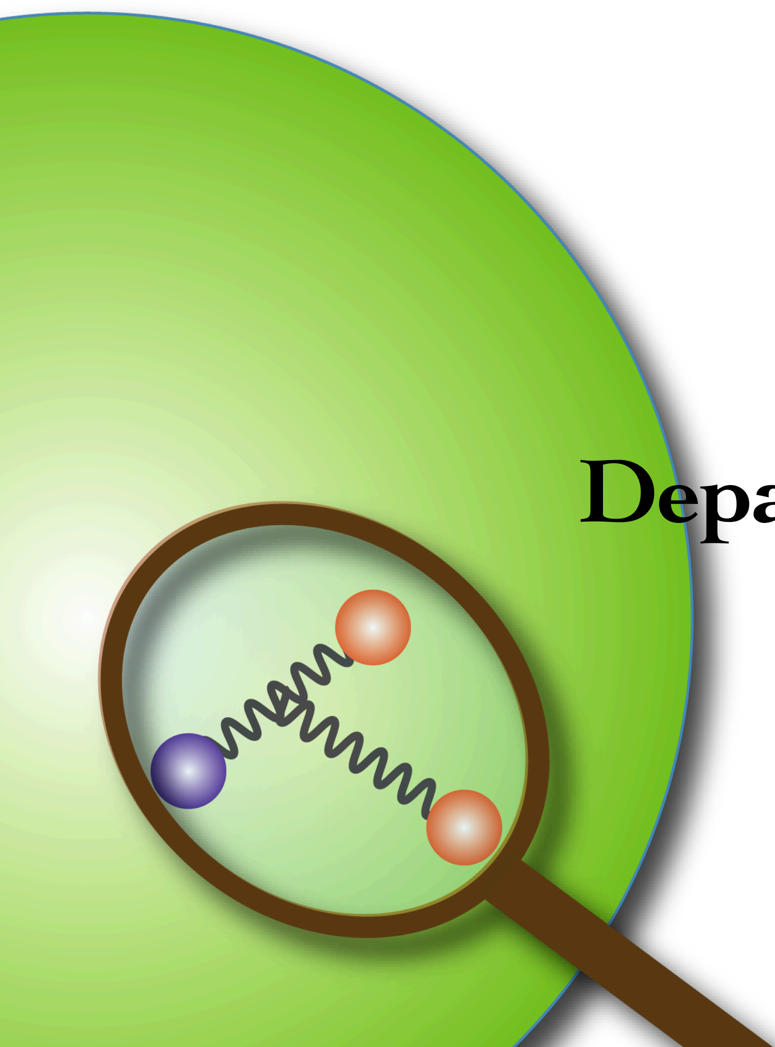
Proton-^{3}He Scattering at Intermediate Energies



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SPIN2021, October 18th, 2021

p-^{3}He Collaboration

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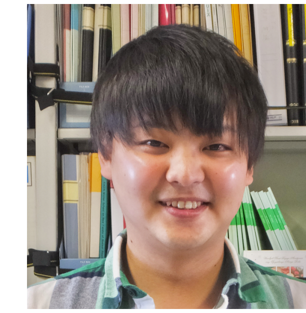
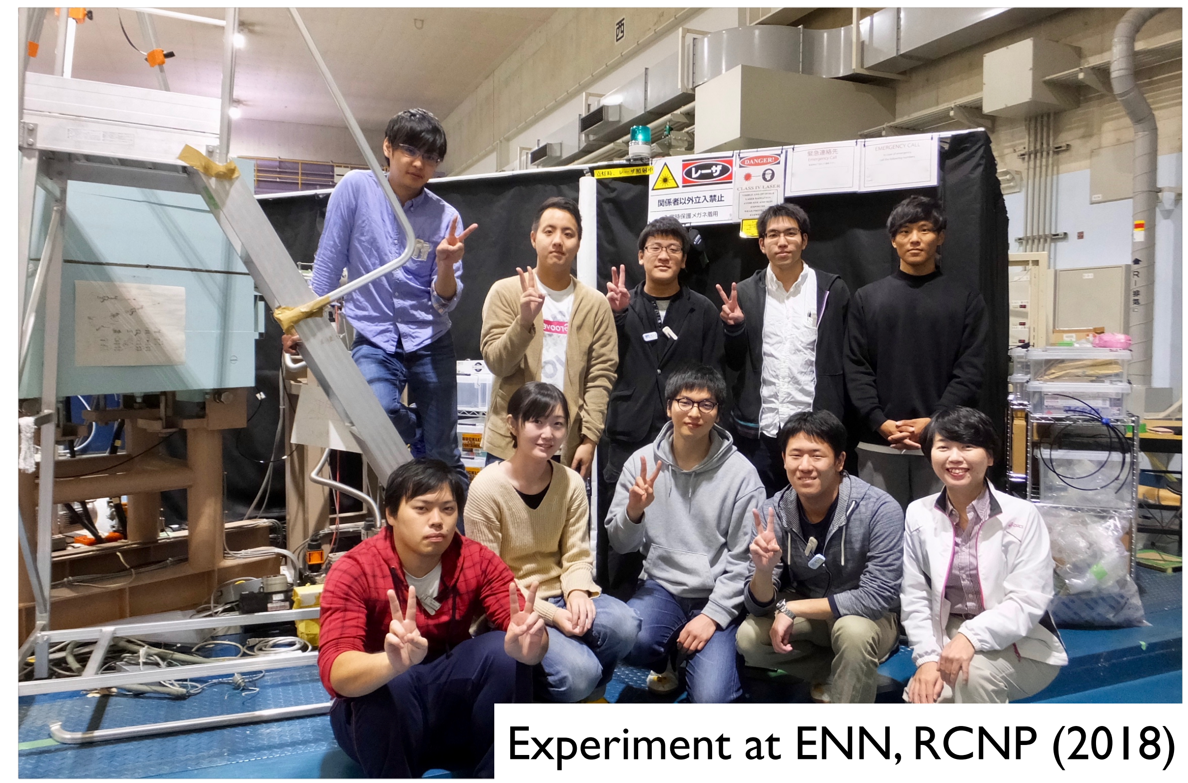
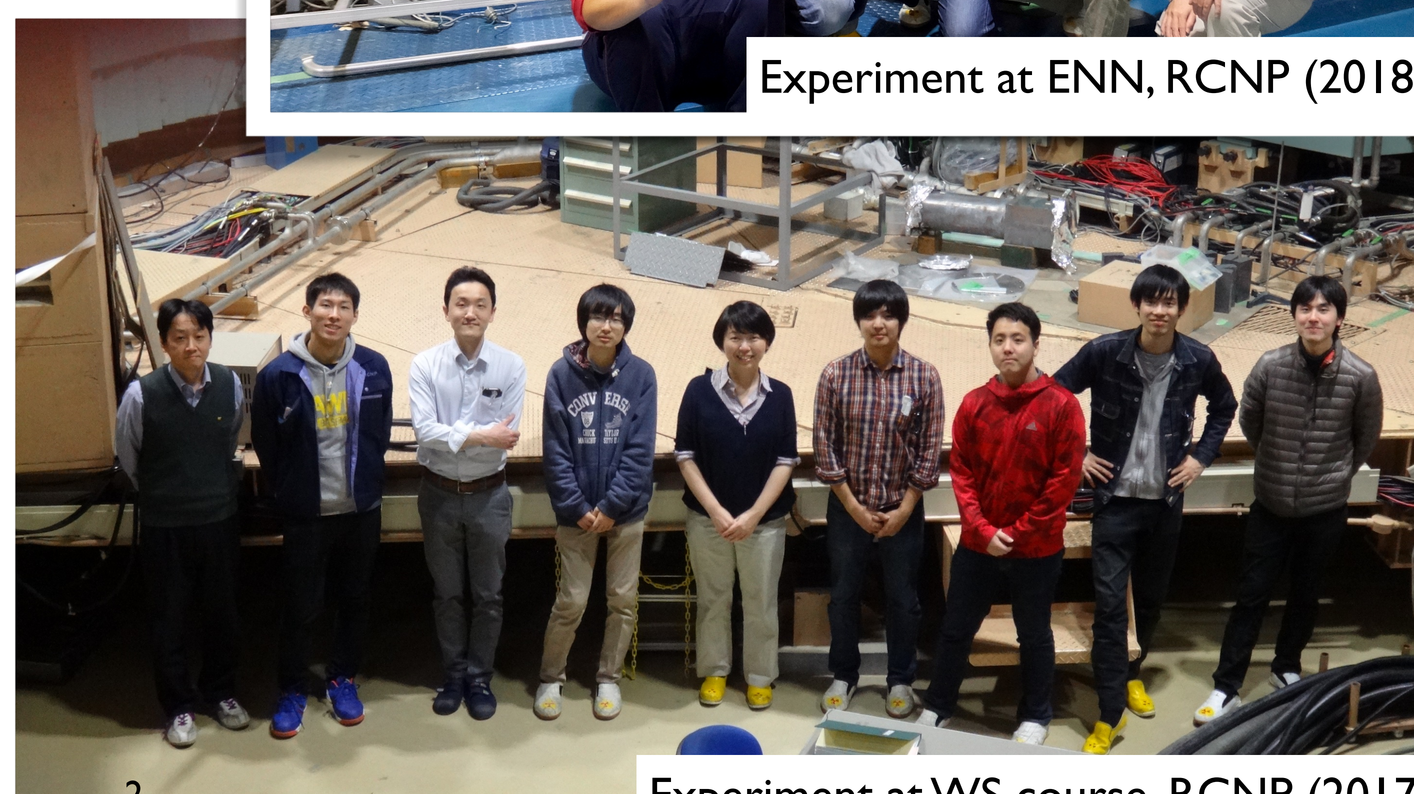


S. Nakai



Experiment at ENN, RCNP (2018)

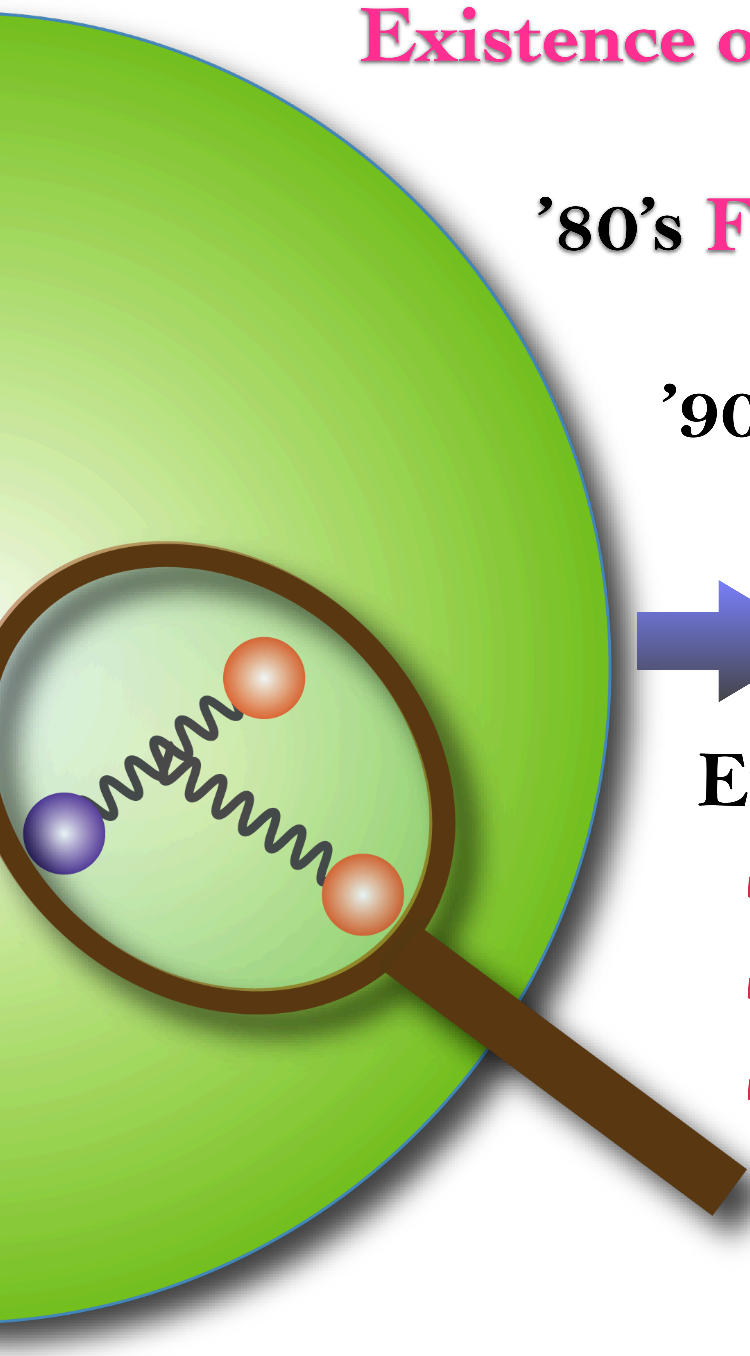


Experiment at WS course, RCNP (2017)

Three-Nucleon Force (3NF)

- nuclear forces acting in systems more than $A > 2$ nucleons -

Key to fully understand properties of nucleus



Existence of 3NF was predicted in 1930's (after Yukawa's meson theory).

