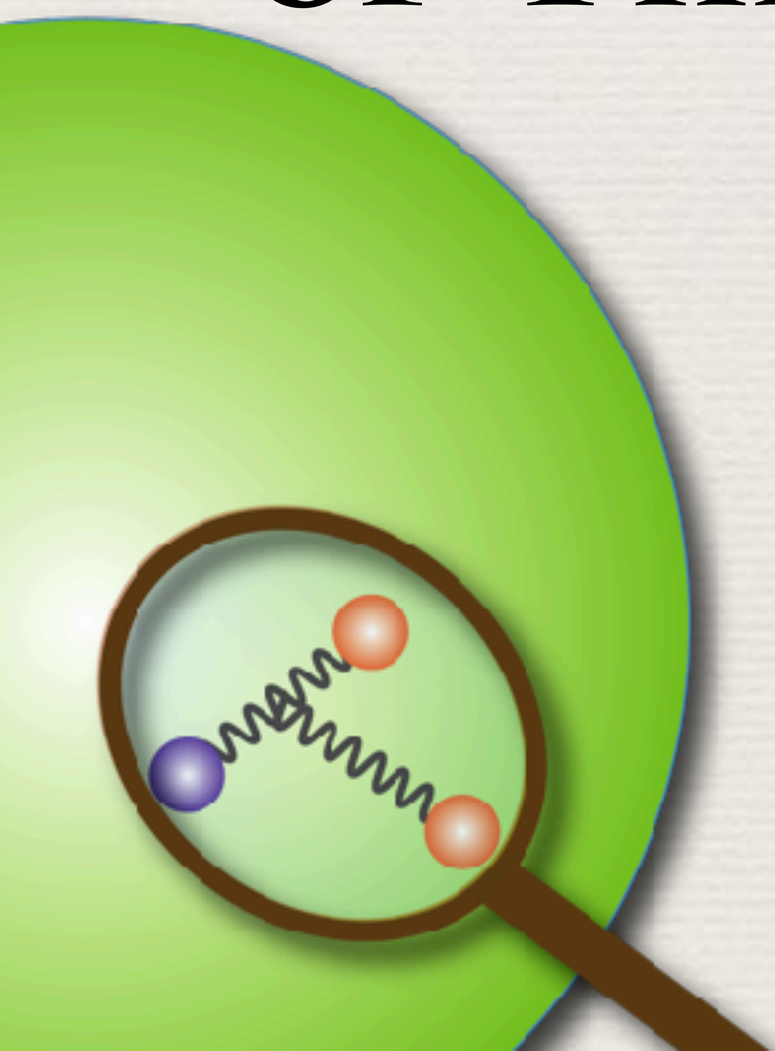
Experimental Study of Three-Nucleon Forces

Part I



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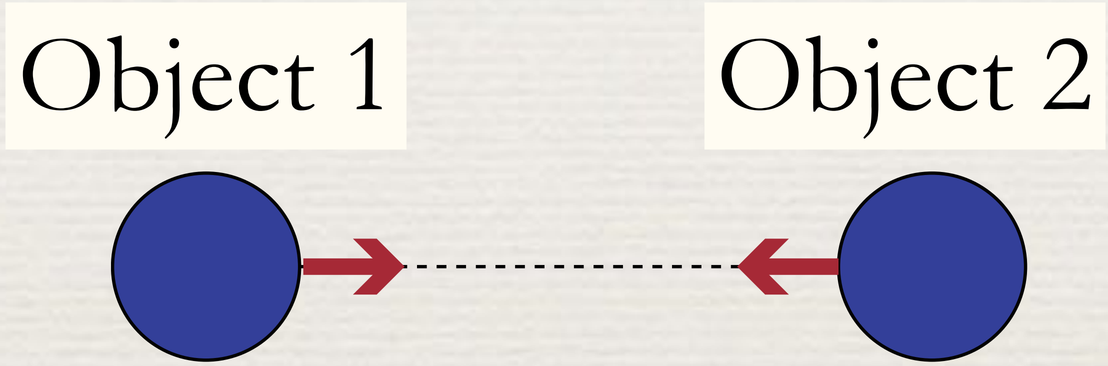
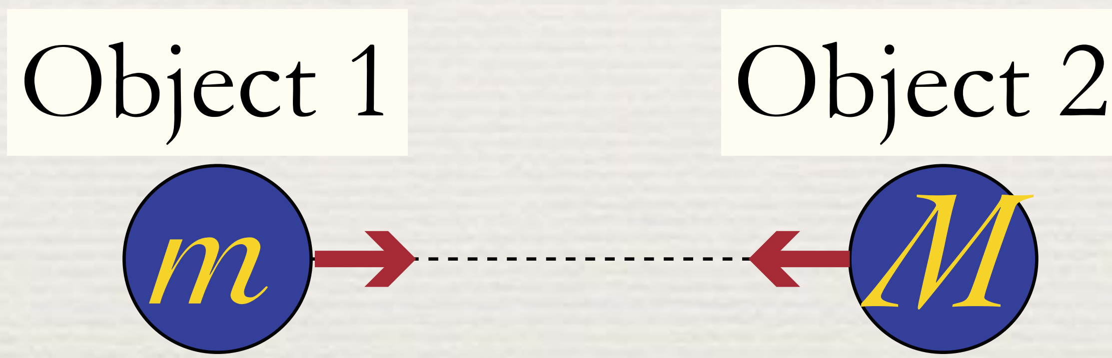
Nuclear Physics

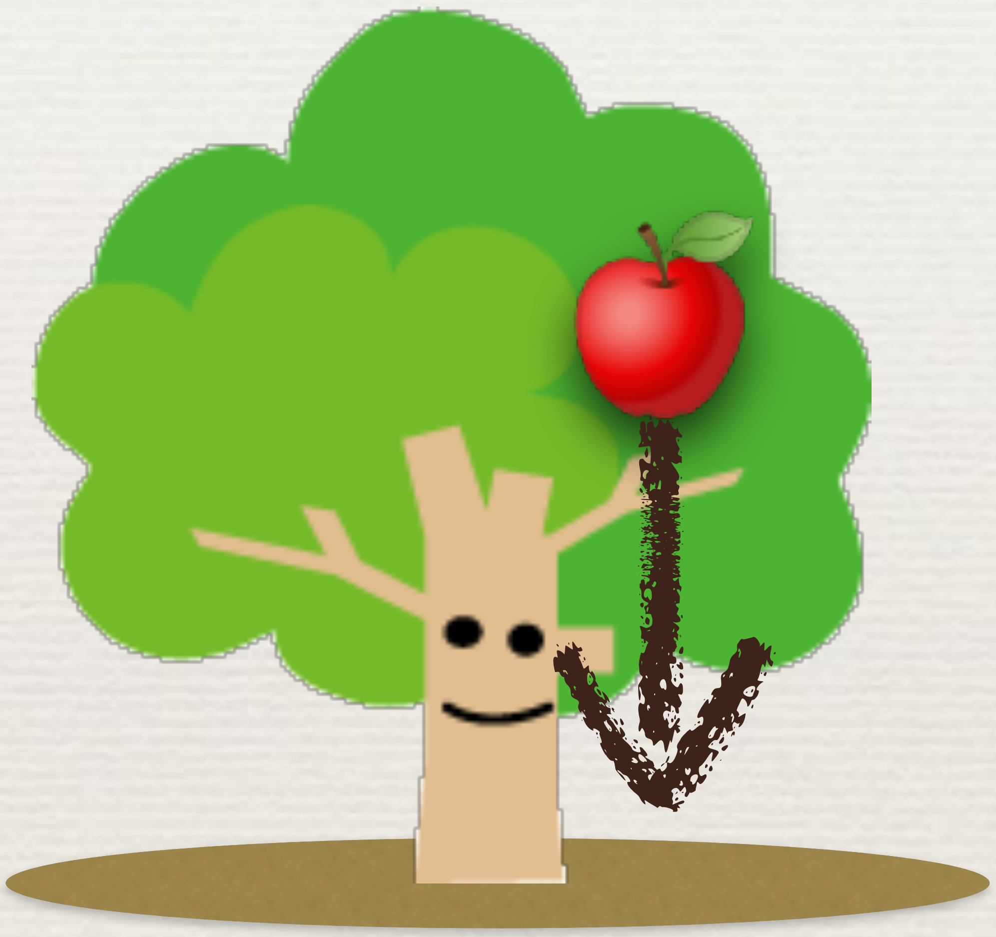
- started in the beginning of the 20th century.
- Today's talk is on forces acting among 3-nucleons.

Forces - basic concept-



Forces - basic concept-

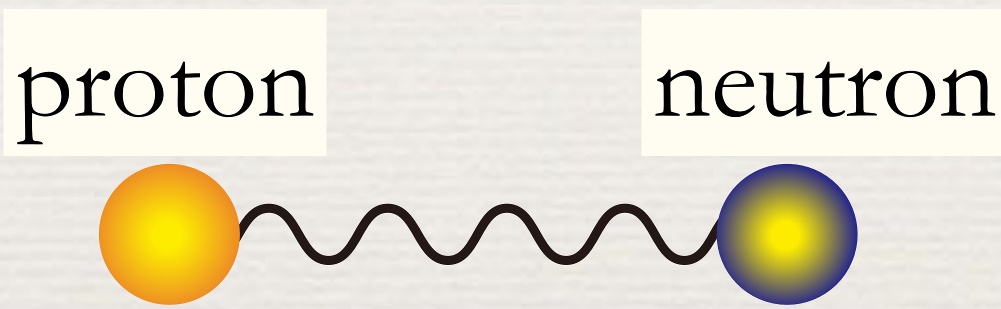




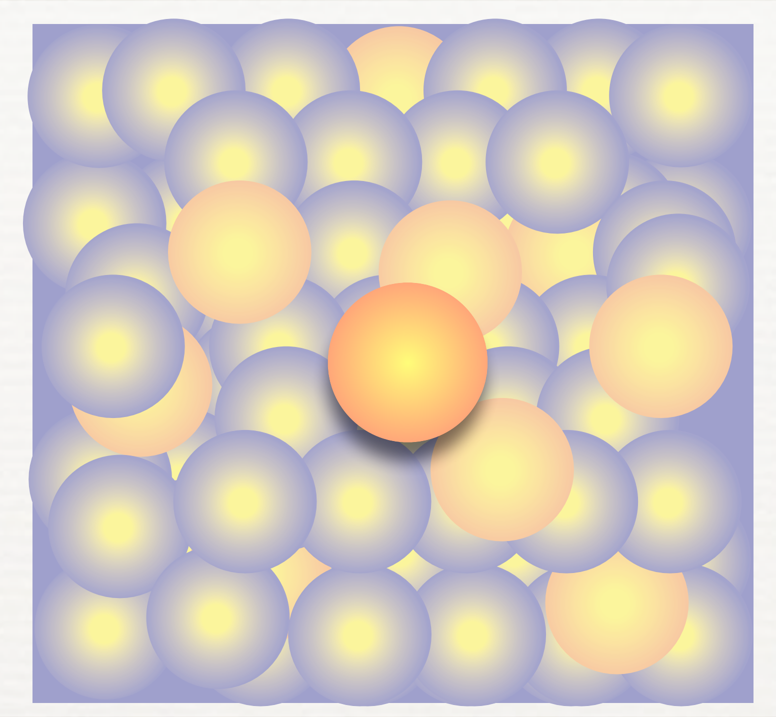
$$F = G\frac{mM}{r^2}$$

$$\sum_i F_i = \ldots = mg$$

Forces - basic concept-



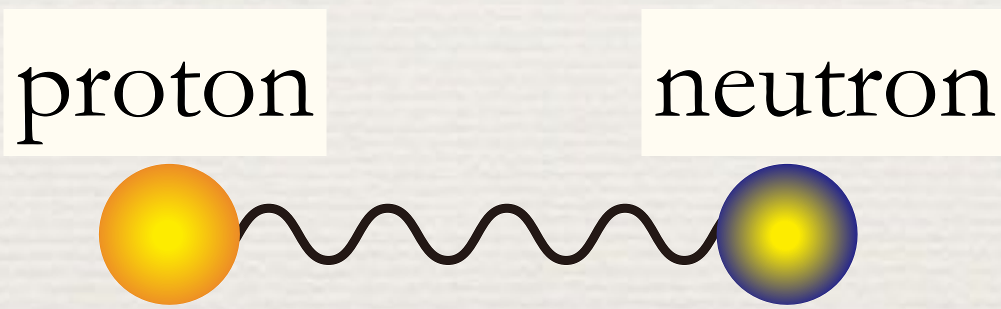
2-nucleon Forces



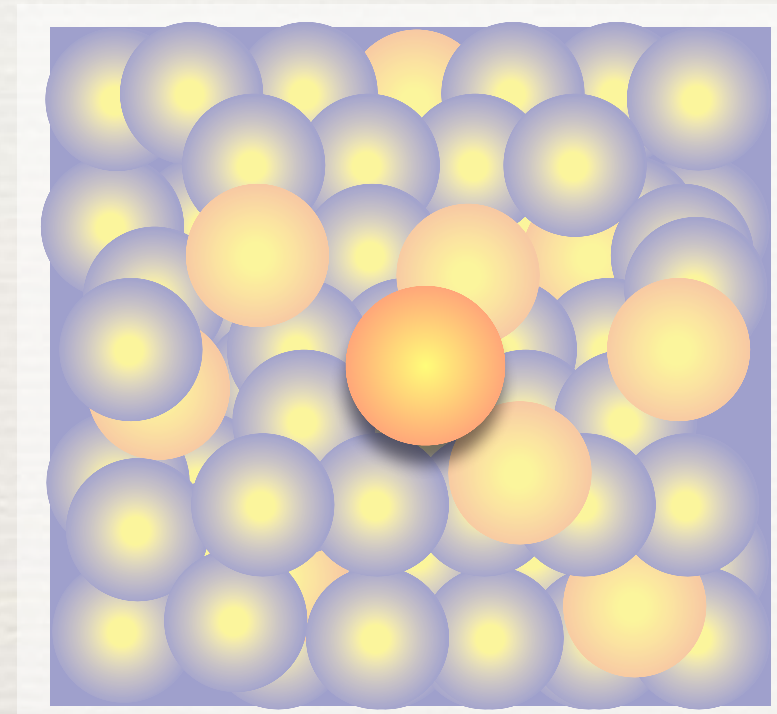
Forces in Medium

$$V_{2N} \longrightarrow V = \sum_{i,j} V_{ij}$$

Forces - basic concept-

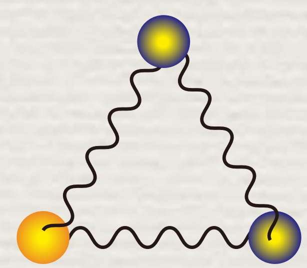


2-nucleon Forces



Forces in Medium

$$V_{2N}$$



$$V_{3N} = V_{ijk}$$

$$V = \sum_{i,j} V_{ij}$$

Earth-Moon-Satellite Gravitational Interactions

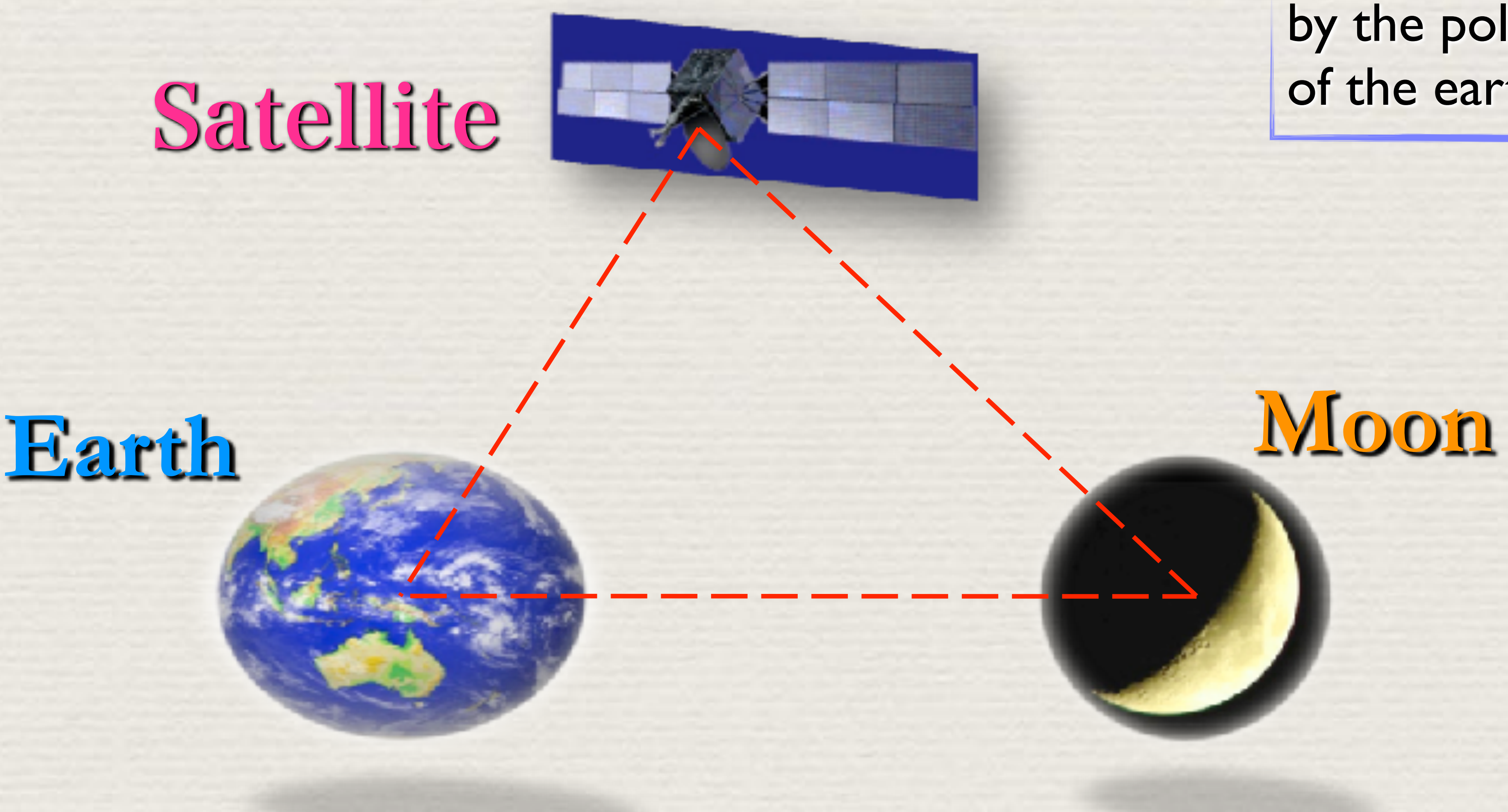
Two-Body Interaction： Gravity

$$H = \frac{1}{2}\left(\frac{P_m^2}{m} + \frac{P_M^2}{M}\right) + \frac{GMm}{r}$$

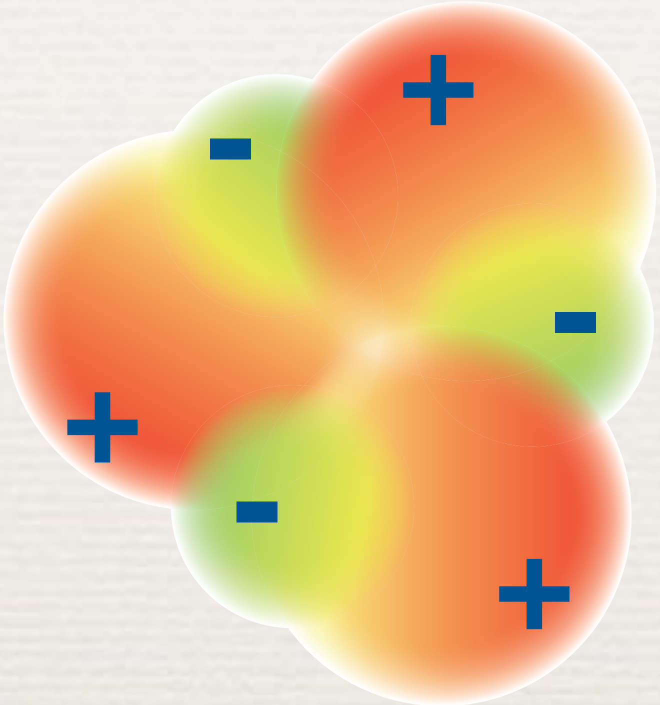
Three-Body Interaction：

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

by the polarizations of the ocean water of the earth by the moon's gravity



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

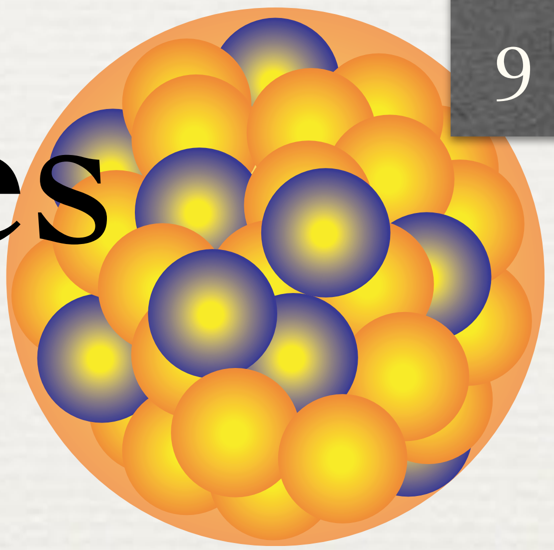
B.M. Axilrod and E. Teller, J. Chem. Phys. 11, 299 (1943).
Y. Muto, J. Phys.-Math. Soc. Japan, 17, 629 (1943).

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).

Three-Body Forces in Nuclei



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

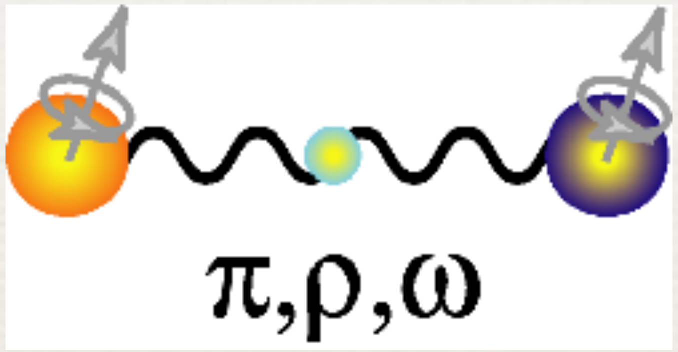
— Where and How ? —

	Solar System	Atom	Nucleus
Length	10^{8} m	10^{-10} m	10^{-15}m
Interaction	Gravity	Electro-Magnetic	Strong
Coupling Constant	10^{-38}	10^{-2}	1
$\frac{V(3BF)}{V(2BF)}$	0.001%	a few %	?

Before Three-Body Forces in Nuclei …

Nuclear Force ~ Yukawa's Idea ~

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

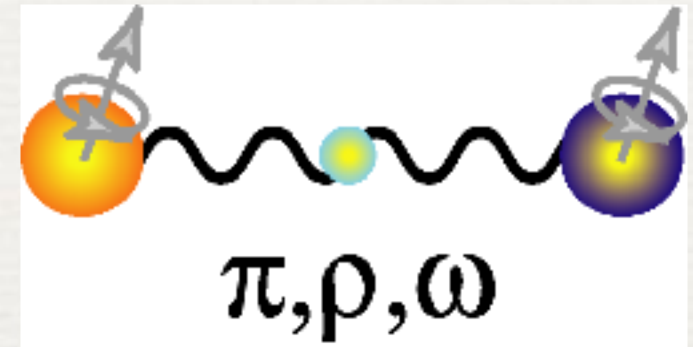


Nuclear force is explained by exchanging a 'virtual particle' (meson) between **two nucleons**.

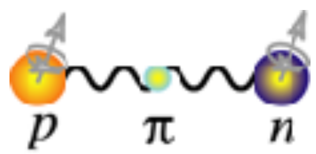
- ☑ Force ⇔ Exchange of Particles
  → Field Theory
- ☑ Origin of Strong Force
- ☑ Quantum Mechanics & Relativity

Nuclear Force

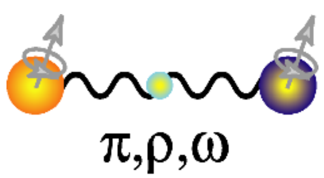
Yukawa's Meson Theory
Proc. Phys. Math. Soc. Jpn. 17, 48 (1935)



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)

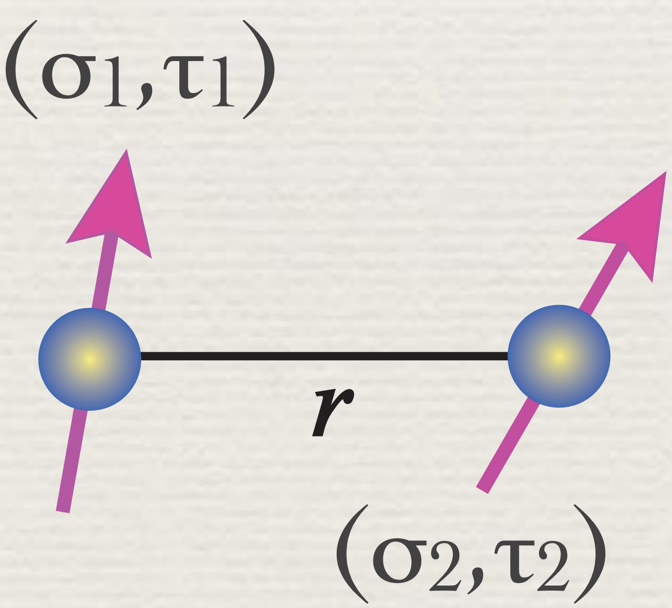
Deuteron Properties

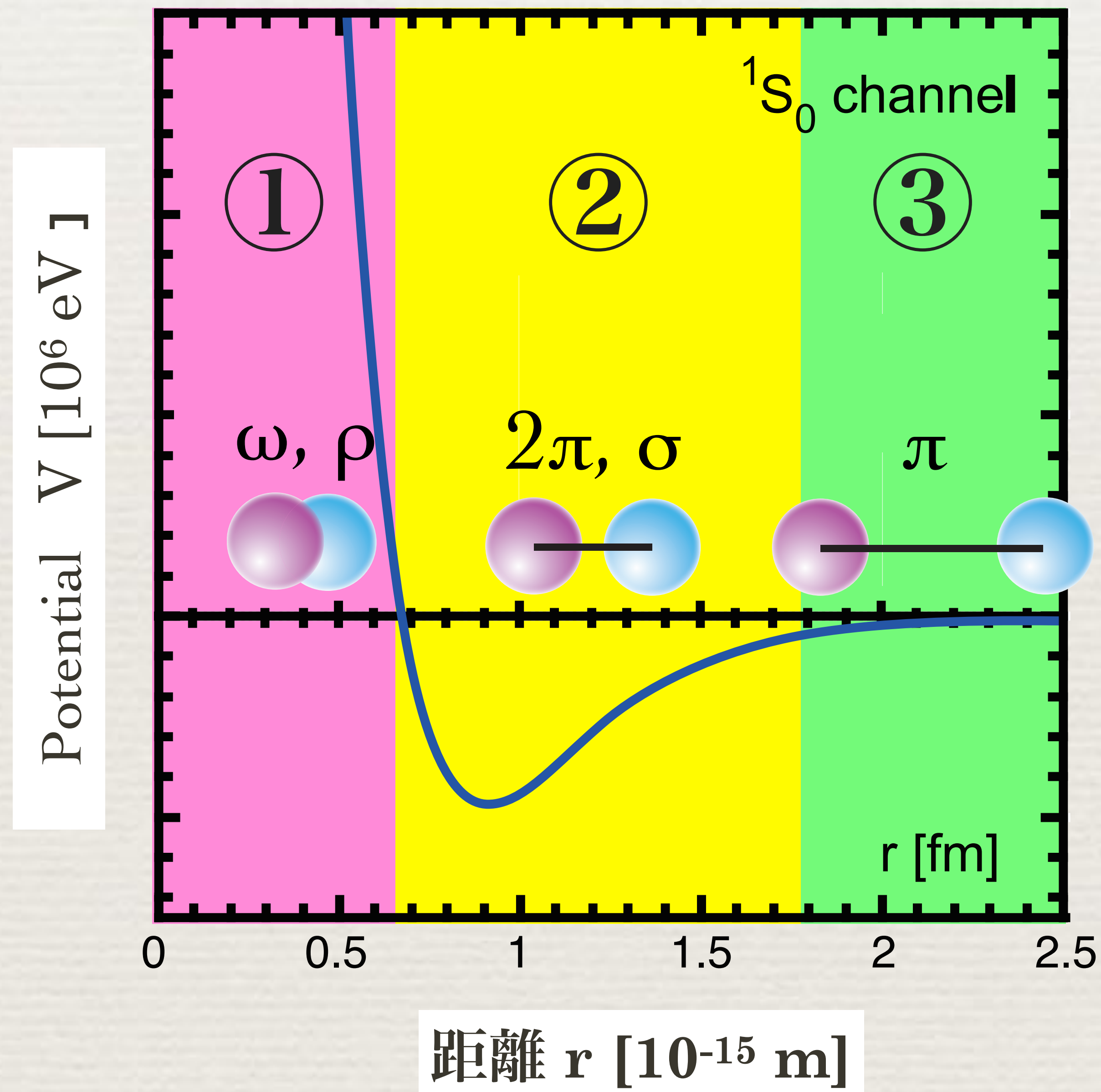
1990's Realistic Modern Nucleon-Nucleon Forces (2-Nucleon F)

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

Nuclear Force – 2-Nucleon Force –

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





σ : Nucleon Spin

τ : Iso-spin (p (uud) or n (ddu)?)

$$= V_0(r) + V_\sigma(r)\,\sigma_1\cdot\sigma_2 + V_\tau(r)\,\tau_1\cdot\tau_2 + V_{\sigma\tau}(r)\,(\sigma_1\cdot\sigma_2)(\tau_1\cdot\tau_2)$$
$$+ V_T S_{12} + V_{T\tau} S_{12}\tau_1\cdot\tau_2 + V_{LS} L\cdot S + V_{LS\tau}(L\cdot S)(\tau_1\cdot\tau_2) + \ldots$$

Bulk Properties of Nuclear Forces

1. short range (finite range)

2. attractive at intermediate range

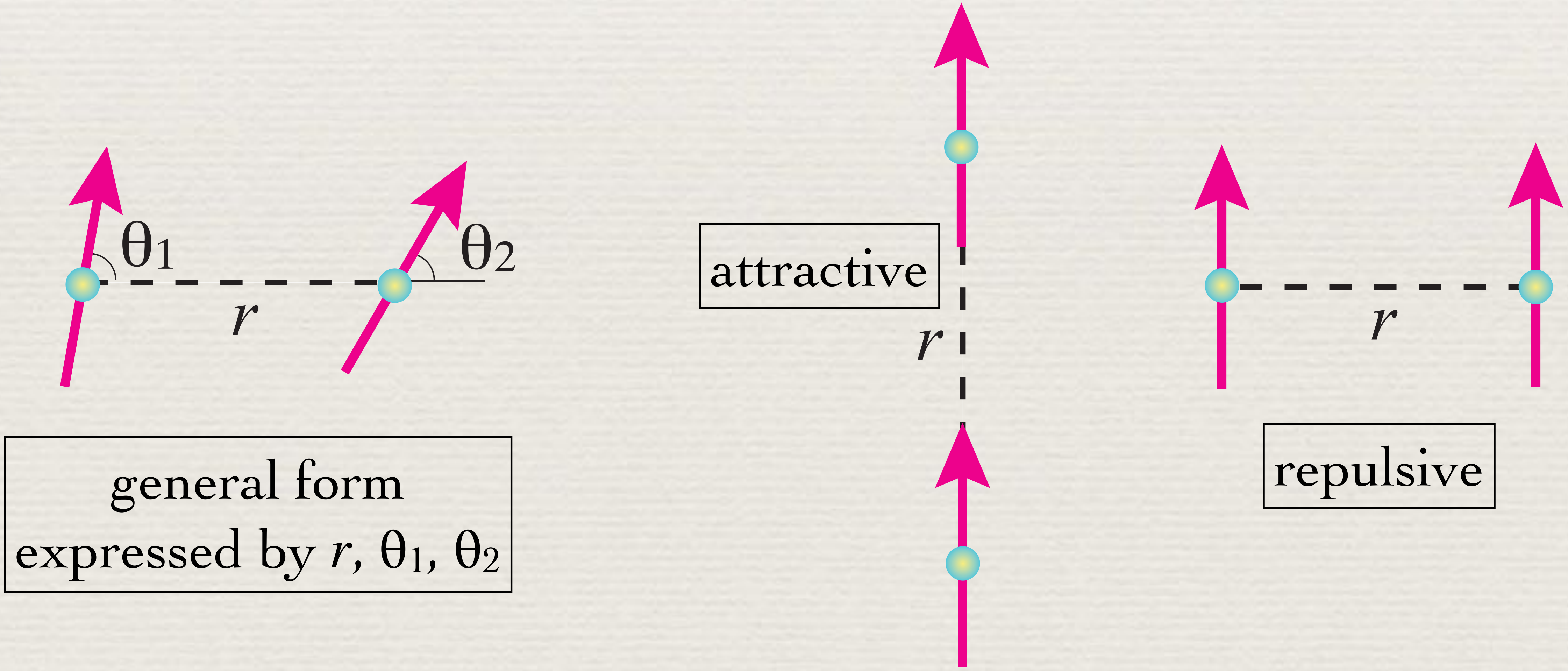
3. repulsive core at short range

4. spin-dependent / non-central force
   : Tensor force, Spin-Orbit force etc...

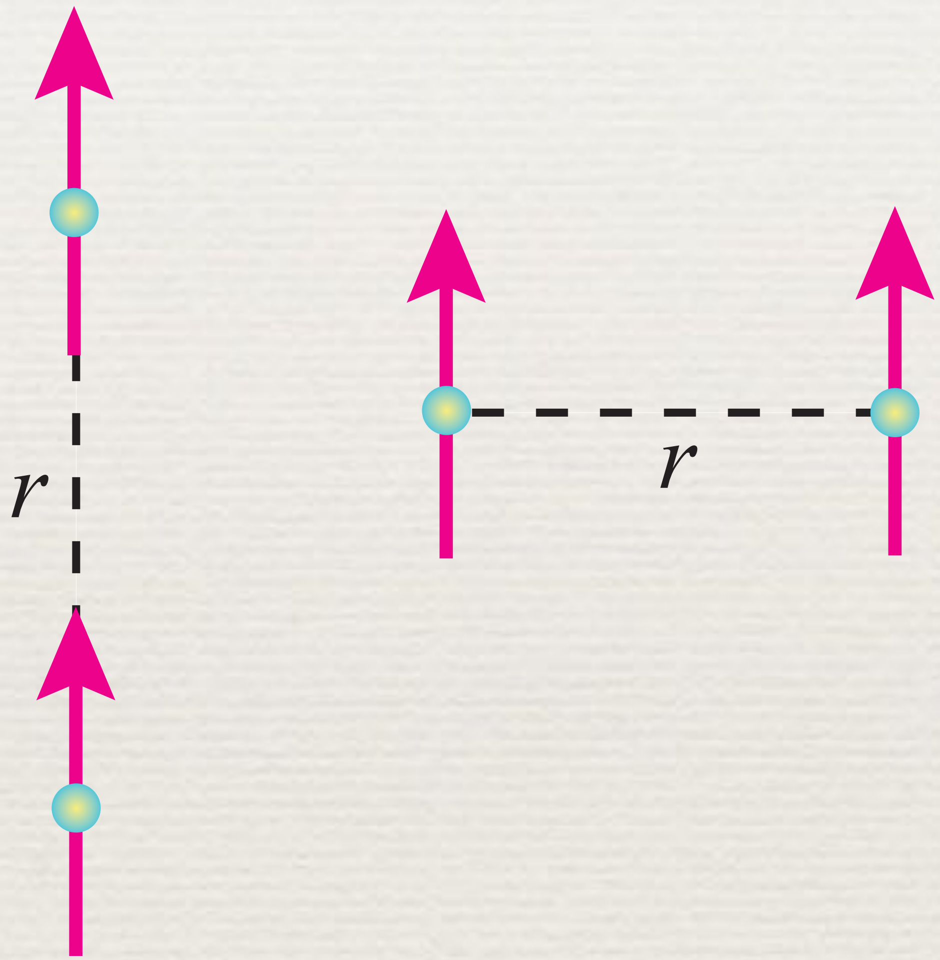
4. spin-dependent non-central force

Tensor Force

$$
\begin{aligned}
V_{\text{tensor}} &\equiv (-S_{12}) \\
&= -3\,(\vec{\sigma_1}\cdot\hat{r})\,(\vec{\sigma_2}\cdot\hat{r}) + \vec{\sigma_1}\cdot\vec{\sigma_2}
\end{aligned}
$$

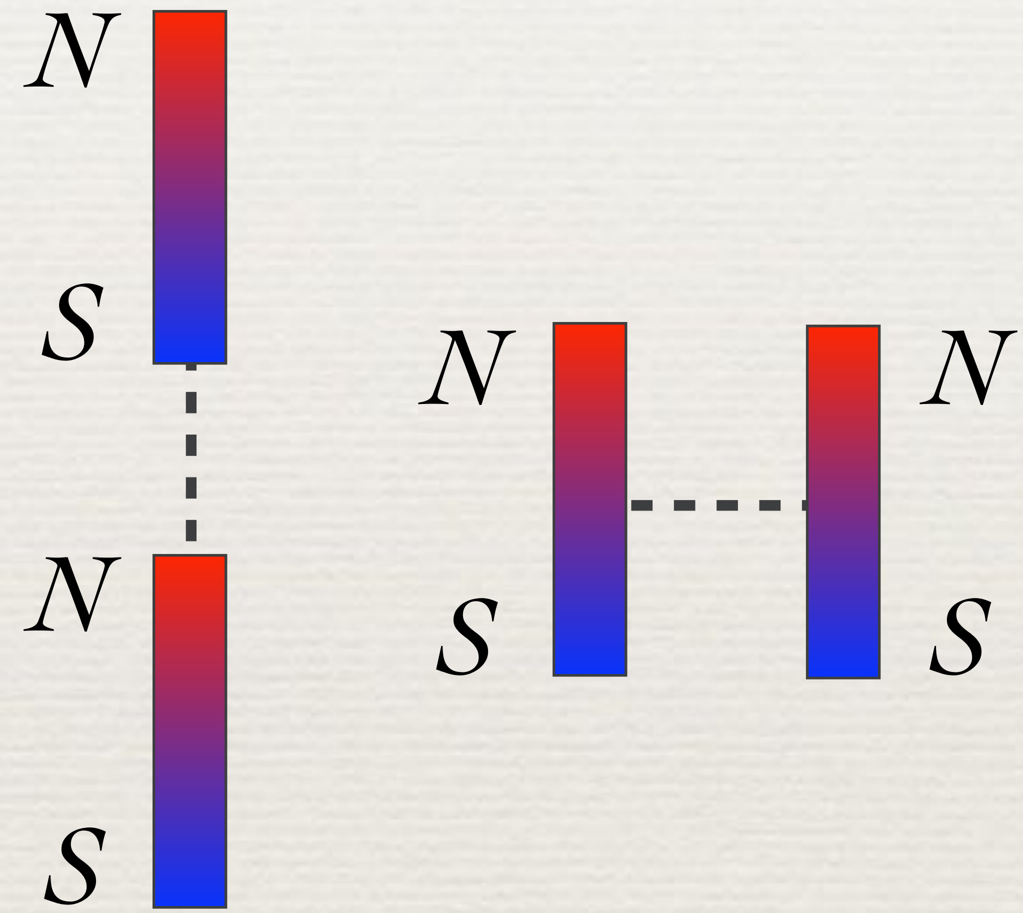


Tensor Force



attractive

repulsive



attractive

repulsive

Tensor Force

Evidence of Tensor Force in Nuclei

1. Deuteron (A=2, Z=1)
   - Non-zero quadrupole moment $Q \neq 0$
   - Magnetic moment $\mu_p + \mu_n \neq \mu_d$
2. NN Scattering
   mixing parameter ε

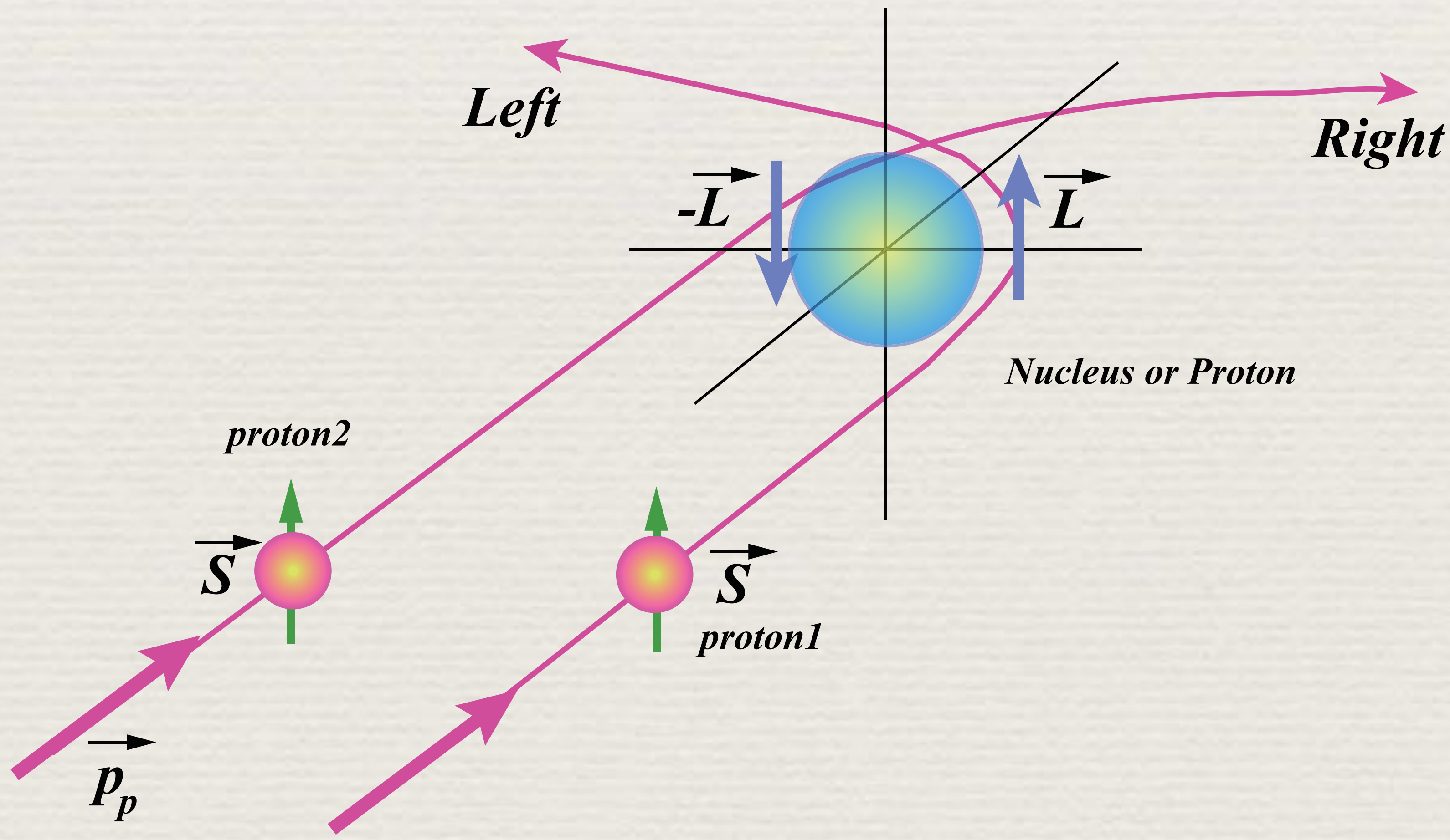
requires
D-state ($l=2$) contribution of two-nucleon system

→ Tensor Force
(non-central force)

4. spin-dependent non-central force

Spin-Orbit Force

$$V_{LS} = \vec{L} \cdot \vec{S}$$



Spin-Orbit Force

P wave (l=1)

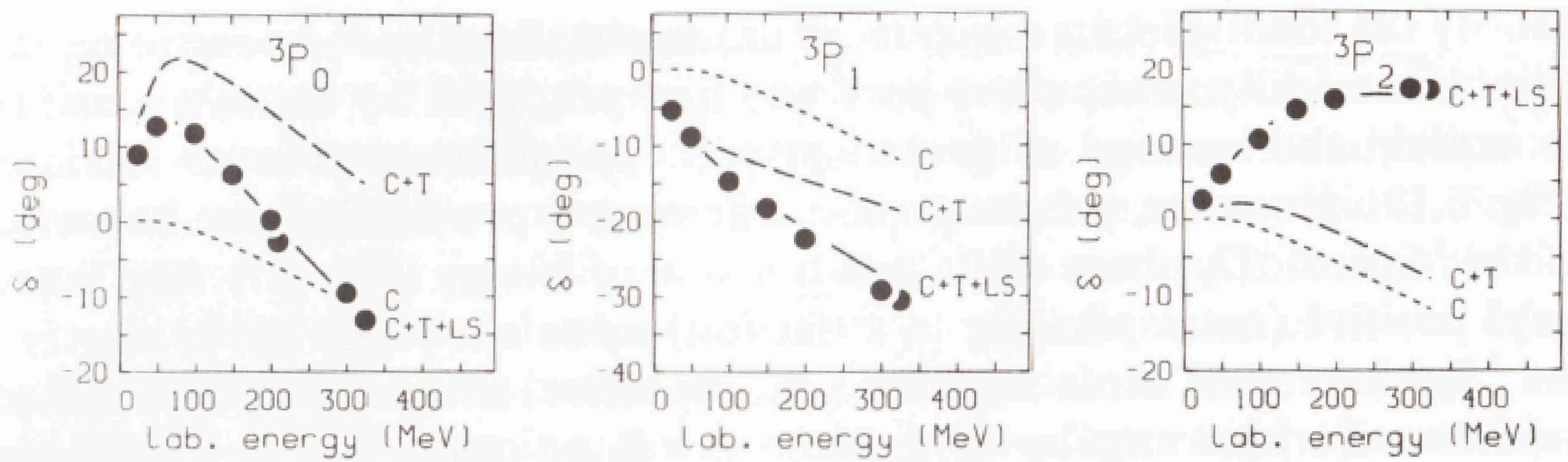
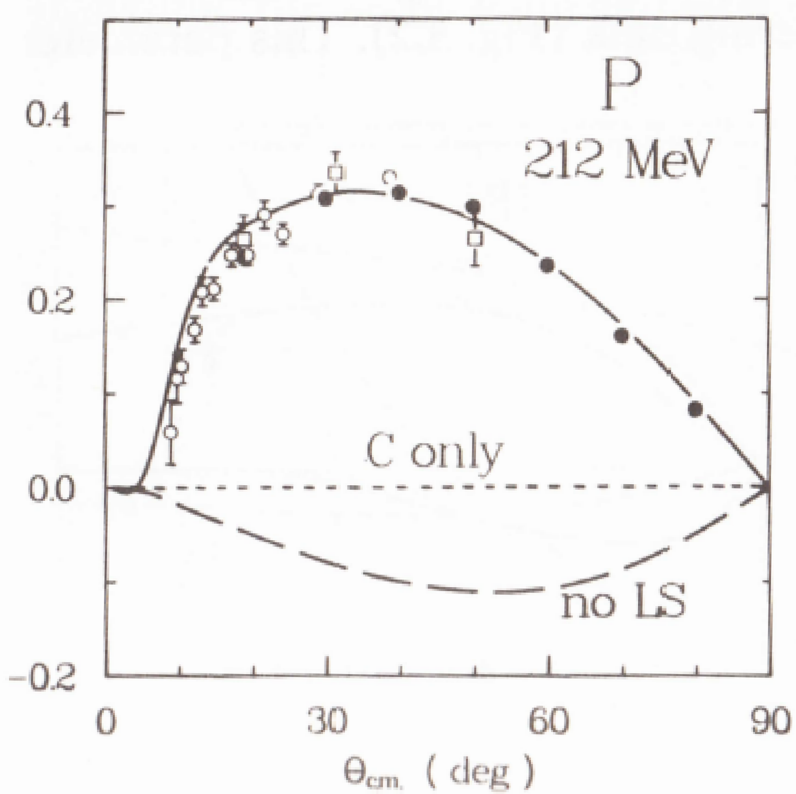


Fig. 3.3. *NN* phase shifts in triplet *P* waves. Shown are predictions using a central force only (C), central plus tensor (C + T), and central plus tensor plus spin–orbit force (C + T + LS). The dots represent energy-independent phase shift analyses (Arn+ 83, Dub+ 82).

