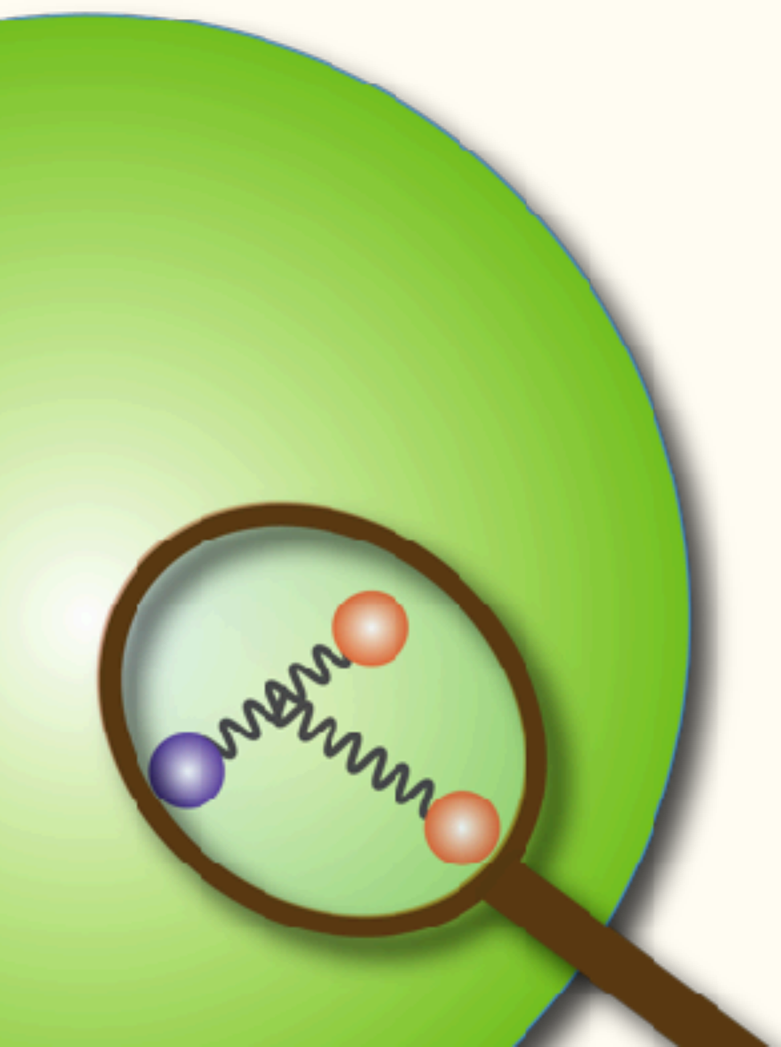
東京工業大学
Tokyo Institute of Technology

Experiment of Few-Nucleon Scattering to Explore Three-Nucleon Forces



Tokyo Institute of Technology

Kimiko Sekiguchi

25 EFB

August 3rd, 2023

Three-Nucleon Force (3NF)

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

Key to fully understand properties of nucleus

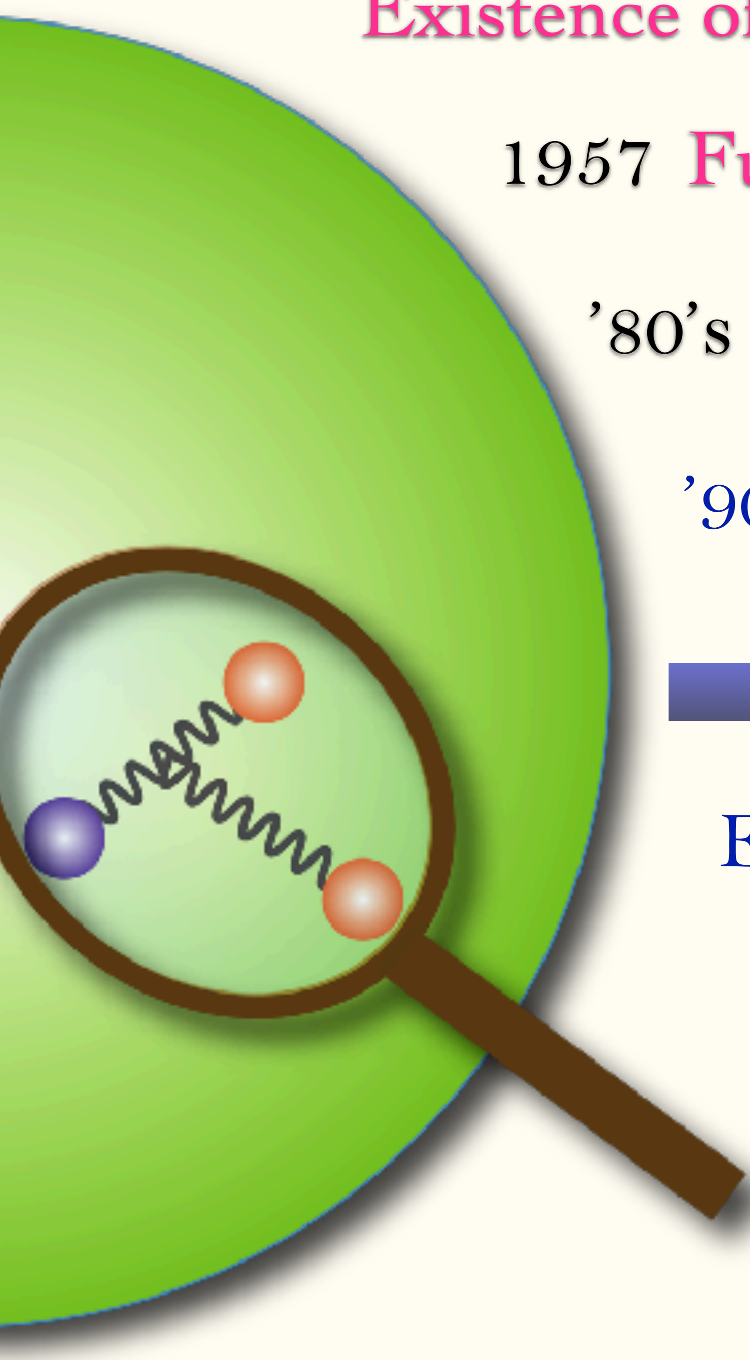
Existence of 3NF was predicted in 1930's (after Yukawa's meson theory).

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

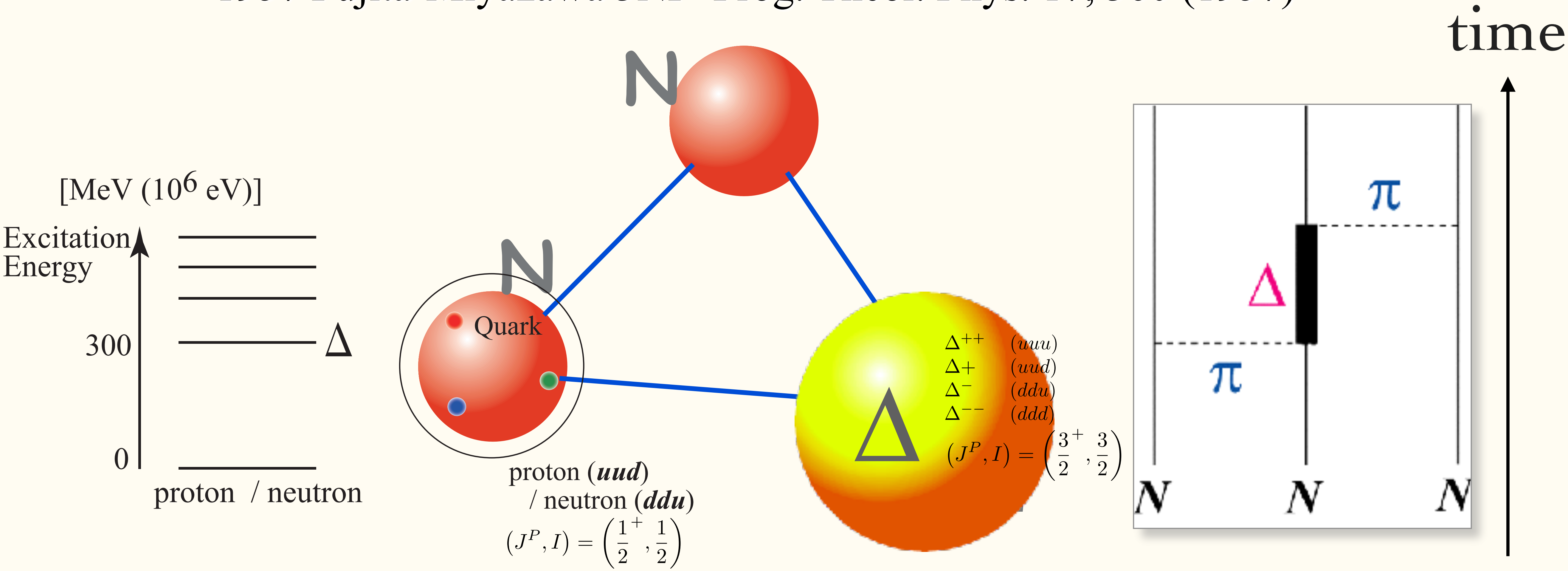
- Nucleon-Deuteron Scattering at Intermediate Energies
- Biding Energies / Levels of Light Mass Nuclei
- Equation of State of Nuclear Matter

etc ...

Three-Nucleon Force

- **2π-exchange 3NF :**
  - **Main Ingredients : Δ-isobar excitations in the intermediate**

    1957 Fujita-Miyazawa 3NF Prog. Theor. Phys. 17, 360 (1957)



3NF naturally arises due to the inner structure of Nucleon.

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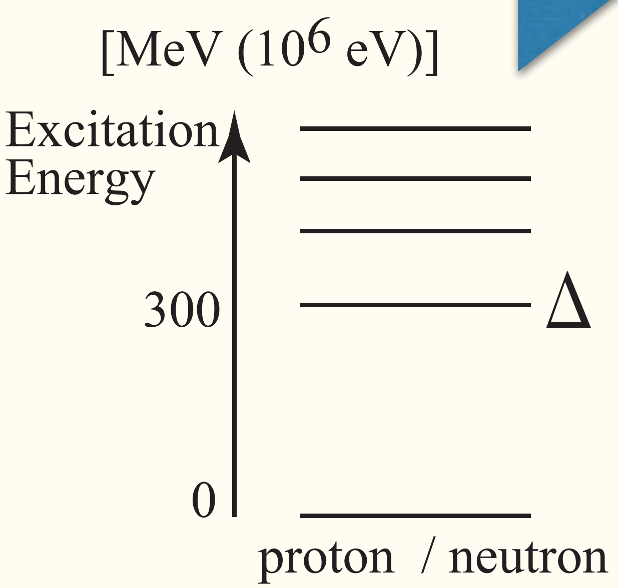
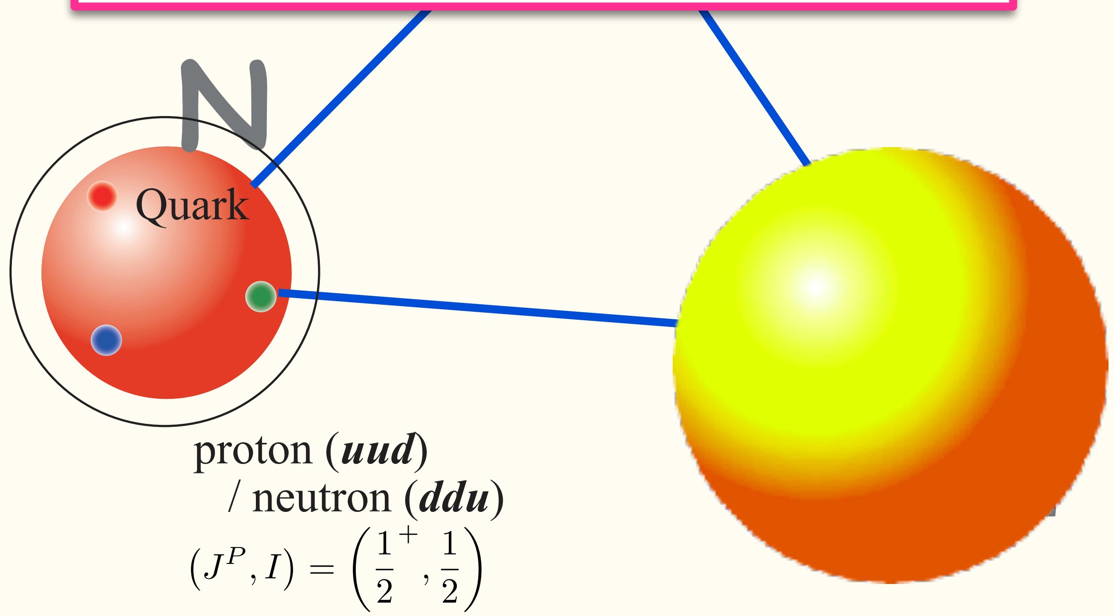
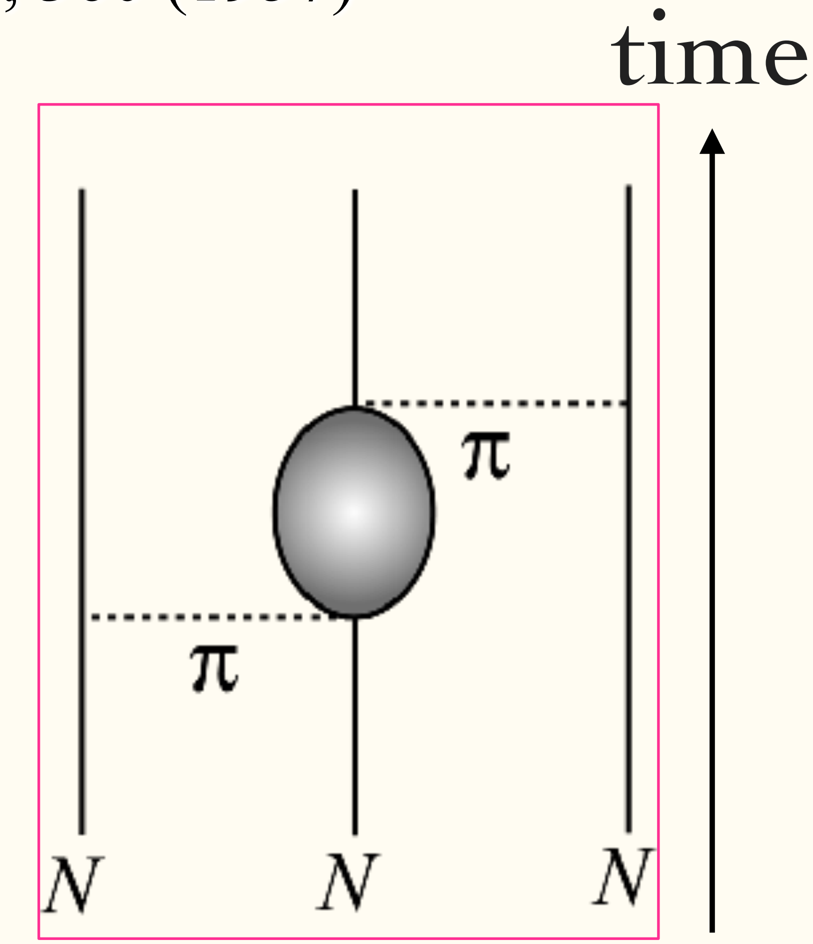
- Tucson-Melbourne (TM)
- Urbana IX
- Brazil, Texas etc…







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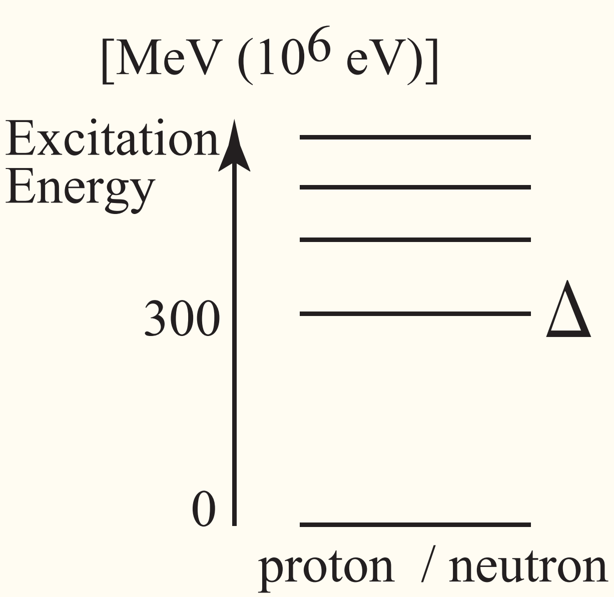
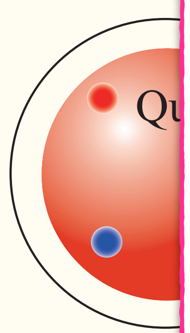
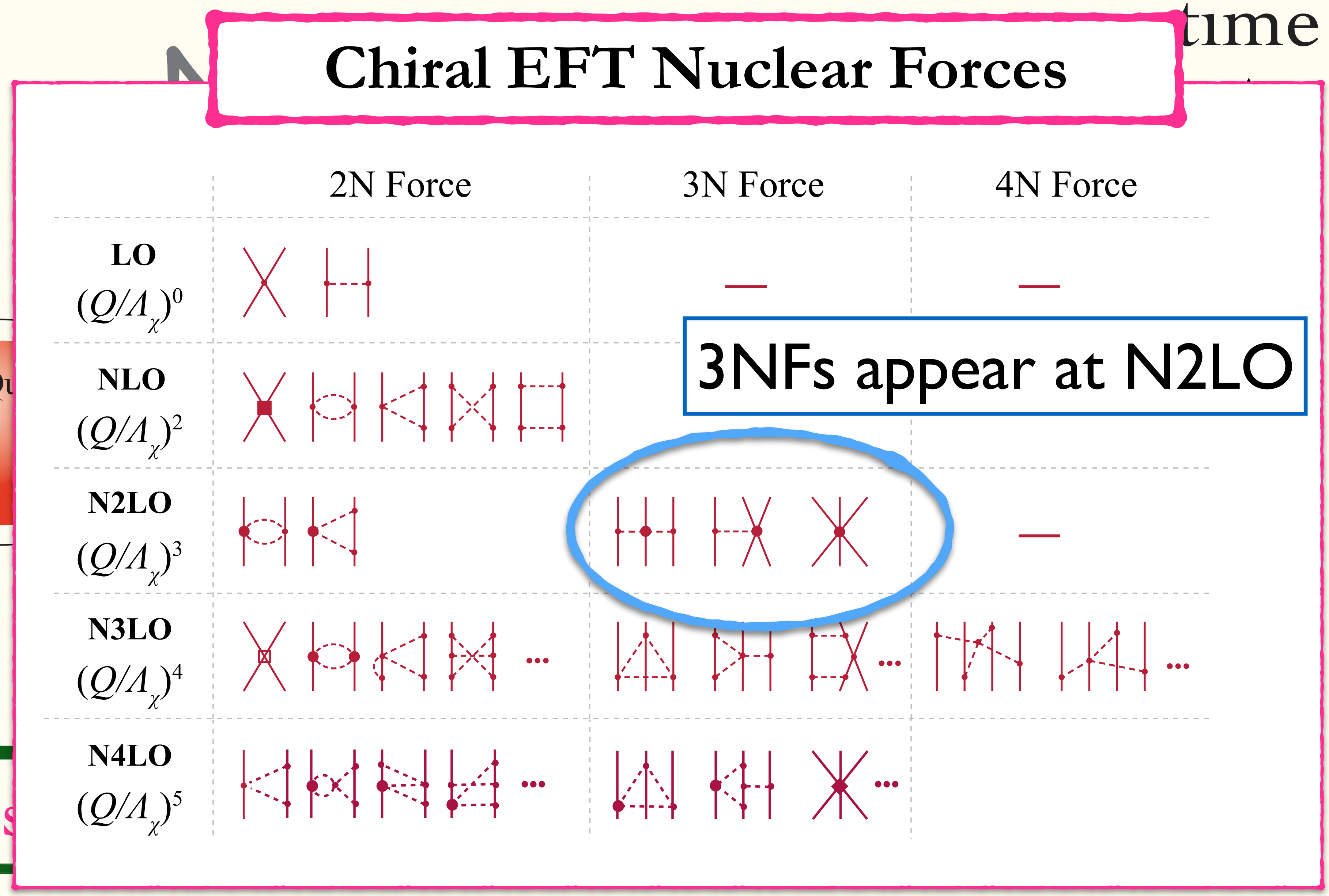
time



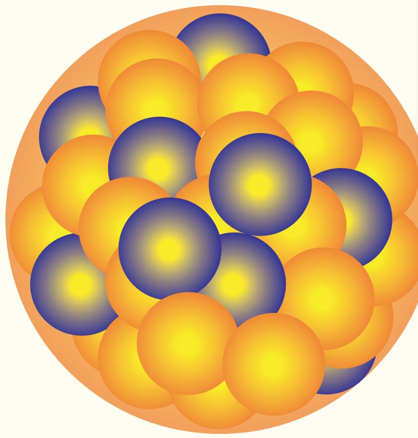




3NF naturally aris

Where ?

3NFs in A>3 - ① -



3NFs in Finite Nuclei

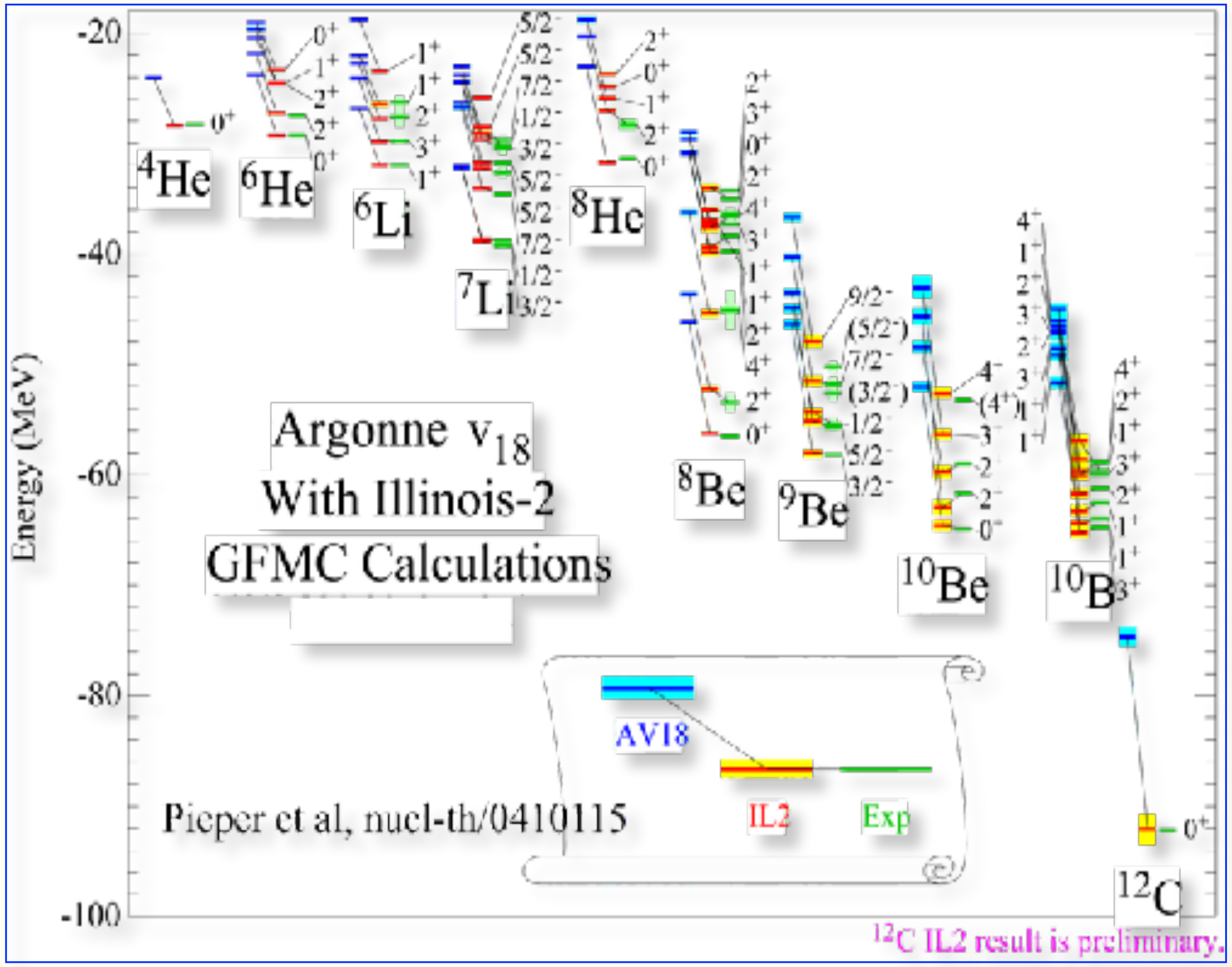
Ab Initio Calculations for Light Nuclei ($A \lesssim 12$) : ^{4}He to ^{12}C

- Green's Function Monte Carlo
- No-Core Shell Model etc..
    - 2NF provide less binding energies
    - 3NF : well reproduce the data

      IL2 3NF (Illinois-II 3NF) :

      2π-exchange 3NF

      + 3π-ring with Δ-isobar



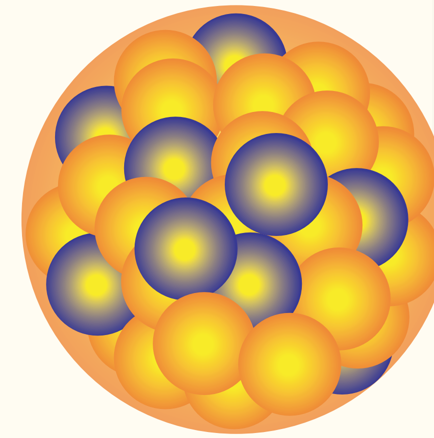
3NF effects in B.E.

