Study of Three Nucleon Force

- Old but New Nuclear Force -

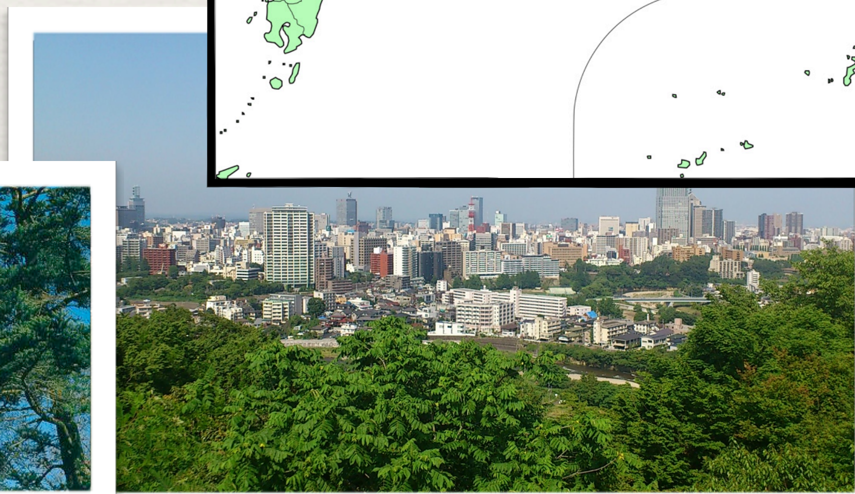
Kimiko Sekiguchi
Department of Physics, Tohoku University

Seminar for Toshiko Yuasa Prize at Orsay, March 17th, 2015

東北大学

Tohoku University

- Location : **Sendai**
- Established in 1907, the third oldest Imperial University in Japan (1st: Univ. of Tokyo in 1877, 2nd: Kyoto Univ. in 1897)
  - 10 schools, including Science, Engineering, Medicine, Law, Arts and Letters, Agriculture etc...
- Students : 10,000 (undergraduate), 7700 (graduate)



Today's talk is on forces acting in nuclei.

Nuclear Physics

started in the beginning of the 20th century.

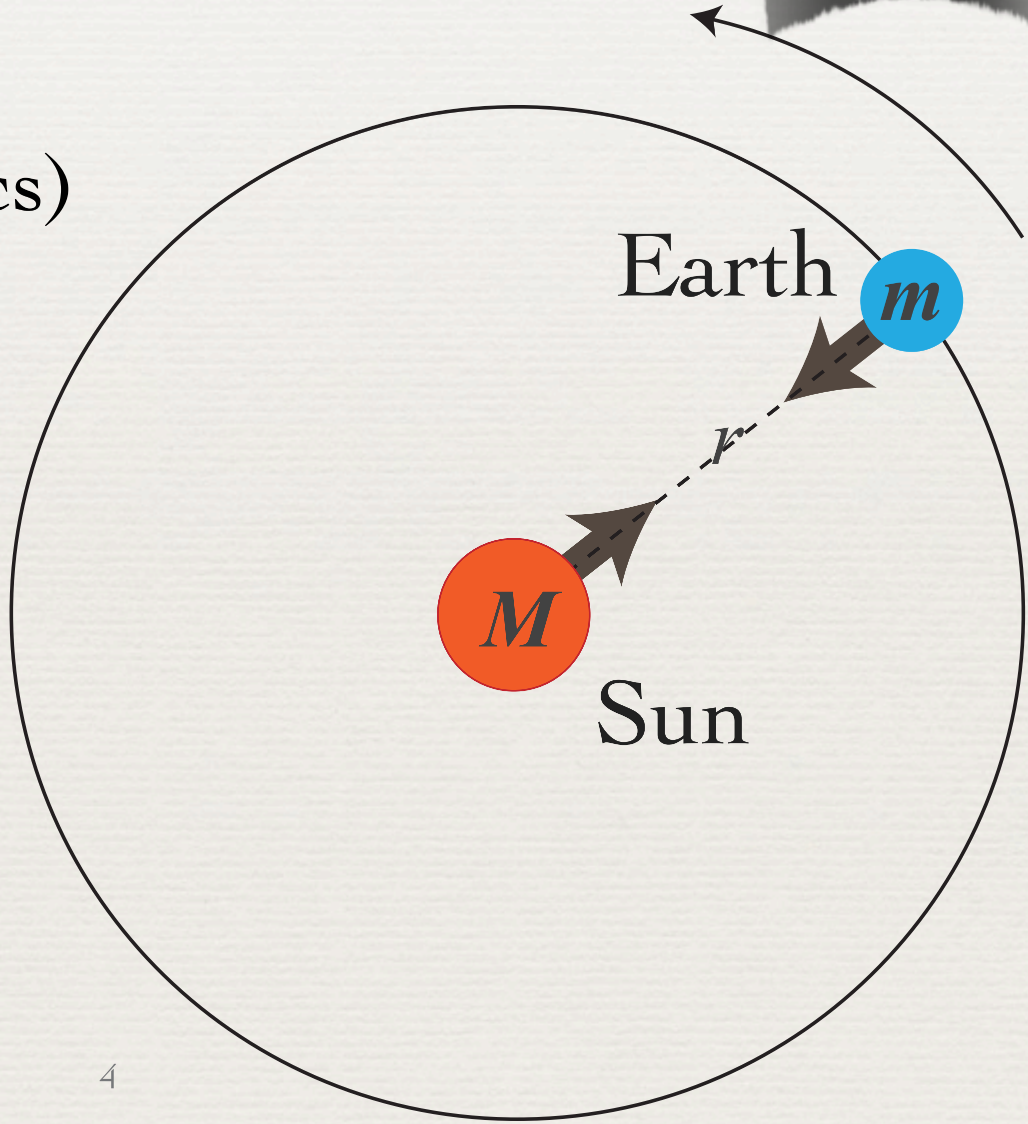
What kinds of forces did we know 100 years ago?

Gravity

Classical Mechanics
(Newtonian Mechanics)

Attractive Force

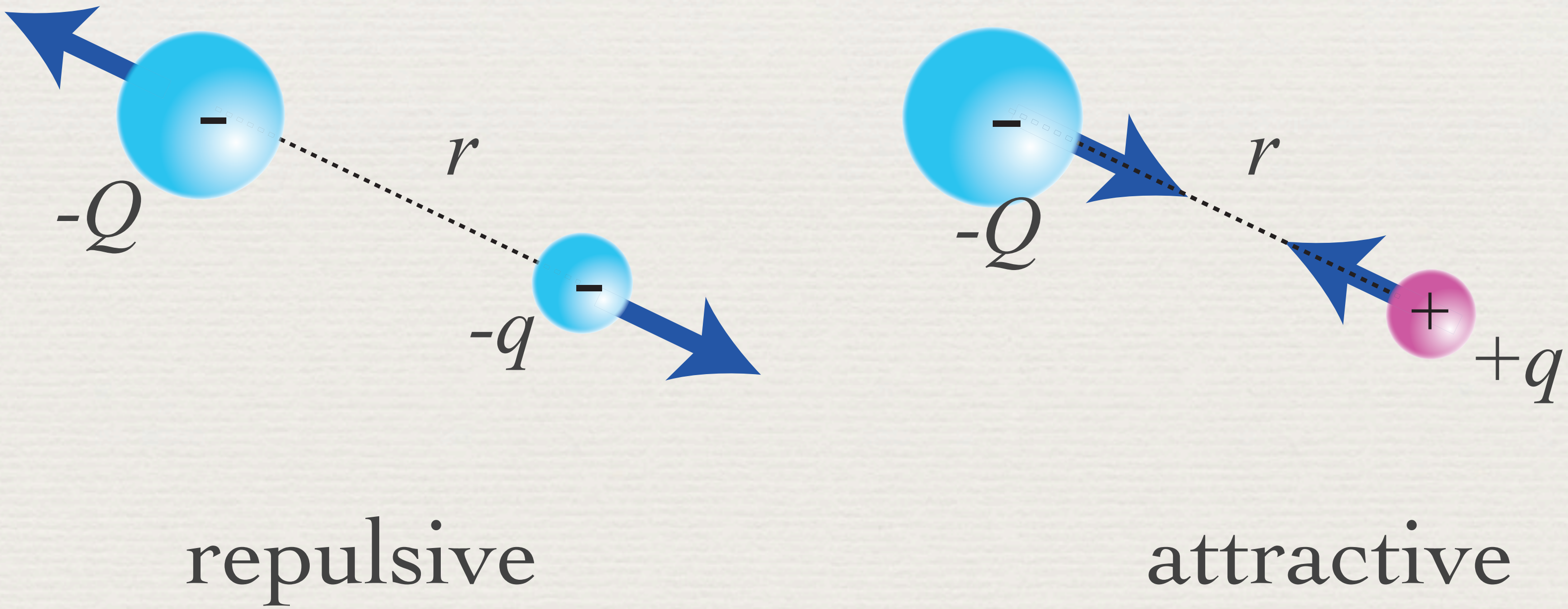
$$F = G\frac{mM}{r^2}$$



Coulomb Force

Force between electrically charged particles

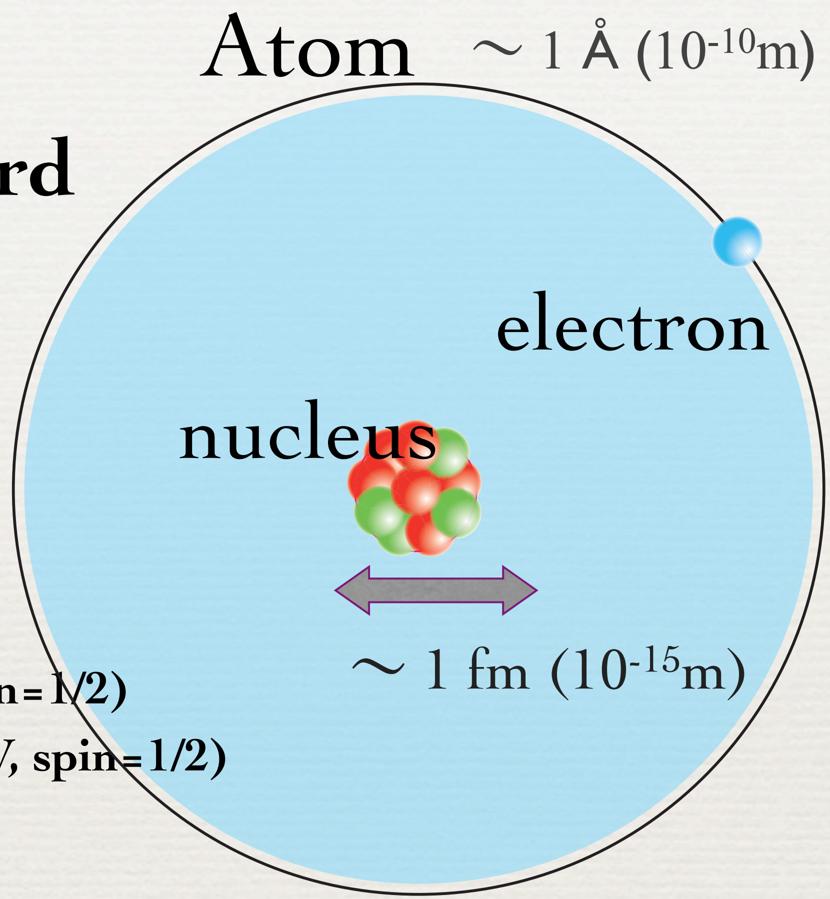
$$F = \frac{1}{4\pi\varepsilon_0}\frac{qQ}{r^2}$$



Nucleus

1911: discovered by Rutherford

- **Center of Atom**
  - Radius : 10^{-5} of Atomic R.
  - Mass : 99% of Atomic Mass
- **Compact System of nucleons**
  - Proton (Charge=$+e$, Mass = 939 MeV, spin=1/2)
  - Neutron (Charge=neutral, Mass = 938 MeV, spin=1/2)

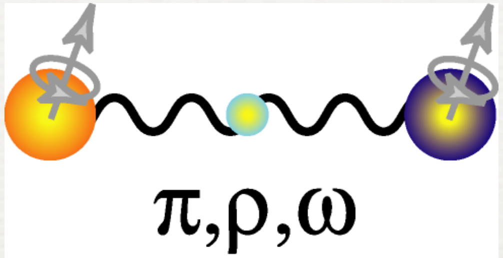


How to fold "charged" protons and "neutral" neutrons in a very small space ?

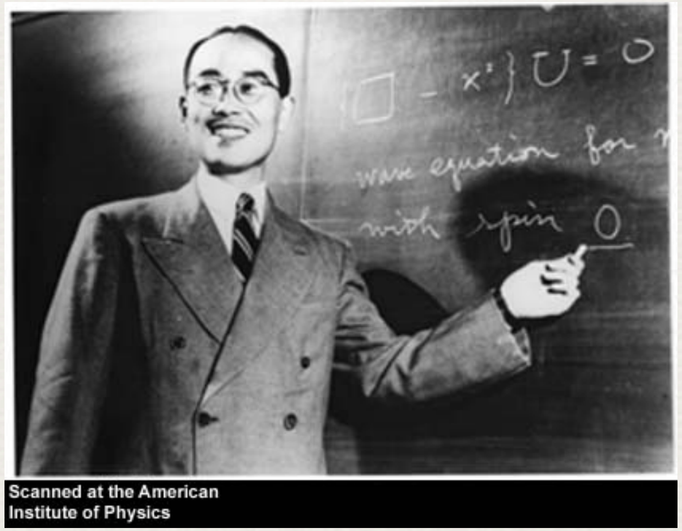
1920's : Establishment of Quantum Mechanics

Nuclear Force ~ Yukawa's Idea ~

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



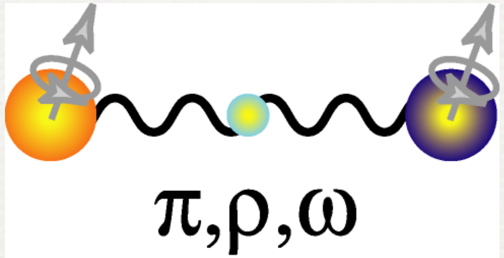
Nuclear force is explained by exchanging a 'virtual particle' (meson) between two nucleons.



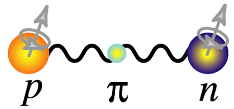
- ☑ Force ⇔ Exchange of Particles
  → Field Theory
- ☑ Origin of Strong Force
- ☑ Quantum Mechanics & Relativity

Nuclear Force

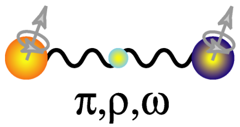
Yukawa's Meson Theory
Proc. Phys. Math. Soc. Jpn. 17, 48 (1935)



Theory



One Pion Exchange Model



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

Experiment

Nucleon-Nucleon Scattering

(**dσ/dΩ and Spin Observables**)

Deuteron Properties

1990's Realistic Modern Nucleon-Nucleon Forces (2NFs),

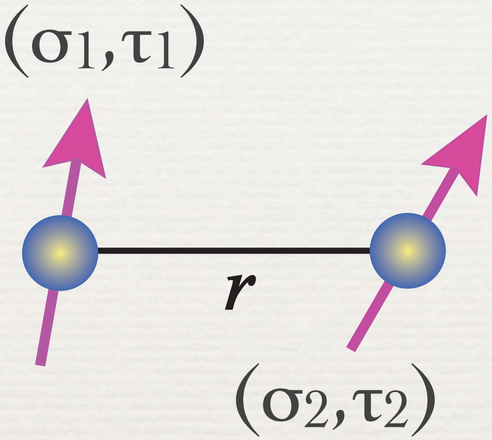
e.g. CD Bonn, Argonne v18, Nijmegen I & II,

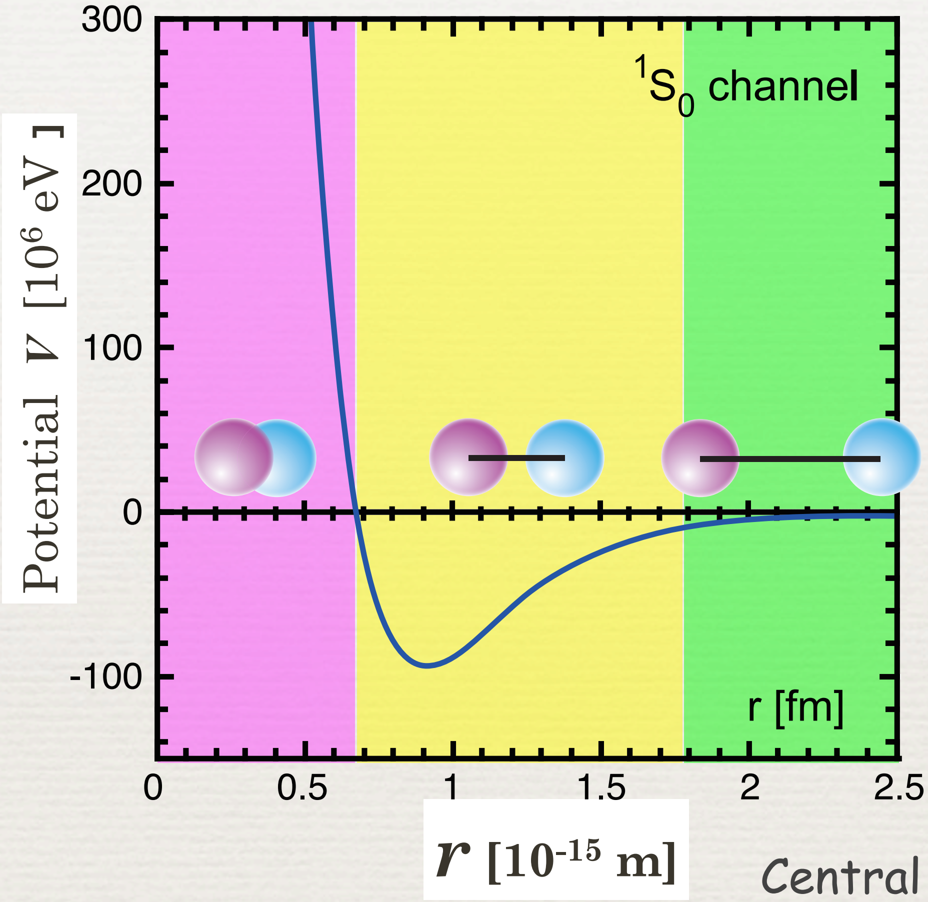
reproduce 3500 NN scattering exp. data with high precision, $\chi^2 \sim 1$.