'80's First evidence of 3NF : Binding Energies of Triton (^3H)

'90's Realistic Nucleon-Nucleon Potential (CD Bonn, AV18, Nijmegen I, II)

→

Evidence / Candidates of 3NF Effects

- Nucleon-Deuteron Scattering at Intermediate Energies
- Biding Energies / Levels of Light Mass Nuclei
- Equation of State of Nuclear Matter

etc ...

Few-Nucleon Scattering

a good probe to study the dynamical aspects of 3NFs.

- ✓ Momentum dependence
- ✓ Spin & Iso-spin dependence

Direct Comparison between Theory and Experiment

- Theory : Faddeev / Faddeev-Yakubovsky Type Calculations

  Rigorous Numerical Calculations of 3, 4N System

2NF Input	3NF Input	2NF & 3NF Input
• CDBonn • Argonne V18 (AV18) • Nijmegen I, II, 93	• Tucson-Melbourne • Urbana IX etc..	• Chiral Effective Field Theory

- Experiment : Precise Data
  - $d\sigma/d\Omega$, Spin Observables (A_i, K_{ij}, C_{ij})

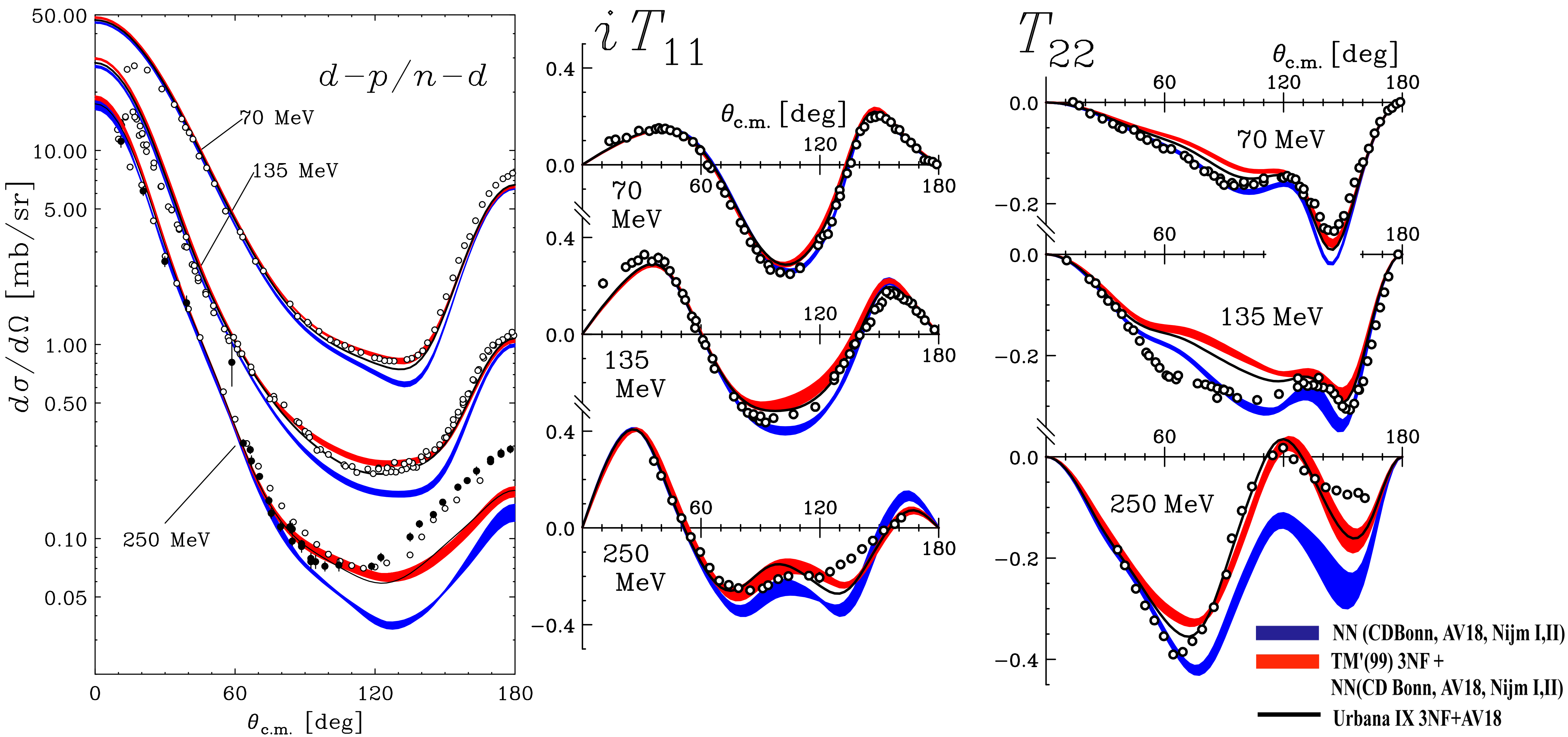
Extract fundamental information of Nuclear Forces.

3NF effects in proton-deuteron scattering at 70-250 MeV

K. S. et al., Phys. Rev. C 65, 034003 (2002),
K. Hatanaka et al., Phys. Rev. C. 66, 044002 (2002),
Y. Maeda et al., Phys. Rev. C 76, 014004 (2007),
K. S. et al., Phys. Rev. C 89, 064007 (2014) etc…

Solid base for study of detailed properties of 3NFs

- Clear signatures of 3NF Effects in the cross section minimum.
- 3NF effects become larger with increasing an incident energy.
- Spin dependent parts of 3NFs are deficient.



p+^{3}He Scattering

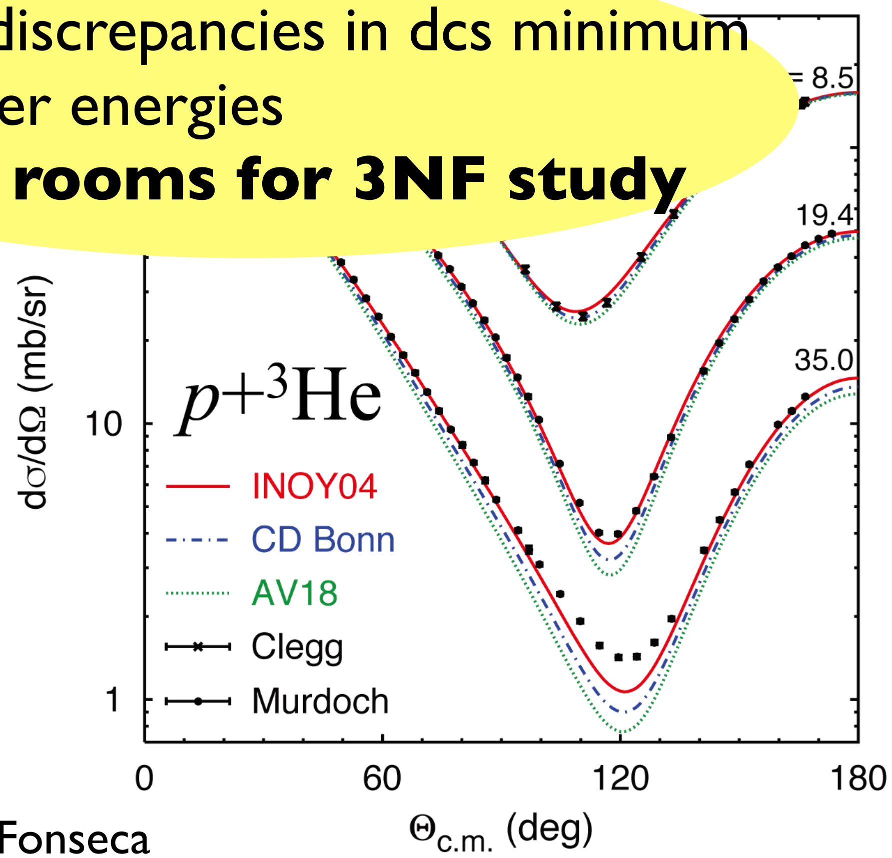
1. Four Nucleon Scattering *First Step from Few to Many*
2. Isospin Dependence of 3NFs : T=3/2 3NFs
3. Large 3NF effects *in cross section minimum at intermediate energies*

Theory in Progress

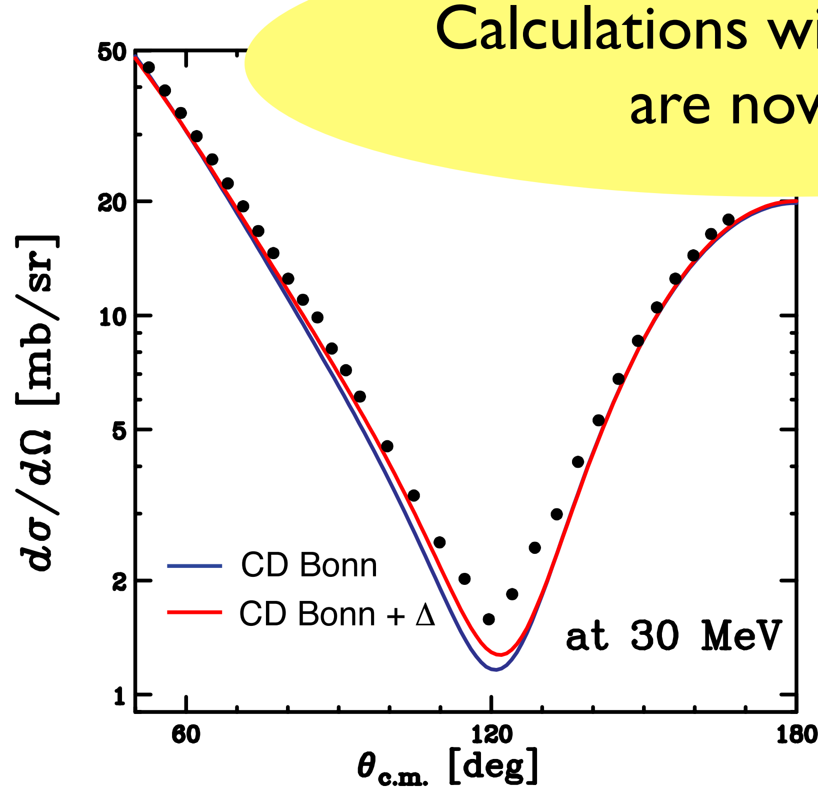
Calculations above 4-body breakup threshold energy are available by A. Deltuva et al.

