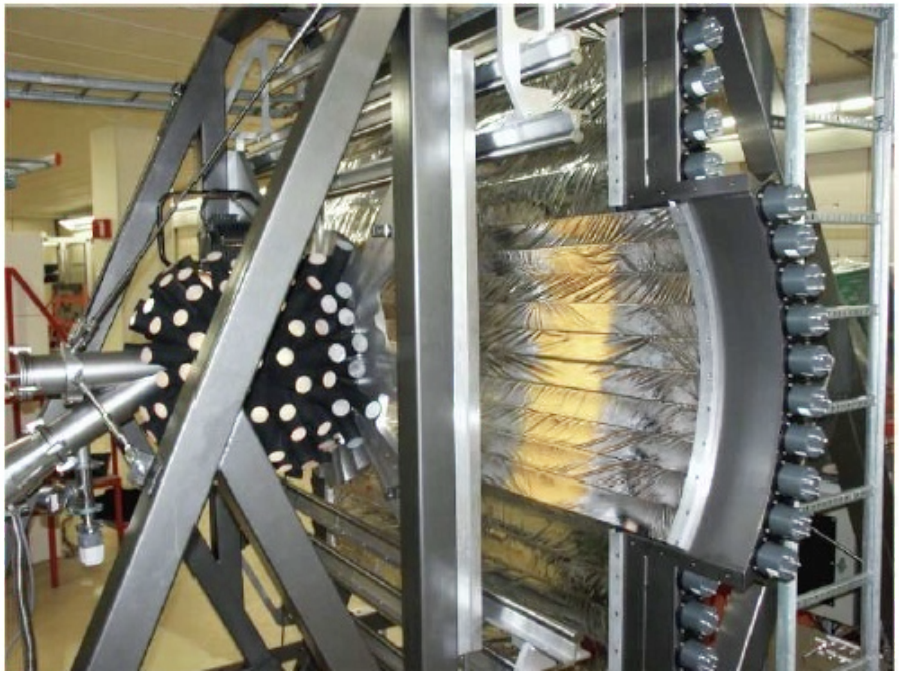
Few-Nucleon System Dynamics Studied via Deuteron-Deuteron Collisions at 160 MeV



Outline:

1. Goals and motivations,
2. 3N systems question marks,
3. 4N systems - theory,
4. Experiment dd@ 160 MeV (BINA@ KVI) and results on elastic scattering, proton transfer and breakup,
5. Outlook: dd@ 350MeV (WASA@ COSY).

KVI

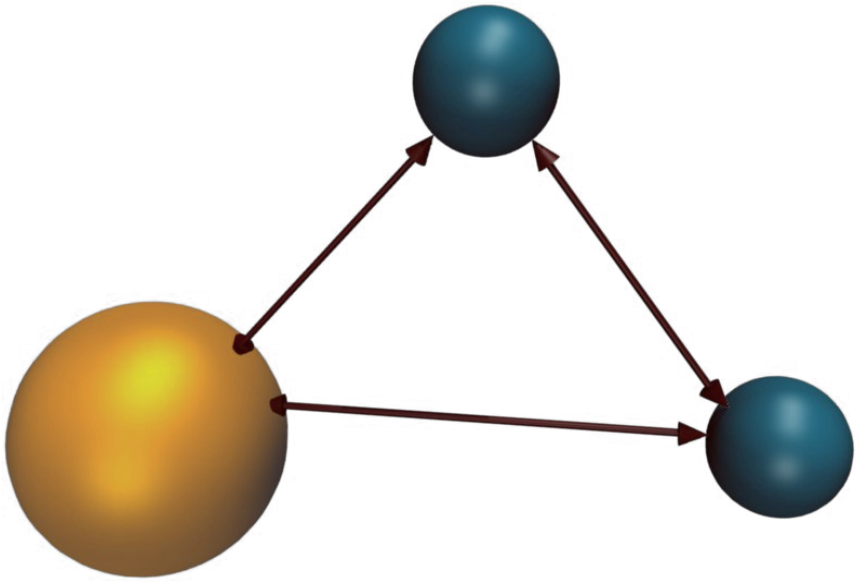
Izabela Ciepał, IFJ PAS

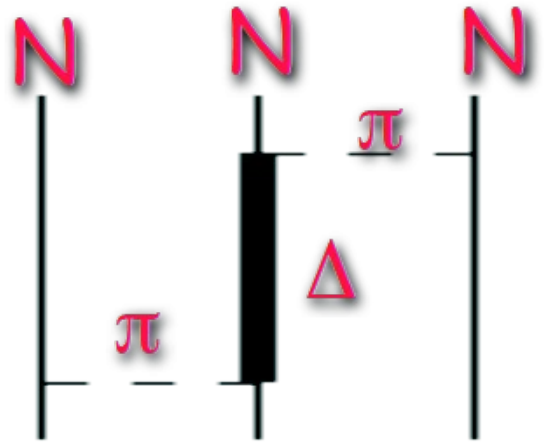
Motivations

- Tremendous progress in the solution of numerical exact *ab initio* calculations of observables involving 4N reactions, below and above breakup threshold,
- Studies of 4N systems are much more difficult from the computational point of view than 3N,
- **Challenges**: a number of resonances (in the low energy region), many input and output channels, isospin dependence, …
- Higher sensitivity to 3NF effects, "rich" structure of 4N observables (maxima and minima) important for testing interaction models,
- **Recent accurate calculations** for p-^{3}He and n-^{3}H (AGS, FY, HH),
- Complete knowledge of the 3N interaction

Very few datasets exist to test recent calculations, especially for breakup: @ 130, 160 MeV (KVI Groningen), better situation for transfer channels and elastic scattering

Additional Part of the System Dynamics: 3N Force





Fujita-Miyazawa 3NF

Prog. Theor. Phys. 17(1957) 360

$$H = -\sum_{i=1}^{3} \frac{\hbar^2}{2m_i} + \sum_{i>j=1}^{3} v_{ij} + V$$

3NF models

2NF input:

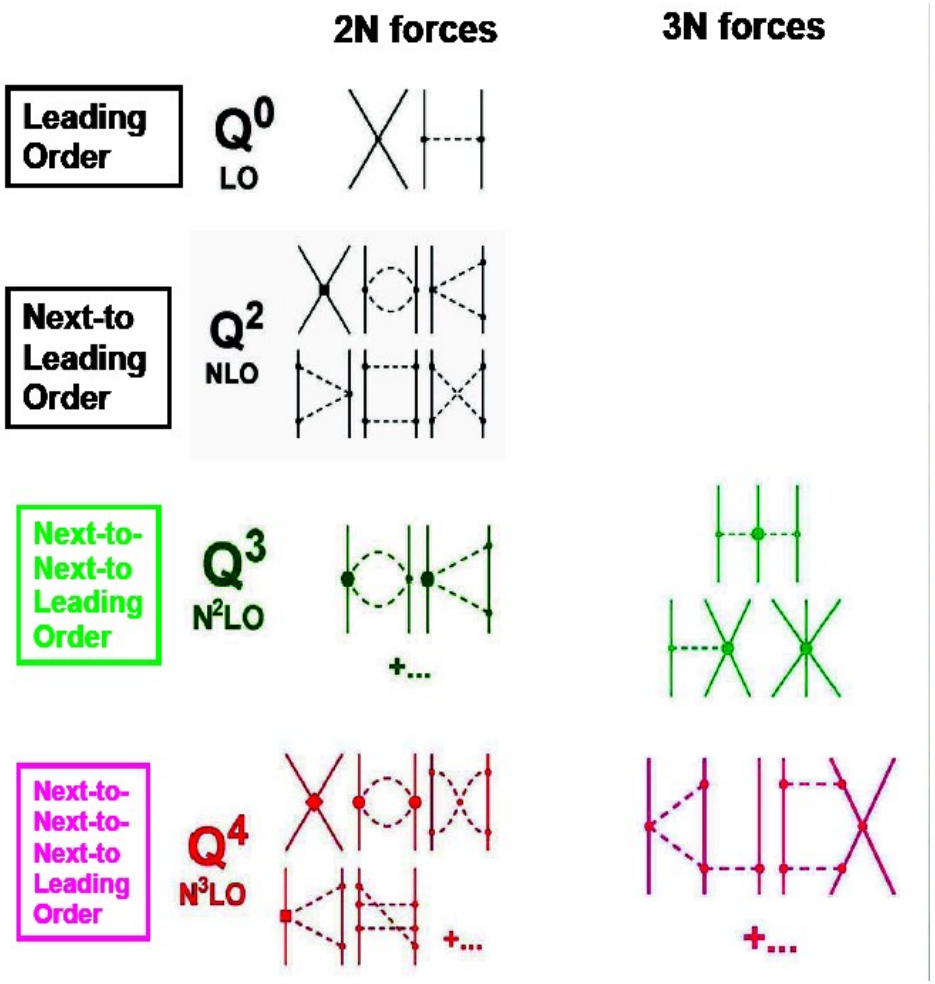
- CD Bonn
- Argonne V18
- Nijmegen I, II
- …..

+

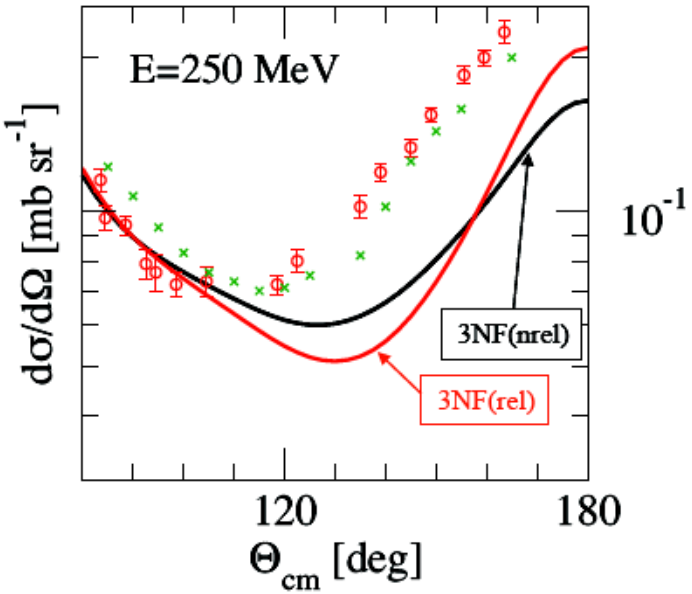
3NF input:

- Tucson-Melbourne TM99
- Urbana IX
- ……

Chiral Forces

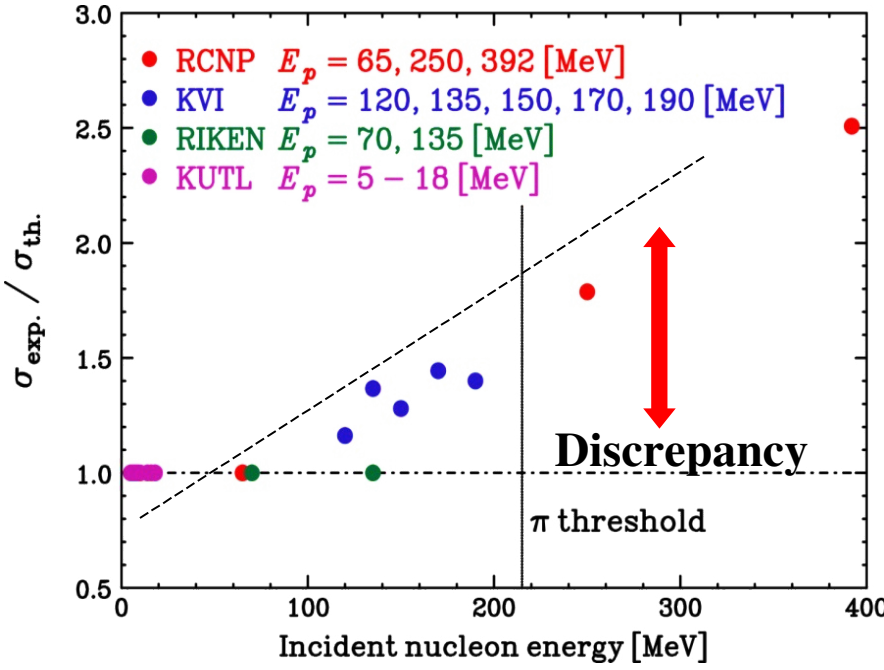


Elastic scattering & 3NF effects



H. Witala et al,
Phys. Rev. C 83, 044001 (2011)

πρ3NF ?
ρρ3NF ?
relativity ?
others ?



