Experiments on Three-Nucleon Forces - recent topics -

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January 29th, 2025

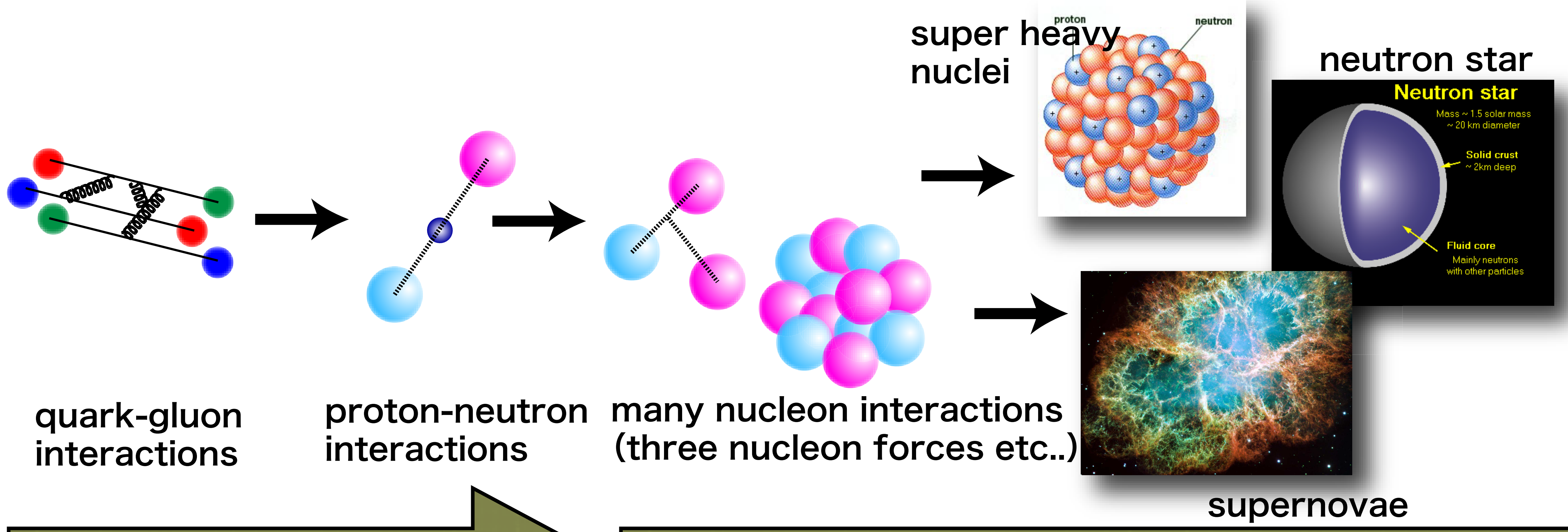
Frontier of Nuclear Force Study

History

1935 Yukawa's meson theory - Two-Nucleon Forces (2NFs)

1990's Realistic Modern Nucleon-Nucleon Potentials (CD Bonn, Argonne v18, Nijmegen)

- To understand Nuclear Forces from Quarks ~ Lattice QCD ~
- To understand Nuclei and Nuclear Matter from bare Nuclear Forces ~ with 3-Nucleon Forces ~

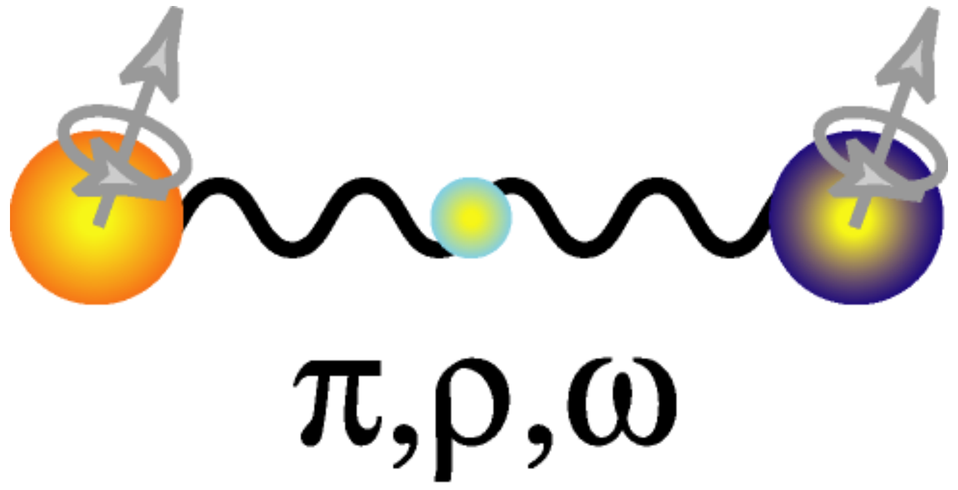


Consistent Understanding from quarks to the Universe

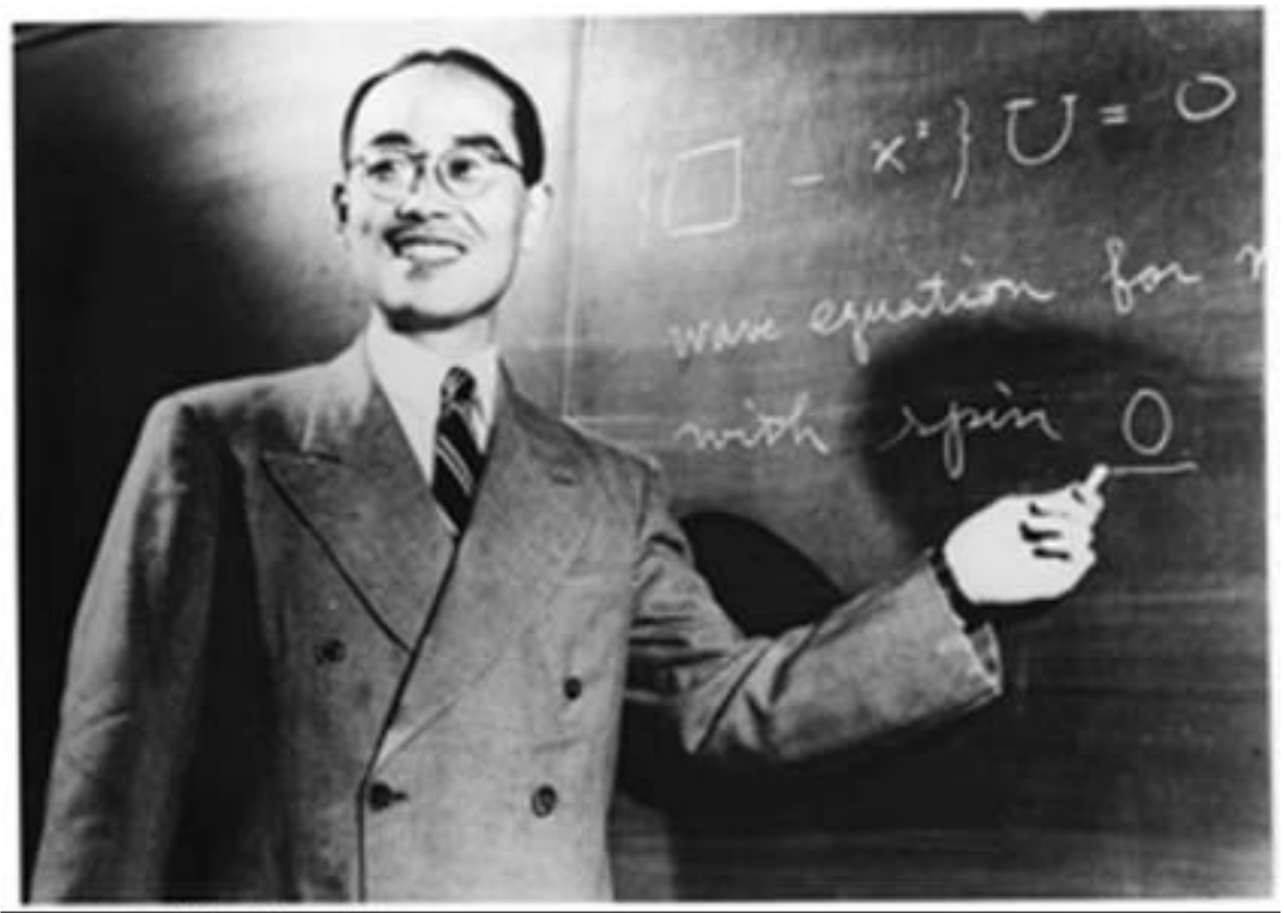
Before Three-Nucleon Forces …

Nuclear Force ~ Yukawa's Idea ~

Yukawa's Meson Theory
Proc. Phys. Math. Soc. Jpn. 17, 48 (1935)



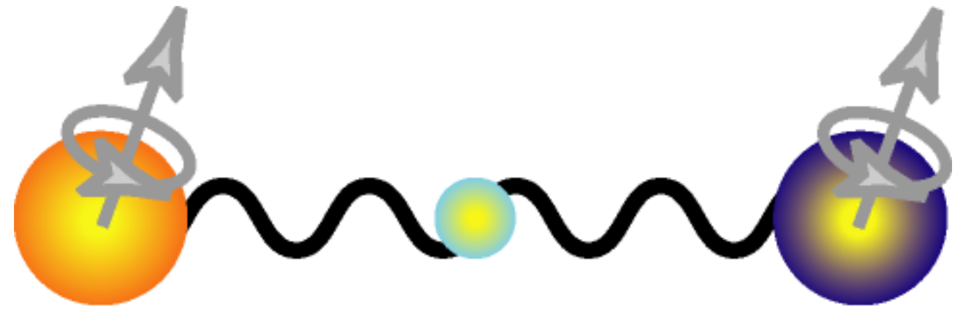
Nuclear force is explained by exchanging a 'virtual particle' (meson) between two nucleons.



Scanned at the American Institute of Physics

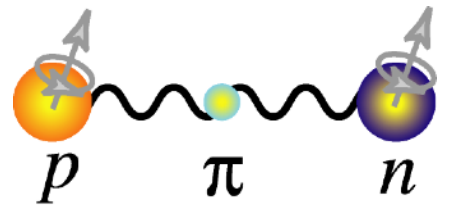
Nuclear Force

Yukawa's Meson Theory
Proc. Phys. Math. Soc. Jpn. 17, 48 (1935)



π,ρ,ω

Theory



One Pion Exchange Model

π,ρ,ω

One Boson Exchange Model
Heavier Meson Exchange
e.g. ρ, ω

Experiment

Nucleon-Nucleon Scattering

(Cross Section
& Spin Observables)

Deuteron Properties

1990's Realistic Modern Nucleon-Nucleon Potentials,
e.g. CD Bonn, Argonne V_{18}, Nijmegen I, and II,
reproduce 4000 NN scattering exp. data with high precision, χ^2 /datum~ 1 .

Three-Nucleon Force (3NF)

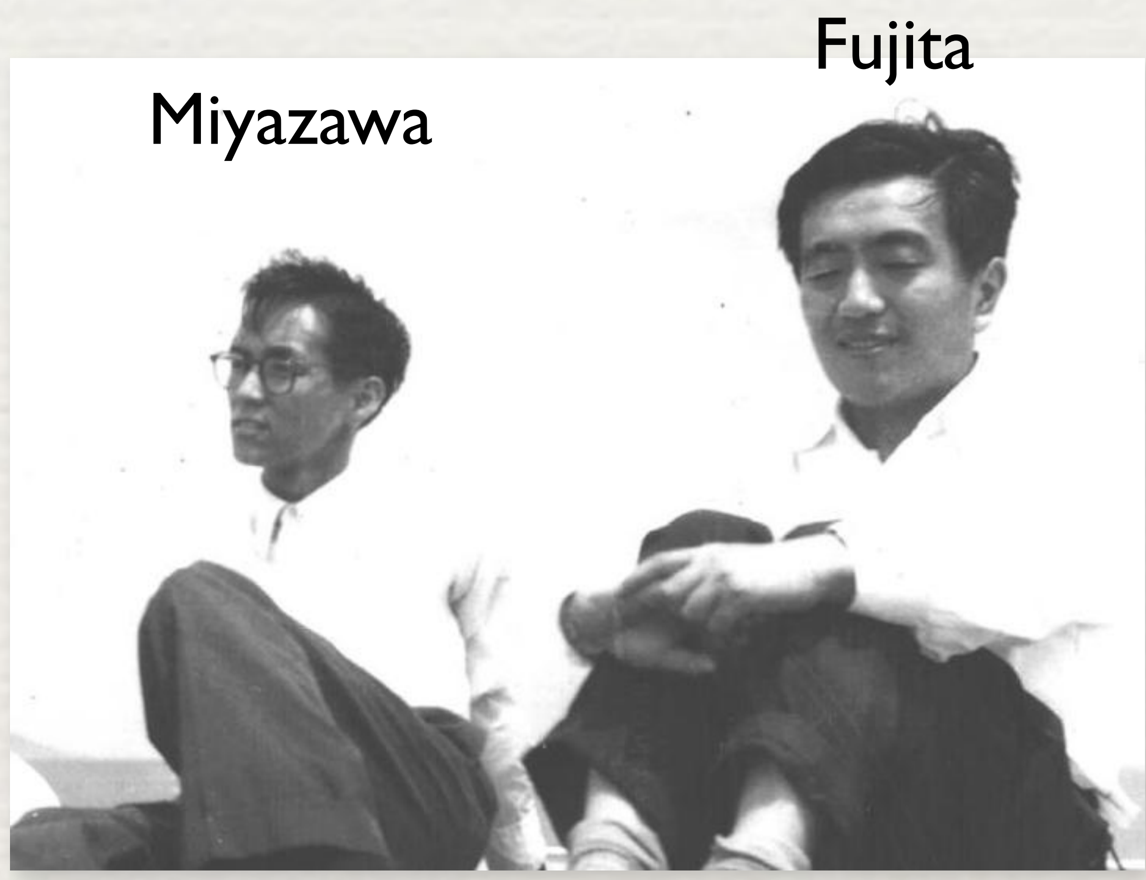
- nuclear forces acting in systems more than $A > 2$ nucleons -

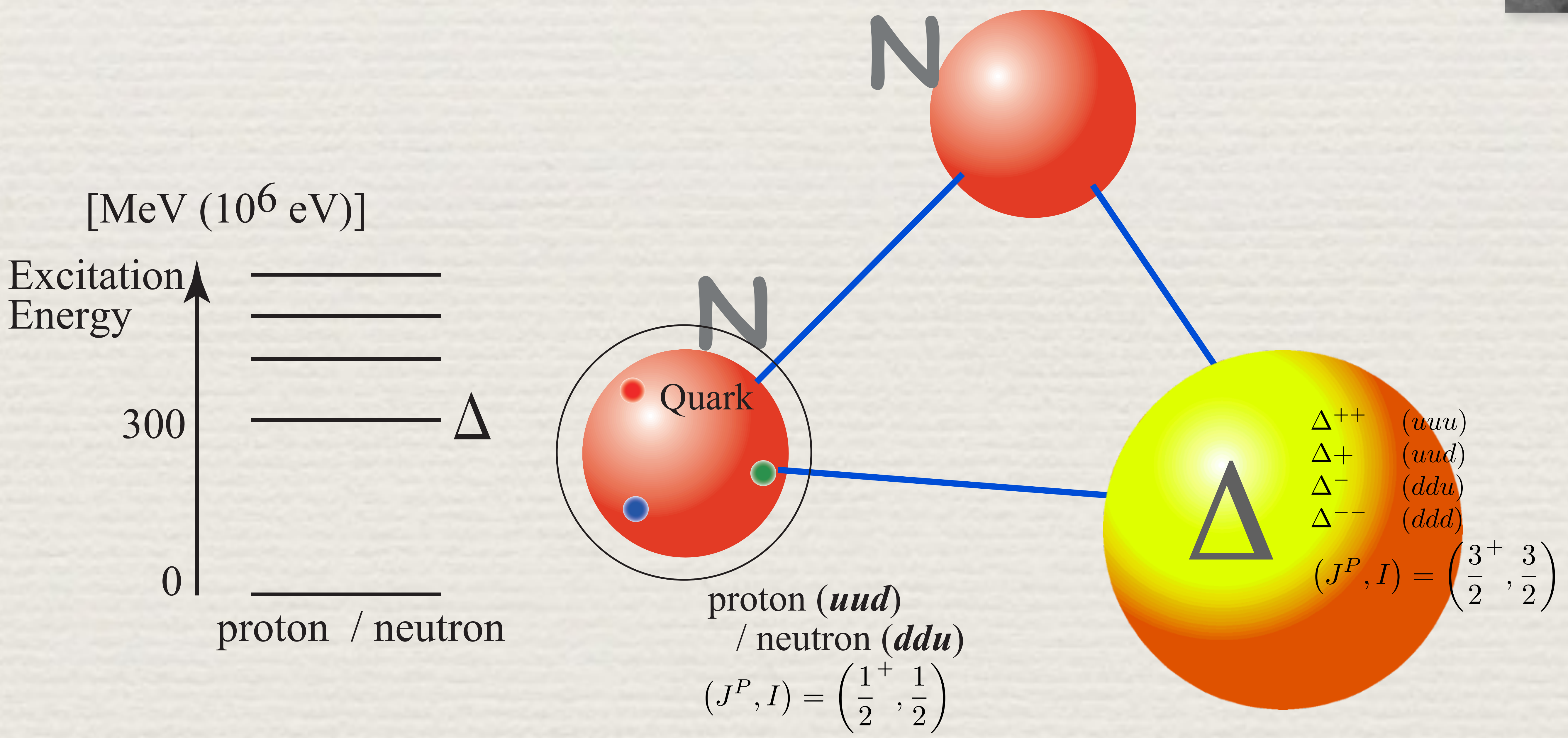
2π-exchange 3NF :

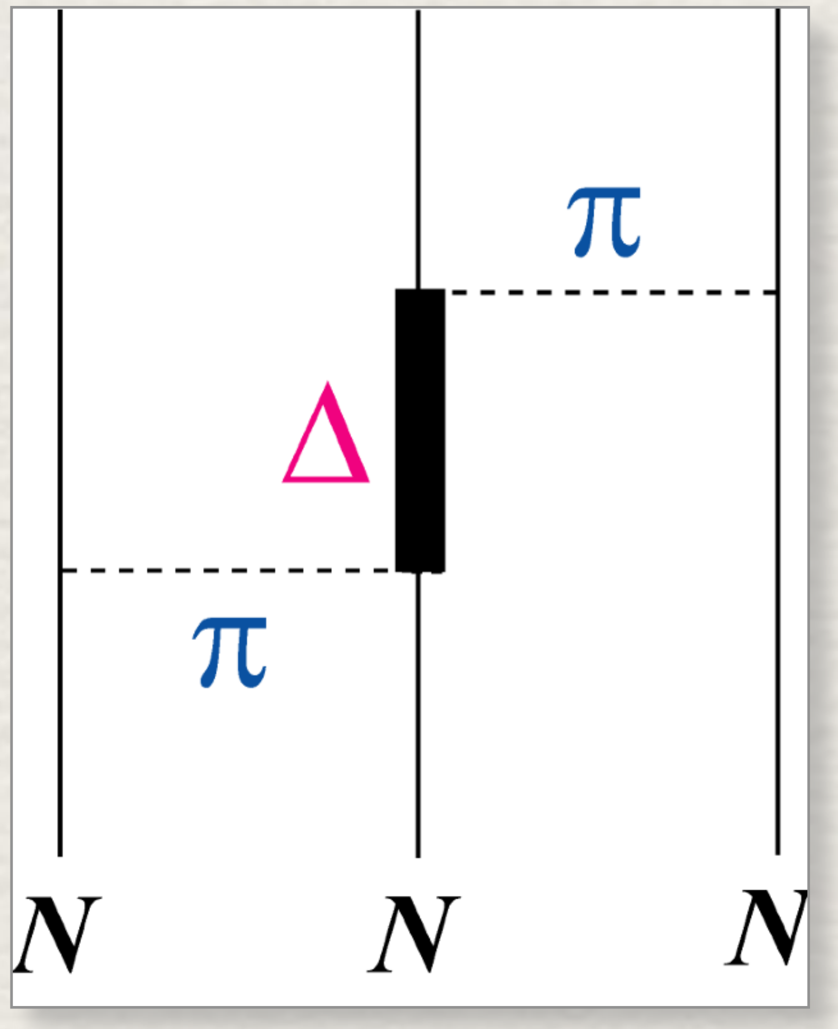
1957 Fujita-Miyazawa 3NF

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

- Main Ingredients : Δ-isobar excitations in the intermediate







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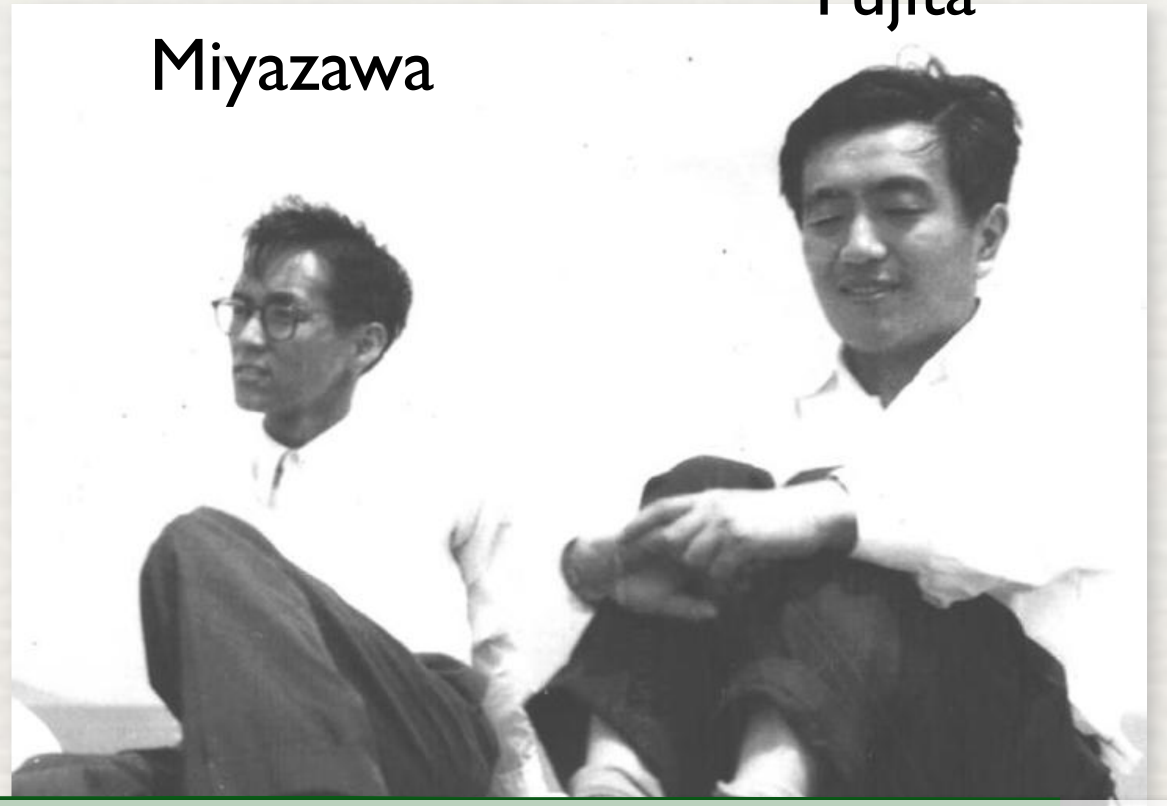
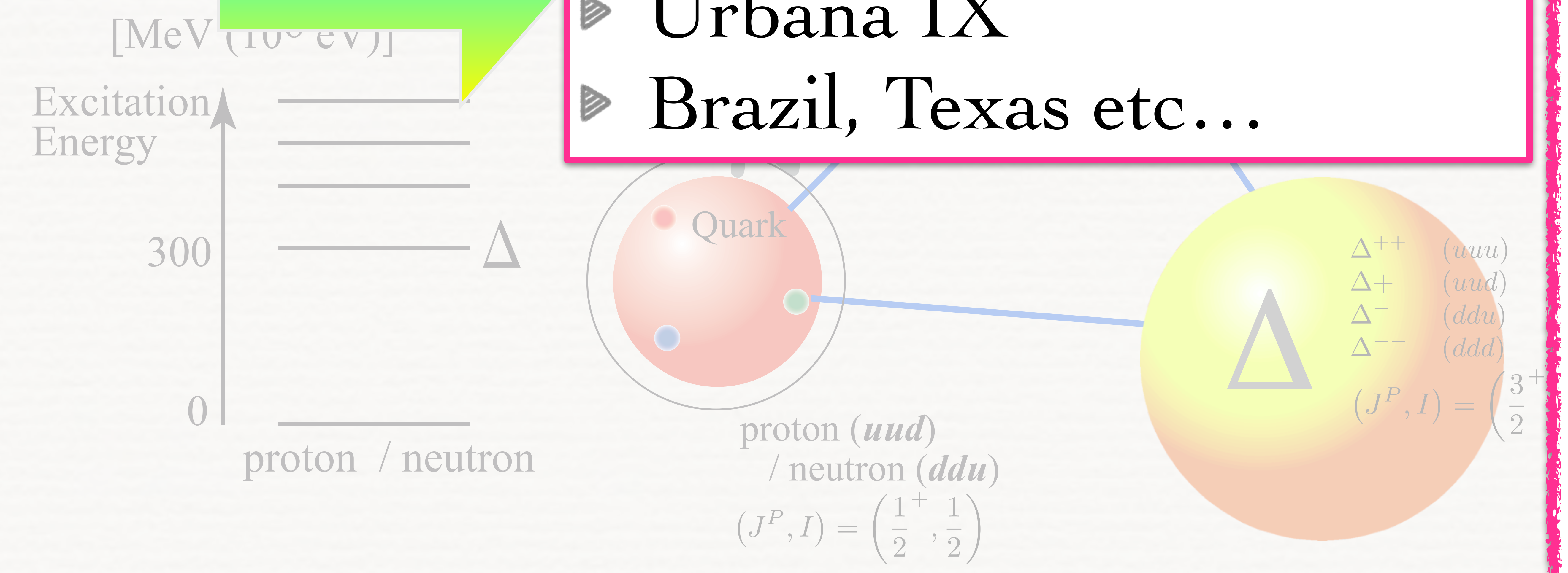
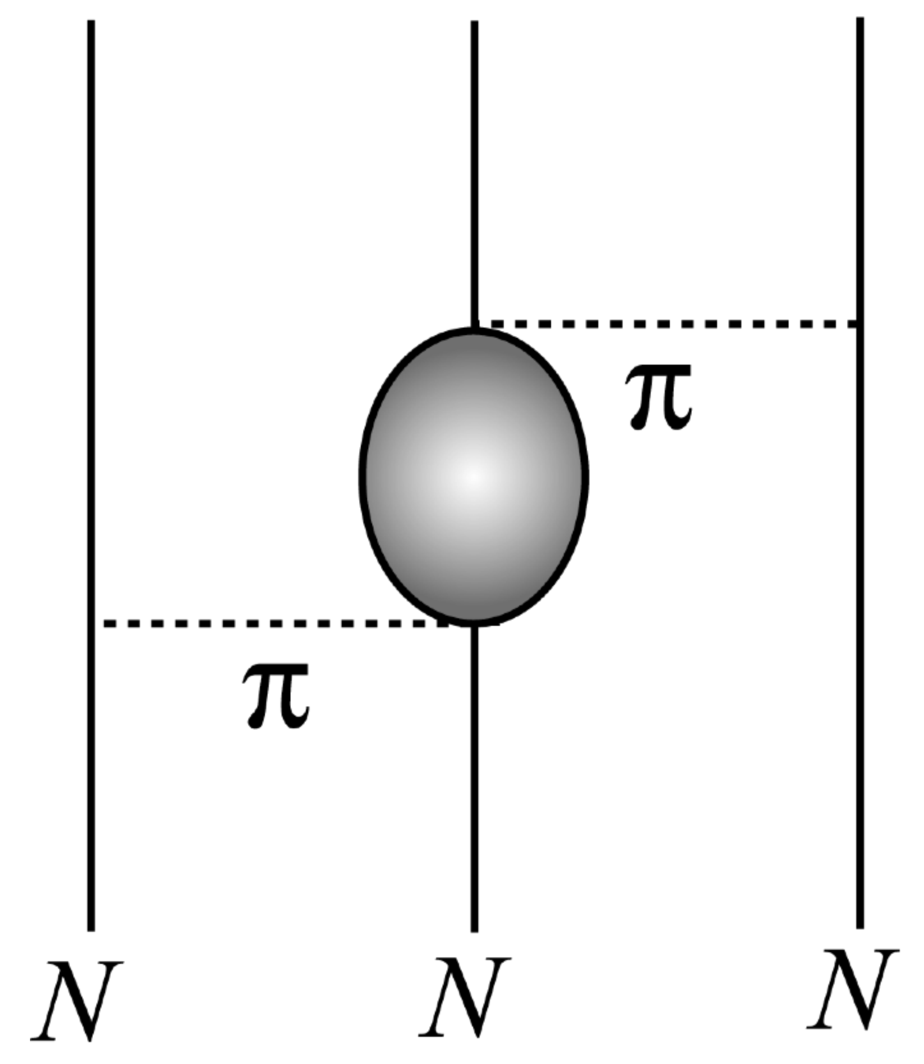