Short $\boldsymbol{r}$: repulsive

Intermediate $\boldsymbol{r}$: attractive

Long $\boldsymbol{r}$: weak attractive





σ : spin

τ : iso-spin

Central Force (Leading Order)

$$= V_0(r) + V_\sigma(r)\,\sigma_1 \cdot \sigma_2 + V_\tau(r)\,\tau_1 \cdot \tau_2 + V_{\sigma\tau}(r)\,(\sigma_1 \cdot \sigma_2)(\tau_1 \cdot \tau_2)$$

$$+ V_T S_{12} + V_{T\tau} S_{12} \tau_1 \cdot \tau_2 + V_{LS} L \cdot S + V_{LS\tau}(L \cdot S)(\tau_1 \cdot \tau_2) + \ldots$$

Tensor Force

Spin-Orbit Force

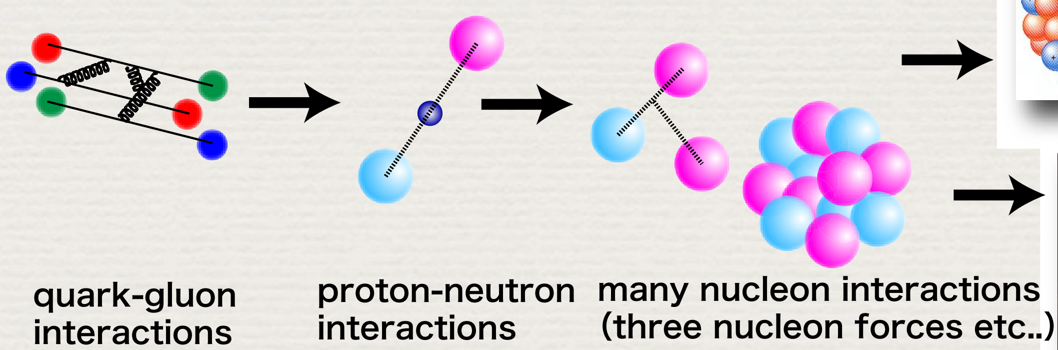
Nuclear forces have strong state-dependence.

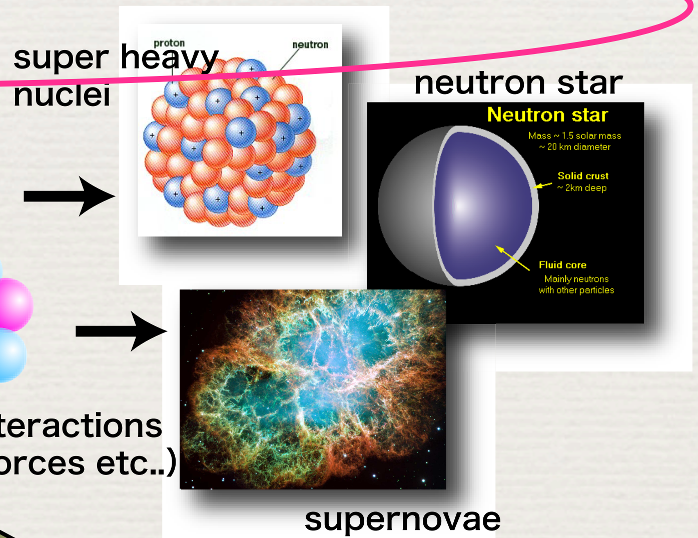
Frontier of Nuclear Force Study

1990's Realistic Modern Nucleon-Nucleon Forces (2NFs)

→ **We have "reliable" two nucleon forces.**

- To understand Nuclear Forces from Quarks (elementary particles)
- To understand Nuclei and Nuclear Matter from bare Nuclear Forces
  ~ 2NF & 3NF ~





Consistent Understanding from quarks to the Universe

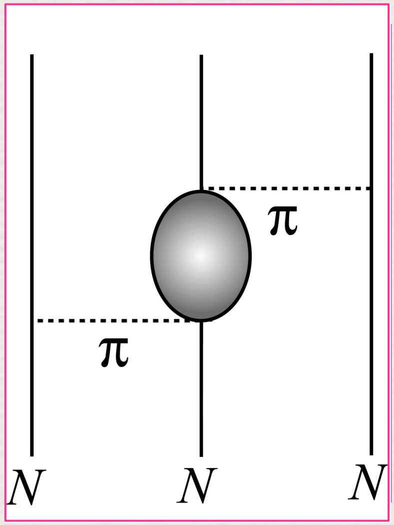
Three Nucleon Force

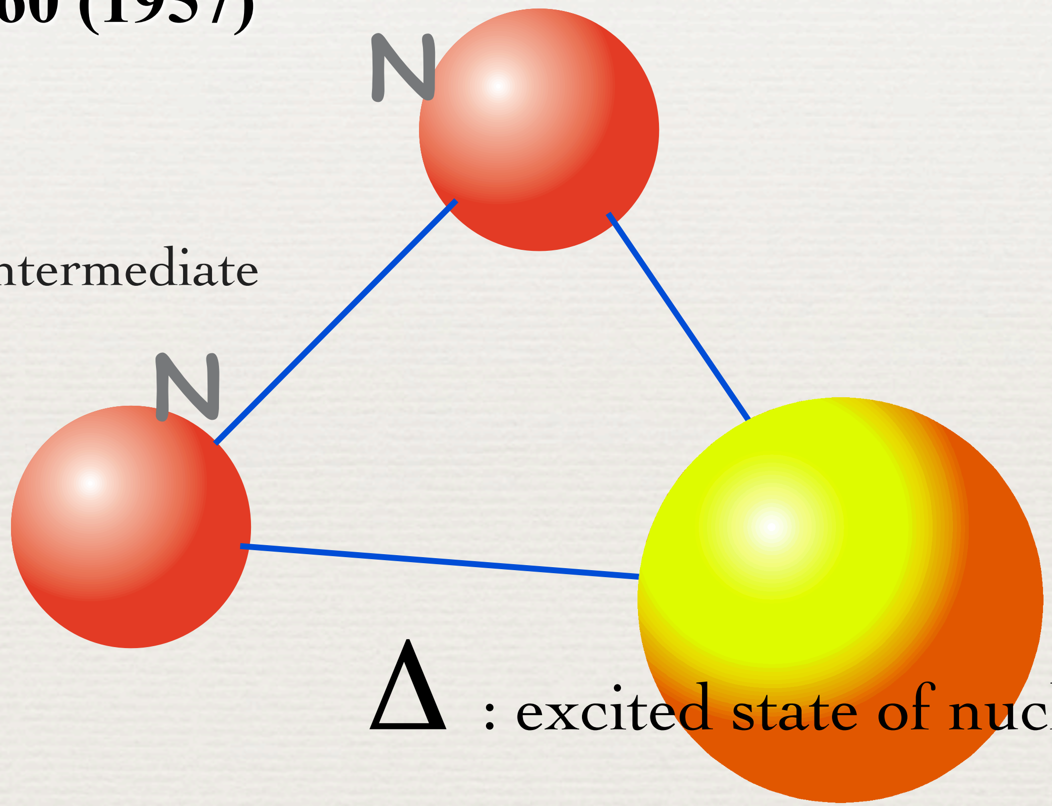
Hard to approach 3NFs experimentally.

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

$$m_\Delta c^2 = 1232 \text{ MeV}$$

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

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

How to approach Three Body Forces ?

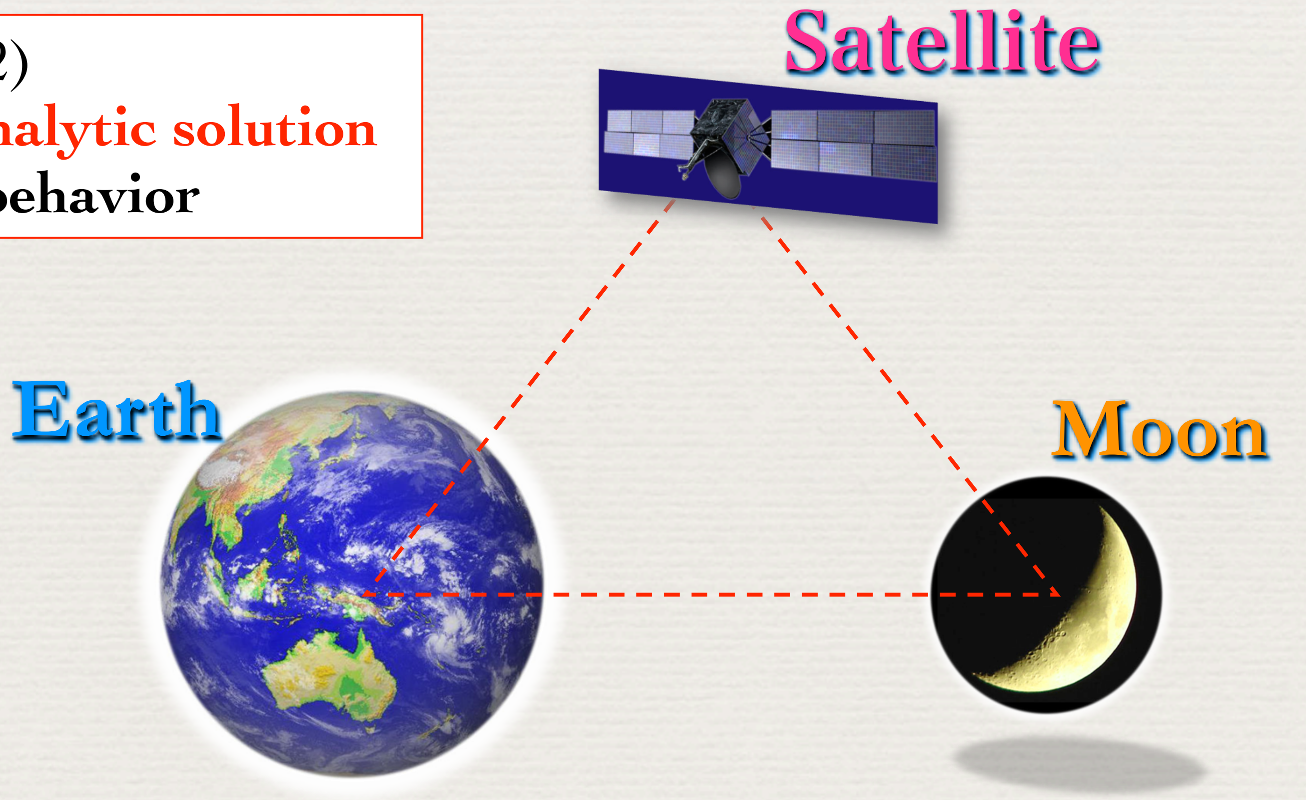
1. Exact Solution of Three Body System
2. Establishment of Two Body Force
3. High Precision Experiment

Three Body Problem
in Classical Mechanics

Earth-Moon-Satellite Gravitational Interactions

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

H. Poincaré (1892)
- non-existence of analytic solution
- sometime chaotic behavior



Three Body Problem

in Quantum Mechanics

CAN BE SOLVED EXACTLY!

- **Uncertainty Principle by Heisenberg**

$$\Delta p \Delta x \sim \hbar = h/2\pi$$

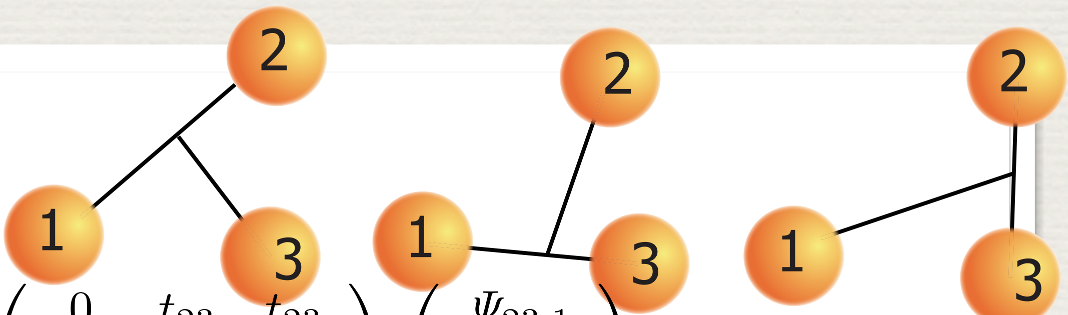
→ reduce '**Degrees of Freedom**' for Equations of Motion

- **Faddeev Theory (L.D. Faddeev, 1961)**

Exact solution of three body system in Q.M.

$$H = H_0 + V_{12}^{NN} + V_{23}^{NN} + V_{31}^{NN}$$

$$\Psi = \Psi_{23,1} + \Psi_{31,2} + \Psi_{12,3}$$



$$\begin{pmatrix} \Psi_{23,1} \\ \Psi_{31,2} \\ \Psi_{12,3} \end{pmatrix} = \begin{pmatrix} \phi_{23,1} \\ \phi_{31,2} \\ \phi_{12,3} \end{pmatrix} + G_0 \begin{pmatrix} 0 & t_{23} & t_{23} \\ t_{31} & 0 & t_{31} \\ t_{12} & t_{12} & 0 \end{pmatrix} \begin{pmatrix} \Psi_{23,1} \\ \Psi_{31,2} \\ \Psi_{12,3} \end{pmatrix}$$

How to approach Three Nucleon Forces ?

1. **Exact Solution of Three Nucleon System**
2. **Establishment of Two Nucleon Force**
3. **High Precision Experiment**

Triton (^{3}H) Binding Energy

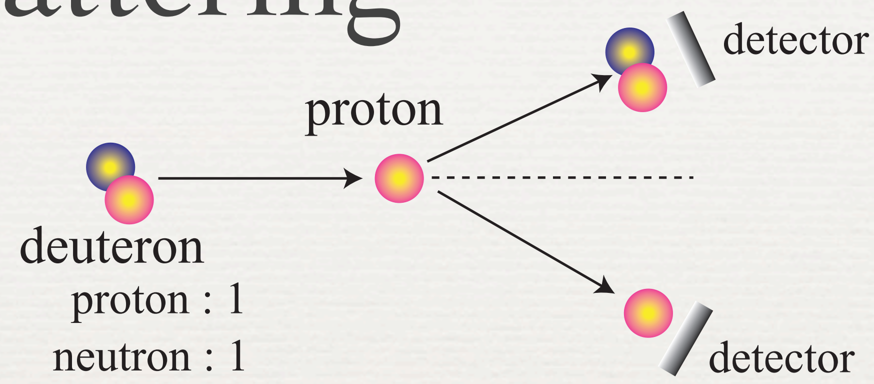
Triton (^{3}H)

- **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.**

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).

Deuteron-Proton Scattering



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

Direct Comparison between Theory and Experiment

- Theory : Faddeev Calculations

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 information of Three Nucleon Forces

dp Scattering

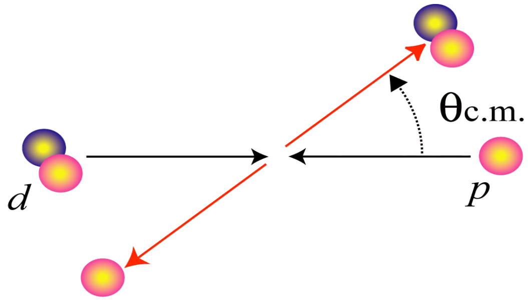
- $d + p \longrightarrow d + p$

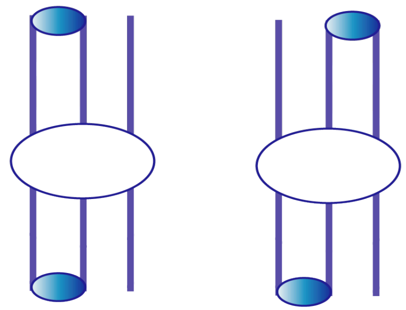
$\theta_{c.m.} = 0° \sim 180°$

Momentum transfer

q =0 - 3.4 fm^{-1}

(at E = 135 MeV/A)



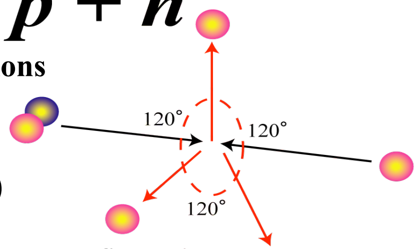


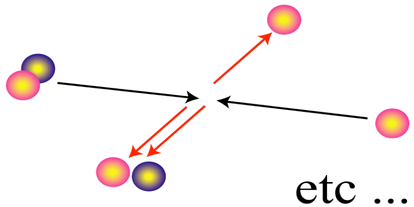
- $d + p \longrightarrow p + p + n$

Many kinematical configurations

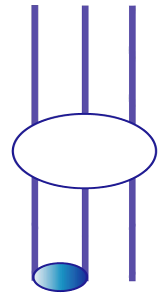
q =0 - 3 fm^{-1}

(at E = 135 MeV/A)





etc ...

