SPIN2014, 24 October 2014

Development of Neutron Polarization Measurement System for Studying *NN* Interaction in Nuclear Medium

Department of Physics, Kyushu University

Jumpei YASUDA

The importance of nuclear medium effect

◉ **Nucleus**

- quantum many-body system consists of nucleons
- size of nucleon : ~ 0.8 fm
- average nucleon distance in nucleus : ～1.8 fm

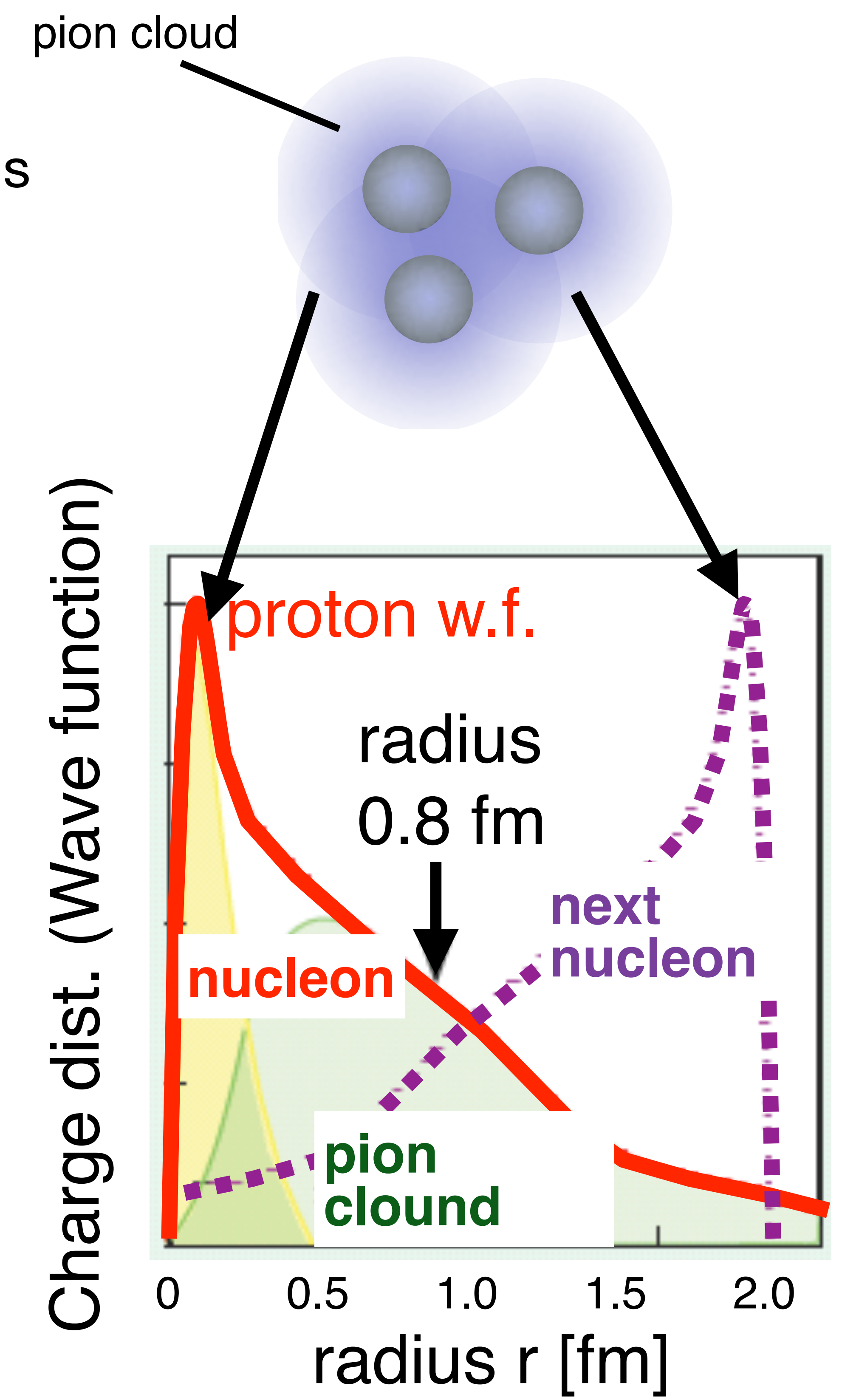
➡ **nucleons are overlap in nucleus**

◉ **In nuclear medium**

- **Change the nucleon・meson properties ?**

➡ **Modified the *NN* int. in nuclear medium ?**

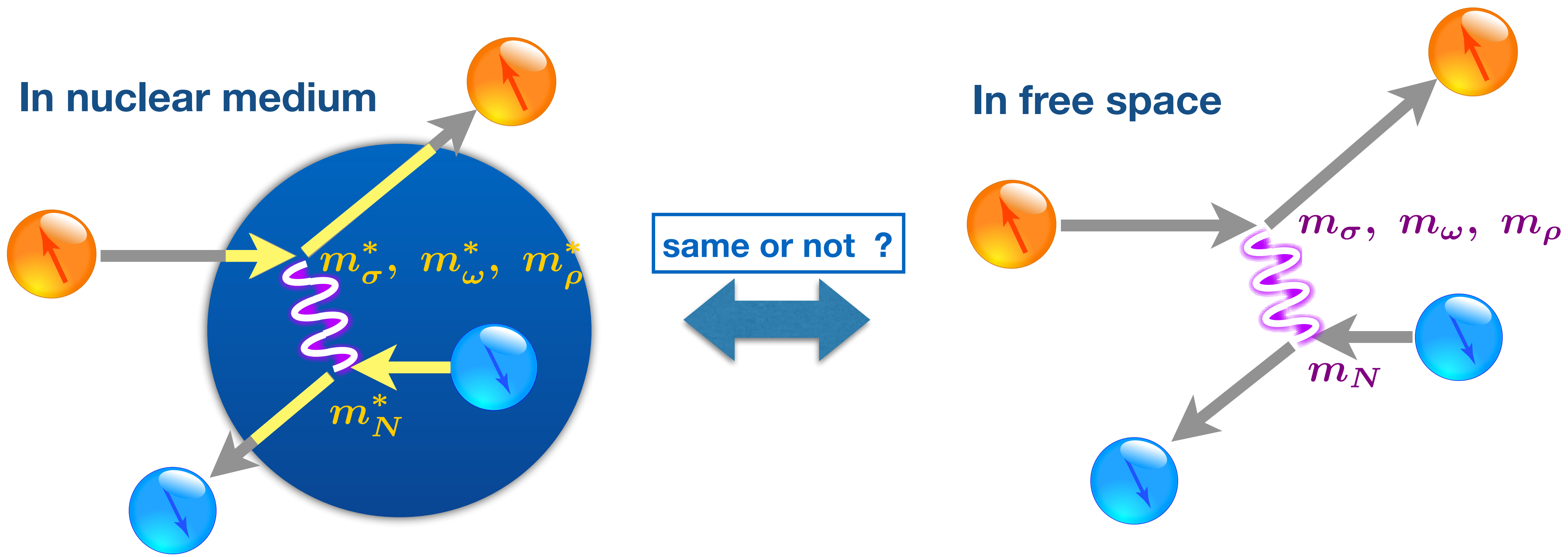
➡ **Nuclear medium effect is crucial for understanding nuclear system.**



How to study the medium effect

- **Quasi-elastic knock out reaction**
  - intermediate kinetic energy ~ 300 MeV
  - de Broglie wave length < average nucleon distance (~2 fm)
    - ▸ **incident nucleon directly interact with an in-medium nucleon**

- **Comparison of *NN* scattering in free space and in nuclear medium**
  - Medium effects on *NN* int.
  - Density dependence



Spin observables and medium effects

◉ Origin of medium effects

- ☑ Fermi motion
- ☑ Distortions
- ☑ Pauli blocking

} controllable

- ☐ **Modification of meson mass and coupling constants**
  - ☆ **Restoration of chiral symmetry in nuclear medium**

◉ Meson property

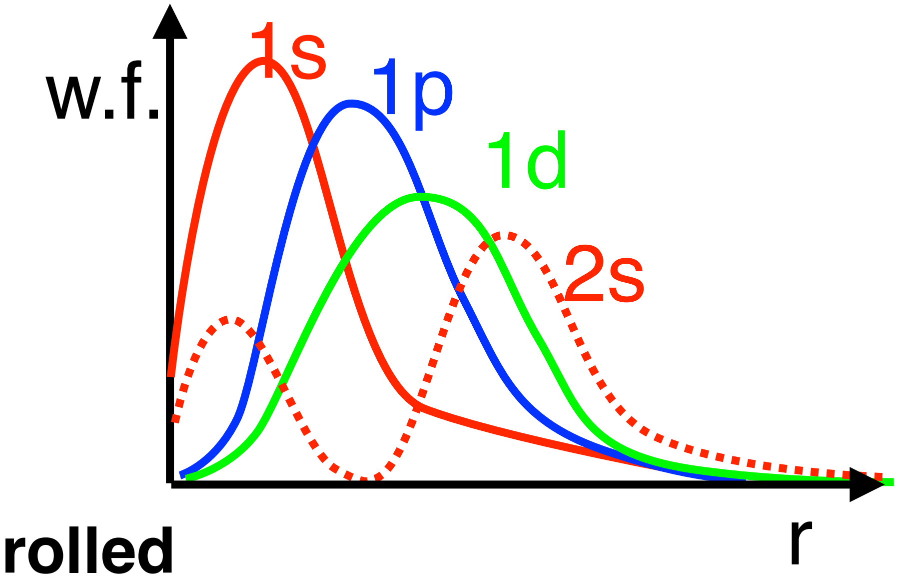
	σ	ω	ρ
mass (MeV/c²)	~550	770	782.6
range (fm)	~0.18	0.128	0.126
Potential	$V^{\sigma} = g^2_{\sigma NN}\frac{1}{k^2+m^2_{\sigma}}\left(-1+\frac{q^2}{2M_N^2}-\frac{k^2}{8M_N^2}-\frac{LS}{2M_N^2}\right)$	$V^{\omega} = g^2_{\omega NN}\frac{1}{k^2+m^2_{\omega}}\left(1-3\frac{LS}{2M_N^2}\right)$	$V^{\rho} = g^2_{\rho NN}\frac{k^2}{k^2+m^2_{\rho}}\left(-2\sigma_1\sigma_2+S_{12}(\hat{k})\right)\tau_1\tau_2$

- **σ, ω, ρ have large mass compared with π (138.03 MeV/c²)**
  - ▸ short range interaction
- **σ, ω, ρ have different spin dependence term**

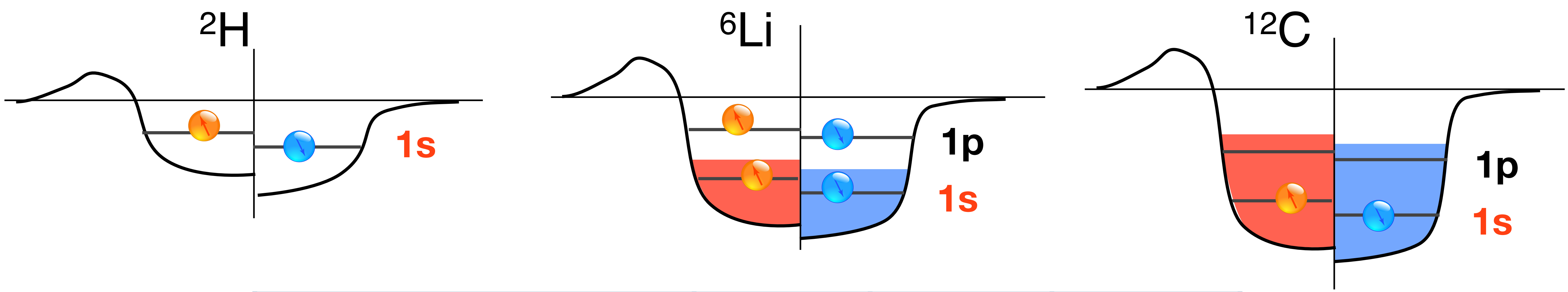
➡ Spin observables are important to understand how each meson modified in nuclear medium.

