Three-Nucleon Force Effects in Few-Nucleon Scattering

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Earth-Moon-Satellite Gravitational Interactions

Two-Body Interaction :

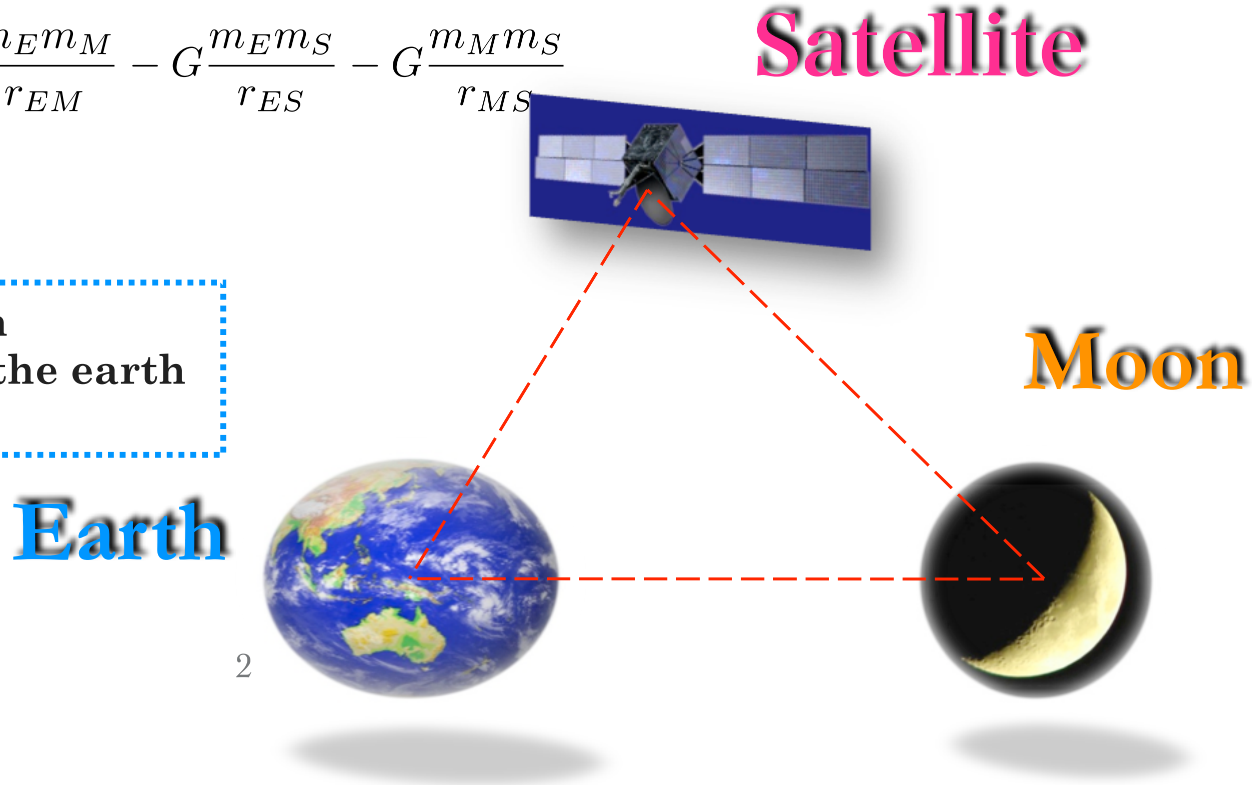
$$H = \frac{1}{2}\left(\frac{P_E^2}{m_E} + \frac{P_M^2}{m_M}\right) - G\frac{m_E m_M}{r_{EM}}$$

Three-Body Interaction :

$$H = \frac{1}{2}\left(\frac{P_E^2}{m_E} + \frac{P_M^2}{m_M} + \frac{P_S}{m_S}\right) - G\frac{m_E m_M}{r_{EM}} - G\frac{m_E m_S}{r_{ES}} - G\frac{m_M m_S}{r_{MS}}$$

$$+V(\vec{r}_E, \vec{r}_M, \vec{r}_S)$$

Effects of Polarization
of the ocean water of the earth
by the moon's gravity



2

Triplet of Atoms
van der Waals Type Three-Body Force

Two-Body Interaction： Electro-Magnetic

$$V_{12} = \frac{C\alpha^3}{r_{12}^6}$$

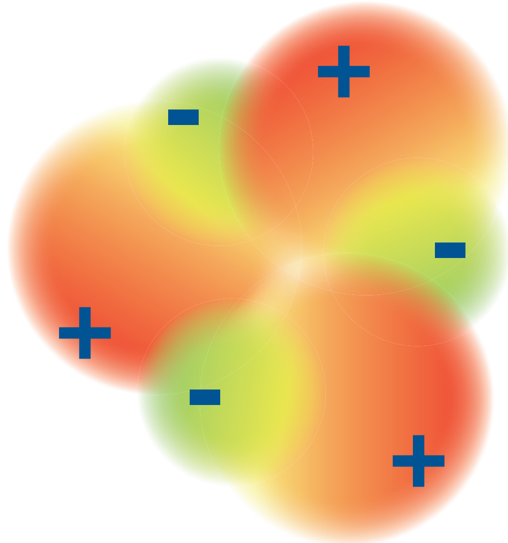
Three-Body Interaction：

$$V_{123} = C\frac{3\cos\gamma_1\cos\gamma_2\cos\gamma_3 + 1}{r_{12}^3 r_{23}^3 r_{31}^3}$$

Effects of Polarization
of the electron density distribution

Axilrod-Teller-Muto three-body expression

B.M. Axilrod and E. Teller, J. Chem. Phys. 11, 299 (1943).
Y. Muto, J. Phys.-Math. Soc. Japan, 17, 629 (1943).



Interaction Energy [kcal/mol]

	2BF	3BF
(NH_3) dimer	-1.43	0.00
(H_2O) dimer	-1.80	-0.01
Benzene – H_2O	-2.35	0.15
Benzene – NH_3	-2.15	0.14

O. A. von Lilienfeld, and A. Tkatchenko, J. Chem. Phys. 132, 234109 (2010).

How about Three-Nucleon Forces ?

- Nucleus : a compact system of nucleons (protons, neutrons)
- Nuclear Force : Strong Interaction ··· Short and Strong
- Effects of Three Body Forces in Nuclei

— Where and How ? —

	Solar System	Atom	Nucleus
Length	10^8 m	10^{-10} m	10^{-15}m
Interaction	Gravity	Electro-Magnetic	Strong
Coupling Constant	<< 1	10^{-2}	1
$\frac{V(3BF)}{V(2BF)}$	0.001%	a few %	?

Three-Nucleon Force (3NF)

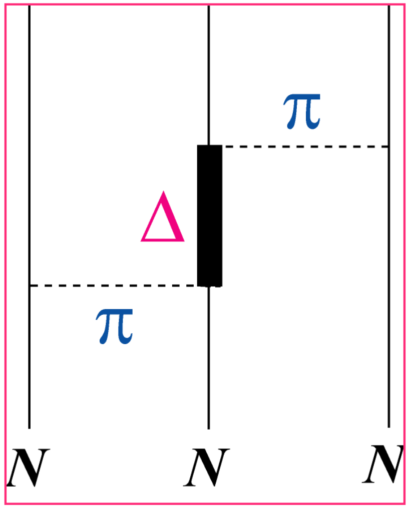
1957 Fujita-Miyazawa 3NF

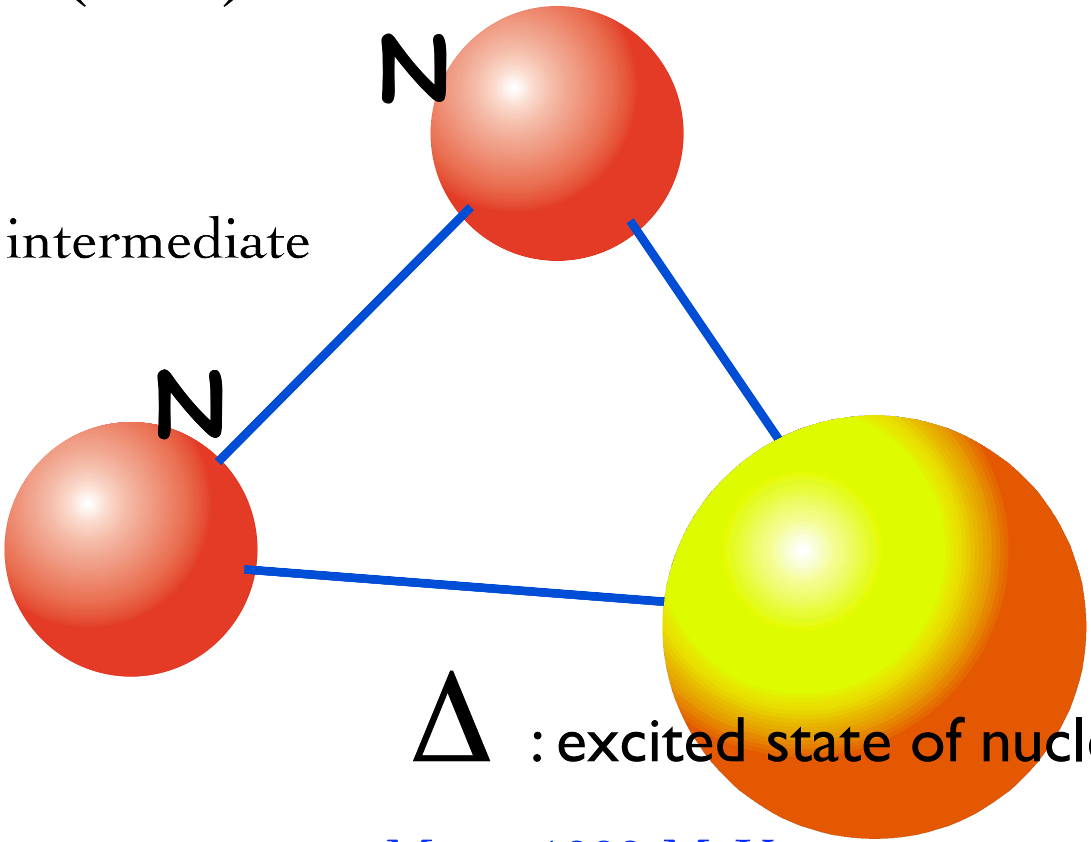
Prog. Theor. Phys. 17, 360 (1957)

2π-exchange 3NF :

- Main Ingredients :

  Δ-isobar excitations in the intermediate





Δ : excited state of nucleon

$M_\Delta = 1232$ MeV

$(J^\pi, T) = \left(\frac{3}{2}^+, \frac{3}{2}\right)$

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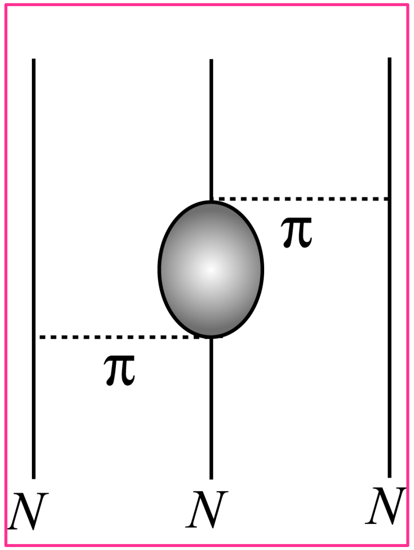