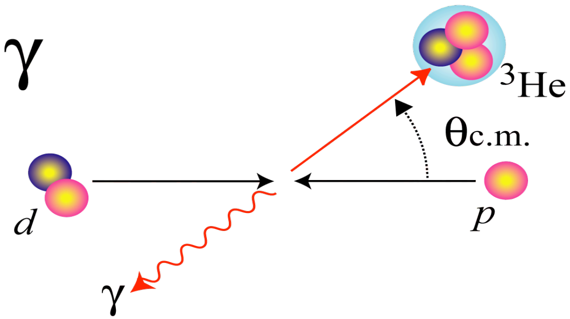


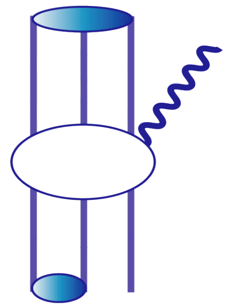
- $d + p \longrightarrow {}^3He + \gamma$

$\theta_{c.m.} = 0° \sim 180°$

q =1.5 - 2.5 fm^{-1}

(at E = 135 MeV/A)



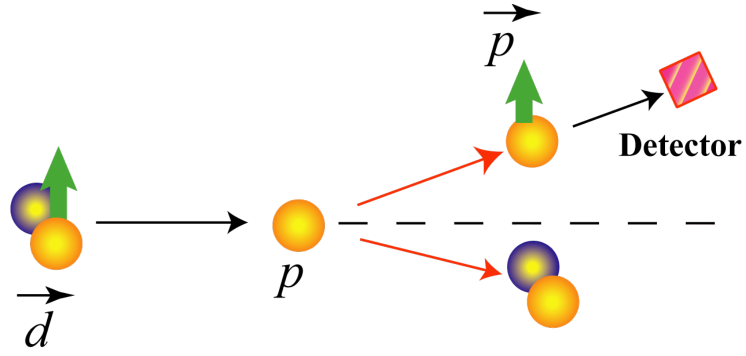


Observable for dp Scattering

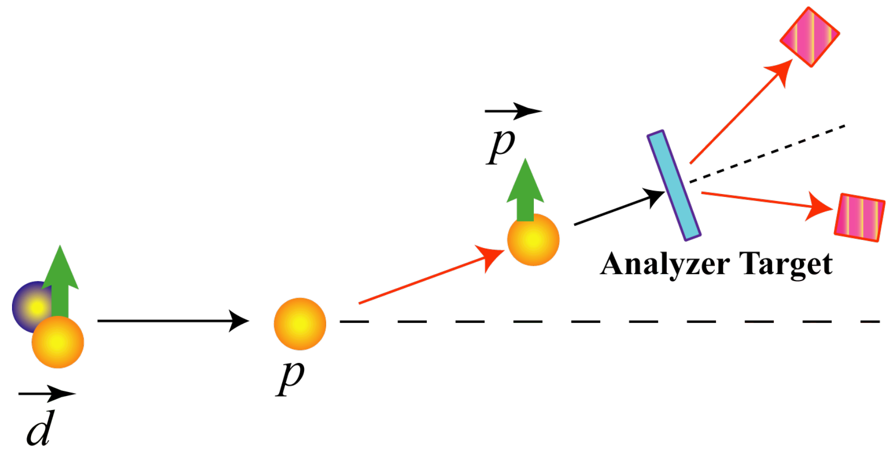
- **Differential Cross Section**
  - **Overall Strength**
  - ➢ **Absolute Quantity : normalization to *pp or np* data**

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

- **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**

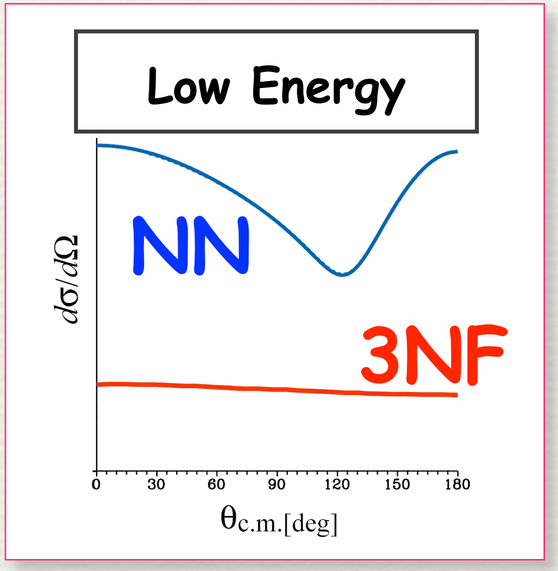


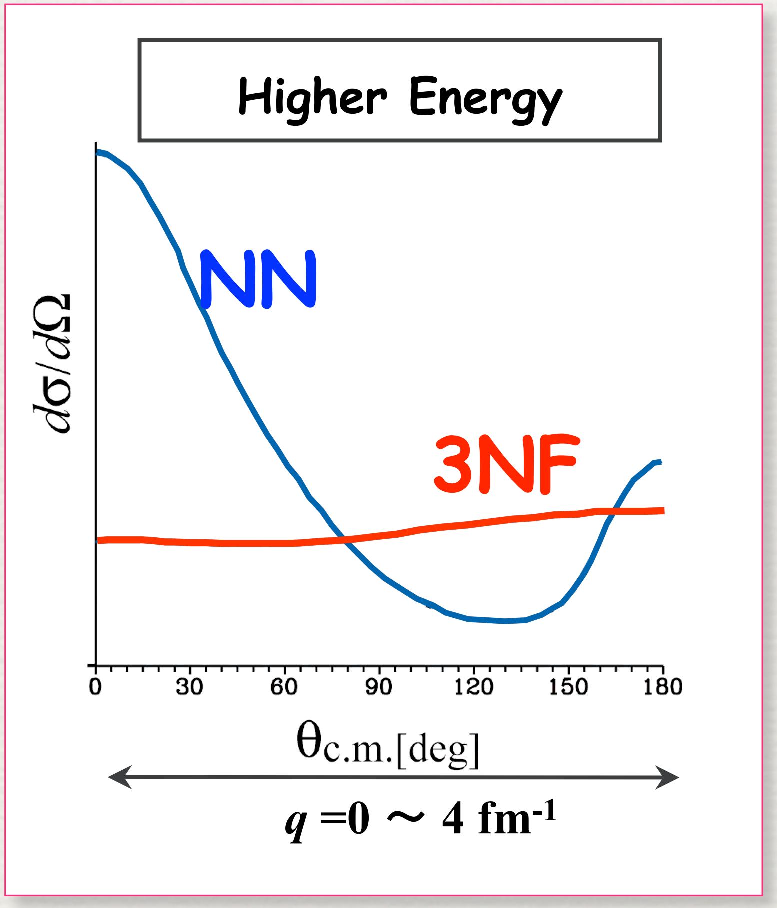
  - **Polarization Transfer Coefficient : $K_{ij}^{l'}$**
  - **Spin Correlation Coefficients C_{ij}**
    - **Spin-Spin interaction**

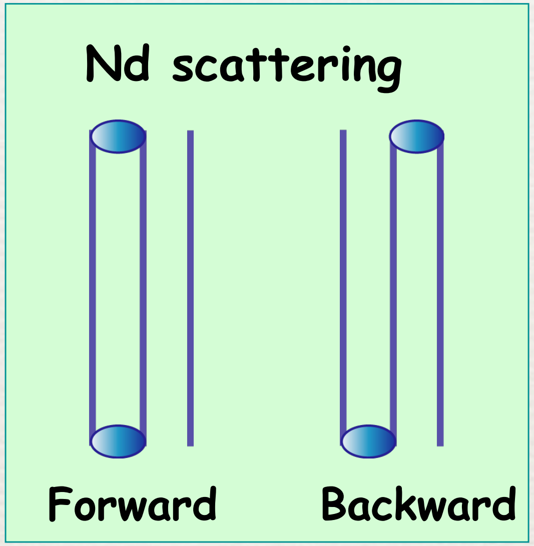


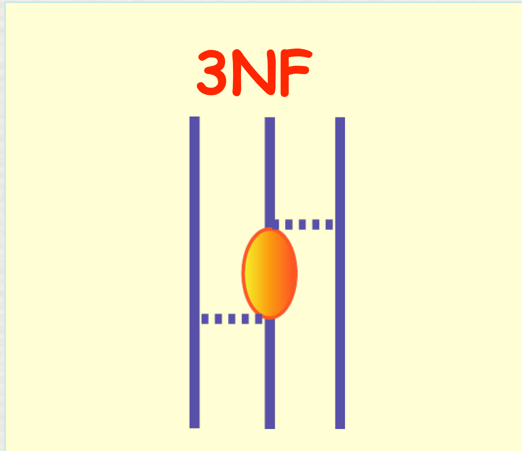
Where is the hot spot for 3NF ?

Predictions by H. Witala et al. (1998)
Cross Section minimum for Nd Scattering at 100-200 MeV/A

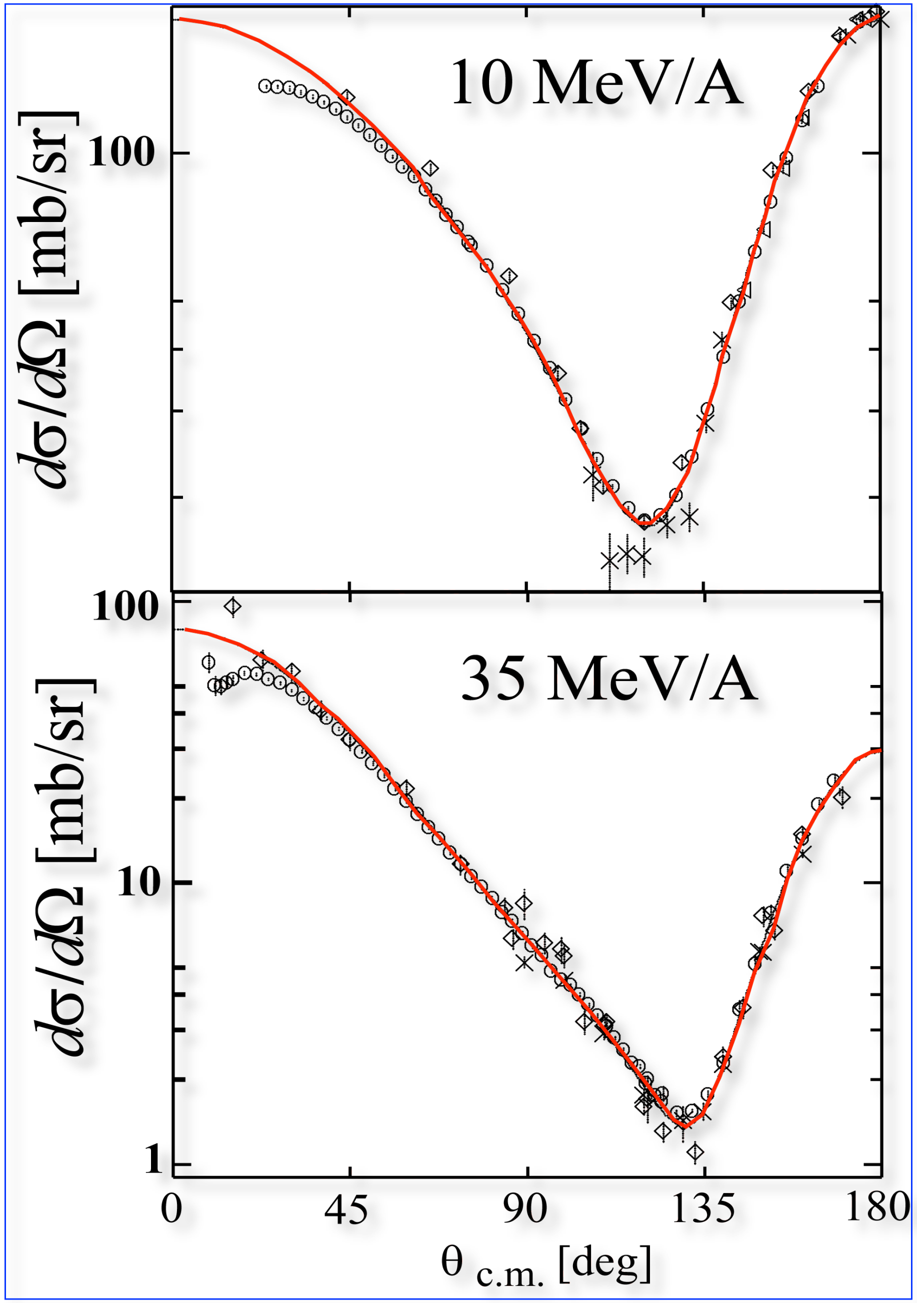








dp Scattering at Low Energies (E ≤ 30 MeV/A)



- High precision data are explained by Faddeev calculations based on 2NF.

No signatures of 3NF.

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

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

3-Nucleon Scattering Exp. by Dr. Toshiko Yuasa at Orsay

PHYSICAL REVIEW C VOLUME 15, NUMBER 1 JANUARY 1977

Test of proton-induced ^{2}H breakup: Investigation for the special kinematic condition of collinearity

N. Fujiwara,* E. Hourany,† H. Nakamura-Yokota,‡ F. Reide, and T. Yuasa
Institut de Physique Nucléaire, Université de Paris-Sud, 91406-Orsay, France

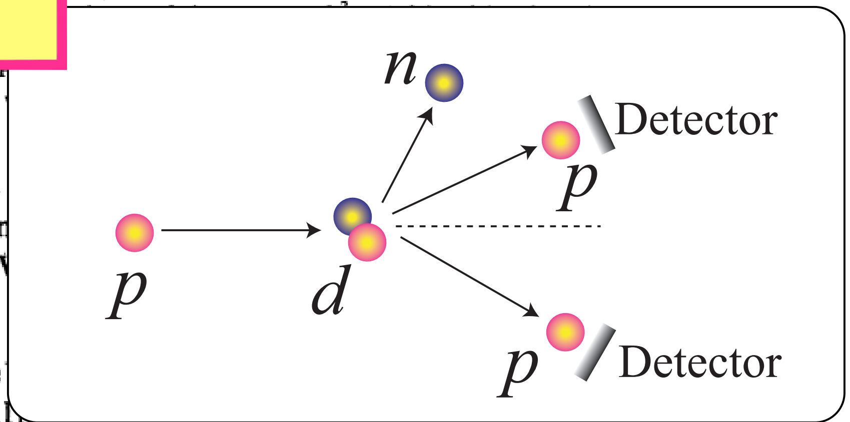
(Received 14 July 1976; revised manuscript received 11 October 1976)

- $p+d \rightarrow p+p+n$ at 156 MeV
  - high precision data

the $(p,2p)$ and the (p,pn) reactions in
dition: The three nucleons are collinear
so we performed experiments having
a peak in the region far from the final-

Ballot with Benoist-Gueutal. The model gives a smooth minimum,
and sensitive to θ_3. The fixed-scattering-center approximation
$d^3\sigma/d\Omega_1 d\Omega_2 dE_1$ spectrum in the entire region fairly well except
this peak difficult to explain by the fixed-scattering-center approxi
This peak is similar to that observed by Lambert *et al.* at 23 Me

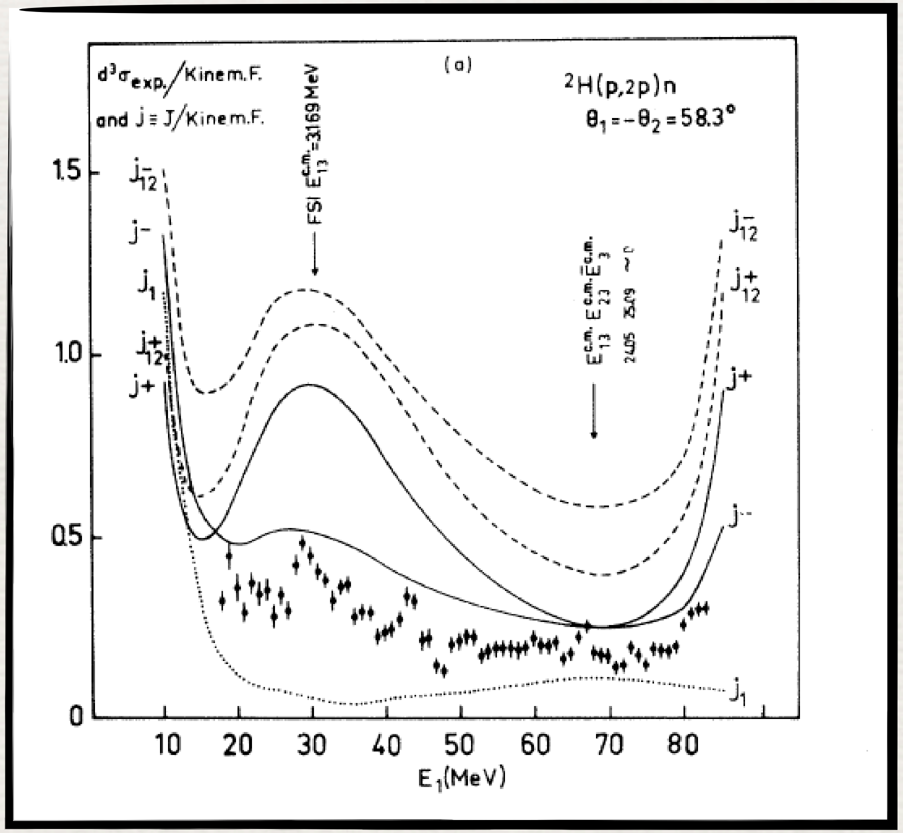
[NUCLEAR REACTIONS ^{2}H$(p,2p)$, ^{2}H(p,pn), $E=156$ Me
final-state nucleons coll]



Phys. Rev. C 15, 4 (1977)

3-Nucleon Scattering Exp. by Dr. Toshiko Yuasa at Orsay

- $p + d \rightarrow p + p + n$ at 156 MeV
  - high precision data

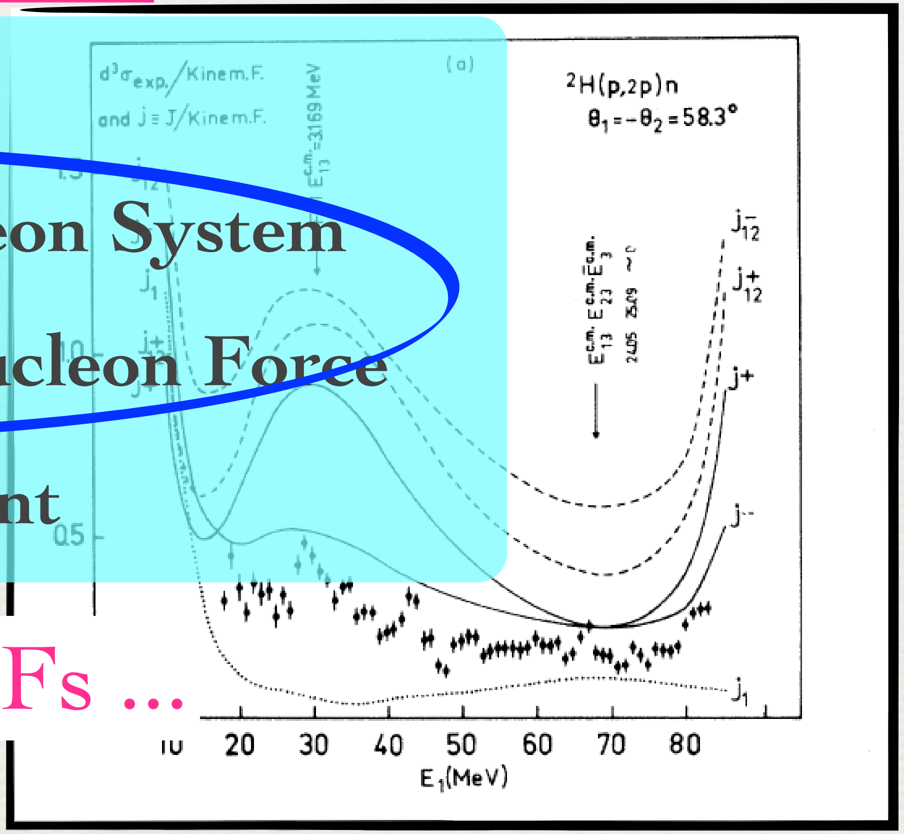


3-Nucleon Scattering Exp. by Dr. Toshiko Yuasa at Orsay

- $p + d \rightarrow p + p + n$ at 156 MeV
  - high precision data

How to Approach 3NFs ?

1. Exact Solution of 3-Nucleon System
2. Establishment of Two Nucleon Force
3. High Precision Experiment



too early to discuss on 3NFs ...

