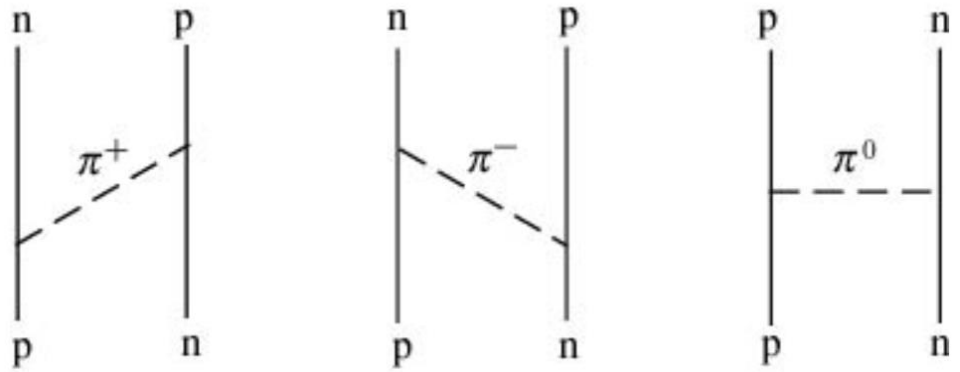
Analysis of the elastic and three-body break-up channel in deuteron-deuteron scattering at 65 MeV/nucleon

Reza Ramazani Sharifabadi

Why d-d scattering?

- N-N interaction is described by exchange of mesons.



- High-precision NN models were developed based on Yukawa's theory:

CD-Bonn 2000

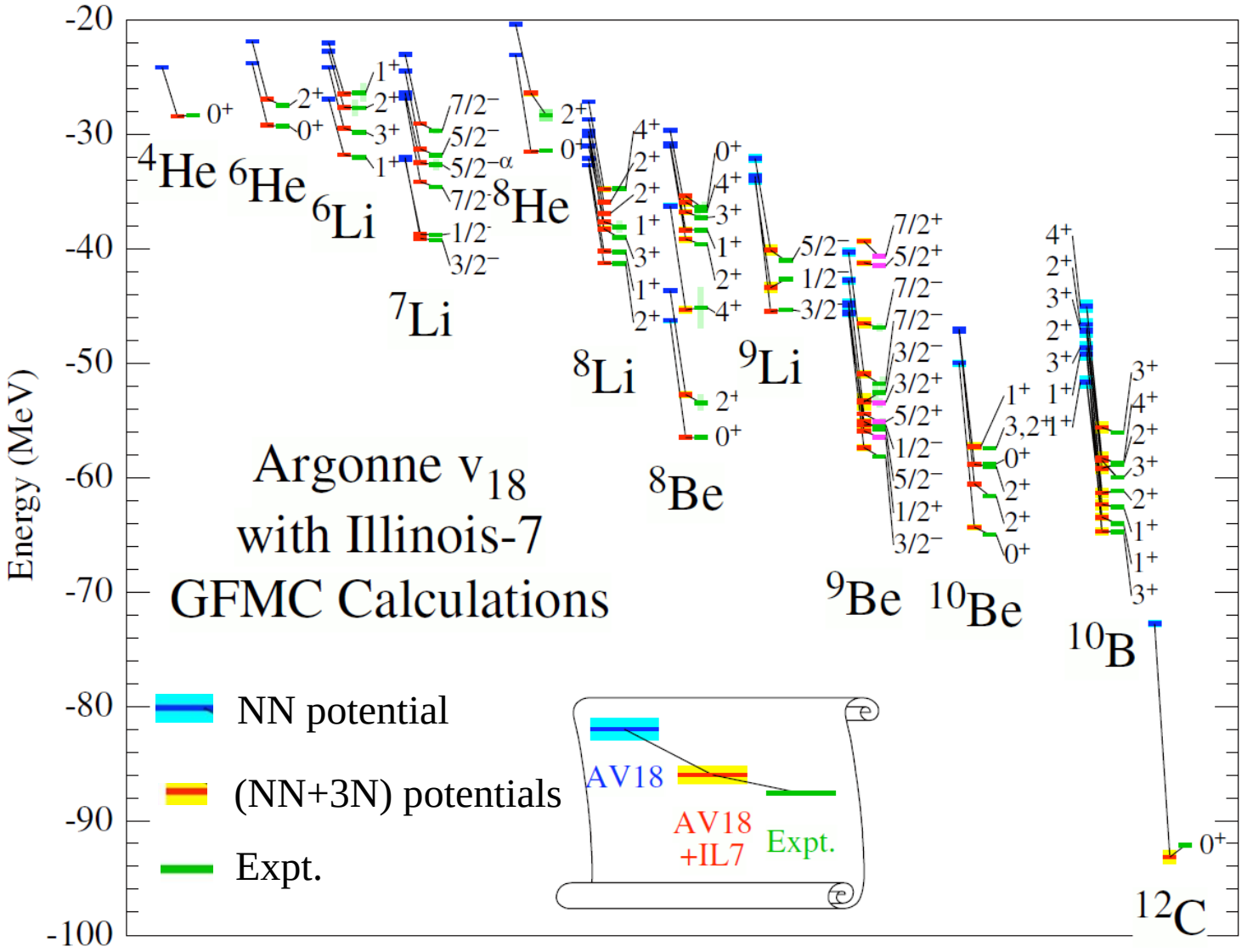
Argonne *V*18 (AV18)

Nijmegen I, II

…..

Why d-d scattering?

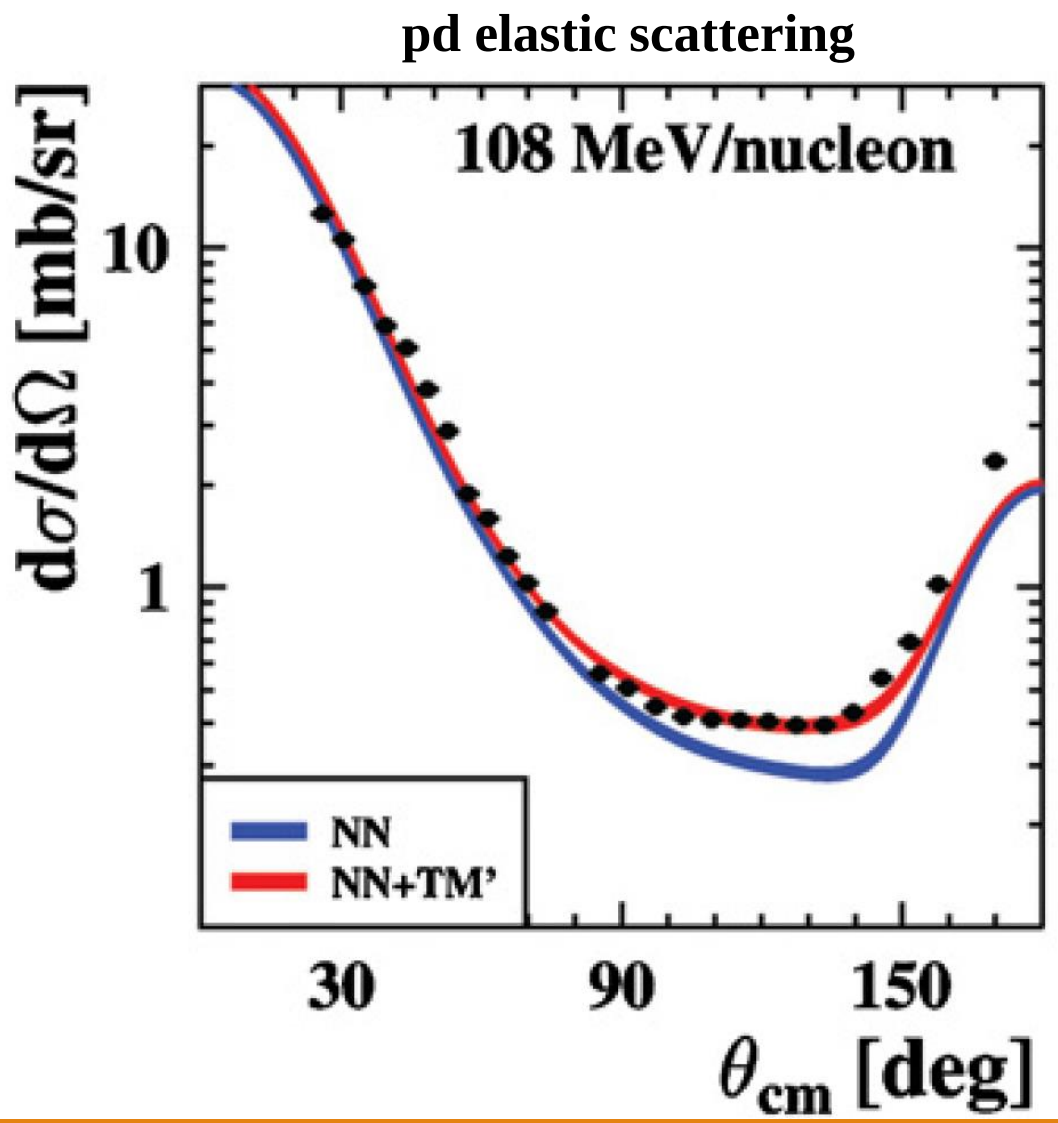
- Ab-initio calculations of binding energies using NN and 3N potentials as input
- Two-nucleon force gives discrepancies for A>2.
- Additional three-nucleon effects, (3NF) generally gives a better agreement with experiment.



S. C. Pieper, private communication, (2011).

Why d-d scattering?

- Two-nucleon force shows discrepancies.
- Additional 3NF generally gives a better agreement with experiment in cross section but for the spin observables has different trends.

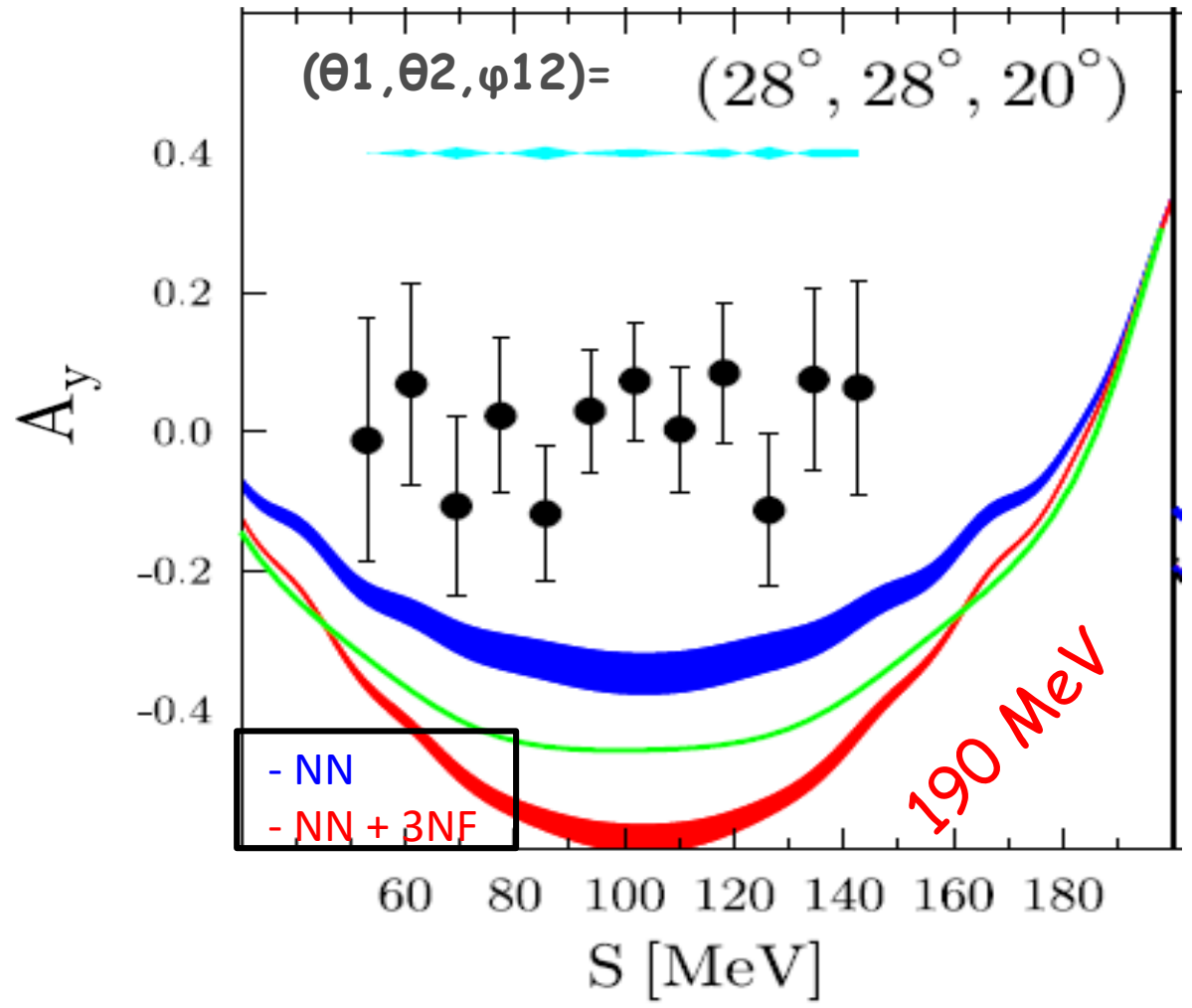


K. Ermisch, *et al . Phys. Rev. Lett.* **86** 5862, (2001).

Why d-d scattering?

