Study of in-medium NN interactions by using (p,pN) reactions

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量子クラスターで読み解く物質の階層構造
Clustering as a window on the hierarchical structure of quantum systems
Clusters & Hierarchies

Contents

Review: *Nuclear medium effects in NN interactions*

- Relation between three nucleon force and two nucleon force “in nuclear medium”
- A_y reduction (puzzle) in p-p scattering in nuclear medium [(p,2p)]
- Medium effects on spin transfers and n-p scattering in nuclear medium [(p,np)]

This project: *Experimental determination of in-medium NN interactions*

Testing the validity of theoretical treatments (DWIA) for loosely-bound orbits

- DWIA analyses are reliable to pin down the nuclear medium effects

Development of the 2nd-FPP for K_{ij} measurements

Comments and summary

- Phenomenological correlation between A_y reduction and EMC/SRC effects

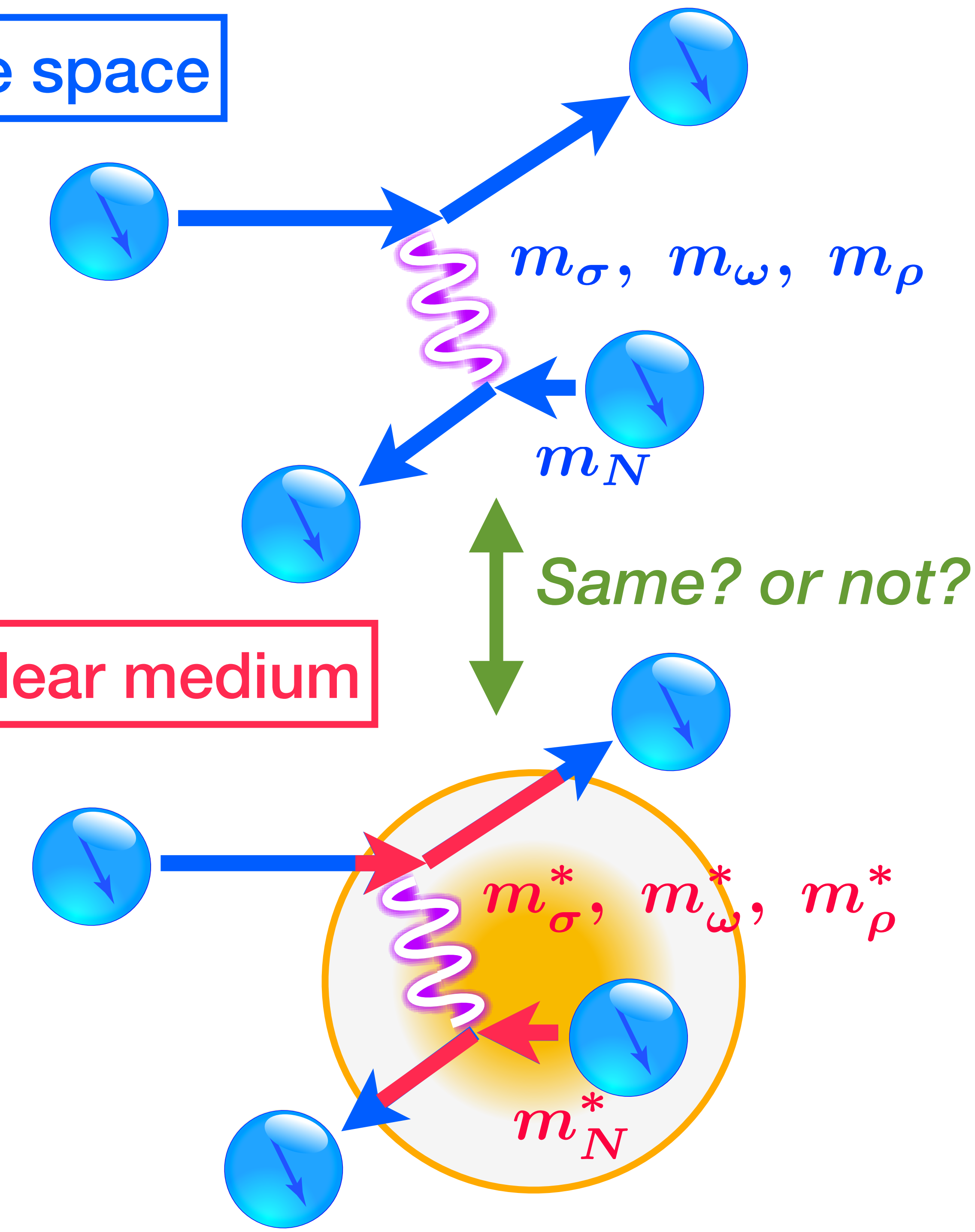
Motivation *—Study of NN int. in nuclear field—*

