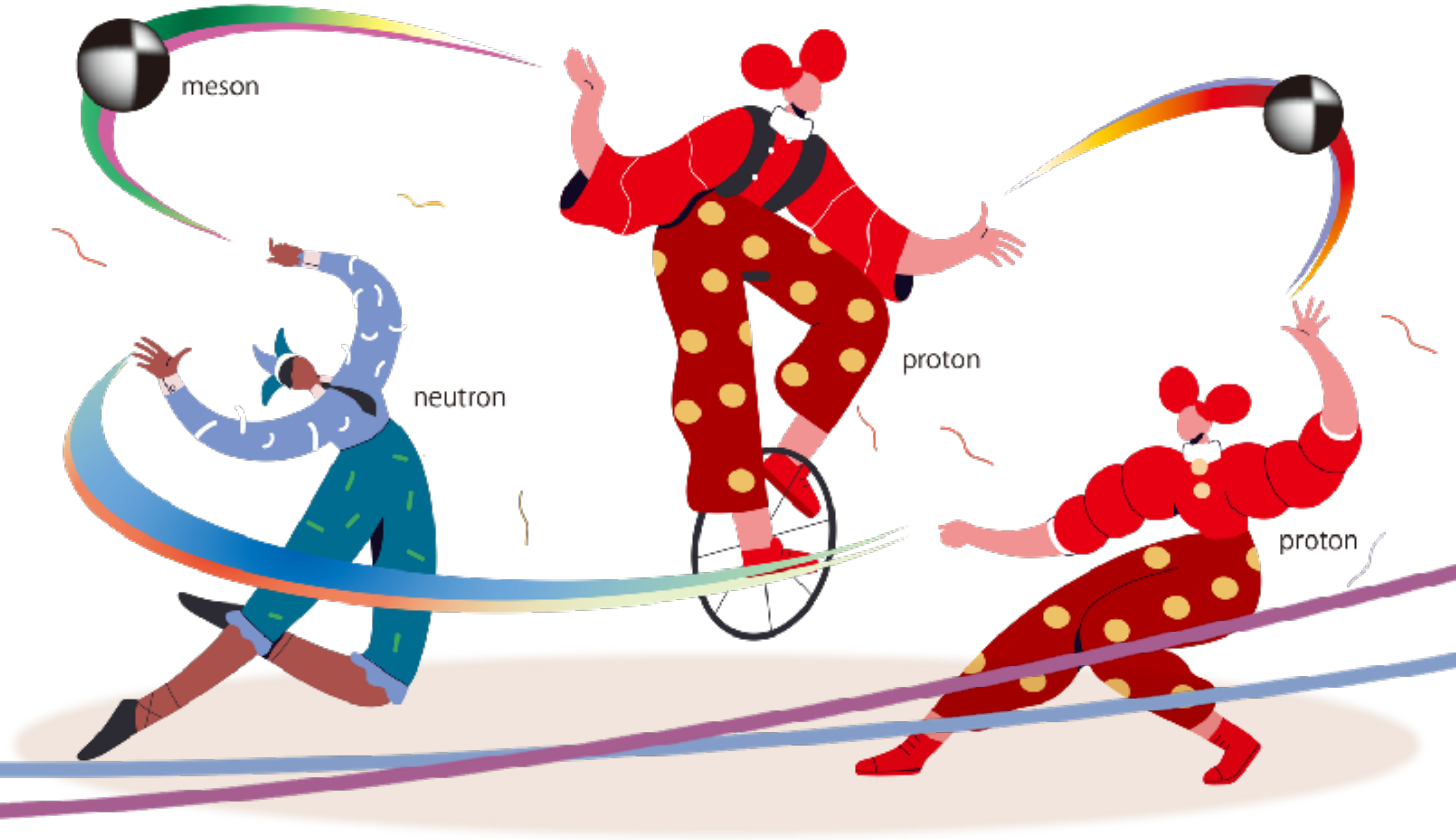
Experiments to Explore Three-Nucleon Forces

Kyoto University / RIKEN

Kimiko Sekiguchi



TOMOE

Three-Nucleon Force (3NF)

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

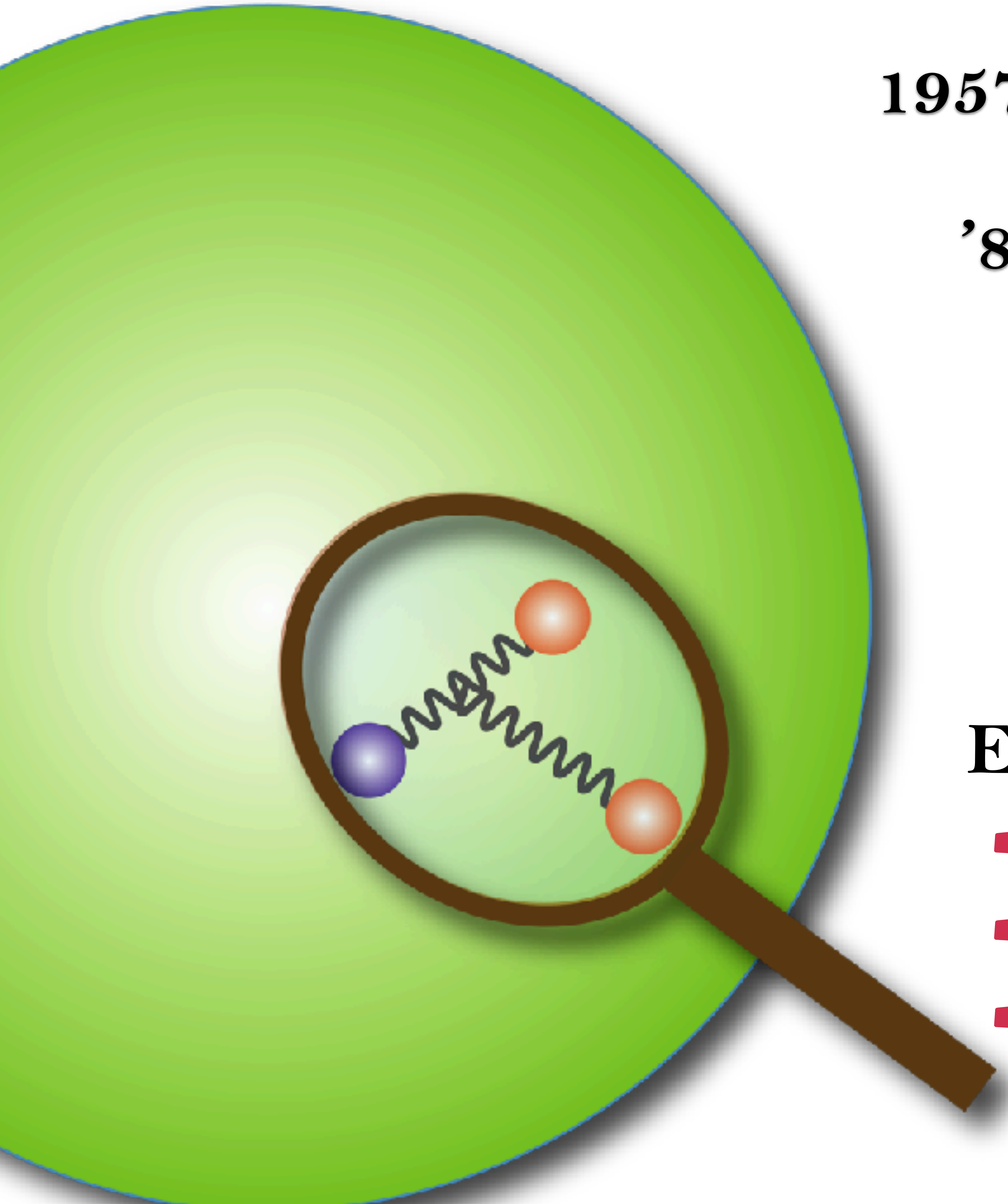
Key to fully understand properties of nucleus

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

1957 **Fujita-Miyazawa 3NF**

'80's **First indication** of 3NF : Binding Energies of Triton

'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 Calculations**

  Rigorous Numerical Calculations of 3, 4N System

  2NF Input
  - CDBonn
  - Argonne V18 (AV18)
  - Nijmegen I, II, 93

  3NF Input
  - Tucson-Melbourne
  - Urbana IX

  etc..

  2NF & 3NF Input
  - Chiral Effective Field Theory

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

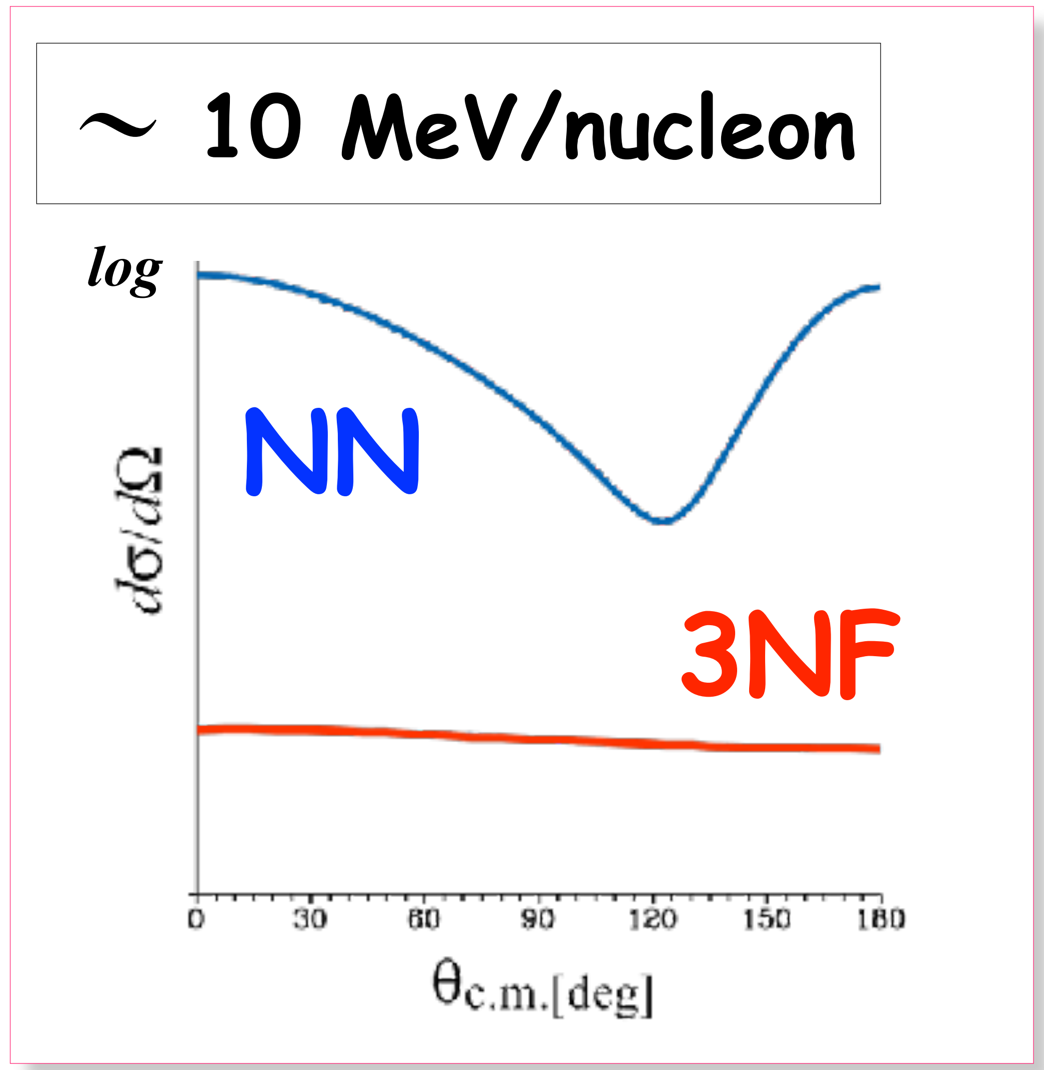
Extract fundamental information of Nuclear Forces

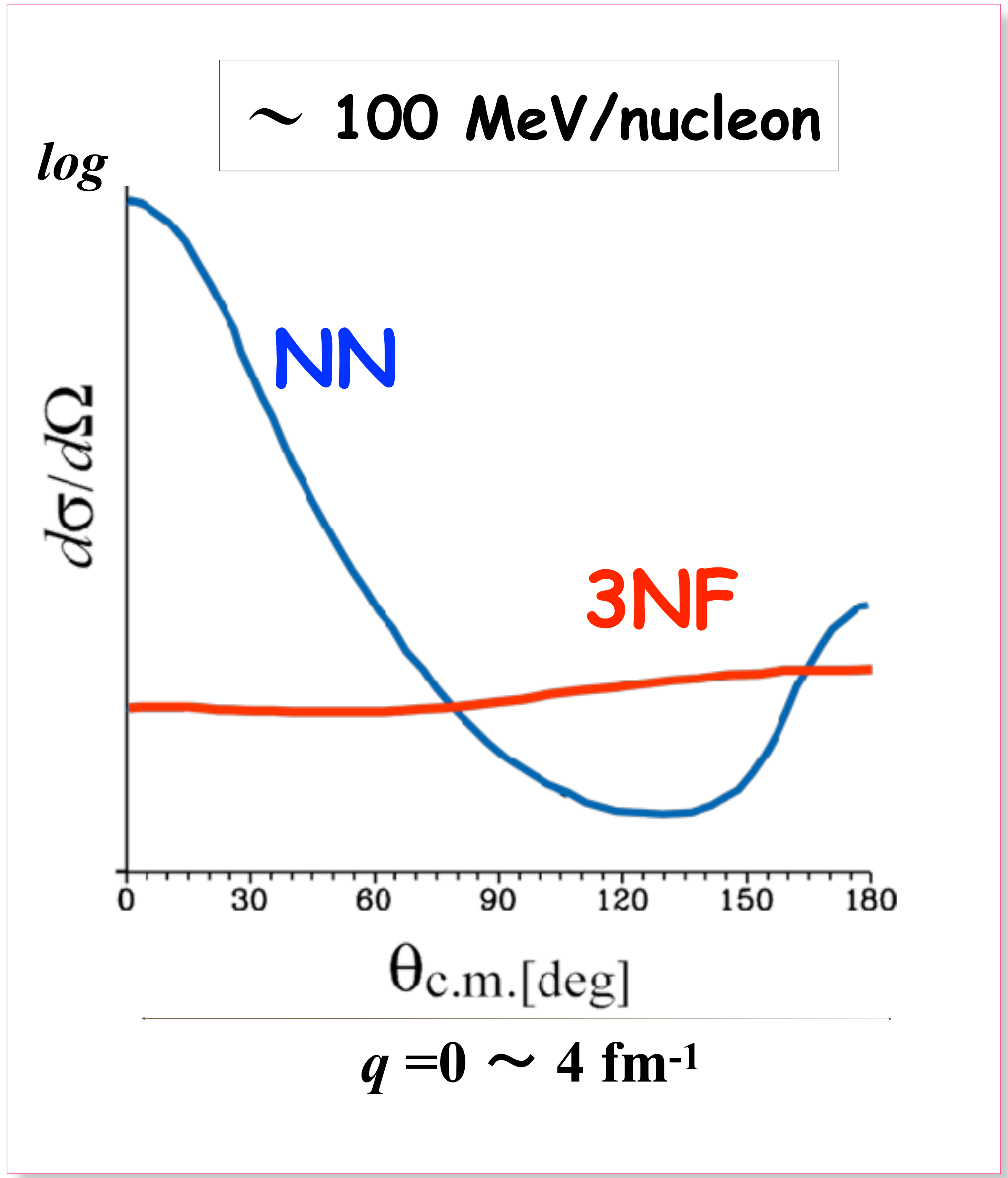
Where is the hot spot for 3NFs ?