→ new possibilities for 3NF study in 4N scattering at higher energies

Large discrepancies in dcs minimum at higher energies
New rooms for 3NF study



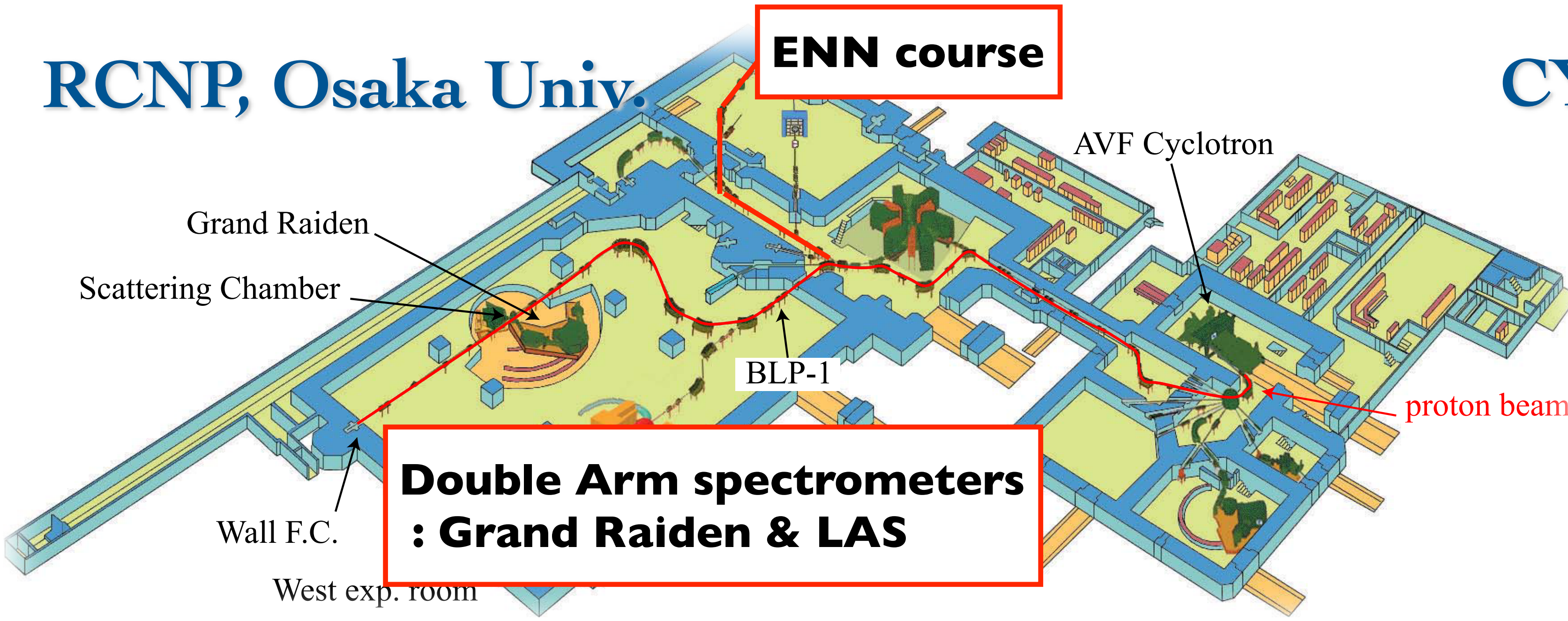
Calculations with 3NFs are now in progress !



A. Deltuva and A.C. Fonseca
Phys. Rev. C 87, 054002 (2013)

Experiments of p+^{3}He at Intermediate Energies from RCNP & CYRIC

RCNP, Osaka Univ.



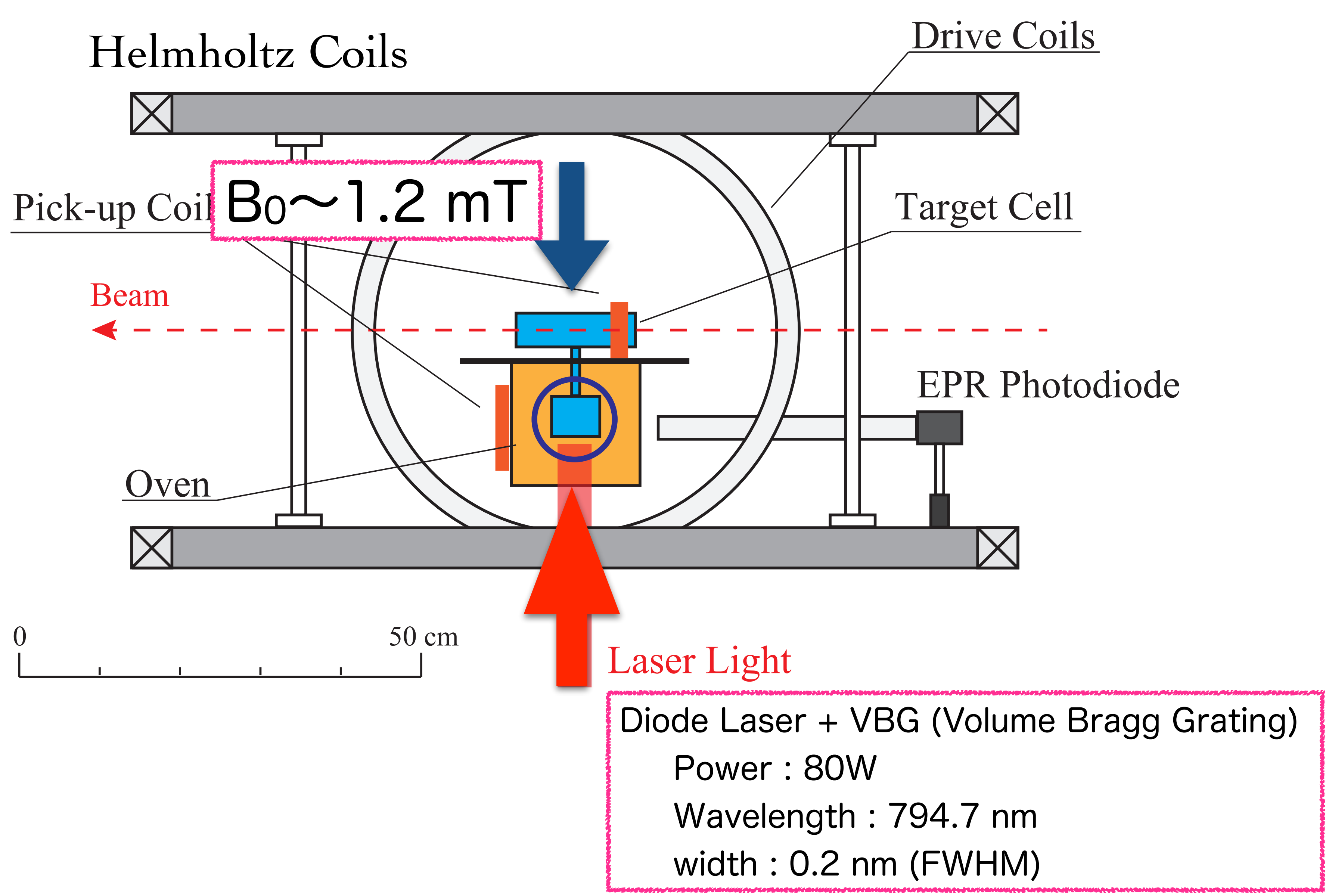
- Polarized p beam : 10 - 420 MeV
  - Polarizations : < 70 %
- Beam Intensity : $< \ 1\mu A$

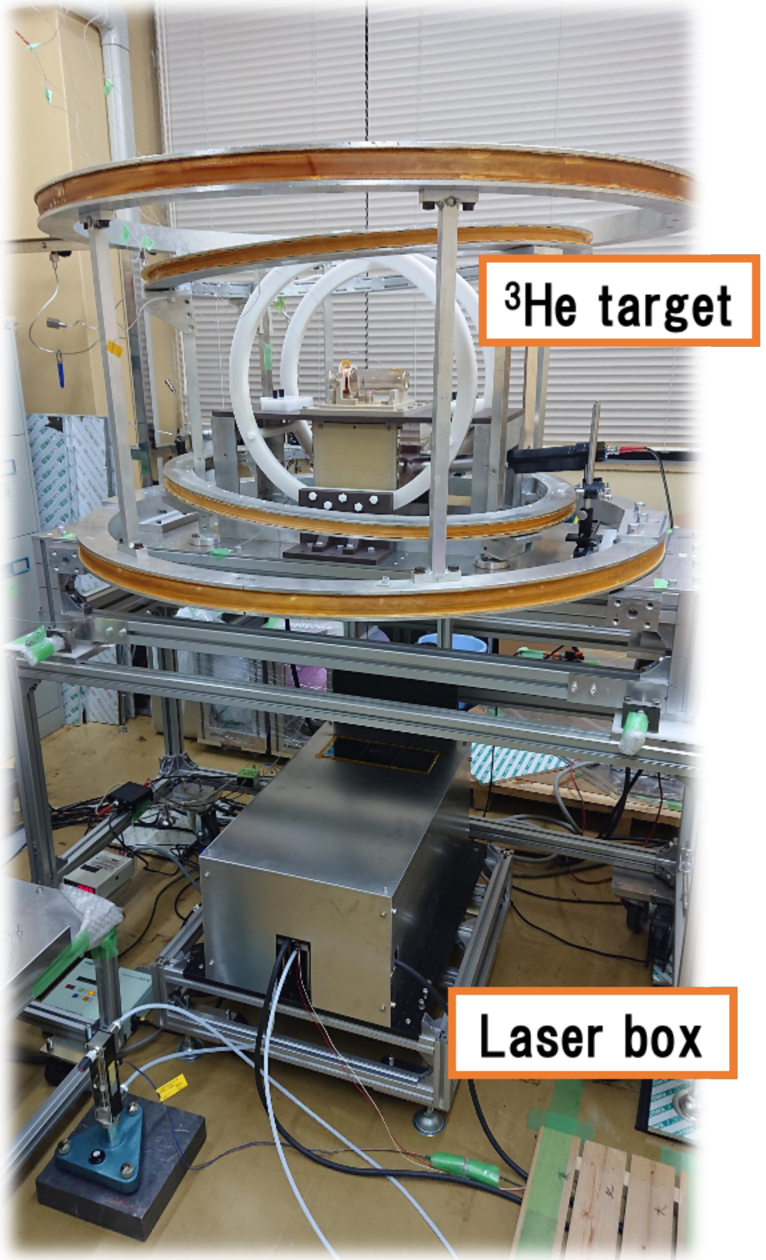
CYRIC, Tohoku Univ.