How to study the density dependence

- **Radial wave function of each L**
  - only s-orbit (L=0) has no centrifugal force
    - deeply bound
    - can be high density



- **Effective nuclear density can be defined and controlled**



$1s_{1/2}$ knockout	2H	6Li	12C
Effective density (relative to ρ0)	5%	20%	30%

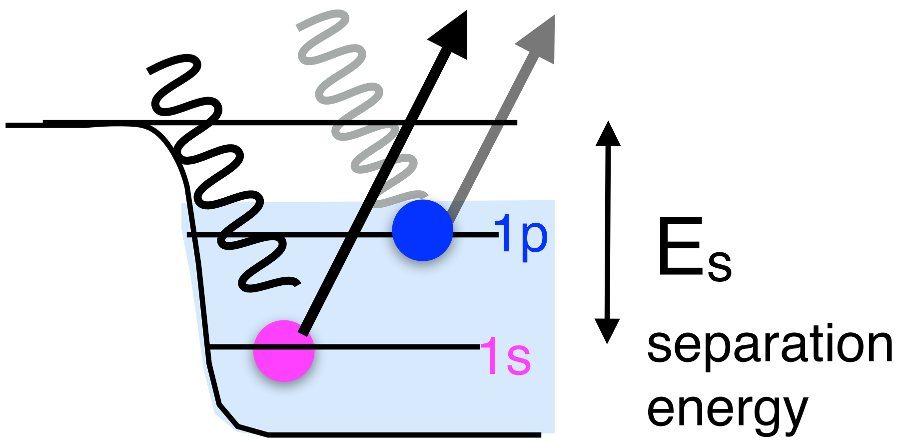
Measuring s-orbit provide a good basis for studying density dependence

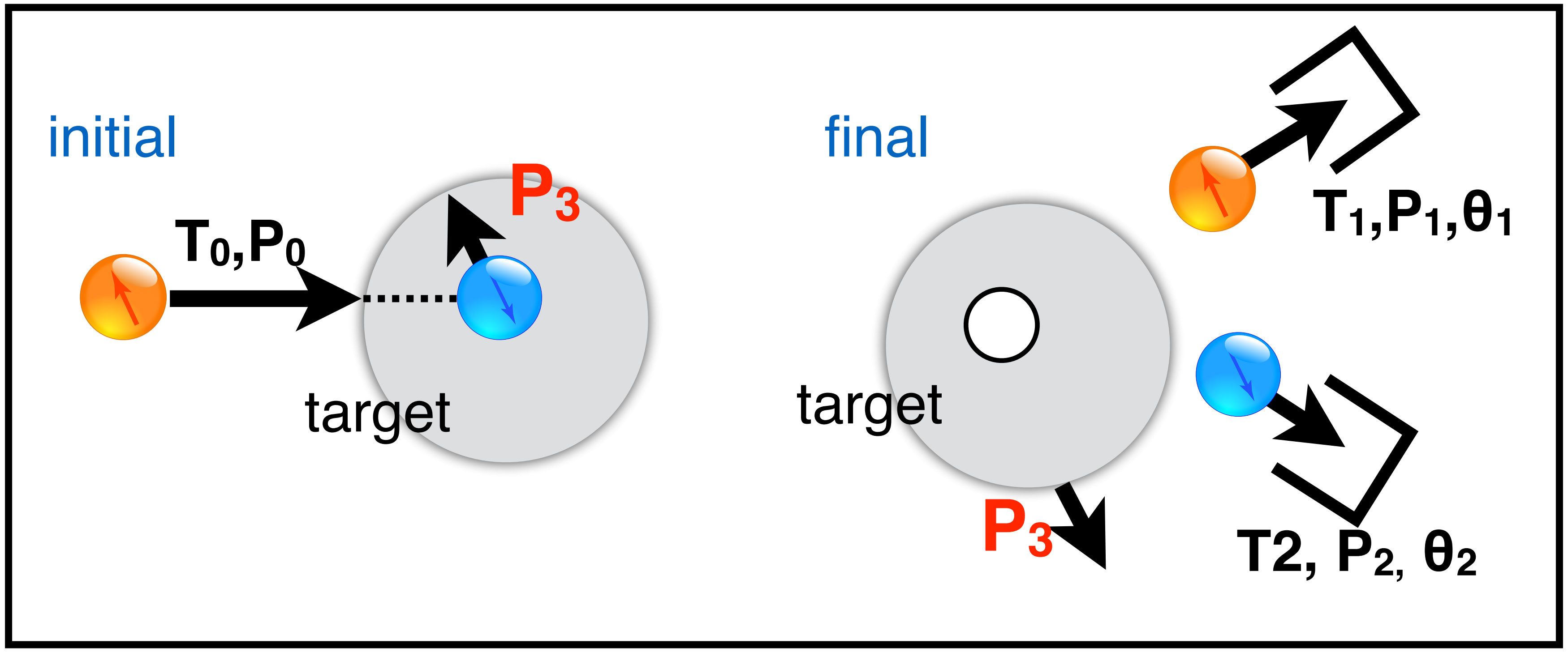
Separation 1s-orbit via (*p,pN*) reaction

◉ Exclusive (*p,pN*) measurement

- measure both of two outgoing nucleons are explicitly detected
  - measure kinetic energy (T), momentum (P) and angle (θ)
  - ▸ recoil momentum P_3 (T_3) can be determined from the momentum and energy conservation
  - ▸ Separation energy can be specify
    - $Es = T_0 - (T_1 + T_2 + T_3)$

➡ Specify the 1s-orbit

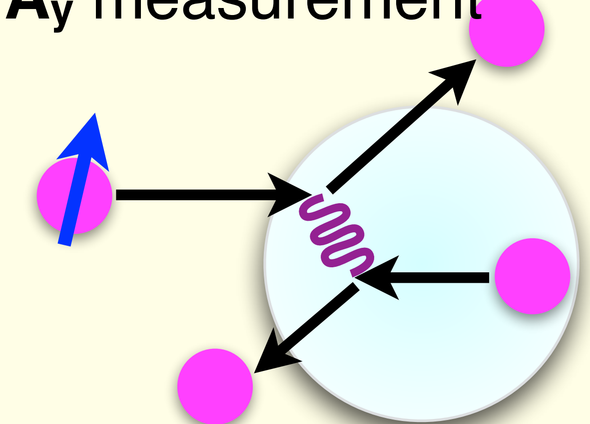
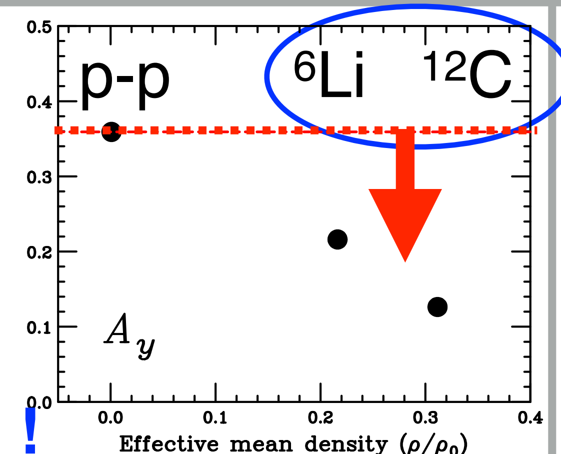
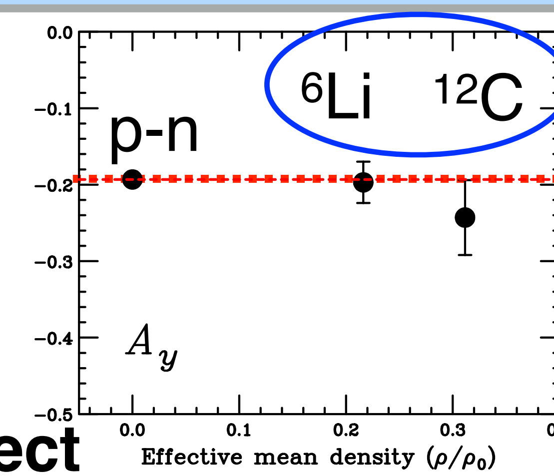
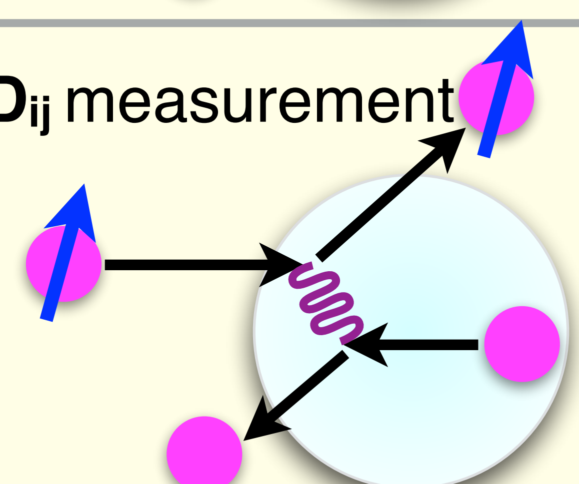
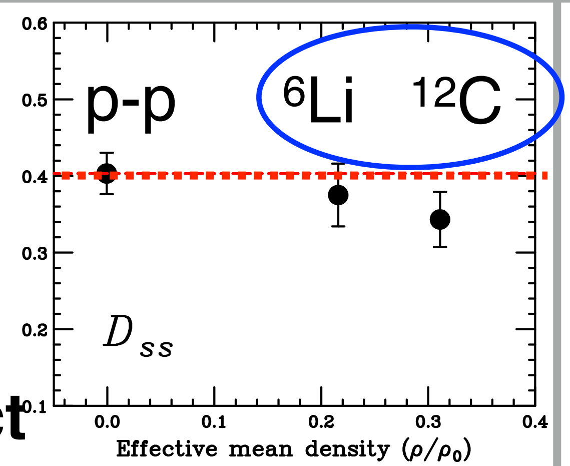