- Tucson-Melbourne (TM)
- Urbana IX
- Brazil, Texas etc…



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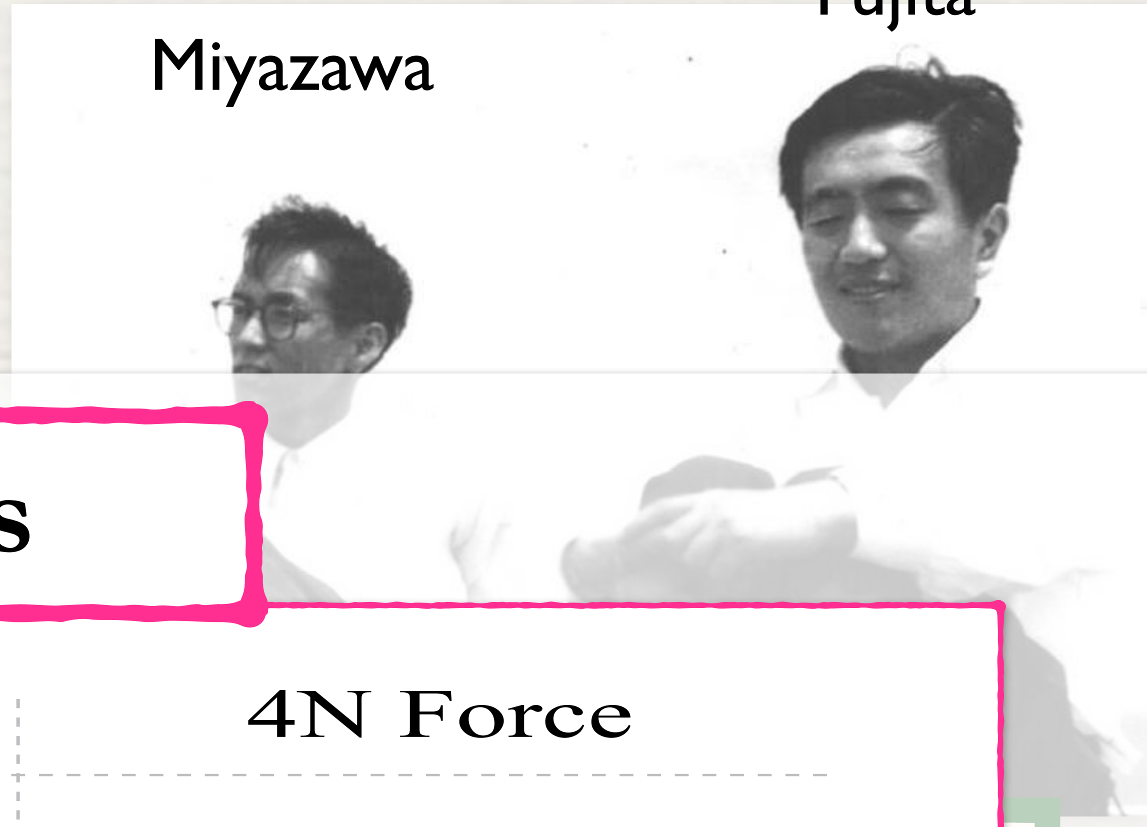
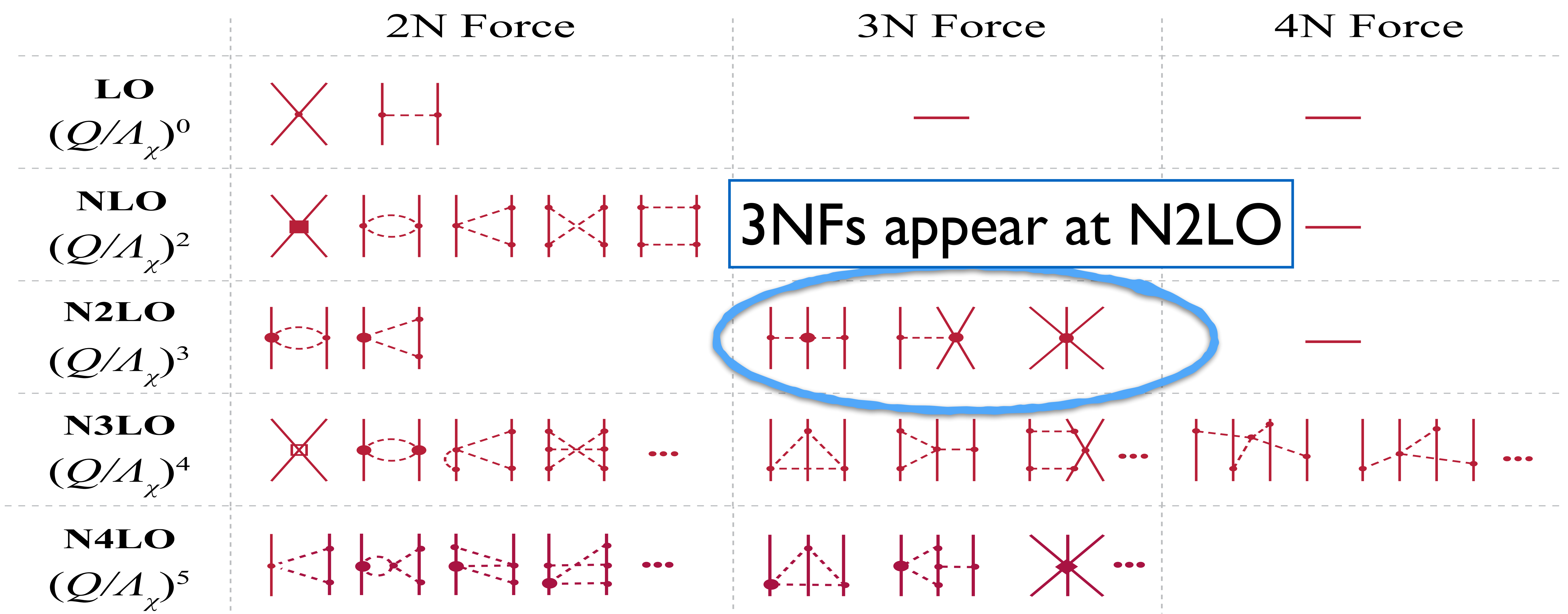


Prog. Theor. Phys. 17, 360 (1957)

- Main Ingredients

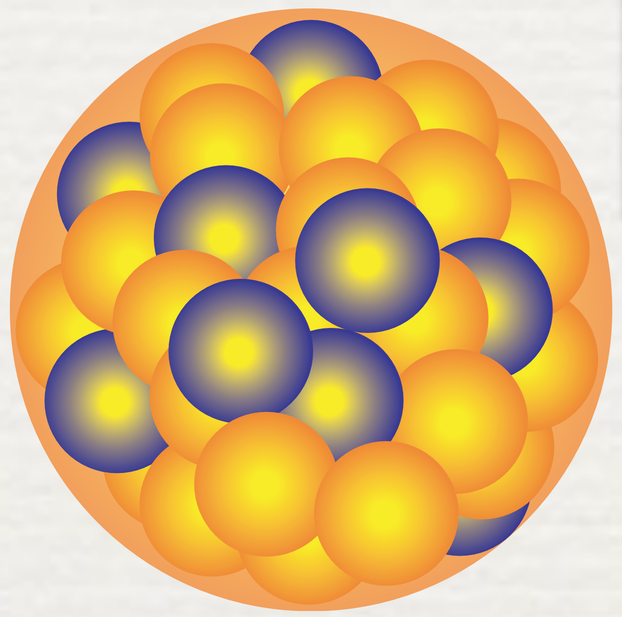
Chiral EFT Nuclear Forces



S. Weinberg, Phys. Lett. B 251, 288 (1990).
U. van Kolck, Phys. Rev. C 49, 2932 (1994).
E. Epelbaum, H.-W. Hammer, U.-G. Meißner, Rev. Mod. Phys. 81, 1773 (2009)
R. Machleidt, D.R. Entum, Phys. Rep. 503, 1 (2011)

Where ?

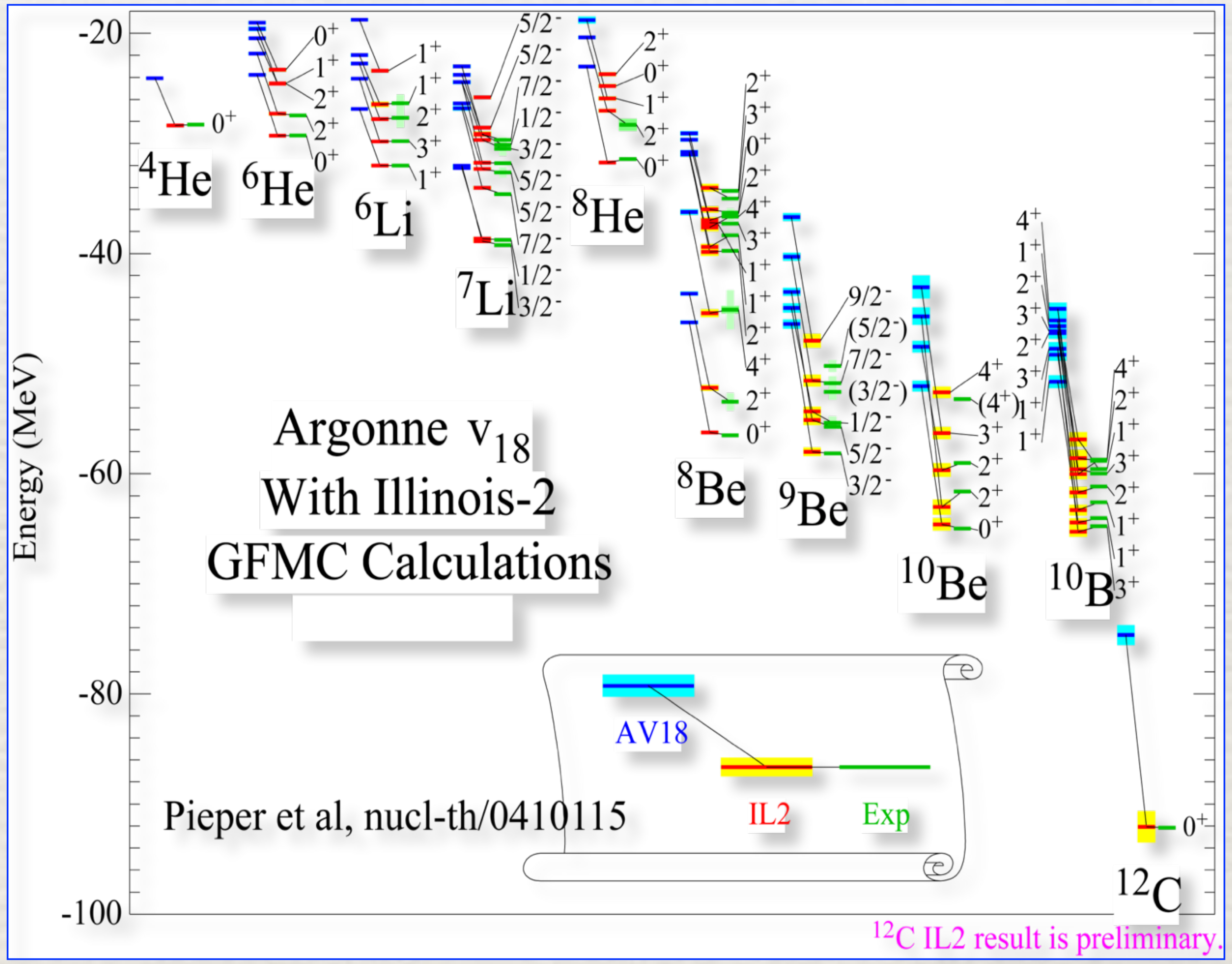
3NFs in A>3 - ① -



3NFs in Finite Nuclei

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

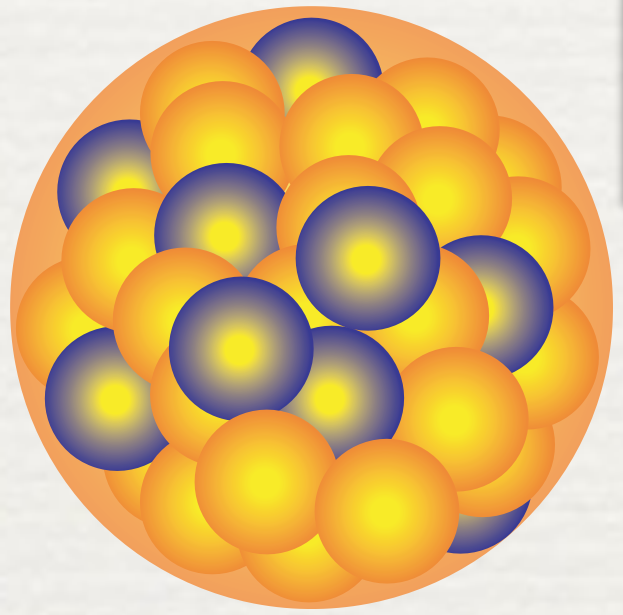
- **Green's Function Monte Carlo**
- **No-Core Shell Model** etc..



- 3NF effects in B.E.
  - 10-25%
  - Attractive

Note :
Isospin 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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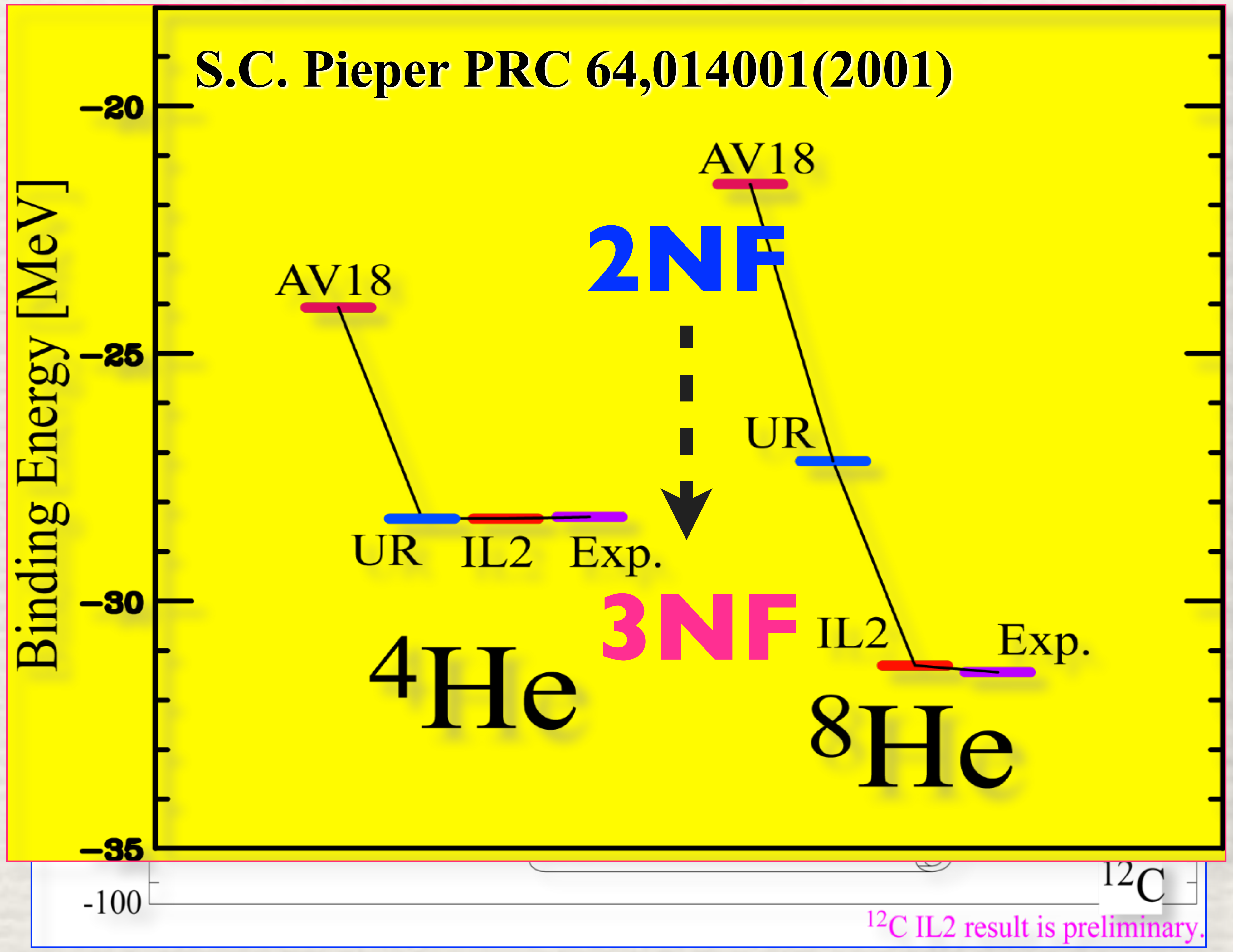


3NFs in A>3 - ① -

3NFs in Finite Nuclei

Ab Initio Calculations for Light Nuclei

- Quantum Monte Carlo
- No-Core Shell Model
- Coupled cluster theory
- Nuclear Lattice Simulations
- Self-consistent Green's function method

etc.

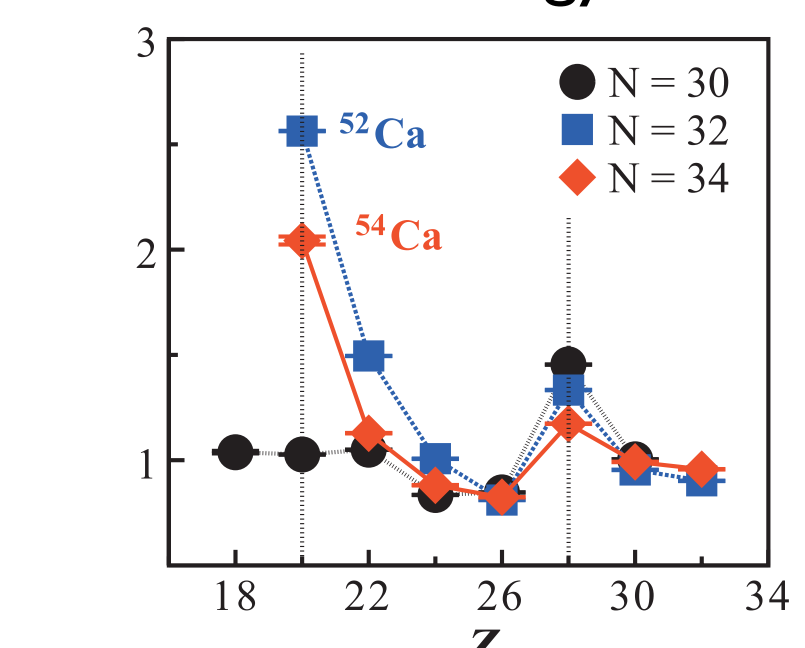
Heavy Mass Nuclei (*up to* ^{208}Pb)

3NFs provide key mechanisms,

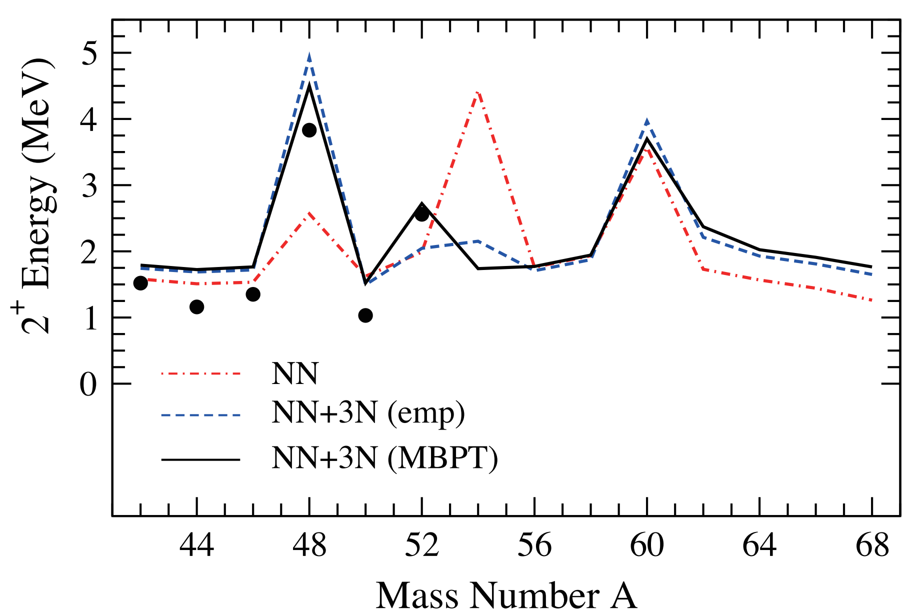
- Shell-evolution,
- Limits of Atomic Nuclei etc.

Experiment at RIBF

2_1^+ Energy of ^{54}Ca ⇒ Shell Closure at N=34

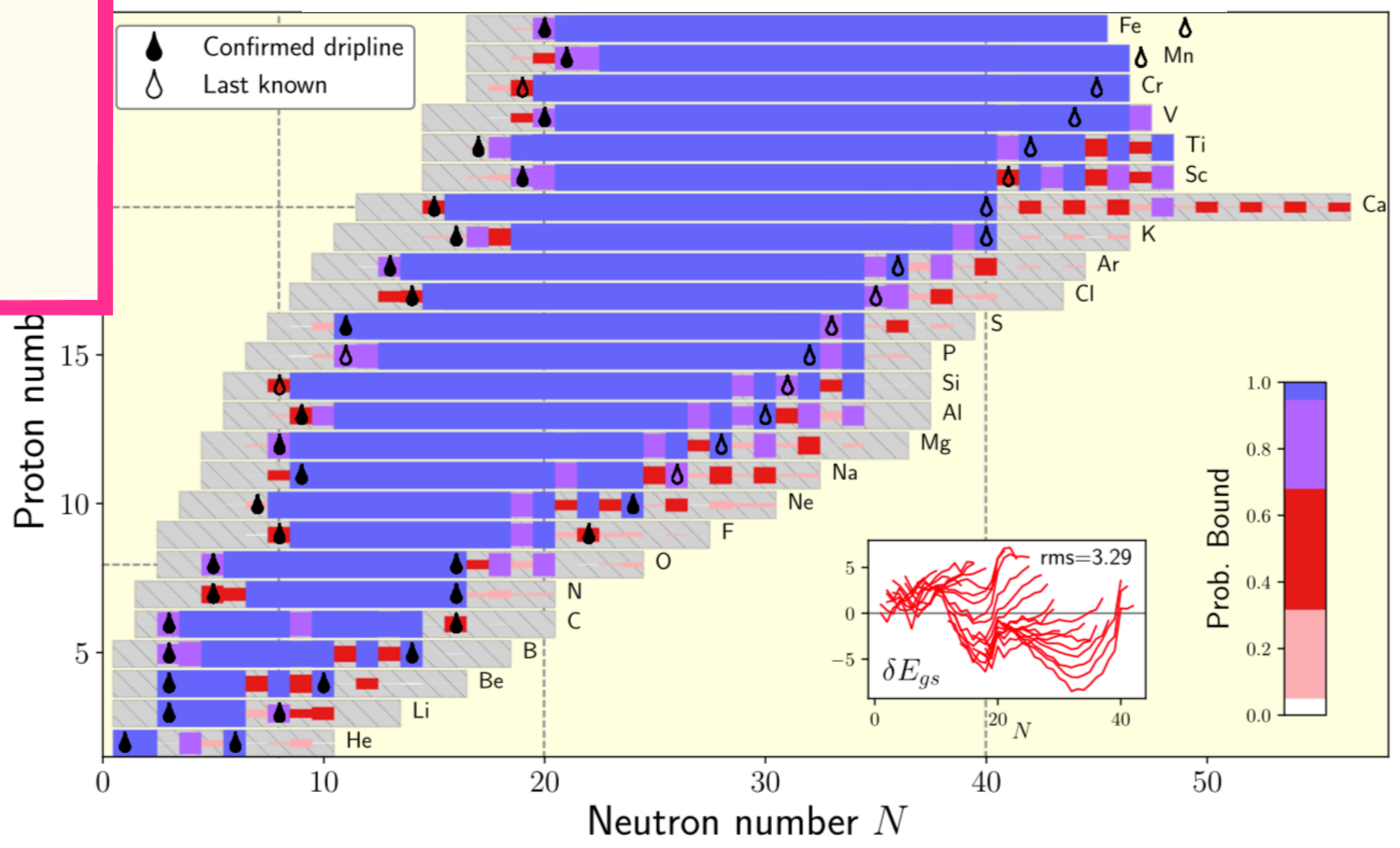


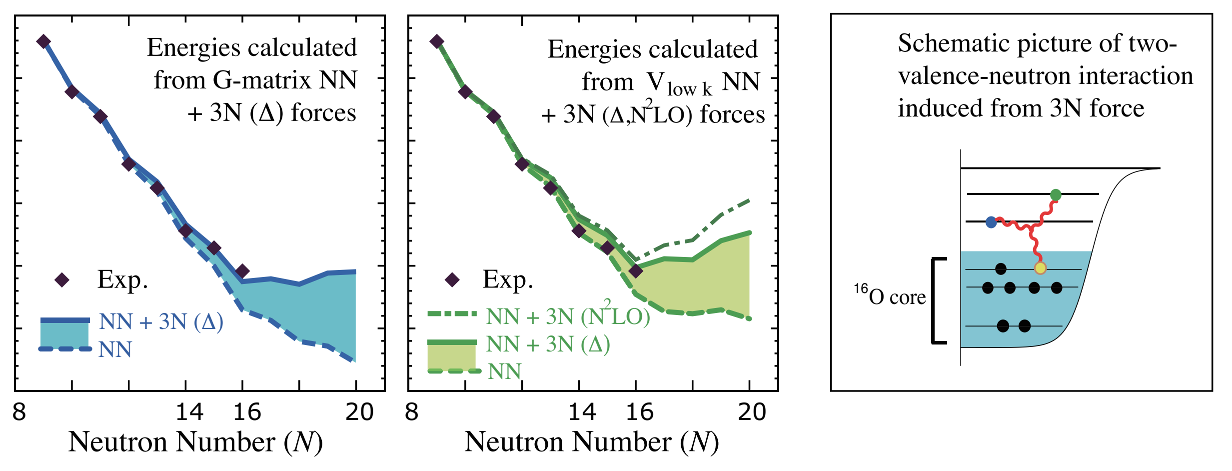
Nature 502, 207 (2013)



Holt et al., JPG40, 075105 (2013)

Phys. Rev. Lett. **126**, 022501 (2021)