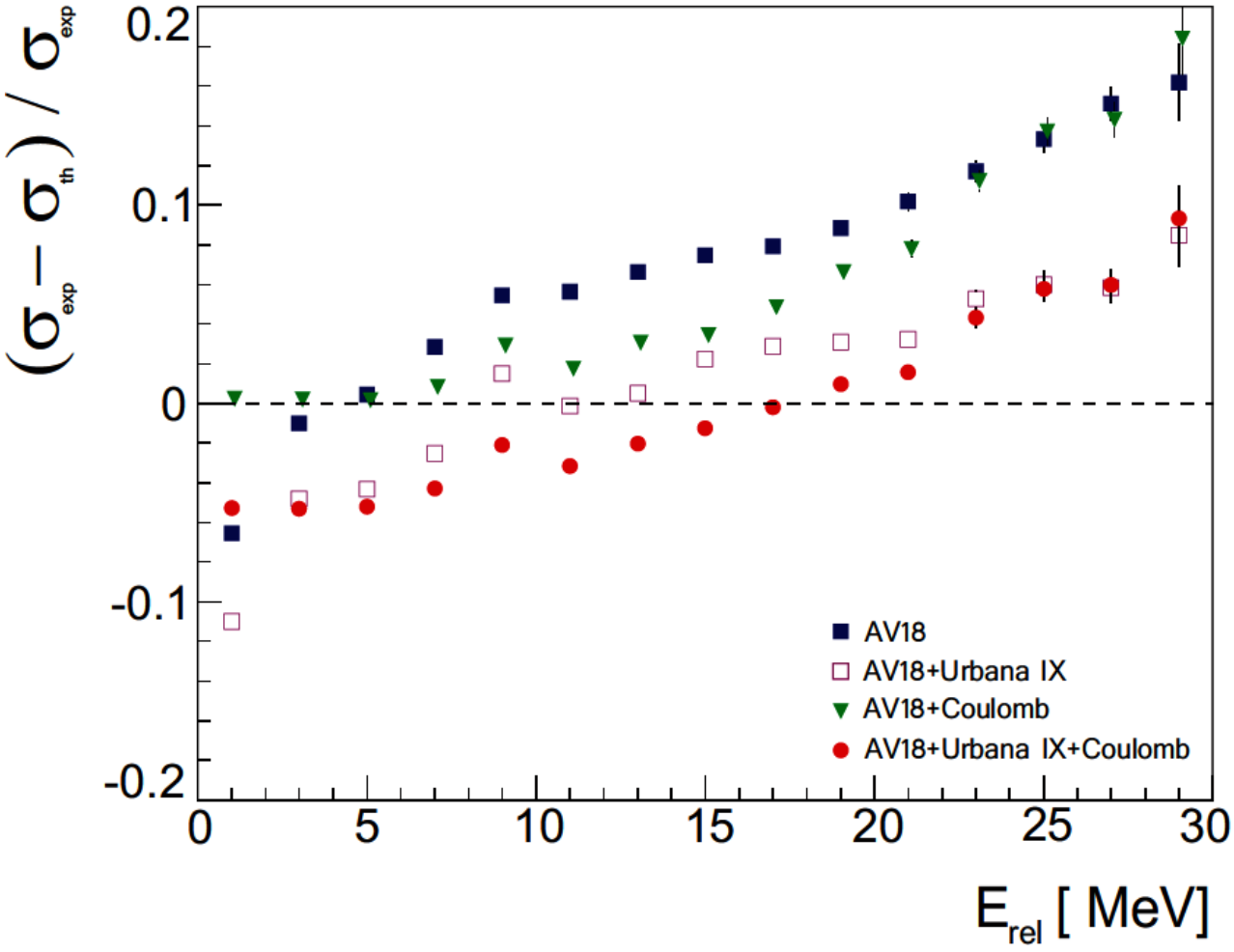
pictures from K. Sagara

The spin part of 3NF is still not under control in theory

At lower energies:

- **A_y puzzle (NN P-waves)**
- **Space Star anomaly**

dp breakup @ 130 MeV: Coulomb force & 3NF

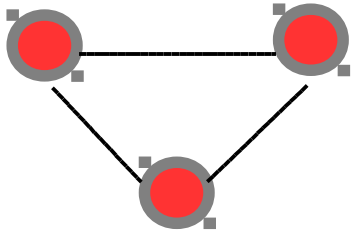
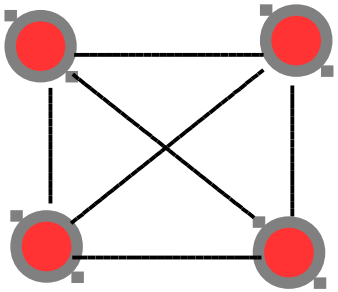


Coulomb force + 3NF gives much better agreement with the data !

4N systems studies

4N - a new quality in nuclear forces studies

- many input and output channels (resonances),
- higher sensitivity (in comparison to 3N) for 3NF,
- chance for investigation of isospin dependencies,
- extra sensitivity to NN force models (isospin symmetry of NN P-waves),
- role of 4NF.

	2NF	3NF	4NF	
	1			
	3	1		1/3
	6	4	1	2/3

2NF>>3NF>>4NF

$\langle V_{NN} \rangle$ ~ 20 MeV/pair

$\langle V_{3NF} \rangle$ ~ 1 MeV/triplet

$\langle V_{4NF} \rangle$ < 0.1 MeV/quartet

x2

4N calculations - summary

d+d → d+d
d+d → n+^{3}He
d+d → p+t

calculations above the 4N breakup threshold (10, 12.3 and 25 MeV)

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

p+^{3}He → p+^{3}He
n+^{3}He → n+^{3}He
n+^{3}He → p+ t

calculations above the 4N breakup threshold (up to 35 MeV)

A. Deltuva, A. C. Fonseca,
Phys. Rev. C 95, 024003 (2017)

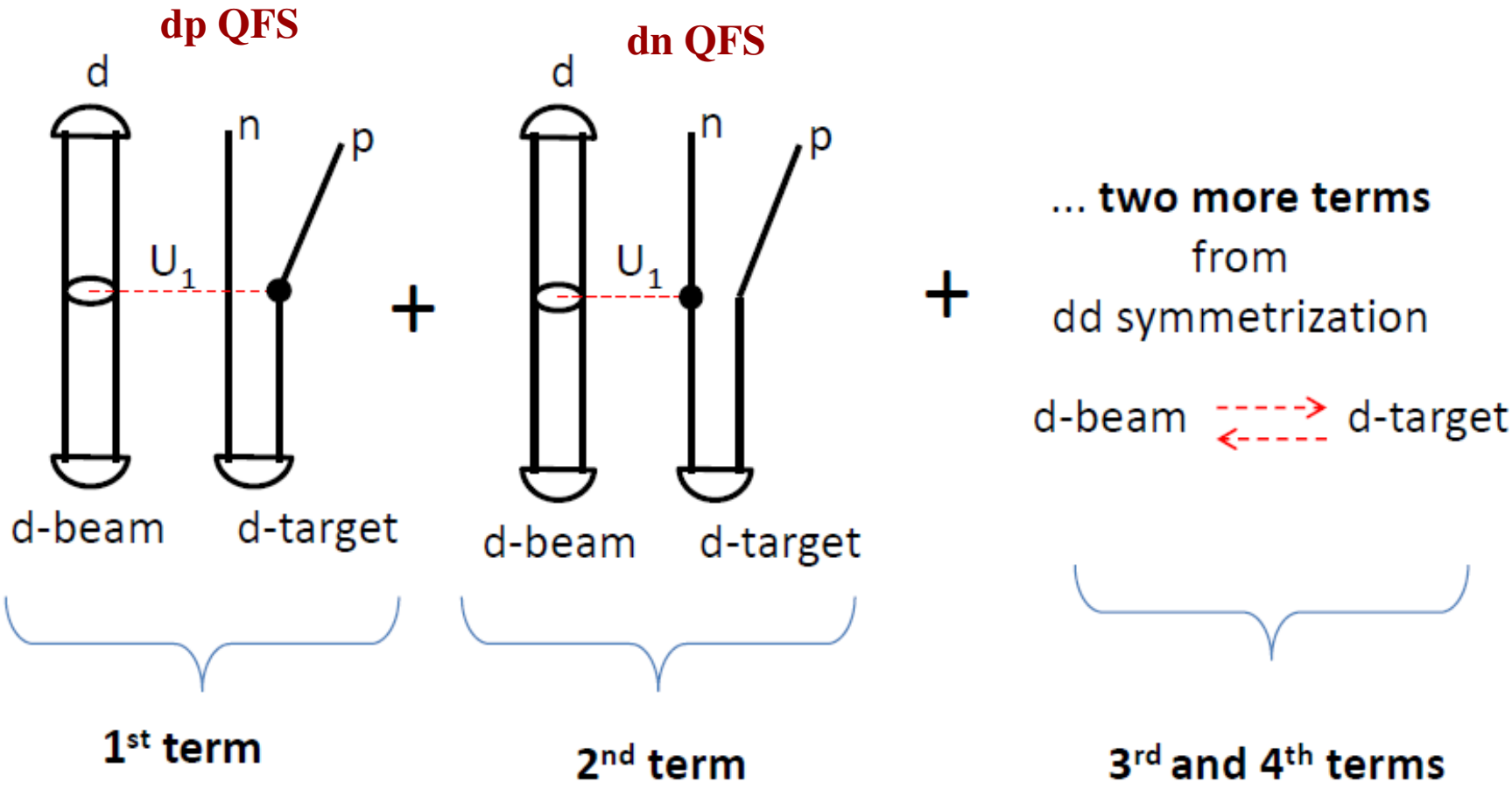
d+d → d+p+n

calculations near QFS @ 130, 160 MeV
Single Scattering Approximation (SSA)

A. Deltuva, A. C. Fonseca
Phys. Rev. C93, 044001 (2016)

4N systems – Single Scattering Approximation (SSA)

estimate of d-d breakup cross sections at higher energies:
first term in the Neumann series expansion of AGS 3-cluster breakup operator (taken from exact solution of the AGS 3-nucleon equations)