Comparison of NN scattering *in free space* and *in nuclear medium*

- Medium effects on NN int.
- Density dependence

Origin of medium effects

- ☑ Fermi motion
- ☑ Distortions
- ☑ Pauli blocking
- ☐ Modification of meson mass and coupling constants (*Brown-Rho scaling*)
    - ☆ Restoration of chiral symmetry in nuclear medium
- ☐ Modification of nucleon spinor (*3NF effects*)
    - ☆ Relativistic distortion effects



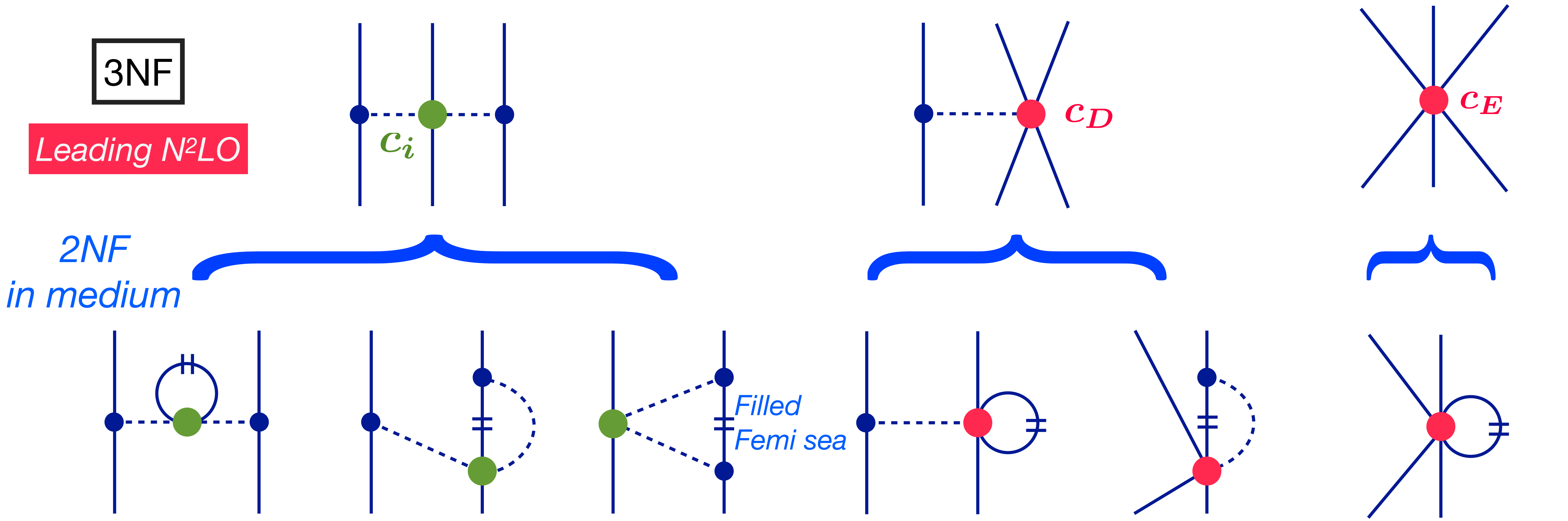
Spin observables are sensitive to relevant NN t-matrix components
A_y and D_{ij} have been measured for (p,pN)

In-medium 2NF generated by 3NF

N.Kaiser, and W.Weise, Phys. Rev. C 79, 054331 (2009).

Density dependent correction to 2NF from the leading order 3NF at one-loop order

Bare one-pion exchange (OPE) : $V_{NN}^{1\pi} = -\frac{g_A^2 M_N}{16\pi f_\pi^2} \vec{\tau}_1 \cdot \vec{\tau}_2 \frac{\vec{\sigma}_1 \cdot \vec{q}\, \vec{\sigma}_2 \cdot \vec{q}}{m_\pi^2 + q^2}$



Pion self energy in medium	Vertex corr. to OPE	Pauli blocking on TPE	Vertex corr. to OPE	Vertex corr. to SR-2NF	Short-range repulsion

$f_\pi^2 \to f_\pi^2 + 2c_3\rho$ $\quad g_A \to g_A^*(\rho)$ $\quad$ ρ-dep. **LS** $\quad g_A \to g_A \frac{C_D}{2f_\pi^2 \Lambda_\chi}\rho$ $\quad$ ρ-dep. **repulsion** (S,T,p-indep.)

Density dependent effects on 2NF by 3NF are naturally (naively) expected.

Relativistic description for in-medium 2NF

F. Sammarruca et al., PRC 86, 054317 (2012).

Relativistic model based on Dirac eq.

