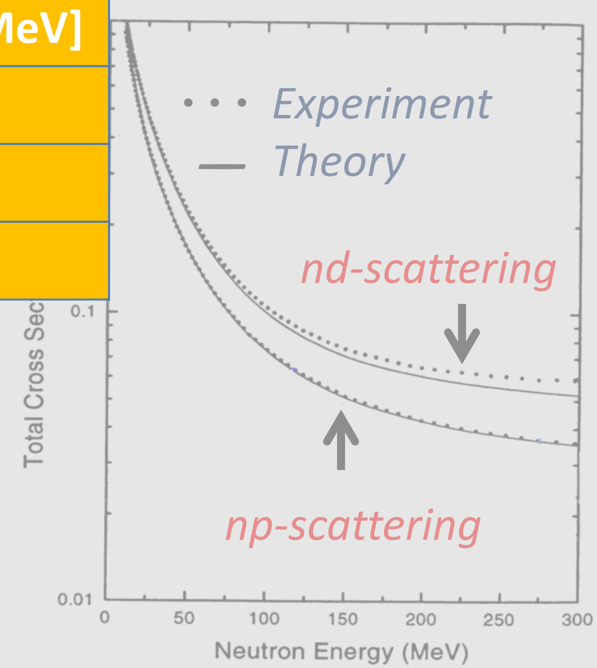
➢ even for the simplest Atom
e.g. ^{3}**H** and ^{3}**He**

Model	^{3}H [MeV]	^{4}He [MeV]
2NF	7.62	24.2
2NF +3NF	8.47	28.3
Experiment	8.48	28.4



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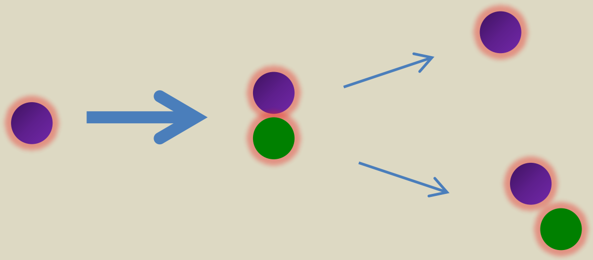
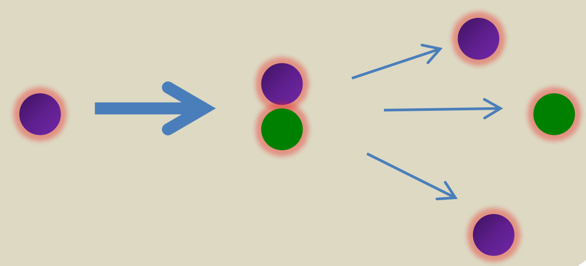
Nucleon - Deuteron Scattering
(Relatively Simplest but not simple):

Elastic: N + d → N + d

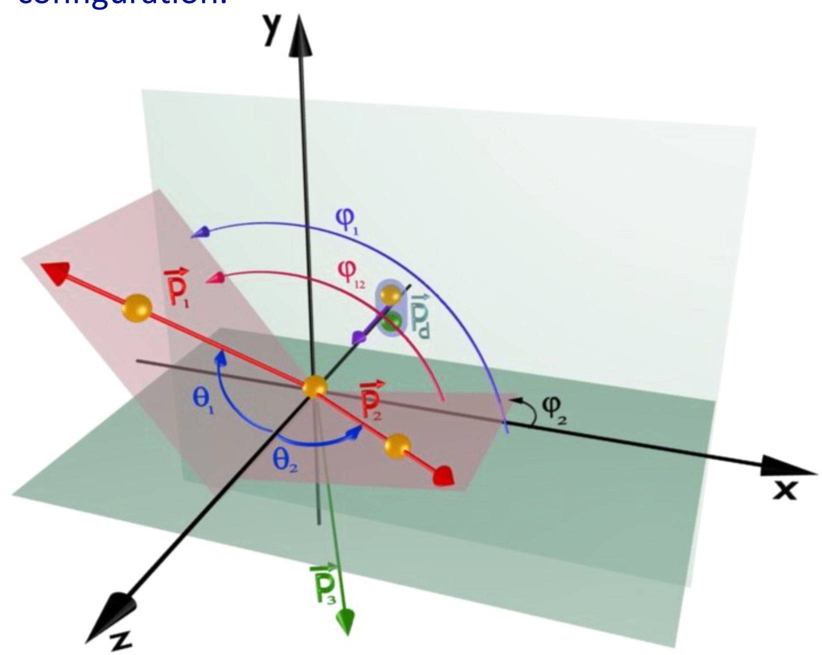


Breakup: N + d → N + p + n



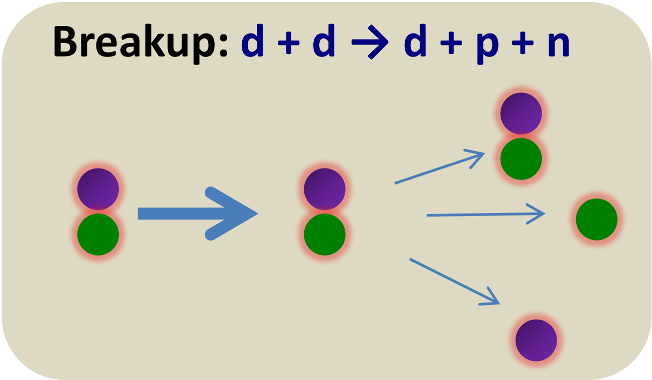
- Well-defined kinematic relations

- rich phase-space: a large amount of kinematical configuration.