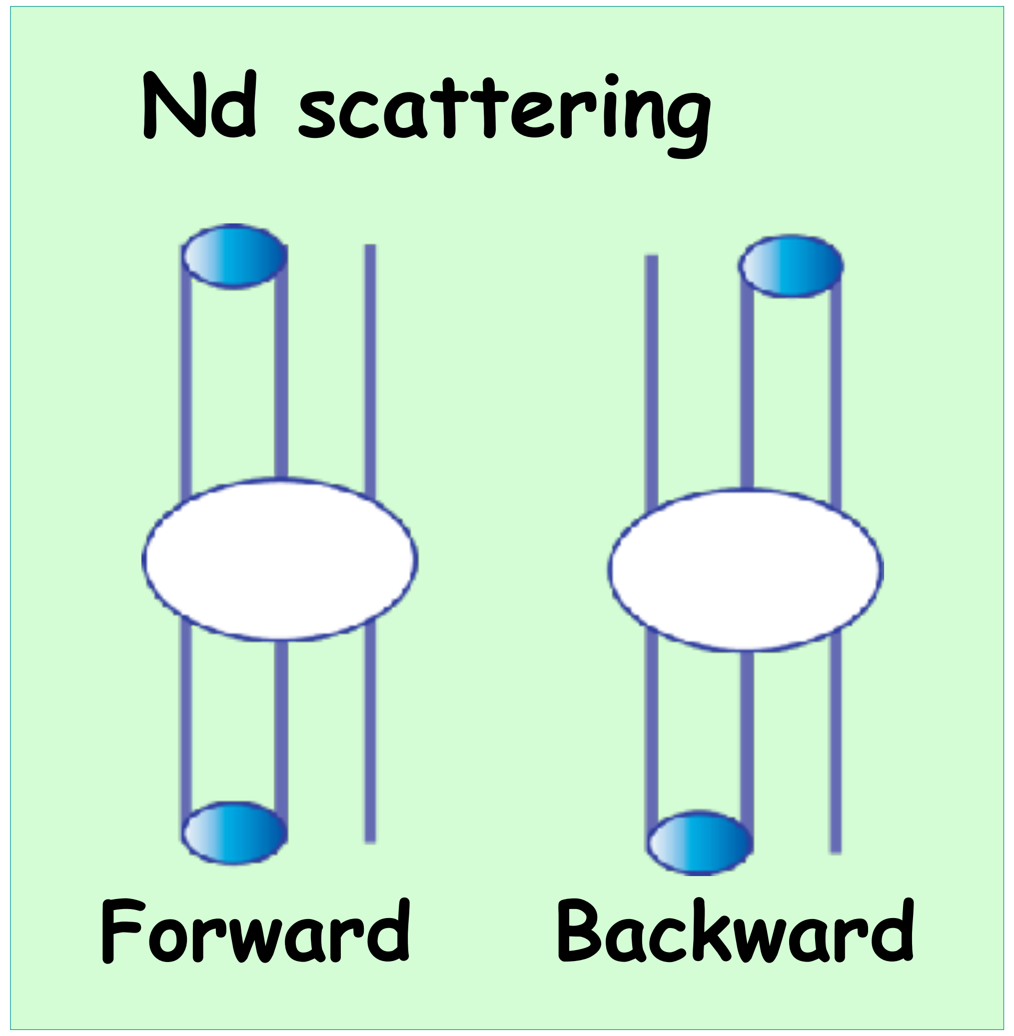
Nucleon-Deuteron Scattering - 3N Scattering -

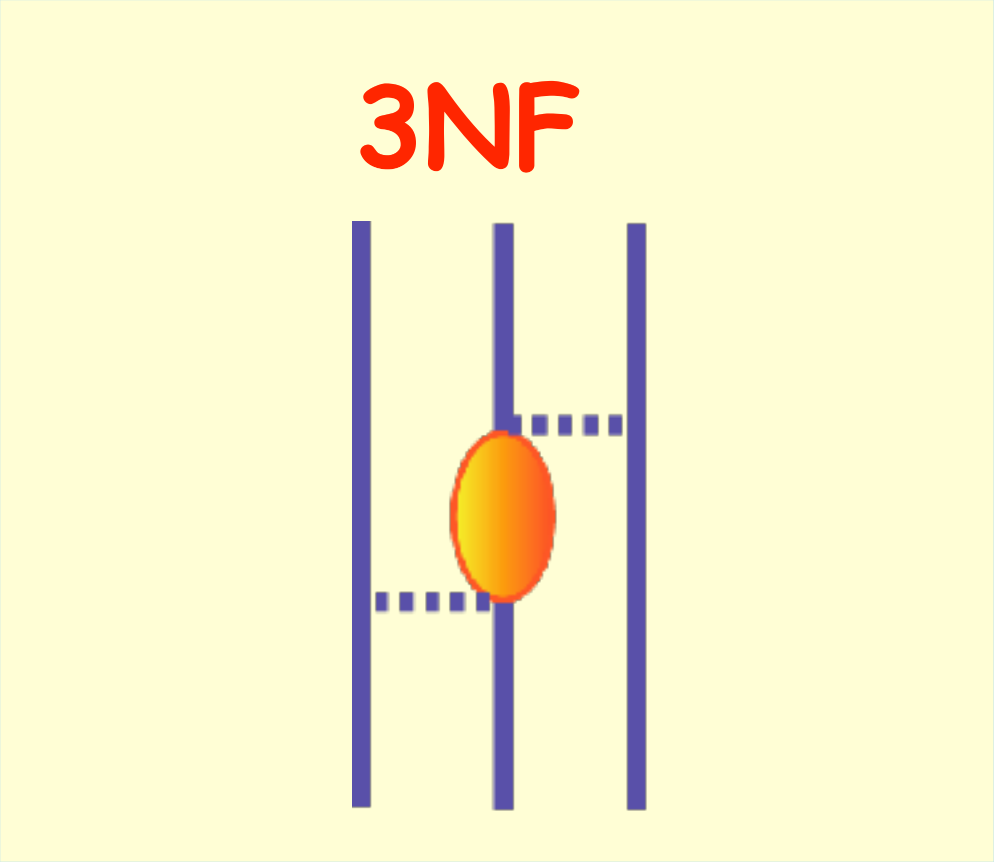
Predictions by H. Witala et al. (1998)

Cross Section minimum for Nd Scattering at ~ 100 MeV/nucleon

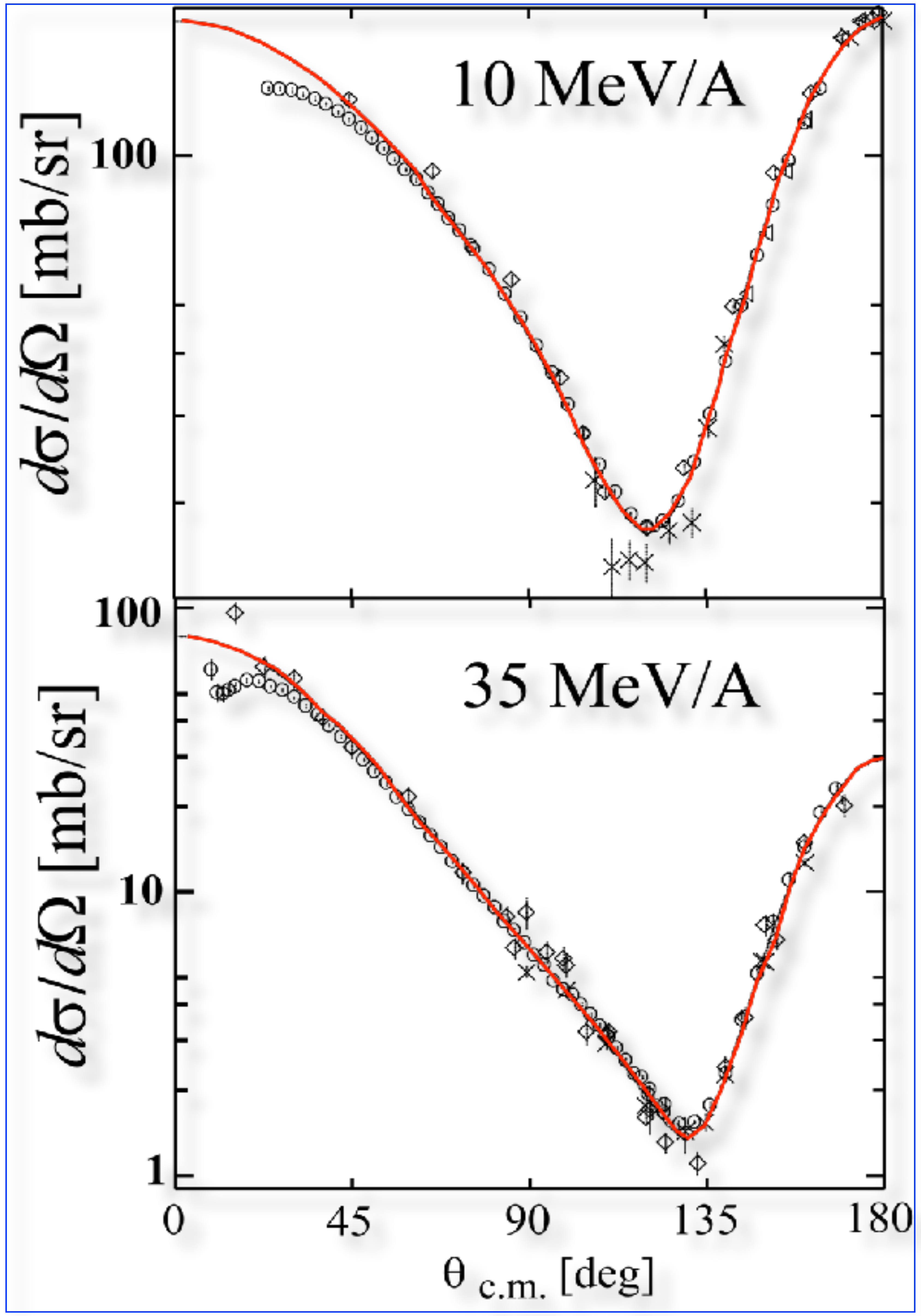








Nd Scattering at Low Energies ($E \leq 30$ MeV/A)



- High precision data are explained by Faddeev calculations based on 2NF.
  (Exception : A_y, iT_{11})

No signatures of 3NF

Exp. Data from
Kyushu, TUNL, Cologne etc..

W. Glöckle et al., Phys. Rep. 274, 107 (1996).

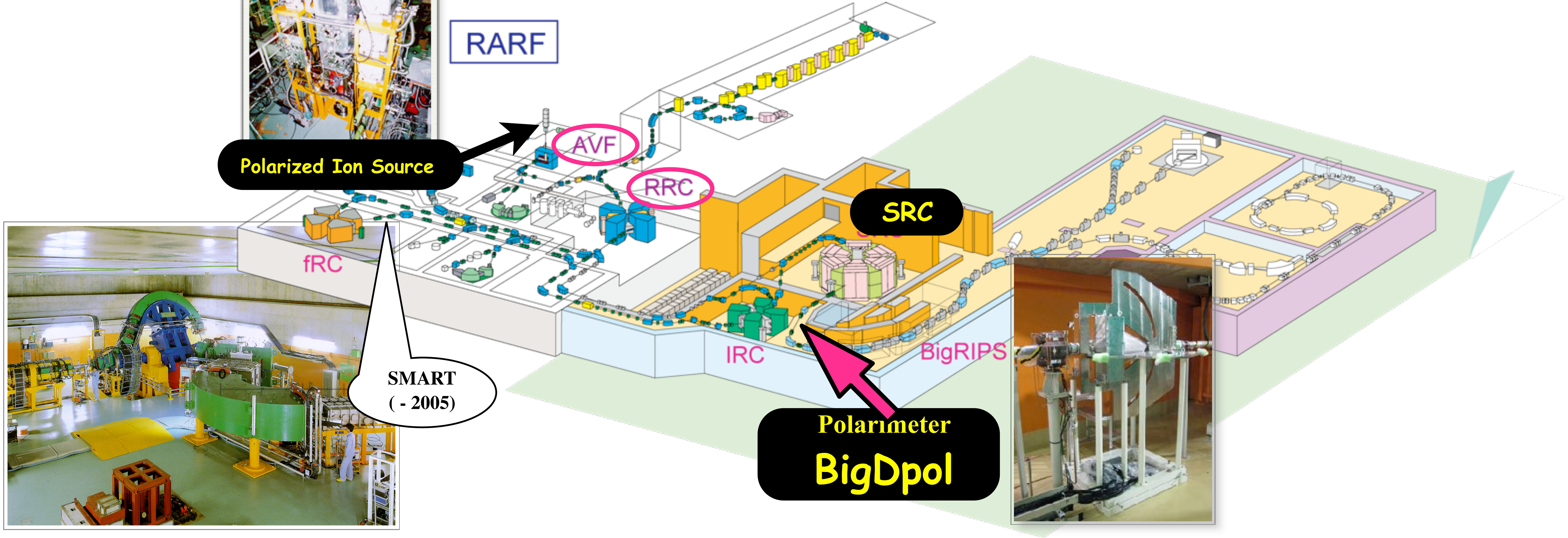
This talk

- Experimental study of nucleon-deuteron scattering at intermediate energies (70-300 MeV/nucleon)
  - Nd scattering & “semi-phenomenological NN” + 3NF
  - Nd scattering & χEFT nuclear forces
- Experimental study of proton-^{3}He scattering
- New Project in Japan : ERATO TOMOE Project

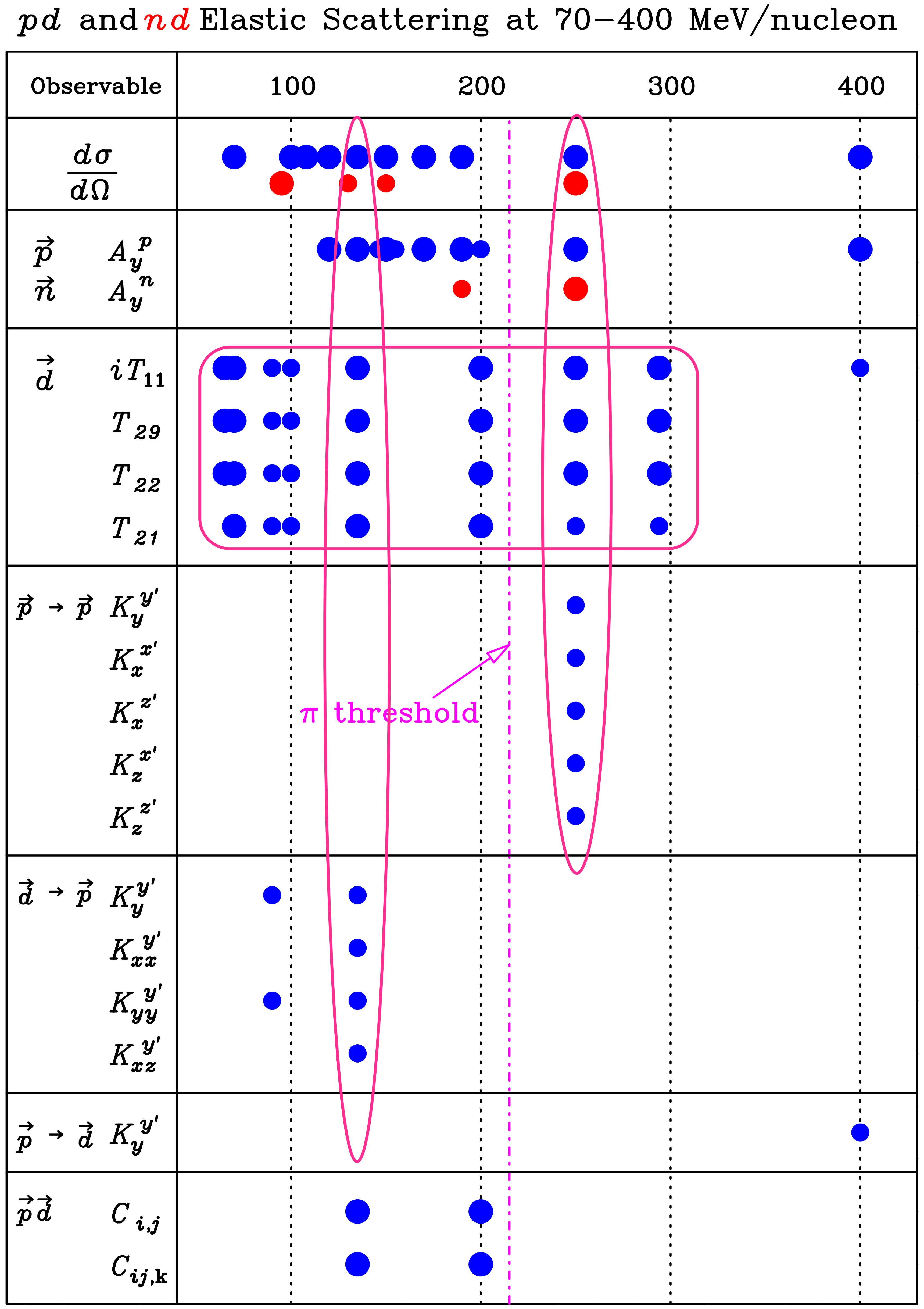
RIKEN RI Beam Factory (RIBF)

- Polarized *d* beam
  - acceleration by AVF+RRC : 65-135 MeV/nucleon
  - acceleration by AVF+RRC+SRC : 190-300 MeV/nucleon
  - polarization : 60-80% of theoretical maximum values
- Beam Intensity : < 100 nA

Spin axis of polarized d beams is freely controlled !