Medium effect studied through spin observables

◉ Spin observables

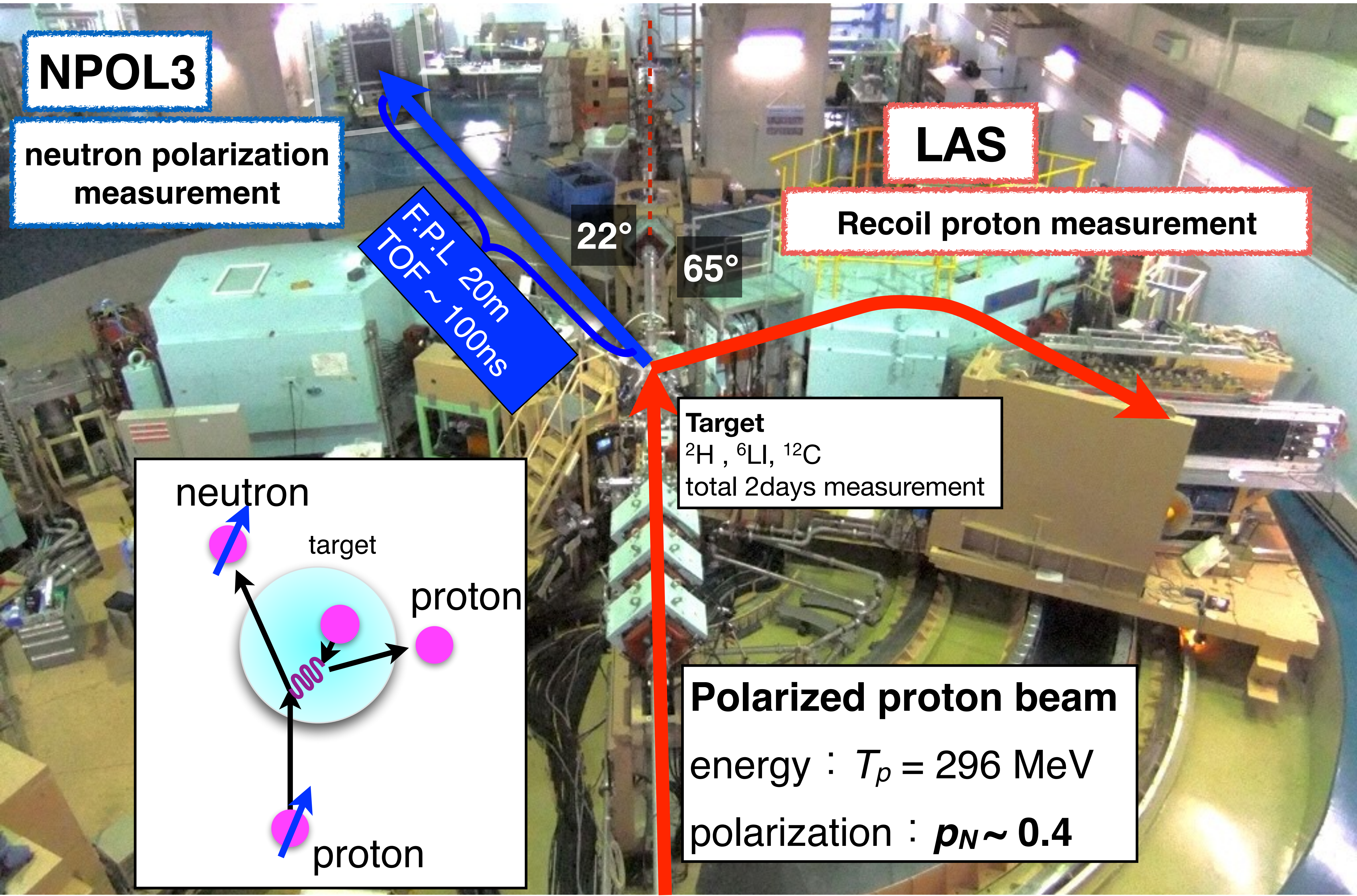
- Analyzing power (A_y) : sensitive to the relative **phase** of NN int.
- Polarization transfer (D_{ij}) : sensitive to the relative **amplitude** of NN int
  - **medium effect in A_y is significantly different between [p-p] & [p-n]**
  - ▶ **How about the medium effect in D_{NN} in [p-n] ??**

	p-p [n-n] (p,2p)	p-n (p,np)
A_y measurement 	Free  **Medium effect !**	Free  **No medium effect**
D_{ij} measurement 	Free  **No medium effect**	? ➡ Very interesting !!

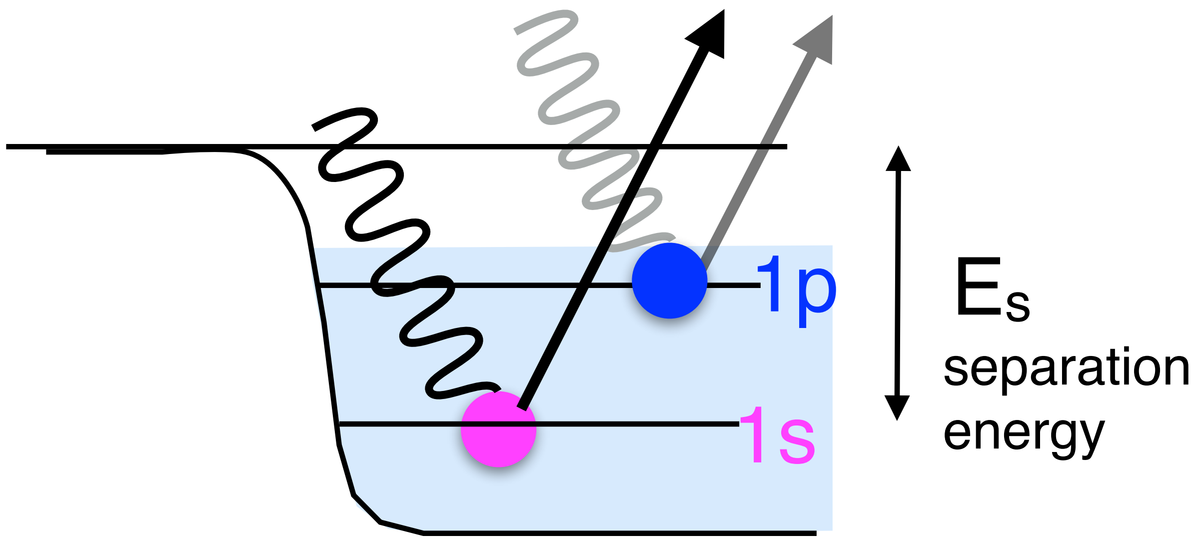
Purpose of this work

- **Develop the measurement system for D_{NN} in (p,np) reaction**
  - ☐ 1s-orbit separation
  - ☐ Neutron polarization measurement