Vector Polarization



5. charge independence

Interaction of *pp, nn, & pn*

pp = *nn* : charge symmetry

pp/nn = *pn* : charge independence

Scattering Length a via Partial wave analysis of NN scattering at low energies

$$a_{pp} = -17.3 \pm 0.4 \text{ fm}$$
$$a_{nn} = -18.8 \pm 0.5 \text{ fm}$$
$$a_{pn} = -23.74 \pm 0.02 \text{ fm}$$

→ Charge independence breaking

NN potential (e.g. Bonn Potential)

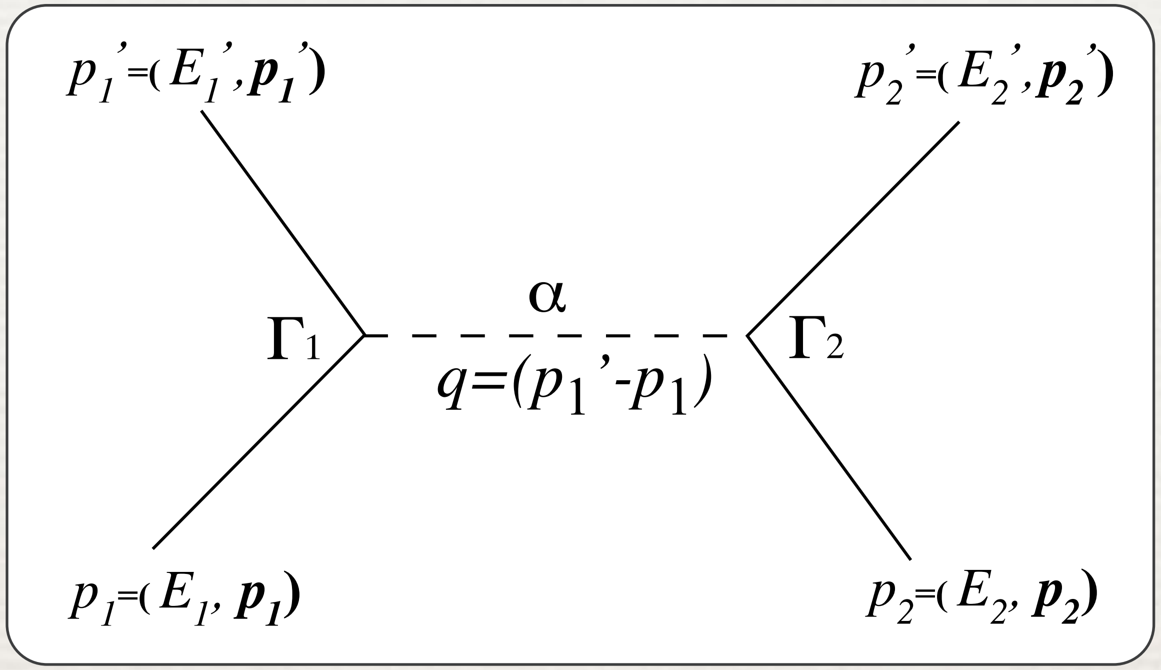
One-Pion Exchange Potential

One-Boson Exchange Potential

$$\frac{\bar{u}_1(p_1')\Gamma_1 u_1(p_1) P_\alpha \bar{u}_2(p_2')\Gamma_2 u_2(p_2)}{(p_1' - p_1)^2 - m_\alpha^2}$$

$u(p)$: Dirac spinor

$\dfrac{P_\alpha}{(p_1' - p_1)^2 - m_\alpha^2}$: Meson Propagator



πNN Lagrangian

$$\mathcal{L}_{\pi NN} = -\frac{f_{\pi NN}}{m_\pi}\overline{\psi}\gamma_5\gamma_\mu\tau\psi \cdot \partial^\mu \phi_\pi \longrightarrow \Gamma$$

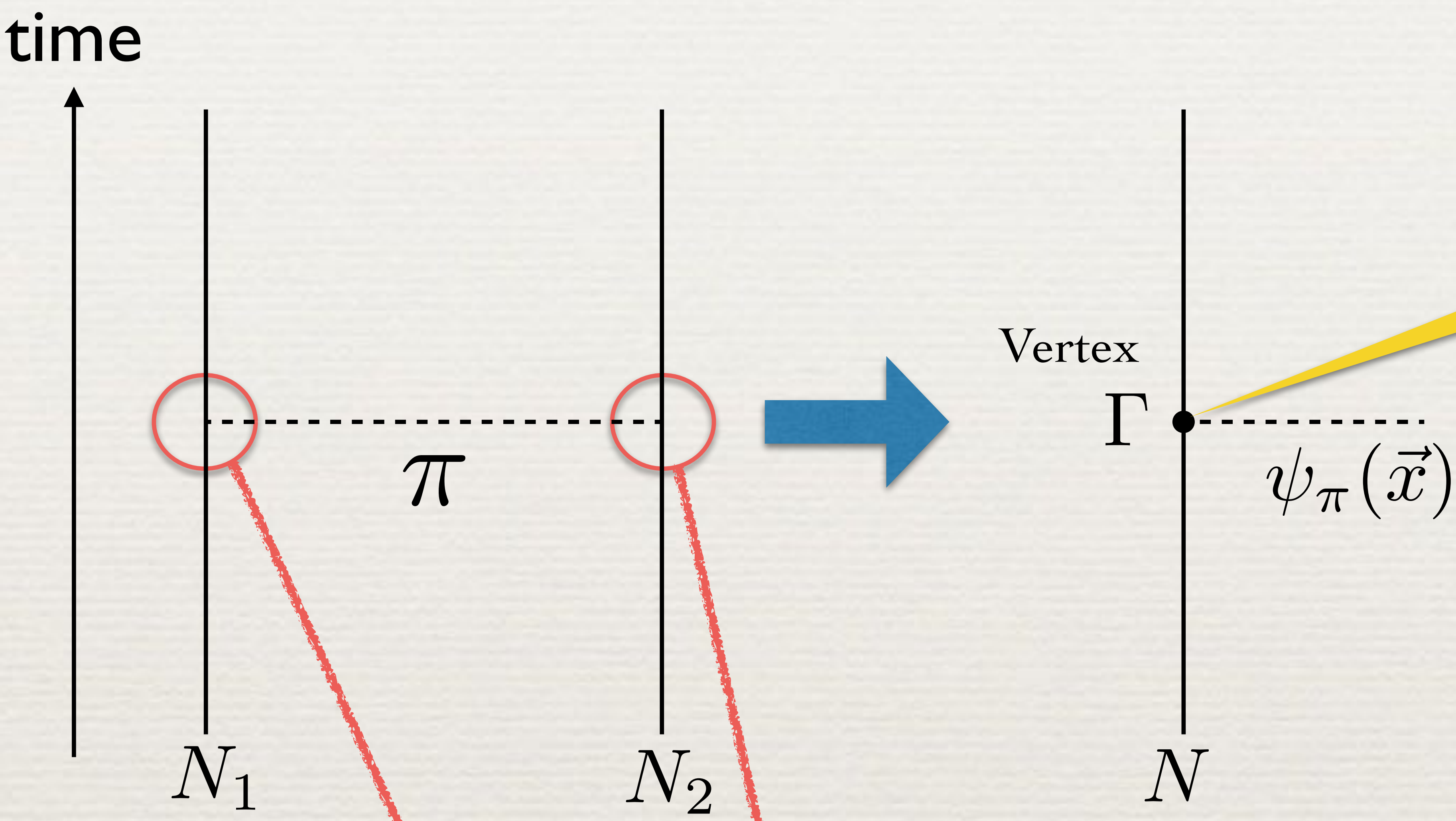
One-Pion Exchange Potential

$$V_\pi = \frac{f_\pi^2}{m_\pi^2}\frac{\overline{u}(p_1')\gamma_5\gamma_\mu(p_1 - p_1')^\mu u(p_1)\ \overline{u}(p_2')\gamma_5\gamma_\nu(p_2' - p_2)^\nu u(p_2)}{(p_1 - p_1')^2 - m_\pi^2}\ \tau_1 \cdot \tau_2$$

Taking the limit of non-relativity…

$$V_\pi = \frac{f_\pi^2}{3m_\pi^2}\frac{\mathbf{k}^2}{\mathbf{k}^2 + m_\pi^2}\left[-\sigma_1 \cdot \sigma_2 - S_{12}(\hat{\mathbf{k}})\right]\ \tau_1 \cdot \tau_2$$

$(p_1 - p_1')^2 = -\mathbf{k}^2$



$$\Gamma\,\psi_\pi(\vec{x})$$

$\psi_\pi(\vec{x})$: pseudo scaler

↓

Γ : pseudo scaler

$\vec{\sigma}\cdot\vec{p}$

Scaler

$$\frac{(\vec{\sigma_1}\cdot\vec{p})\,(\vec{\sigma_2}\cdot\vec{p})}{m_\pi^2+\vec{p}^{\,2}}$$

Propagator

Finally

$$V_\pi = -\frac{f_{\pi NN}^2}{m_\pi^2} \frac{(\vec{\sigma_1} \cdot \vec{p})(\vec{\sigma_2} \cdot \vec{p})}{m_\pi^2 + \vec{p}^{\,2}} \vec{\tau_1} \cdot \vec{\tau_2}$$

$$S_{12}(\hat{p}) = 3(\vec{\sigma_1} \cdot \hat{p})(\vec{\sigma_2} \cdot \hat{p}) - \vec{\sigma_1} \cdot \vec{\sigma}_2$$

Tensor Operator

Then

$$V_\pi = \frac{f_{\pi NN}^2}{2m_\pi^2} \frac{\vec{p}^{\,2}}{m_\pi^2 + \vec{p}^{\,2}} \left(-\vec{\sigma}_1 \cdot \vec{\sigma}_2 - S_{12}(\hat{q}) \right) \vec{\tau_1} \cdot \vec{\tau_2}$$

attractive

$\pi(138)$	$V_\pi = \frac{f_\pi^2}{3m_\pi^2}\frac{\mathbf{k}^2}{\mathbf{k}^2+m_\pi^2}\left[-\sigma_1\cdot\sigma_2 - S_{12}(\hat{\mathbf{k}})\right]\ \tau_1\cdot\tau_2$	long range tensor (attractive)
$\sigma(600)$	$V_\sigma = g_\sigma^2\ \frac{1}{\mathbf{k}^2+m_\sigma^2}\left(-1+\frac{\mathbf{q}^2}{2M_N^2}-\frac{\mathbf{k}^2}{8M_N^2}-\frac{\mathbf{L}\cdot\mathbf{S}}{2M_N^2}\right)$	Intermediate range attractive (central), LS
$\omega(782)$	$V_\omega = g_\omega^2\frac{1}{\mathbf{k}^2+m_\omega^2}\left(1-3\frac{\mathbf{L}\cdot\mathbf{S}}{2M_N^2}\right)$	Short range repulsive(central), LS
$\rho(770)$	$V_\rho = \frac{f_\rho^2}{12M^2}\frac{\mathbf{k}^2}{\mathbf{k}^2+m_\rho^2}\left(-2\sigma_1\sigma_2+S_{12}(\hat{\mathbf{k}})\right)\tau_1\tau_2$	Short range tensor (repulsive)

Realistic NN potential

- NN potentials which reproduce deuteron properties and 3000-4000 nucleon-nucleon scattering data and with high precision (χ^2/dataum ~ 1).
  - CD Bonn : R. Machleidt, Phys. Rev. C **63**, 024001 (2001)
  - Argonne V_{18} : R.B. Wiringa et al., Phys. Rev. C **51**, 38 (1995)
  - Nijmegen I, II : V.G.J. Stoks et al., Phys. Rev. C **49**, 2950 (1994)

	CD-Bonn	AV_{18}	Nijm I	Nijm II	Exp.
Character	Nonlocal	Local	Nonlocal	Local	
NN Scattering Data					
N_{data}	3058	4301	4301	4301	
χ^2/datum	1.03	1.09	1.03	1.03	
Deuteron Properties					
Quadr. moment [fm^2]	0.270	0.270	0.2719	0.2707	0.2859(3)
Asymptotic D/S state	0.0255	0.0250	0.0253	0.0252	0.0256(4)
D-state probab. [%]	4.83	5.76	5.664	5.635	

Number of parameters to be fitted to NN data : about 40

2N Systems

Two-Nucleon Systems

- Deuteron
- Nucleon-Nucleon Scattering

S wave(l=0)

	State	Iso-Spin	System	Scattering Length a [fm]
deuteron	$^3S_1$	$T=0$	np	5.424
Unbound States	$^1S_0$	$T=1$	np	-23.7
			pp	-17.3
			nn	-18.8

$^{2S+1}L_J$

J : Total Spin ***J=L+S***
S : Spin of Two fermion systems
L : Angular Momentum

Deuteron

- Two nucleon bound system
- $(J^{\pi}, T) = (1^{+}, 0)$
- Binding Energy : 2.22456612(48) MeV
- Electric quadrupole moment : $Q \neq 0$
- Magnetic moment : $\mu_d = 0.85741(8)\mu_N$

$$\mu_p + \mu_n \neq \mu_d$$

} $^3S_1 + {}^3D_1$

	CD-Bonn	Argonne v_{18}	Nijmegen I	Ihaho $N^3LO(500)$	Exp.
B_d(MeV)	2.224575	2.224575	2.224575	2.224575	2.22456612(48)
Matter radius r_d(fm)	1.966	1.967		1.975	1.975(3)
Q (fm^2)	0.270	0.270	0.272	0.275	0.2859(3)
P_D(%)	4.85	5.76	5.664	4.51	—

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Nucleon-Nucleon Scattering

- *pp*, *nn*, *pn* Systems (poor data of *nn* scattering)
  - Observables
    - Cross Section : Magnitudes
    - Spin Observables : Spin dependence
  - Scattering amplitudes

Observables

- **Cross Section** $\frac{d\sigma}{d\Omega}$
  - **Overall Strength**

$$\frac{d\sigma}{d\Omega} = |f(\theta)|^2$$

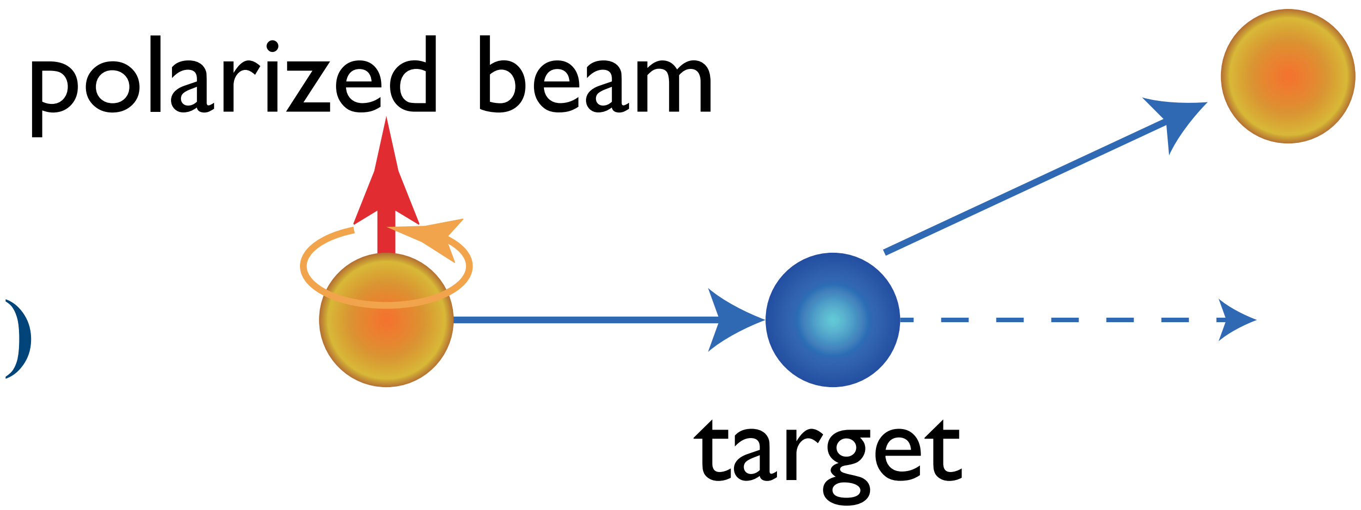
$$f(\theta) = -\frac{(2\pi)^{3/2}}{4\pi} \int \exp(-\mathbf{q}\cdot\mathbf{r}') \, V(r') d\mathbf{r}'$$

Fourier Transform of Nuclear Potential

➤ **Measurement : Absolute Quantity is required (very hard !).**

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

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

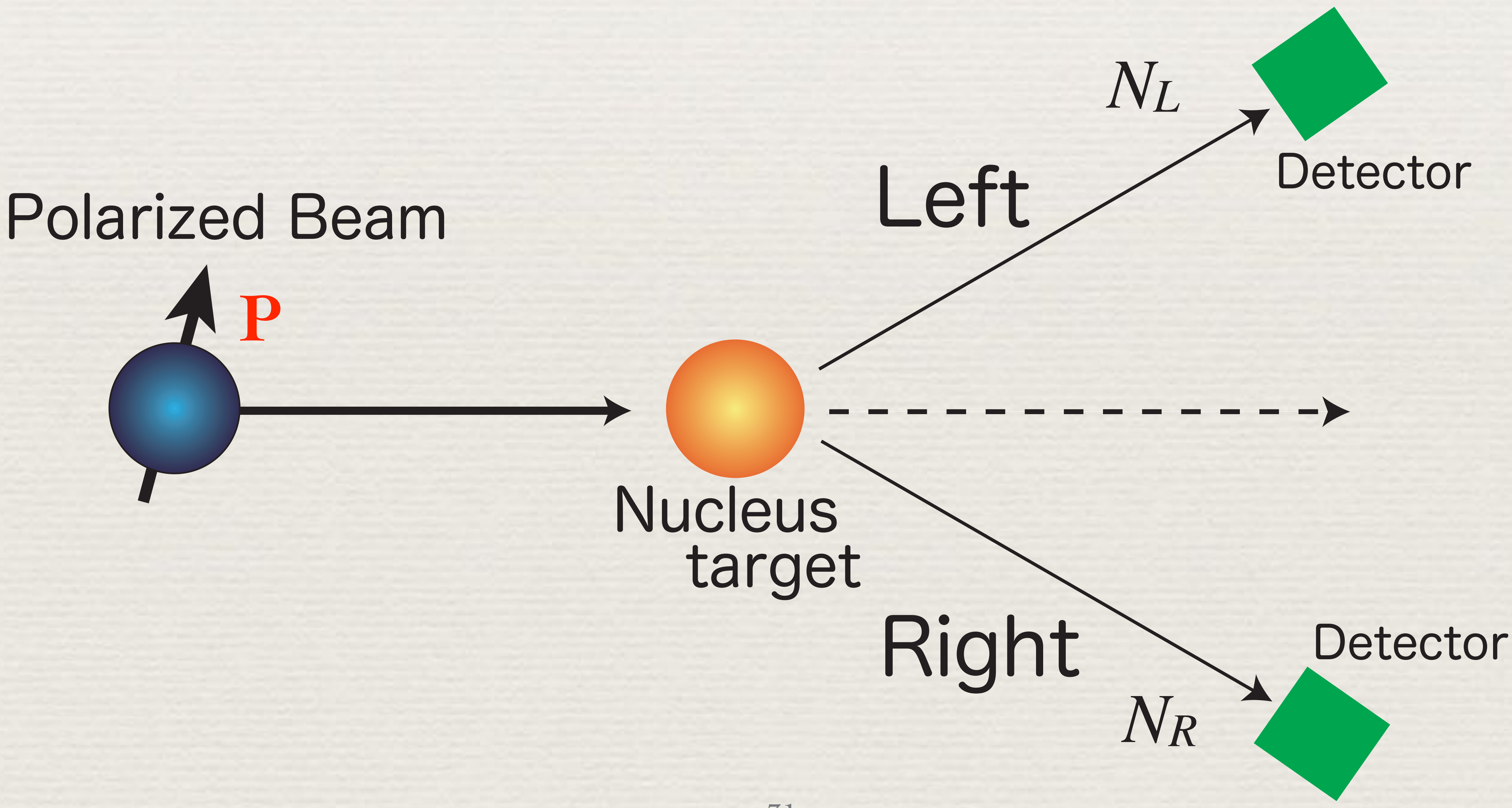


Measurement of Polarization

$$\text{Asymmetry} = P \cdot A = \frac{N_L - N_R}{N_L + N_R}$$

P : **Beam Polarization**

A : **Analyzing Power**



NN (pp or pn) Scattering : Partial Wave Analysis

$$f(\theta) = \frac{1}{k} \sum_{l=0}^{\infty} (2l+1)\, e^{i\delta_l} \sin(\delta_l) P_l(\cos\theta)$$

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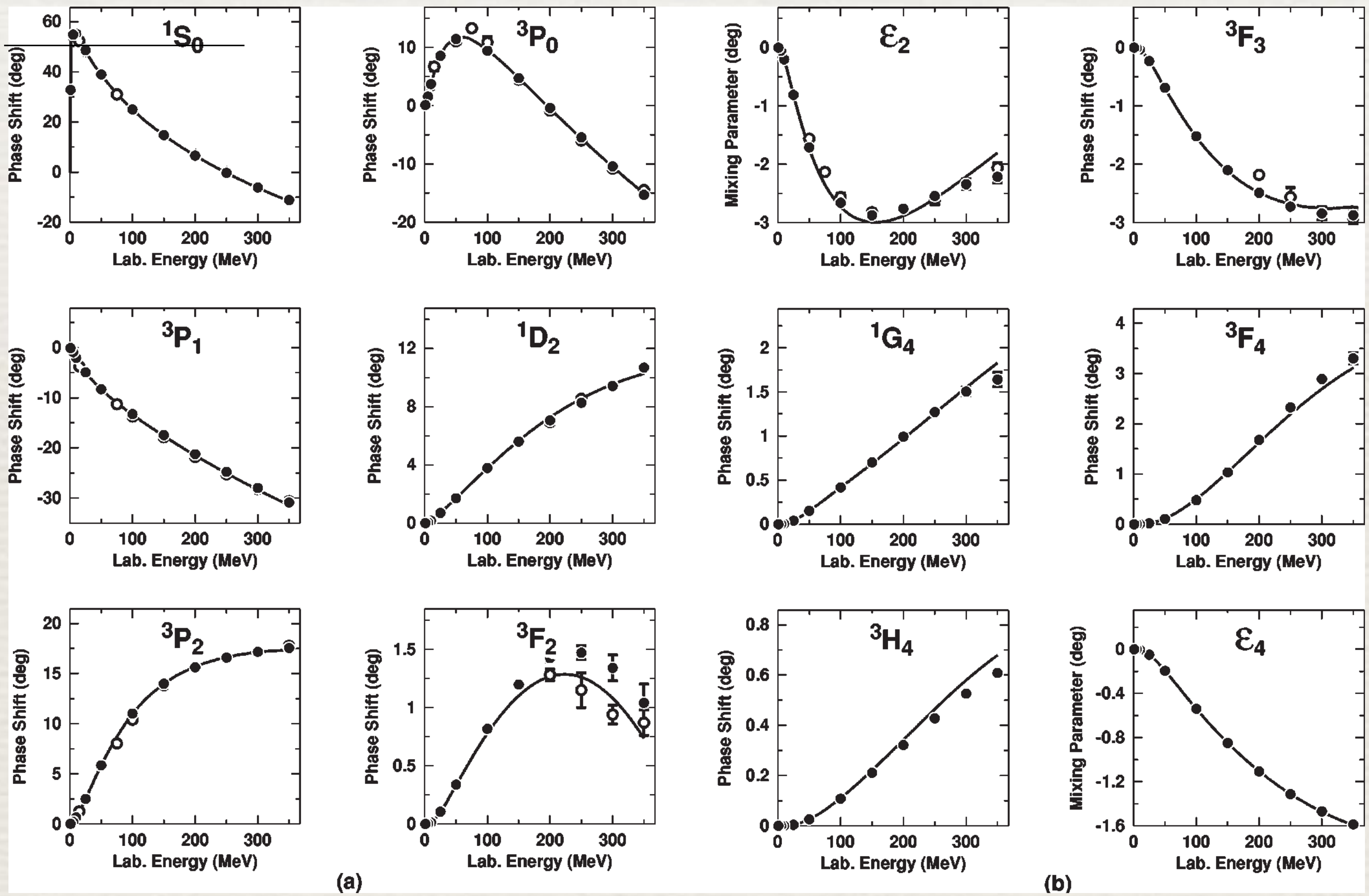
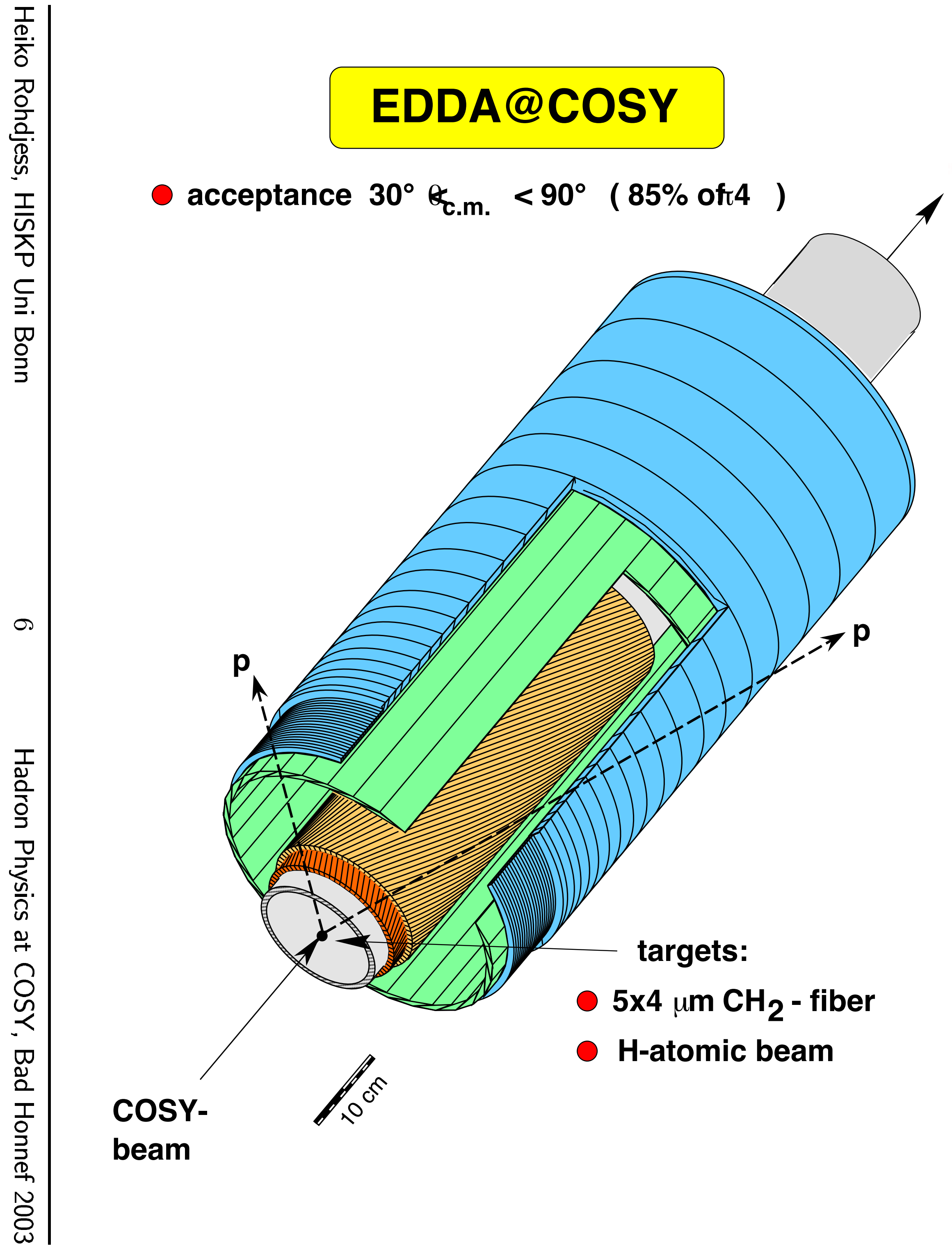
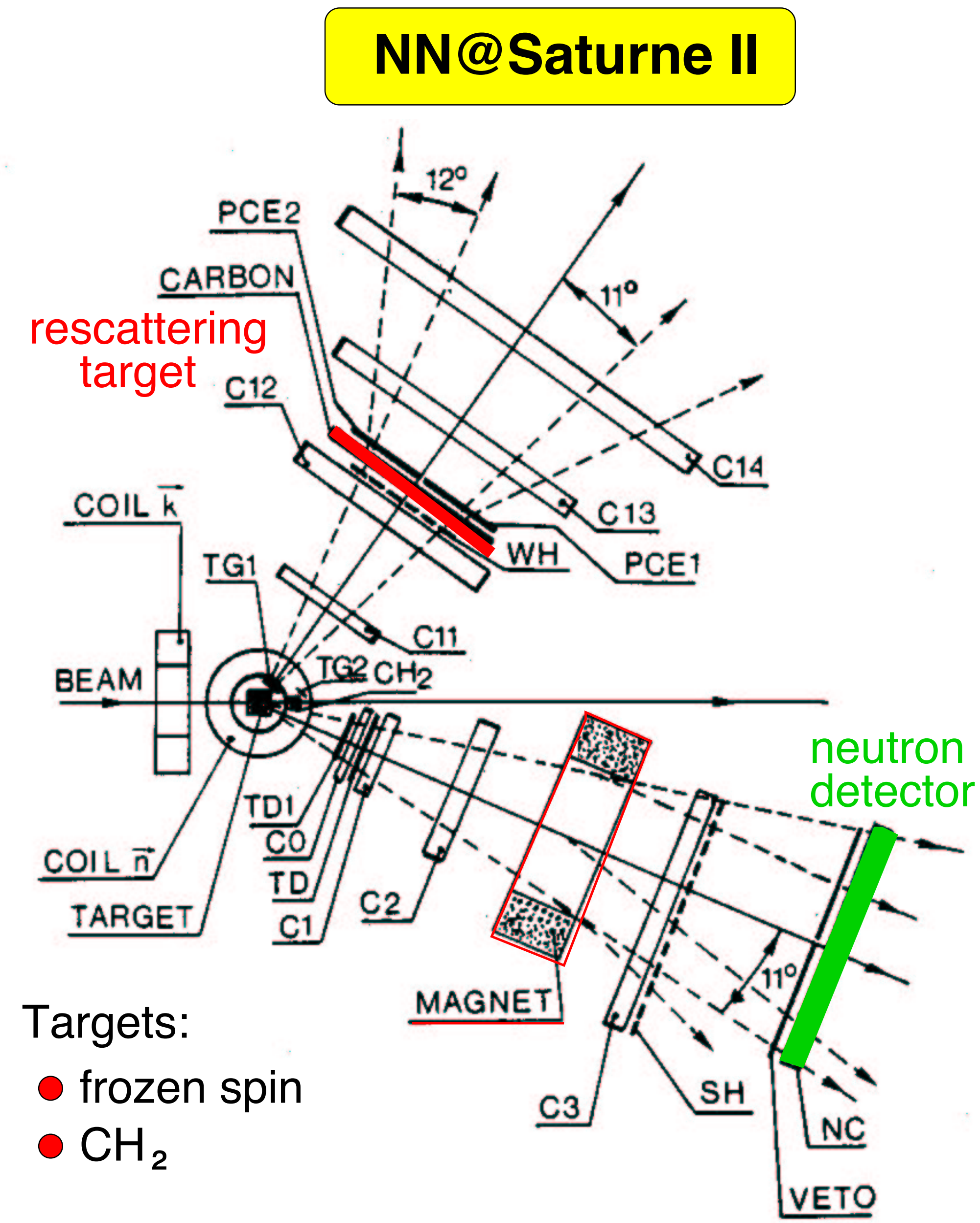


FIG. 6. *pp* phase parameters in partial waves with $J \leqslant 4$. The solid line represents the predictions by the CD-Bonn potential. The solid dots and open circles are the results from the Nijmegen multienergy *pp* phase shift analysis [46] and the VPI single-energy *pp* analysis SM99 [49], respectively.

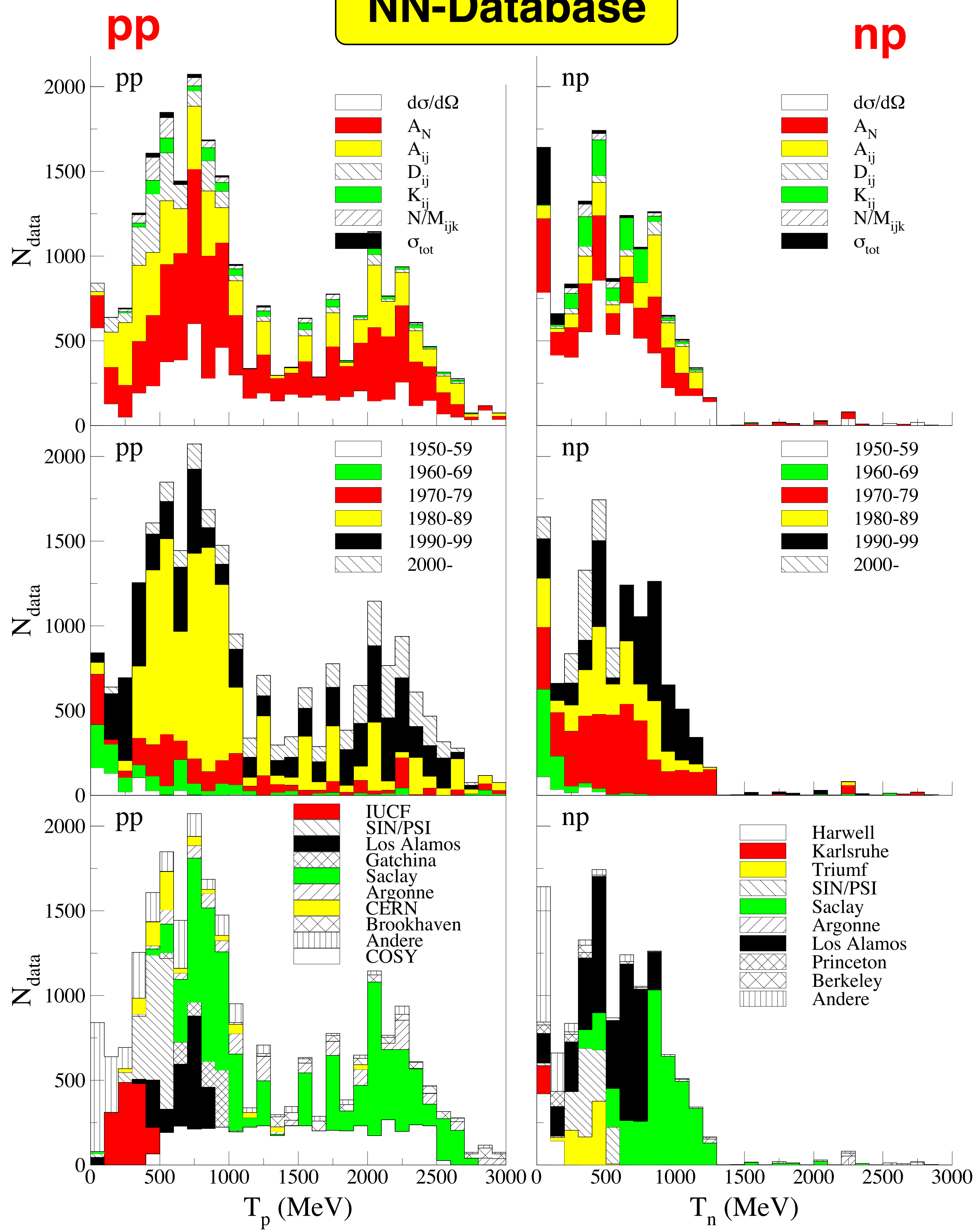
NN Scattering

- Experiments





NN-Database


pp
np
pp
np
dσ/dΩ
A_N
A_{ij}
D_{ij}
K_{ij}
N/M_{ijk}
σ_{tot}
1950-59
1960-69
1970-79
1980-89
1990-99
2000-
IUCF
SIN/PSI
Los Alamos
Gatchina
Saclay
Argonne
CERN
Brookhaven
Andere
COSY
Harwell
Karlsruhe
Triumf
SIN/PSI
Saclay
Argonne
Los Alamos
Princeton
Berkeley
Andere
N_{data}
T_p (MeV)
T_n (MeV)
0
500
1000
1500
2000
2500
3000

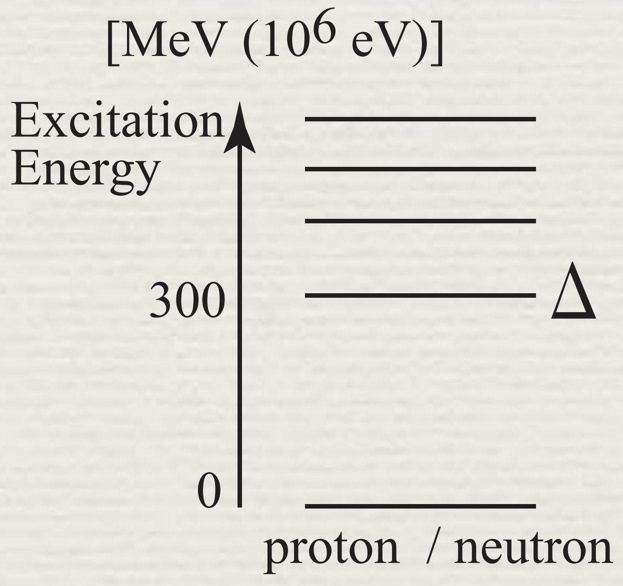
35

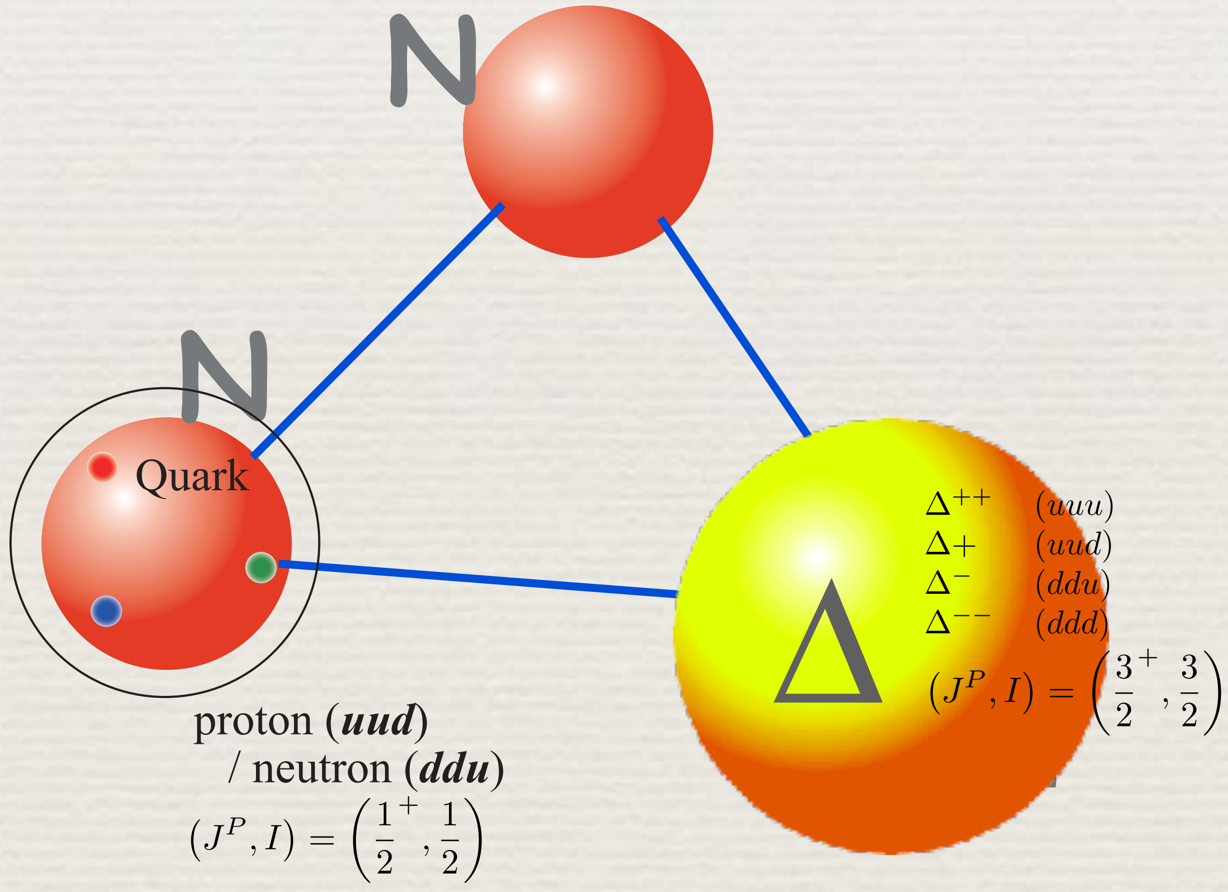
Three-Nucleon Forces

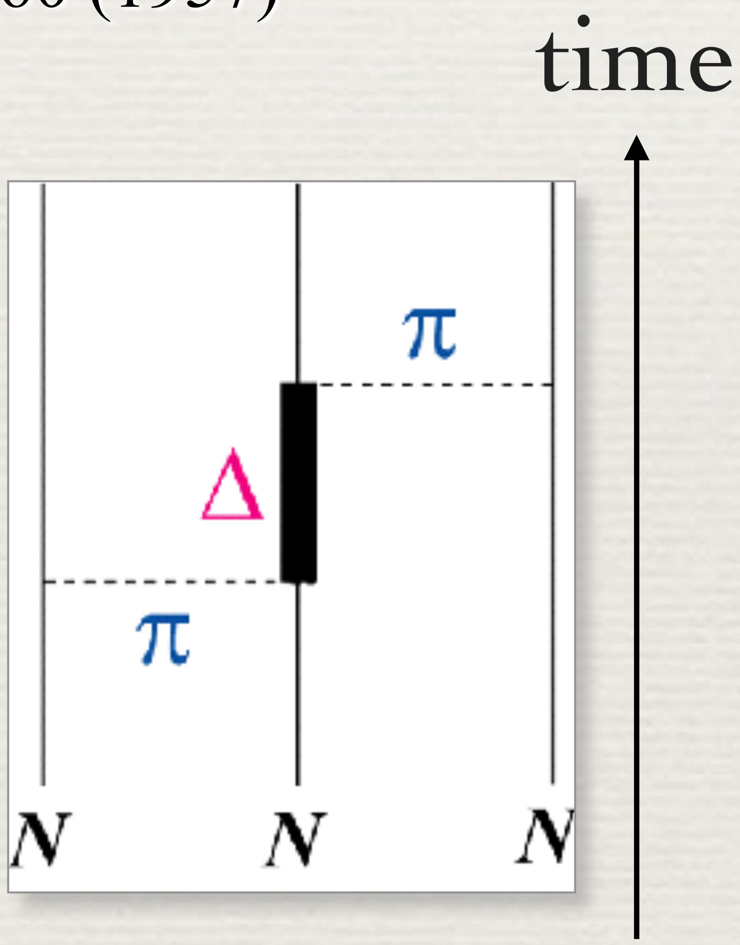
Three-Body Forces in Nuclei
– 3-Nucleon Force –

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

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



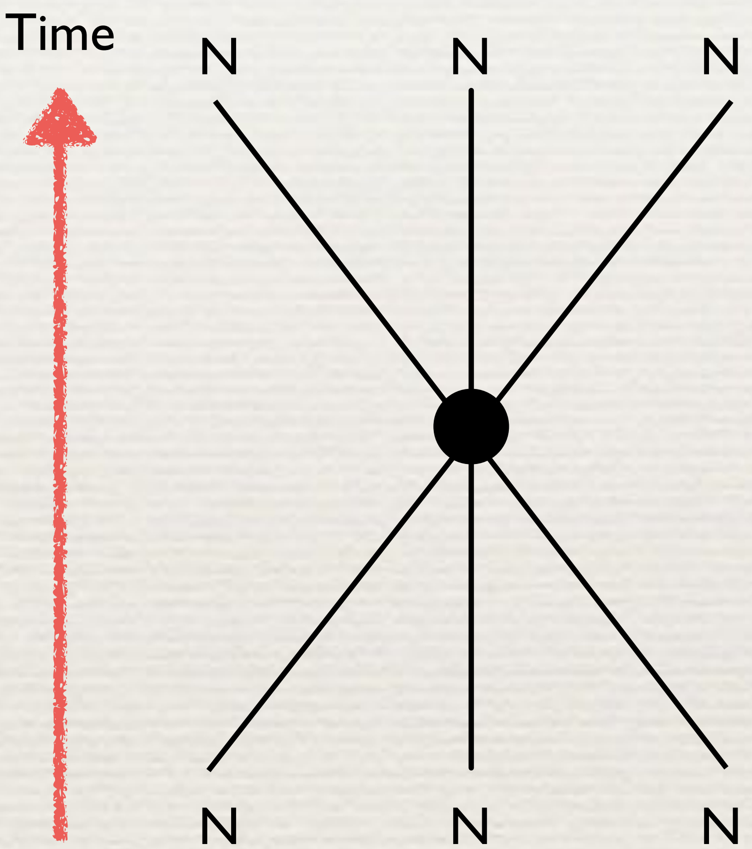


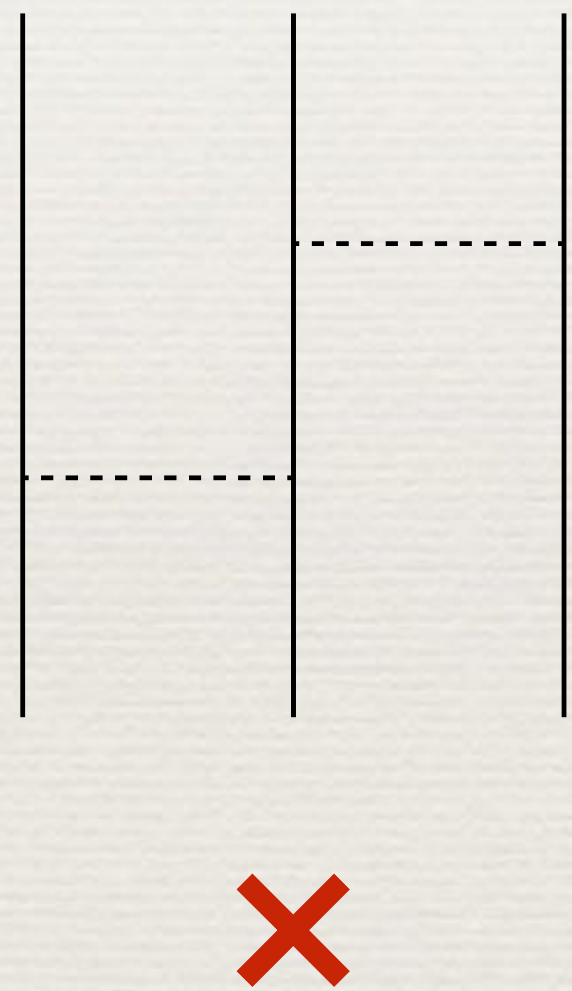


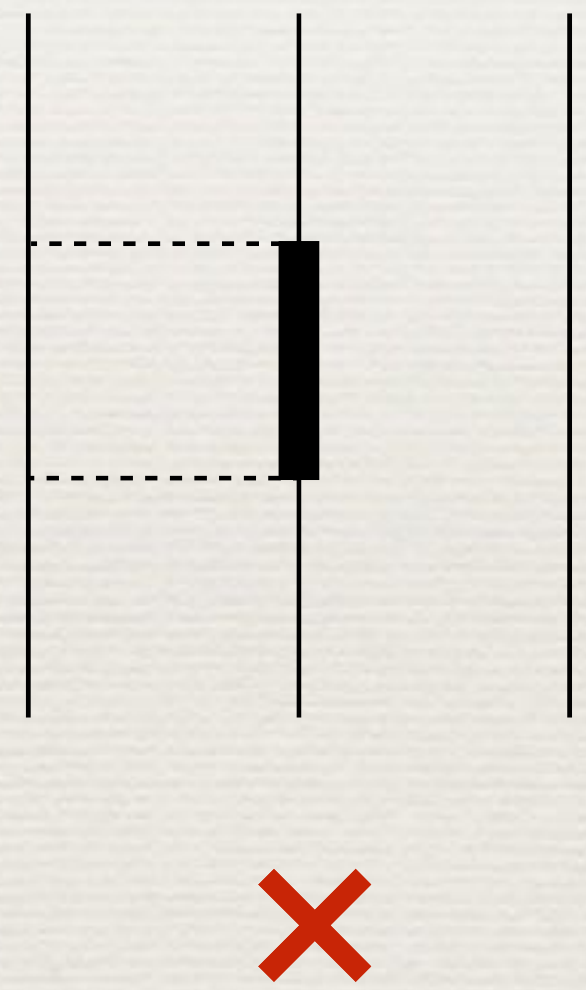
3NF naturally arises due to the inner structure of Nucleon.