Nd Elastic Scattering Data at Intermediate Energies

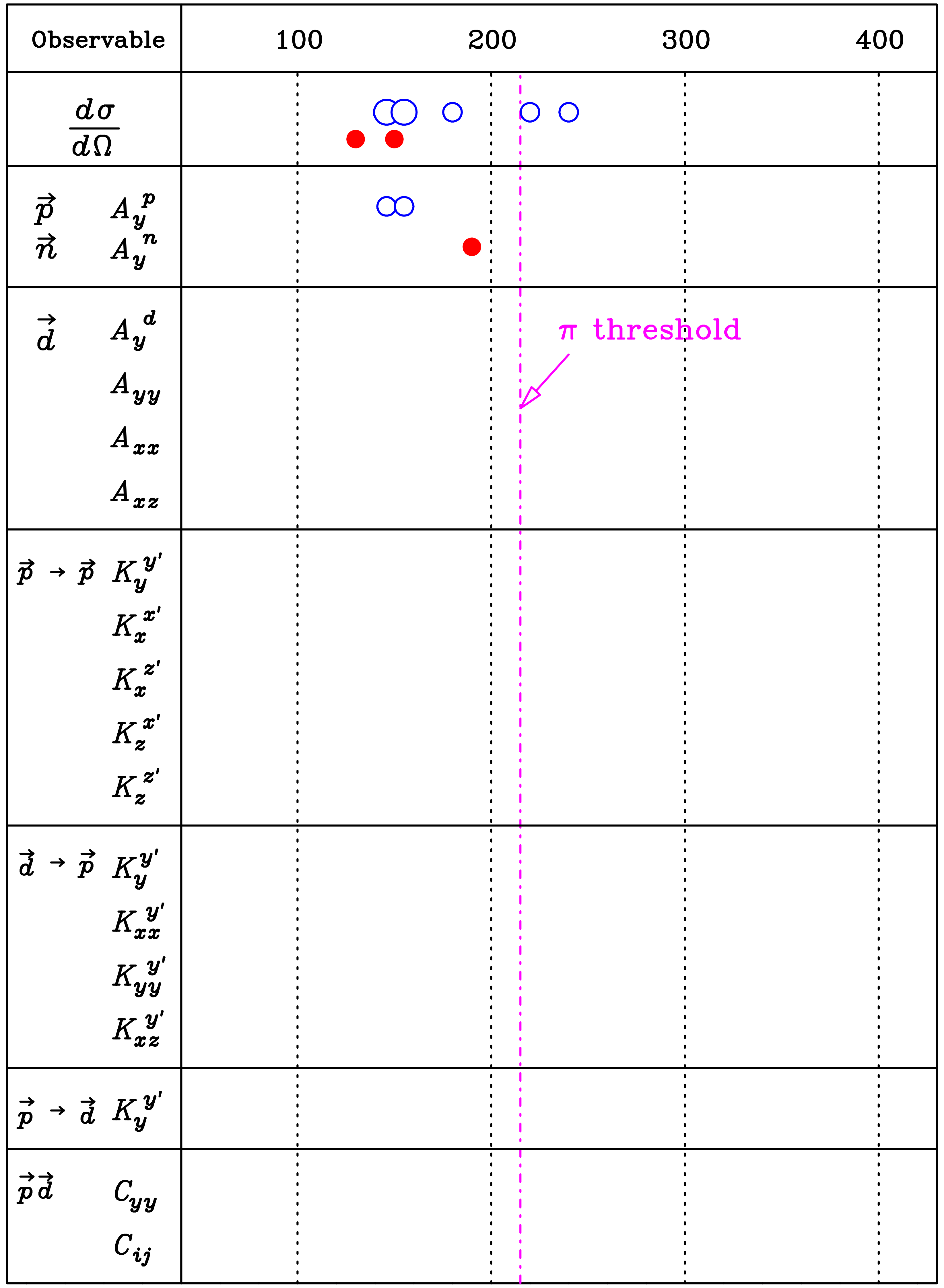


~2025

- **High precision data set of**
  ***dσ/dΩ* & Analyzing Powers**
  from RIKEN, RCNP, KVI, IUCF

Nd Elastic Scattering Data at Intermediate Energies

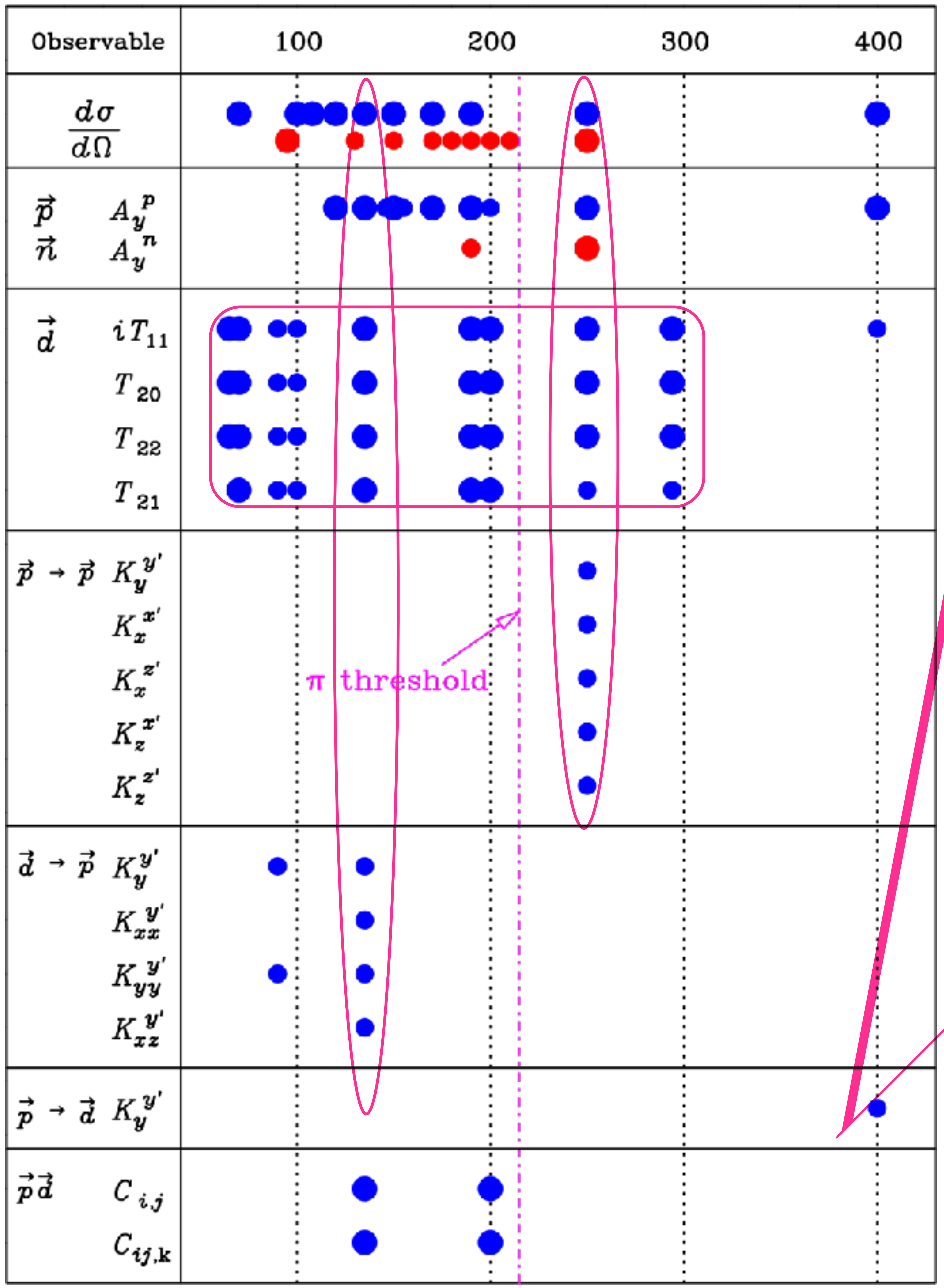
pd and *nd* Elastic Scattering at 70–400 MeV/A



~1998

Nd Elastic Scattering Data at Intermediate Energies

pd and nd Elastic Scattering at 65–400 MeV/nucleon



~2025

- **High precision data set of**
  ***dσ/dΩ* & Analyzing Powers**
  from
  RIKEN, RCNP, KVI, IUCF, LANSCE
  etc.

After ~ **90** Years of

Yukawa's Meson Thory (1935)

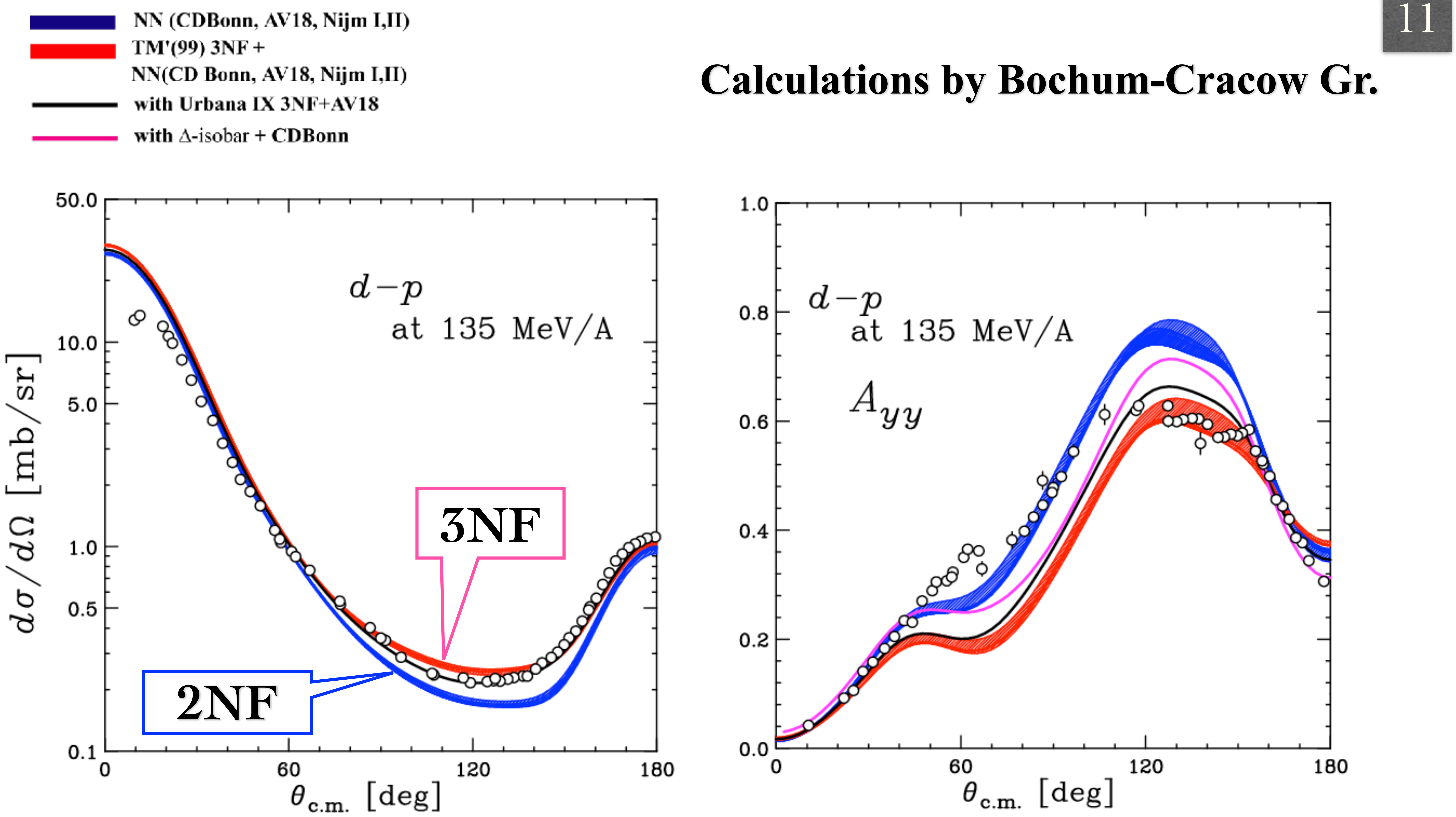
&

After ~ ***70*** Years of

Fujita-Miyazawa 3NF (1957)

Quantitative discussions on 3NFs start via Theor. & Exp. .

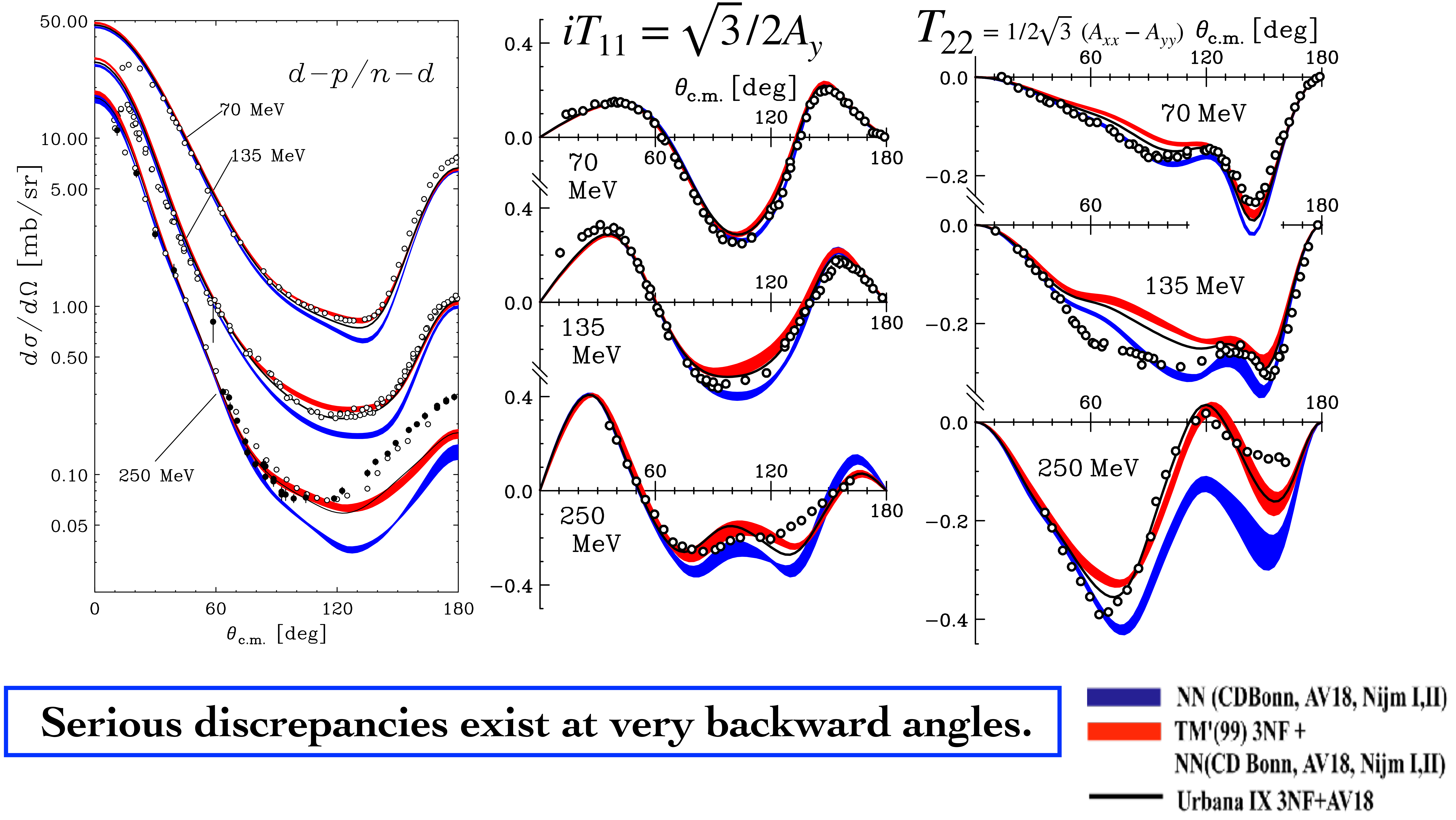
Calculations by Bochum-Cracow Gr.



2π-exchange 3NFs (Tucson-Melbourne, Urbana IX) : Good Agreement
: First Clear Signatures of 3NF effects in 3-Nucleon Scattering

Spin observables : Defects of spin-dependent parts of 3NFs

Energy Dependent Study for *dp* Scattering
- Cross Section & Analyzing Powers -



Serious discrepancies exist at very backward angles.

Summary of Results of Comparison for *dp* elastic scattering

- Cross section at ~100 MeV/nucleon
  - First clear signature of 3NF effects in 3N scattering
    - Magnitudes of 3NFs is O.K. .
- Spin observables
  - Not always described by 2π-3NFs
    - Defects of spin-dependent parts of 3NFs
- At higher energies …
  - Serious discrepancy at backward angles
    - Short Range 3NFs are required.

χEFT & *dp* elastic scattering

- χEFT 2NFs have achieved to high-precision.

  5th order of NN potentials (N4LO+) reproduce pp(np) data with χ^2/datum=1.00

  P. Reinert, H. Krebs, E. Epelbaum EPJA 54, 86 (2018)

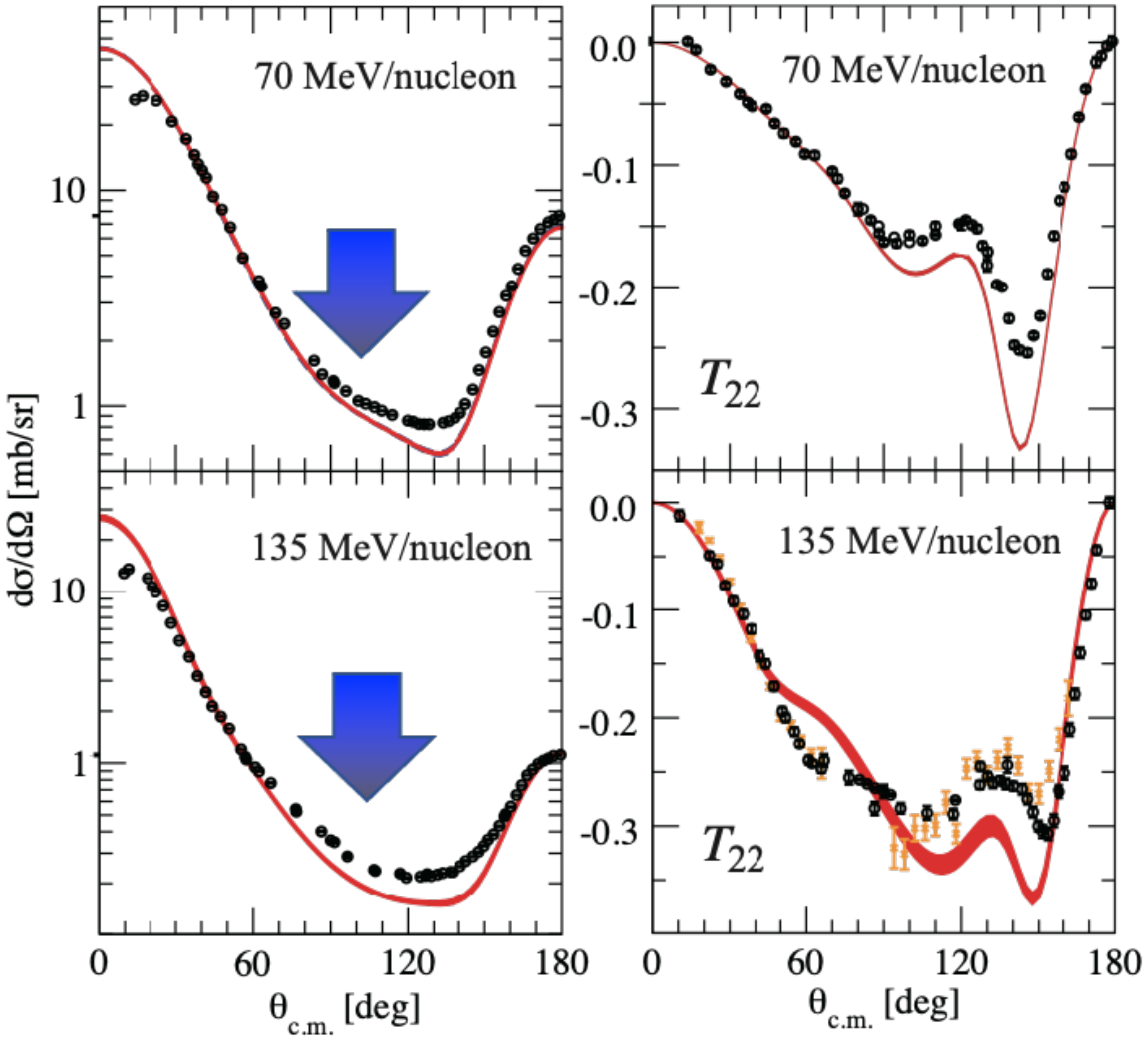
- *dp* elastic scattering data at around 100 MeV show necessities of the N4LO 3NFs.