- 10-25%
- Attractive

Note :

T=3/2 3NFs (three-neutron force) play important roles to explain B.E. in neutron rich nuclei.

3NFs in A>3 - ① -



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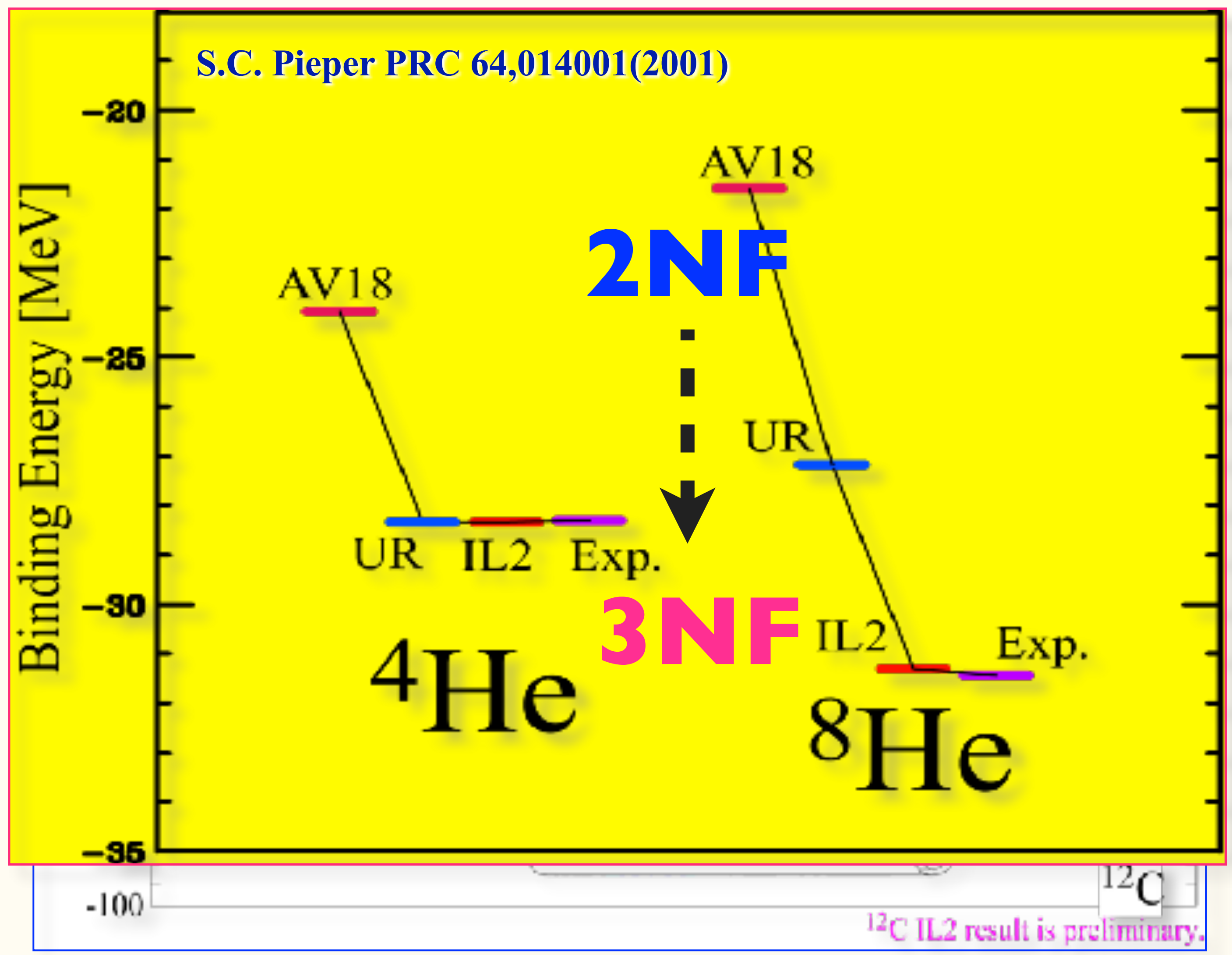

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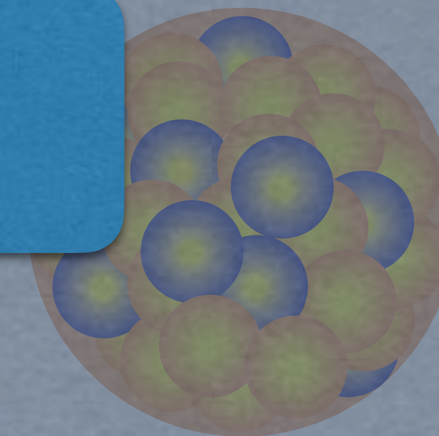


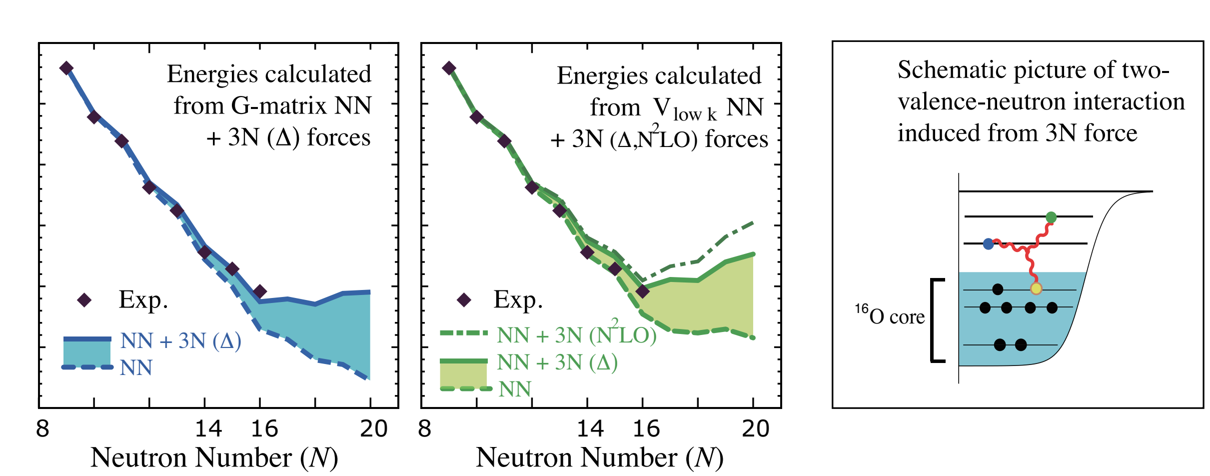
3NFs in Finite Nuclei

Ab Initio Calculations for Light Nuclei $(A \lesssim 12)$: ^{4}He to ^{12}C

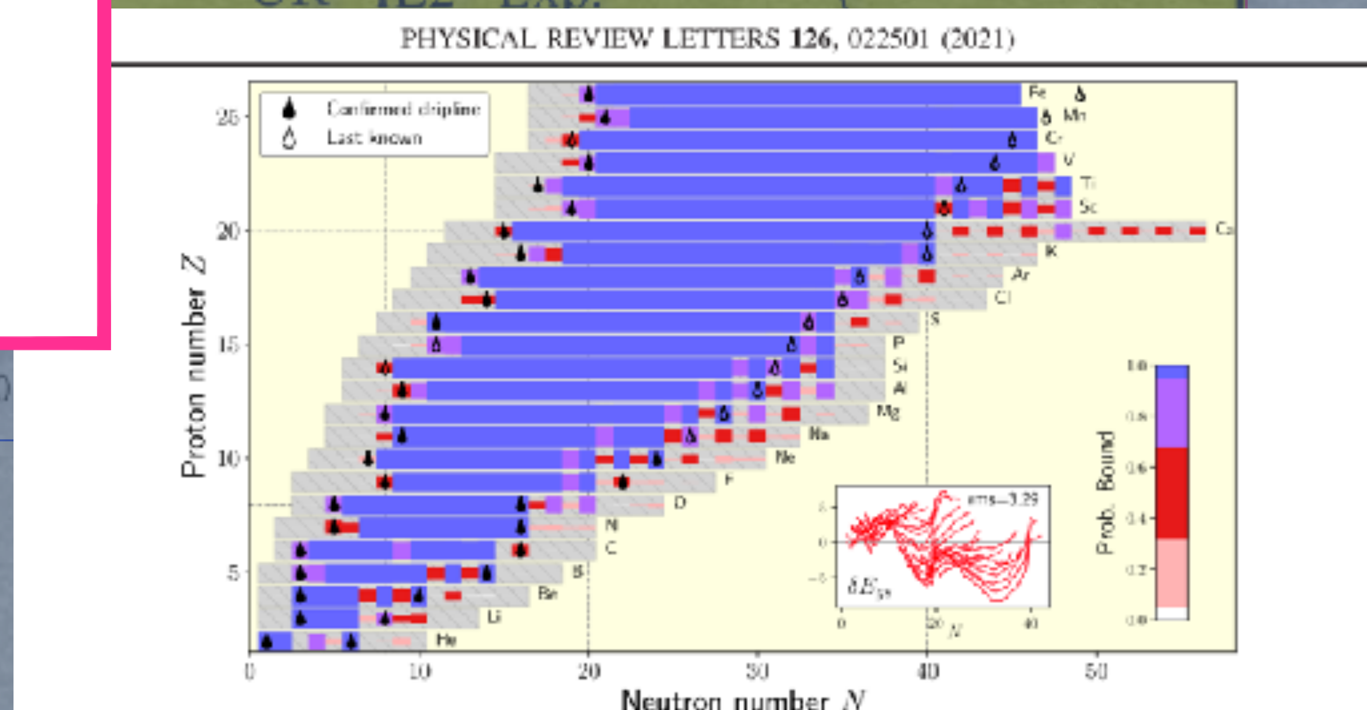
- Green's Function M... e Carlo
- No-Core Shell M... ..

Medium Mass Nuclei

3NFs provide key mechanisms,
e.g. shell-evolution,
boundaries of nuclear stability.



Otsuka et al.,Phys. Rev. Lett. 105, 032501 (2010)



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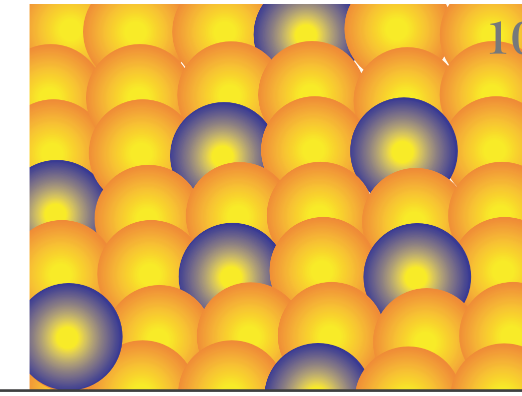
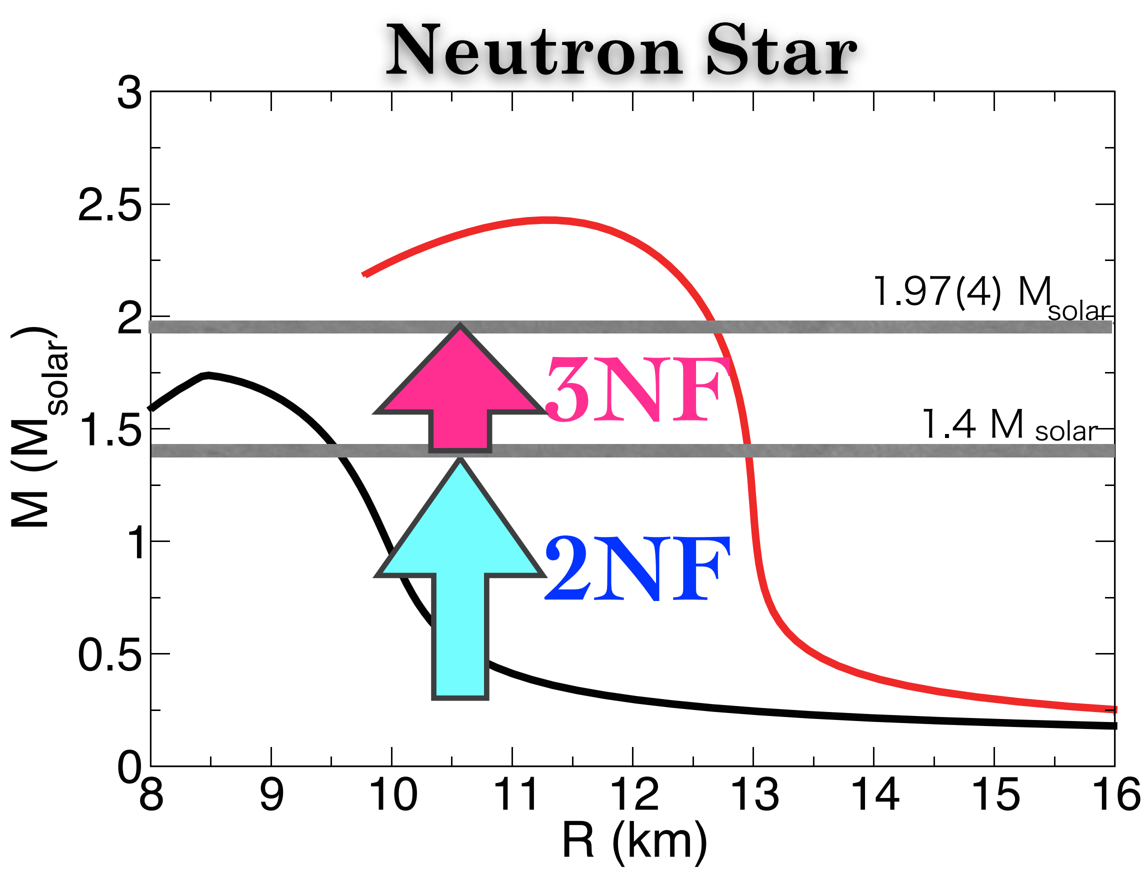
3NFs in A>3 - ② -



3NFs in Infinite Nuclei - Neutron Star -



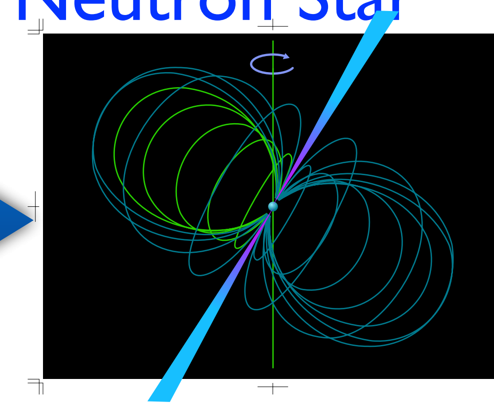
A. Akmal et al., PRC 58, 1804('98)

- 3NF in Nuclei is required…
  - Short & Repulsive
- Large effects at high density.

"Endpoint of stellar evolution"

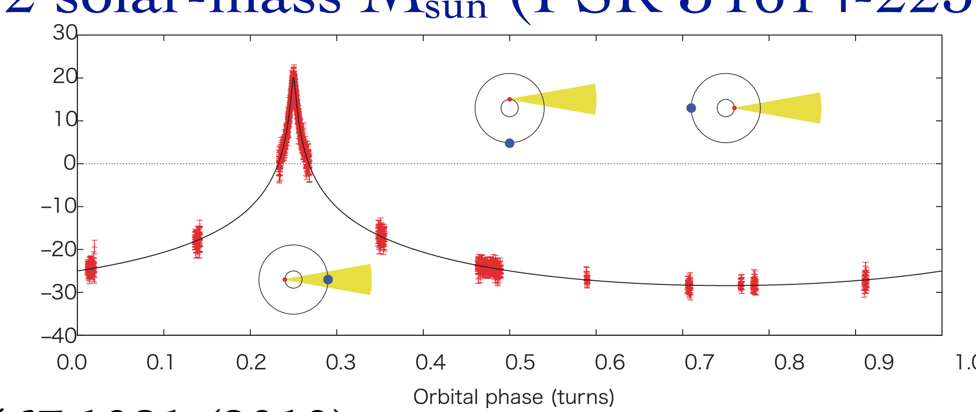
Supernovae Explosion

Neutron Star



Black Hole

Discovery of Heaviest Neutron Star with 2 solar-mass M_{sun} (PSR J1614-2230)



Nature 467 1081 (2010)

How ?

Two & Three-Nucleon Force

①. Repulsive

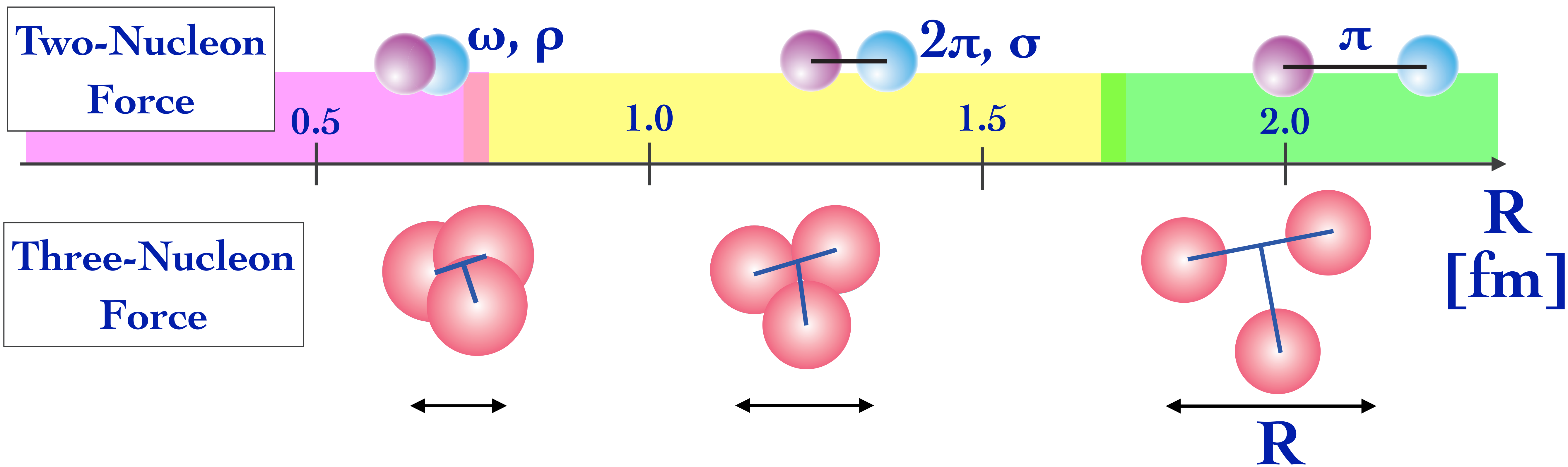
-Short Range-

②. Attractive (strong)

-Intermediate Range-

③. Attractive (weak)

- Long Range -



3NFs are momentum, spin, and iso-spin dependent.

Nuclear Matter
Neutron Star

Nuclear Structure

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 study of 3NFs ?