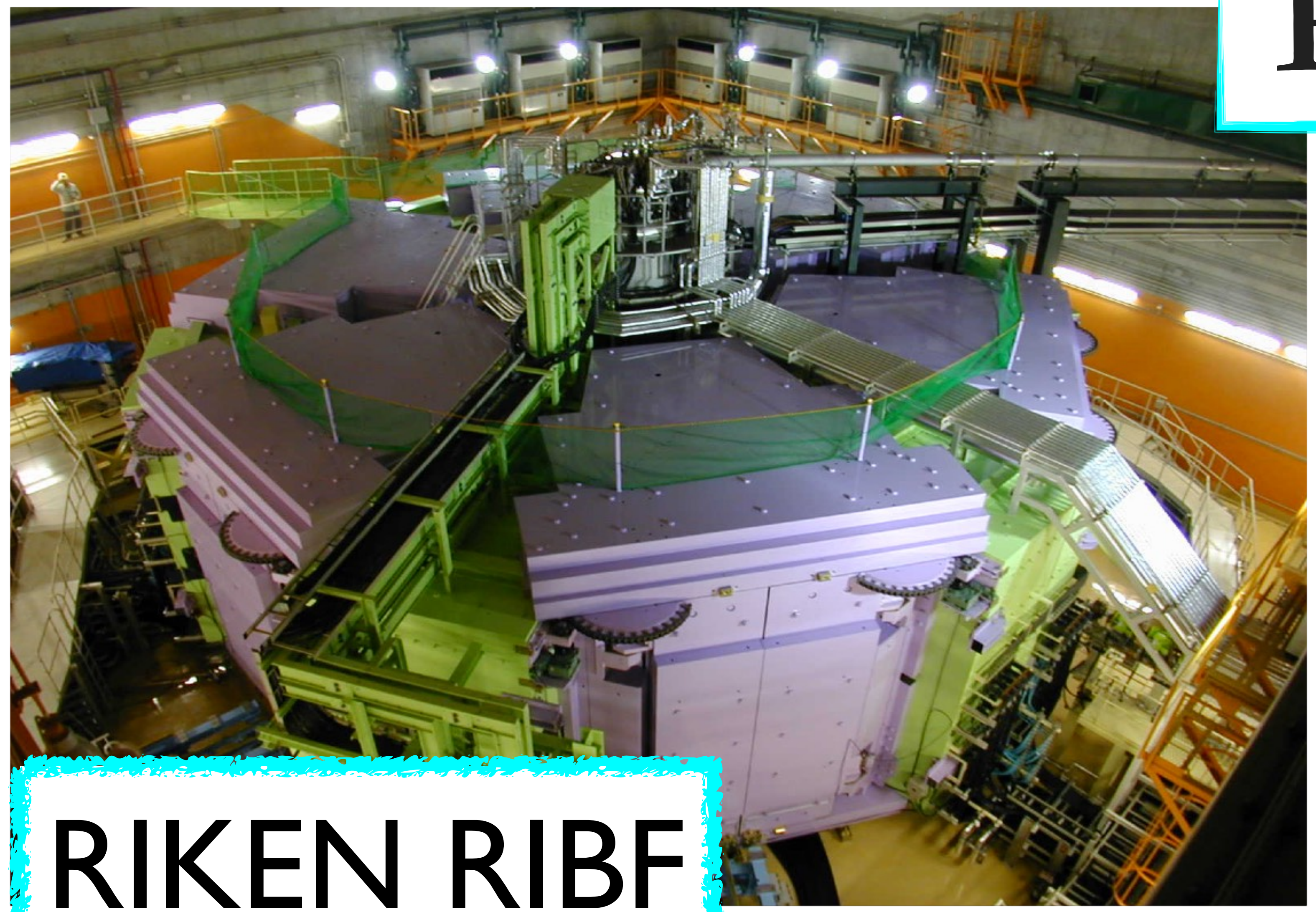


Otsuka et al. Phys. Rev. Lett. 105

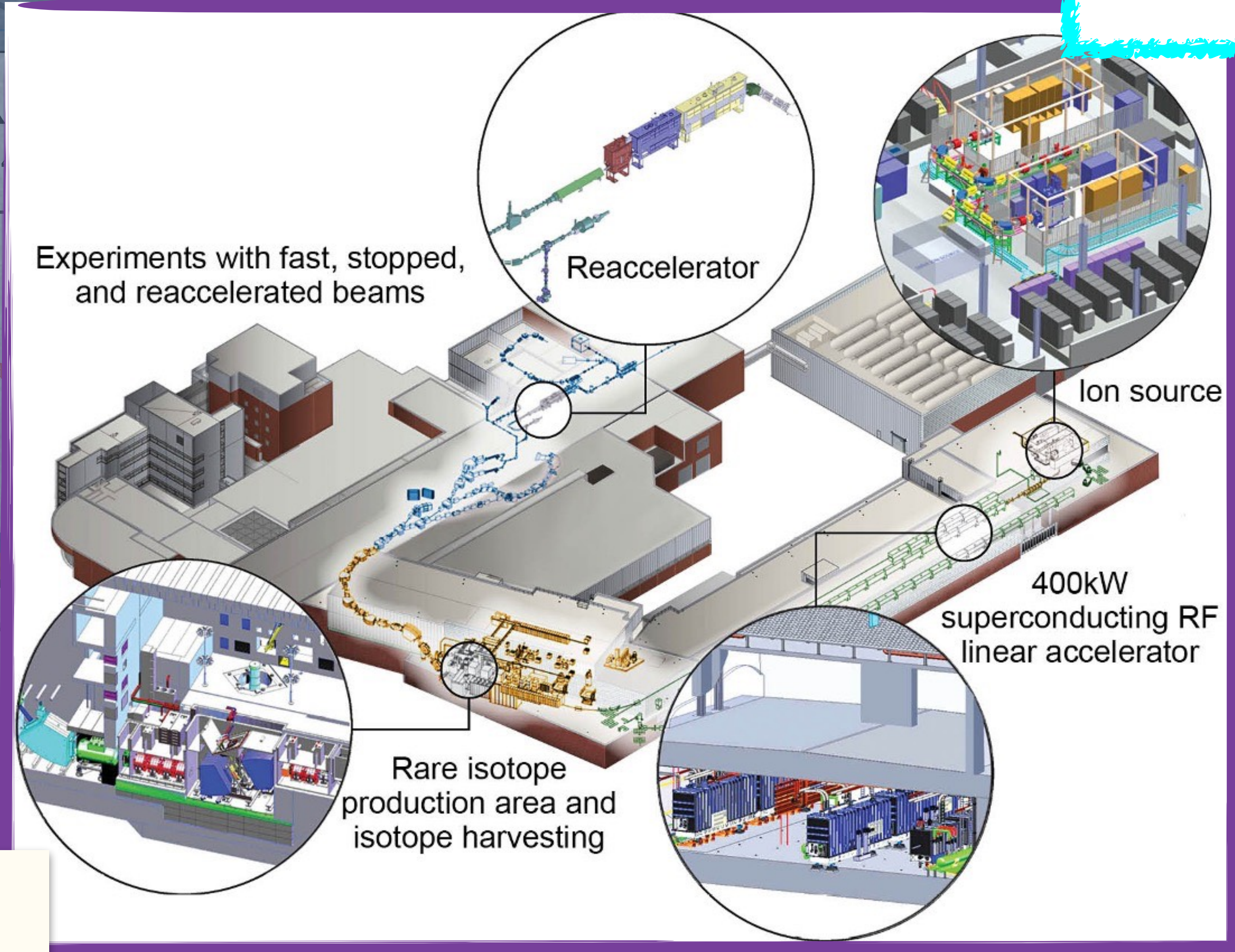
3NFs in A>3 - ① -

3NFs in Finite Nuclei

Experiment

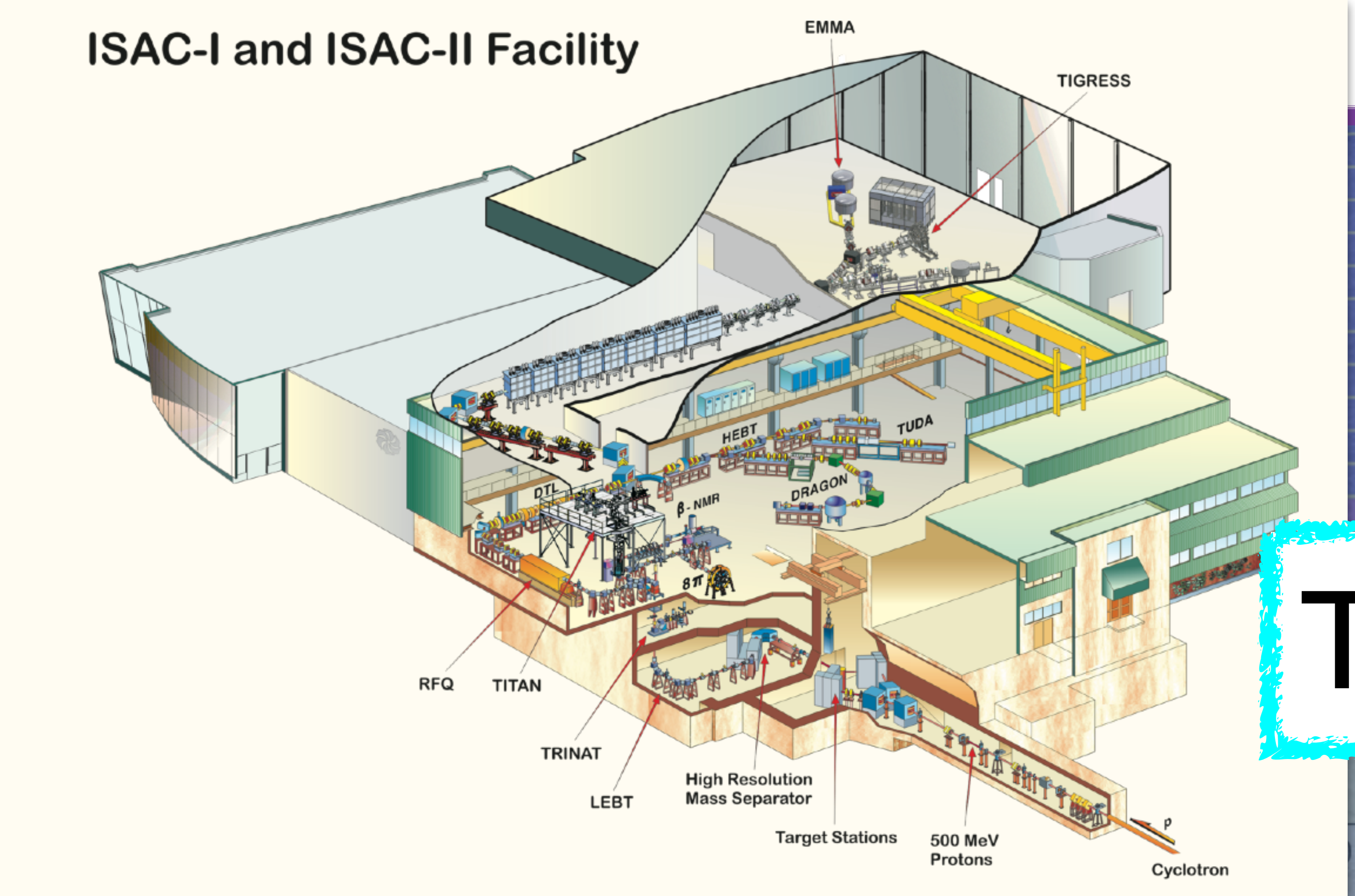


RIKEN RIBF



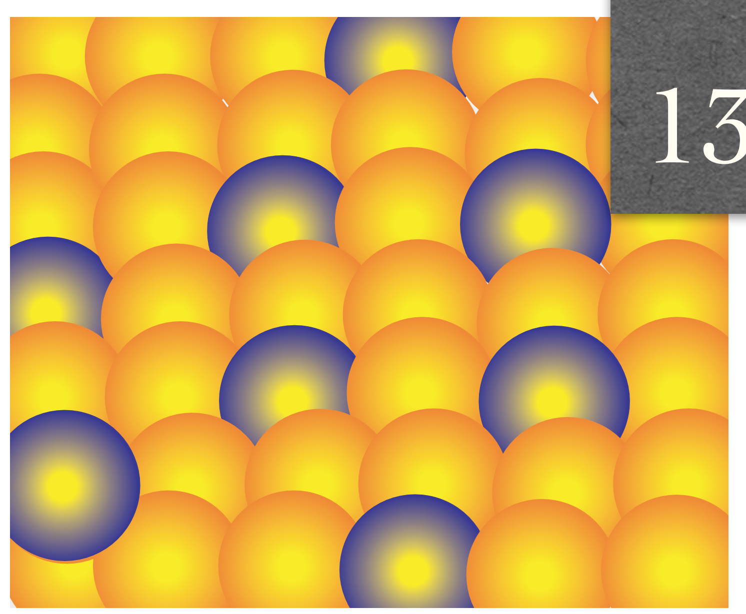
FRIB

GSI/FAIR
GANIL
ISOLDE
RAON
HIAF
etc.



TRIUMF ISAC-I & II

3NFs in A>3 - ② -

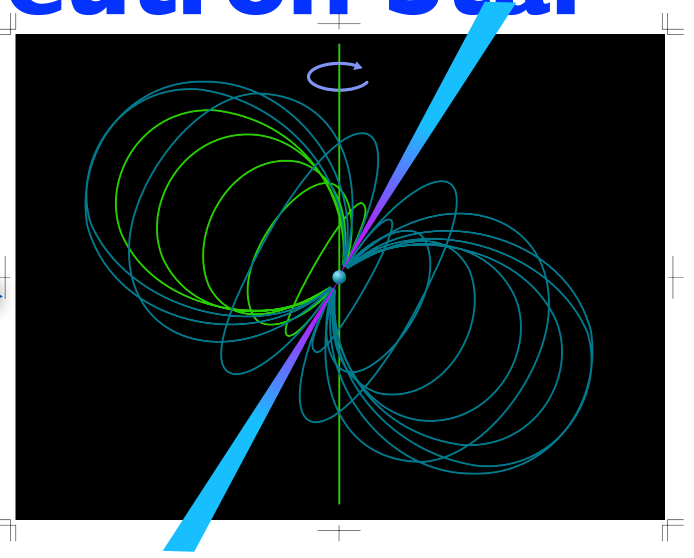


3NFs in Infinite Nuclei - Neutron Star -

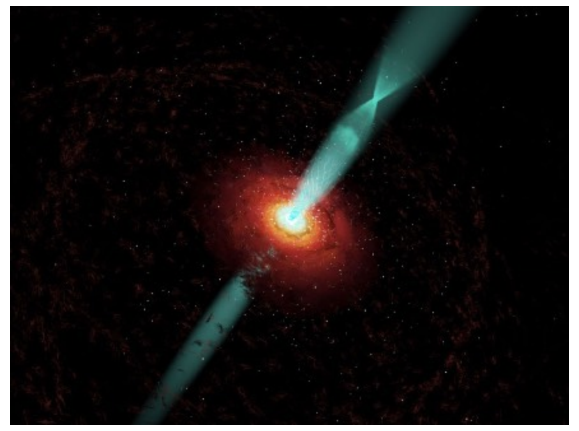
"Endpoint of stellar evolution"

Supernovae Explosion

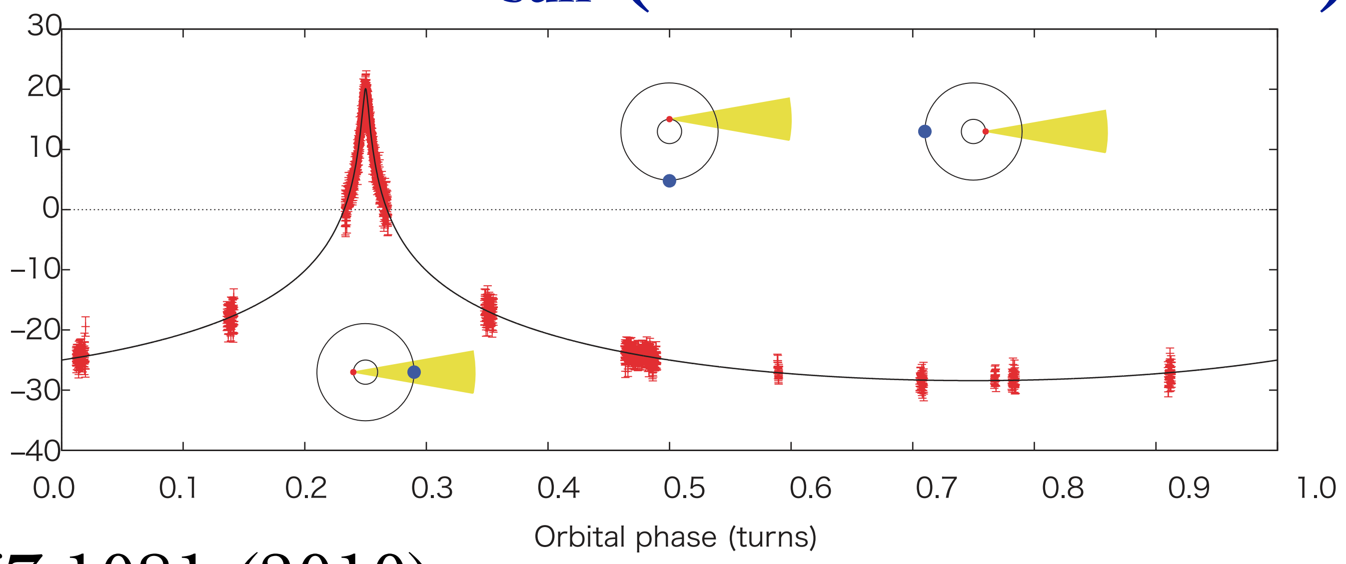
Neutron Star



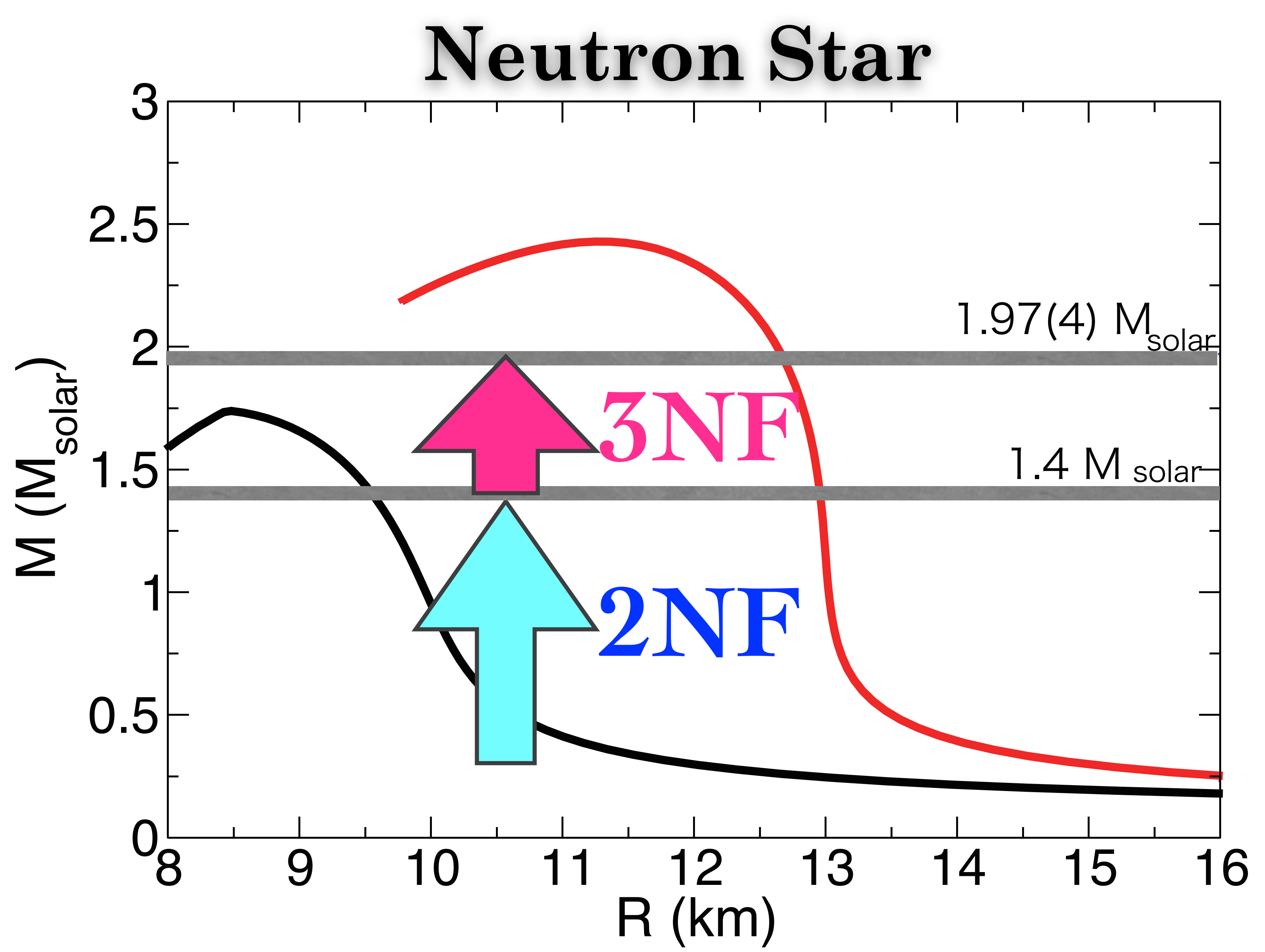
Black Hole



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



Nature *467* 1081 (2010)



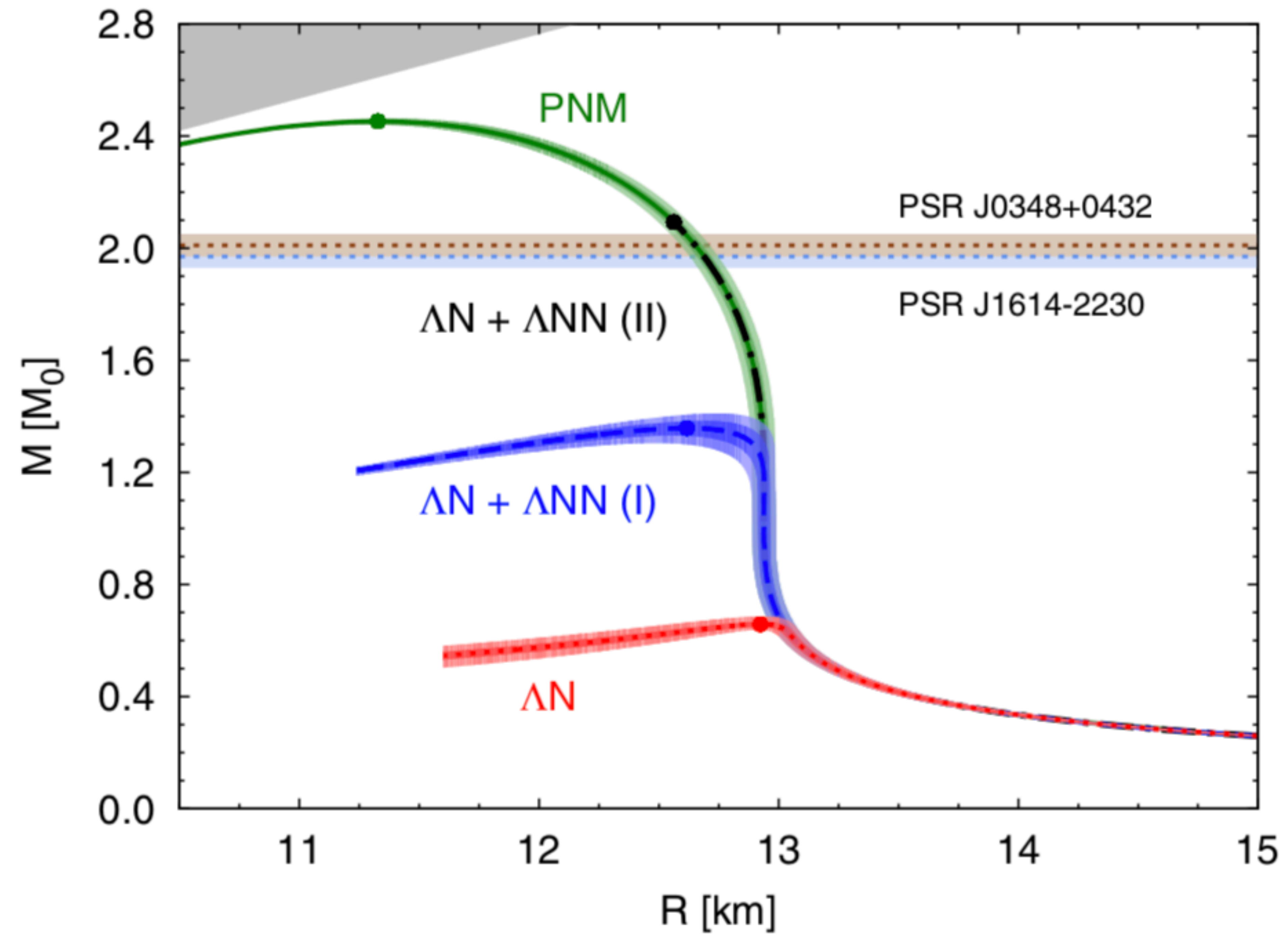
A. Akmal et al., PRC 58, 1804('98)

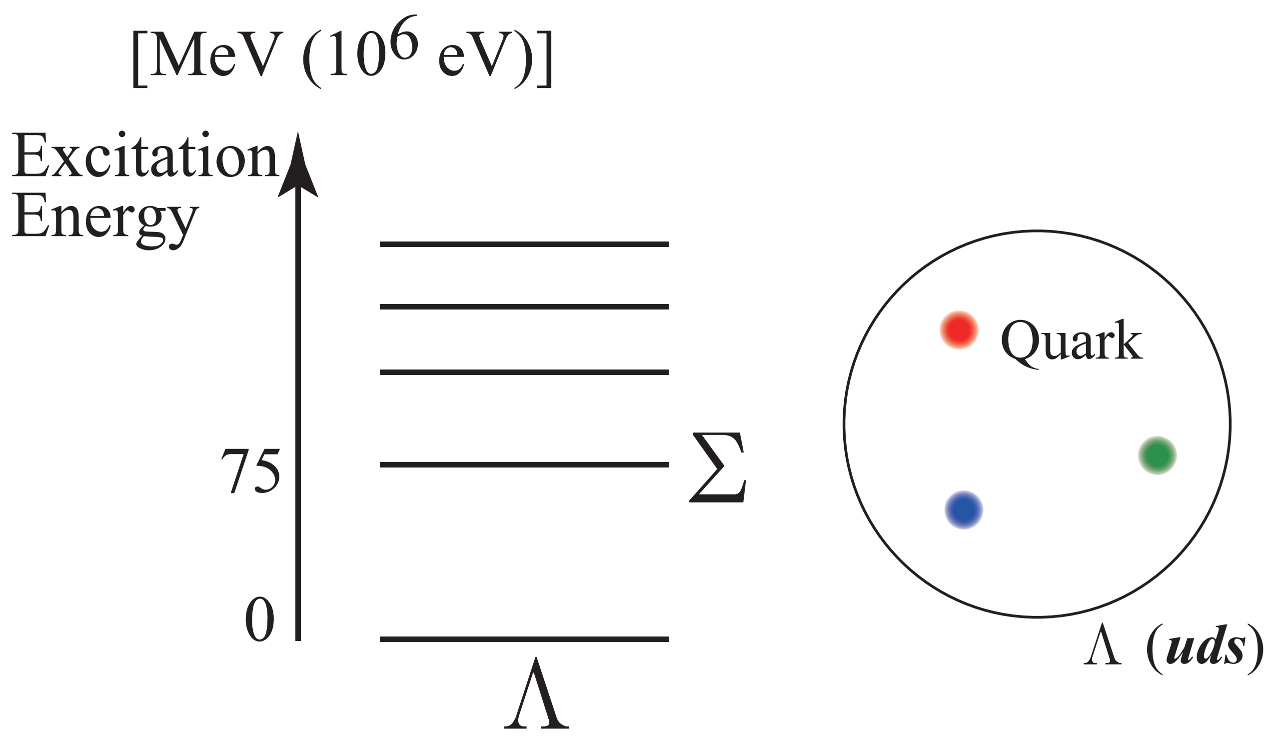
- 3NF
  - Short & Repulsive
  - Large effects at high density.

3NFs in A>3 - ② -

3NFs in Infinite Nuclei - Neutron Star -

NNN + NNΛ in Infinite Nuclei





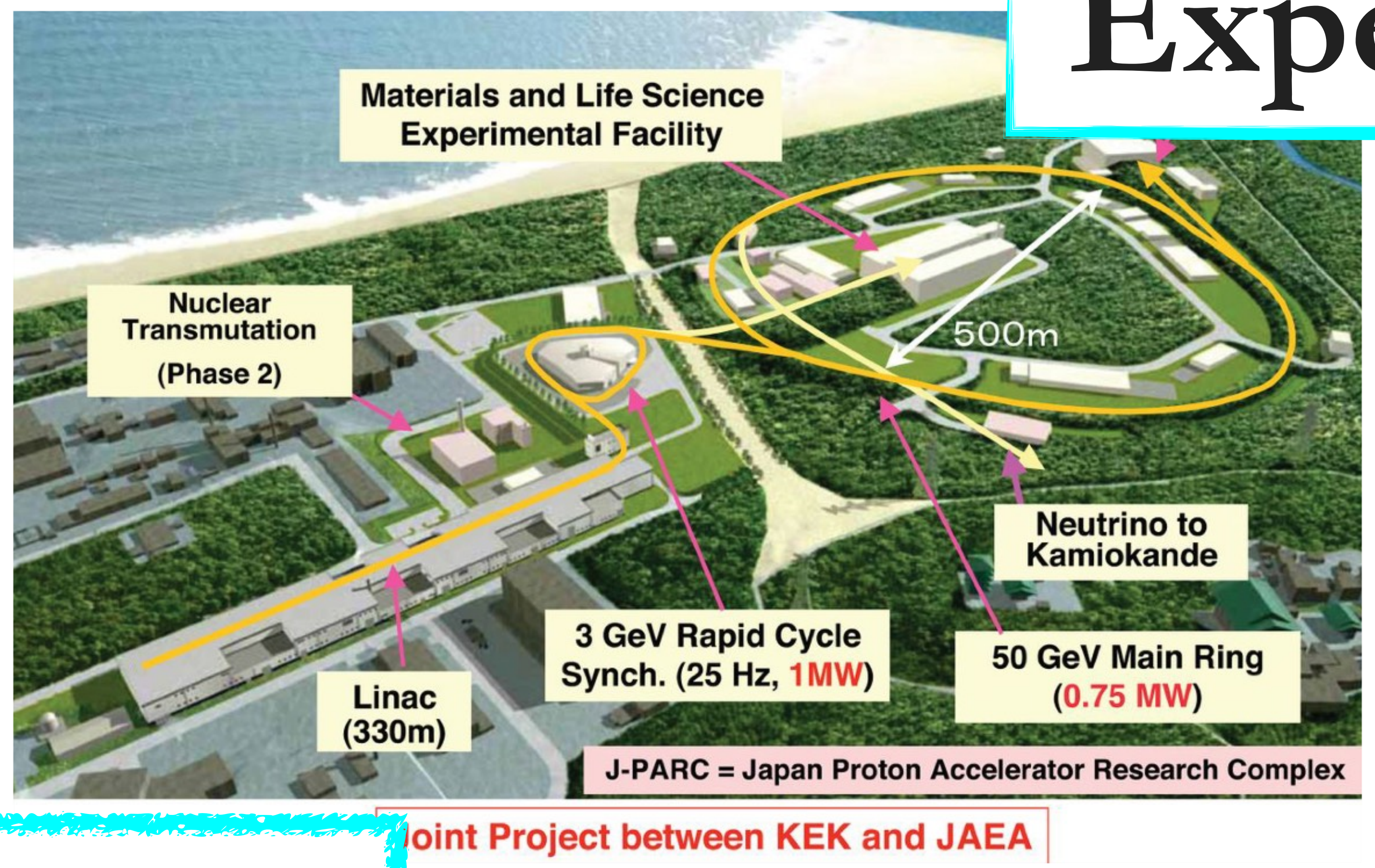
D. Lonardoni et al., Phys. Rev. Lett. 114, 092301 ('15)

3NFs in A>3 - ② -

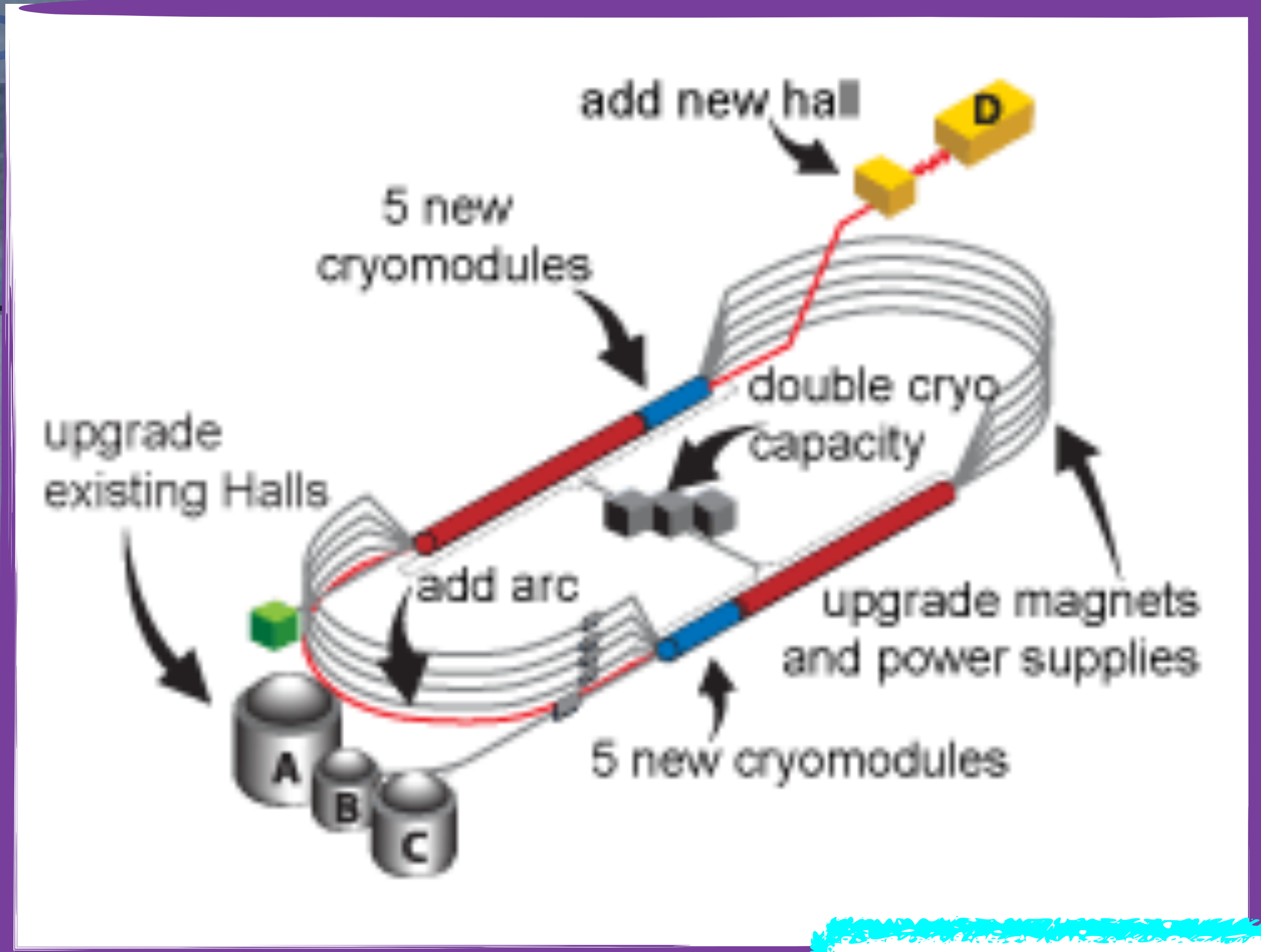
3NFs in Infinite Nuclei - Neutron Star -