Cross section minimum region
for *dp* elastic scattering
at ～100MeV/nucleon is
"Golden window" for the N4LO 3NFs.

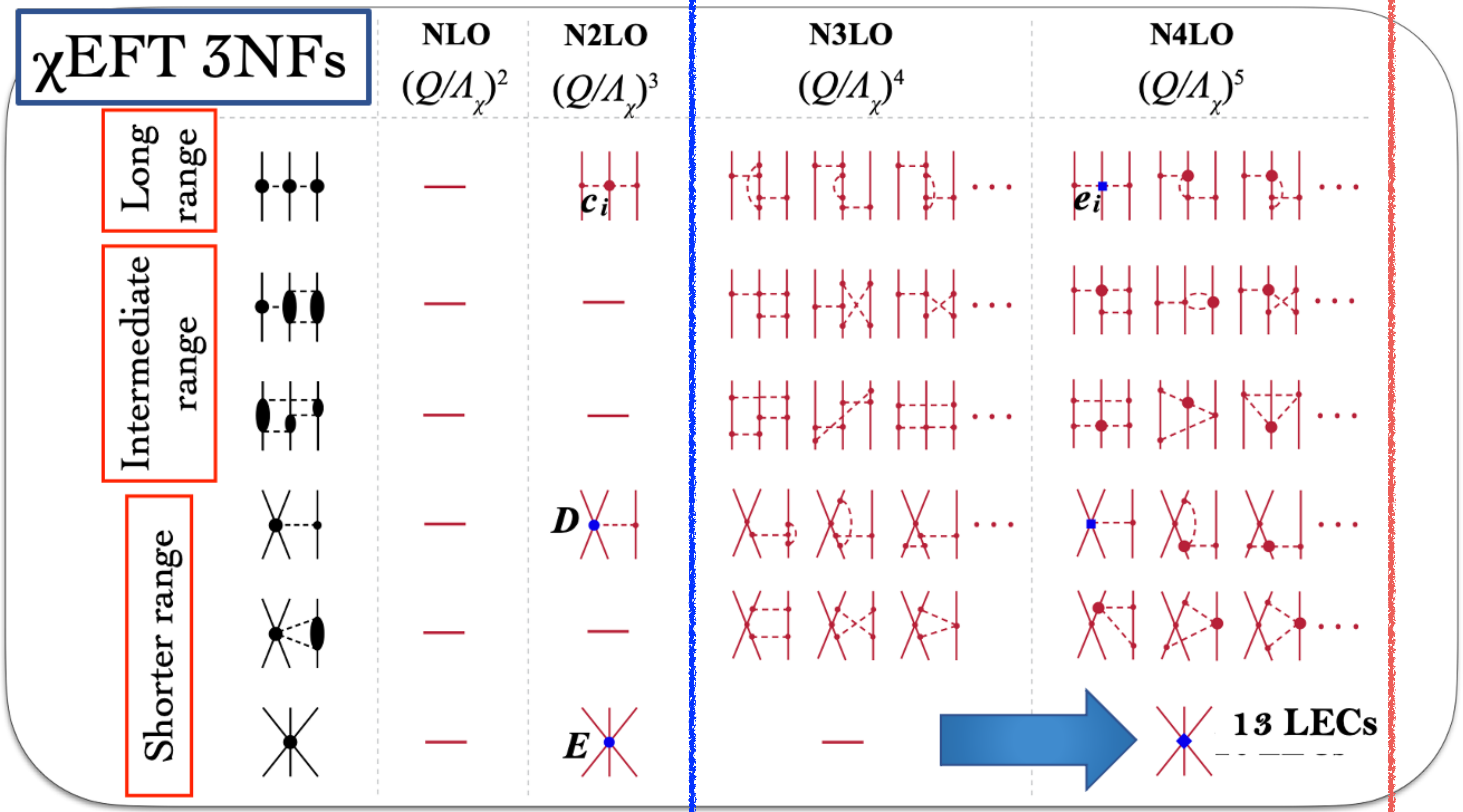
LENPIC collaboration,
Phys. Rev. C 98, 014002 (2018)

dp scattering & N4LO χEFT 2NFs

K. S. et al., Phys. Rev. C 96, 064001 (2017)



χEFT 3NFs

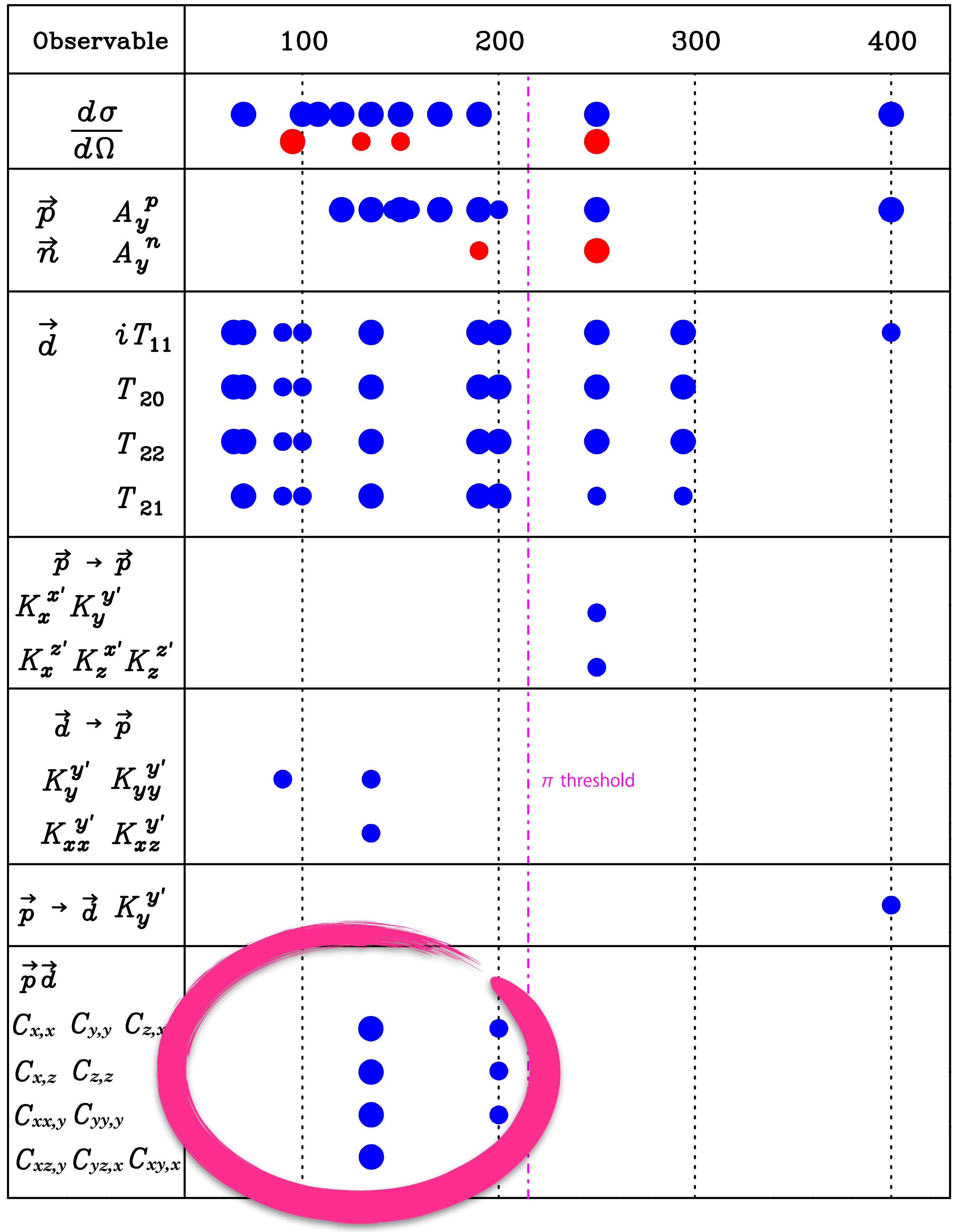


L. Girlanda, et al., Phys. Rev. C 84, 014001 (2011)
L. Girlanda, et al., Phys. Rev. C 102, 019903 (2020).

New Experiment at RIKEN

Measurement of Spin Correlation Coefficients for *dp* elastic scattering at ∼100 MeV/nucleon

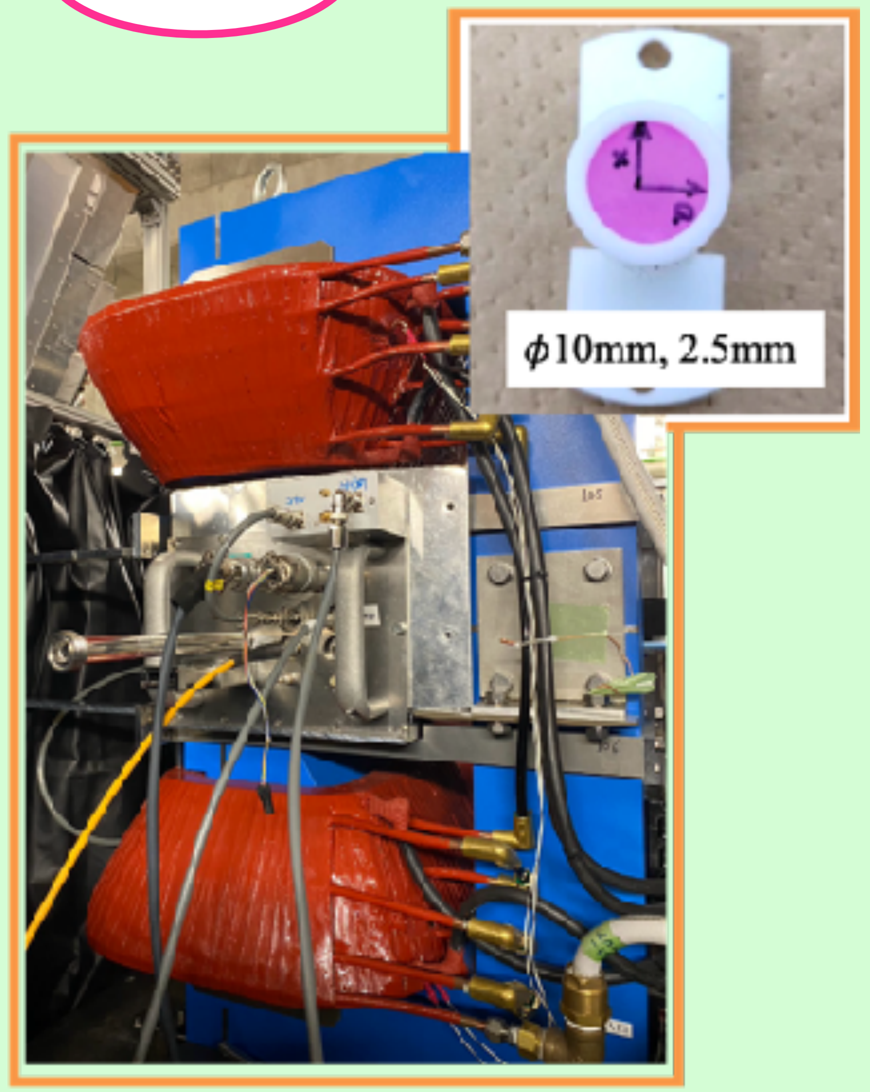
pd and *nd* Elastic Scattering at 65–400 MeV/nucleon



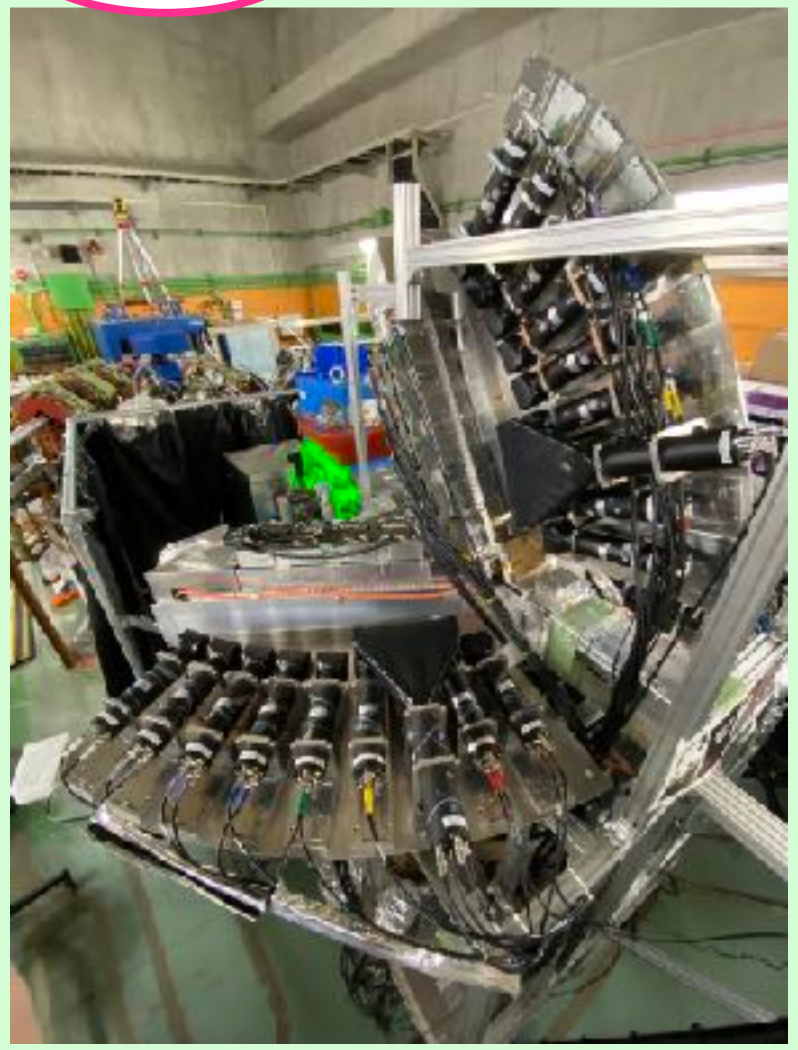
- for investigation of N4LO 3NFs
  - determination of LECs of N4LO 3NFs from *dp* scattering data
- Observables to be measured : $C_{y,y}$, $C_{x,x}$, $C_{z,x}$, $C_{xx,y}$, $C_{yy,y}$, $C_{xz,y}$, $C_{yz,x}$, $C_{xy,x}$

pol.d beam + pol.p solid target + KuJyaku detector

New!



New!