- p beam : 10 - 80 MeV
- Beam Intensity : 10-20 nA

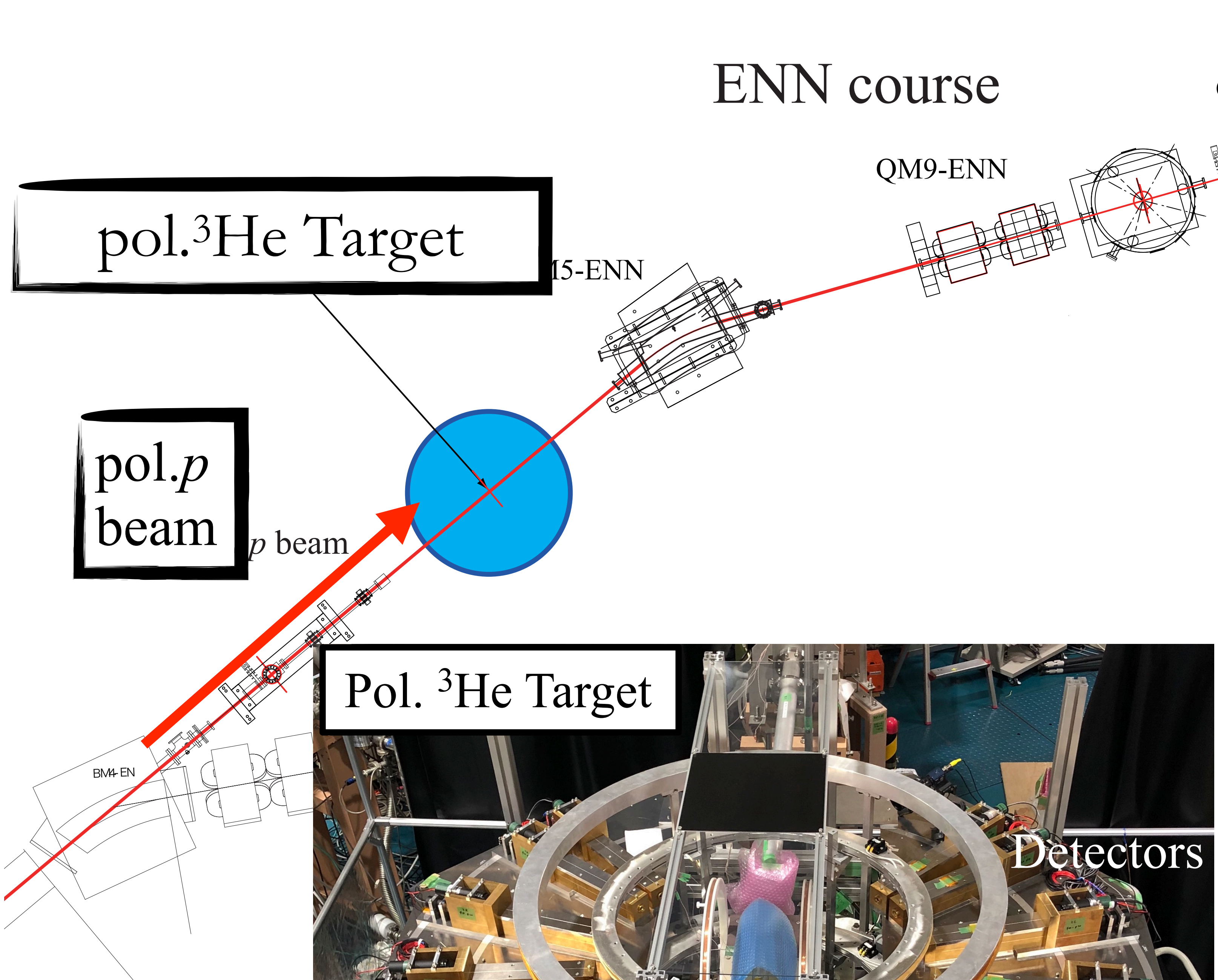
Polarized ^{3}He Target System

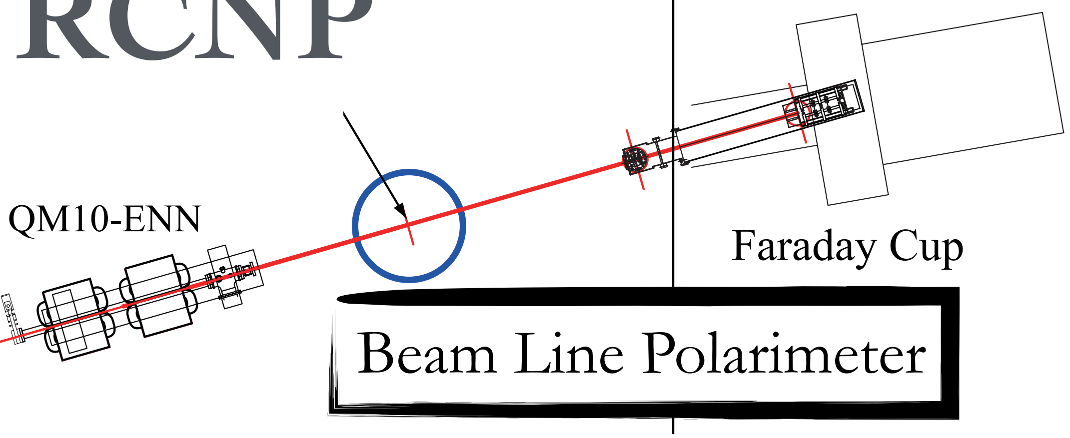
- Polarization Method :
  - (Alkali-Hybrid) Spin Exchange Optical Pumping
- Polarization (current) : 50%, Relaxation time : about 40 hrs
- Calibration of absolute values : EPR & neutron-transmission

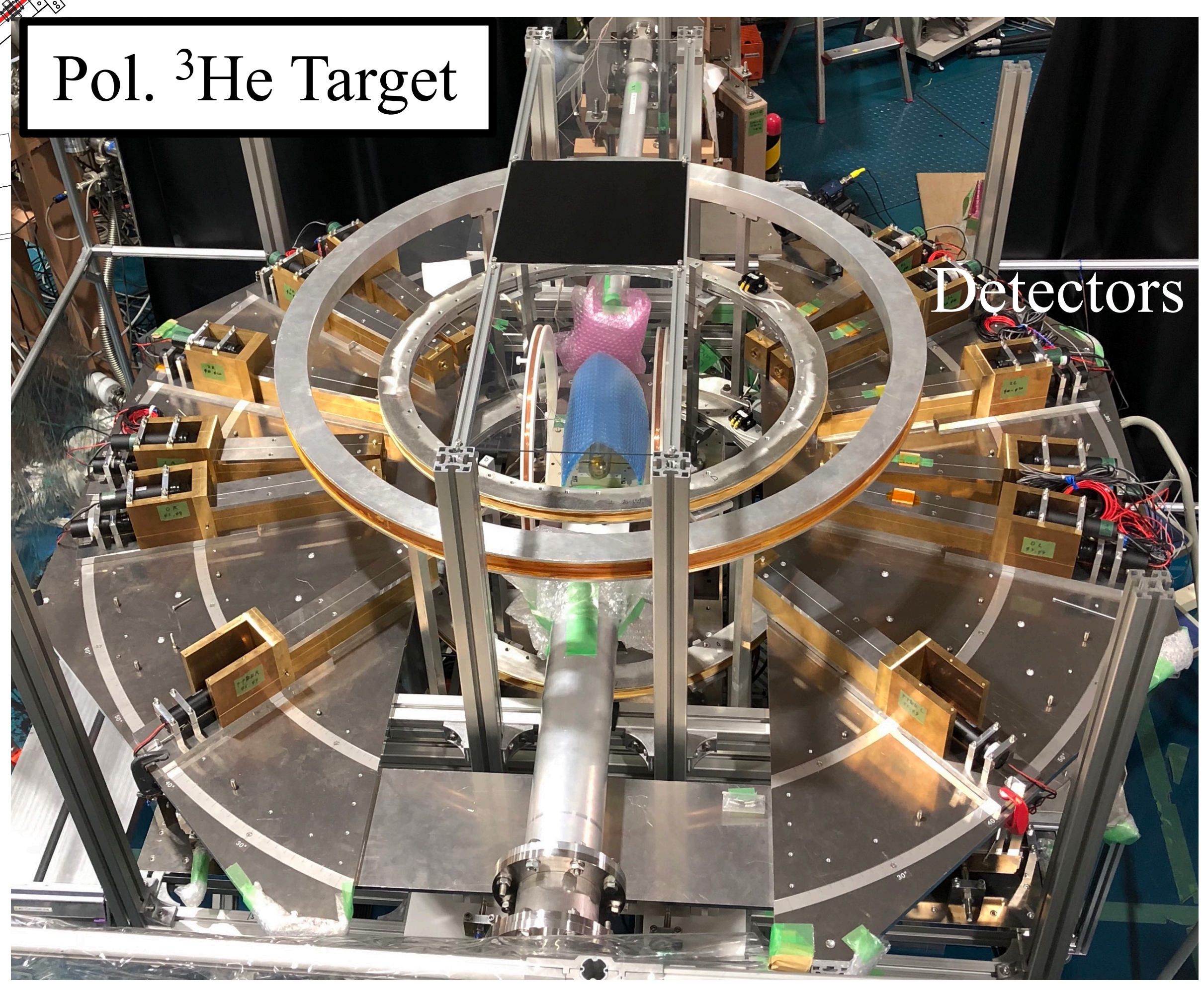




pol.p+pol.^{3}He experiment at RCNP







- Polarized p at 65, 100 MeV
  - Polarization : 40-50 %
  - B.I. = 10 - 30 nA
- Target : pol.^{3}He gas target
  - polarization : 30-40%
- Observables :

$$A_y(p),\ A_y(^3\mathrm{He}),\ C_{y,y}$$

- Measured Angles

$$\theta_{\mathrm{c.m.}} = 47^\circ - 156^\circ$$

- Detectors

  dE : Plastic Scintillator (0.5 mm^t)
  E : NaI(Tl) (55 mm^t)
  2 sets × 6 angles = 12 sets

Summary of Measurements for p+^{3}He

Incident Energy	70 MeV	50 MeV	65 MeV	65 MeV	100 MeV
Beam	p	p	pol. p	pol. p	pol. p
Observables	A_{0y}	A_{0y}	$d\sigma/d\Omega$, A_y	A_y, A_{0y}, $C_{y,y}$	A_y, A_{0y}, $C_{y,y}$
Measured Angles ($\theta_{c.m.}$)	46° –141°	47° –120°	27° –170°	47° –133°	47° –149°
Facility	CYRIC, Tohoku Univ.	CYRIC, Tohoku Univ.	RCNP, Osaka Univ.	RCNP, Osaka Univ.	RCNP, Osaka Univ.
Exp. Course	41 course	41 course	WS course	ENN course	ENN course