A. Deltuva, A. C. Fonseca Phys. Rev. C 93, 044001 (2016)

4N systems – Single Scattering Approximation (SSA)

estimate of d-d breakup cross sections at higher energies:
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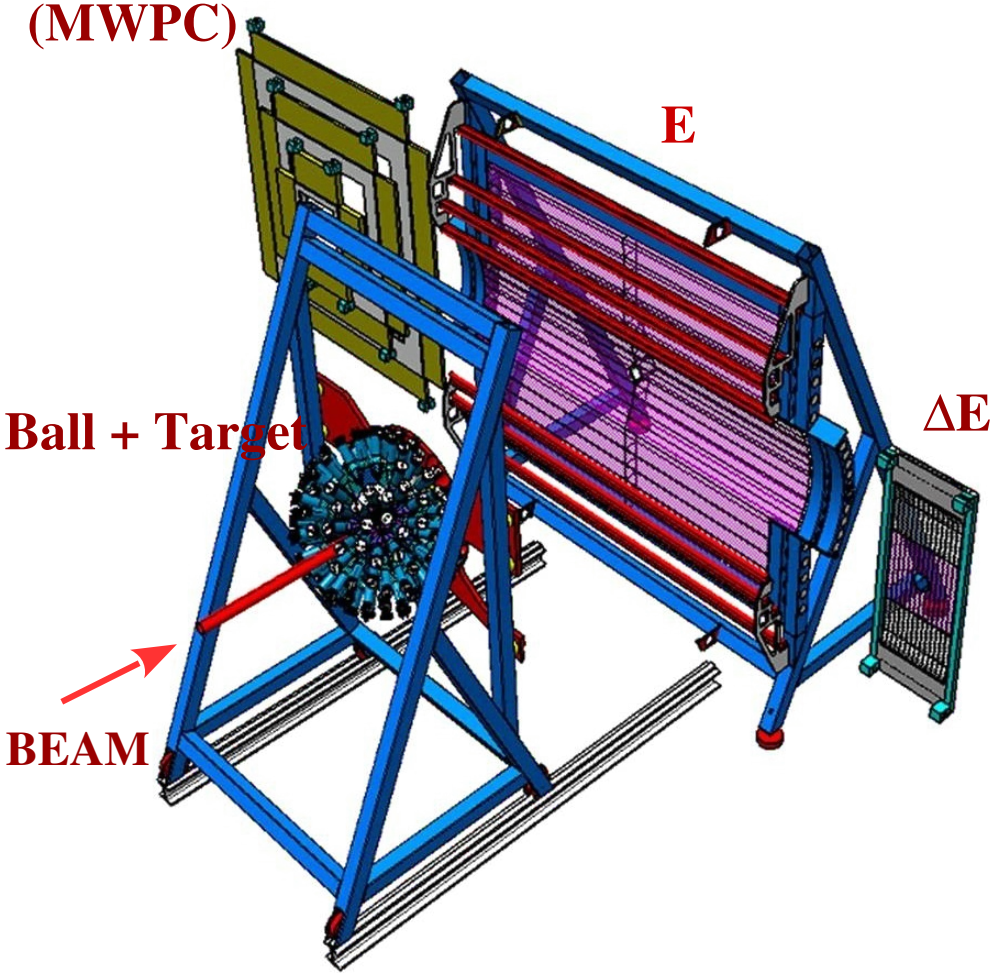
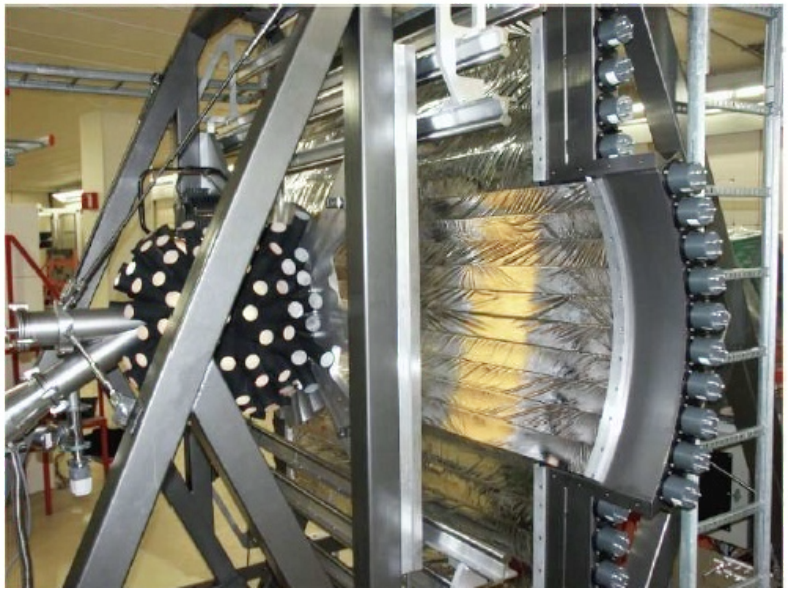
Simplified reaction mechanism → calculations are reliable:

1. high enough beam energy,
2. $E_n \sim 0$,
3. high relative *n-d* ans *n-p* energy

BINA-Big Instrument for Nuclear-polarisation Analysis

KVI





Experiment @ 160 MeV

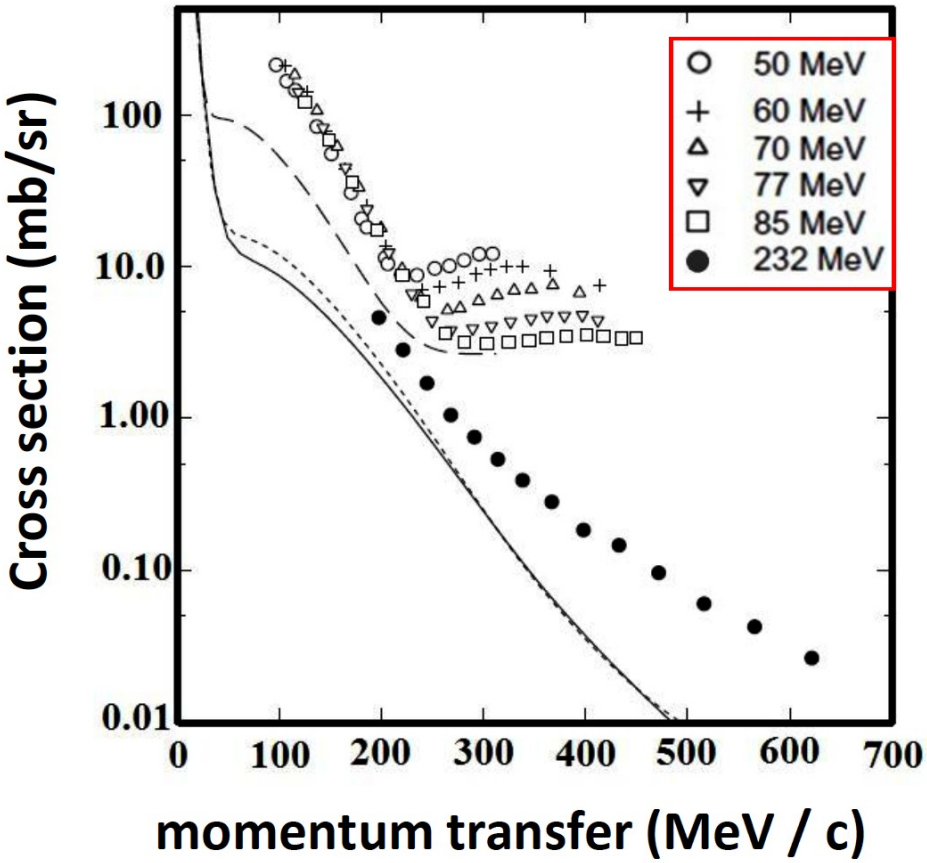
- experiment performed at **KVI** with **BINA**,
- beam: deuteron,
- energy: 160 MeV,
- target: Liquid Deuterium.

d+d – even more complicated system

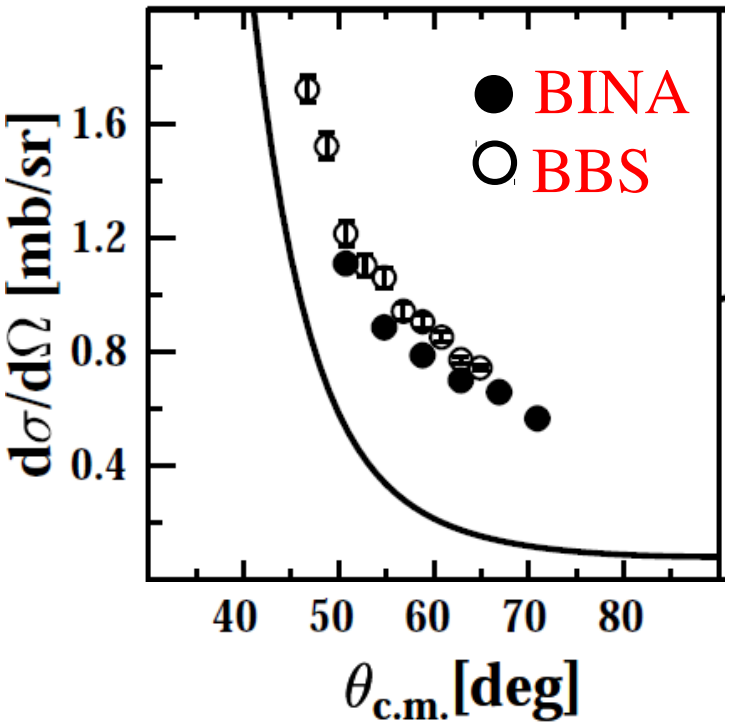
d+d → d+d	elastic scattering
d+d → d+p+n	3-body breakup
d+d → p+p+n+n	4-body breakup
d+d → d+p+(n_{spec})	QFS
d+d → p+p+($2n_{spec}$)	double QFS
d+d → n+^{3}He	proton transfer
d+d → p+^{3}H	neutron transfer