Sensitivities of the LEC (C_{Ei}) in N4LO 3NFs

Yuko Saito, Ph.D. thesis (2025)

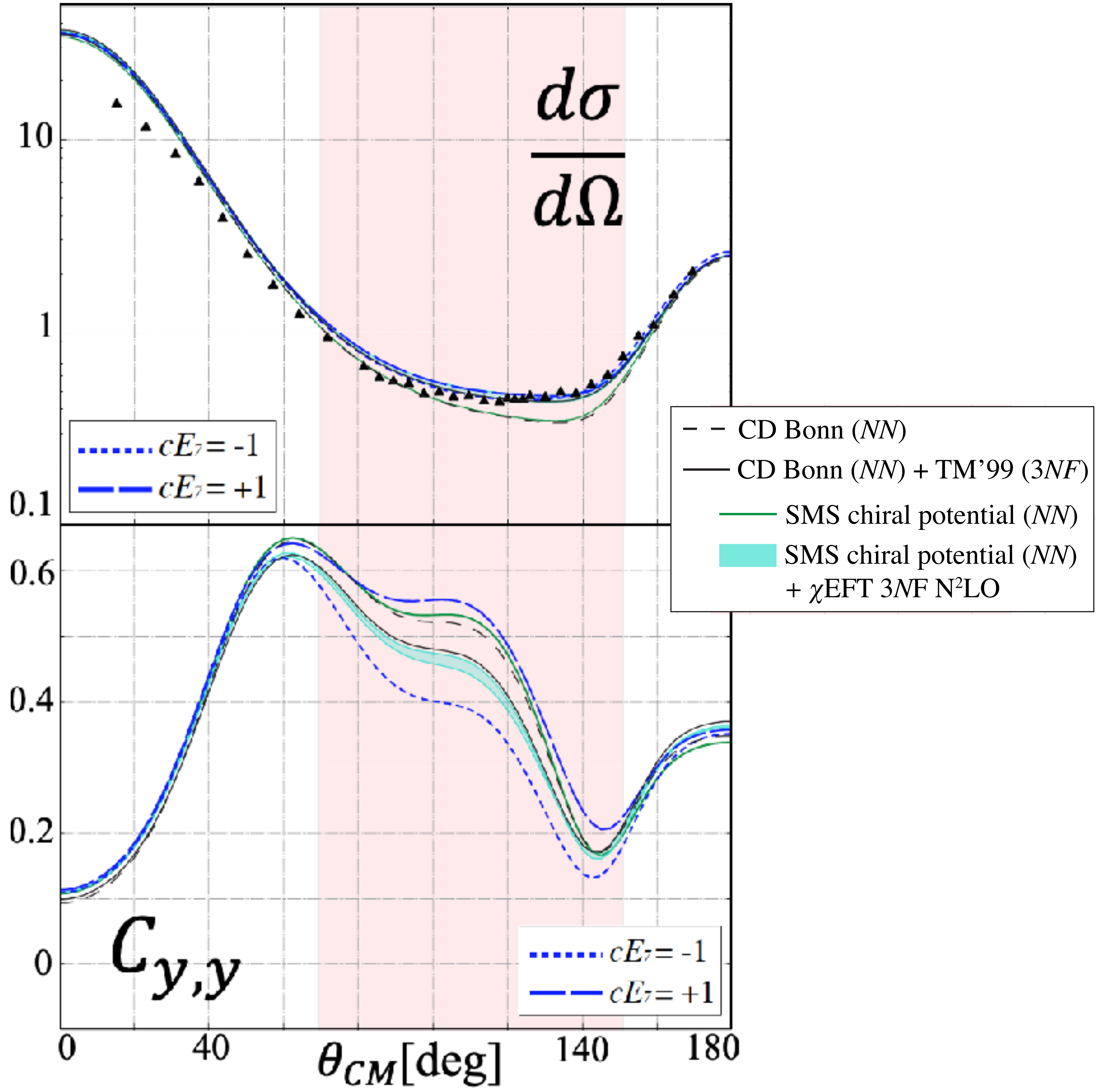
Investigations on ***d*-*p*** elastic scattering
to determine the LECs (c_{E_i}) in χEFT's 3*N*F N[4]LO
→ Collaboration of experimental and theoretical approaches

$c_{E_1}, c_{E_7}, c_{E_5}$:

- significant effect (0.1-0.2) from LECs
  for <u>multiple spin observables</u> at $\theta_{CM} = 70°\text{-}140°$
  → effective for determining the c_{E_i}

❖ while a specific constant c_{E_i} may explain data for one observable at certain angles, it does not necessarily do so for others.

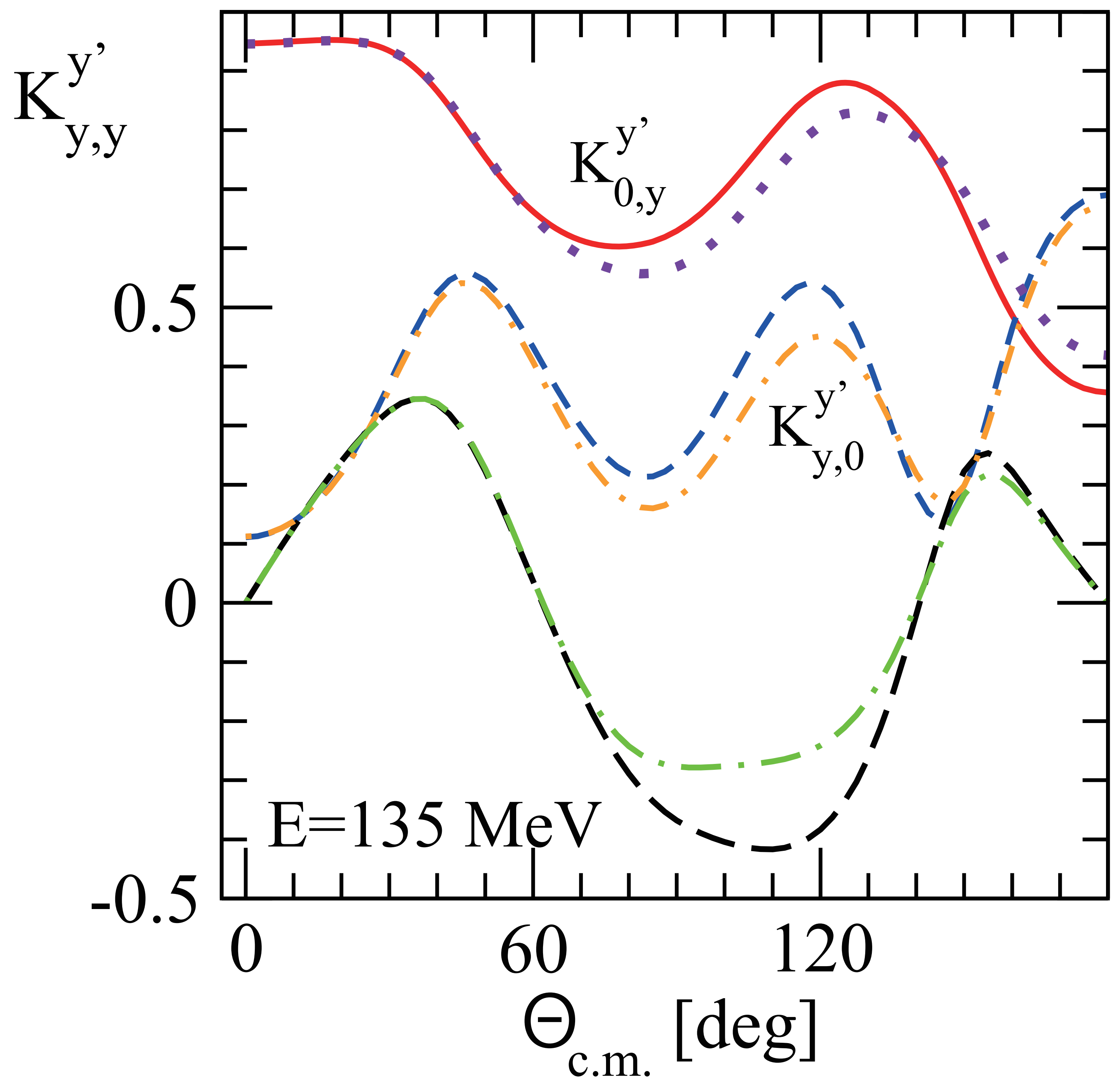
high-precision data from <u>multiple spin observables</u>
in ***d*-*p*** elastic scattering
→ essential to determine 11 c_{E_i}

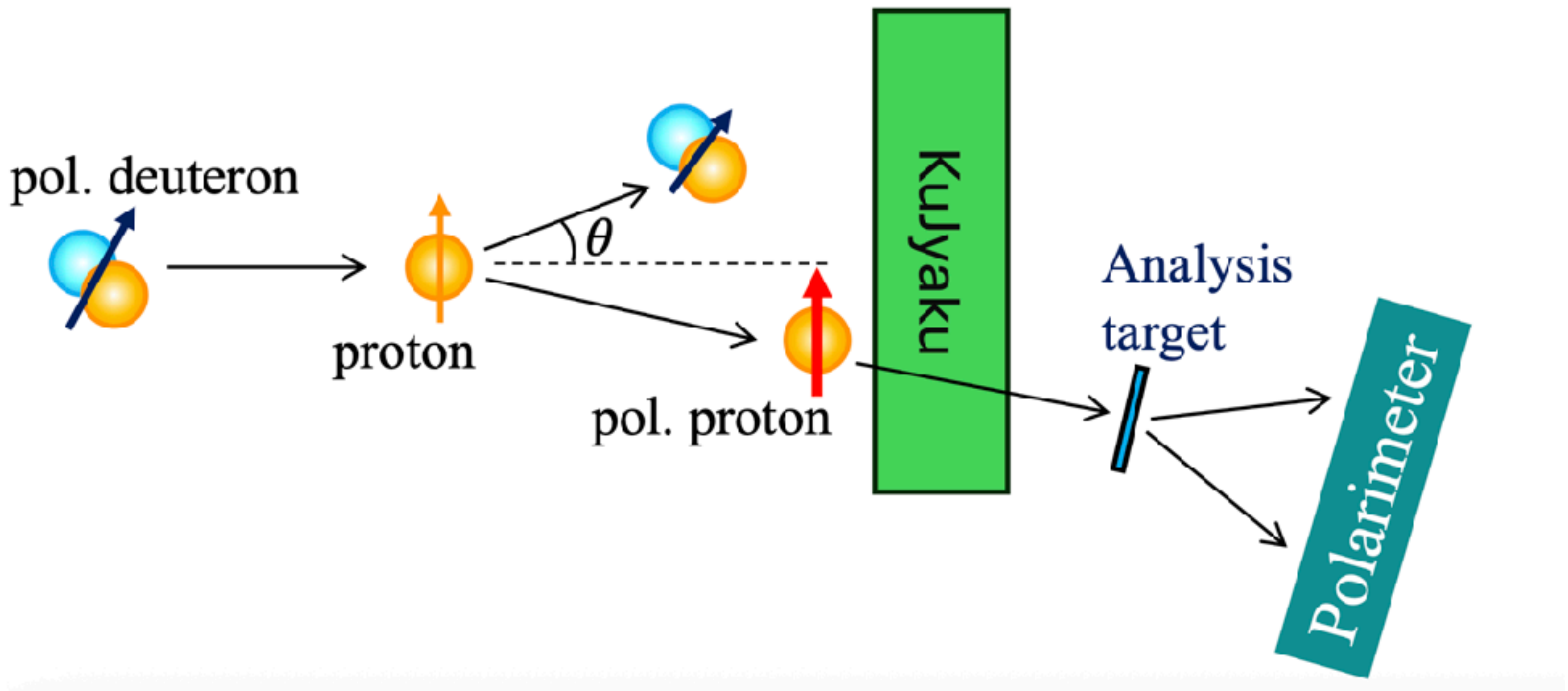


Further step

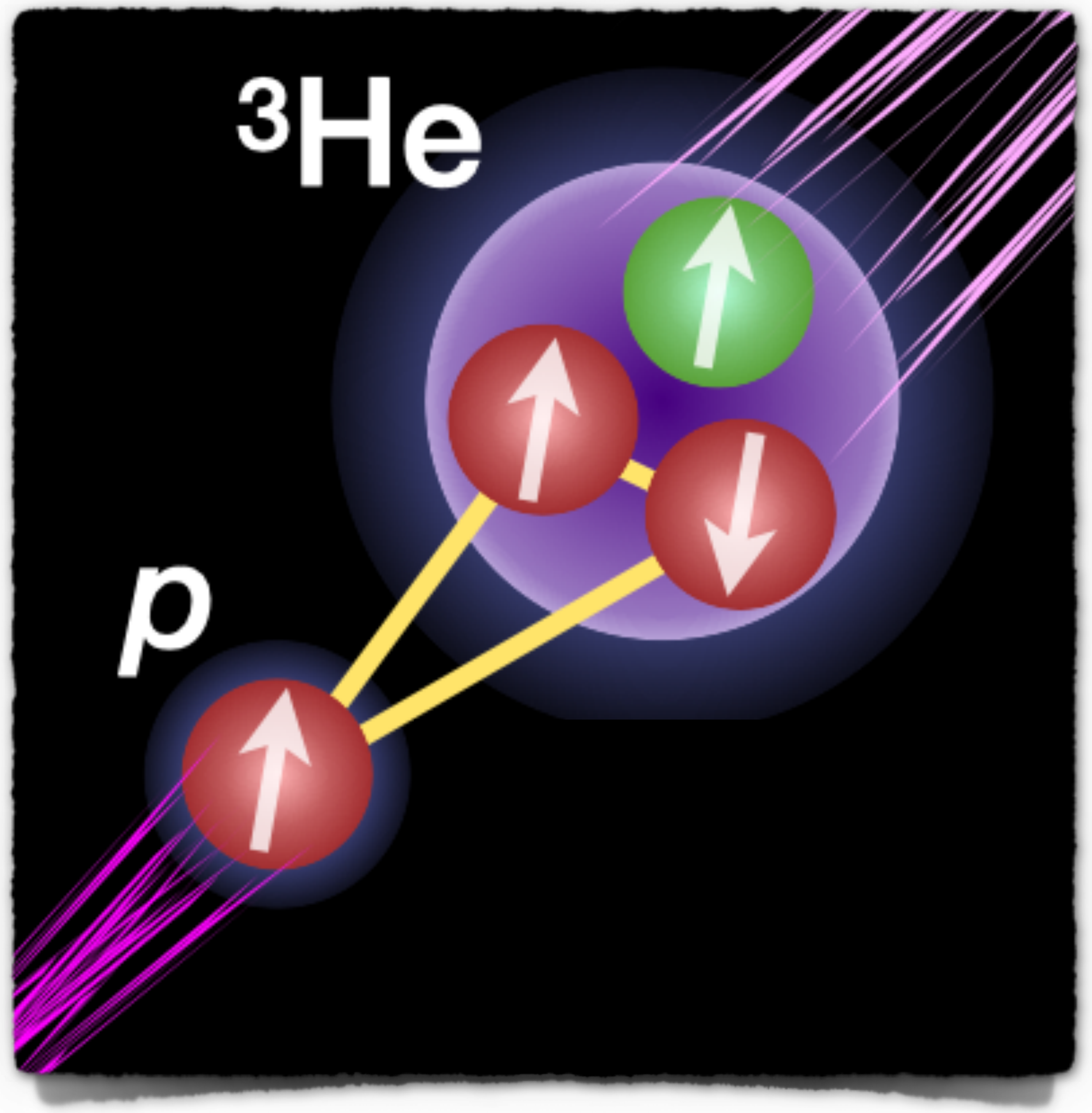
H. Witala, J. Golak, R. Skbinski, H. Sakai, K.S , Phys. Rev. C 111, 044003(2025)

- Double Spin Polarization Observables are very sensitive to 3NFs.





p-^{3}He scattering

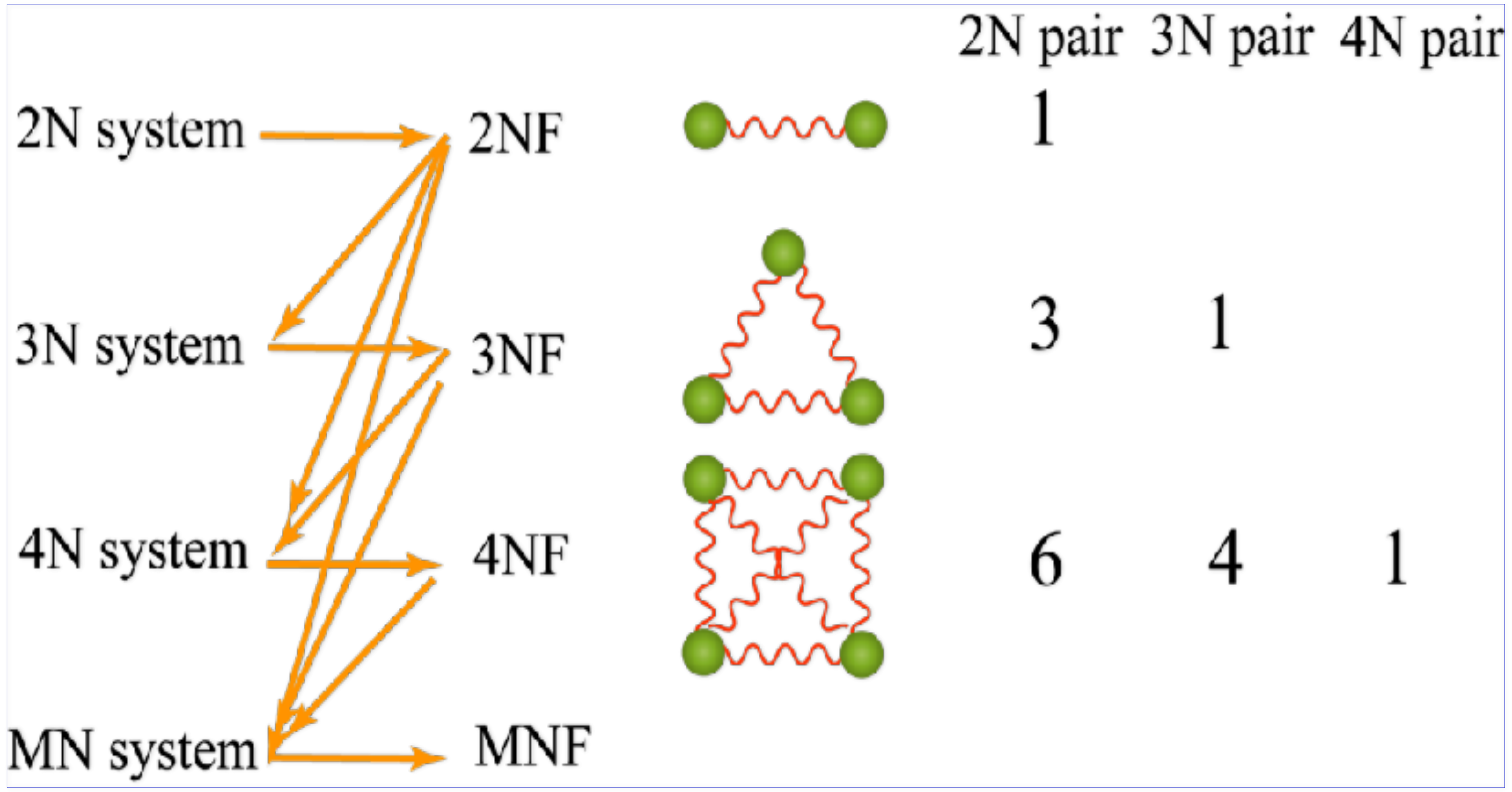


- Approach iso-spin dependence of 3NFs
  - T=3/2 3NFs

    for neutron-rich nuclei, neutron star

- 4-nucleon scattering
  - First Step from Few to Many
  - Larger effects of 3NFs ?