- Two-nucleon force shows discrepancies.

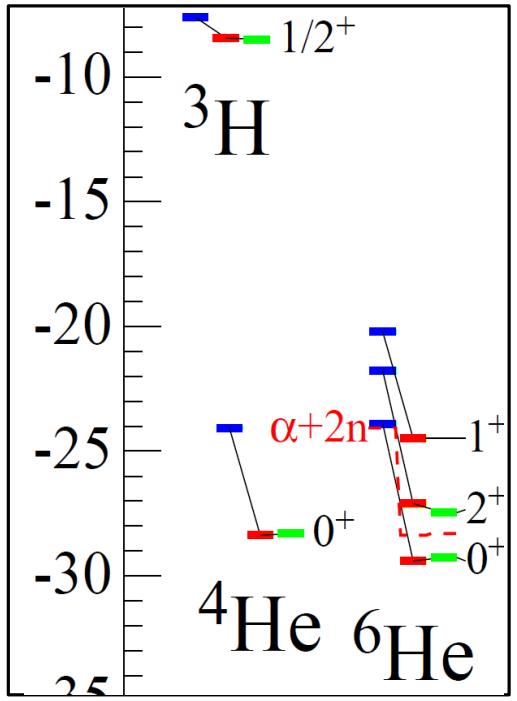
- Additional 3NF generally gives a better agreement with experiment in cross section but for the spin observables has different trends.

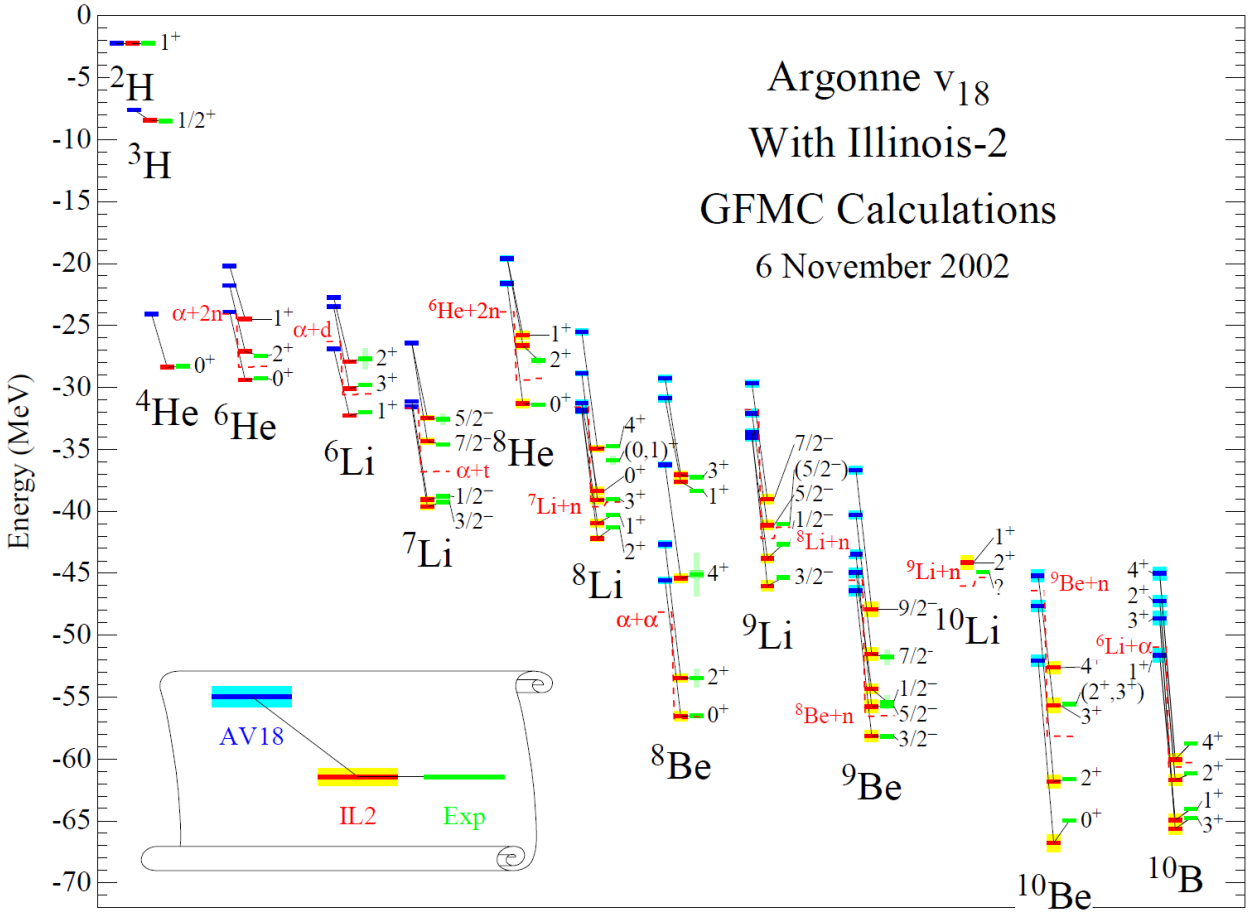


K. Ermisch, *et al . Phys. Rev. Lett.* **86** 5862, (2001).

Why d-d scattering?

- **3NF effects are significantly enhanced in magnitude in 4-body system.**

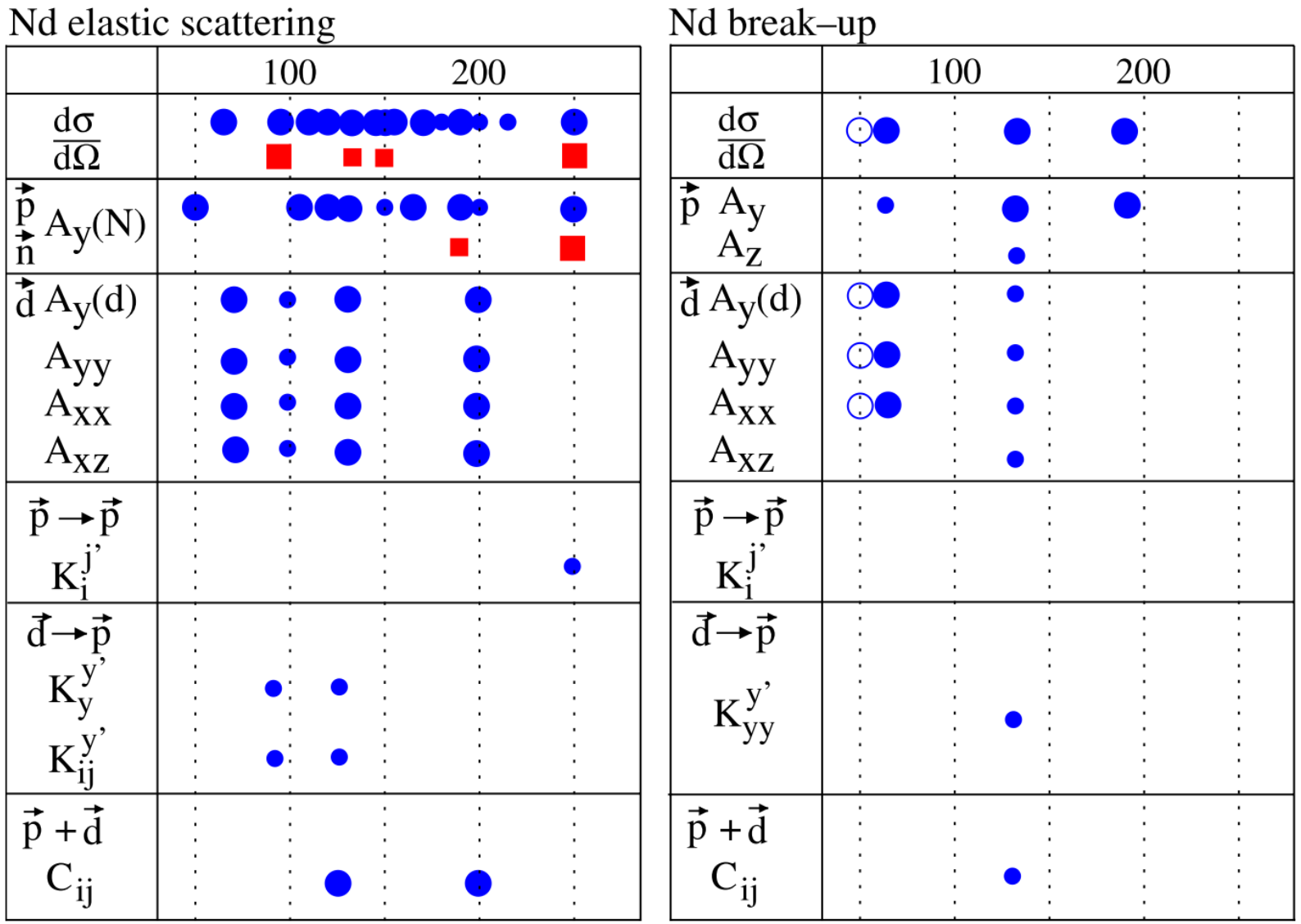




K. Ermisch, *et al . Phys. Rev. Lett.* **86** 5862, (2001).

Why d-d scattering?

- **3NF effects are significantly enhanced in magnitude in 4-body system,**
- **Expanding the experimental database in four-body system.**



K. Ermisch, *et al . Phys. Rev. Lett.* **86** 5862, (2001).

Why d-d scattering?