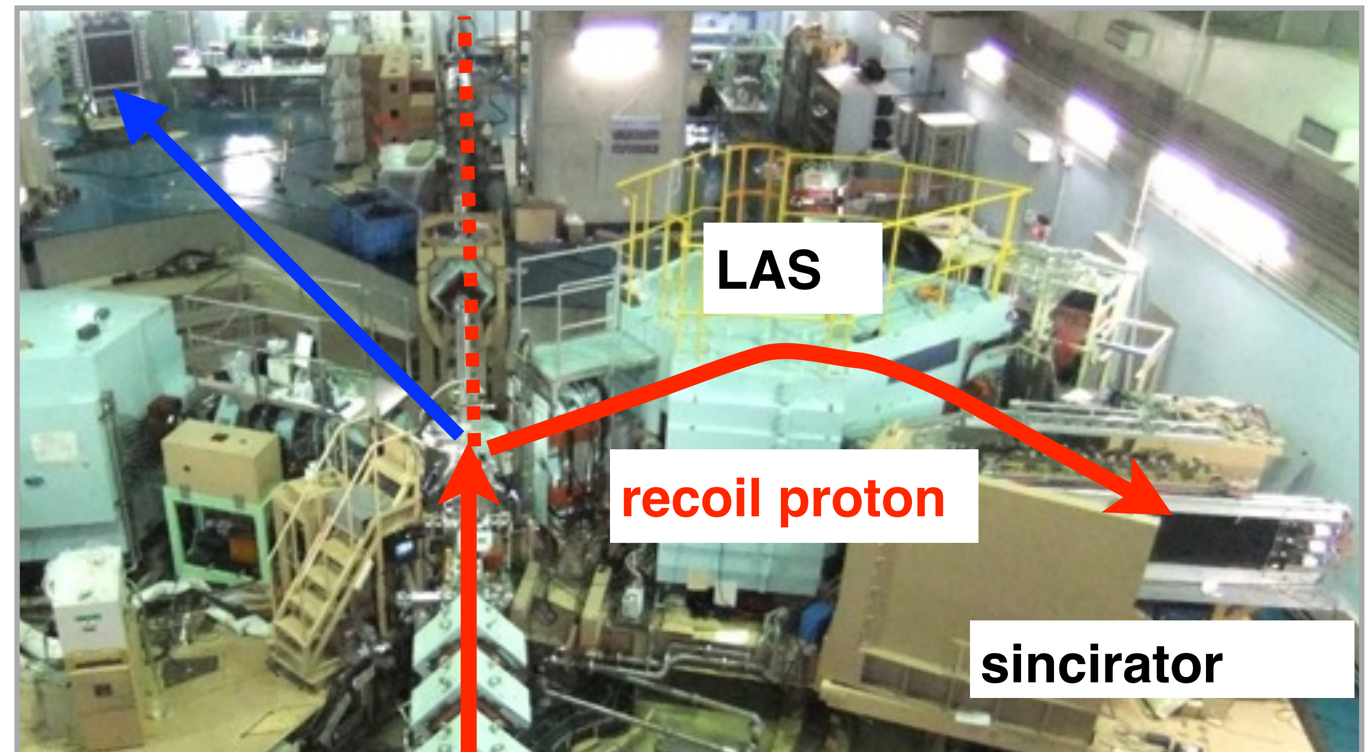
Test experimental setup @ RCNP



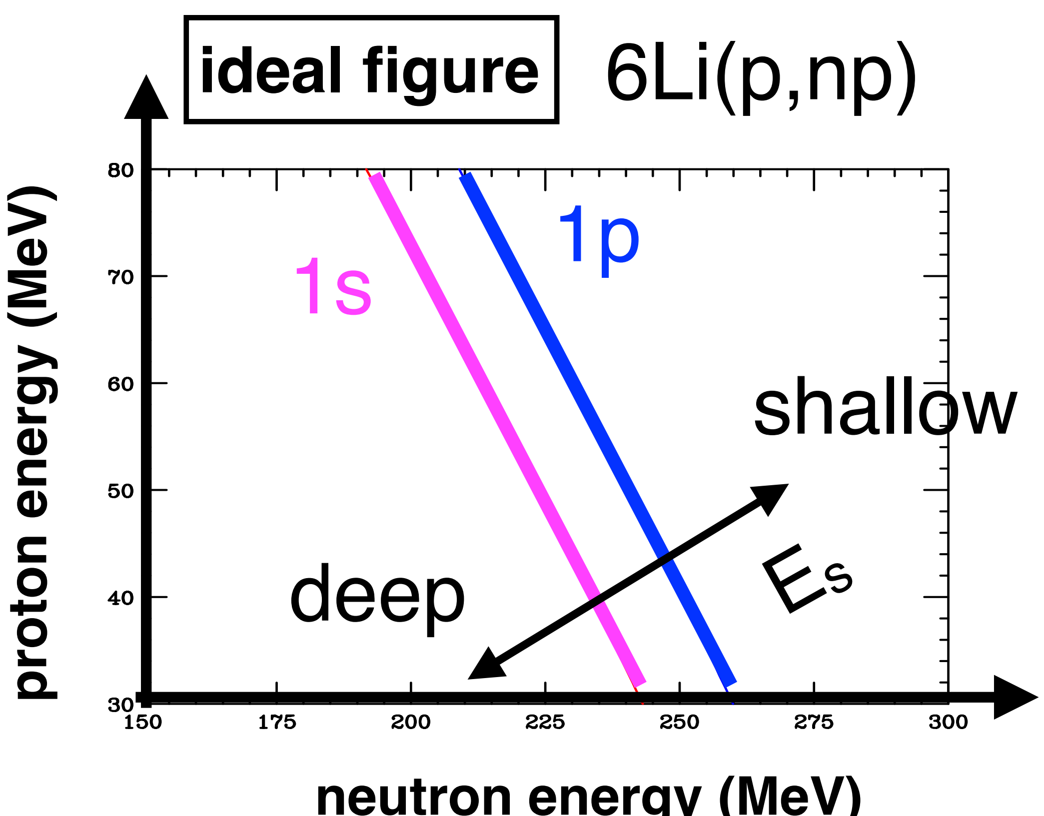
Exclusive(p,np)measurement

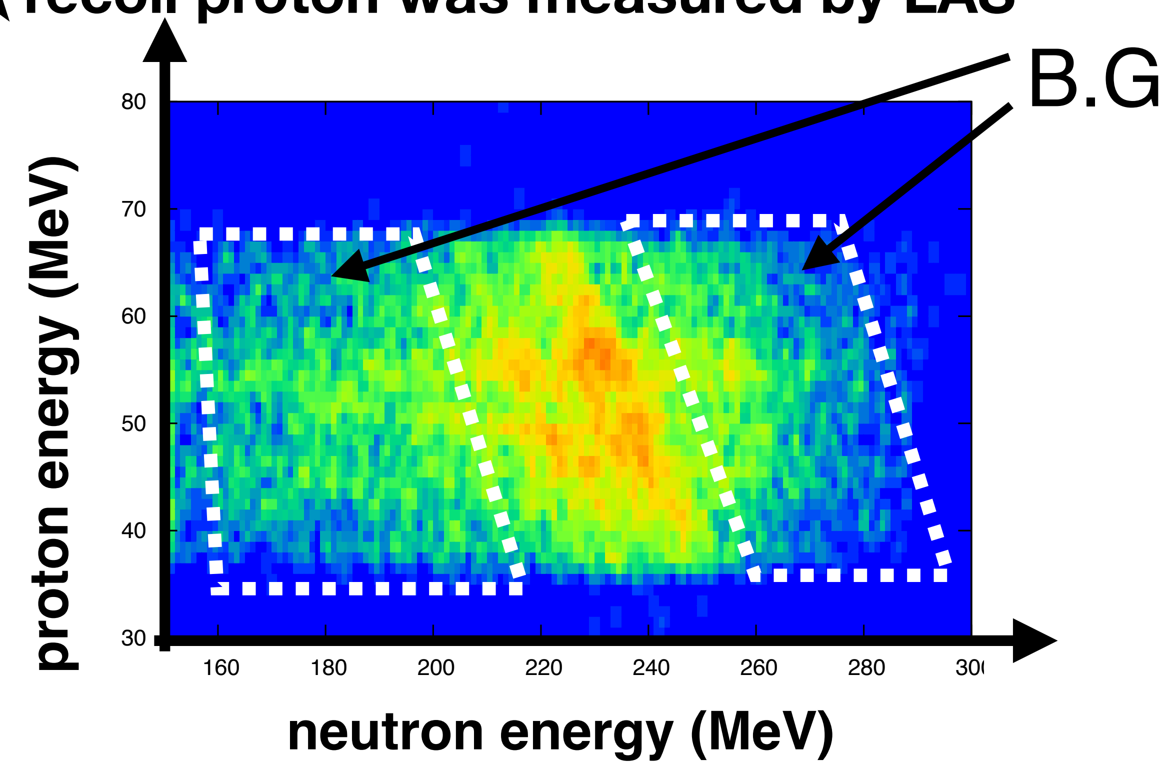


★need to separate 1s & 1p



★recoil proton was measured by LAS





➡need to suppress the B.G.

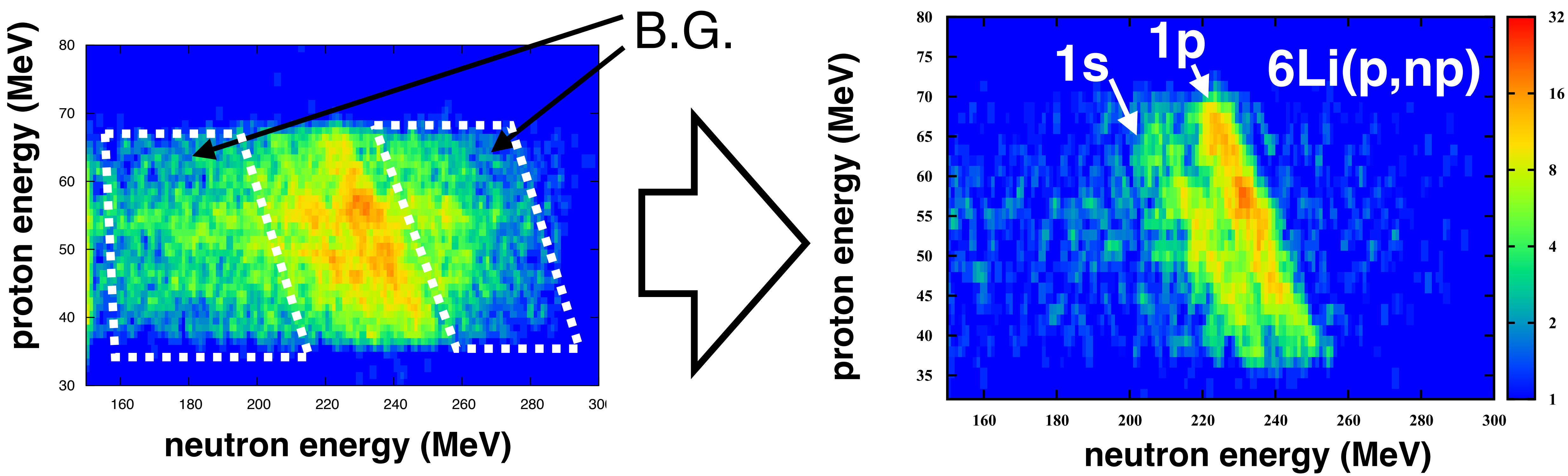
Exclusive(p,np) measurement

◉ **Analysis by using kinematic condition / NPOL-LAS time difference**

✓ select the double scattering particle by NPOL3：constrain on the neutron from target

✓ subtract accidental coincidence：constrain on the particle from same target

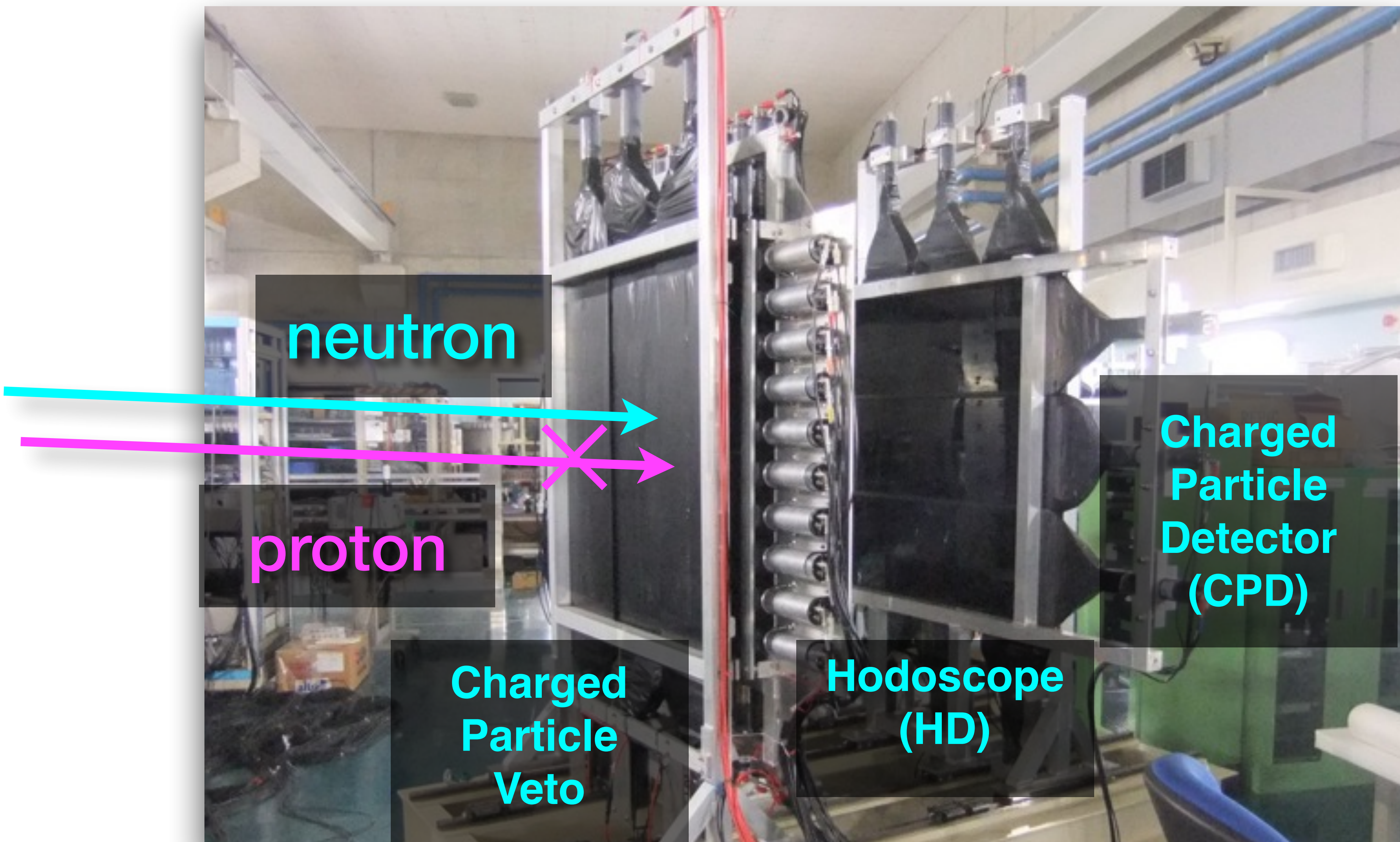
➡ **reduce the B.G. & success to separate 1s 1p orbit**



