Experiments of Few-nucleon scattering to Explore Three-Nucleon Forces

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Opportunities and Challenges in Few-Body Physics: Unitarity and Beyond

Three-Nucleon Force (3NF)

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

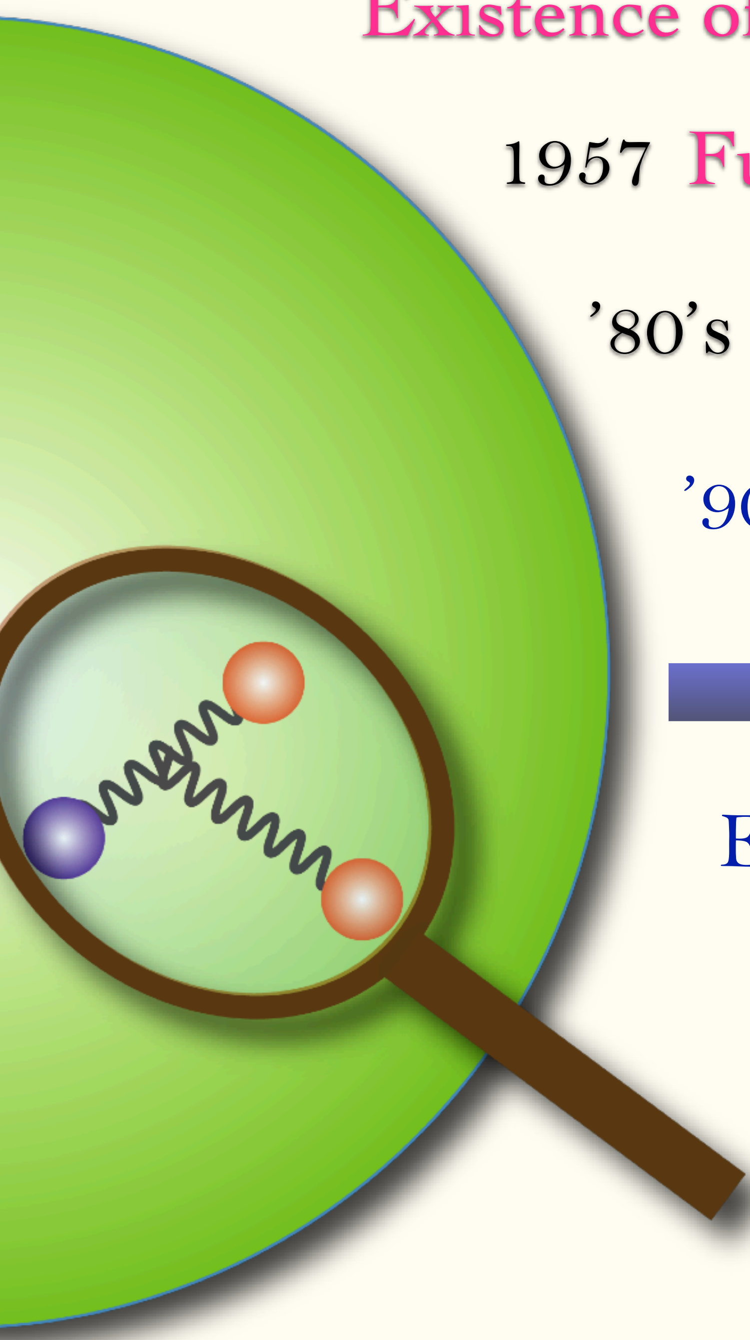
Key to fully understand properties of nucleus

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

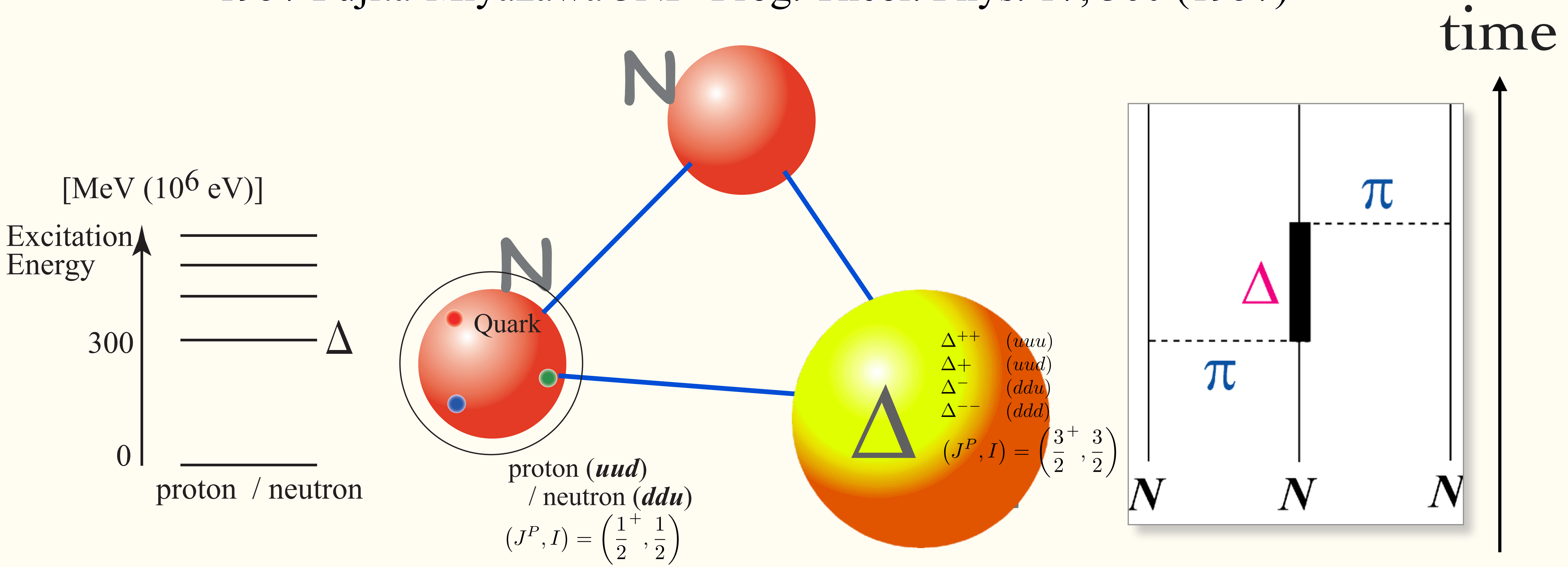
- Nucleon-Deuteron Scattering at Intermediate Energies
- Biding Energies / Levels of Light Mass Nuclei
- Equation of State of Nuclear Matter

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.

Three-Nucleon Force

- **2π-exchange 3NF :**
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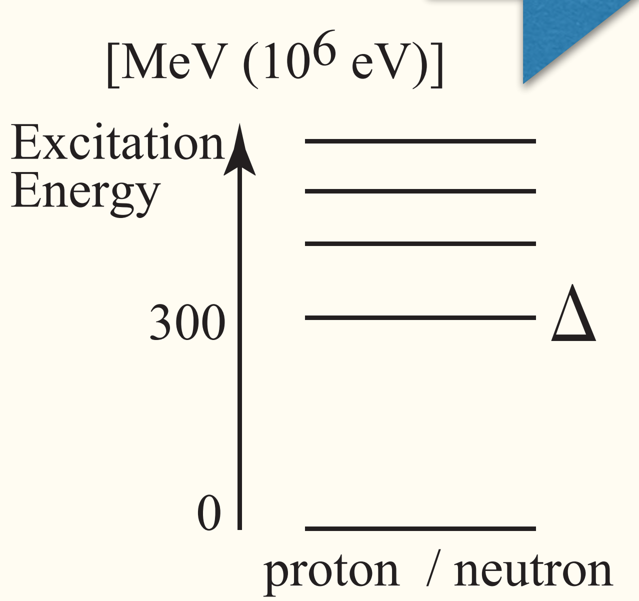
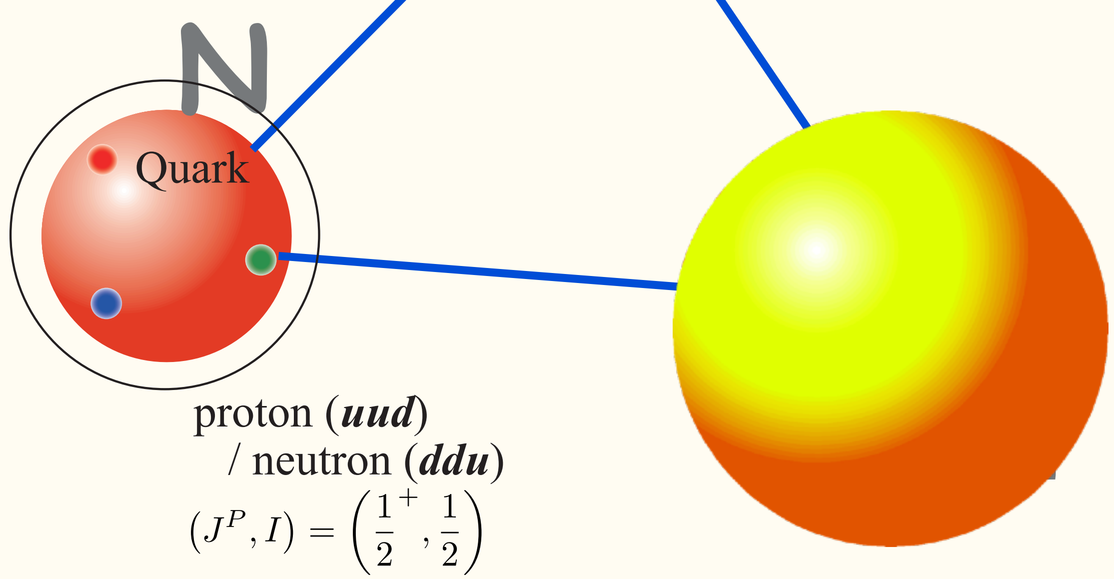
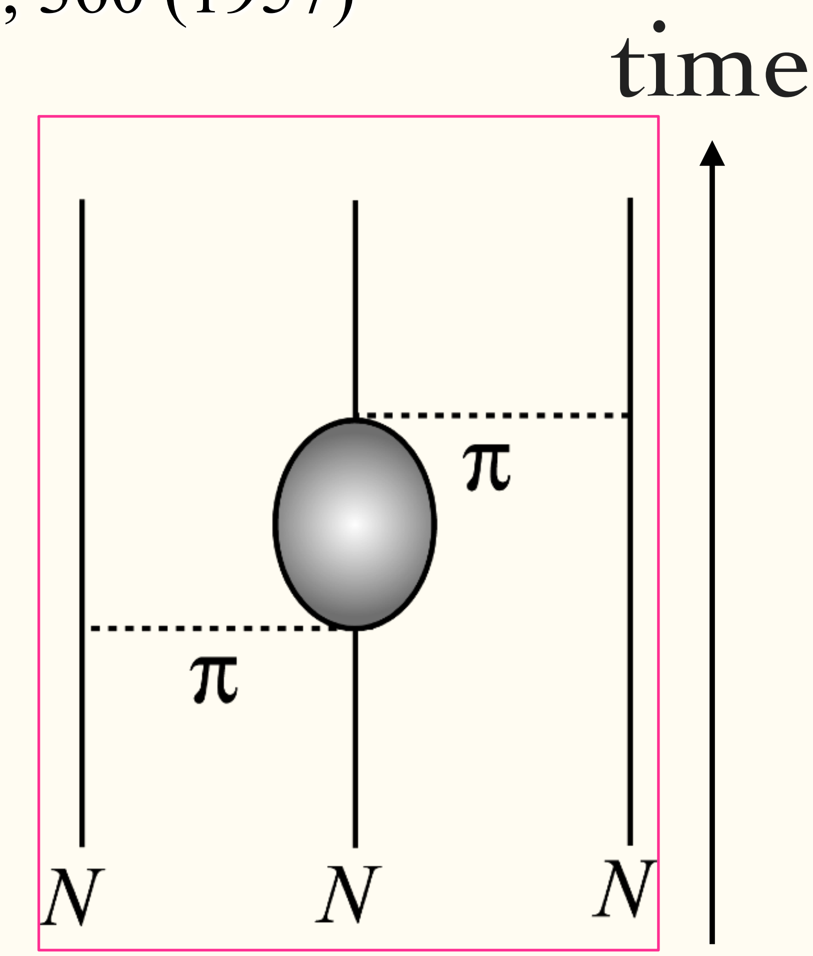
- Tucson-Melbourne (TM)
- Urbana IX
- Brazil, Texas etc…







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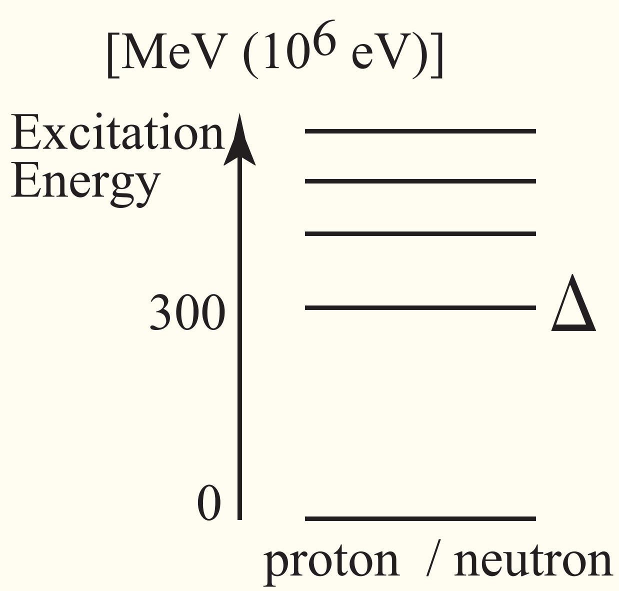
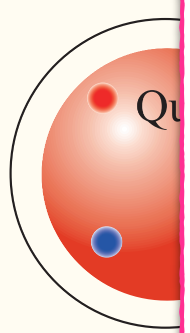
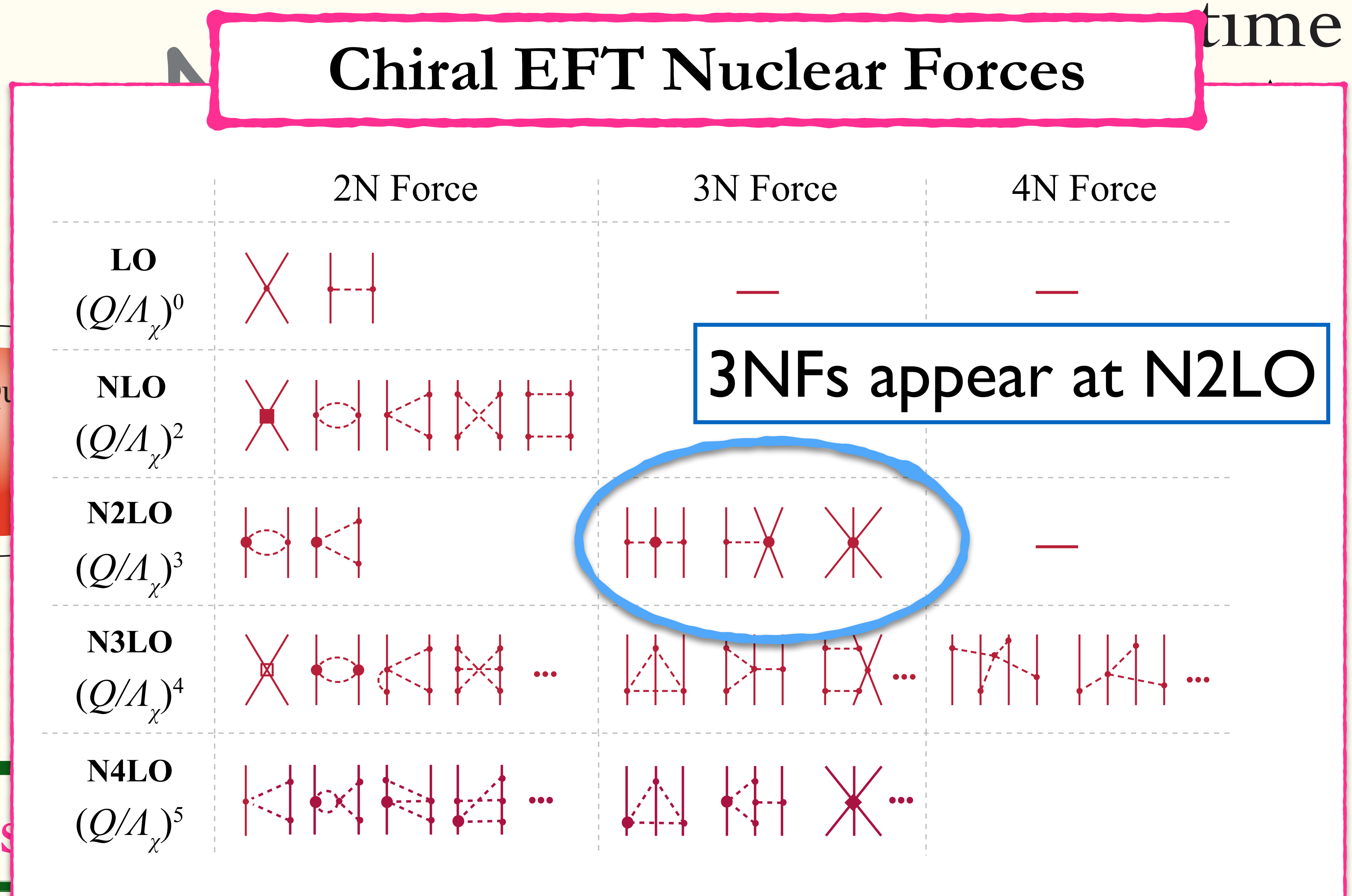
time



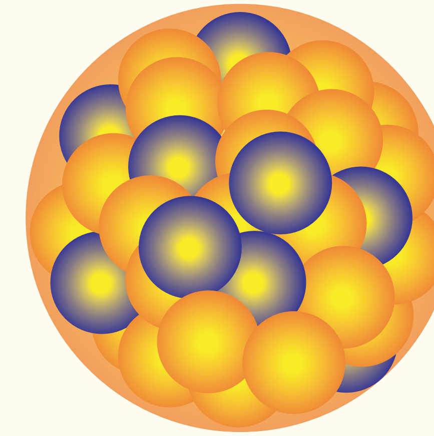




3NF naturally aris

Where ?