deuteron-nucleon breakup
reaction is well suited to
study 3N interactions

4N System - a step forward

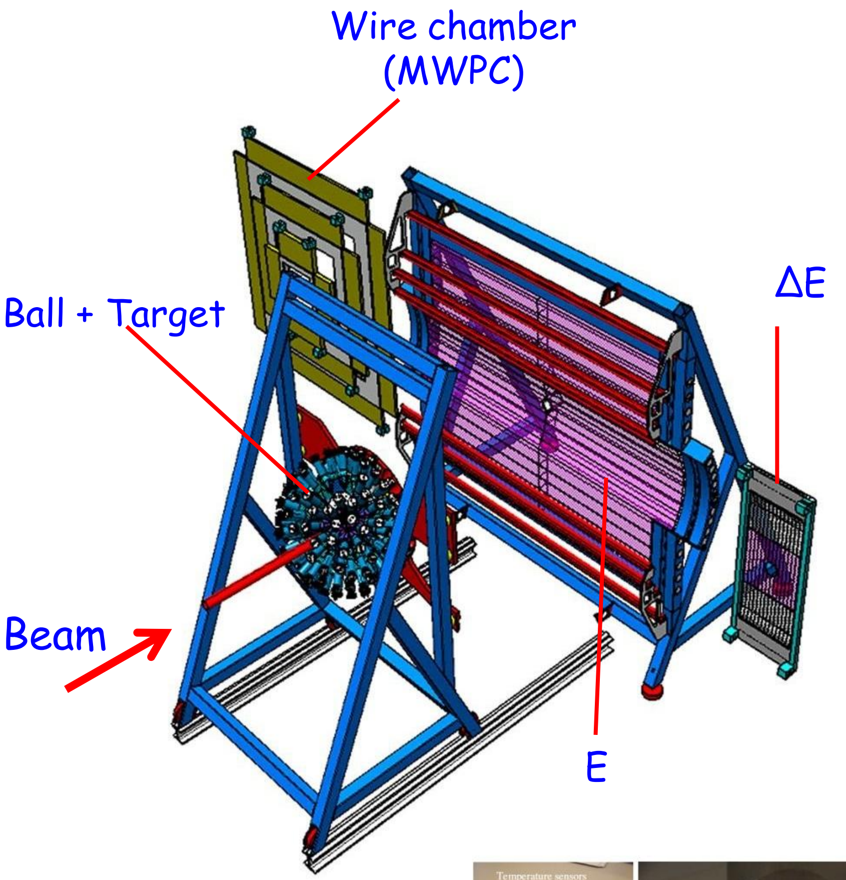


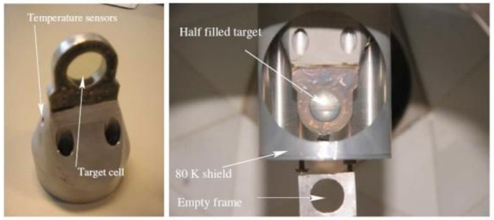
- rich phase-space: a large amount of kinematical config.

In the same manner, we investigate dd->dpn breakup

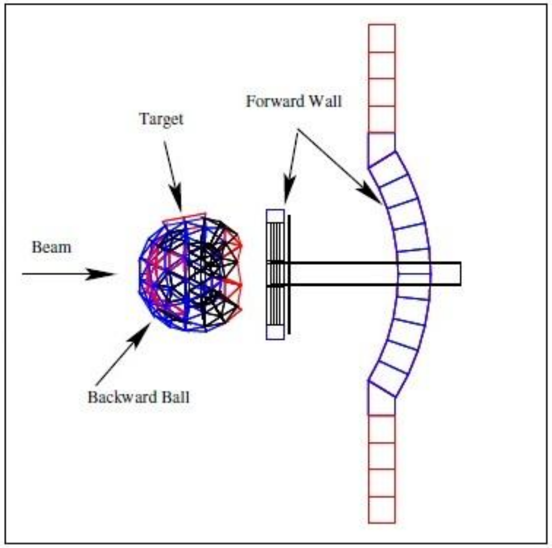
BINA Detector

Dedicated for few-body studies!
High-precision data !