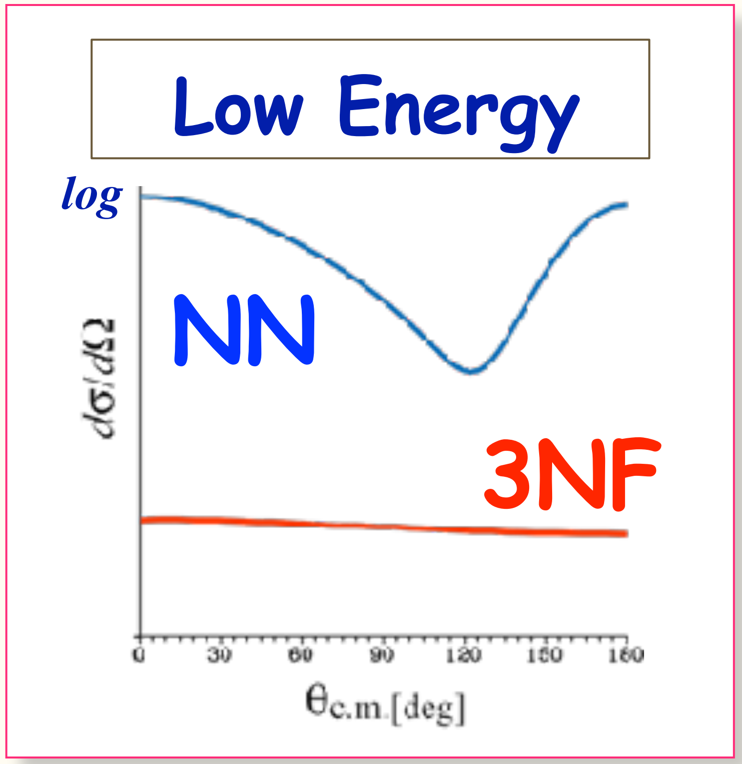
Nucleon-Deuteron Scattering

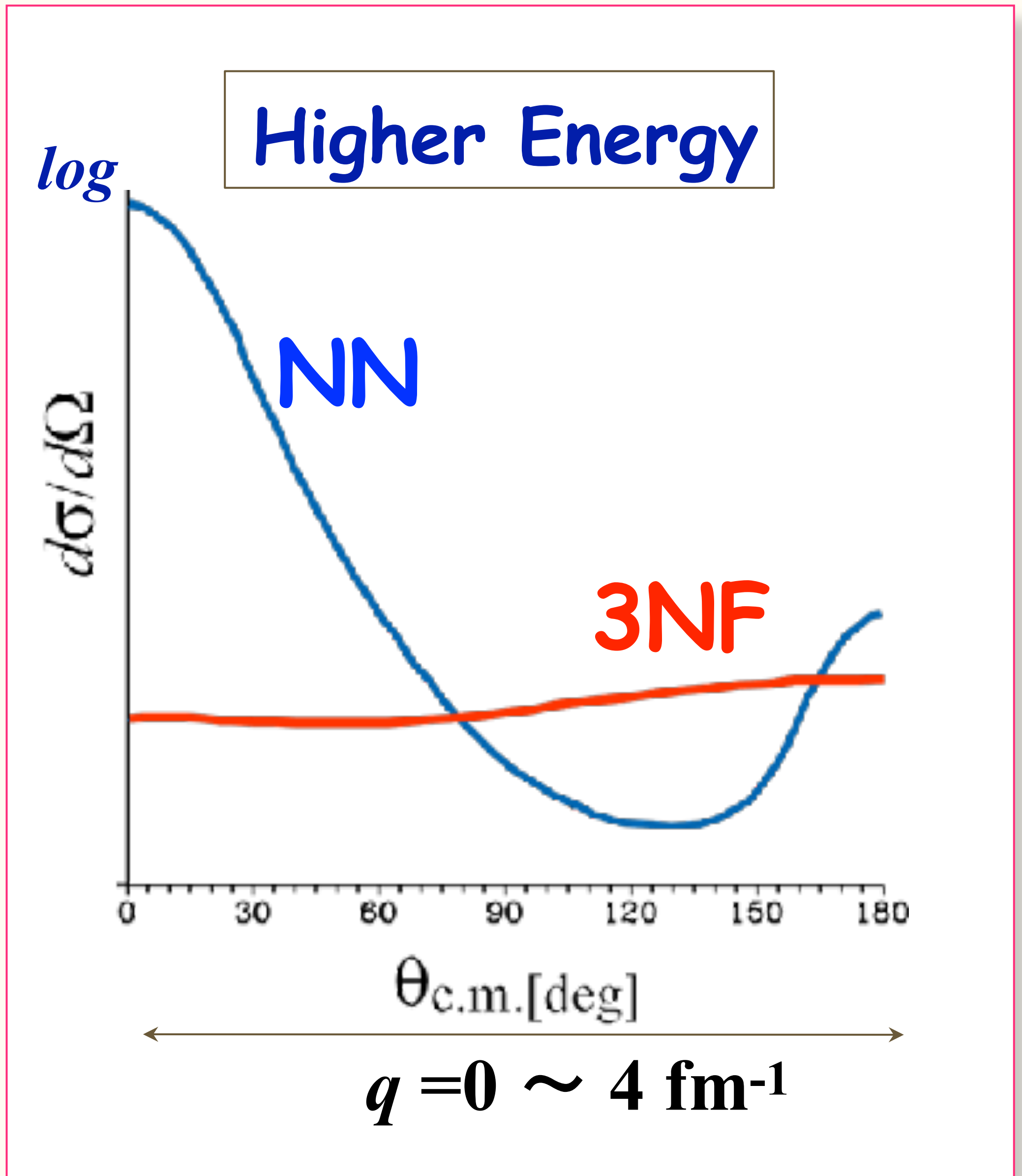
To study momentum & spin dependences

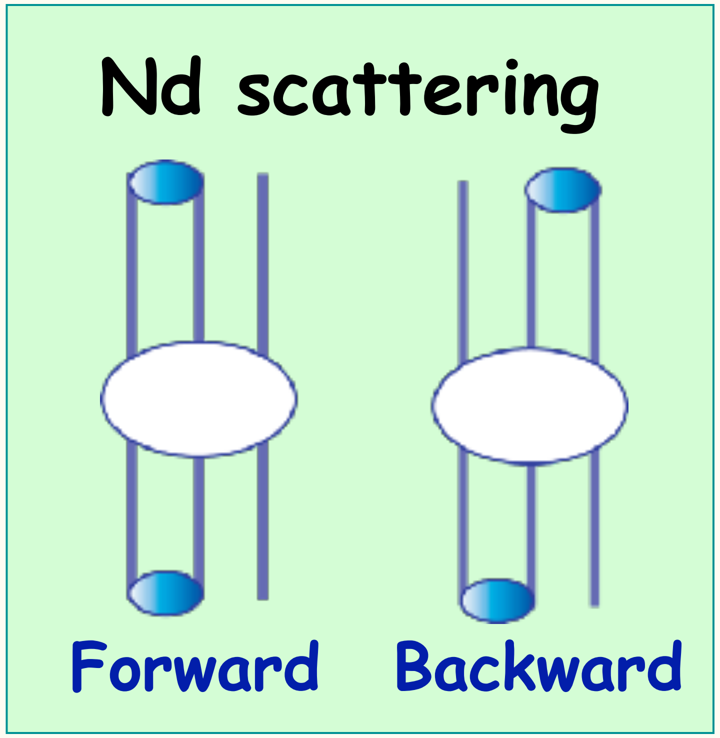
Iso-spin dependence : T=1/2 only

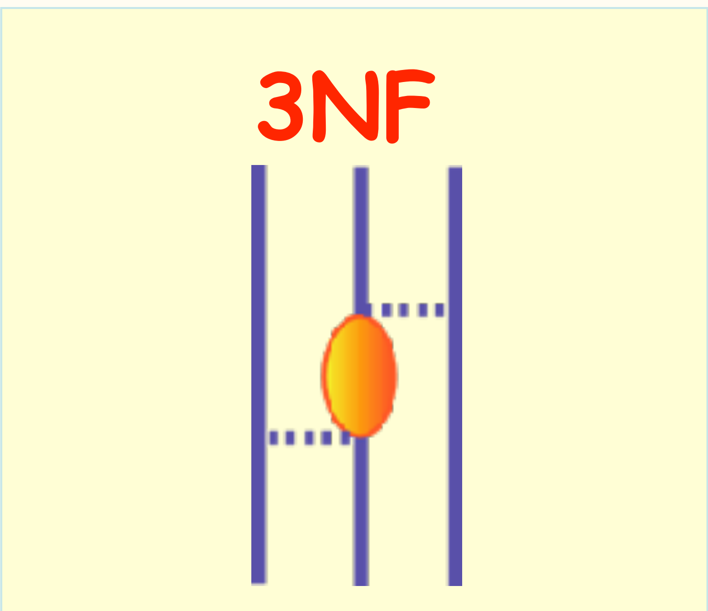
Predictions by H. Witala et al. (1998)

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

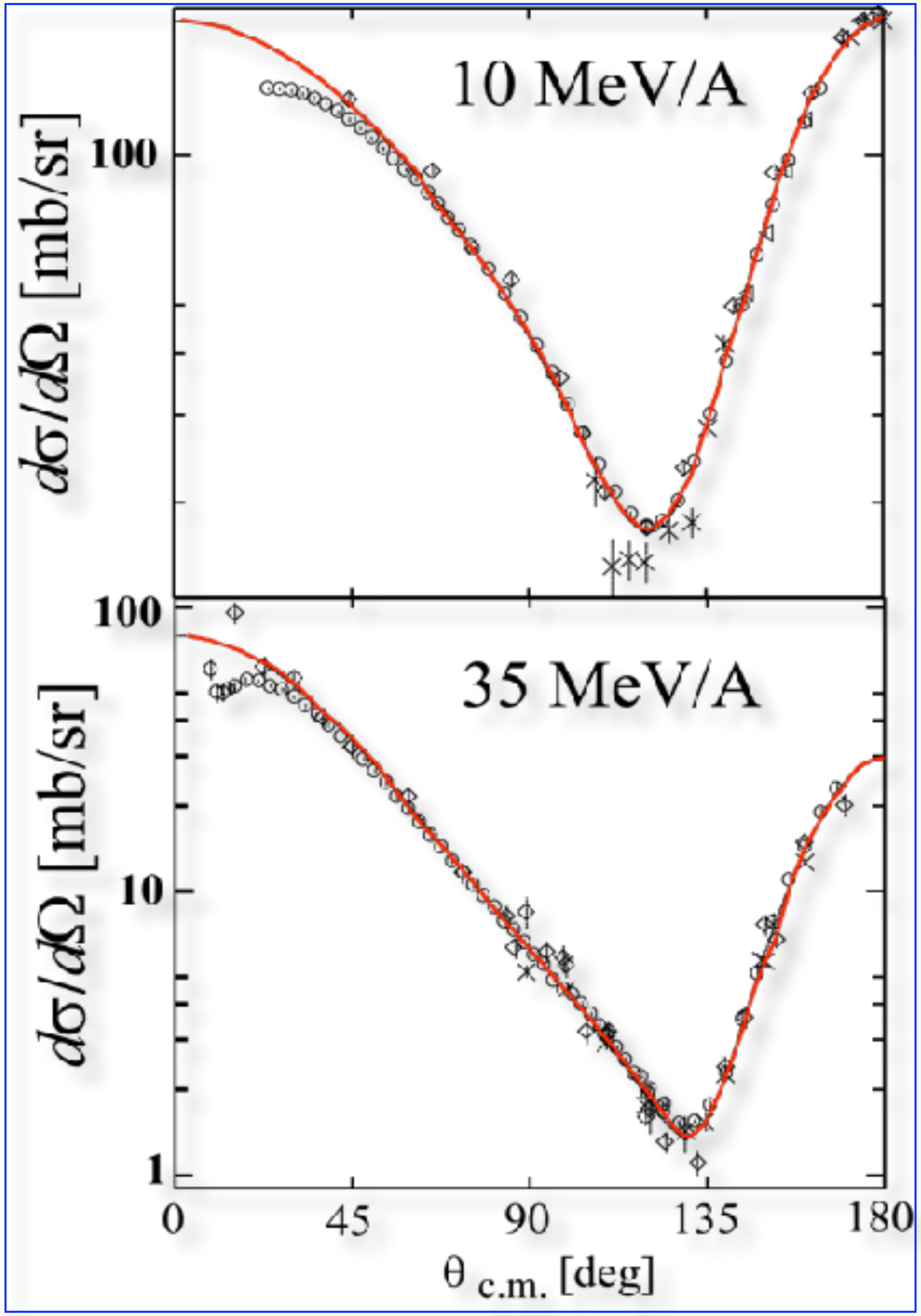








Nd Scattering at Low Energies ($E \leq 30$ MeV/A)



- 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..

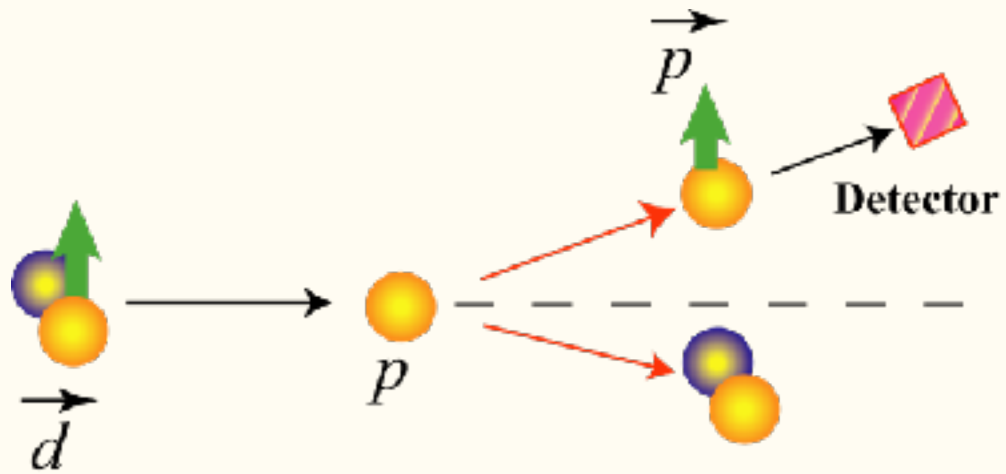
W. Glöckle et al., Phys. Rep. 274, 107 (1996).

Observables for *Nd* Scattering

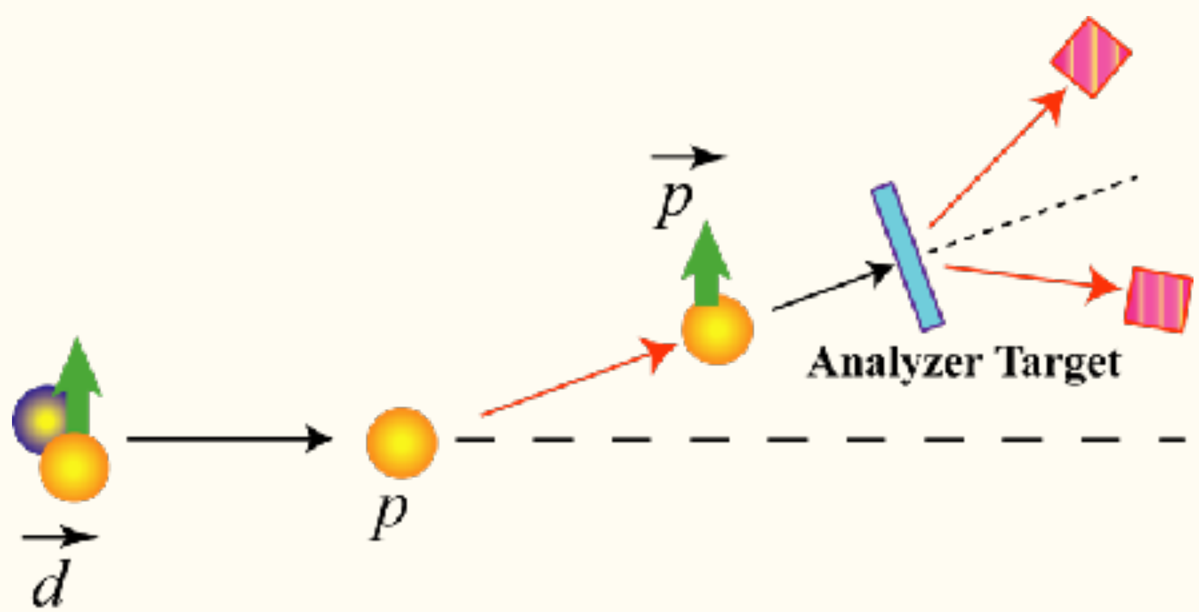
- **Differential Cross Section**
  - **Overall Strength**
  - **Absolute Quantity : normalization to *pp or np* data**

$$\frac{d\sigma}{d\Omega} = \frac{\text{yields}}{(\text{target thickness})\times(\text{beam charge})\times(\text{solid angle})\times(\text{efficiency})}$$

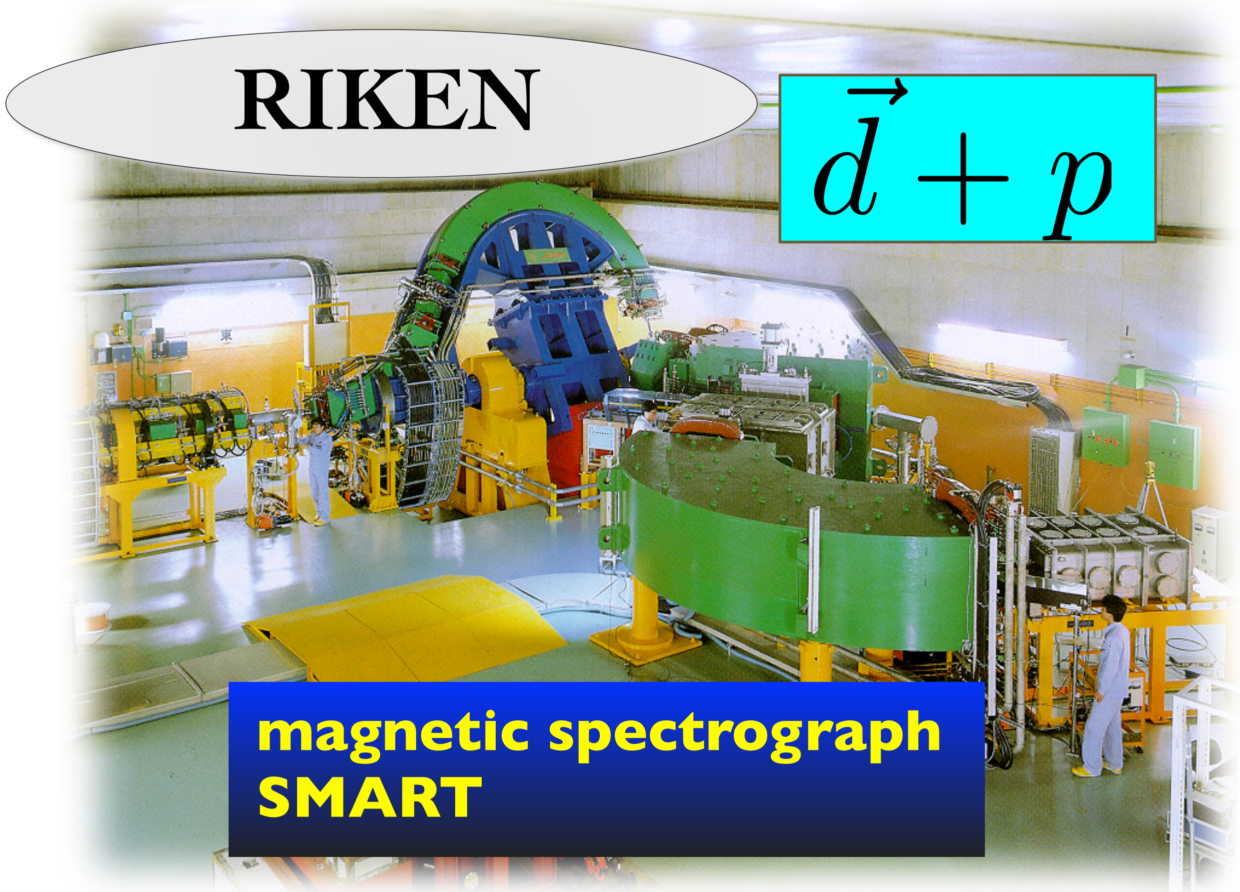
- **Spin Observables :**
  - **Analyzing Powers**
    - **Vector Analyzing Power : iT_{11}**
      - **$(L \cdot S)$ interaction**
    - **Tensor Analyzing Power : T_{20}, T_{21}, T_{22}**
      - **Tensor interaction (D-state)**
      - **Higher order $(L \cdot S)$ interaction**

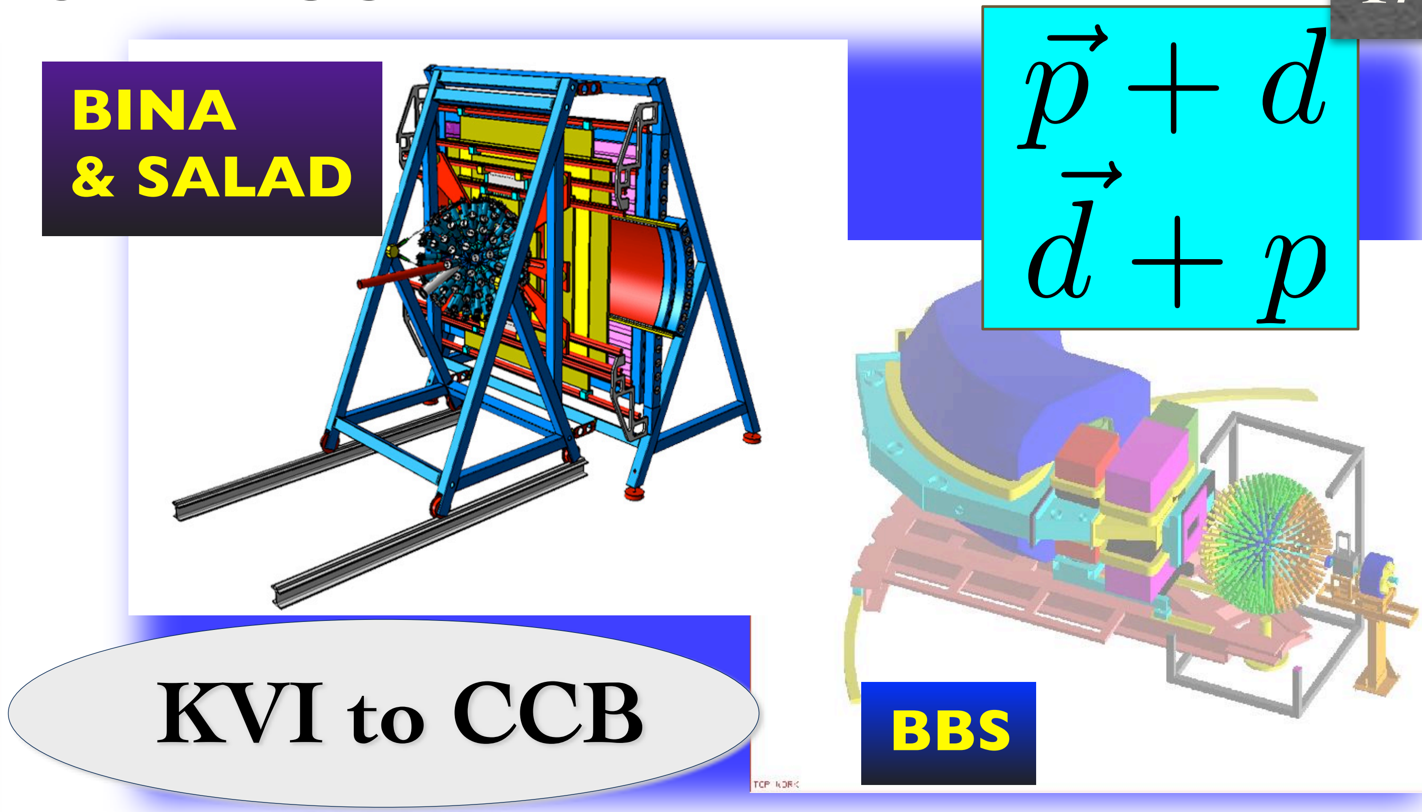


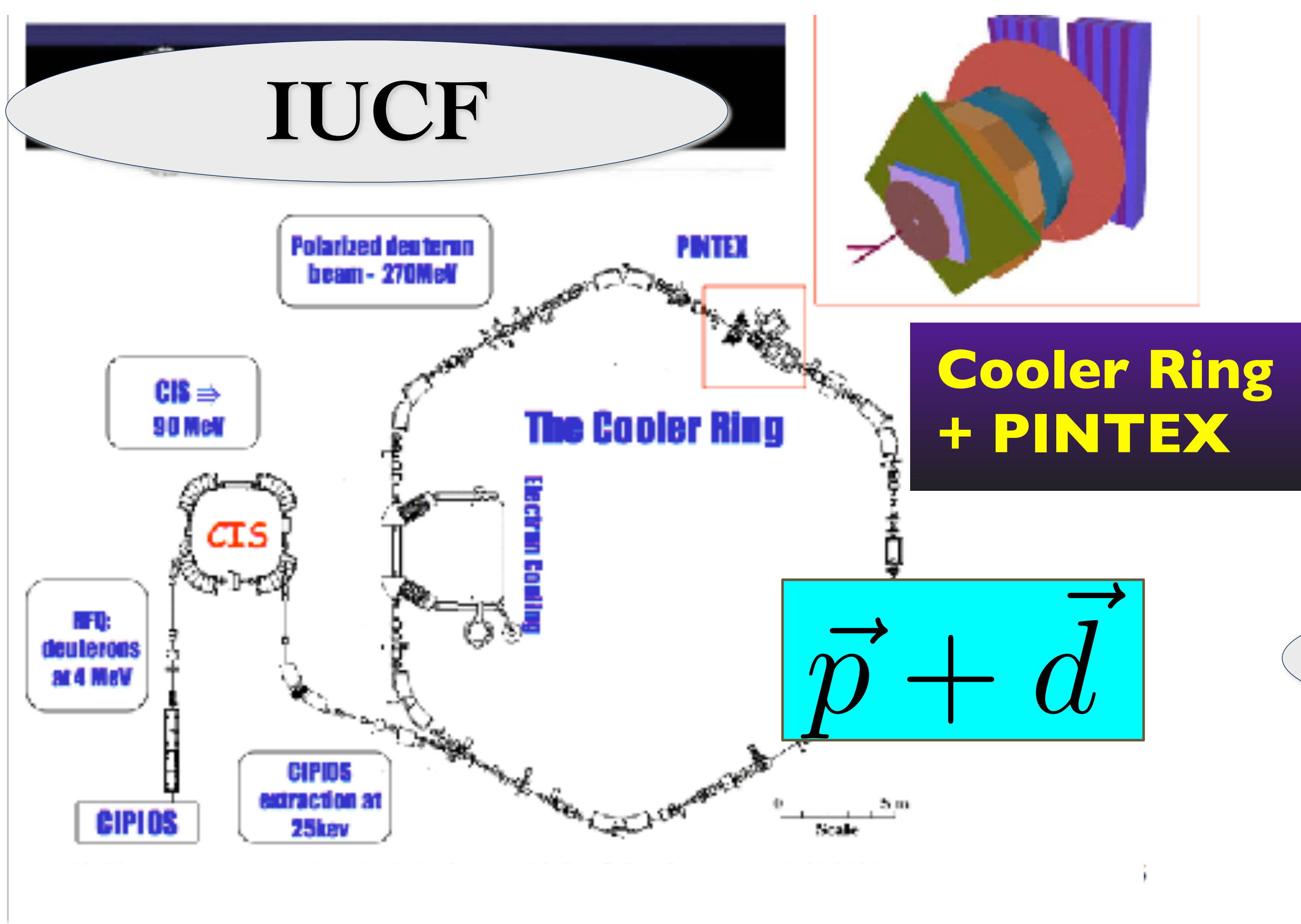
  - **Polarization Transfer Coefficient : $K_{ij}^{l'}$**
  - **Spin Correlation Coefficients : $C_{ij,k}$**
    - **Spin-Spin interaction**