- **3NF effects are significantly enhanced in magnitude in 4-body system,**
- **Expanding the experimental database in four-body system.**

dd elastic scattering

	100	200
$\frac{d\sigma}{d\Omega}$		•
iT_{11}	•	•
T_{22}		•
T_{20}		•
T_{21}		
$K_i^{j'}$		
$K_y^{y'}$		
$K_{ij}^{y'}$		
C_{ij}		

dd break–up

	100	200
$\frac{d\sigma}{d\Omega}$		
$\vec{d}$ iT_{11}		
T_{22}		
T_{20}		
T_{21}		
$K_i^{j'}$		
$K_{yy}^{y'}$		
C_{ij}		

K. Ermisch, *et al . Phys. Rev. Lett.* **86** 5862, (2001).

Outline of data analysis

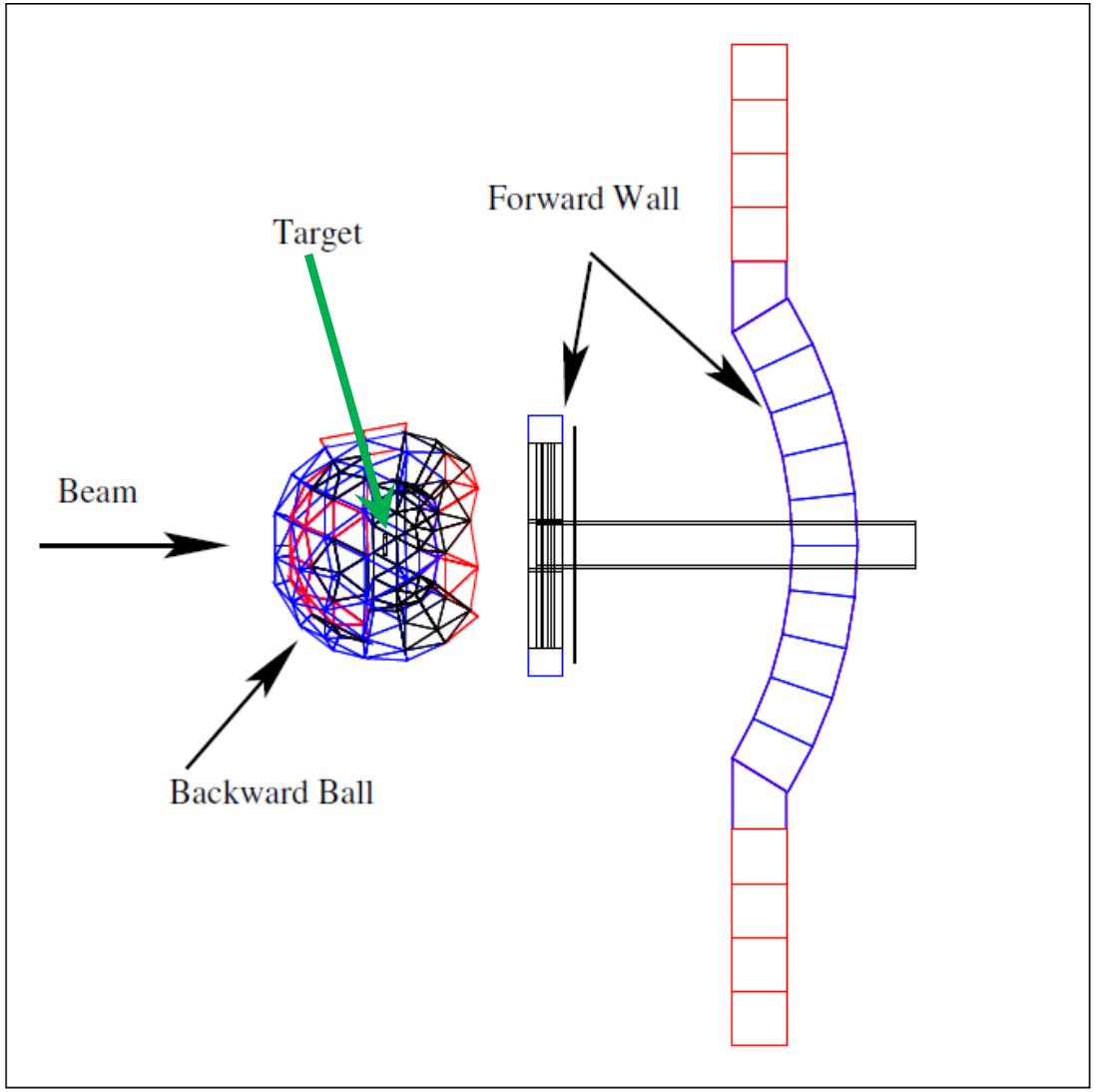
d-d scattering channels:

- $\vec{d} + d \rightarrow d + d$, d-d elastic channel
- $\vec{d} + d \rightarrow d + p + n$, Three-body break-up channel
- $\vec{d} + d \rightarrow {}^{3}H + p$, neutron transfer channel
- $\vec{d} + d \rightarrow {}^{3}He + n$, proton transfer channel
- $\vec{d} + d \rightarrow p + p + n + n$, four-body break-up

Experimental Setup

BINA (**B**ig **I**nstrument for **N**uclear-Polarization **A**nalysis)

- Forward Wall:
  - ✓ MWPC (Multi-Wire Proportional Chamber),
  - ✓ ΔE-E detectors
- Backward Ball:
  - ✓ 149 Phoswich Scintillators,
  - ✓ As detector and scattering chamber



Experimental Setup

BINA (**B**ig **I**nstrument for **N**uclear-Polarization **A**nalysis)

- Forward Wall:
  - ✓ MWPC (Multi-Wire Proportional Chamber),
  - ✓ ΔE-E detectors
- Backward Ball:
  - ✓ 149 Phoswich Scintillators,
  - ✓ As detector and scattering chamber

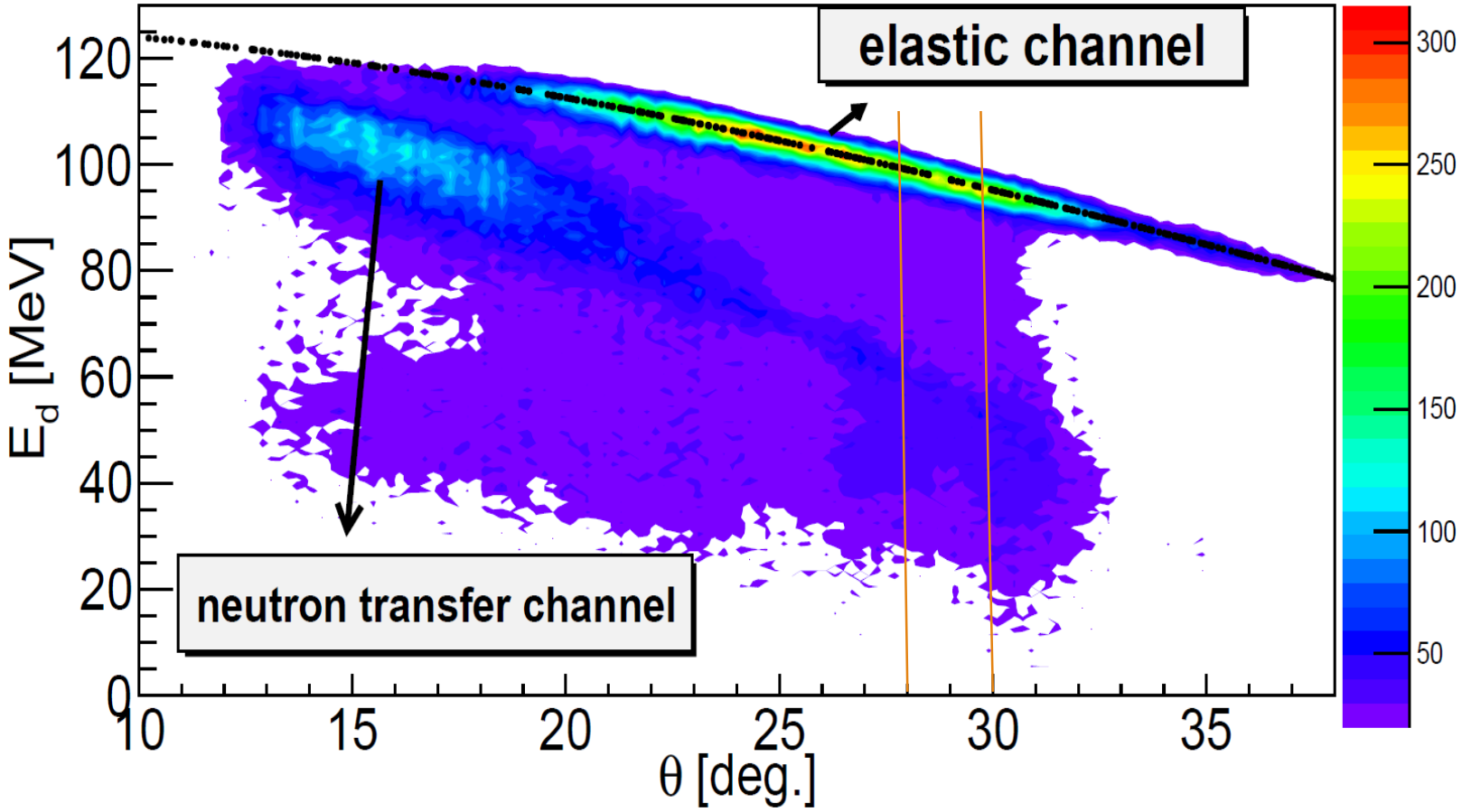
Analysis of elastic channel

university of groningen

kvi - center for advanced radiation technology

Cross section for d-d elastic channel:

- Select d-d events:



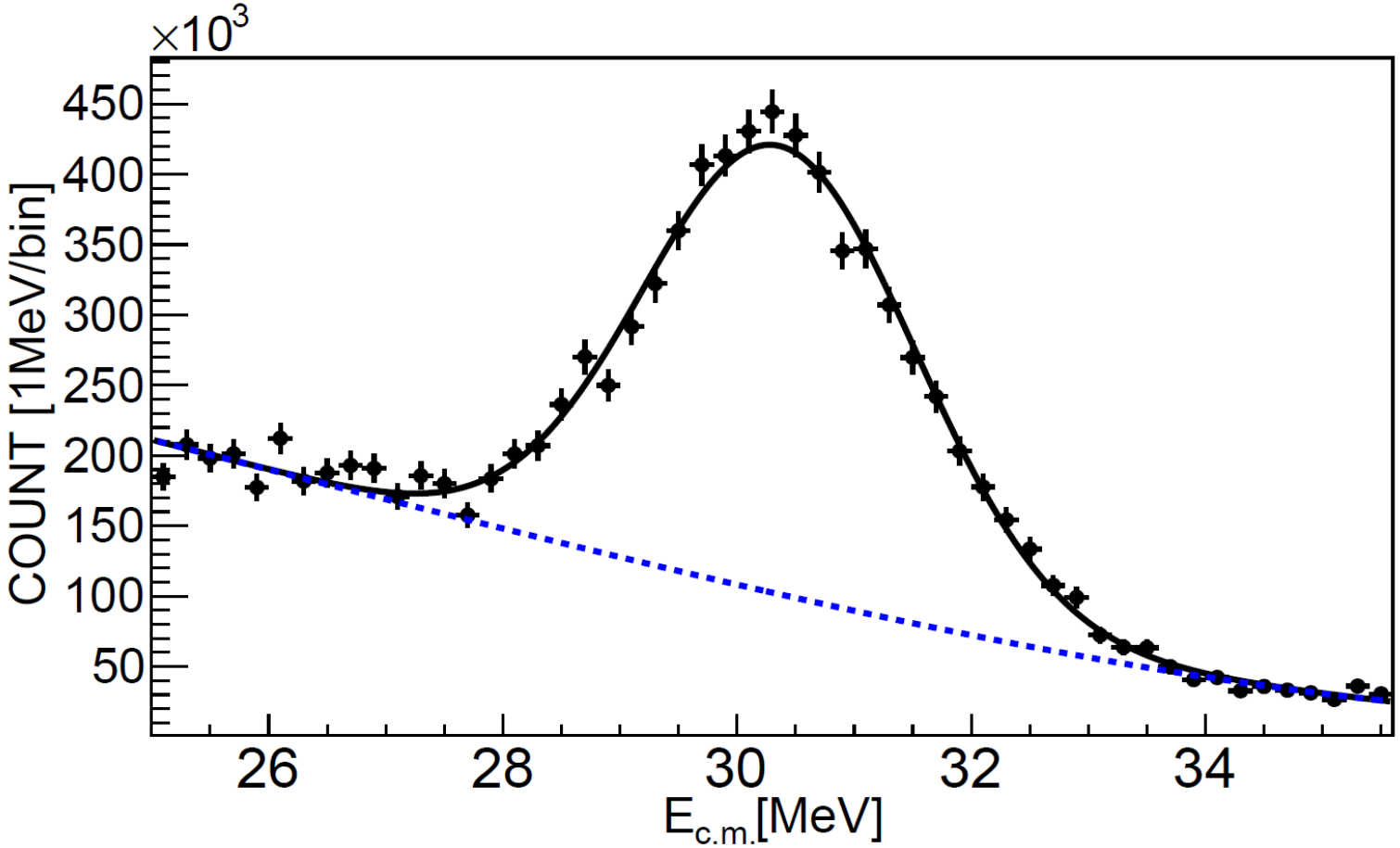
Analysis of elastic channel

university of groningen

kvi - center for advanced radiation technology

Cross section for d-d elastic channel:

- Project on the energy axis
- Use a polynomial + Gaussian fit
- Background subtraction



Analysis of elastic channel

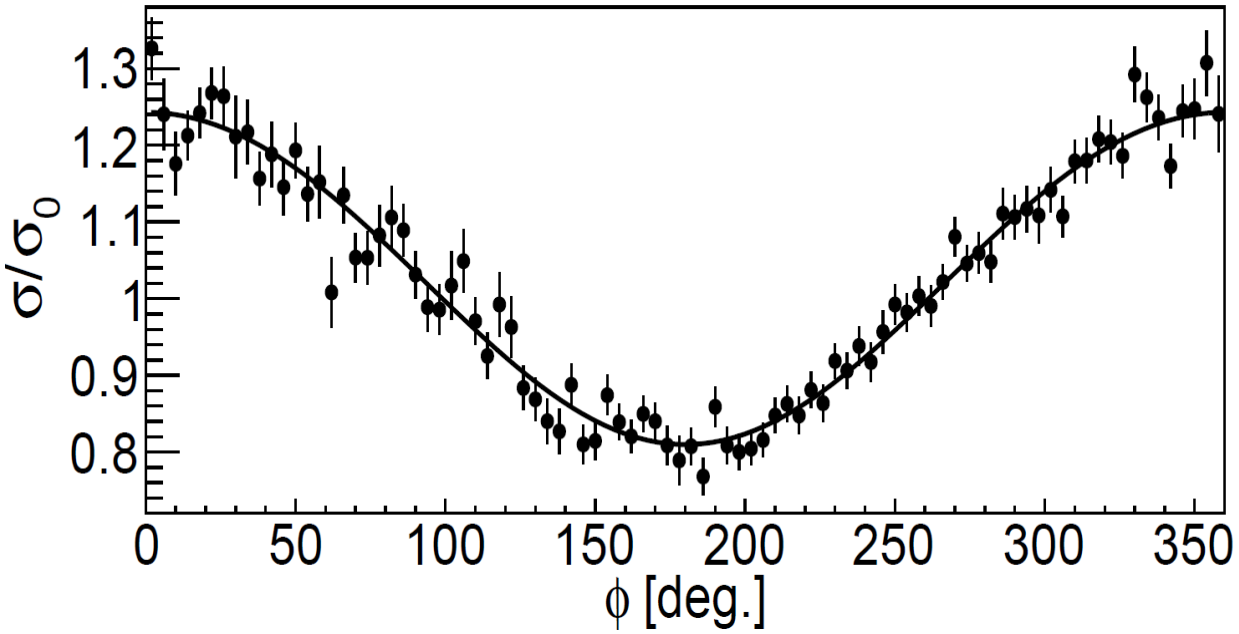
university of groningen

kvi - center for advanced radiation technology

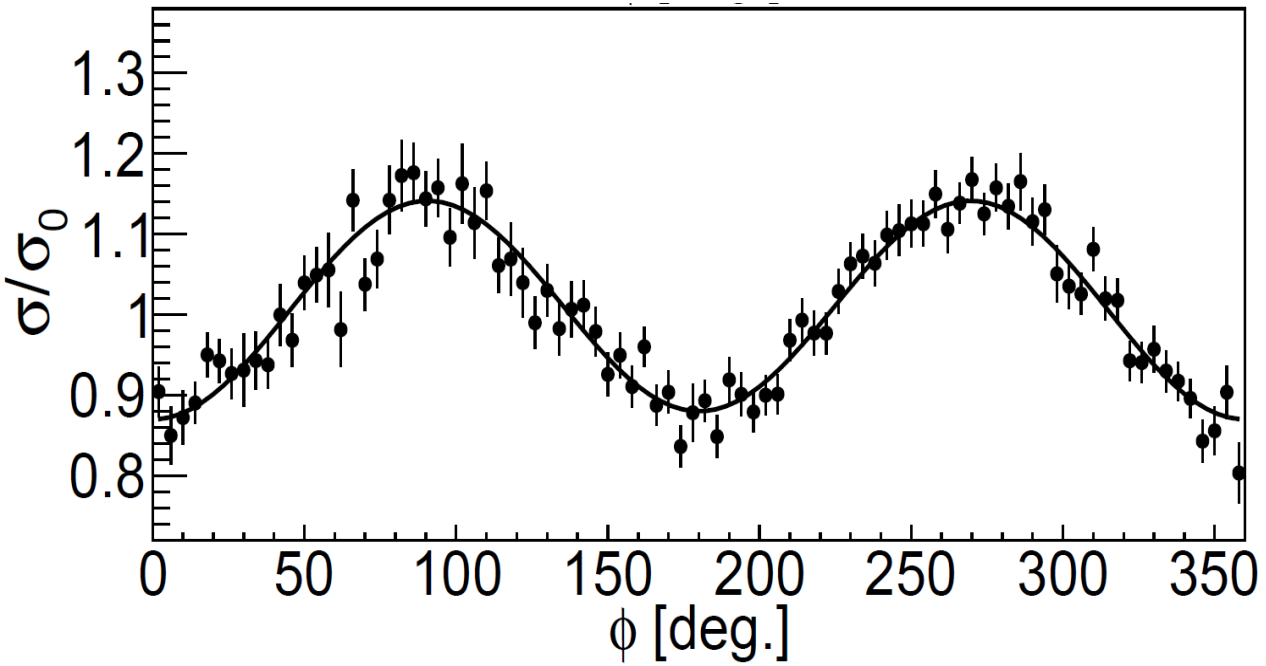
Analyzing powers for d-d elastic channel:

$$\sigma(\theta,\phi) = \sigma_0(\theta)[1+\frac{3}{2}p_z A_y(\theta)\cos(\phi)-\frac{1}{4}p_{zz}A_{zz}(\theta)+\frac{1}{4}p_{zz}(A_{zz}(\theta)+2A_{yy}(\theta))\cos(2\phi)],$$

$p_{ZZ} = 0$ && $p_Z \neq 0$

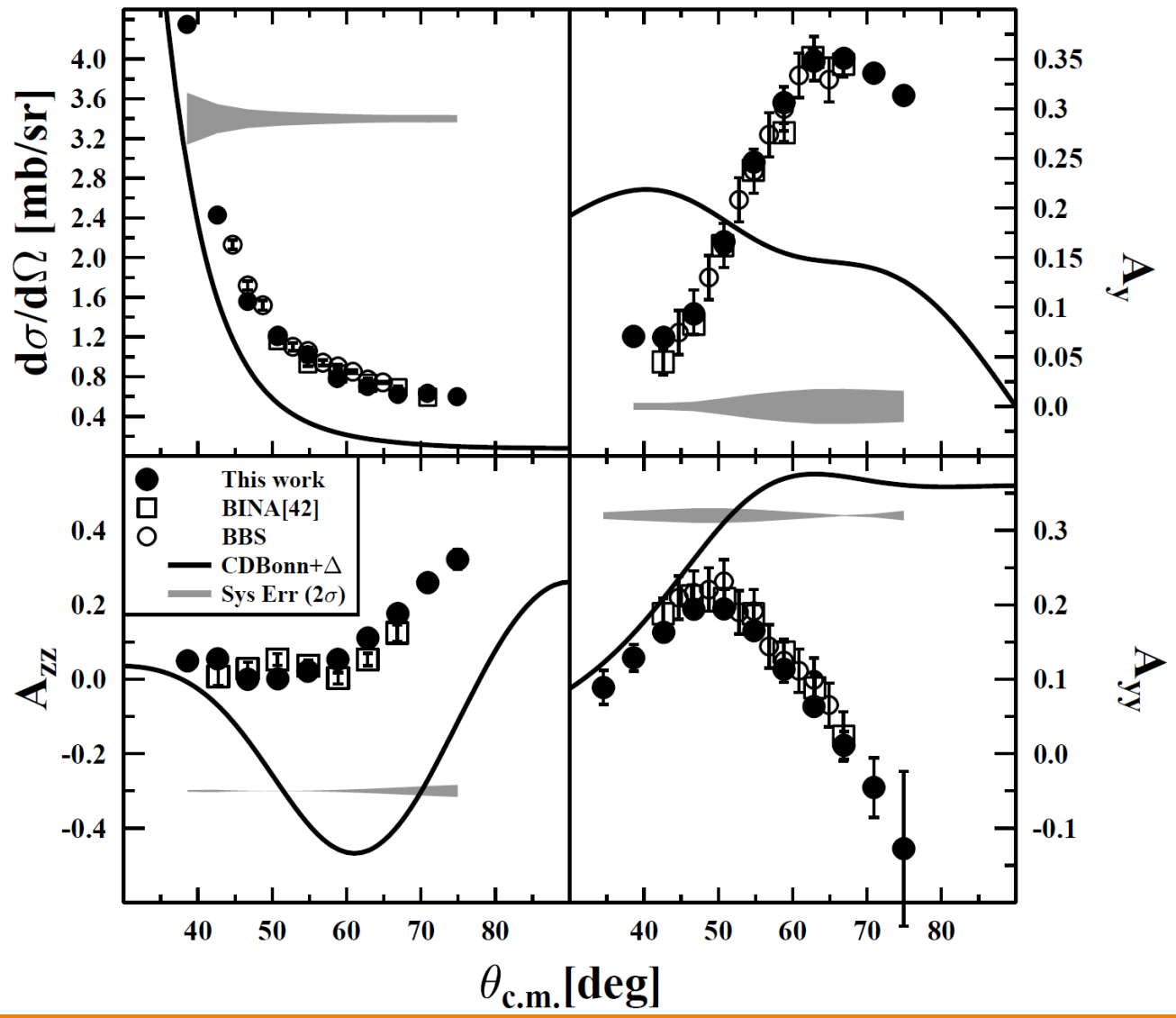


$p_Z = 0$ && $p_{ZZ} \neq 0$



Cross section and analyzing powers of elastic channel

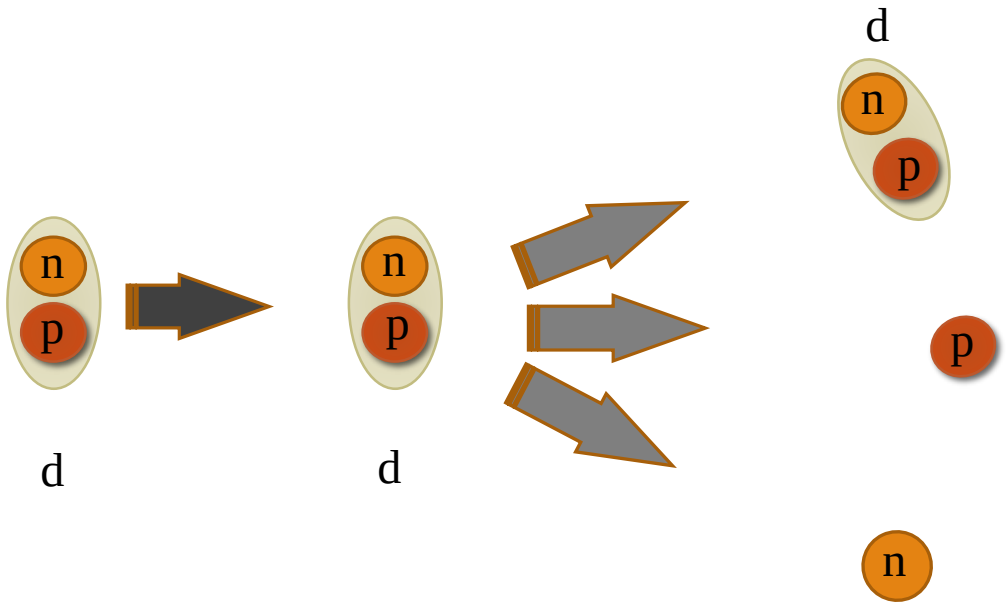
- World's most precise data at intermediate energies.
- Results agree very well with independent data taken with a magnetic spectrometer (BBS).
- Lack of ab-initio calculations for elastic d+d process at these energies.