Strong scalar field induces "spinor distortion"
(reduction of nucleon mass)

$$u = \sqrt{\frac{E+M_N}{2M_N}} \begin{pmatrix} 1 \\ \frac{\vec{\sigma}\cdot\vec{p}}{E+\underline{M_N+U_S}-U_V} \end{pmatrix} \chi$$

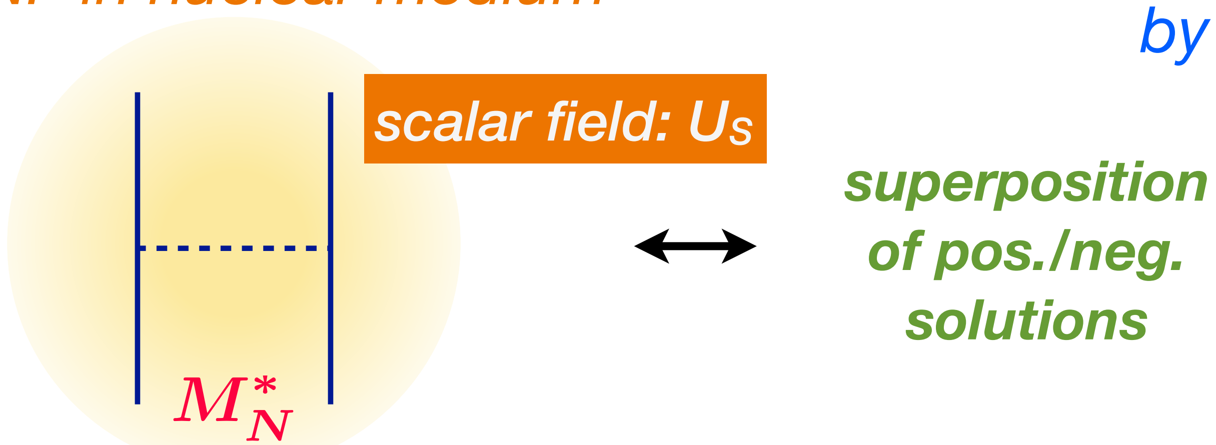
Spinor distortion

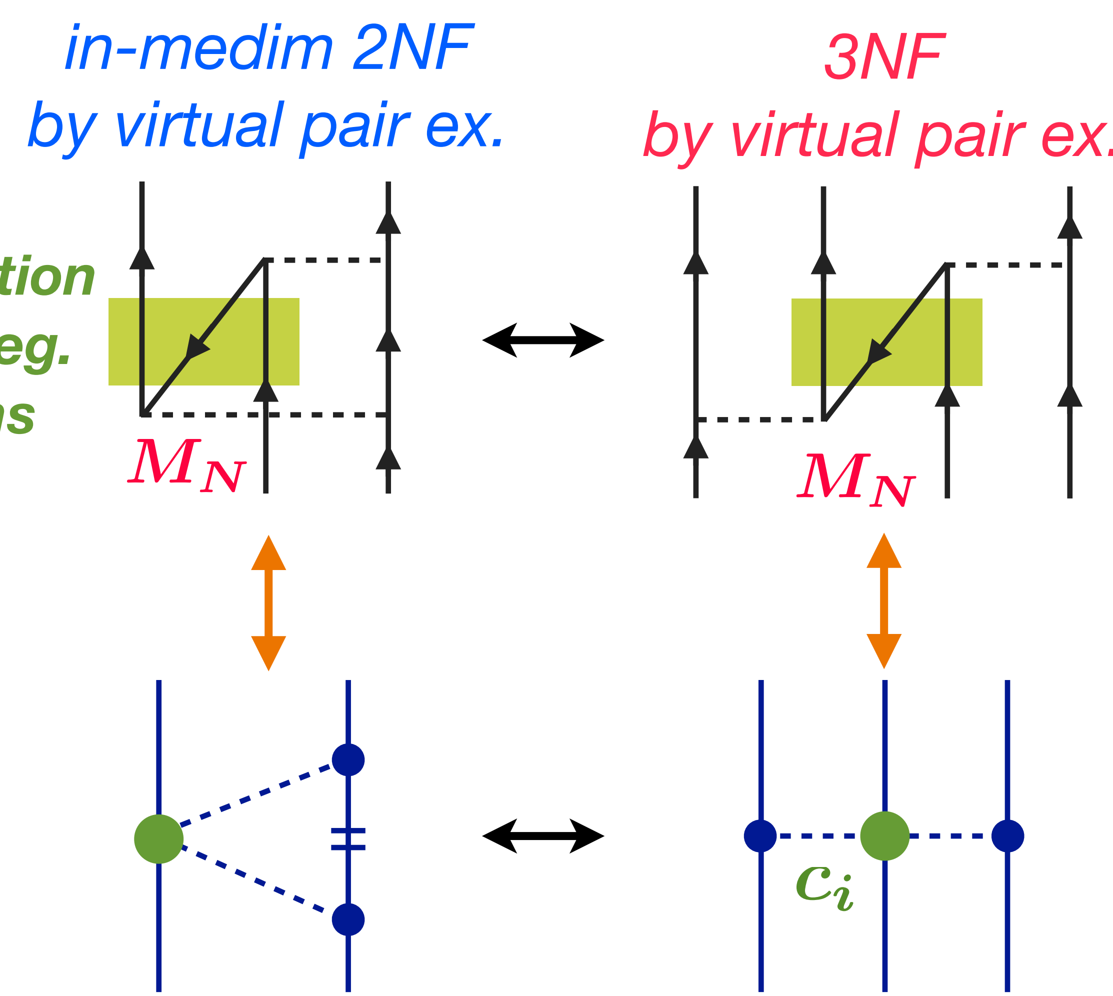
$$M_N \to M_N^* = M_N + U_S$$

Spinor distortion can be written as ***a superposition of pos./neg. solutions*** with "free" M_N