Precise Measurement of *d-p* scattering at RIKEN

$$d + p \longrightarrow d + p$$

1 **Differential Cross Section and All Deuteron Analyzing Powers**

(A_y , A_{yy} , A_{xx} , A_{xz}) at 70, 100, 135, 250, 300 MeV/A

- **Whole Angular Range : θ c.m. = 10°－180°**

2. **Deuteron to Proton Polarization Transfer Coefficients at 135 MeV/A**

- **Double Scattering Experiment : Measurement of Polarizations of Recoil Protons**
- **Angular range : θ c.m. = 90°－180°**
- **Strong sensitivities to Three Nucleon Force**

$$d + p \longrightarrow p + p + n$$

- **Extension from Elastic to Breakup**
- **Limited kinematical configurations : sensitive to 3NF**
    - **Polarization Transfer Coefficient at 135 MeV/A**

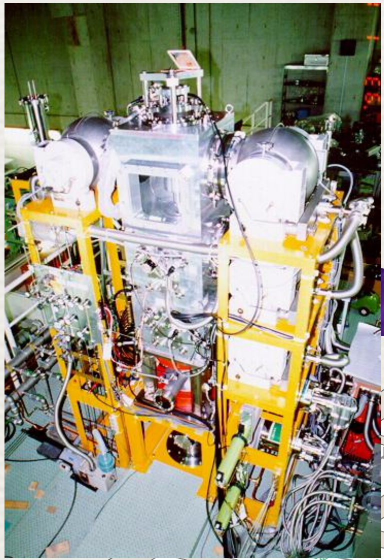
d-p elastic scattering
at RIKEN Accelerator Research Facility

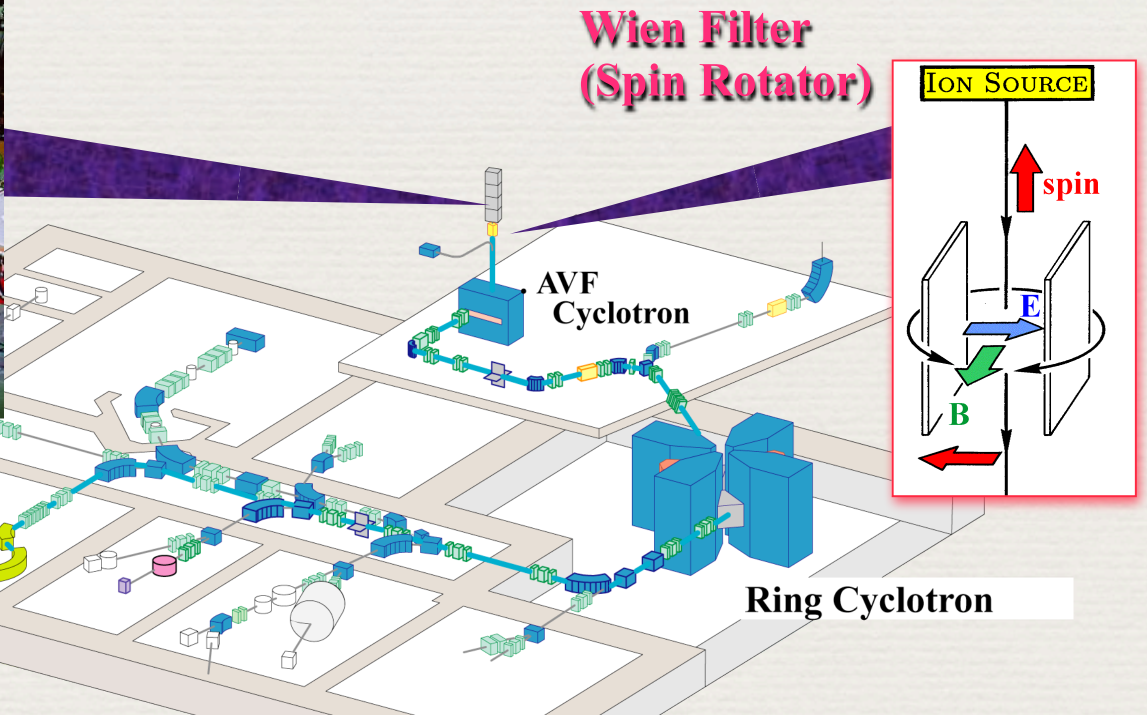
AVF + Ring cyclotrons

pol. *d* beams 65 ∼135 MeV/A
Beam Intensity : 200 pnA

Spin symmetry axis of polarized d beams is freely controlled !

- Spin axis is controlled by Spin Rotator prior to acceleration.
- Single-turn extraction feature of RARF
  maintain the polarization amplitudes
  Beam polarizations : 60-80%

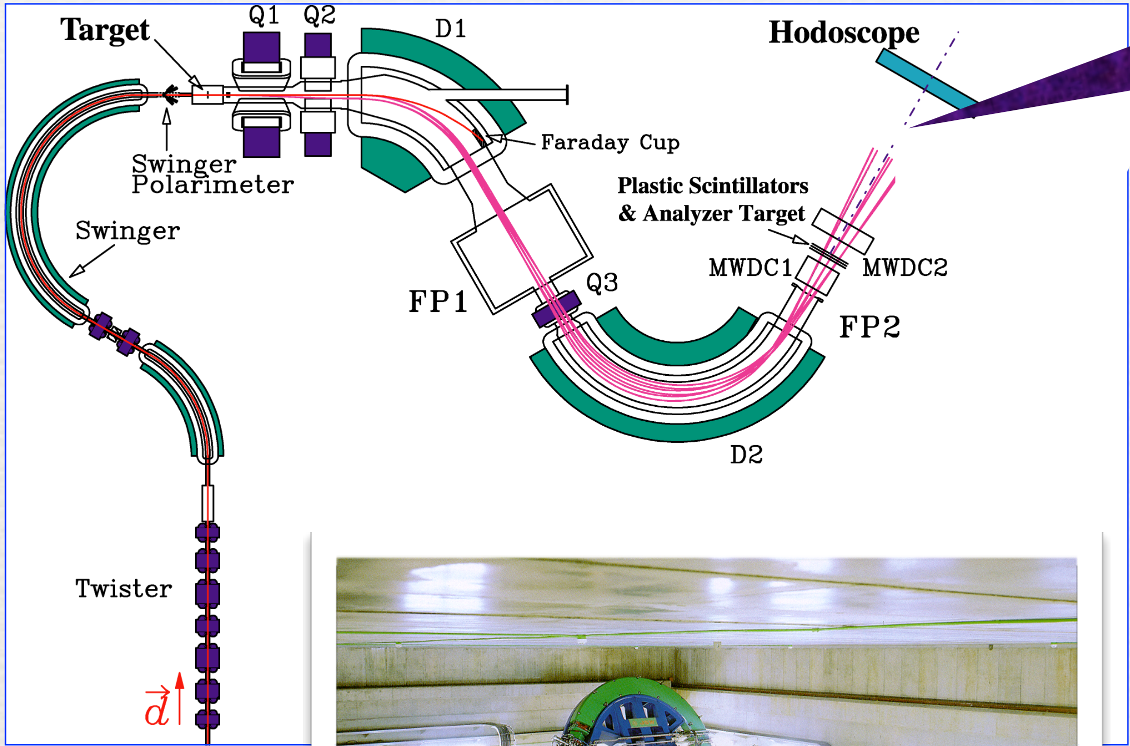


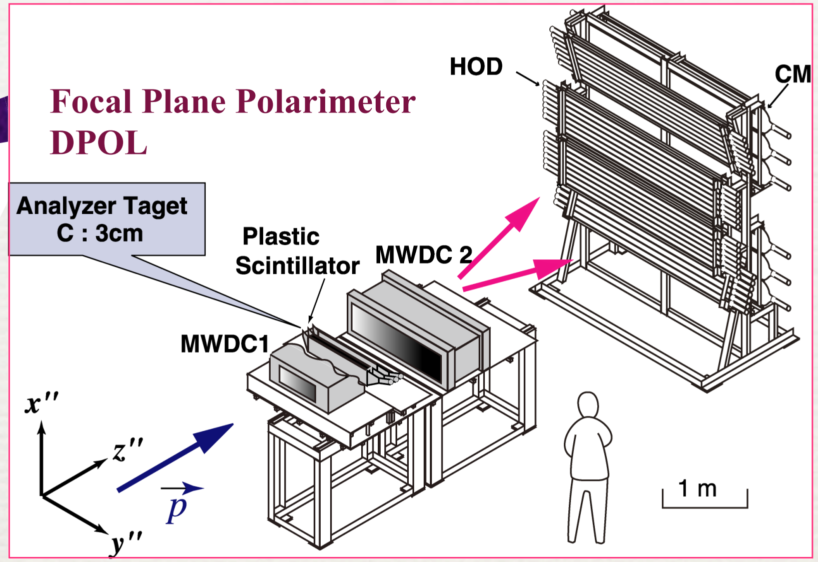


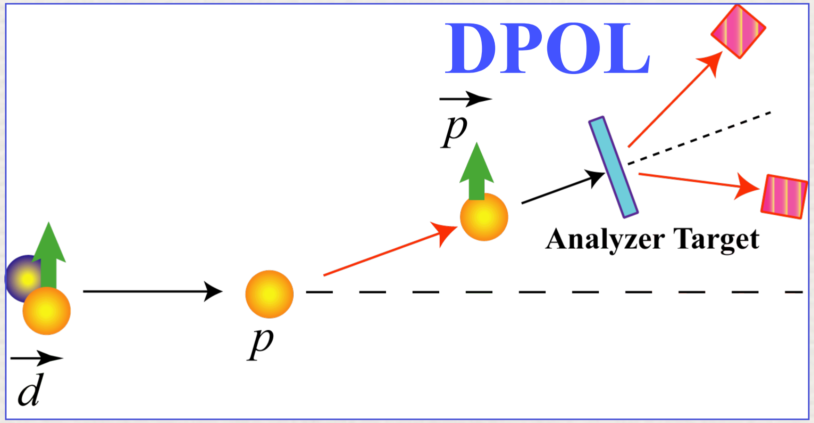
Refs. of RIKEN Polarized Ion Source
H. Okamura, AIP Conf. Proc. 293, 84 (1994)
H. Okamura, AIP Conf. Prof. 343, 123 (1995)

SMART at RIKEN (- 2005)

Swinger and Magnetic Analyzer with Rotator and Twister







d-*p* elastic scattering
Differential Cross section

Determination of Absolute Values of the Cross Section

1. ***d*** + ***p*** at 135 MeV/A (70 MeV/A)

   beam ***d*** → H_2^+

2. measure ***p*** + ***p*** 135 MeV (70MeV)

   Same Exp. Setup
   - **Target CH_2**
   - **Faraday Cup**
   - **Detection System**

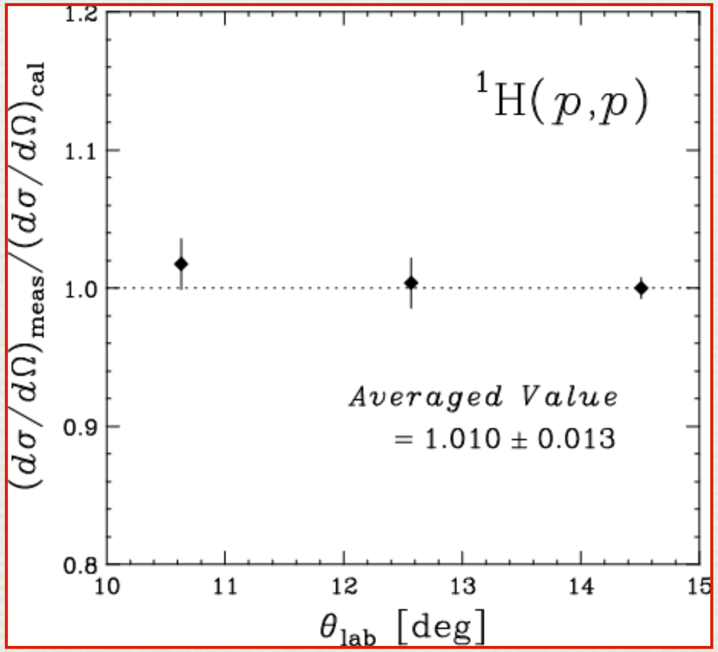
3. Direct Comparison with *NN* phase-shift solution(SAID)

$$(d\sigma/d\Omega)_{\text{exp}} \;/\; (d\sigma/d\Omega)_{\text{SAID}}$$
$$= 1.010 \pm 0.013$$

⟶ Systematic Error : 2%

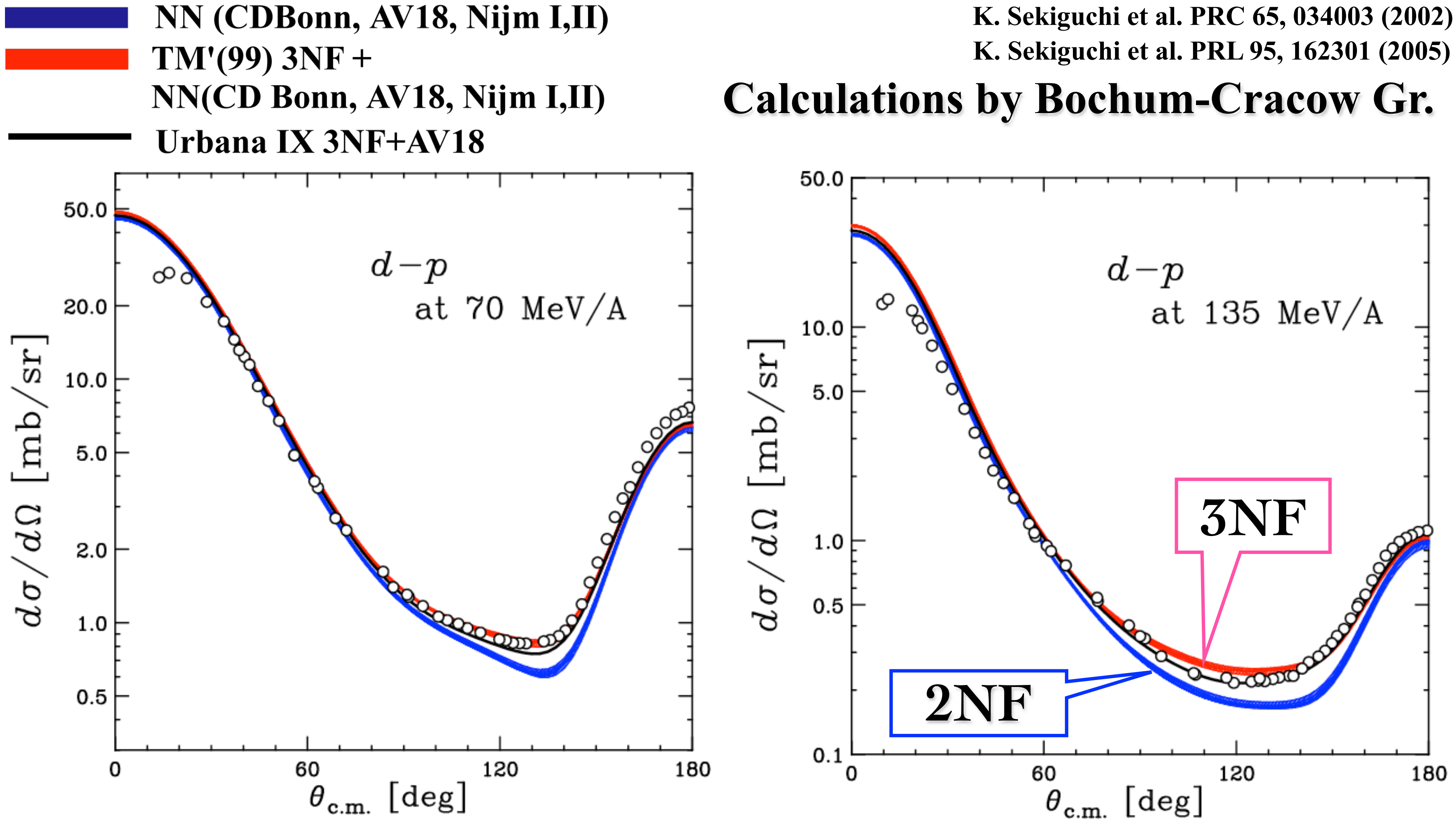
pp scattering at 135 MeV

Ratio = ***d***σ/***d***Ω(exp) / ***d***σ/***d***Ω (calc.)



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

Calculations by Bochum-Cracow Gr.