used for the data normalization

d-d elastic scattering: theory vs data

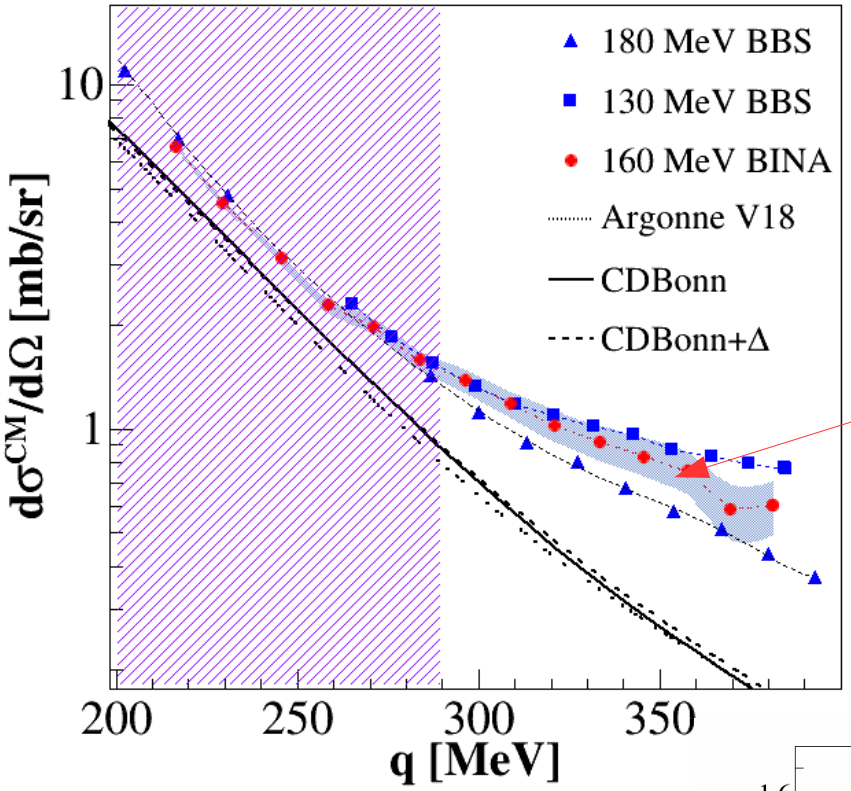


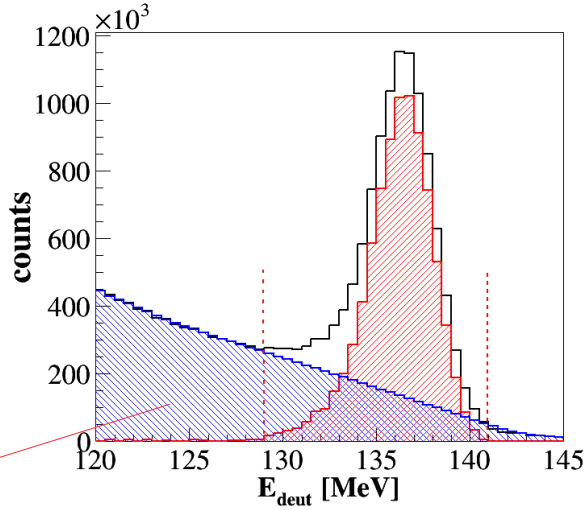
data @ 130 MeV



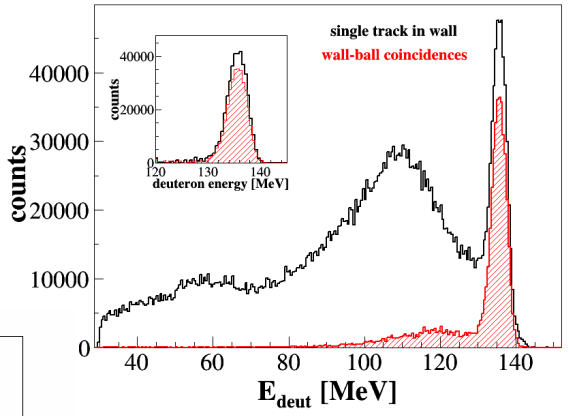
calculations by A. C. Fonseca :	52 MeV 191 MeV 232 MeV

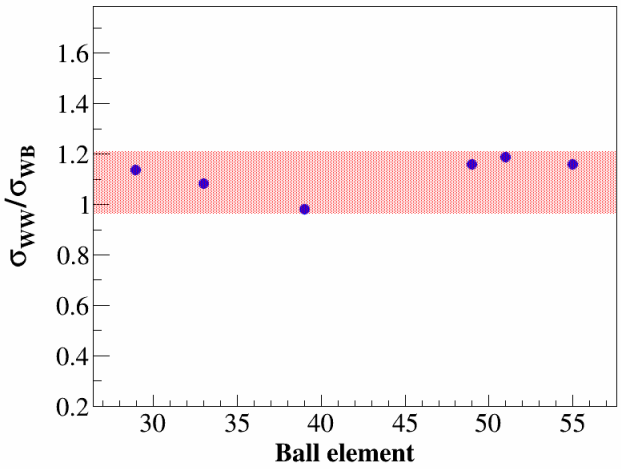
d-d elastic scattering@ 160 MeV



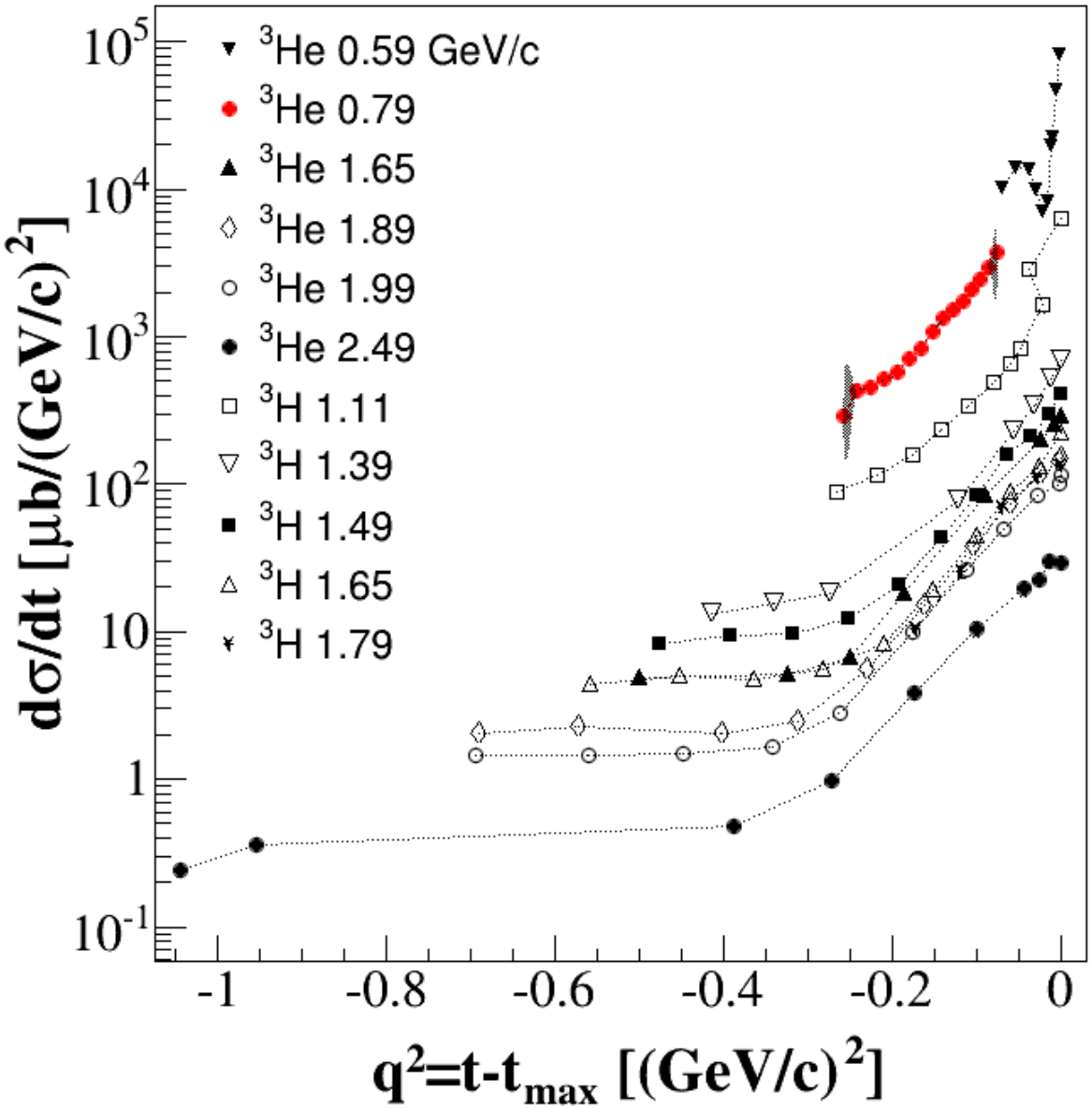


singles vs coincidences





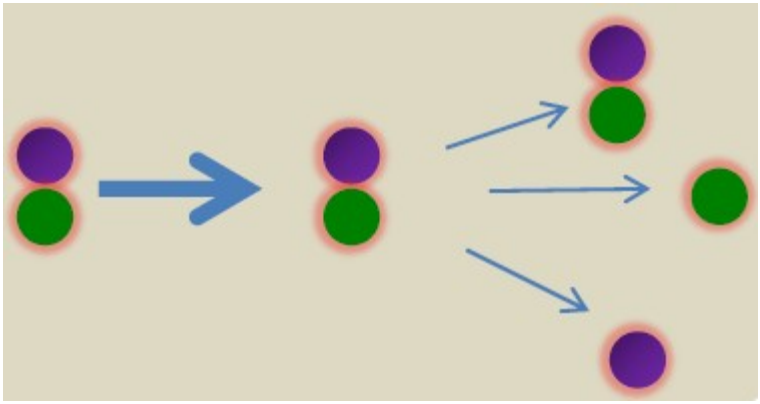
d+d → n+^{3}He @ 160 MeV

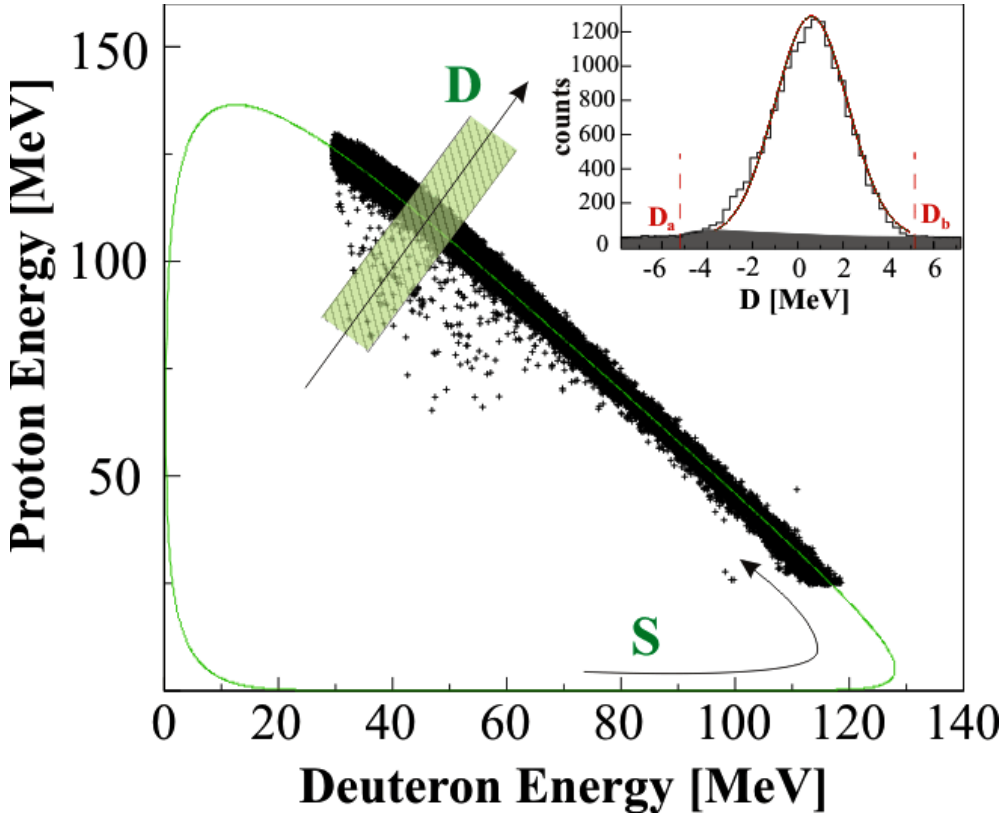


I. Ciepał et al.,
Phys. Rev. C 99, 014620 (2019)

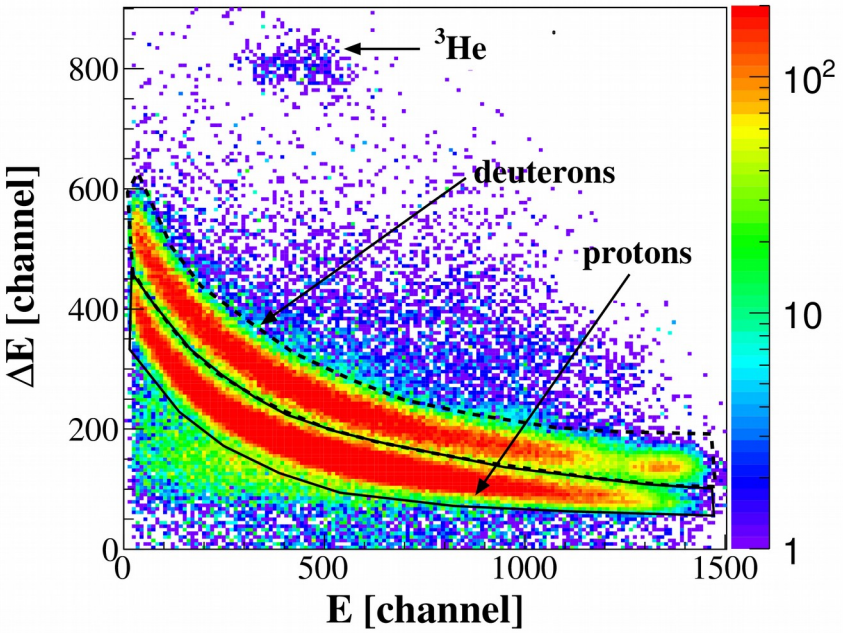
Data included into EXFOR:
https://www-nds.iaea.org/exfor/