3NFs in A>3 - ① -

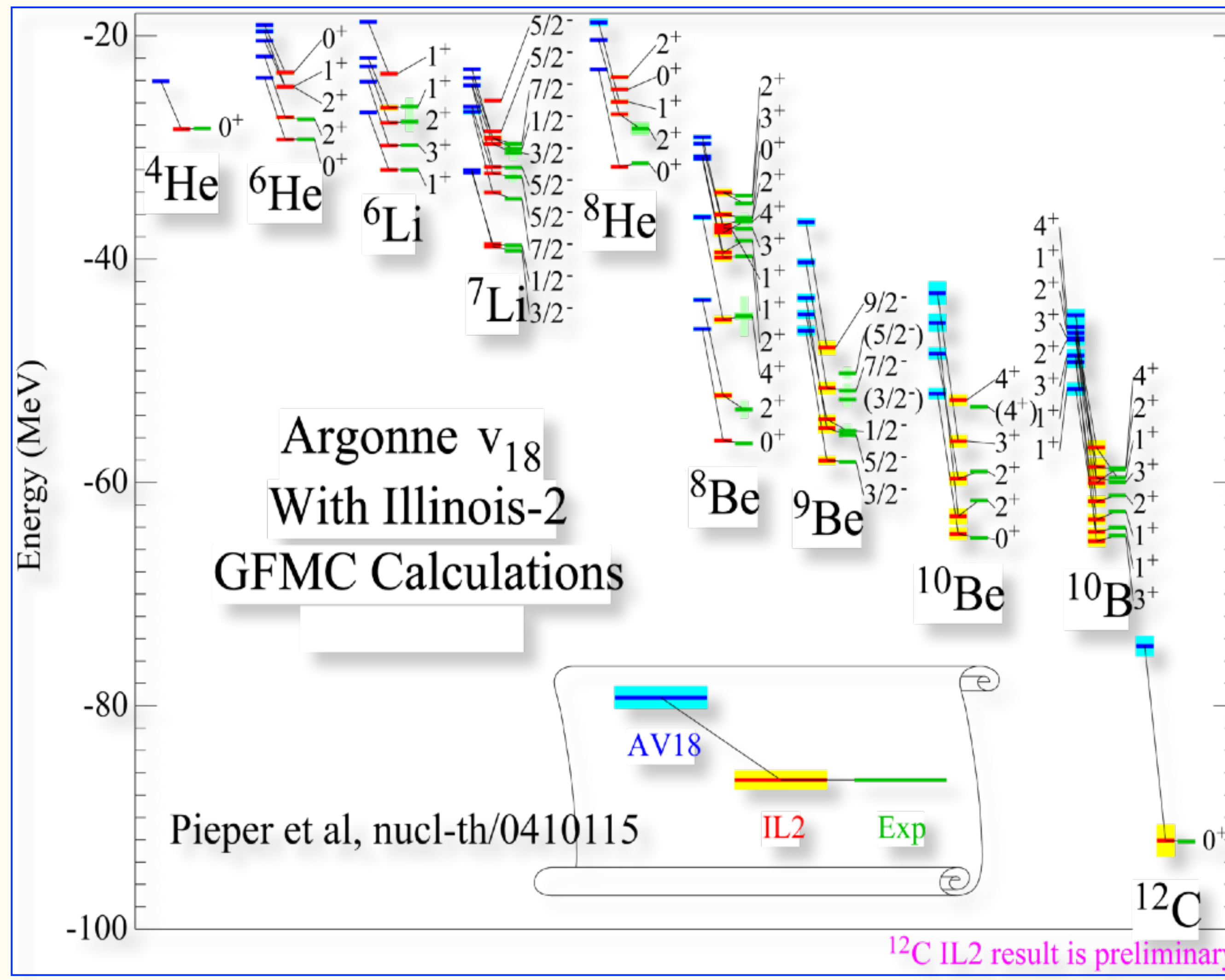


3NFs in Finite Nuclei

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

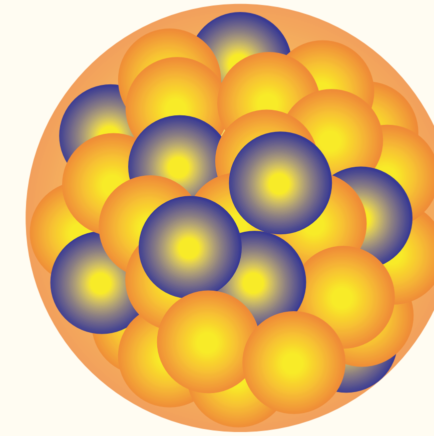
    IL2 3NF (Illinois-II 3NF) :
    2π-exchange 3NF
    + 3π-ring with Δ-isobar



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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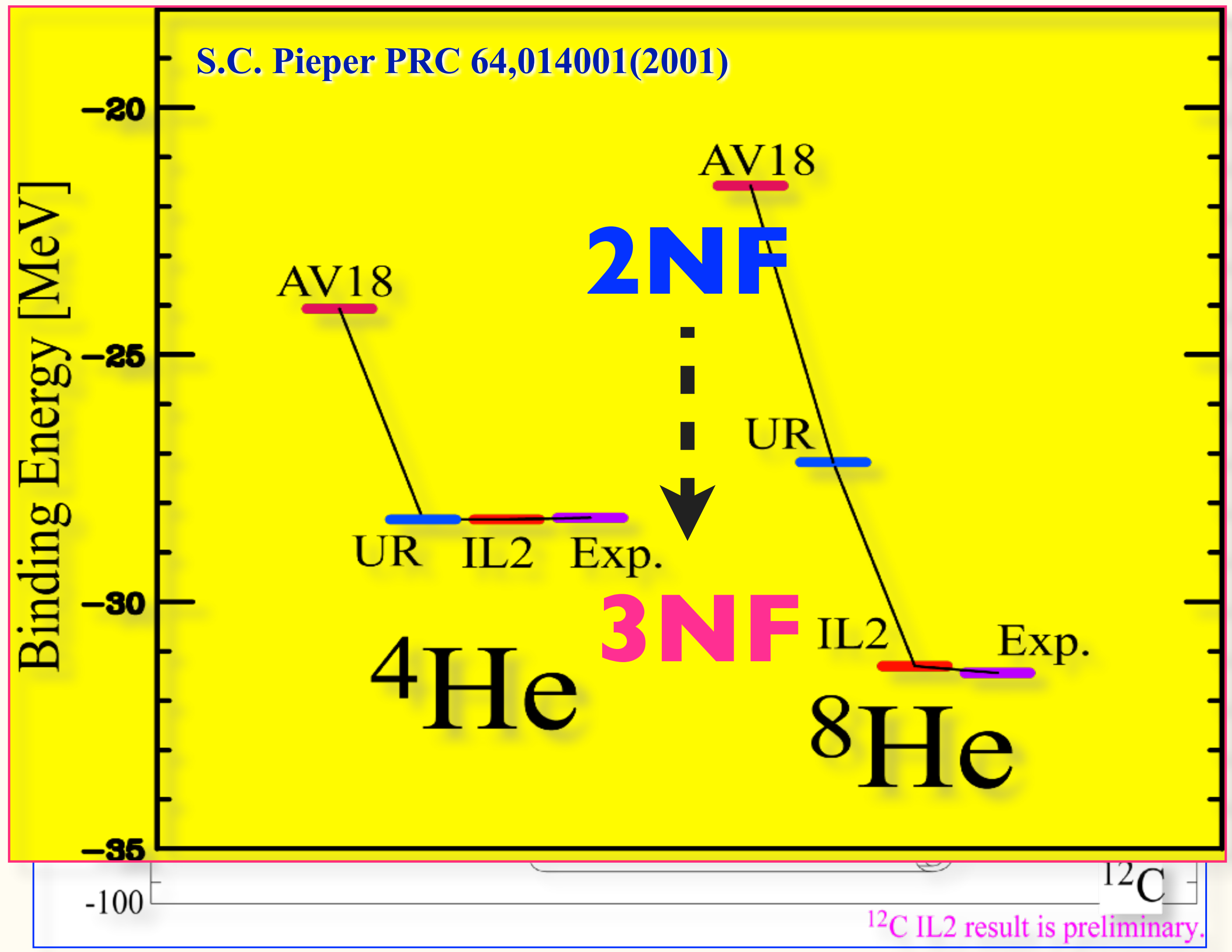

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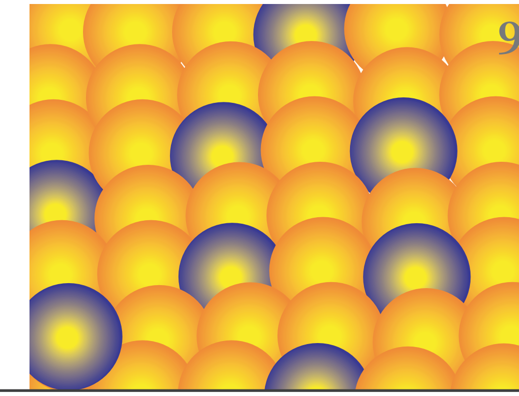
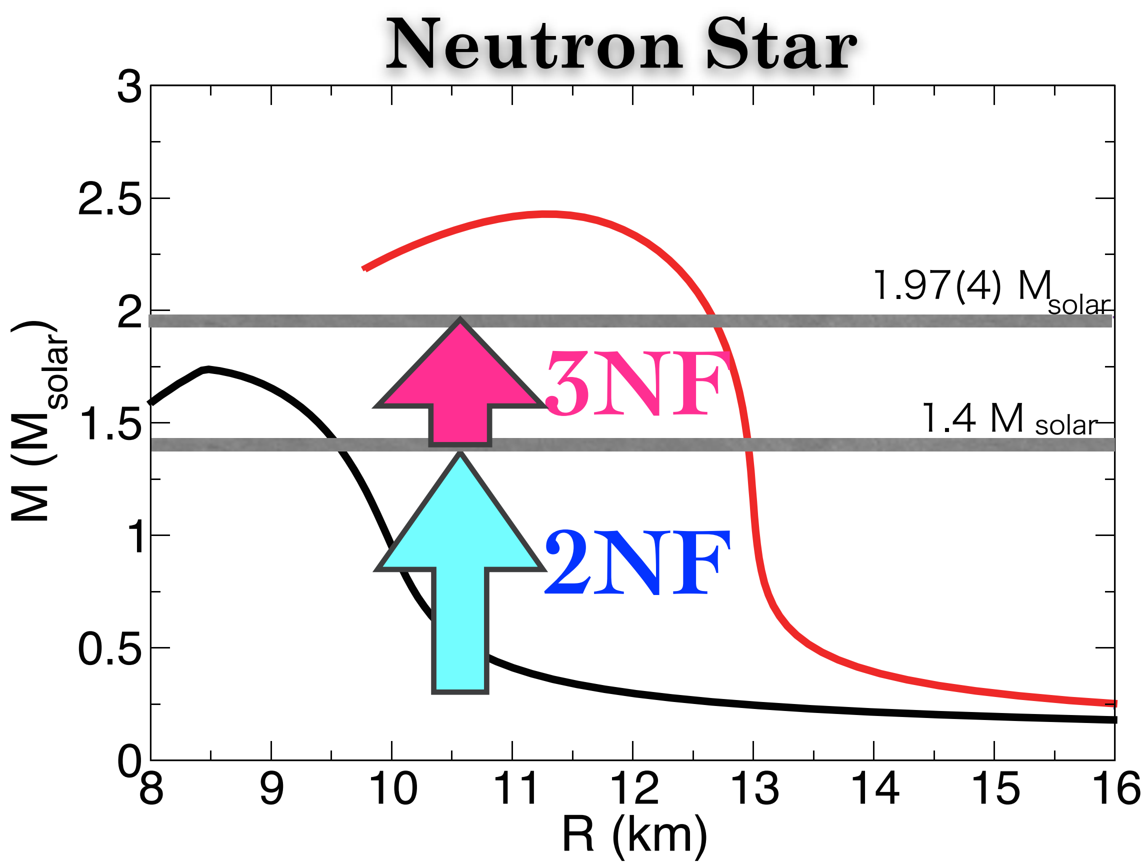


3NFs in Infinite Nuclei - Neutron Star -



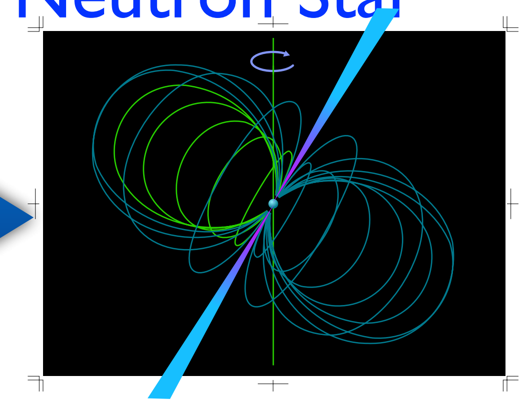
A. Akmal et al., PRC 58, 1804('98)

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

"Endpoint of stellar evolution"

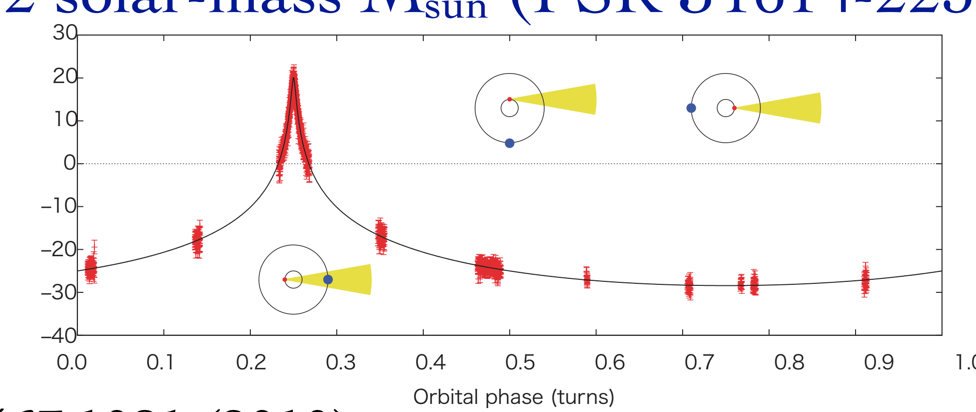
Supernovae Explosion

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

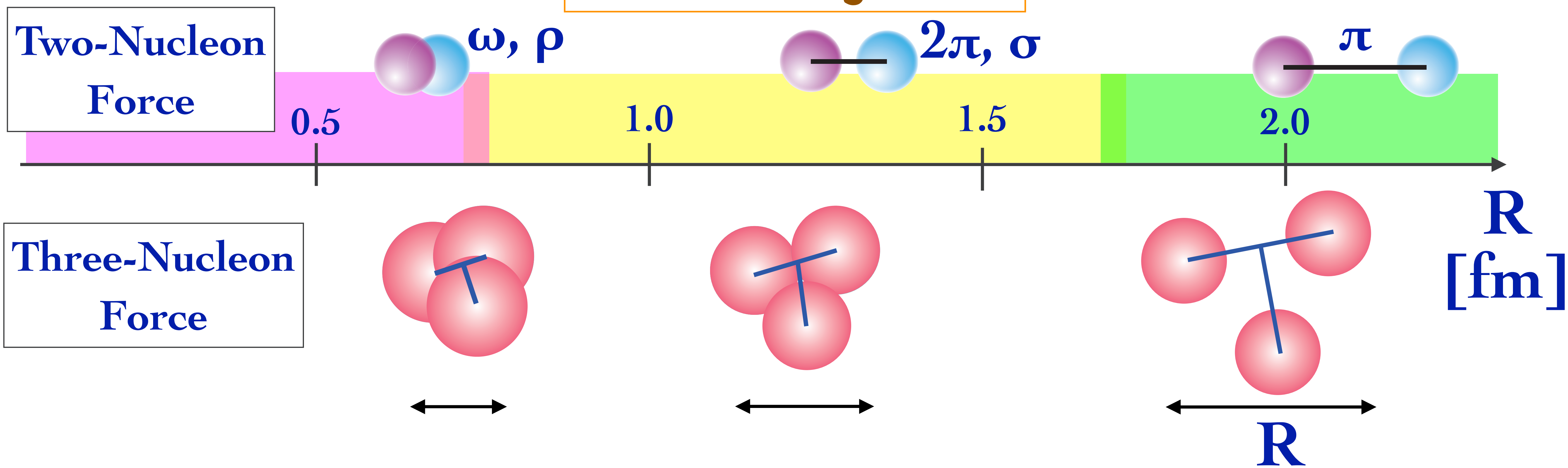
-Short Range-

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	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

Where is the hot spot for study of 3NFs ?