TARGET



4N System – a step forward

STATUS: Poor knowledge

Theory:

-> difficult (Technically & computationally)

-> available (not exact) models fail

-> ab-initio calculations for very low energies

-> recent progress by A. Deltuva

Experiment:

- Old data, at low energies
- Most of the data for dd elastic scattering
- Breakup data – very scarse
  (KVI dd breakup data at 130 MeV)

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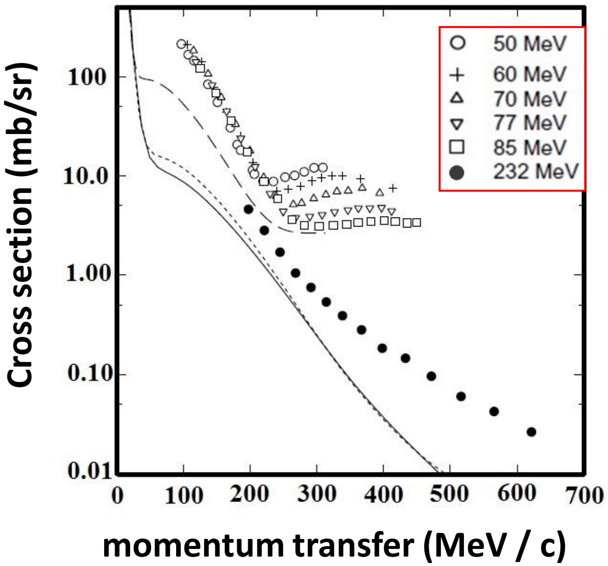
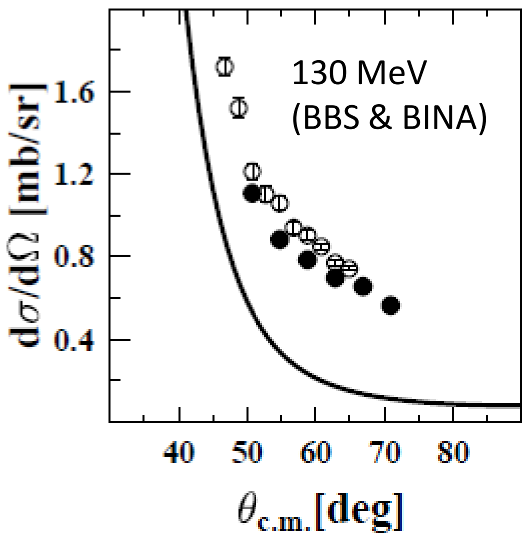
dd elastic scattering: theory vs experimental data



C. Alderliesten, Phy Rev C, 18(5), 1978
A. Micherdzinska, Phys Rev C 75, 2007

calculations by A. C. Fonseca :	52 MeV (dashed)
	191 MeV (dotted)
	232 MeV (solid)



From KVI, BINA and BBS

Approximation used in Alt-Grassberger-Sandhas (AGS) equation for 4N ***CD-Bonn + Δ*** *potential.*

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Situation of 4N-study today
SIMILAR TO
situation of 3N-study 2 decades ago

Data Analysis

- Experiment performed at KVI with BINA in April 2011.
  beam: **deuteron**,
  energy: **160 MeV**,
  target: **Liquid Deuterium**

d+d - EVEN MORE COMPLICATED SYSTEM

$d + d \rightarrow d + d$	... elastic scattering
$d + d \rightarrow d + p + n$	... three-body breakup
$d + d \rightarrow p + p + n + n$	... four-body breakup
$d + d \rightarrow d + p\ (+\ n_{spectator})$	... QFS
$d + d \rightarrow p + p\ (+2n_{spectator})$	... double QFS
$d + d \rightarrow {}^3H + p$	... neutron transfer
$d + d \rightarrow {}^3He + n$	... proton transfer

Quasi free scattering:

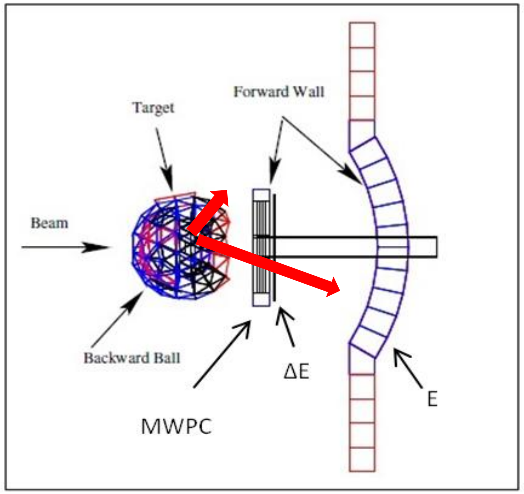
dd ->dp (neutron spectator)