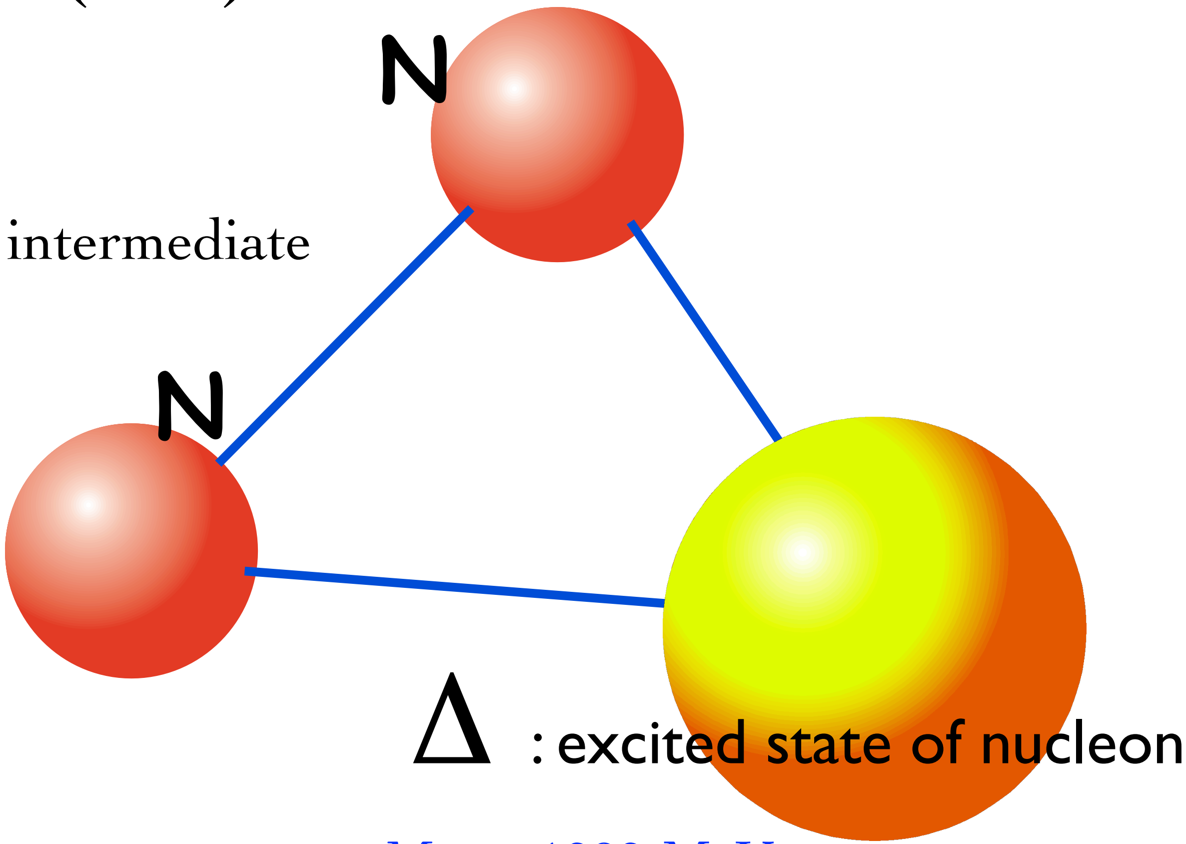

$M_\Delta = 1232$ MeV

$(J^\pi, T) = \left(\frac{3}{2}^+, \frac{3}{2}\right)$

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

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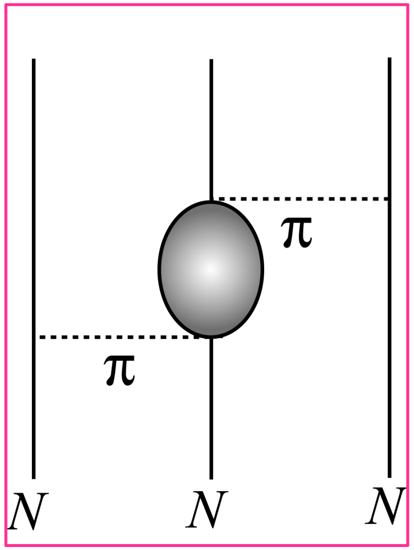

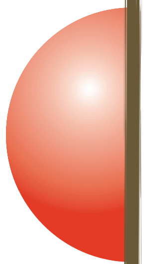

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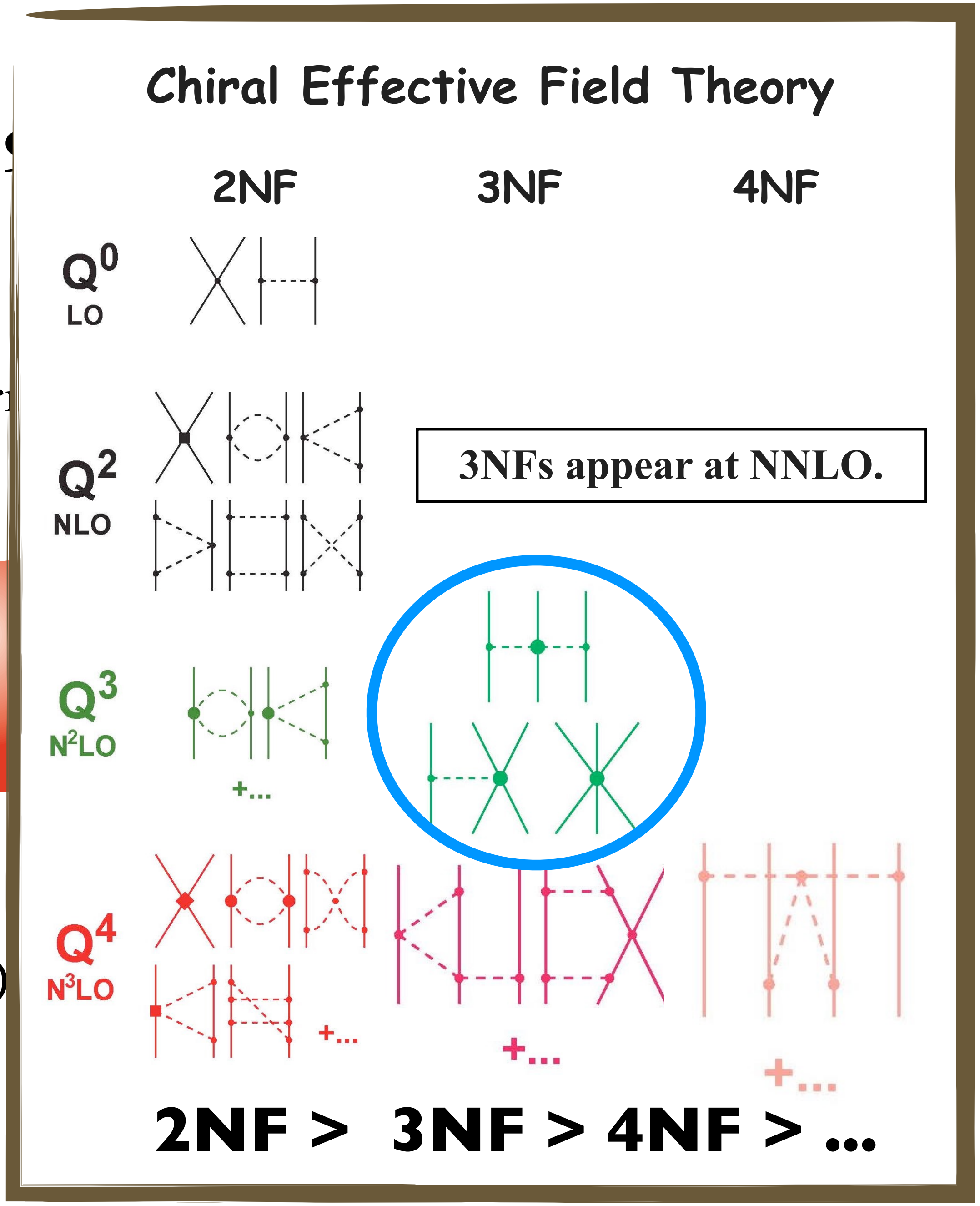
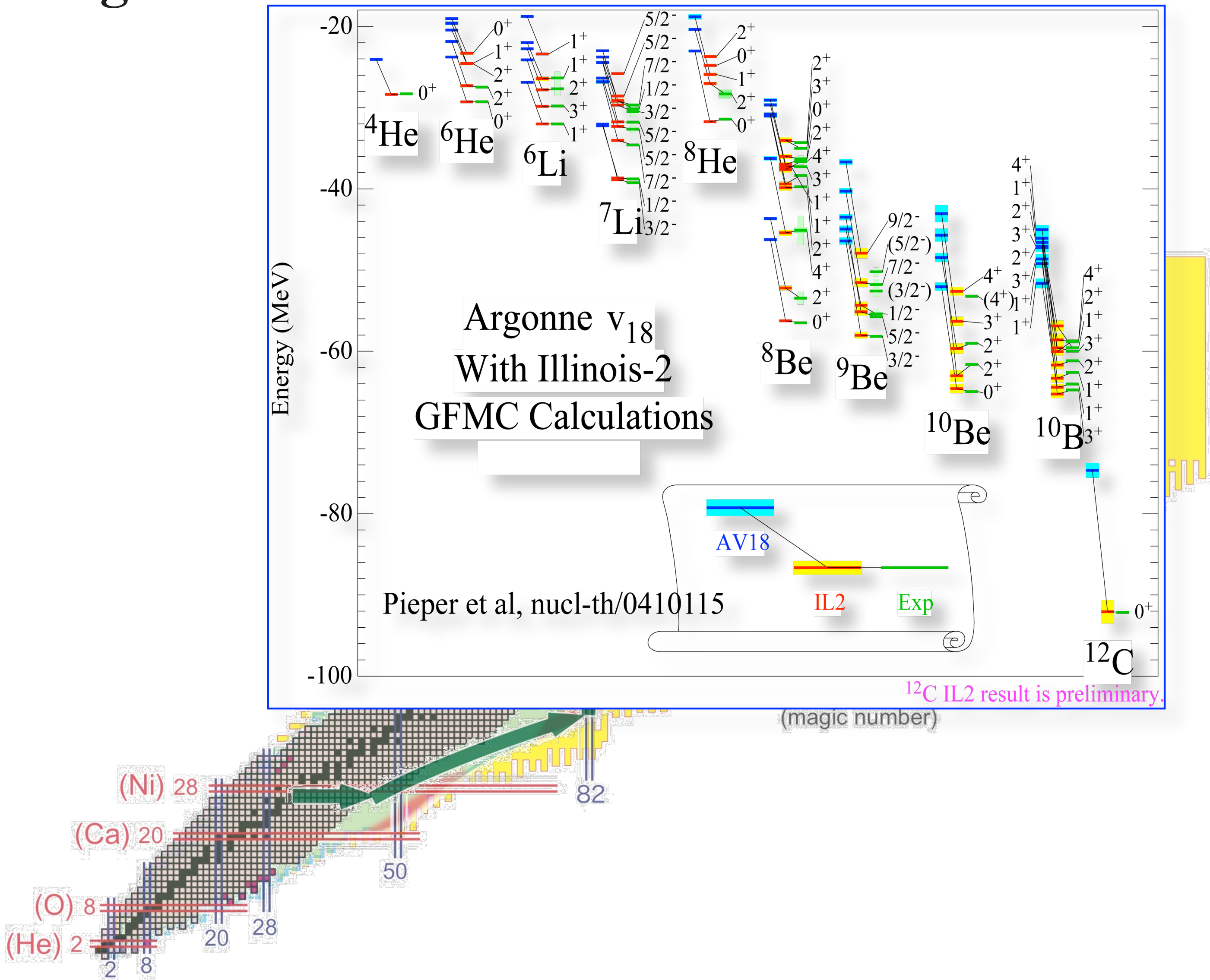