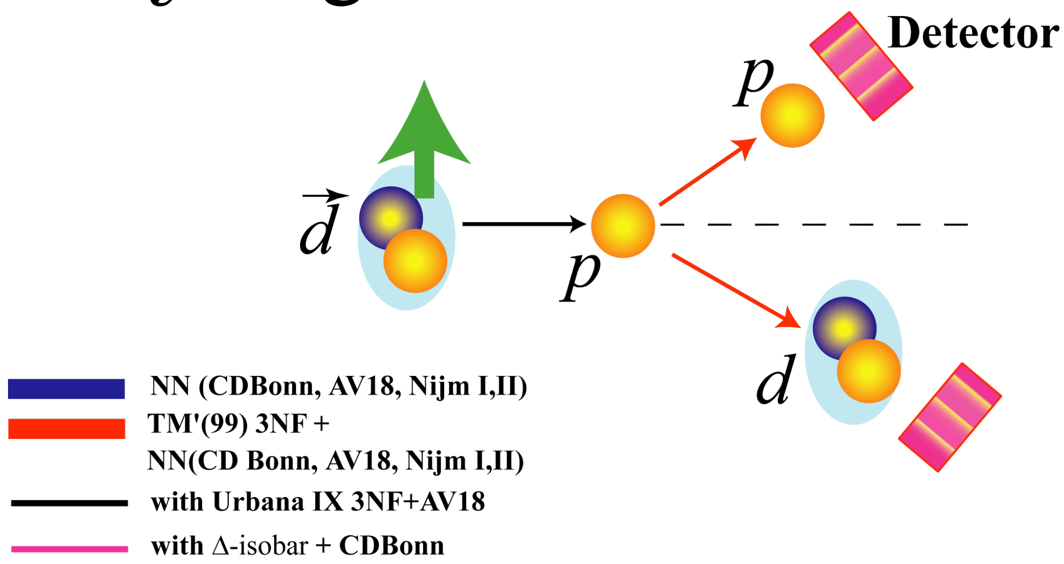
2NF (CDBonn, AV18, Nijmegen I,II)
: Large discrepancy in Cross Section Minimum (~ 30%)

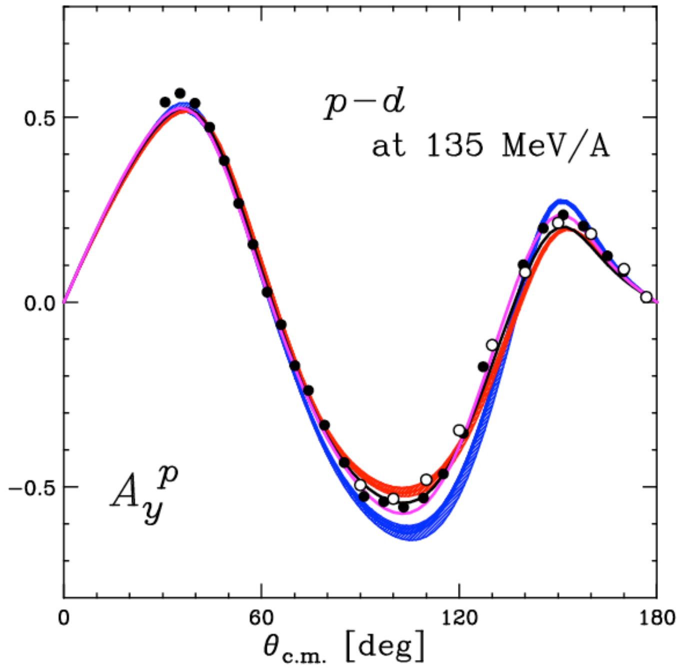
2π-exchange 3NFs (Tucson-Melbourne, Urbana IX) : Good Agreement
: First Clear Signatures of 3NF effects in 3-Nucleon Scattering

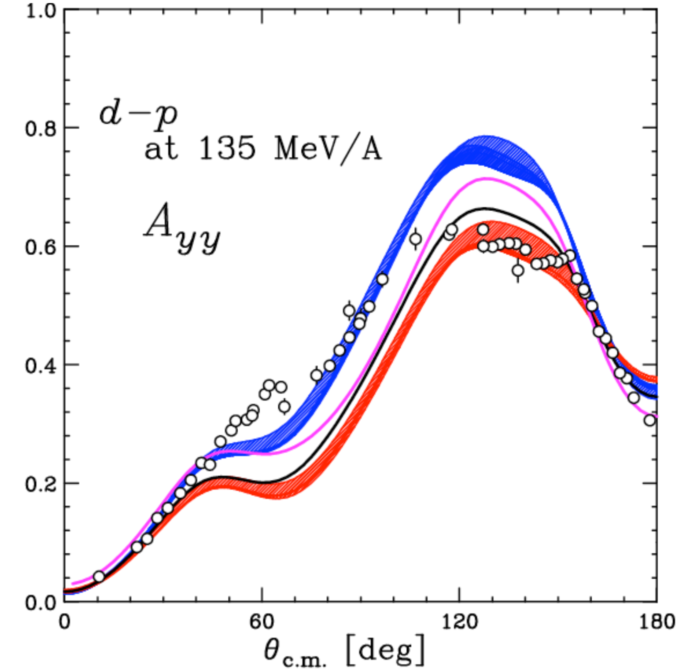
d-*p* elastic scattering
Spin Observables

Analyzing Powers

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







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

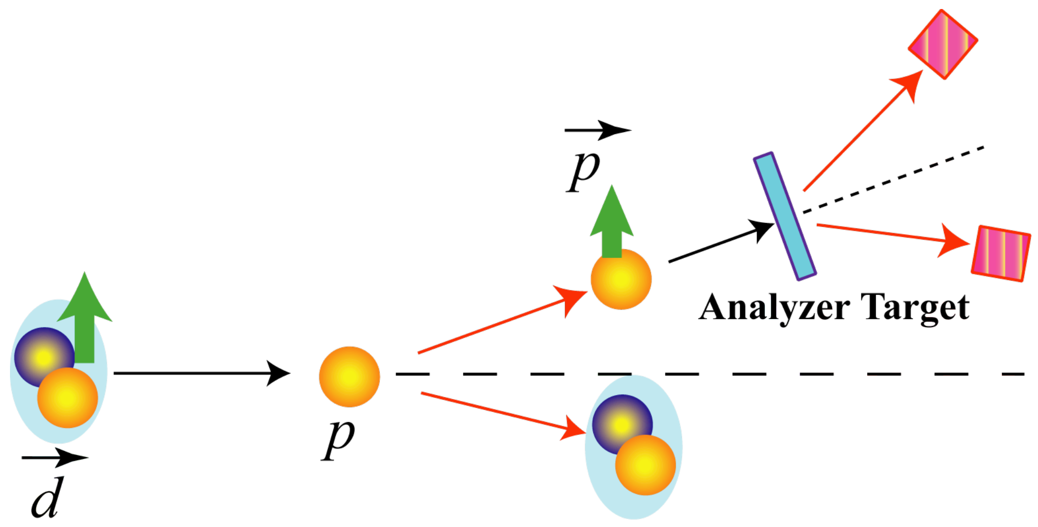
3NF (Tucson-Melbourne, Urbana IX, Δ-isobar) :

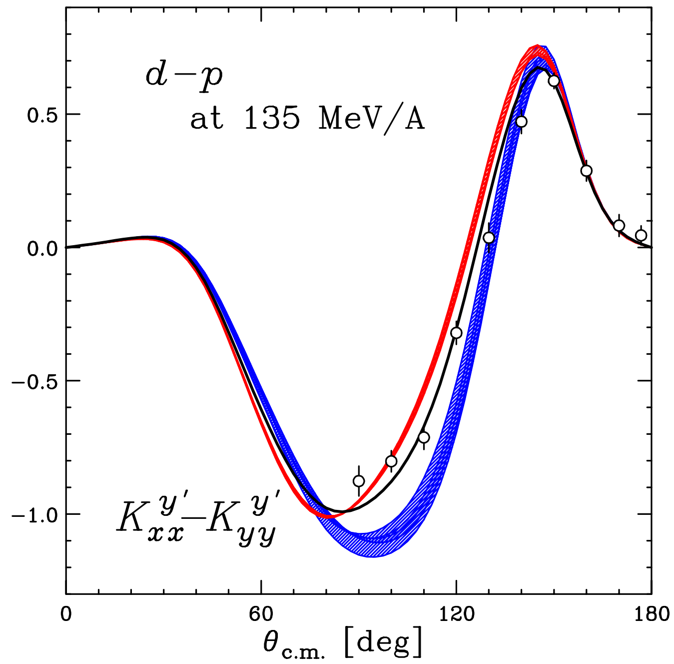
Vector Analyzing Power A_y^p
: Good Agreement

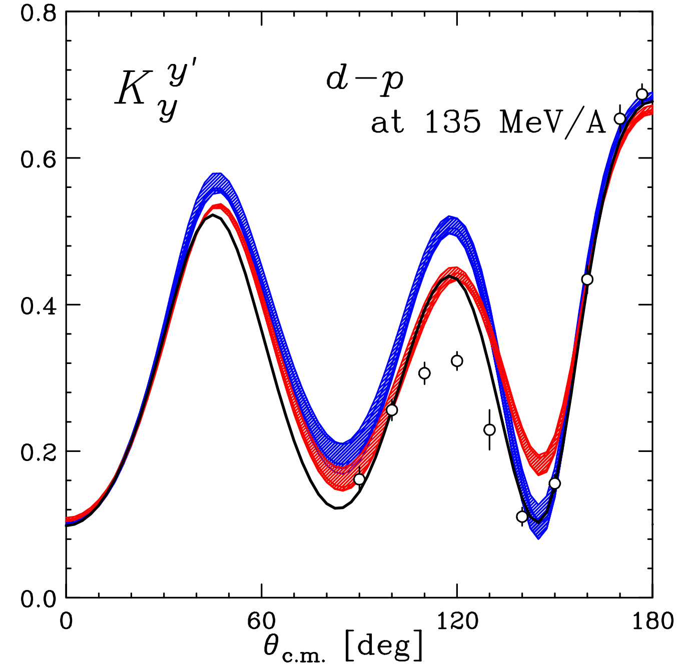
Tensor Analyzing Power A_{yy}
: No superiority

K. Sekiguchi et al. PRC 70, 014001(2004)

Polarization Transfer Coefficients







3NF :

$K_{xx}^{y'}-K_{yy}^{y'}$: Good Agreement

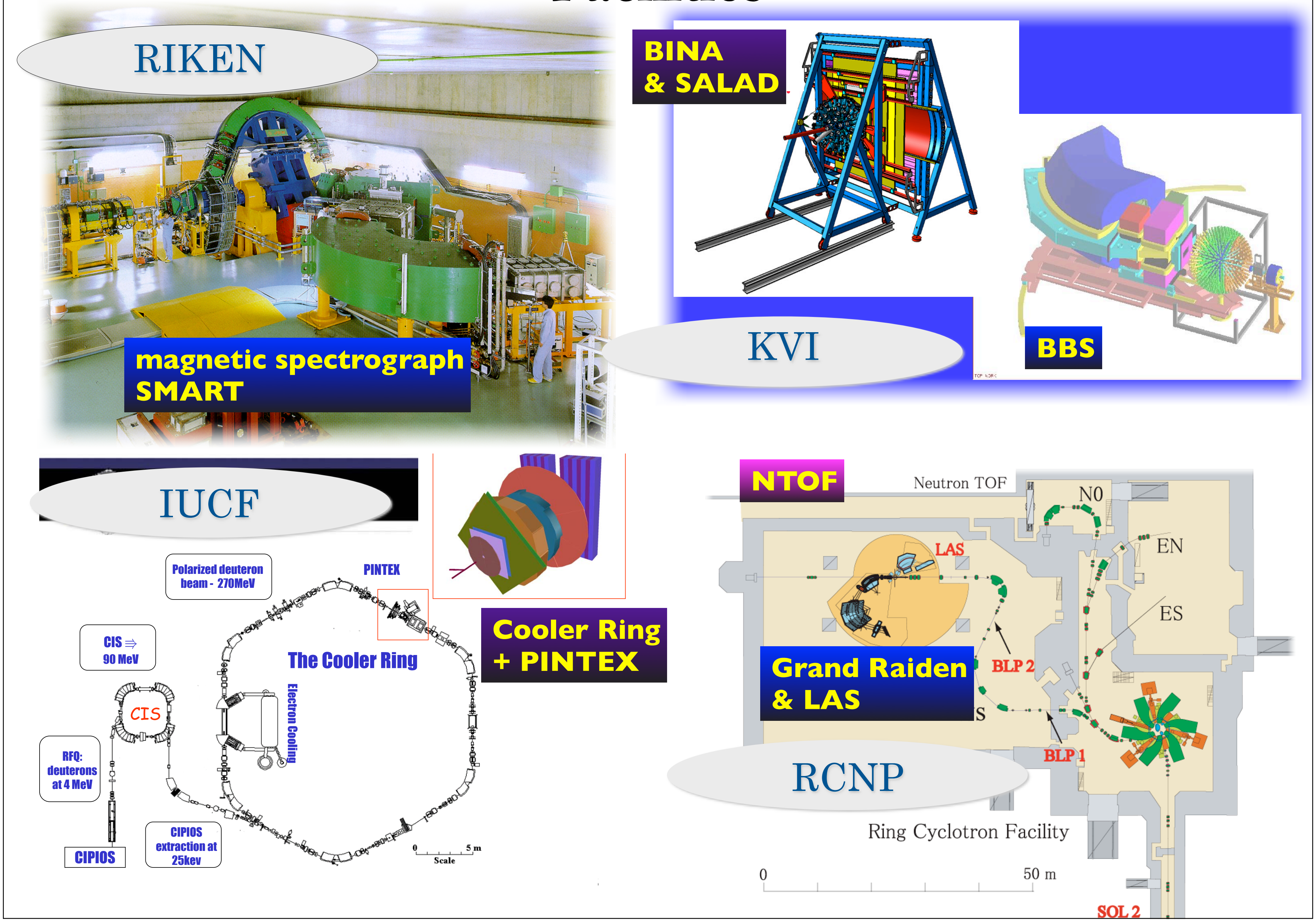
$K_y^{y'}$: Direction : O.K.

Magnitude : not enough

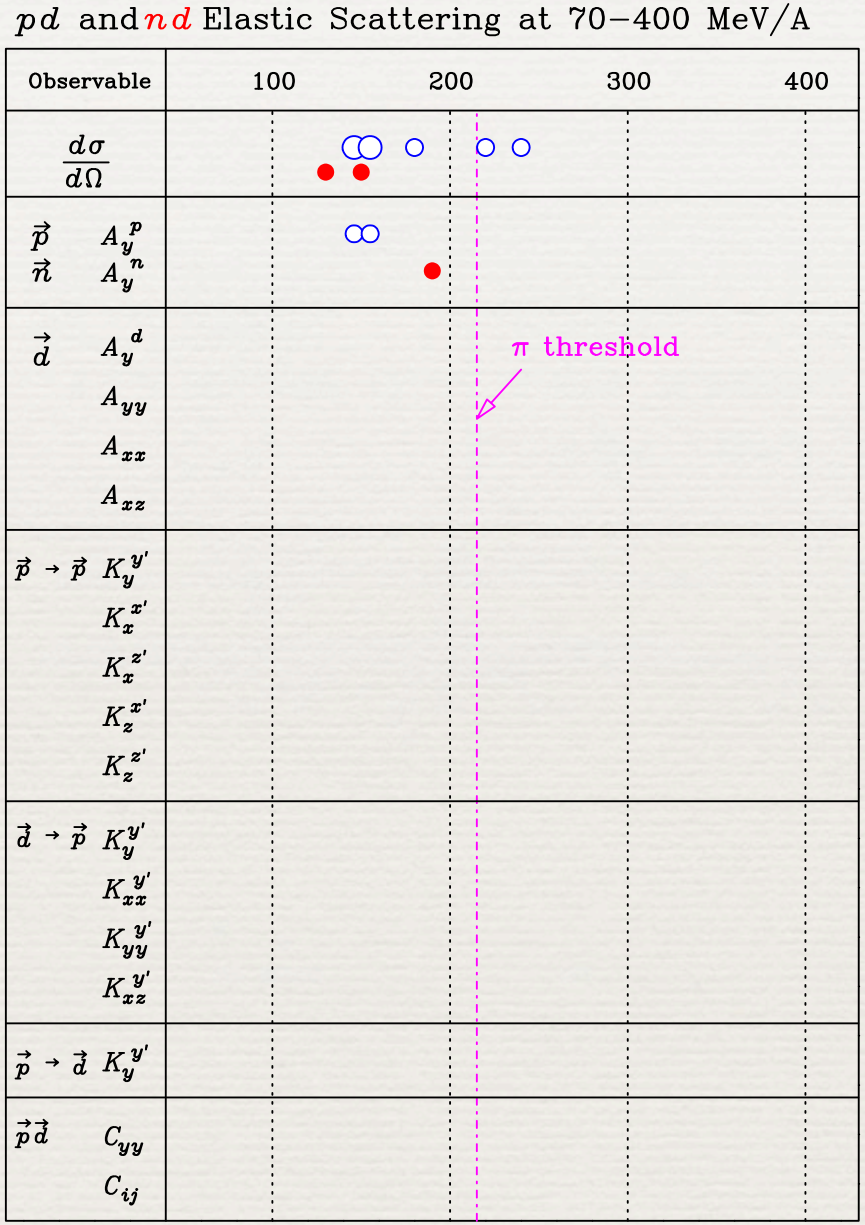
Results of Comparison

- Cross section
  - First clear signature of 3NF effects in 3N scattering
  - Magnitudes of 3NFs is O.K. .
- Spin observables
  - Not always described by adding 3NFs
  - Defects of spin-dependent parts of 3NFs

Facilities


RIKEN
magnetic spectrograph SMART
BINA & SALAD
KVI
BBS
IUCF
Polarized deuteron beam - 270MeV
PINTEX
CIS ⇒ 90 MeV
The Cooler Ring
Electron Cooling
CIS
RFQ: deuterons at 4 MeV
CIPIOS
CIPIOS extraction at 25kev
0 5 m Scale
Cooler Ring + PINTEX
NTOF
Neutron TOF
N0
EN
ES
LAS
BLP 2
BLP 1
Grand Raiden & LAS
RCNP
Ring Cyclotron Facility
0 50 m
SOL 2

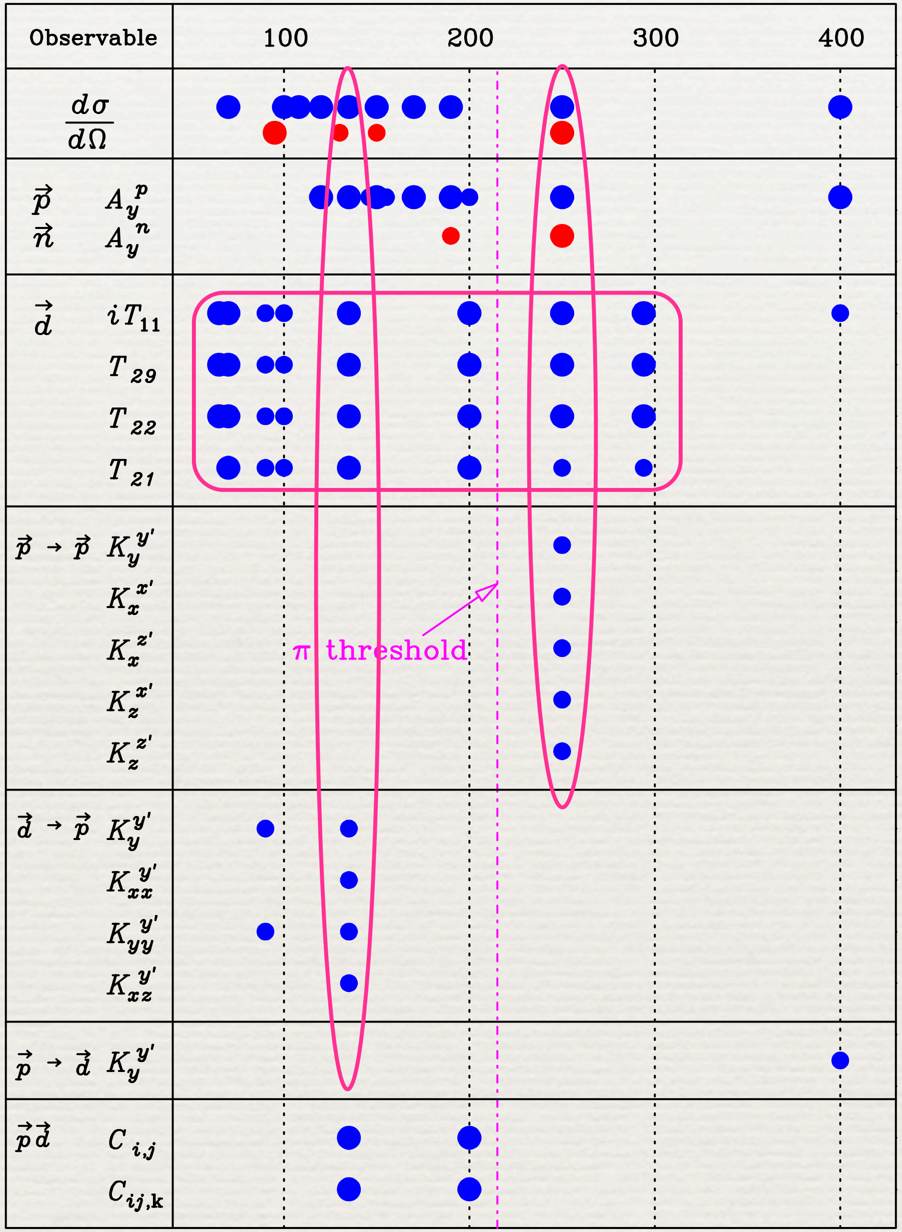
Nd Elastic Scattering Data at Intermediate Energies



~1998

Nd Elastic Scattering Data at Intermediate Energies

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



~2015

- **High precision data of**
  ***dσ/dΩ* & Spin Observables**
  from RIKEN, RCNP, KVI, IUCF

After **60** Years of
Fujita-Miyazawa 3NF (1957)
&
After **40** Years of Yuasa's Exp. (1977)

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

in Progress

Quantitative discussions on three-nucleon forces start
via Theor. & Exp. .