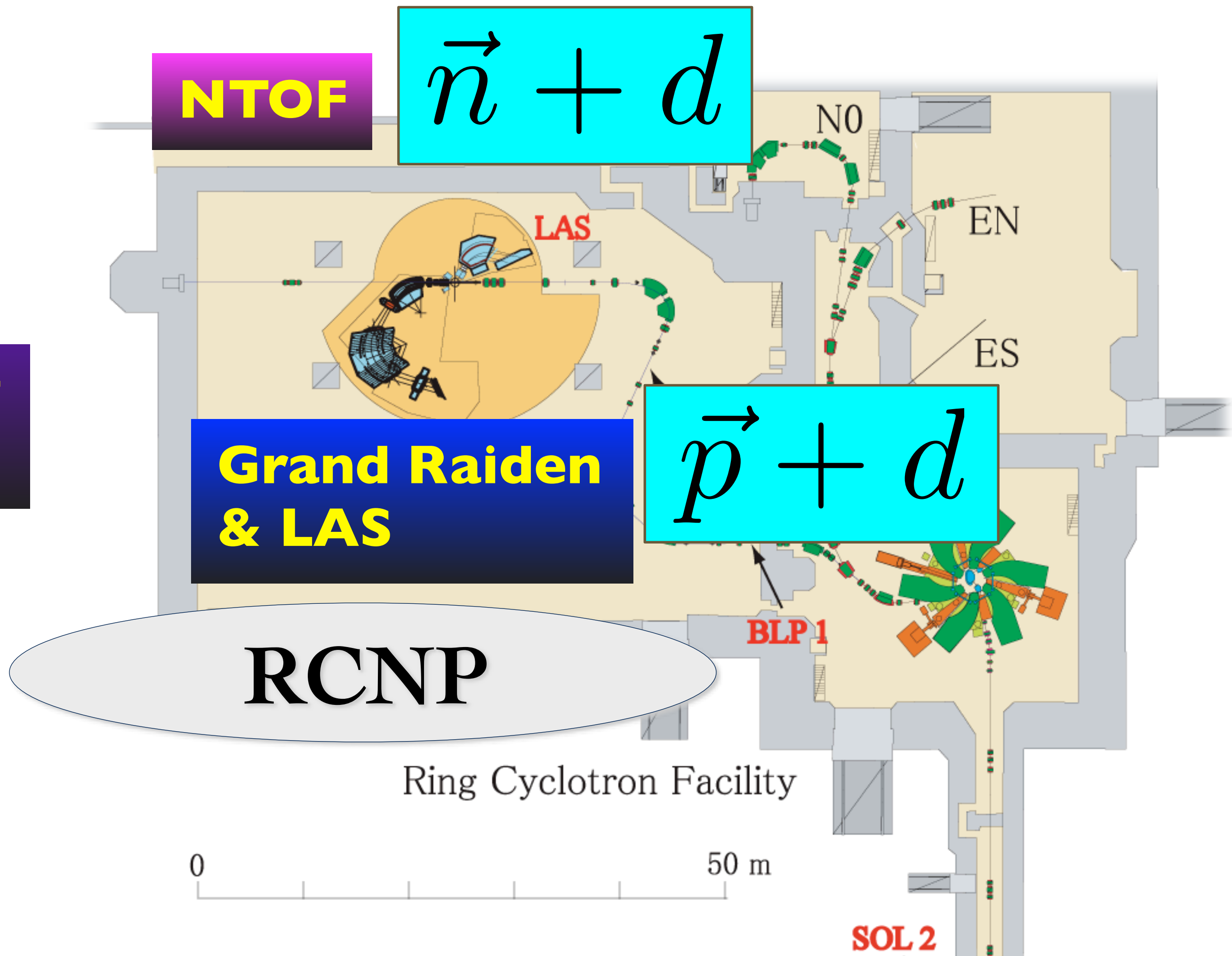


Facilities


RIKEN
$\vec{d} + p$
magnetic spectrograph
SMART


BINA
& SALAD
$\vec{p} + d$
$\vec{d} + p$
KVI to CCB
BBS

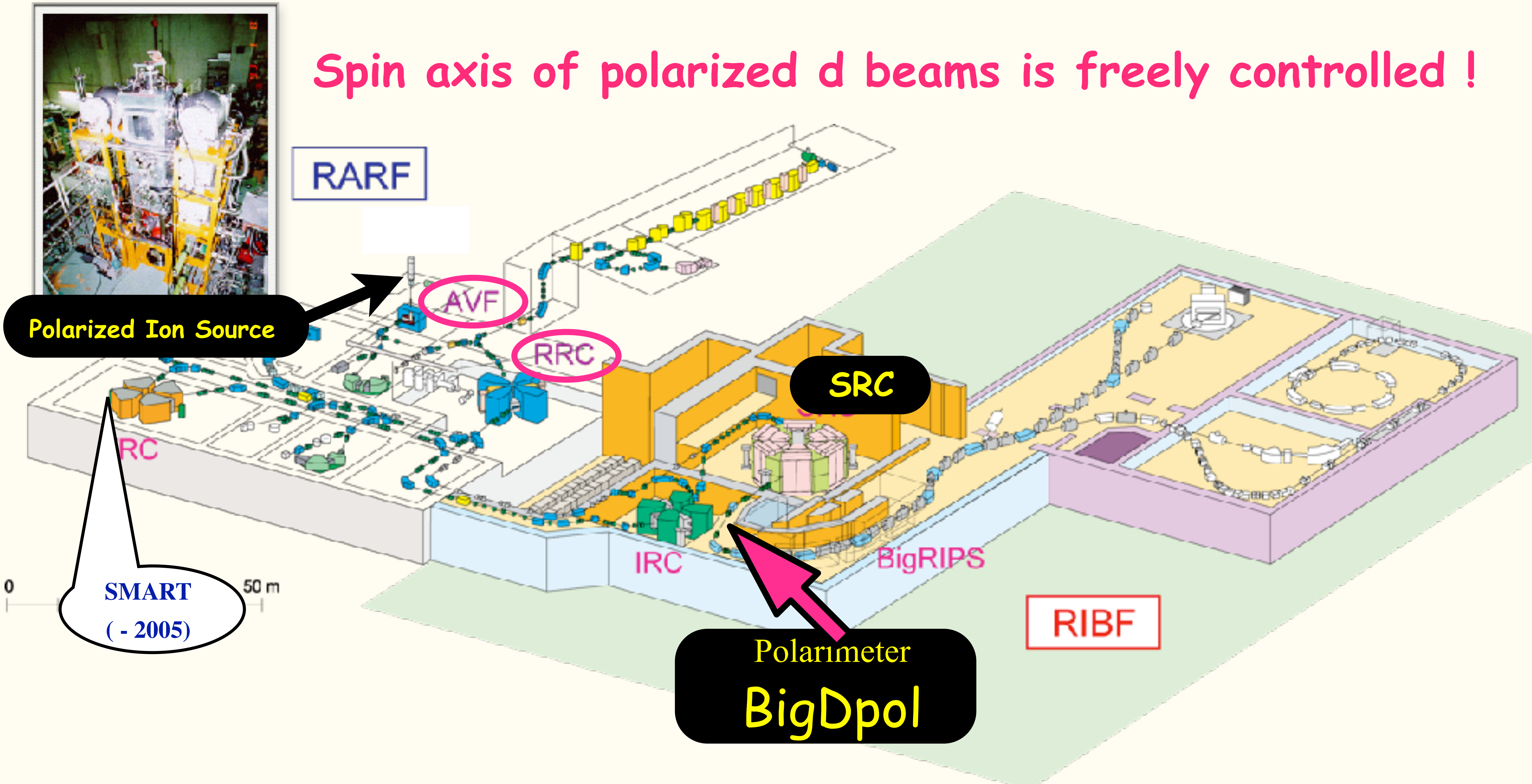

IUCF
Polarized deuteron
beam - 270MeV
PINTEX
CIS ⇒
90 MeV
CIS
The Cooler Ring
Electron Cooling
Cooler Ring
+ PINTEX
$\vec{p} + \vec{d}$
CIPIOS
Scale


NTOF
$\vec{n} + d$
N0
EN
ES
LAS
Grand Raiden
& LAS
$\vec{p} + d$
BLP 1
RCNP
Ring Cyclotron Facility
0
50 m
SOL 2

RIKEN RI Beam Factory (RIBF)

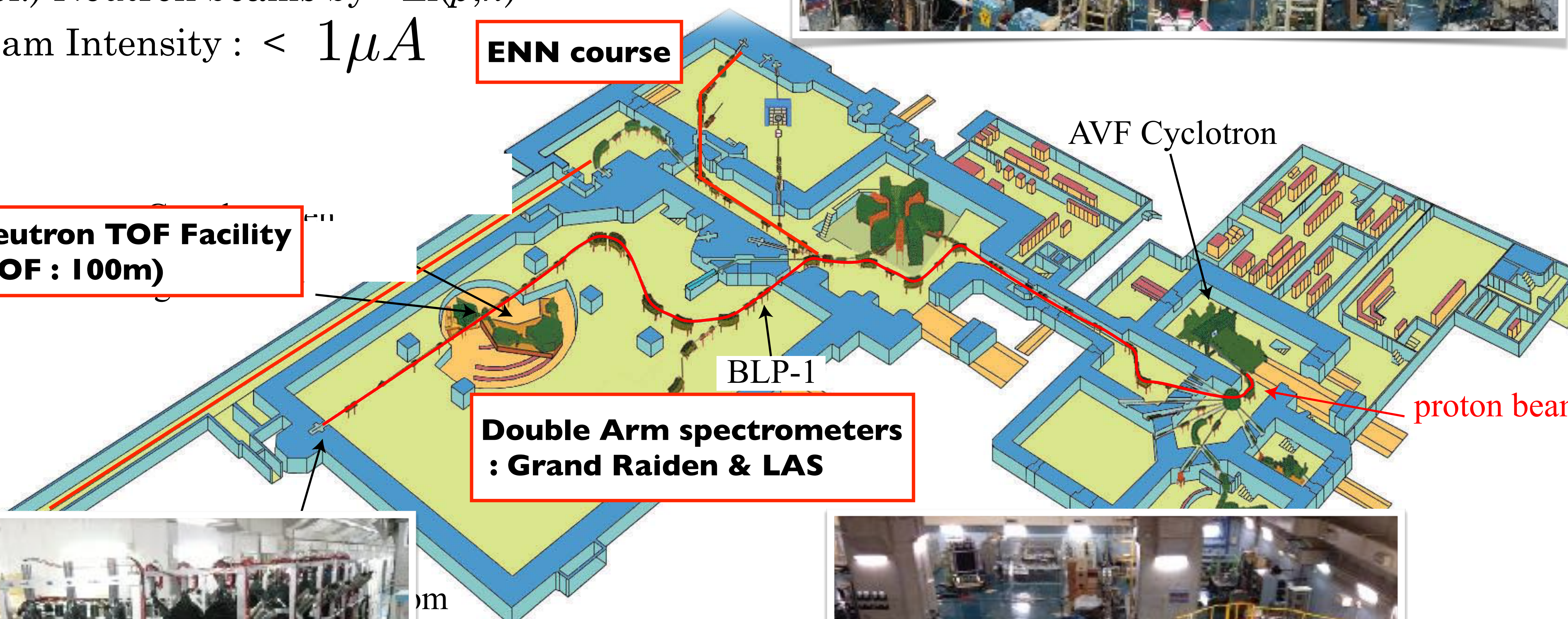
- Polarized *d* beam
  - acceleration by AVF+RRC : 65-135 MeV/nucleon
  - acceleration by AVF+RRC+SRC : 190-300 MeV/nucleon
  - polarization : 60-80% of theoretical maximum values
- Beam Intensity : < 100 nA

Spin axis of polarized d beams is freely controlled !



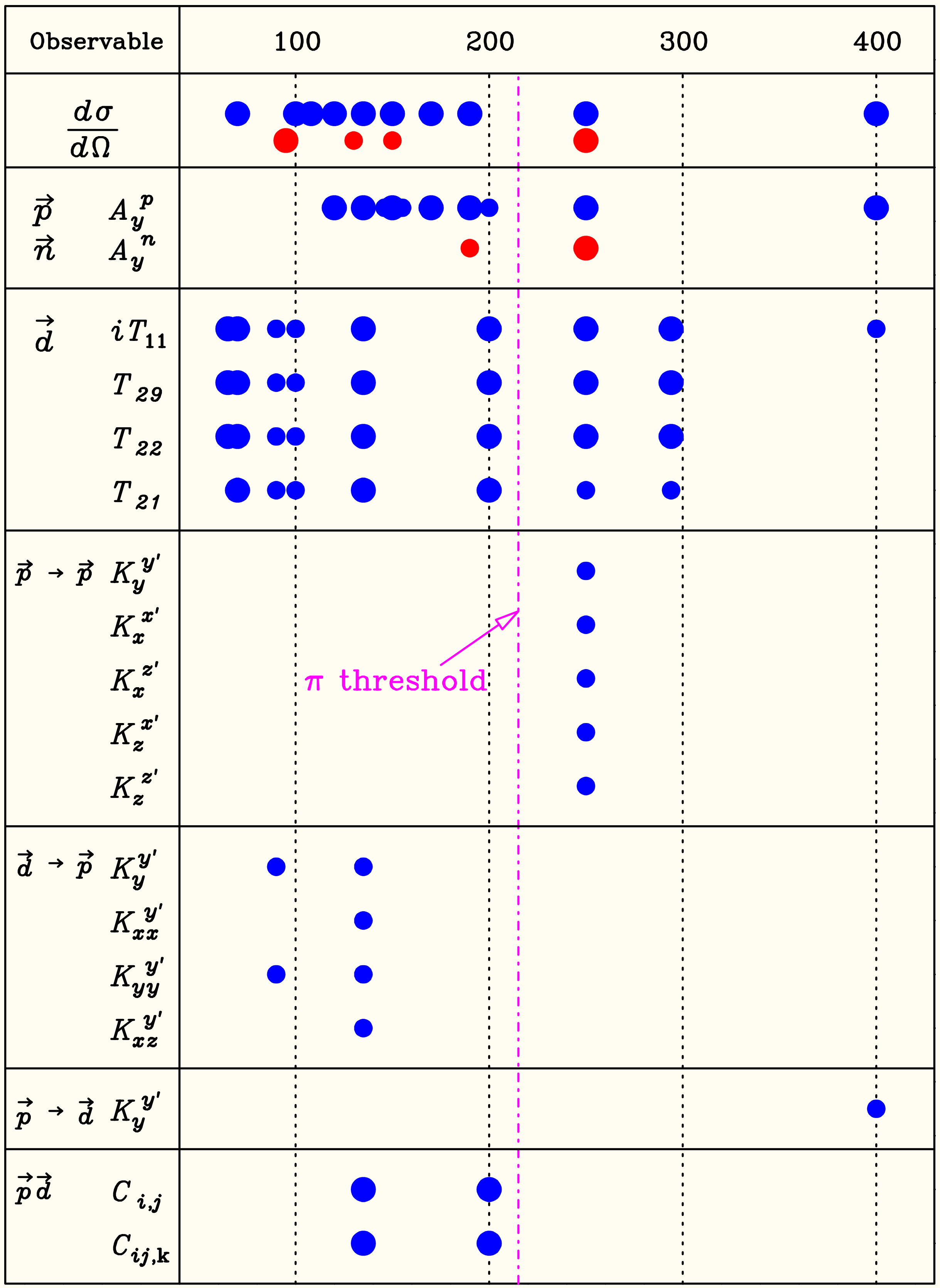
RCNP, Osaka University

- Polarized *p* beam : 10 - 420 MeV/nucleon
- Polarized *d* beam : 5 - 100 MeV/nucleon
  - Polarizations : < 70 %
- (pol.) Neutron beams by ^{7}Li(p,n)
- Beam Intensity : < $1\mu A$



Nd Elastic Scattering Data at Intermediate Energies

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



~2023

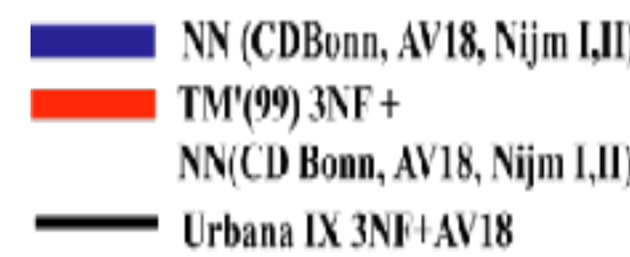
- **High precision data set of**
  ***dσ/dΩ* & Analyzing Powers**
  from RIKEN, RCNP, KVI, IUCF

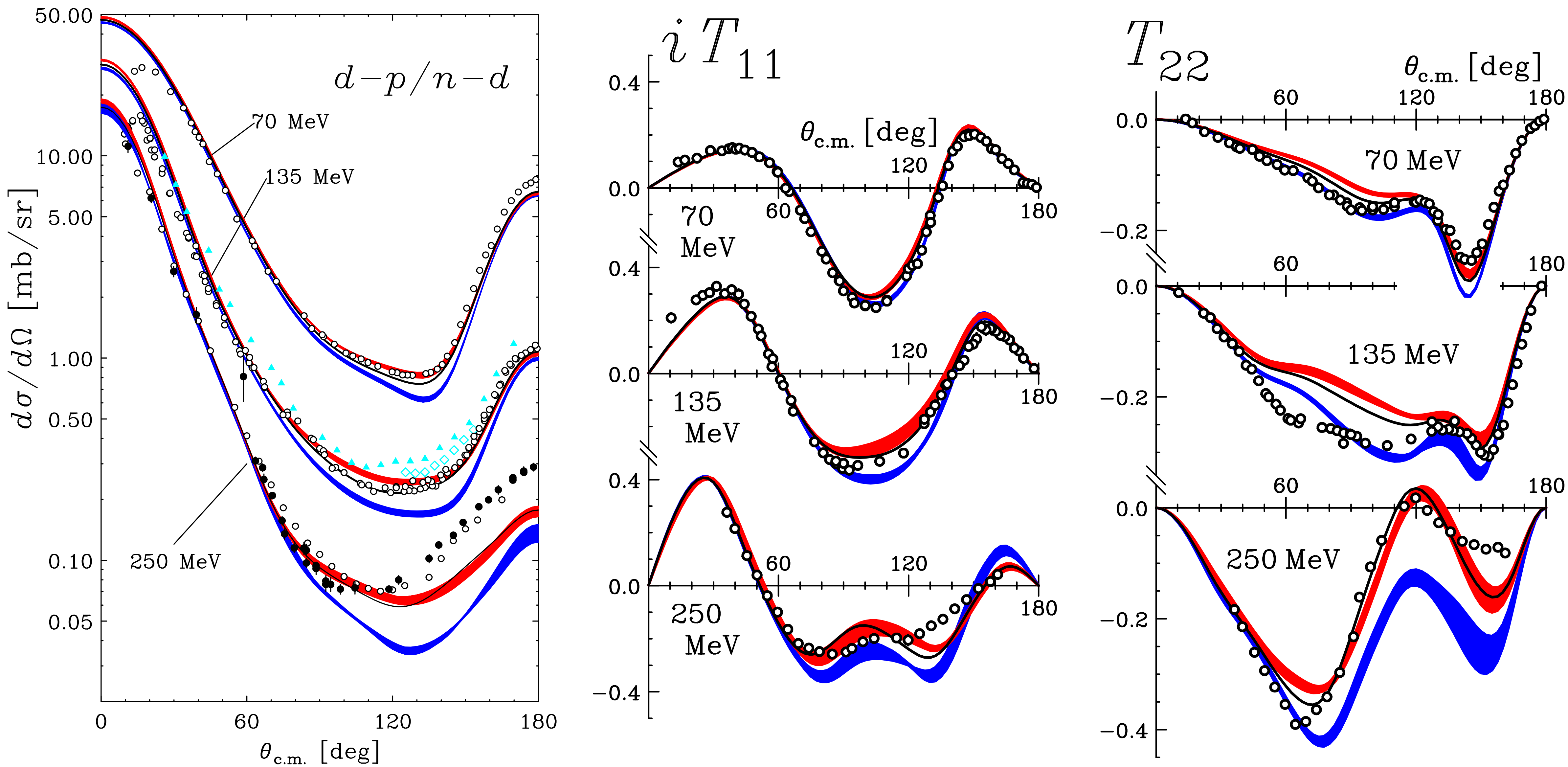
- Energy dependent data
  - ✓ dσ/dΩ
  - ✓ Proton Analyzing Power
  - ✓ Deuteron Analyzing Powers

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…

- 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.
- Serious discrepancy at backward angles at higher energies