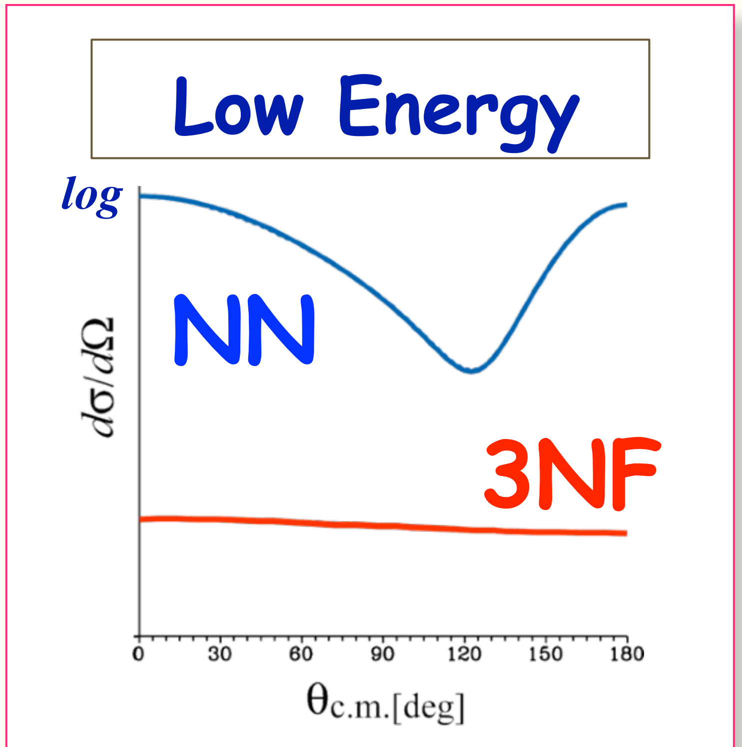
Nucleon-Deuteron Scattering

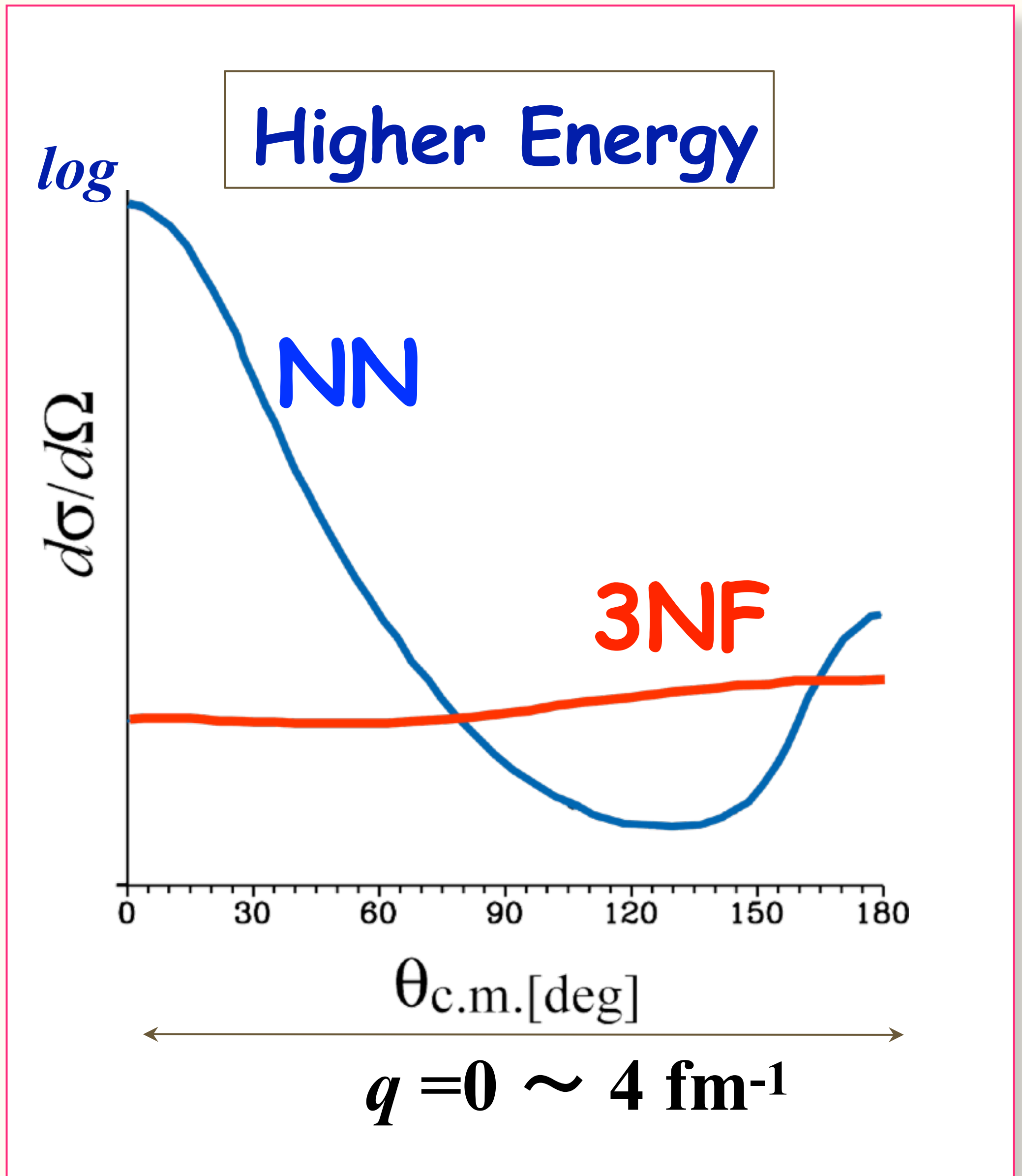
To study momentum & spin dependences

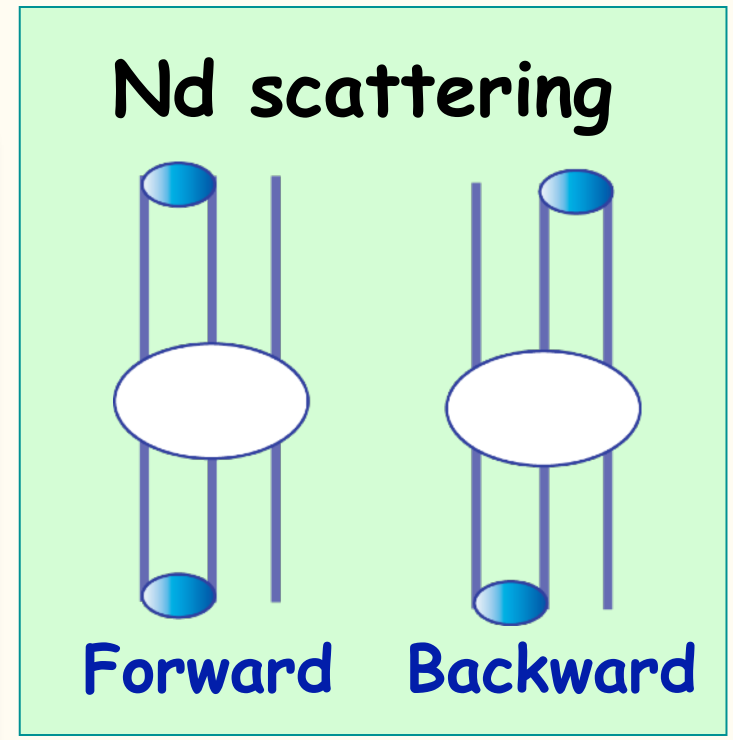
Iso-spin dependence : T=1/2 only

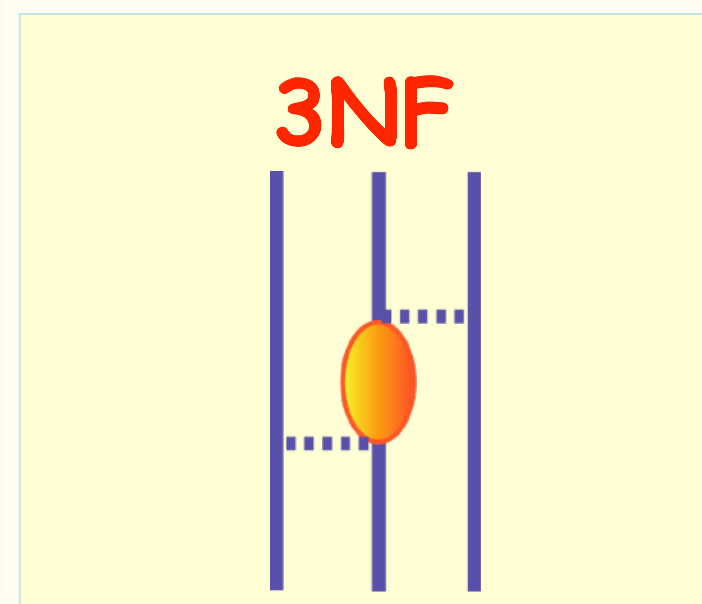
Predictions by H. Witala et al. (1998)

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

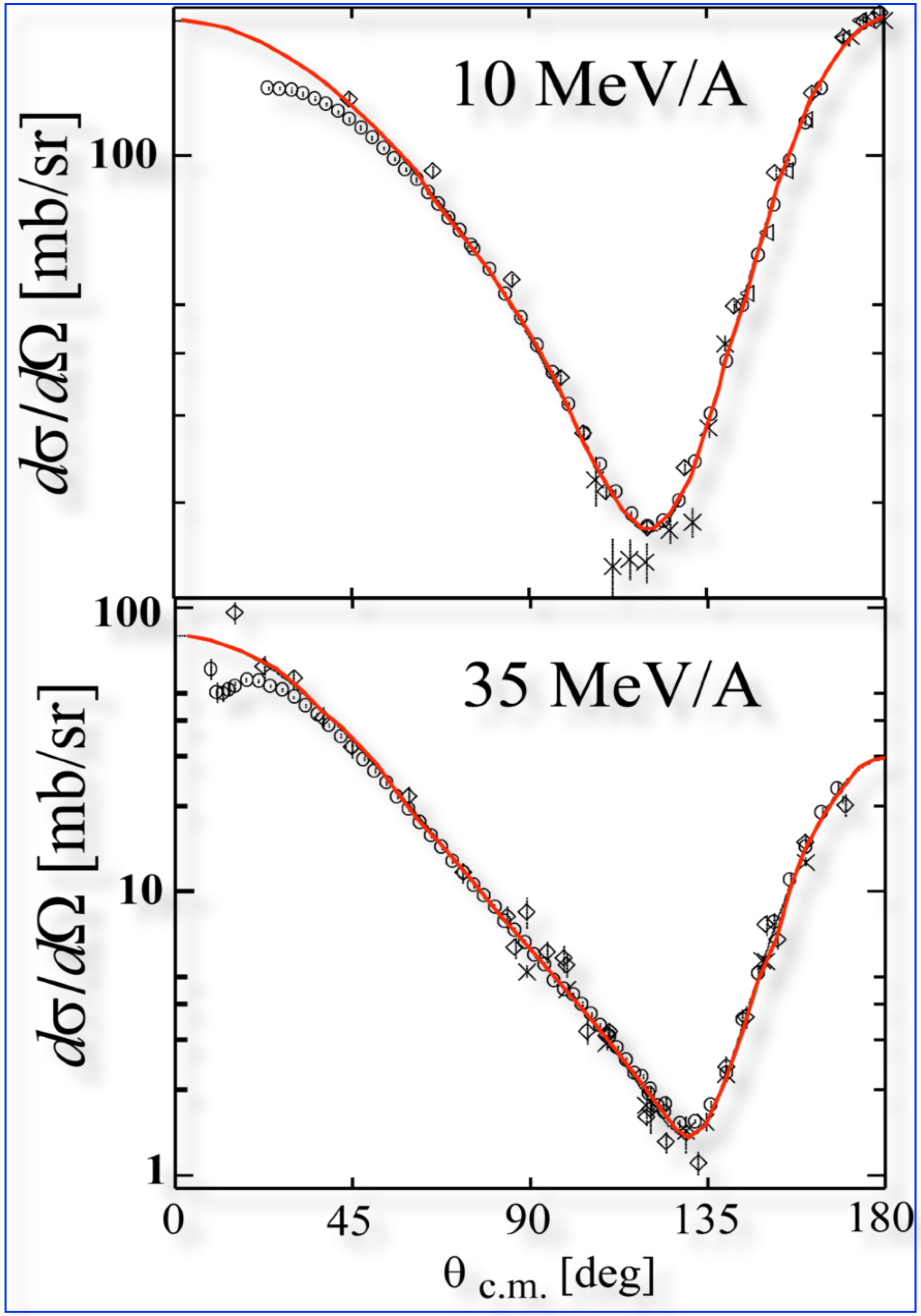








Nd Scattering at Low Energies ($E \leq 30$ MeV/A)



- 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..

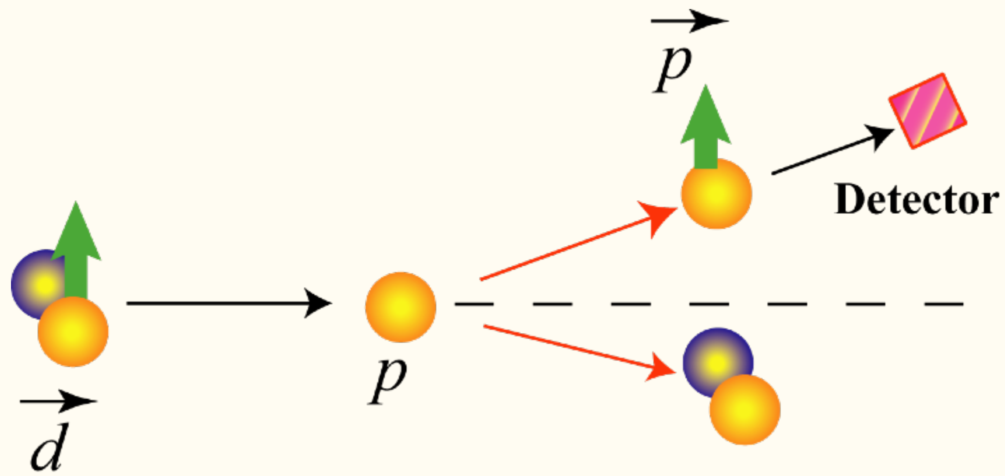
W. Glöckle et al., Phys. Rep. 274, 107 (1996).