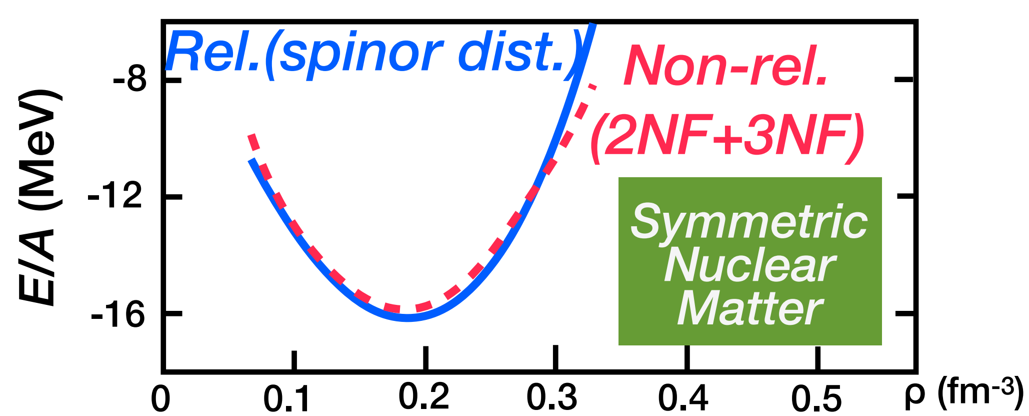
- Closely related to 3NF

2NF in nuclear medium





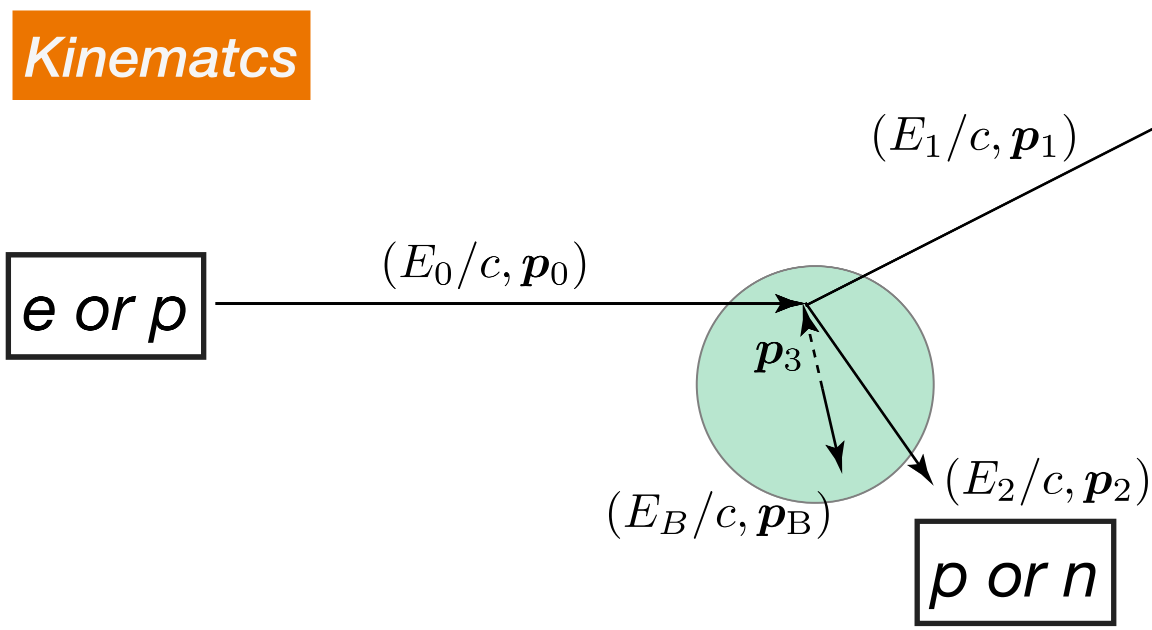
Non-relativistic model based on chiral EFT

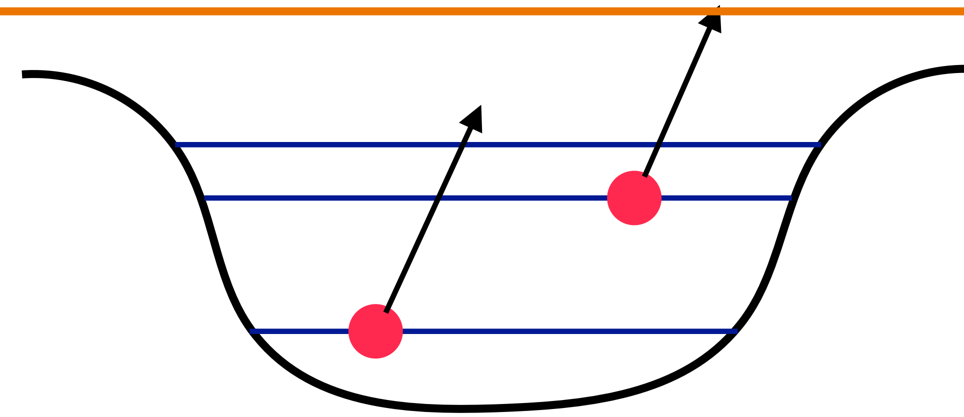


Medium effect through 3NF can be incorporated in rel. model through ***"spinor distortion"***.