Summary of Measurements for p+^{3}He

Incident Energy	70 MeV	50 MeV
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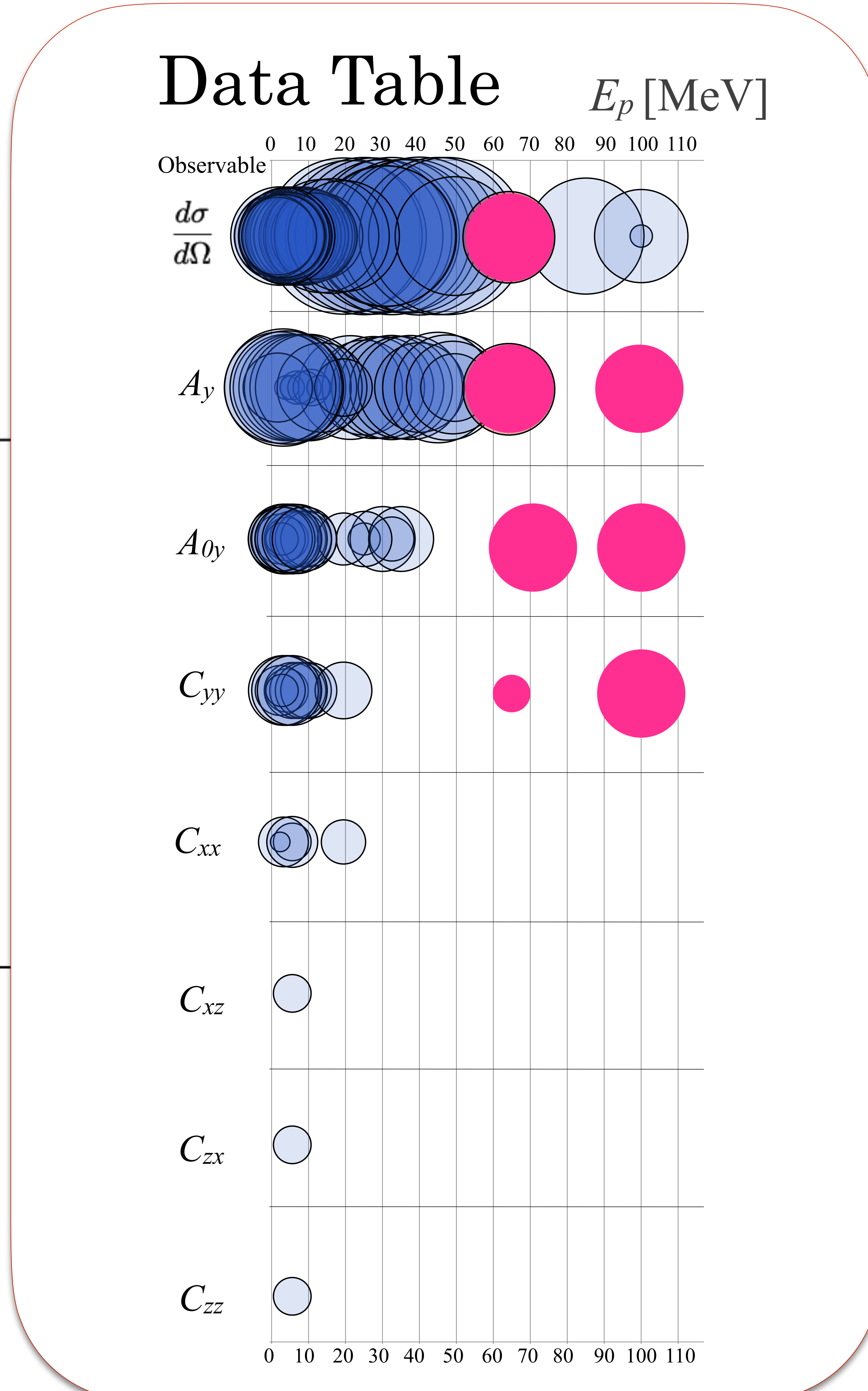
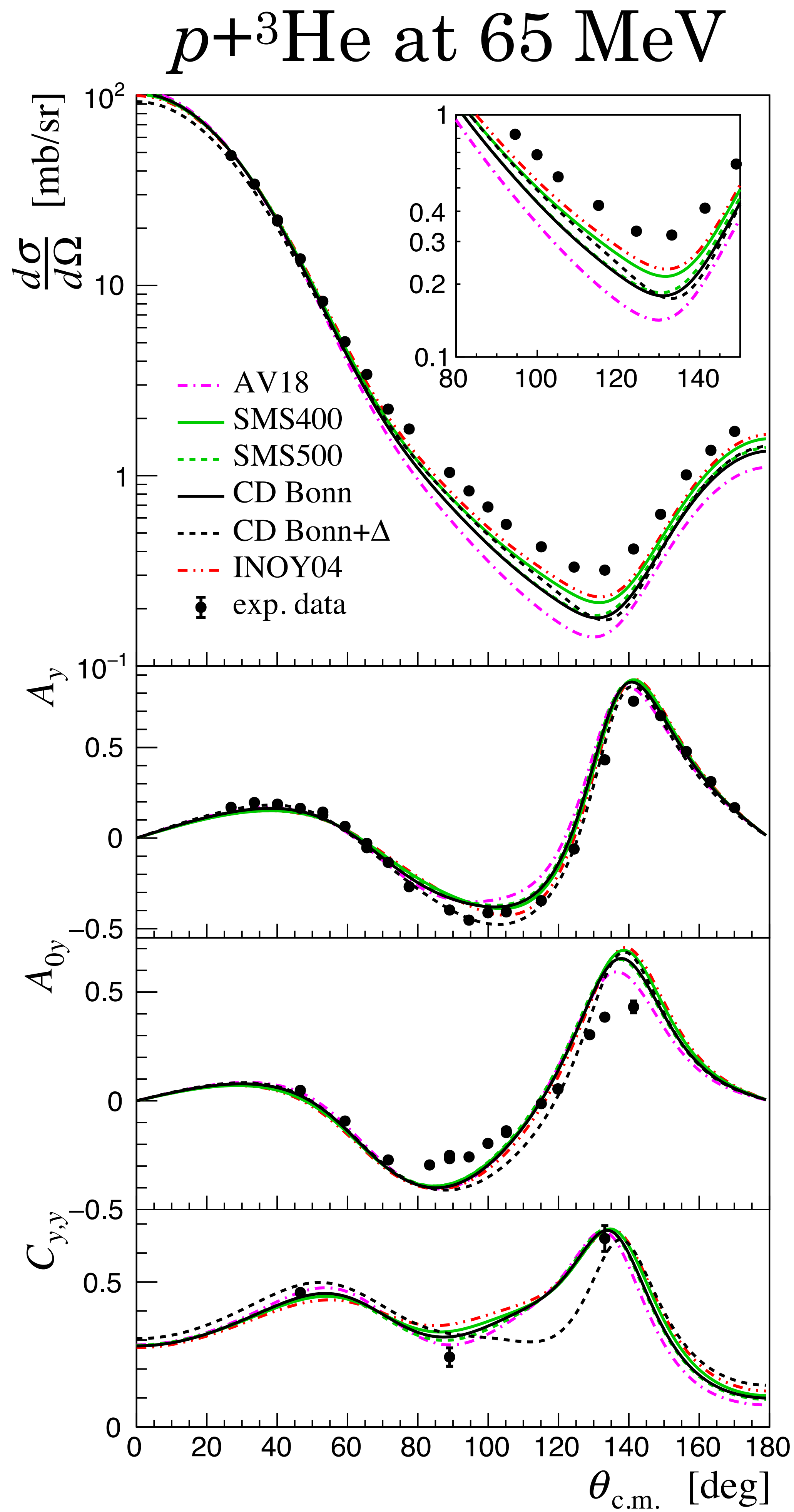


data from RCNP/CYRIC

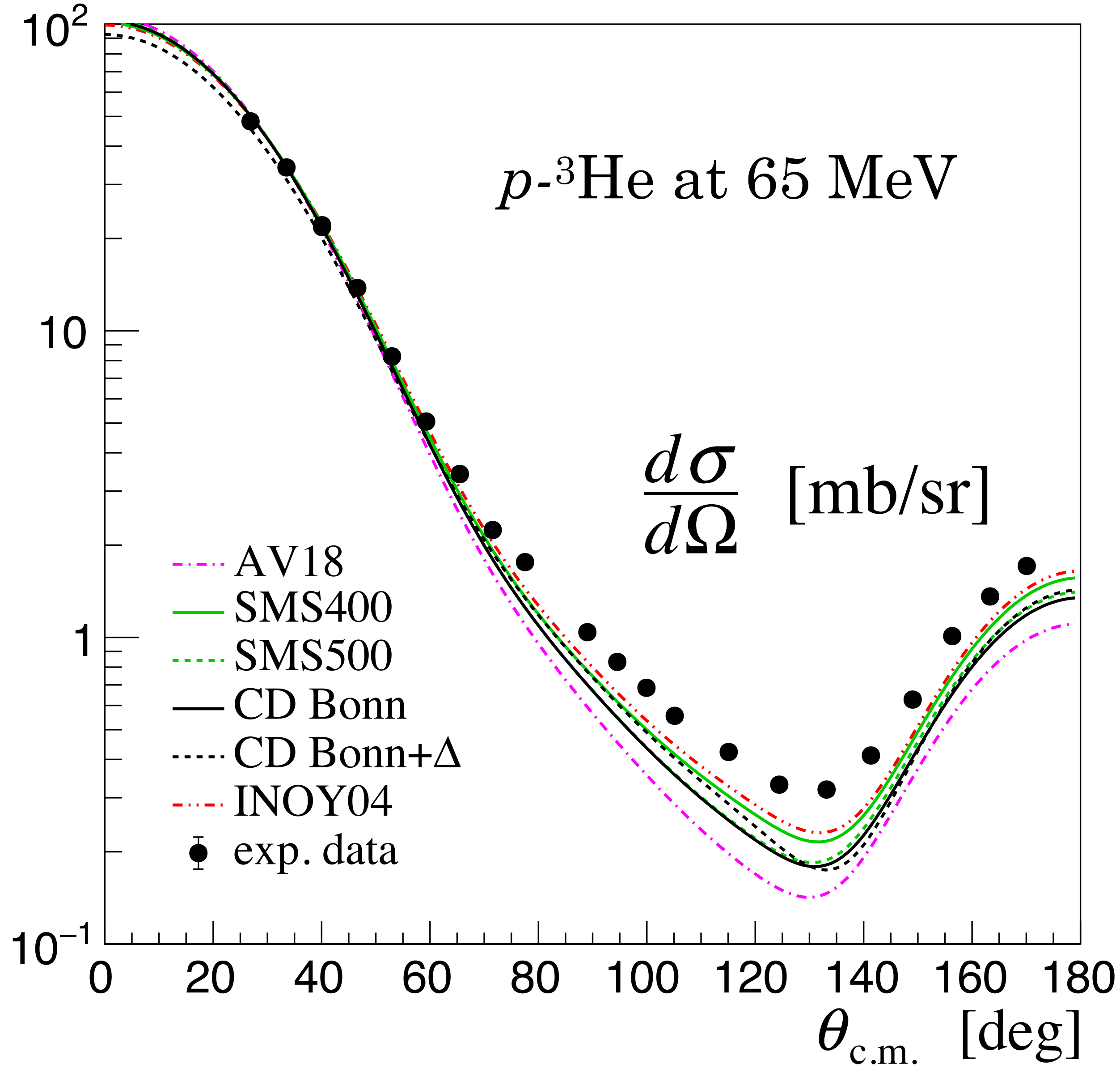
New Data Set of p+^{3}He at Intermediate Energies