Observables for *Nd* Scattering

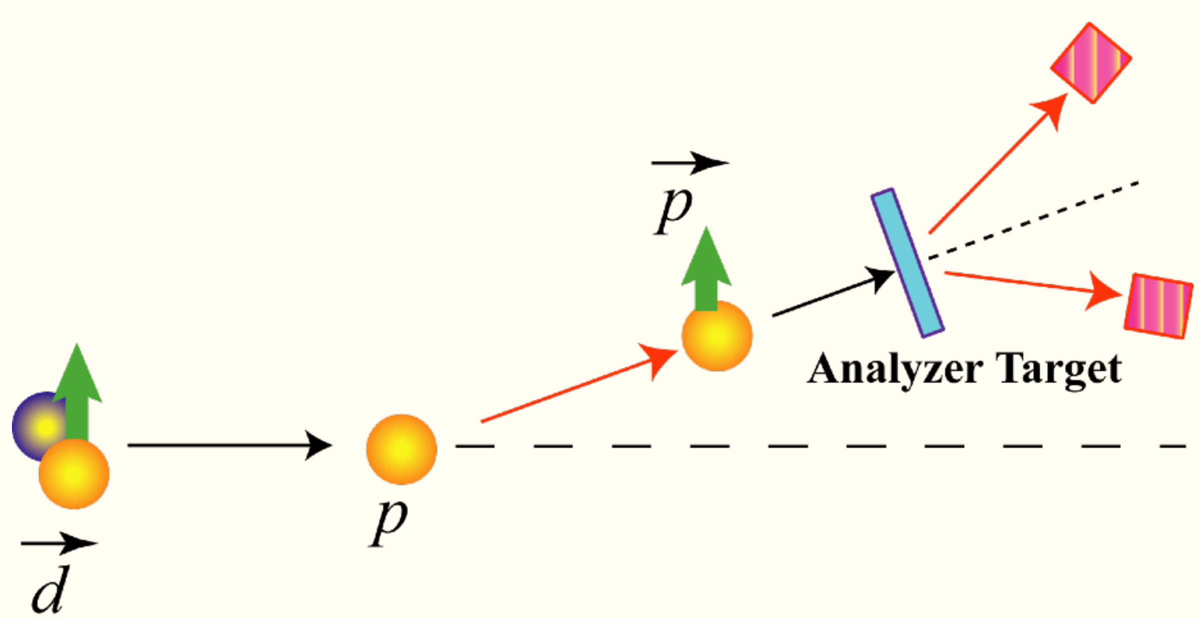
- **Differential Cross Section**
  - **Overall Strength**
  - ➢ **Absolute Quantity : normalization to *pp or np* data**

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

- **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**



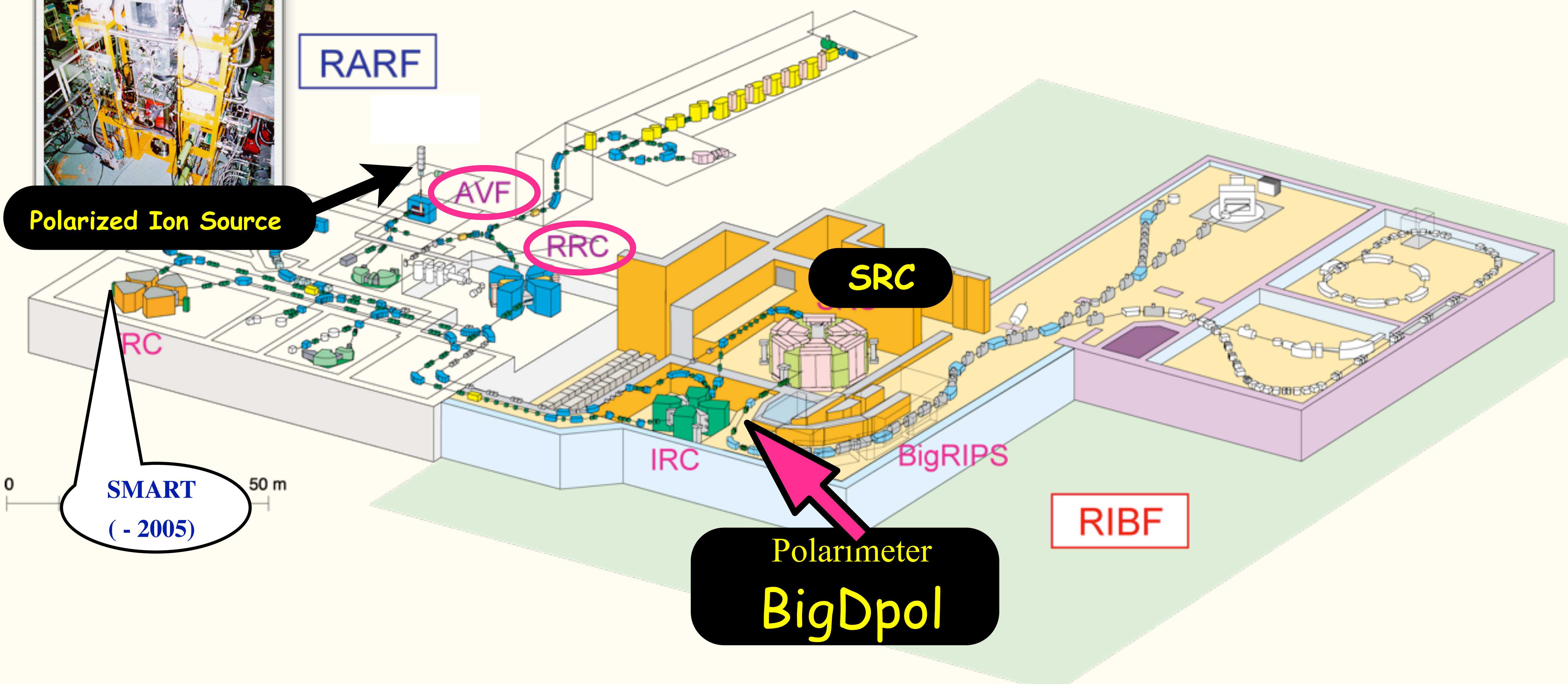
  - **Polarization Transfer Coefficient : $K_{ij}^{l'}$**
  - **Spin Correlation Coefficients : $C_{ij,k}$**
    - **Spin-Spin interaction**



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 !

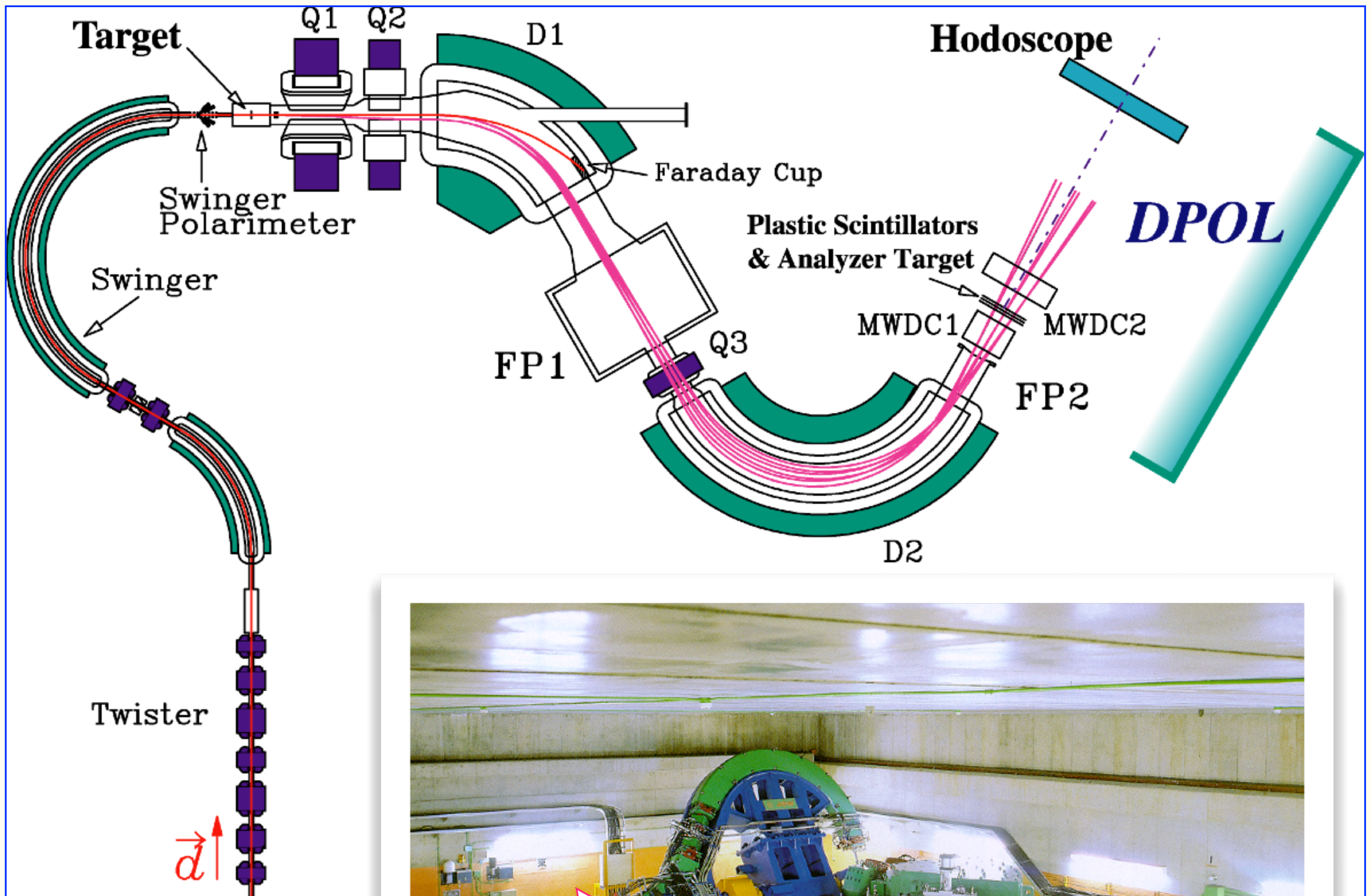


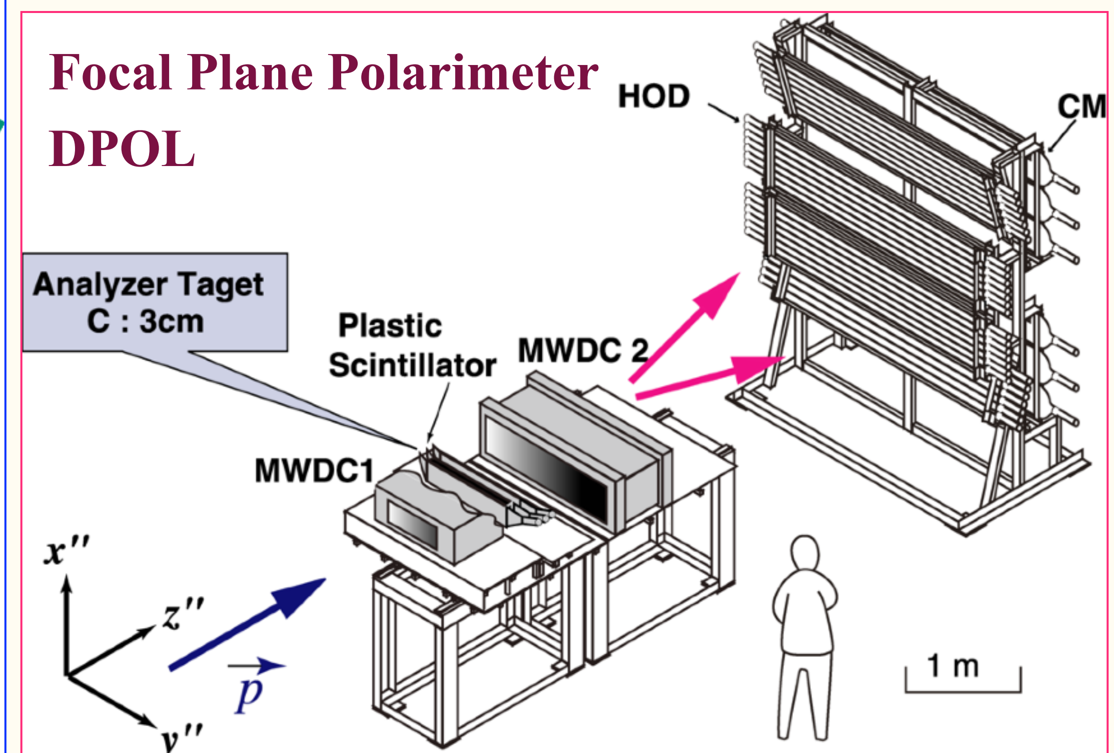
SMART at RIKEN (- 2005)

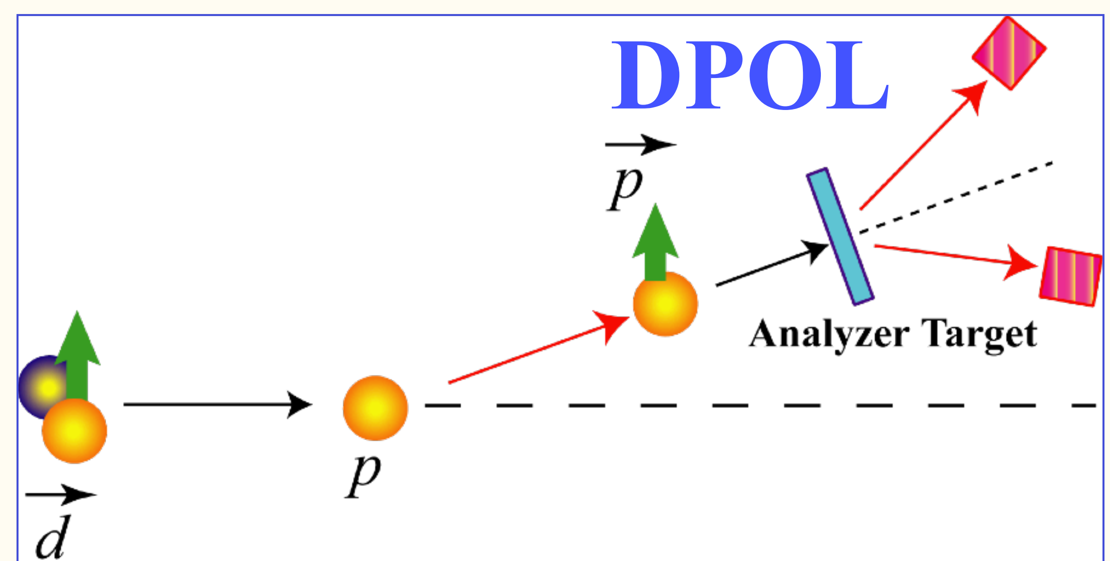
Swinger and Magnetic Analyzer with Rotator and Twister

N. Nakamoto et al., Phys. Lett. B 367, 60 (1996),
H. Sakai et al., Phys. Rev. Lett. 84, 5288 (2000),
K. S. et al., Phys. Rev. C 65, 034003 (2002),
K. S. et al., Phys. Rev. C 70, 014001 (2004),
K. S. et al., Phys. Rev. Lett. 95, 162301 (2005),
K. S. et al., Phys. Rev. C 79, 054008 (2009)

- Differential Cross Section at 70, 135 MeV/nucleon
- All Deuteron Analyzing Powers at 70, 100, 135 MeV/nucleon
- Deuteron to Proton Polarization Transfer Coefficients at 135 MeV/nucleon