Exclusive nucleon knockout reactions

Kinematcs





E_B (binding energy) ***and***
p_3 (Fermi momentum)
can be specified

Exclusive nucleon knockout reaction provides a direct means to study s.p. properties

(e,e'p)

- Distortion effect is less serious
- Interaction is well known

(p,pN) [(p,2p) and (p,pn)] = ***NN scattering in nuclear medium***

- Large cross section is suited for systematic studies
- Spin degrees of freedom provide useful information
- Inverse-kinematics exp. is feasible

(p,pN) can be used also for assessing "in-medium" NN force
(Spin obs. are less sensitive to initial and final state interactions)

The reaction mechanism is simple enough to deduce the medium effect on NN force.

Estimation of effective mean density for (p,pN)

TW, K.Ogata, and T.Noro, PPNP 96, 32 (2017).
J.Ryckebusch, W.Cosyn, and M.Vanhalst, PRC 83, 054601 (2011).

Triple differential c.s. of (p,pN) is expressed as

$$\sigma = |T|^2 \quad T = \int_0^\infty D(R)\,dR \qquad D(R) \equiv \int \chi_2^*(R)\chi_1^*(R)\phi(R)\chi_0(R)R^2 d\Omega$$

Transition matrix density, $\delta^{\rm Tr}(R)$, can be defined as

$$\delta^{\rm Tr}_{\rm real}(R) \equiv {\rm Re}\left[\frac{D(R)}{\int_0^\infty D(R)dR}\right]\sigma \rightarrow \int_0^\infty \delta^{\rm Tr}_{\rm real}(R)dR = \sigma$$