Three-Nucleon Forces

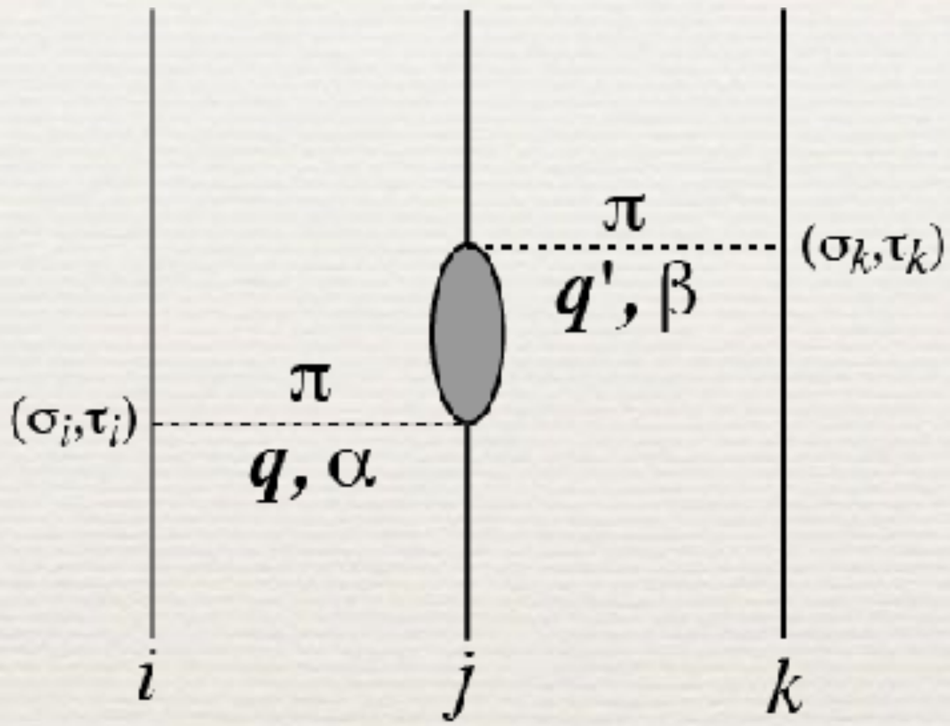
- nuclear forces acting in systems more than $A > 2$ nucleons -







2-pion exchange 3NF



$$V_{3NF} = \sum_{\text{cyclic}} V^{(j)}_{3NF},$$

J.L.Friar et al., Phys. Rev. C 59, 53(1999)

$$V^{(j)}_{3NF} = \frac{g^2}{4m_N^2} \frac{\vec{\sigma}_i \cdot \boldsymbol{q}}{\boldsymbol{q}^2 + m_\pi^2} \frac{\vec{\sigma}_k \cdot \boldsymbol{q}'}{\boldsymbol{q}'^2 + m_\pi^2} F^2_{\pi NN}(\boldsymbol{q}^2) F^2_{\pi NN}(\boldsymbol{q}'^2) \left[\mathcal{O}^{\alpha\beta} \tau_i^\alpha \tau_k^\beta \right],$$

$$\mathcal{O}^{\alpha\beta} = \xi^{\alpha\beta} \left[\boldsymbol{a} + \boldsymbol{b}\, \boldsymbol{q} \cdot \boldsymbol{q}' + \boldsymbol{c} (\boldsymbol{q}^2 + \boldsymbol{q}'^2) \right] - \boldsymbol{d} \left(\tau_j^\gamma \epsilon^{\alpha\beta\gamma} \vec{\sigma}_j \cdot \boldsymbol{q} \times \boldsymbol{q}' \right) ,$$

- Low momentum expansion of πN Scattering amplitudes
- Cut-off of $F_{\pi NN}$: fit to B.E. of ^{3}H

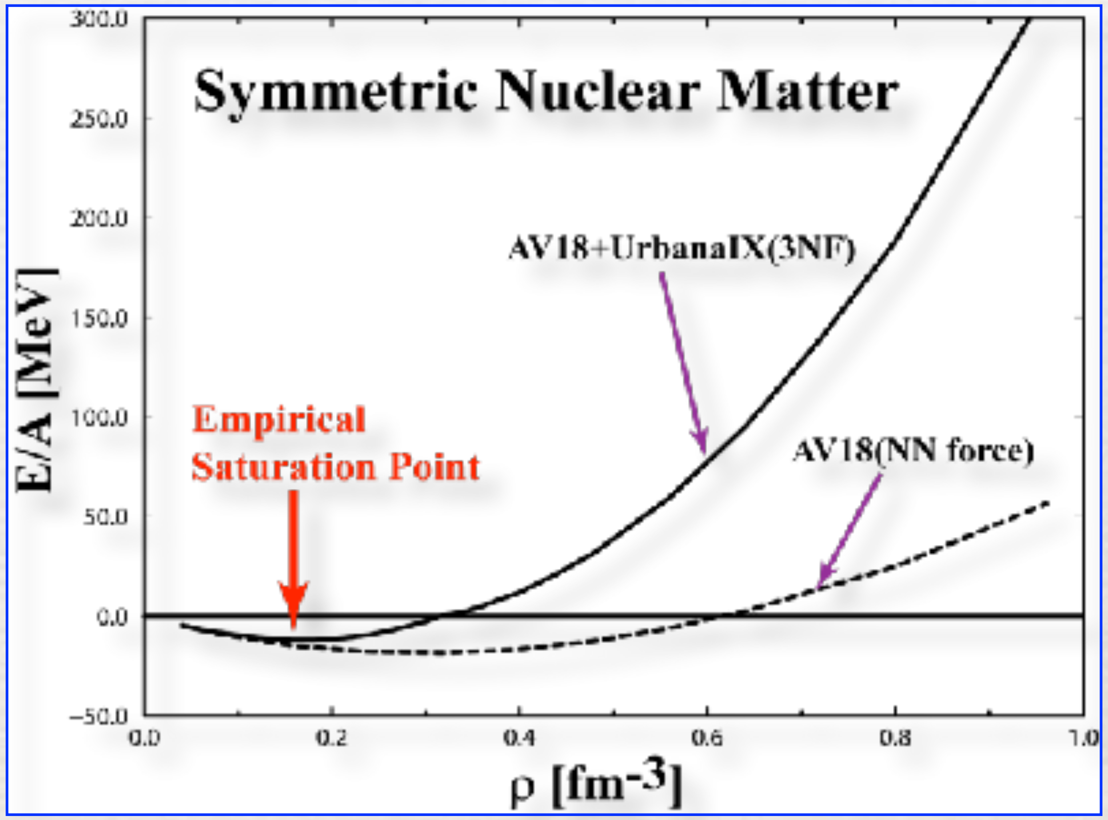
Urbana-IX 3NF

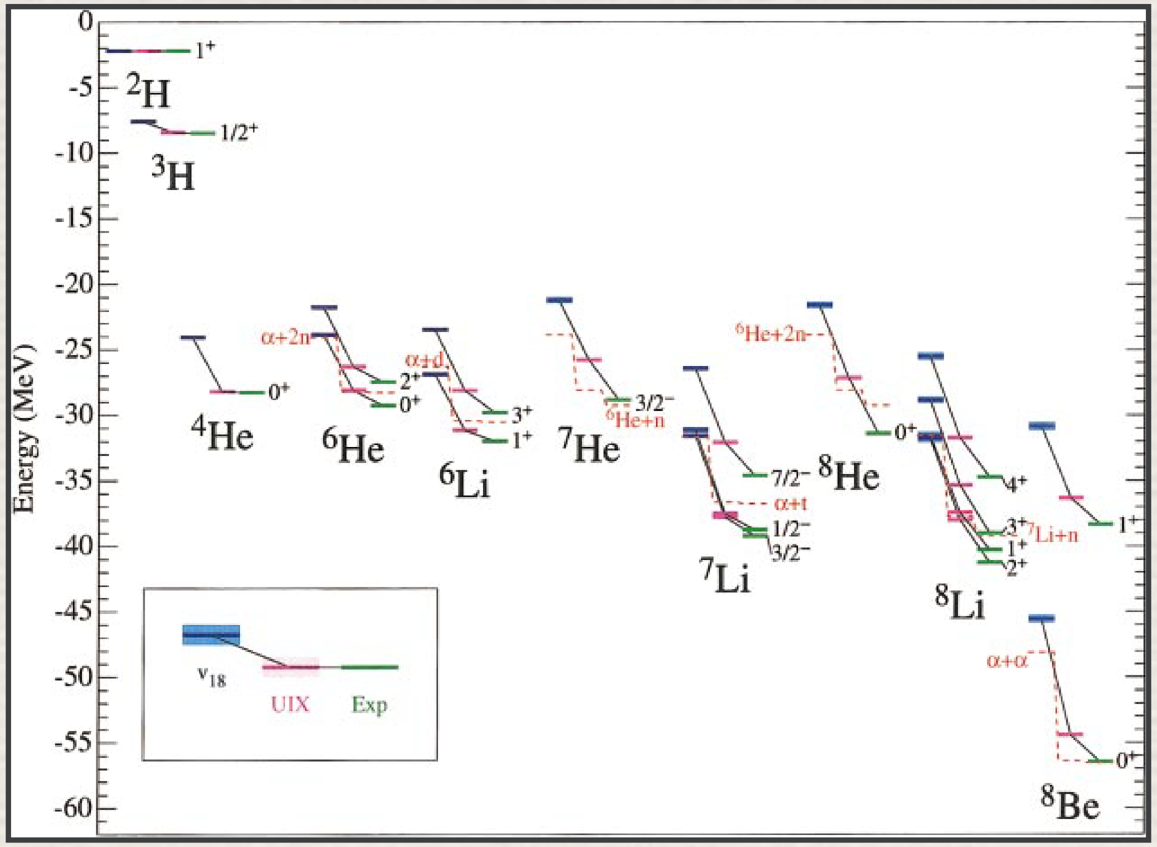
B. S. Pudliner, V. R. Pandharipande, J. Carlson, S. C. Pieper, and R. B. Wiringa, Phys. Rev. C **56**, 1720 (1997).

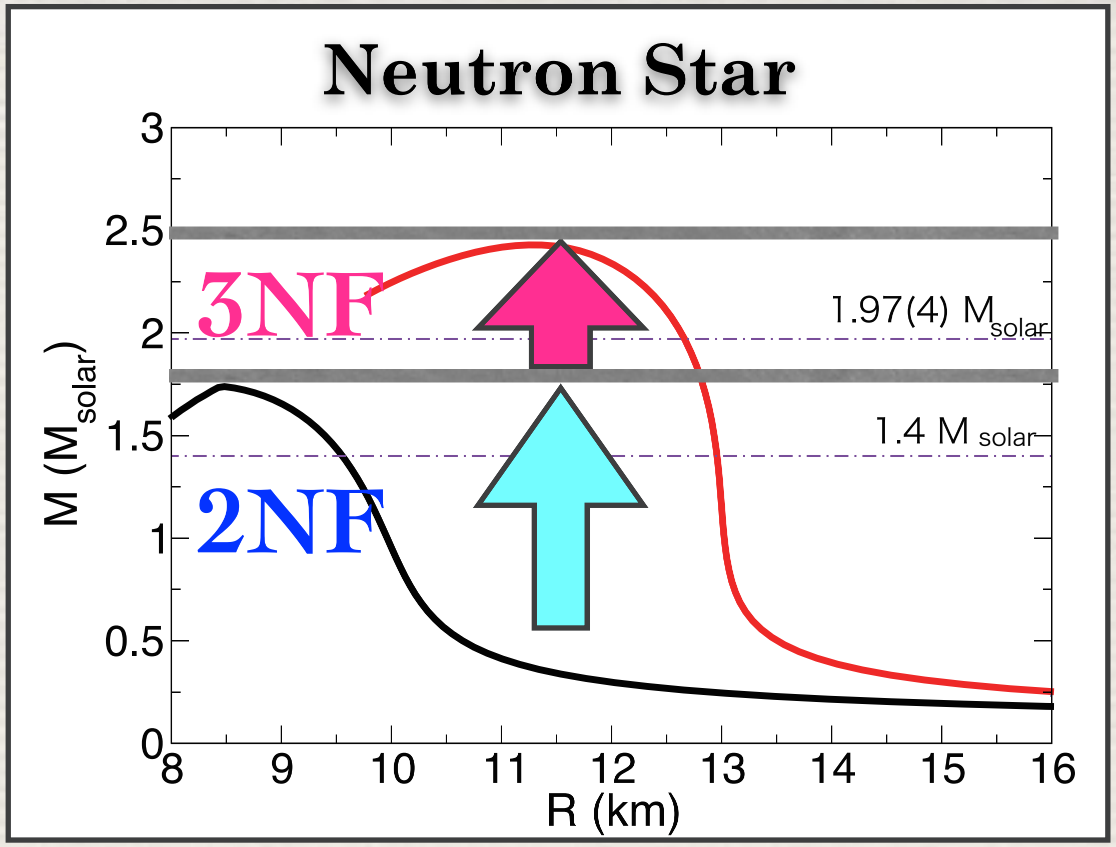
- 2π-exchange (Fujita-Miyazawa 3NF)
  + phenomenological short-range 3NF $V_{2\pi} + V_R$
- 2 parameters

  $A_{2\pi}$: Binding Energy of ^3H

  U_0 : Saturation Point of Symmetric Nuclear matter







A. Akmal et al., Phys. Rev. C 58, 1804('98)

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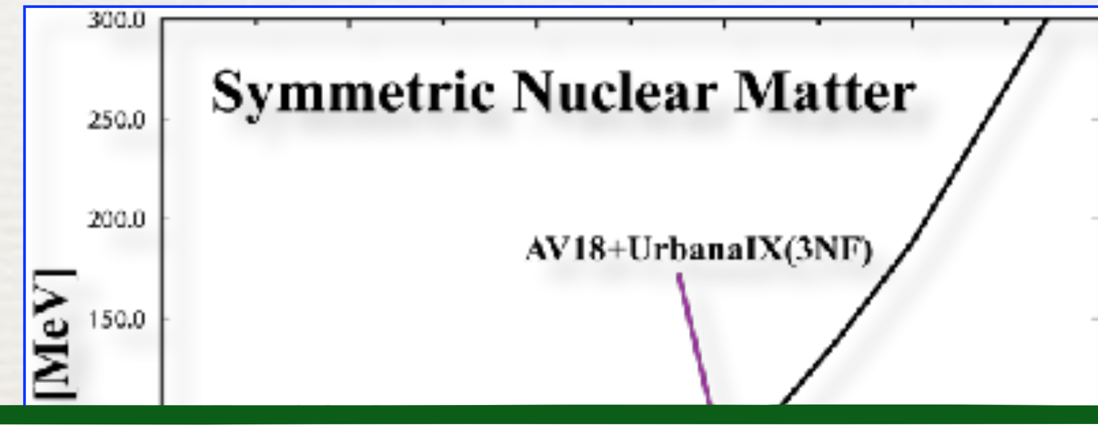
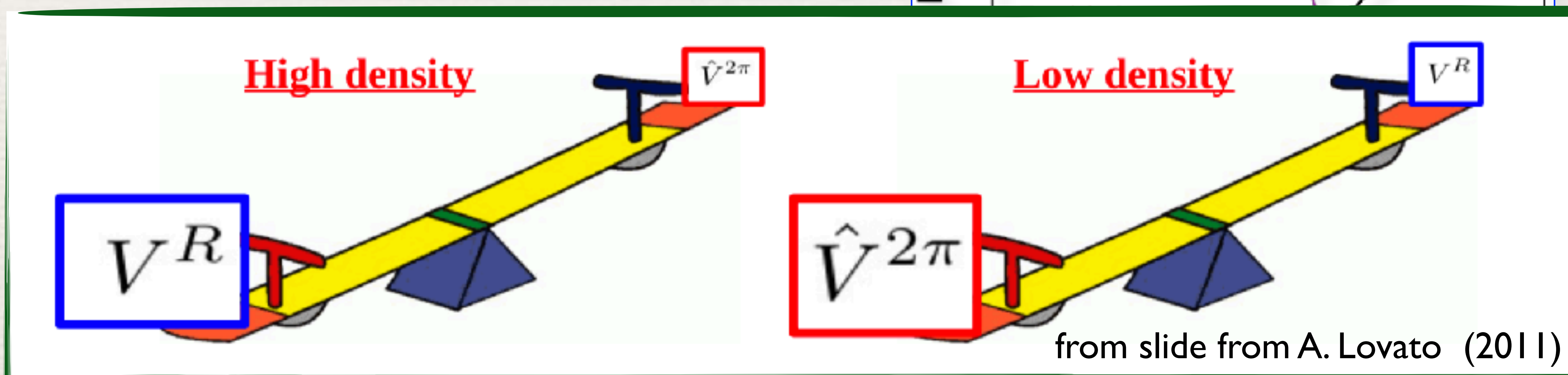
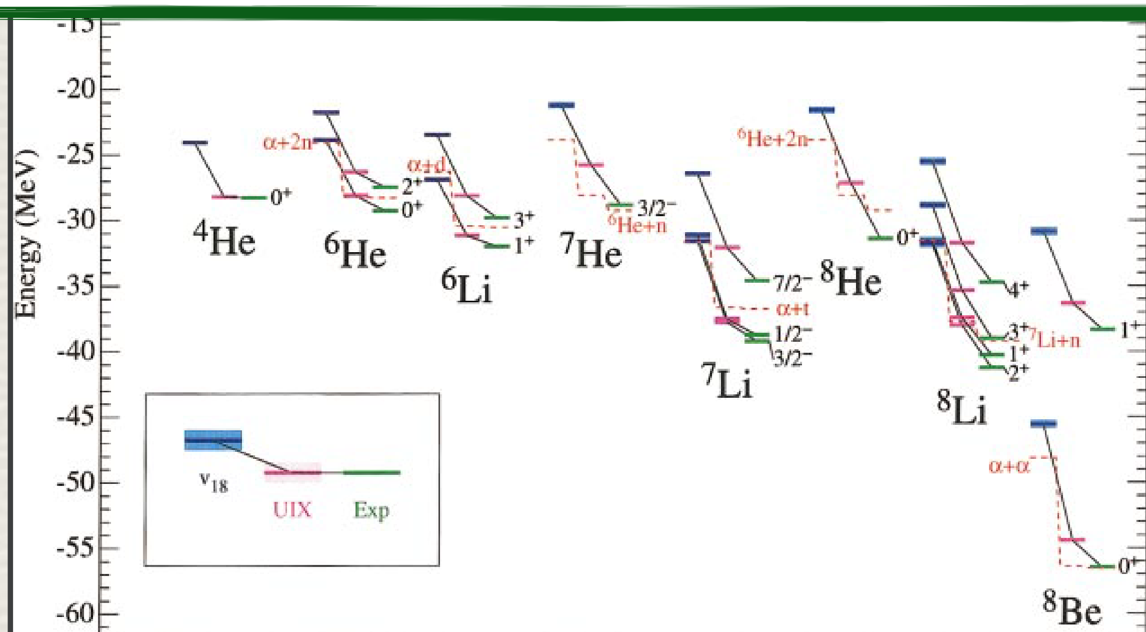
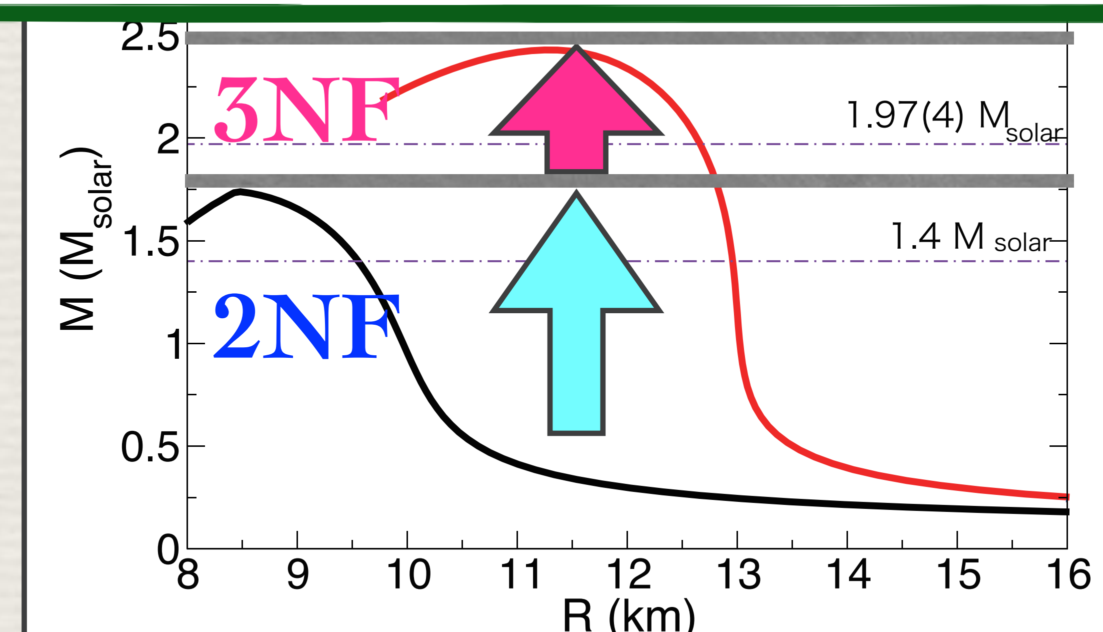








A. Akmal et al., Phys. Rev. C 58, 1804('98)

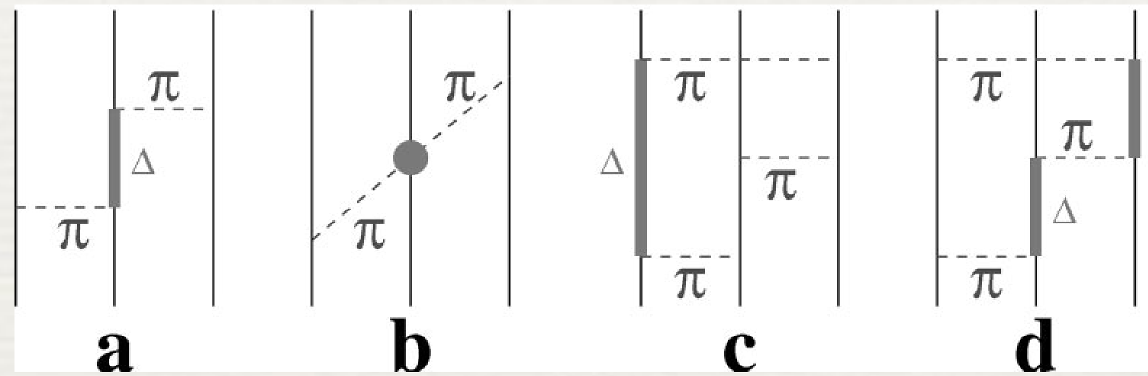
Illinois-3NF

- Extension of Urbana-IX 3NF
- 2π-exchange (πN scattering S-wave : b)

  (πN scattering P-wave : a)

  + 3π-ring with one Δ (c, d)

  + phenomenological short range



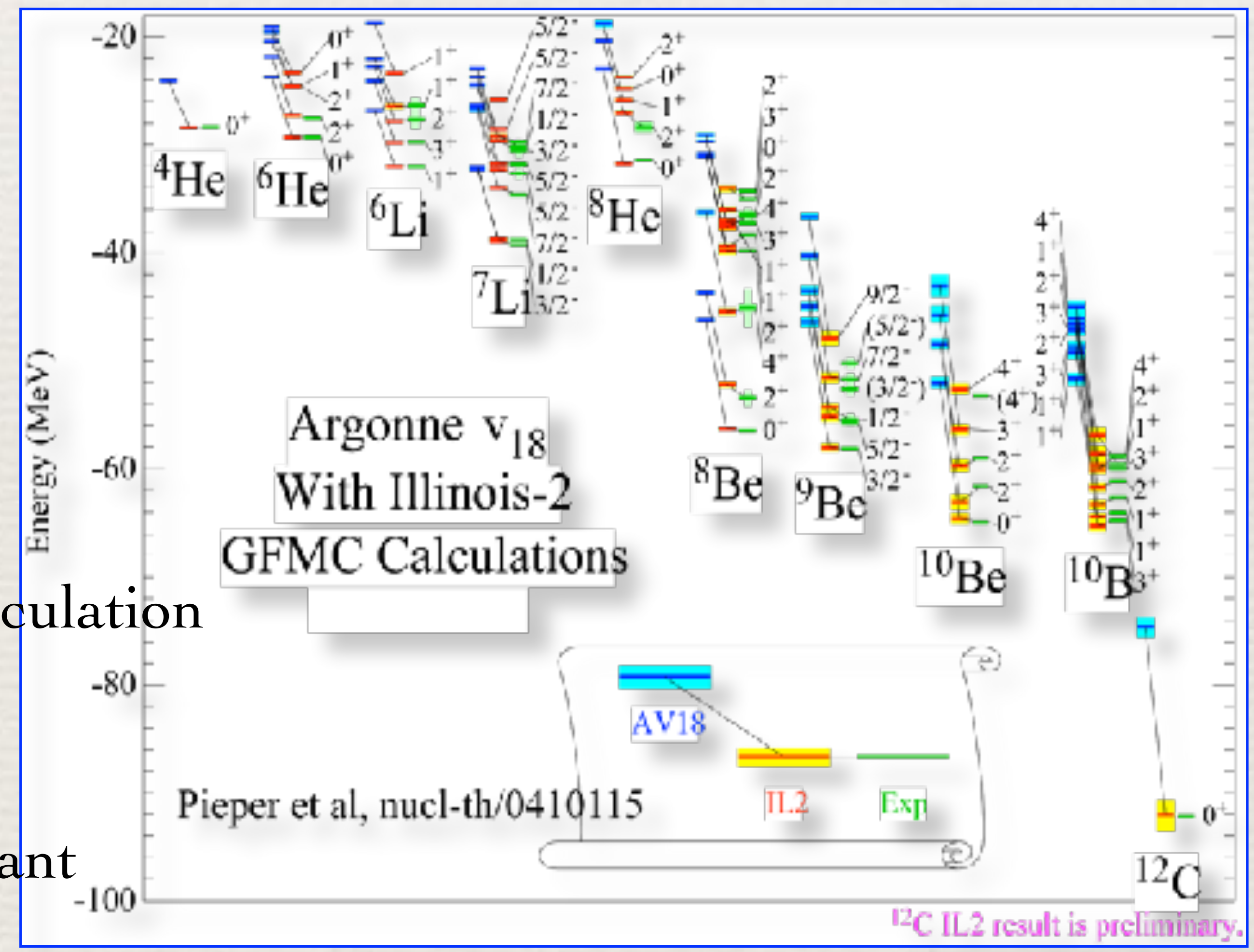
- 5 parameters (including short-range 3NF)

  Binding Energies of 17 light nuclei

- Applied to light nuclei $A \leq 12$

  with combination of AV18 NN potential

  → Green Function Monte Carlo (GFMC) Calculation



- p-shell Nuclei
  - Isospin channels of T=3/2 3NF are important

    in neutron-rich nuclei ?

  - 3π-ring 3NF : remarkable T=3/2 3NFs

S.C.Pieper, K. Varga, and R. B. Wiringa, Phys. Rev. C 66, 44310 (2002)

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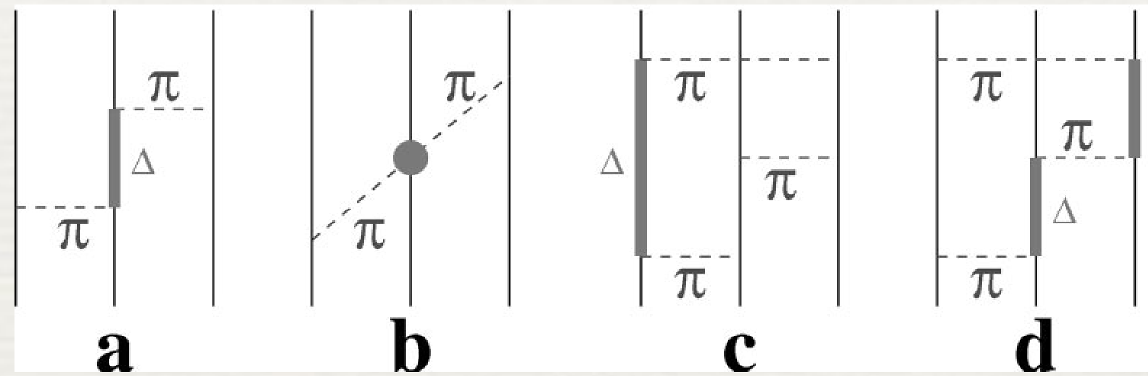
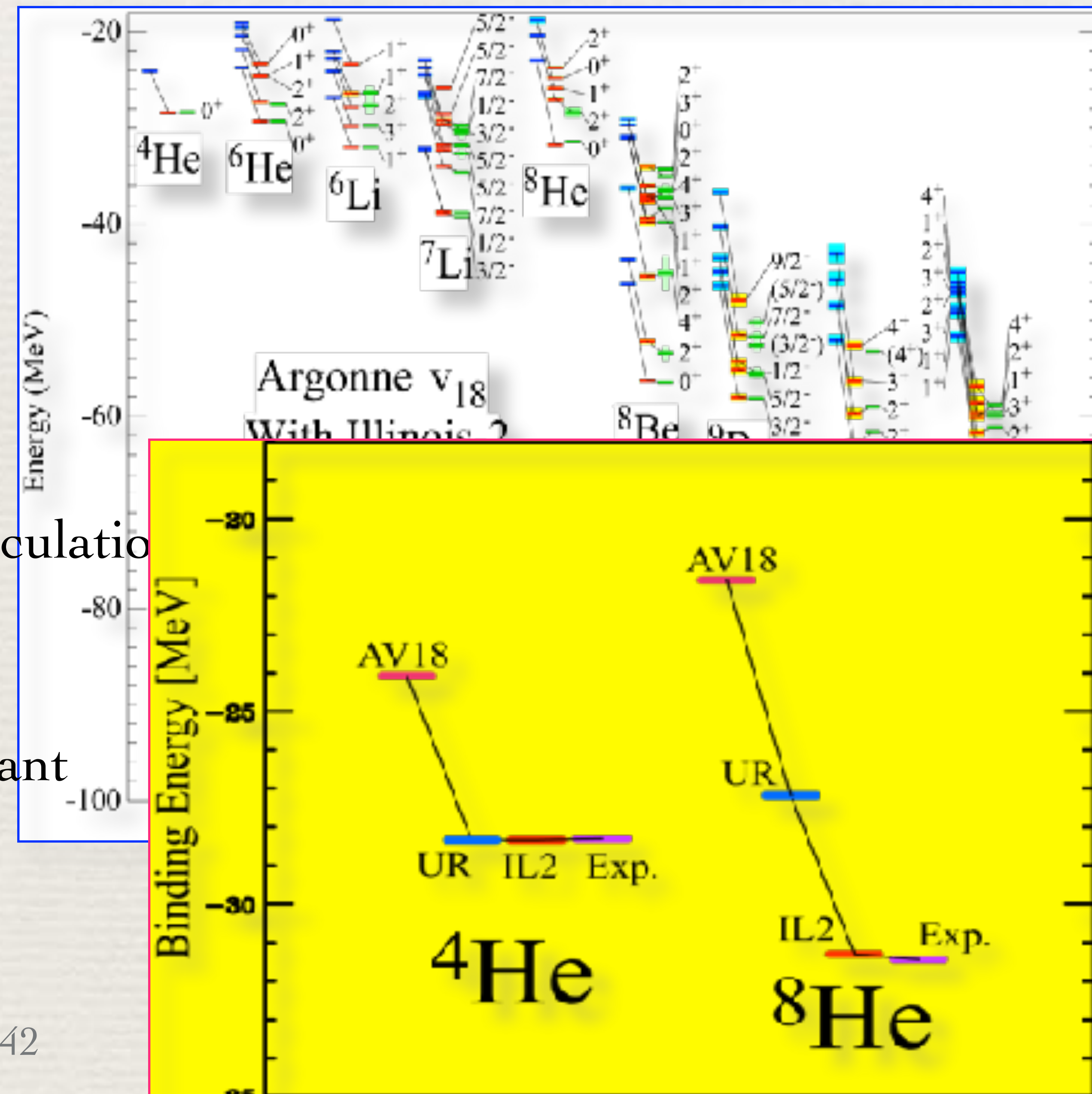




a,

2-meson exchange 3NF in ^{3}H B.E.

SHORT-RANGE THREE-NUCLEON FORCES AND LOW… PHYSICAL REVIEW C **69**, 034008 (2004)

TABLE IV. Triton binding energies and their differences (in MeV) calculated for various model Hamiltonians with different *NN* potentials and contributions to the 3*N* force added consecutively. All πNN vertices in the 3*N* forces of this table are calculated in PV coupling. The columns labeled E_t show the triton binding energies, while the ones labeled ΔE_t indicate the differences between the binding energies of consecutive rows, indicating the effect of the corresponding 3*N* force component.

	Reid		Paris		Nijmegen 93		Bonn B	
3NF	E_t	ΔE_t	E_t	ΔE_t	E_t	ΔE_t	E_t	ΔE_t
No 3NF	−7.230		−7.383		−7.756		−8.100	
$+\pi\pi(a')$	−7.279	−0.049	−7.439	−0.056	−7.811	−0.055	−8.159	−0.059
$+\pi\pi(b)$	−8.739	−1.460	−8.939	−1.500	−9.471	−1.660	−9.624	−1.465
$+\pi\pi(d)$	−9.100	−0.361	−9.220	−0.281	−9.782	−0.311	−9.847	−0.223
$+\pi\rho(\mathrm{KR})$	−9.017	0.083	−9.118	0.102	−9.635	0.147	−9.672	0.175
$+\pi\rho(\Delta^{+})$	−8.849	0.168	−8.961	0.157	−9.464	0.171	−9.506	0.166
$+\pi\rho(\Delta^{-})$	−8.747	0.102	−8.821	0.140	−9.285	0.179	−9.325	0.181
$+\pi\rho(T)$	−8.772	−0.025	−8.850	−0.029	−9.316	−0.031	−9.352	−0.027
$+\pi\sigma(Z)$	−8.273	0.499	−8.213	0.637	−8.663	0.653	−8.658	0.694
$+\pi\sigma(N^{*})$	−8.711	−0.438	−8.610	−0.397	−9.145	−0.482	−9.055	−0.397
$+\pi\omega(Z)$	−9.213	−0.502	−9.380	−0.770	−9.977	−0.832	−9.956	−0.901
$+\pi\omega(N^{*})$	−8.735	0.478	−8.898	0.482	−9.370	0.607	−9.524	0.432

Nuclear Forces linked to QCD

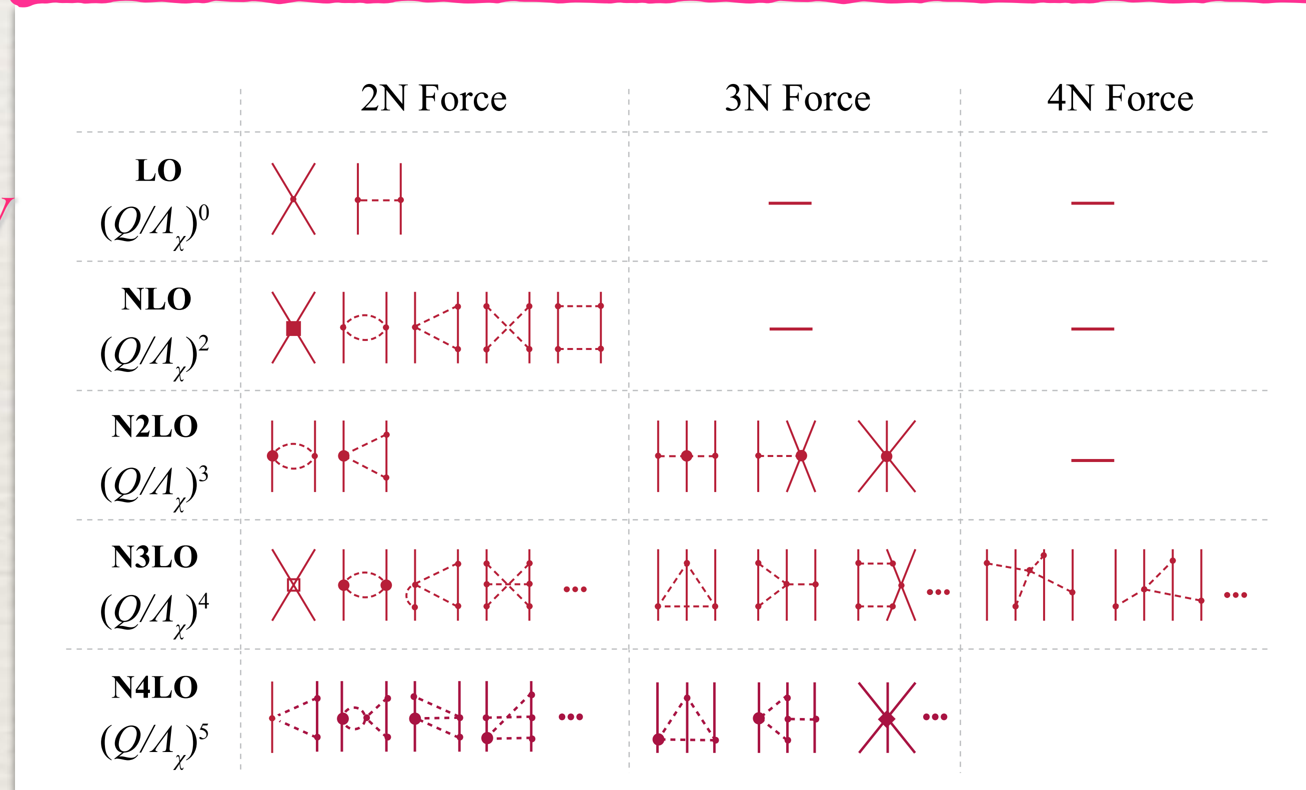
Nuclear Forces based on Chiral Effective Field Theory

- 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

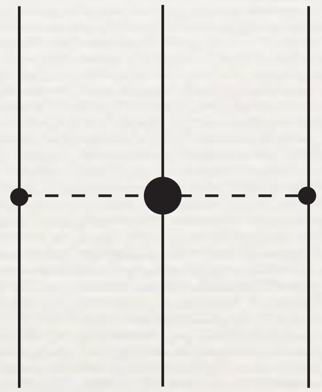
- **Nuclear forces** **(2NF, 3NF, …)**
  and currents are derived
  in a consistent way.

- **Hierarchy of Nuclear Forces** :
  2NF > 3NF > 4NF
  The first 3NF appears in NNLO.

Layout of χEFT Nuclear Forces

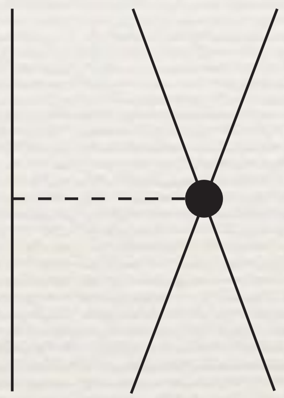


3NFs in χEFT (N2LO)

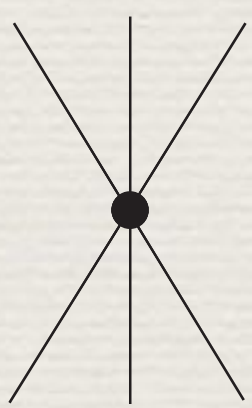


$$V^{3NF}_{2PE} = \left(\frac{g_A}{2f_\pi}\right)^2 \sum_{i\neq j\neq k} \frac{(\vec{\sigma}_i\cdot\vec{q}_i)(\vec{\sigma}_j\cdot\vec{q}_j)}{(q_i^2+m_\pi^2)(q_j^2+m_\pi^2)} F^{ab}_{ijk}\tau^a_i\tau^b_j$$

$$F^{ab}_{ijk}\tau^a_i\tau^b_j = \delta^{ab}\left[-\frac{4c_1 m_\pi^2}{f_\pi^2}+\frac{2c_3}{f_\pi^2}\vec{q}_i\cdot\vec{q}_j\right]+\frac{c_4}{f_\pi^2}\sum_c \epsilon^{qbc}\tau^c_k\vec{\sigma}_k\cdot[\vec{q}_i\times\vec{q}_j]$$



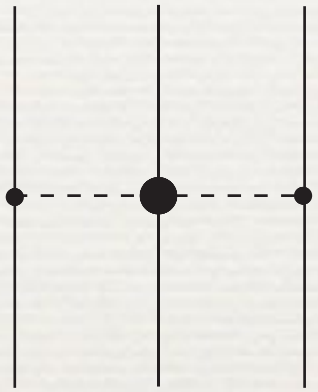
$$V^{3NF}_{1PE} = -D\frac{g_A}{8f_\pi^2}\sum_{i\neq j\neq k}\frac{\vec{\sigma}_i\cdot\vec{q}_j}{q_j^2+m_\pi^2}(\vec{\tau}_i\cdot\vec{\tau}_j)(\vec{\sigma}_i\cdot\vec{q}_j)$$



$$V^{3NF}_{ct} = E\frac{1}{2}\sum_{j\neq k}\tau_j\cdot\tau_k$$

Parameters D, E to be determined by Experimental data

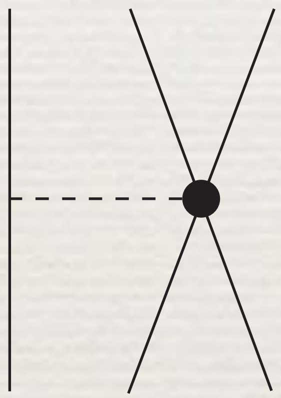
3NFs in χEFT (N2LO)



$$V^{\rm 3NF}_{\rm 2PE} = \left(\frac{g_A}{2f_\pi}\right)^2 \sum \frac{(\vec{\sigma}_i \cdot \vec{q}_i)(\vec{\sigma}_j \cdot \vec{q}_j)}{\cdots} F^{ab}_{ijk}\tau^a_i\tau^b_j$$

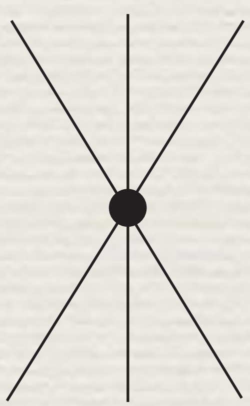
central + tensor + spin orbit + rank 3

$$F^{ab}_{ijk}\tau^a_i\tau^b_j = \delta^{ab}\left[-\frac{4c_1 m_\pi^2}{f_\pi^2} + \frac{2c_3}{f_\pi^2}\vec{q}_i \cdot \vec{q}_j\right] + \frac{c_4}{f_\pi^2}\sum_c \epsilon^{abc}\tau^c_k \vec{\sigma}_k \cdot [\vec{q}_i \times \vec{q}_j]$$



$V^{\rm 3NF}_{\rm 1PE}$ … $\sum_{i \neq j \neq k}$ …

central + tensor



$V^{\rm 3NF}_{\rm c}$ … $\sum_{j \neq k}$ …

central

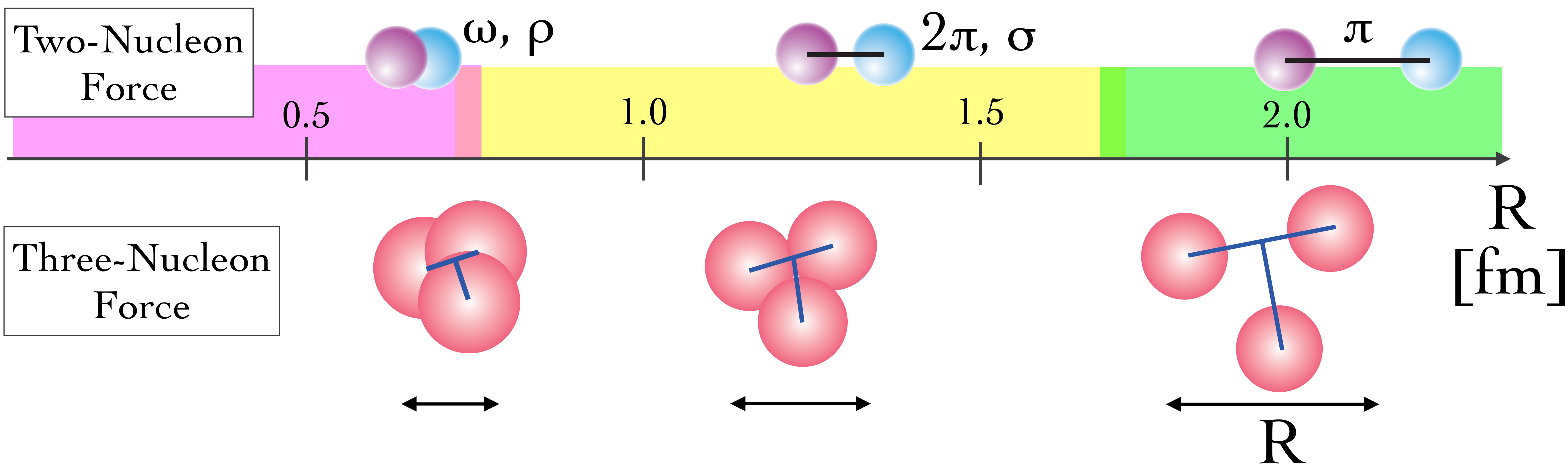
T. Fukui, by courtesy

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

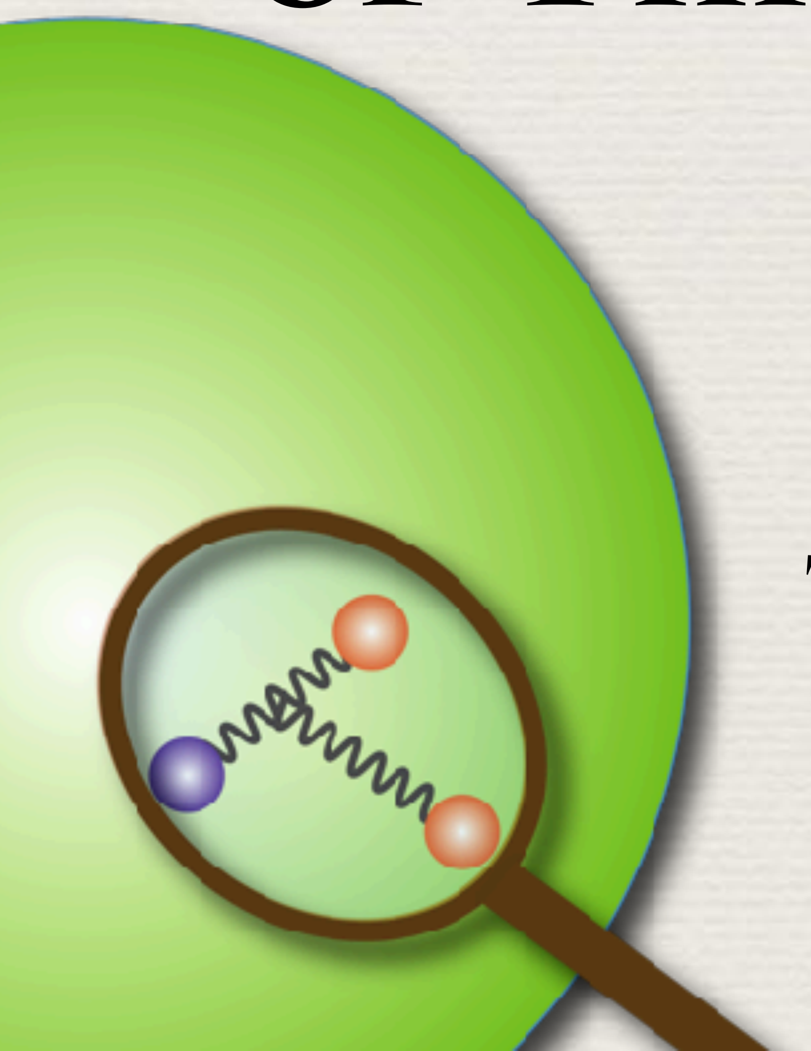
End of Part 1

Experimental Study of Three-Nucleon Forces

Part II

Department of Physics
Tokyo Institute of Technology

Kimiko Sekiguchi



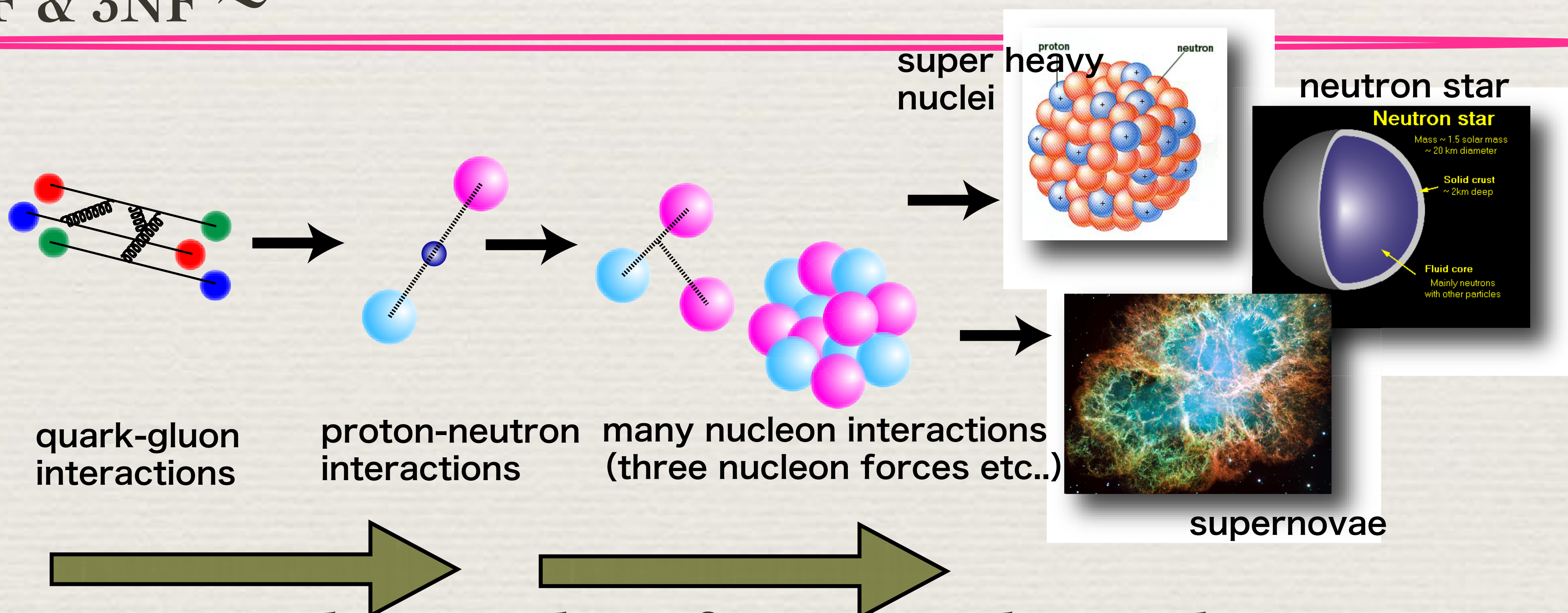
Tokyo Tech

Frontier of Nuclear Force Study

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

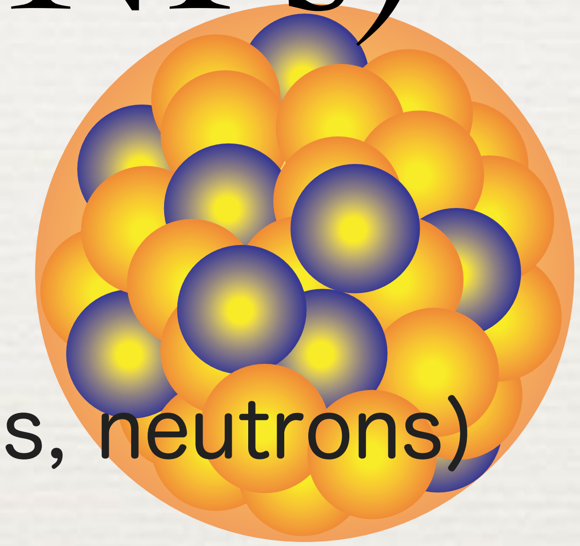
→ **We have "reliable" two nucleon forces.**

- 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 Forces (3NFs) in Nuclei



- 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	10^{-38}	10^{-2}	1
$\frac{V(3BF)}{V(2BF)}$	0.001%	a few %	?