Three-Nucleon Force is now taken as
one key element to understand fundamental properties of nuclei.

- Nuclear Forces linked to QCD
- Three Nucleon Forces in A>3

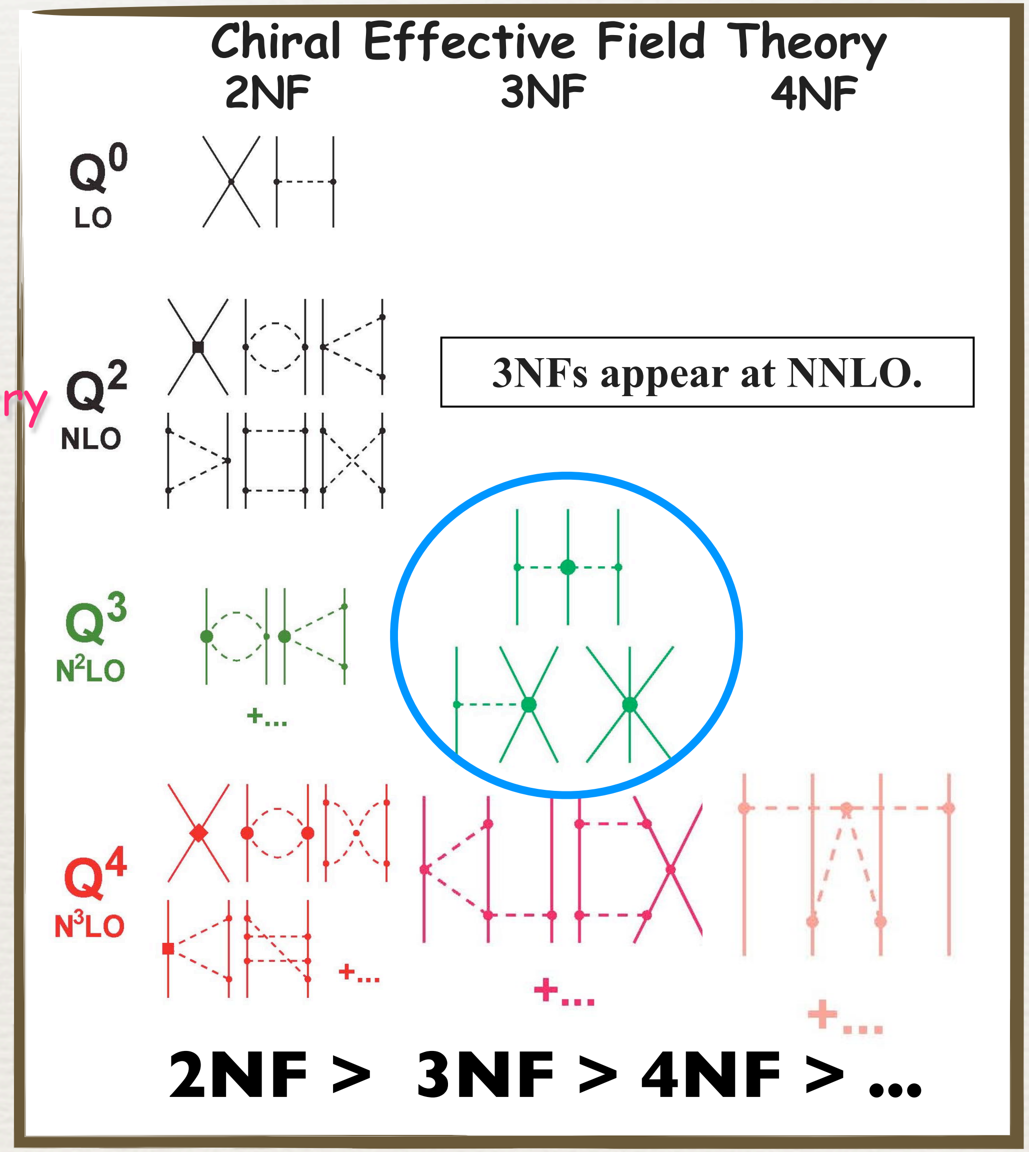
Nuclear Forces linked to QCD

- Nuclear Forces based on Chiral Effective Field Theory

- Link to QCD
  Lagrangian :
  includes all the terms consistent
  with the assumed symmetries :
  Lorentz and iso-spin Invariance
  & Spontaneously Broken Chiral Symmetry
  Interactions :
  π + Nucleon + contact terms

- **Nuclear forces** (2NF, 3NF, ...)
  and currents are derived
  in a consistent way.
- **Hierarchy of Nuclear Forces** :
  2NF > 3NF > 4NF
  The first 3NF appears in NNLO.

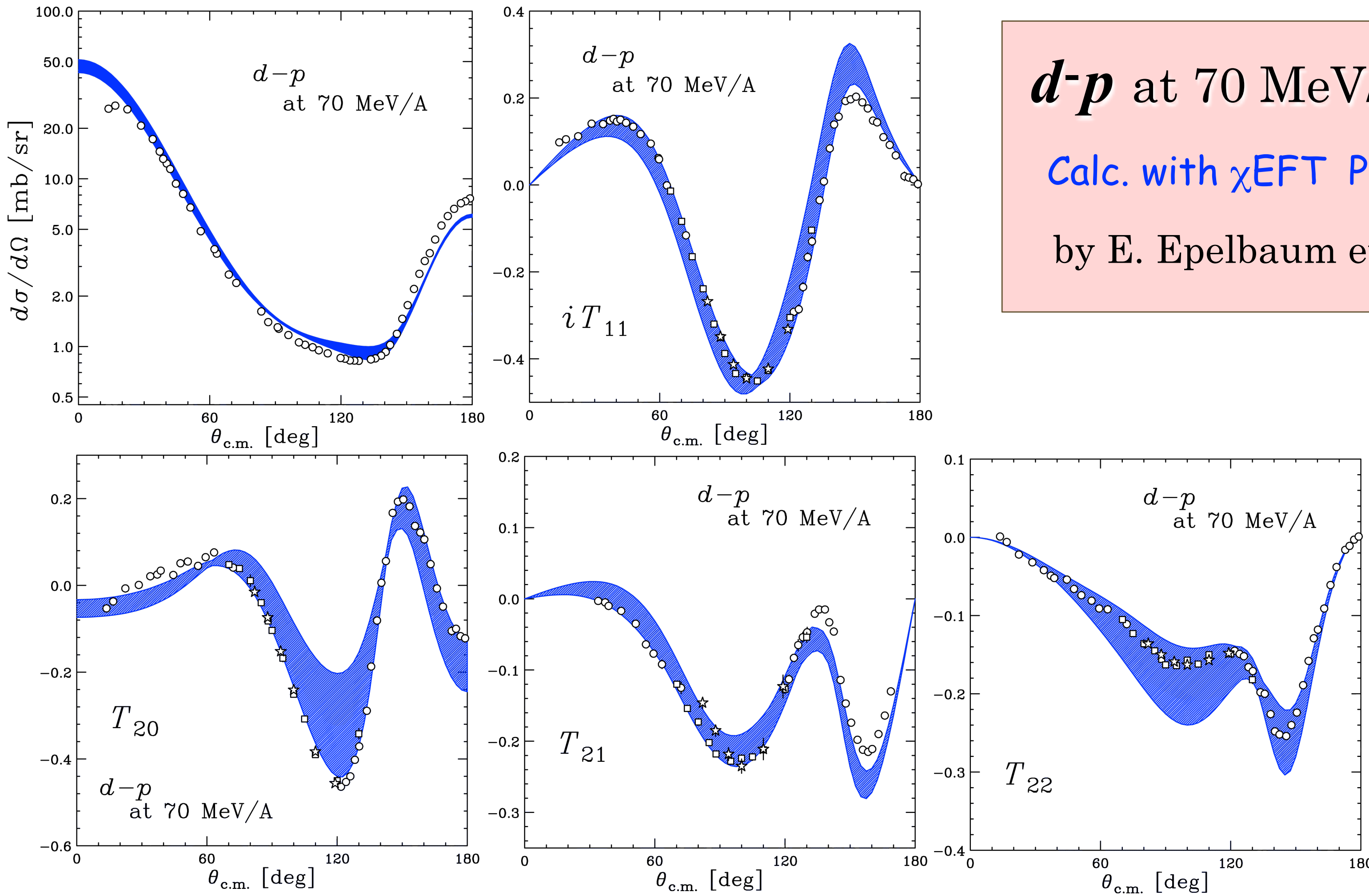
- Only works at energies below
  pion-mass scale.



How does Chiral EFT pot. describe the Nd elastic scattering ?

So far calc. based on χEFT pot. is available below 100 MeV/nucleon.

Various types of 3NFs, including 2π3NF, appear in N^2LO, N^3LO.
Theory in Progress : up to N^3LO (NN + NNN) for higher energies



d-p at 70 MeV/nucleon

Calc. with χEFT Pot. (N2LO)

by E. Epelbaum et al.

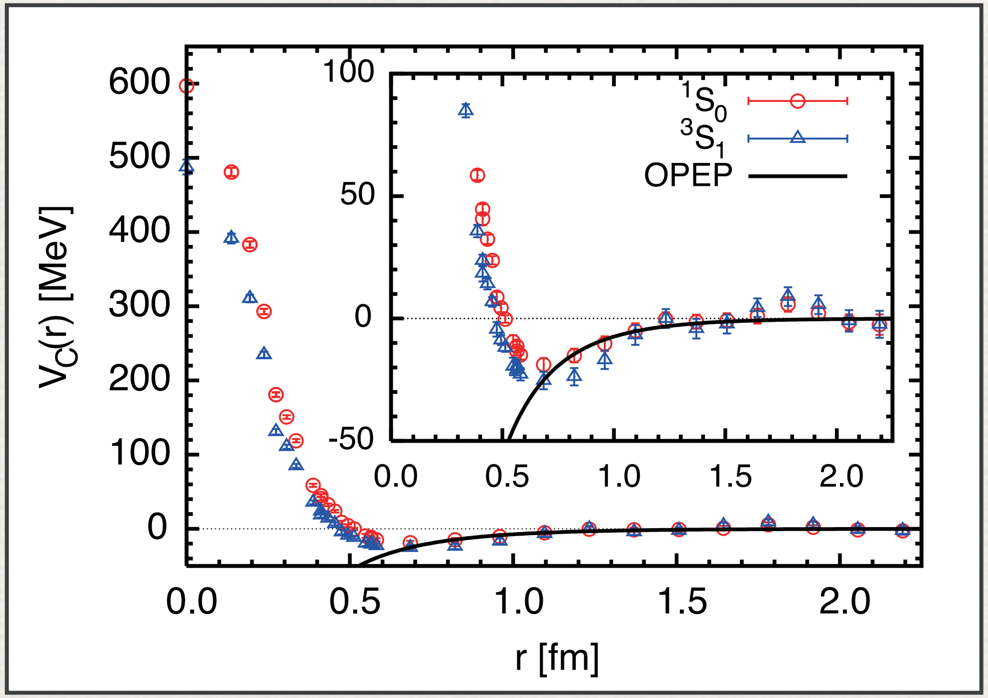
Nuclear Forces linked to QCD

- Nuclear Forces from Lattice QCD

  Ishii, Aoki, Hatsuda, Phys. Rev. Lett. 99, 022001 (2007)

  - Lattice QCD simulations succeeded in providing bulk properties of nucleon-nucleon forces.

  - Study of 3NFs from Lattice QCD is in progress.
    Doi et al (HAL QCD Coll.)
    Prog. Theor. Phys. 127, 723 (2012)



Three Nucleon Force in A>3

3NFs in A>3 - I -

3NFs in Finite Nuclei

Ab Initio Calculations for Light Nuclei

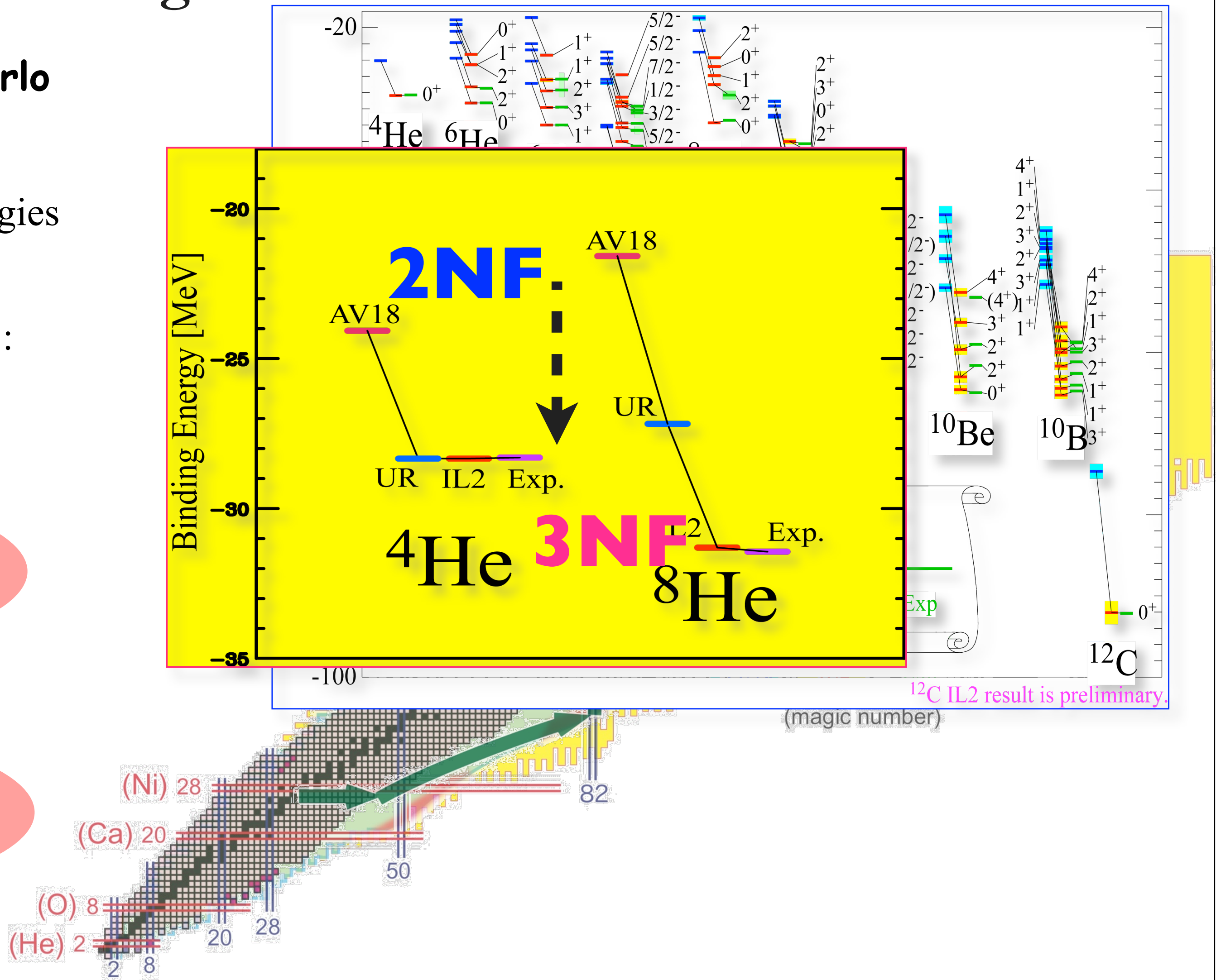
- ***Green's Function Monte Carlo***
- ***No-Core Shell Model*** etc..

  - 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 :
T=3/2 3NFs play important roles to explain B.E. in neutron rich nuclei.