Neutron detector NPOL3

◉Neutron detector

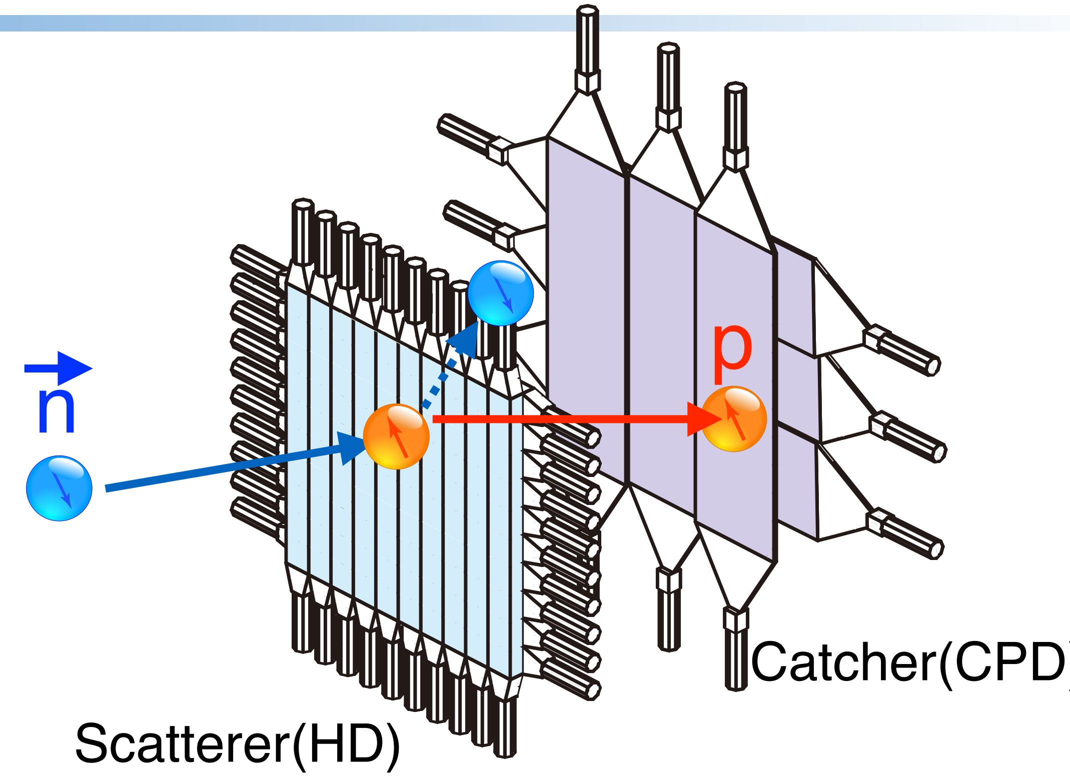
- 20 sets of 100cm x 10cm x 5cm hodoscopes (HD)
- Charged particle veto (CPV) : 105cm × 35cm × 0.5cm
- Solid angle : 2.5 msr (flight pass length 20m)



Neutron polarization measurement

◉ **Neutron polarization measurement**

- n+p scattering in HD
- detect the double scattering proton by CPD
- **double scattering asymmetry**
  → neutron polarization

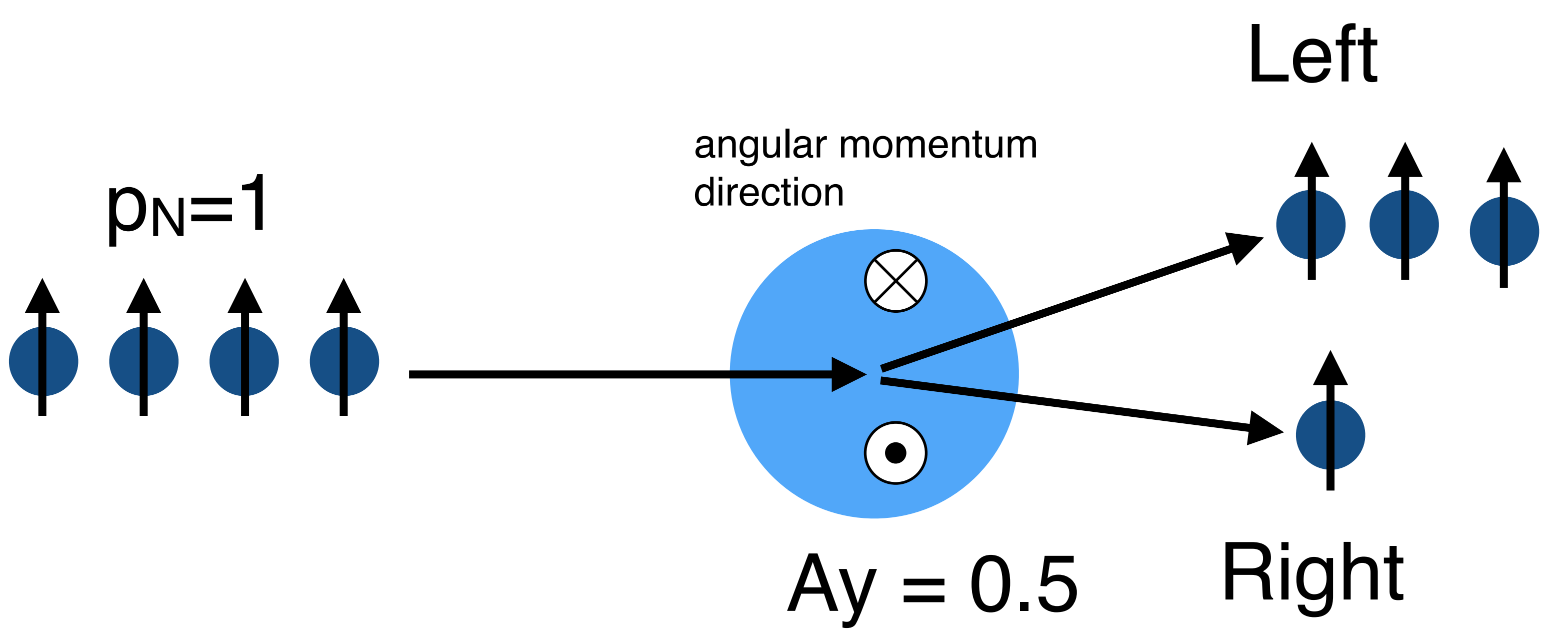


$$p'_N = \frac{\epsilon}{\langle A_{y;\mathrm{eff}} \rangle}$$

p'_N: neutron pol.

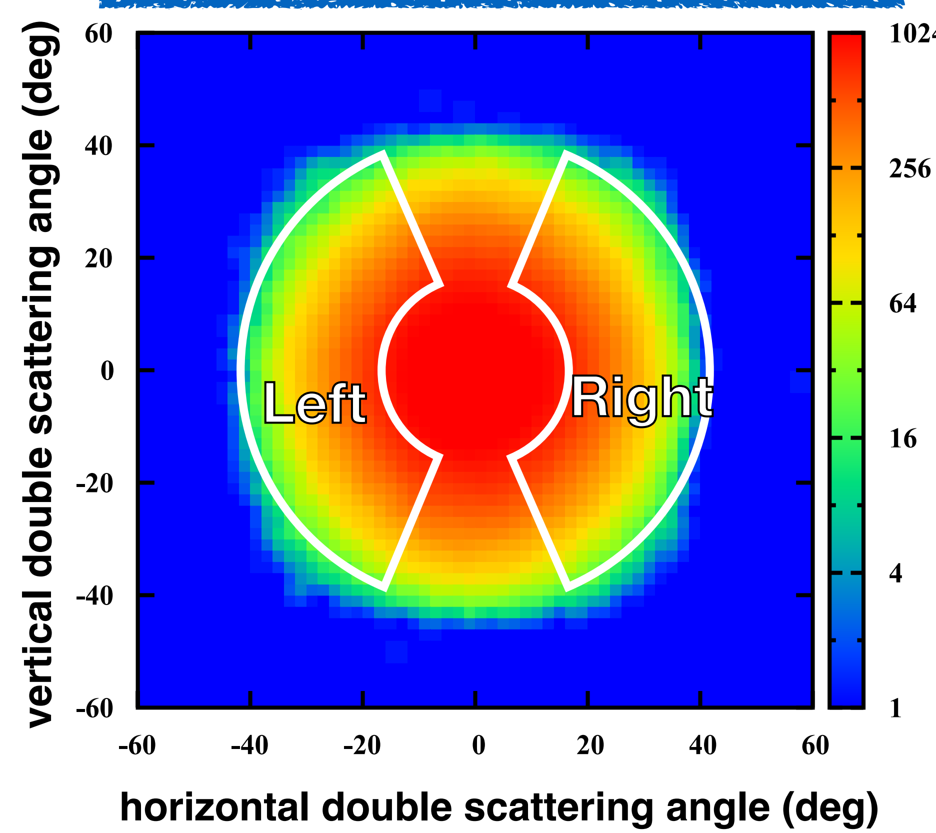
ϵ: scattering asymmetry

$\langle A_{y;\mathrm{eff}} \rangle$: effective analyzing power



asymmetry caused by the LS force

double scattering distribution



Neutron polarization measurement

◉ **Determination of $A_{y;eff}$**

- use neutron from $^2H(p,n)$ reaction
  - polarization is well known : $p_N \sim 0.03$