NNN + NNΛ in Infinite Nuclei

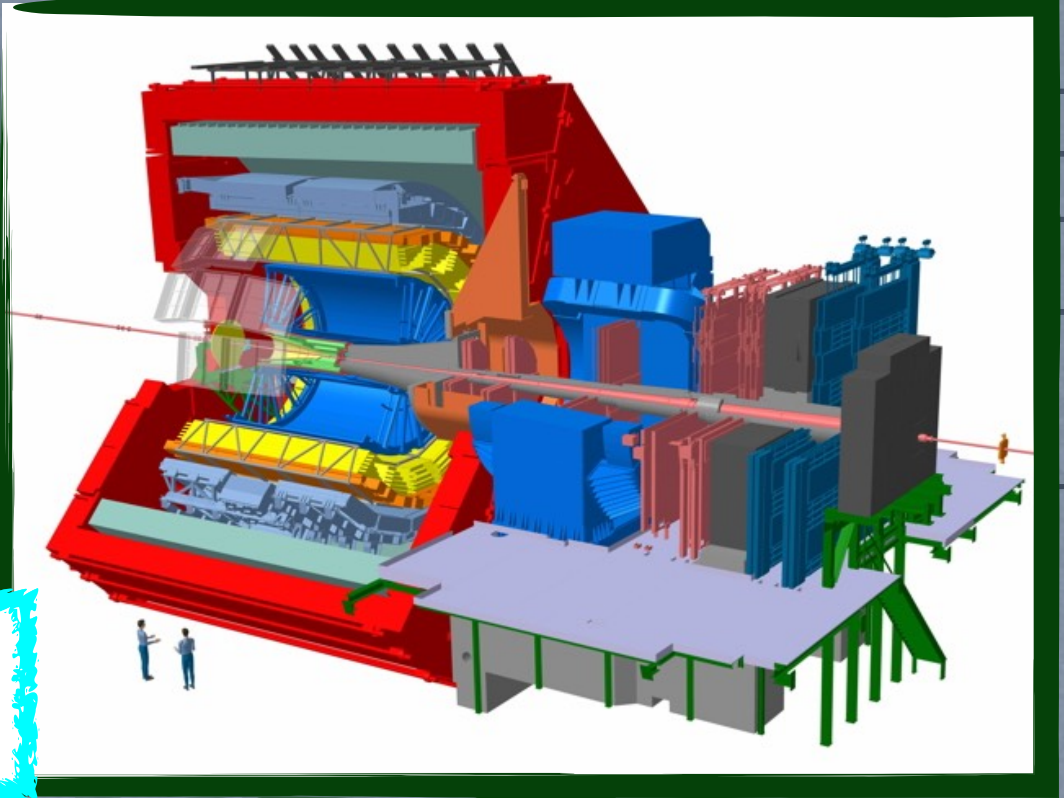
Experiment



J-PARC



JLab



LHC/ALICE

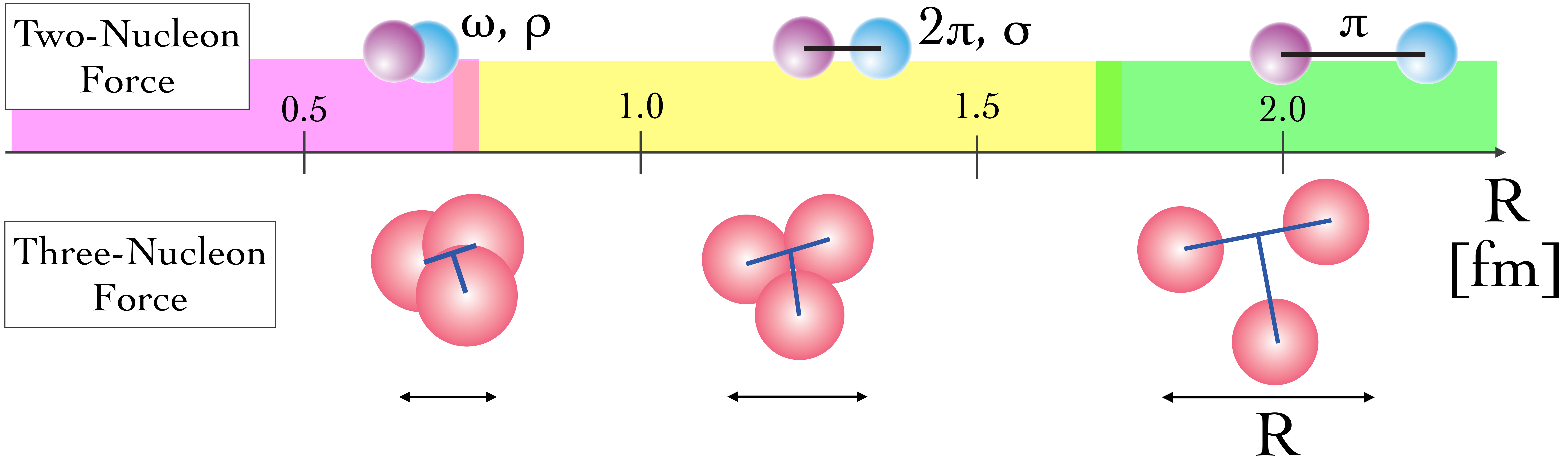
D. Lonardoni et al., Phys. R

How ?

- 3NF is a key to understand nuclear phenomena quantitatively.
- How to constrain the properties of 3NF ?

Two & Three-Nucleon Force

①. Repulsive	②. Attractive (strong)	③. Attractive (weak)
-Short Range-	-Intermediate Range-	- Long Range -



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

Nuclear Matter
Neutron Star

Nuclear Structure

Few-Nucleon Systems

How to approach Three-Nucleon Forces ?

Direct Comparison between Theory and Experiment

1. Exact Solution of Three-Nucleon System

   Faddeev Theory : Exact solution of three-body systems

2. Establishment of Two-Nucleon Forces

   Realistic 2NFs :
   reproduce 4000 NN scattering exp. data
   with high precision, $\chi^2 \sim 1$.

3. High Precision Experiment

   e.g. Our experiment

Extract information of Three-Nucleon Forces

Triton (^{3}H) Binding Energy

Triton (^{3}H)

- A=3 (Z=1, N=2)
- 2NF provides less binding energies by **0.5 ∼ 1 MeV**.
- 3NF fill the gap between the data and the calculations based on 2NFs.
- The cut-off Λ is determined to reproduce ^{3}H binding energy.

$$F_{\pi NN}(q^2) = \frac{\Lambda^2 - m_\pi^2}{\Lambda + q^2}$$

First results of Faddeev calculations

- C.R. Chen, G. L. Payne, J. L. Friar and B. F. Gibson, Phys. Rev. C 33, 1740 (1986)
- T. Sasakawa, and S. Ishikawa, Few-Body Syst. 1, 3 (1986)

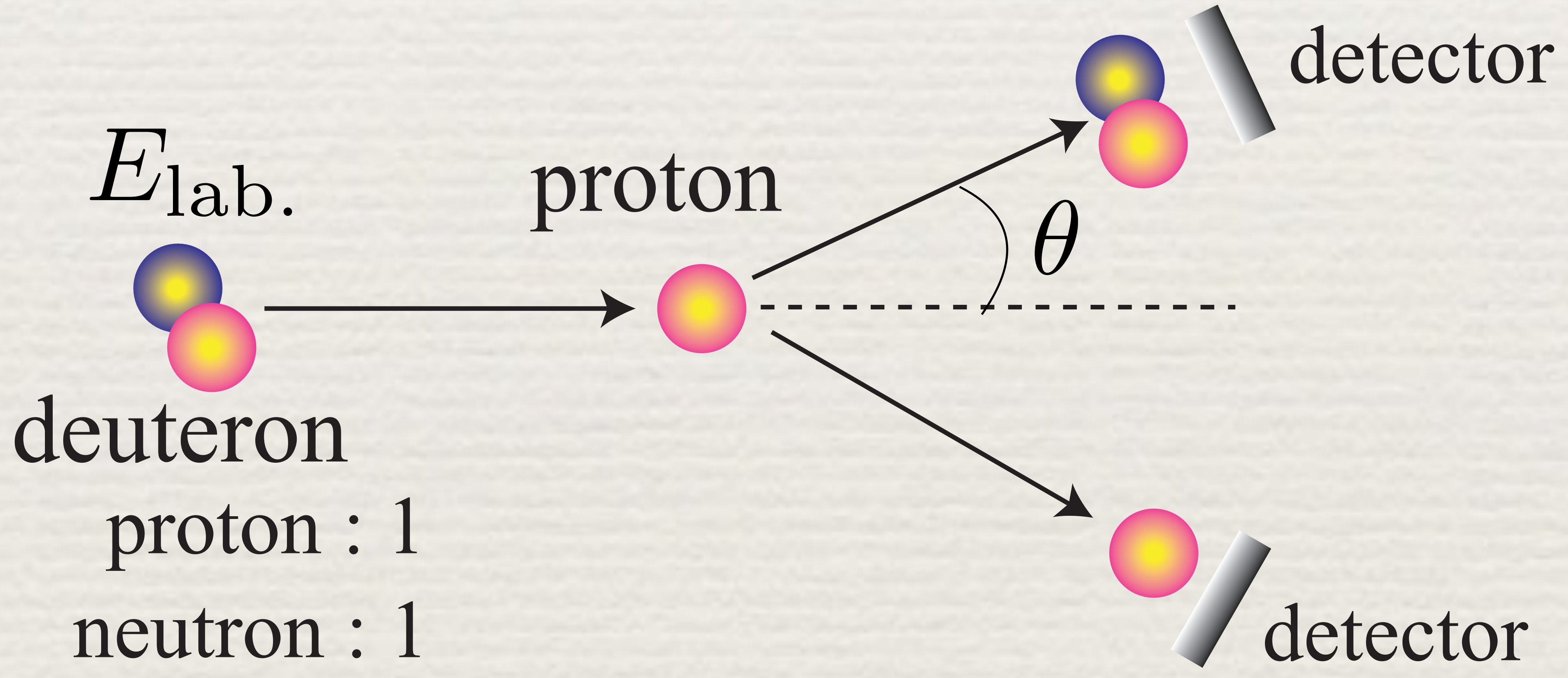
Potential	E_B [MeV] (w/o 3NF)	E_B [MeV] (with 3NF)	Λ/m_π
CDBonn	7.953	8.483	4.856
AV18	7.576	8.479	5.215
Nijm I	7.731	8.480	5.147
Nijm II	7.709	8.477	4.990
Nijm 93	7.664	8.480	5.207
Exp.	8.481821(4) [MeV]		

A. Nogga *et al.*, Phys. Rev. C**65**, 054003 (2002).

Three-Nucleon Scattering

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

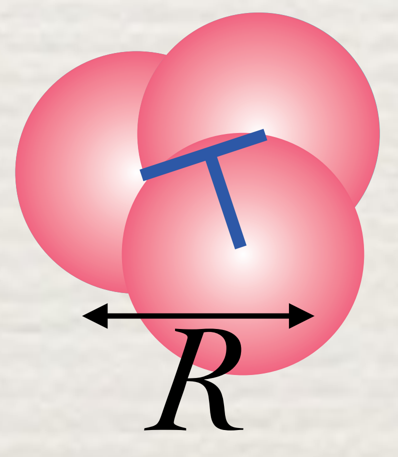
- ✓ **Momentum dependence (R-dependence)**
- ✓ **Spin-dependence**



$$\frac{d\sigma}{d\Omega}(\theta) \propto \left| \int \exp(-\mathbf{q}\cdot\mathbf{r}')V(r)d\mathbf{r}' \right|^2$$

Nuclear Potential

Angular Dependent Cross Section :
Fourier Transform of Nuclear Potential



$qR \sim \hbar$

$R \sim$ a few fm

$q \sim 200$ MeV/c

$E_{lab.} \sim 100$ MeV/A

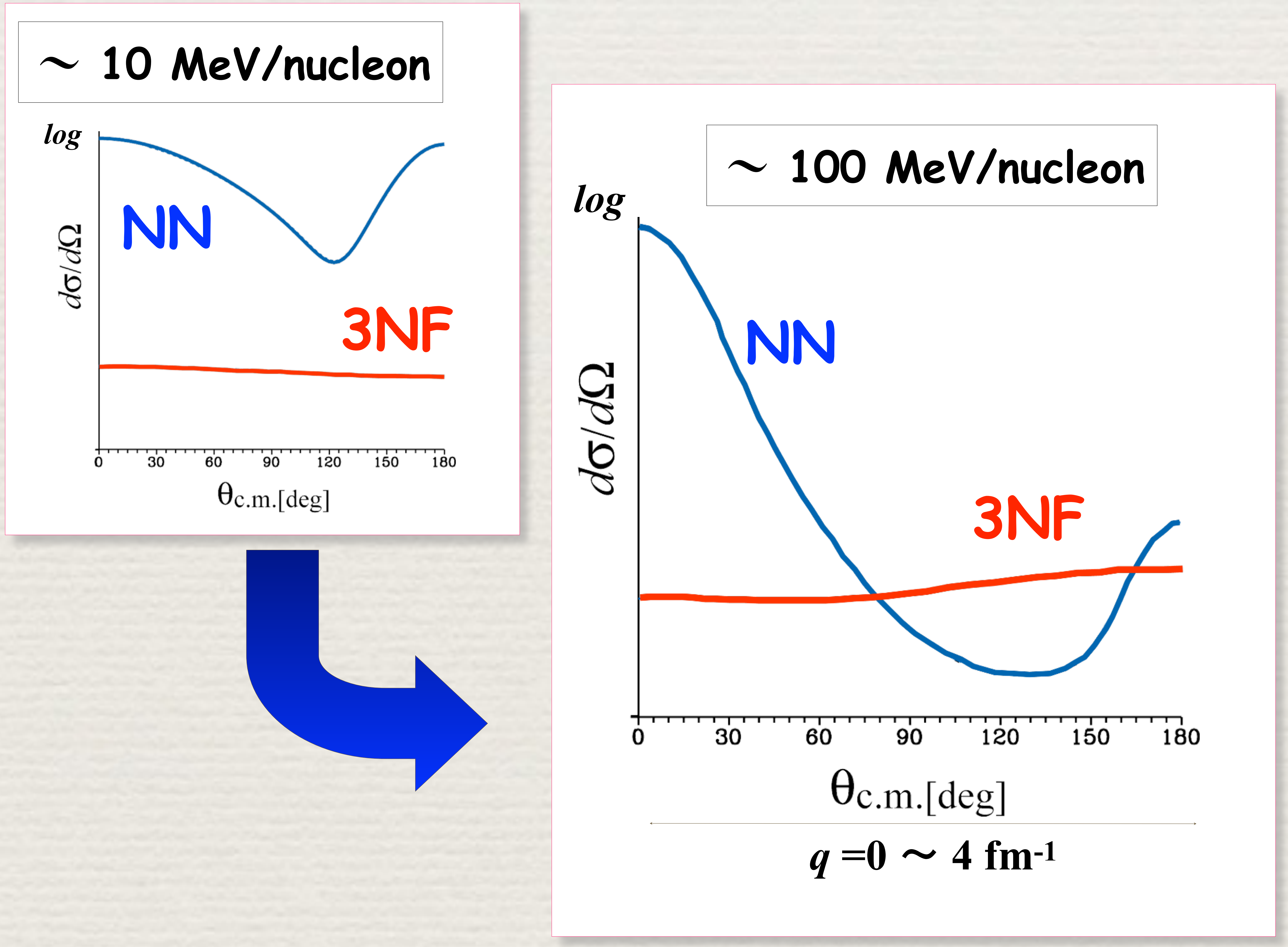
One can change R by adjusting $E_{lab.}$

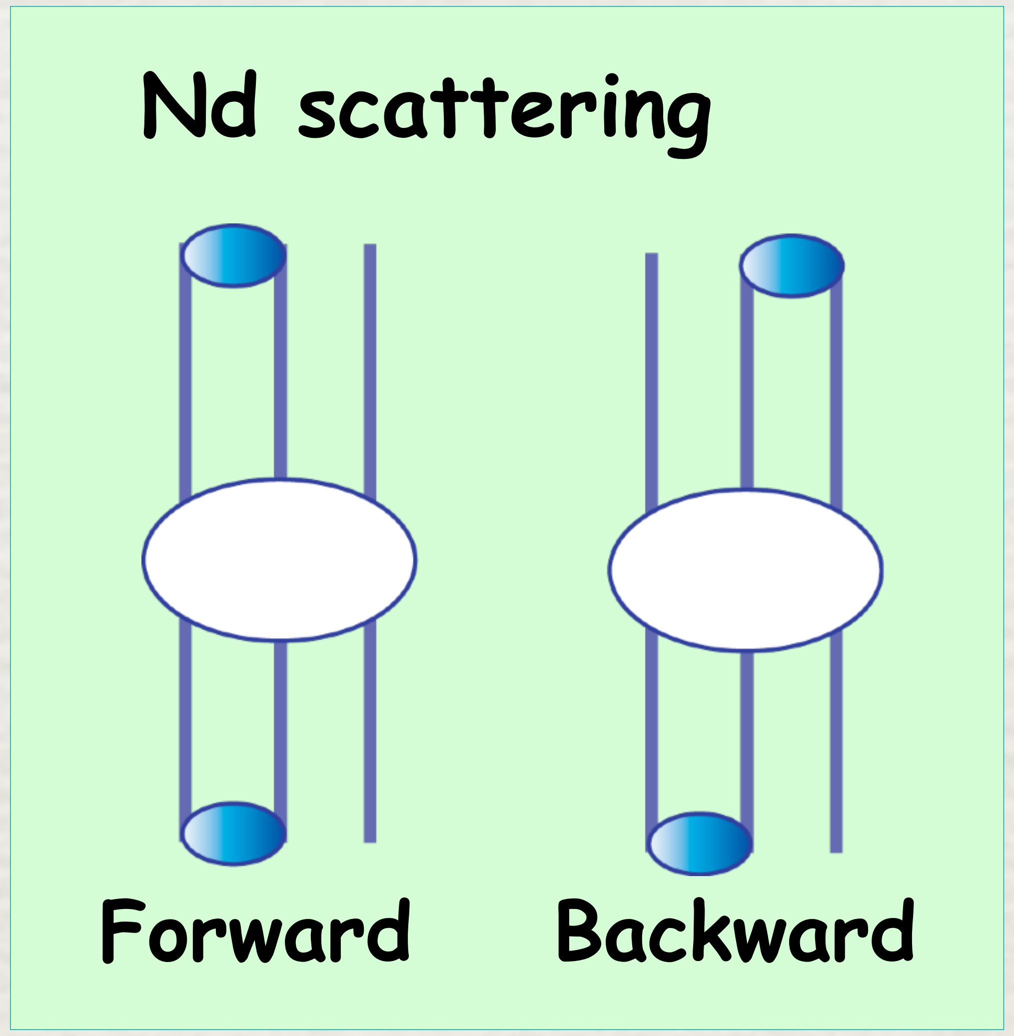
Where is the hot spot for 3NFs ?

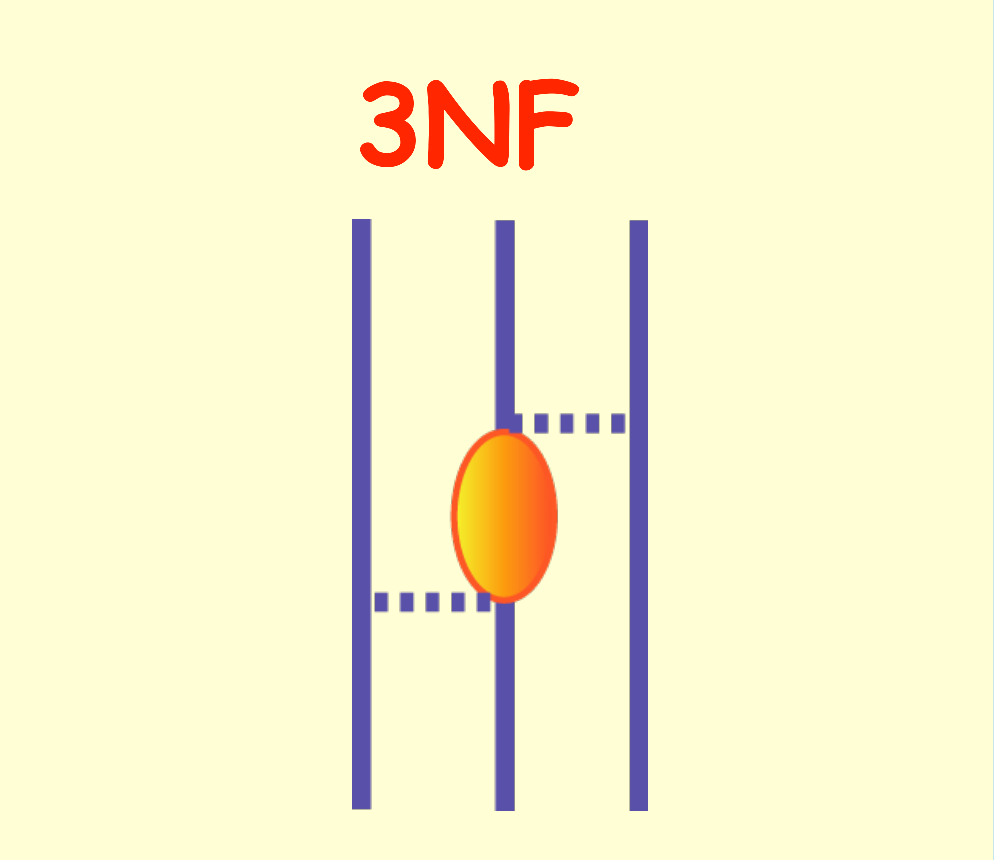
Nucleon-Deuteron Scattering - 3N Scattering -

Predictions by H. Witala et al. (1998)

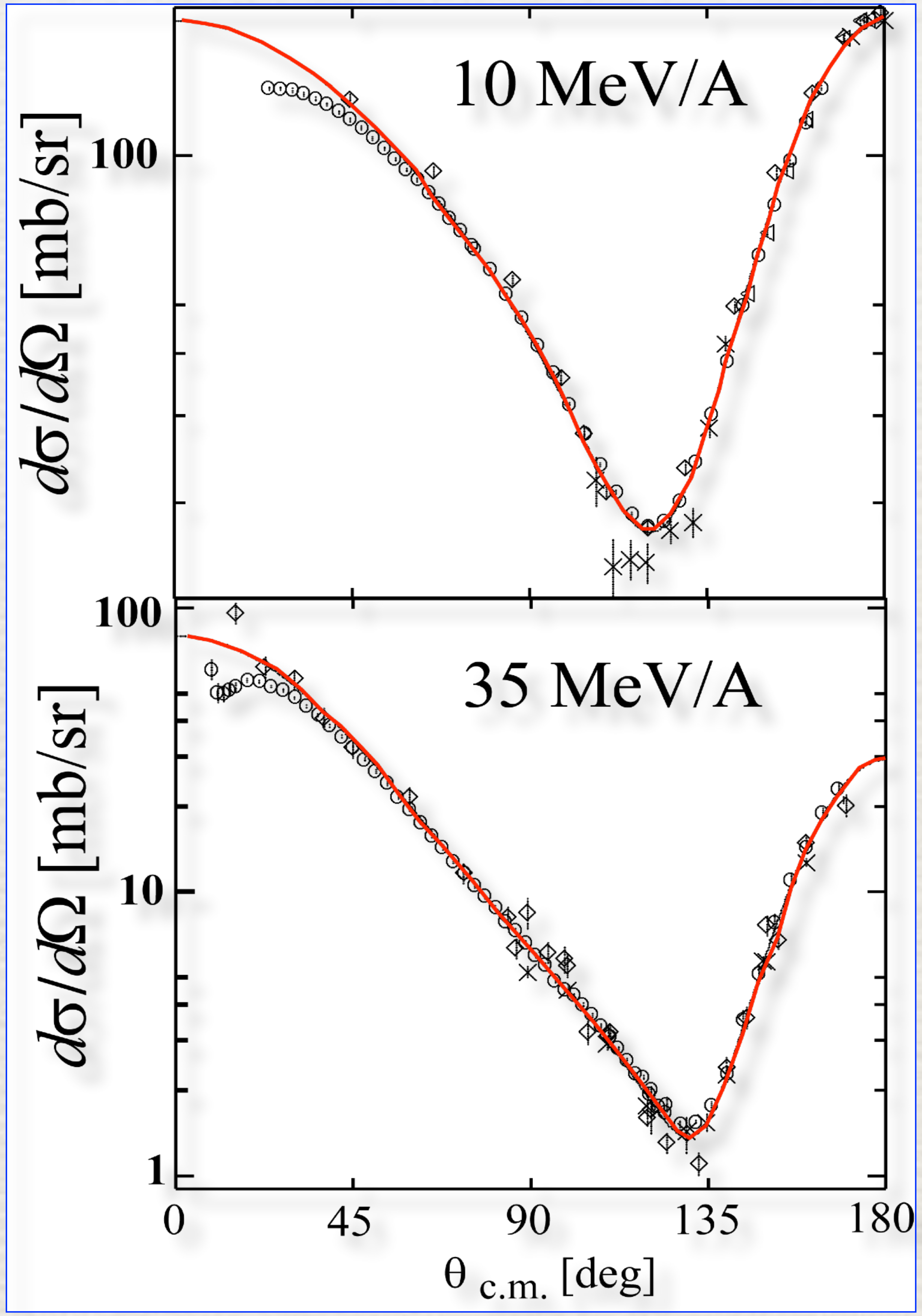
Cross Section minimum for Nd Scattering at ~ 100 MeV/nucleon







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})

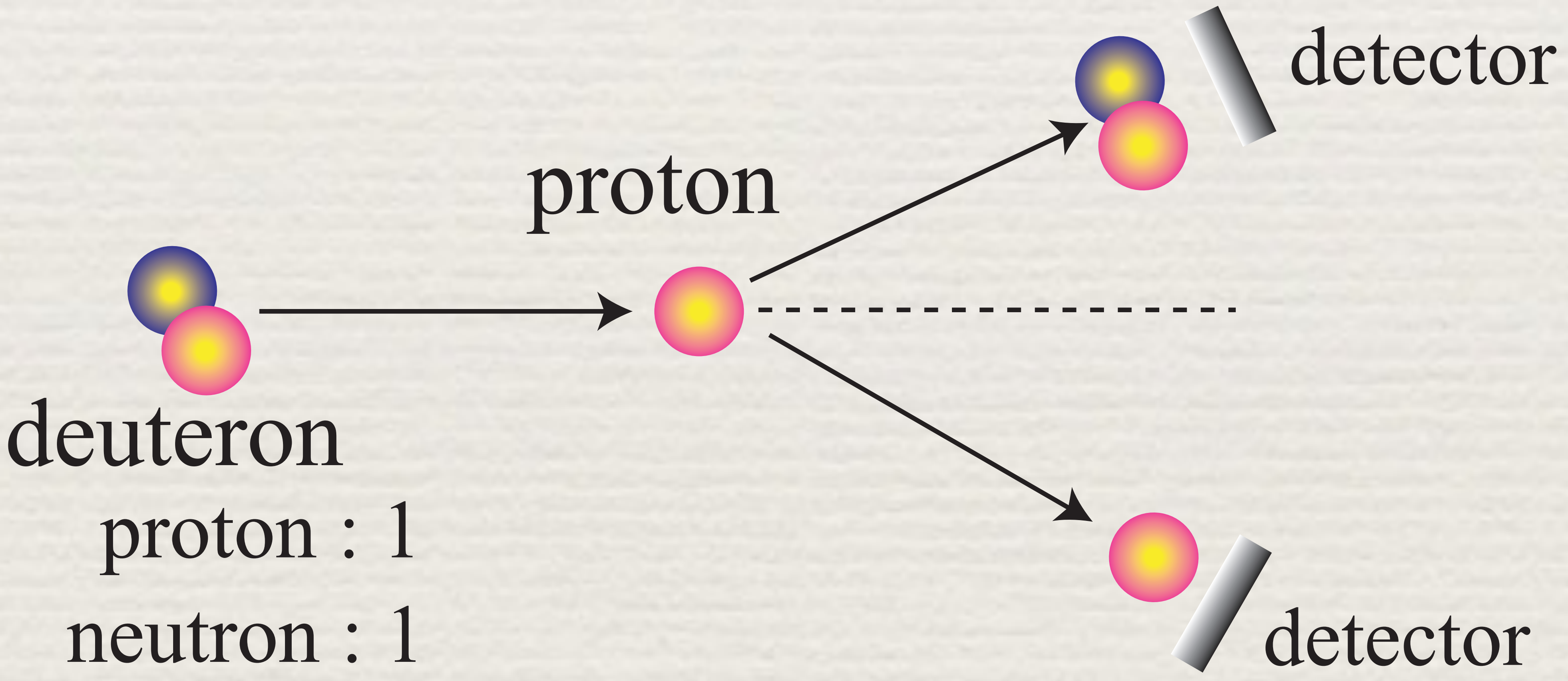
No signatures of 3NF

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

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

deuteron-nucleon scattering

at ∼100 MeV/nucleon

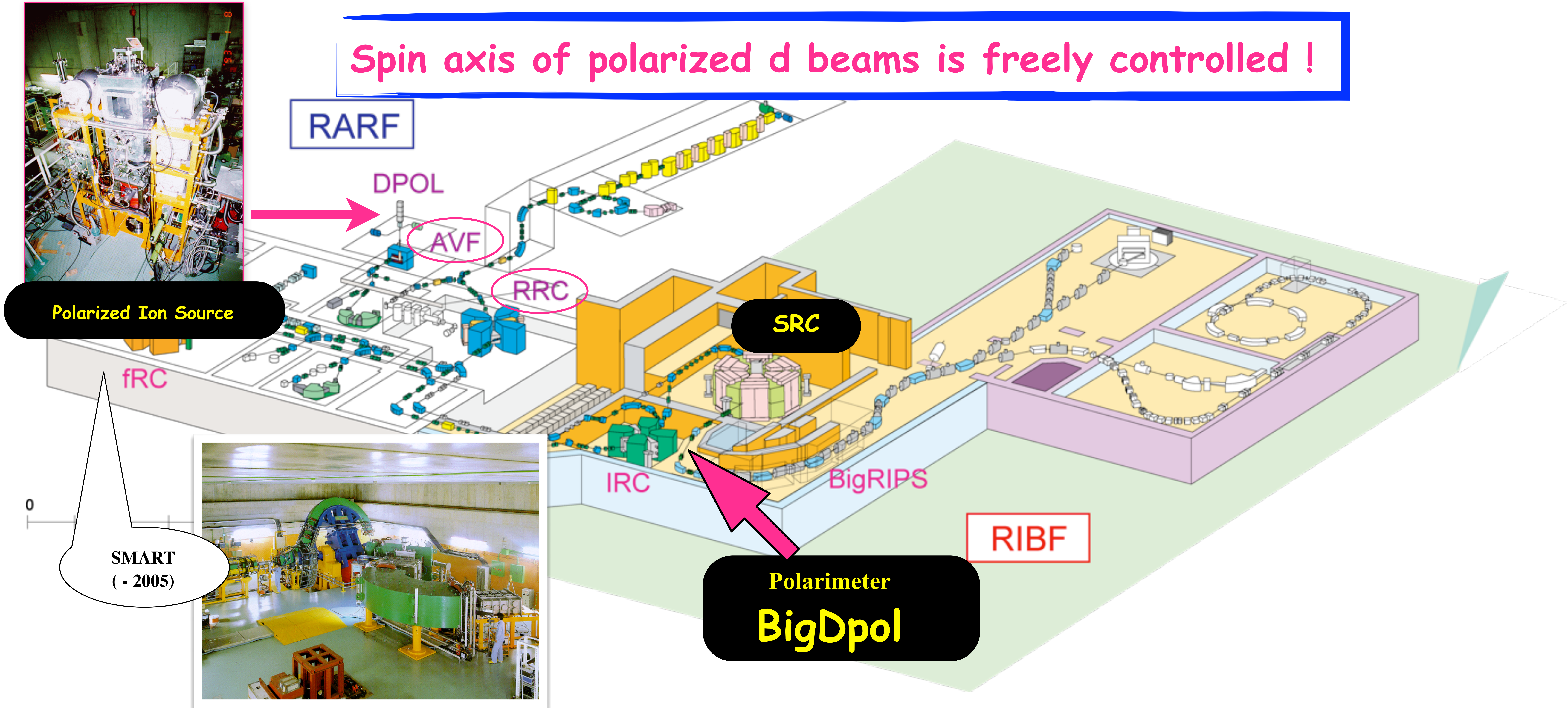


RIKEN RI Beam Factory (RIBF)