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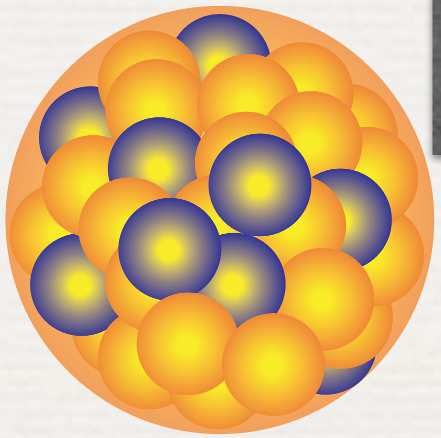
Where ?

3NFs in A>3 - ① -



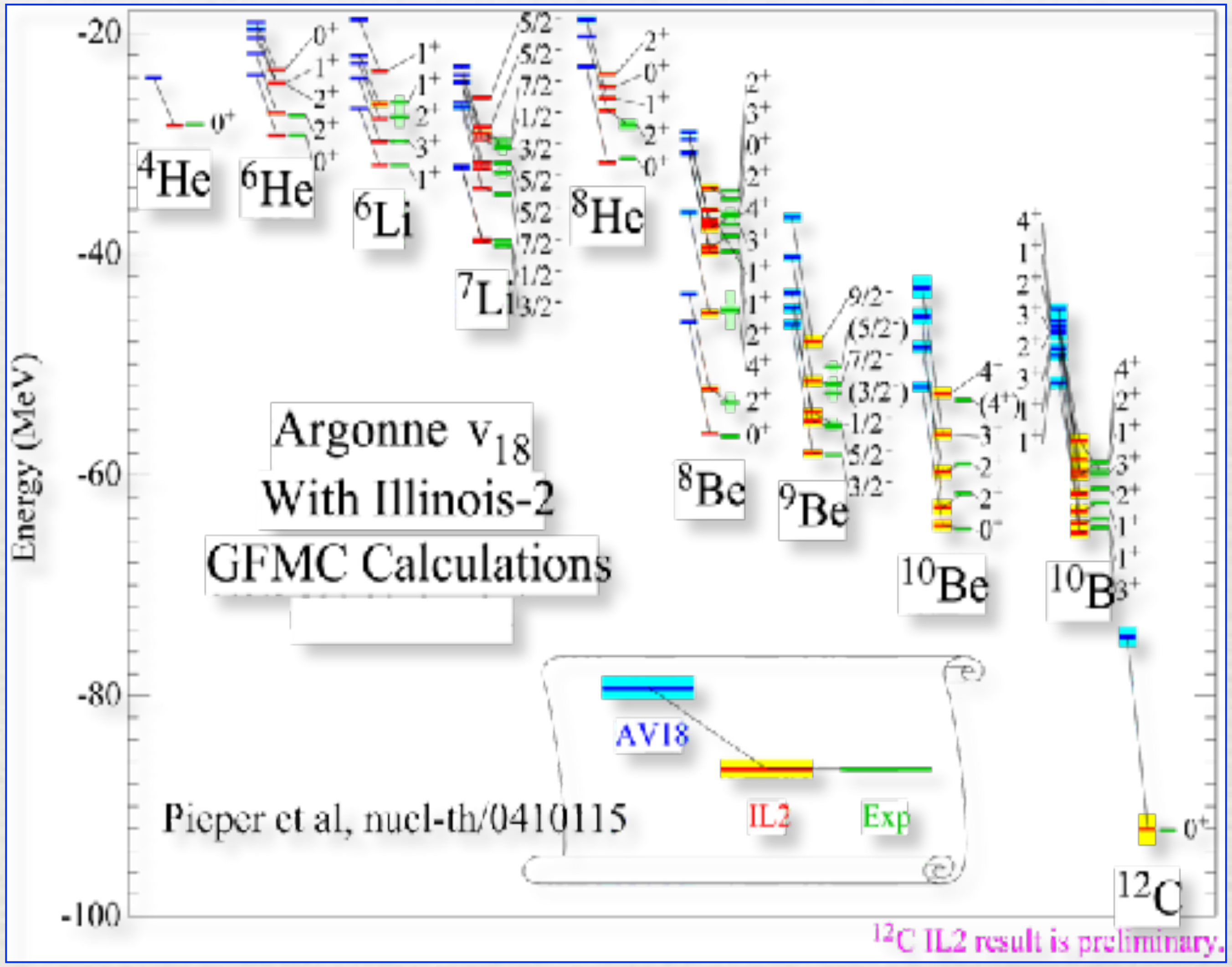
3NFs in Finite Nuclei

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

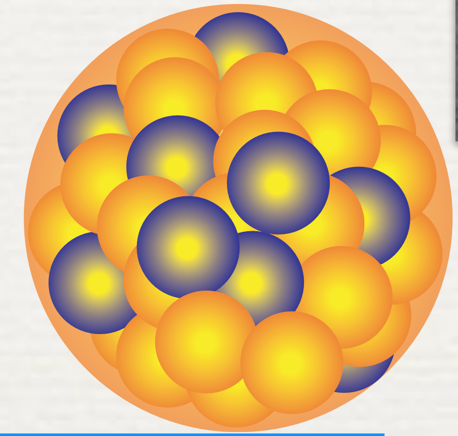
IL2 3NF (Illinois-II 3NF) :
2π-exchange 3NF
+ 3π-ring with Δ-isobar



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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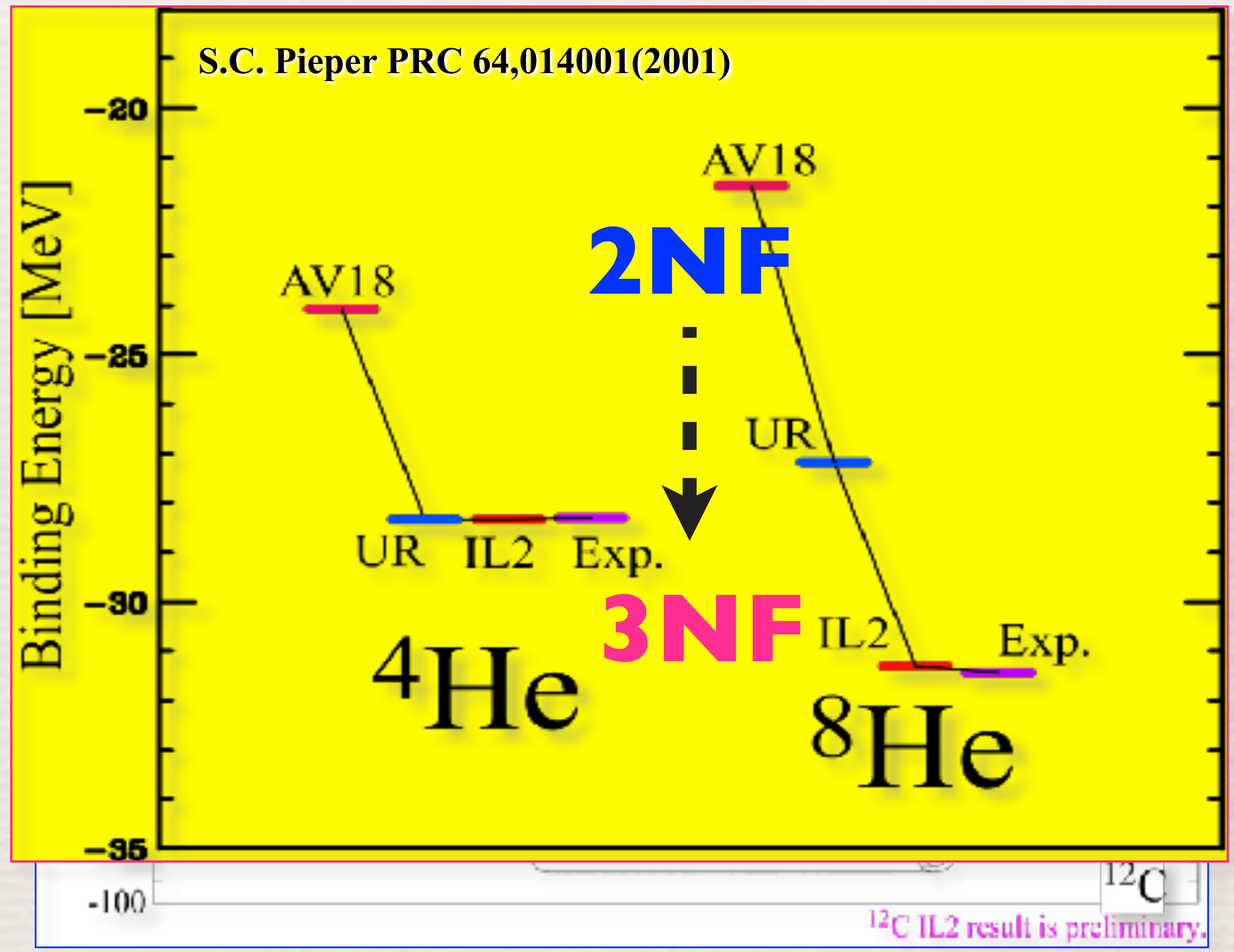

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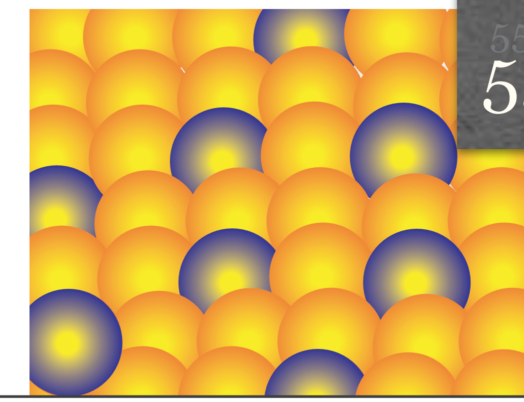
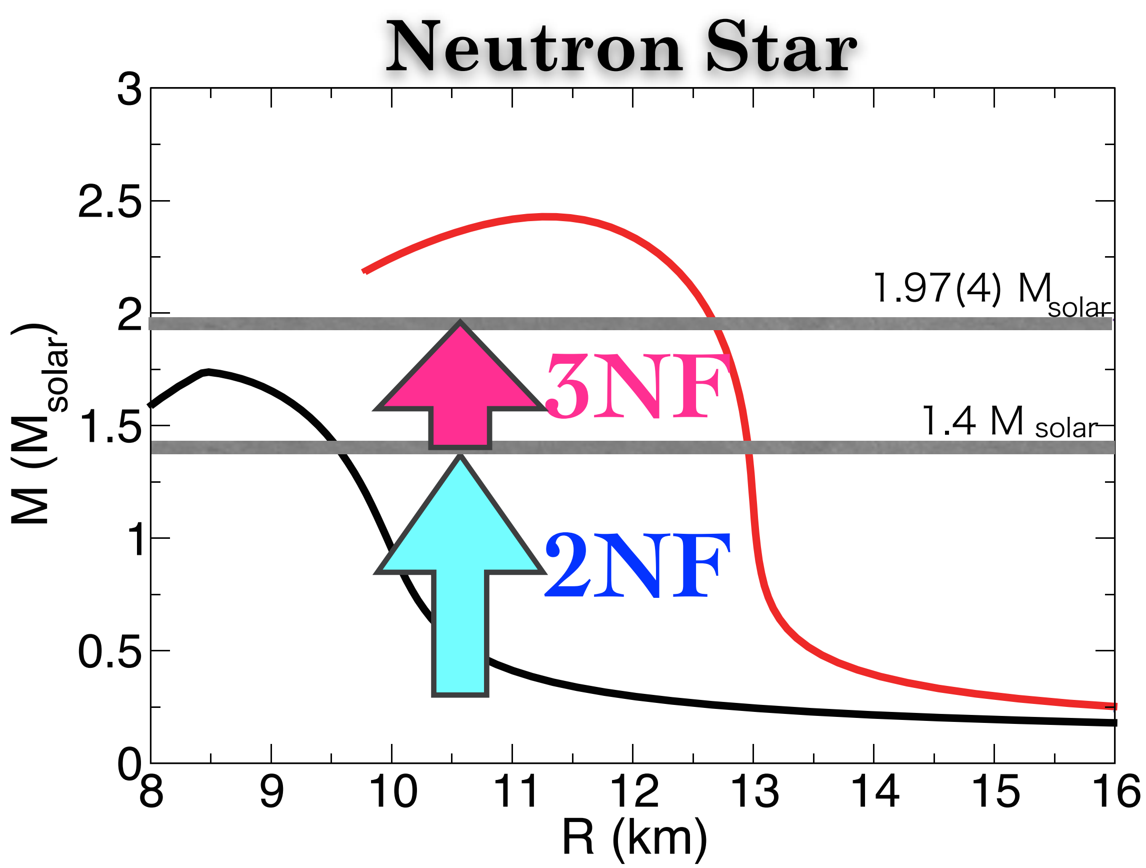


3NFs in A>3 - ② -

3NFs in Infinite Nuclei - Neutron Star -



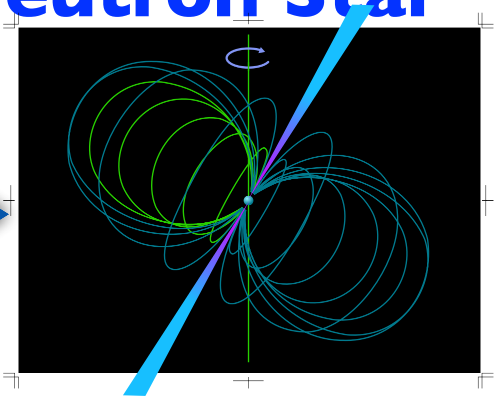
A. Akmal et al., PRC 58, 1804('98)

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

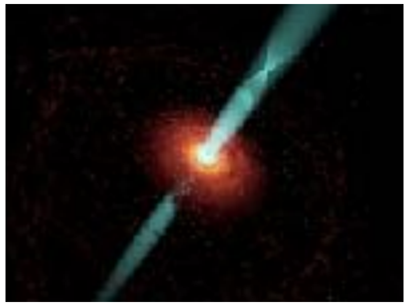
"Endpoint of stellar evolution"

Supernovae Explosion

Neutron Star

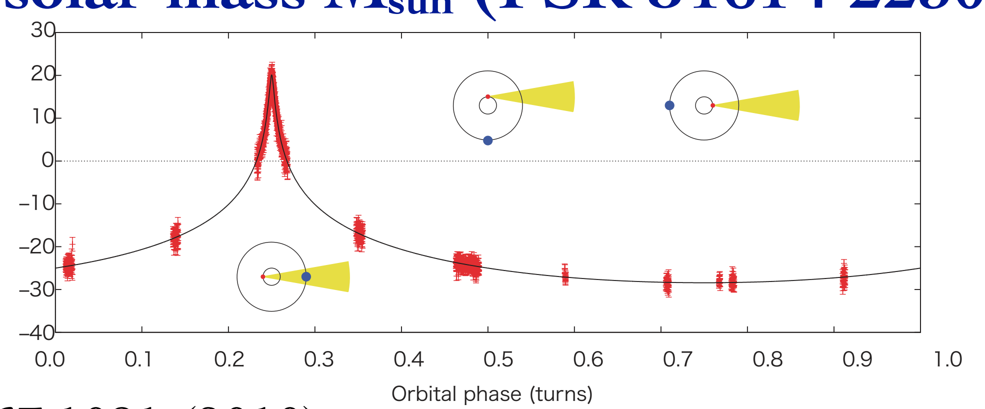


Black Hole



Discovery of Heaviest Neutron Star

with 2 solar-mass M_{sun} (PSR J1614-2230)



Nature *467* 1081 (2010)

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How ?

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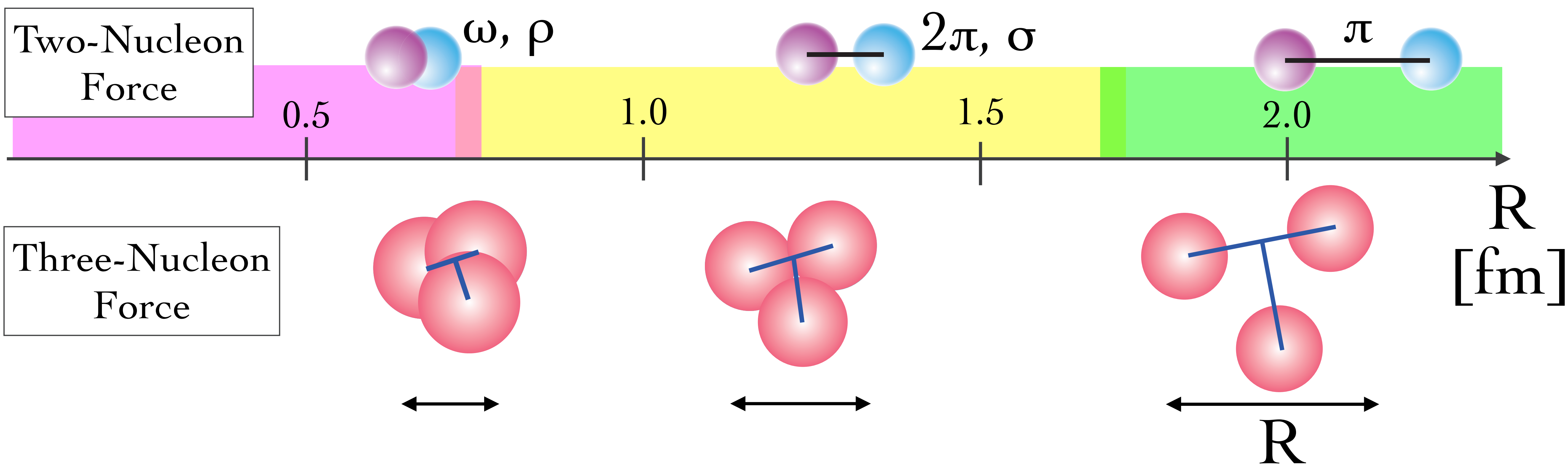


3NFs are momentum, spin, and iso-spin dependent.

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 3500 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

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

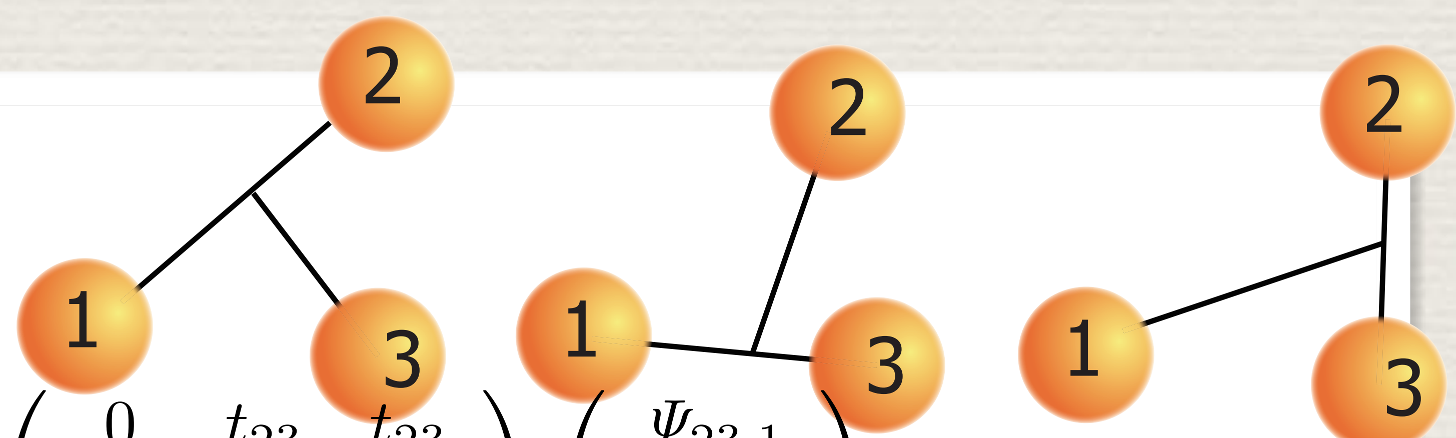
- **Faddeev Theory (L.D. Faddeev, 1961)**

Exact solution of three body system in Q.M.

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

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

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



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.

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

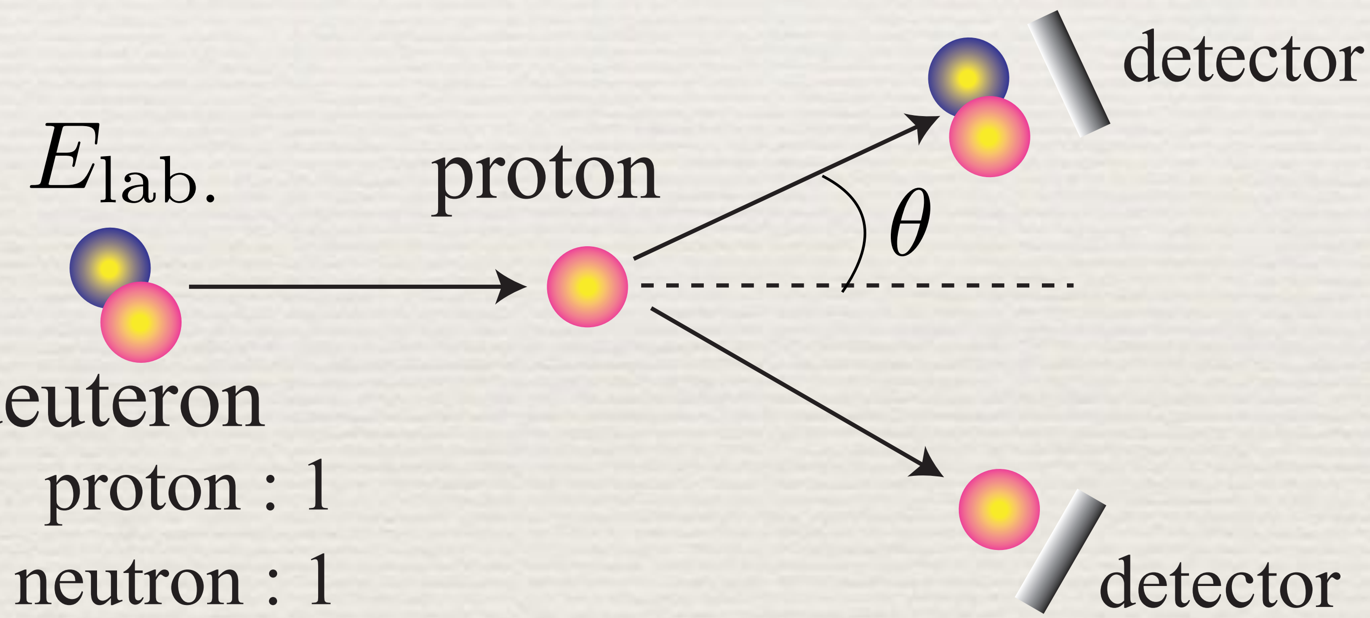
Potential	E_B [MeV] (w/o 3NF)	E_B [MeV] (with 3NF)	Λ/m_π
CDBonn	7.953	8.483	4.856
AV18	7.576	8.479	5.215
Nijm I	7.731	8.480	5.147
Nijm II	7.709	8.477	4.990
Nijm 93	7.664	8.480	5.207
Exp.	8.481821(4) [MeV]		

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

Three-Nucleon Scattering

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

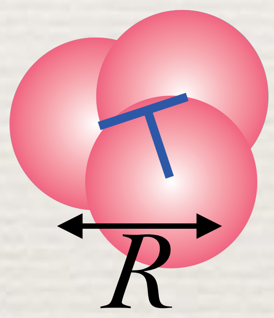
- ✓ **Momentum dependence (R-dependence)**
- ✓ **Spin-dependence**



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

Nuclear Potential

Angular Dependent Cross Section :
Fourier Transform of Nuclear Potential



$qR \sim \hbar$

$R \sim 1 \times 10$ fm

$q \sim 200$ MeV/c

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

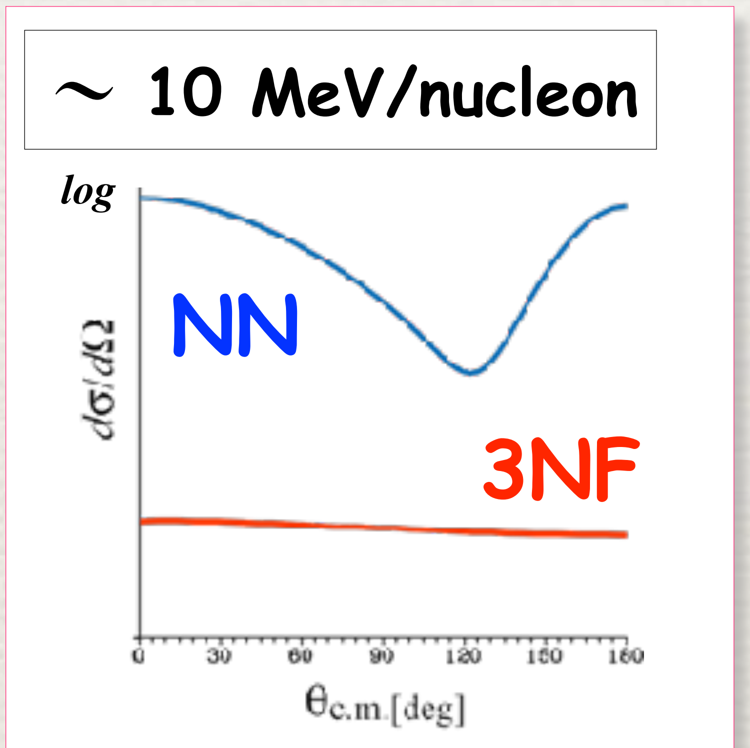
One can change R
by adjusting $E_{lab.}$

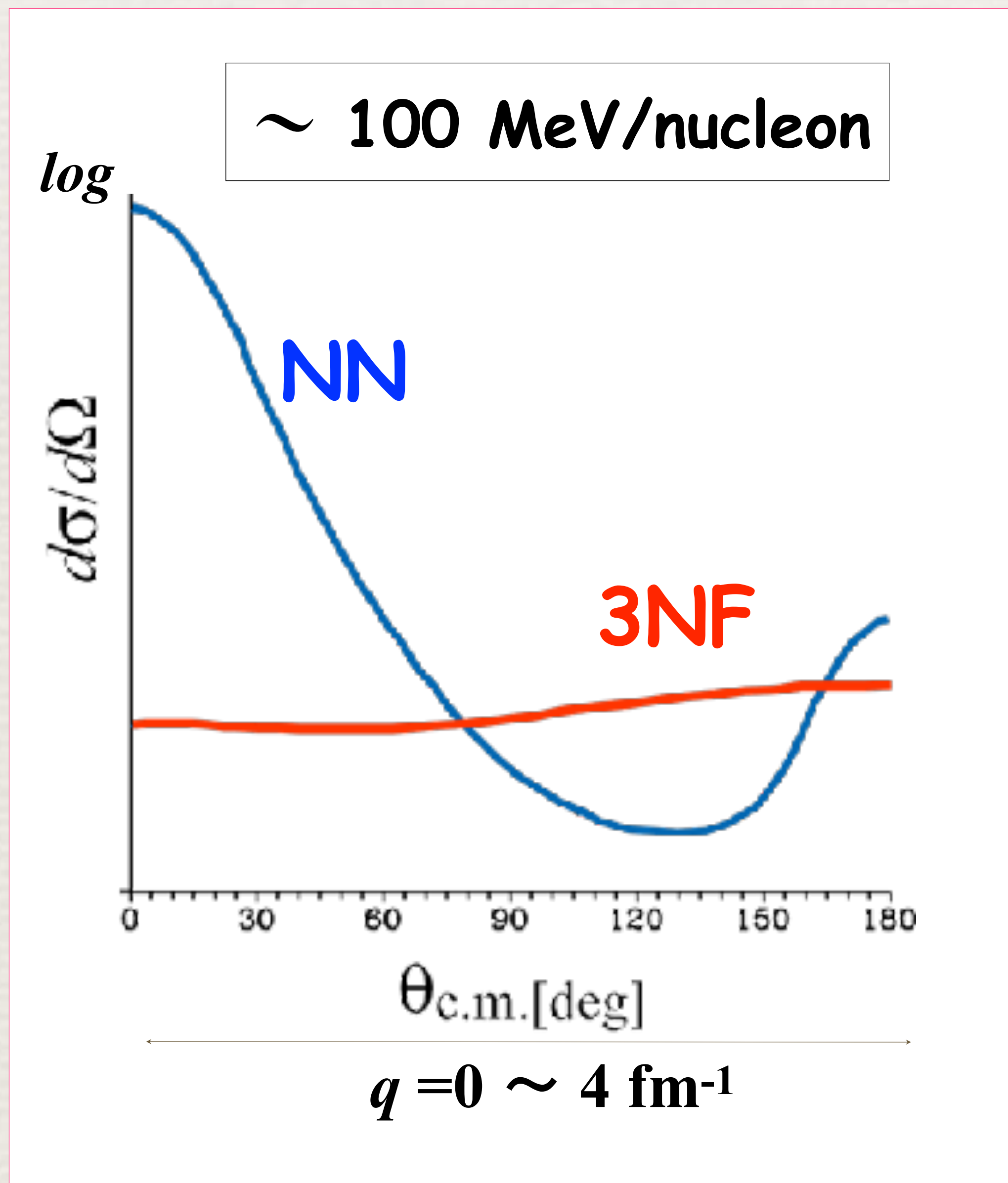
Where is the hot spot for 3NFs ?

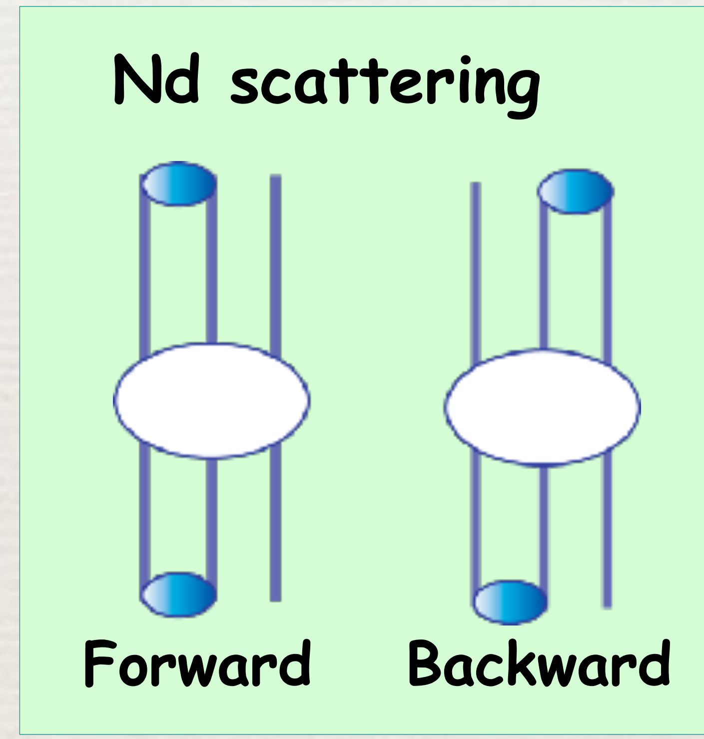
Nucleon-Deuteron Scattering - 3N Scattering -

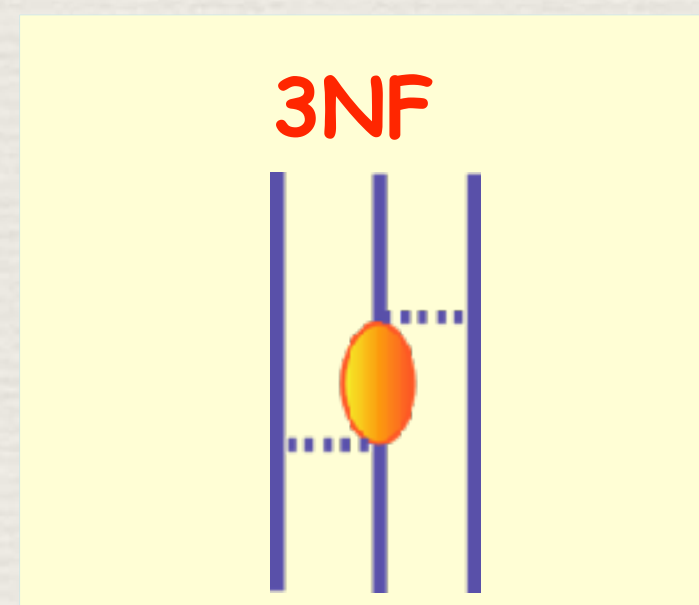
Predictions by H. Witala et al. (1998)

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

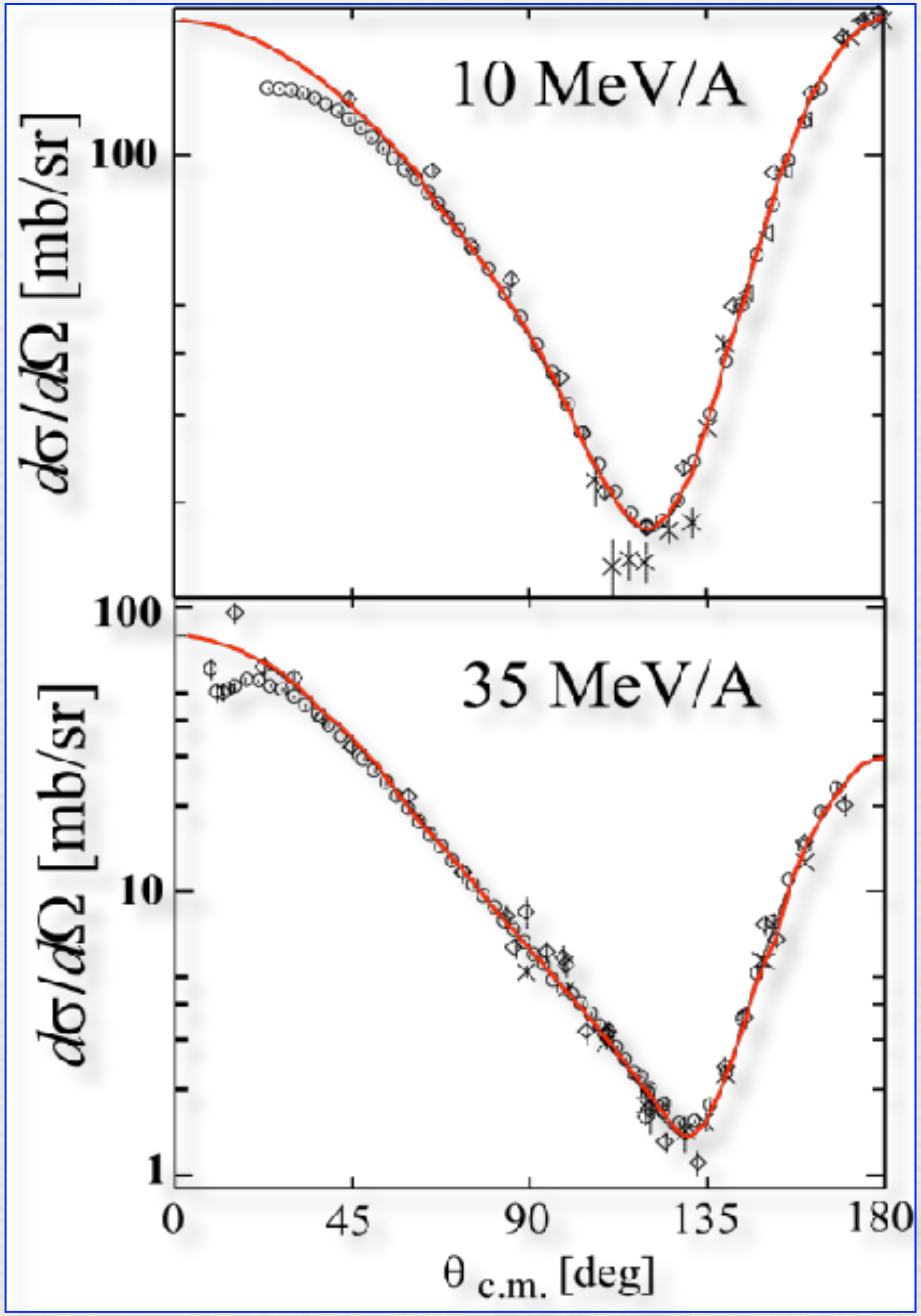








Nd Scattering at Low Energies ($E \leq 30$ MeV/A)



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

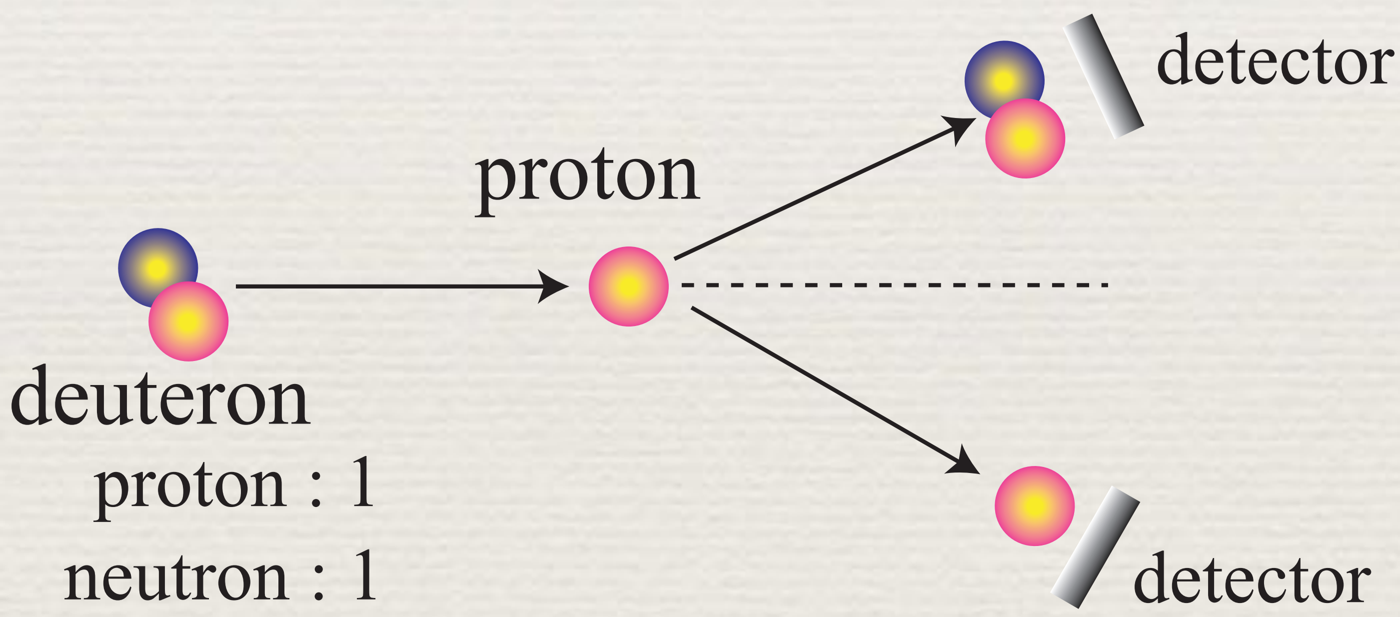
No signatures of 3NF

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

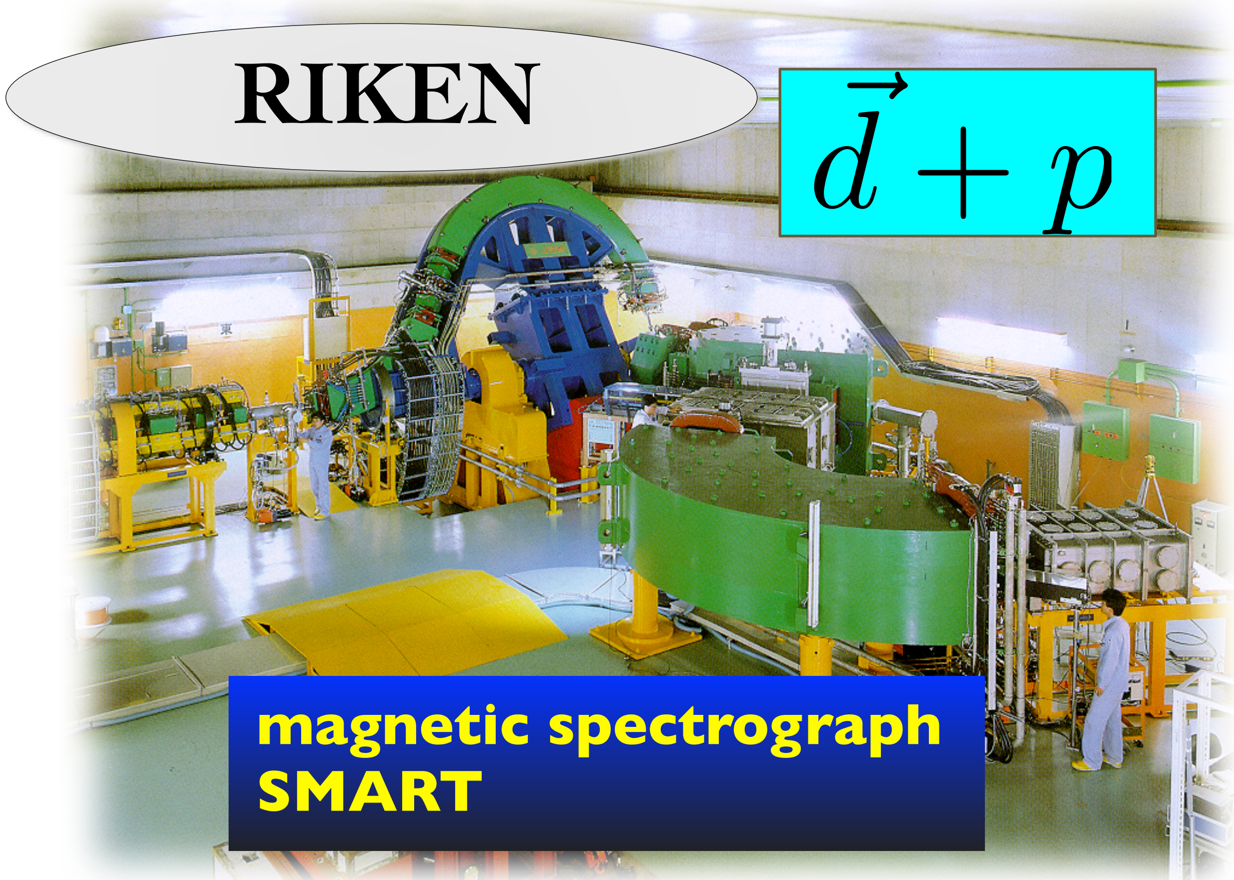
W. Glöckle et al., Phys. Rep. 274, 107 (1996).