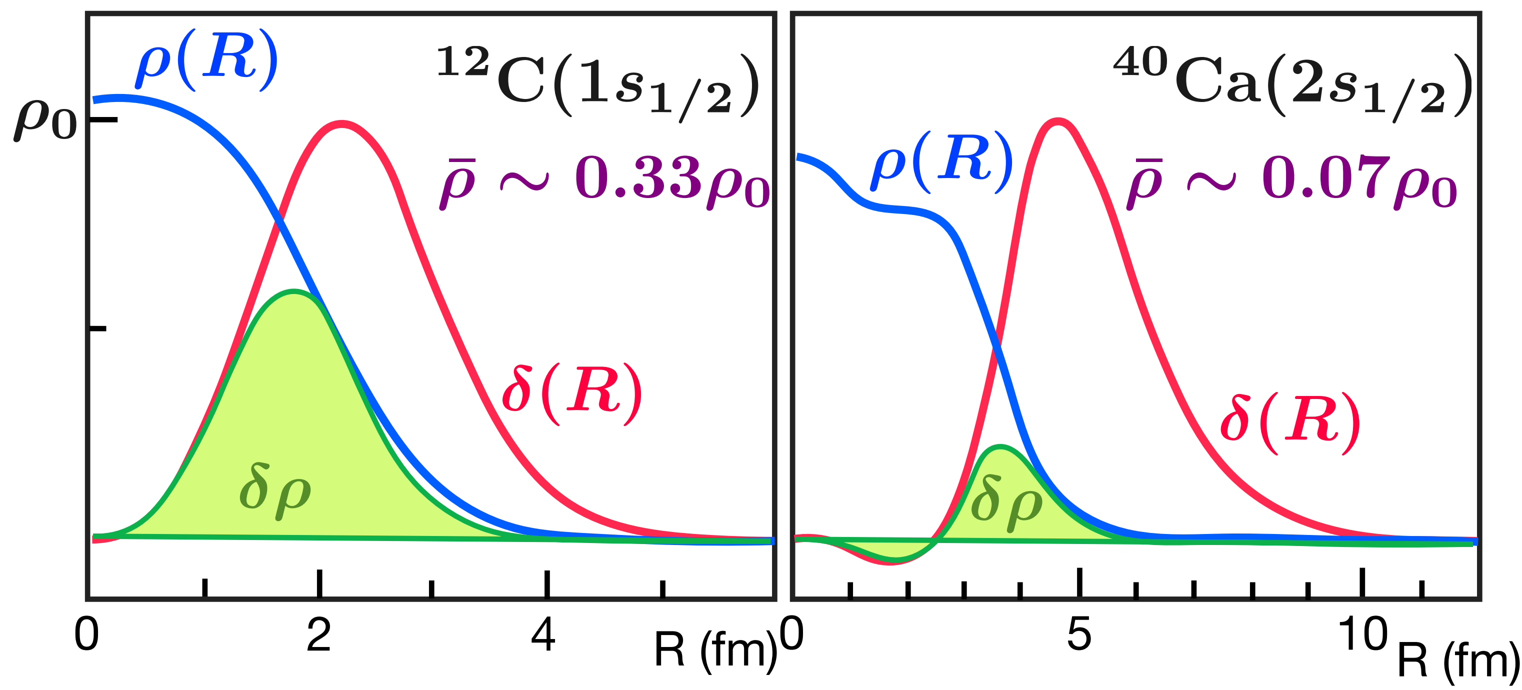
contribution to σ at R

$$\left(\delta^{\rm Tr}_{\rm imag}(R) \equiv {\rm Im}\left[\frac{D(R)}{\int_0^\infty D(R)dR}\right]\sigma \rightarrow \int_0^\infty \delta^{\rm Tr}_{\rm imag}(R)dR = 0\right)$$

Then, effective mean density, $\bar{\rho}$, can be introduced as

$$\boxed{{\rm Re}\,\bar{\rho} = \frac{\int_0^\infty \rho(R)\delta^{\rm Tr}_{\rm real}(R)dR}{\int_0^\infty \delta^{\rm Tr}_{\rm real}(R)dR}}$$

(In most cases, ${\rm Re}\bar{\rho} \gg {\rm Im}\bar{\rho}$)



We can control $\bar{\rho}$ by selecting target nuclei and orbits from 0 to ~40% of ρ_0

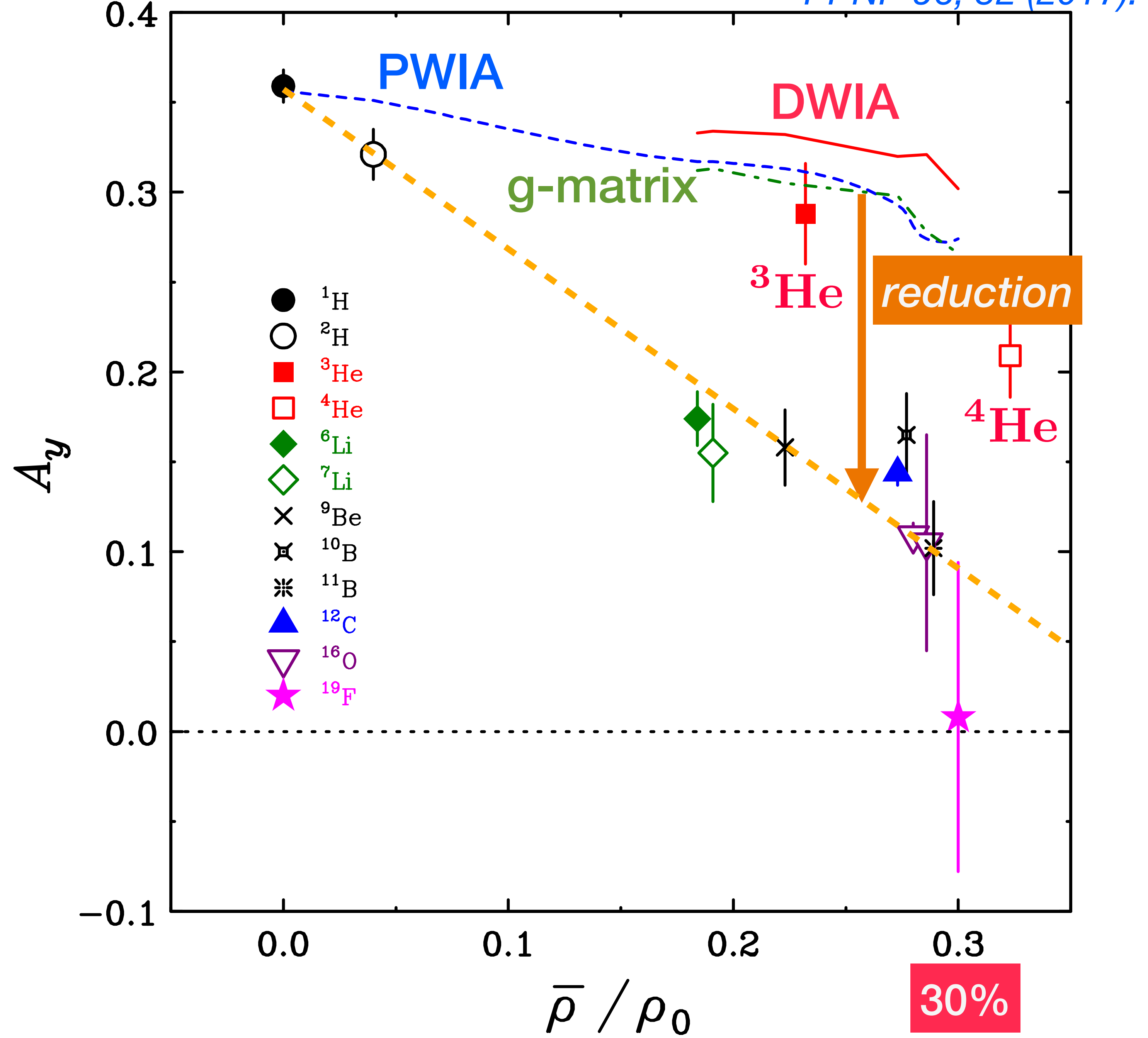
A_y reduction for p-p in nuclear medium

T.Noro et al., PRC 72, 041602 (2005).
TW, K.Ogata, and T.Noro, PPNP 96, 32 (2017).