Polarized deuteron beam

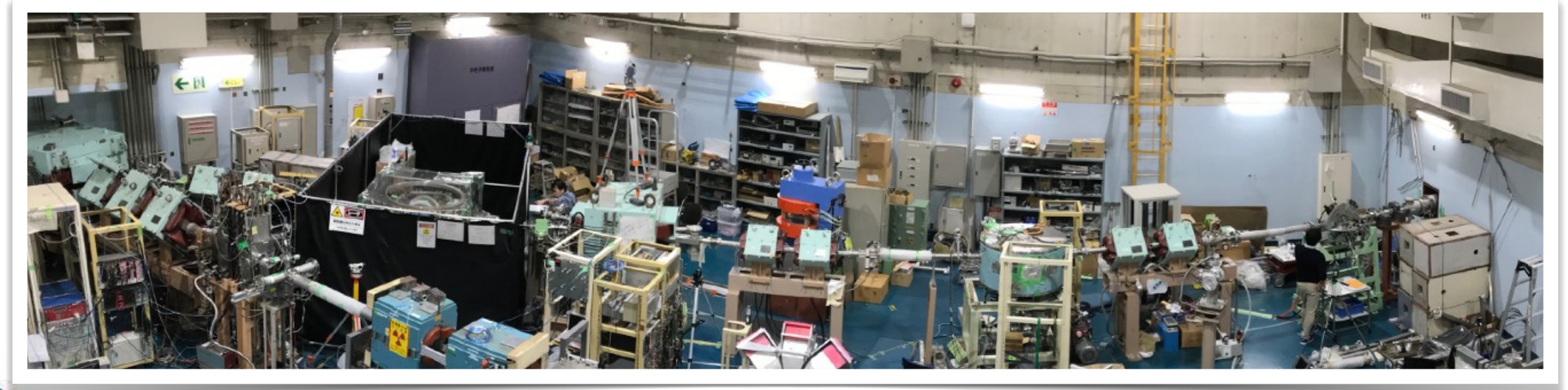
- acceleration by AVF+RRC : 65-135 MeV/nucleon
- acceleration by AVF+RRC+SRC : 190-300 MeV/nucleon
- polarization : 60-80% of theoretical maximum values

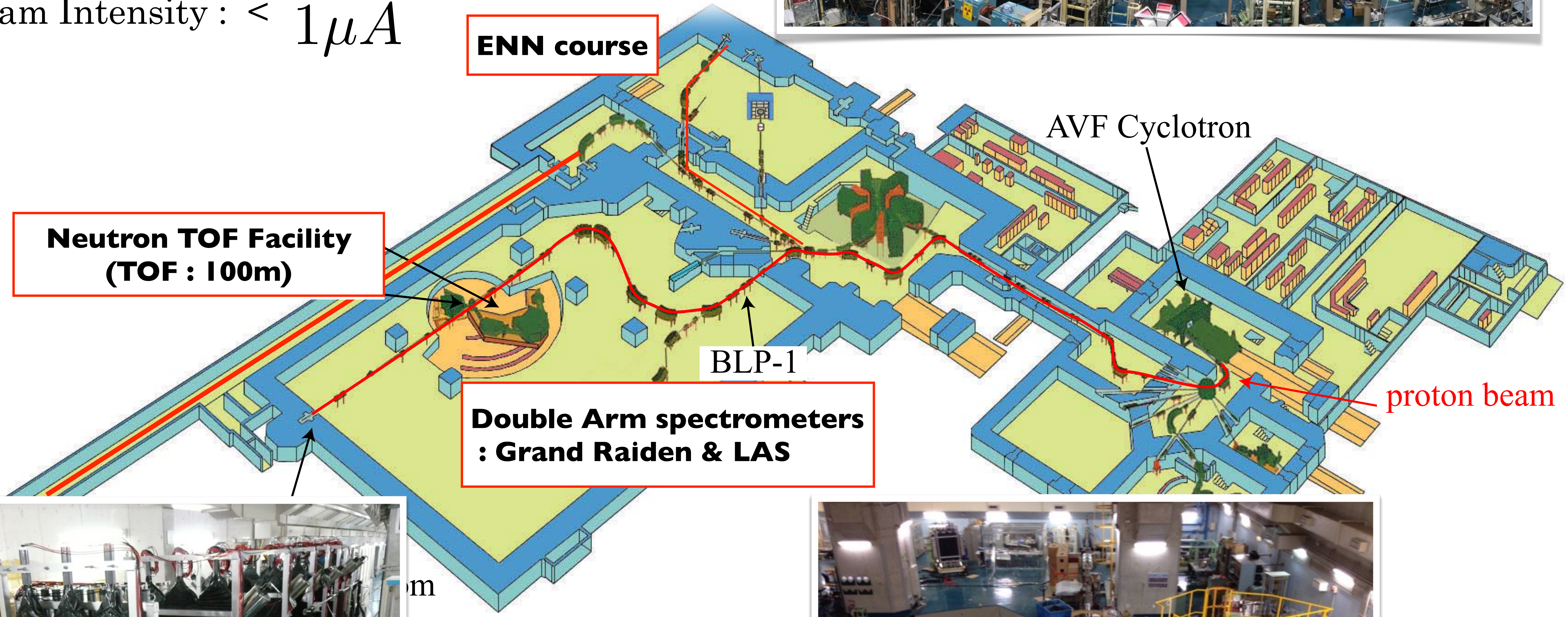
- Beam Intensity : < 100 nA

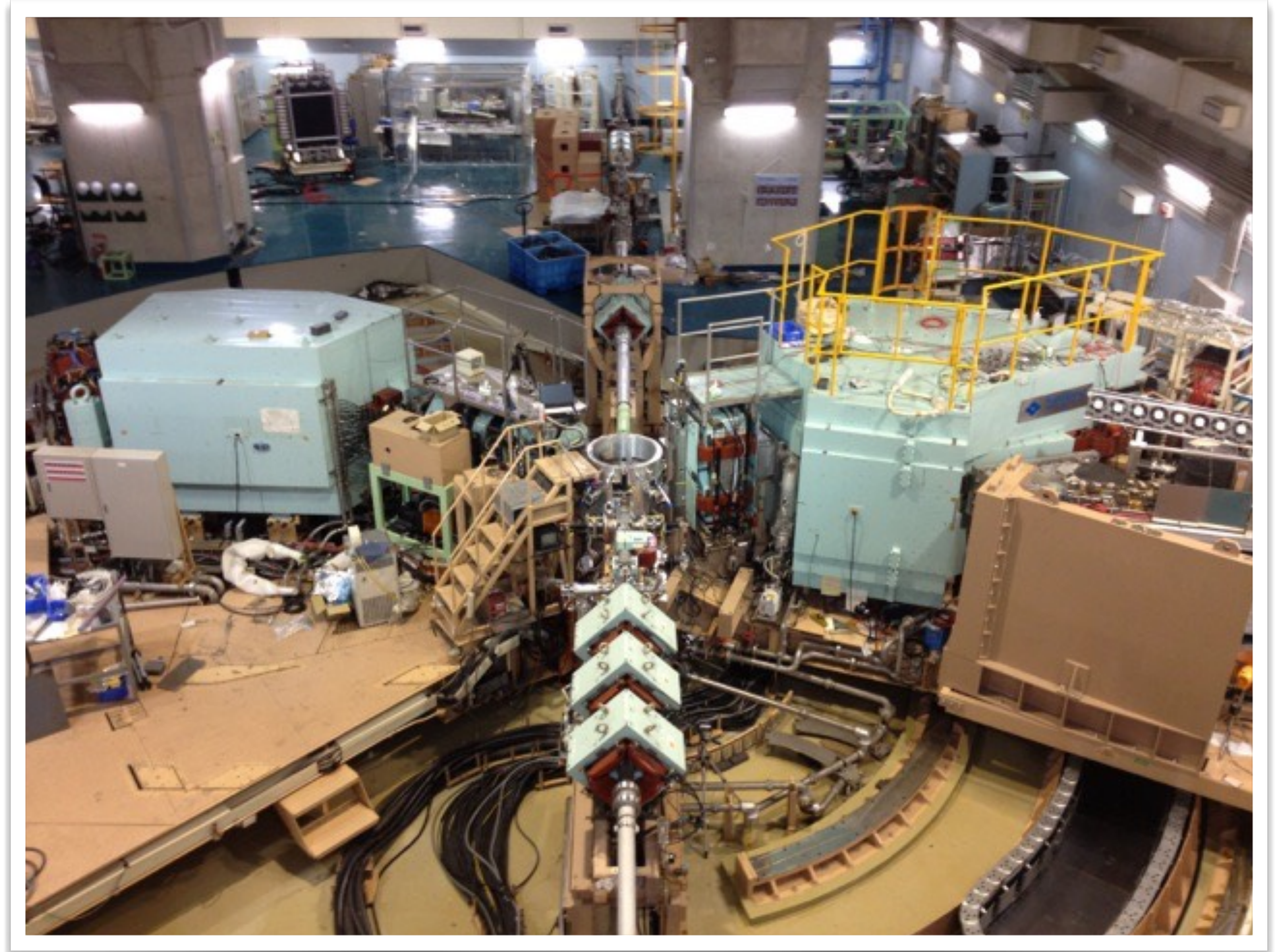


RCNP, Osaka University

- 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 : < $1\mu A$







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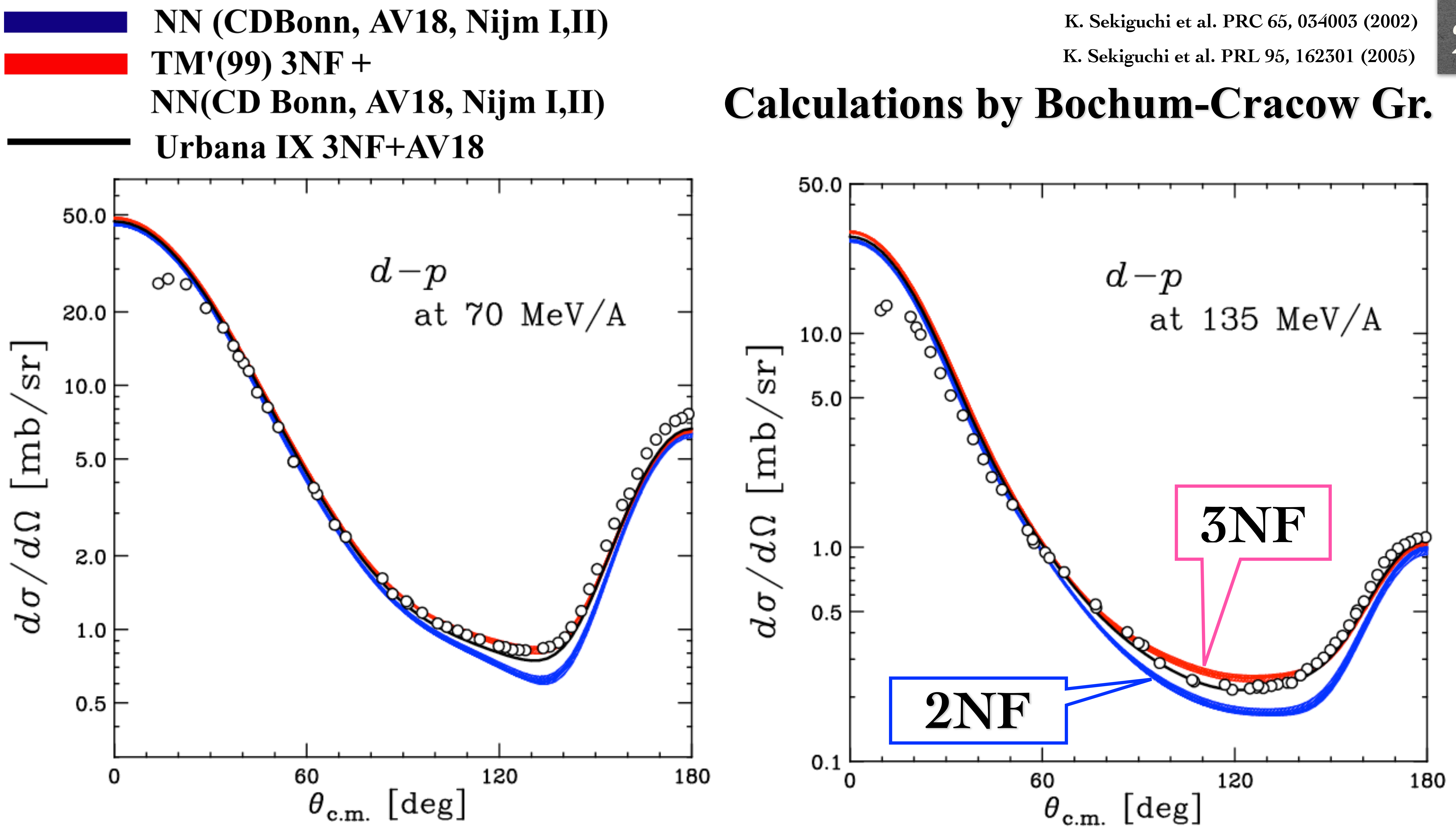
Differential Cross section

K. Sekiguchi et al. PRC 65, 034003 (2002)
K. Sekiguchi et al. PRL 95, 162301 (2005)

Calculations by Bochum-Cracow Gr.

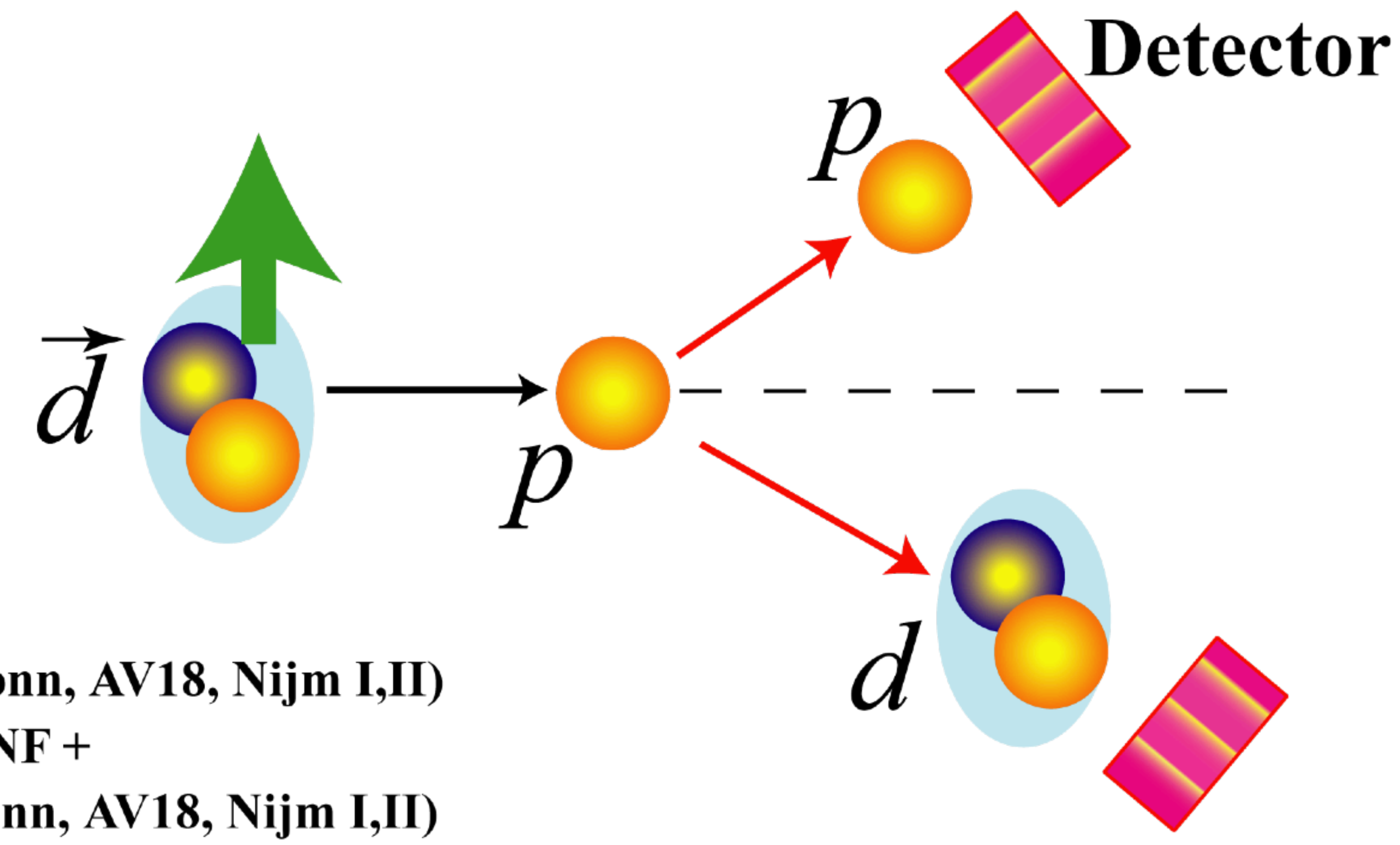


2NF (CDBonn, AV18, Nijmegen I,II)
: Large discrepancy in Cross Section Minimum (~ 30%)

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

Spin Observables

Analyzing Powers



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

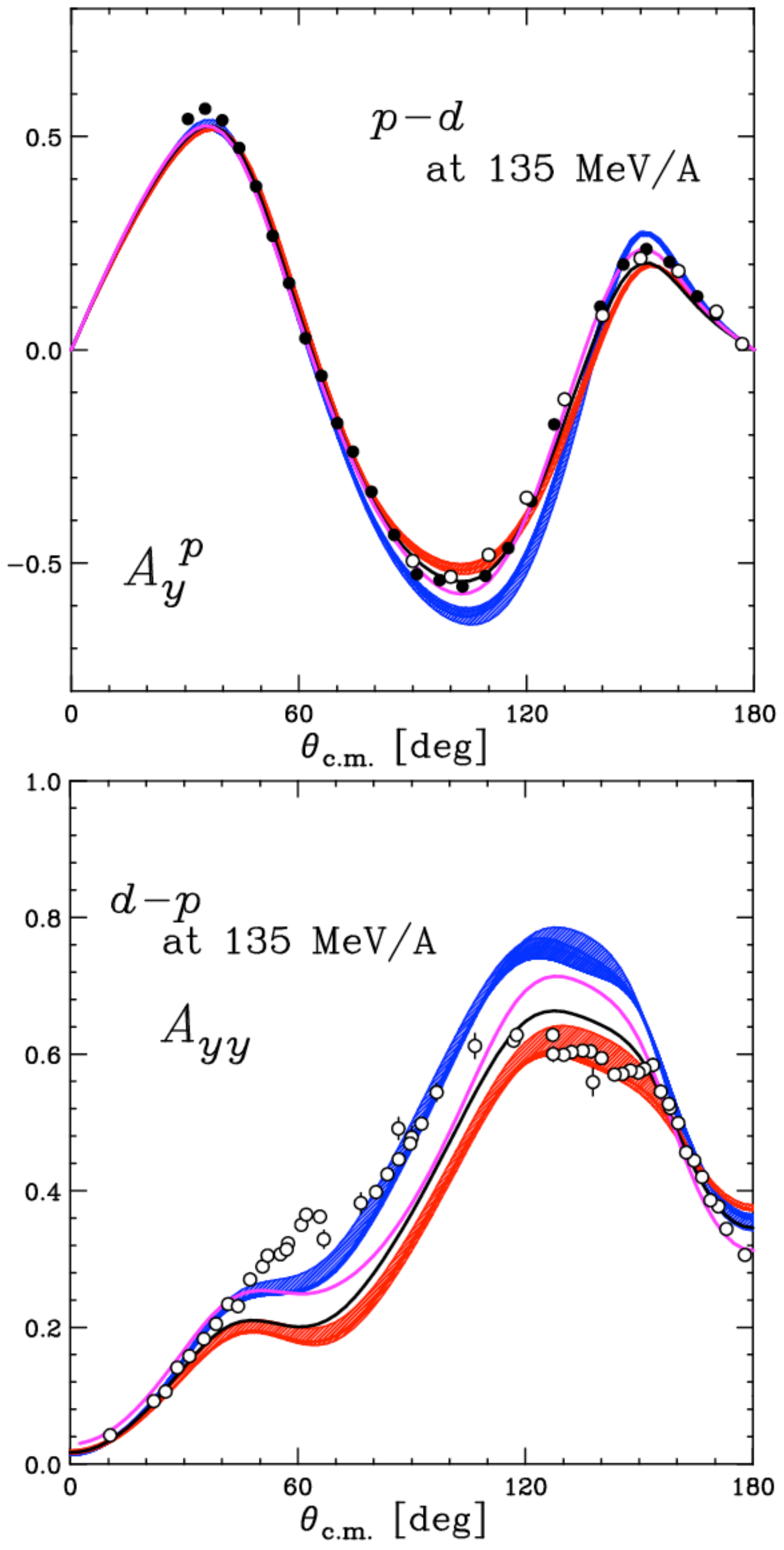
2NF (CDBonn, AV18, Nijmegen I,II) :
Large discrepancy
in Cross Section Minimum

3NF (Tucson-Melbourne, Urbana IX, Δ-isobar) :

Vector Analyzing Power A_y^p
: Good Agreement

Tensor Analyzing Power A_{yy}
: No superiority

K. Sekiguchi et al. PRC 65, 034003 (2002)

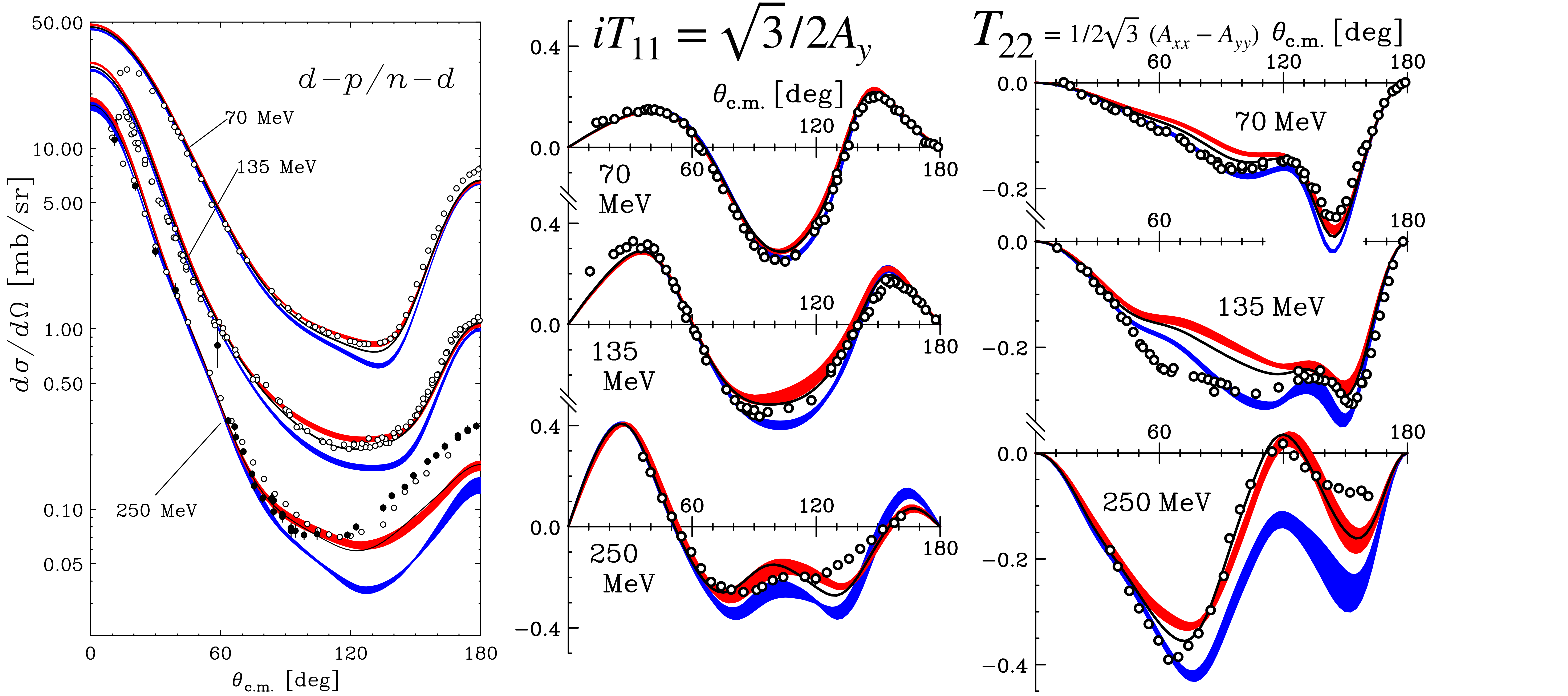


30

Energy Dependence

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

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



Serious discrepancies exist at very backward angles.

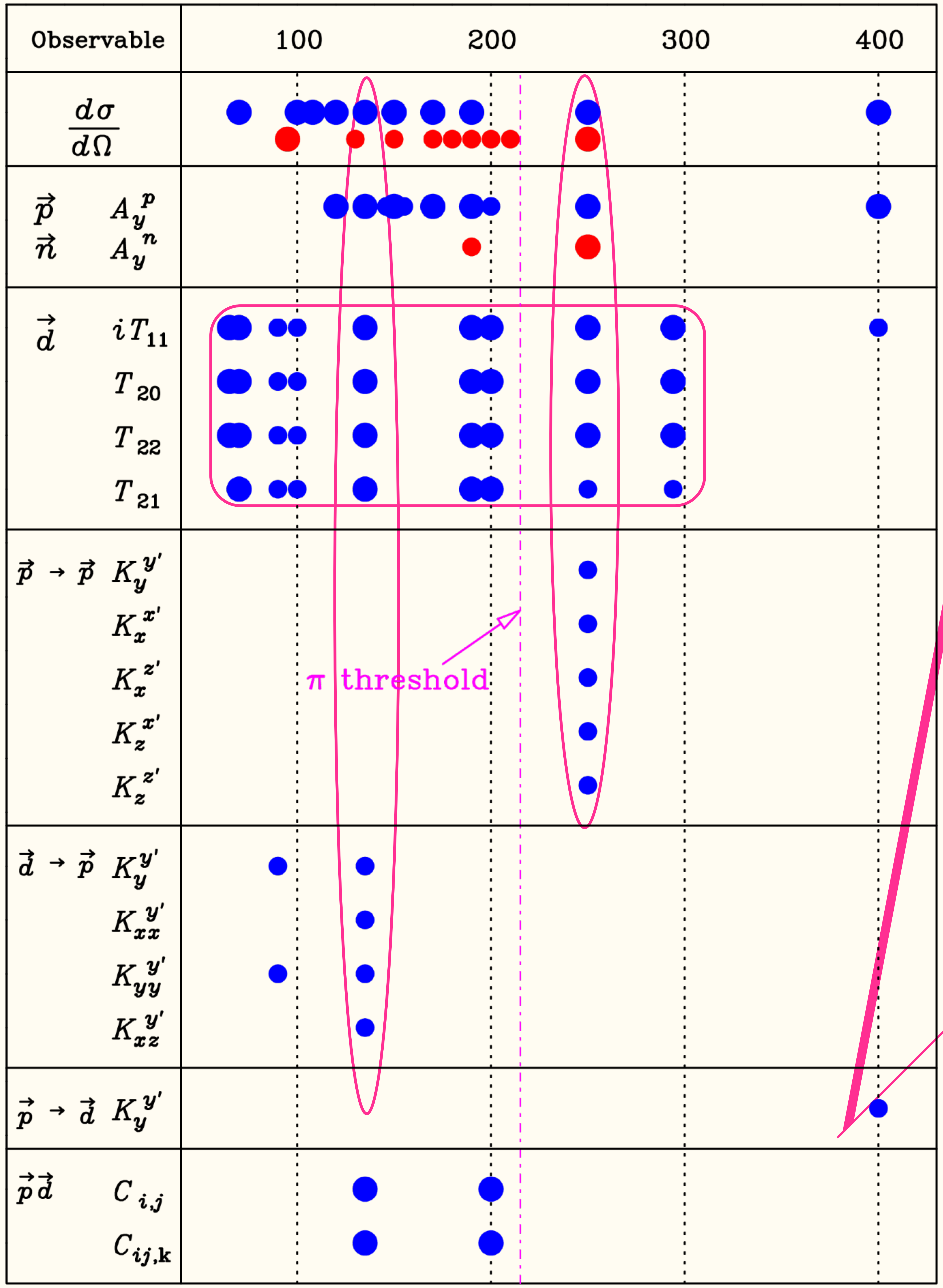
Short Range 3NFs are essential.