A. Watanabe, S. Nakai, et al. , Phys. Rev. C **103**, 044001 (2021)

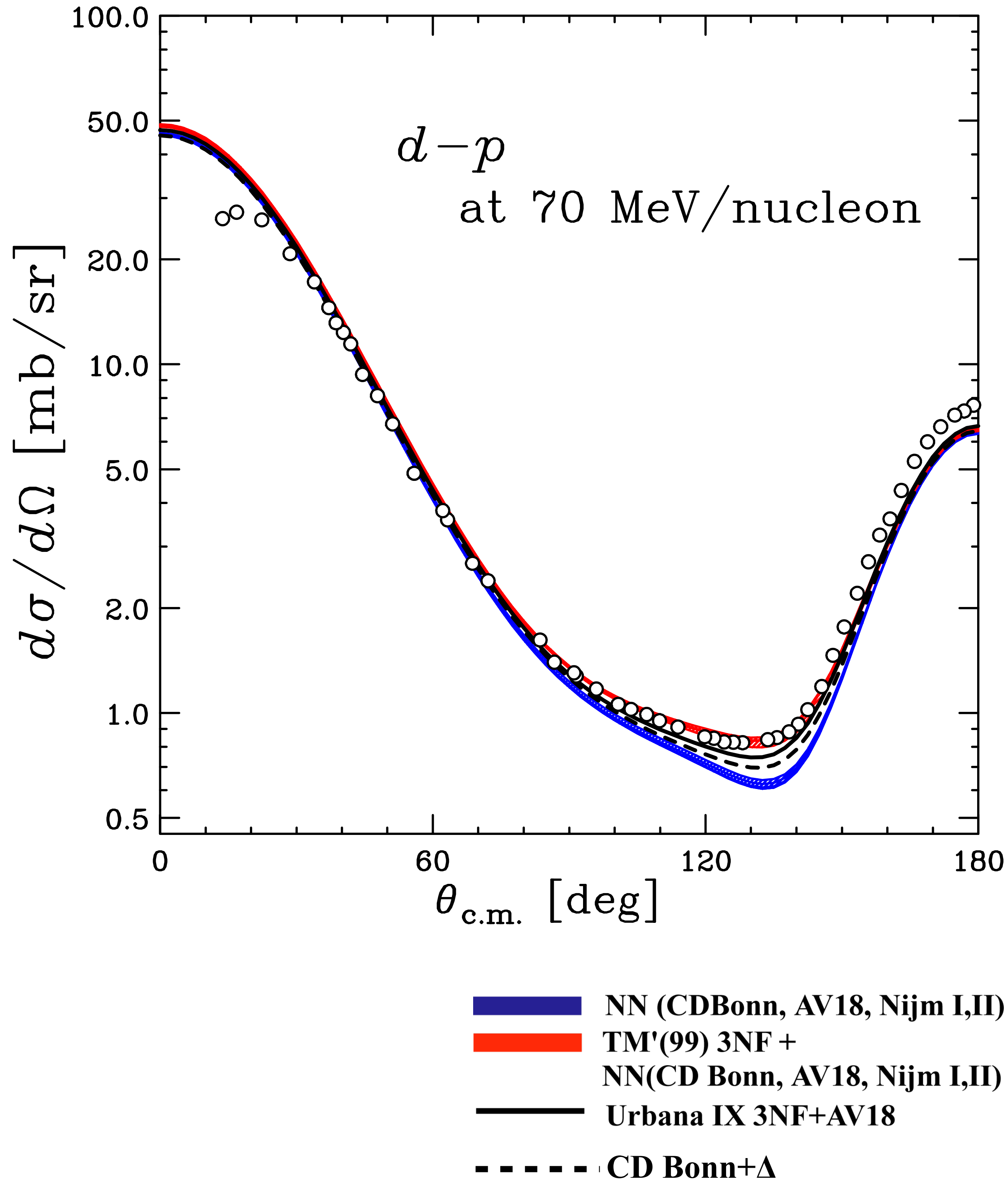
- Results of Comparison between Th.&Exp.
    - Cross Section Minimum Region
        - Cross Section
            - All Calc. with 2NF underestimate.
        - Spin Observables :
            - Large discrepancy in A_y(^{3}He)
            - Large Δ-isobar Effects (calc.) in $C_{y,y}$



p-^{3}He v.s. d+p



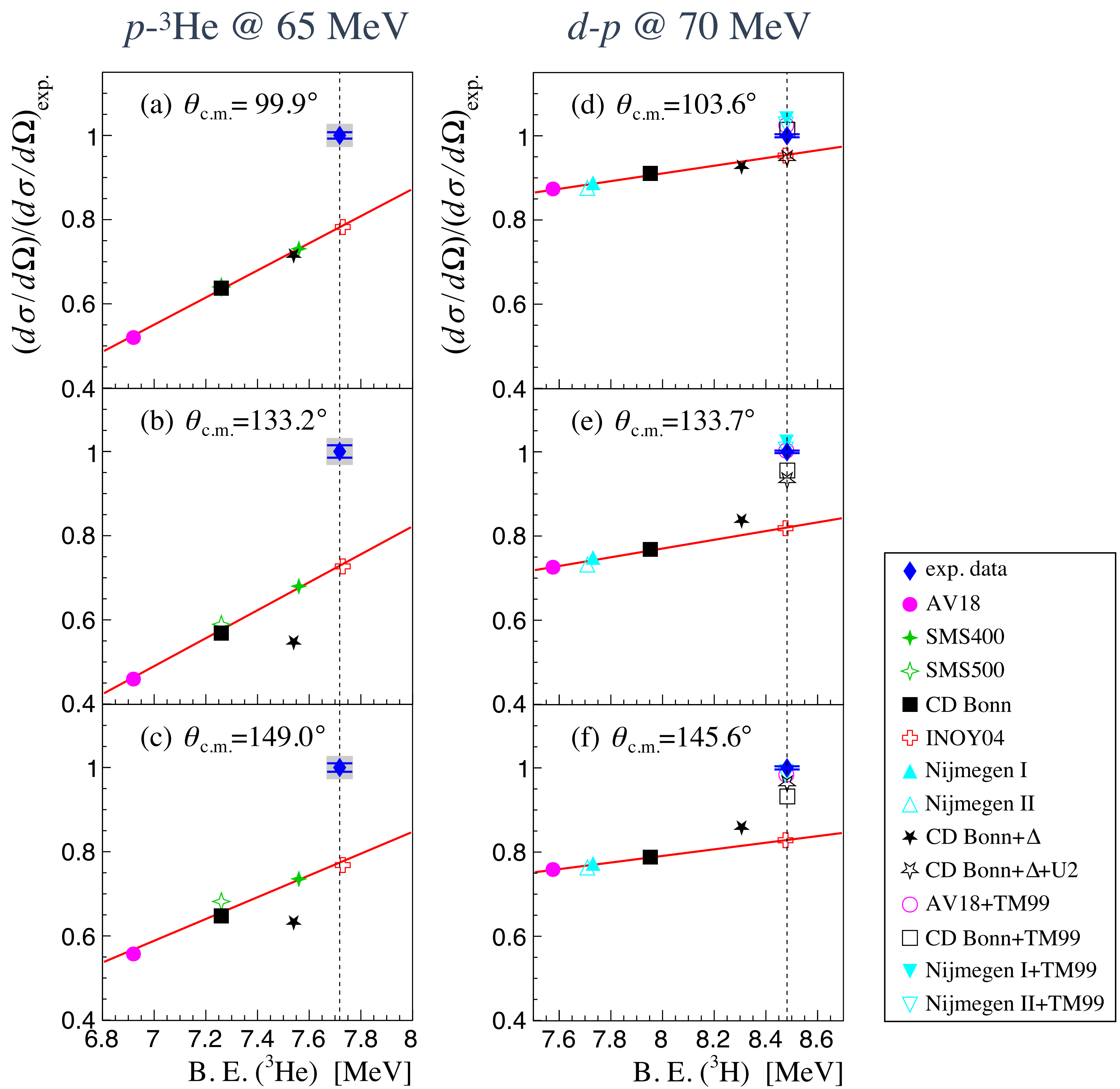
p-^{3}He at 65 MeV
$\frac{d\sigma}{d\Omega}$ [mb/sr]
AV18
SMS400
SMS500
CD Bonn
CD Bonn+Δ
INOY04
exp. data
$\theta_{c.m.}$ [deg]



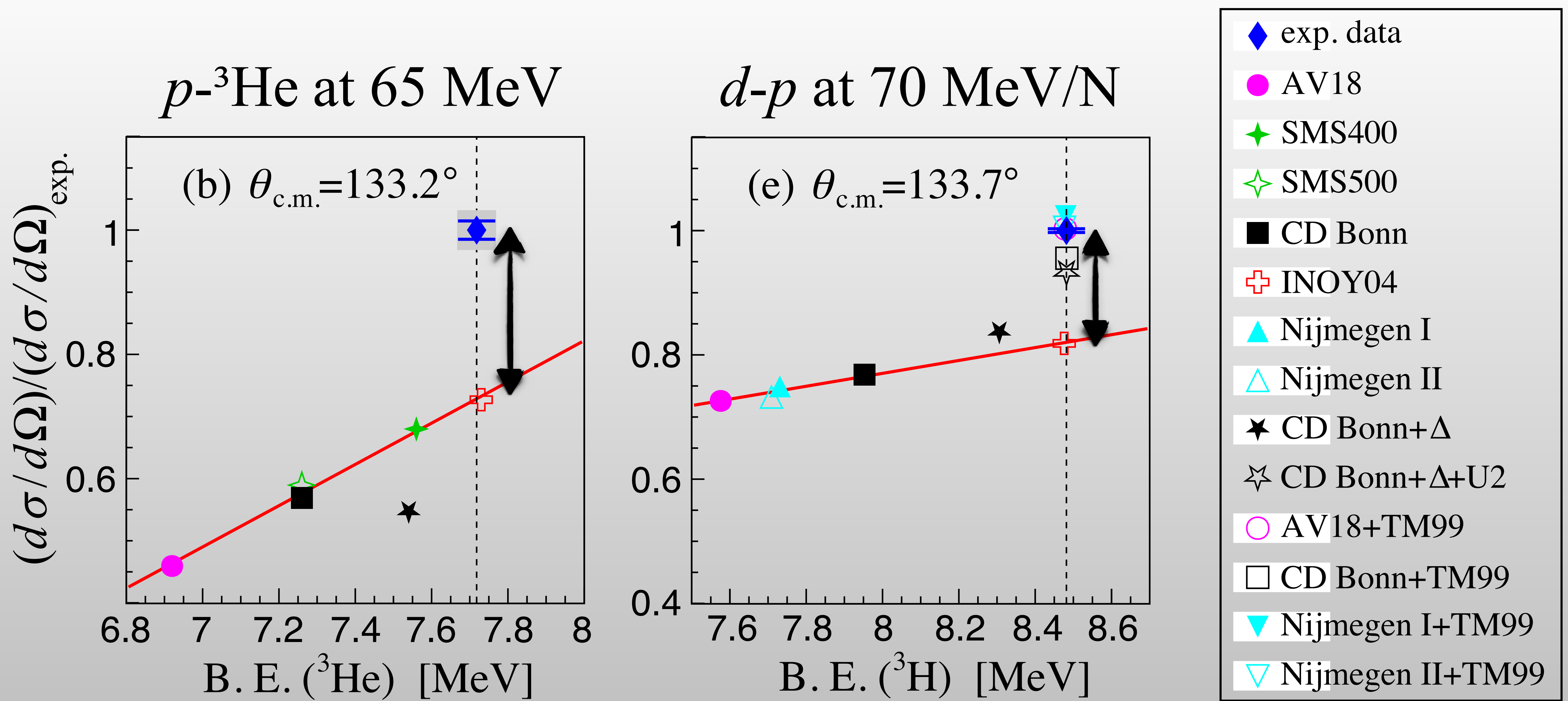
$d-p$
at 70 MeV/nucleon
$d\sigma/d\Omega$ [mb/sr]
$\theta_{c.m.}$ [deg]
NN (CDBonn, AV18, Nijm I,II)
TM'(99) 3NF +
NN(CD Bonn, AV18, Nijm I,II)
Urbana IX 3NF+AV18
CD Bonn+Δ

Cross Section Minimum & 3N B.E.