A_y of (p,2p) [p-p in nuclear medium] for s/p-shell nuclei at 392 MeV

Density dependence

- Monotonic decrease of the density
  - Distortion effect is small
  - Conventional g-matrix could not explain this trend
- Exception of ^{3}He/^{4}He
  - Too small for applying concept of nuclear density?



Ay of p-p in nuclear medium are reduced as a function of density.

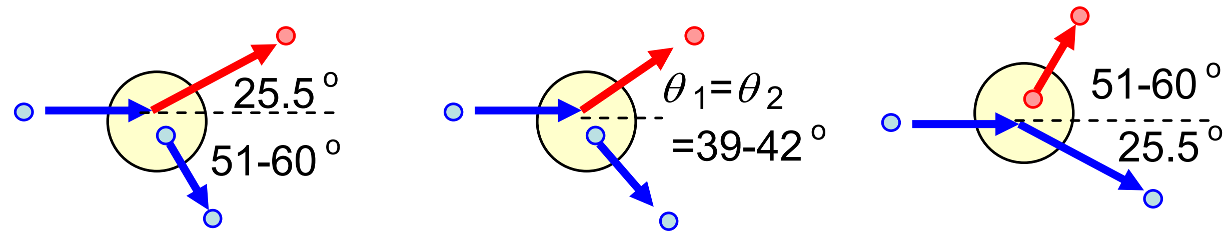
・Distortion effect and conventional medium effect (g-matrix) could NOT explain.

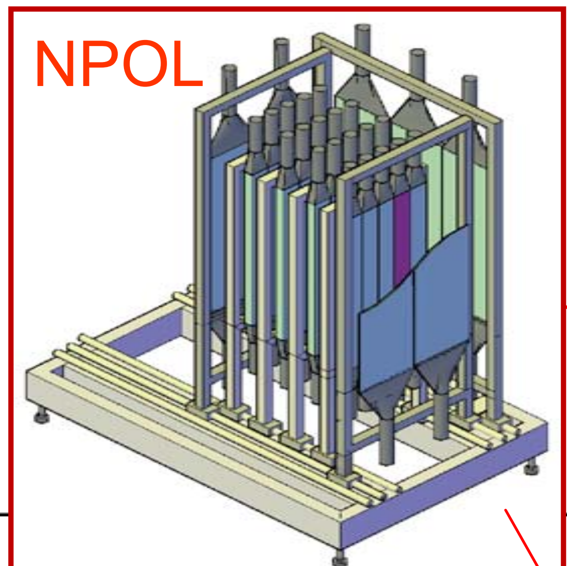
→ *How about n-p in nuclear medium (isospin dependence) ?*