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.

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 **68** Years of
Fujita-Miyazawa 3NF (1957)

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

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Recent Progress and Future Aspects

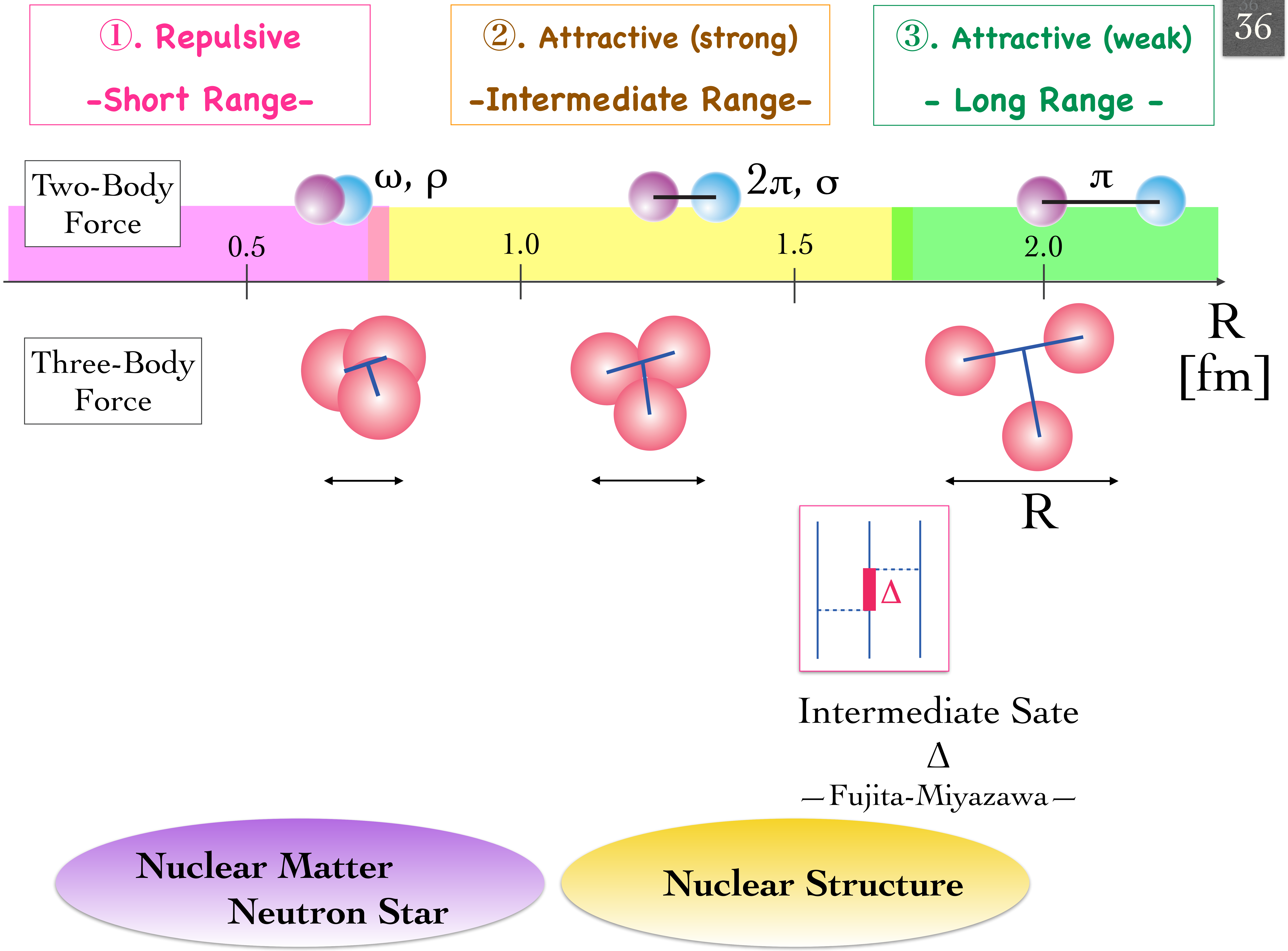
So far …

Nucleon-Deuteron Scattering at ~100 MeV/nucleon

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

From here

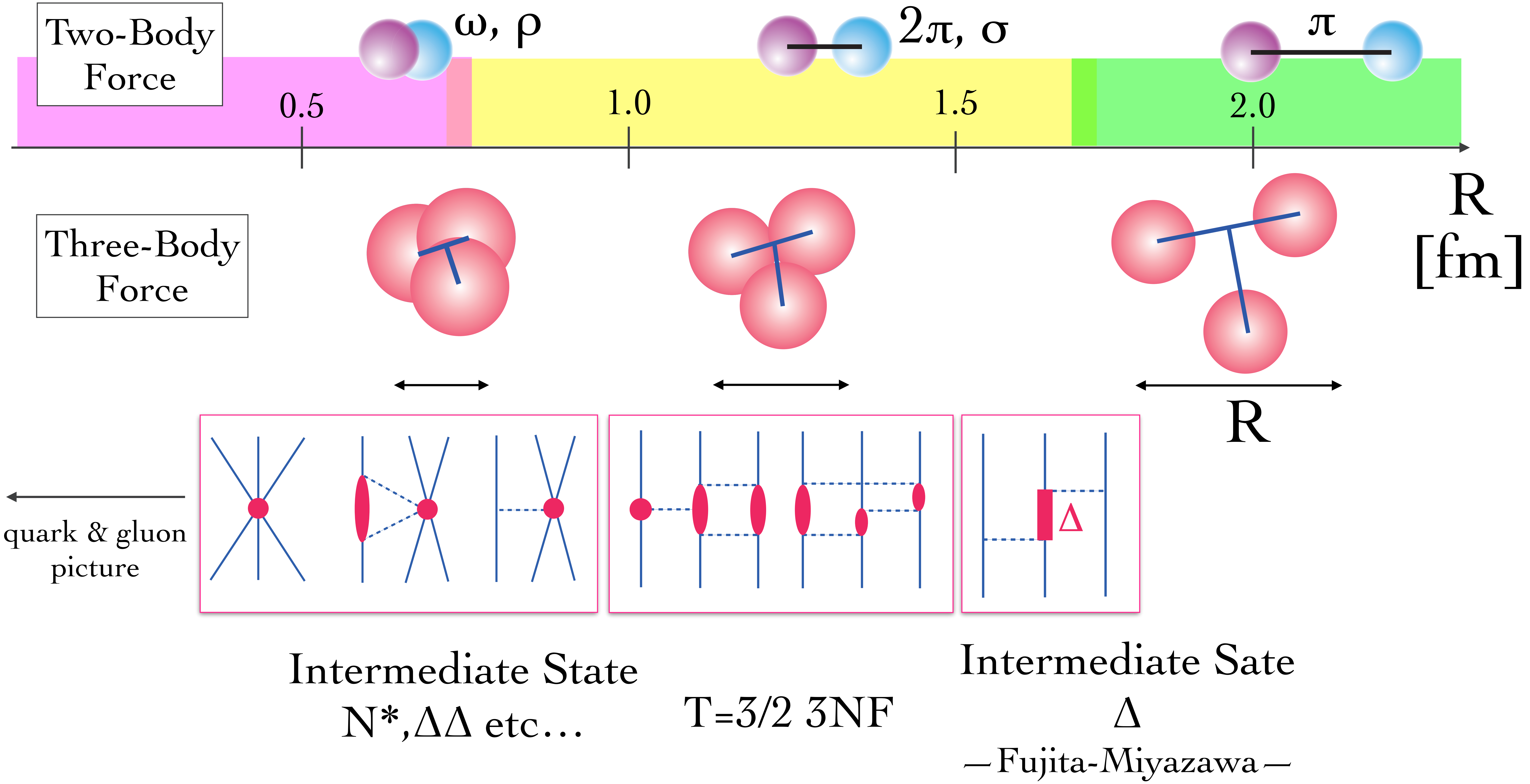
- **Deuteron-Proton Scattering at ~100 MeV/N :** *Golden window of 3NFs*
  - Determine 3NFs based on χEFT Nuclear Potential
  - High-precision measurement of Spin Correlation Coefficients
- **Proton-^{3}He Scattering at ~100 MeV/N :** *New Probe of 3NF Study*
  - 3NFs of isospin channel of T=3/2
  -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


①. Repulsive
-Short Range-
②. Attractive (strong)
-Intermediate Range-
③. Attractive (weak)
- Long Range -
Two-Body Force
ω, ρ
2π, σ
π
0.5
1.0
1.5
2.0
R [fm]
Three-Body Force
R
Δ
Intermediate Sate
Δ
—Fujita-Miyazawa—
Nuclear Matter
Neutron Star
Nuclear Structure

①. Repulsive
-Short Range-

②. Attractive (strong)
-Intermediate Range-

③. Attractive (weak)
- Long Range -



Nuclear Matter
Neutron Star

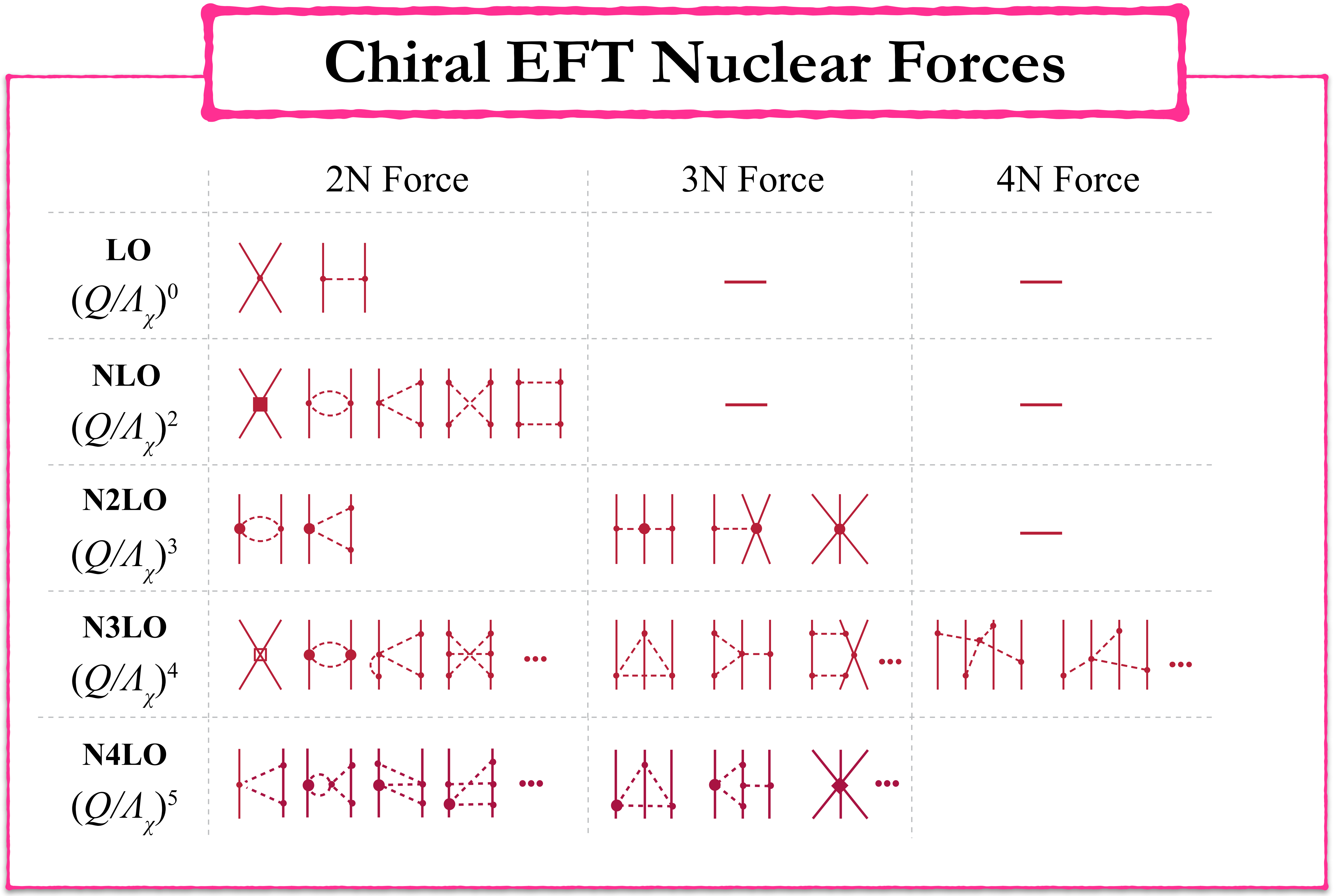
Nuclear Structure

Chiral EFT Nuclear Force & *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)



Chiral EFT Nuclear Force & *dp* elastic scattering

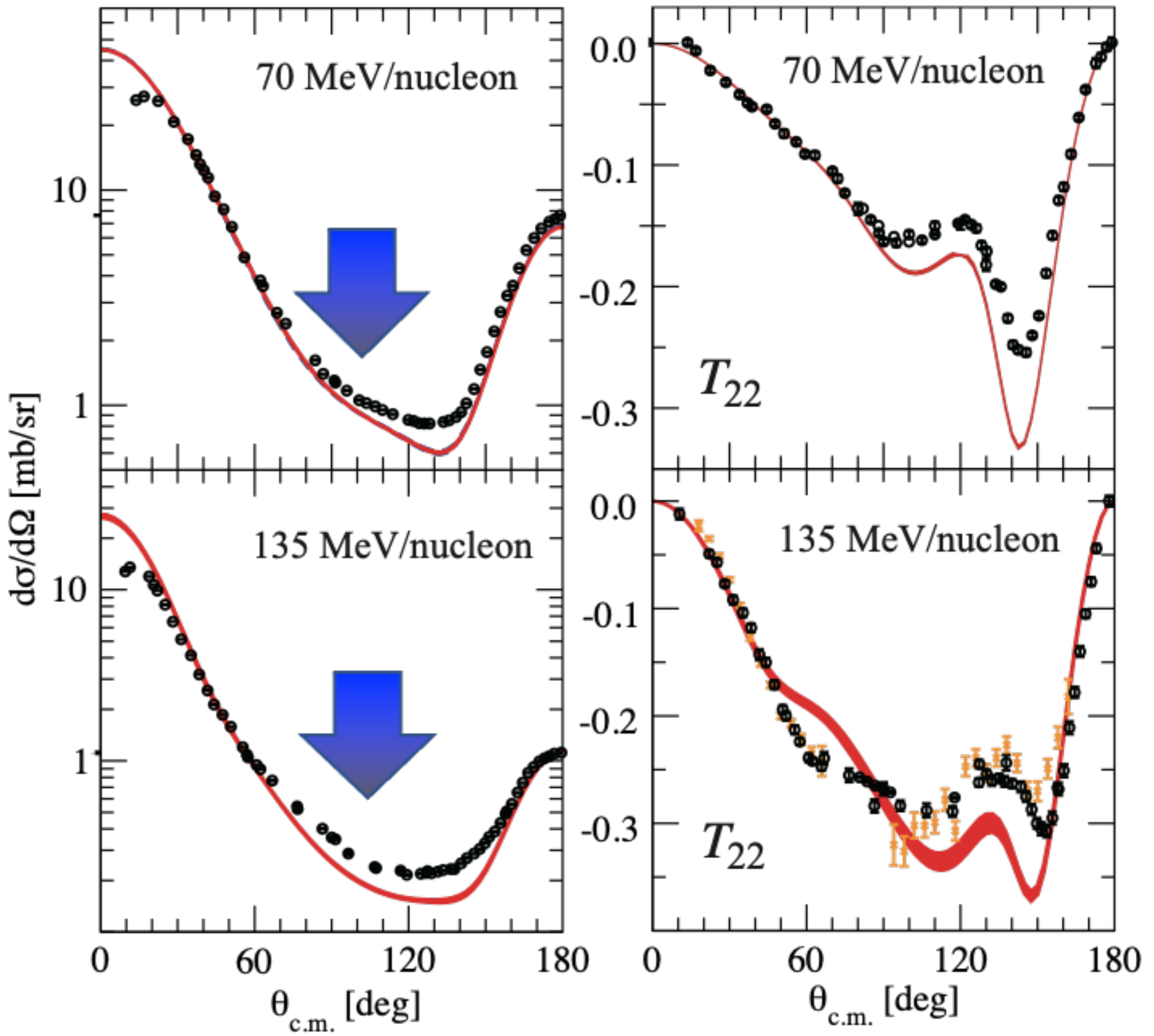
- *dp* elastic scattering data show necessities of the N4LO 3NFs.

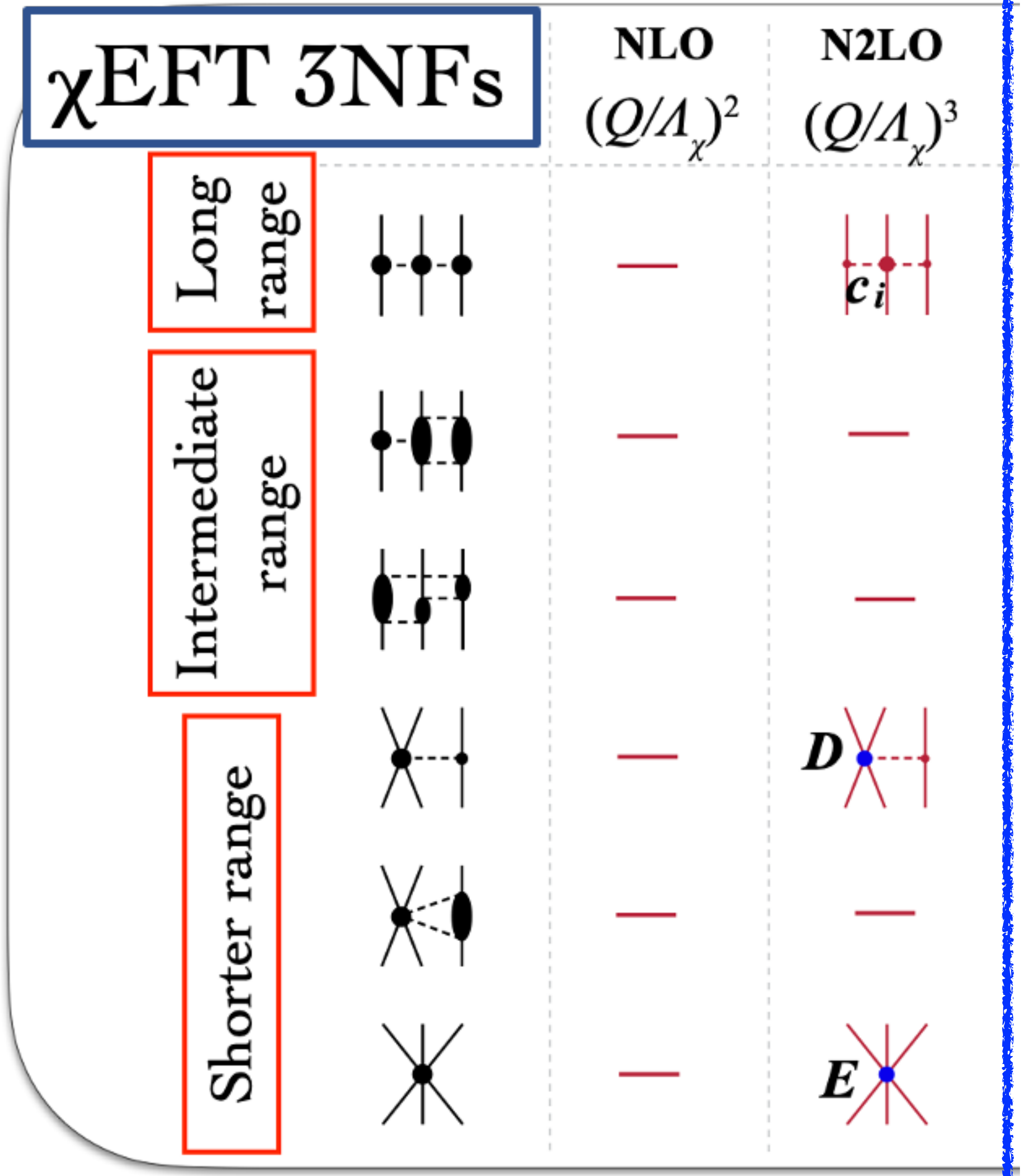
Cross section minimum region for *dp* elastic scattering at ～100MeV/nucleon is "Golden window" for the N4LO 3NFs.

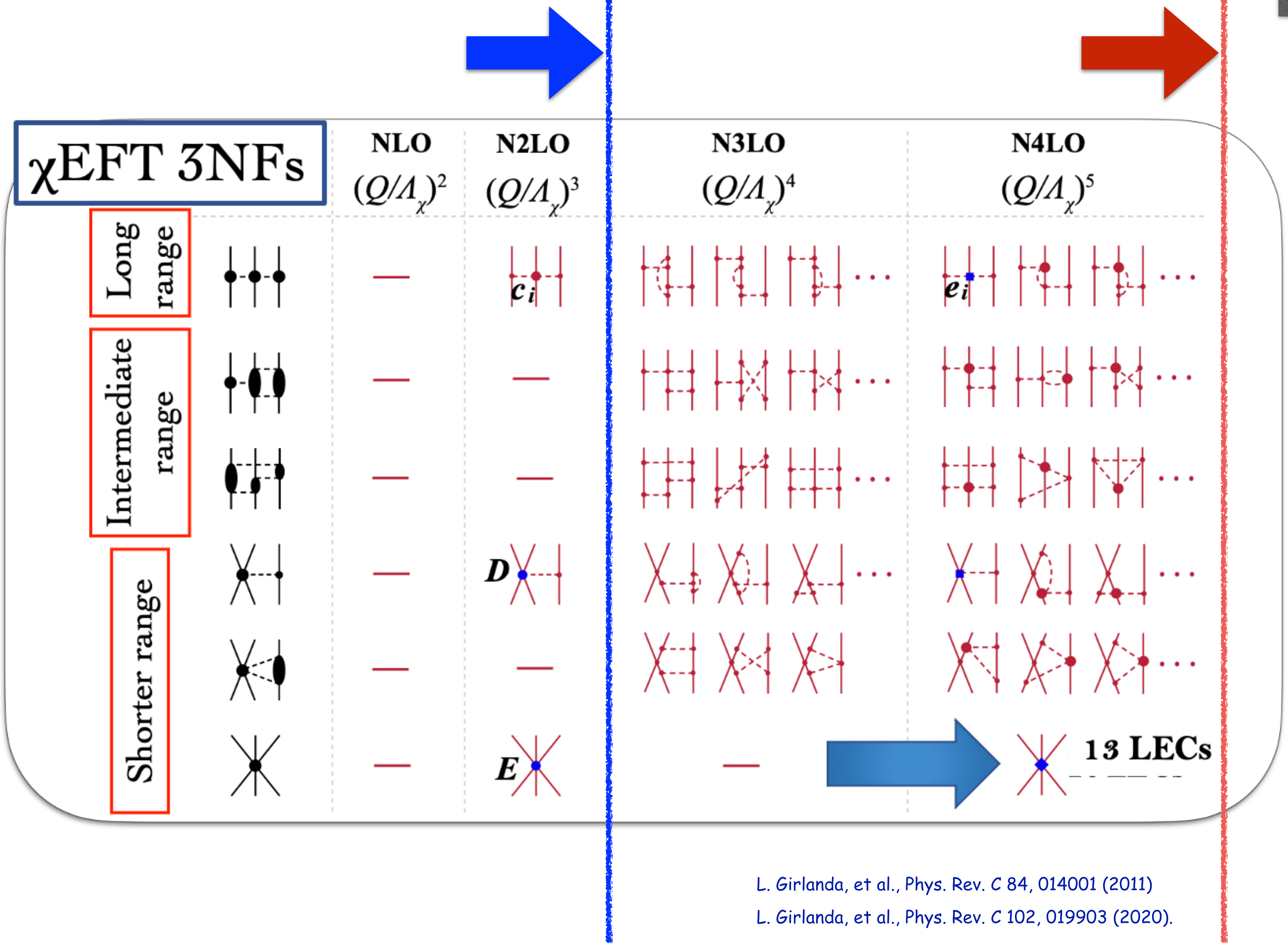
LENPIC collaboration, Phys. Rev. C 98, 014002 (2018)

dp scattering & N4LO χEFT 2NFs

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



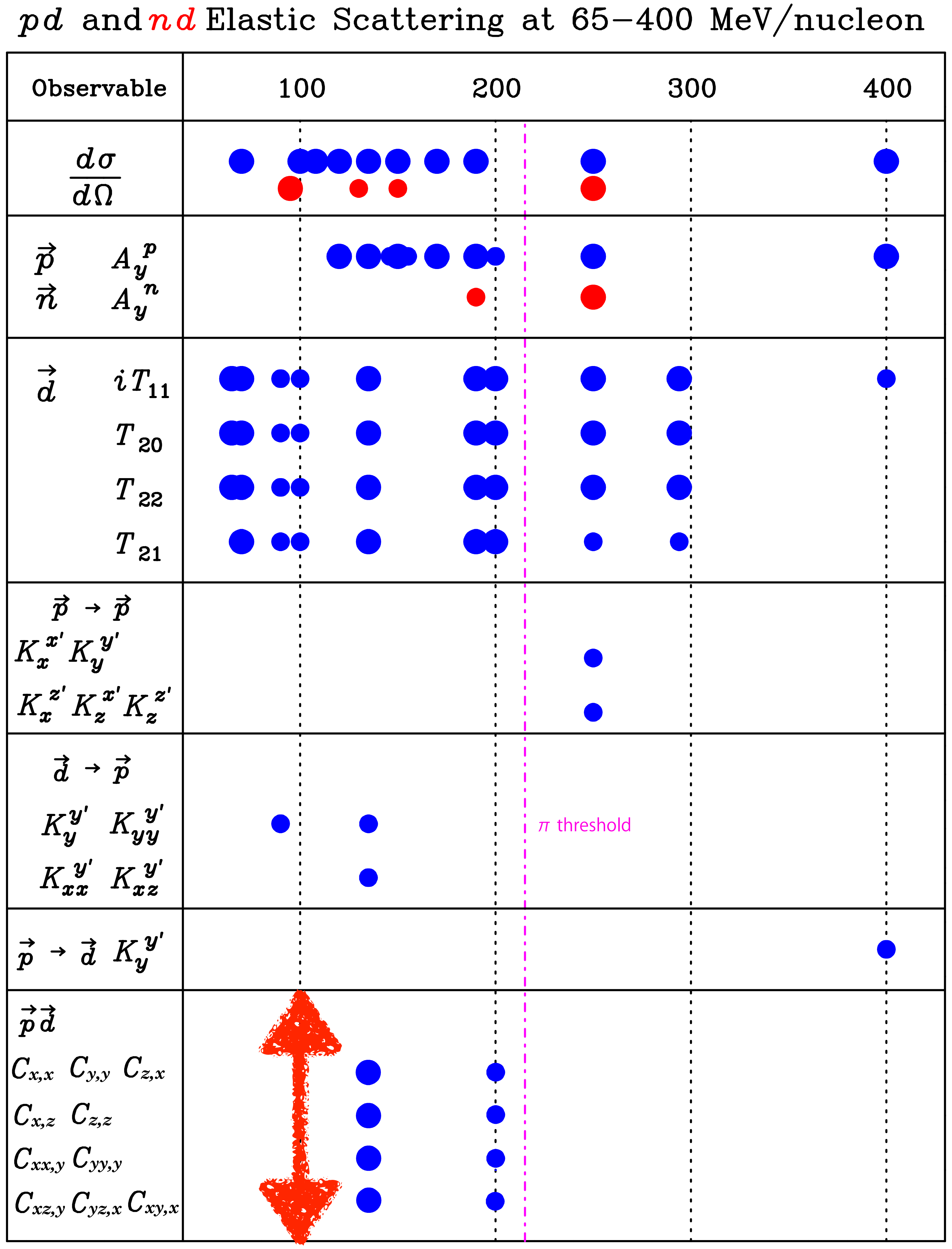

χEFT 3NFs
NLO
$(Q/\Lambda_\chi)^2$
N2LO
$(Q/\Lambda_\chi)^3$
Long range
Intermediate range
Shorter range
c_i
D
E