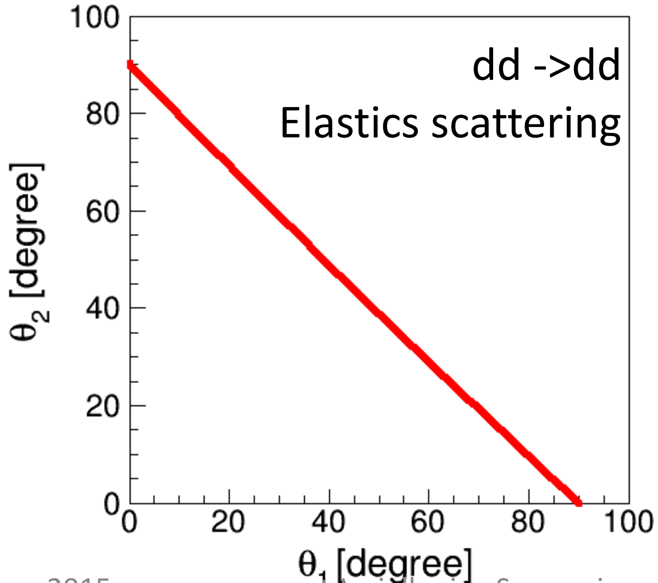
Two possibilities
pd (half of beam energy)
dp (full beam energy)

Event selection

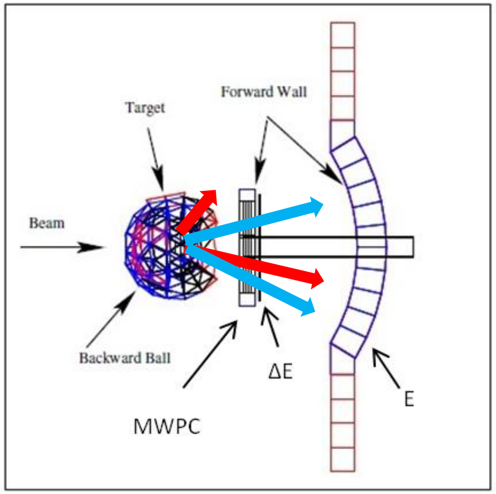
dd elastic scattering

Only possible
in
WALL-BALL
coincidences

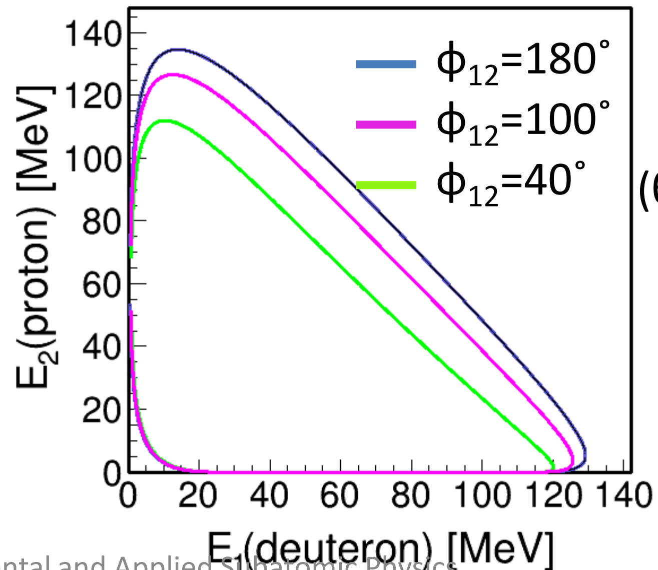




Breakup channels



WALL-BALL
&
WALL-WALL



dd ->dpn
Breakup
(θ_d= θ_p=20 ˚)

Data Analysis

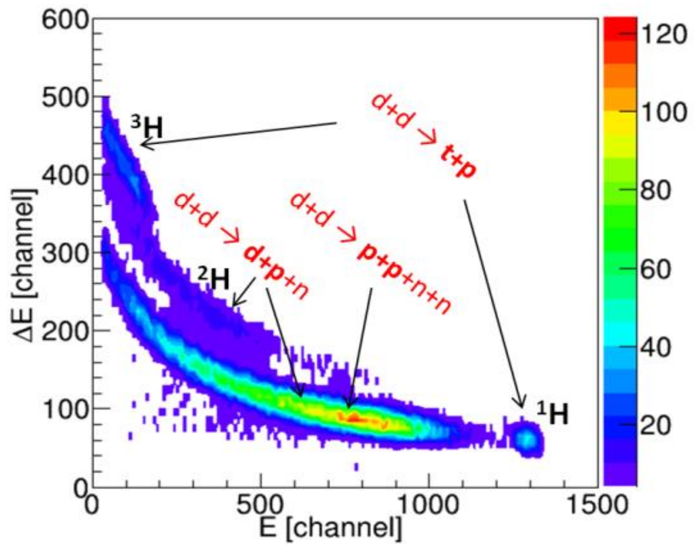
Steps:

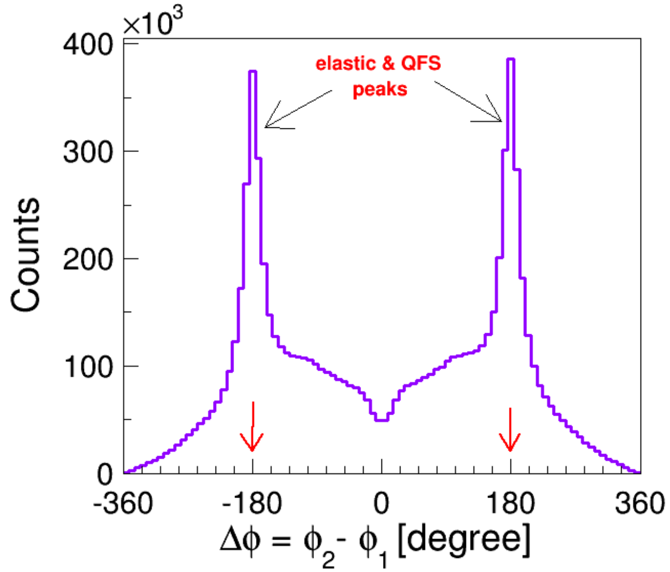
Particle ID → Calibration → Channel discrimination