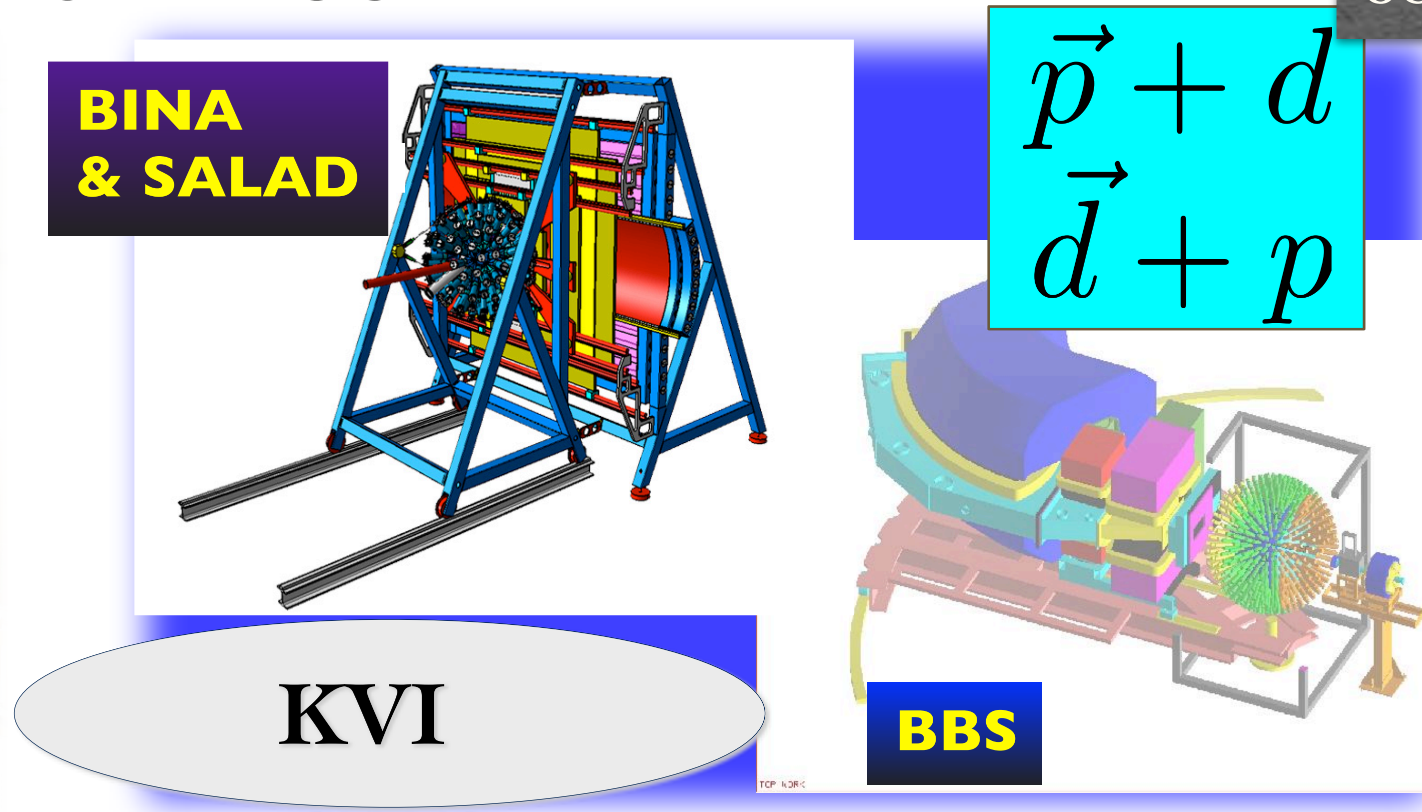
deuteron-nucleon scattering

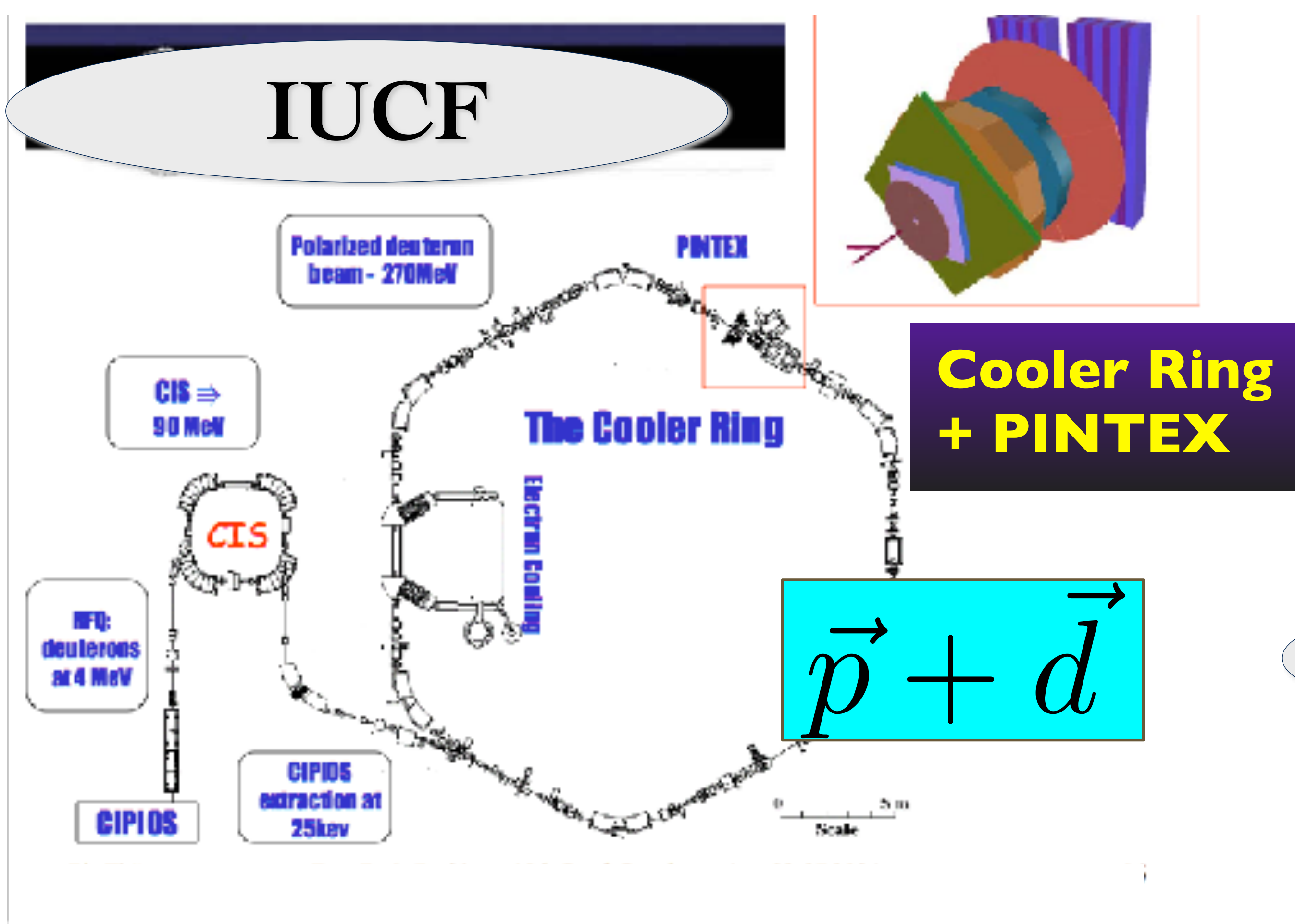
at ∼100 MeV/nucleon

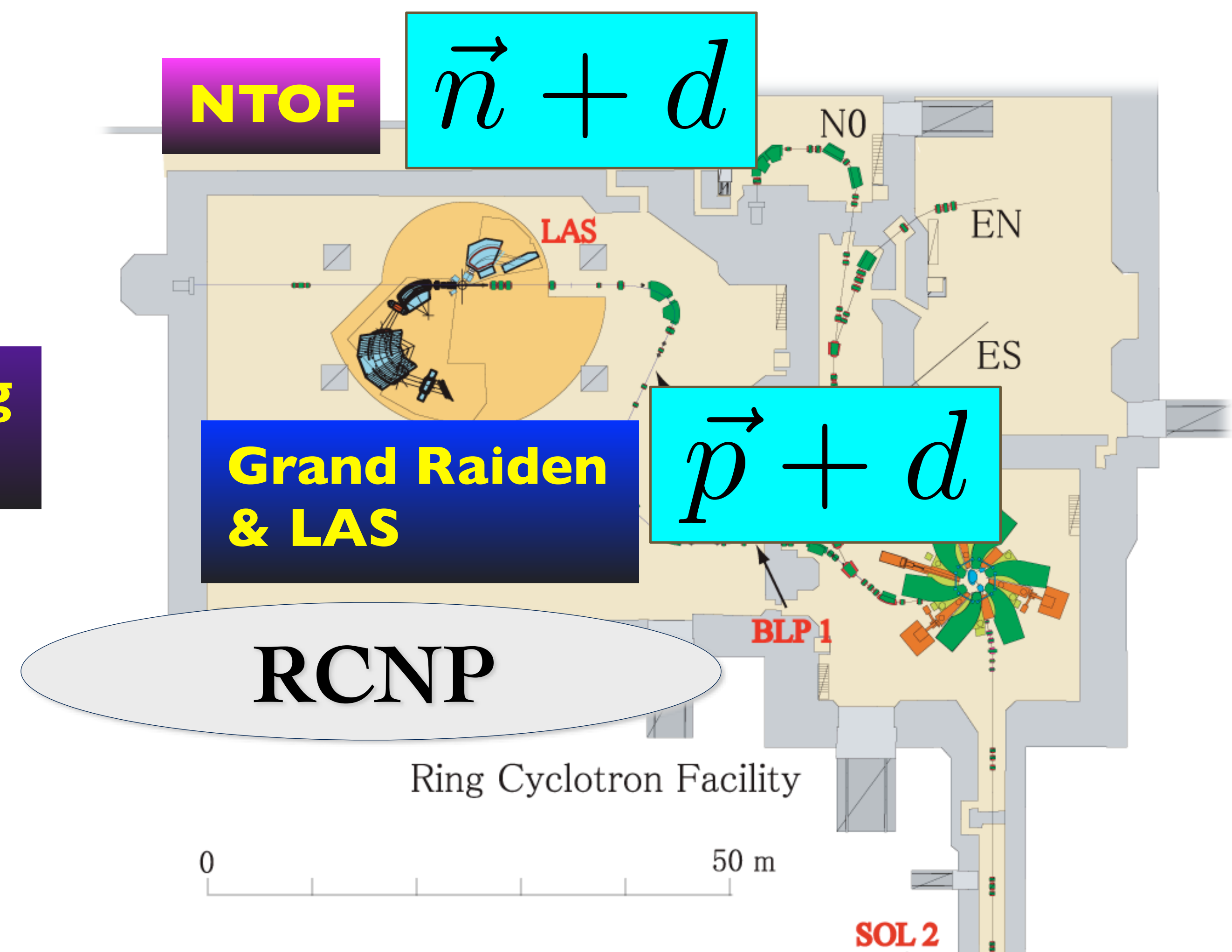


Facilities


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


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

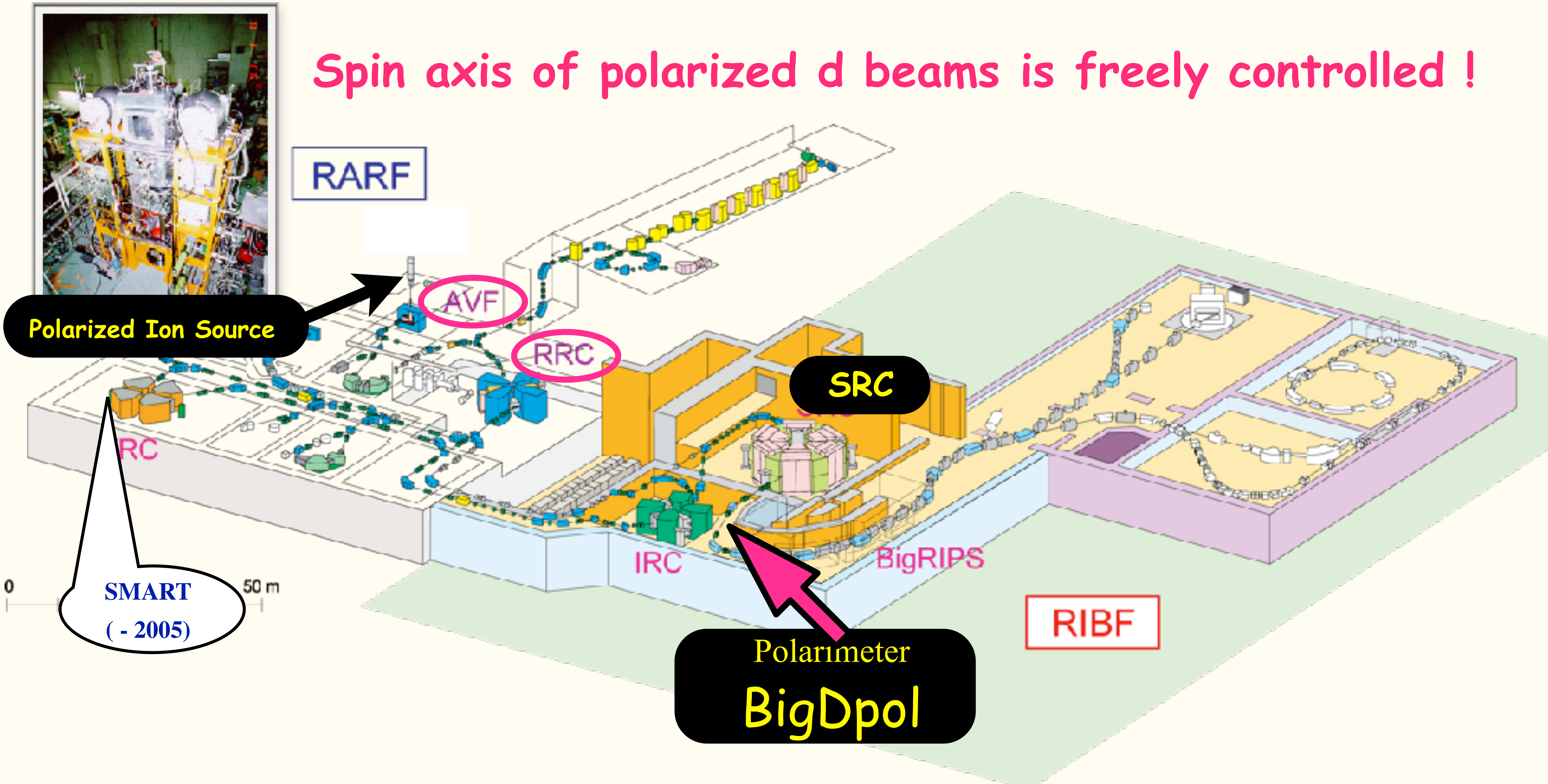

IUCF
Polarized deuteron beam - 270MeV
PINTEX
CIS ⇒ 90 MeV
The Cooler Ring
CIS
Electron Cooling
RFQ: deuterons at 4 MeV
CIPIOS
CIPIOS extraction at 25keV
Scale
Cooler Ring
+ PINTEX
$\vec{p} + \vec{d}$


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

RIKEN RI Beam Factory (RIBF)

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

Spin axis of polarized d beams is freely controlled !

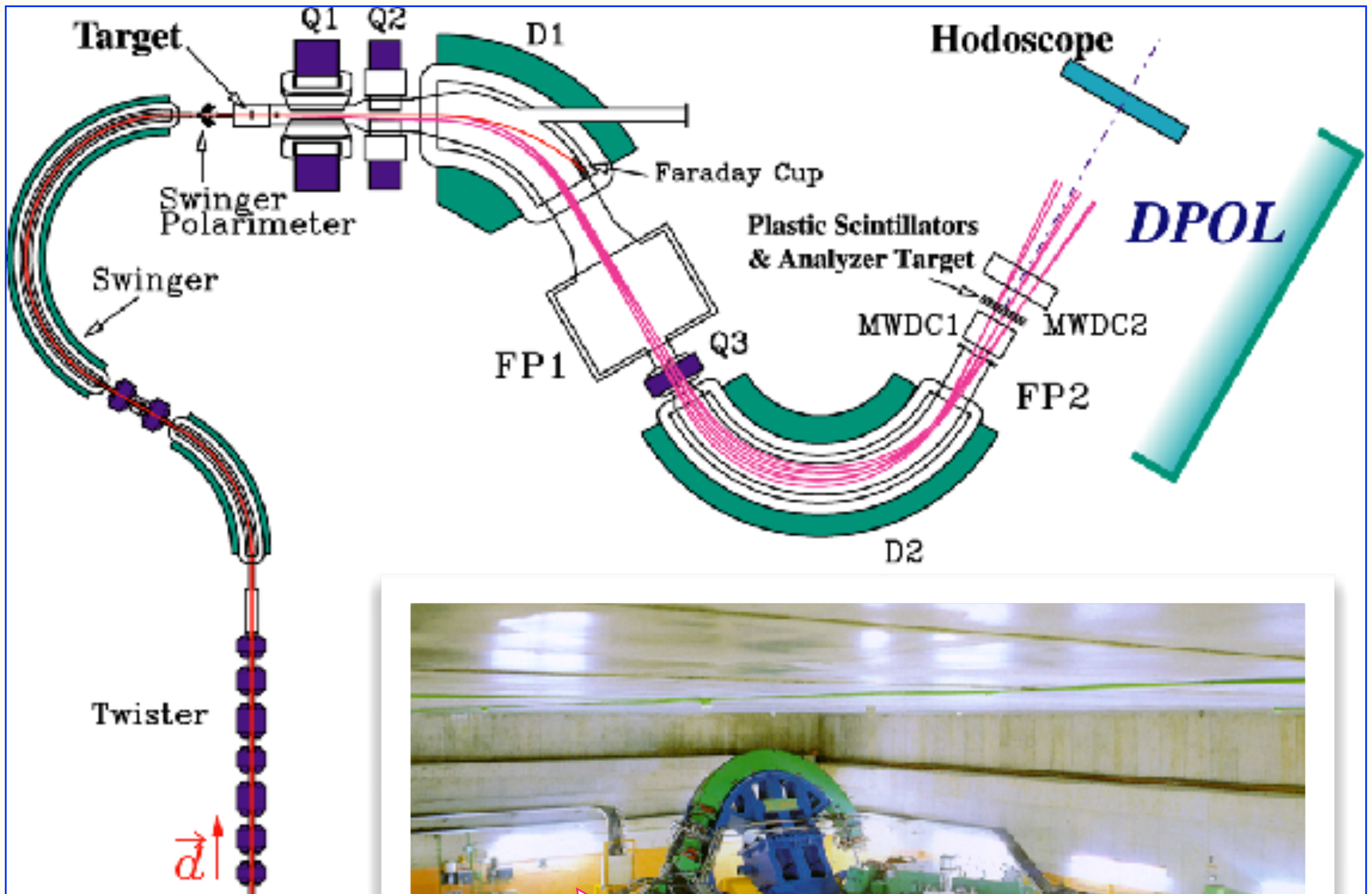


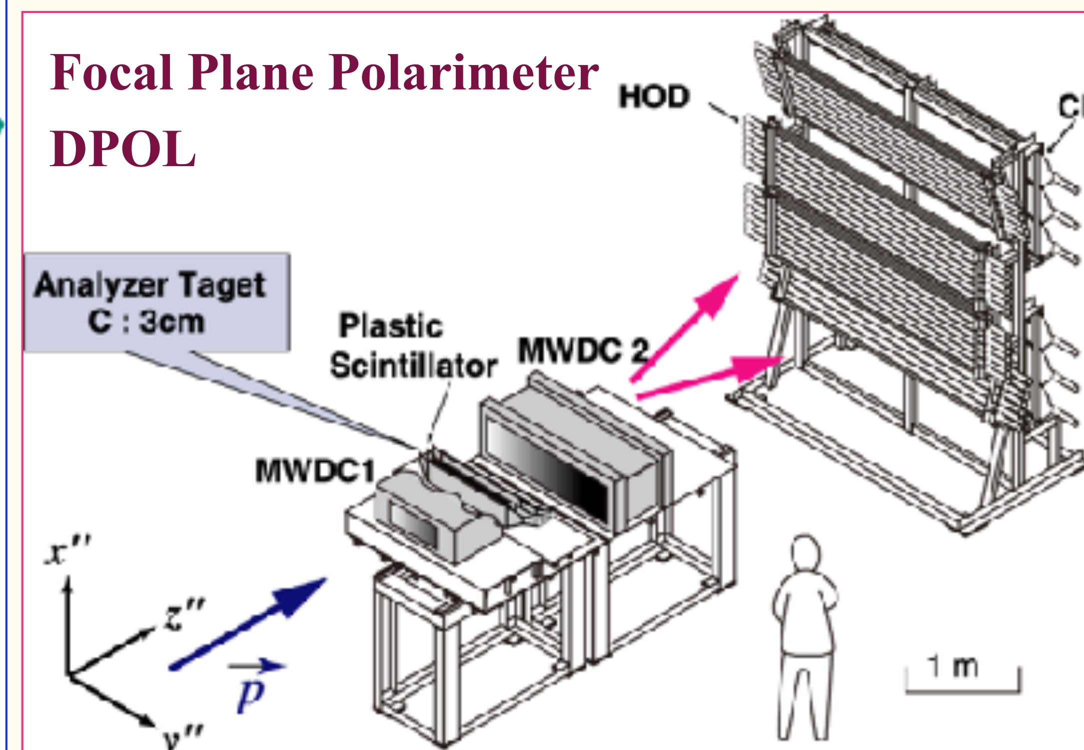
SMART at RIKEN (- 2005)

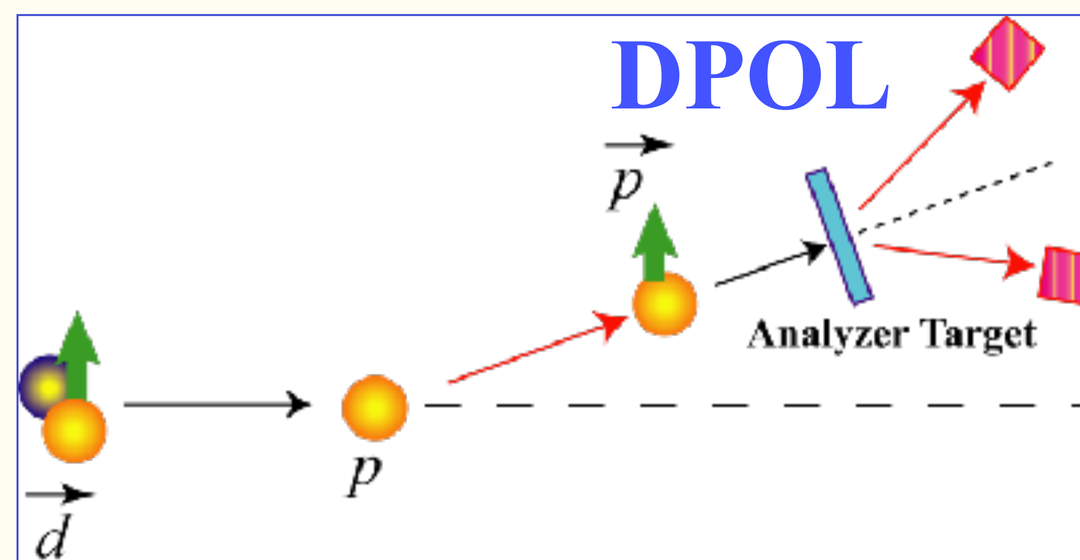
Swinger and Magnetic Analyzer with Rotator and Twister

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



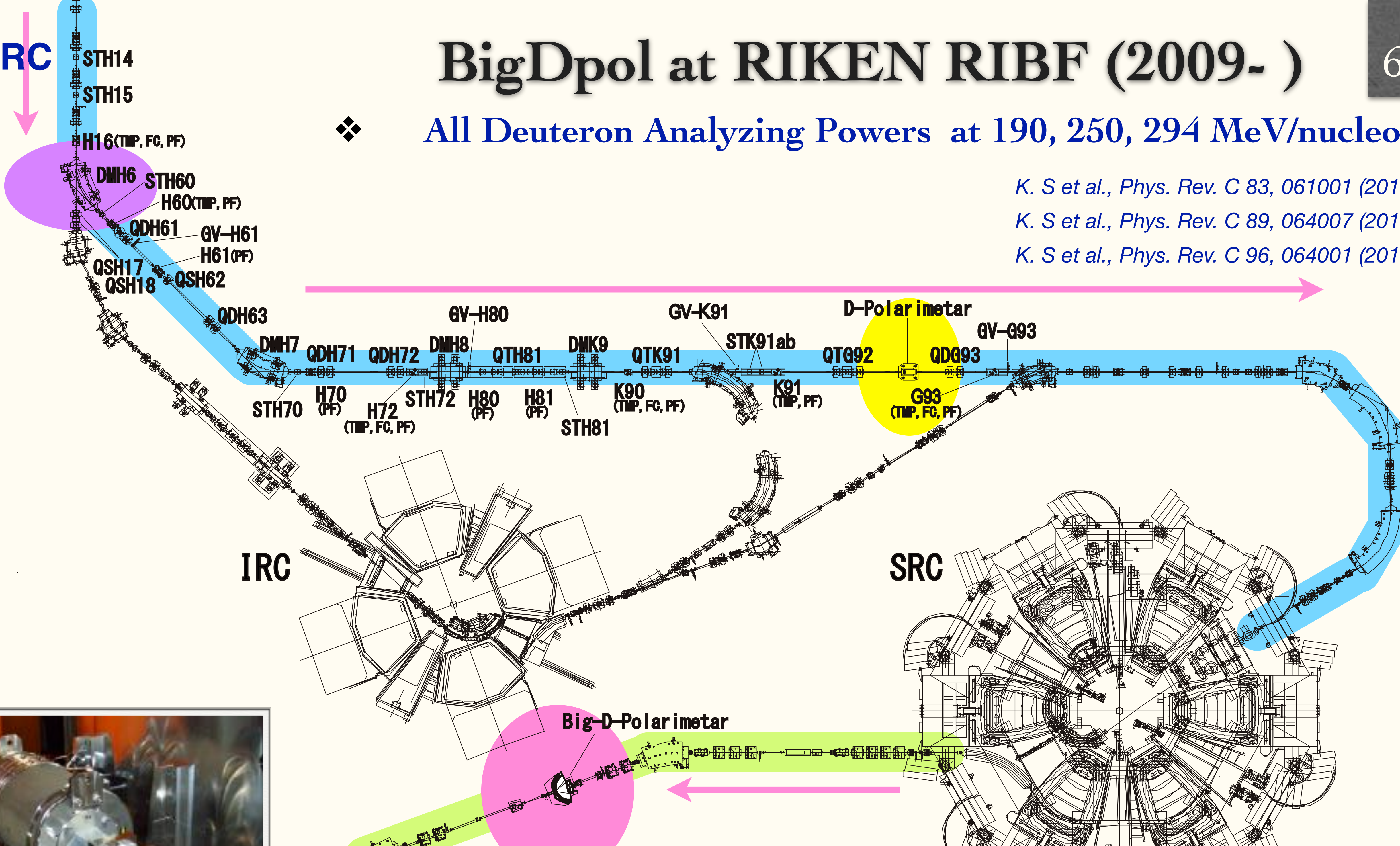




BigDpol at RIKEN RIBF (2009-)

❖ 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)



Faraday cup

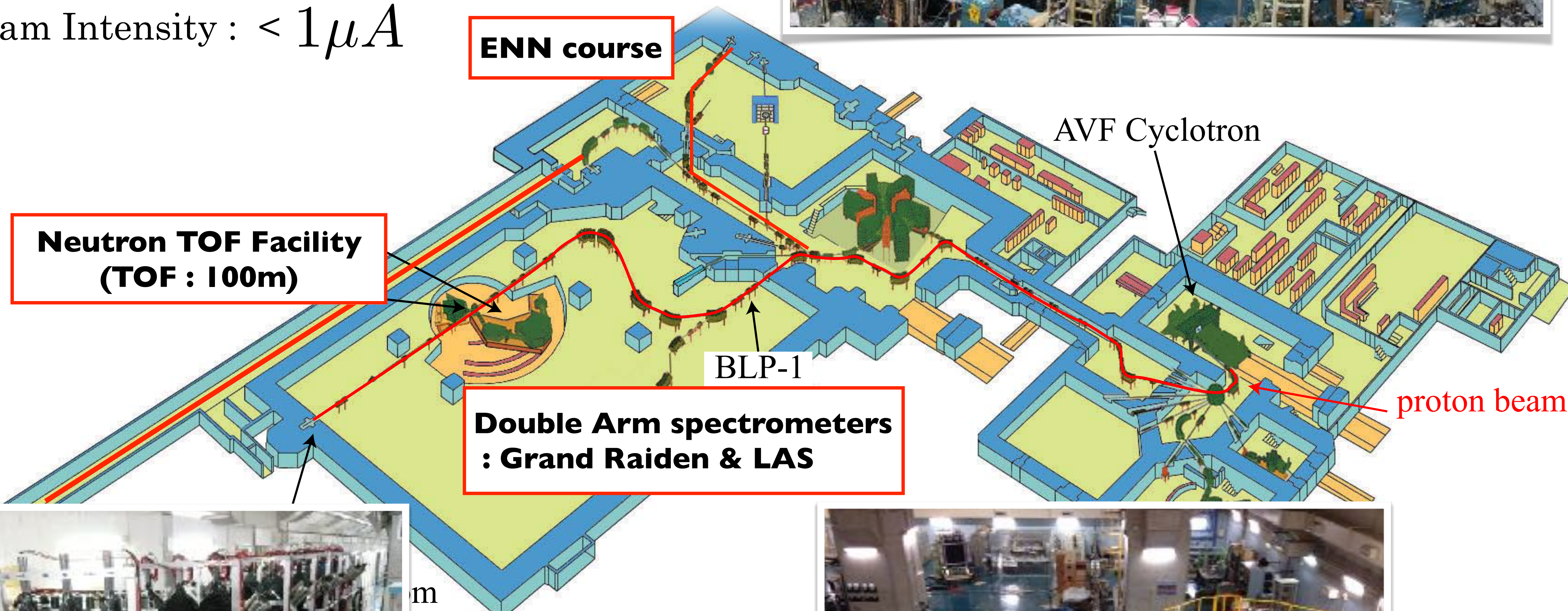
- W(φ3cm×30cm) +Pb(φ25cm×70cm)

BigDpol

- detection system (plastic scintillators)

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 : $< 1\mu A$



Summary of Precise Measurement of *Nd* Elastic Scattering at RIKEN/RCNP

$d + p$

RIKEN

1. **Differential Cross Section at 70, 135 MeV/nucleon**
2. **All Deuteron Analyzing Powers (iT_{11} , T_{20}, T_{21} , T_{22}) at 70, 100, 135, 190, 250, 300 MeV/nucleon**
3. **Deuteron to Proton Polarization Transfer Coefficients at 135 MeV/nucleon**

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

$p + d$

RCNP

1. **Differential Cross Section at 135, 250 MeV**
2. **Proton Analyzing Powers at 250 MeV**
3. **Proton to Proton Polarization Transfer Coefficients at 250 MeV**

K. Hatanaka et al., Phys. Rev. C. 66, 044002 (2002)
K. S. et al., Phys. Rev. Lett. 95, 162301 (2005)

$n + d$

RCNP

1. **Differential Cross Section at 250 MeV**
2. **Neutron Analyzing Powers at 250 MeV**

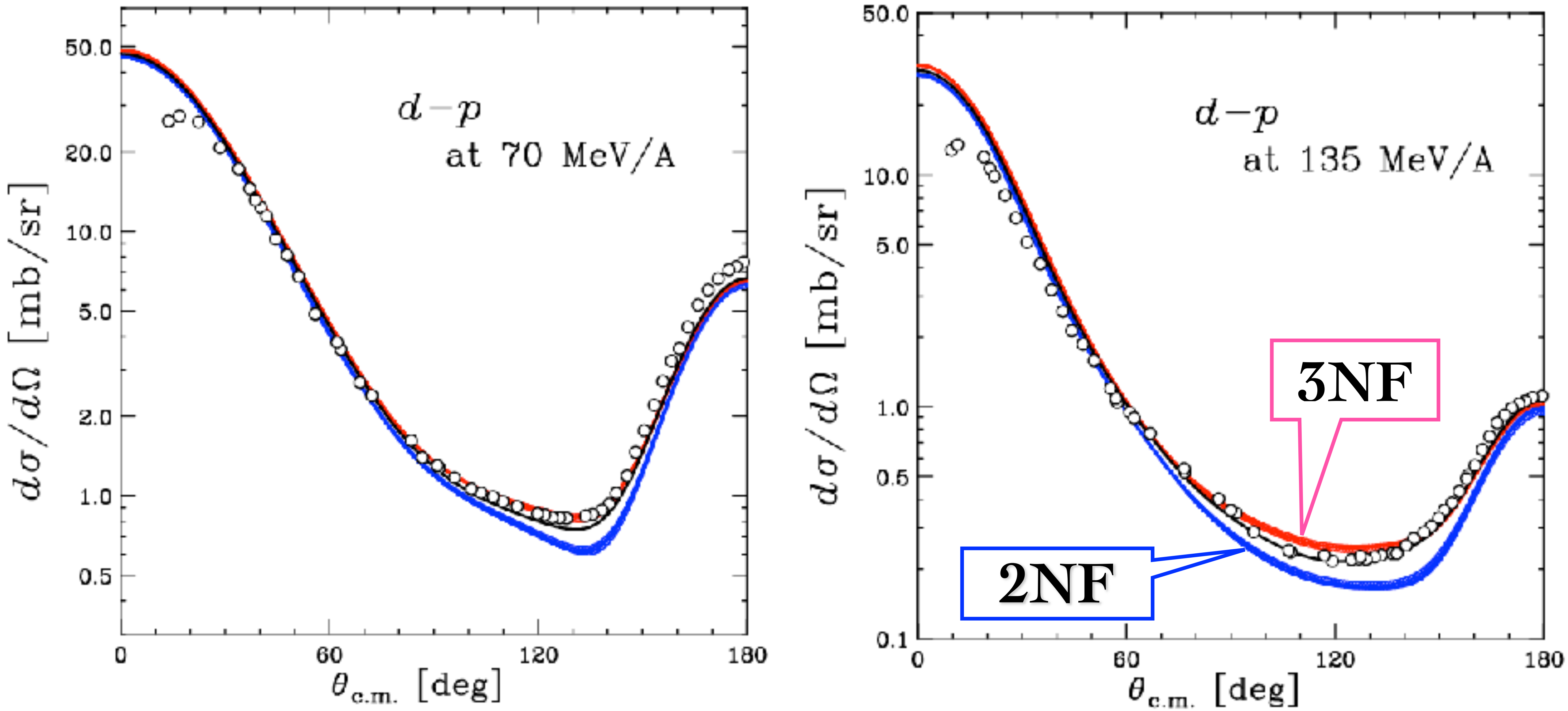
Y. Maeda et al., Phys. Rev. C 76, 014004 (2007)

d-p elastic scattering Differential Cross section

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

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

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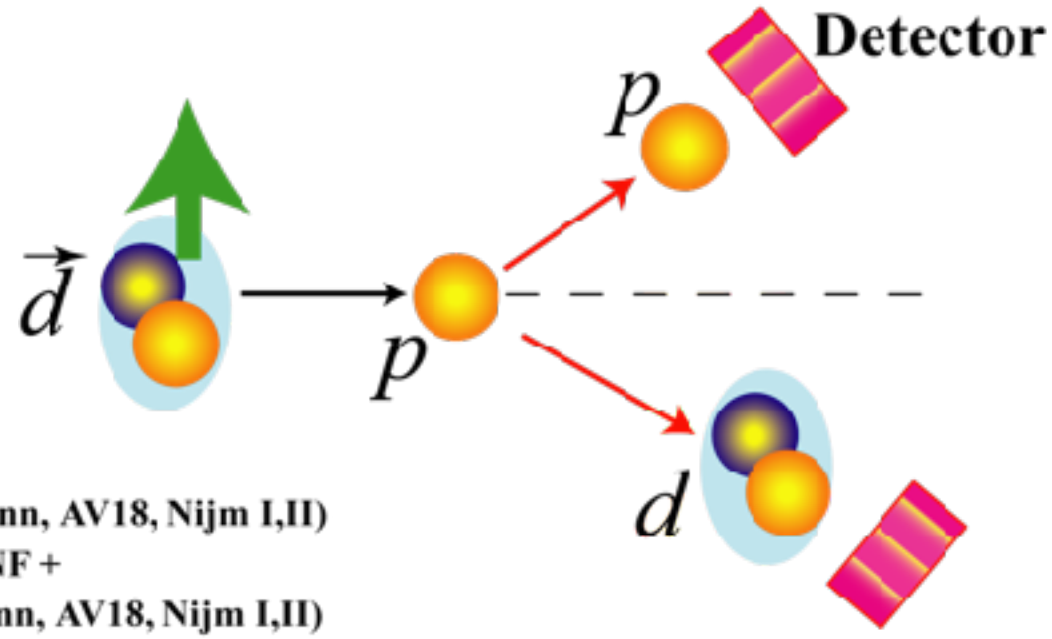
d-p elastic scattering Spin Observables

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

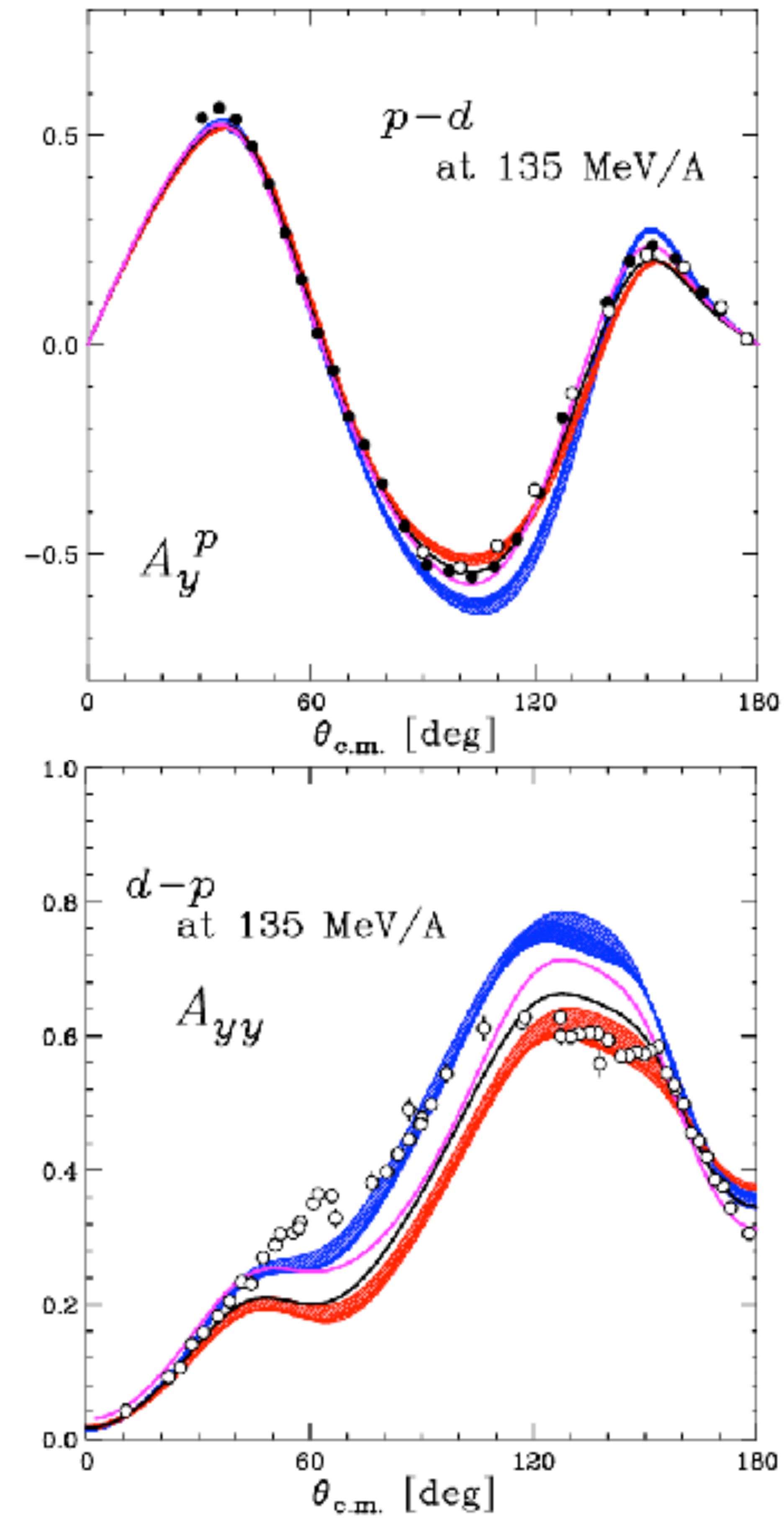
2NF (CDBonn, AV18, Nijmegen I,II) :
Large discrepancy in Cross Section Minimum

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

Vector Analyzing Power A_y^p : Good Agreement

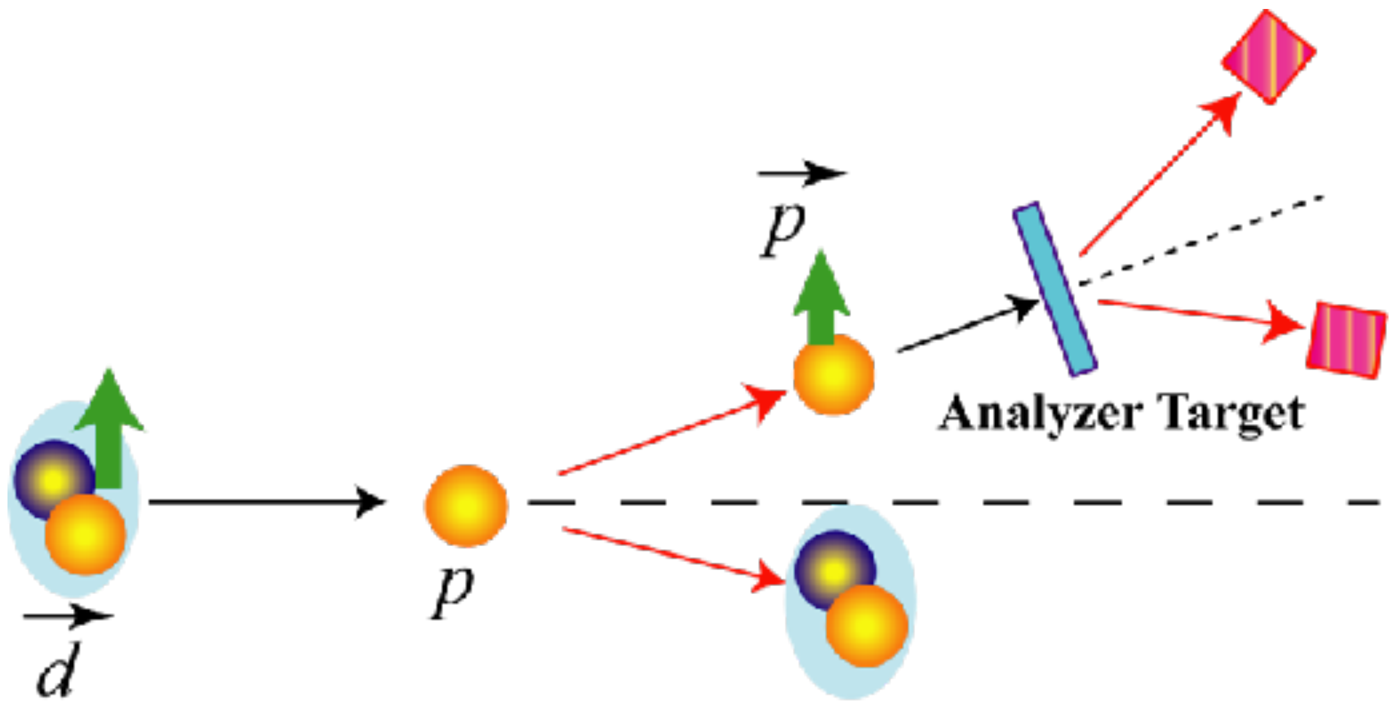
Tensor Analyzing Power A_{yy} : No superiority

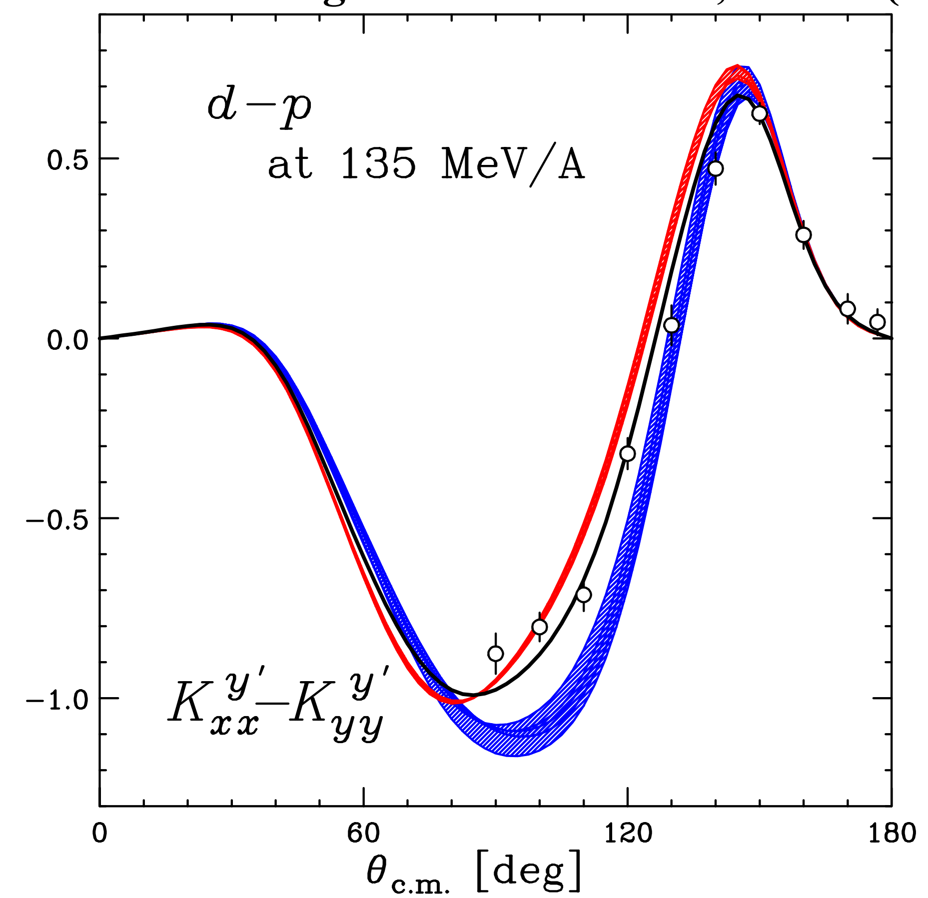
K. Sekiguchi et al. PRC 65, 034003 (2002)

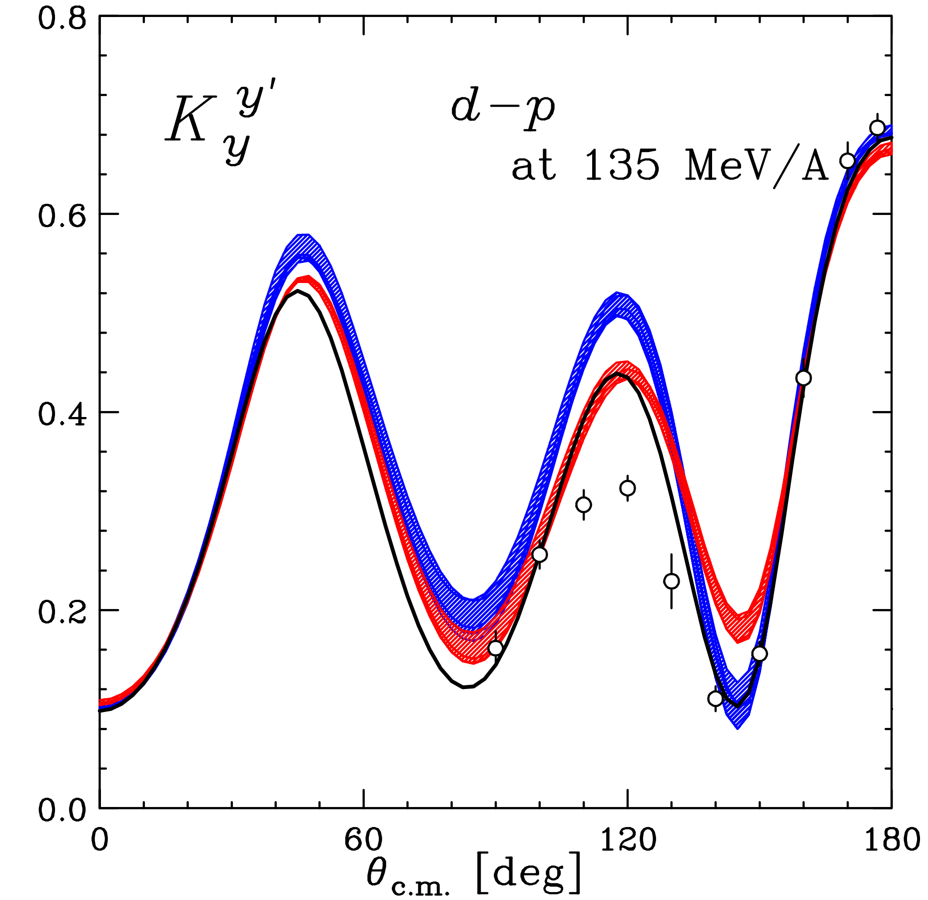


Polarization Transfer Coefficients

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







3NF :

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

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

Magnitude : not enough

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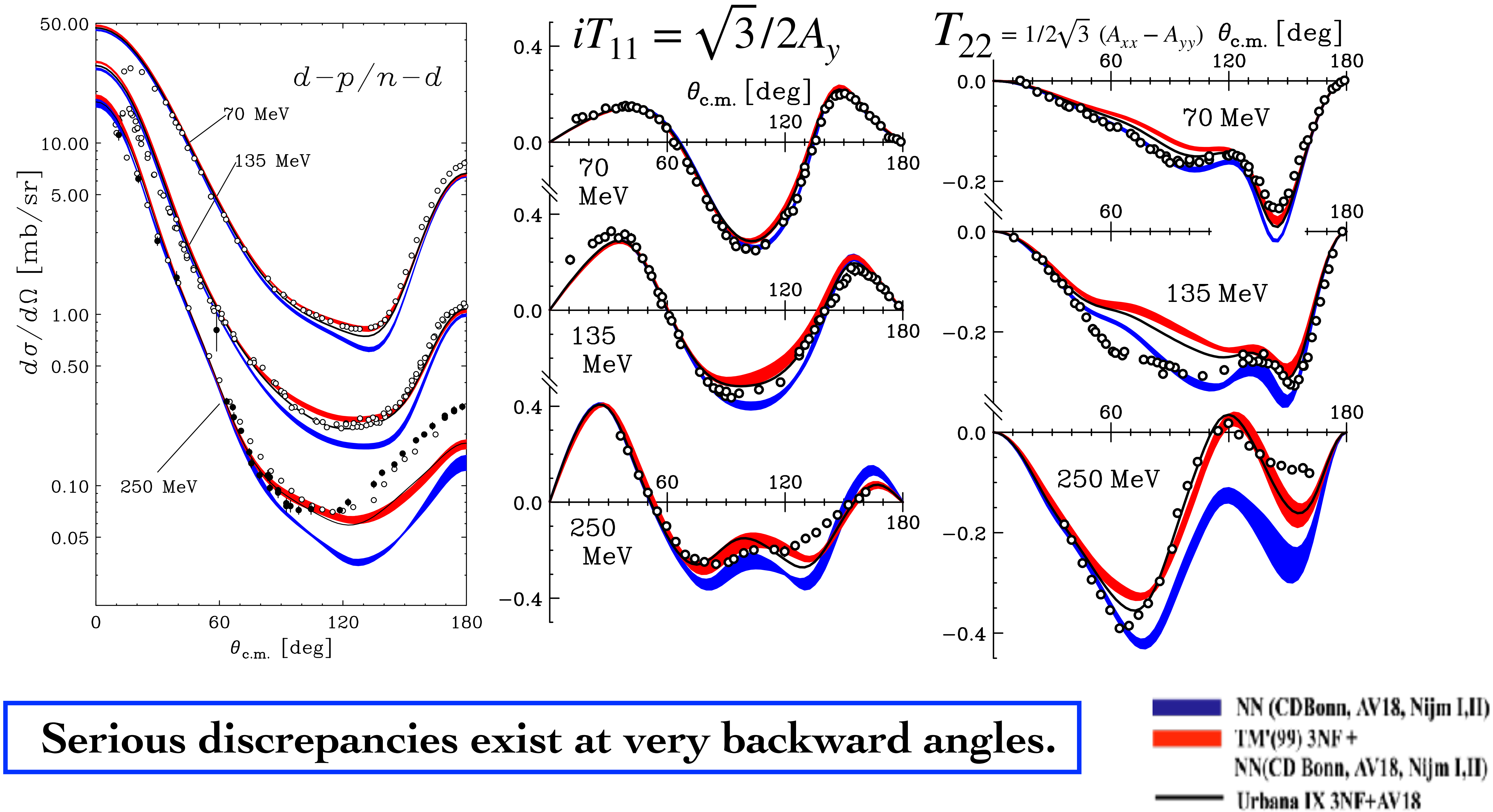
d-p elastic scattering Energy Dependence

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)



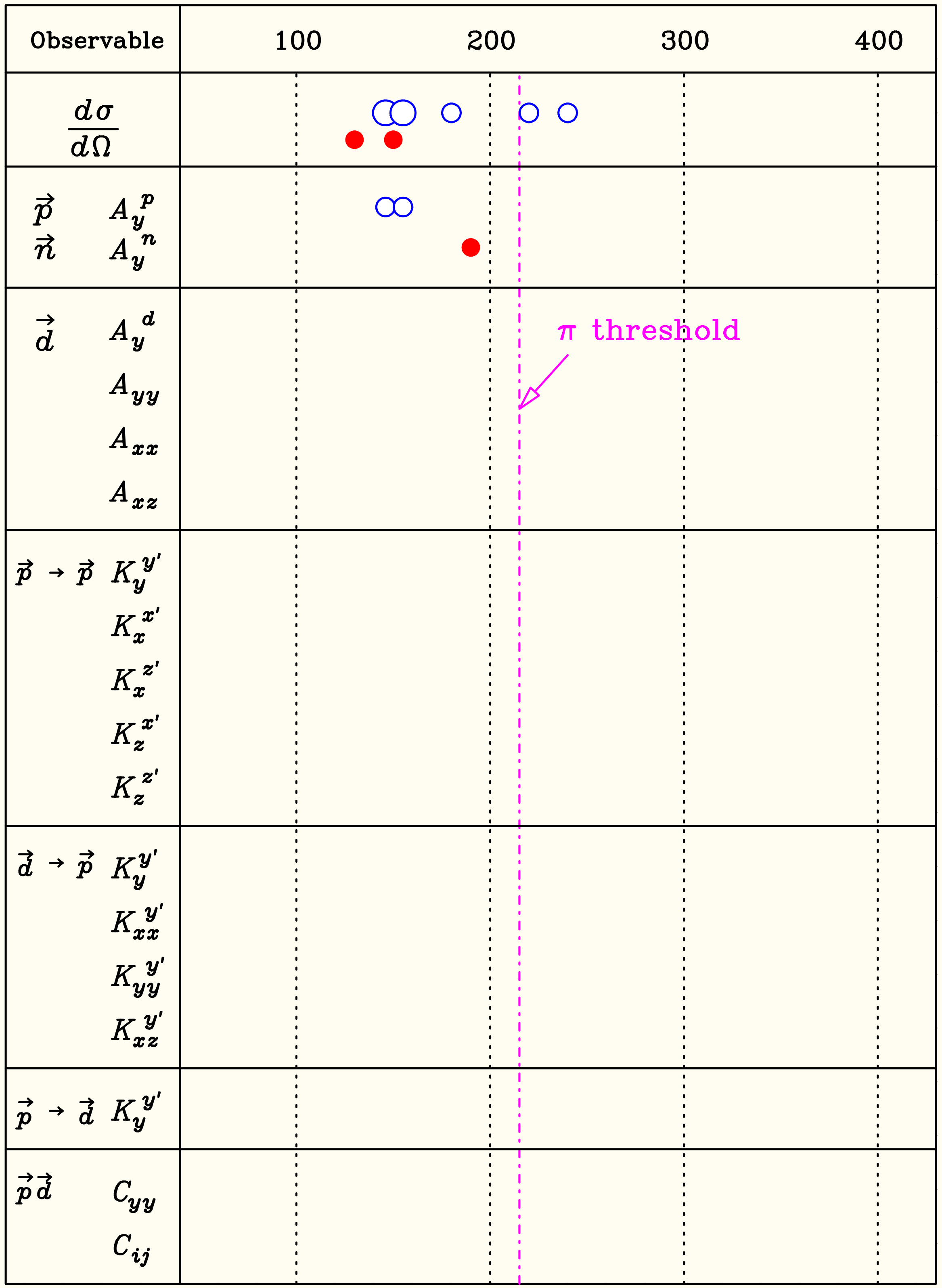
Serious discrepancies exist at very backward angles.