d+d → d+p+n @ 160 MeV





Particle Identification

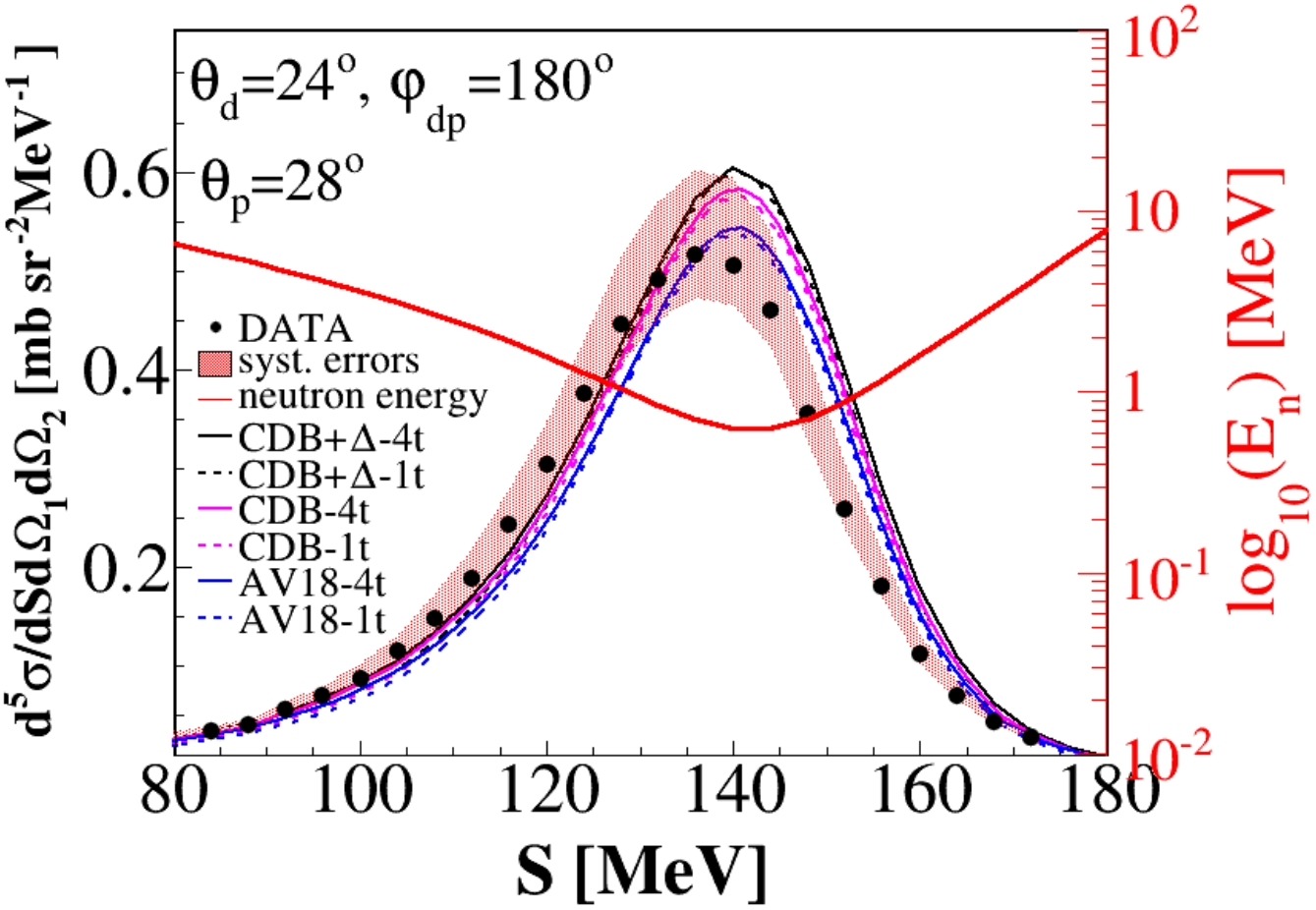


d+d → d+p+n @ 160 MeV around QFS

I. Ciepał et al.,
Phys. Rev. C 100, 024003 (2019)

I. Ciepał et al.,
Few-Body Syst 60, 44 (2019)

SSA calculations by Arnas Deltuva

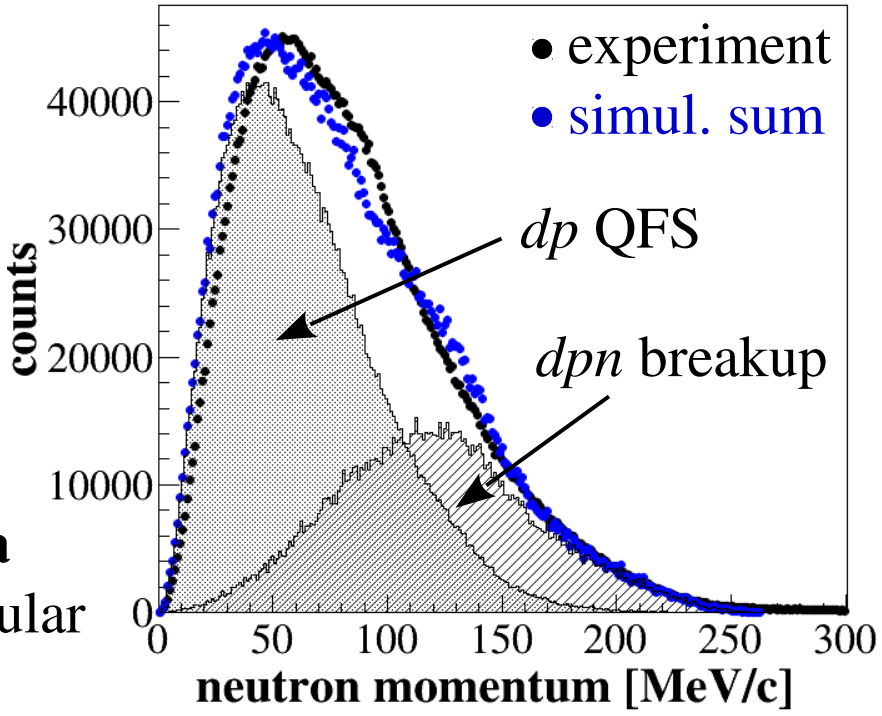


d+d → d+p+n @ 160 MeV around QFS

I. Ciepał et al.,
Phys. Rev. C 100, 024003 (2019)

around QFS = we analyze the data under conditions:

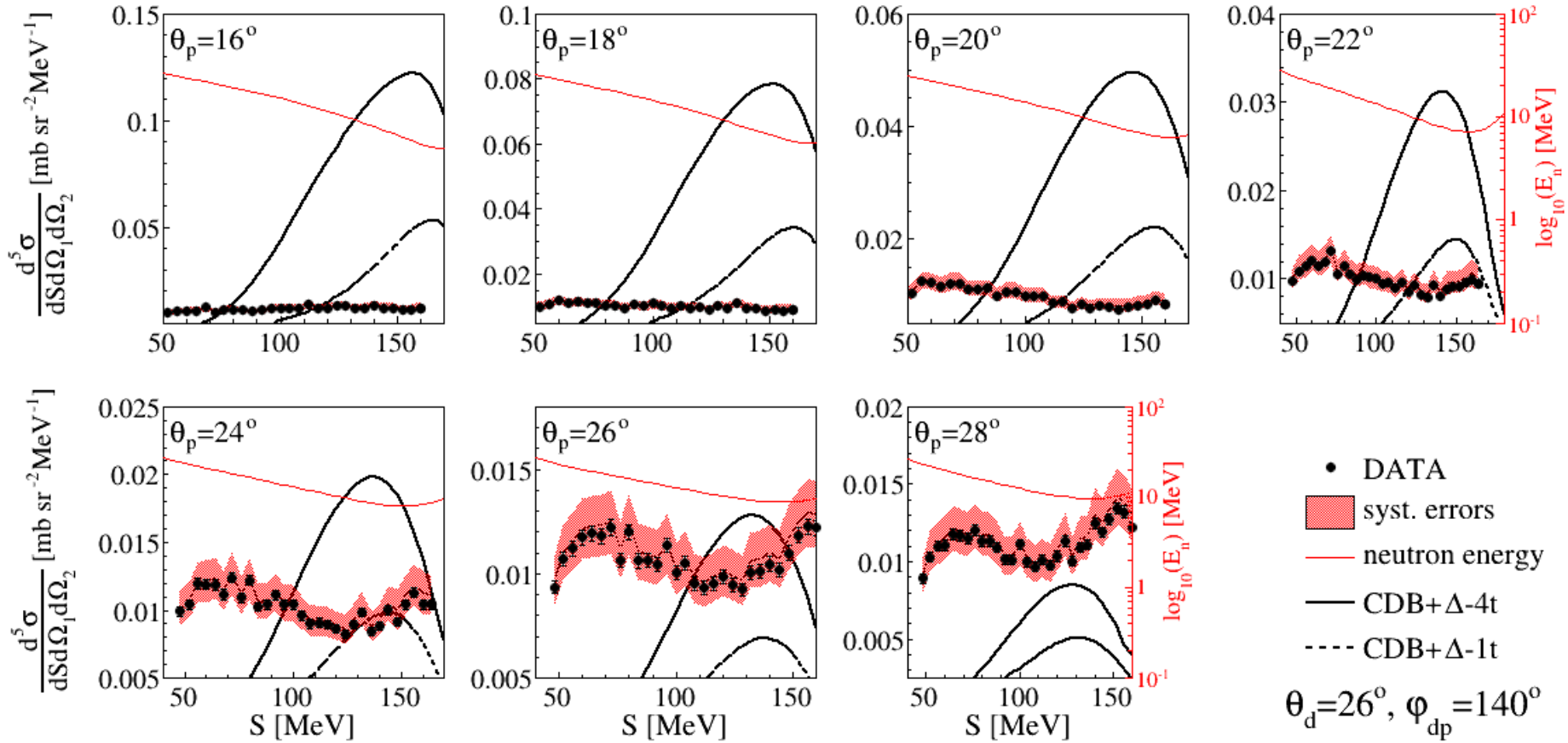
- detector acceptance (θ_d, θ_p: 15^o-29^o) → target breakup,
- neutron from deuteron target (Fermi momentum ~ 80 MeV/c) → spectator,
- φ_{dp}: 135^o-185^o,
- the data were sorted according to the neutron energy E_n,