Scaling Relation between the cross sections with the NN potentials & the 3N binding energies



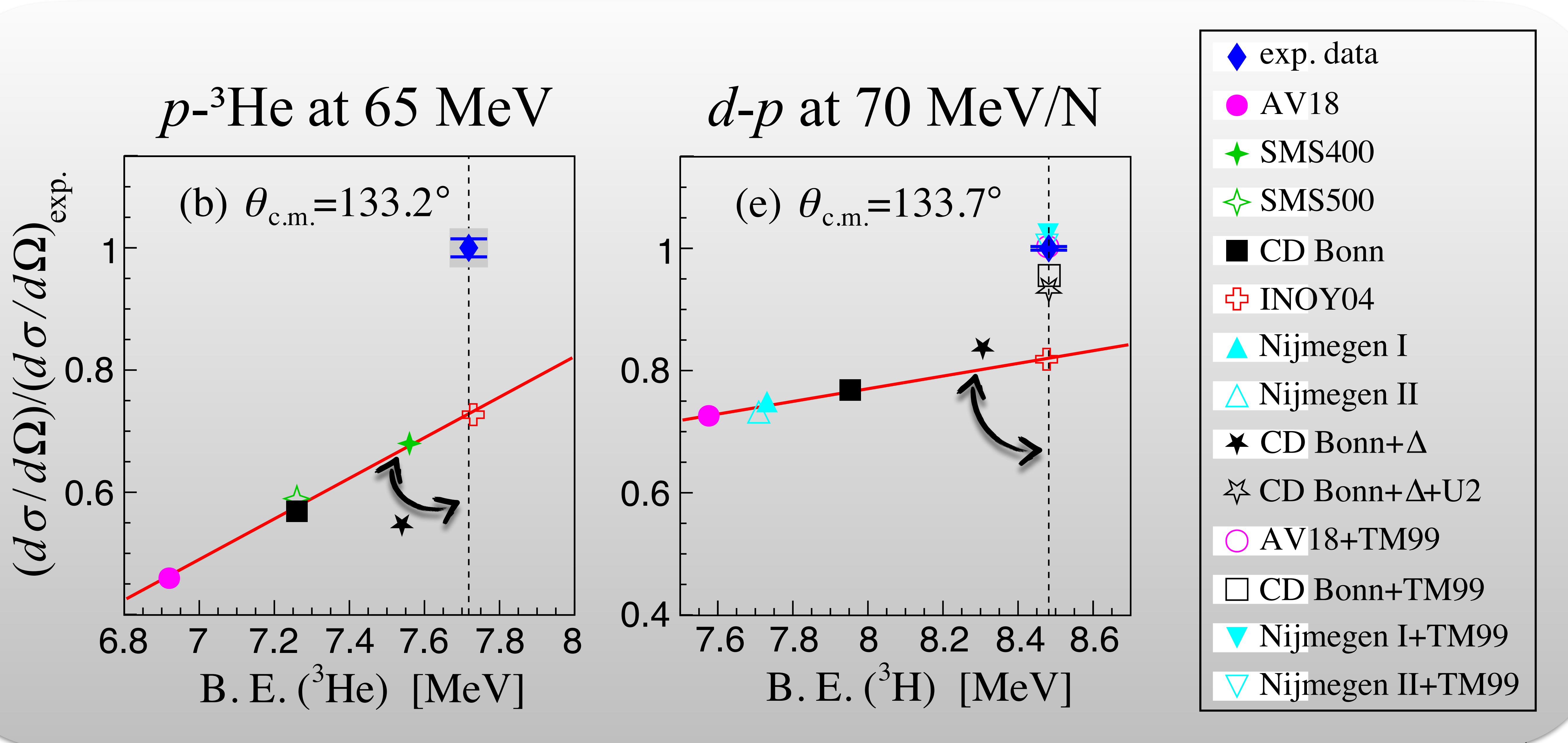
Cross Section Minimum & 3N B.E.



- Linear correlation exits for the NN potentials.

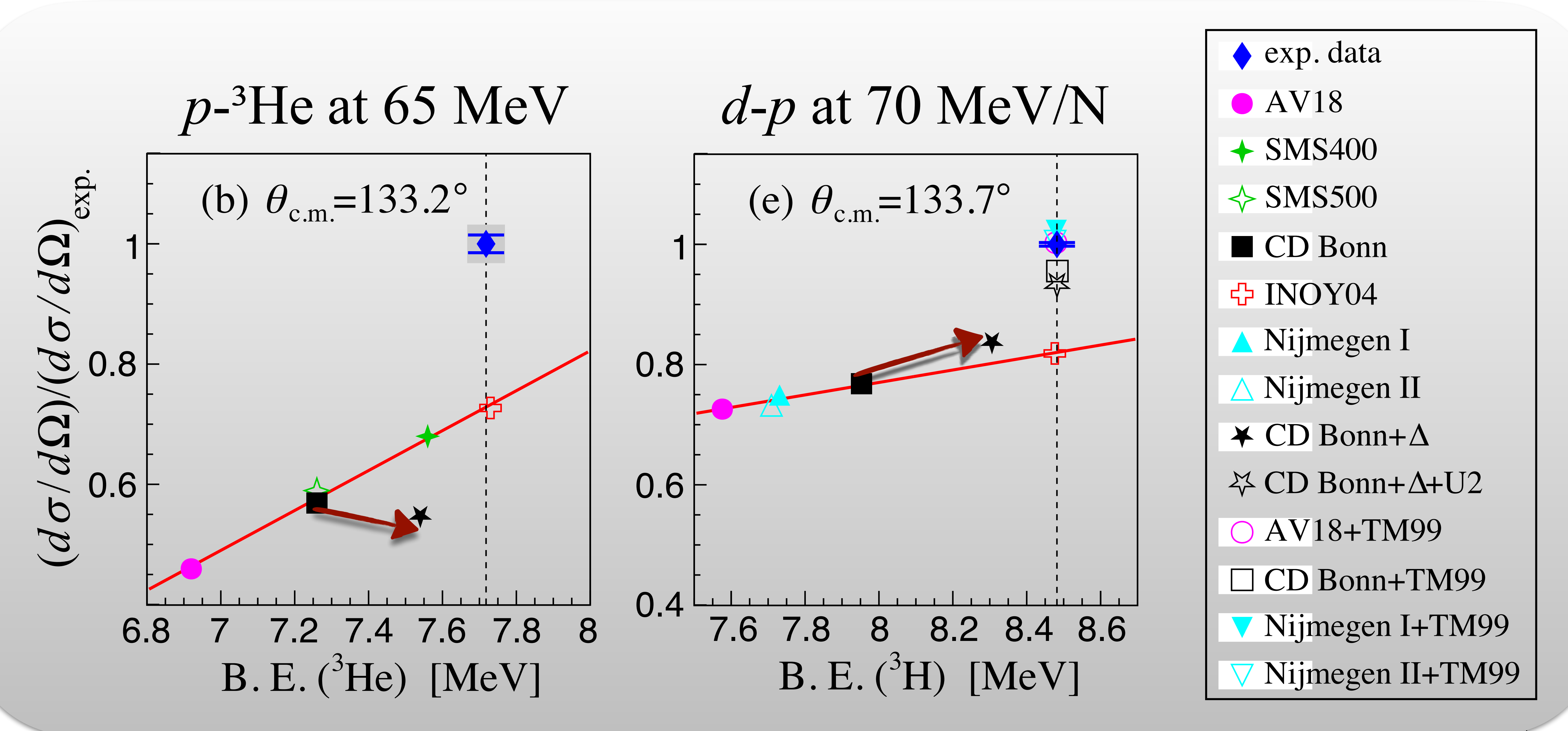
- Cross section with a NN potential which reproduces the experimental B.E. (3N) underestimate the experimental value.
  - ***p*-^{3}He** : 20–30 % ***d*-*p*** : 10–20 %
  - The discrepancies are explained by 3NF in *d*-*p* scattering.

Cross Section Minimum & 3N B.E.



- Gradient of the correlation lines (NN potential dependence)
  - ***p*-³He** : 0.3 / MeV, ***d-p*** : 0.1 / MeV
  - Less dependence in ***d-p*** : dominance of spin quartet states (S=3/2)

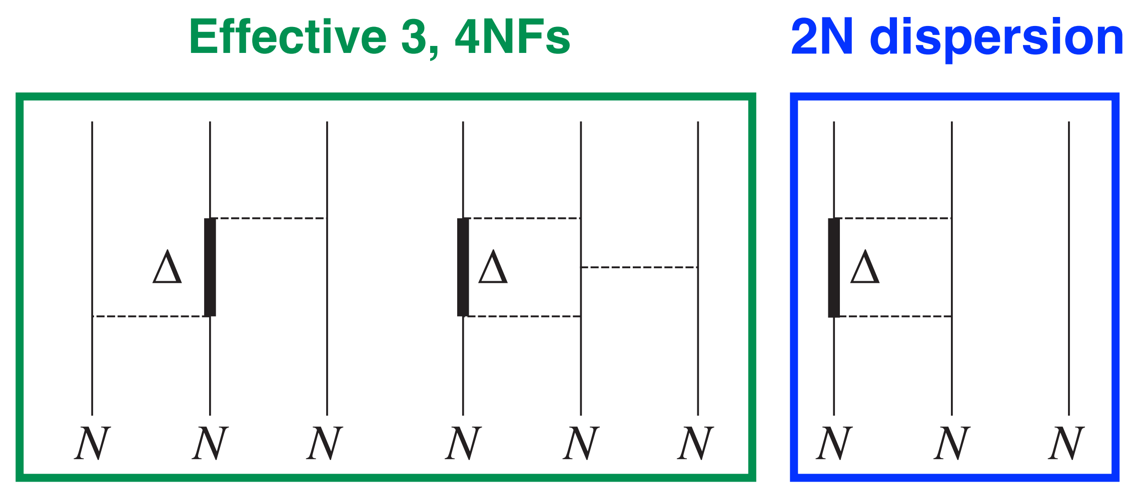
Cross Section Minimum & 3N B.E.



- Δ-isobar effects
  - ***d-p*** : Δ-isobar effects improve the agreements to the data.
  - ***p*-³He** : CD-Bonn+Δ moves in an opposite direction to the exp. data.

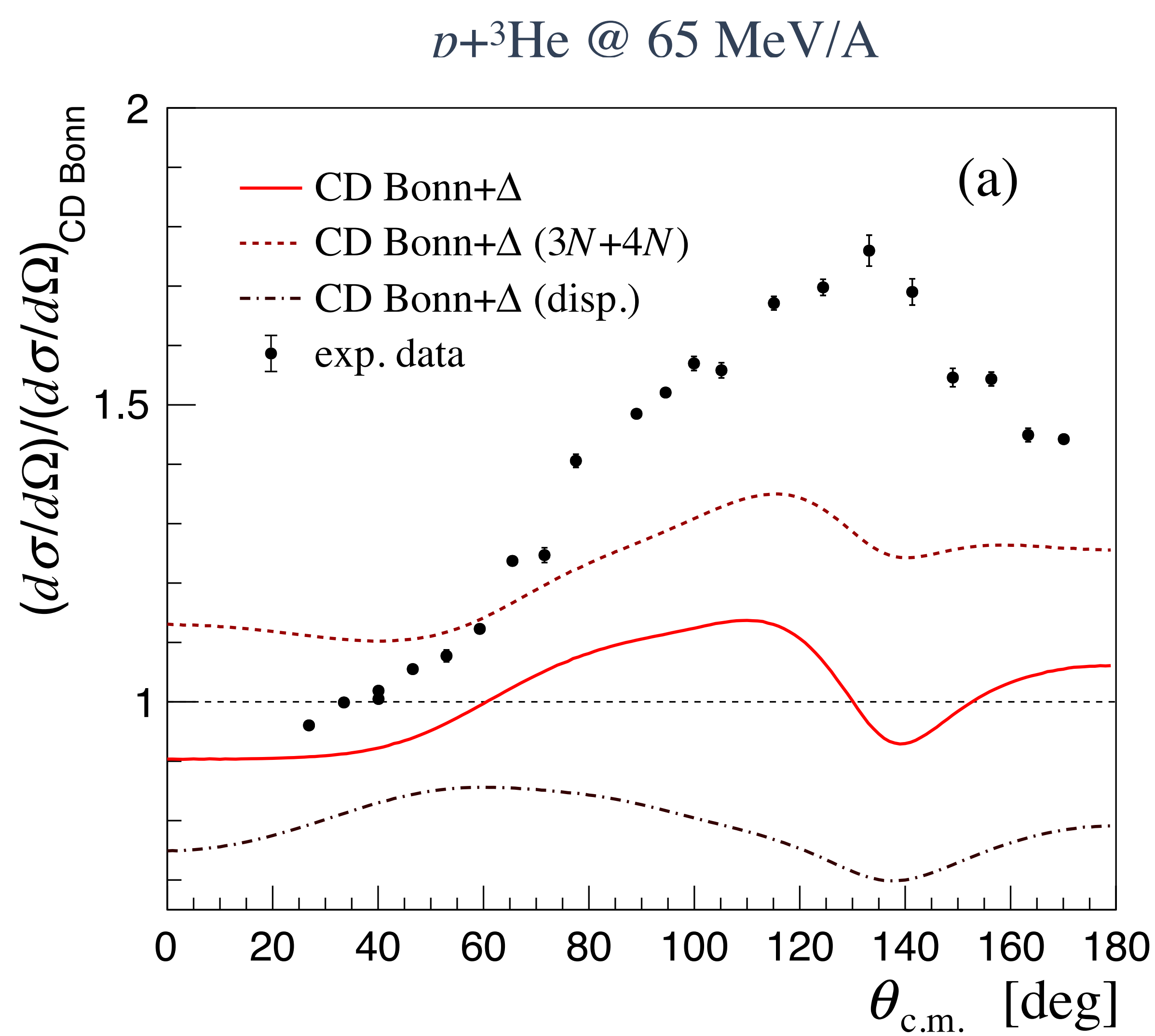
Δ-isobar Effects

- NN-NΔ coupled channel approach
  - ✦ ***3, 4NFs*** :
    - Effective 3 & 4NFs with single Δ-isobar
    - 3N binding : stronger (attractive).
  - ✦ ***2N dispersion***
    - 2N interaction including Δ-isobar.
    - 3N binding : weaken (repulsive)



Deltuva and A.C.Fonseca, P.U. Sauer
Phys. Lett. B 660, 471 (2008).