Where can we find 3NF effects ? - I -

3NFs in Finite Nuclei

Ab Initio Calculations for Light Nuclei

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



Where can we find 3NF effects ? - I -

3NFs in Finite Nuclei

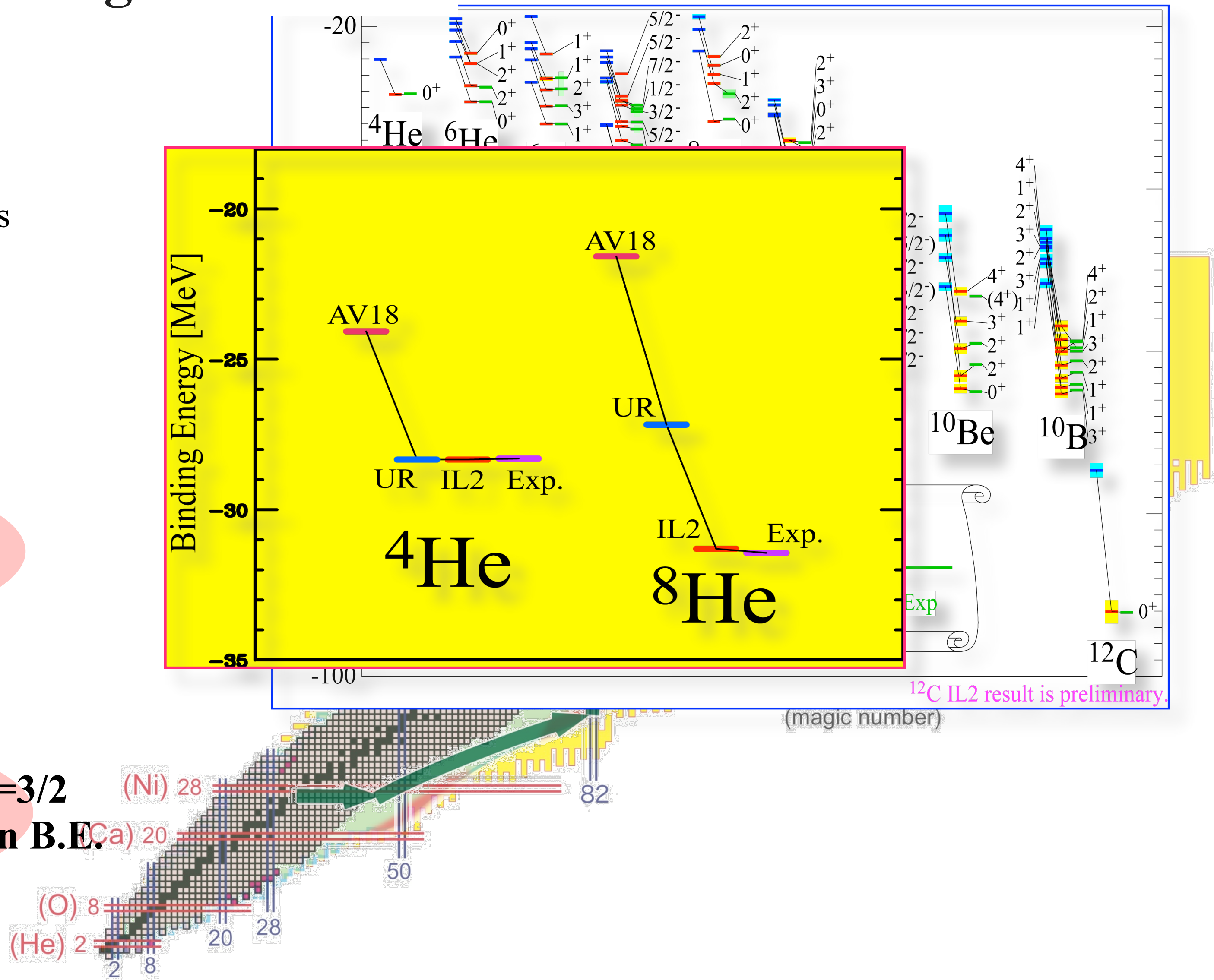
Ab Initio Calculations for Light Nuclei

- ***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**

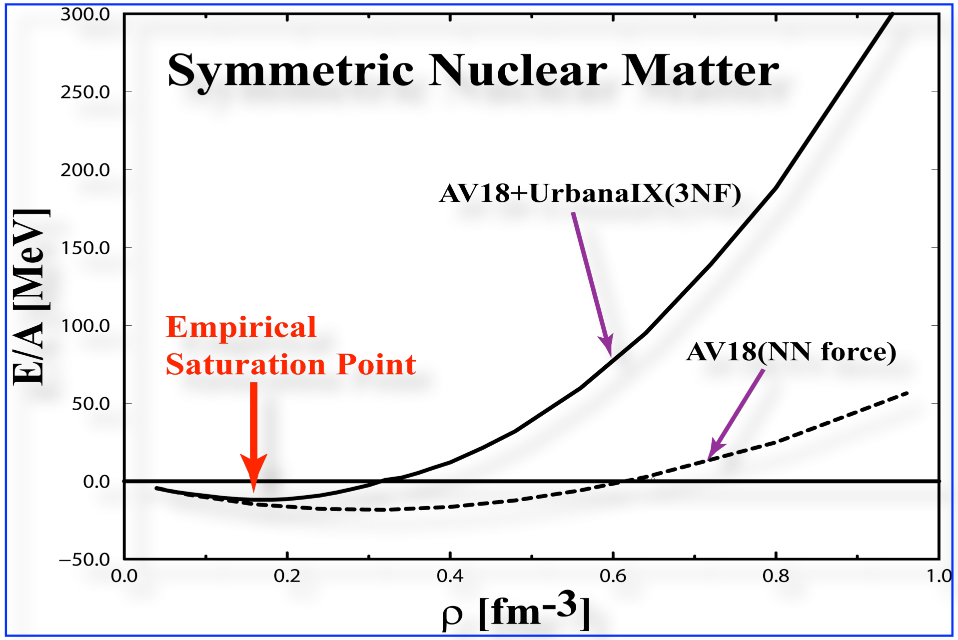


Note :
3NFs with iso-spin states of T=3/2 play important roles to explain B.E. in neutron rich nuclei.

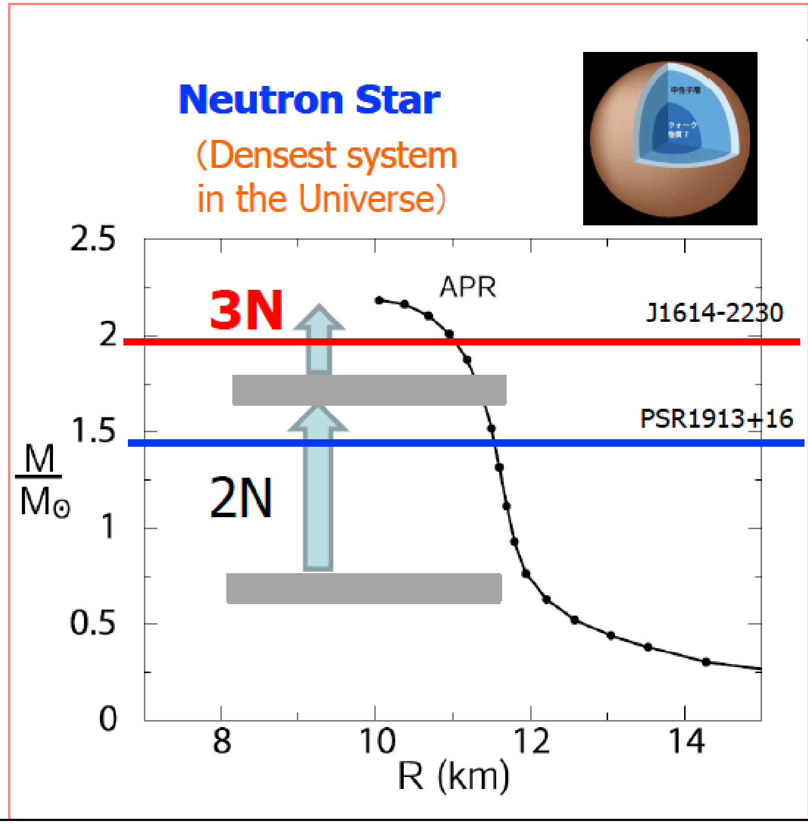
Where can we find 3NF effects ? - II -

3NFs in Infinite Nuclei

Short-range 3NFs play important roles at high density.



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



- All NN potentials (AV18, Nijmegen I,II, CD Bonn) provide larger saturation point of Nuclear Matter.
- 3NF
  - shift to the empirical saturation point
  - significant at higher density

- Short range repulsive terms of 3NFs (3-Baryon Fs) are needed to understand 2 M(sun) neutron star.

- 3NF is a key to understand nuclear phenomena quantitatively.
- 3NF is mainly due to inner structure of Nucleon
- How to constrain the properties of 3NF ?

Few-Nucleon Scattering is a good probe to study the dynamical aspects of 3NFs.