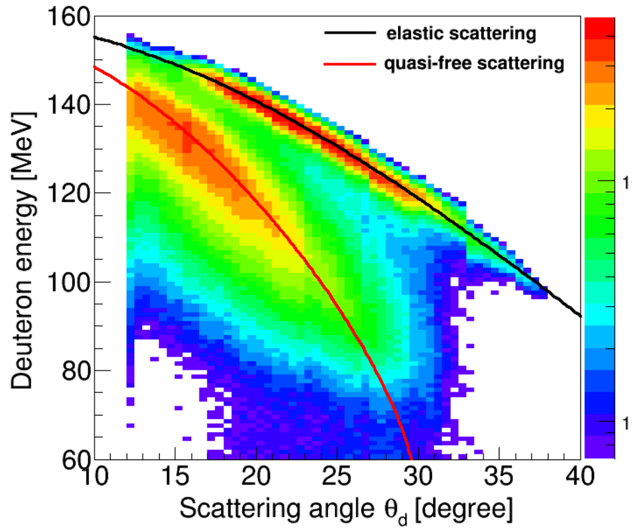
basic assumptions:

Coincidence of two charged particles

Co-planarity, i.e. $\Delta\varphi = \varphi_2 - \varphi_1 = \pm 180^\circ$ (for elastic scattering)

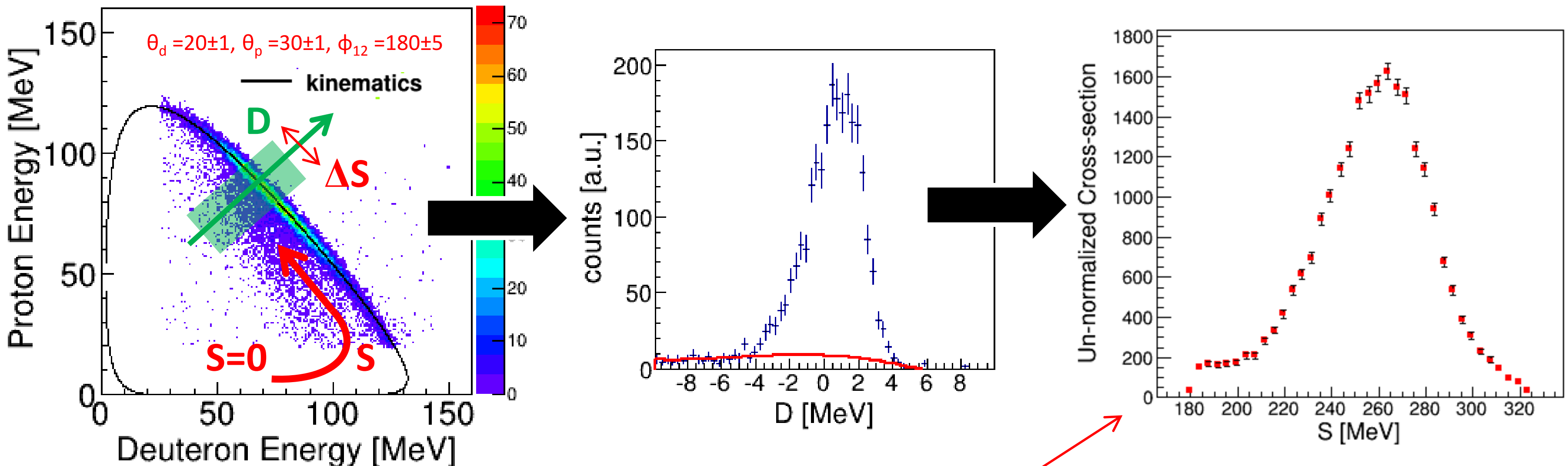






Data Analysis

$^2H(d,dp)n$ breakup reaction



-> Cross section normalised with elastic scattering cross section (of course differential)

$$\frac{d^5\sigma}{d\Omega_1 d\Omega_2 dS}(S,\Omega_1,\Omega_2) = \frac{d\sigma_{el}}{d\Omega_1}(\Omega_1)\cdot\frac{N_{br}(S,\Omega_1,\Omega_2)}{N_{el}(\Omega_1)}\cdot\frac{\Delta\Omega_1^{el}}{\Delta\Omega_1\Delta\Omega_2\Delta S}\cdot\frac{\epsilon^{el}(\Omega_1^{el})\epsilon^{el}(\Omega_2^{el})}{\epsilon(\Omega_1)\epsilon(\Omega_2)}$$