- 4NF effects



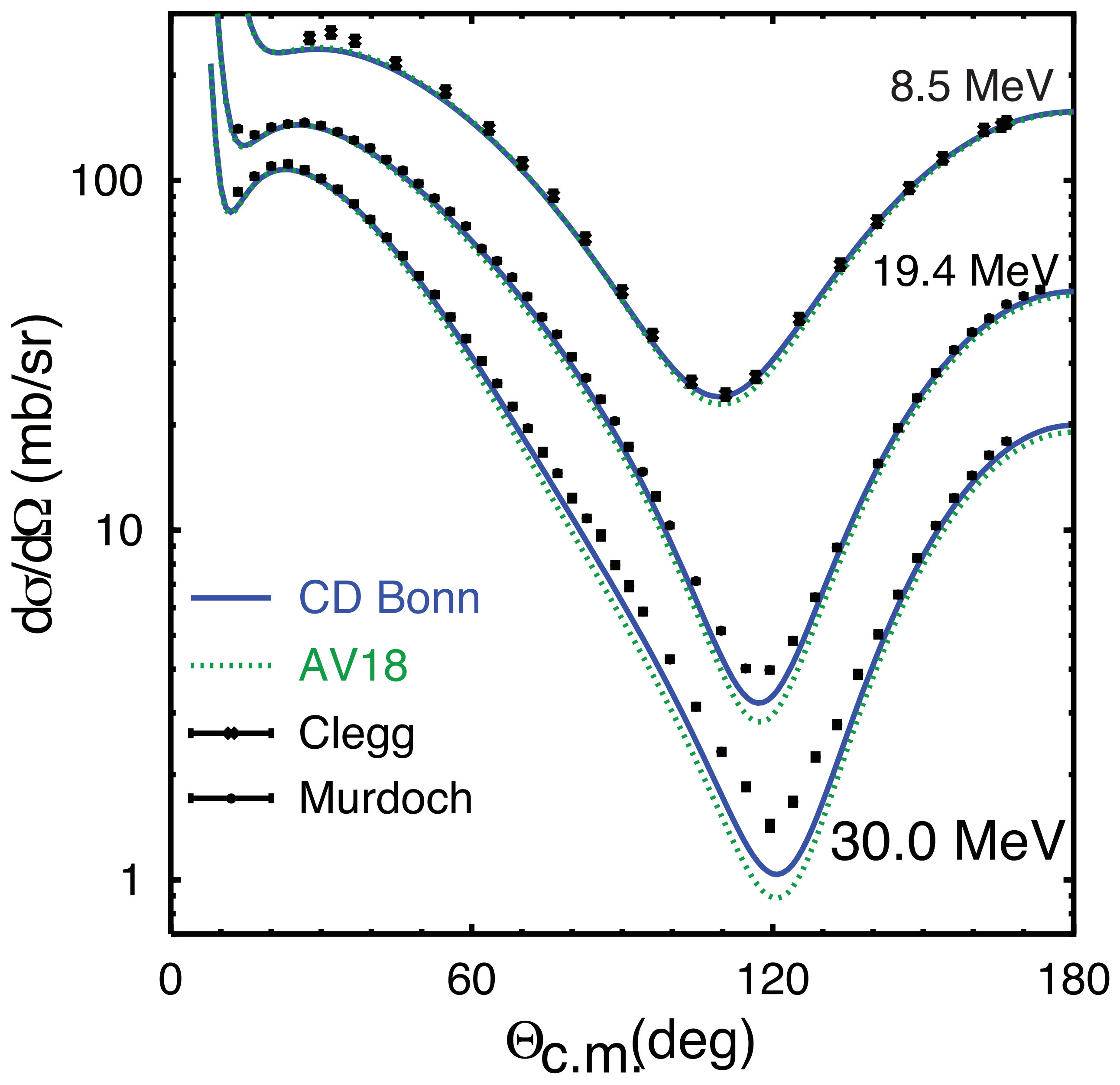
p-^{3}He scattering

Theory in Progress

Calculations above 4-nucleon breakup threshold energy
open new possibilities of 3NF study in 4N-scattering.

up to 35 MeV

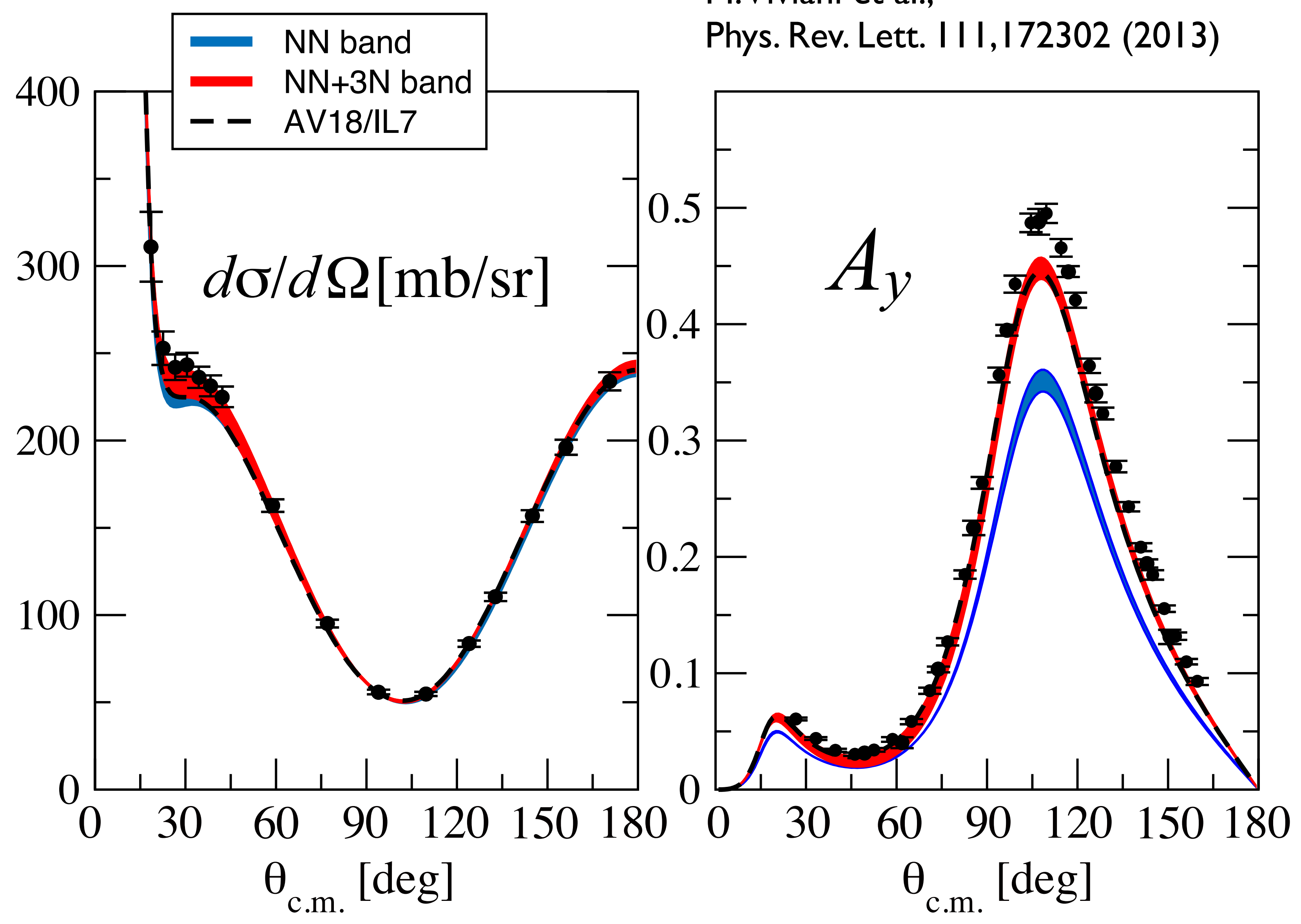
A. Deltuva and A.C. Fonseca
Phys. Rev. C 87, 054002 (2013)



Discrepancies in cross section minimum at higher energies
New rooms for 3NF study

at 5.54 MeV

M.Viviani et al.,
Phys. Rev. Lett. 111,172302 (2013)

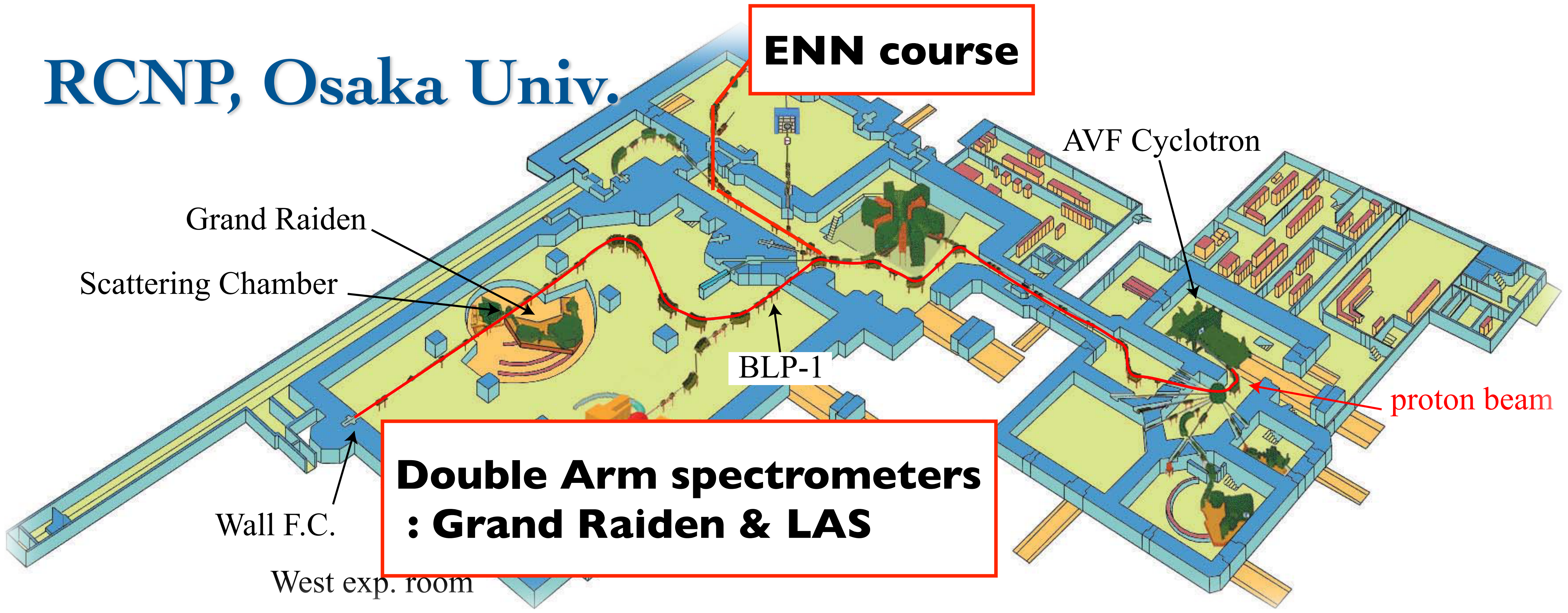


- No signature of 3NFs in cross section
- *Ay(p)* puzzle : 3NFs sensitive to p-shell nuclei improve the agreement to the data.

How about spin observables at higher energy?

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

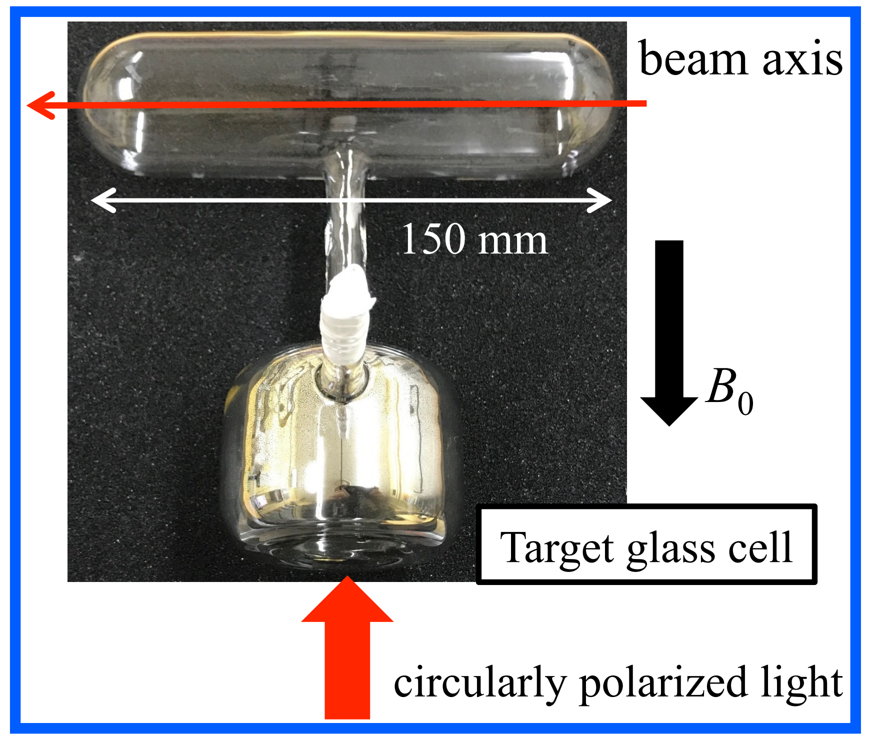
RCNP, Osaka Univ.

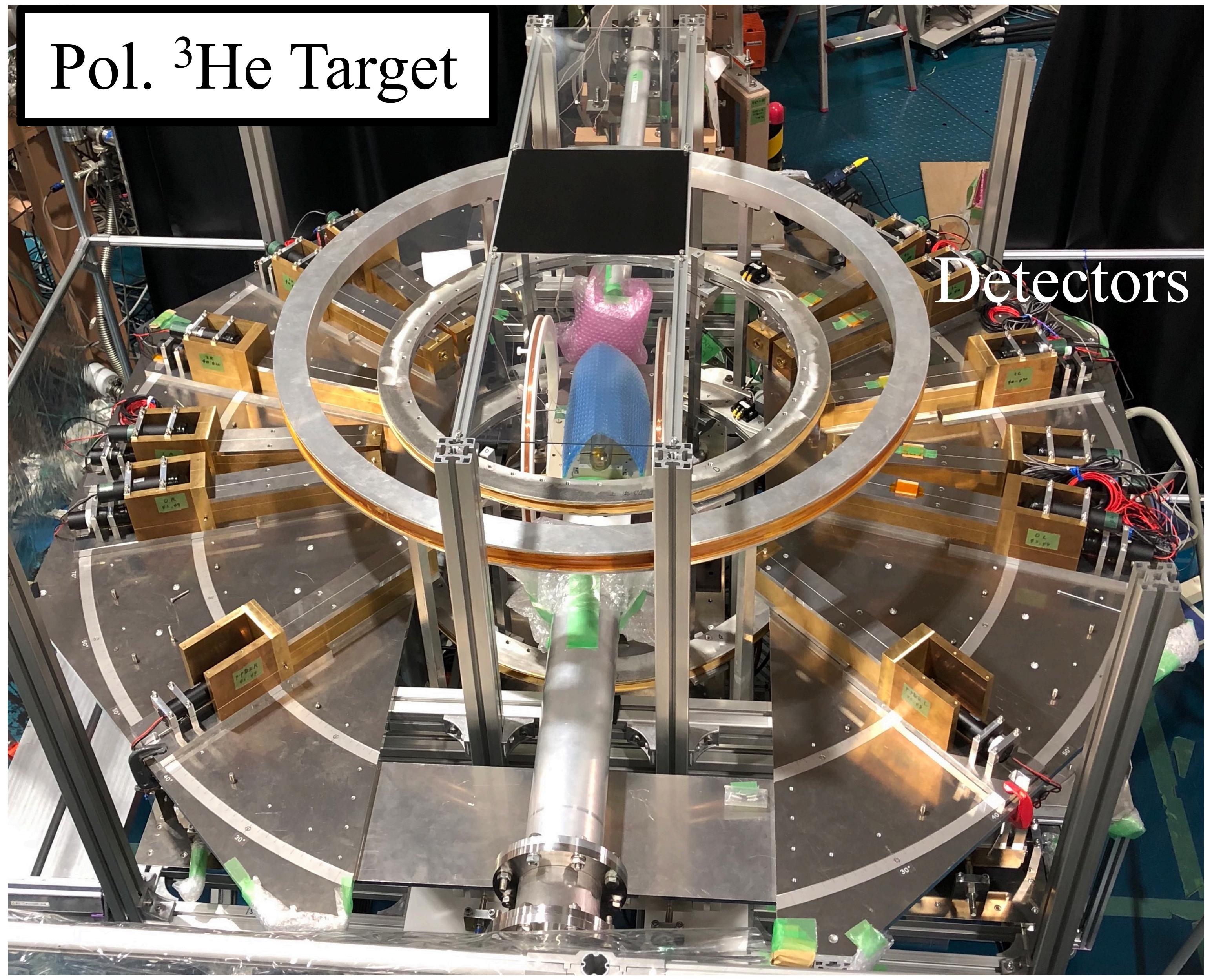


RARiS, Tohoku Univ.