✓ Momentum dependence
✓ Spin dependence
✓ Iso-spin dependence

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})

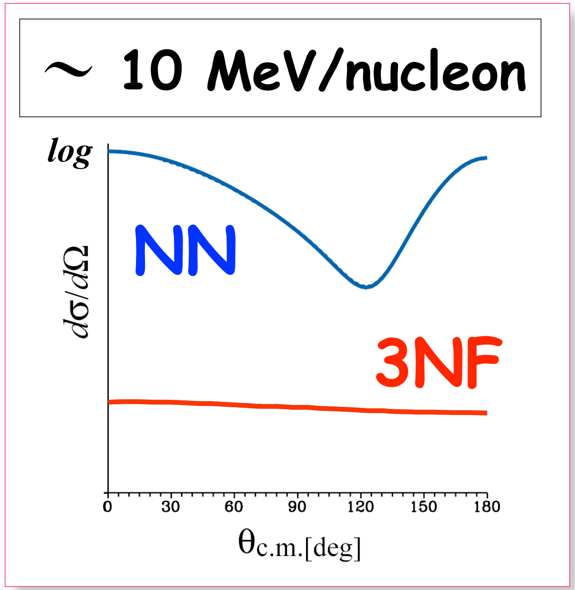
Extract fundamental information of Nuclear Forces

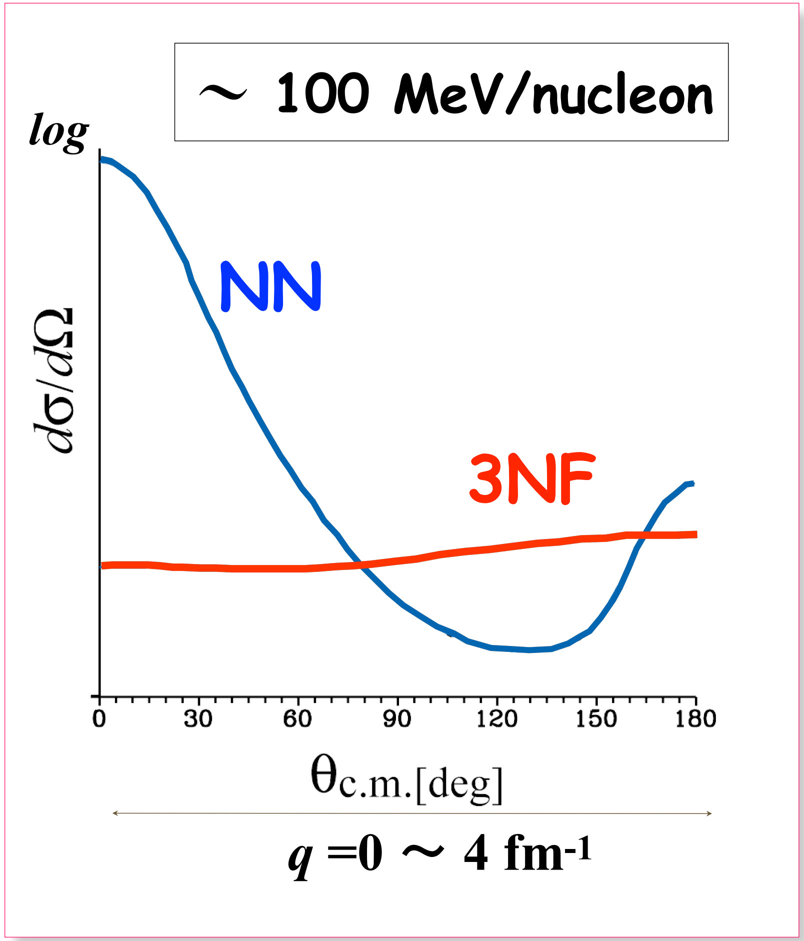
Where is the hot spot for 3NFs ?

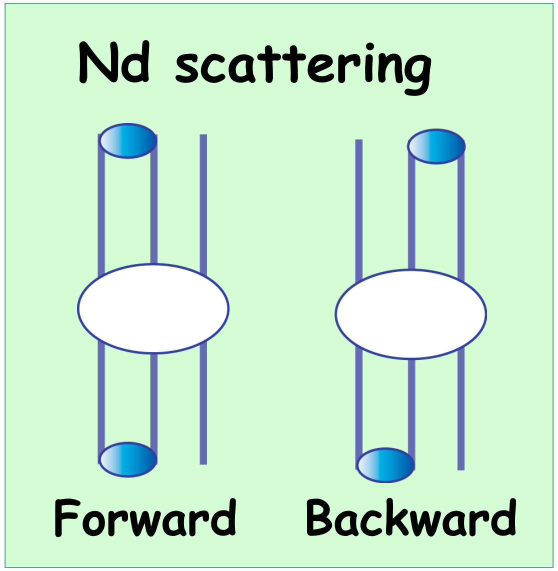
Nucleon-Deuteron Scattering - 3N Scattering -

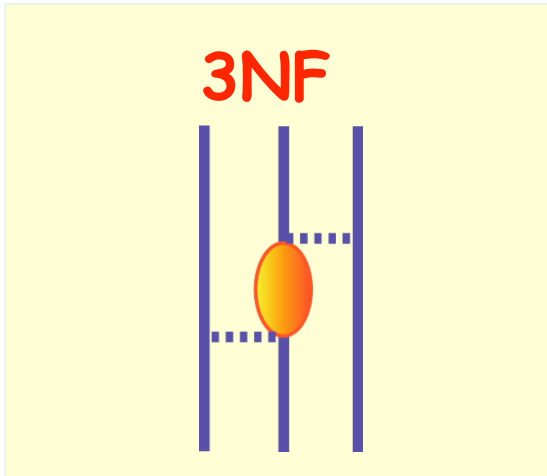
Predictions by H. Witala et al. (1998)

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

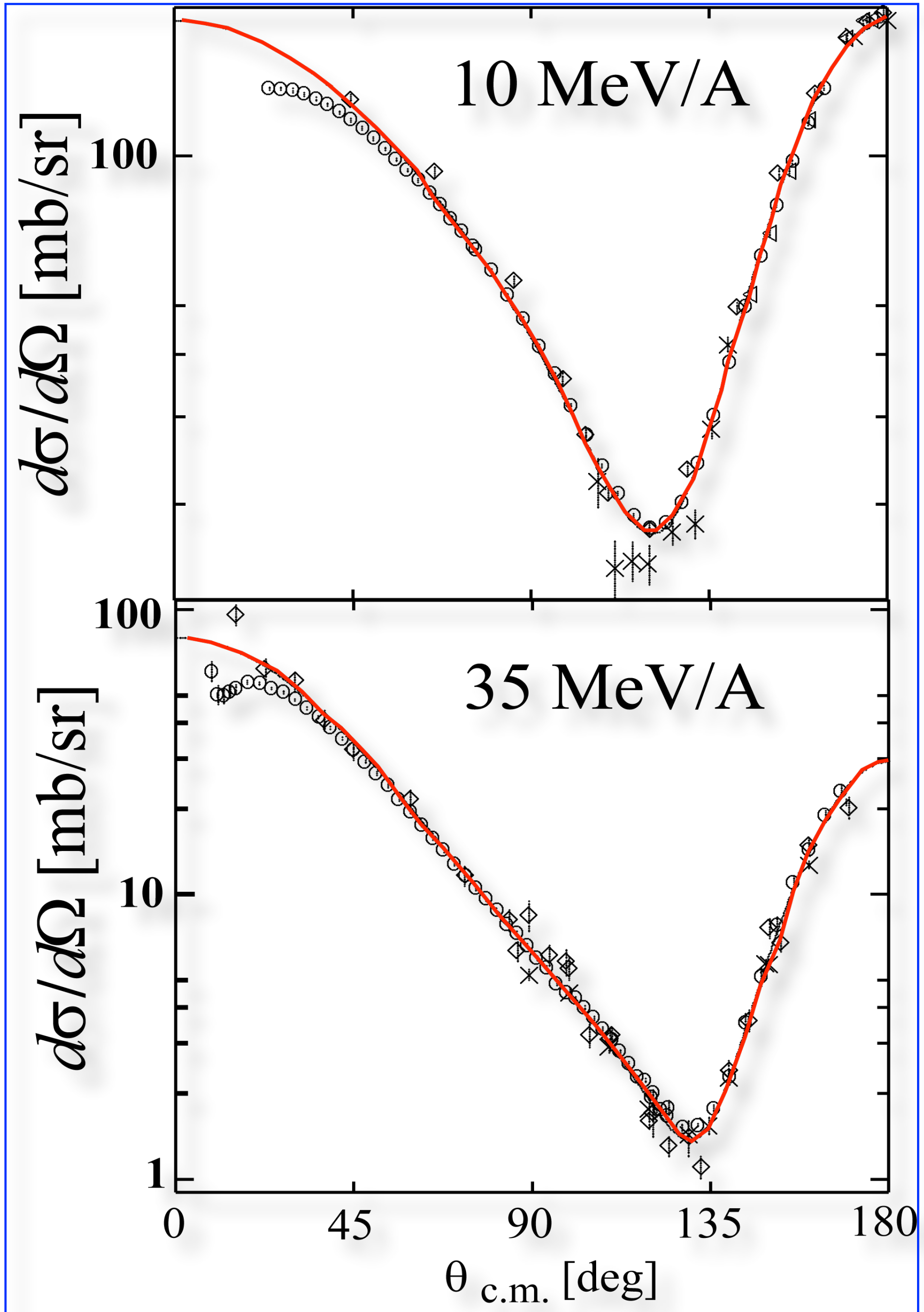








Nd Scattering at Low Energies ($E \leq 30$ MeV/A)



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

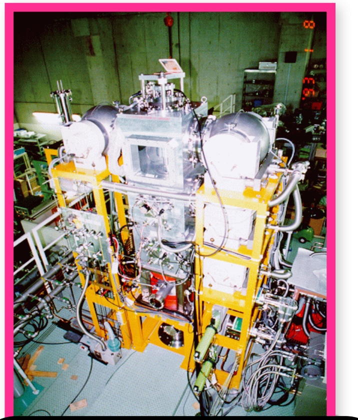
No signatures of 3NF

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

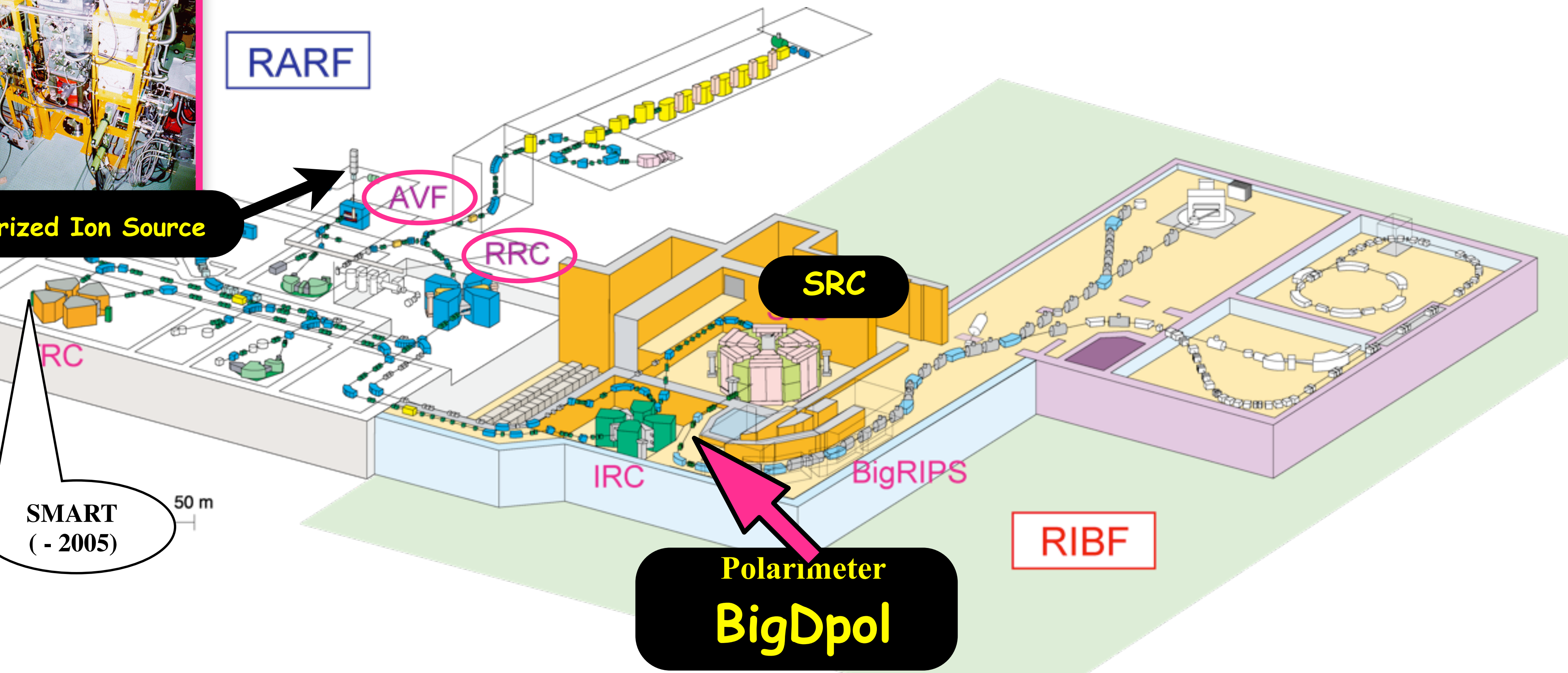
W. Glöckle et al., Phys. Rep. 274, 107 (1996).