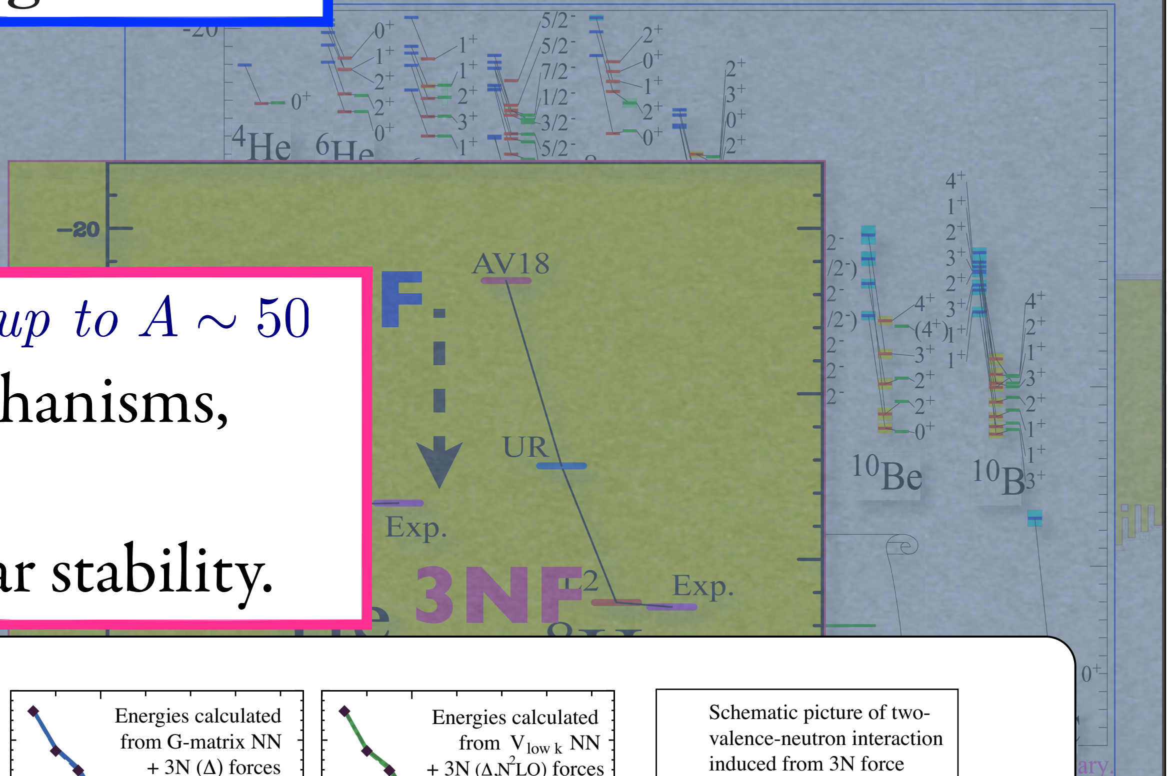
3NFs in A>3 - I -

3NFs in Finite Nuclei

Ab Initio Calculations for Light Nuclei

- Green's Function Monte rlo
- No-Core Shell Model et

  - 2NF provide less binding e ergies
  - 3N

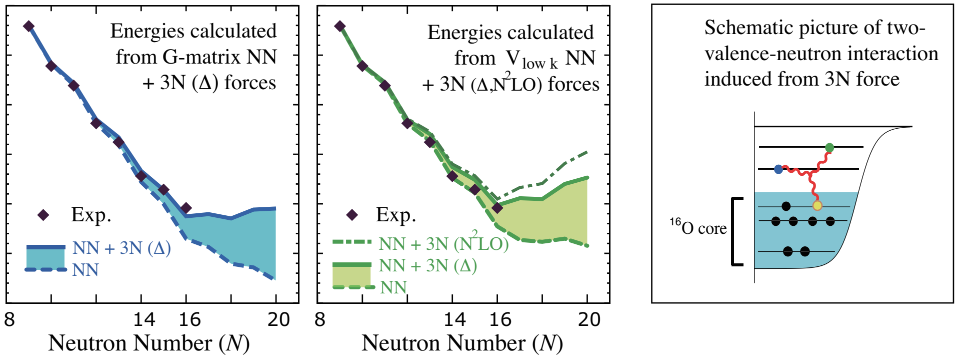


Medium Mass Nuclei *up to* $A \sim 50$

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

roles to explain B.E.
in neutron rich nuclei.

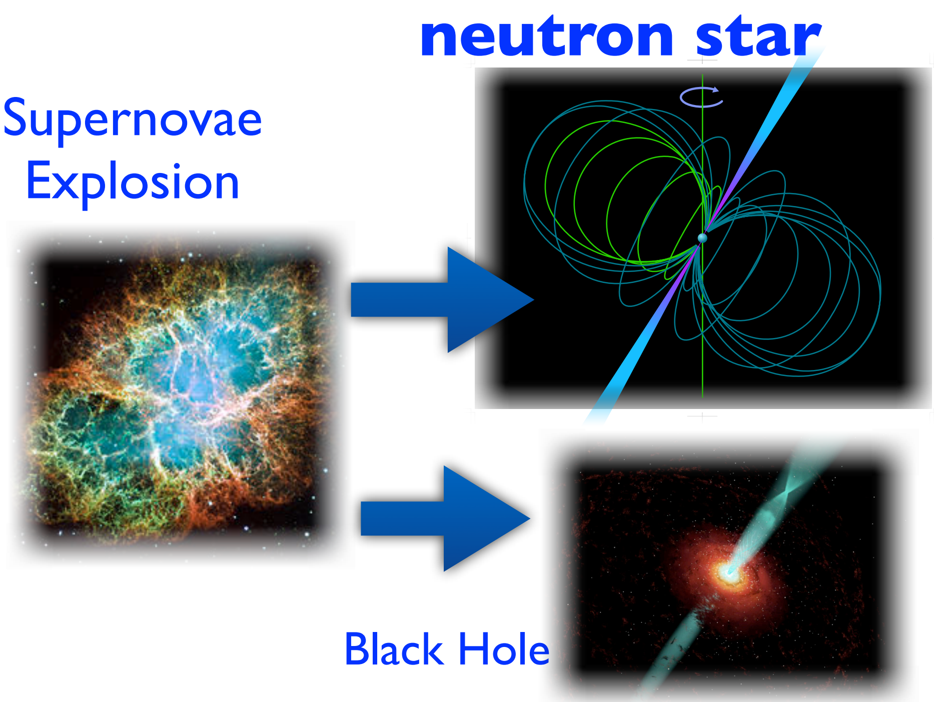
3NF effects in B.E.
- 10-25%
- Attractive



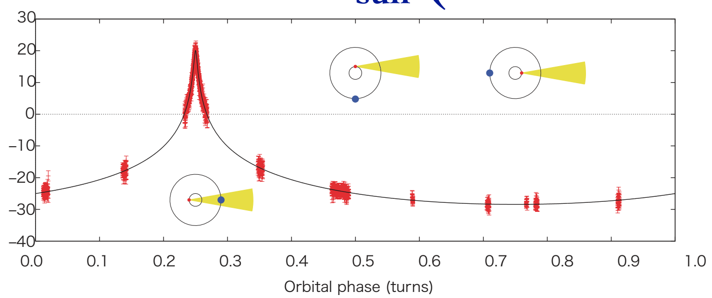
Otsuka et al.,Phys. Rev. Lett. 105, 032501 (2010)

3NFs in A>3 - II -

3NFs in Infinite Nuclei - Neutron Star -

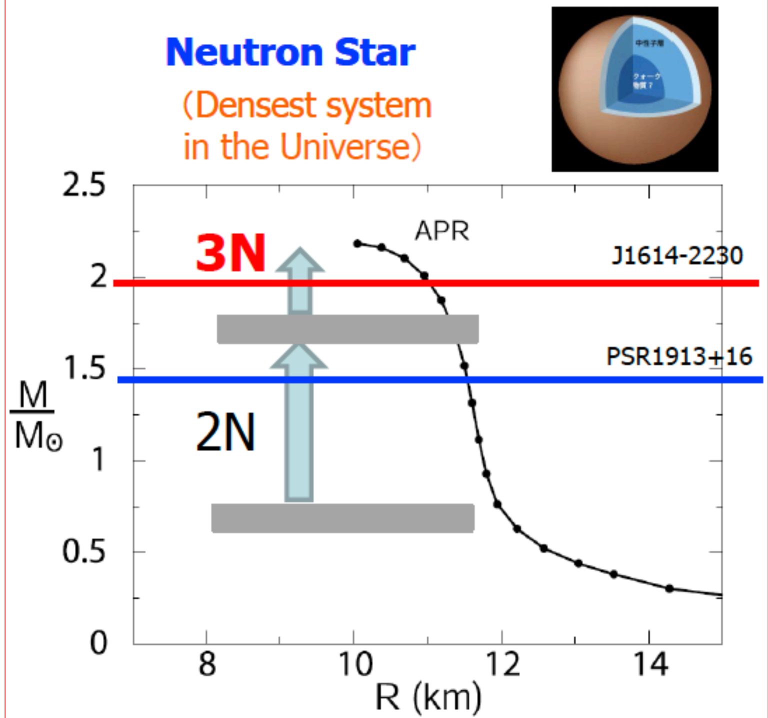


Discovery of Heaviest Neutron Star with $1.97 \pm 0.04\ M_{sun}$ (PSR J1614-2230)



Nature ***467*** 1081 (2010)

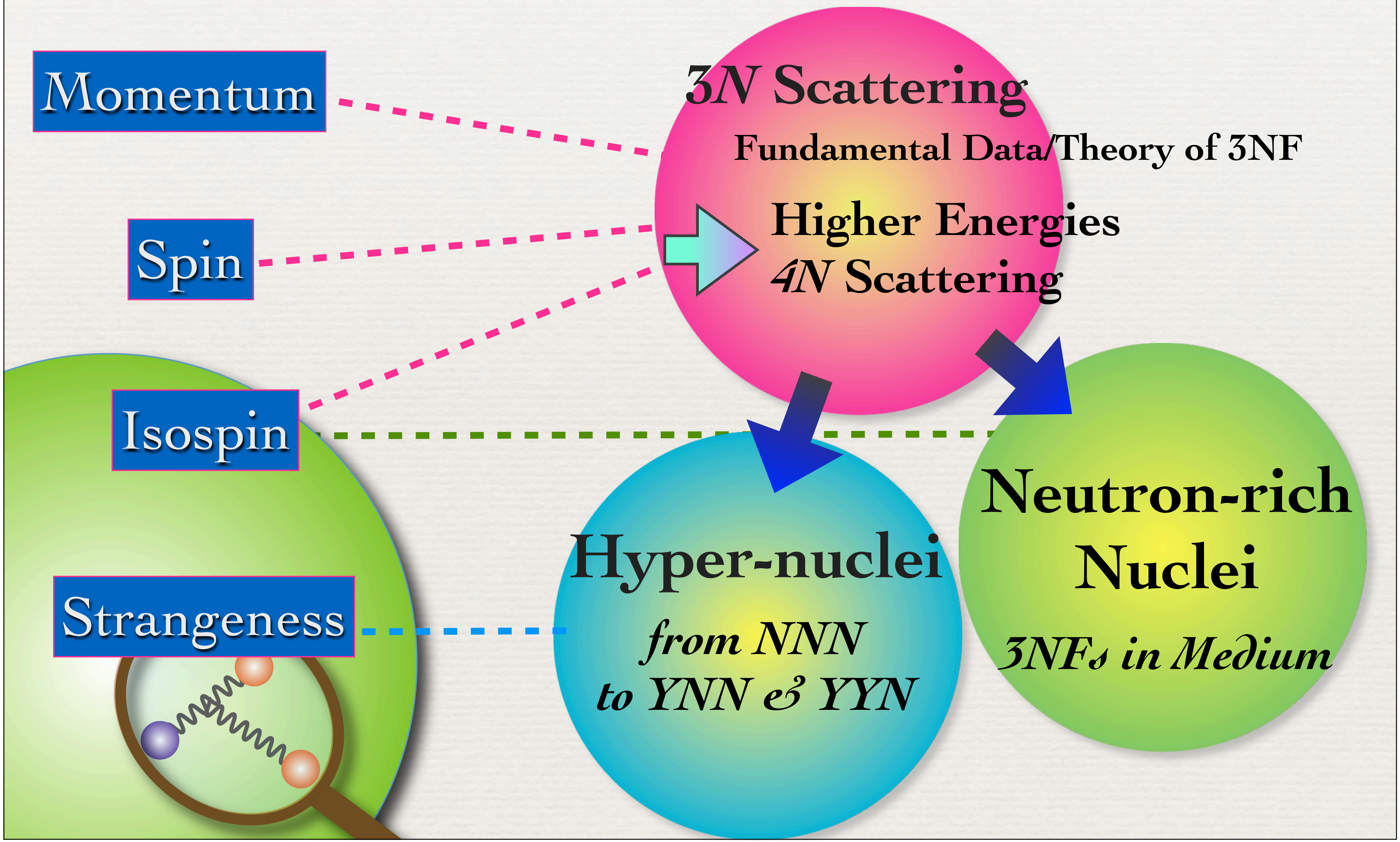
3NFs (probably T=3/2 3NFs) play important roles at high density



Short range repulsive terms of 3NFs (three-neutron forces) are taken as key elements to understand **2 M_{sun}** neutron star.

Perspective of 3NF Study

~Consistent Understanding From Quark to the Universe~

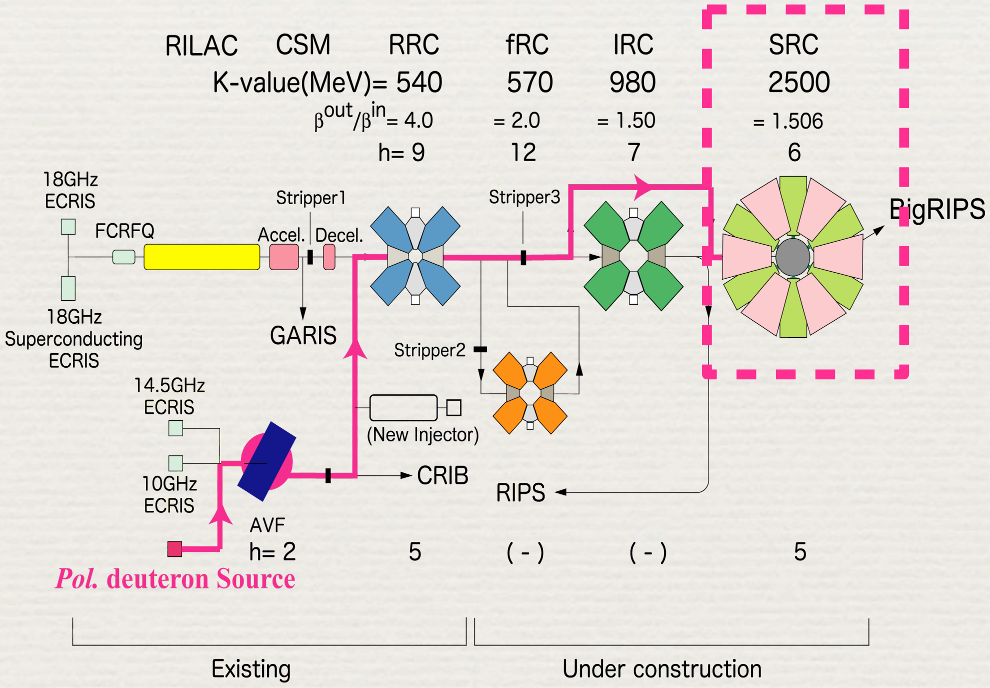


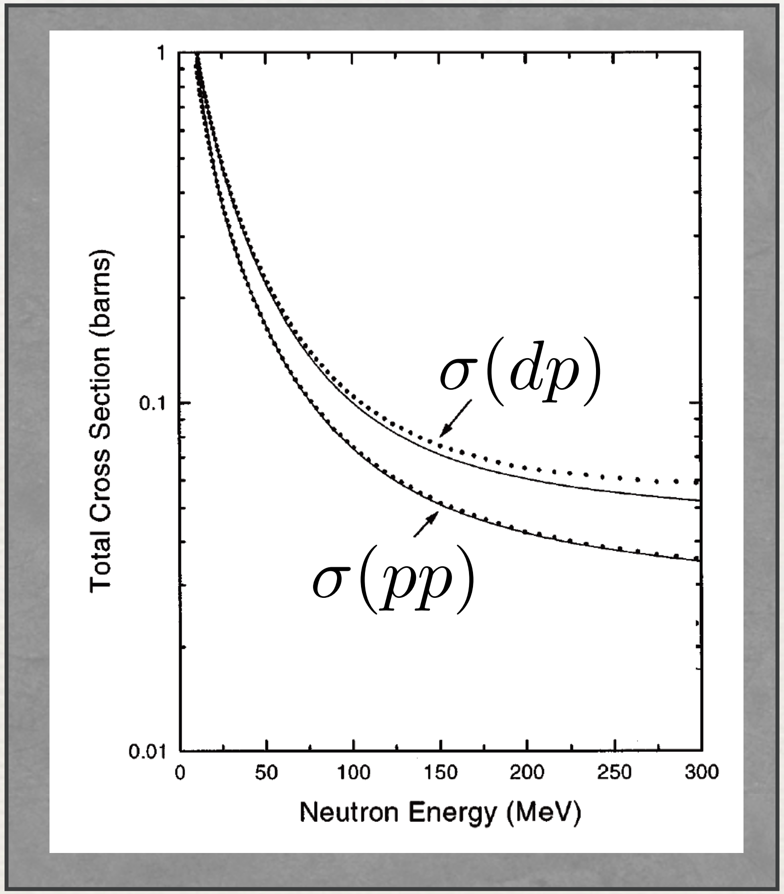
Our Study of 3NFs in Progress

- *d*-*p* Scattering at Higher Energies
- $p+{}^3$He scattering

d-p Scattering at Higher Energies

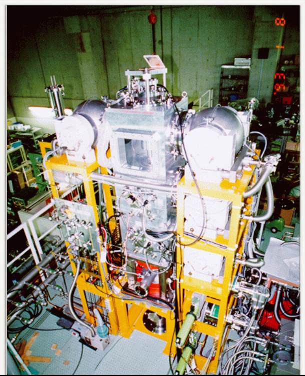
- Effects of 3NFs are relatively enhanced.
- Approach shorter range parts of 3NFs
- RIKEN RI Beam Factory
  pol. d beam 190 - 400MeV/nucleon

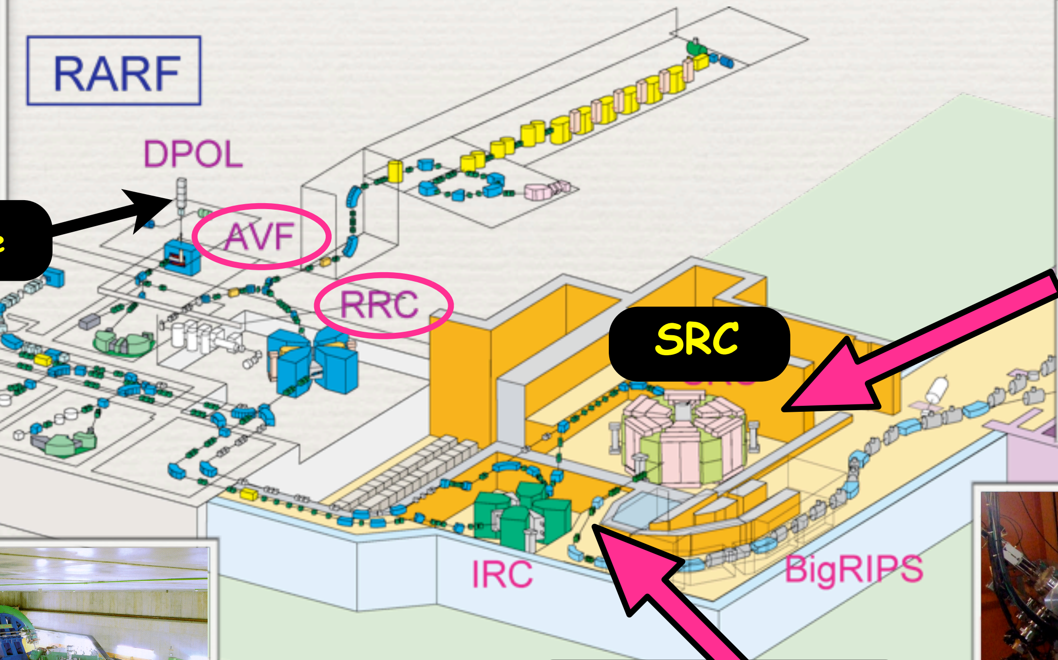


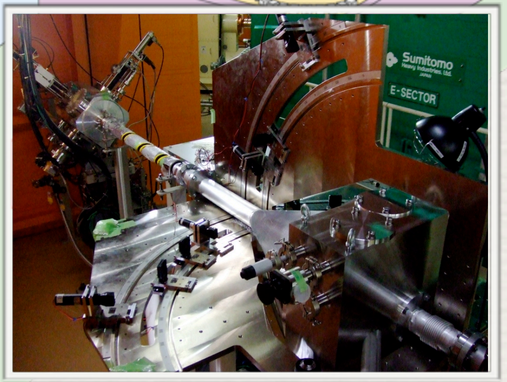


RIKEN RI Beam Factory

- RIBF : pol.d beams up to 400 MeV/nucleon are available
  by "AVF+RRC+ the new cyclotron SRC ".
  - First commissioning/experiment with pol.d beams at 250 MeV/nucleon was performed at the polarimeter BigDpol in 2009.
  - Beam Polarization : 80% of theoretical maximum values