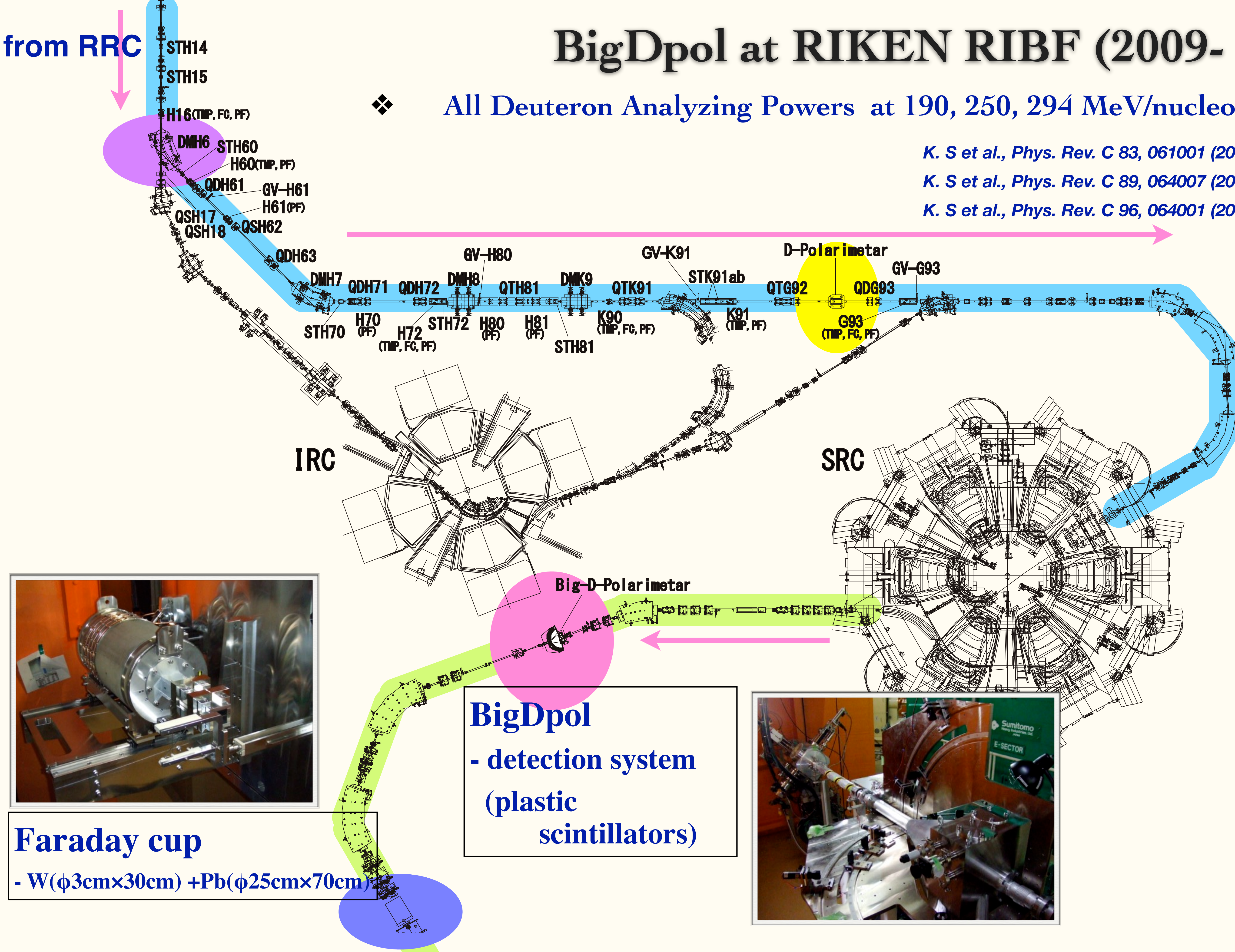




BigDpol at RIKEN RIBF (2009-)

❖ All Deuteron Analyzing Powers at 190, 250, 294 MeV/nucleon

K. S et al., Phys. Rev. C 83, 061001 (2011)
K. S et al., Phys. Rev. C 89, 064007 (2014)
K. S et al., Phys. Rev. C 96, 064001 (2017)

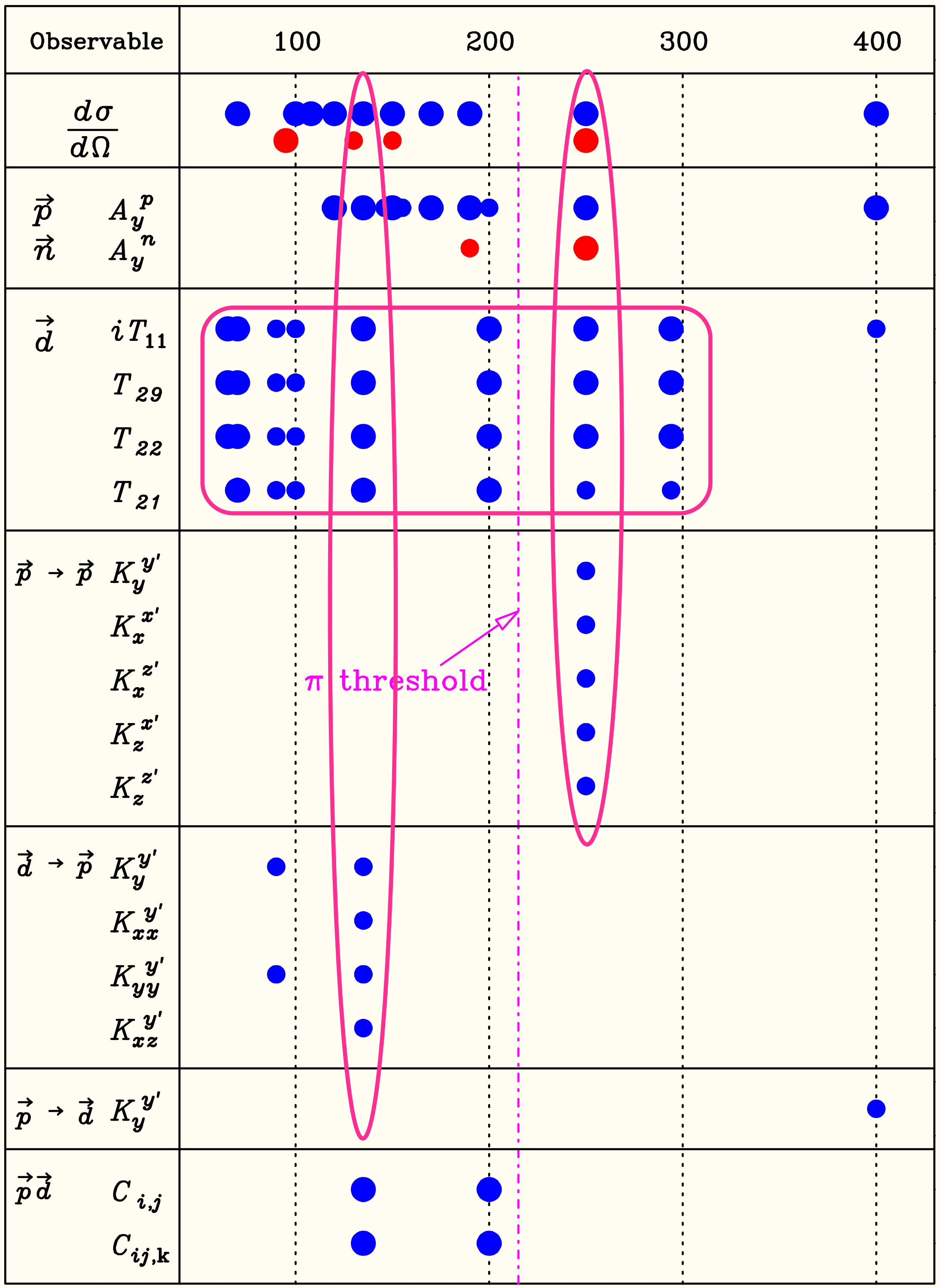


BigDpol
- detection system
(plastic scintillators)

Faraday cup
- W(φ3cm×30cm) +Pb(φ25cm×70cm)

Nd Elastic Scattering Data at Intermediate Energies

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

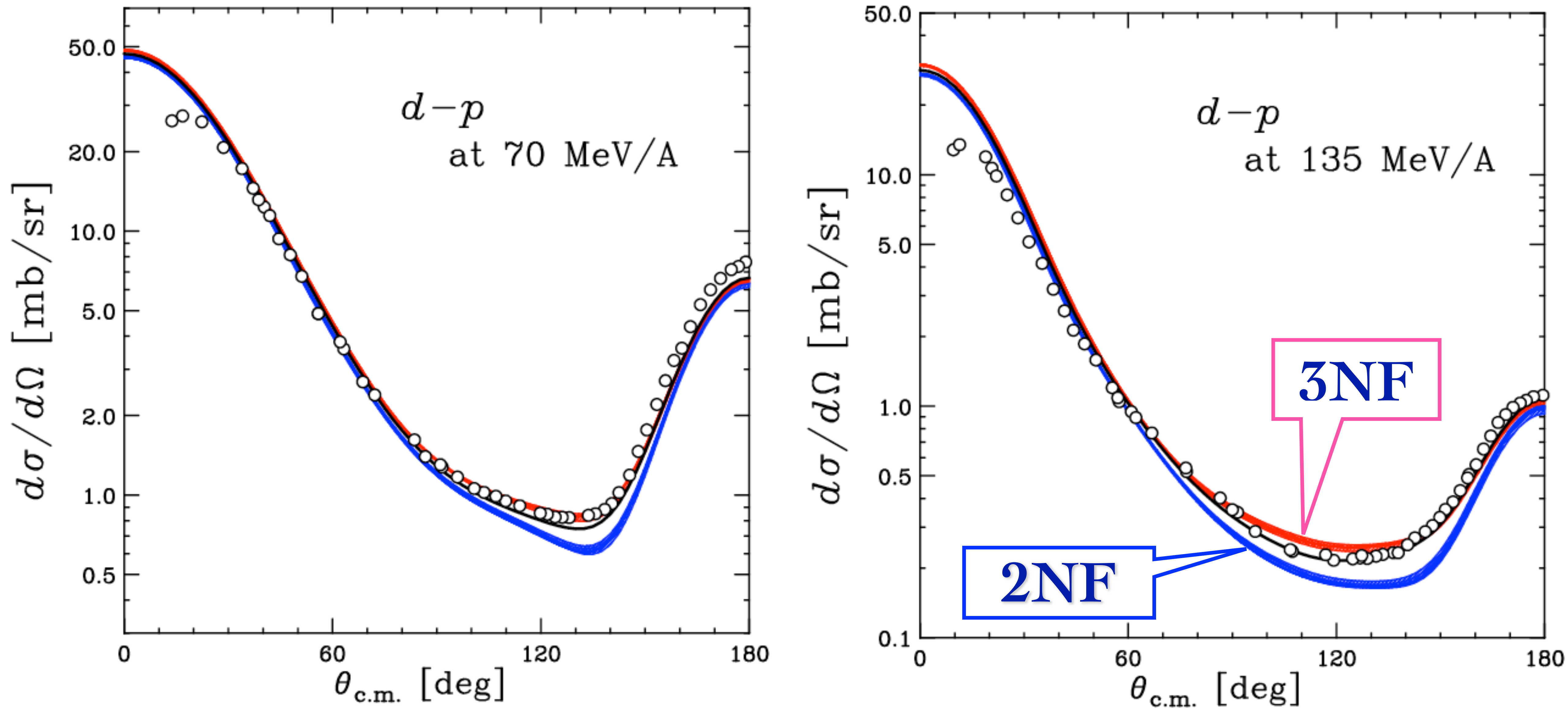


~2022

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

Calculations by Bochum-Cracow Gr.

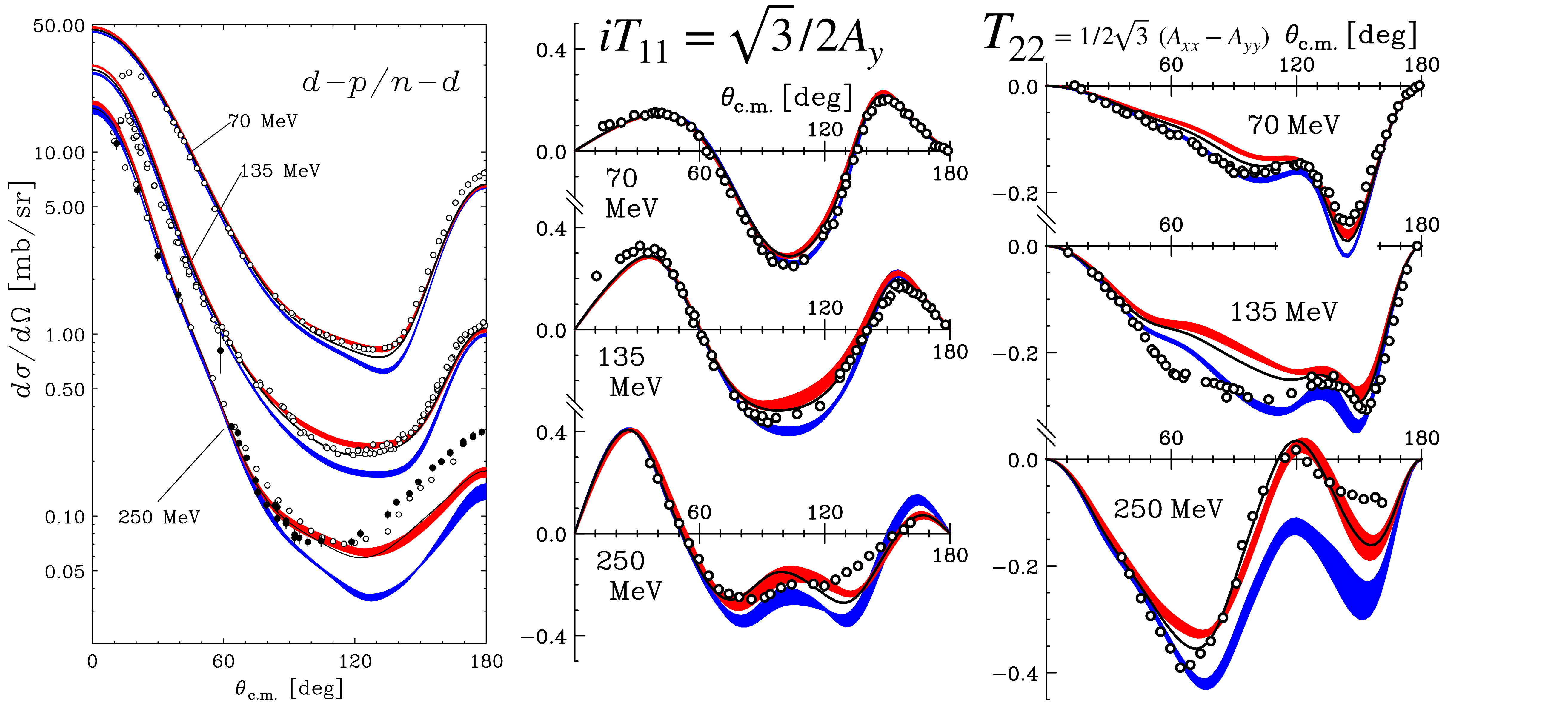
NN (CDBonn, AV18, Nijm I,II)
TM'(99) 3NF + NN(CD Bonn, AV18, Nijm I,II)
Urbana IX 3NF+AV18



2NF (CDBonn, AV18, Nijmegen I,II)
: Large discrepancy in Cross Section Minimum (~ 30%)

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

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



Defects of spin-dependent parts of 3NF models

Serious discrepancies exist at very backward angles.

Summary of Results of Comparison for *dp* elastic scattering

- Cross section at $\sim$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.

in Progress : Experiment (3-nucleon force)

So far ...

Nucleon-Deuteron Scattering at ~100 MeV/nucleon

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

from here ...

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)

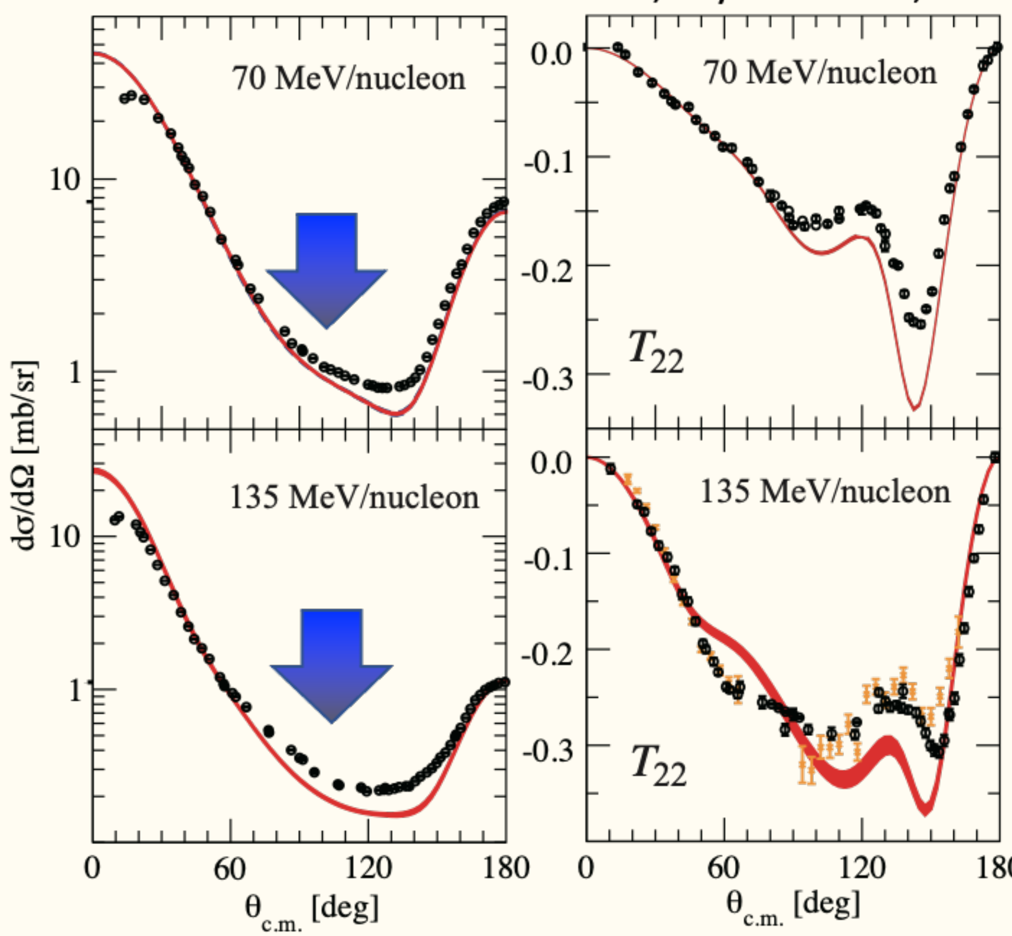
- *dp* elastic scattering data show necessities for the N4LO 3NFs.