A. Ramazani-Moghaddam-Arani, Ph.D. thesis, University of Groningen, (2009).

Analysis of 3-body break-up channel

Kinematics of three-body breakup channel:



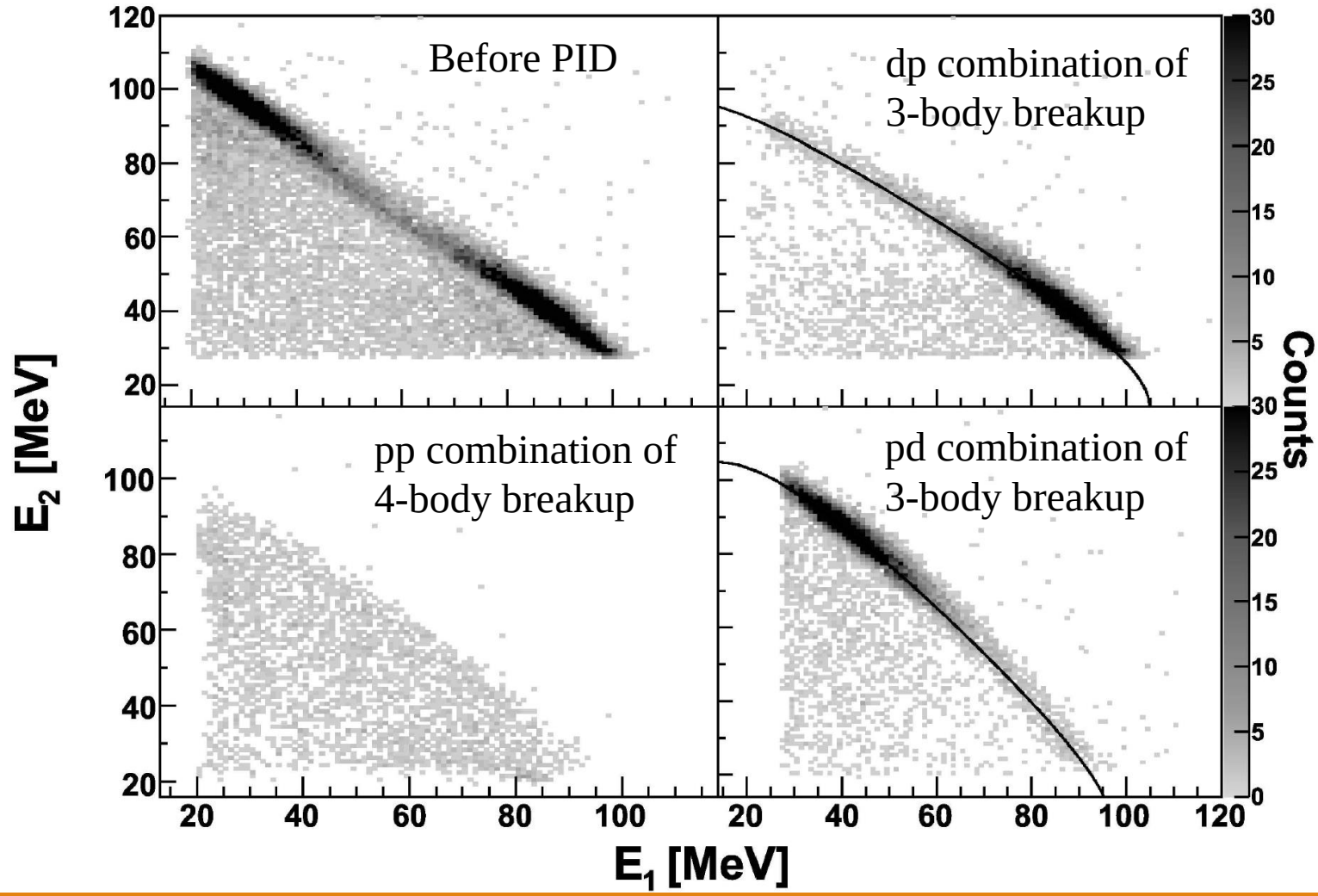
Analysis of 3-body break-up channel

university of groningen

kvi - center for advanced radiation technology

$(\theta_1, \theta_2, \phi_{12}) = (25°, 25°, 180°)$

Particle identification (PID) by using time-of-flight (TOF) information.



A. Ramazani-Moghaddam-Arani, Ph.D. thesis, University of Groningen, (2009).

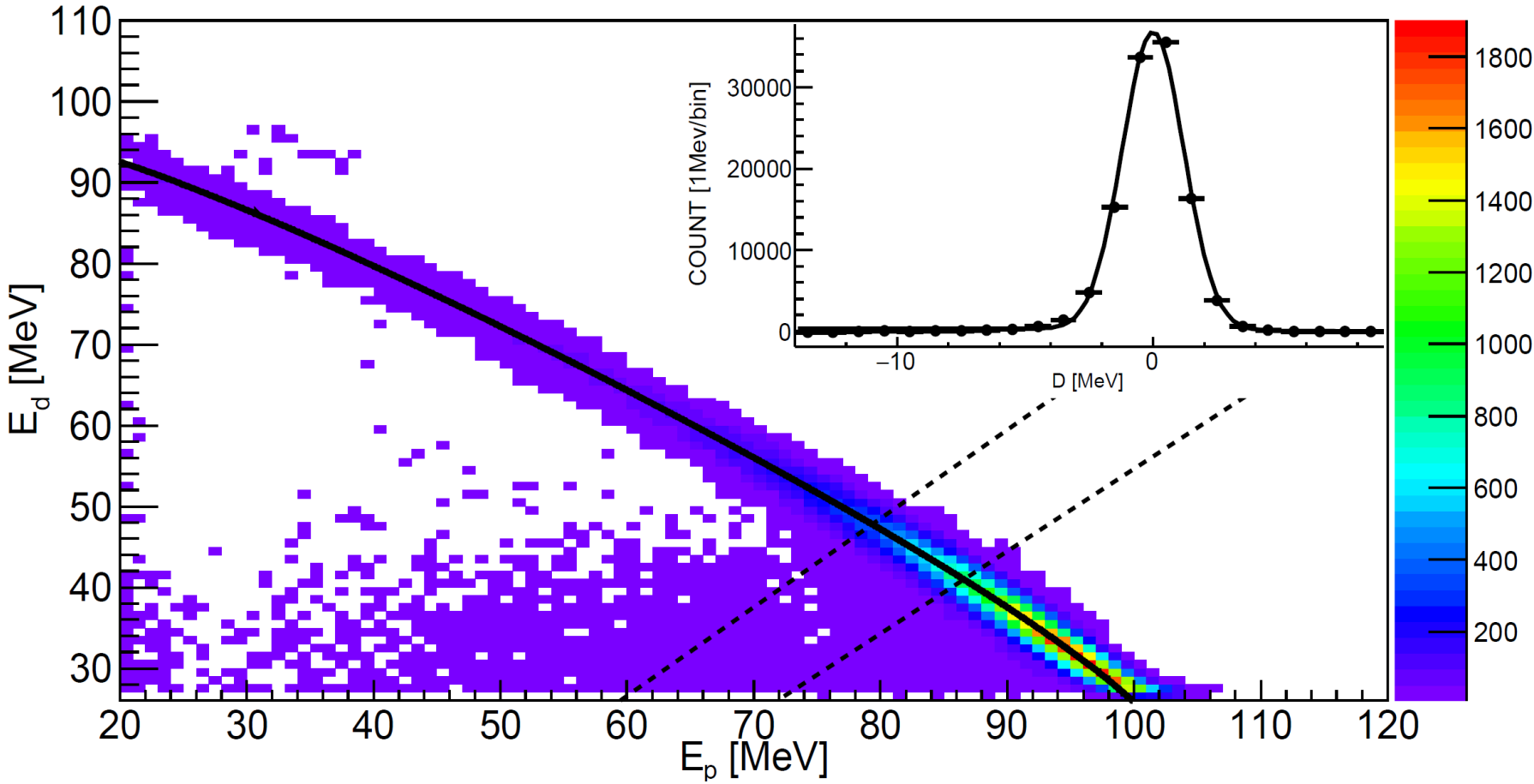
Analysis of 3-body break-up channel

university of groningen

kvi - center for advanced radiation technology

Three-body breakup:

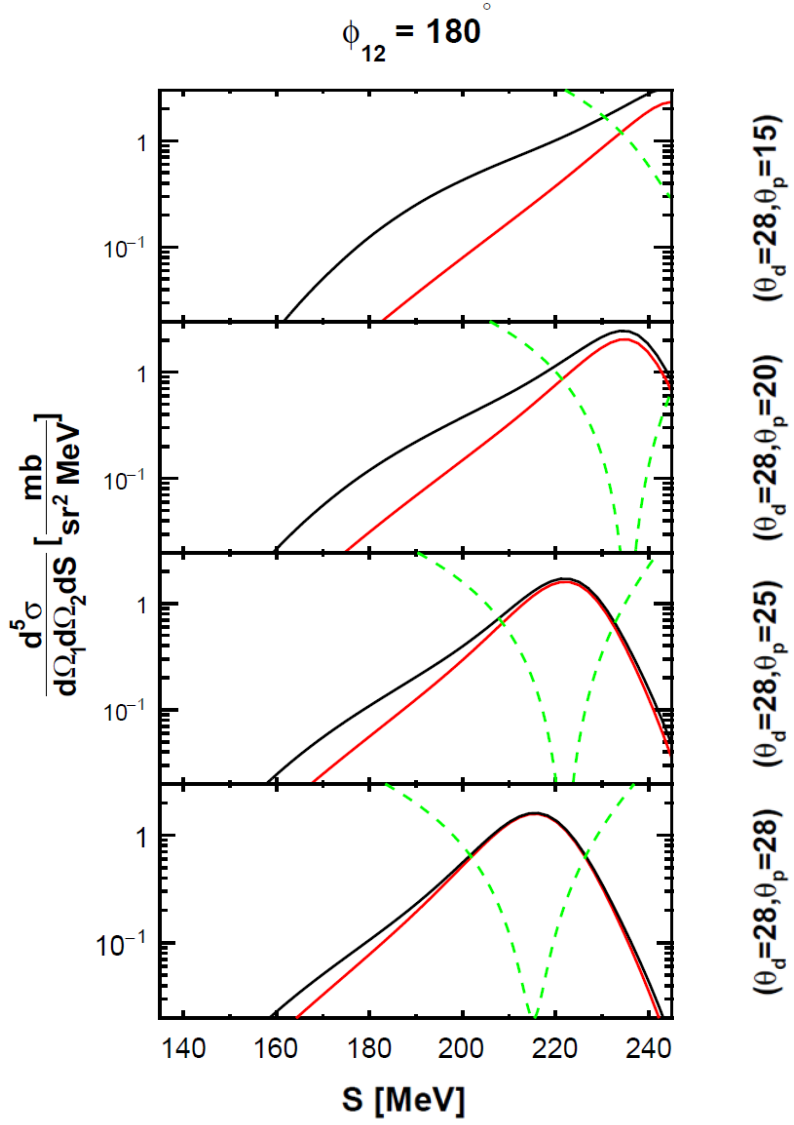
- projecting perpendicular to the S-curve
- Use a polynomial + Gaussian fit
- Background subtraction