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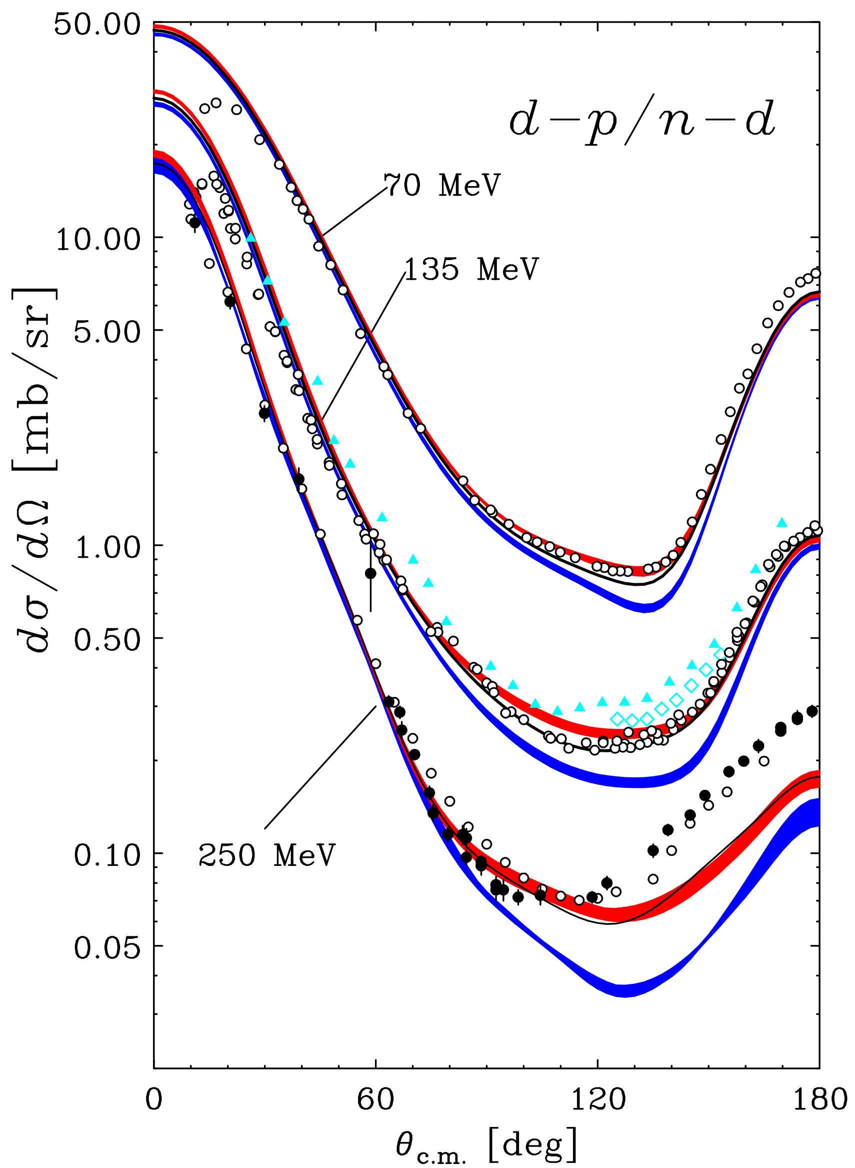
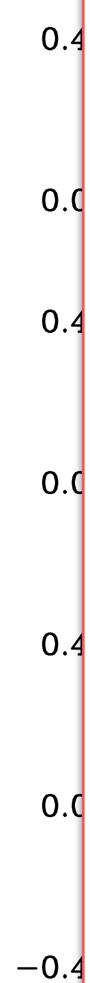
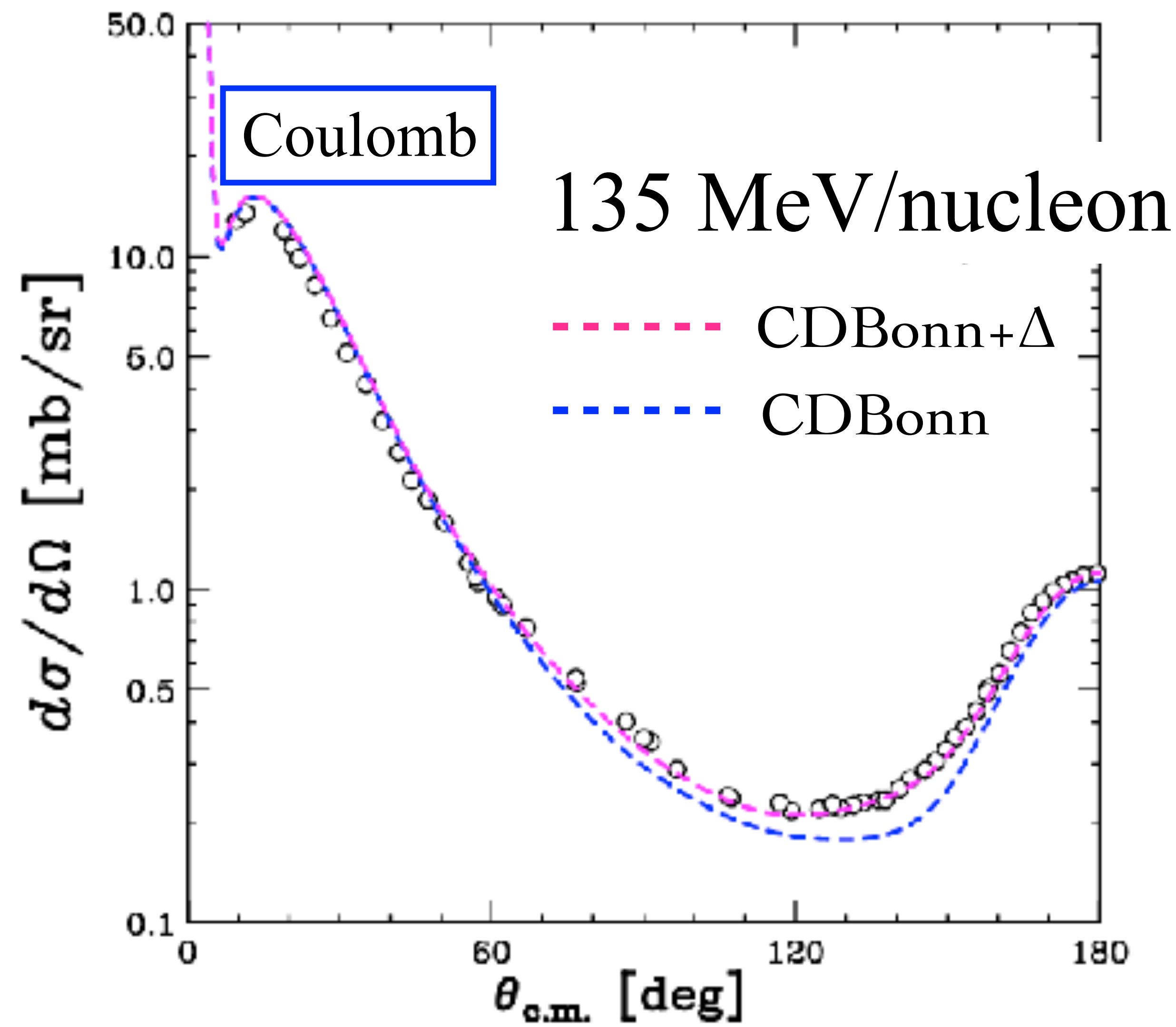




Coupled channel approach with Nucleon & Δ-isobar



A. Deltuva et al., PRC 68, 024005 (2003)
A. Deltuva et al., PRC 71, 054005 (2005)

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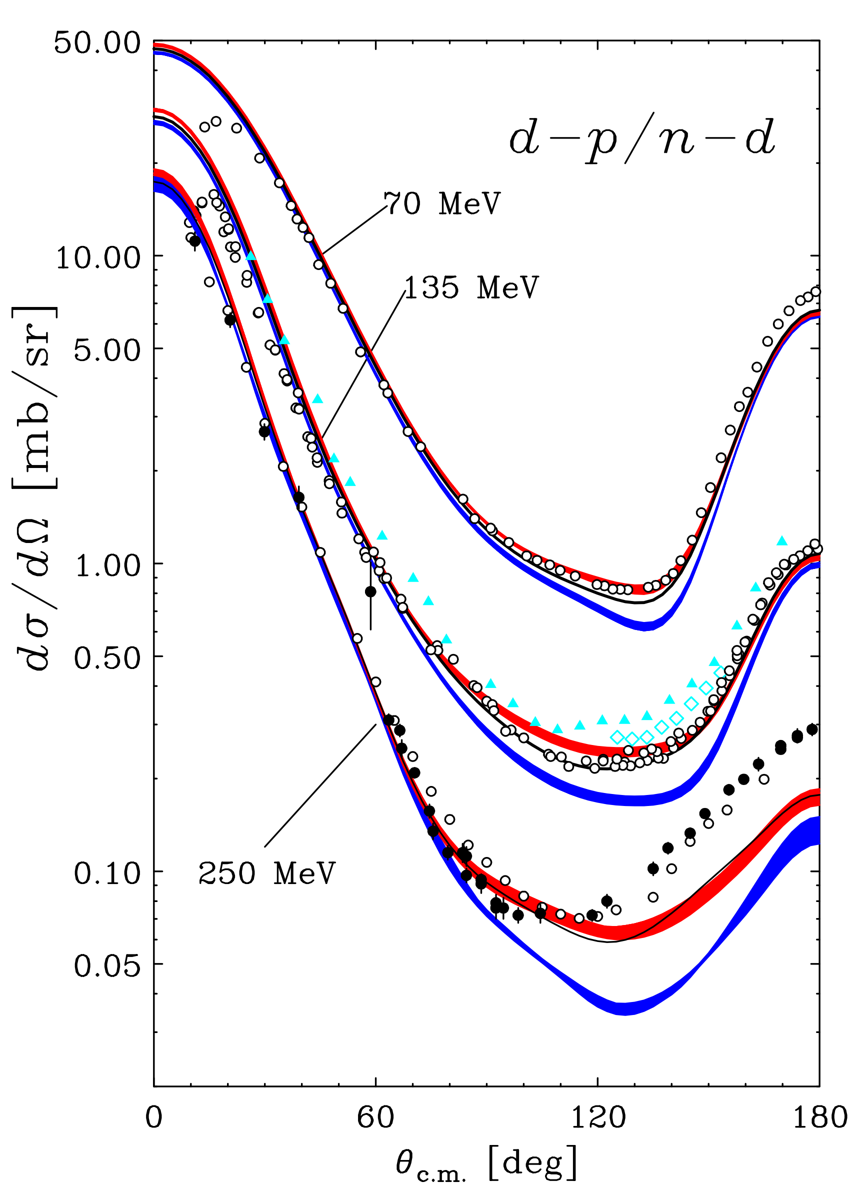
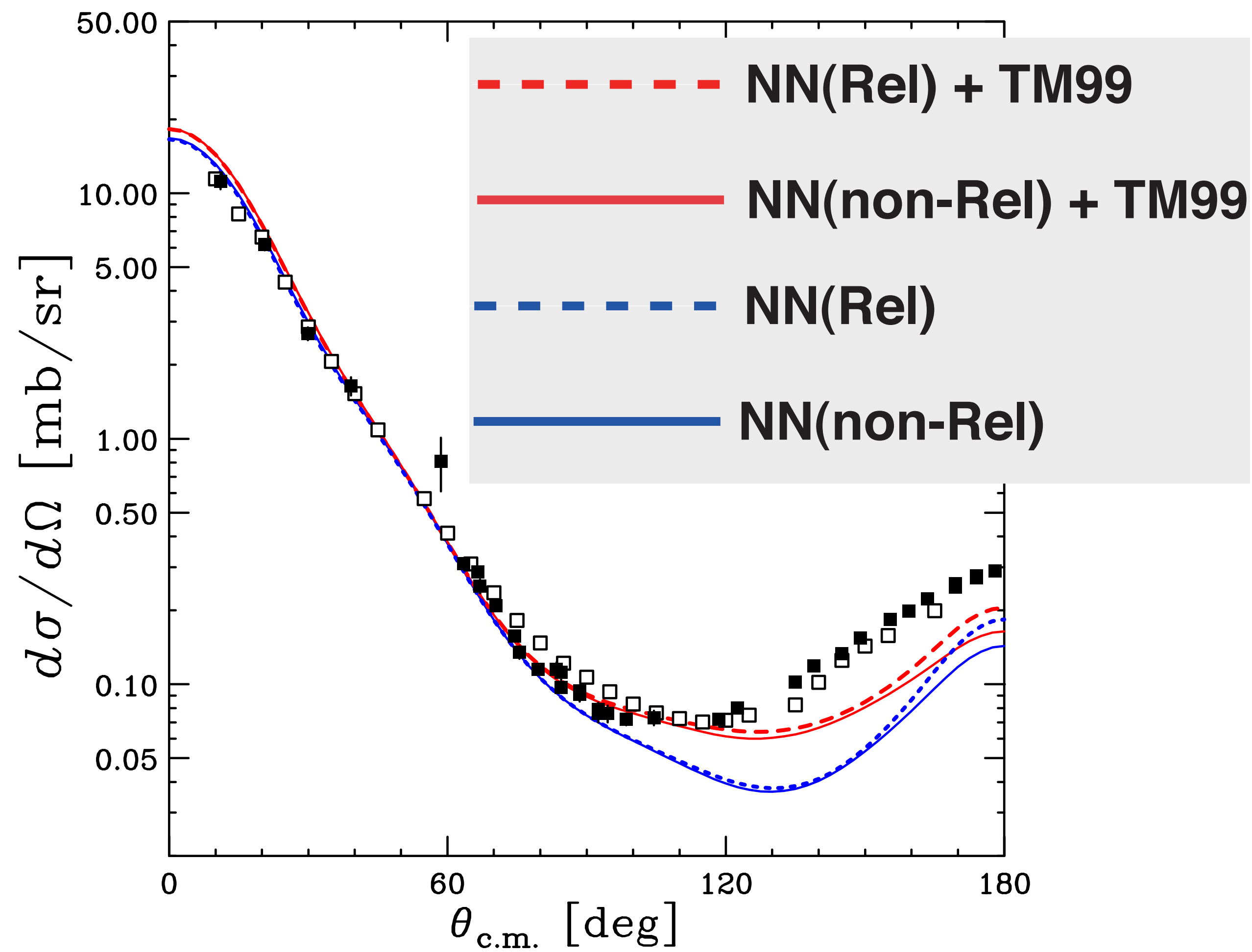


Relativistic Faddeev Calculations with TM'99 3NF

pd/nd @ 250 MeV



Relativistic effects are visible at backward angles, but small.

K. Sekiguchi et al., Phys. Rev. C89, 064007 (2014)

So far …

Nucleon-Deuteron Scattering at ~100 MeV/nucleon

- First Evidence of 3NF effects
- Defects of existing 3NF models

From Now

- **Deuteron-Proton Scattering at ~100 MeV/N :** *Golden window of 3NFs*
  - Determine 3NFs based on χEFT Nuclear Potential
  - High-precision measurement of Spin Correlation Coefficients
- **Proton-^{3}He Scattering at ~100 MeV/N :** *New Probe of 3NF Study*
  - First Step from Few to Many
  - 3NFs of isospin channel of T=3/2

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)

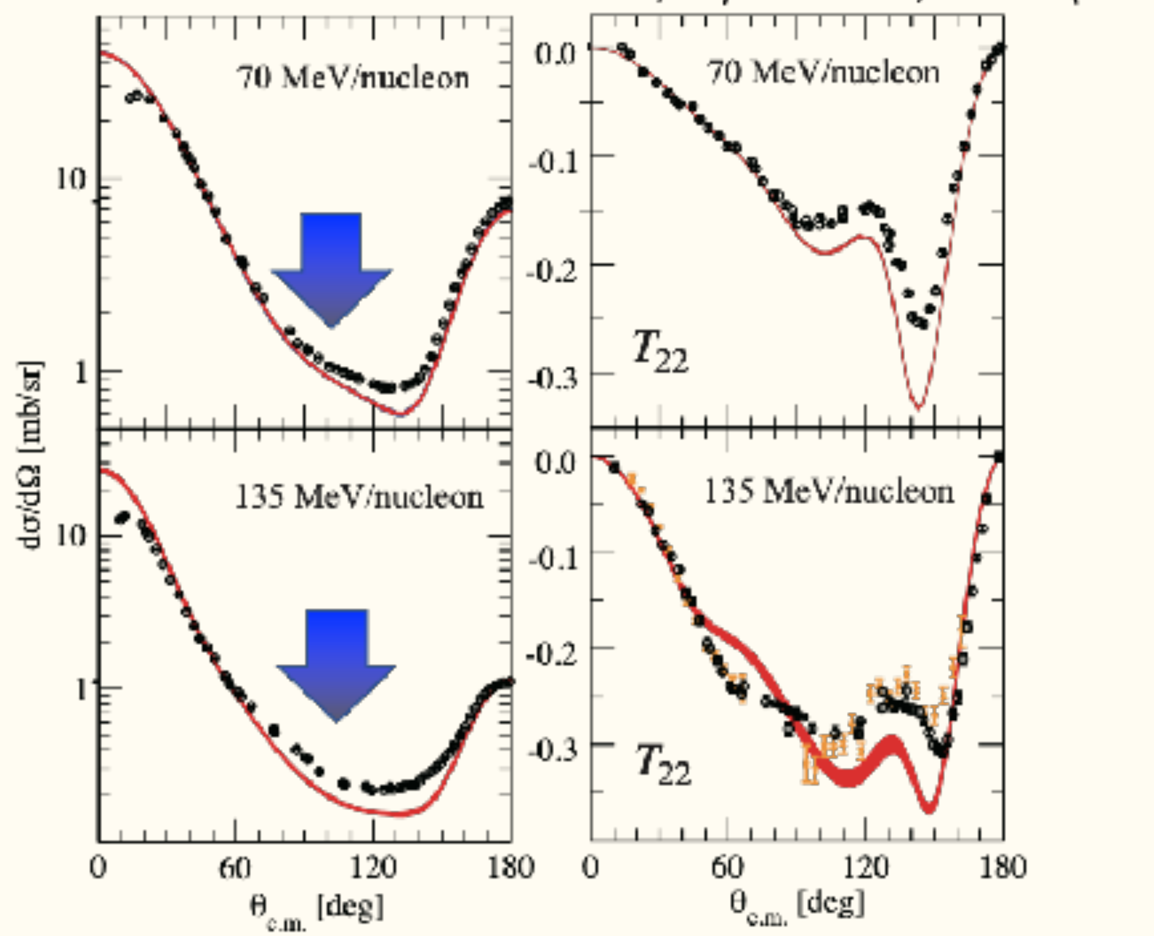
- *dp* elastic scattering data
  show necessities for the N4LO 3NFs.

Cross Section minimum region
for *dp* elastic scattering at ～100MeV/nucleon
are "Golden windows for N4LO 3NFs".

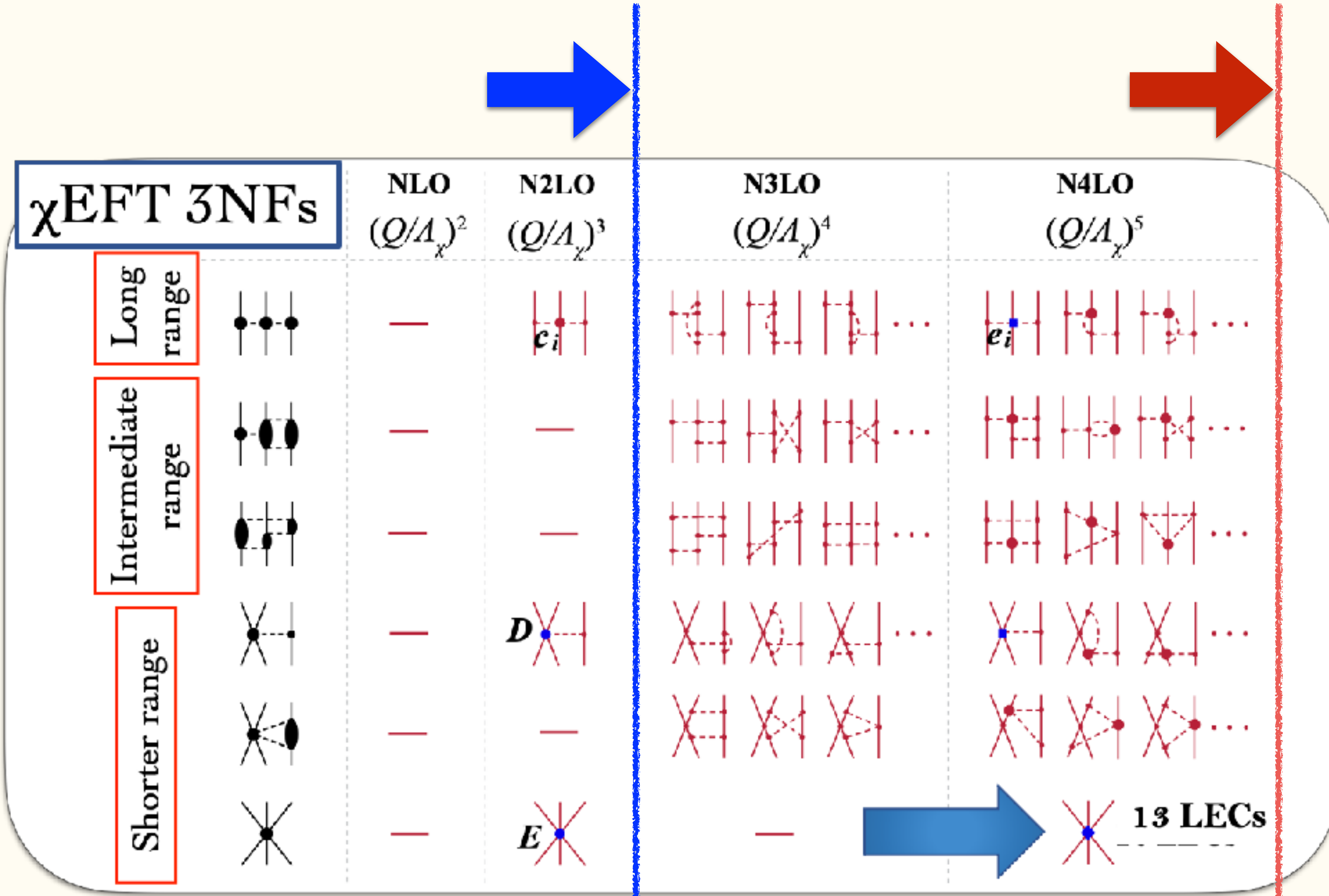
LENPIC collaboration,
Phys. Rev. C 98, 014002 (2018)

dp scattering & N4LO χEFT 2NFs

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



NN Interactions with R = 0.9 fm
E. Epelbaum, H. Krebs, and U.-G. Meißner,
Phys. Rev. Lett. 115, 122301 (2015)

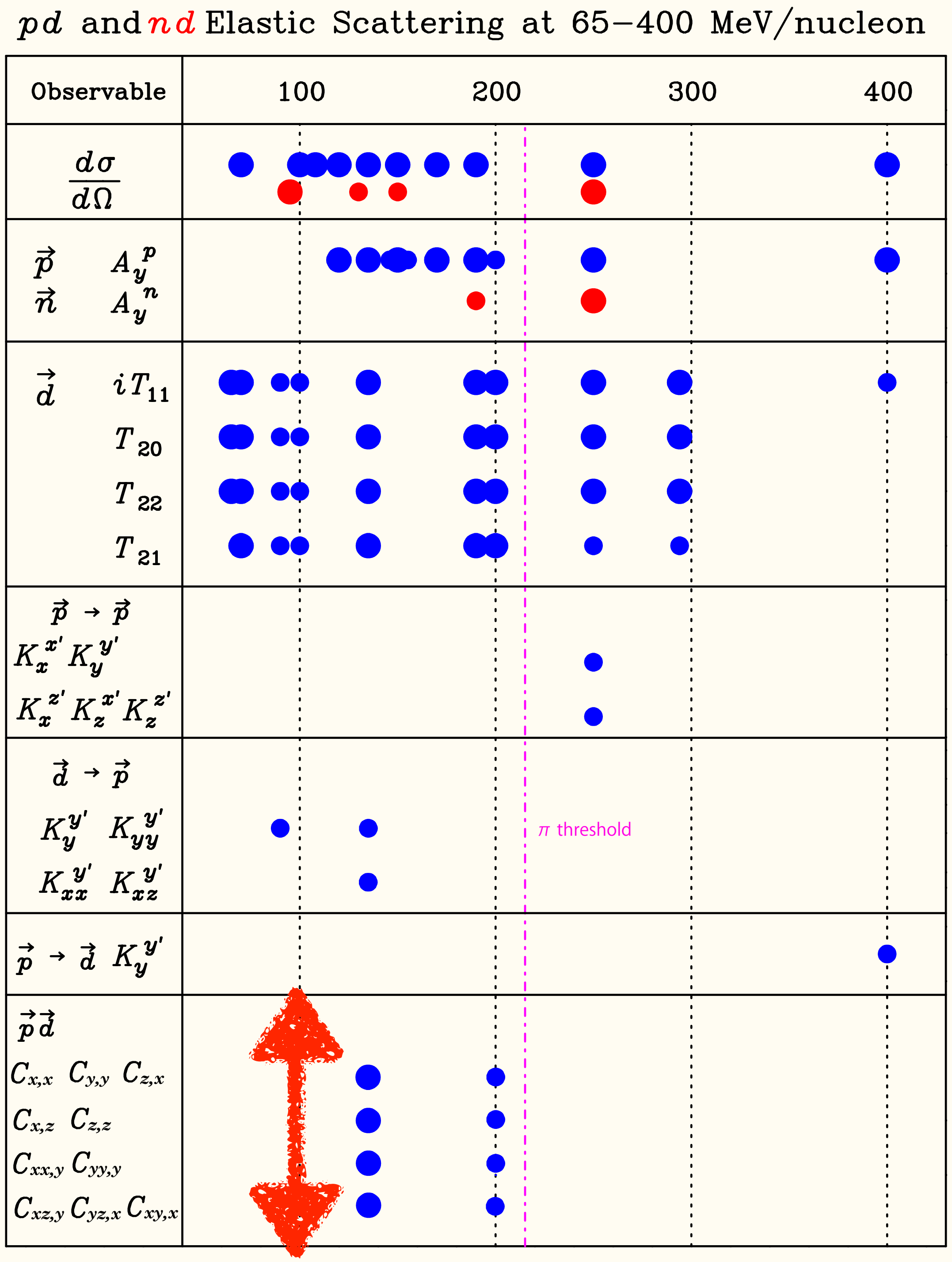


L. Girlanda, et al., Phys. Rev. C 84, 014001 (2011)

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

New Project at RIKEN RIBF

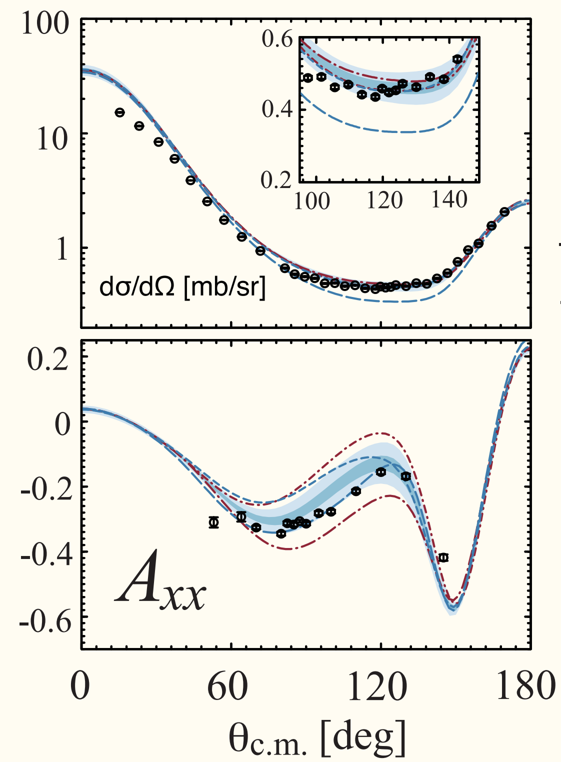
Measurement of Spin Correlation Coefficients for *dp* elastic scattering at 100 MeV/nucleon