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

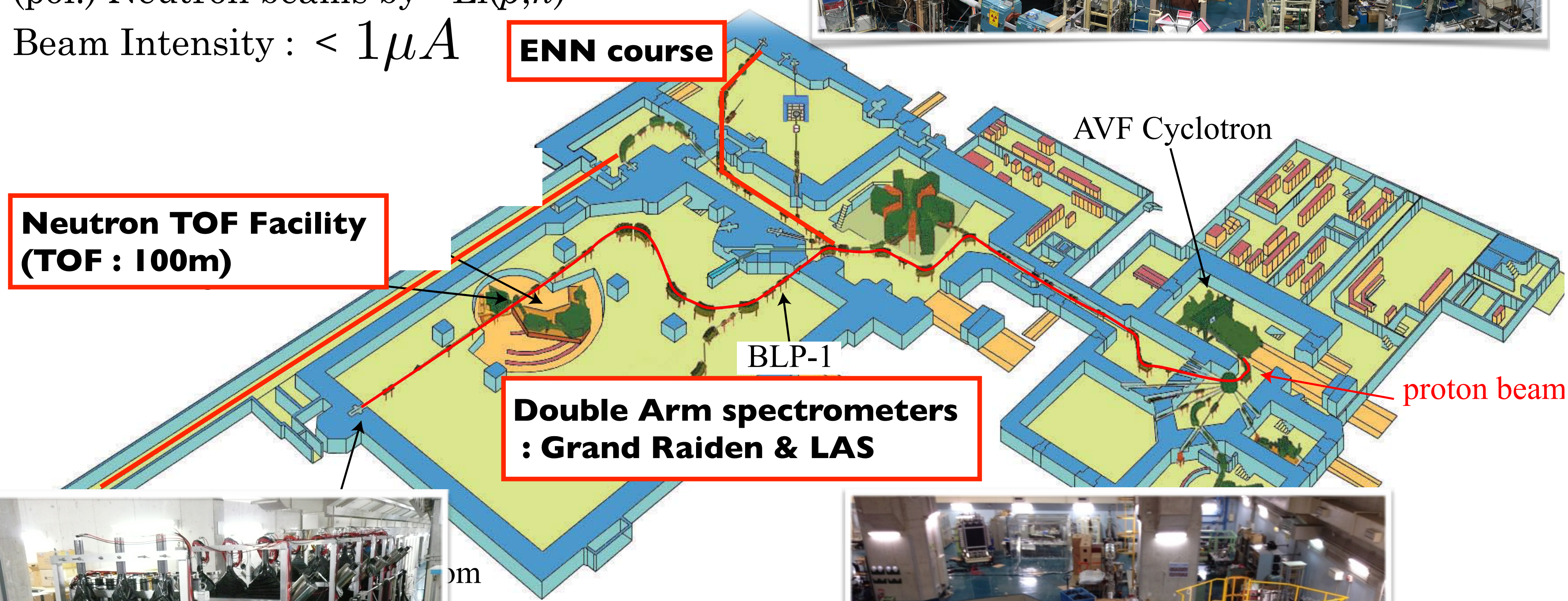


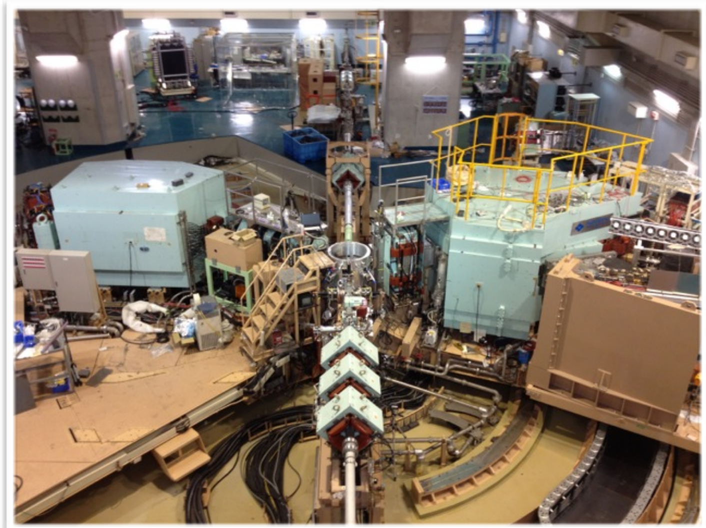
Spin axis of polarized d beams is freely controlled !



RCNP, Osaka University

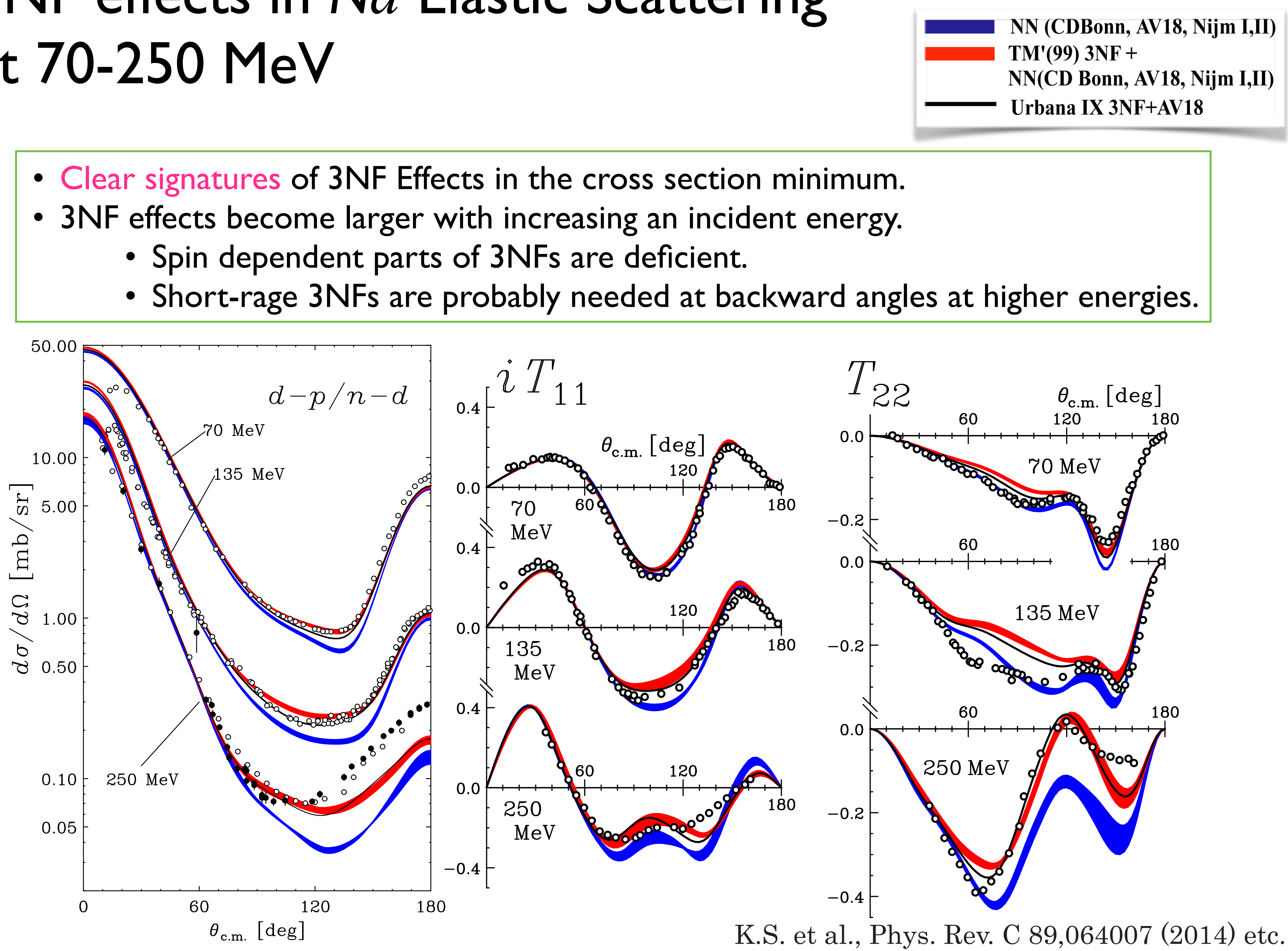
- Polarized p beam : 10 - 420 MeV/nucleon
- Polarized d beam : 5 - 100 MeV/nucleon
  - Polarizations : < 70 %
- (pol.) Neutron beams by $^{7}\mathrm{Li}(p,n)$
- Beam Intensity : $< 1\mu A$





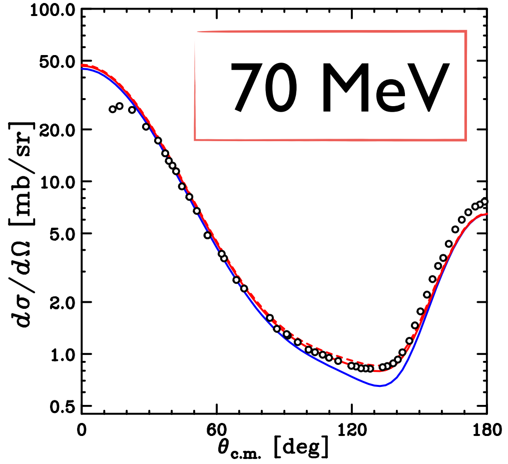
3NF effects in *Nd* Elastic Scattering at 70-250 MeV

- 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.
  - Short-rage 3NFs are probably needed at backward angles at higher energies.



K.S. et al., Phys. Rev. C 89,064007 (2014) etc.

How does Chiral EFT Nuclear Potential work for Nd Elastic Scattering ?