Analysis of 3-body break-up channel

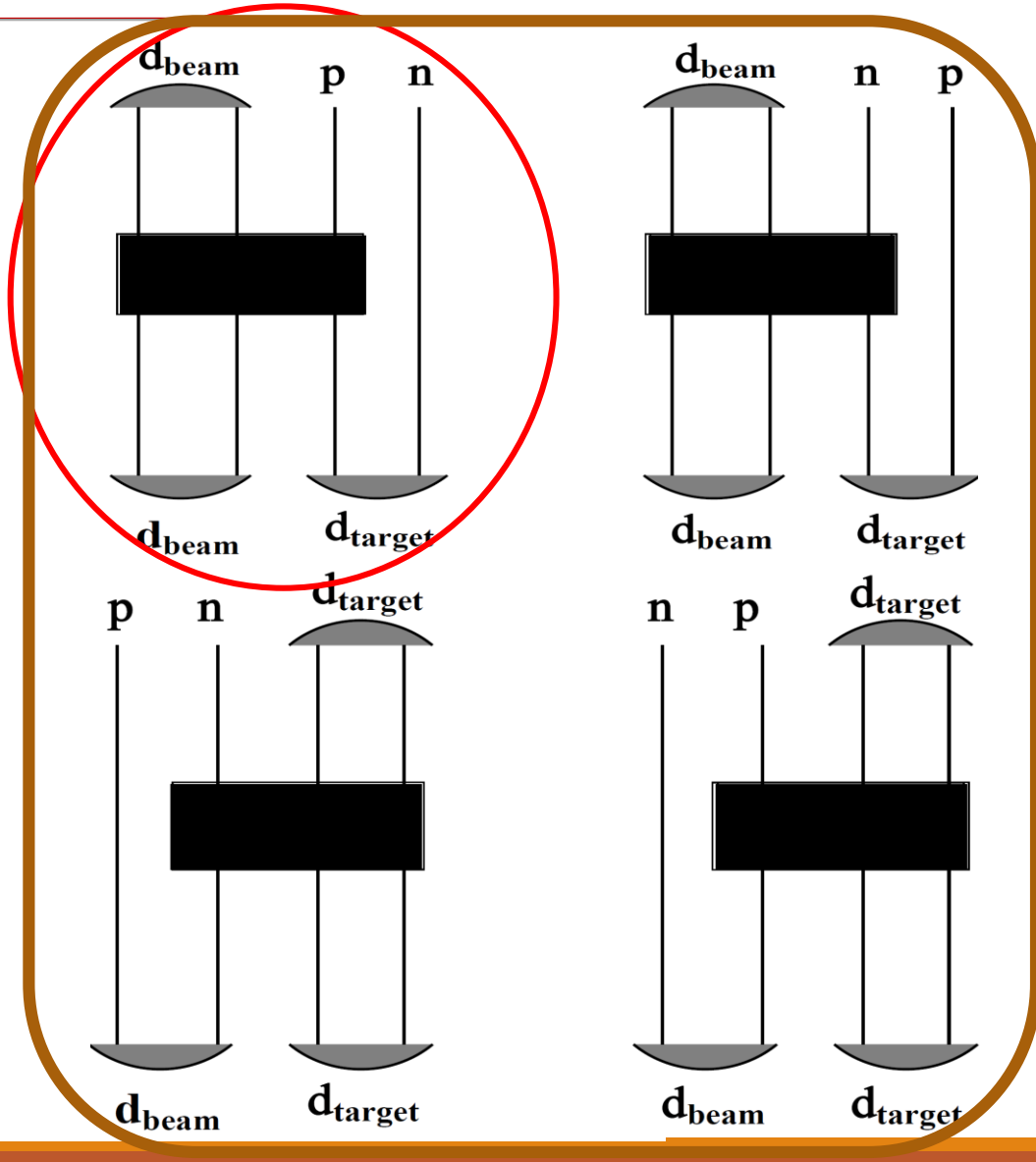
university of groningen

kvi - center for advanced radiation technology



- SSA1

- SSA4

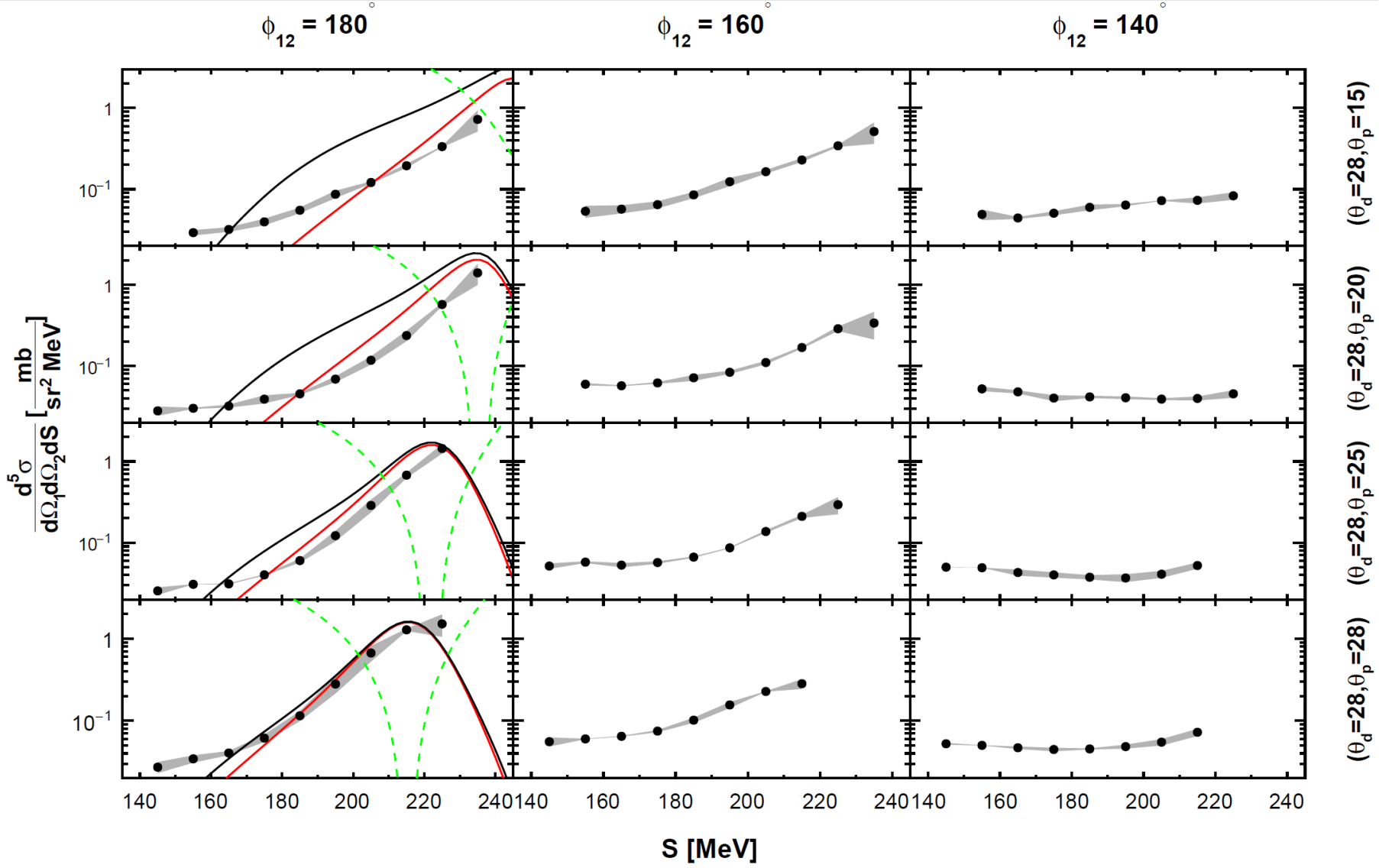


A. Deltuva, et al., Phys. Rev. C 93, 044001 (2016).

Analysis of 3-body break-up channel

university of groningen

kvi - center for advanced radiation technology

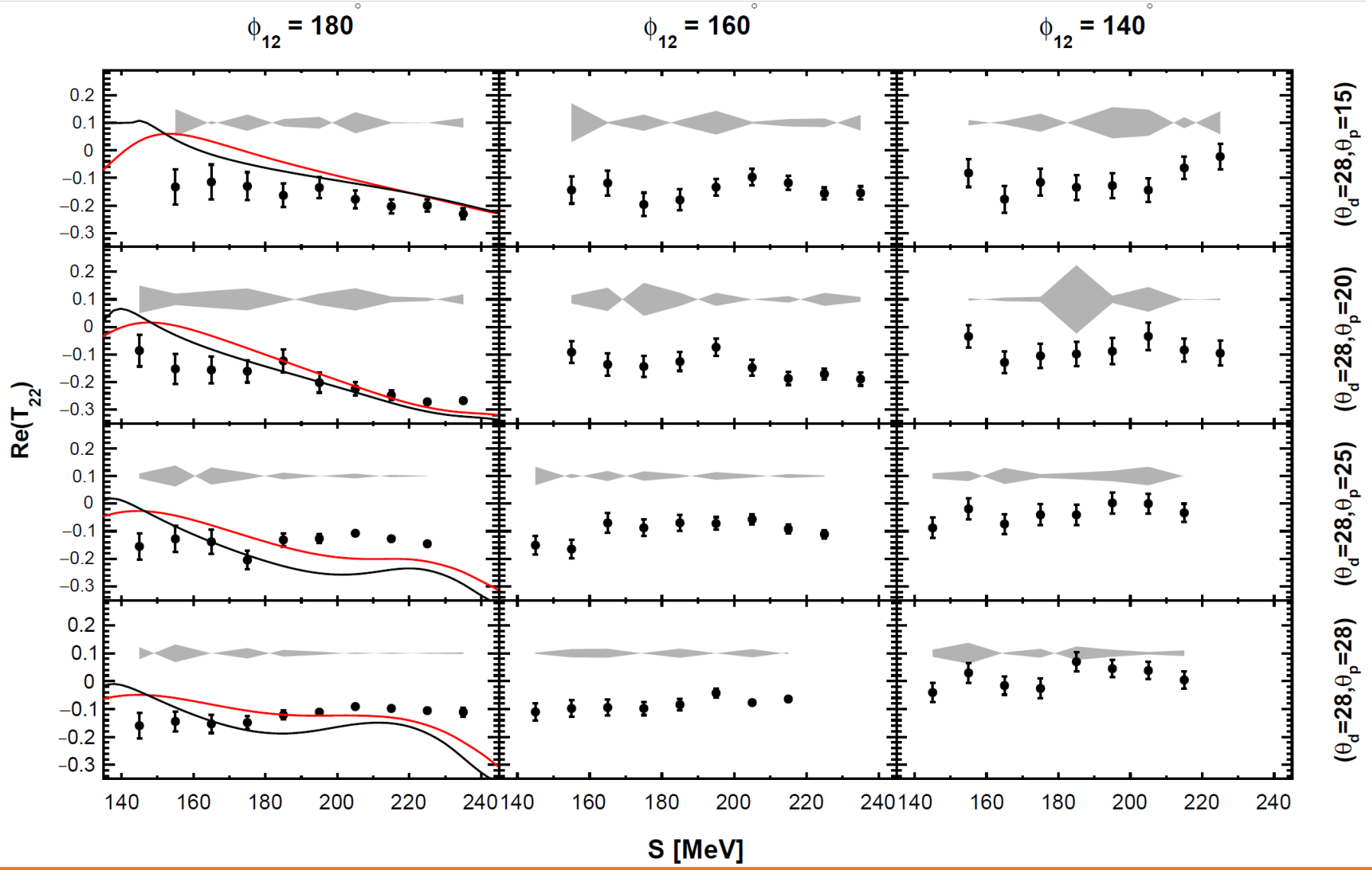


A. Deltuva, et al., Phys. Rev. C 93, 044001 (2016).

Analysis of 3-body break-up channel

university of groningen

kvi - center for advanced radiation technology



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

Summary and outlook

university of groningen

kvi - center for advanced radiation technology

❑ Precision cross section and polarization data in d+d scattering

➢ **Elastic d-d** scattering:

- Perfect agreement with other measurements
- Lack of ab-initio calculations to conclude

➢ T**hree-body break-up** in **d-d** scattering:

- Excellent particle identification of protons and deuterons
- Rich data set of cross sections and analysing powers (5) for 192 configurations.
- Test of the validity of models describing the quasi-free Nd domain.