T. Wakasa PRC **69** 033602, (2004)

◉ **Select the n+p event**

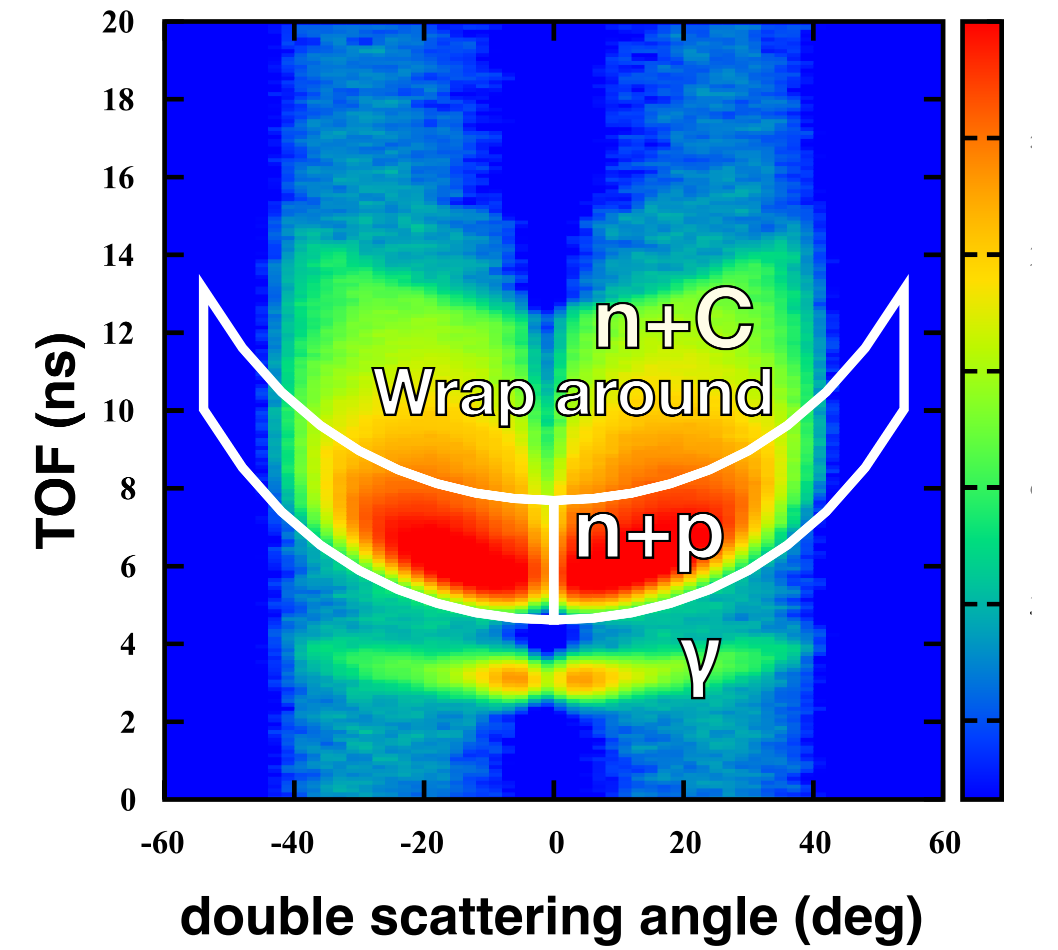
- $A_{y:eff}$ become small by other events (n+C, γ)
  - n+C event (small A_y), γ event (A_y=0)

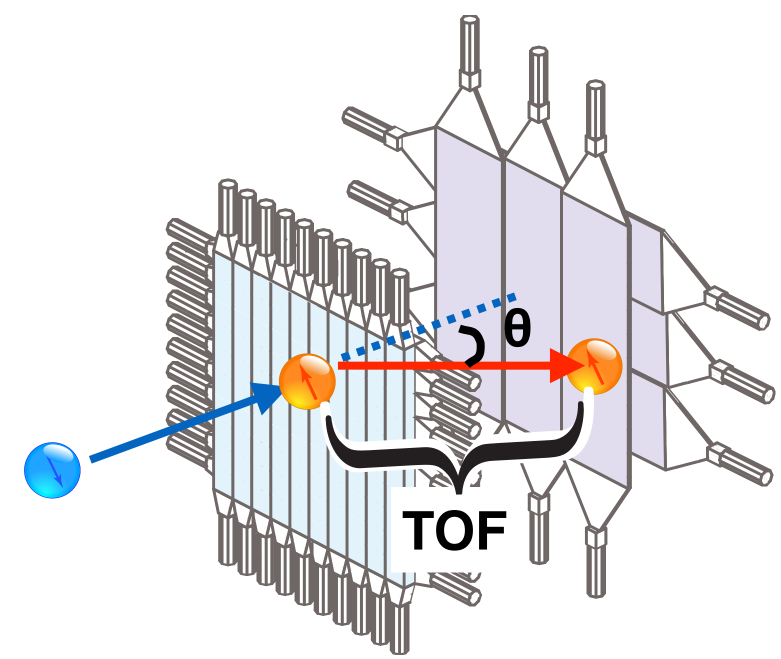
➡ **$A_{y;eff}$ = 0.098 ± 0.055**

➡ **select the n+p event kinematically by using TOF information**

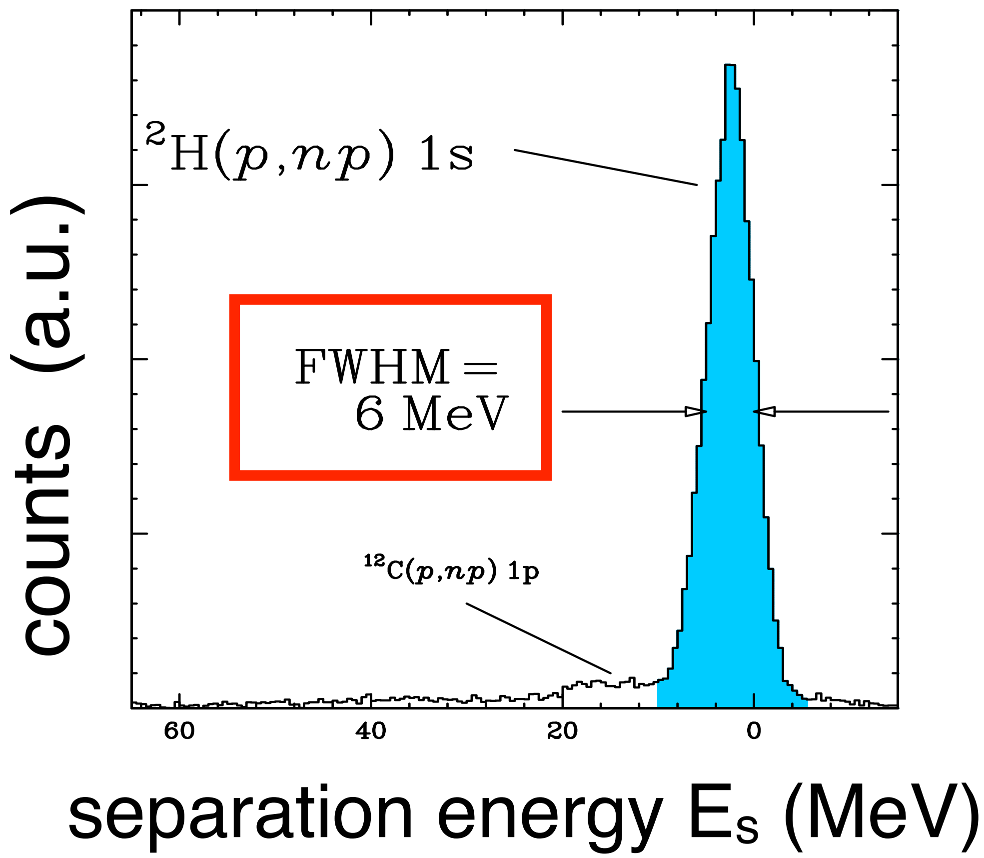
$A_{y;eff}$ = 0.127 ± 0.059

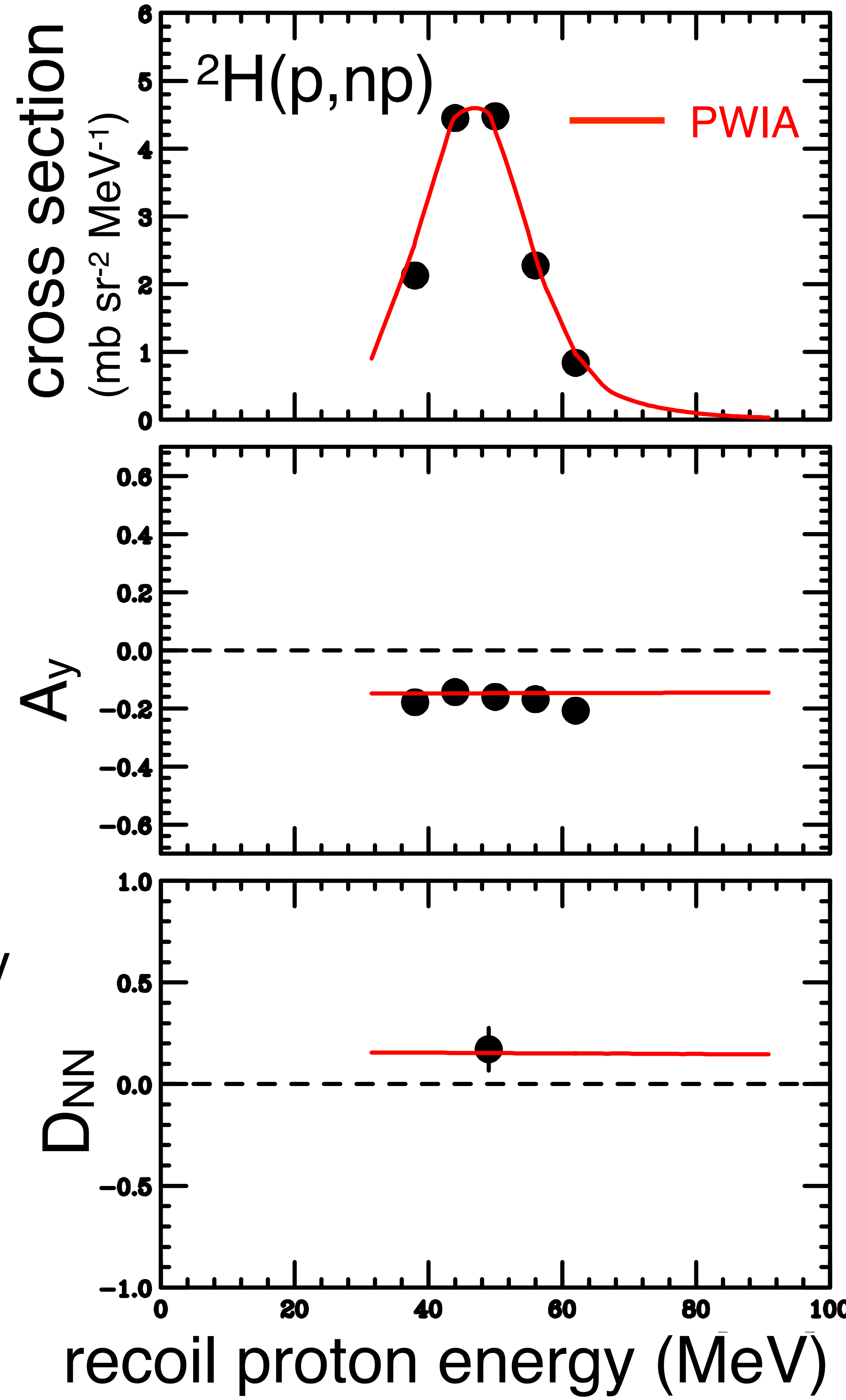
- Figure of merit : FOM = $\varepsilon \times (A_{yeff})^2$ = 0.67 × 10^{-4} ε=0.0042
  - similar performance with INPOL (FOM=0.81, A_{yeff}=0.09)