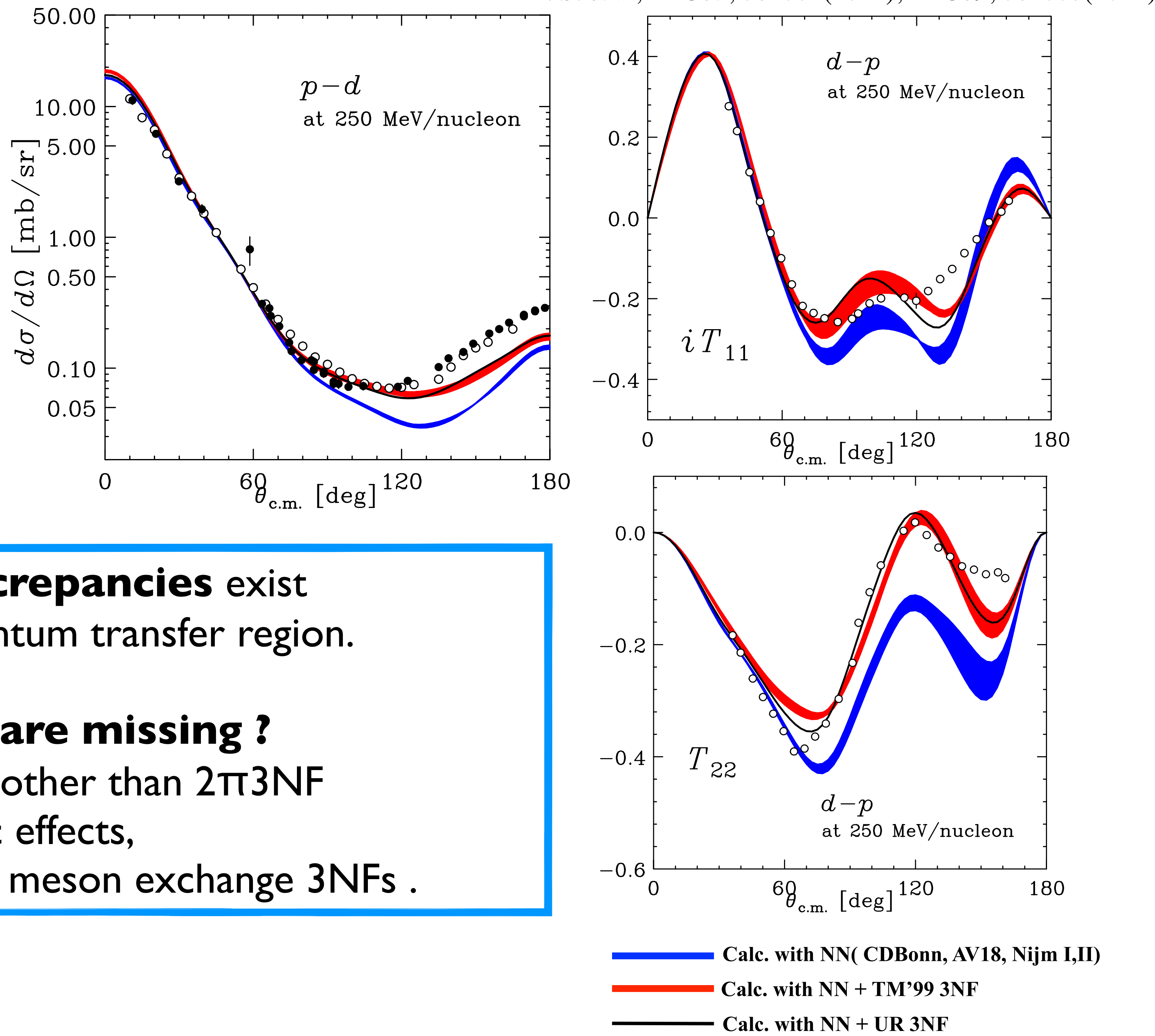






d-p elastic scattering at 250 MeV/nucleon

K. S. et al, PRC83, 061001(2011), PRC89, 064007(2014)



- **Serious discrepancies** exist at high-momentum transfer region.
- **"What" we are missing ?**
  Components other than 2π3NF
  e.g. relativistic effects,
  & heavier meson exchange 3NFs .

$p+{}^3$He scattering

- 4-nucleon scattering

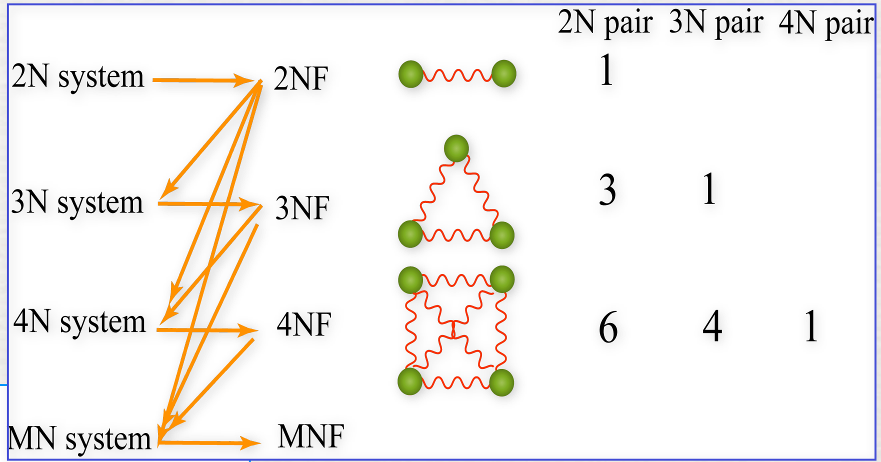
  First Step from Few to Many

- Approach iso-spin dependence of 3NFs

  T=3/2 3NFs

- Large 3NF effects

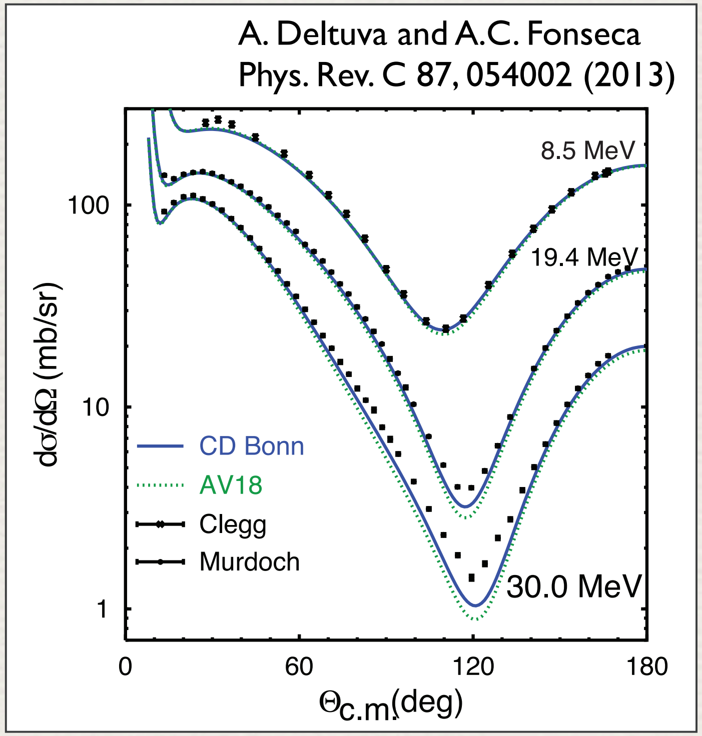
  in cross section minimum at intermediate energies



Theory in Progress

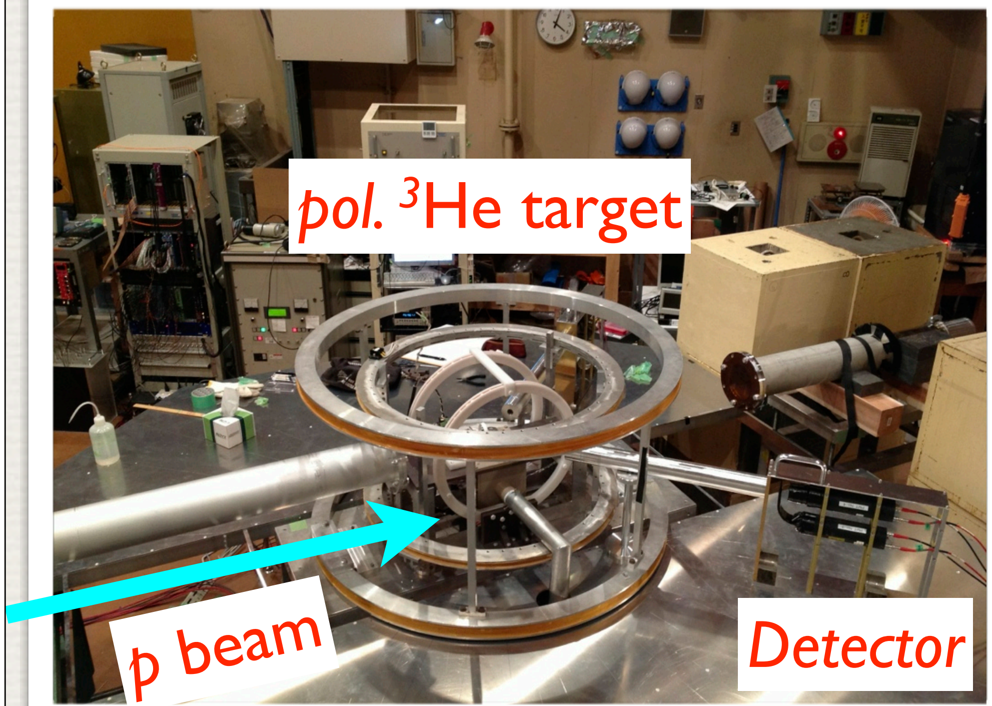
Calculations above 4-body breakup threshold energy

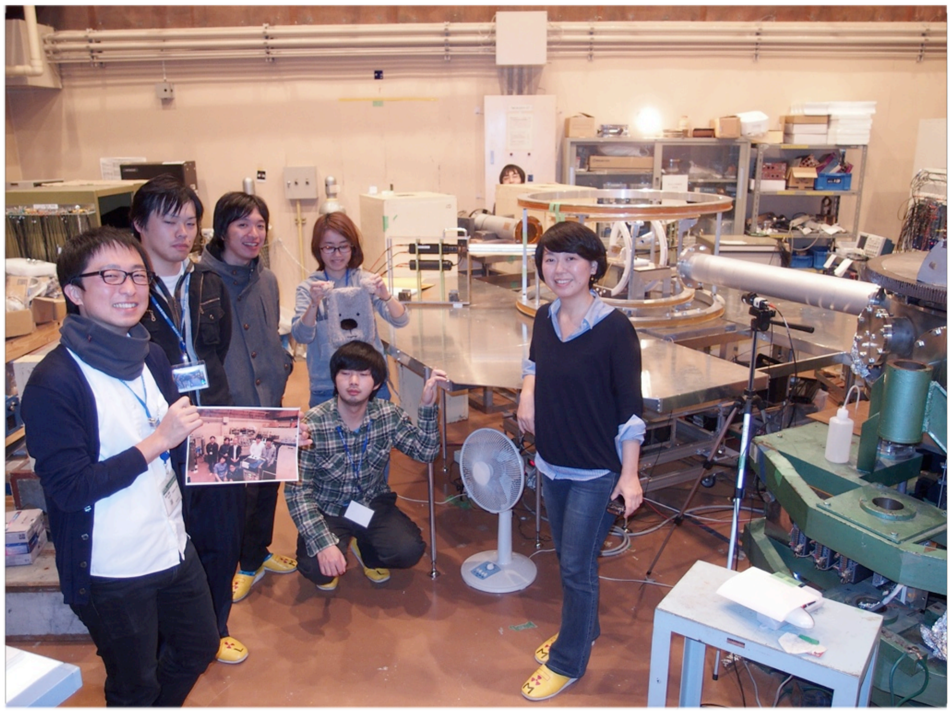
open new possibilities for 3NF study in 4N scat.



pol.^{3}He target for p+^{3}He scattering is under construction at Tohoku University

- **Method : Spin Exchange Optical Pumping**
- **Polarization : about 10% (current)**
- **Planning First Experiment : p+^{3}He at 70 MeV**





Summary

- Study of nuclear force is a hot topic of nuclear physics.
  - Frontiers of nuclear force study
    - to understand nuclear forces from quarks
    - to understand nuclei/matter from 2 & 3NFs

- 3NFs are now taken as key elements to understand nuclei properties, e.g. B.E. of nuclei, EOS of neutron stars.

- Deuteron-proton scattering inspires quantitative discussions on 3NFs - after 40 years of Yuasa's Experiment at Orsay -.

Personally, I want to see 3NFs not observed yet and clarify their roles,

for Consistent understanding from quarks to the Universe.

SMART Gr. Collaboration (~ 2005)

School of Science, University of Tokyo

H. Sakai, K. Yako, S. Sakoda, H. Kato, M. Hatano, T. Saito, N. Uchigashima, H. Kuboki, M. Sasano, Y. Takahashi

RIKEN Nishina Center

N. Sakamoto, T. Ohnishi, K. Sekiguchi

CNS, University of Tokyo

T. Uesaka, T. Kawabata, K. Suda, Y. Maeda, S. Sakaguchi, Y. Sasamoto

CYRIC, Tohoku Univ.

H. Okamura

RCNP, Osaka Univ.

A.Tamii

Tokyo Institute of Technology

Y. Satou

KVI

N. Kalantar-Nayestanaki

K. Ermisch

Kyushu University

T. Wakasa

Saitama University

J. Nishikawa, K. Itoh

RIBF pol.d beam experiment Gr. (2008～)

TOHOKU University

K. Sekiguchi, J. Miyazaki, Y. Wada, T. Taguchi, U. Gebauer, K. Takahashi, T. Mashiko

RIKEN Nishina Center

H. Sakai, N. Sakamoto, T. Uesaka, M. Sasano, M. Dozono, Y. Shimizu

CNS, University of Tokyo

K. Yako, R. Tang, S. Kawase, Y. Kubota, C.S. Lee,

RCNP, Osaka University

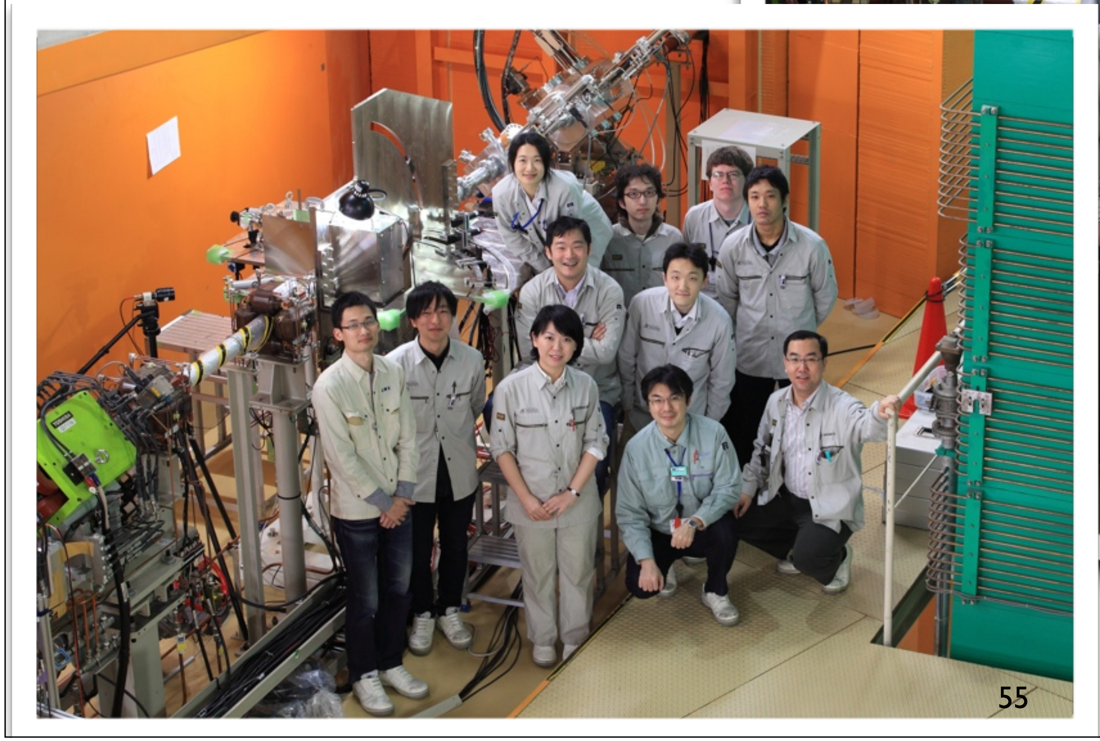
H. Okamura, K. Miki

Kyushu University

T. Wakasa, S. Sakaguchi

Miyazaki University

Y. Maeda, T. Saito



Theoretical Supports from

Ruhr-Universität, Bochum

W. Glöckle, E. Epelbaum

Jagellonian University

H. Witała, J. Golak

Kyushu Institute of Technology

H. Kamada

Forshungszentrum of Jülich

A. Nogga

Hannover University

P.U. Sauer, S. Nemoto

Lisbon University

A. Deltuva, A. Sa. Fonseca

To explore the laws of the nature, step in 1 → 2 → 3 .

道生一
一生二
二生三
三生萬物

道経　第四十二章

老子

The Tao (Way) produced One,
One produced Two,
Two produced Three, and
Three produced Everything.

"Tao-te Ching" by Lao Zi in B.C. 400