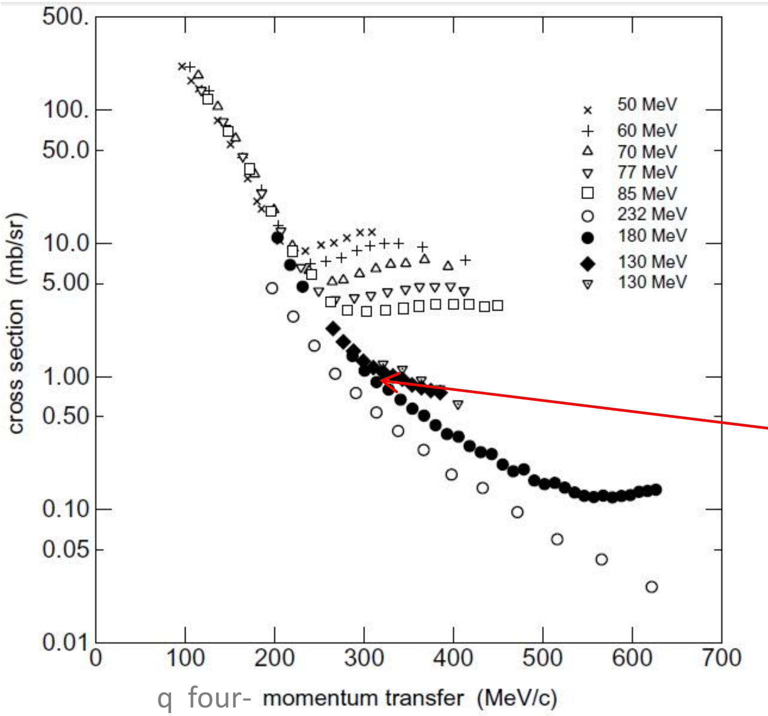
This quantity is needed

counts

angles & energy bins

detector efficiencies

Normalisation of dd elastic data



Invariant quantity **four-momentum transfer**, $q = -t^2$
Where t=Mandelstam variable

Simplified for dd elastic scattering as:

$$t = 2p_{1cm}^2(\cos\theta_{c.m.} - 1)$$

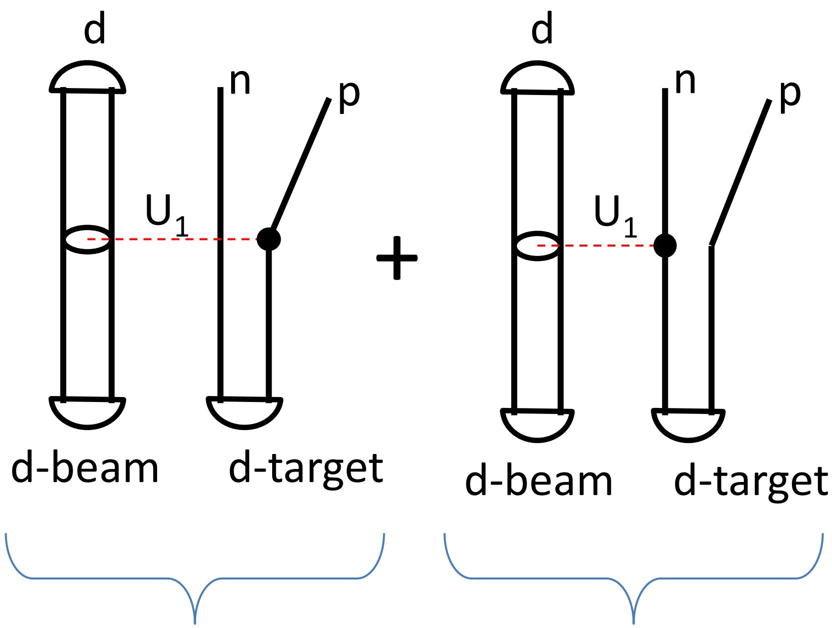
One can extrapolate the 130 MeV and 180 MeV data to extract the 160 MeV.

Most reliable is to take a point at ***scaling region***

Ref: C. D. Bailey, IUCF, PhD Thesis, 2009

RESULTS

CD Bonn + Δ (FIRST calculations by A. Deltuva)



1st term (most important Nd) + **2nd term** + **3rd and 4th terms**

... **two more terms**
from
dd symmetrization

d-beam ⇄ d-target

U_1 = full ***Nd*** scattering operator

$\mathbf{T_{dpn}}=2(1-P_{34})U_1$ = Breakup operator in dN single-scattering approx