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)

Project

Determination of χEFT N4LO 3NFs from *dp* elastic scattering

➡ "High precision 2N+3N forces"

Project of Theory

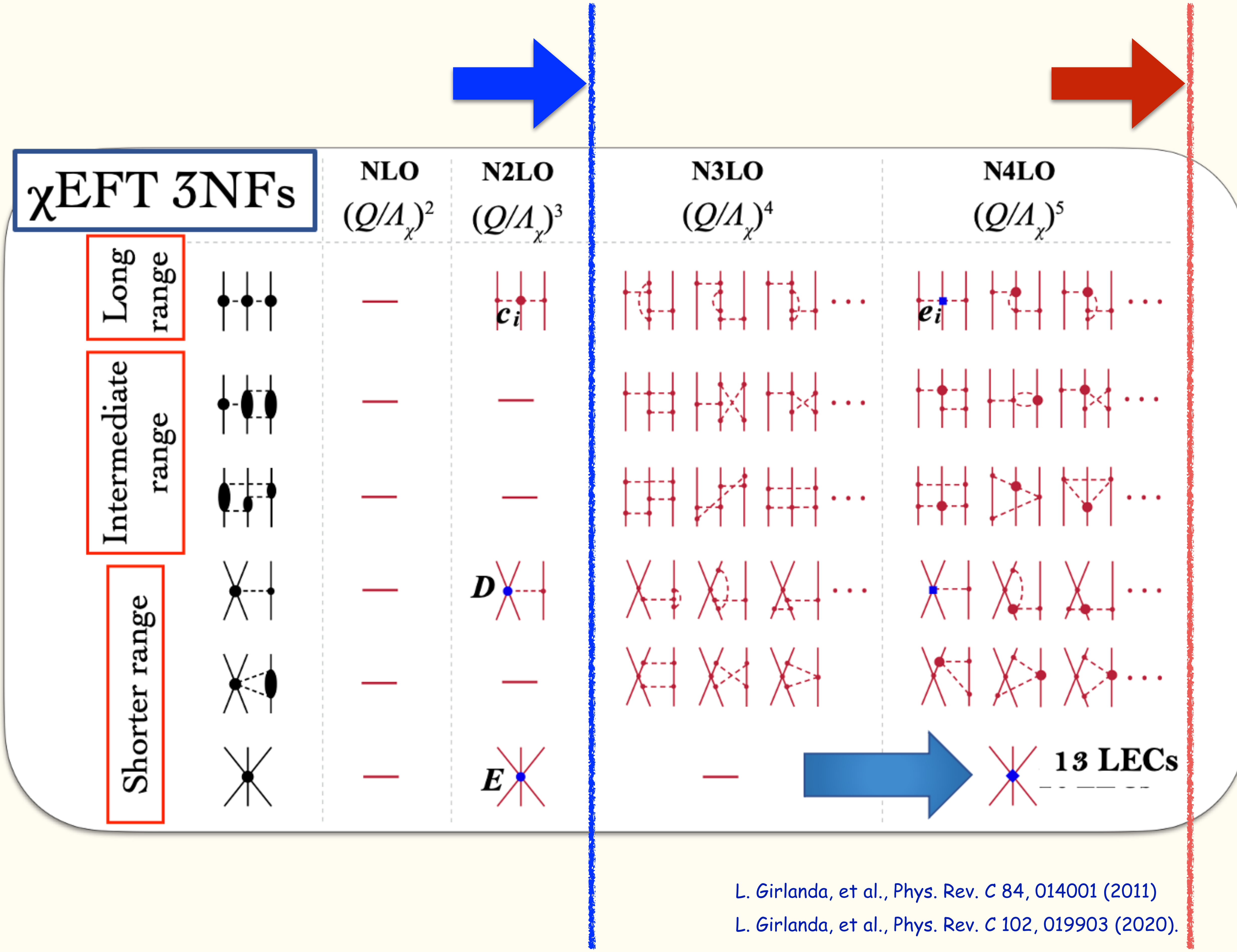
Partial Wave Analysis of *Nd* scattering in the framework of χ EFT

PI : E. Epelbaum

Project of Experiment

Complete set of spin correlation coefficient for *dp* elastic scattering at ~ 100 MeV/nucleon at RIBF

- ✓ To determine Low Energy Constants
- ✓ To test "2N+3N forces"



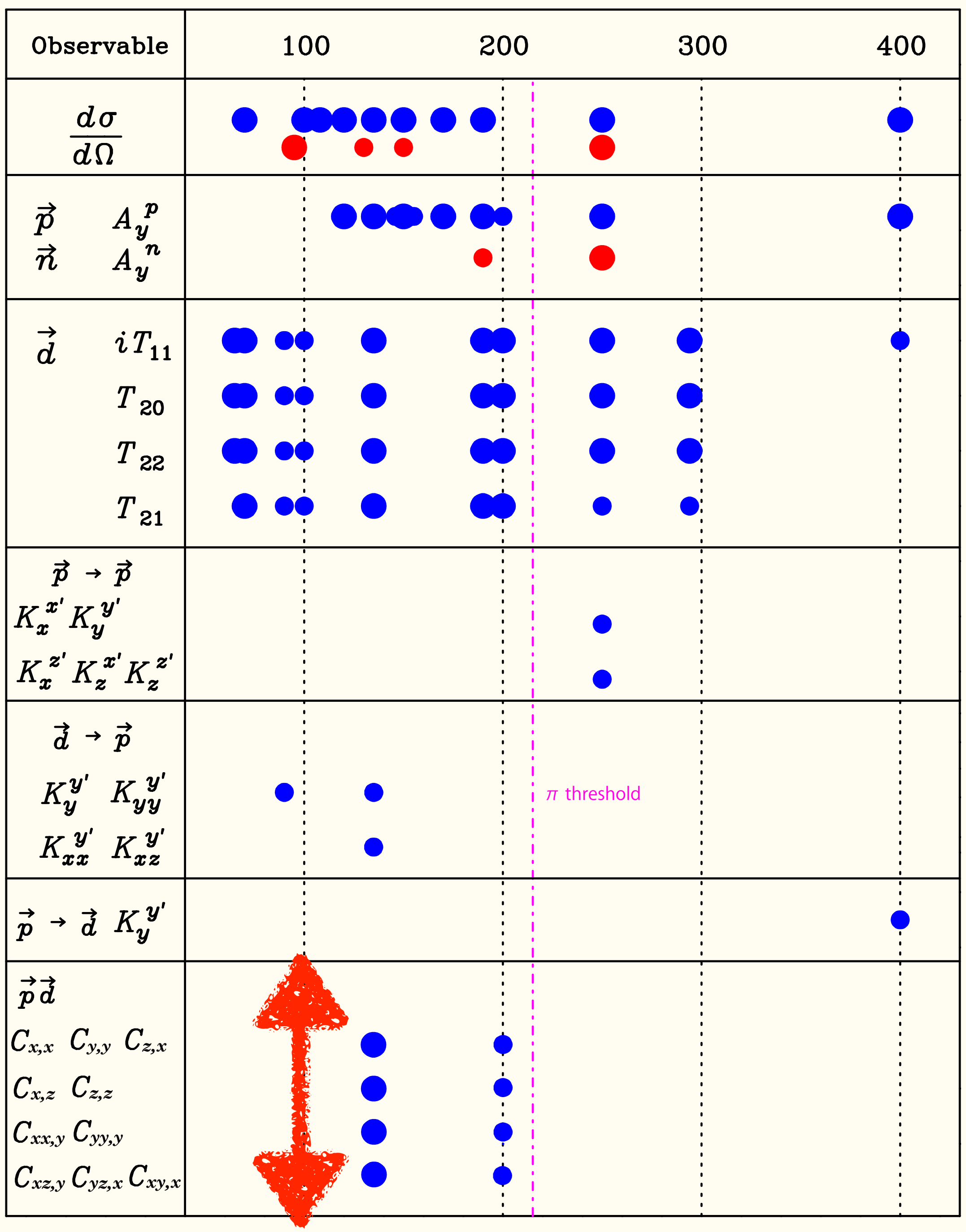
L. Girlanda, et al., Phys. Rev. C 84, 014001 (2011)

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

New Project at RIKEN

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

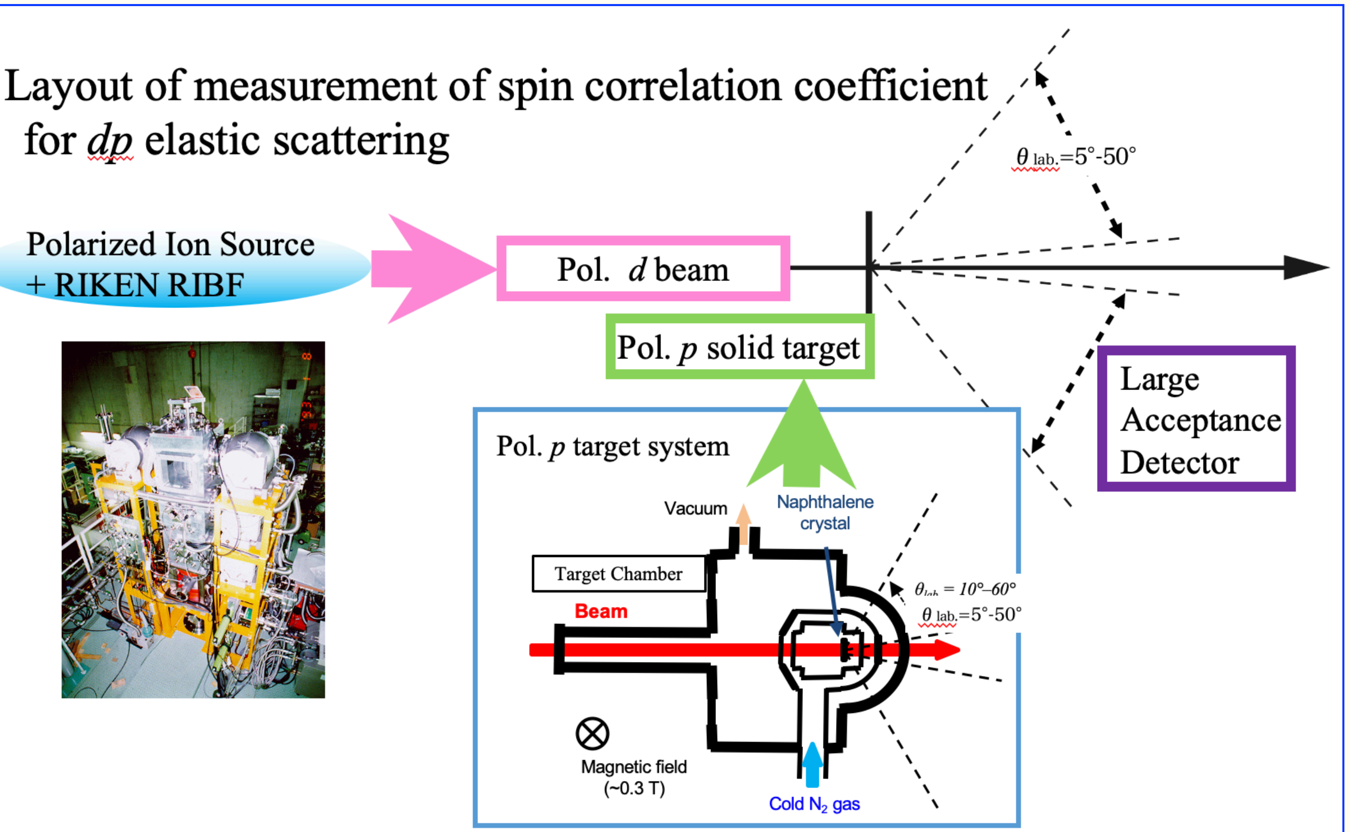
pd and *nd* Elastic Scattering at 65–400 MeV/nucleon



for investigation of N4LO 3NFs

- determination of LECs of N4LO 3NFs from *dp* scattering data
- Isospin T=1/2

Fig.1 : Layout of measurement of spin correlation coefficient for *dp* elastic scattering



Proton+^{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*

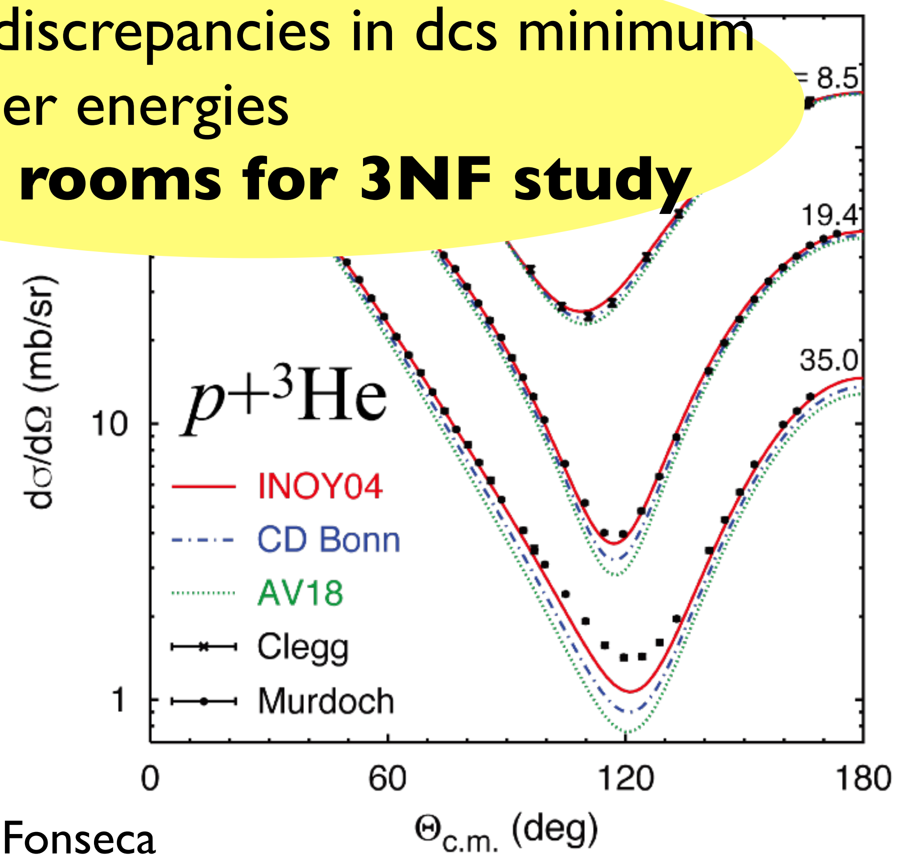
Theory in Progress

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

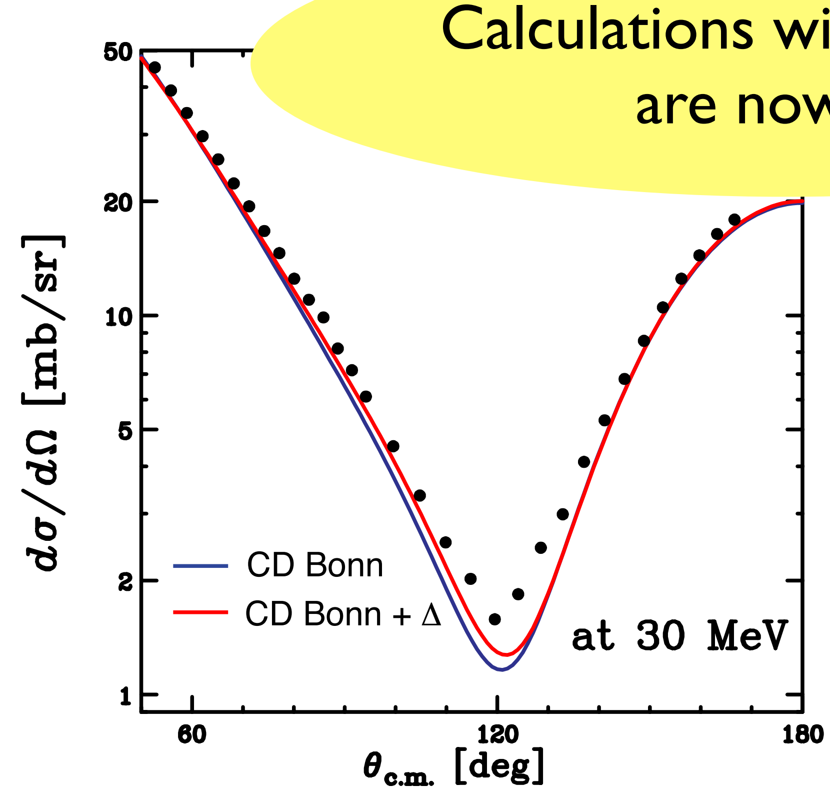
→ new possibilities for 3NF study in 4N scattering at higher energies