N4LO⁺ NN pot. + N2LO 3NF Calculations (Preliminary)

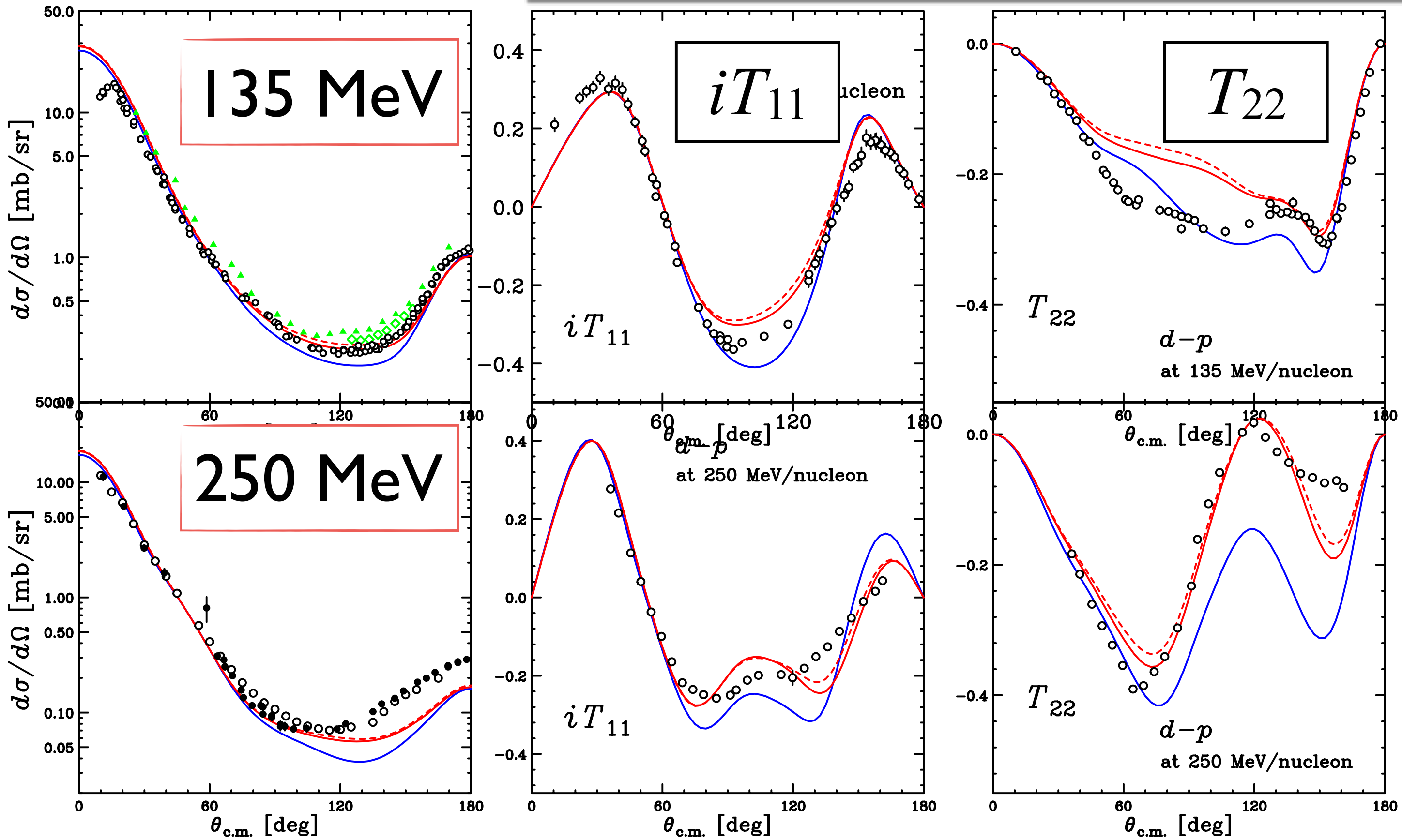
2NF: Semi-local Momentum-Space regularised Chiral NN potentials
P. Reinert, H. Krebs, E. Epelbaum EPJA 54, 86 (2018)

3NF: LECs of N2LO 3NF (D & E terms) are determined
by ^{3}H B.E. & cross section minimum for *Nd* @ 70MeV.

Calculated results are quite similar to phenomenological NN+3NF.

→ 3NFs of higher orders (N3LO & N4LO) are needed !

Nd data are useful to determine LECs of 3N sector.



H. Witala private communications.

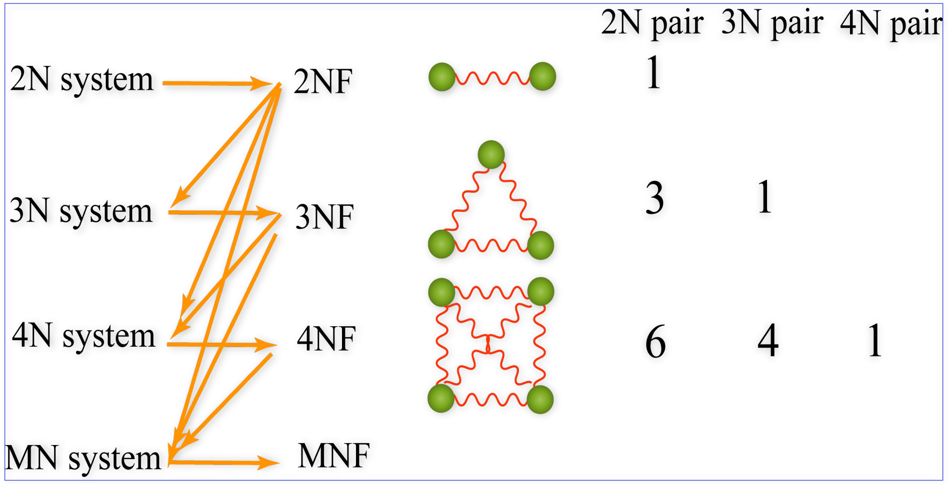
- N4LO+, Λ=450MeV
- C_D= 2.0, C_E= 0.286
- C_D= 4.0, C_E= 0.499

p–^{3}He scattering

～ 4-Nucleon Scattering ～

p-^{3}He scattering

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



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

- 4NF effects

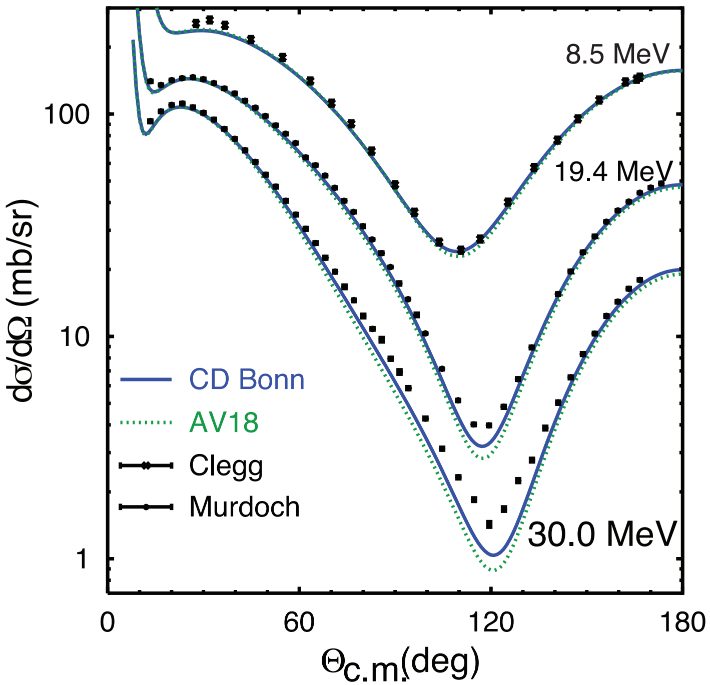
p-^{3}He scattering

Theory in Progress

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

up to 35 MeV

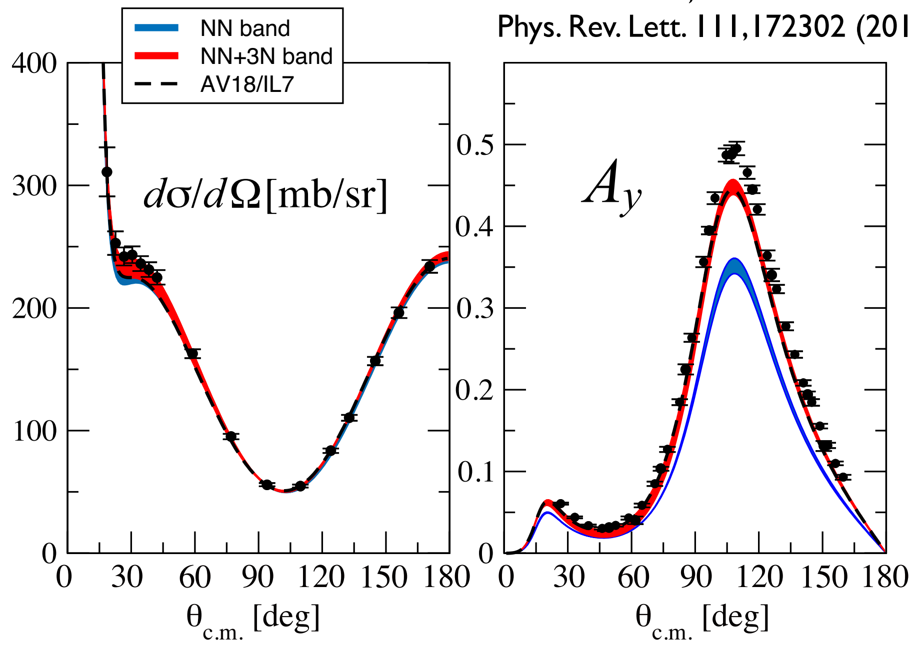
A. Deltuva and A.C. Fonseca
Phys. Rev. C 87, 054002 (2013)



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)



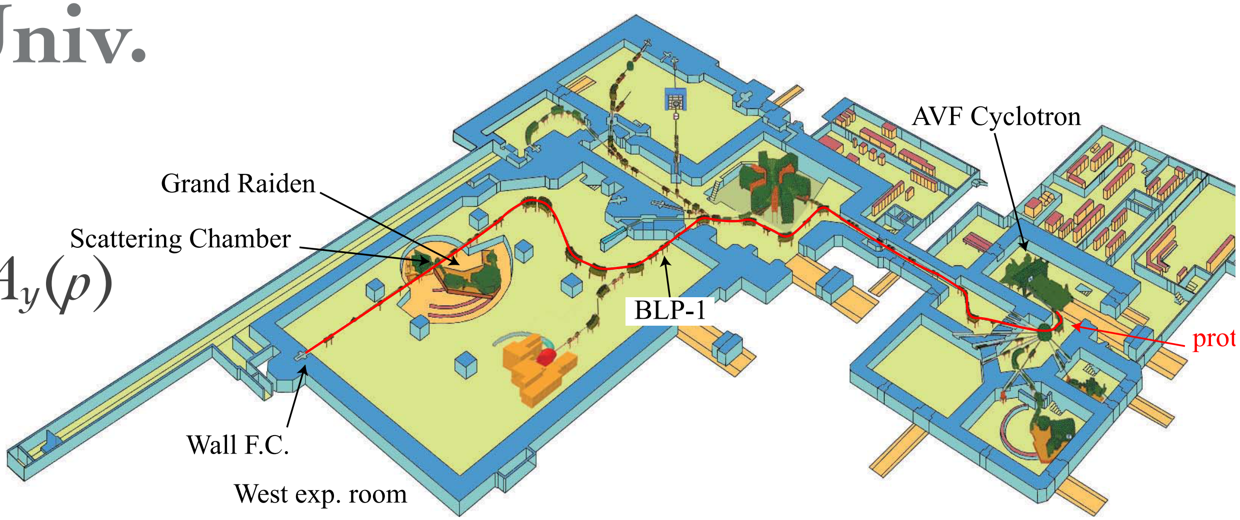
- No signature of 3NFs in cross section
- $Ay(p)$ puzzle : 3NFs sensitive to p-shell nuclei improve the agreement to the data.