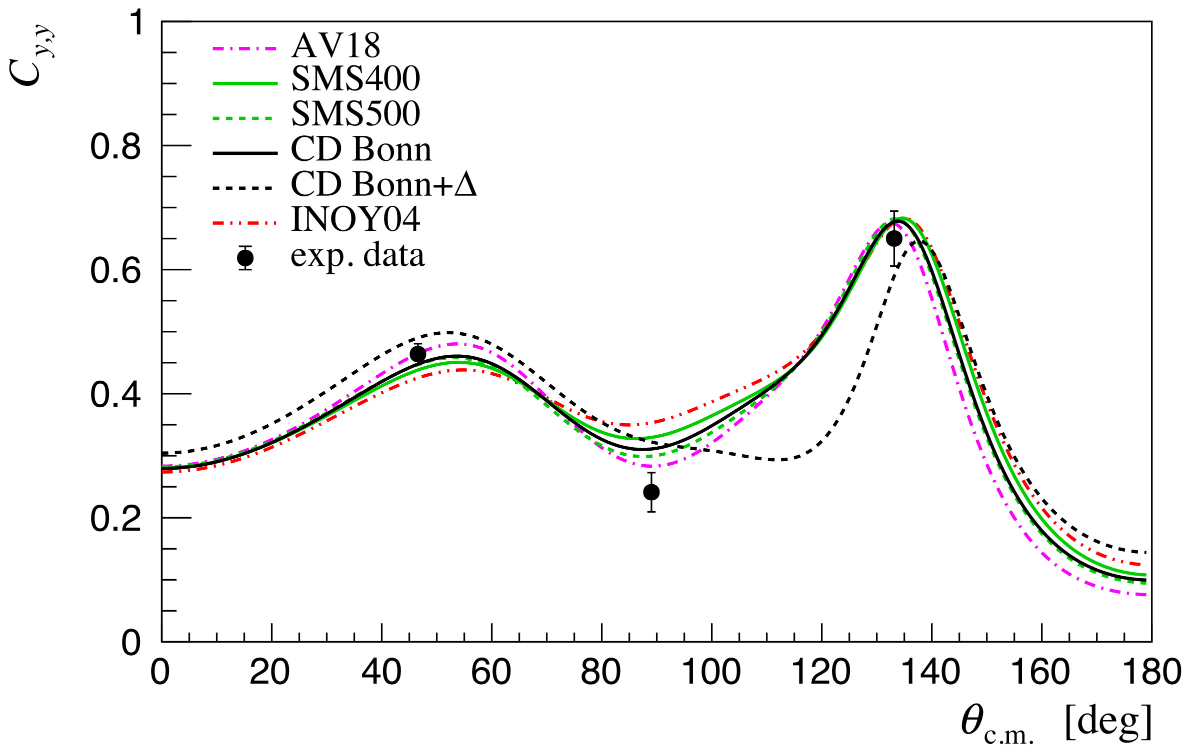
- ***p-³He***
  - Δ-generated 3NFs increase the cross section.
  - Dispersive Δ-isobar effects are strong and opposite to the 3,4NFs.
  - Net Δ-isobar effects are small.

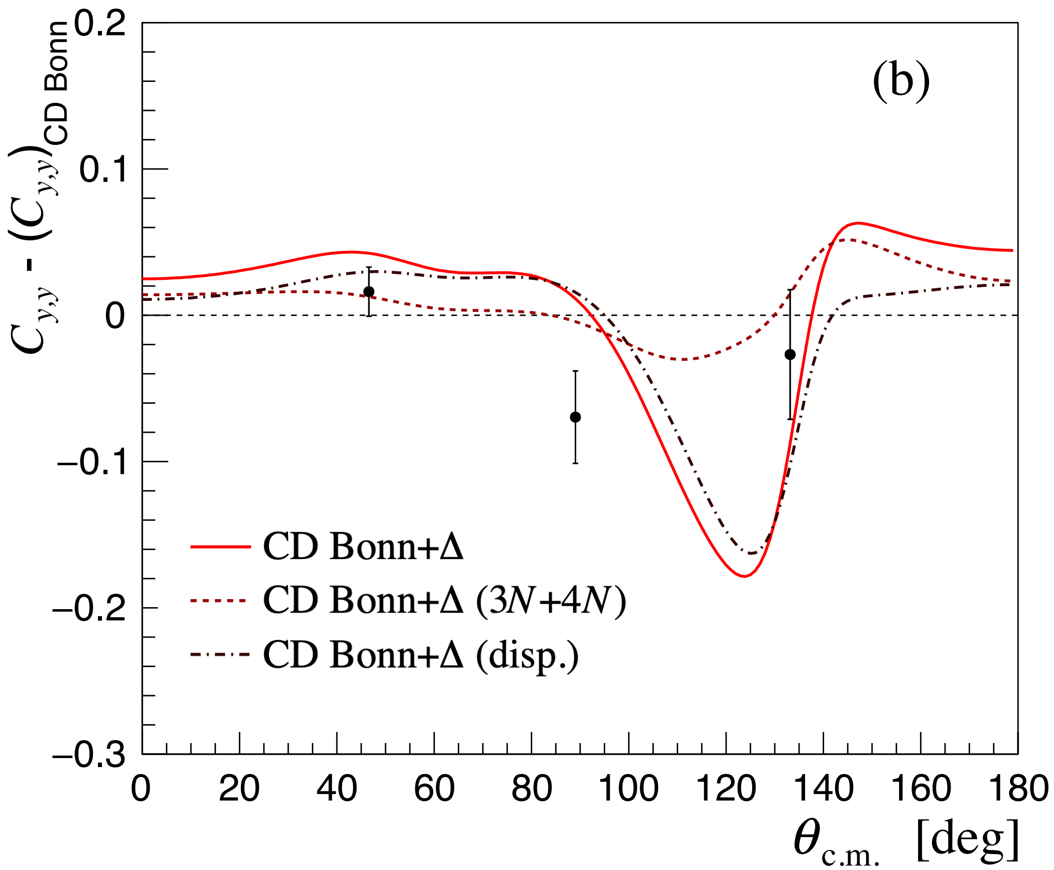


- ***d-p***
  - Δ-generated 3NFs >> 2N dispersive effects [S. Nemoto Ph.D thesis (1999)]

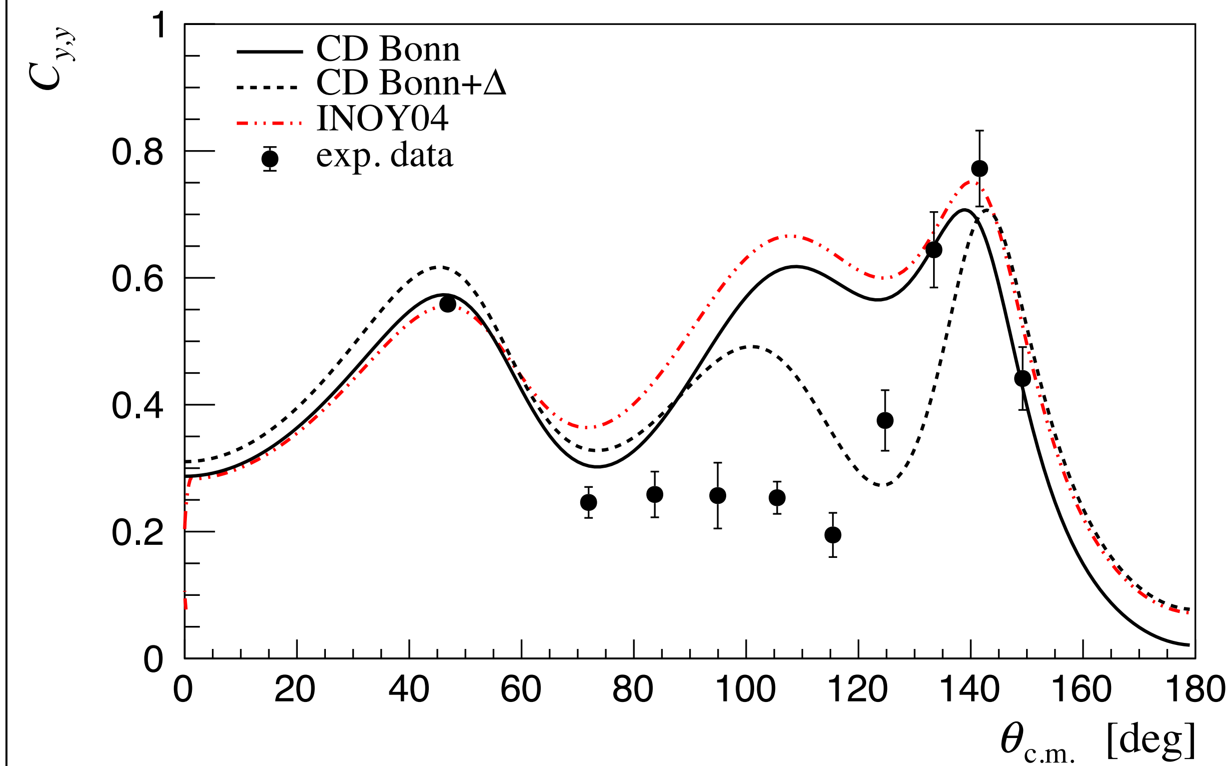
Δ-isobar Effects in Spin Correlation Coefficient $C_{y,y}$

65 MeV





100 MeV



Summary : p-^{3}He elastic scattering at intermediate energies

Direct comparison between Exp. and Th.

Large discrepancy in the cross section minimum angles

Scaling relation between B.E. (3N) and the cross section in p-^{3}He

- $d\sigma/d\Omega$ with NN potential which reproduces B.E.(3N) underestimate the data.
- Similar discrepancies in d-p scattering are resolved by 3NF.

- Relatively larger NN potential dependence
  → reflection of medium & short interactions

Δ-isobar effects by NN+NΔ coupled-channel approach

- p-^{3}He : Large 3NF effects are cancelled by strong 2N dispersive effects.
  - d-p scattering : 3NF >> 2N dispersive
- Large Δ-isobar effects in Spin correlation coefficient $C_{y,y}$

p*-³He** scattering at intermediate energies is an excellent tool to explore the nuclear interactions that could not be accessible in ***d*-*p scattering.

p*-³He** could provide sources of **T=3/2 3NF**. Note, T=1/2 dominant in ***d*-*p.