Large discrepancies in dcs minimum at higher energies

New rooms for 3NF study



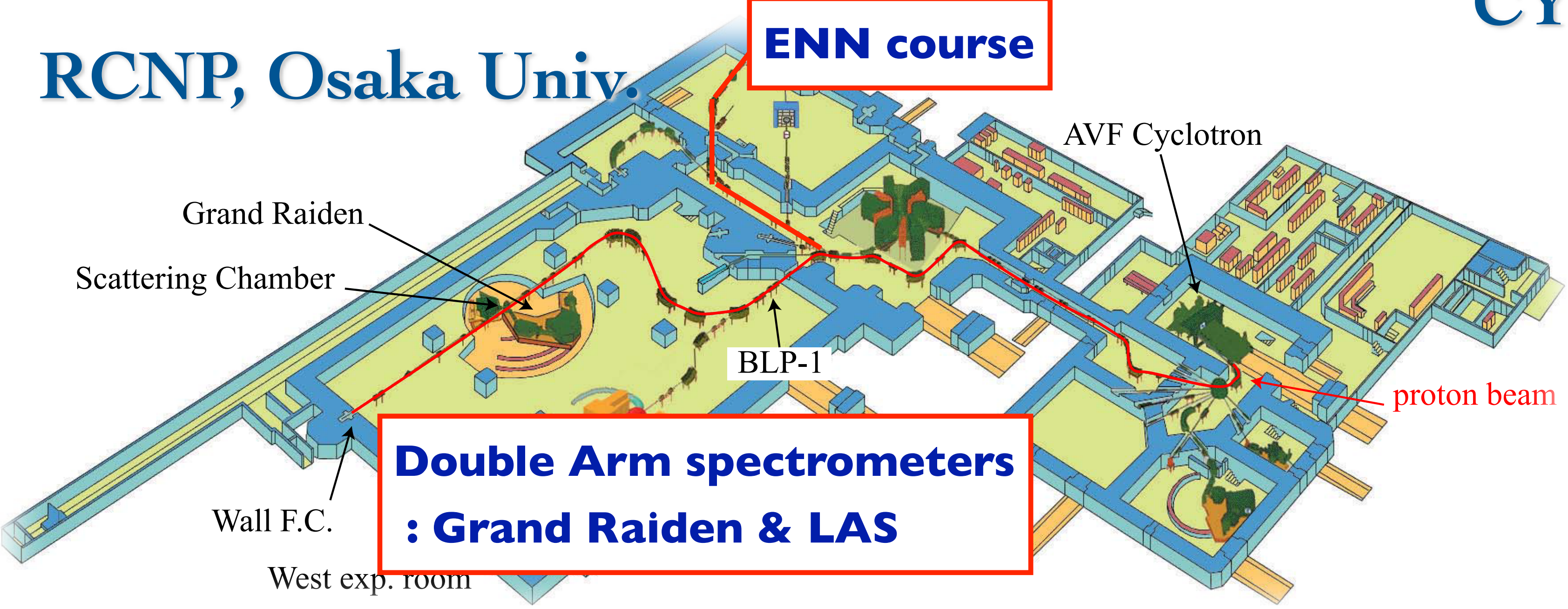
Calculations with 3NFs are now in progress !



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

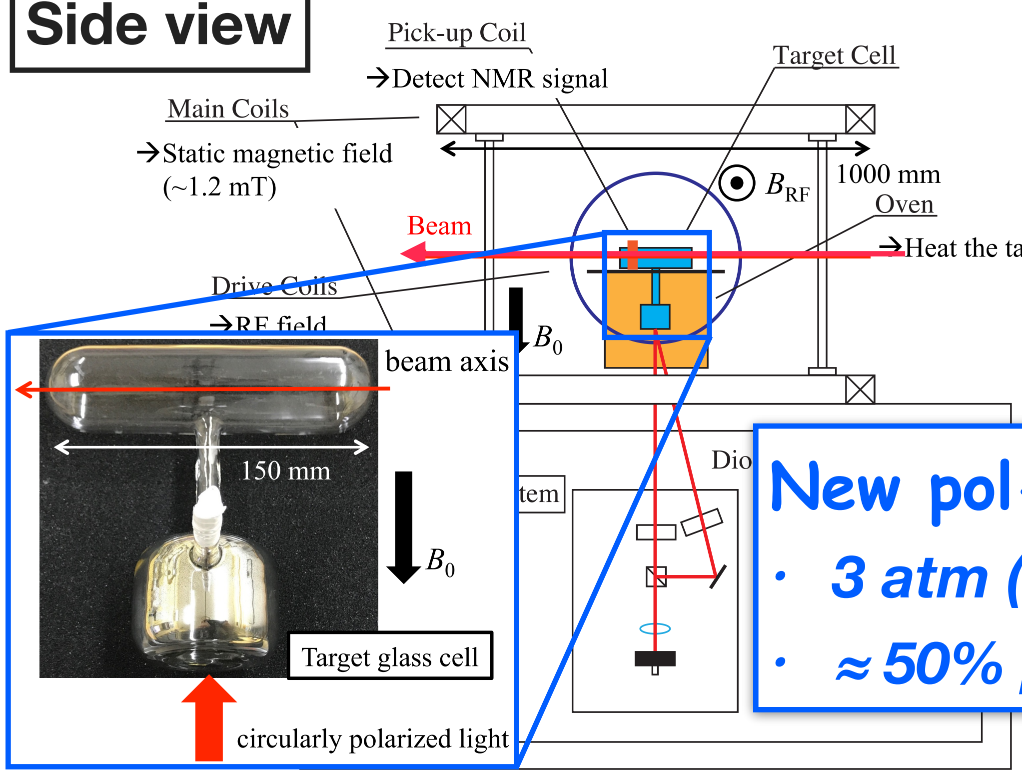
New Experiments of p+^{3}He at Intermediate Energies

RCNP, Osaka Univ.



CYRIC, Tohoku Univ.

Side view



New pol-^{3}He target

- *3 atm (≈2 mg/cm2)*
- *≈50% polarization*

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

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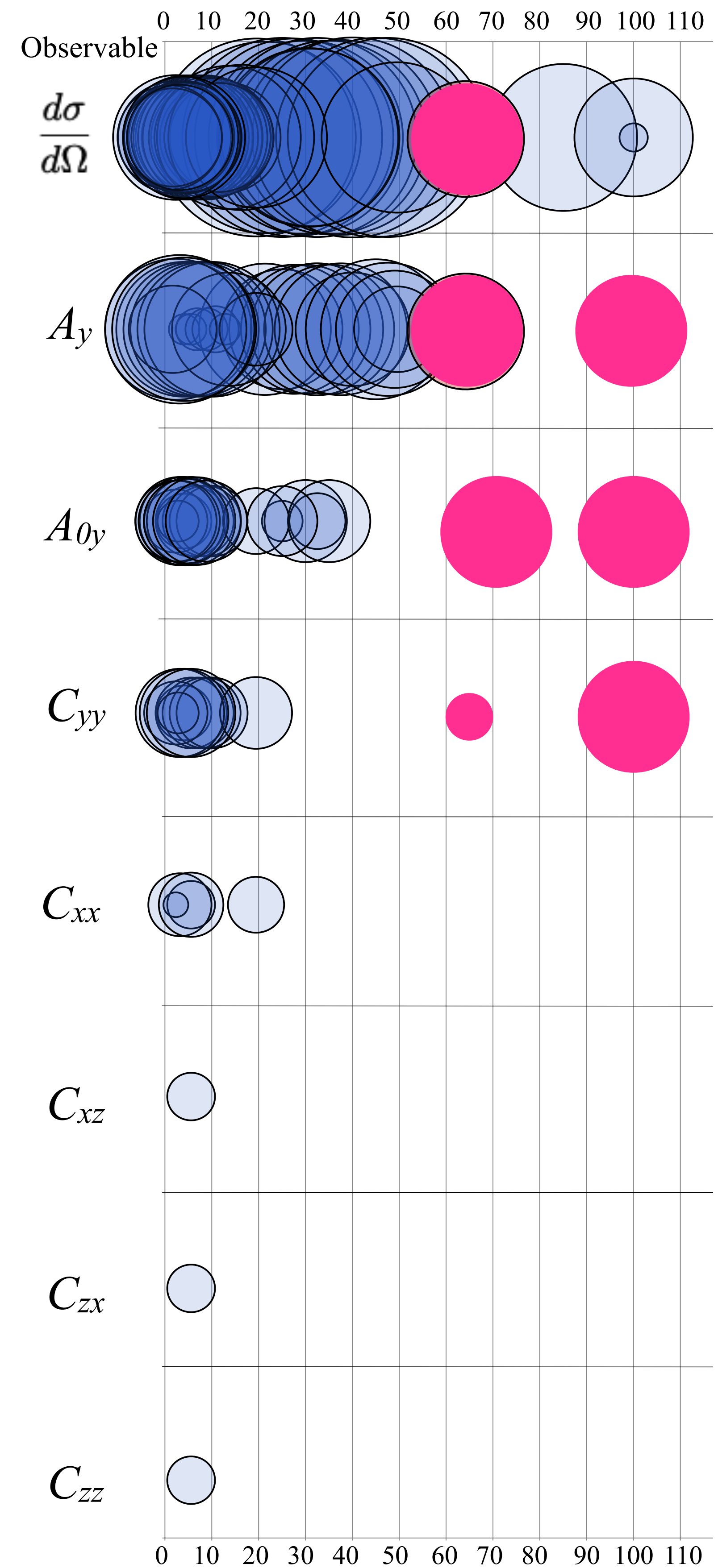
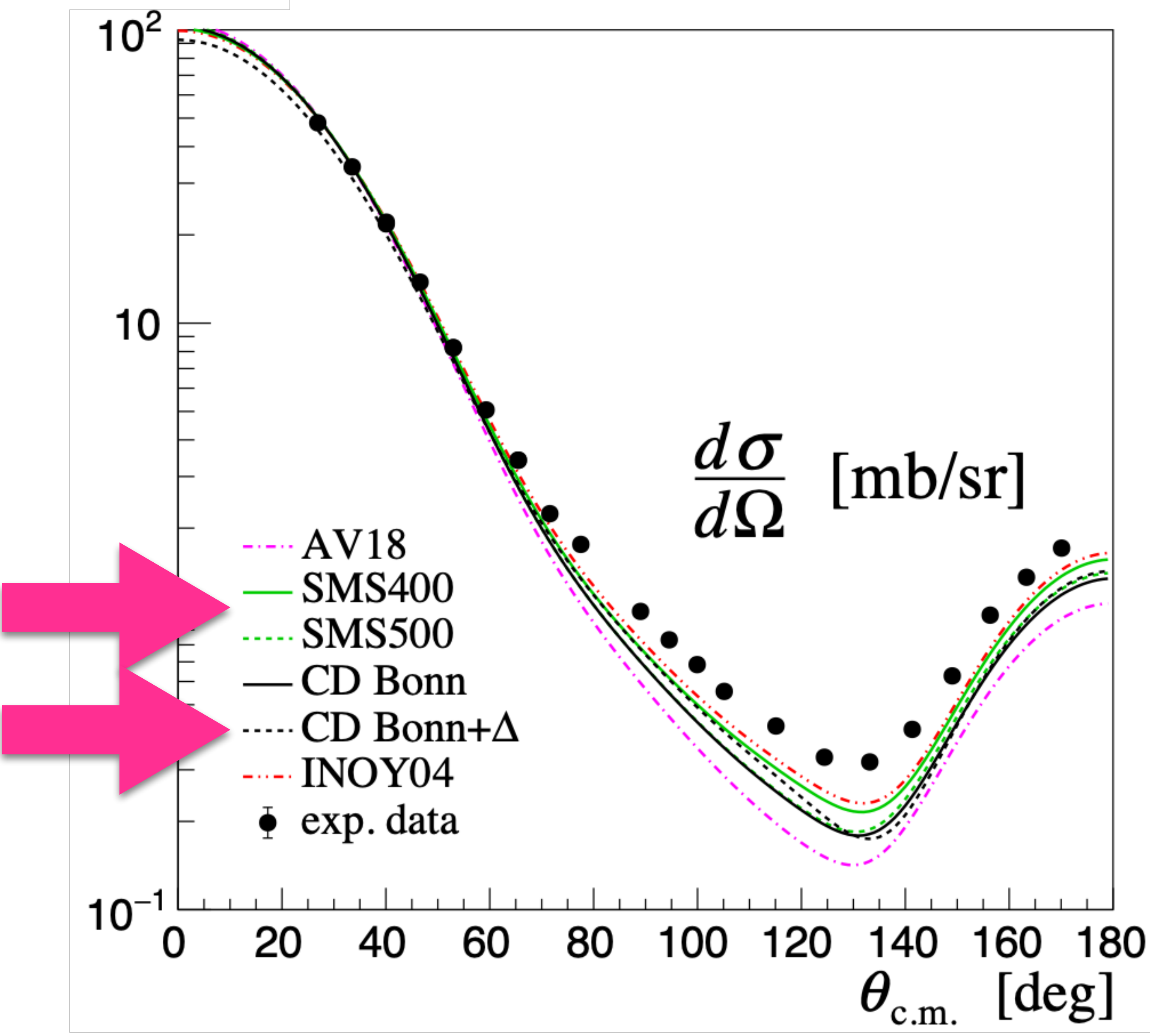
● data from RCNP/CYRIC