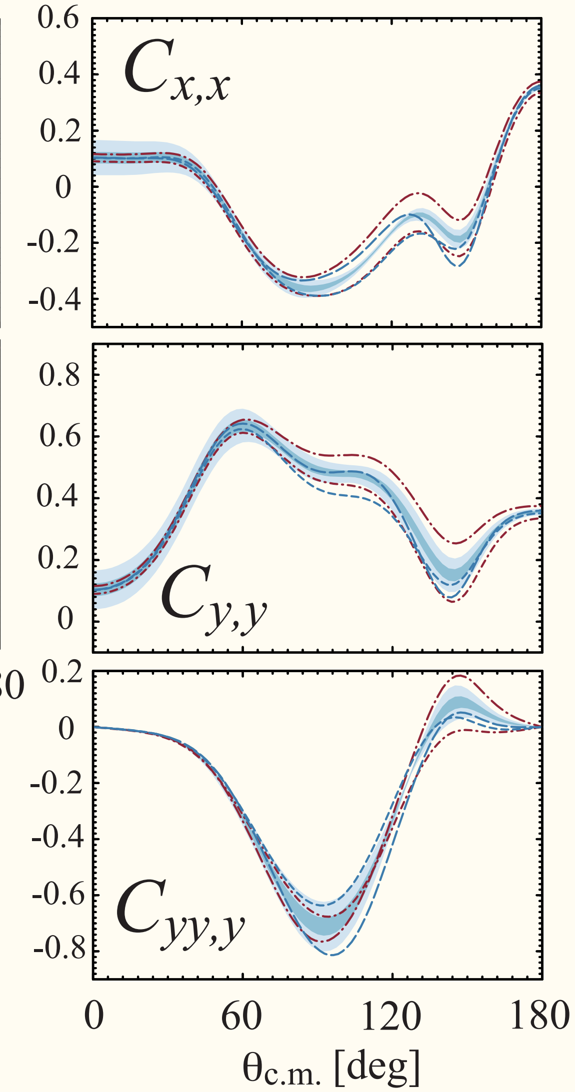


First step :

- Observables : $C_{x,x}$, $C_{y,y}$ and $C_{yy,y}$
- Angles : $\theta_{c.m.}$ = 37°−155°

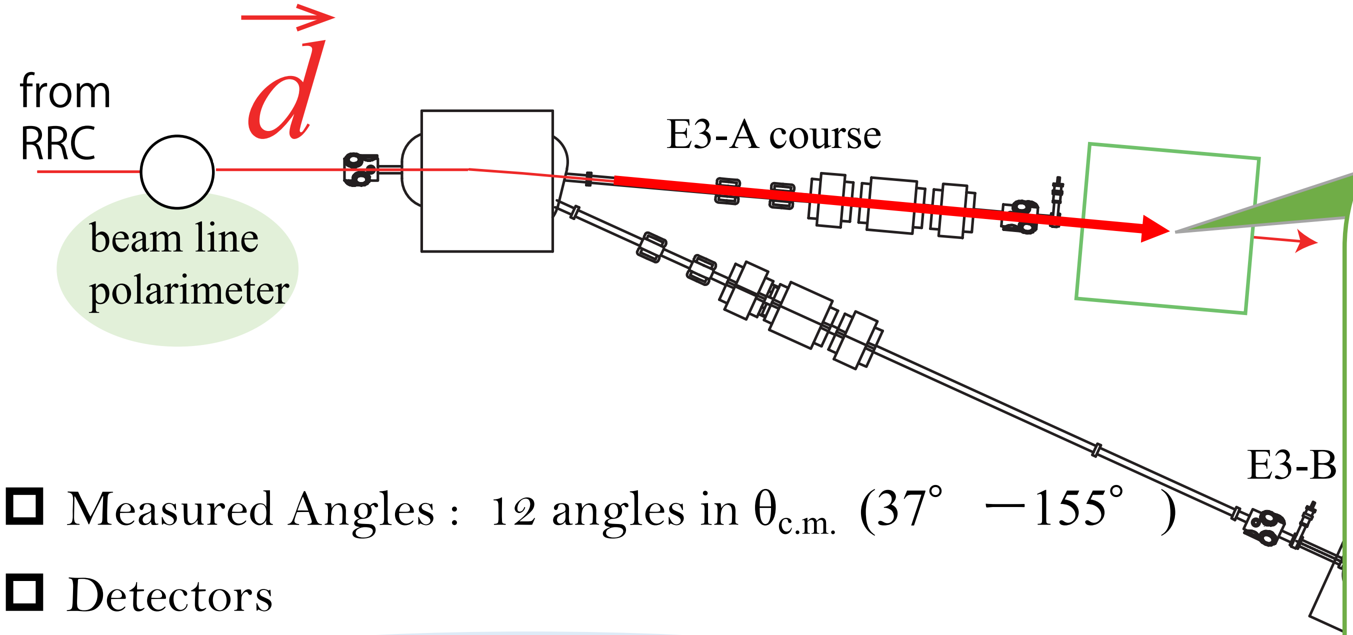
100 MeV/nucleon

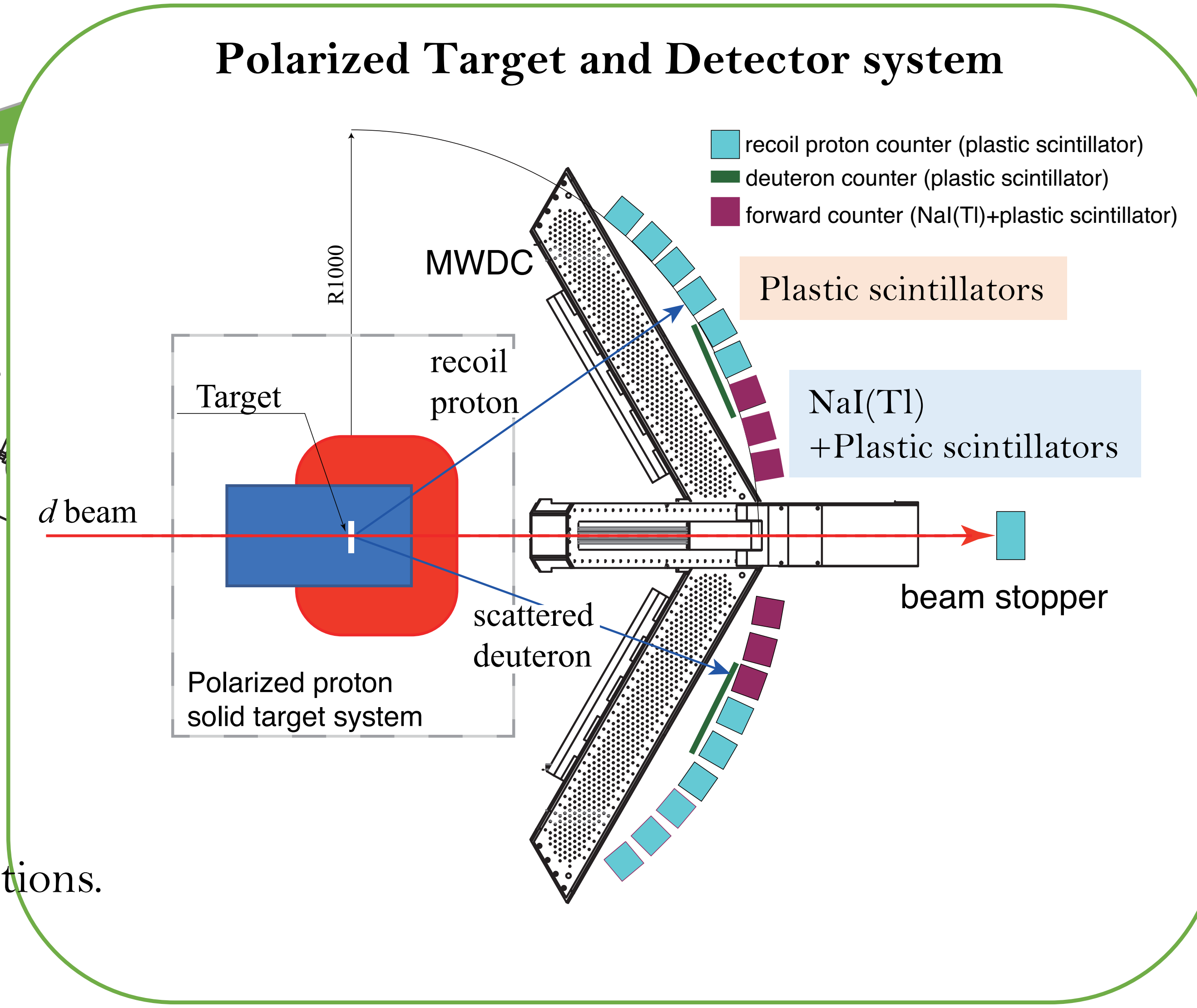




E. Epelbaum et al.,
Eur. Phys. J. A 56, 92 (2020).

Layout of Experiment of the spin correlation coefficients for *dp* Elastic Scattering

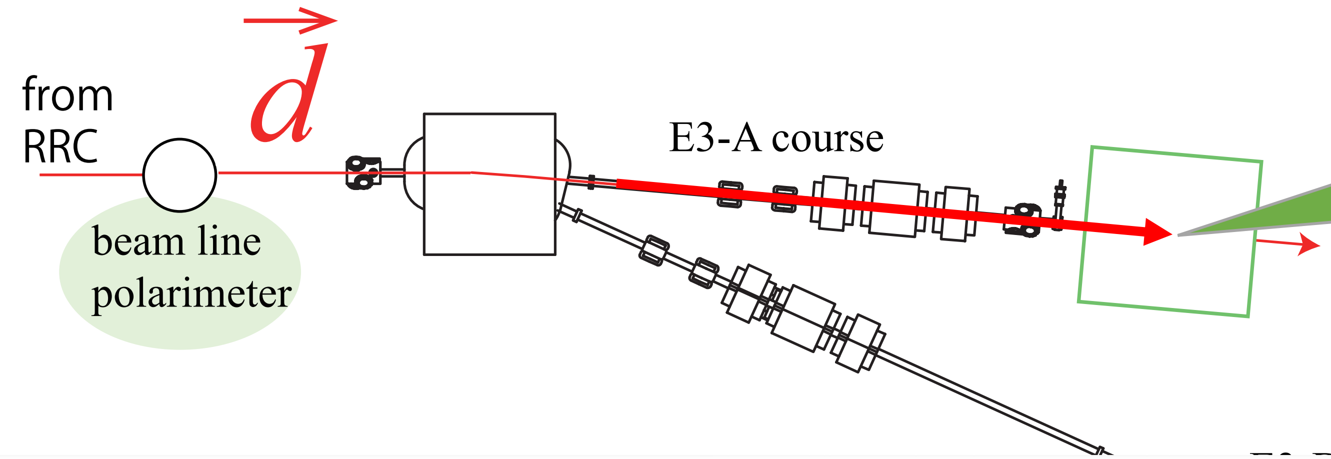


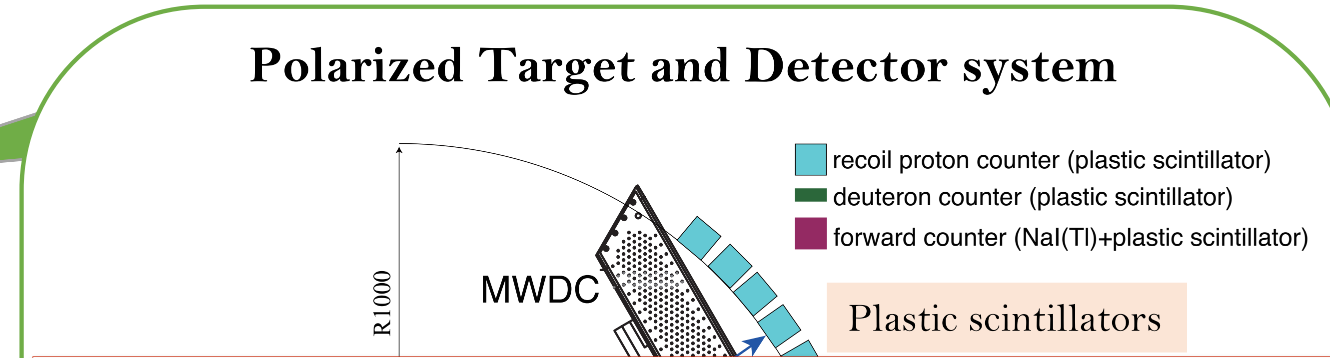


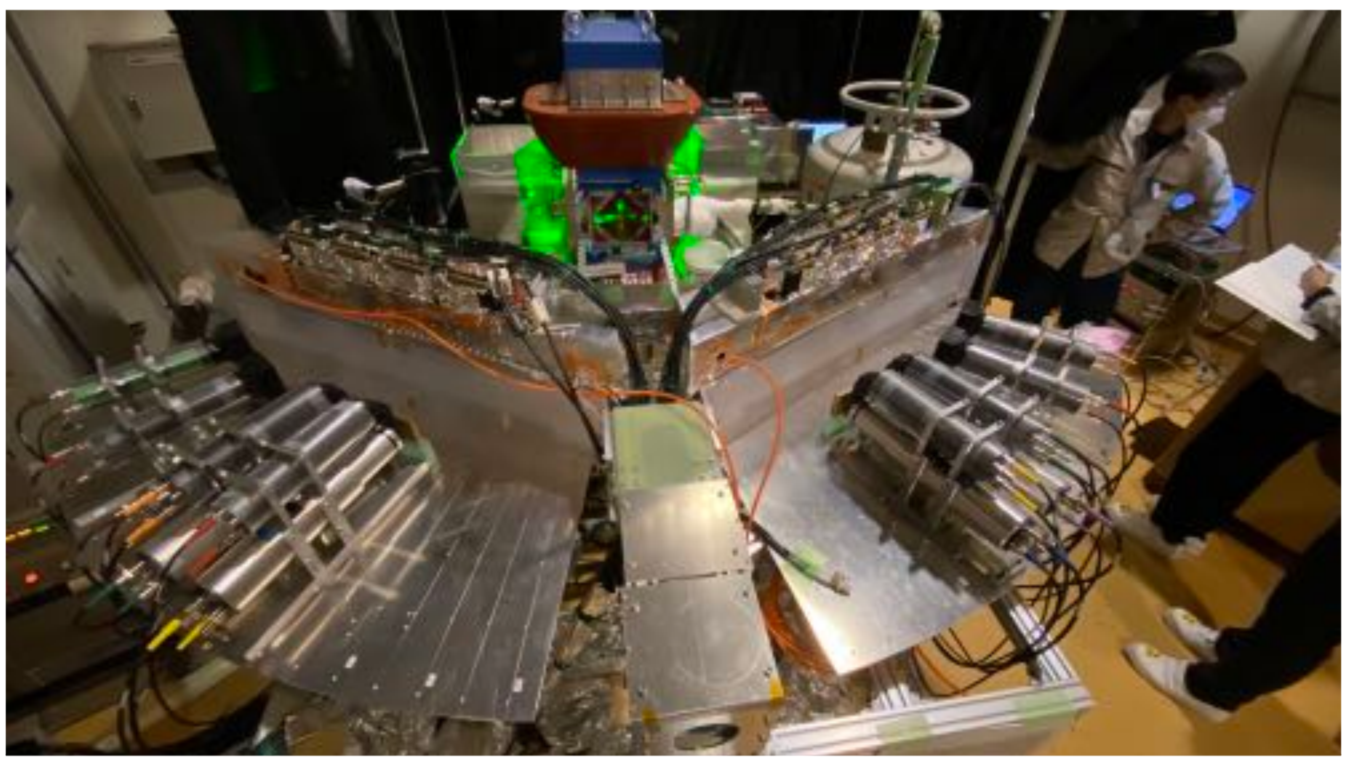
- Measured Angles : 12 angles in $\theta_{c.m.}$ (37° −155°)
- Detectors
  - Forward/Backward angles in c.m.
    : *E-dE* (NaI(Tl)+Plastic scintillators)
  - Middle angles in c.m.
    : Plastic scintillators
    "*d*"&"*p*" are detected in kinematical coincidence conditions.
  - Angular spread : $\Delta\theta$(lab.) = ±2°
  - MWDCs : correction of the scattering angles

All experimental equipments are in preparation now.

Layout of Experiment of the spin correlation coefficients for *dp* Elastic Scattering

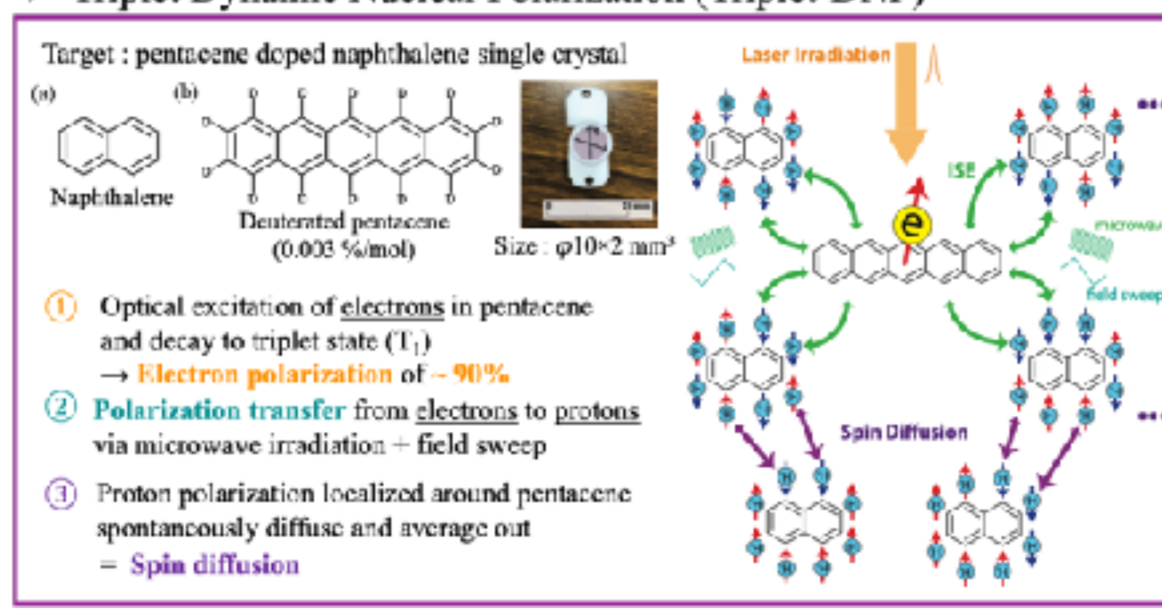






Polarized Solid Proton Target

➢ Triplet Dynamic Nuclear Polarization (Triplet-DNP)



All experimental equipments are in preparation now.