Results for $^{2}H(p,np)$ reaction





◉ **required energy resolution**

- ～ 7 MeV
  - energy difference between 1s and 1p : ~15 MeV

◉ **cross section and Ay for $^{2}H(p,np)$ reaction**

✓ consistent with PWIA calculation

➡ ^{2}H have no medium effect

Result for ^{6}Li(p,np) reaction

◉ **σ, Ay for 6Li(p,np) reaction for 1s state**

✓ theoretical cal. reasonably reproduce the experimental data

➡ consistent with previous result :

no medium effect in Ay for (p,np) reaction

◉ **Polarization transfer D_{NN}**

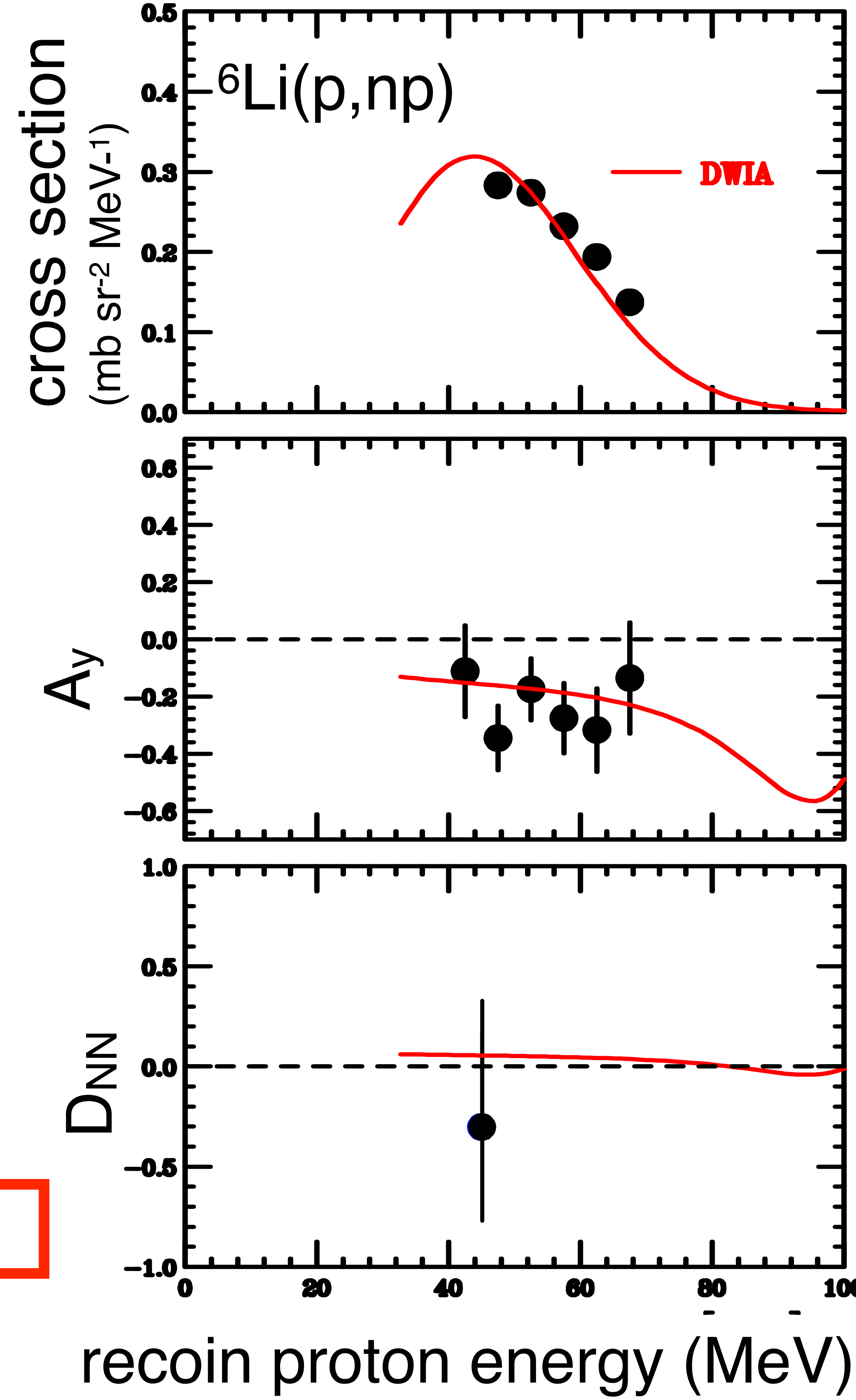
★ **required accuracy : 〜 0.10**

- **Condition at future exp.**
  - 2h (test exp.)→ 76h (future exp.)
  - polarization p_N : 0.40 → 0.70

    ↖ trouble at ion source

  ➡ **accuracy 0.04**

➡ **sufficient accuracy for studying medium effect**



Result for ^{6}Li(p,np) reaction

◉ **σ, Ay for 6Li(p,np) reaction for 1s state**

✓ theoretical cal. reasonably reproduce the experimental data

➡ consistent with previous result :

no medium effect in Ay for (p,np) reaction

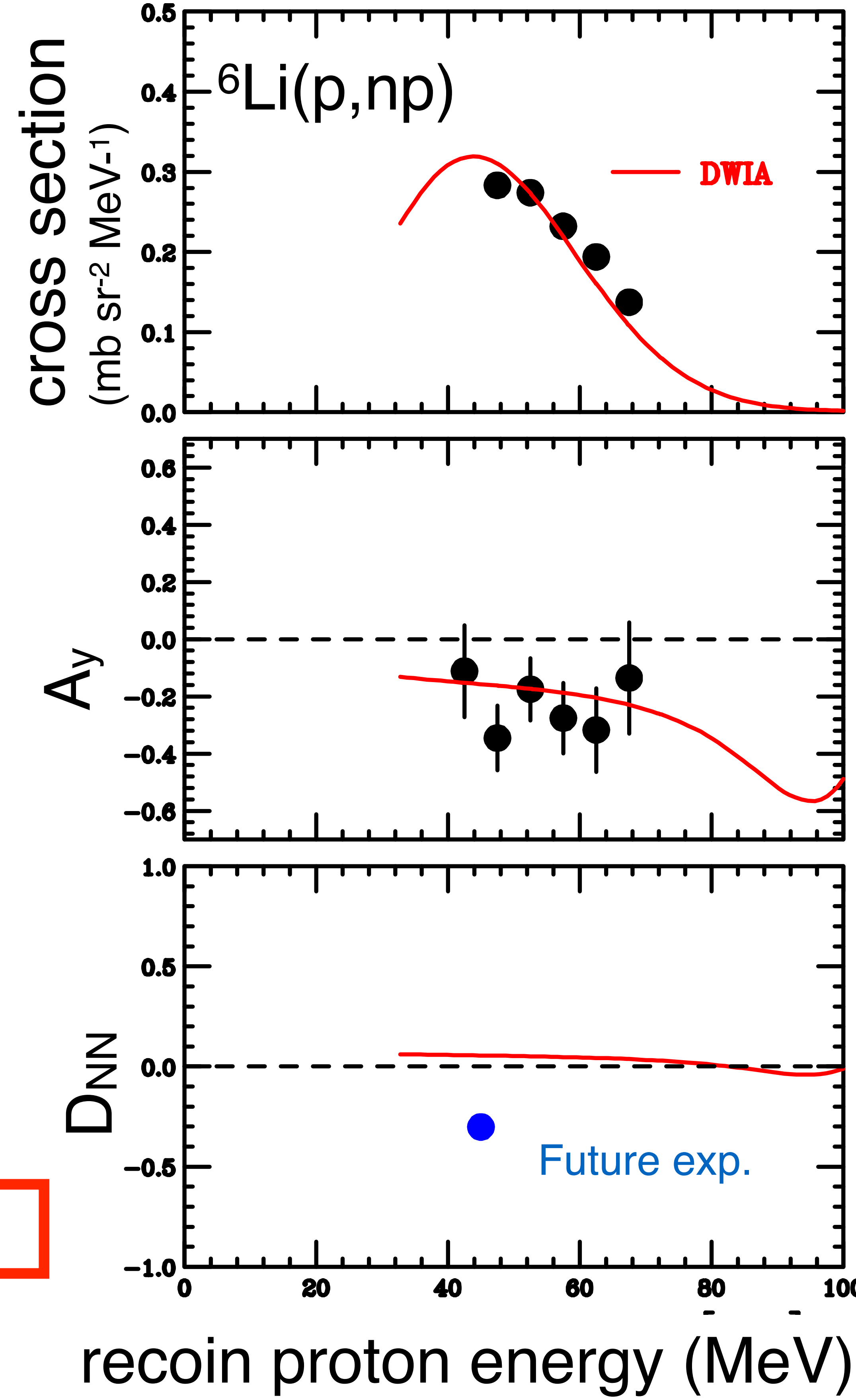
◉ **Polarization transfer D_{NN}**

★ **required accuracy : ～ 0.10**

- **Condition at future exp.**
  - 2h (test exp.)→ 76h (future exp.)
  - polarization p_N : 0.40 → 0.70 ↖ trouble at ion source

➡ **accuracy 0.04**

➡ **sufficient accuracy for studying medium effect**



Summary

- **Medium effect is important to understand the nuclear system**

- **($\vec{p}$,$n\vec{p}$) reaction is a powerful tool to studying the medium effect on NN int.**
  - 1s orbit —> density dependence
  - spin observables —> pin down the effect of σ, ω, ρ

  ✓ **<u>An experimental method and setup has been established</u>**

  ✓ separate 1s-orbit : energy resolution 6MeV

  ✓ neutron polarization : Effective analyzing power : $A_{yeff} = 0.127 \pm 0.05$

- **Future experiment [^{6}Li,^{12}C(p,np)] planned to be performed next year**
  - studying how the NN interaction modified in nuclear medium