- Pol.^{3}He gas target
  : Alkali-Hybrid SEOP type

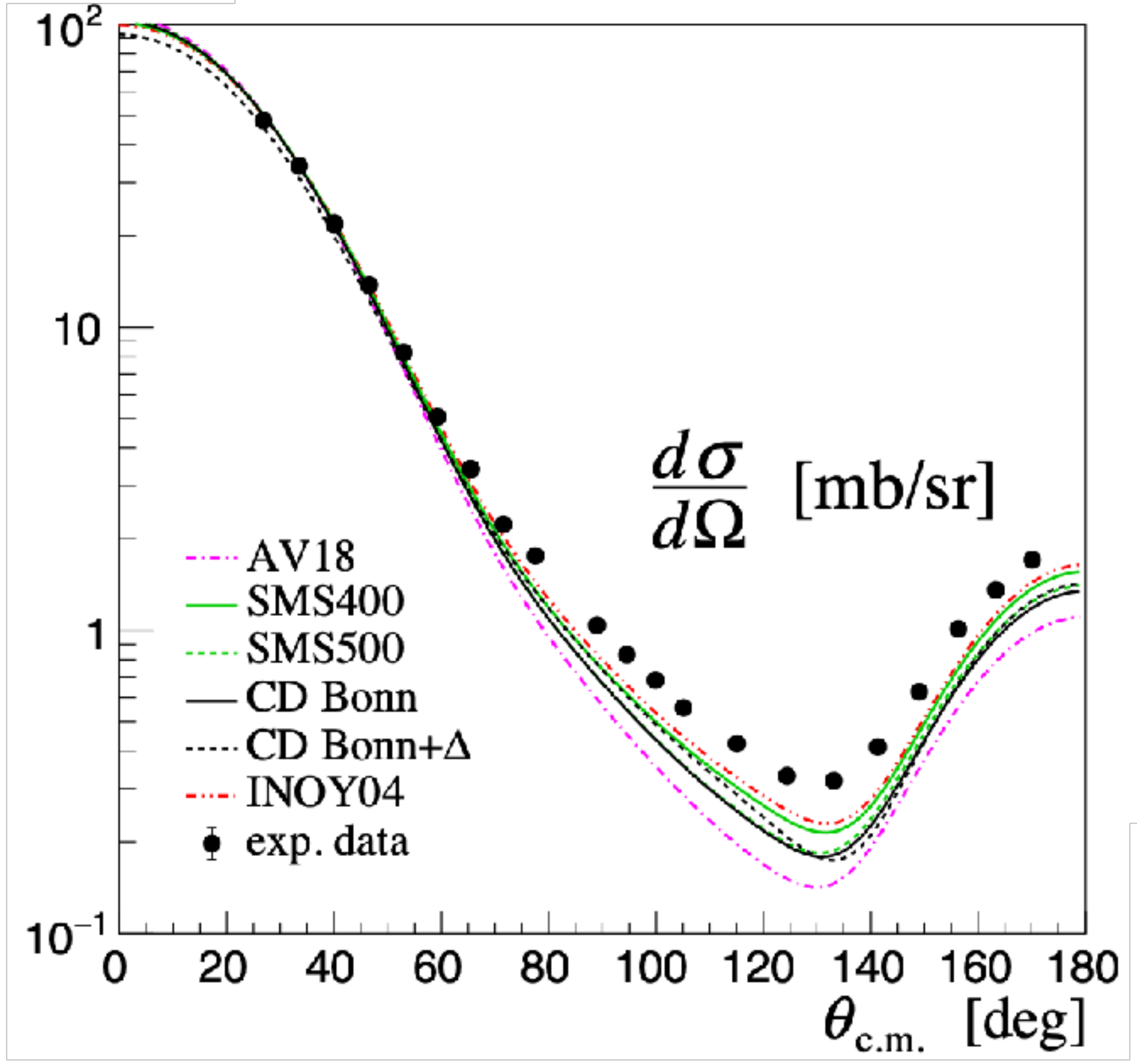
  polarization : 30-40% as of 2018
  (beam on target)



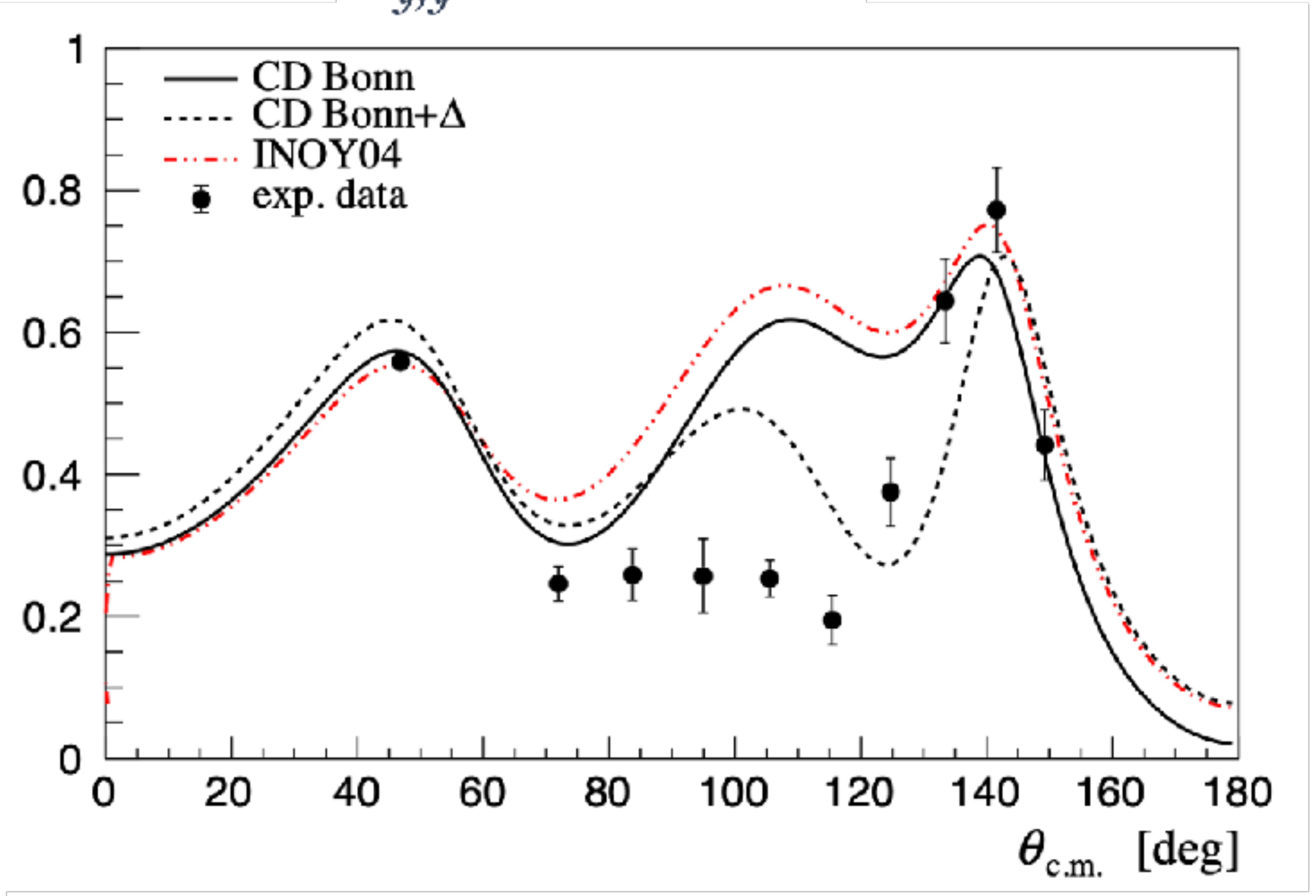


New Data of p+^{3}He at Intermediate Energies

Cross Section at 65 MeV

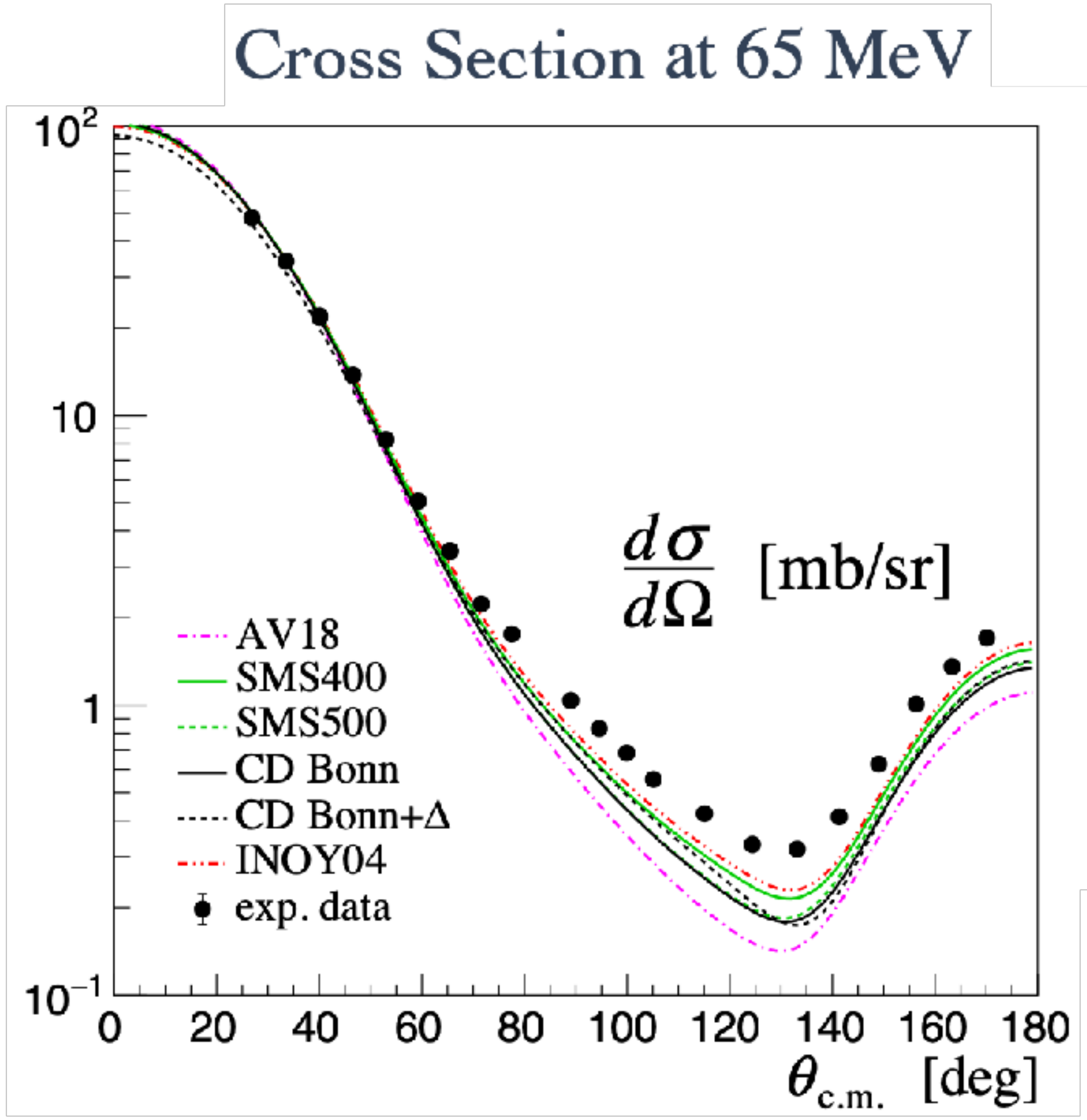


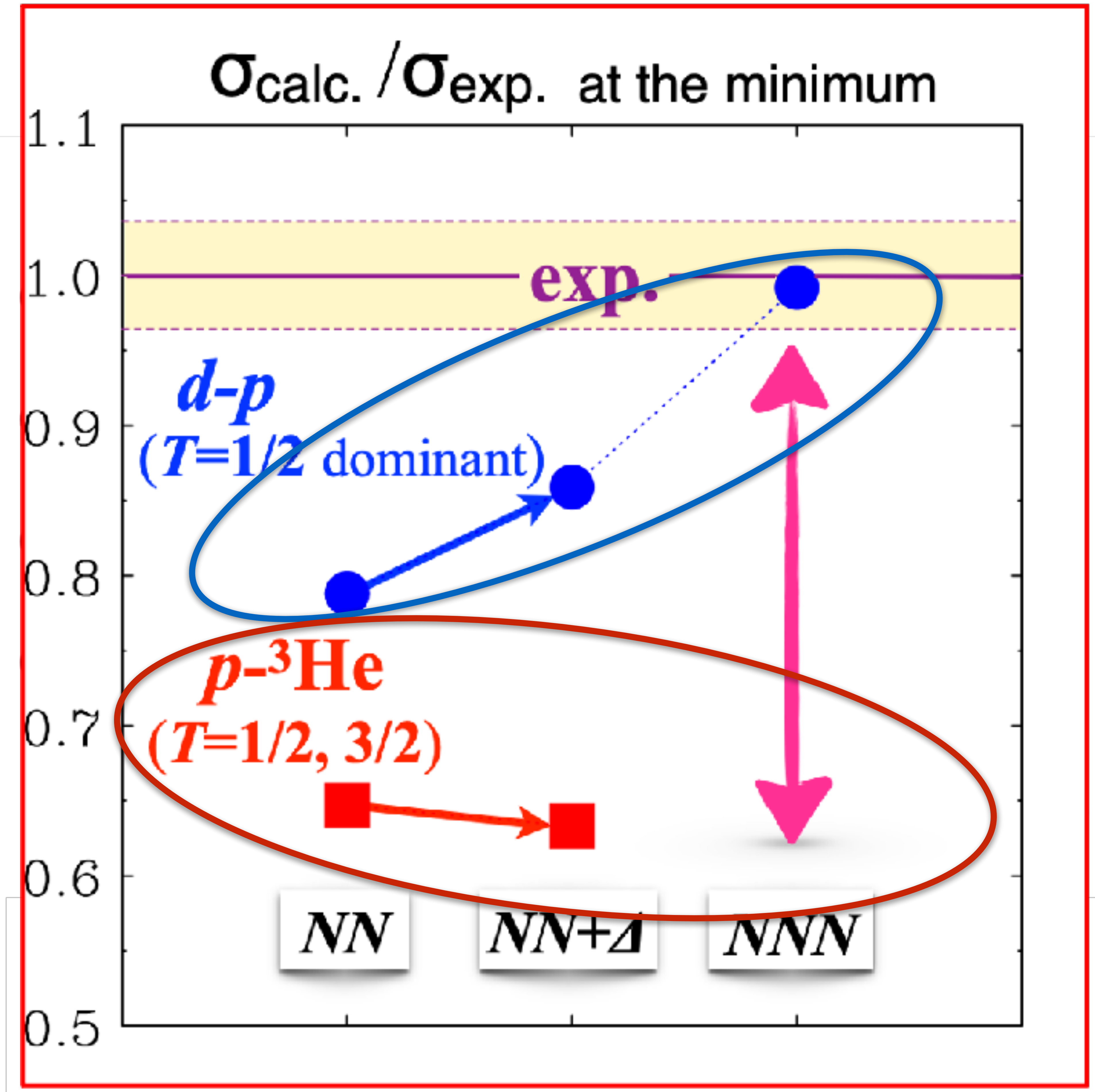
$C_{y,y}$ at 100 MeV



A.Watanabe et al., Phys. Rev. C 103, 044001 (2021)
A.Watanabe et al., Phys. Rev. C 106, 054002 (2022)