Poster by Yuko Saito

$p+^3$He Scattering

Talk by Atomu Watanabe

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*

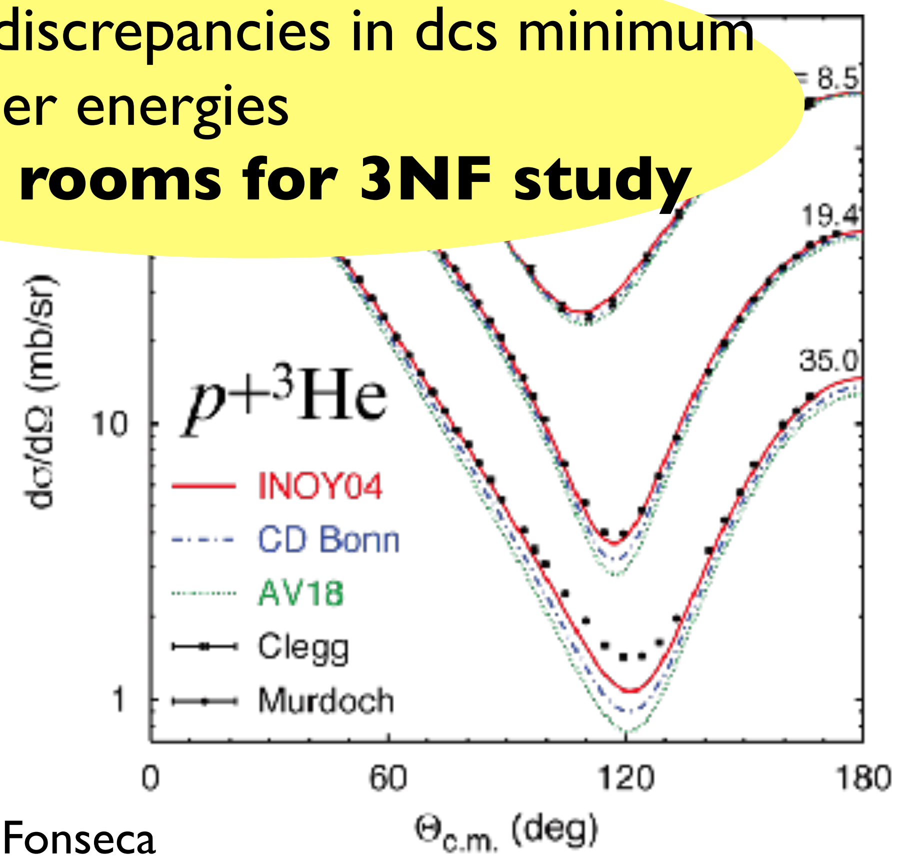
Theory in Progress

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

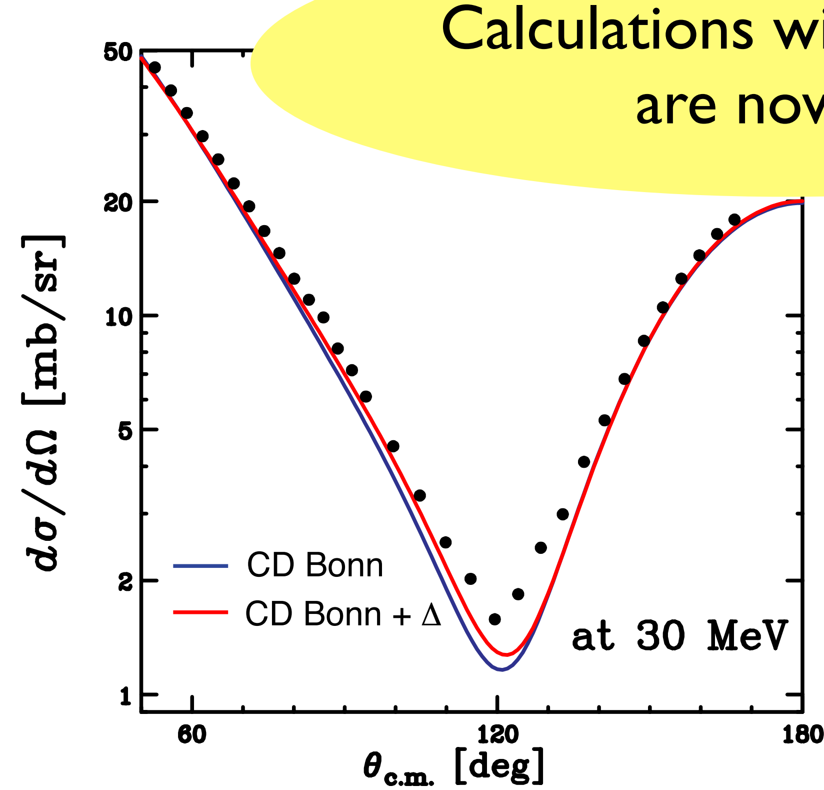
→ new possibilities for 3NF study in 4N scattering at higher energies

Large discrepancies in dcs minimum at higher energies

New rooms for 3NF study



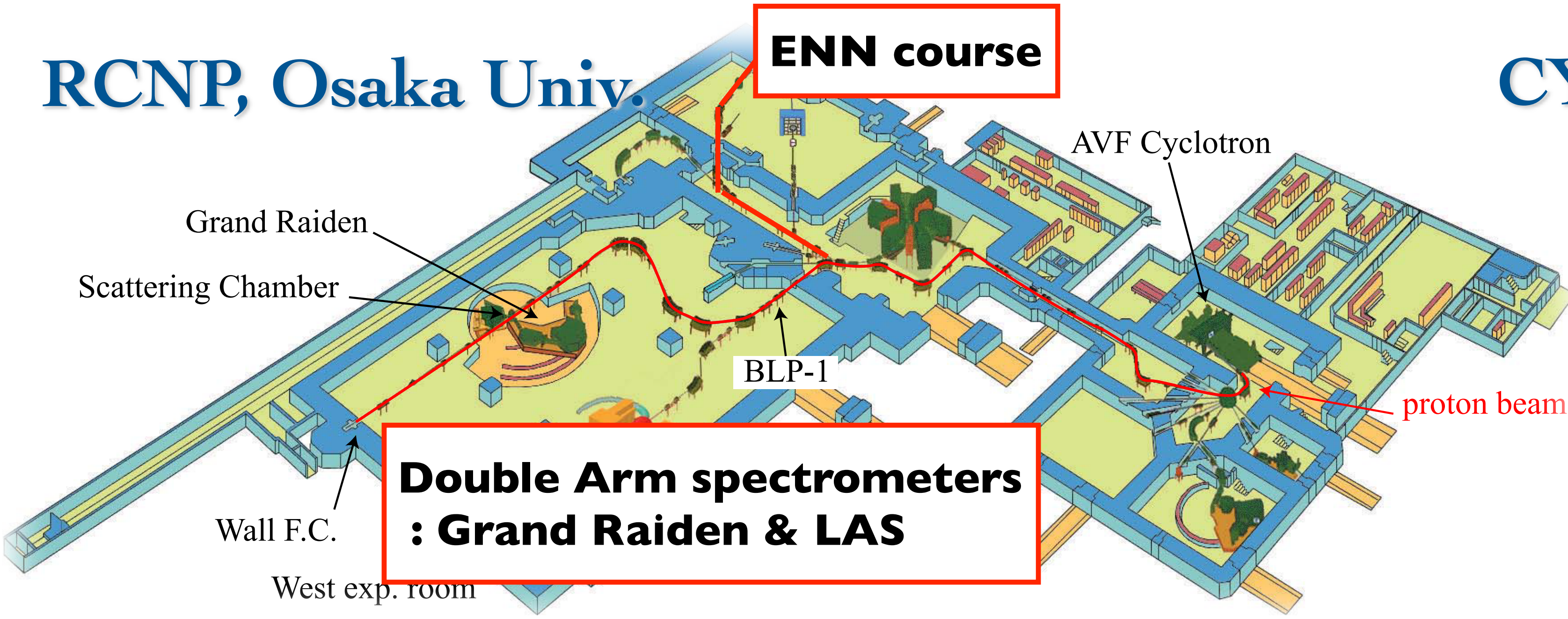
Calculations with 3NFs are now in progress !



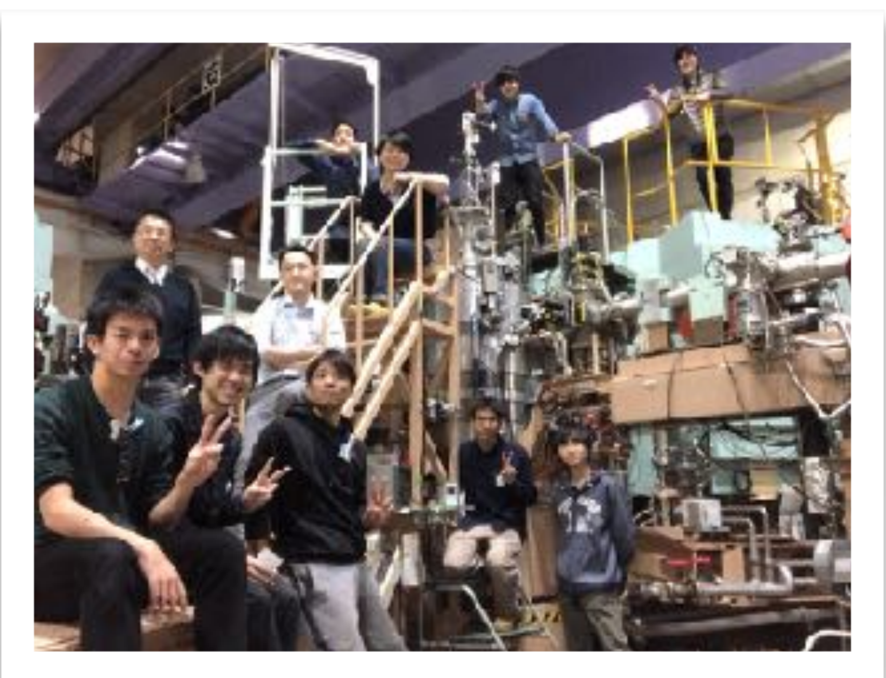
A. Deltuva and A.C. Fonseca
Phys. Rev. C 87, 054002 (2013)

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

RCNP, Osaka Univ.



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



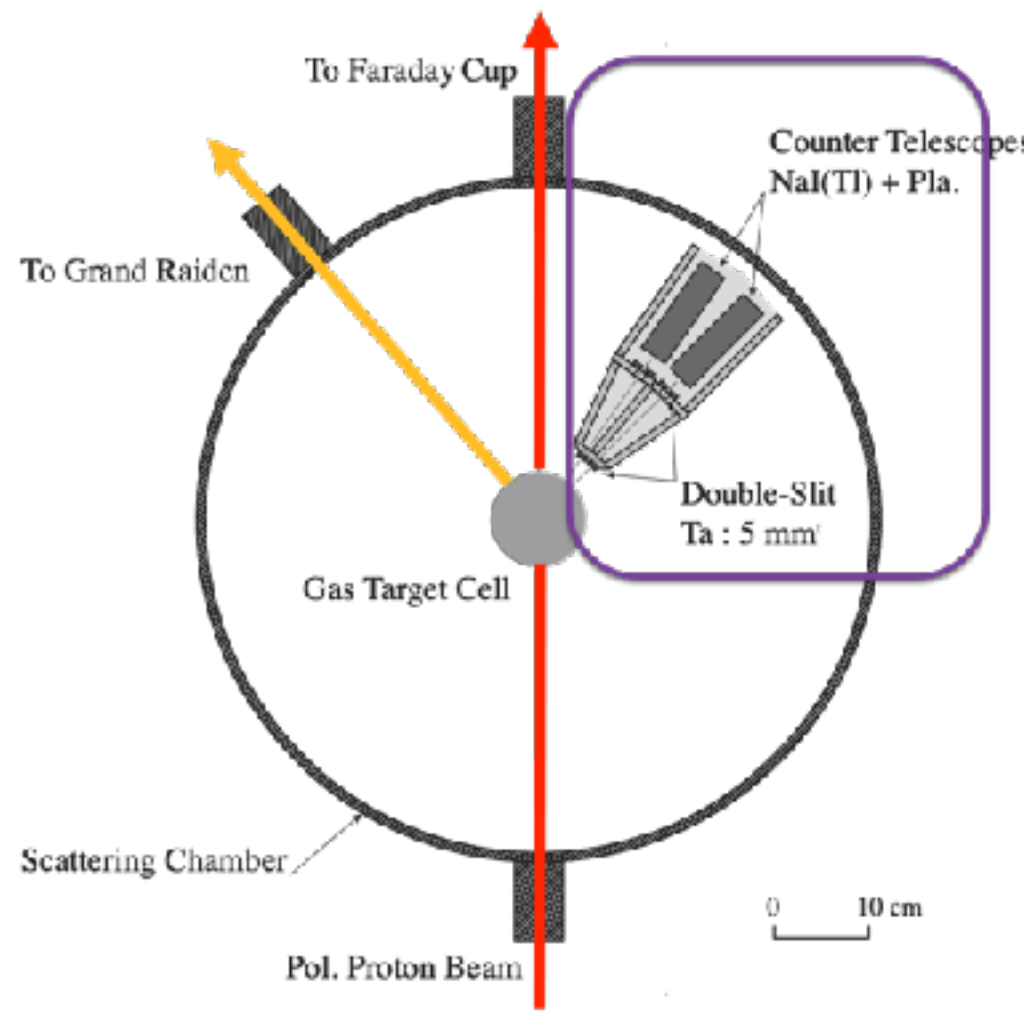
CYRIC, Tohoku Univ.

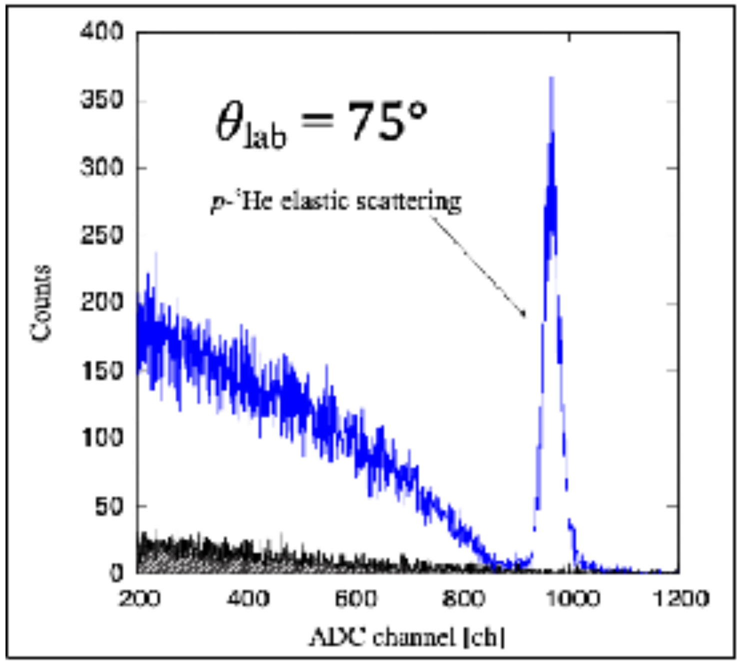
- p beam : 10 - 80 MeV
- Beam Intensity : 10-20 nA

Measurement of the Cross Section at RCNP

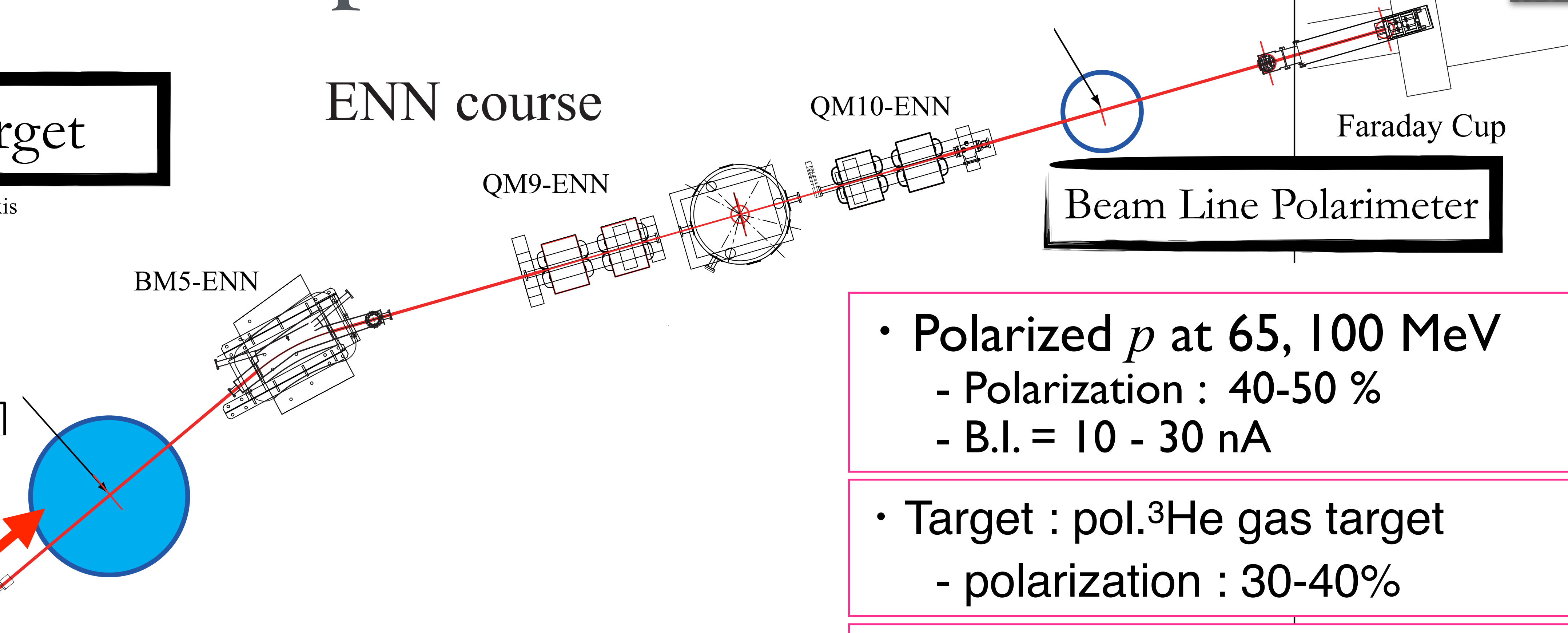
Measurement Condition

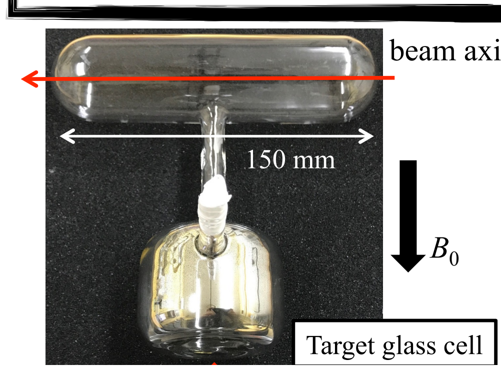
- Beam Energy 65 MeV
- Target : ^{3}He gas
  with double slit system
  - 1 atm, room temperature
- Detector system
  - ΔE-E detectors (Plastic+NaI(Tl))
    in the scattering chamber
  - Grand Raiden : beam monitor
- Measured Angles :
  $$\theta_{\mathrm{c.m.}} = 27^\circ - 170^\circ \, (\theta_{\mathrm{lab.}} = 20^\circ - 165^\circ)$$
- *pp* scattering
  with the same detection setup
  - estimate of the overall systematic uncertainties

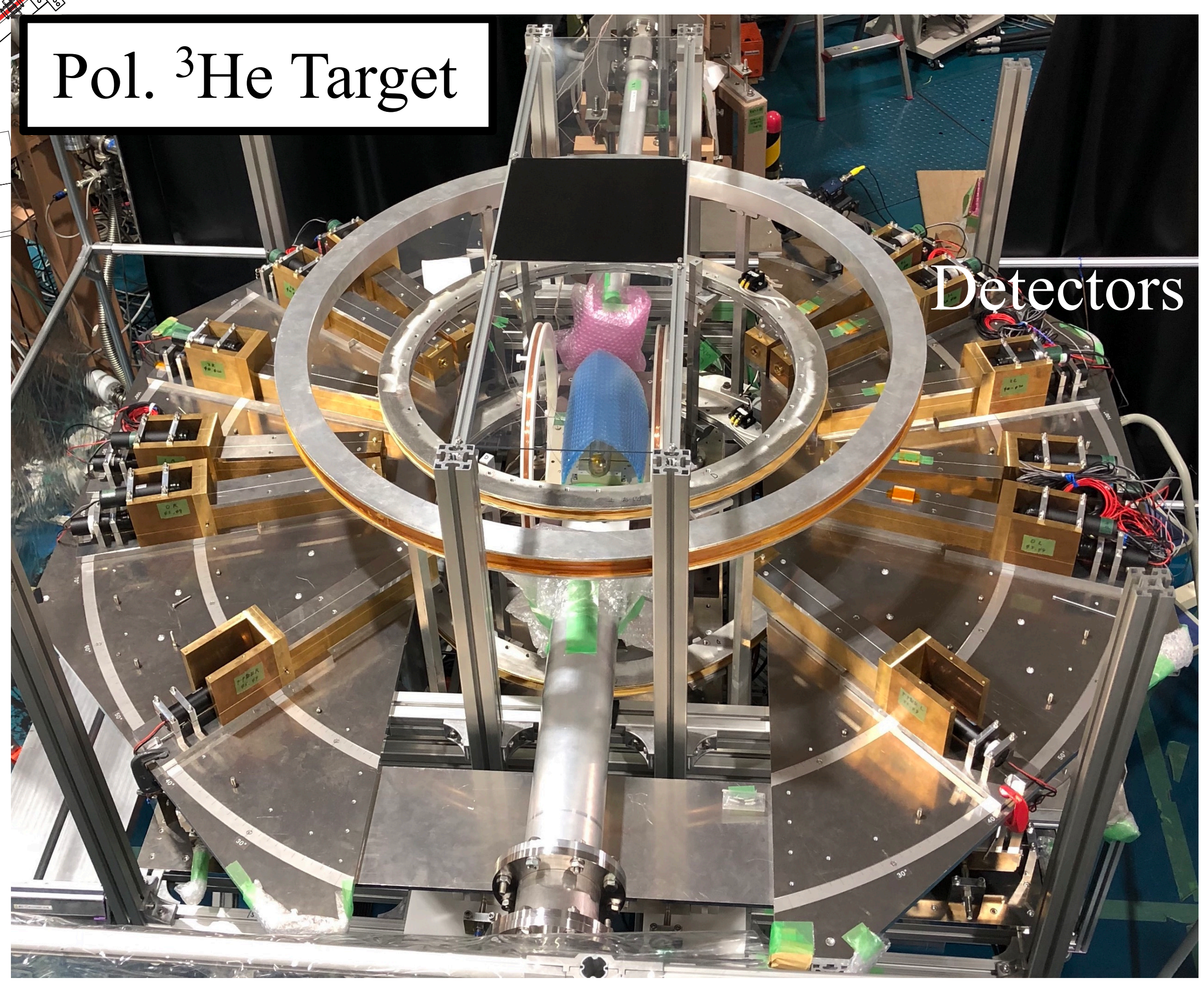




pol.p+pol.³He experiment at RCNP







- Polarized p at 65, 100 MeV
  - Polarization : 40-50 %
  - B.I. = 10 - 30 nA

- Target : pol.³He 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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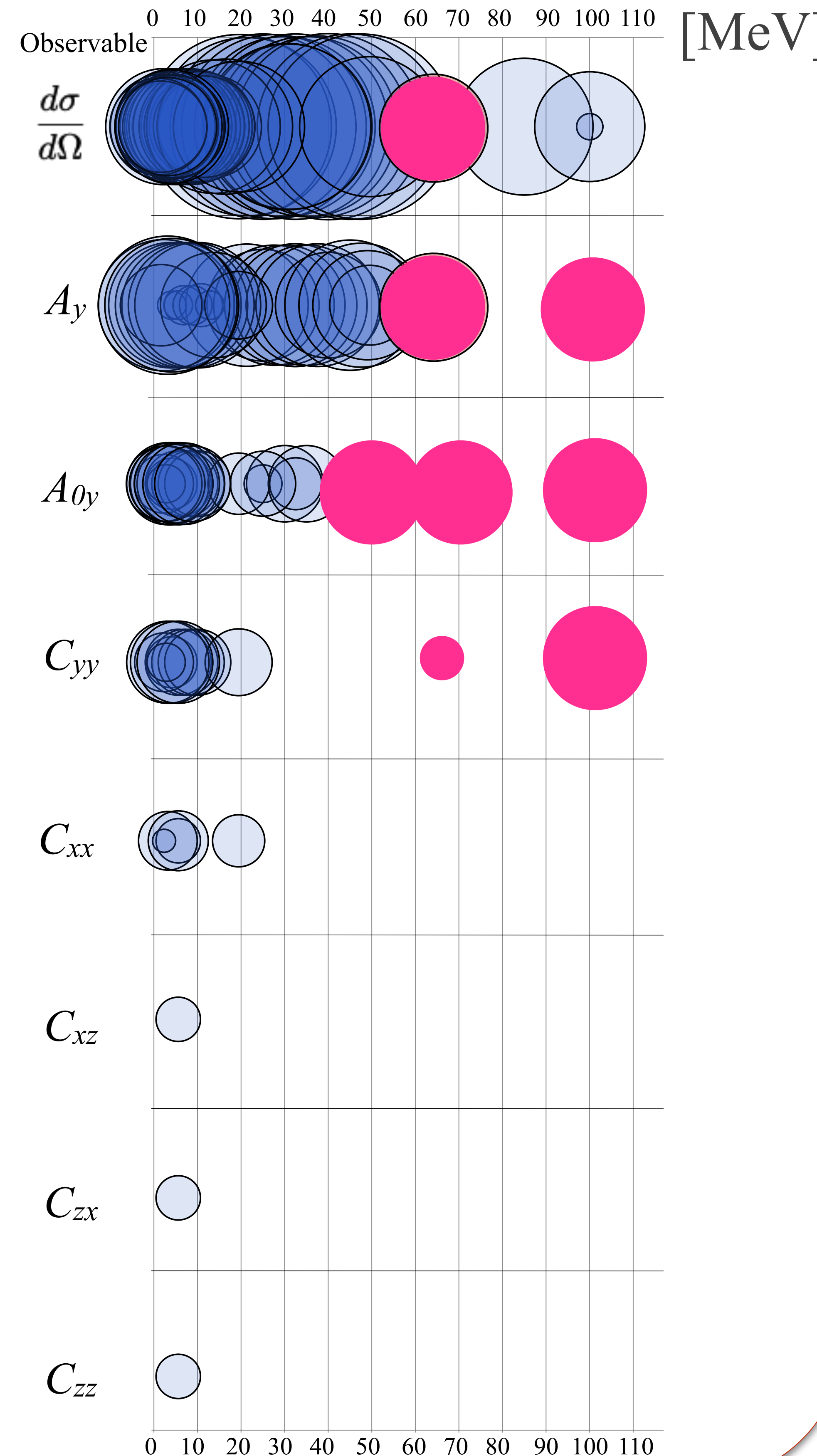
Facility	CYRIC, Tohoku Univ.	CYRIC, Tohoku Univ.
Exp. Course	41 course	41 course