How about spin observables at higher energy?

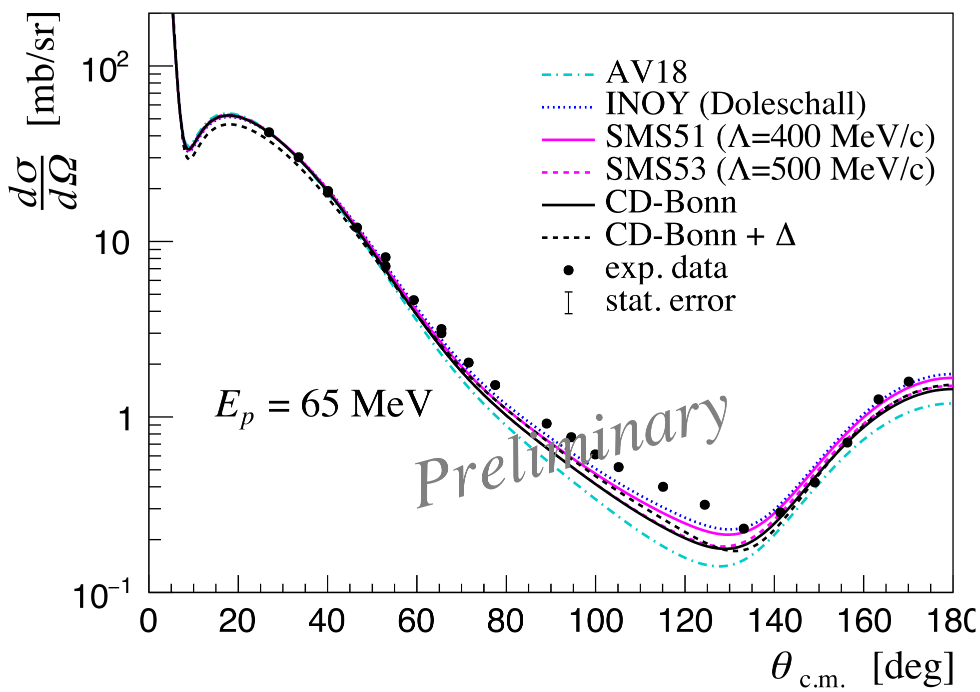
New $d\sigma/d\Omega$ & Proton Analyzing Power exp./data from RCNP, Osaka Univ.

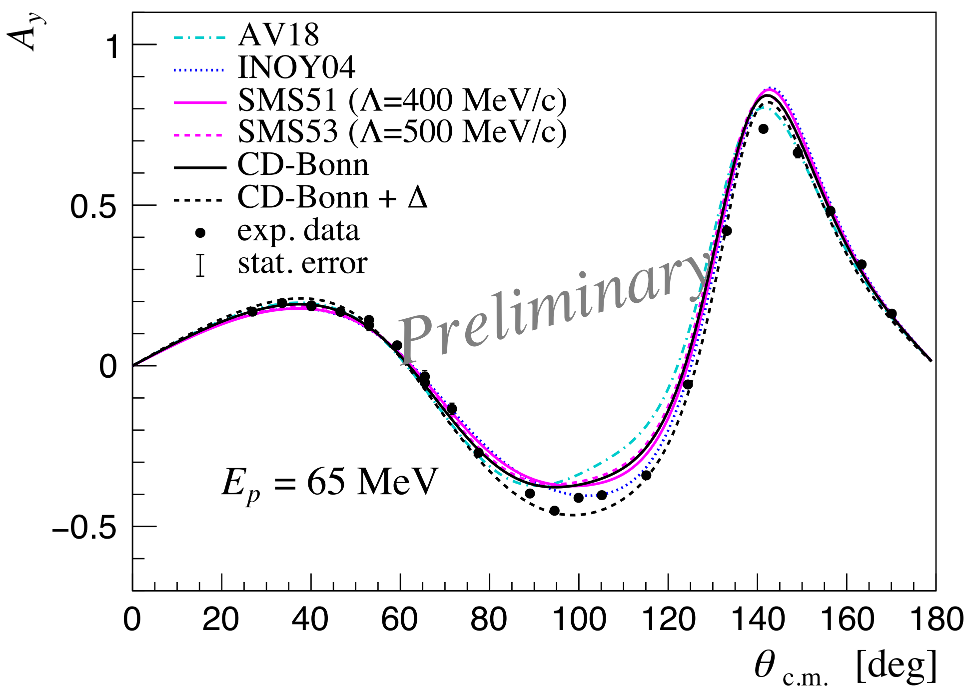
$\vec{p} + {}^3\mathrm{He}$ at 65 MeV

- Observables : Cross section & $A_y(p)$
- Angles : $\theta_{\mathrm{c.m.}} = 27^\circ - 170^\circ$