Data Table

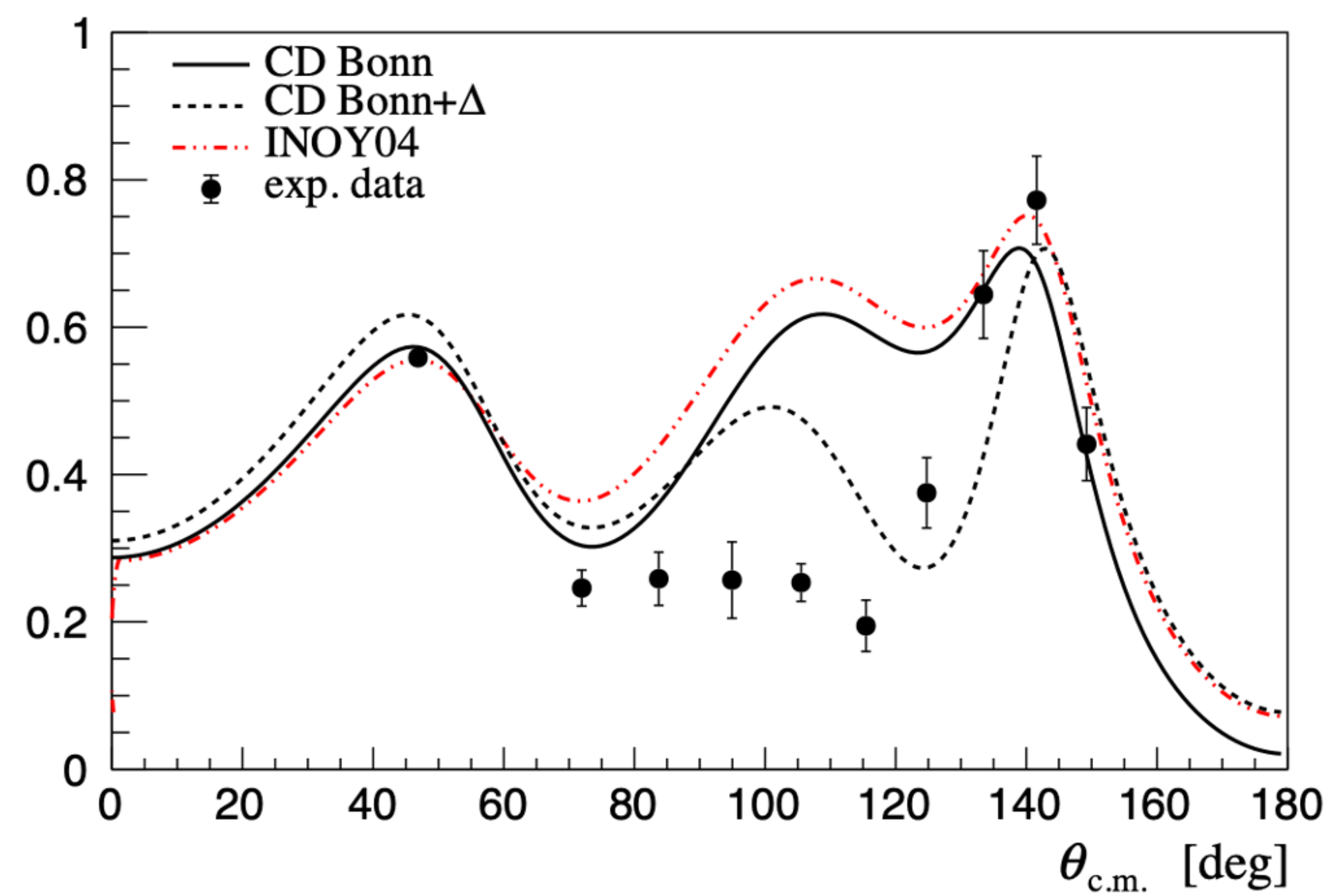


New Data of p+^{3}He at Intermediate Energies

Cross Section at 65 MeV



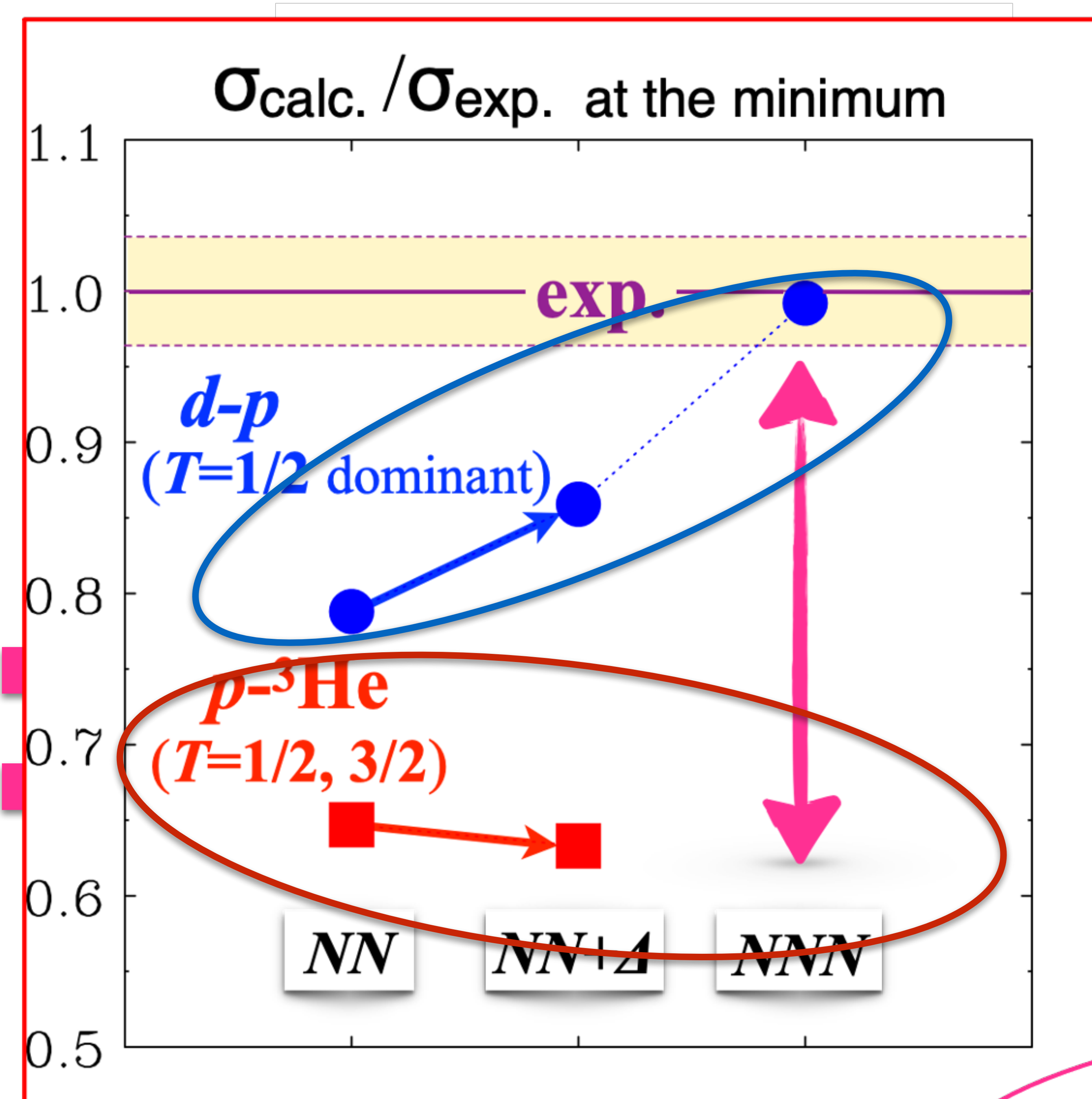
$C_{y,y}$ at 100 MeV



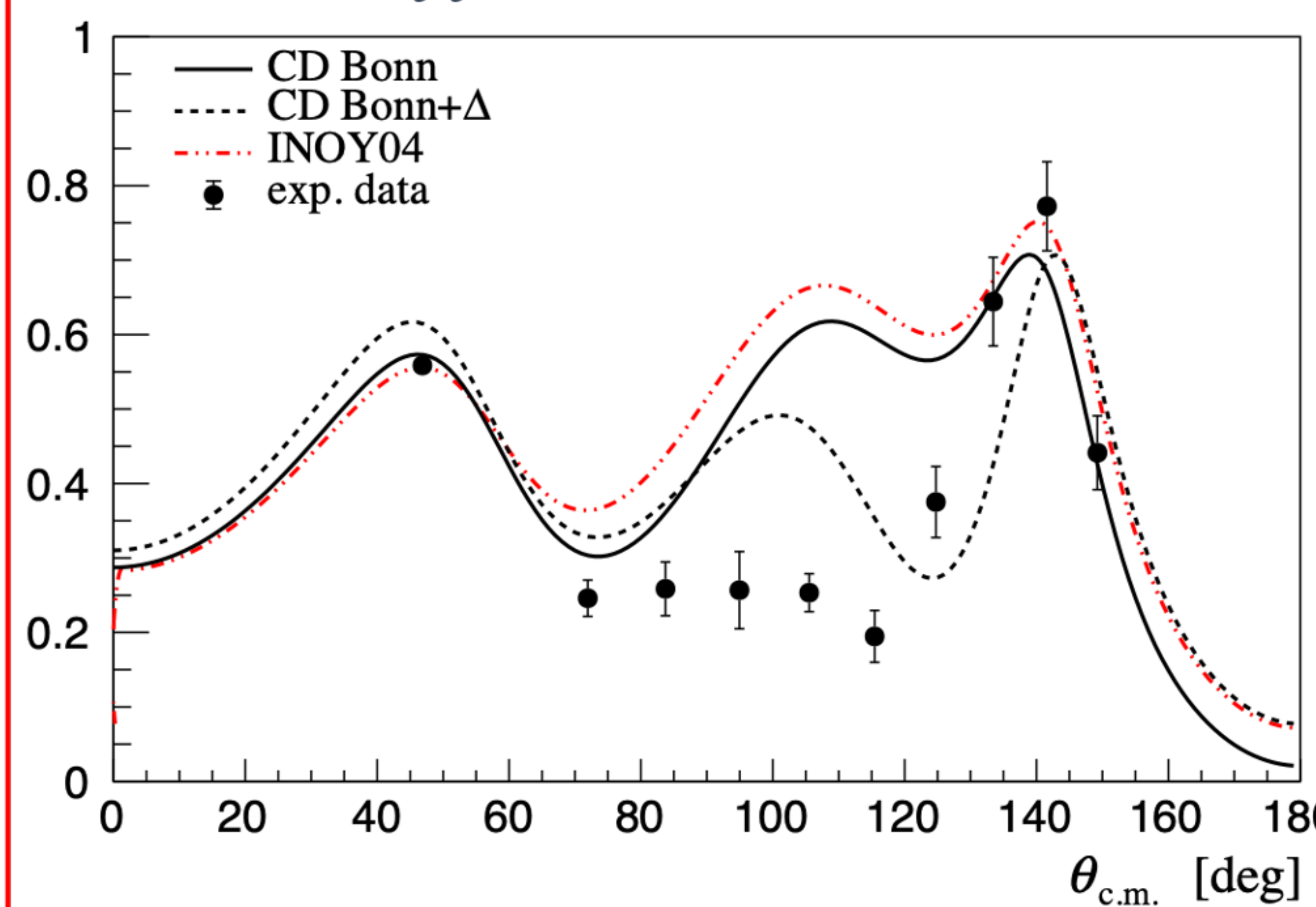
Calculations by A. Deltuva

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

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



$C_{y,y}$ at 100 MeV



Calculations by A. Deltuva

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

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

Summary

3NFs are key elements to fully understand nuclear properties;
a few-, many-, and infinite-nucleon systems.

dp scattering at ~100 MeV/nucleon inspires
quantitative discussions on 3NFs.

Determination of 3NFs based on χEFT
from few-nucleon scattering data is about to start.

- *dp* scattering : LECs of 3NFs
- *p*-^{3}He scattering : iso-spin dependence / test χEFT 3NFs

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Theoretical Supports by

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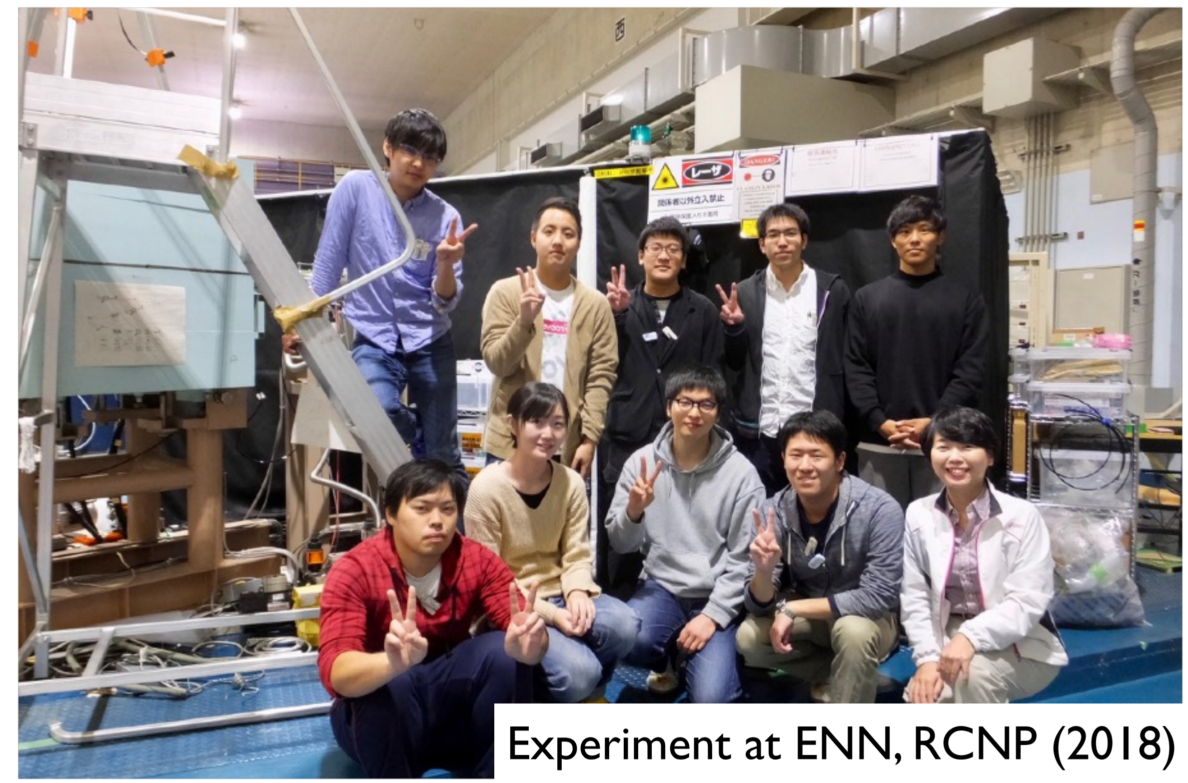
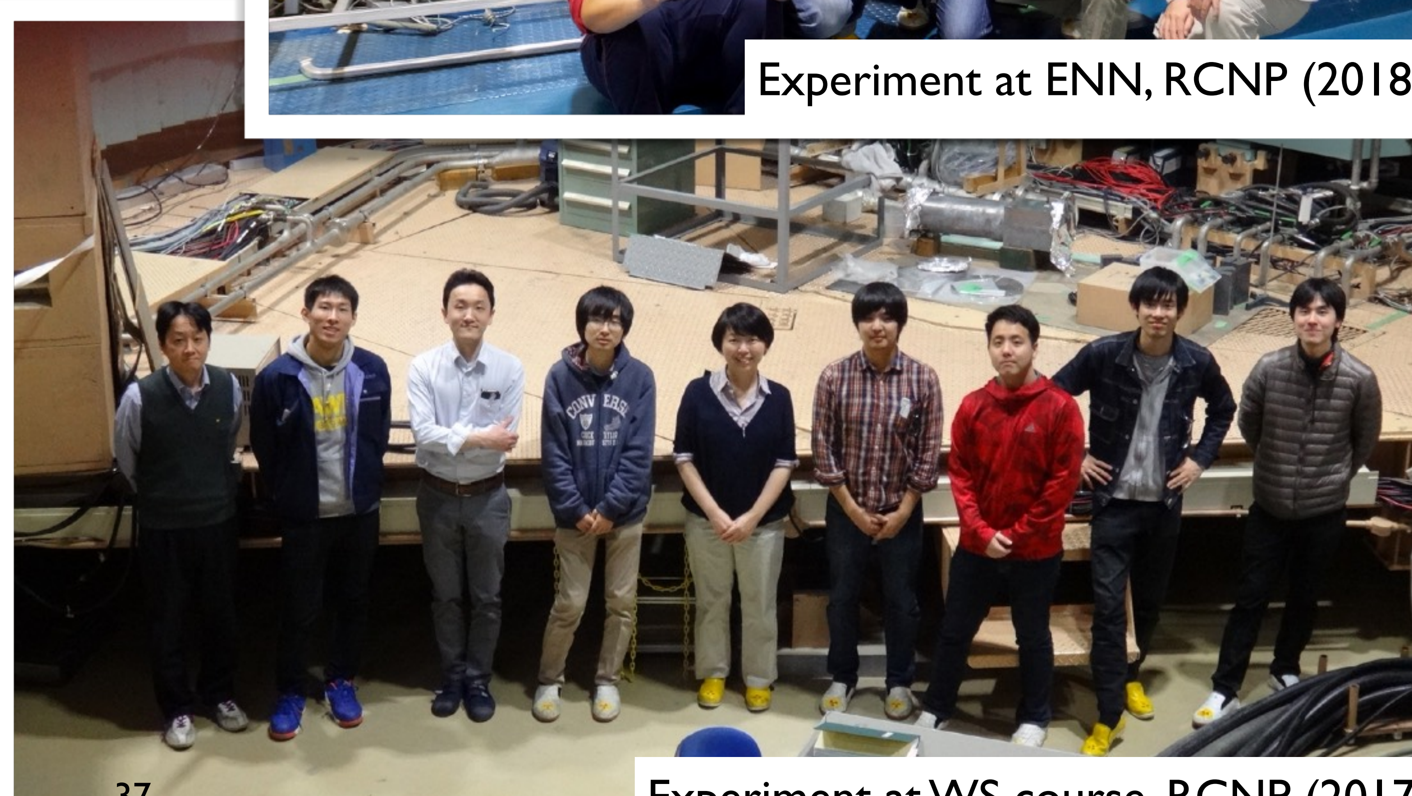
S. Ishikawa(Hosei)



Experiment at ENN, RCNP (2018)



Experiment at WS course, RCNP (2017)

Theoretical Supports

- LENPIC Collaboration
  especially from
  - Ruhr-Universität, Bochum
    - E. Epelbaum, H. Krebs
  - Jagellonian University
    - H. Witała, J. Golak, R. Skibinski
  - Kyushu Institute of Technology
    - H. Kamada
  - Forshungszentrum of Jülich
    - A. Nogga

at Bad Honnef (2006)

- Vilnius University
  - A. Deltuva
- INFN, Pisa
  - M. Vivian, A. Kievsky
- Hannover University
  - P. U. Sauer, S. Nemoto
- Lisbon University
  - A. Sa. Fonseca