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

New Experiment at RIKEN

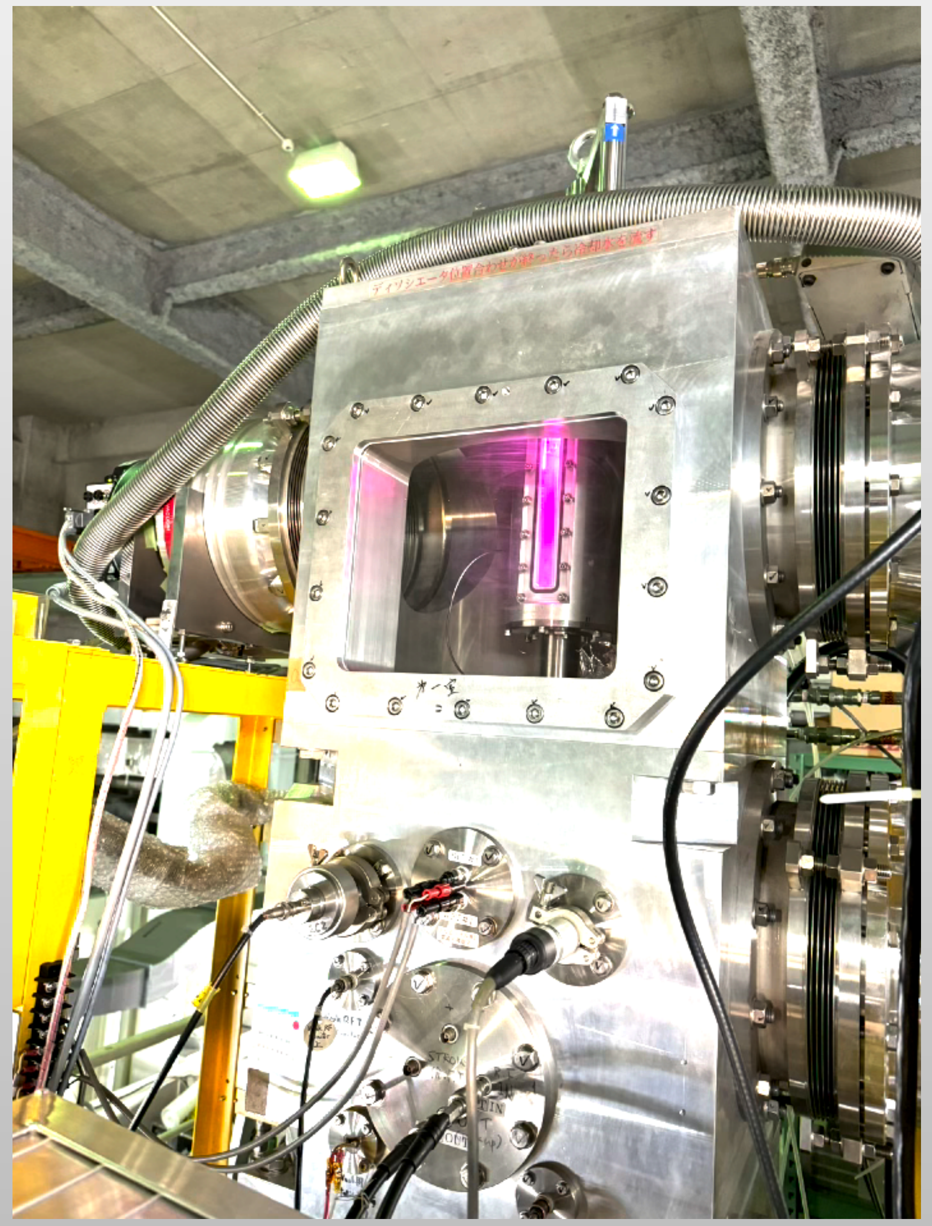
Measurement of Spin Correlation Coefficients for *dp* elastic scattering at ～100 MeV/nucleon

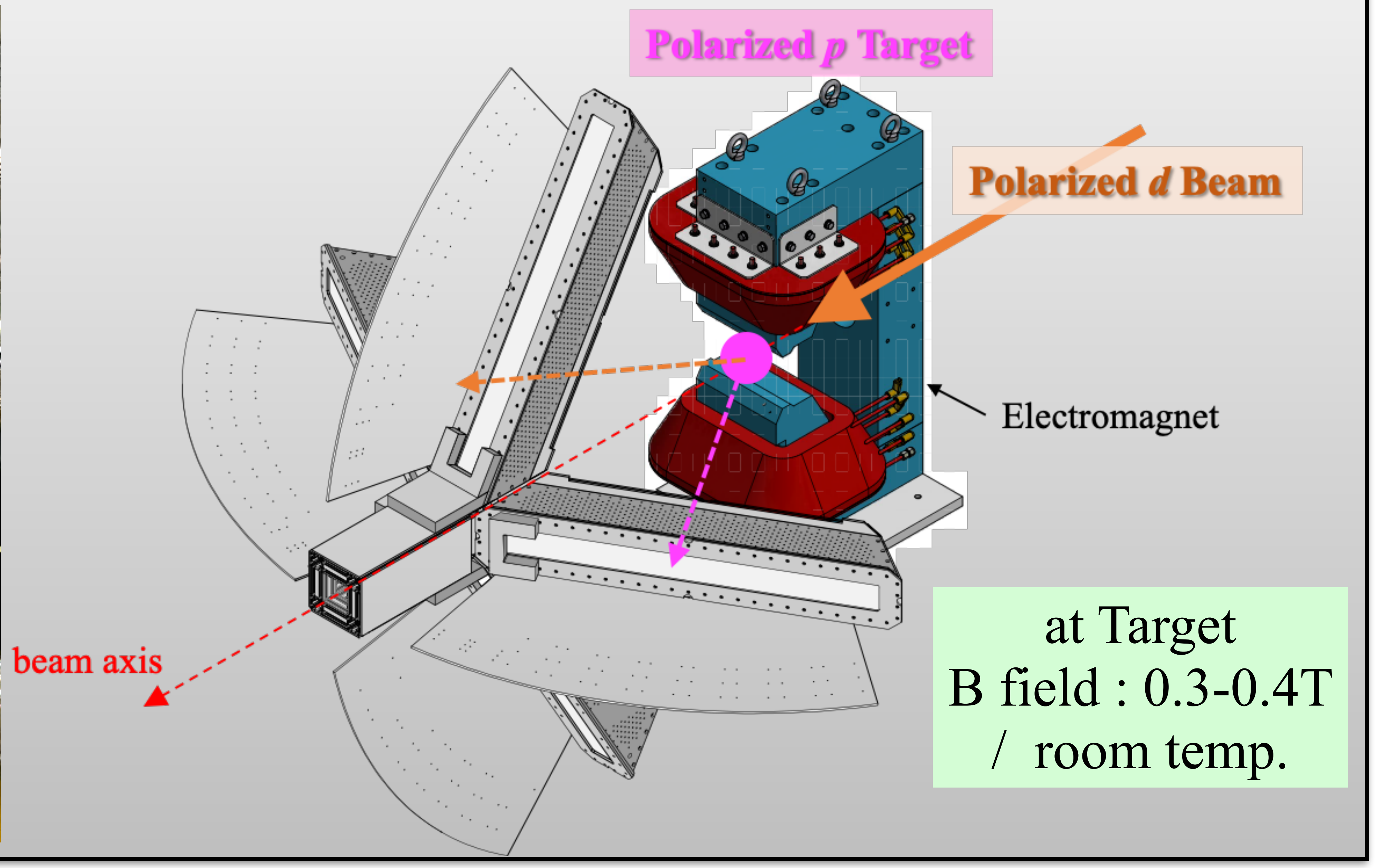


for investigation of N4LO 3NFs

- determination of LECs of N4LO 3NFs from *dp* scattering data

pol.d beam + new pol. p target
+ new detector system





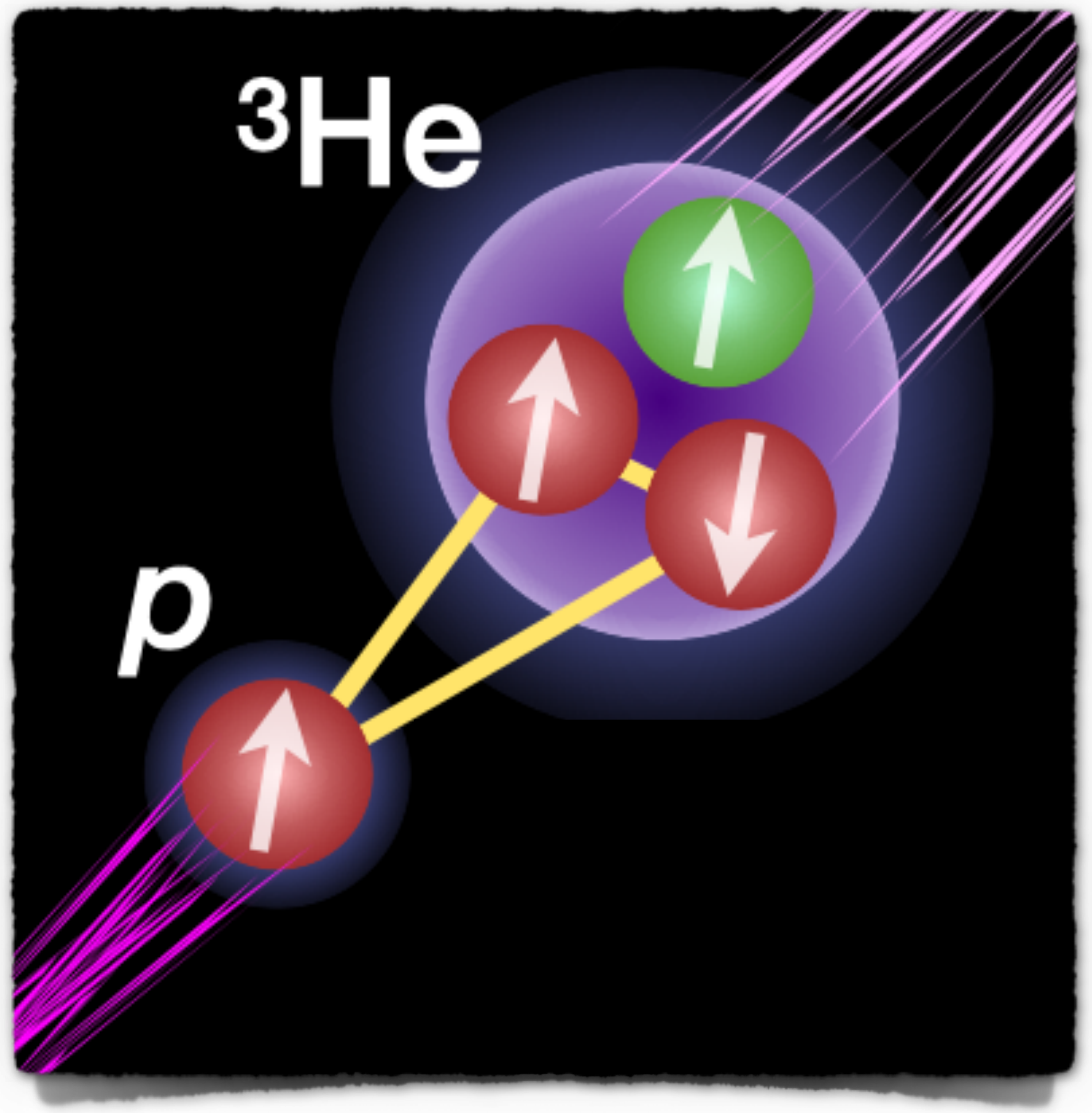
p-^{3}He scattering

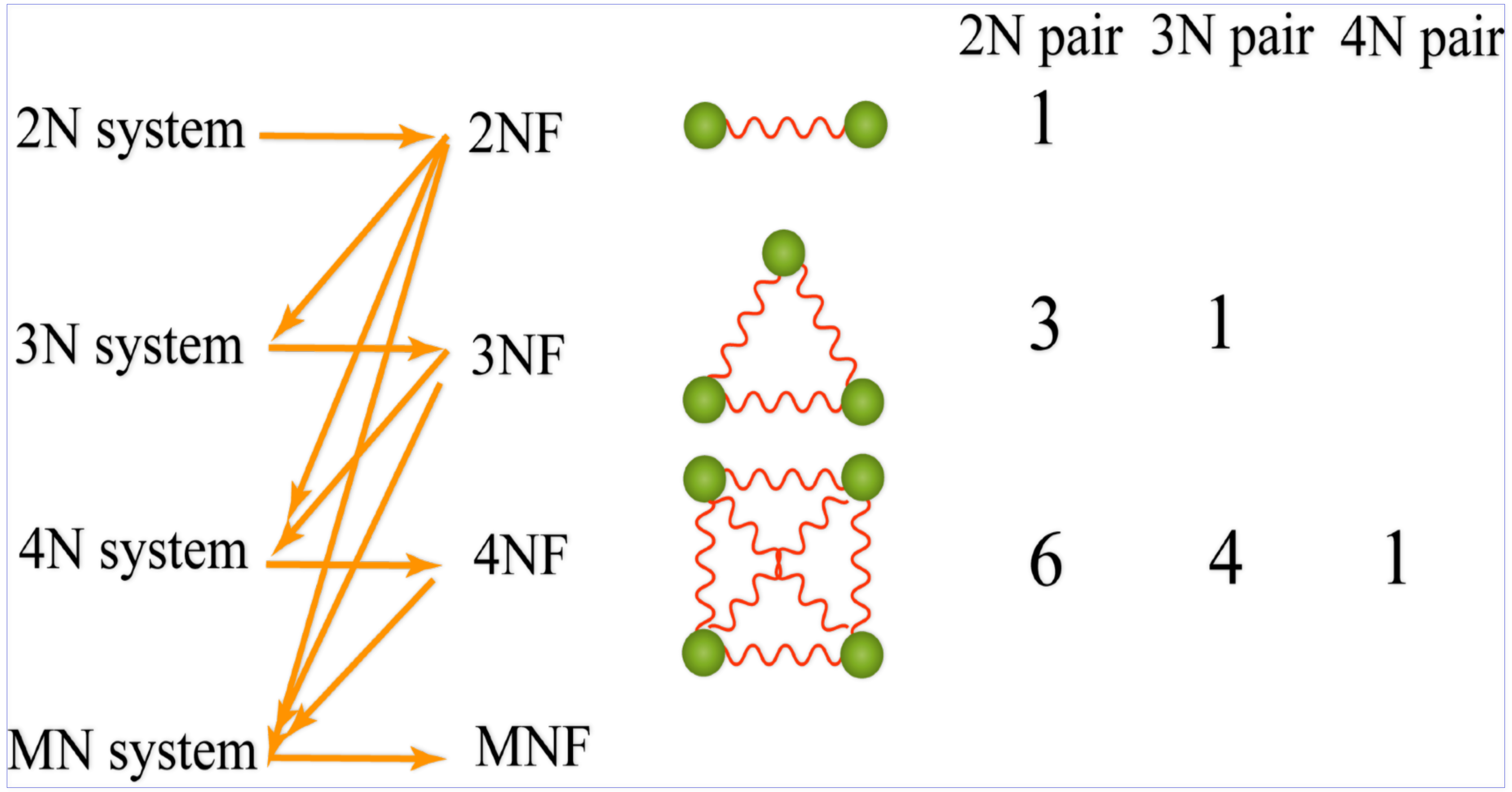
- Approach iso-spin dependence of 3NFs
  T=3/2 3NFs

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

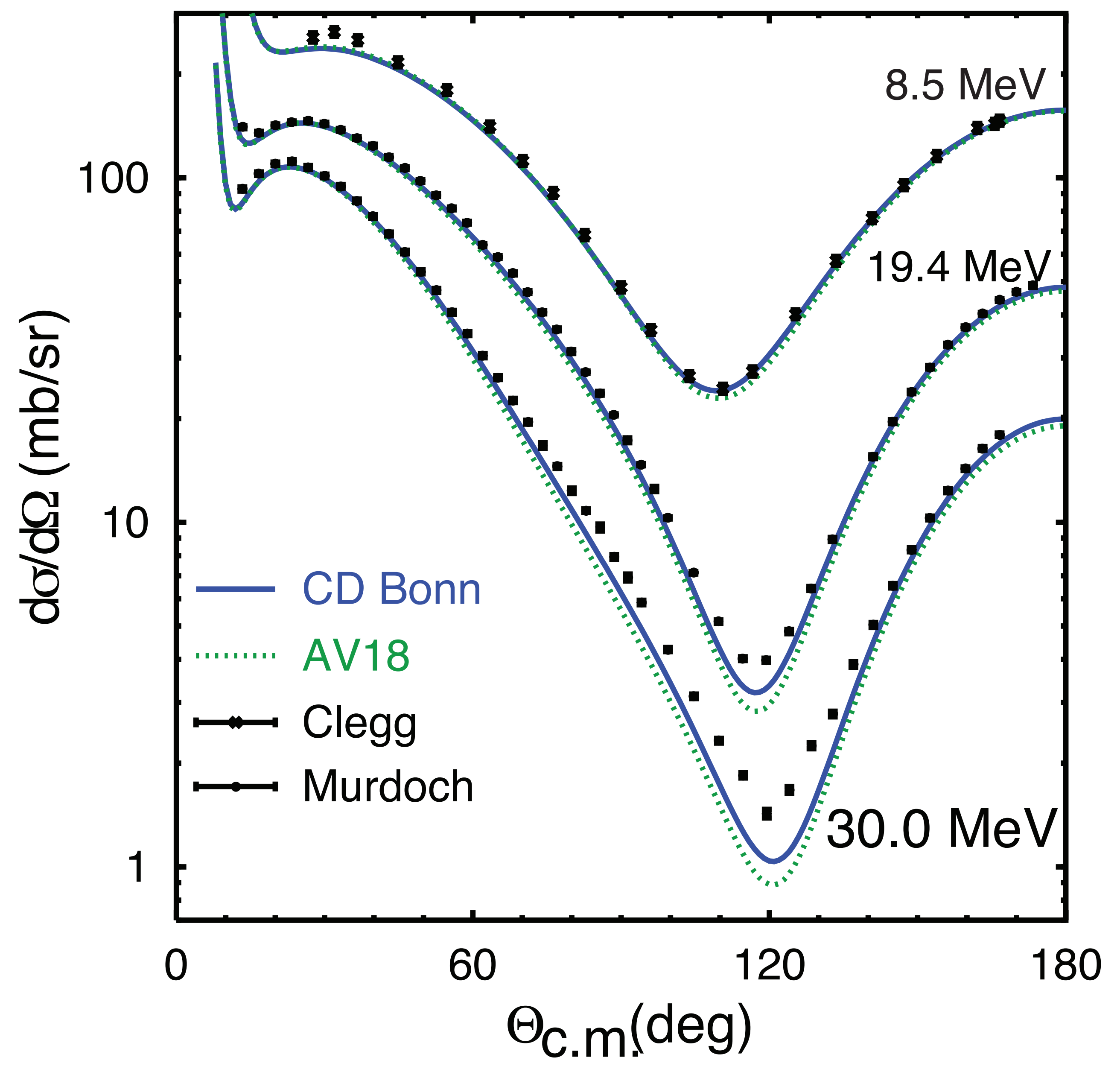
Theory in Progress

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)

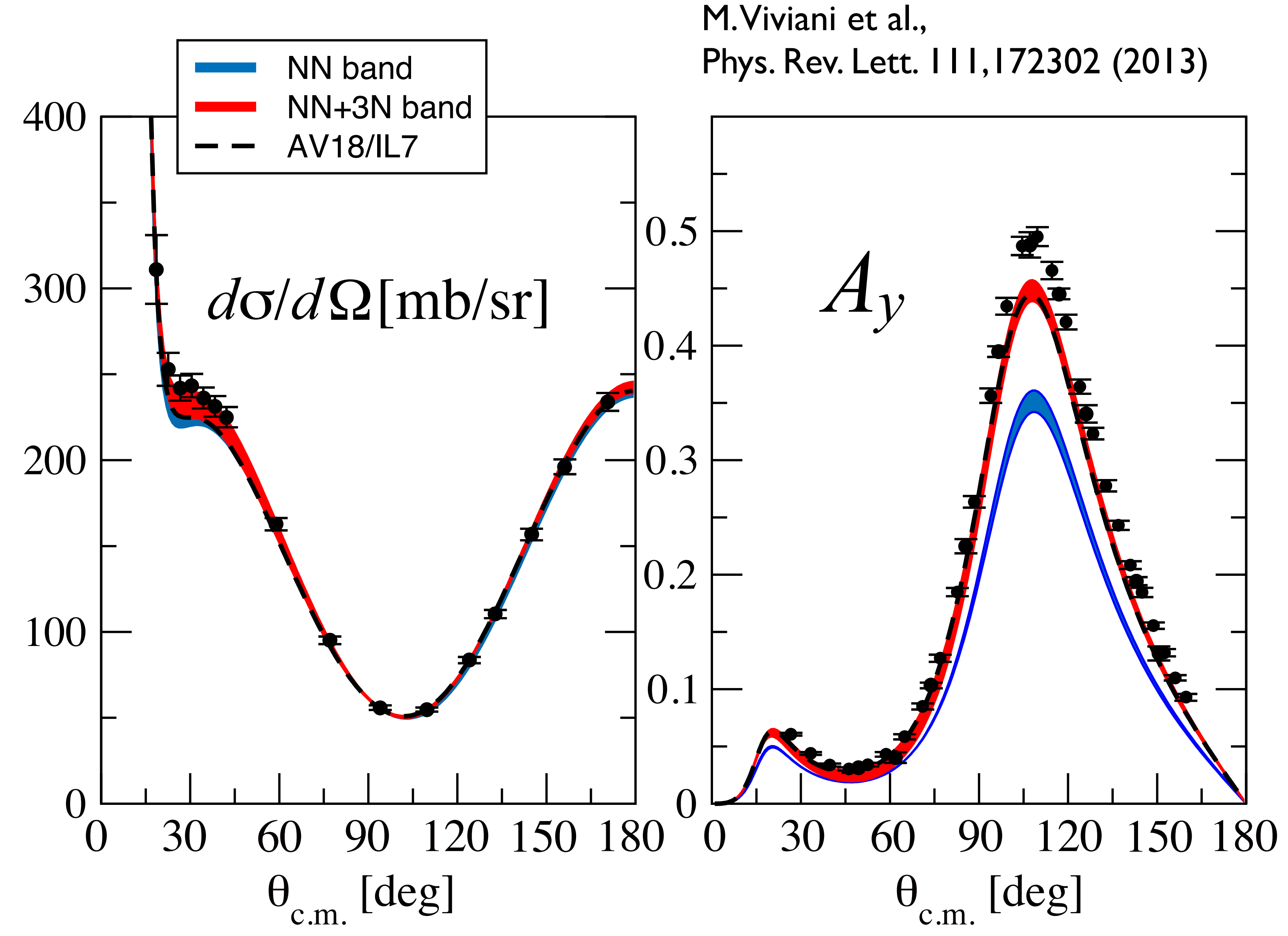


Discrepancies in cross section minimum at higher energies

New rooms for 3NF study

at 5.54 MeV

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

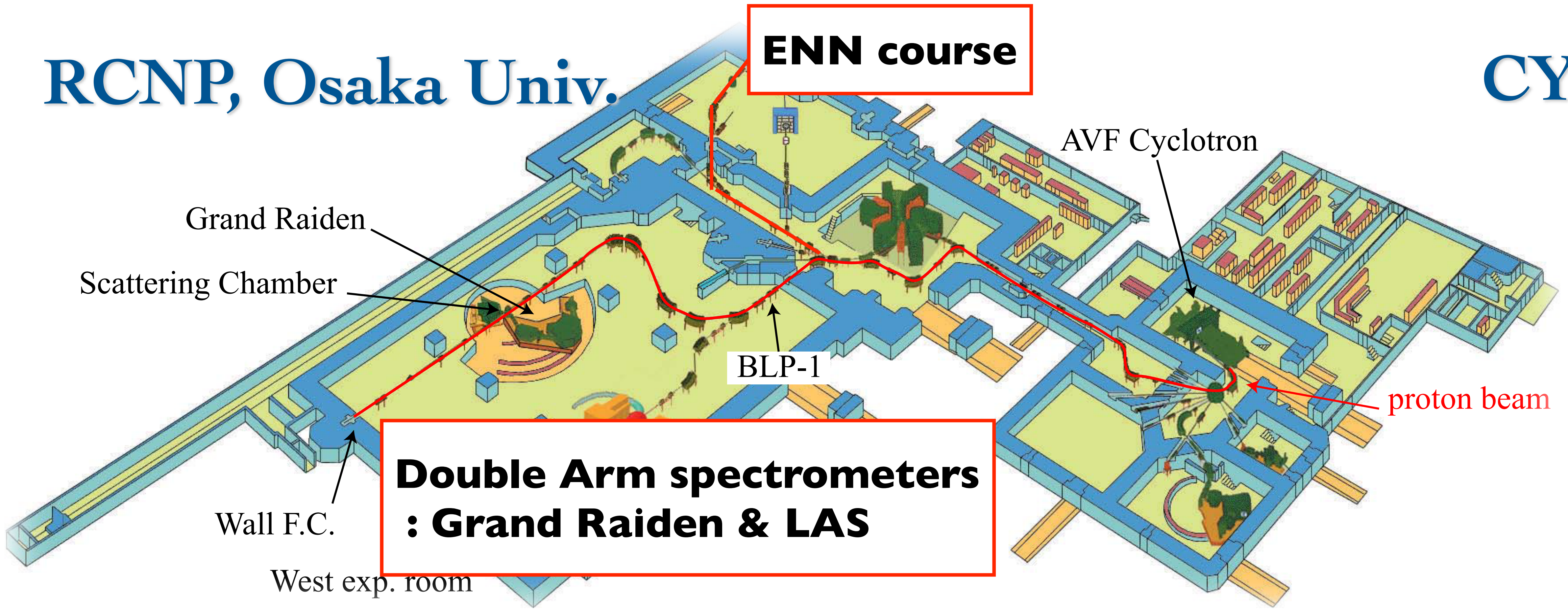


- No signature of 3NFs in cross section
- *Ay(p)* **puzzle** : 3NFs sensitive to p-shell nuclei improve the agreement to the data.

How about spin observables at higher energy?

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

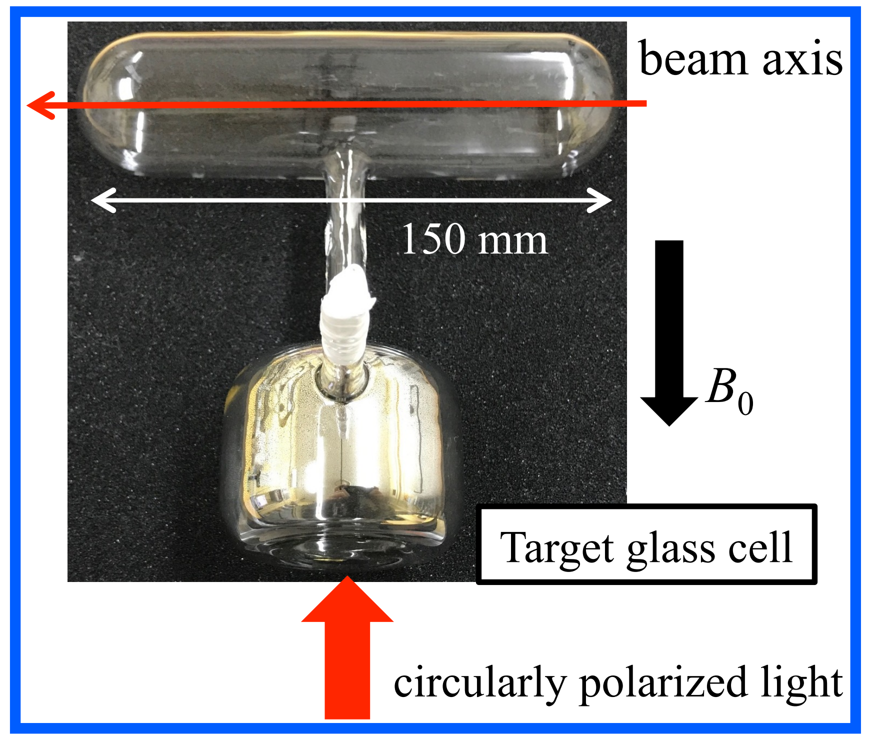
RCNP, Osaka Univ.

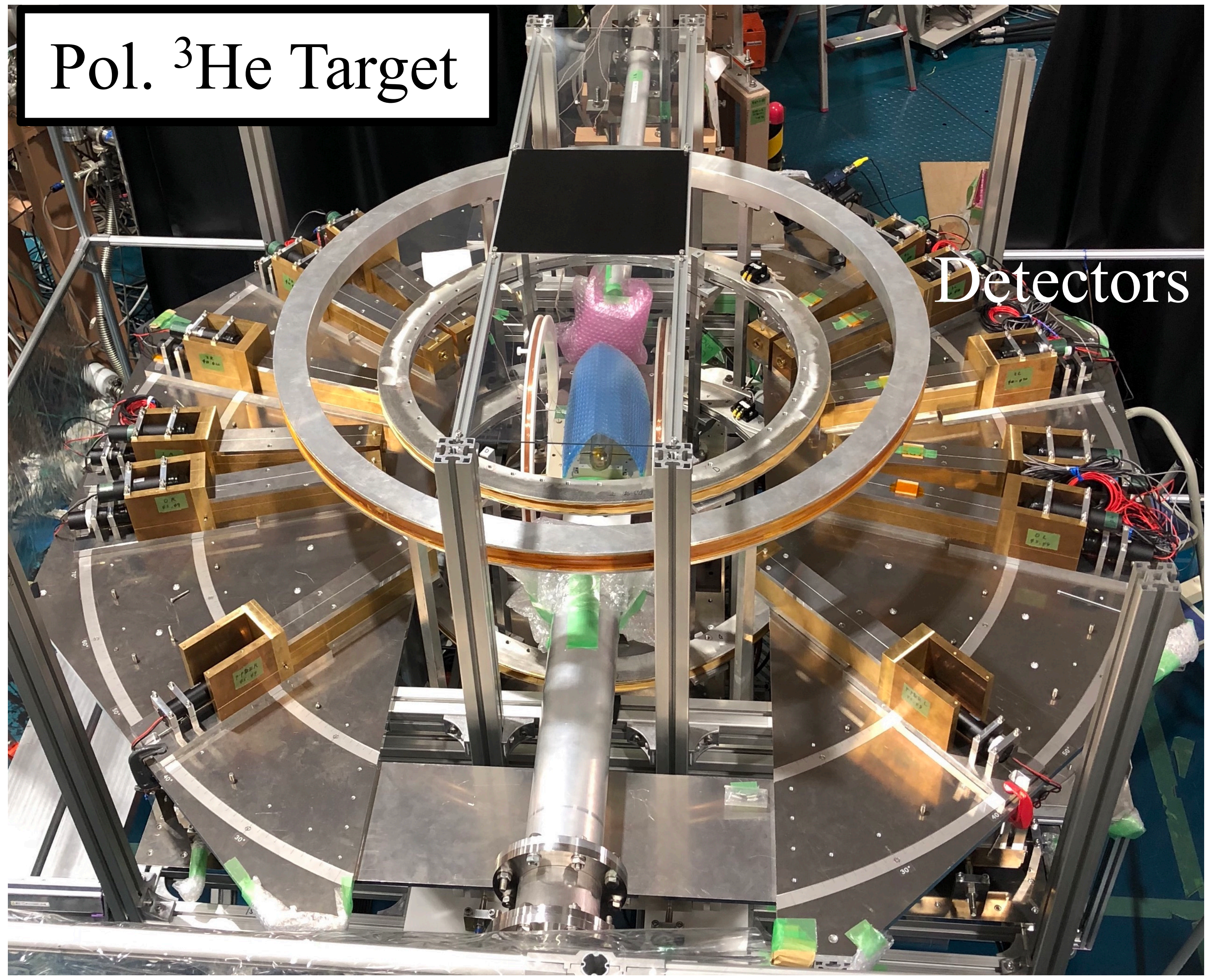


CYRIC, Tohoku Univ.