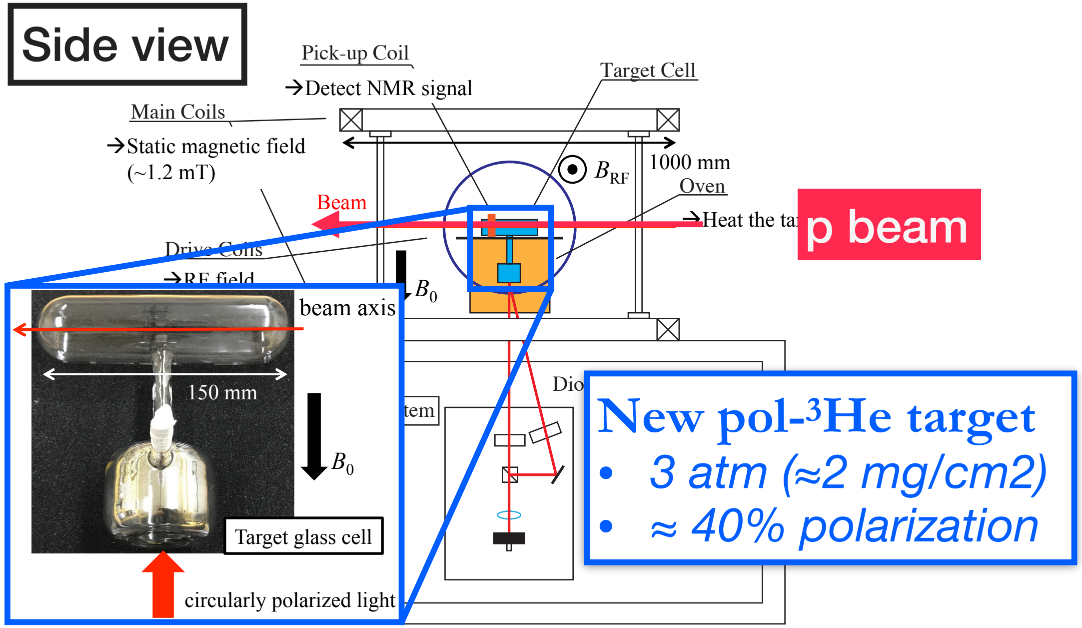
Calculations by A. Deltuva

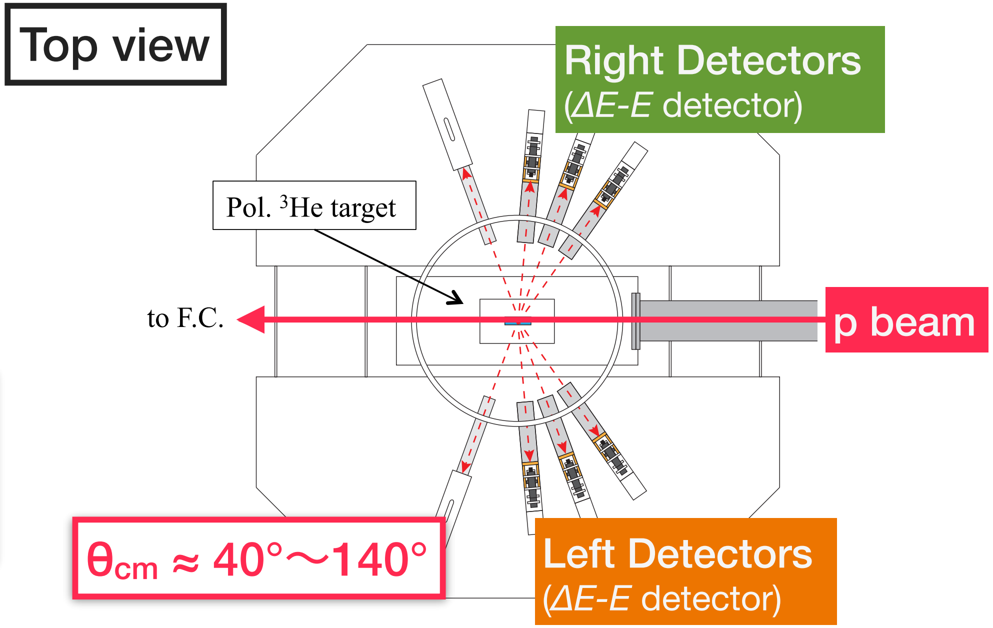


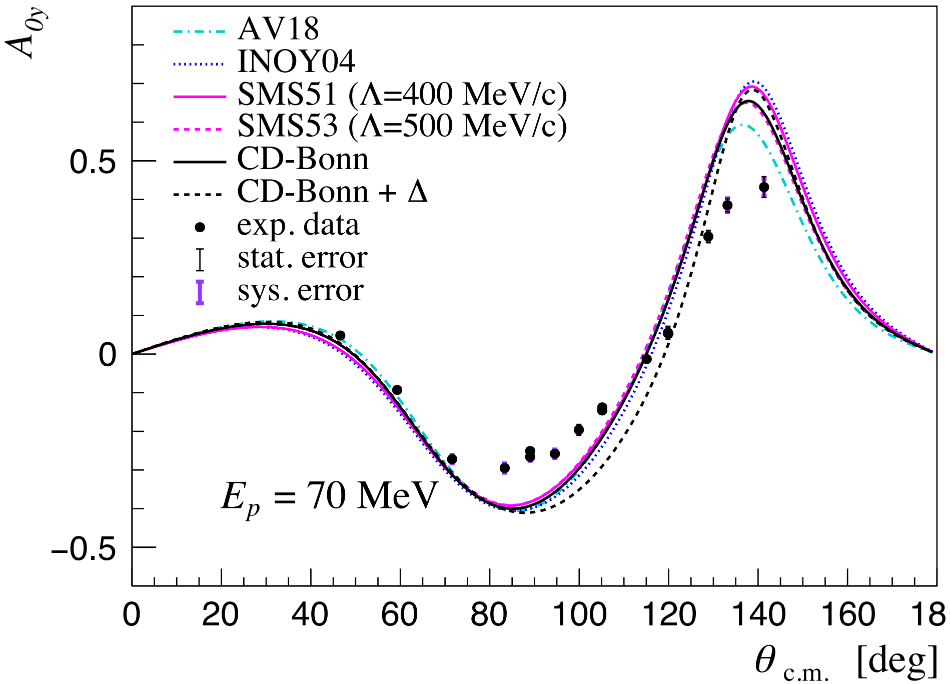


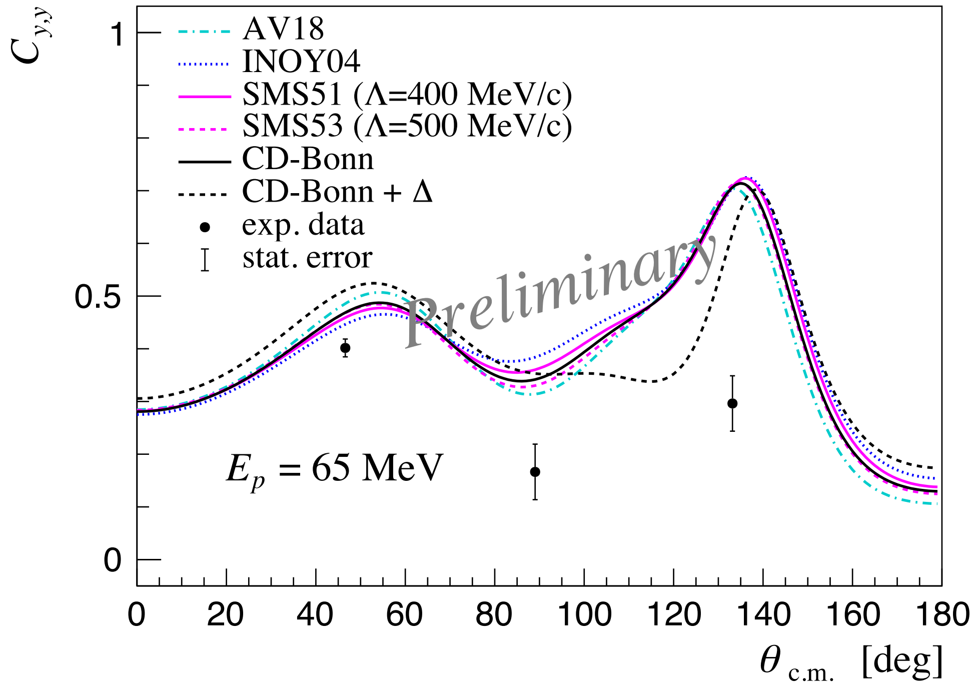
3NF effects can be seen in the cross section minimum.

New ^{3}He Analyzing Power & C_{yy} exp./data from CYRIC & RCNP









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 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 ?

It is interesting to see how ChEFT NN+NNN potentials explain the data.

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

Future Plan

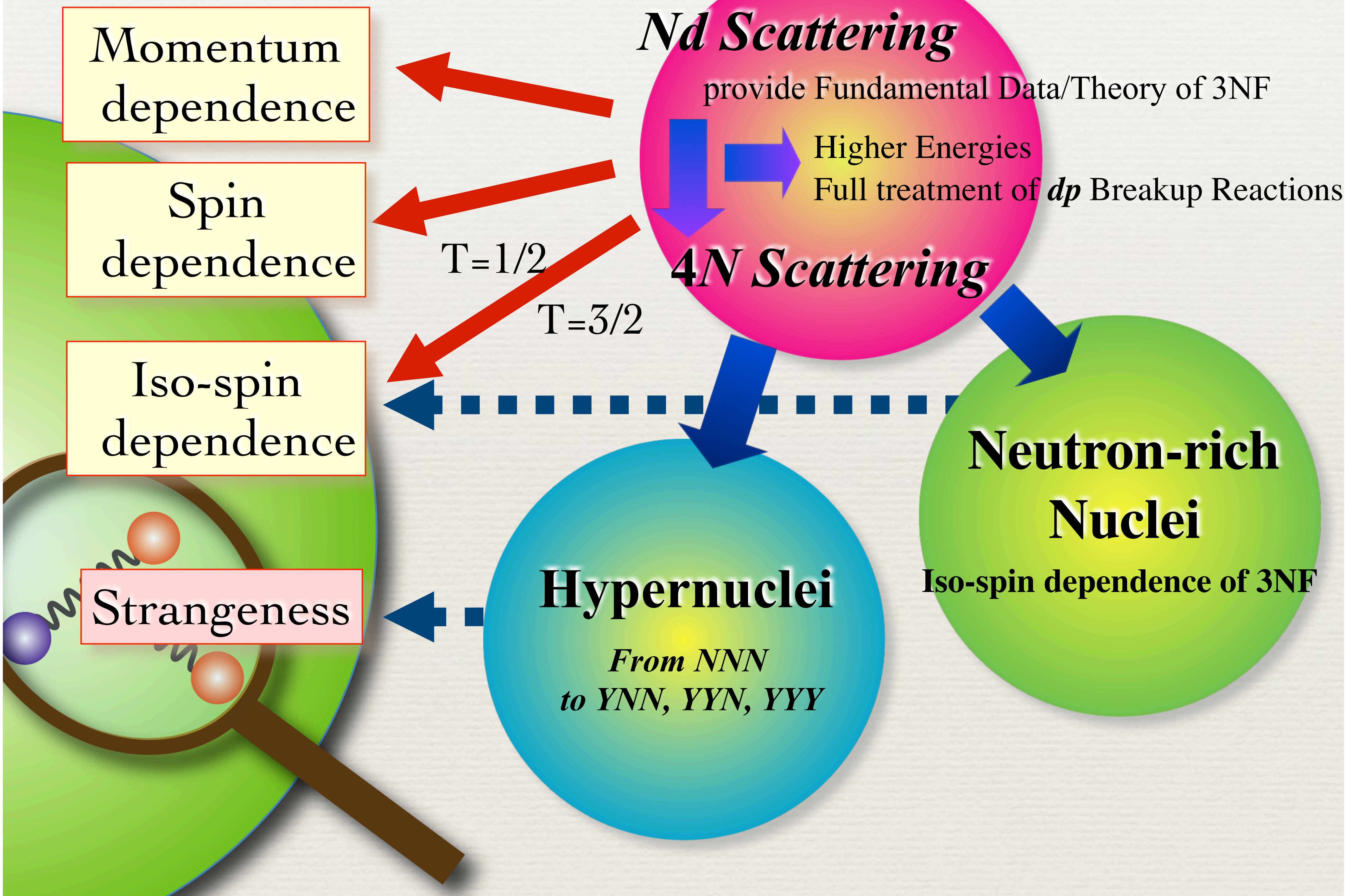
Nucleon-Deuteron Scattering :
Energy dependent study of Spin Correlation Coefficients

p-^{3}He Scattering : Complete set of spin observables & Energy dependence

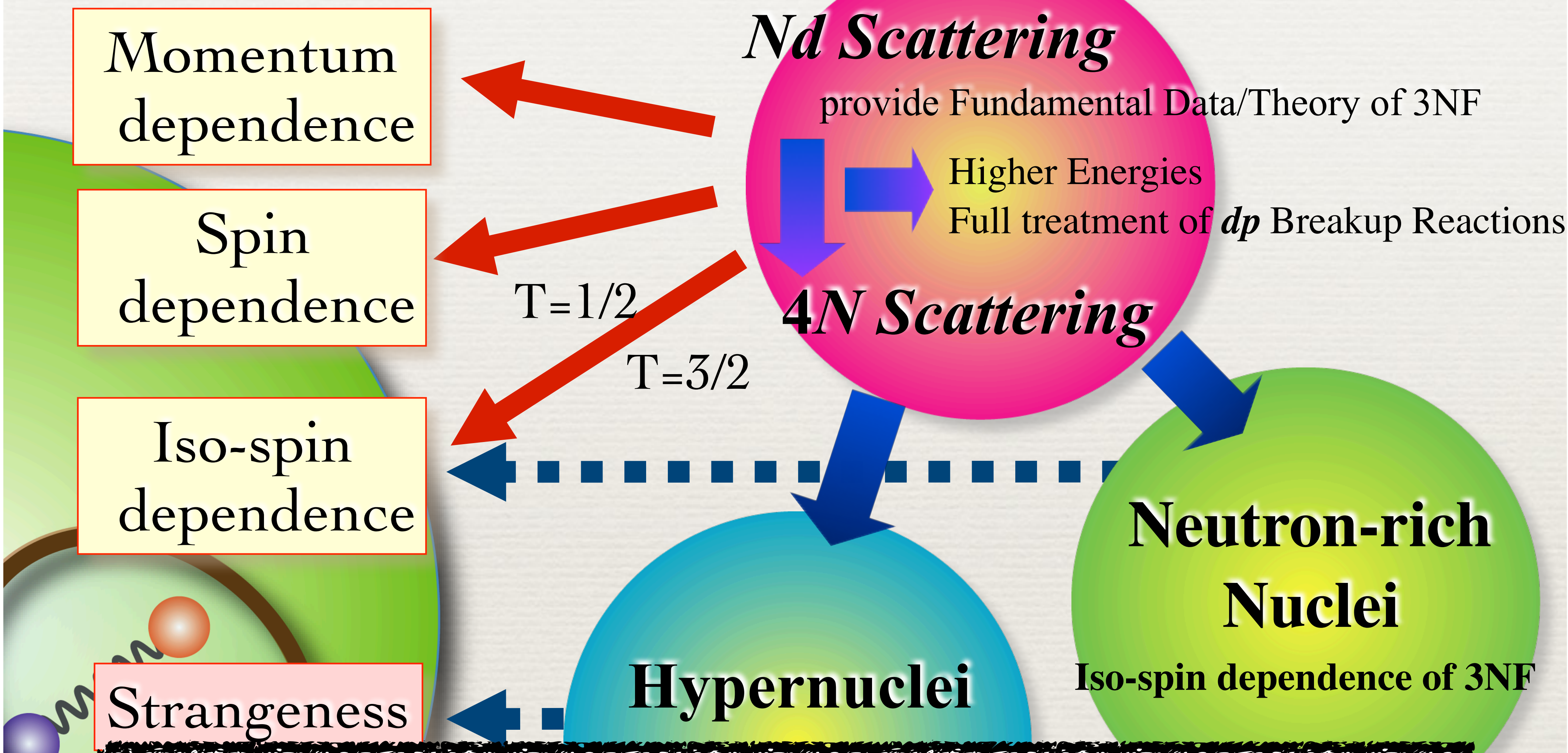
Study of T=3/2 three-nucleon systems (3p, 3n-states) (Spokesperson : K. Miki)

Study of 3NF effects in Nuclear Reaction (Spokesperson : T. Wakasa)

Perspective of 3NF Study



Perspective of 3NF Study



It could be interesting …
How and Where 3B-Forces are defined / appear
in other hierarchical structures.

RIBF-*d*. Collaboration

Tohoku University

K. Sekiguchi, K. Miki, Y. Wada, A. Watanabe, D. Eto, T. Akieda, H. Kon, J. Miyazaki, T. Taguchi, U. Gebauer, K. Takahashi, T. Mashiko

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Kyushu University

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T. Wakui