Breakup amplitude: **<dpn|$\mathbf{T_{dpn}}$|dd>**$_{\text{symmetrized}}$

RESULTS

Un-normalized cross section distribution

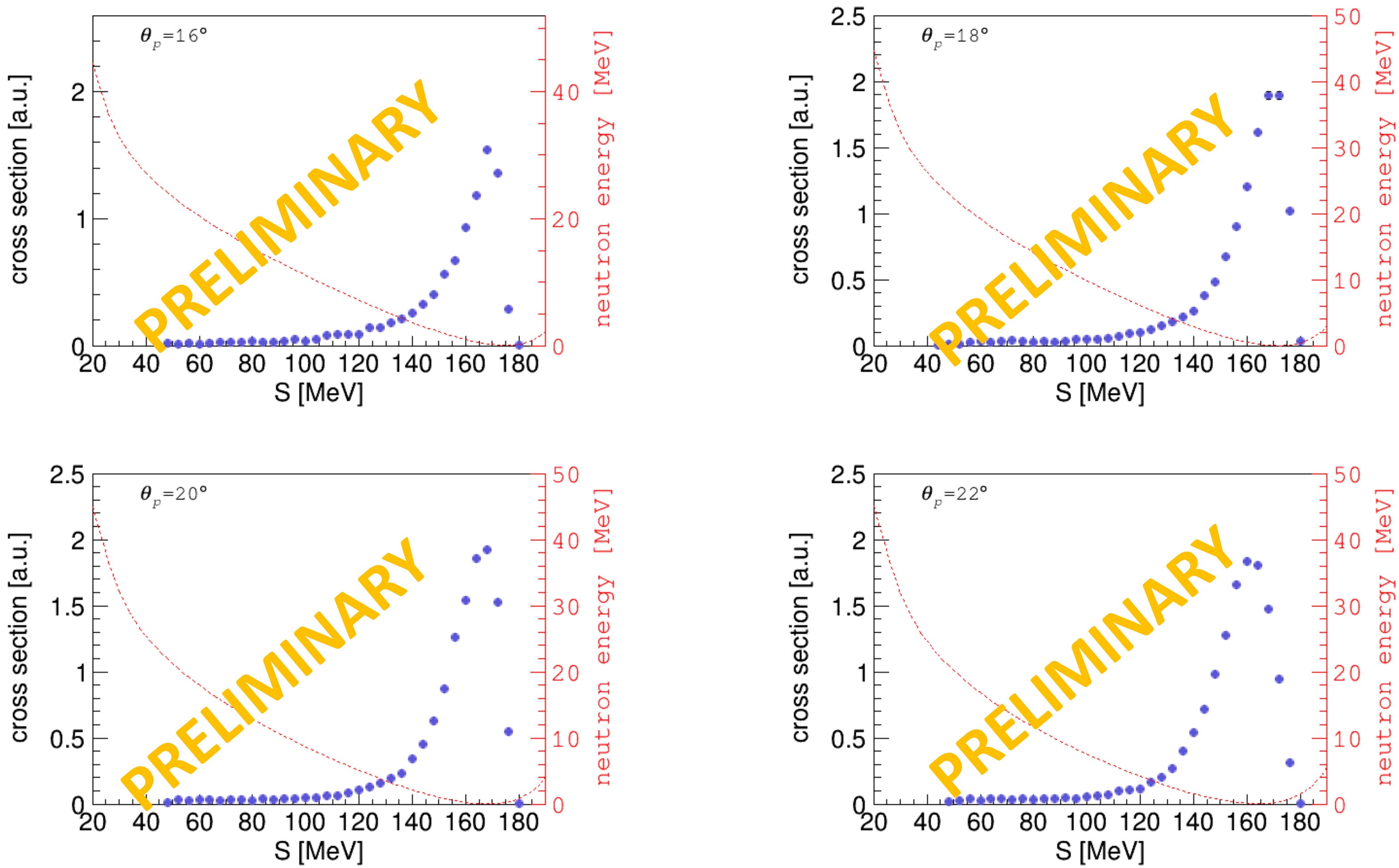
Sample cross sections

$\theta_d = 26^\circ$, $\phi_{dp} = 180^\circ$

scaled with arbitrary factor

just to compare shape with predictions

Neutron energy (when close to 0 i.e. spectator)