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

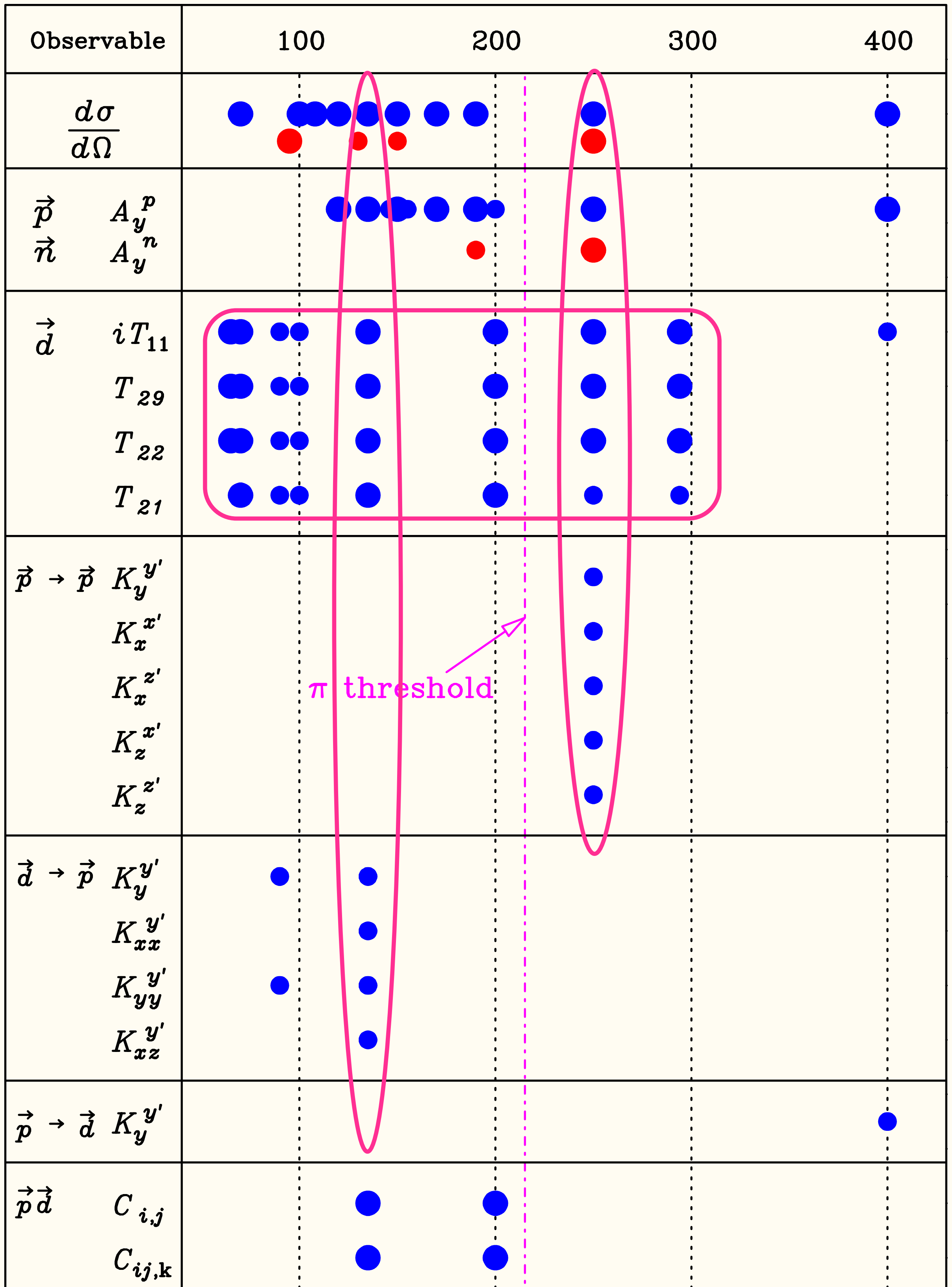
pd and *nd* Elastic Scattering at 70–400 MeV/A



~1998

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**

After about **90** Years of Yukawa's Meson Thory (1935)

&

After **65** Years of Fujita-Miyazawa 3NF (1957)

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

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Recent Study
and Future Aspects

in Progress : Theory

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

Three-Nucleon Force is
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

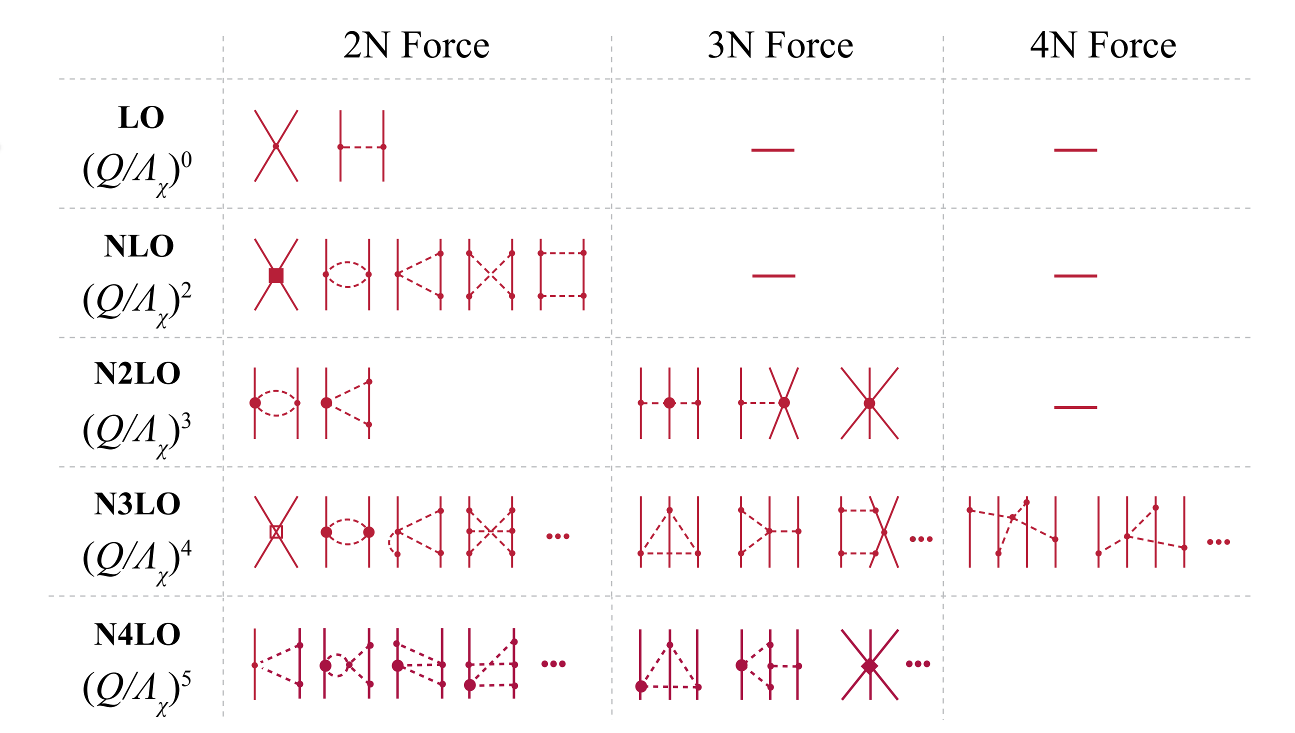
Nuclear Forces based on Chiral Effective Field Theory

- 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.

Layout of χEFT Nuclear Forces

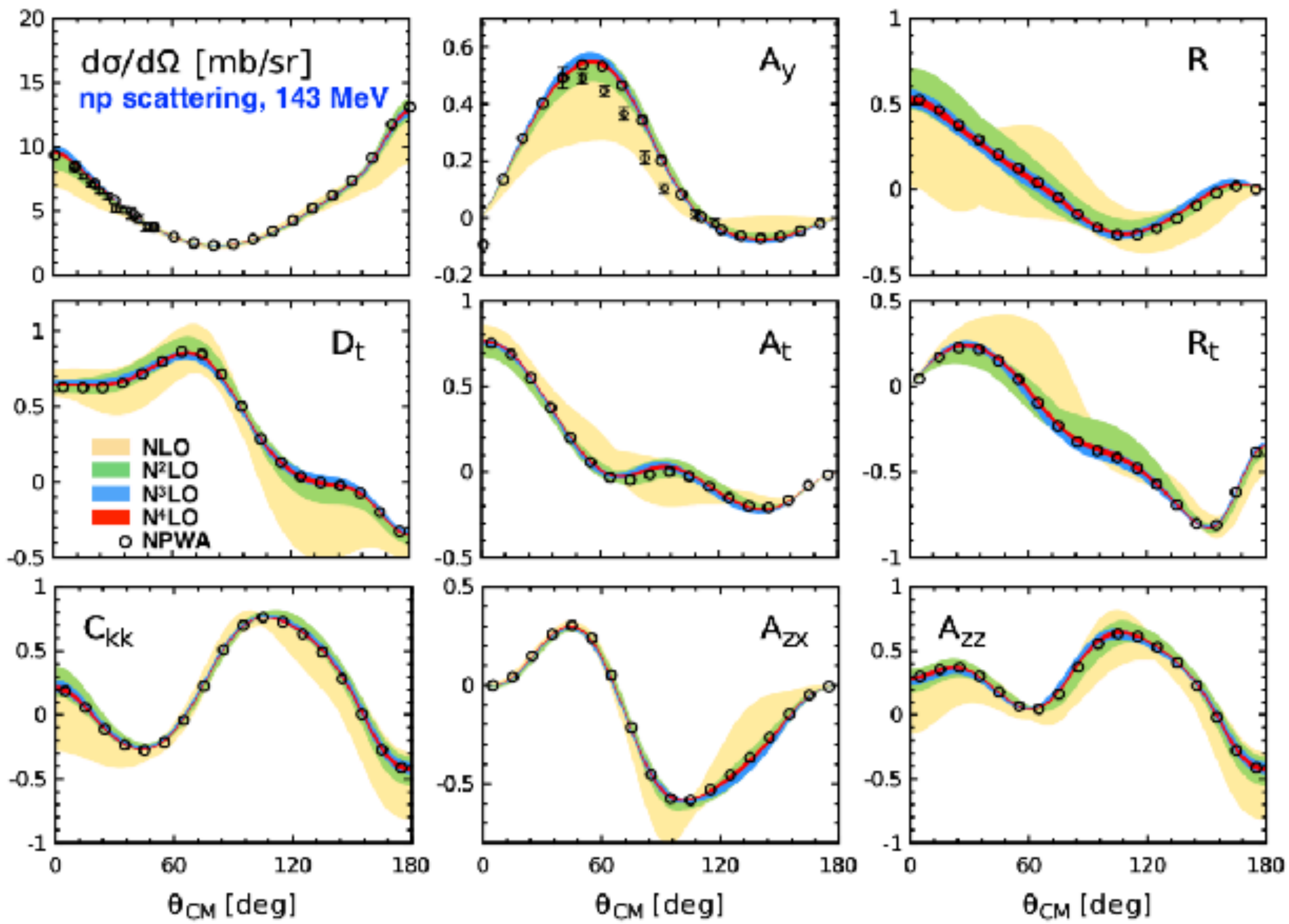


The 2N system

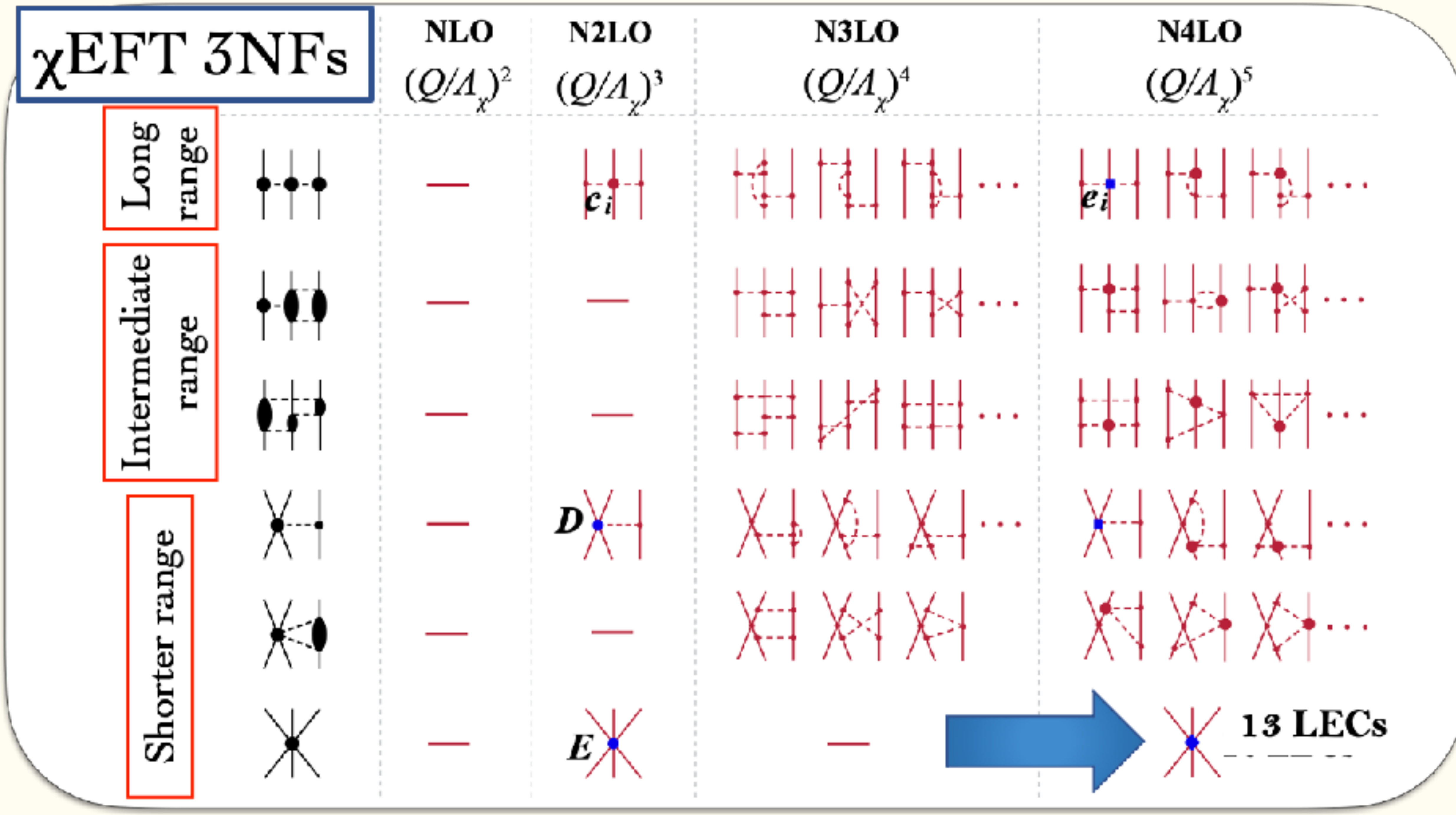
Experience in the 2N sector: how far should one go to obtain a precise description of data?

	LO	NLO	N^2LO	N^3LO	N^4LO^+
χ^2/datum (np, 0 – 300 MeV)	75	14	4.1	2.01	1.06
χ^2/datum (pp, 0 – 300 MeV)	1380	91	41	3.43	1.00

P. Reinert, H. Krebs, EE, EPJA 54 (2018) 88



χEFT N^4LO 2NF has achieved to **high precision**.
Number of parameters to be fitted to NN data : 28



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

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

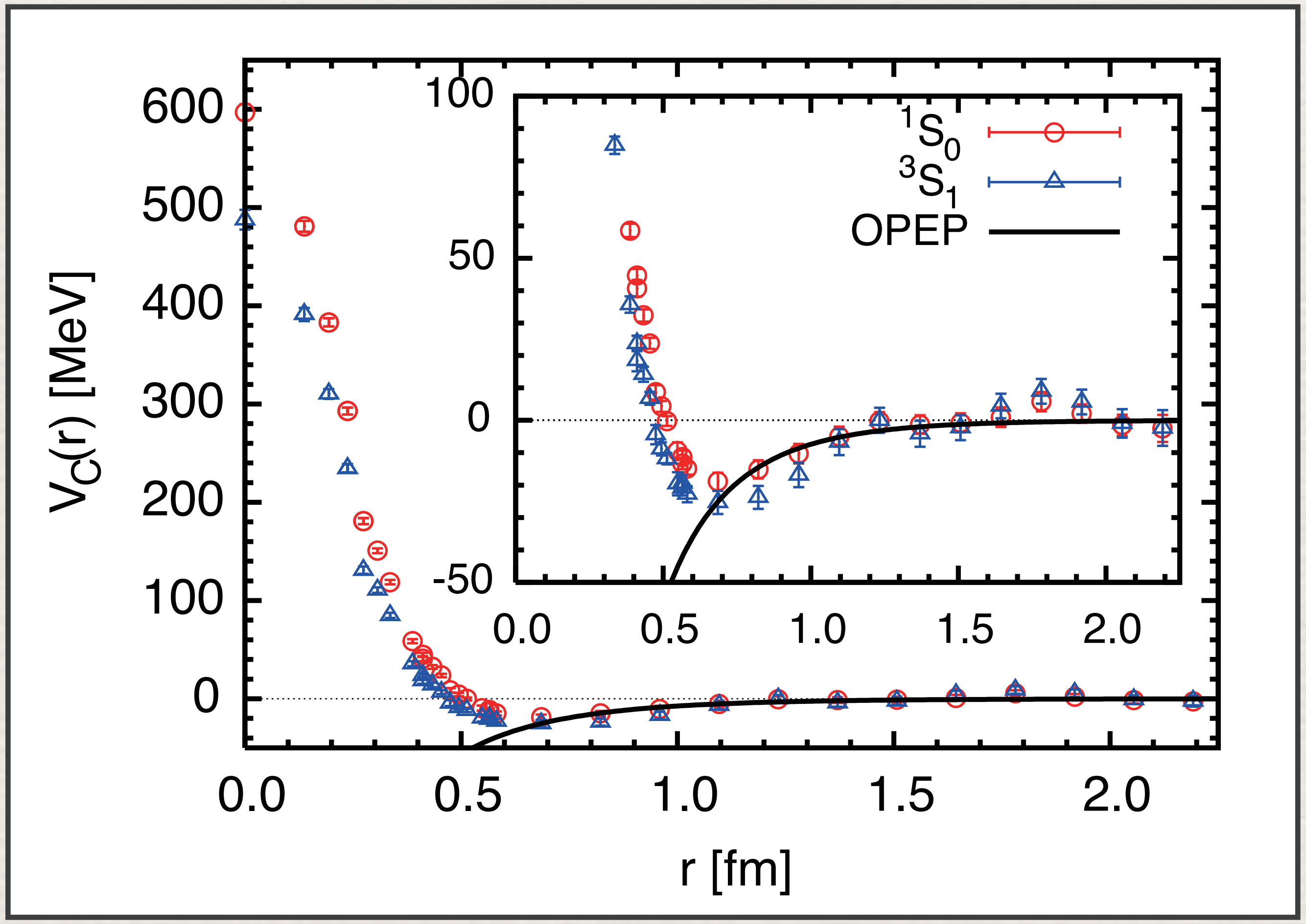
Nuclear Forces linked to QCD

- 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)



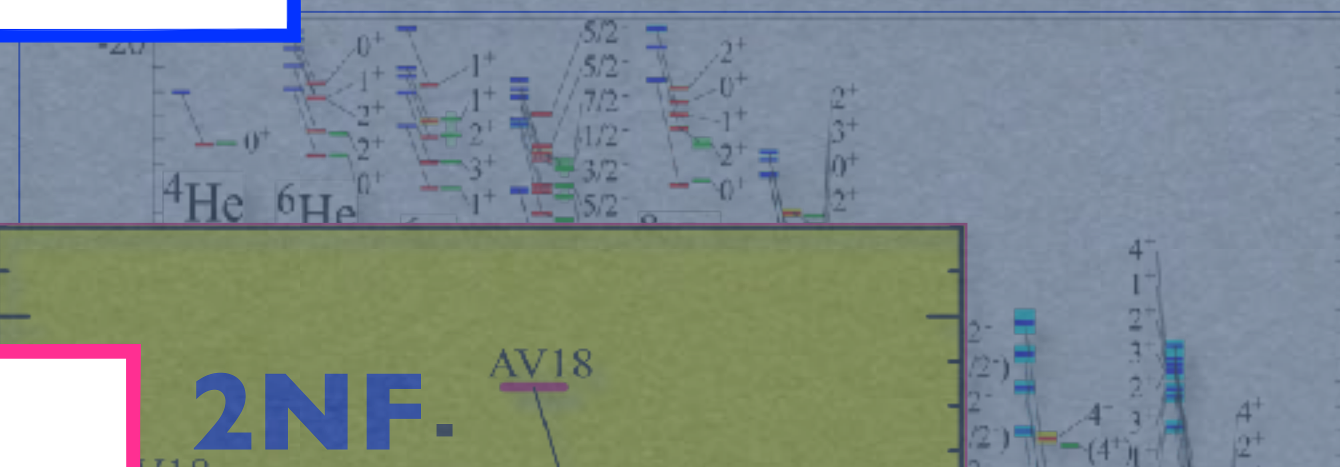
Three Nucleon Force in A>3

3NFs in A>3 - ① -

3NFs in Finite Nuclei

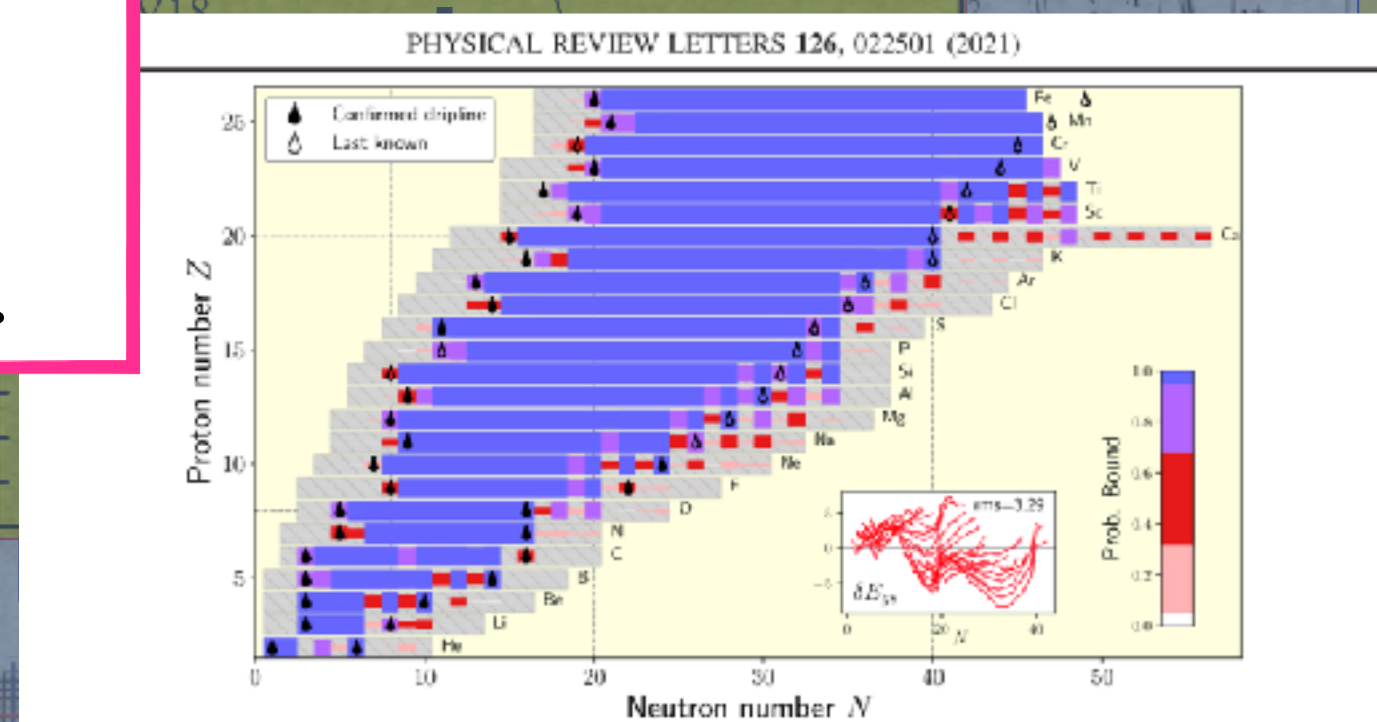
Ab Initio Calculations for Light Nuclei

- Green's Function M[...]te Carlo
- No-Core Shell Mo[...] etc..
  - 2NF provide less bin[...]ng energies



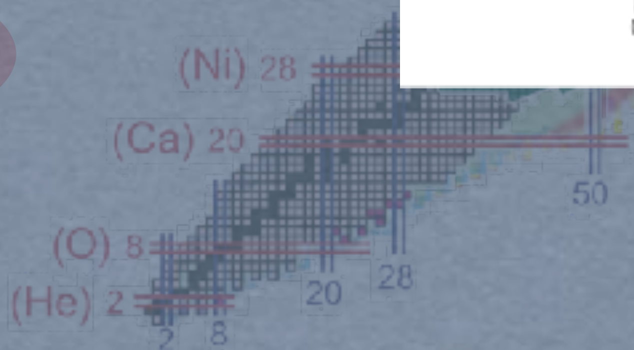
Medium Mass Nuclei

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

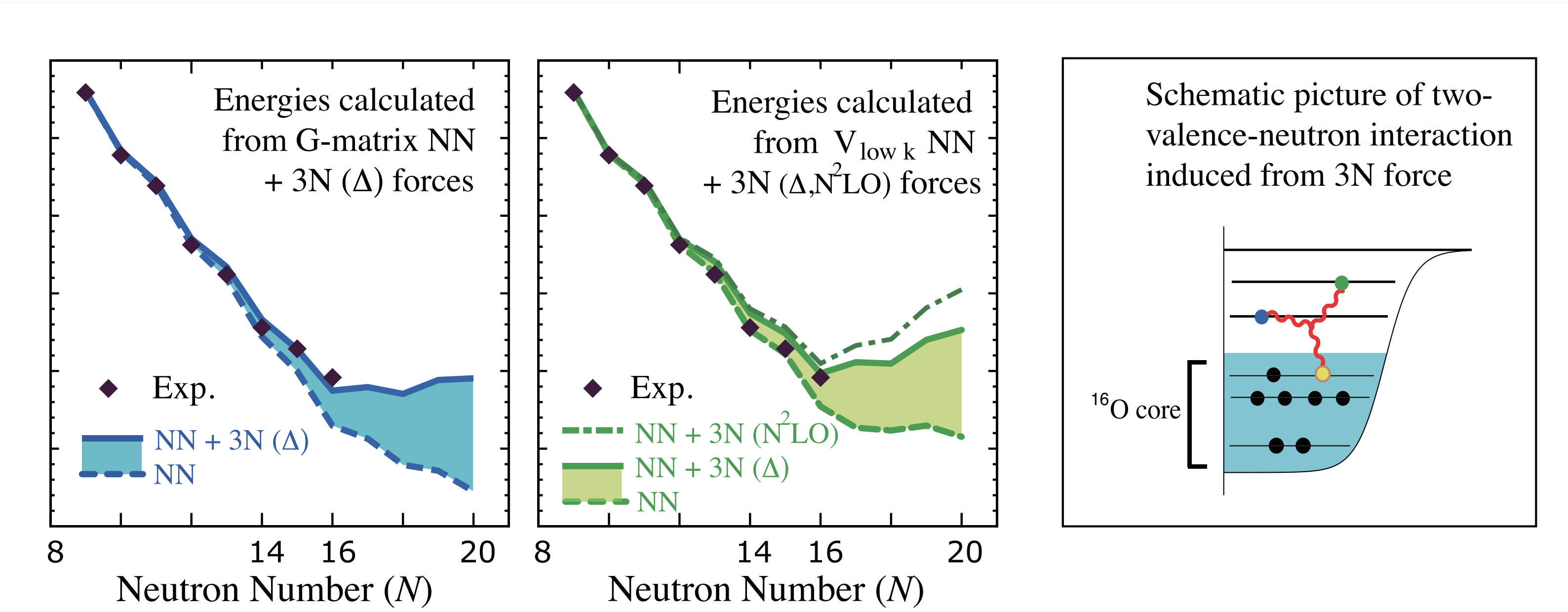


roles to explain B.E.
in neutron rich nuclei.

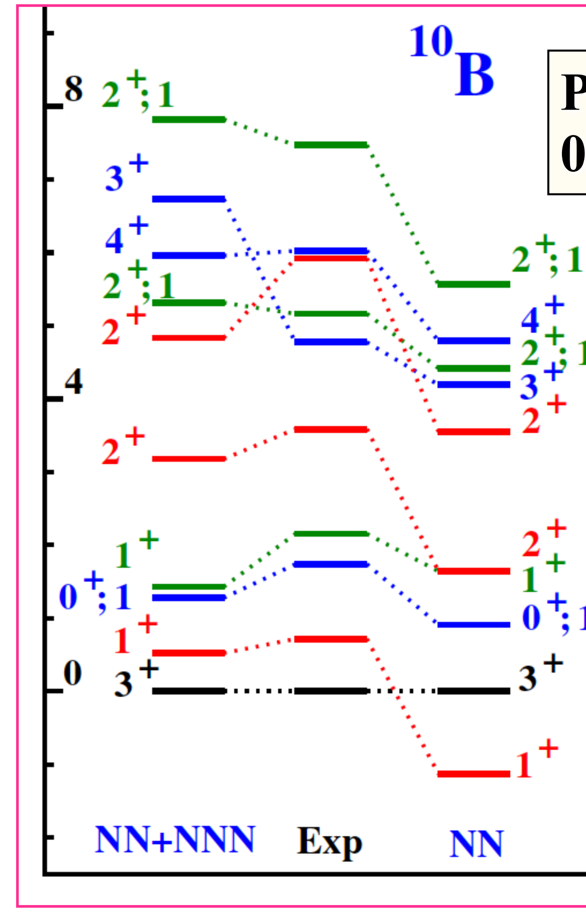
3NF effects in B.E.
- 10-25%
- Attractive



Nuclear Structure and χEFT Nuclear Potential



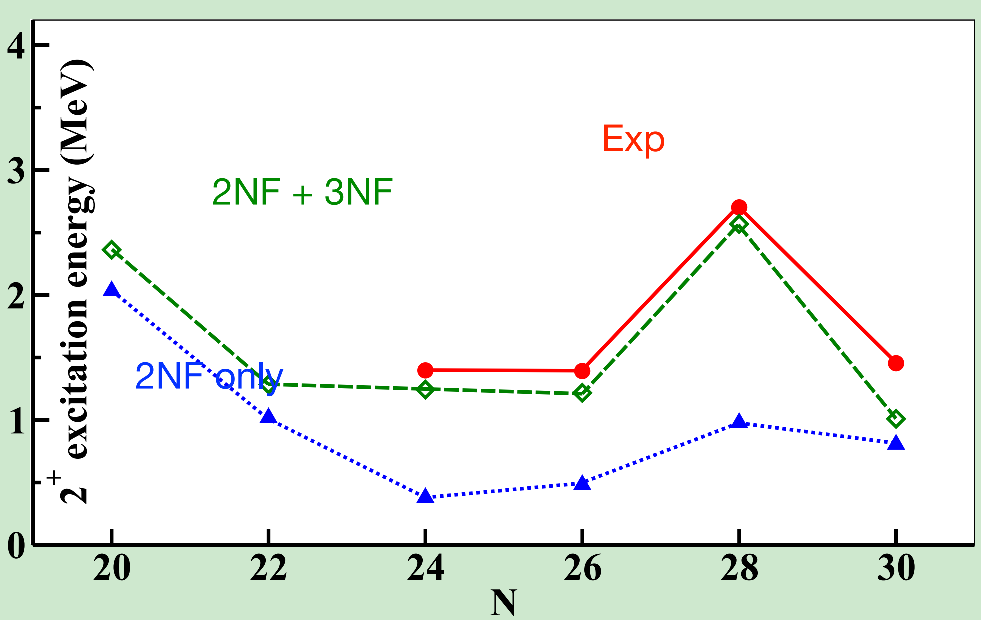
Otsuka et al.,Phys. Rev. Lett. 105, 032501 (2010)

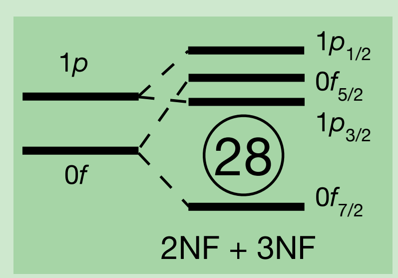


P. Navratil, PRL 99, 042501 (2007)

***pf*-shell nuclei** (Ni isotopes)

Ma, Fukui et al., PRC **100**, 034324 (2019)





Contribution of Each term of the N2LO 3NF in ⁶Li
T. Fuku et al. EPJ web of conference **223**, 01018 (2019)

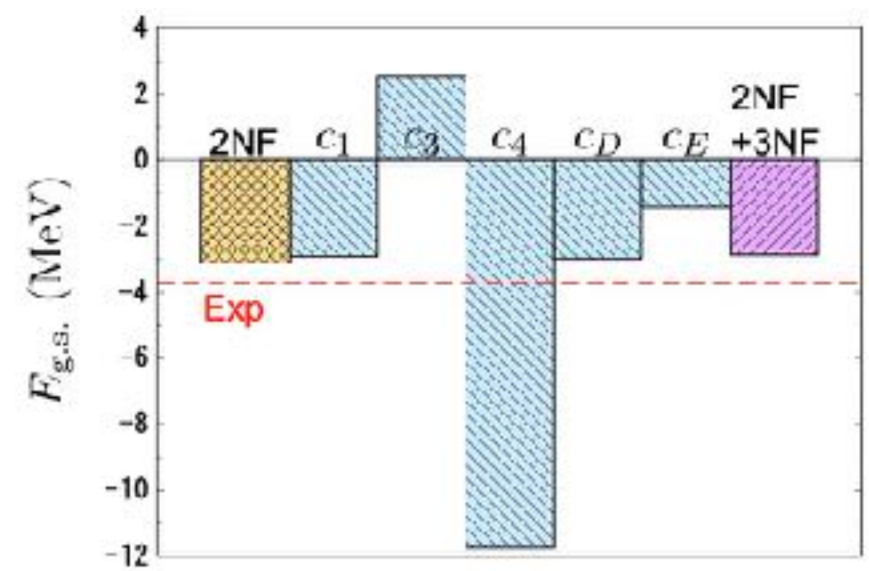
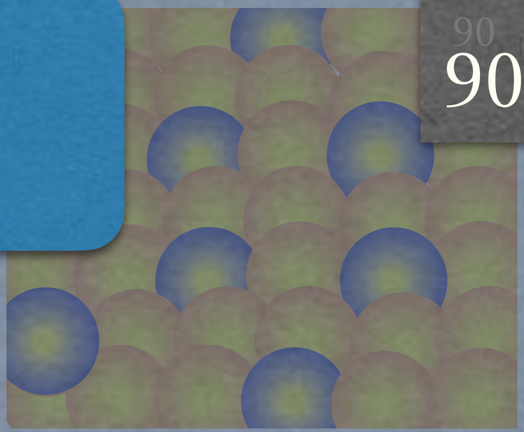


Figure 3. The individual contribution of each term of the 3NF to $E_{g.s.}$ of ⁶Li. See text for details.

3NFs in A>3 - ② -



3NFs in Infinite Nuclei - Neutron Star -

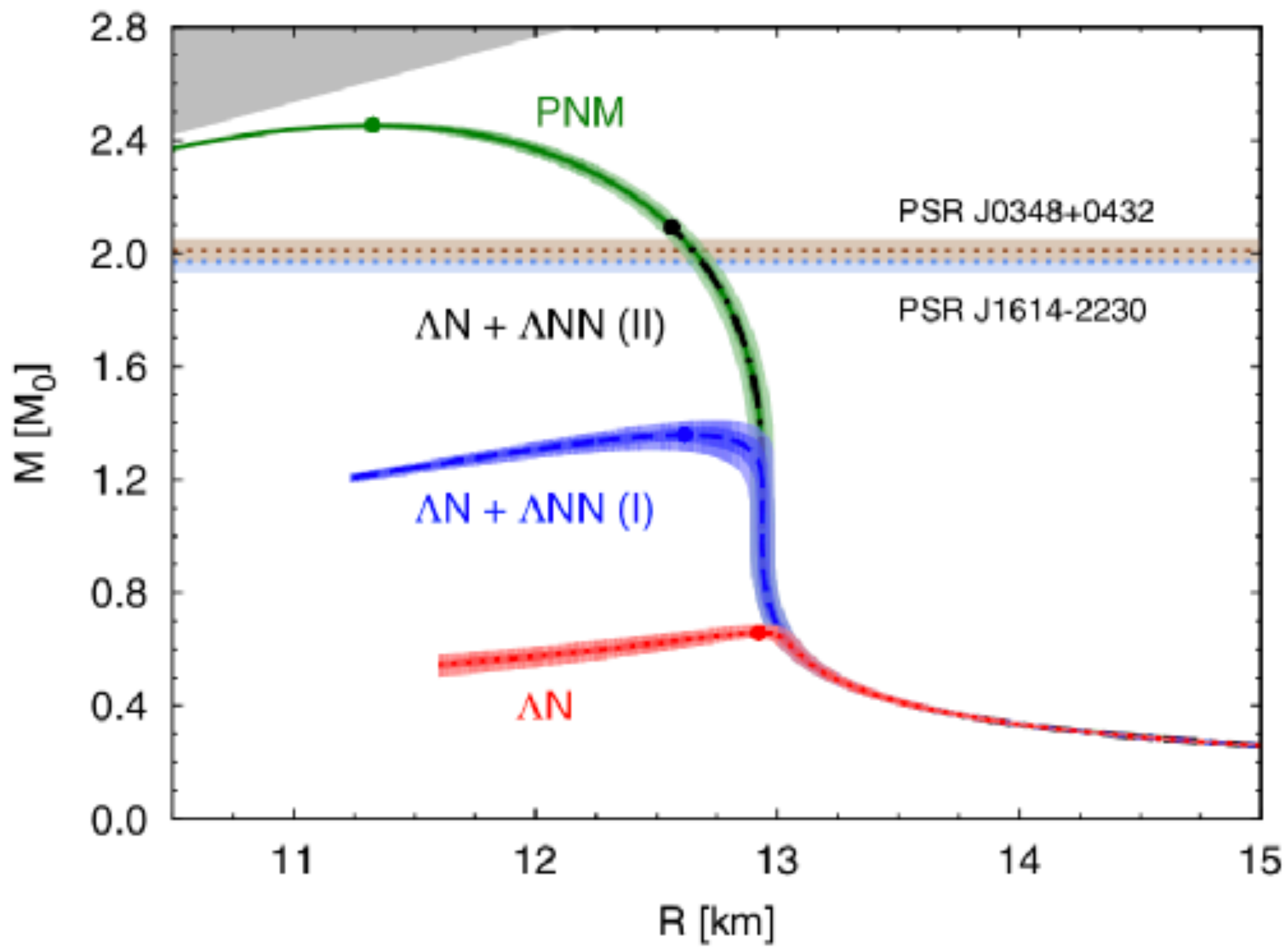
核物質の状態方程式

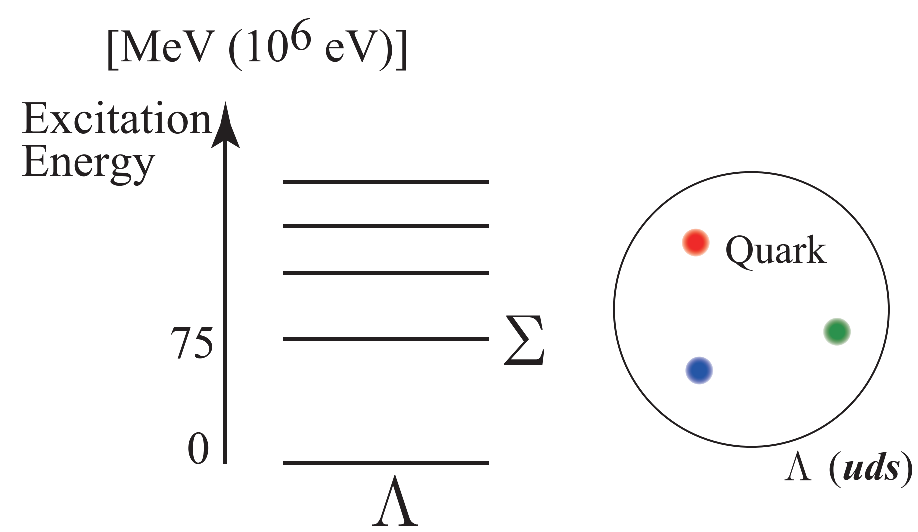
A. Akmal et al., PRC 58, 1804('98)

Symmetric Nuclear Matter

Neutron Star

NNN(nnn) + NNΛ in Infinite Nuclei - Neutron Star -





D. Lonaldoni et al., Phys. Rev. Lett. 114, 092301 (2015)

in Progress : Experiment

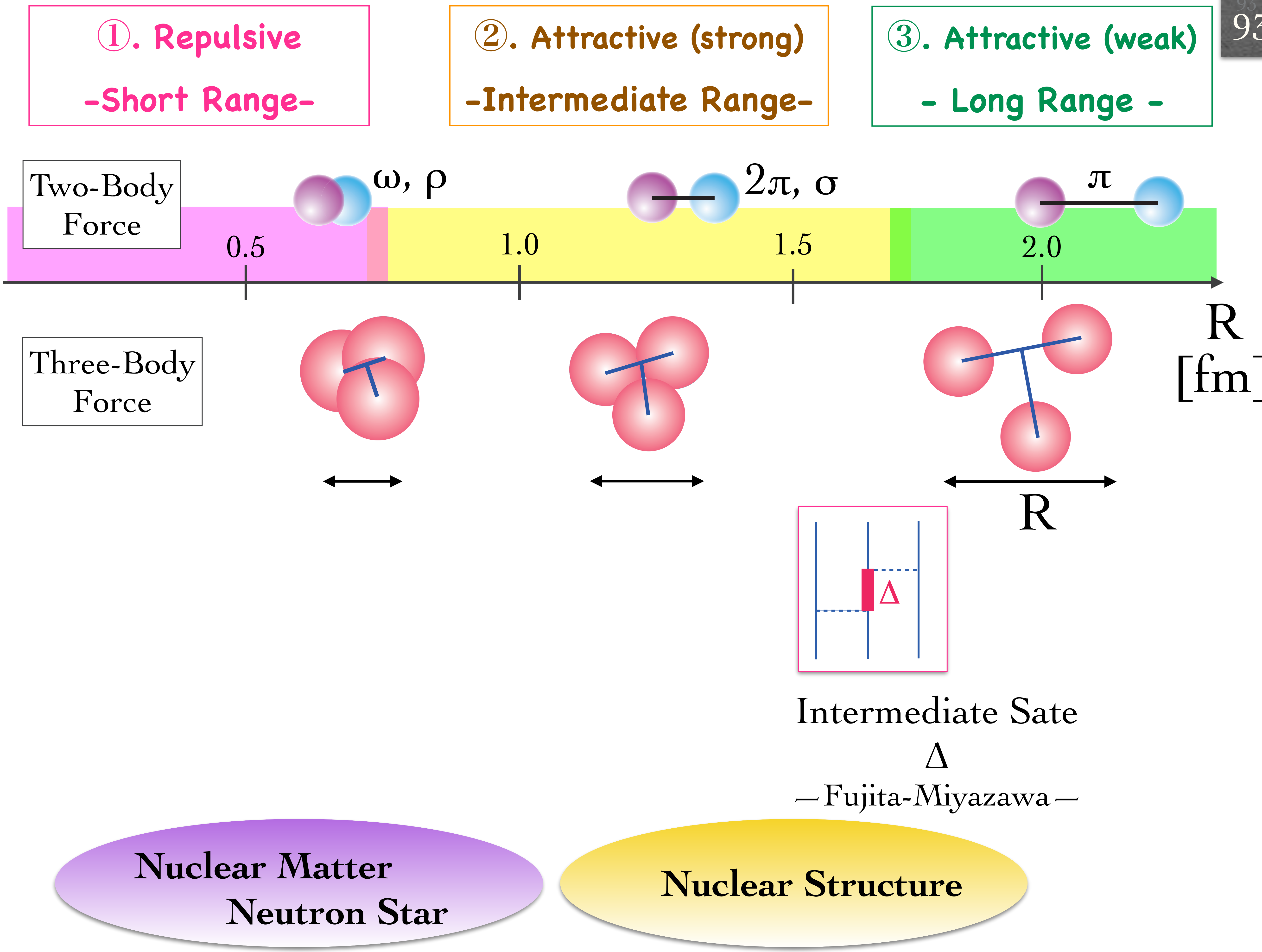
So far …

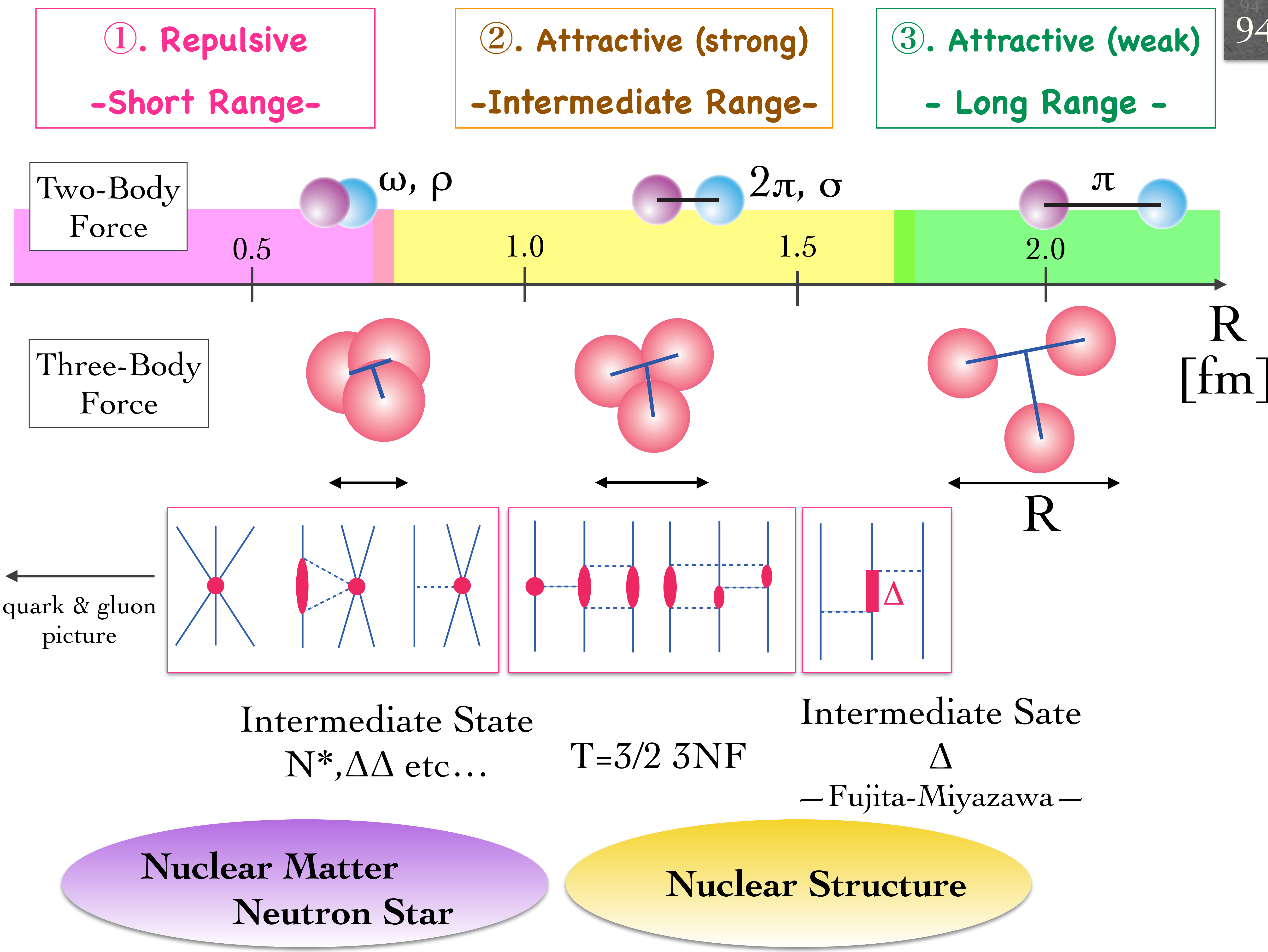
Nucleon-Deuteron Scattering at ~100 MeV/nucleon