❖ analysis of three-body break-up with neutron detection to study isospin degrees-of-freedom.

Collaboration

university of groningen

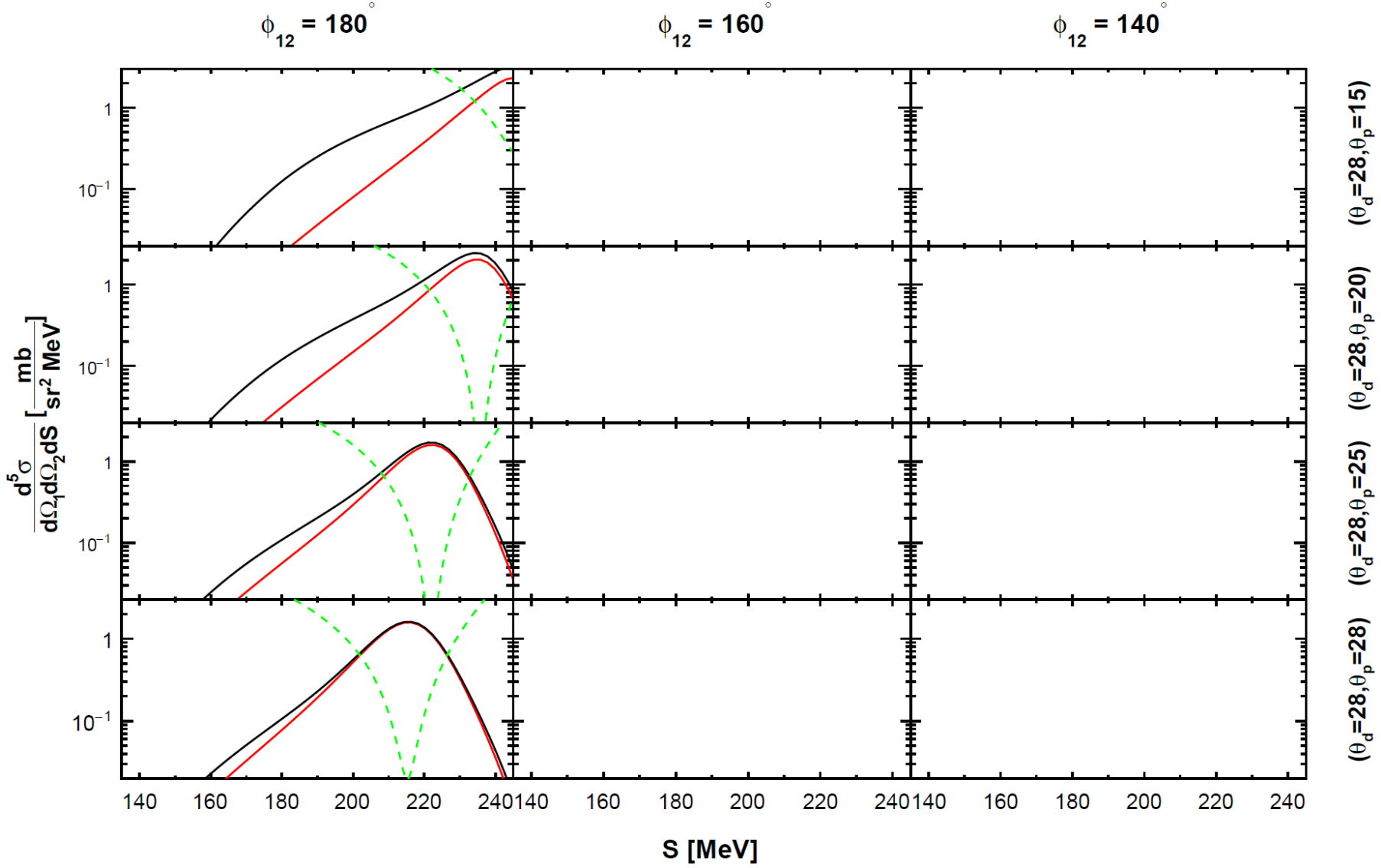
kvi - center for advanced radiation technology

Collaboration

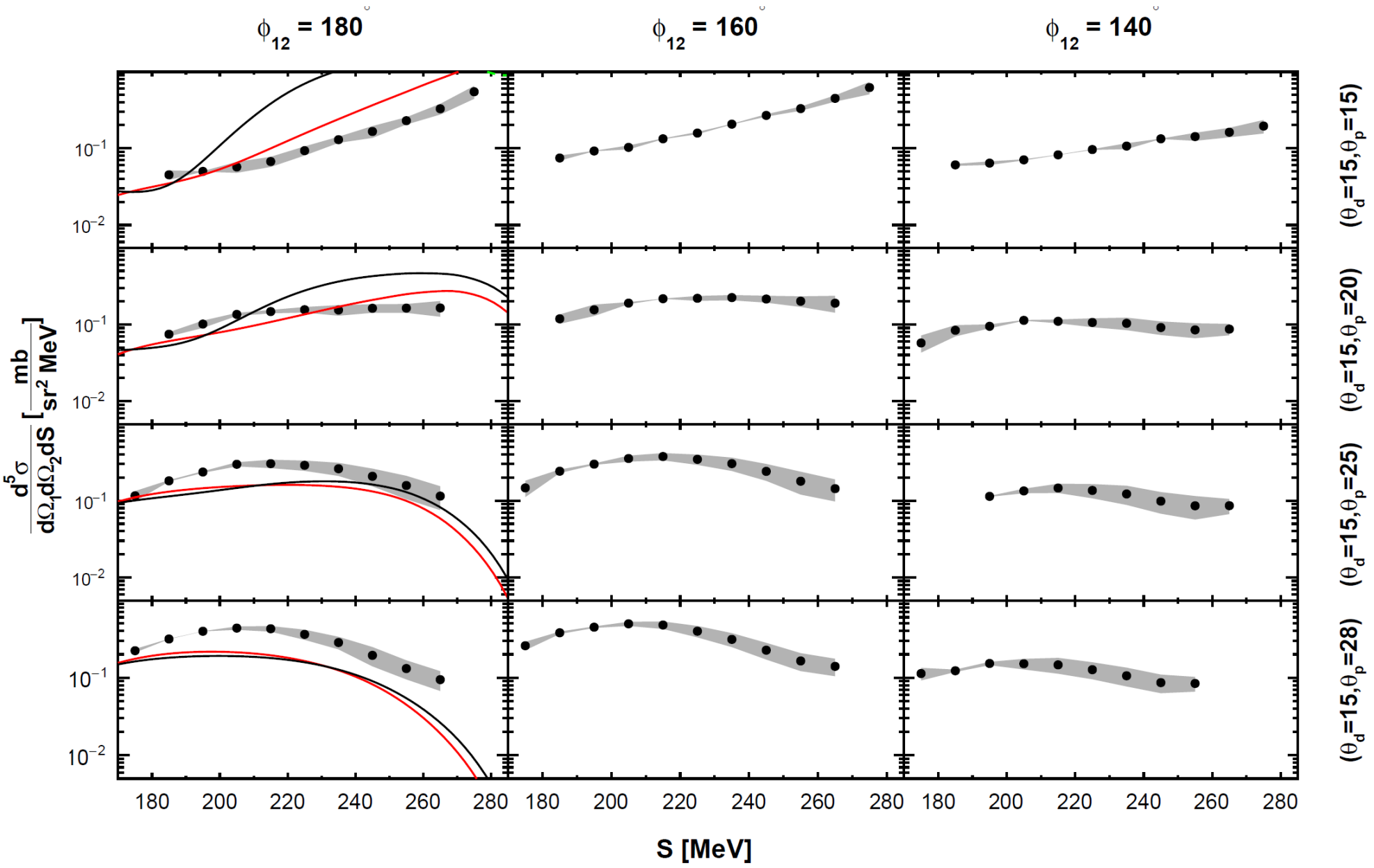
R. Ramazani-Sharifabadi , M.T. Bayat, N. Kalantar-Nayestanaki, St. Kistryn, A. Kozela, M. Mahjour-Shafiei, J. G. Messchendorp, M . Mohammadi-Dadkan, A. Ramazani-Moghaddam-Arani, E. Stephan, and H. Tavakoli-Zaniani