Collaborators

Kyushu University

T. Wakasa, T. Fukunaga, Y. Nishio, K. Ohnaka, S. Sakaguchi, T. Noro, Y. Maeda

RCNP, Osaka University

K. Hatanaka, A. Tamii, K. Miki

University of Miyazaki

Y. Maeda

Tohoku University

K. Sekiguchi, T. Taguchi, Y. Wada

CYRIC, Tohoku University

Y. Sakemi

CNS, University of Tokyo

M. Dozono

Summary

- **Medium effect is important to understand the nuclear system**

- **($\vec{p}$,$n\vec{p}$) reaction is a powerful tool to studying the medium effect on NN int.**
  - 1s orbit —> density dependence
  - spin observables —> pin down the effect of σ, ω, ρ

✓ **An experimental method and setup has been established**

✓ separate 1s-orbit : energy resolution 6MeV

✓ neutron polarization : Effective analyzing power : $A_{yeff} = 0.127 \pm 0.05$

- **Future experiment [^{6}Li,^{12}C(p,np)] planned to be performed next year**
  - studying how the NN interaction modified in nuclear medium

Back up

Result for $^{12}C(p,np)$ reaction

- **σ, Ay for $^{12}C(p,np)$ reaction for 1s state**

  ✓ theoretical cal. reasonably reproduce the experimental data

  ➡ consistent with previous result :

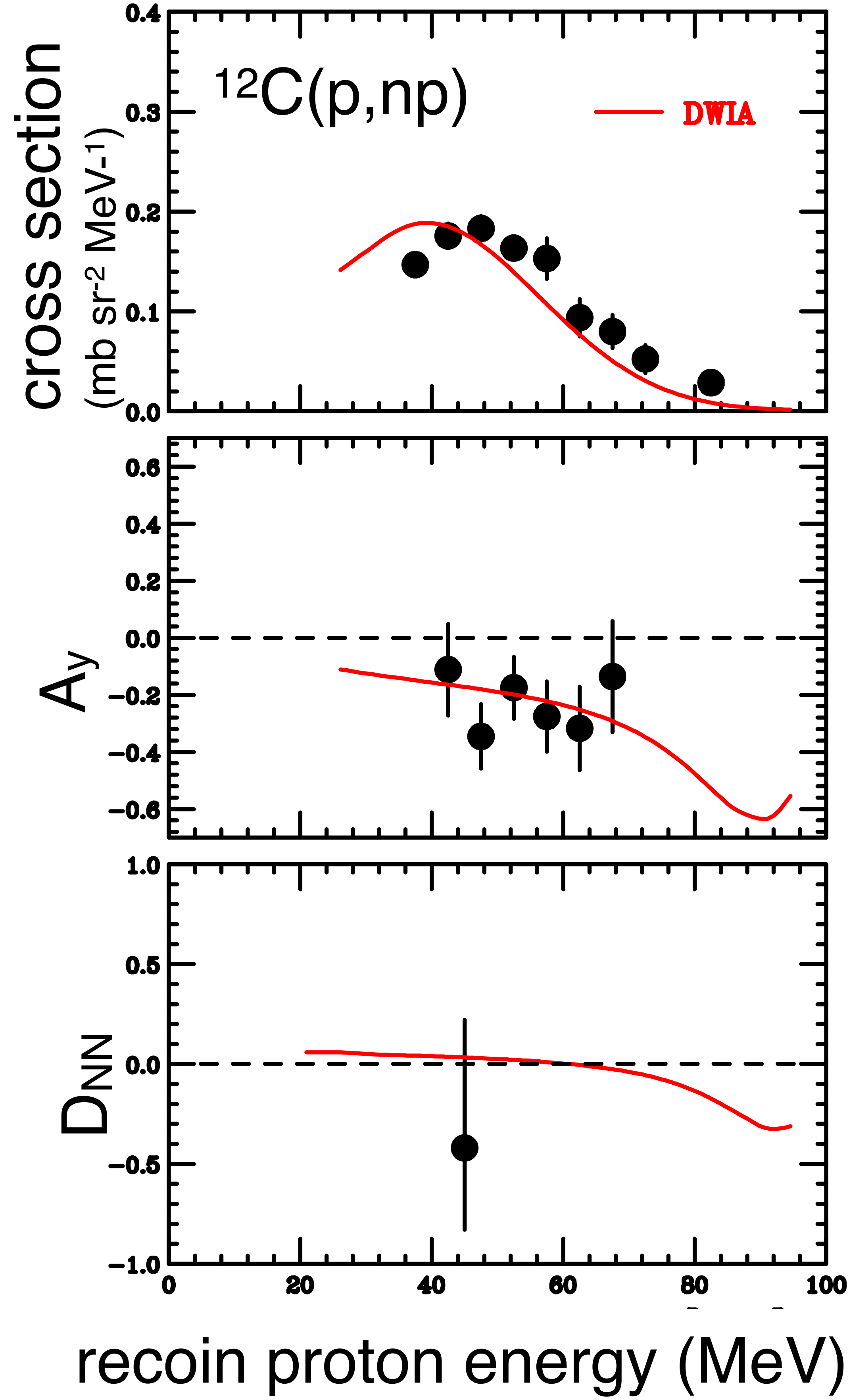
  no medium effect in Ay for (p,np) reaction

- **Polarization transfer D_{NN}**

  ★ **required accuracy : ~ 0.10**

  - **Condition at future exp.**
    - 5h (test exp.)→ 126h (future exp.)
    - polarization p_N : 0.40 → 0.70 ↖ trouble at ion source

  ➡ **accuracy 0.04**



Why D_{NN} for (p,np)

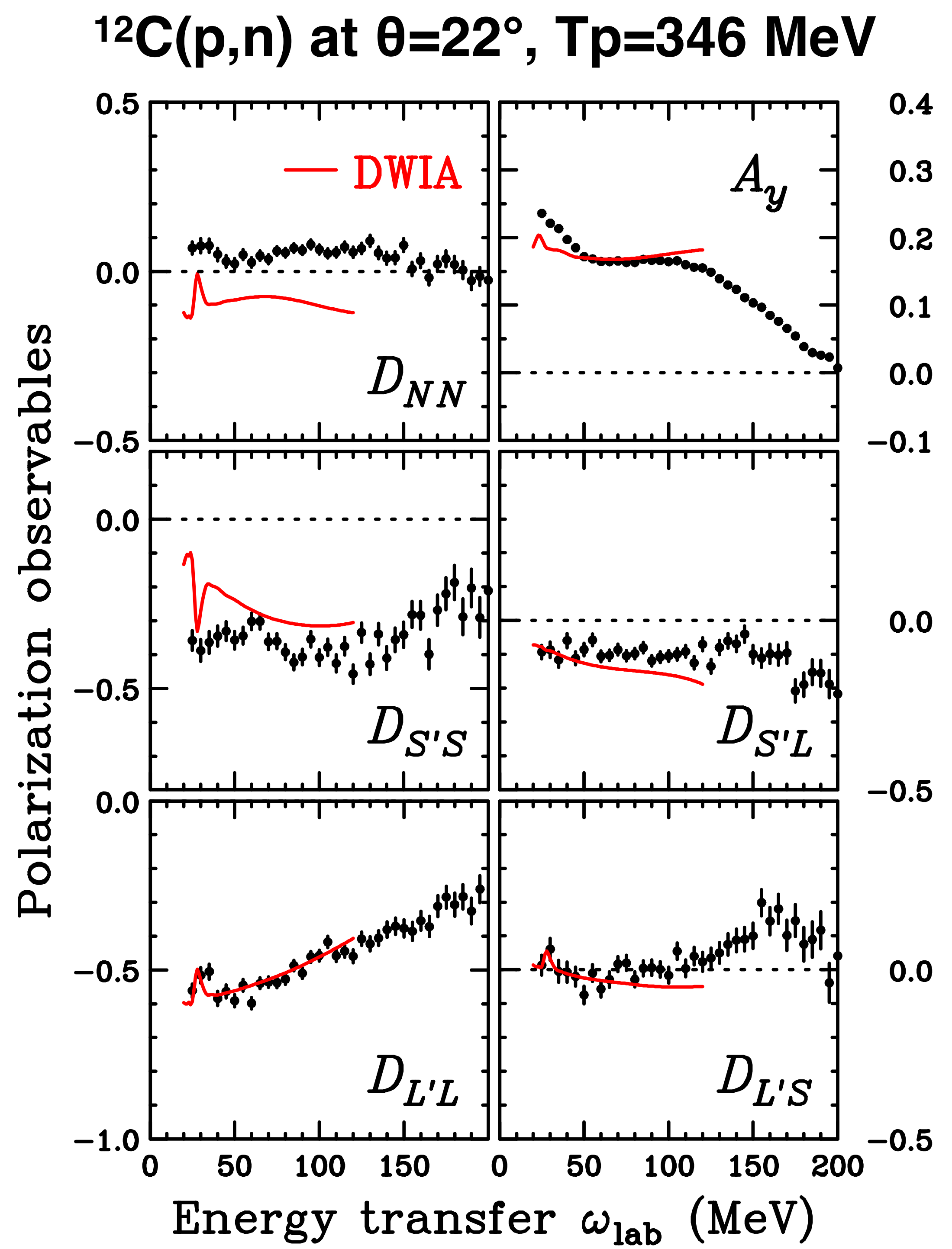
◉ **Physical consideration**

- Spin observables for inclusive (p,n)
  - **D_{NN} is much deviated from DWIA**
  - Ay, $D_{L'L}$, $D_{L's}$, … are reasonably reproduced by DWIA

➡ **Medium effect would be significantly seen in D_{NN} for (p,np)**

◉ **Experimental consideration**

- **We can measure D_{NN} w/o neutron spin-rotation magnet**
- $D_{L'L}$ and $D_{L's}$ require neutron spin-rotation magnet



D_{NN} is suitable for the first measurement

Nuclear Force : One-Boson-Exchange

- Various meson-nucleon couplings and their contributions to the nuclear force as obtained from One-Boson-Exchange

Coupling	*Bosons (Strength of Coupling)* $I=0$ [1]	$I=1$ $[\tau_1 \cdot \tau_2]$	*Characteristics of Predicted Forces* *Central* [1]	*Spin-Spin* $[\sigma_1 \cdot \sigma_2]$	*Tensor* $[S_{12}]$	*Spin-Orbit* $[L \cdot S]$
ps	η (weak)	π (strong)	—	weak, coherent with *v*, *t*	strong	—
s	σ (strong)	δ (weak)	strong, attractive	—	—	coherent with *v*
v	ω (strong)	ρ (weak)	strong, repulsive	weak coherent with *ps*	opposite to *ps*	strong, coherent with *s*
t	ω (weak)	ρ (strong)	—	weak, coherent with *ps*	opposite to *ps*	—

R. Machleidt, Advances in Nucl. Phys., Vol. **19**, (1989)