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

from here …

- *d-p* Scattering at ~100 MeV/nucleon : *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/nucleon : *New Probe of 3NF Study*
  - First Step from Few to Many
  - 3NFs of isospin channel of T=3/2


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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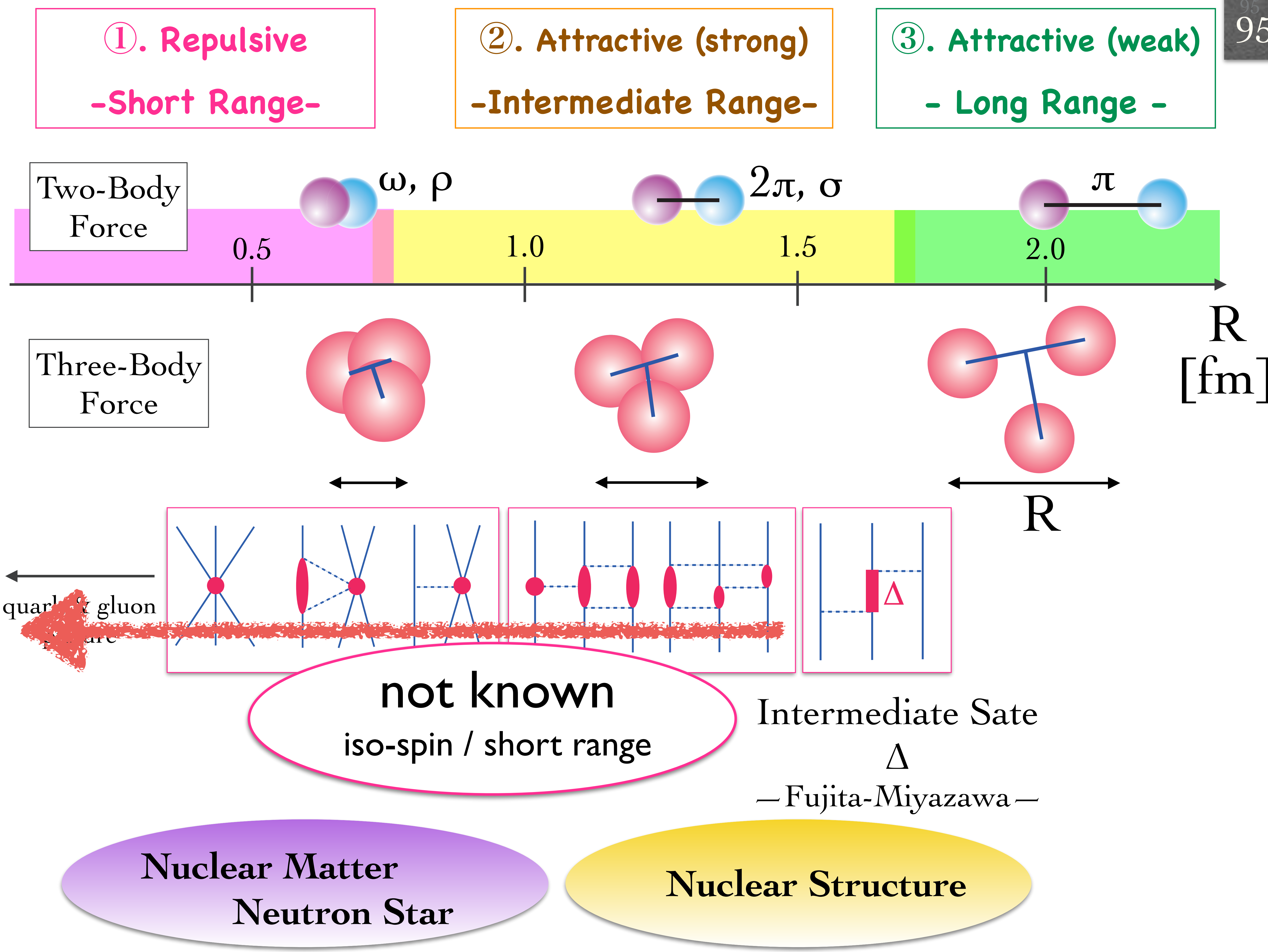
2π, σ
π
0.5
1.0
1.5
2.0
R [fm]
Three-Body Force
R
quark & gluon picture
Δ
Intermediate State N*,ΔΔ etc…
T=3/2 3NF
Intermediate Sate Δ
—Fujita-Miyazawa—
Nuclear Matter Neutron Star
Nuclear Structure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Two-Body Force
ω, ρ
2π, σ
π
0.5
1.0
1.5
2.0
R [fm]
Three-Body Force
R
gluon
Δ
not known
iso-spin / short range
Intermediate Sate
Δ
—Fujita-Miyazawa—
Nuclear Matter
Neutron Star
Nuclear Structure

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)

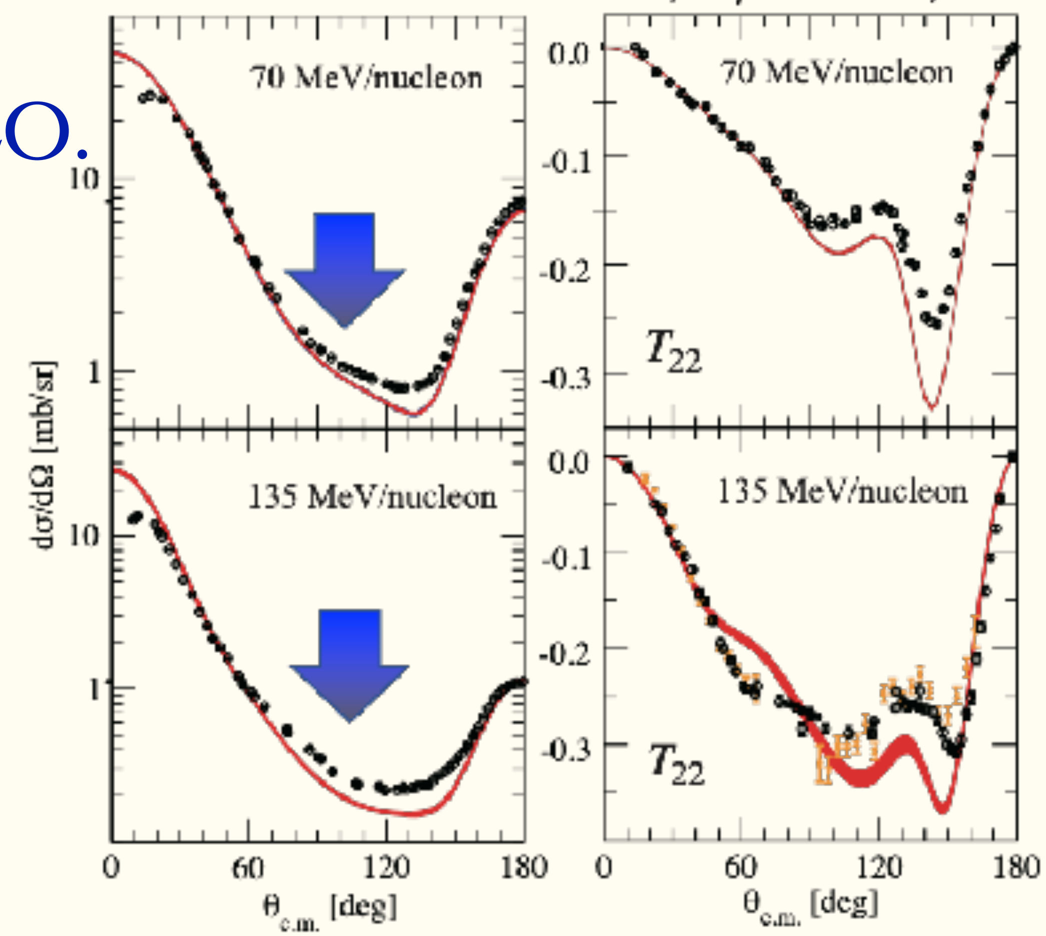
- *dp* elastic scattering data show necessities of 3NFs up to the N4LO.

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)

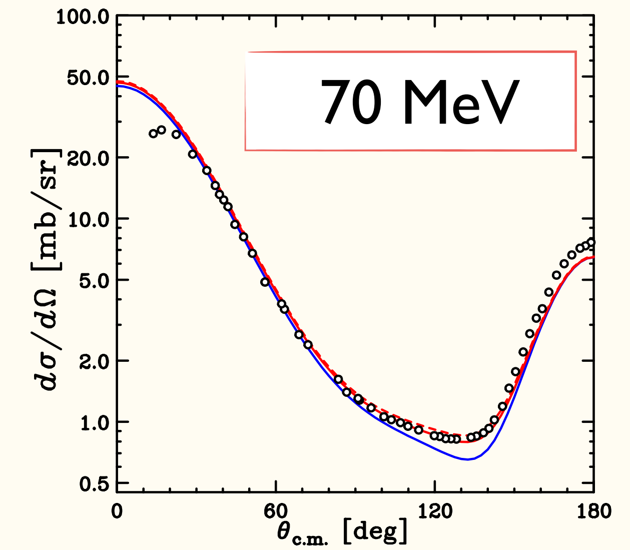
χEFT & *dp* elastic scattering

- Calculations of N4LO⁺ NN with N2LO 3NF (Preliminary)

  2NF : Semi-local Momentum-Space regularized Chiral NN potentials

  P. Reinert, H. Krebs, E. Epelbaum EPJA 54, 86 (2018)

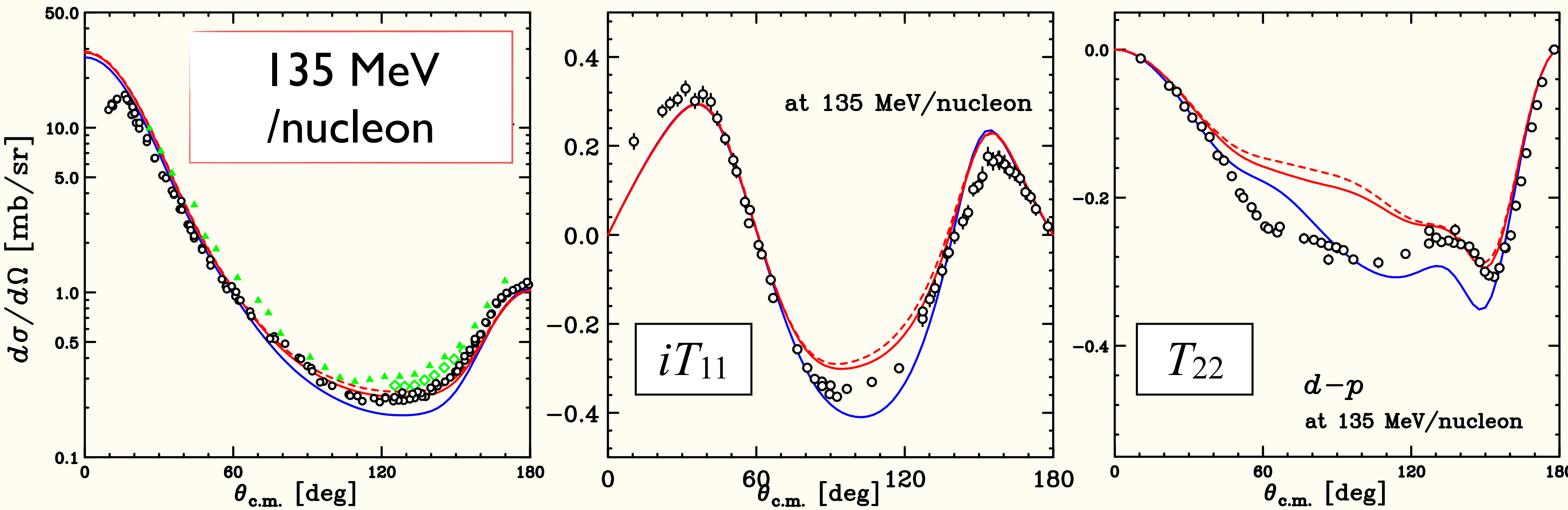
  3NF : LECs of N2LO 3NF (D & E terms) are determined by ^{3}H B.E. & cross section minimum for *Nd* @ 70MeV.

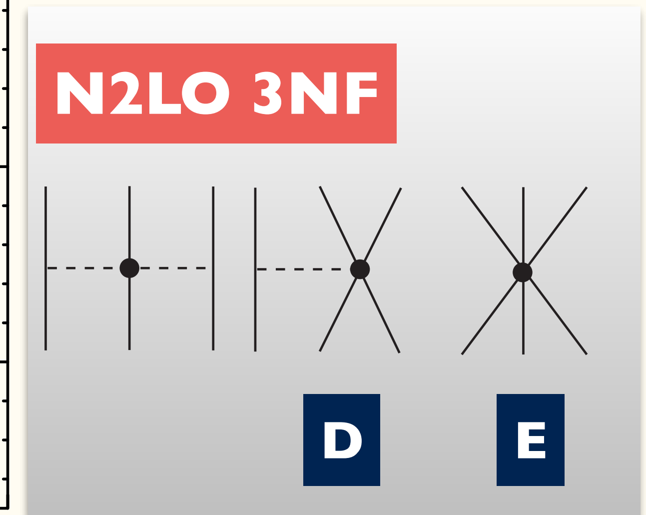


N4LO+, Λ=450MeV

C_D= 2.0, C_E= 0.286

C_D= 4.0, C_E= 0.499





calculations : H. Witala private communications.

- **Spin observables & C.S. at higher energies : N3LO&N4LO 3NFs are needed.**
- **Cross section minimum region : Golden Window for the higher-order 3NFs.**

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

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

→ "High precision 2N+3N forces"

Project of Theory

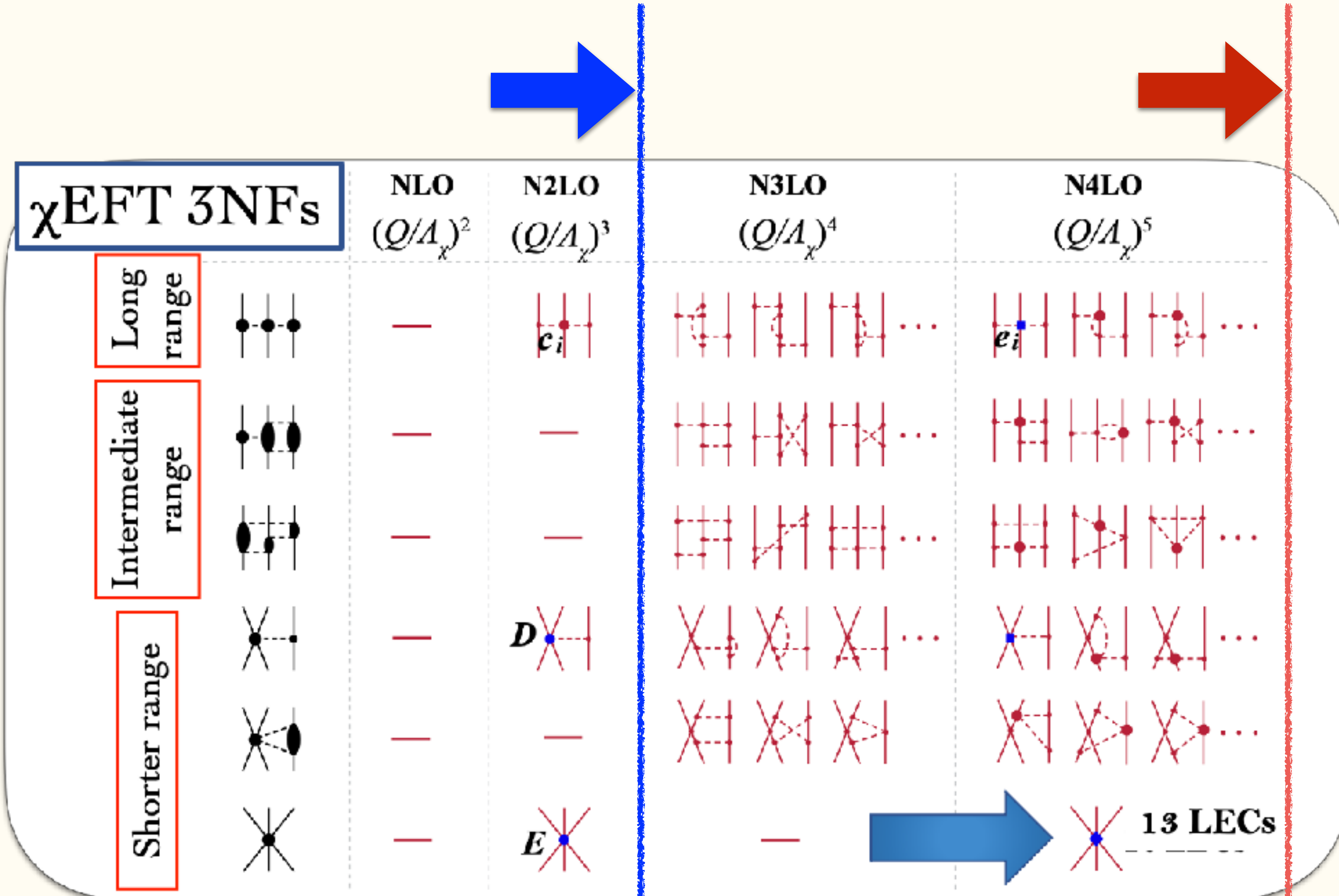
Partial Wave Analysis of *Nd* scattering in the framework of χ EFT

PI : E. Epelbaum (Bochum / LENPIC Collaboration)

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"



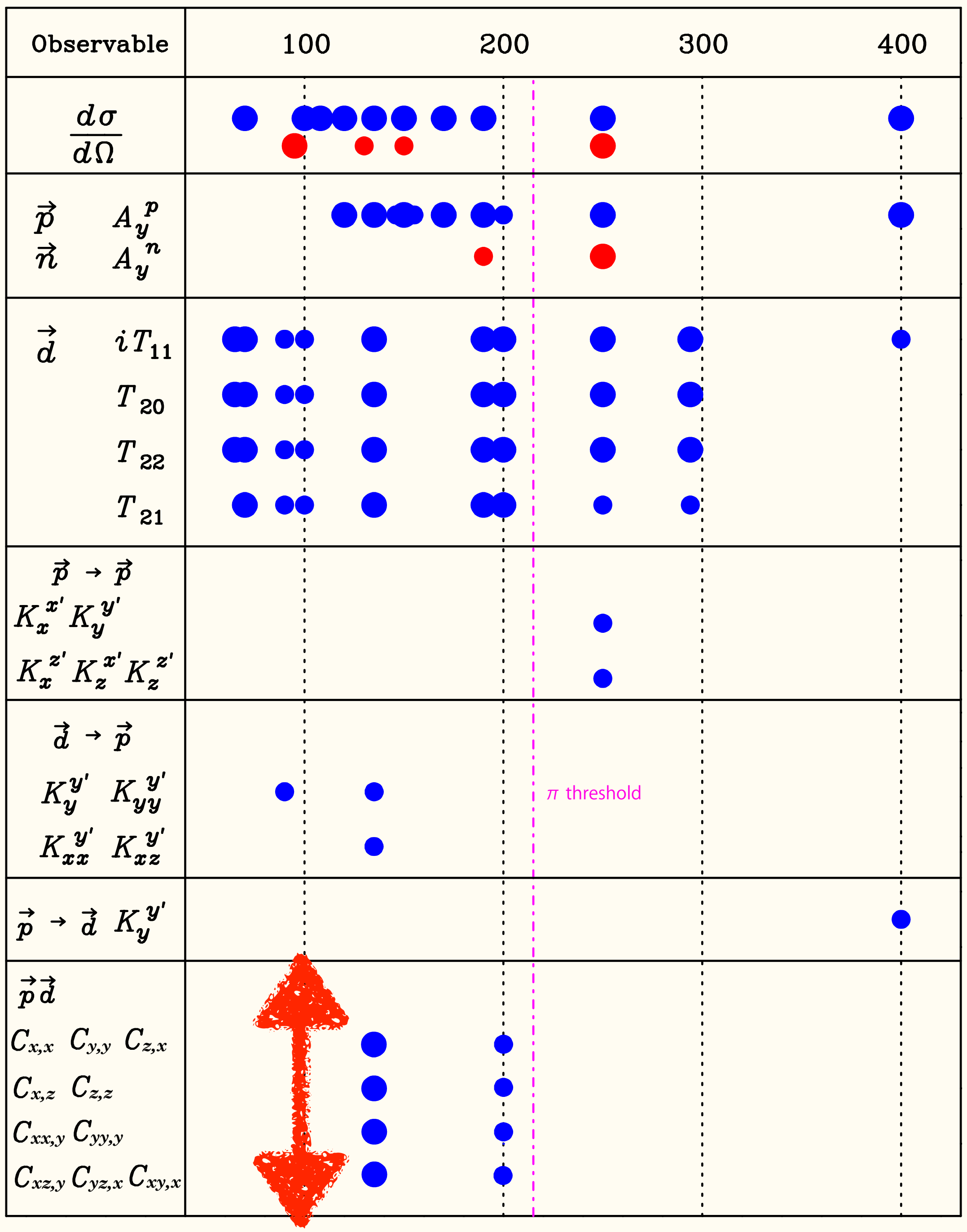
L. Girlanda, et al., Phys. Rev. C 84, 014001 (2011)

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

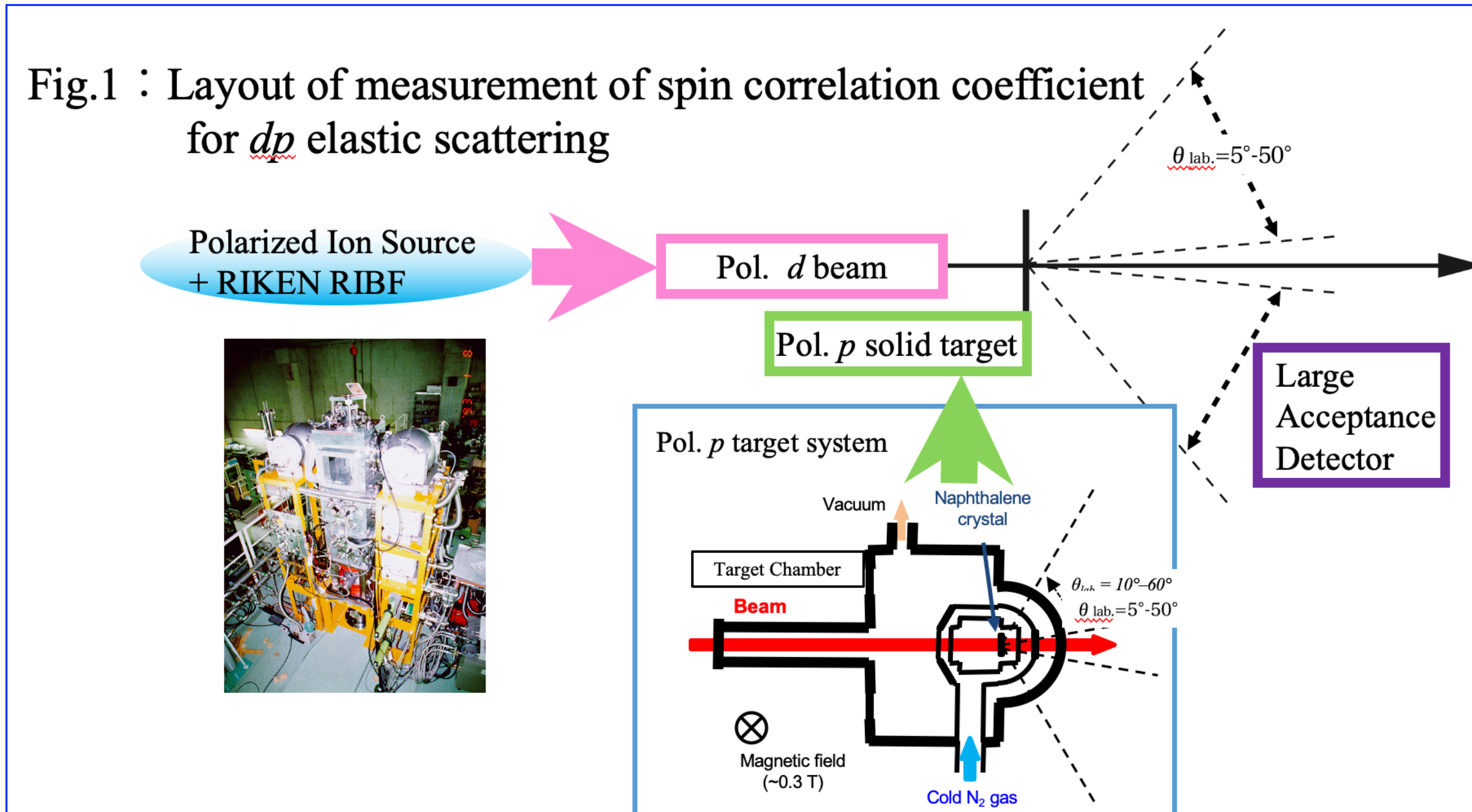


Fig.1 : Layout of measurement of spin correlation coefficient for *dp* elastic scattering

dp Scattering

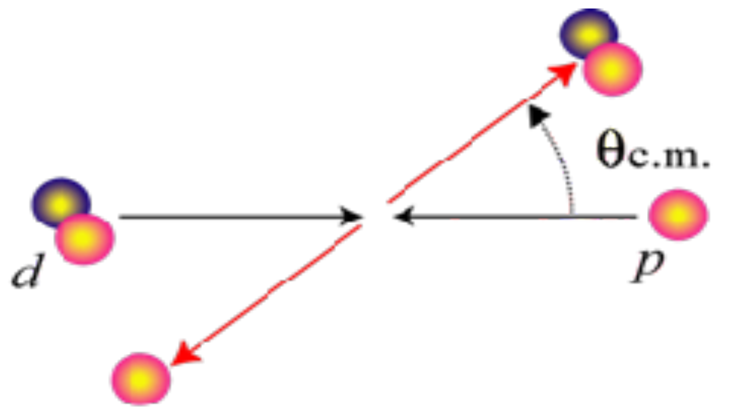
- $d + p \longrightarrow d + p$

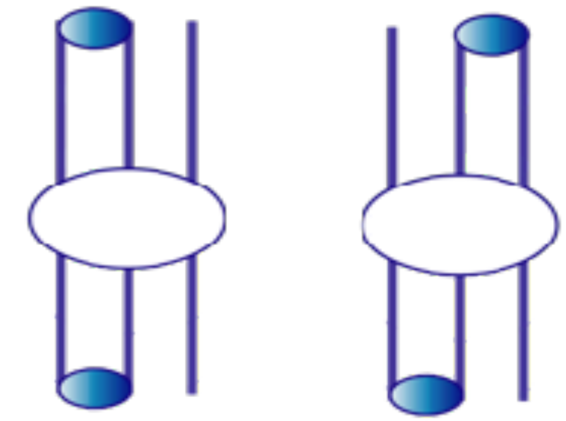
$\theta_{c.m.} = 0° \sim 180°$

Momentum transfer

q =0 - 3.4 fm^{-1}

(at E = 135 MeV/A)



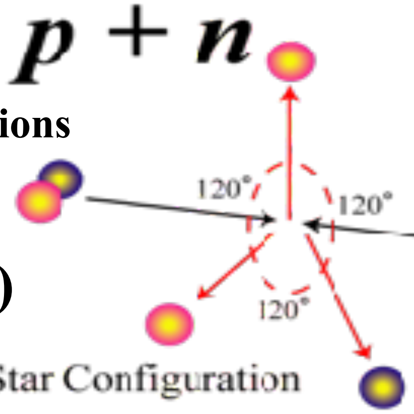


- $d + p \longrightarrow p + p + n$

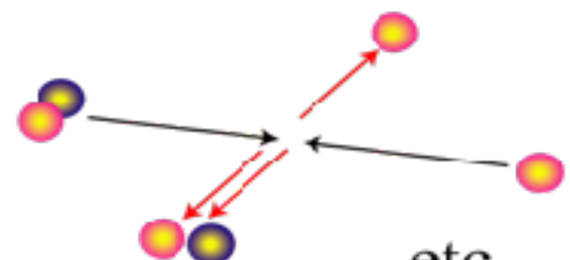
Many kinematical configurations

q =0 - 3 fm^{-1}

(at E = 135 MeV/A)

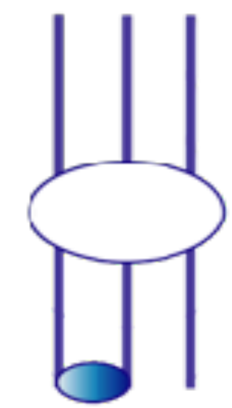


Star Configuration



Final State Interaction

etc ...

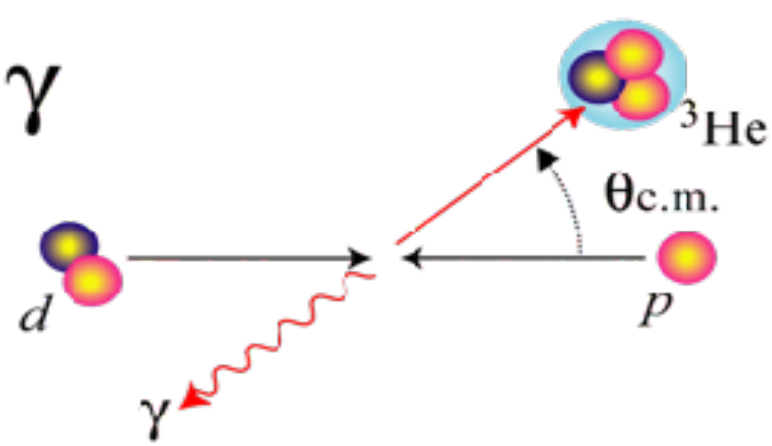


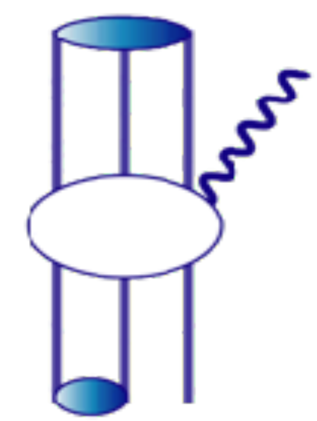
- $d + p \longrightarrow {}^3He + \gamma$

$\theta_{c.m.} = 0° \sim 180°$

q =1.5 - 2.5 fm^{-1}

(at E = 135 MeV/A)



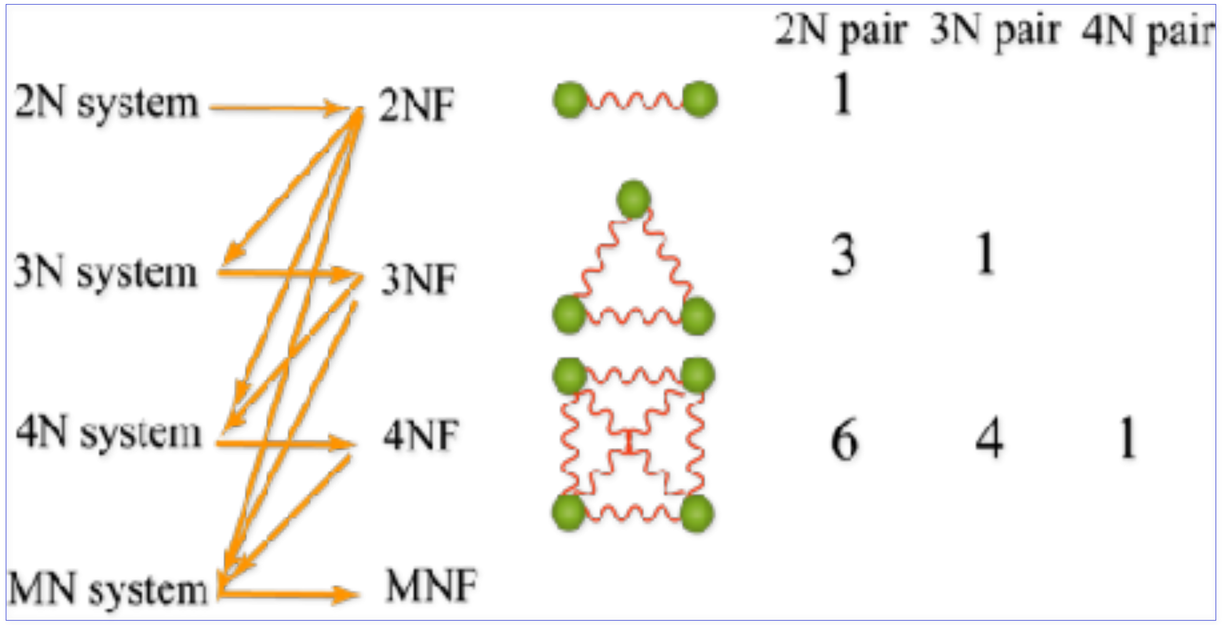


p-^{3}He scattering

- **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

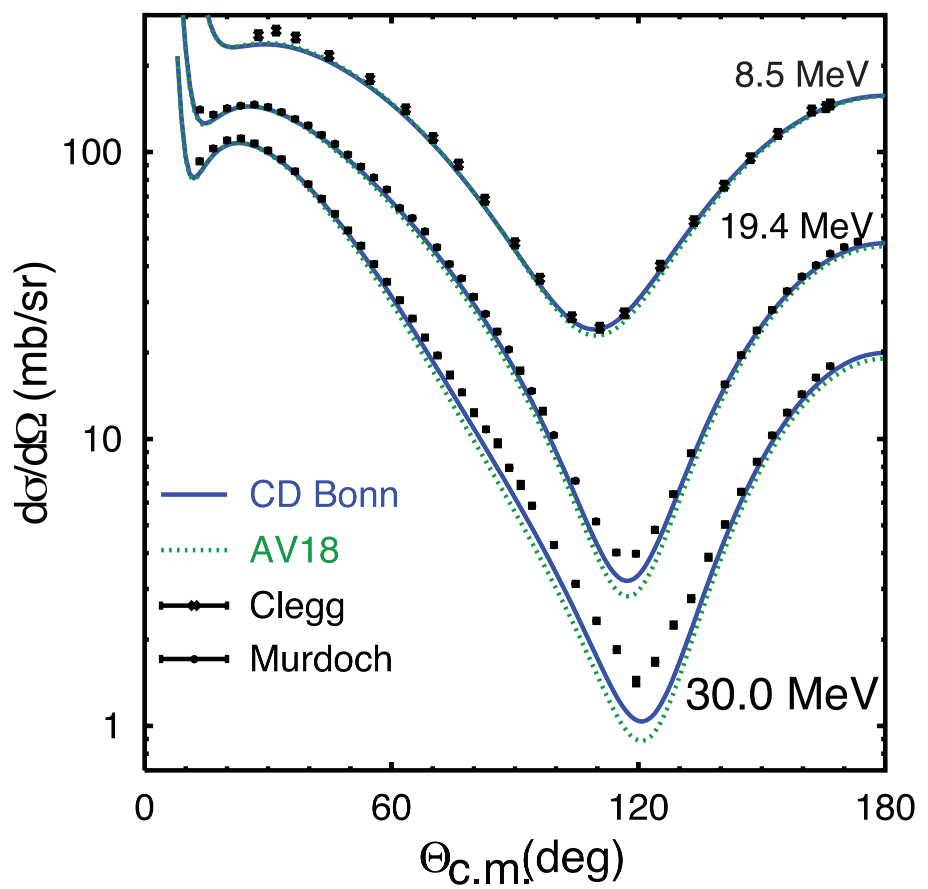
Theory in Progress

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)

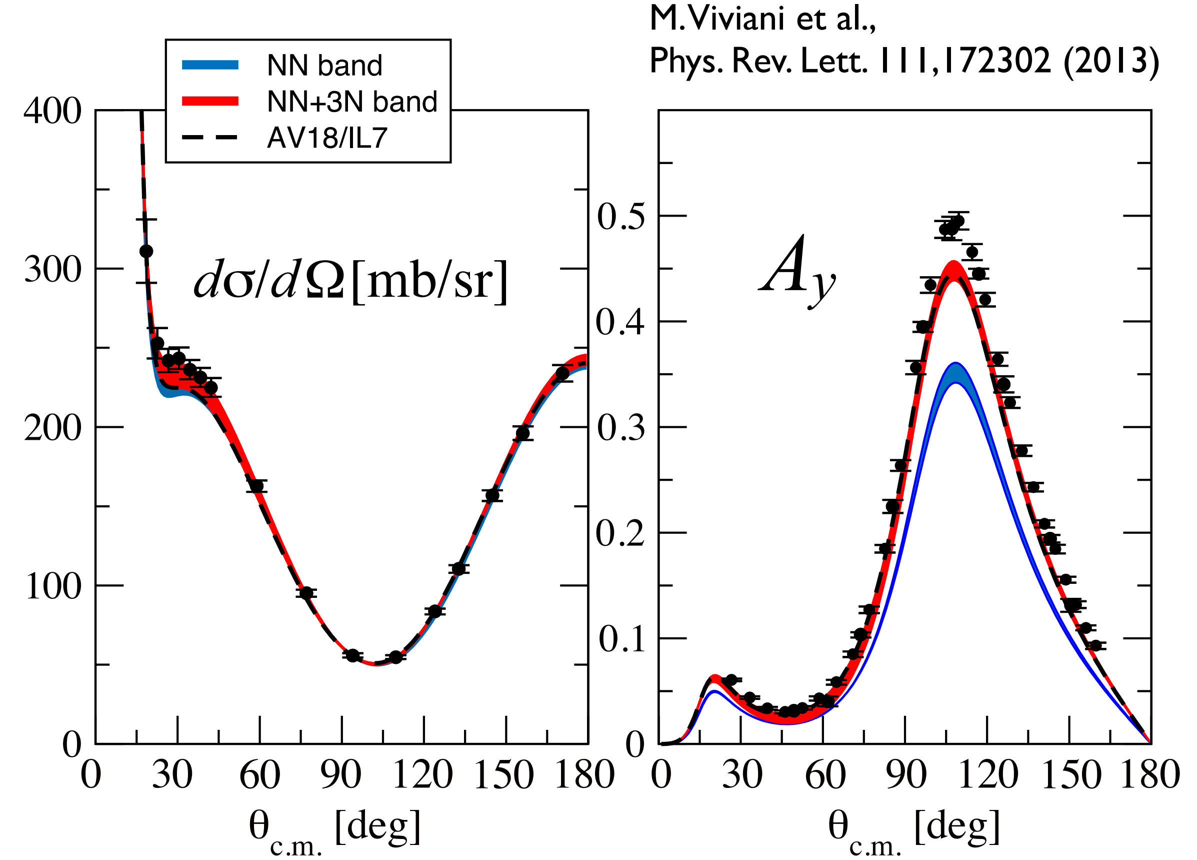


Discrepancies in cross section minimum at higher energies

New rooms for 3NF study

at 5.54 MeV

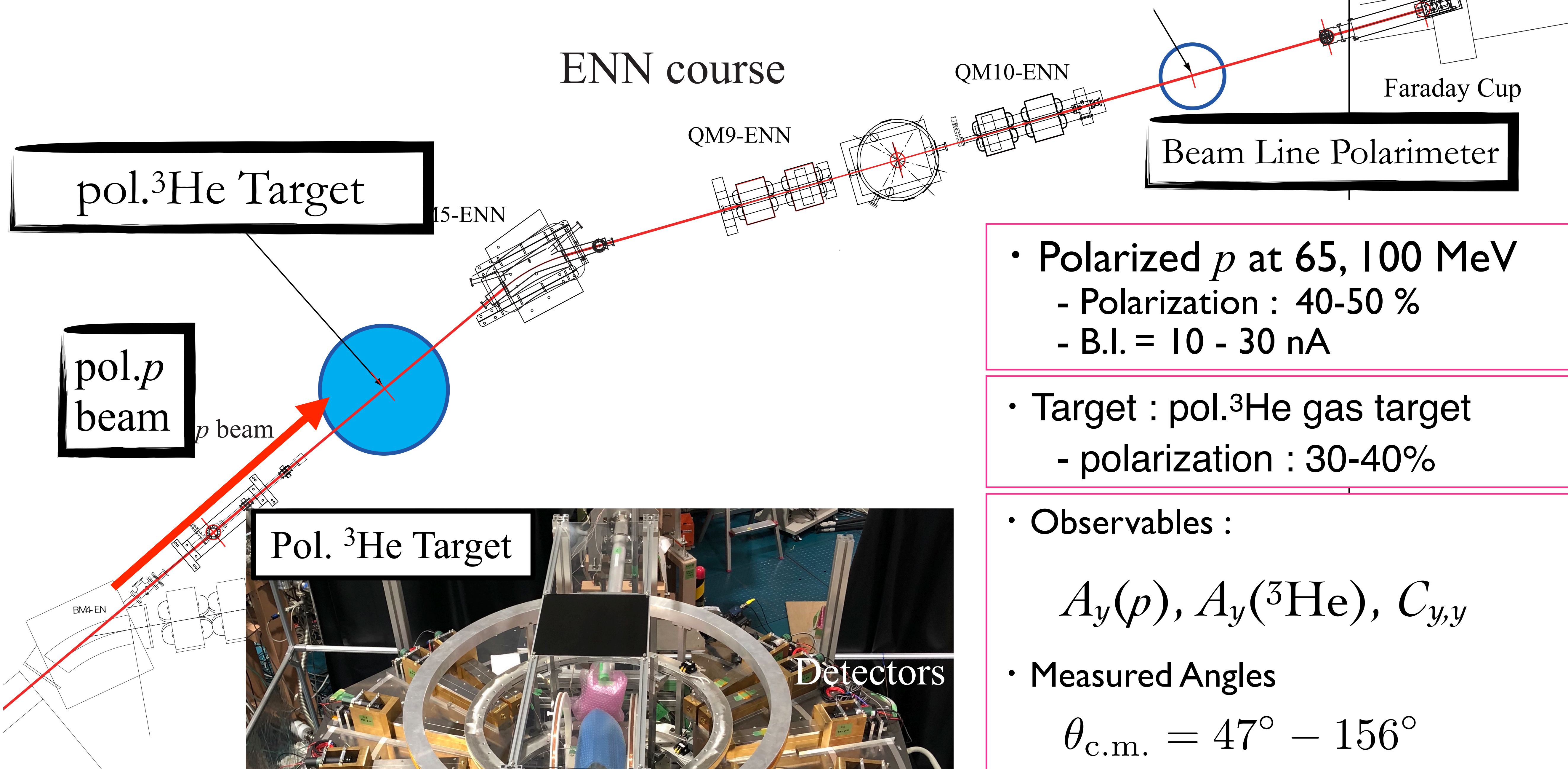
M. Viviani et al.,
Phys. Rev. Lett. 111, 172302 (2013)

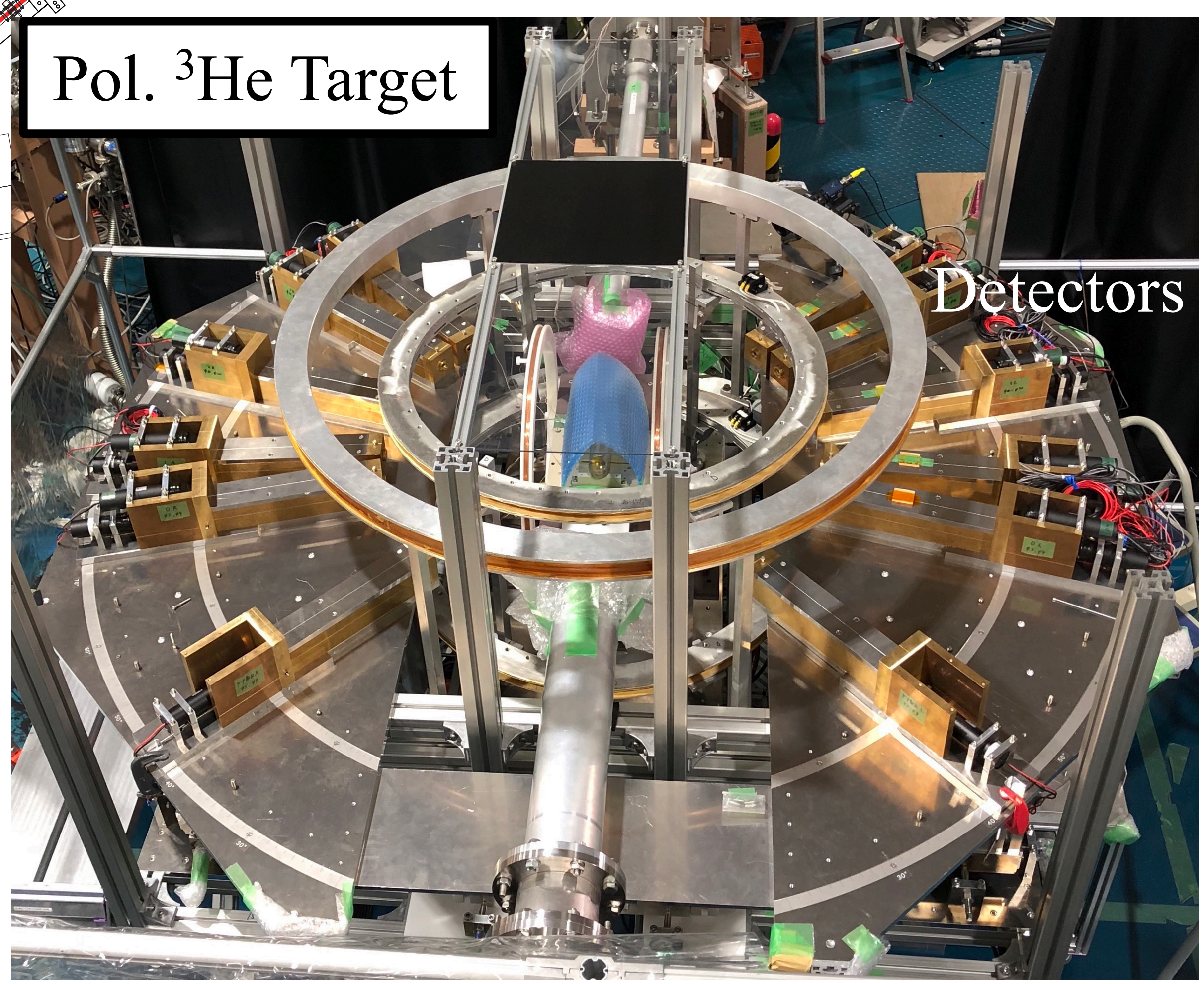


- No signature of 3NFs in cross section
- $Ay(p)$ puzzle : 3NFs sensitive to p-shell nuclei improve the agreement to the data.