PLUTO simulations vs. data
sensitivity of the selected angular range to the QFS kinematics

d+d → d+p+n @ 160 MeV around QFS

I. Ciepał et al.,
Phys. Rev. C 100, 024003 (2019)



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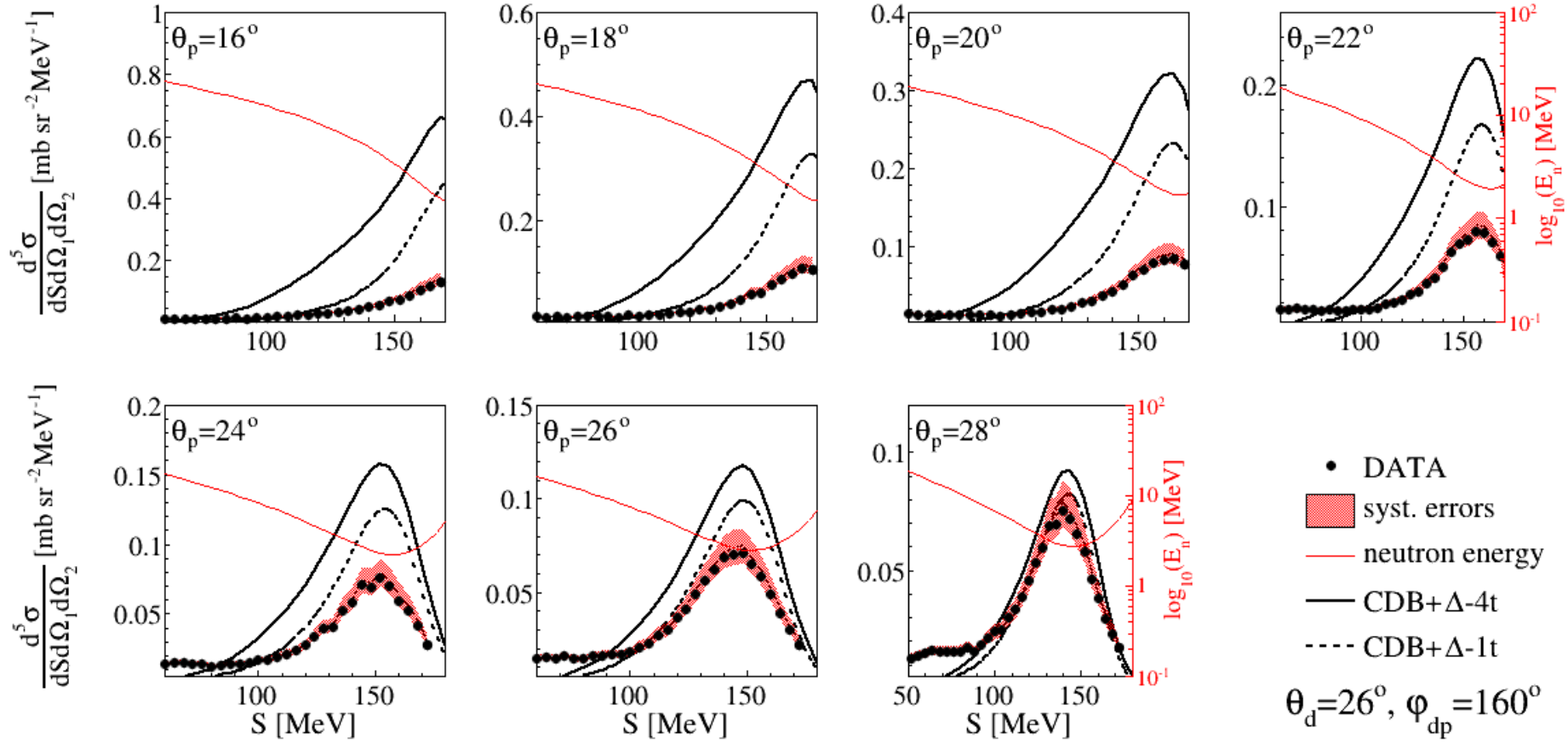

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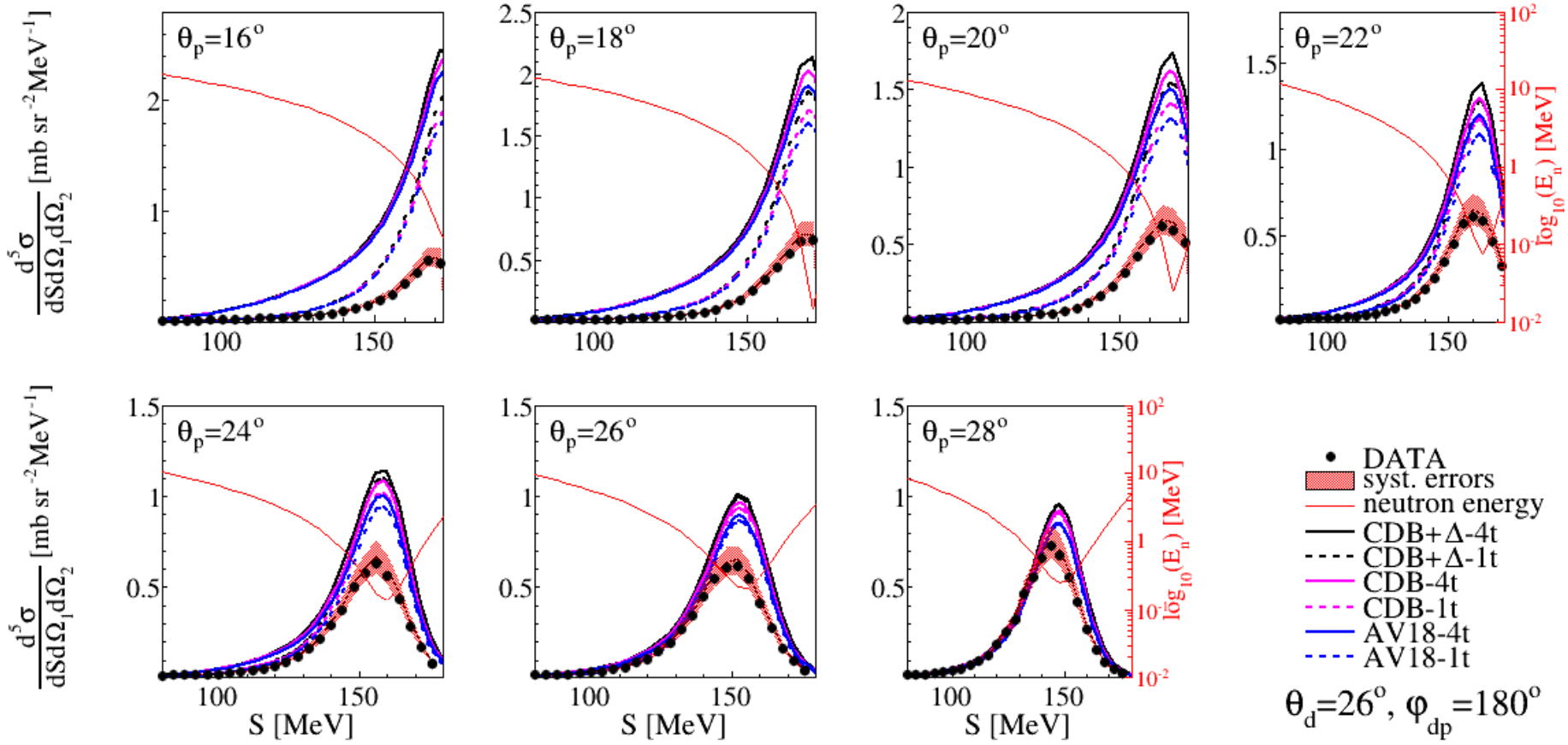
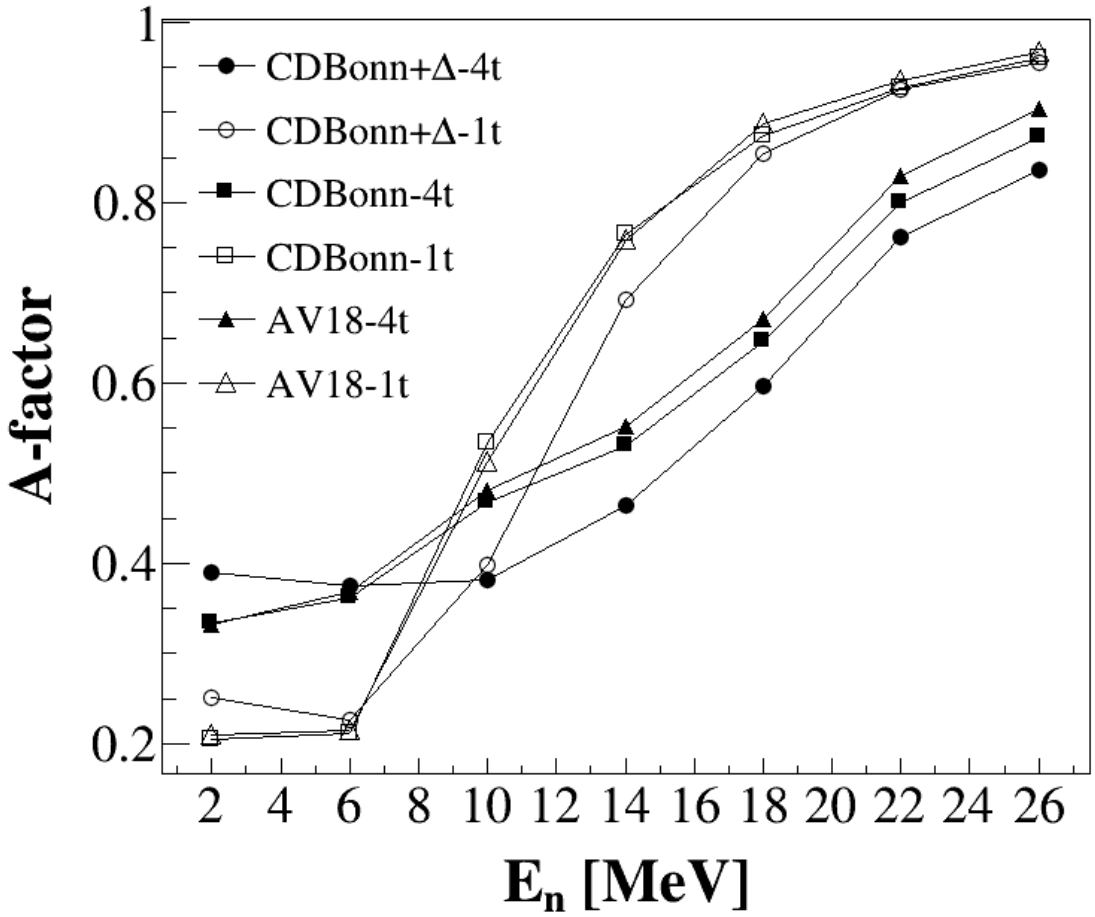