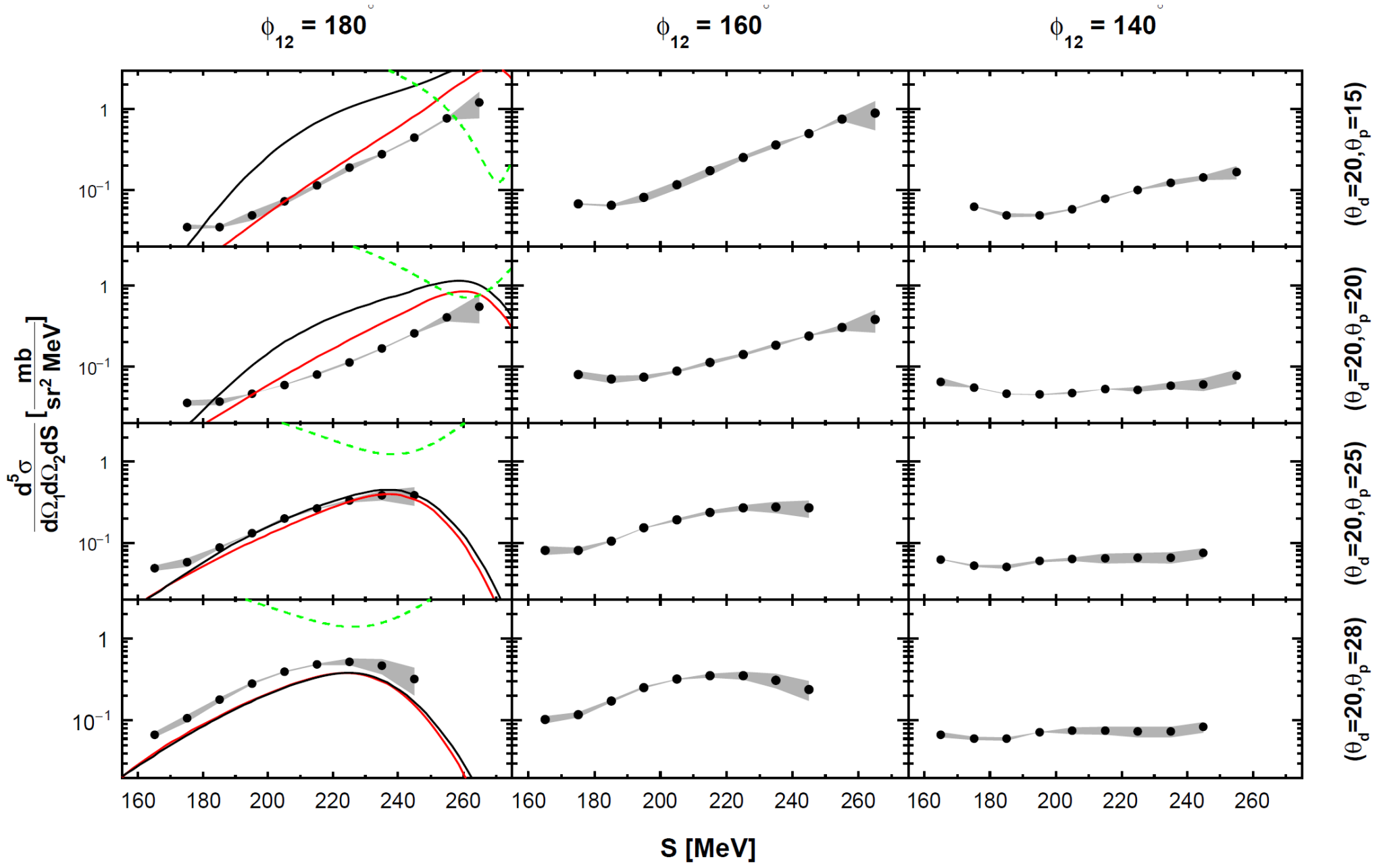
Thank you for your attention

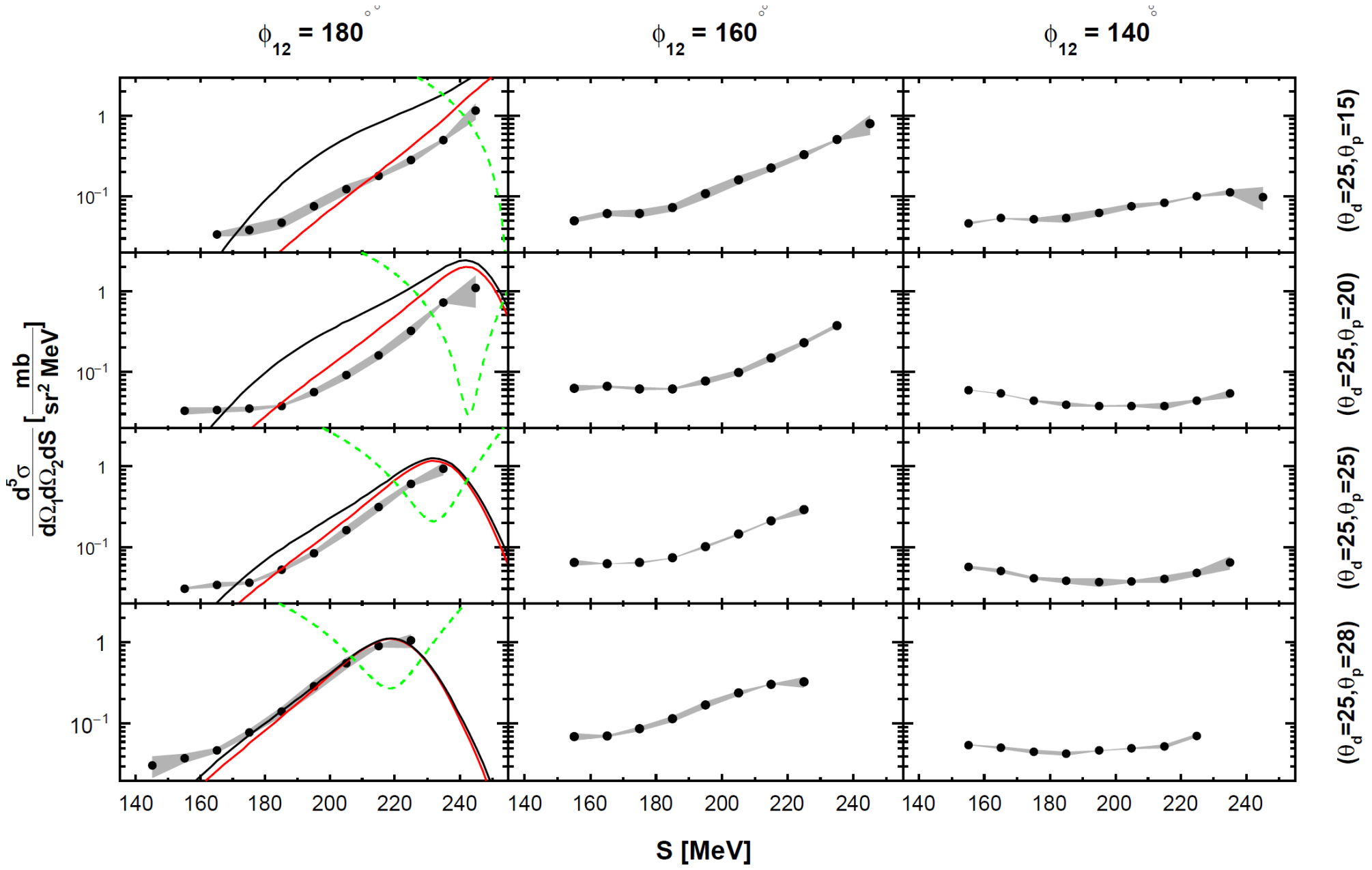
Analysis of 3-body break-up channel



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


$\phi_{12} = 180^\circ$
$\phi_{12} = 160^\circ$
$\phi_{12} = 140^\circ$
$\frac{d^5\sigma}{d\Omega_1 d\Omega_2 dS}$ [$\frac{mb}{sr^2\,MeV}$]
10^{-1}
10^{-2}
180
200
220
240
260
280
S [MeV]
$(\theta_d=15,\theta_p=15)$
$(\theta_d=15,\theta_p=20)$
$(\theta_d=15,\theta_p=25)$
$(\theta_d=15,\theta_p=28)$


$\phi_{12} = 180^{\circ}$
$\phi_{12} = 160^{\circ}$
$\phi_{12} = 140^{\circ}$
$\frac{d^5\sigma}{d\Omega_1 d\Omega_2 dS}$ [$\frac{mb}{sr^2\ MeV}$]
1
10^{-1}
160 180 200 220 240 260
S [MeV]
$(\theta_d=20,\theta_p=15)$
$(\theta_d=20,\theta_p=20)$
$(\theta_d=20,\theta_p=25)$
$(\theta_d=20,\theta_p=28)$


$\phi_{12} = 180^{\circ}$
$\phi_{12} = 160^{\circ}$
$\phi_{12} = 140^{\circ}$
$\frac{d^5\sigma}{d\Omega_1 d\Omega_2 dS}$ [$\frac{mb}{sr^2\ MeV}$]
1
10^{-1}
140
160
180
200
220
240
S [MeV]
$(\theta_d=25,\theta_p=15)$
$(\theta_d=25,\theta_p=20)$
$(\theta_d=25,\theta_p=25)$
$(\theta_d=25,\theta_p=28)$

Outline of Data Analysis

Cross section of any reaction with polarized beam:

- For practical purposes, the analysing powers are also written in the spherical coordinate system:

$$\mathrm{Re}(\mathrm{iT}_{11}) = \frac{\sqrt{3}}{2} A_y,$$

$$\mathrm{Im}(\mathrm{iT}_{11}) = -\frac{\sqrt{3}}{2} A_x,$$

$$\mathrm{Re}(\mathrm{T}_{20}) = \frac{1}{\sqrt{2}} A_{zz},$$

$$\mathrm{Re}(\mathrm{T}_{21}) = -\frac{1}{\sqrt{3}} A_{xz},$$

$$\mathrm{Im}(\mathrm{T}_{21}) = -\frac{1}{\sqrt{3}} A_{yz},$$

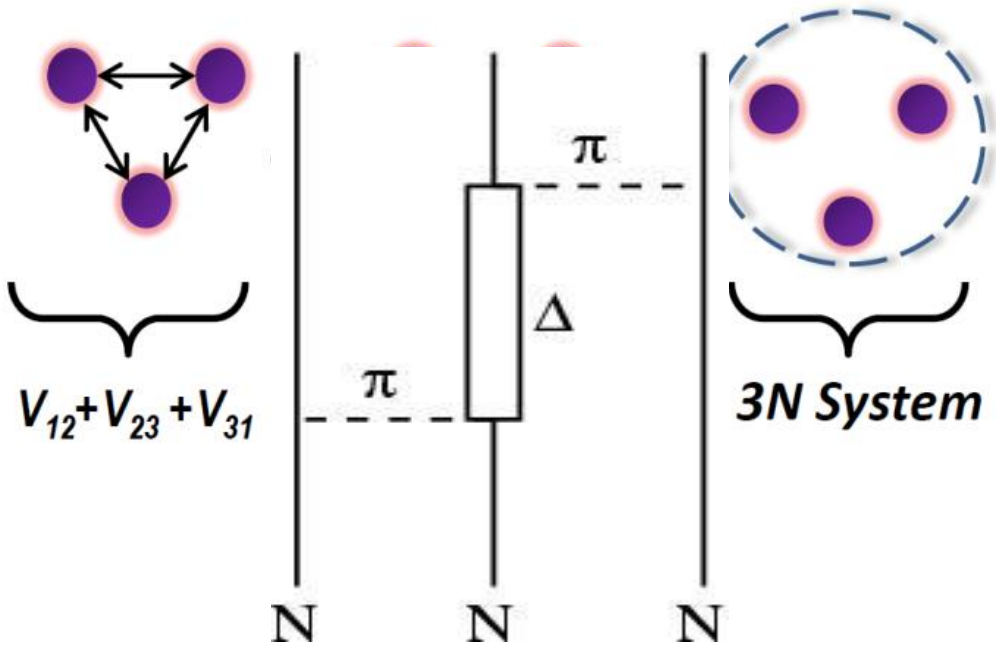
$$\mathrm{Re}(\mathrm{T}_{22}) = \frac{1}{2\sqrt{3}} (A_{xx} - A_{yy})$$

$$\mathrm{Im}(\mathrm{T}_{22}) = \frac{1}{\sqrt{3}} A_{xy}.$$

Why d-d Scattering

- 3NF effects is considered as a additional term in the potential,

- Based on two-pion exchange when the third particle is in the Δ isobar excitation.



- Some of the common 3NFs
  - Tucson-Melbourn (TM)
  - Urbana IX
  - Brazil
  - …..

Prog. Theor. Phys. 17, 360 (1957)

Collaboration

university of groningen

kvi - center for advanced radiation technology

Our collaboration

R. Ramazani-Sharifabadi[1,2] , M.T. Bayat[1], N. Kalantar-Nayestanaki[1], St. Kistryn[3], A. Kozela[4], M. Mahjour-Shafiei[2],

J. G. Messchendorp[1], M . Mohammadi-Dadkan[1,5], A. Ramazani-Moghaddam-Arani[6], E. Stephan[7], and H. Tavakoli-Zaniani[1,8]

Thank you for your attention

[1]KVI-CART, University of Groningen, Groningen, The Netherlands,

[2]Department of Physics, University of Tehran, Tehran, Iran,

[3]Institute of Physics, Jagiellonian University, Krakow, Poland,

[4]Institute of Nuclear Physics, PAN, Krakow, Poland,

[5]Department of Physics, University of Sistan and Baluchestan, Zahedan, Iran,

[6]Department of Physics, University of Kashan, Kashan, Iran,

[7]Institute of Physics, University of Silesia, Chorzow, Poland,

[8]Department of Physics, School of Science, University of Yazd, Yazd, Iran

- Why d-d scattering?
- Experimental setup
- Analysis approach
- Results
- Summary and outlook

Outline of data analysis

Polarized deuteron beam and spin-1 particle polarization:

- Vector polarization:

$$p_Z = \frac{N_+ - N_-}{N_+ + N_- + N_0},$$

- Tensor polarization:

$$p_{ZZ} = \frac{N_+ + N_- - 2N_0}{N_+ + N_- + N_0},$$

G. G. Ohlsen, Nucl. Instrum. Meth. **179**, 283 (1981).

Outline of data analysis

Cross section of any reaction with polarized beam:

$$\sigma(\xi) = \sigma_0(\xi)\Big(1 + \frac{3}{2}[p_x A_x(\xi) + p_y A_y(\xi) + p_z A_z(\xi)] + \frac{2}{3}[p_{xy} A_{xy}(\xi) + p_{yz} A_{yz}(\xi) + p_{xz} A_{xz}(\xi)] + \frac{1}{3}[p_{xx} A_{xx}(\xi) + p_{yy} A_{yy}(\xi) + p_{zz} A_{zz}(\xi)]\Big),$$

$$\sigma(\theta,\phi) = \sigma_0(\theta)[1 + \frac{3}{2} p_z A_y(\theta)\cos(\phi) - \frac{1}{4} p_{zz} A_{zz}(\theta) + \frac{1}{4} p_{zz}(A_{zz}(\theta) + 2A_{yy}(\theta))\cos(2\phi)]$$