How about spin observables at higher energy?

pol.p+pol.^{3}He experiment at RCNP





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

- Target : pol.^{3}He gas target
  - polarization : 30-40%

- Observables :

$$A_y(p),\ A_y(^3\mathrm{He}),\ C_{y,y}$$

- Measured Angles

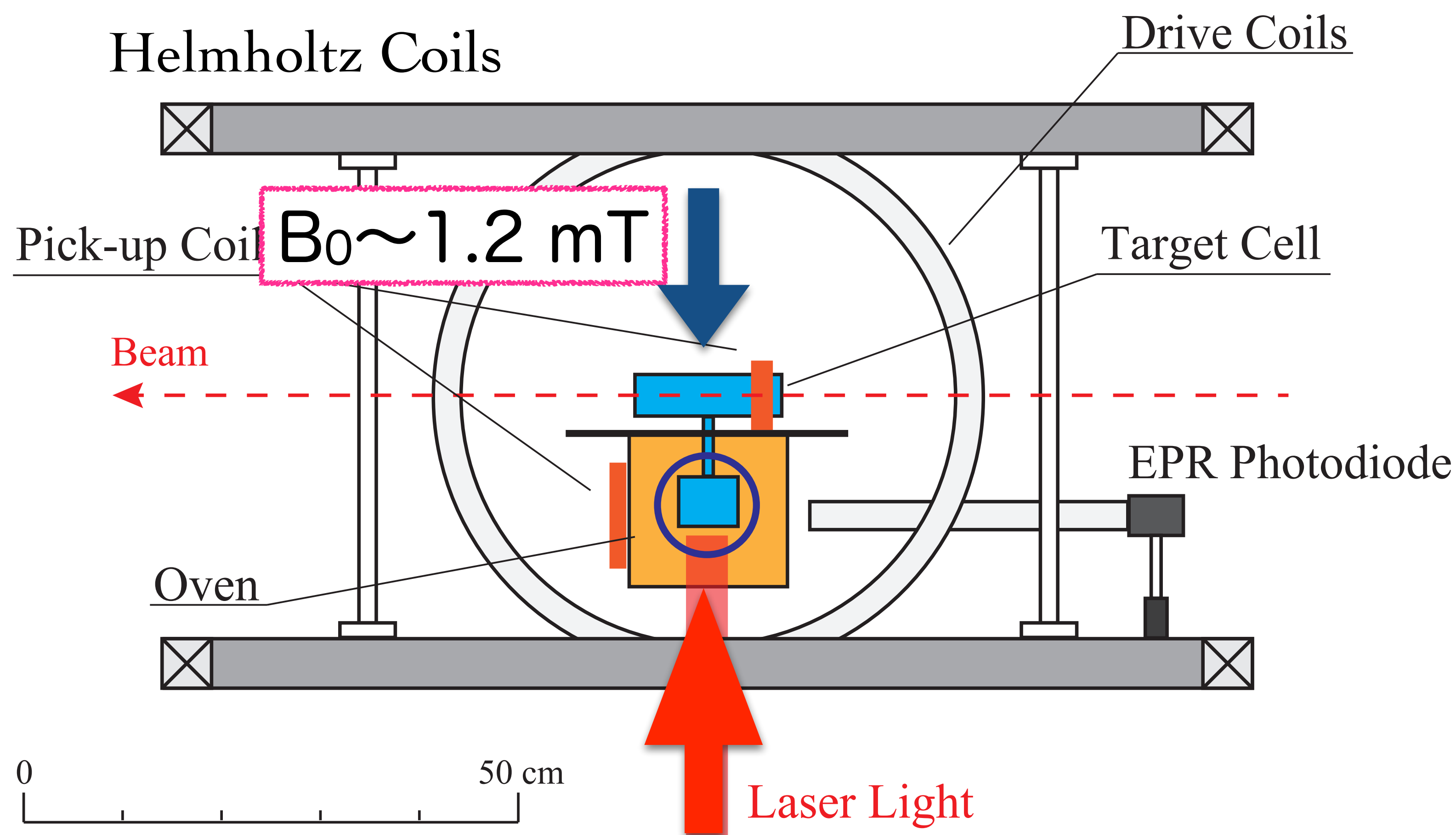
$$\theta_{\mathrm{c.m.}} = 47^\circ - 156^\circ$$

- Detectors

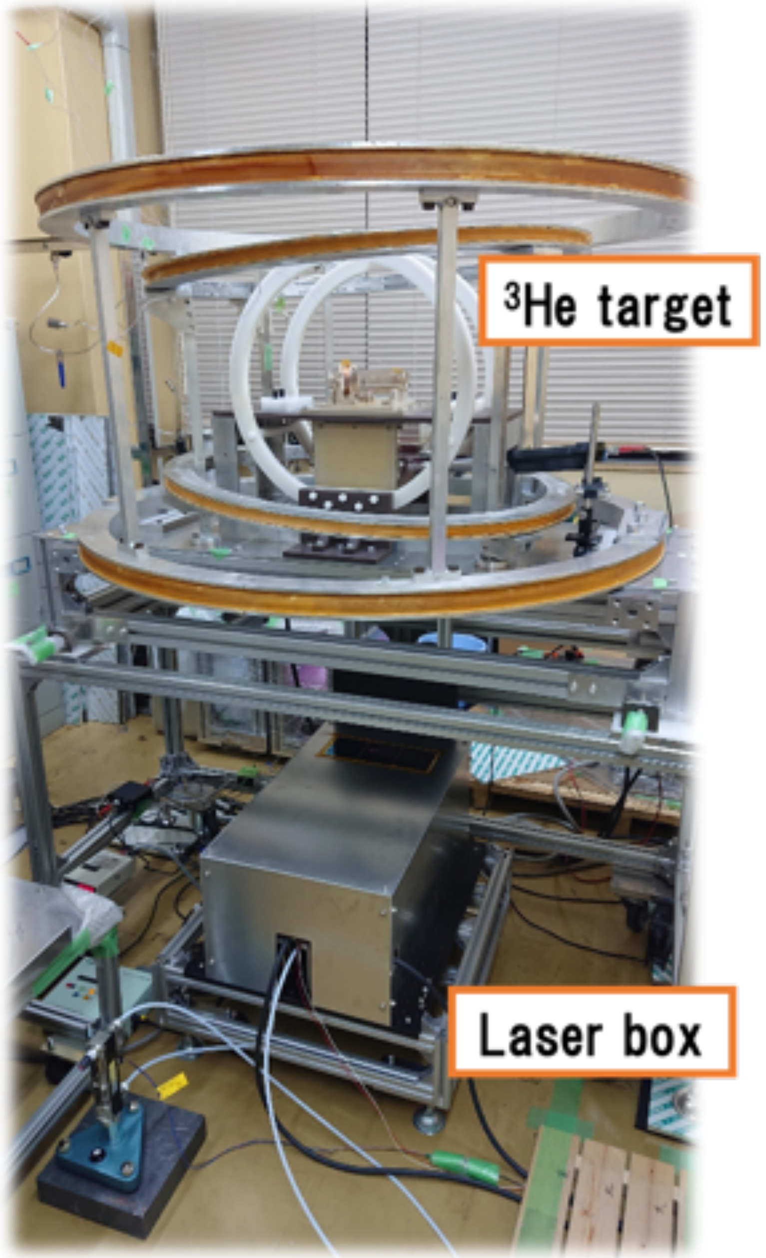
  dE : Plastic Scintillator (0.5 mm^t)
  E : NaI(Tl) (55 mm^t)
  2 sets × 6 angles = 12 sets

Polarized ^{3}He Target System

- Polarization Method :
    - (Alkali-Hybrid) Spin Exchange Optical Pumping
- Polarization (current) : 60%, Relaxation time : about 40 hrs
- Calibration of absolute values : EPR & neutron-transmission



Diode Laser + VBG (Volume Bragg Grating)
Power : 80W
Wavelength : 794.7 nm
width : 0.2 nm (FWHM)



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Summary of Measurements for p+^{3}He

Incident Energy	70 MeV	50 MeV	65 MeV	65 MeV	100 MeV
Beam	p	p	pol. p	pol. p	pol. p
Observables	A_{0y}	A_{0y}	$d\sigma/d\Omega$, A_y	A_y, A_{0y}, $C_{y,y}$	A_y, A_{0y}, $C_{y,y}$
Measured Angles ($\theta_{c.m.}$)	46° –141°	47° –120°	27° –170°	47° –133°	47° –149°
Facility	CYRIC, Tohoku Univ.	CYRIC, Tohoku Univ.	RCNP, Osaka Univ.	RCNP, Osaka Univ.	RCNP, Osaka Univ.
Exp. Course	41 course	41 course	WS course	ENN course	ENN course

Summary of Measurements for p+^{3}He

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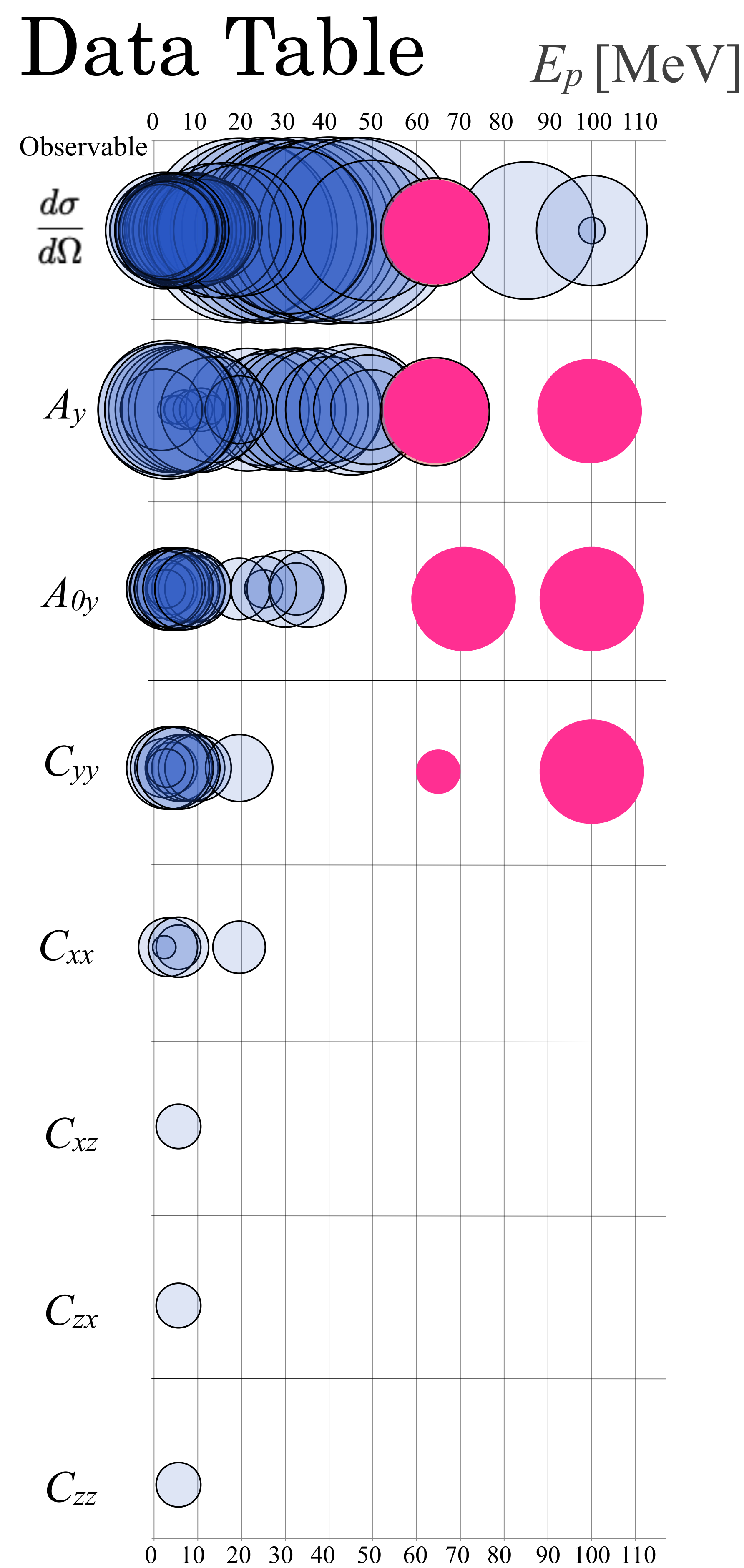
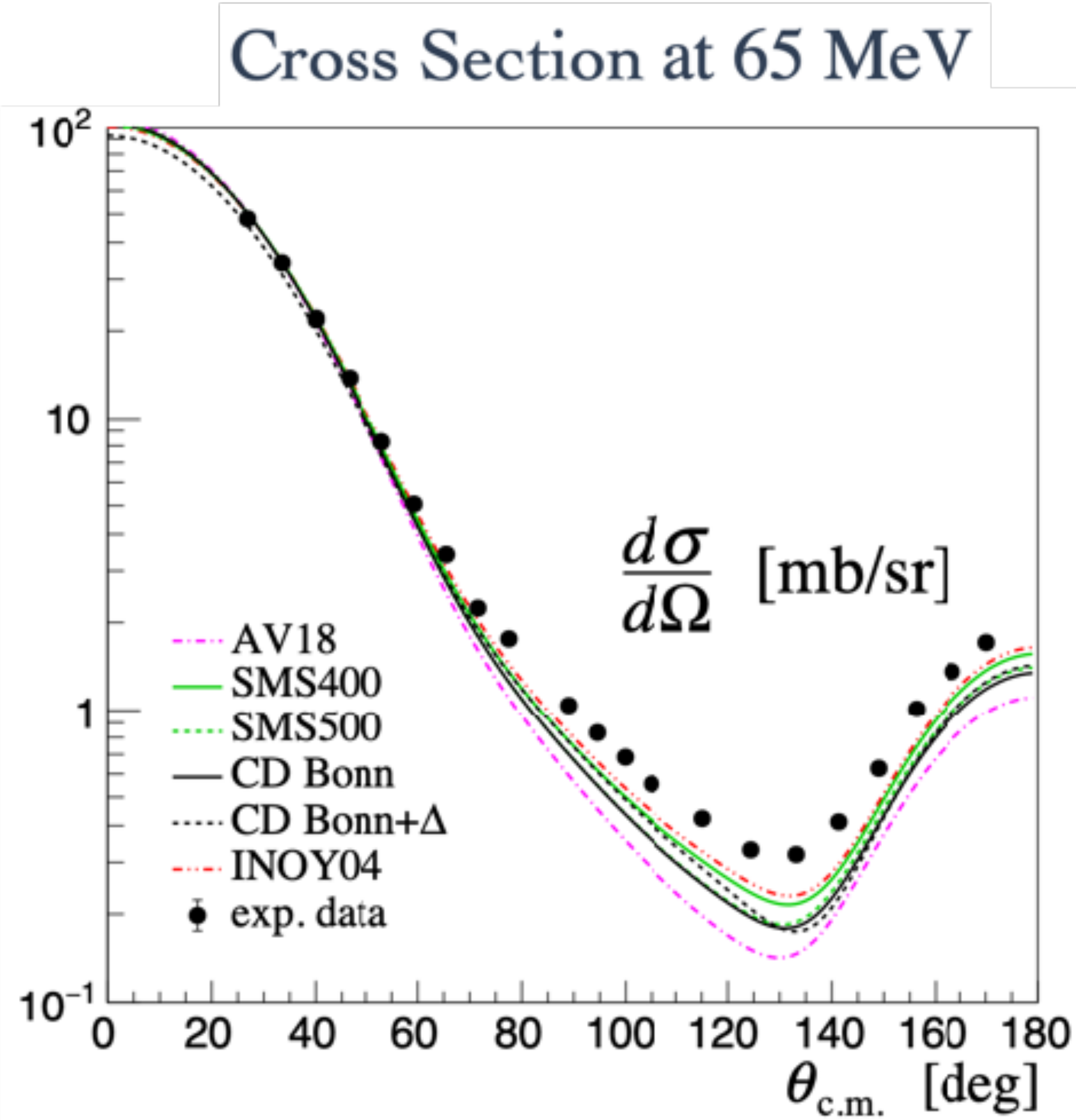
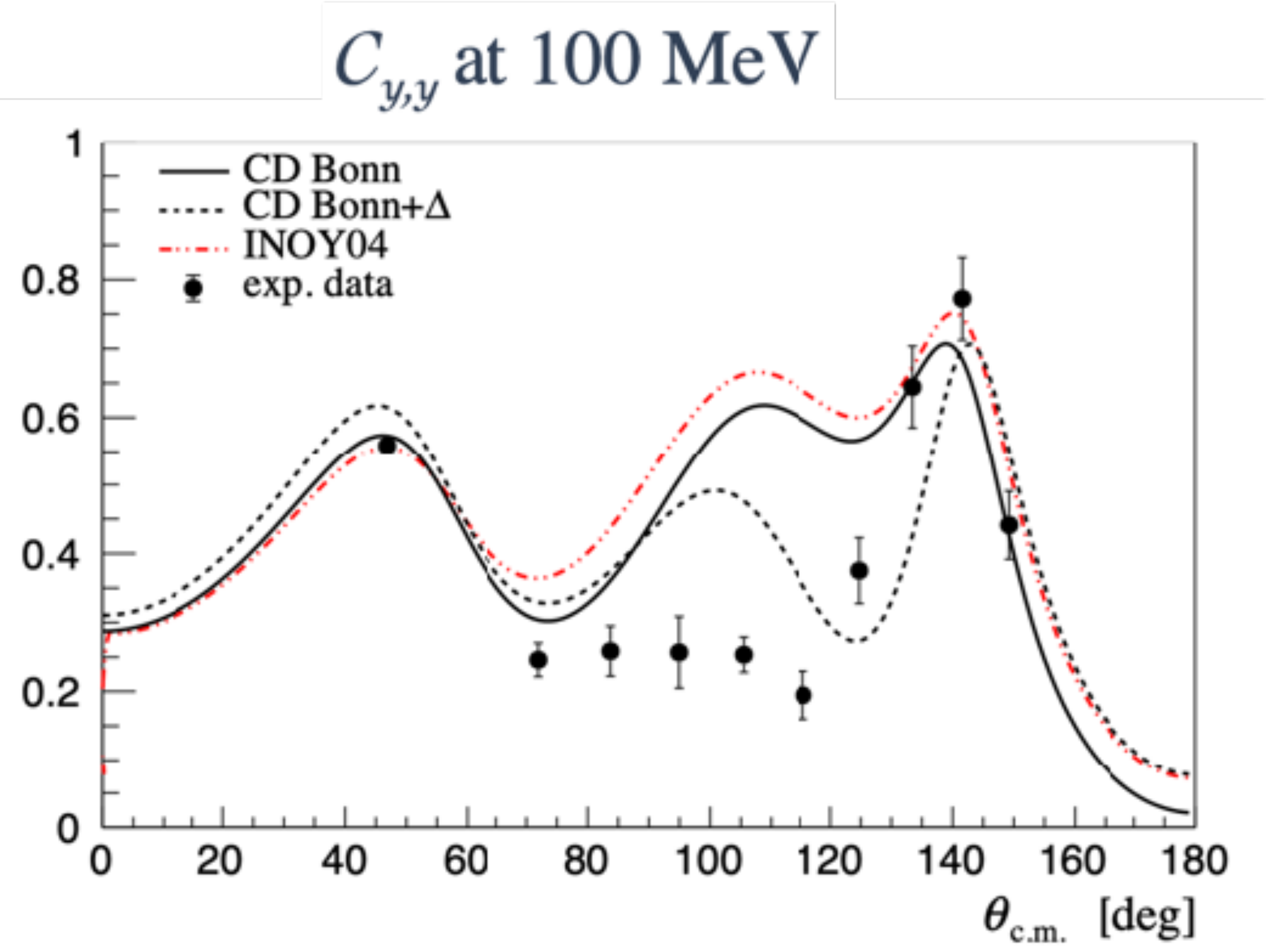
data from RCNP/CYRIC



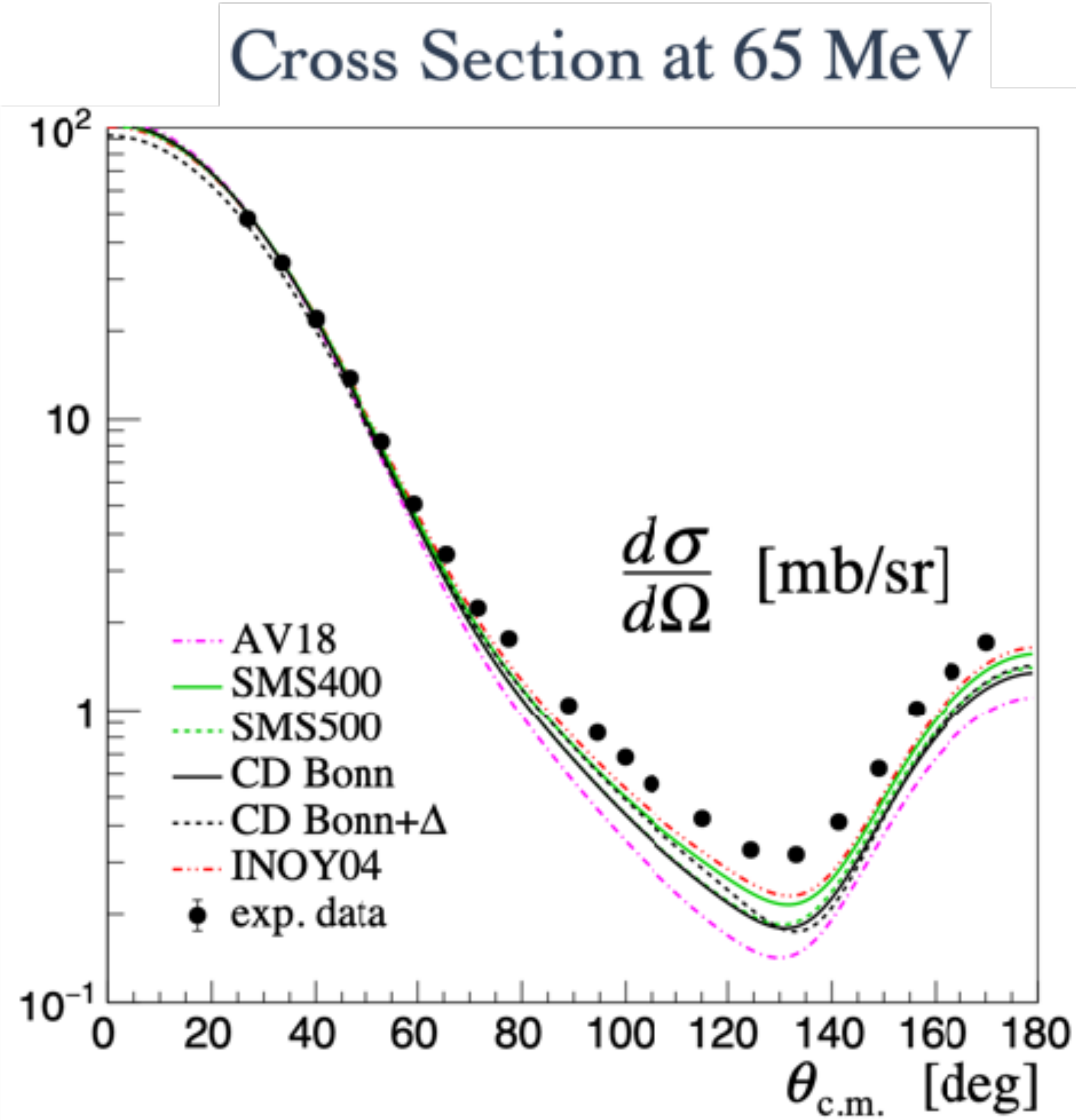
New Data of $p+^3$He at Intermediate Energies

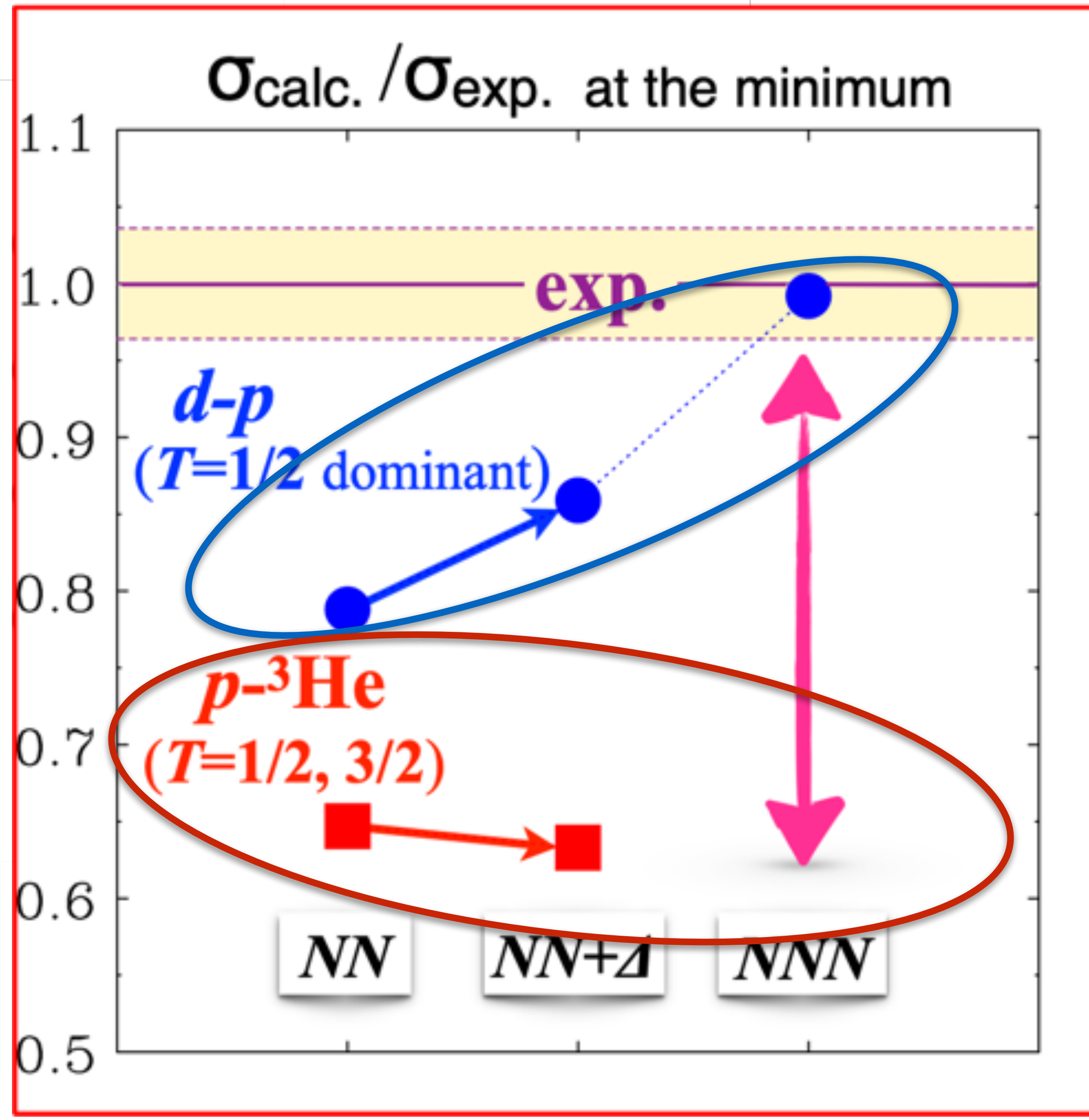




A. Watanabe, S. Nakai, et al. , Phys. Rev. C **103**, 044001 (2021)
Selected as Editors' Suggestion

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

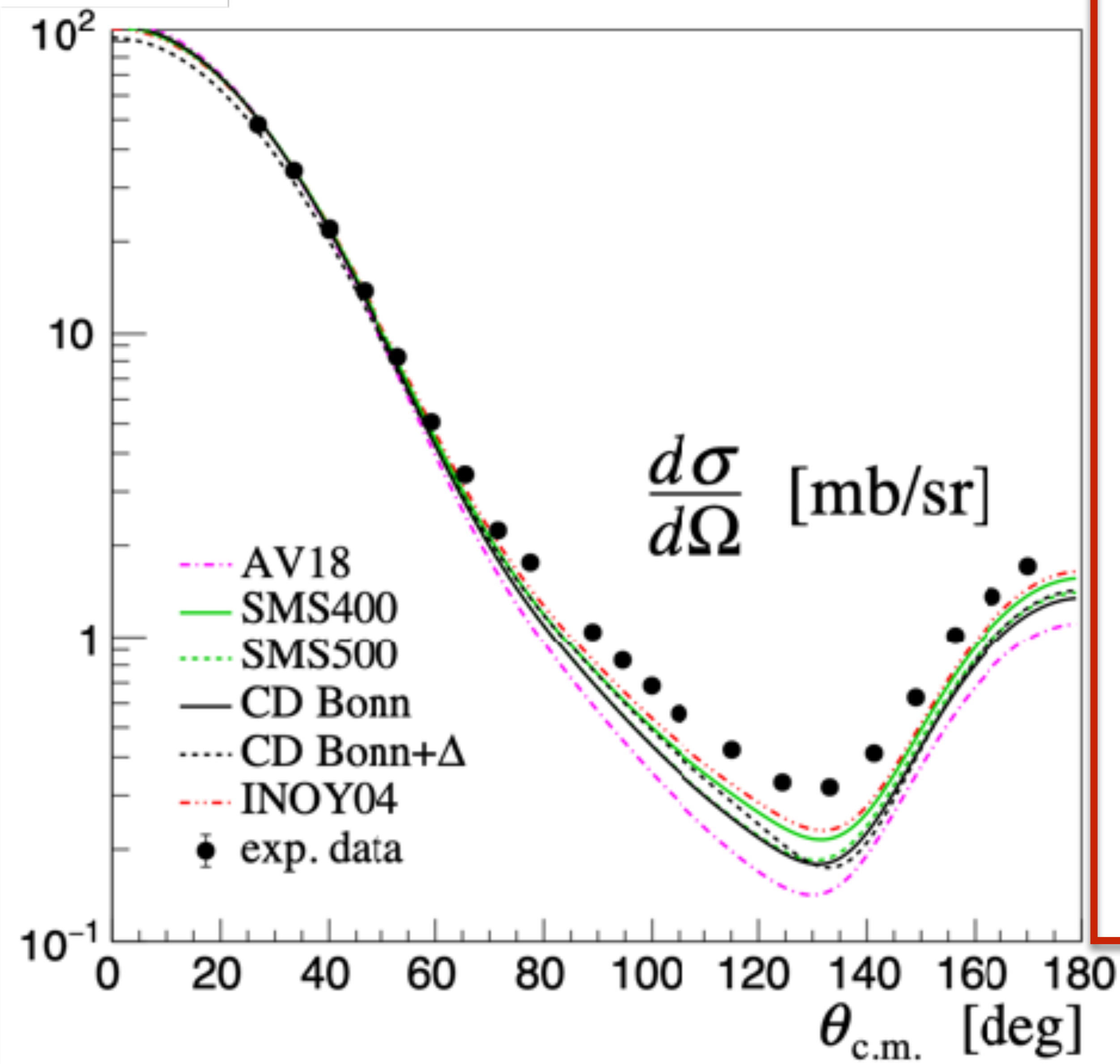


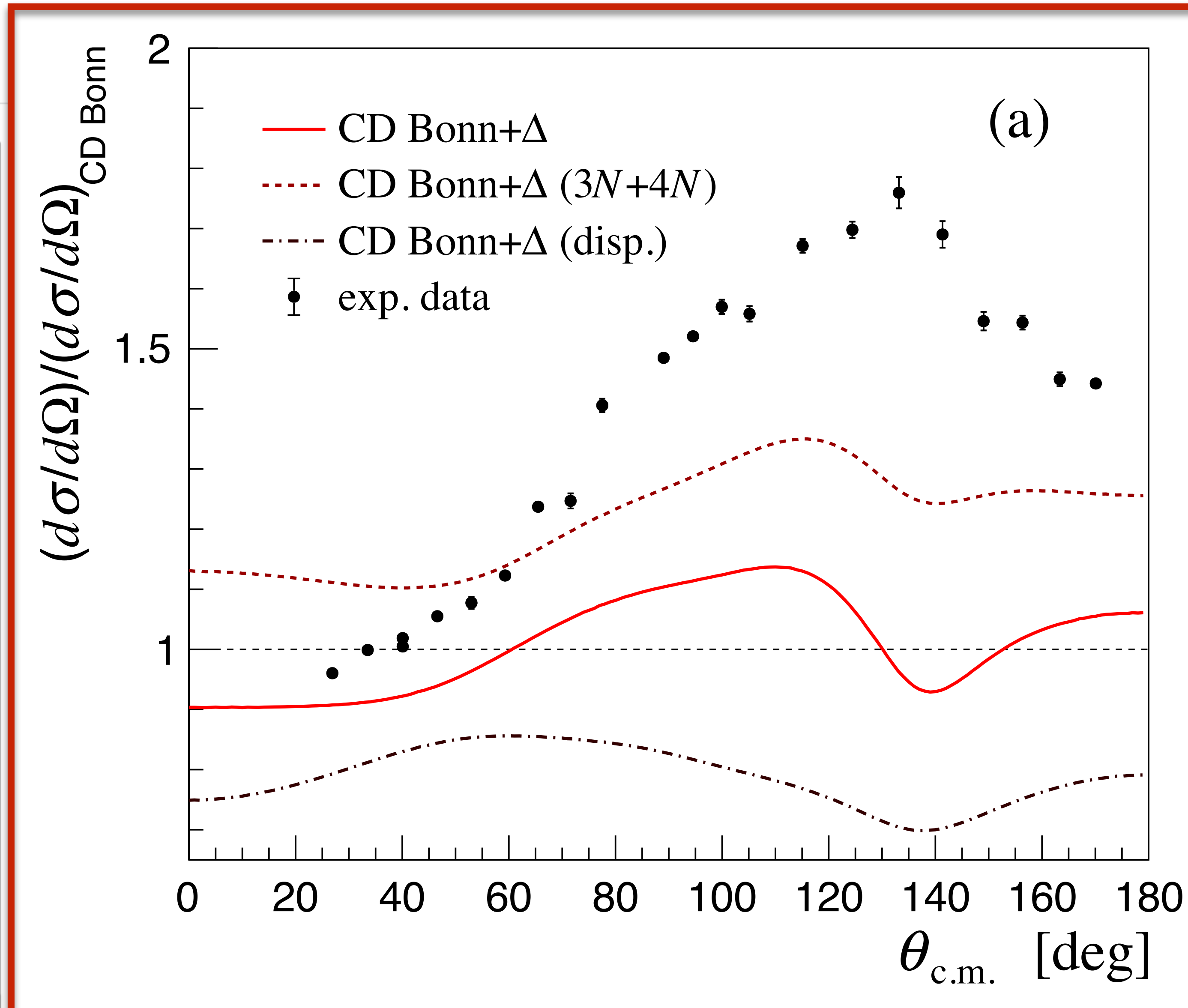


A. Watanabe, S. Nakai, et al. , Phys. Rev. C **103**, 044001 (2021)
Selected as Editors' Suggestion

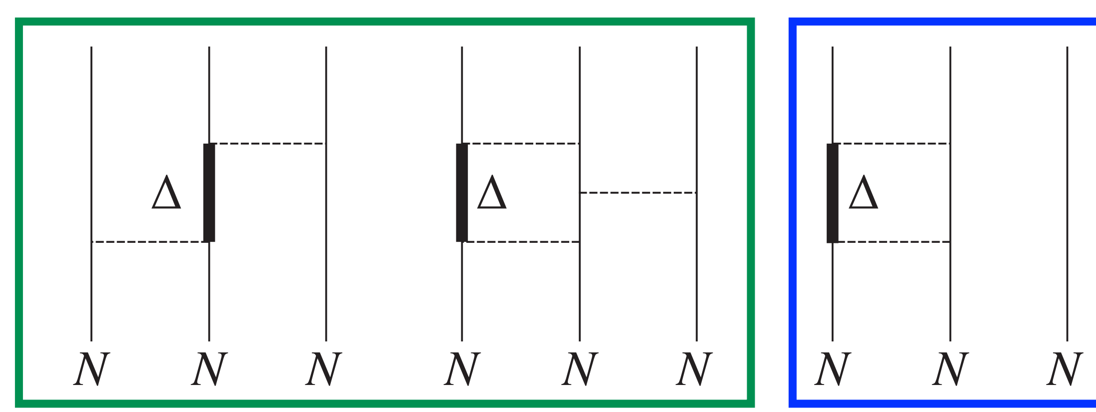
New Data of $p+^{3}$He at Intermediate Energies

Cross Section at 65 MeV



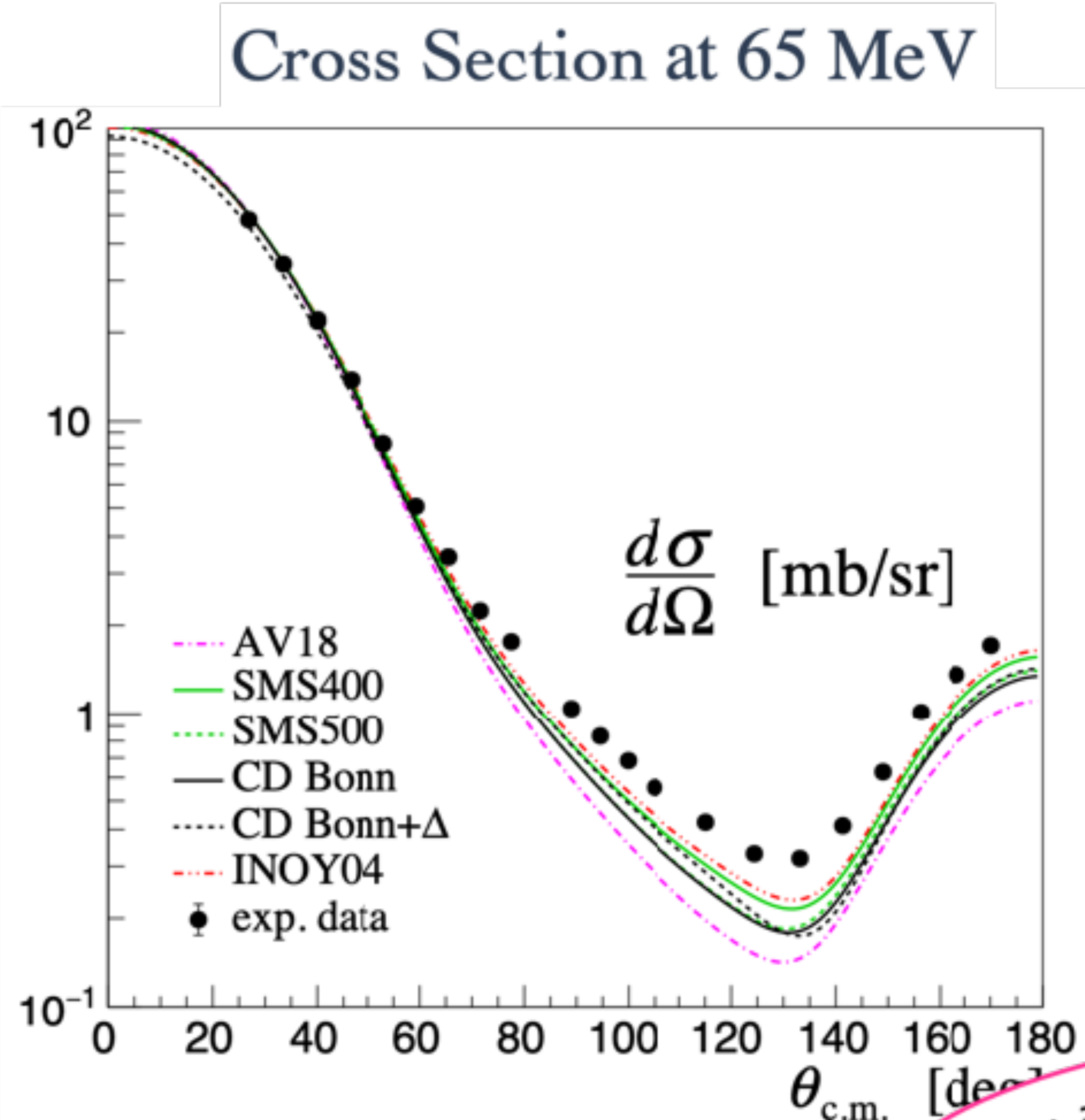


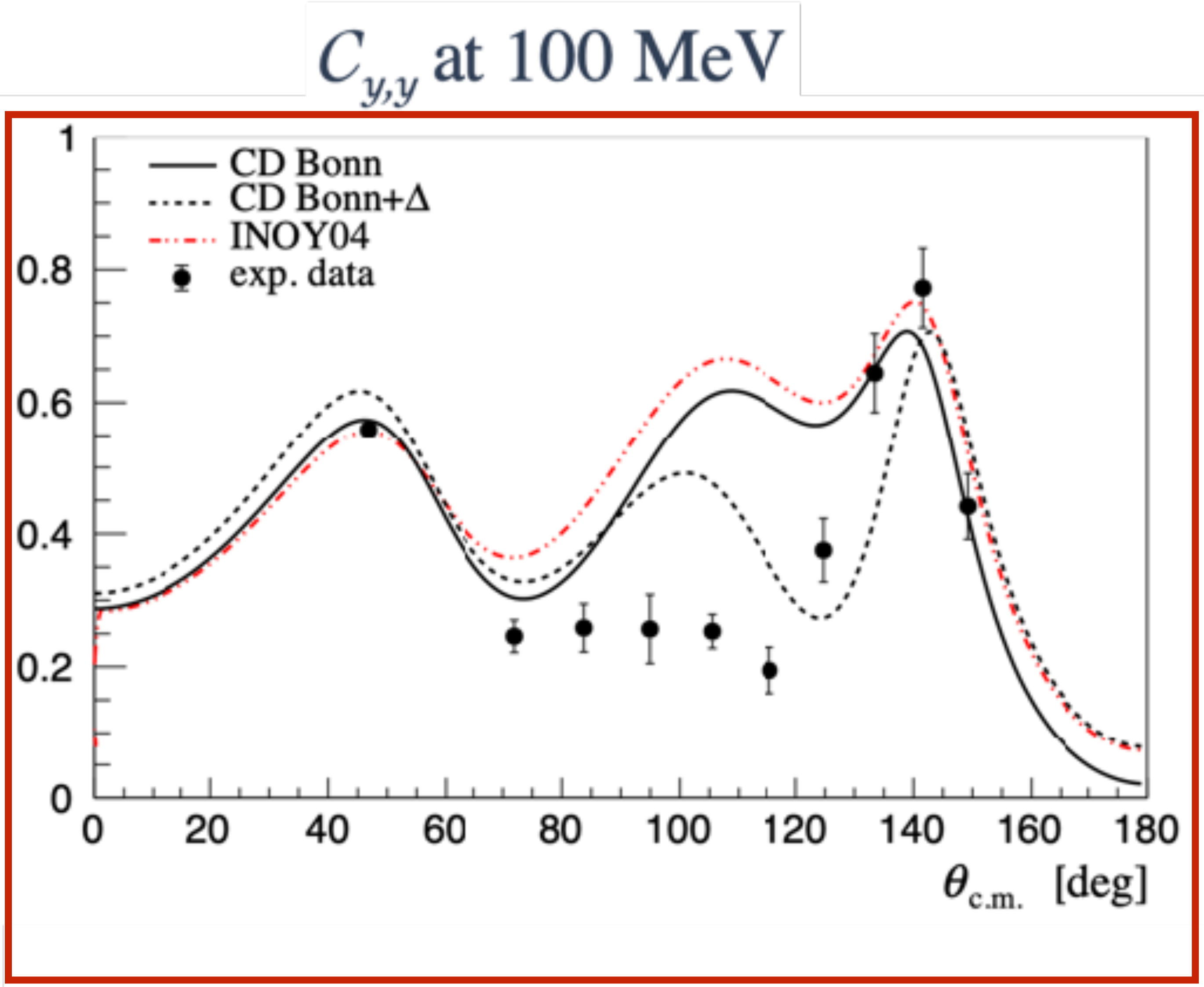
Effective 3, 4NFs **2N dispersion**



A. Watanabe, S. Nakai, et al. , Phys. Rev. C **103**, 044001 (2021)
Selected as Editors' Suggestion

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





$p+{}^{3}He$ 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)
Selected as Editors' Suggestion

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 2 & 3-NFs

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.

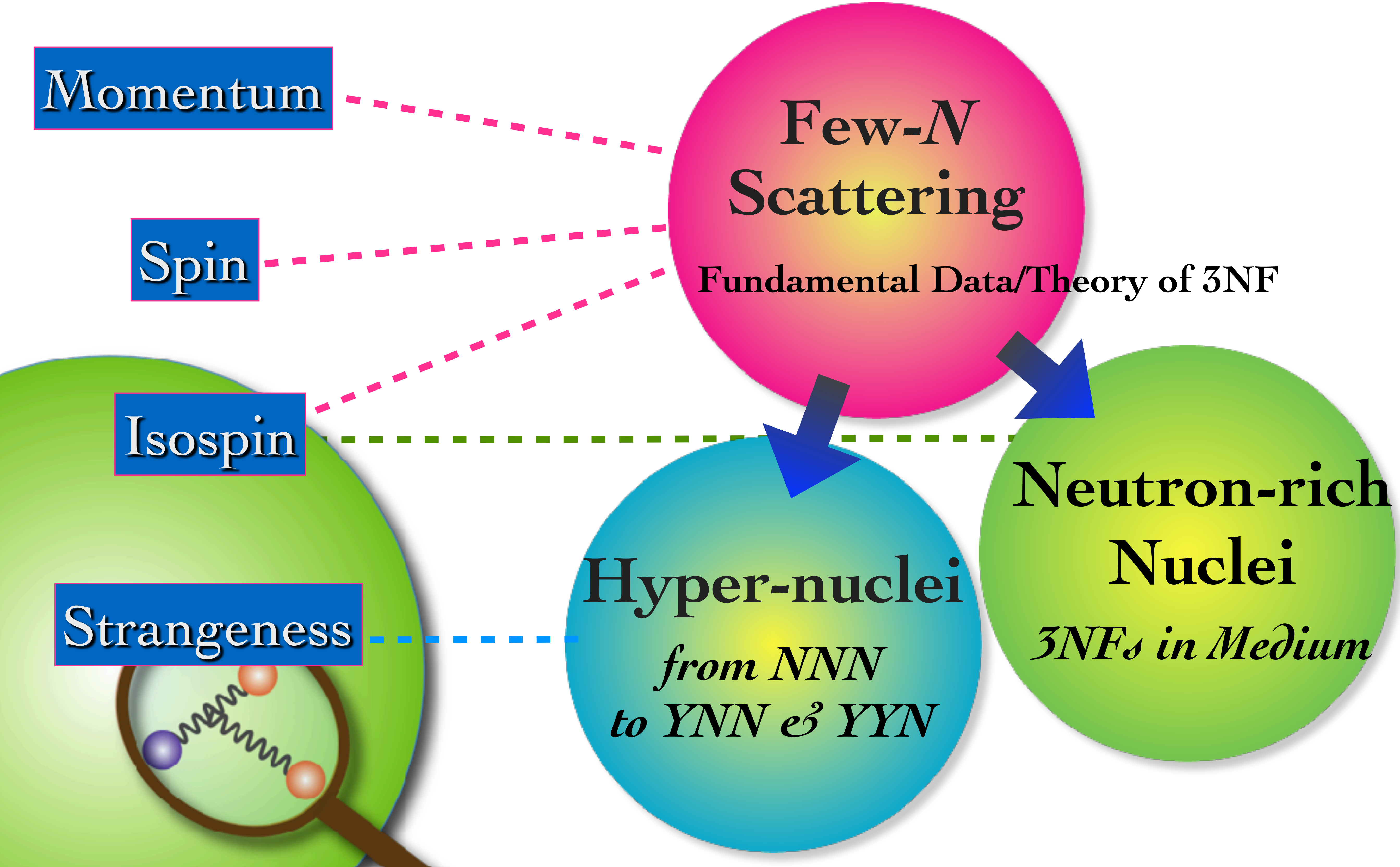
Determination of 3NFs based on χEFT
from few-nucleon scattering data is about to start.

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

towards **High Precision 2N and 3NFs**

Perspective of 3NF Study

~Consistent Understanding From Quarks to the Universe~



RIKEN RIBF-*d.* Collaboration

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Experiment at RIKEN RIBF (2015)

p-^{3}He Collaboration

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Experiment at CYRIC, Tohoku Univ. (2016)

Experiment at RCNP, Osaka Univ. (2018)

Theoretical Supports from

Ruhr-Universität, Bochum
W. Glöckle, E. Epelbaum

Jagellonian University
H. Witała, J. Golak, R. Skibinski

Kyushu Institute of Technology
H. Kamada

Forshungszentrum of Jülich
A. Nogga

Bad Honnef (2006)

Vilnius University
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