Global comaprison

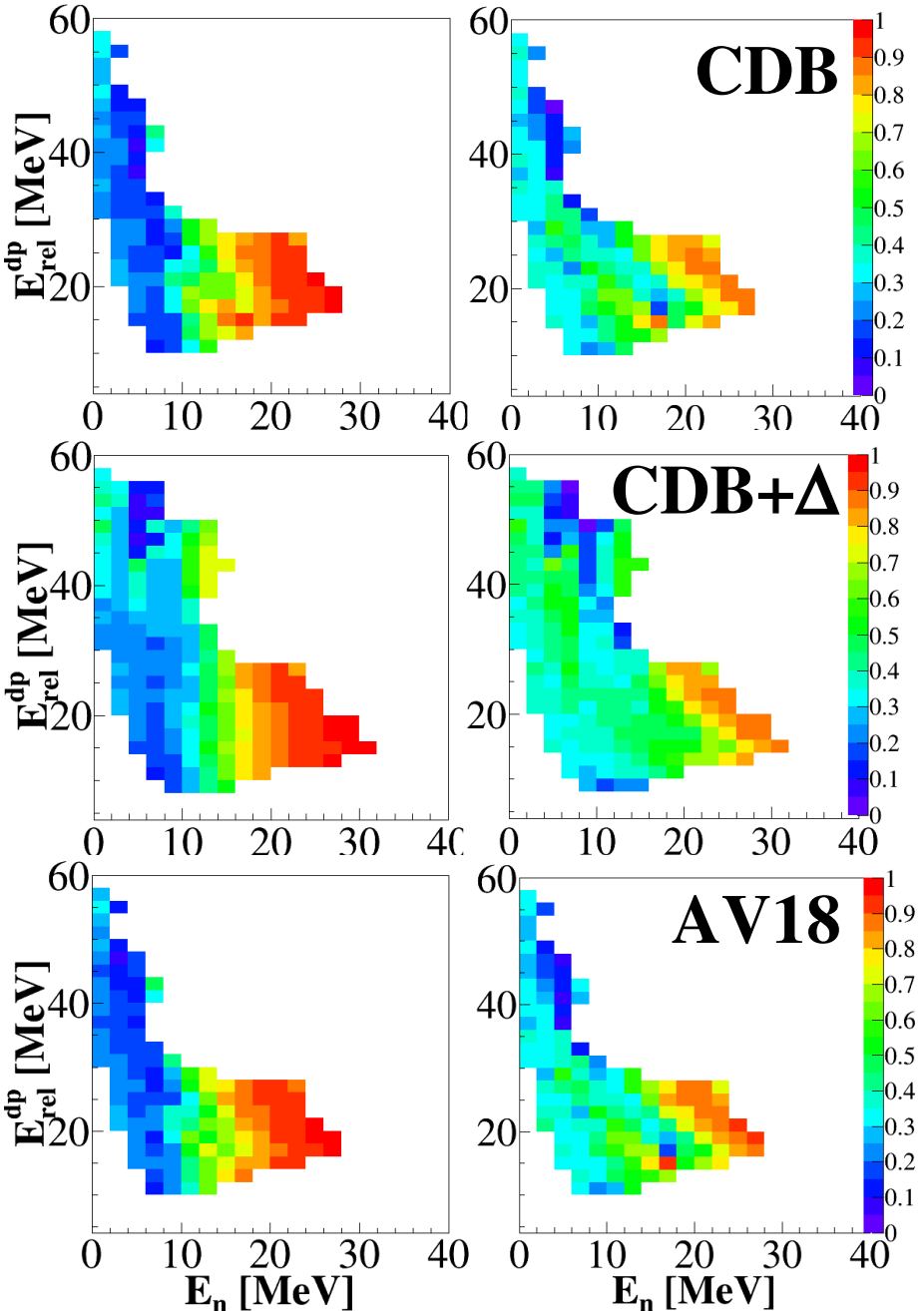


A-factor (instead of χ^2) on z-axis:

$$A \equiv \frac{1}{N} \sum_{i=1}^{N} \frac{\mid \sigma_i^{exp} - \sigma_i^{th} \mid}{\sigma_i^{exp} + \sigma_i^{th}}$$

A [0,1]

1-term 4-term



E_{rel}^{dp} vs E_n

A-factor on z-axis

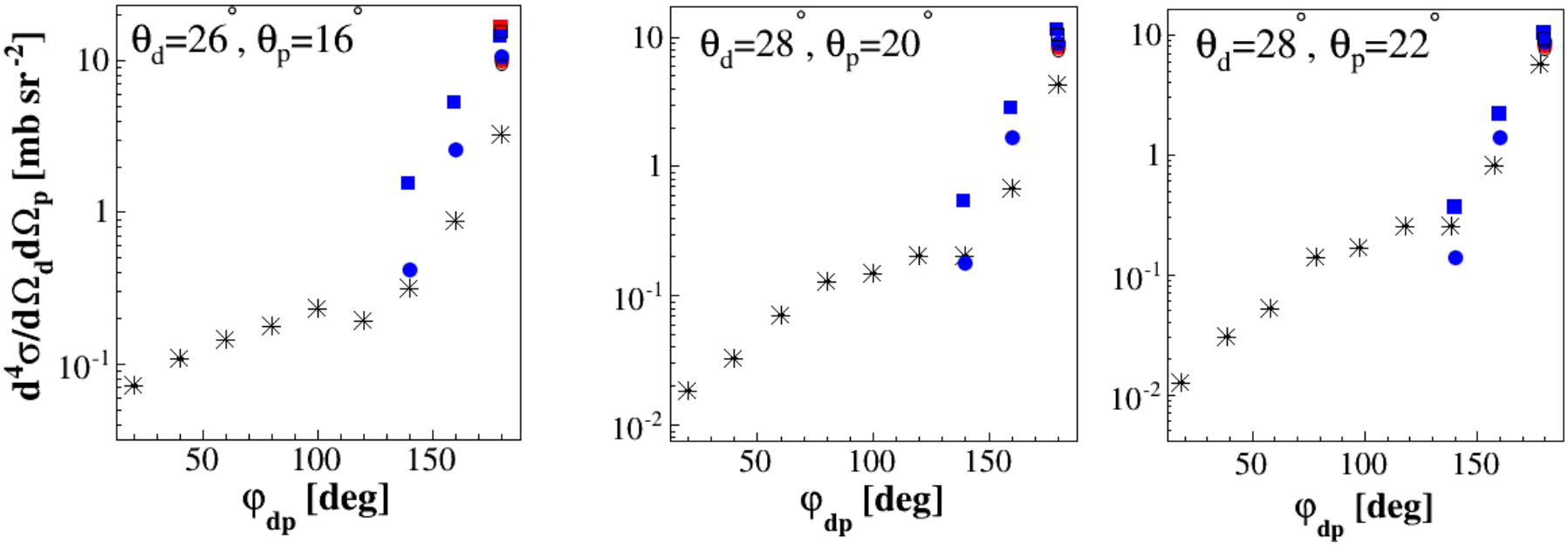
- 1t performs better
- deuteron beam energy of 160 MeV is too low to meet the SSA assumptions

d+d → d+p+n @ 160 MeV

I. Ciepał et al.,
Few-Body Syst 60, 44 (2019)

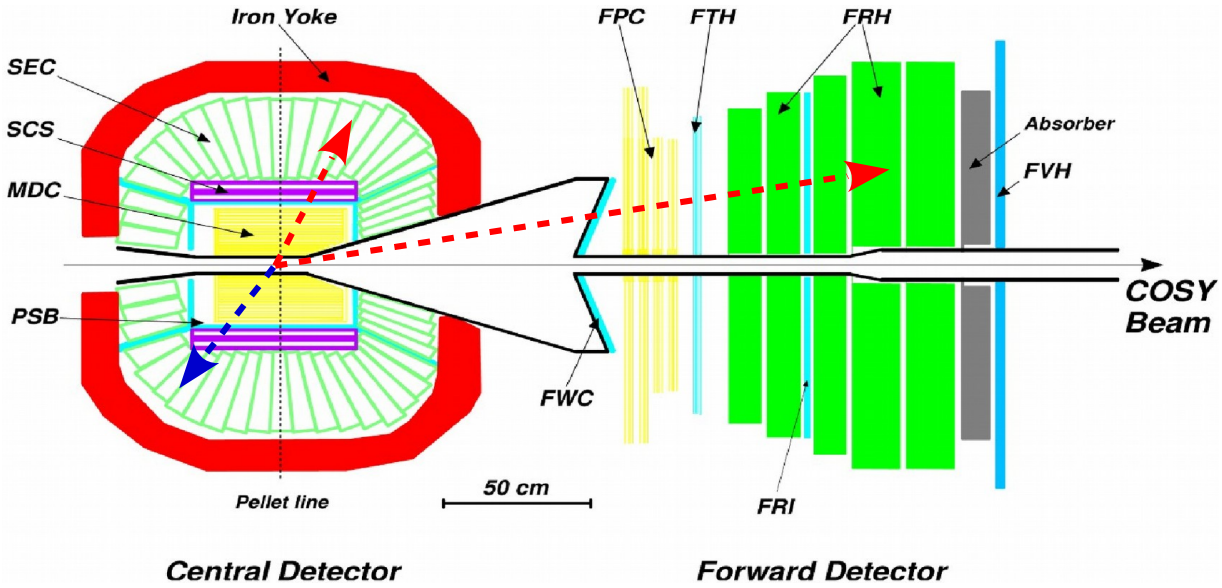
- cross sections obtained also for $\varphi_{dp} < 135^{o}$,
- no theory available so far