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

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





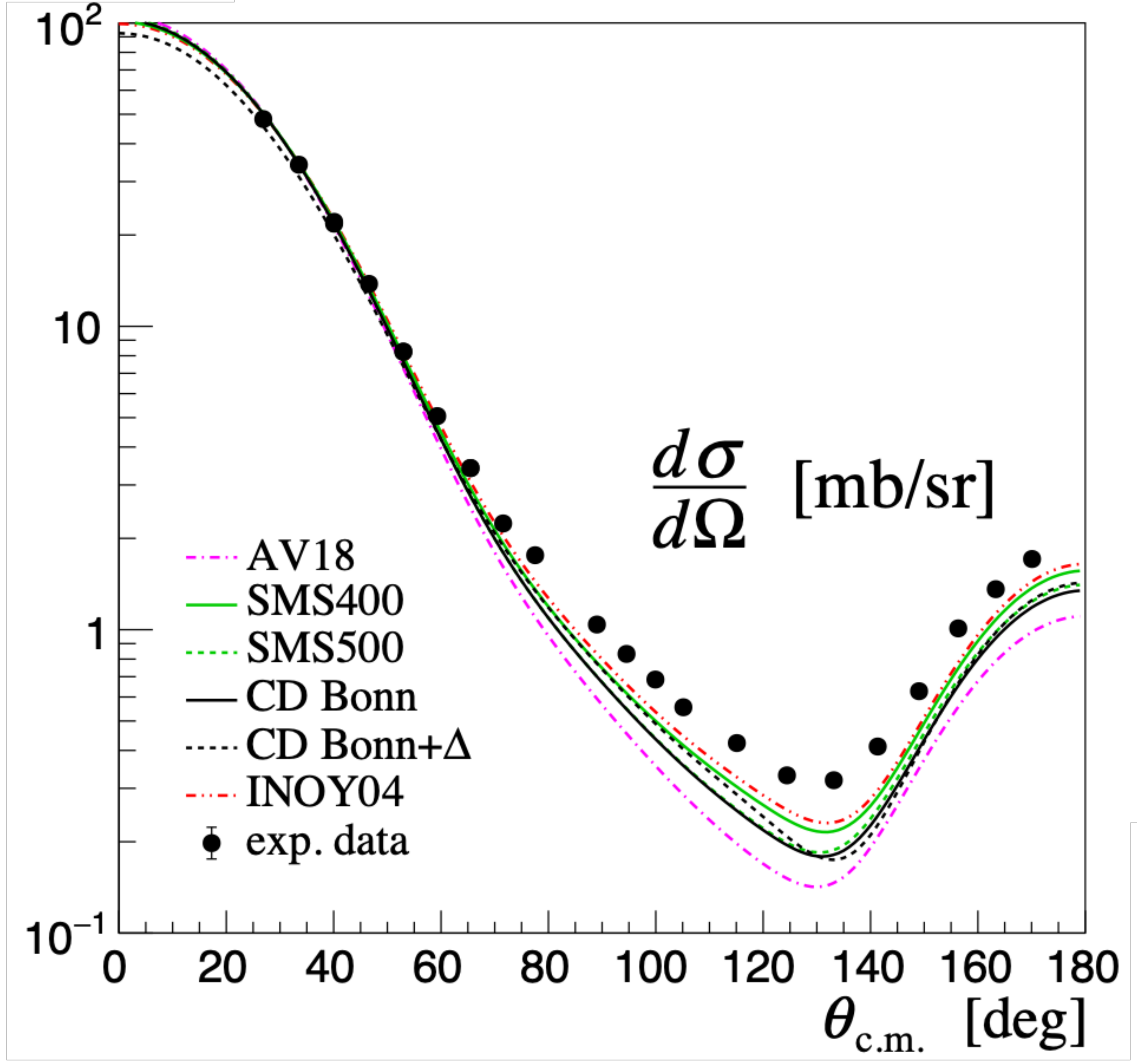
Data of p+^{3}He at Intermediate Energies

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

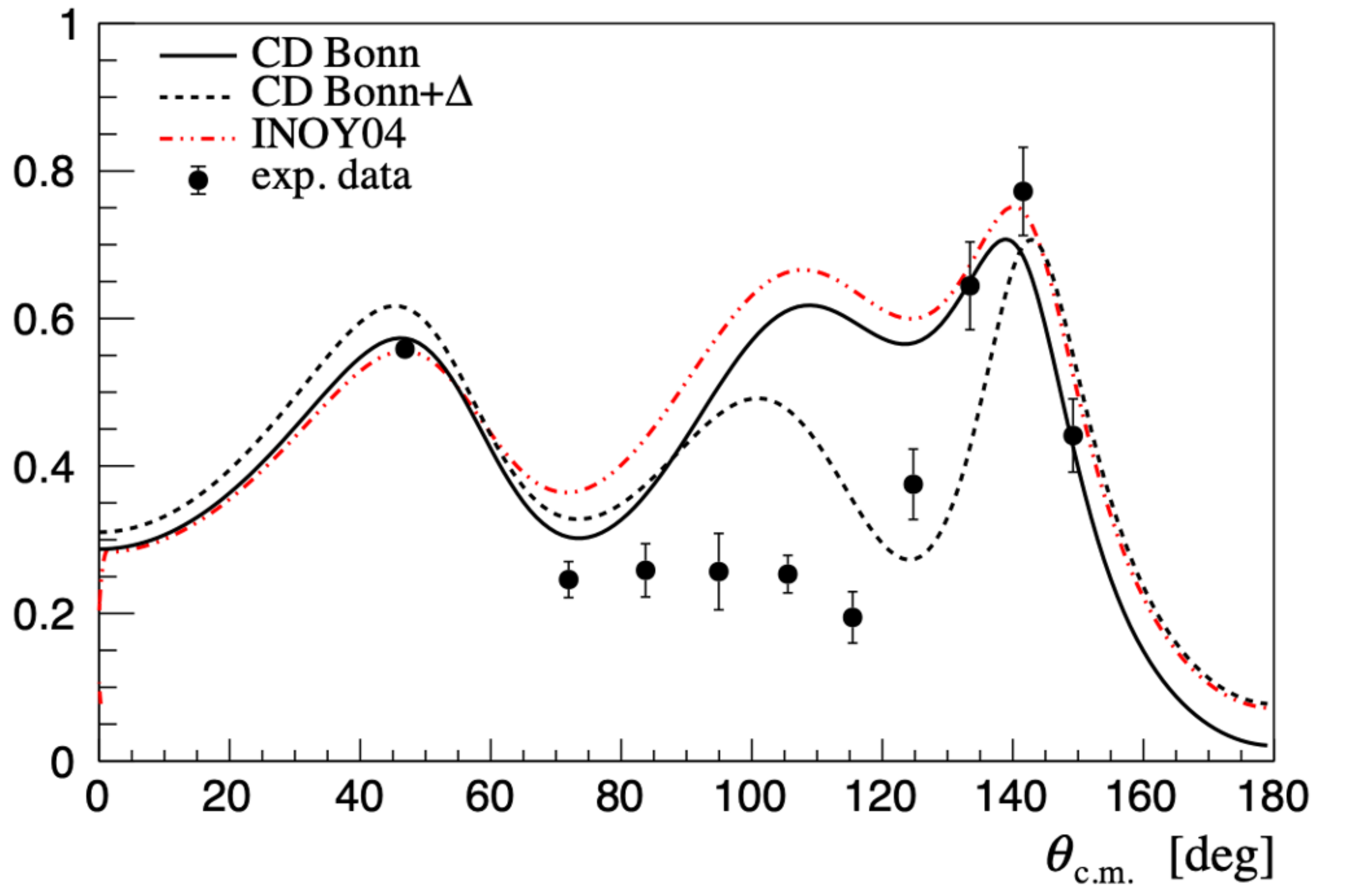
A.Watanabe et al., Phys. Rev. C 106, 054002 (2022)

4N calculations by A. Deltuva

Cross Section at 65 MeV



$C_{y,y}$ at 100 MeV



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

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

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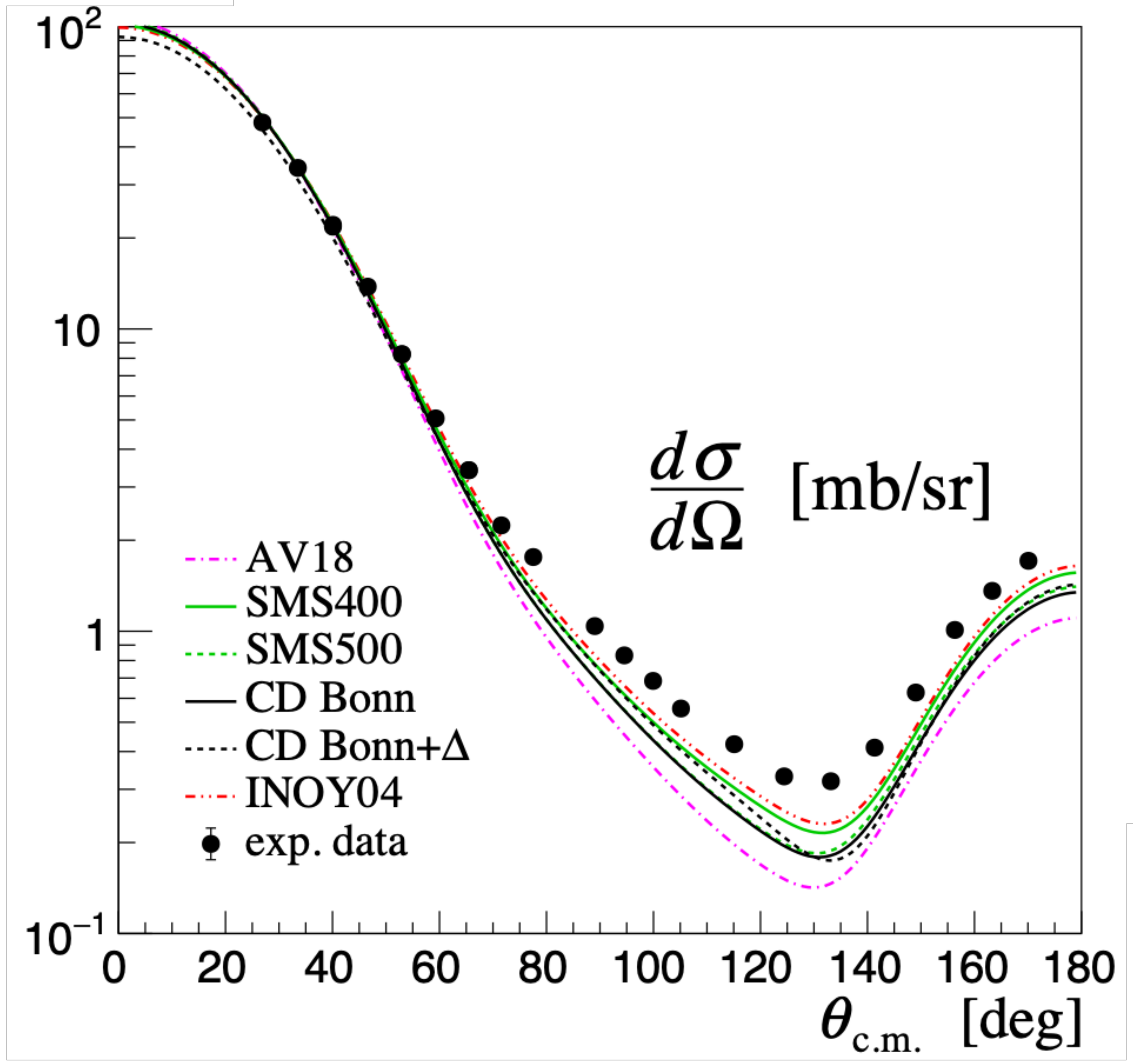
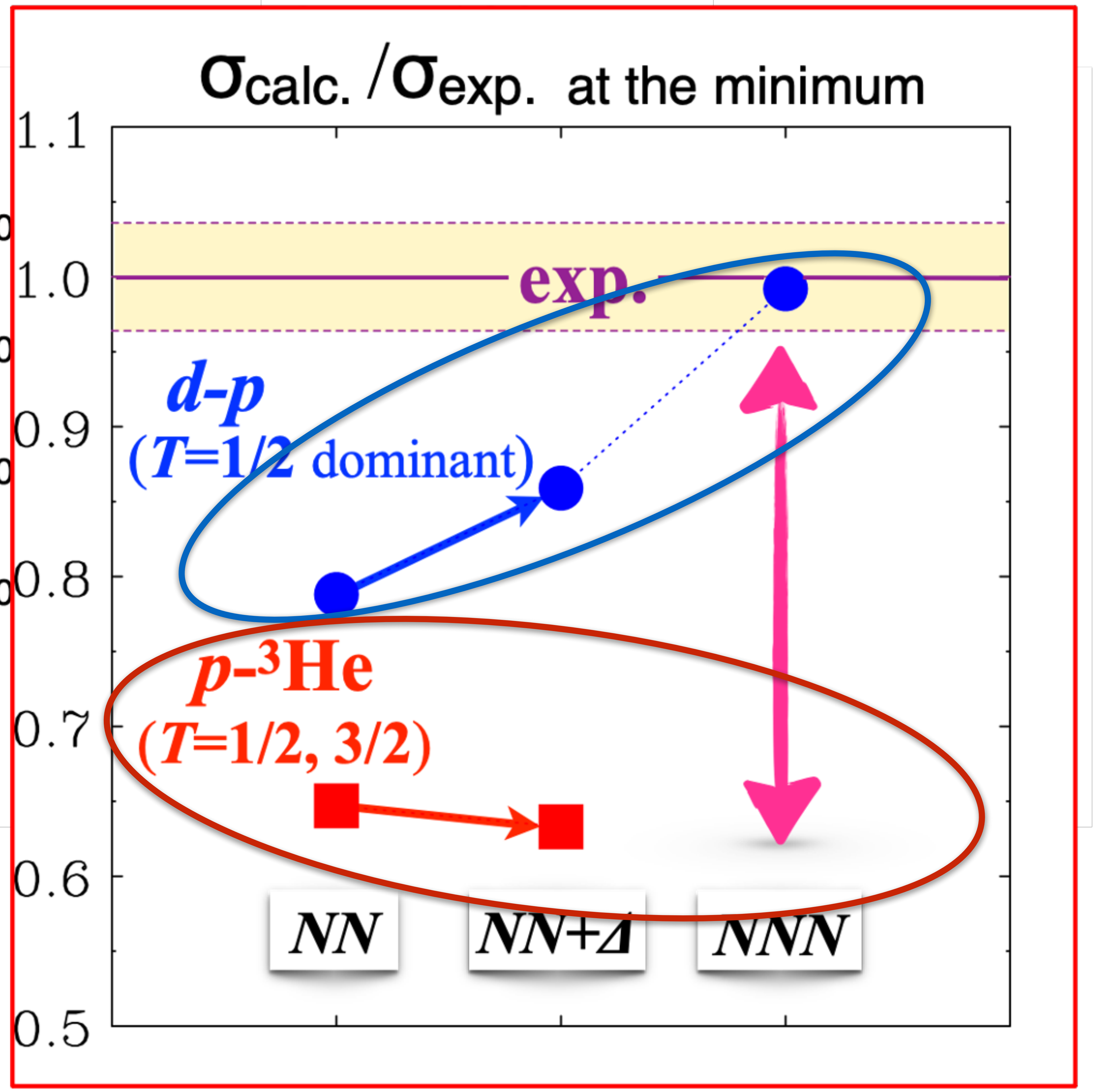
4N calculations by A. Deltuva

Cross Section at 65 MeV



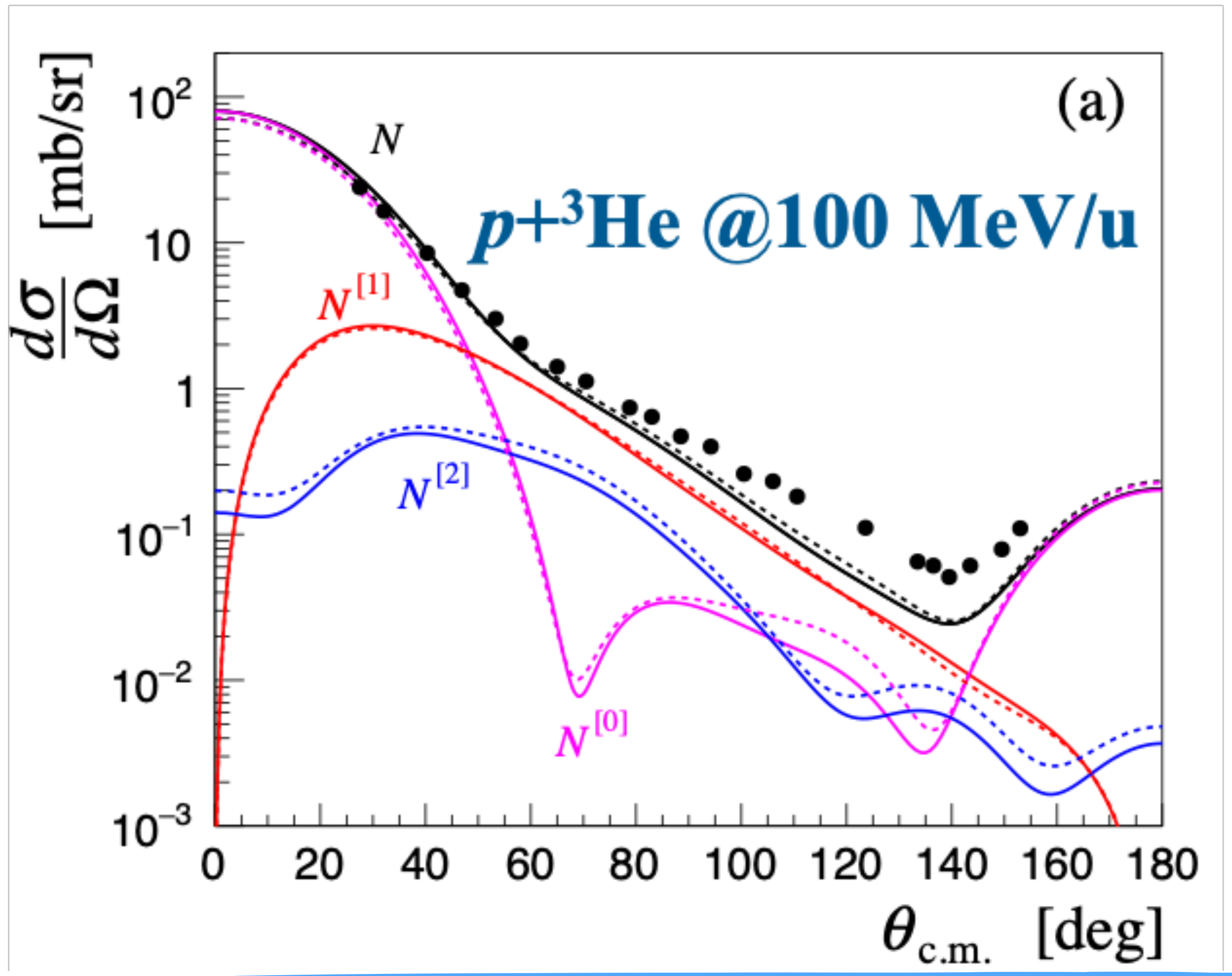


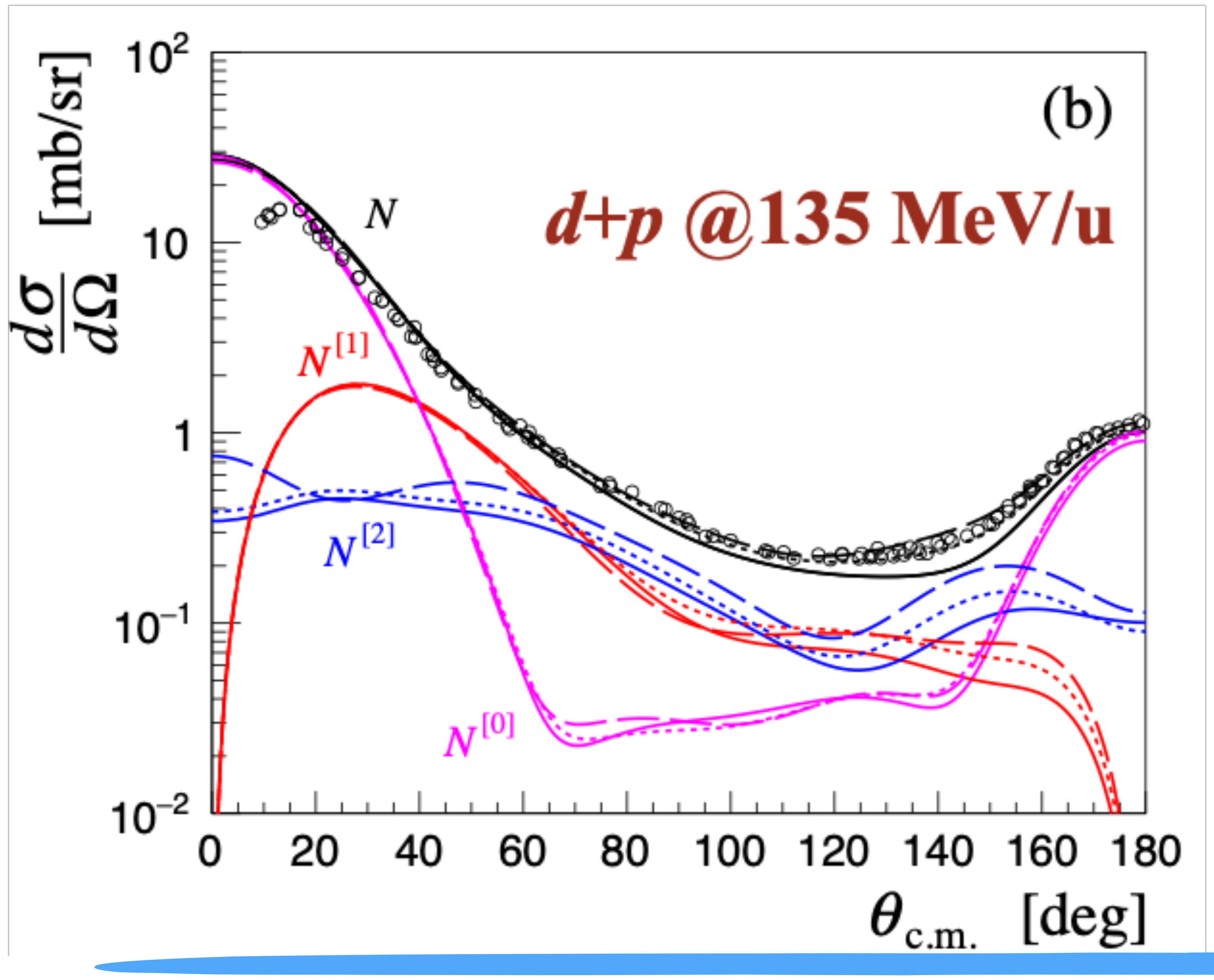
Analysis of p-^{3}He elastic scattering amplitudes

Ref. S. Ishikawa, M. Tanifuji, Y. Iseri, and Y. Yamamoto, PRC **69**, 034001; **72**, 027601.

$$\boldsymbol{M}(\theta_{\text{c.m.}}) = F_0(\theta_{\text{c.m.}}) + (\boldsymbol{s}_p \cdot \boldsymbol{s}_h) F_\sigma(\theta_{\text{c.m.}}) + (\boldsymbol{s}_p \cdot \boldsymbol{n}) F_p(\theta_{\text{c.m.}}) + (\boldsymbol{s}_h \cdot \boldsymbol{n}) F_h(\theta_{\text{c.m.}}) + \left(\hat{S}_T(\boldsymbol{\ell}) - \hat{S}_T(\boldsymbol{m})\right) F_{\ell m}(\theta_{\text{c.m.}}) + \hat{S}_T(\boldsymbol{n}) F_n(\theta_{\text{c.m.}})$$

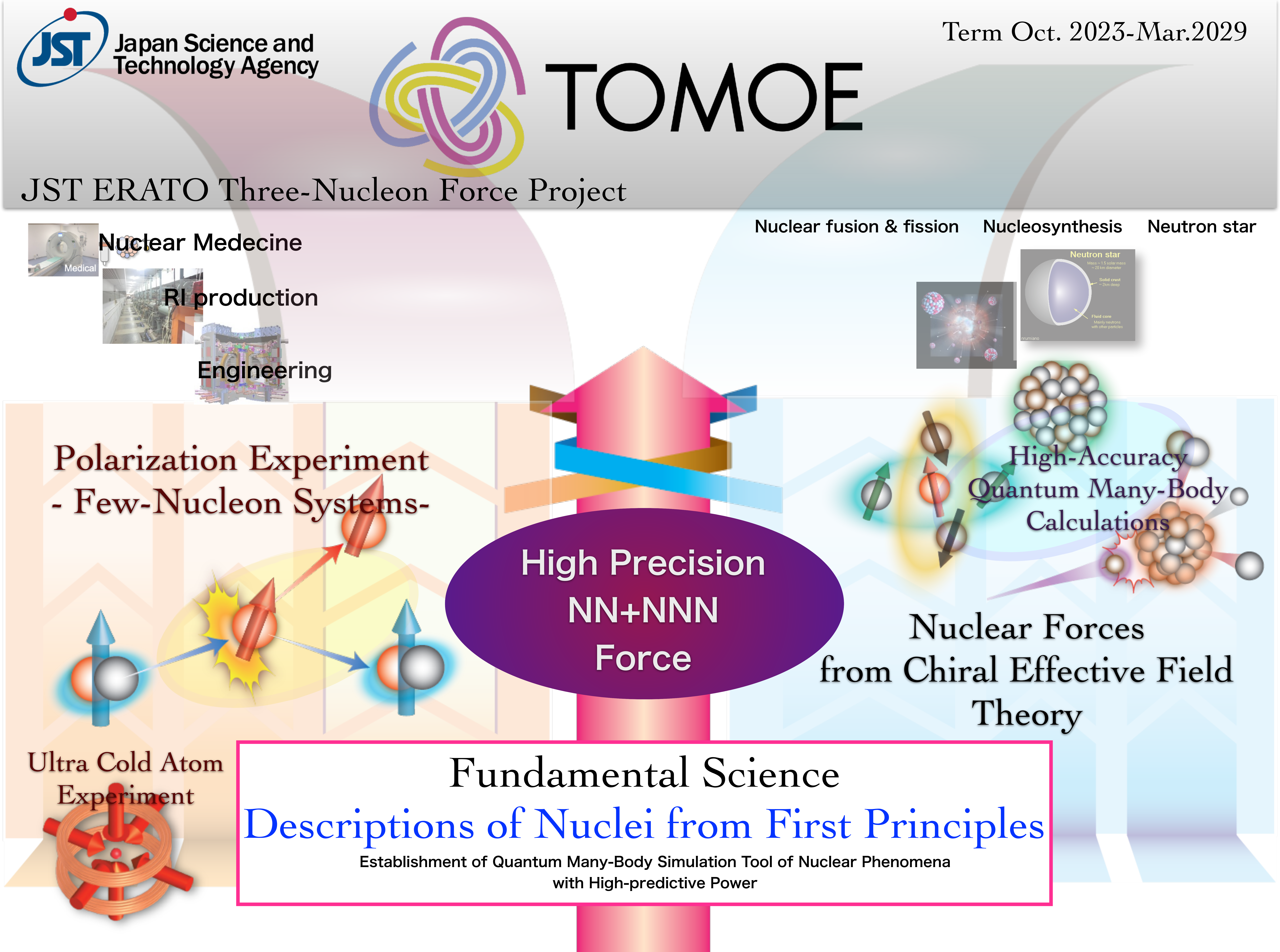
$$\Rightarrow \frac{d\sigma}{d\Omega} = \underbrace{|F_0|^2 + \frac{3}{16}|F_\sigma|^2}_{\text{scalar } (N^{[0]})} + \underbrace{\frac{1}{4}\left(|F_p|^2 + |F_h|^2\right)}_{\text{vector } (N^{[1]})} + \underbrace{18|F_{\ell m}|^2 + 6|F_n|^2}_{\text{tensor } (N^{[2]})}$$





Main : vector components at the cross section minimum

Main : tensor & vector components at the cross section minimum



Japan Science and Technology Agency
TOMOE
Term Oct. 2023-Mar.2029
JST ERATO Three-Nucleon Force Project
Nuclear Medecine
Medical
RI production
Engineering
Nuclear fusion & fission
Nucleosynthesis
Neutron star
Neutron star
Polarization Experiment
- Few-Nucleon Systems-
High Precision
NN+NNN
Force
High-Accuracy
Quantum Many-Body
Calculations
Nuclear Forces
from Chiral Effective Field
Theory
Ultra Cold Atom
Experiment
Fundamental Science
Descriptions of Nuclei from First Principles
Establishment of Quantum Many-Body Simulation Tool of Nuclear Phenomena
with High-predictive Power

Summary

To understand nuclear forces is a hot topic of nuclear physics.

Frontiers of nuclear force study
to understand nuclear forces from quarks
to understand nuclei/matter from NN & 3N-forces

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

deuteron-proton scattering at ~100 MeV/nucleon inspires quantitative discussions of 3NFs.

in Progress of Experiment

- Deuteron-Proton Scattering : Spin Correlation Coefficients at 100 MeV
- Proton-^{3}He Scattering at ~ 100 MeV
  - **Determine 3NFs based on χEFT Nuclear Potential**
  - **3NFs of isospin channel of T=3/2**