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





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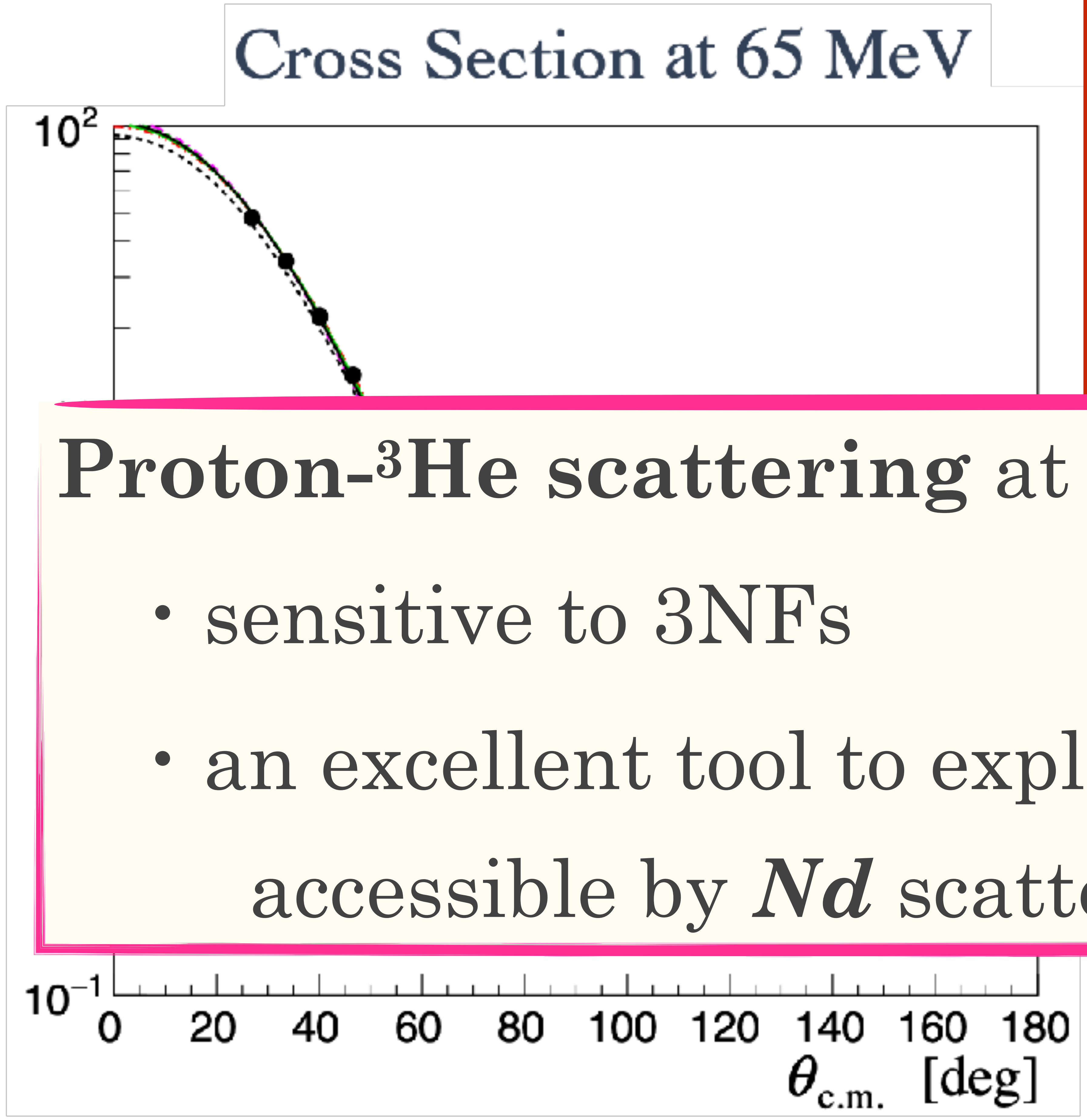
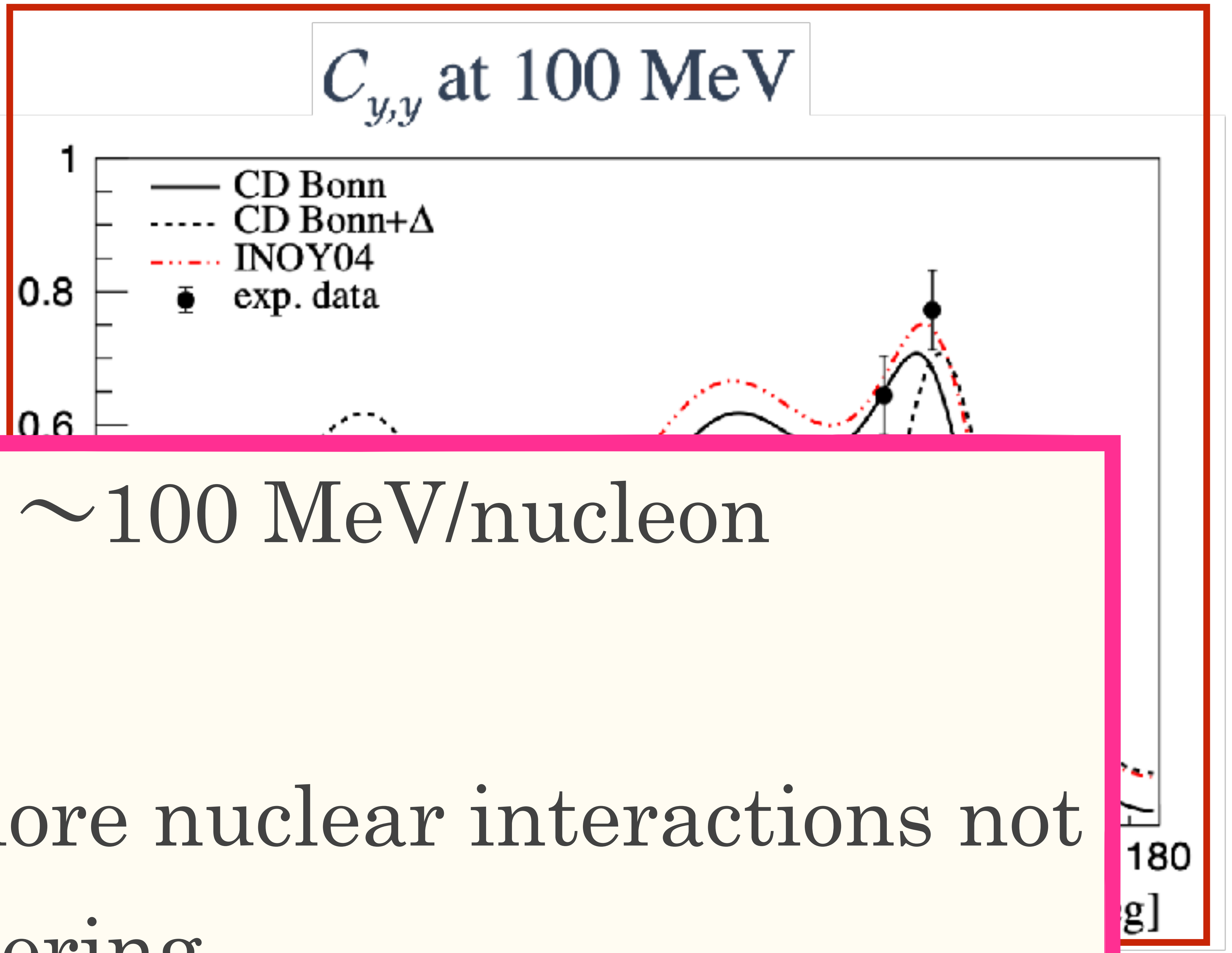




Proton-^{3}He scattering at ∼100 MeV/nucleon

- sensitive to 3NFs
- an excellent tool to explore nuclear interactions not accessible by ***Nd*** scattering

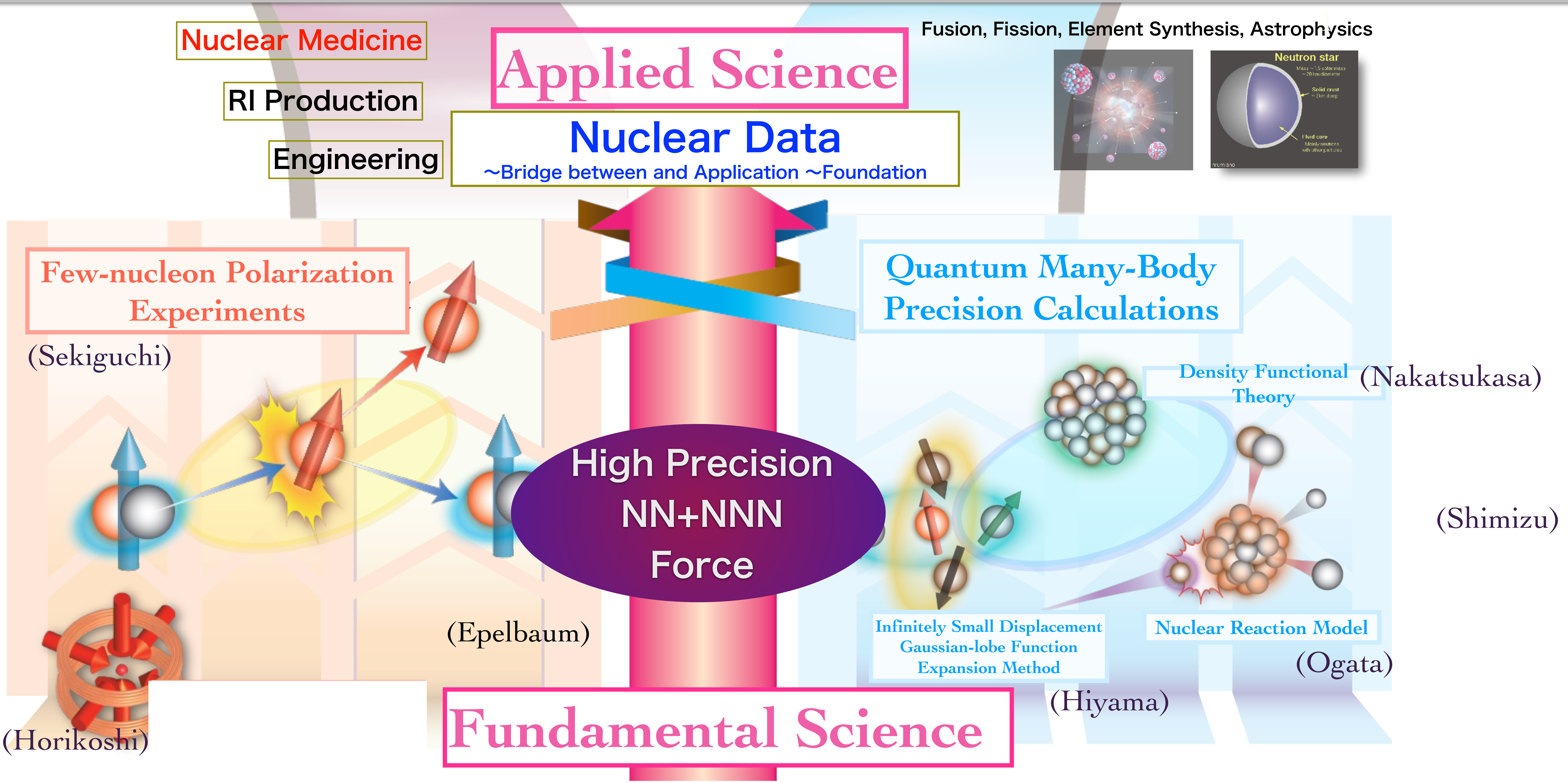
A.Watanabe et al., Phys. Rev. C 103, 044001 (2021)
A.Watanabe et al., Phys. Rev. C 106, 054002 (2022)

Japan Science and Technology Agency

TOMOE

ERATO Three-Nucleon Force Project

Term Oct. 2023-Mar.2029



Summary (1/2)

Three-Nucleon Forces

are key elements to fully understand nuclear properties.
e.g. nuclear binding energies, EOS of nuclear matter

Few-Nucleon Scattering

is a good probe to investigate the dynamics of 3NFs.
- Momentum, Spin & Iso-spin dependence - .

Nucleon-Deuteron Scattering - 3N Scattering -

Precise data of $d\sigma/d\Omega$ and spin observables at 70- 300 MeV/nucleon

Cross Sections : Large discrepancy at backward angles. 3NFs are clearly needed.

Spin Observables : 3NF effects are spin dependent.

Serious discrepancy at backward angles at higher energies : short-range terms of 3NFs ?

Cross section minimum region at around 100 MeV : Golden windows for χEFT 3NFs

Summary (2/2)

Proton-^{3}He Scattering - 4N Scattering -

- Approach to Iso-spin states of T=3/2 3NF
- Rigorous numerical calculations : New possibilities for 3NF study in 4N Scatt.

New Data from CYRIC & RCNP : ^{3}He & p Analyzing powers, & Spin Correlation Coefficient

Cross section minimum region at higher energies : Source of rich information of 3NFs

Spin correlation coefficient : Very sensitive to dynamics of Nuclear forces

New Project in Japan : TOMOE

- High precision 3NFs from Few-Nucleon Experiments & χEFT Nuclear forces
  - Measurement of spin correlation coefficients at 100 MeV/nucleon for investigation of N4LO 3NFs.
  - Determination of LECs N4LO 3NFs from dp scattering data

- Descriptions of various nuclear phenomena based on High precision NN+NNN

RIBF-*d*. Collaboration

RIKEN Nishina Center

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M. Sasano, Y. Shimizu, K. Tateishi

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Department of Physics, Tohoku University

Y. Wada, D. Eto, T. Akieda, H. Kon,
J. Miyazaki, T. Taguchi, U. Gebauer, K. Takahashi, T. Mashiko, K. Miki,
Y. Maruta, T. Matsui, K. Kameya, R. Urayama

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J. Yasuda, A. Ohkura, S. Shindo, U. Tabata, K. Aradono,
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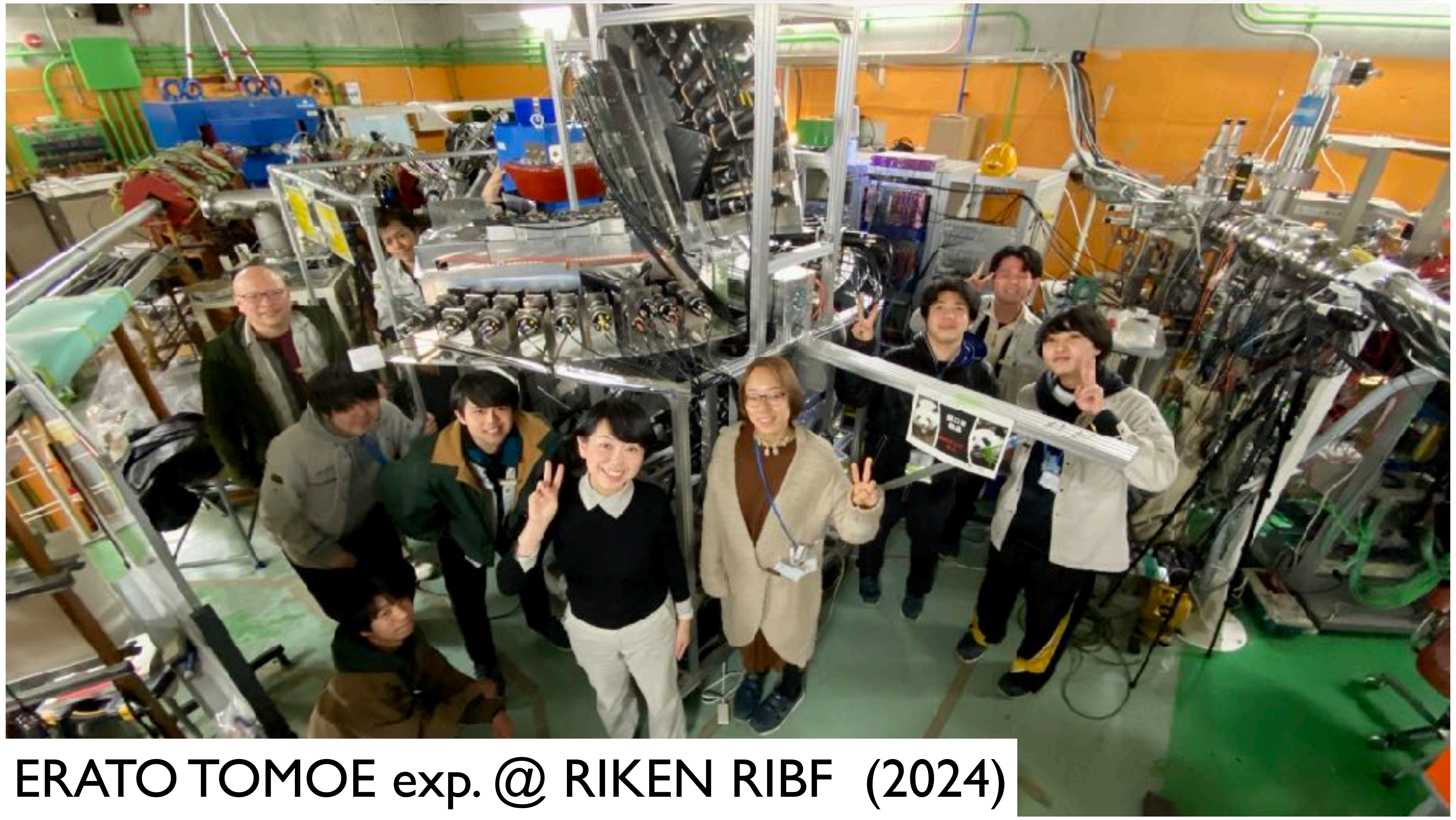
H. Okamura

Kyungpook National University

S. Chebotaryov, E. Milman


RIKEN RIBF (2009)


ERATO TOMOE exp. @ RIKEN RIBF (2024)

p-^{3}He Collaboration

Department of Physics, Tohoku University
K. Sekiguchi, Y. Wada, Y. Shiokawa, A. Watanabe, S. Nakai, K. Miki,
T. Mukai, S. Shibuya, M. Watanabe, K. Kawahara, D. Sakai,
T. Taguchi, D. Eto, T. Akieda, H. Kon, M. Inoue, Y. Utsuki

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N. Kobayashi, A. Inoue, S. Nakamura, D. T. Tran

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H. Kasahara, S. Mitsumoto, H. Oshiro

Miyazaki University
Y. Maeda, K. Nonaka

RIKEN Nishina Center
H. Sakai

RIKEN RANS
Y. Otake, A. Taketani, Y. Wakabayashi

NIRS
T. Wakui

Experiment at CYRIC, Tohoku Univ. (2016)

Experiment at RCNP, Osaka Univ. (2018)

Theoretical Supports from

Ruhr-Universität, Bochum

E. Epelbaum, H. Krebs, A. Filin, S. Heihoff, J. Sola Cava, P. Walkowiak
(Maybe I miss some colleagues…)
W. Glöckle

Jagellonian University

H. Witała, J. Golak, R. Skibinski

Kyushu Institute of Technology

H. Kamada

Forshungszentrum of Jülich

A. Nogga

Vilnius University

A. Deltuva

Hannover University

P. U. Sauer, S. Nemoto

Lisbon University

A. Sa. Fonseca

Hosei University

S. Ishikawa

Bad Honnef (2006)

Bochum (2024)