data from RCNP/CYRIC

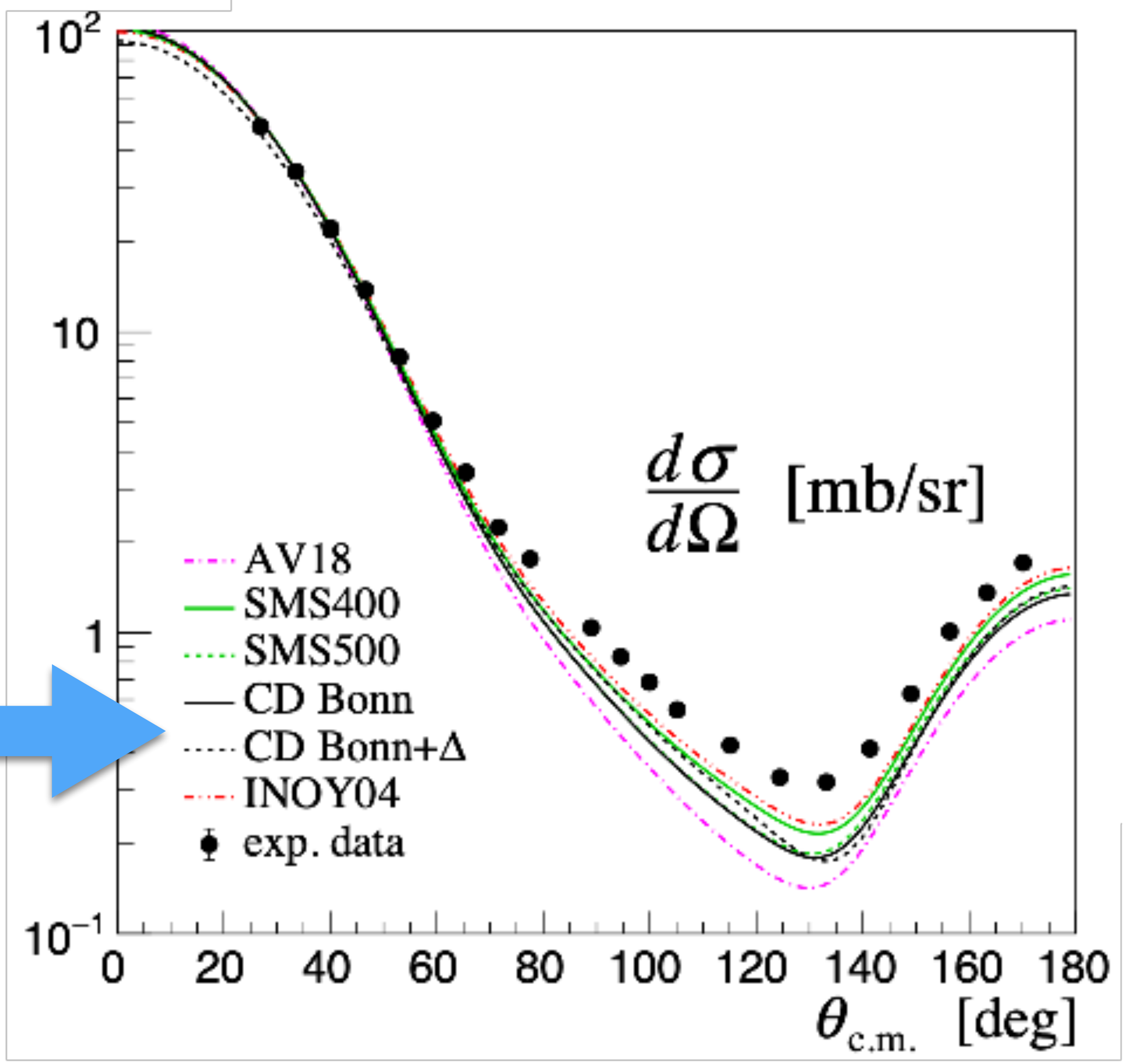
p-^{3}He scattering at 5-100 MeV

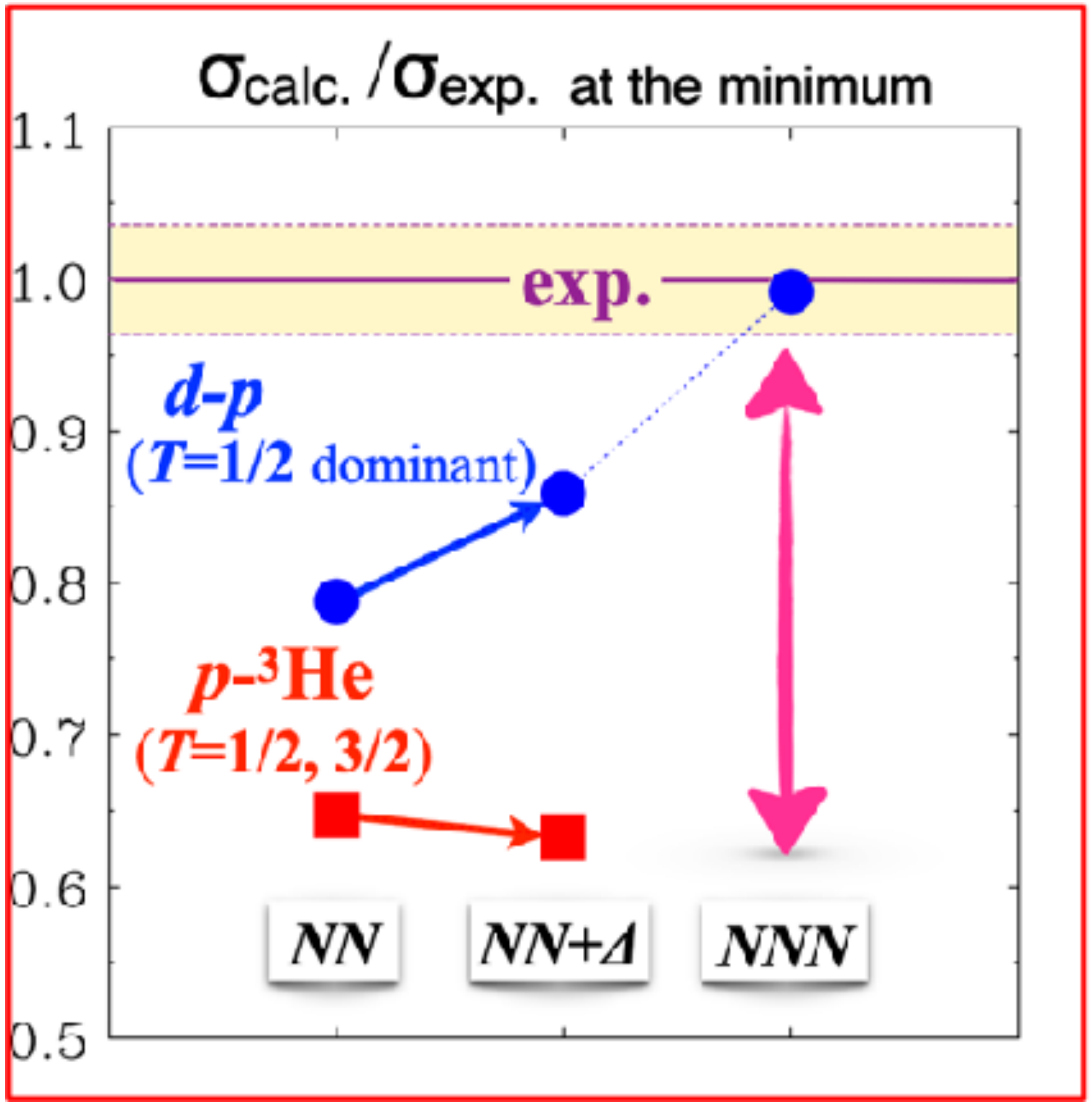


New Data of p+^{3}He at Intermediate Energies

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

Cross Section at 65 MeV



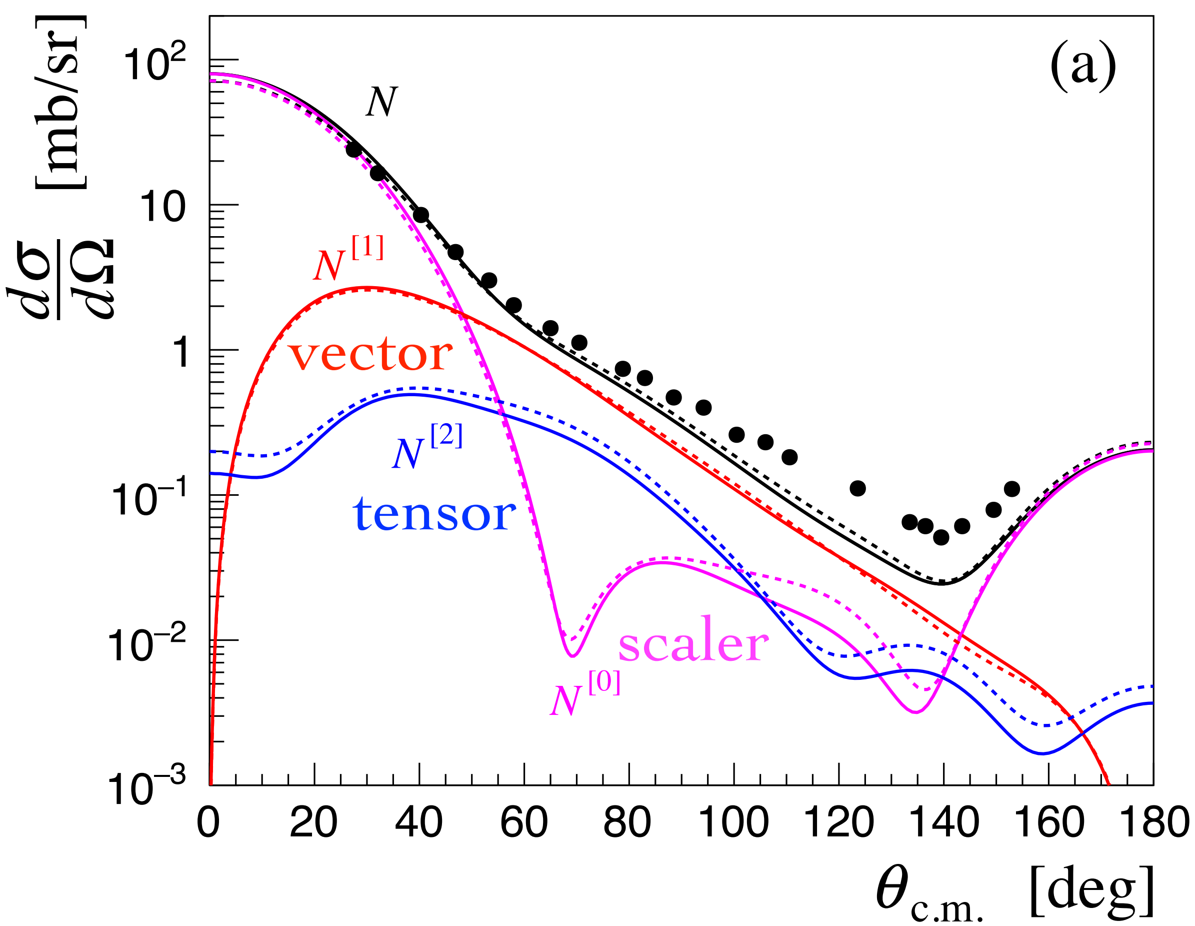


p+^{3}He scattering at intermediate energies is an excellent tool to explore nuclear interactions not accessible by *Nd* scattering.

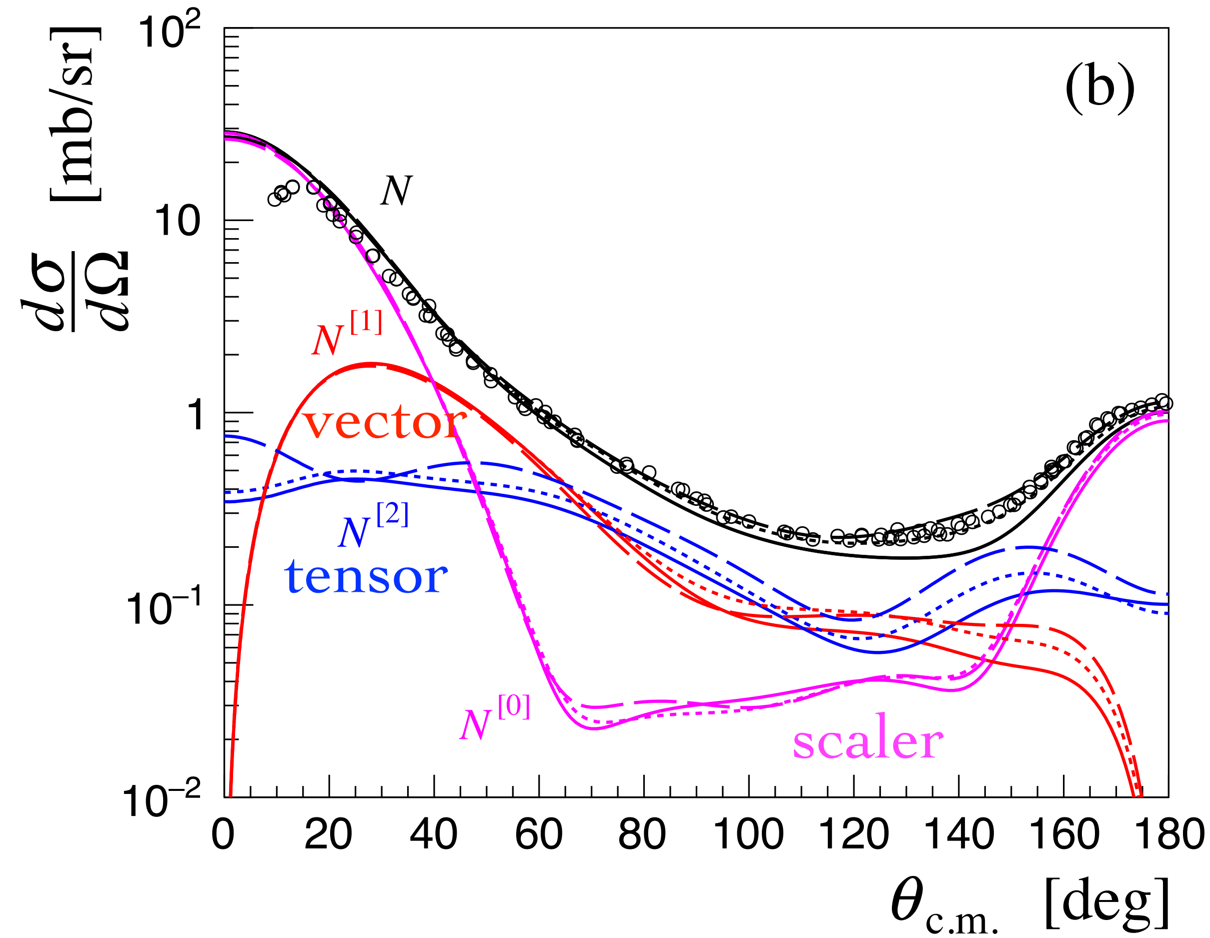
New Data of p+^{3}He at Intermediate Energies

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

p-^{3}He at 100 MeV



d-p at 135 MeV/N



Analysis of Scattering Amplitudes :

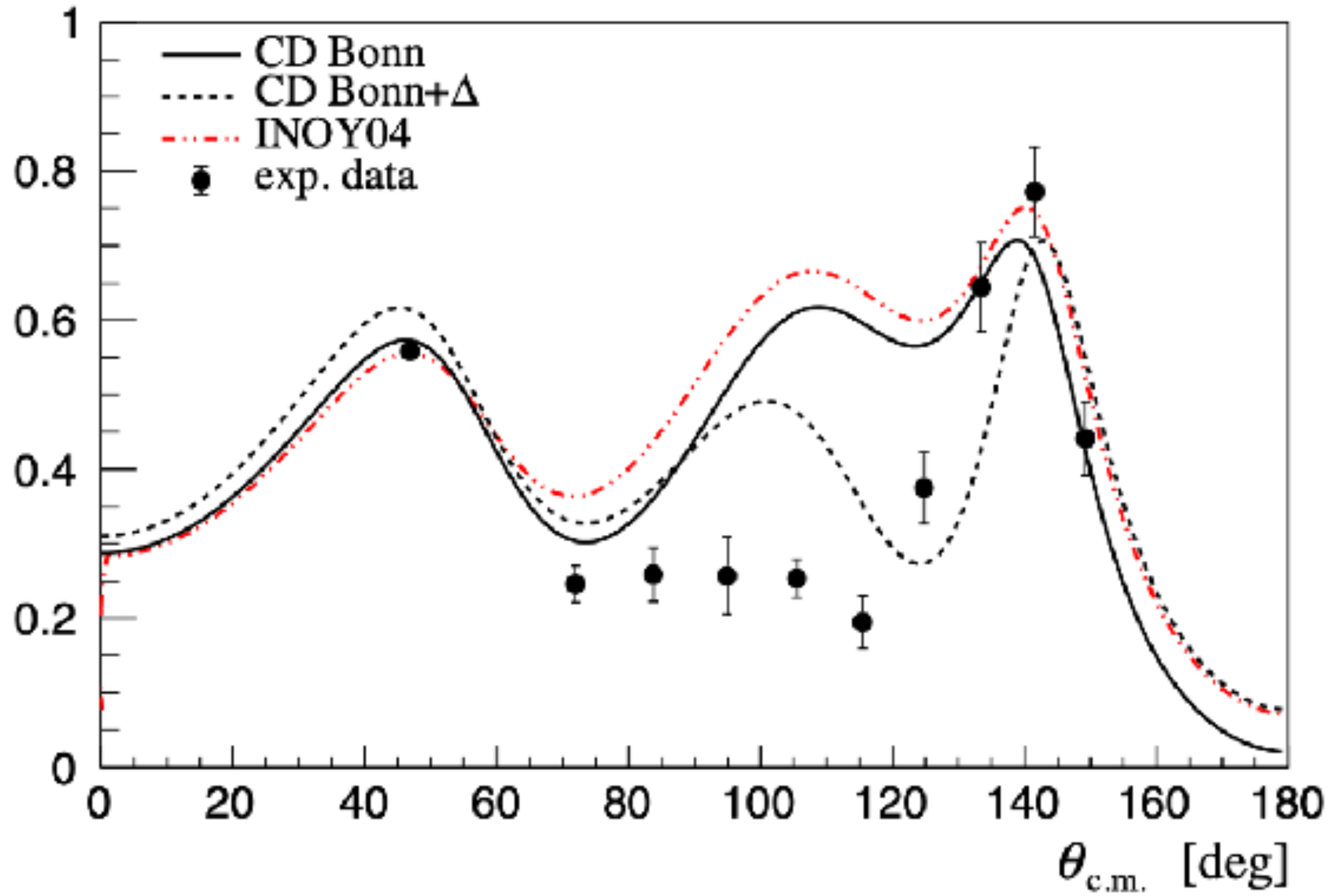
Vector components are sensitive for p-^{3}He,

while vector and tensor components for d-p.

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

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

$C_{y,y}$ at 100 MeV



Spin correlation coefficient $C_{y,y}$ is sensitive to Δ-isobar or those including 3NFs that are masked in nucleon-deuteron elastic scattering.

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 $\partial\sigma/\partial\Omega$ and spin observables at 70- 300 MeV/nucleon from RIKEN/RCNP

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 ?

New Project :
Measurement of spin correlation coefficients at 100 MeV/nucleon
- Determination of LECs N4LO 3NFs from ∂p scattering data
is about to start.

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

RIBF-*d*. Collaboration (2009〜)

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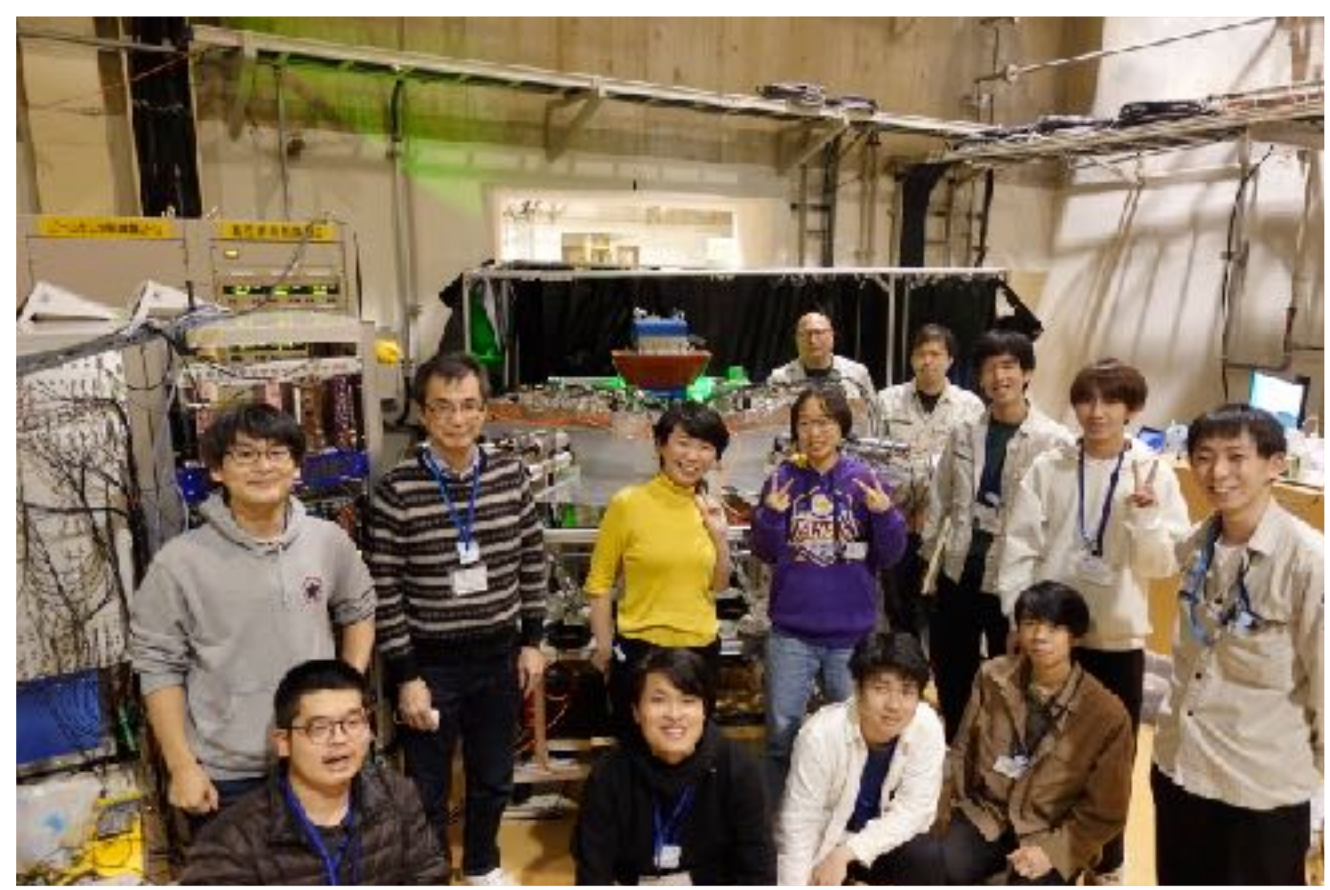

Exp. at HIMAC (2022)

p-^{3}He Collaboration

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T. Wakui

CYRIC, Tohoku Univ. (2016)

RCNP, Osaka Univ. (2018)