DATA
CDBonn-4t
CDBonn-1t
CDBonn+Δ-1t
CDBonn+Δ-4t
AV18-1t
AV18-4t



OUTLOOK

WASA@ COSY d+d @ 350 MeV



$$d+d \rightarrow d(FD) + p(FD)+n$$

$$d+d \rightarrow d(FD) + p(CD)+n$$

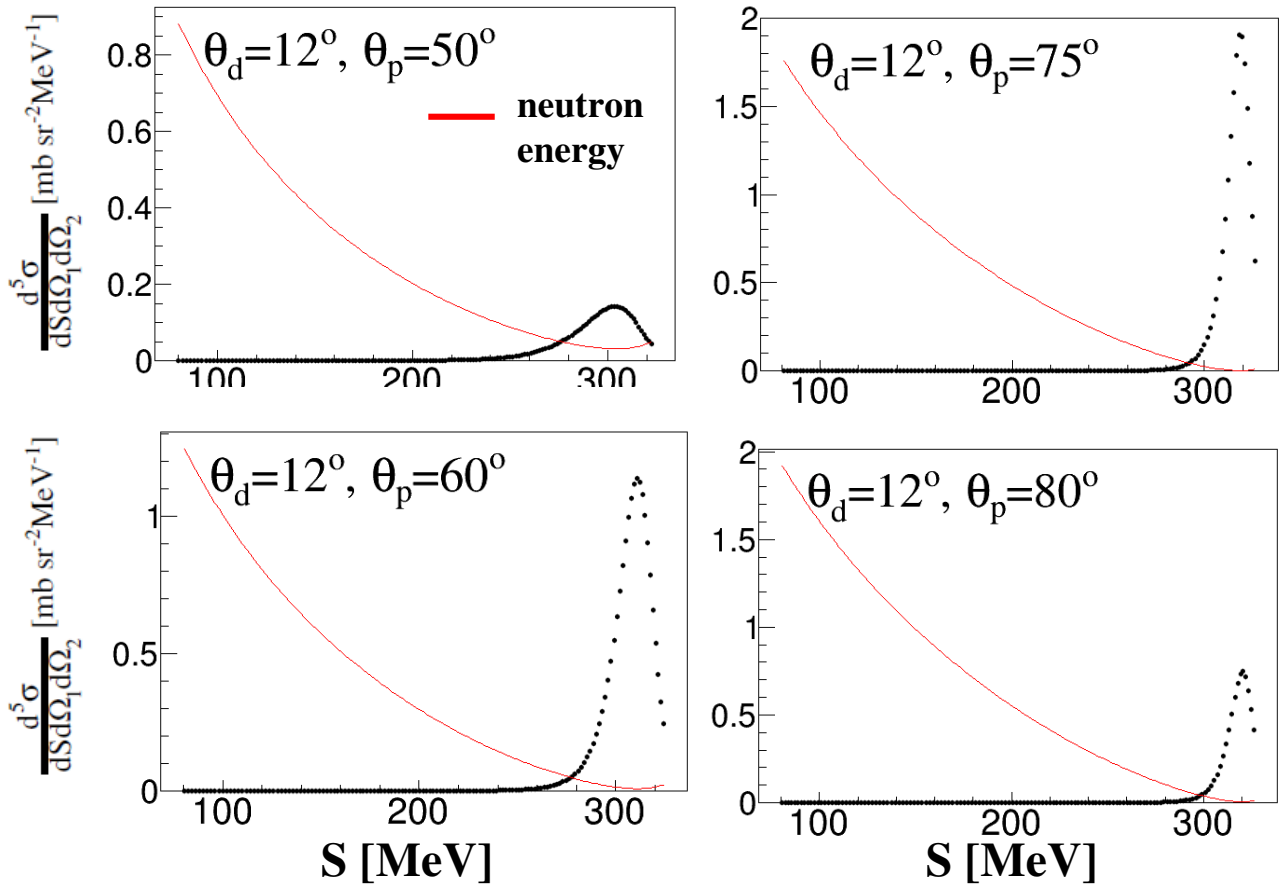
$$d+d \rightarrow d+p+n(CD)$$

OUTLOOK

WASA@ COSY d+d @ 350 MeV

d+d → d(FD) + p(CD)+n

SSA calculations by Arnas Deltuva

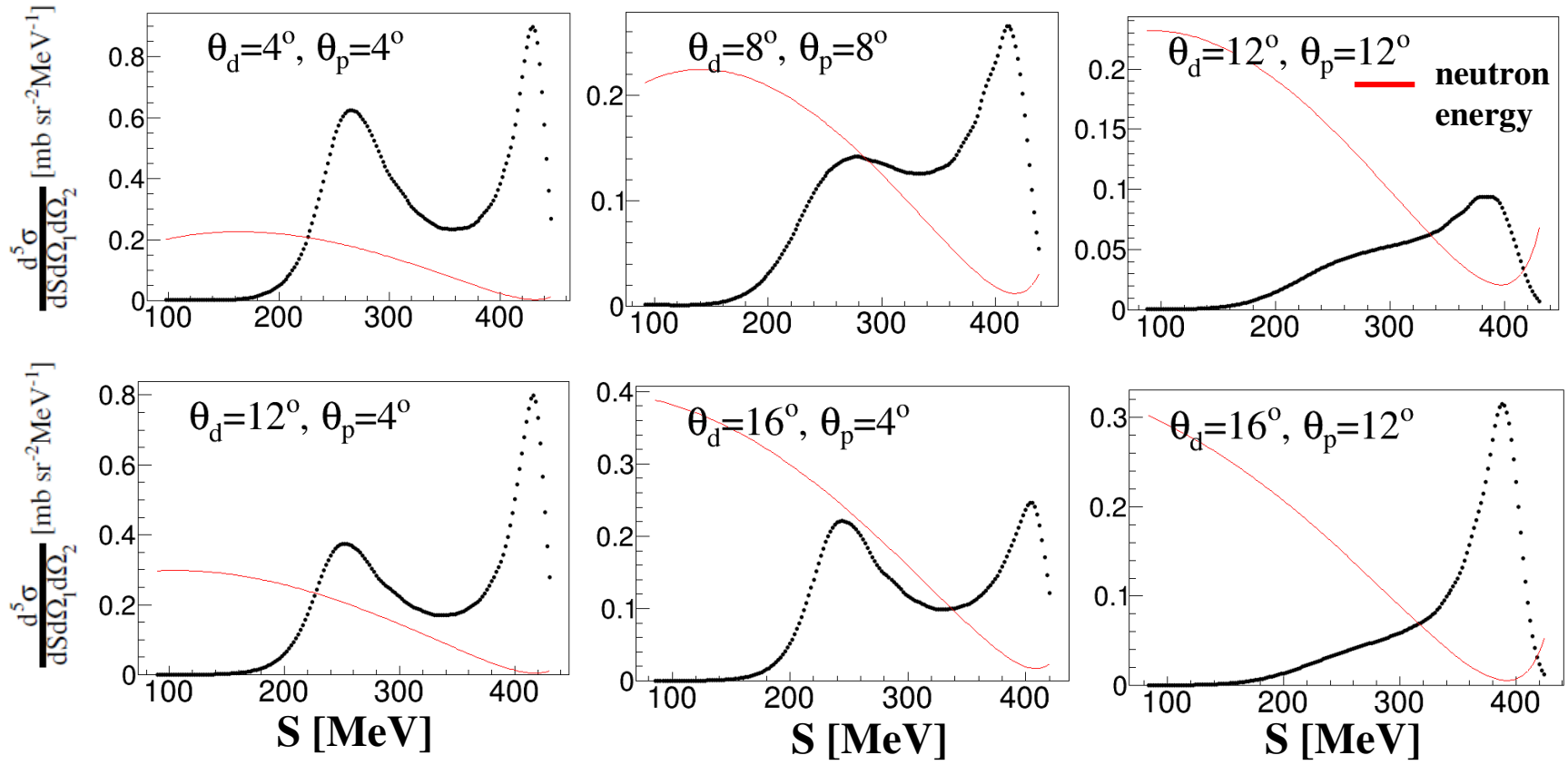


OUTLOOK

WASA@ COSY d+d @ 350 MeV

d+d → d(FD) + p(FD)+n

SSA calculations by Arnas Deltuva



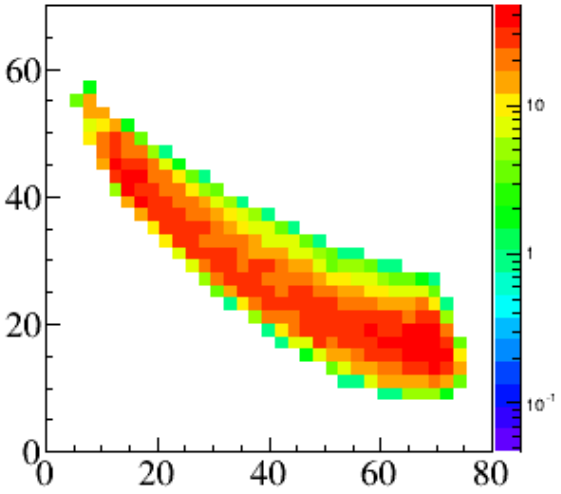
Summary

- ✗ Theoretical calculations exist for dd, p+^{3}He, n+^{3}He for elastic scattering and transfer channels, but still for small energies < 35 MeV
  - ✗ **rapid progress in calculations for 4N systems.**

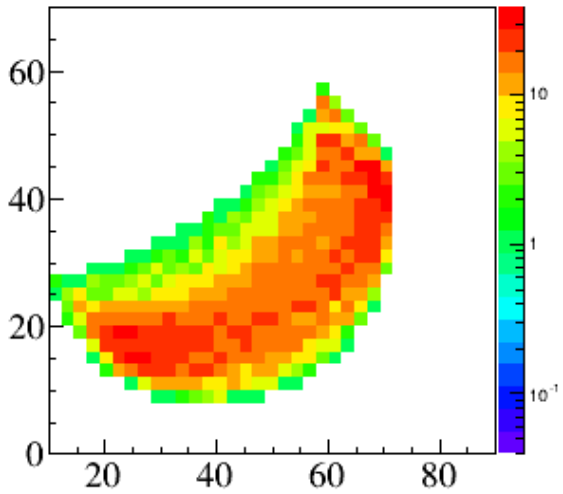
- ✗ Differential cross section for dd → n^{3}He @160MeV was obtained,
- ✗ Set of cross sections for the three body breakup around QFS and away from QFS has been evaluted and comapred to the recent SSA calculations → energy too low to fulfill the SSA asumptions,
- ✗ dd @ 350 MeV data measured with WASA@ COSY can also be used to evaluate the SSA predictions.

THANK YOU
FOR
YOUR ATTENTION !

herel_dp_vs_erel_pn



herel_dp_vs_erel_dn



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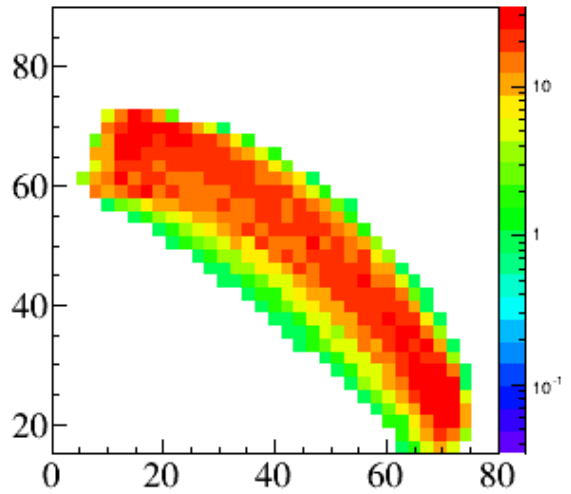
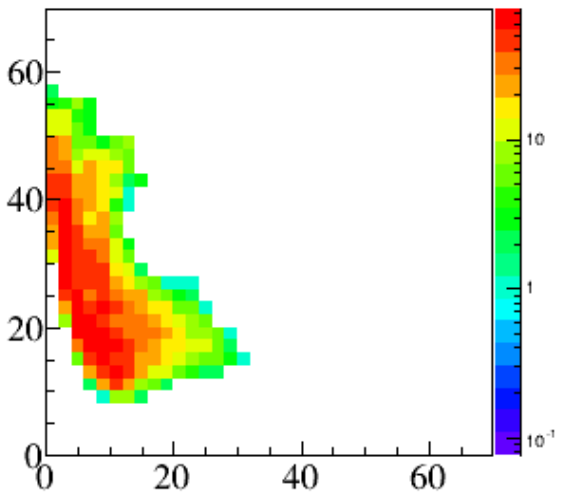


herel_dp_vs_en



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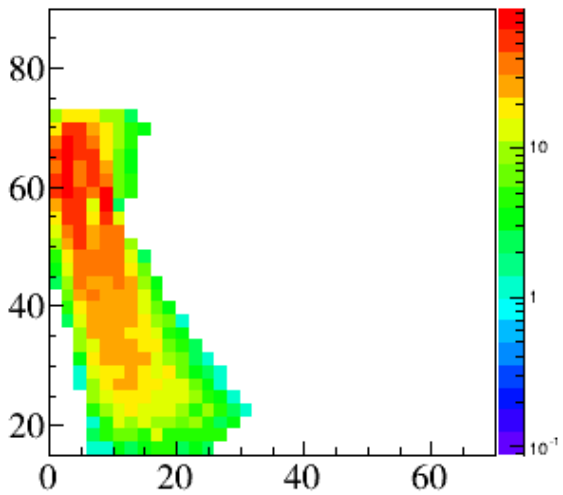

herel_pn_vs_en