RESULTS

Un-normalized cross section distribution

Sample cross sections

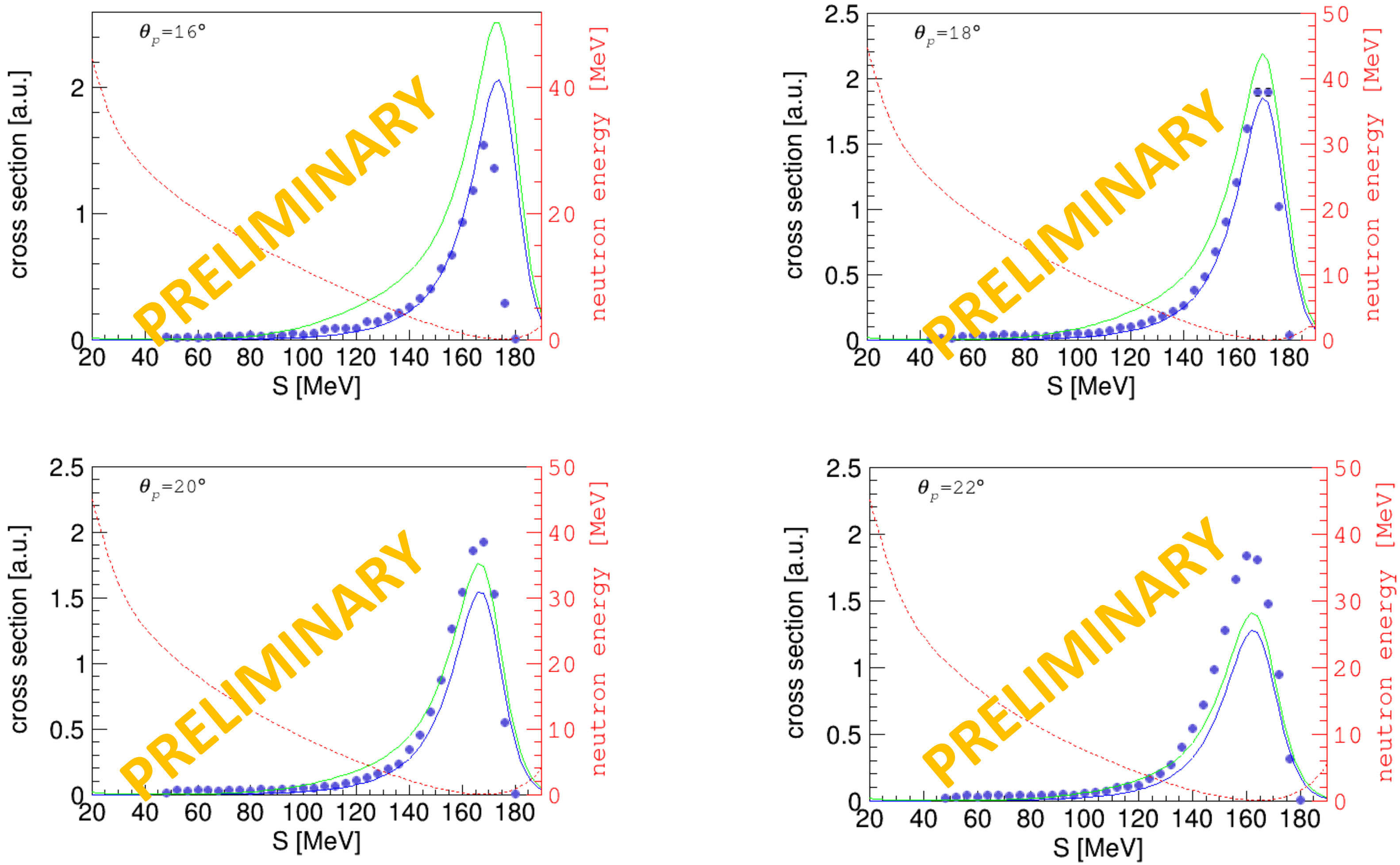
(calculations by A. Deltuva)

$\theta_d = 26^\circ$, $\phi_{dp} = 180^\circ$

Only first term in $\mathbf{T_{dpn}}$ (i.e. dp elastic scattering)

all four terms $\mathbf{T_{dpn}}$ taken into account

Neutron energy (when close to 0 i.e. spectator)



Outlook

- **Detail analysis of systematic effects**

- theoretical progress in 4N is urgently needed, the recent results are very promising

- **3N systems can be further studied with BINA@CCB**

- complementary studies of 4N systems, e.g. in p+3He->p+p+d reaction, are planned

Summary

➢ new set of very precise and numerous experimental data for *dd* breakup at 160 MeV :

normalized cross section for the breakup reaction following combinations of angles:

θ_1, θ_2 = 16˚ – 28˚ (in step of 2˚), ϕ_{12} = 180˚, 160˚, 140˚

(in total about 150 data points)

Thank you for your attention !!!

Introduction

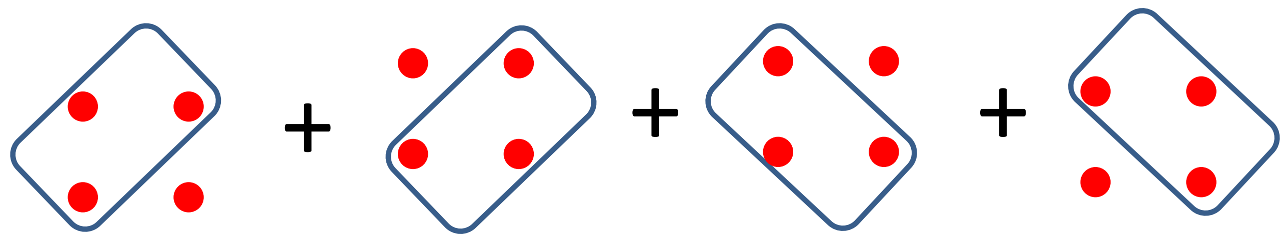
3NF helps but.....

-> some descrepancies (Ay puzzle, star-anomaly, problems with description of analyzing powers at medium energies)

-> a very subtle & hard to detect.

-> it's expected to be enhanced in 4N system.

$$(3NF)_{4n} =$$



3NF/2NF << 1