Extension to (p,pn) measurements

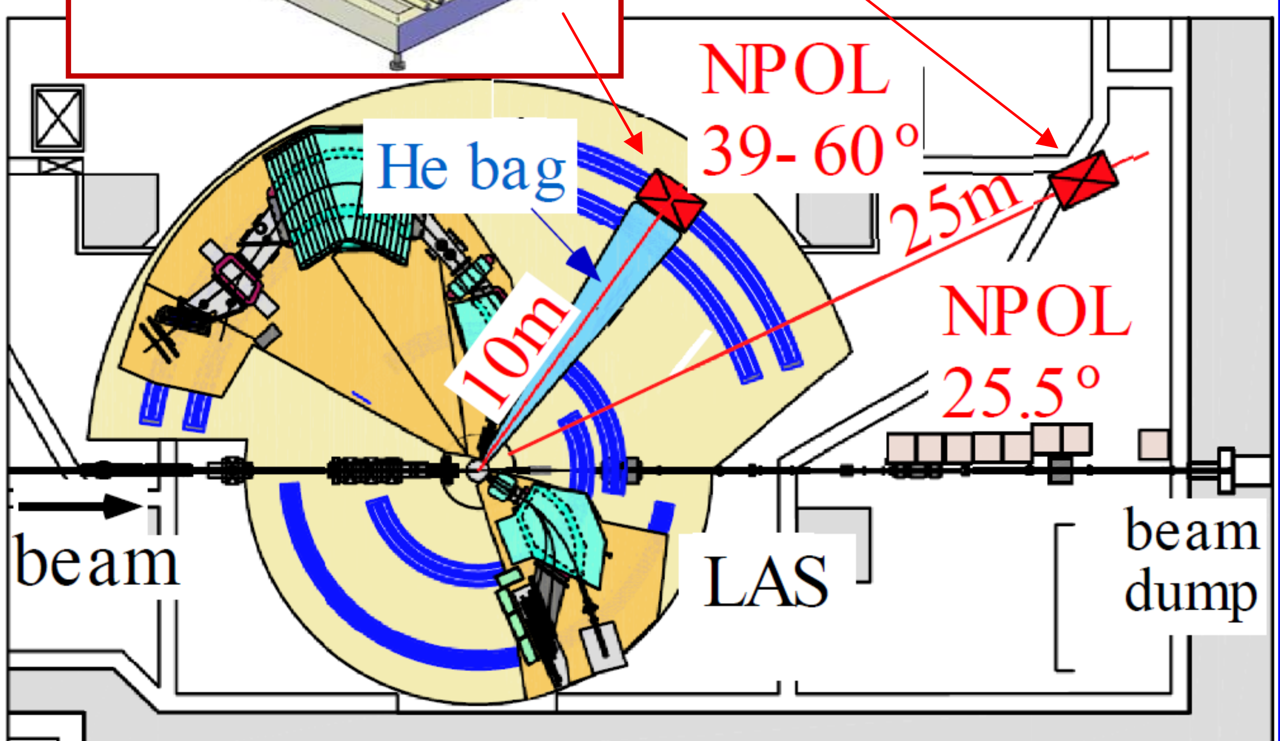
Y. Yamada, Ph.D. thesis, Kyushu University (2010).
TW, K.Ogata, and T.Noro, PPNP 96, 32 (2017).

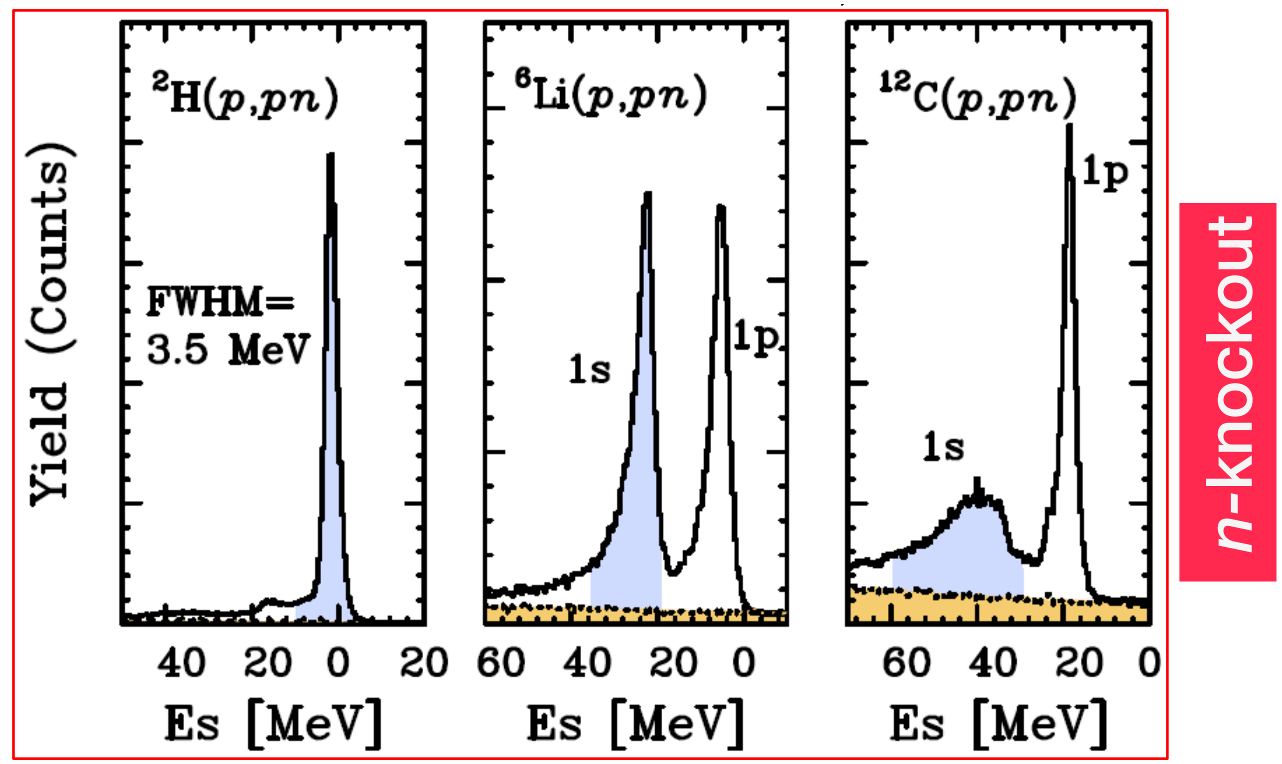
(p,2p), (p,pn), and (p,np) data are measured with a same setup.

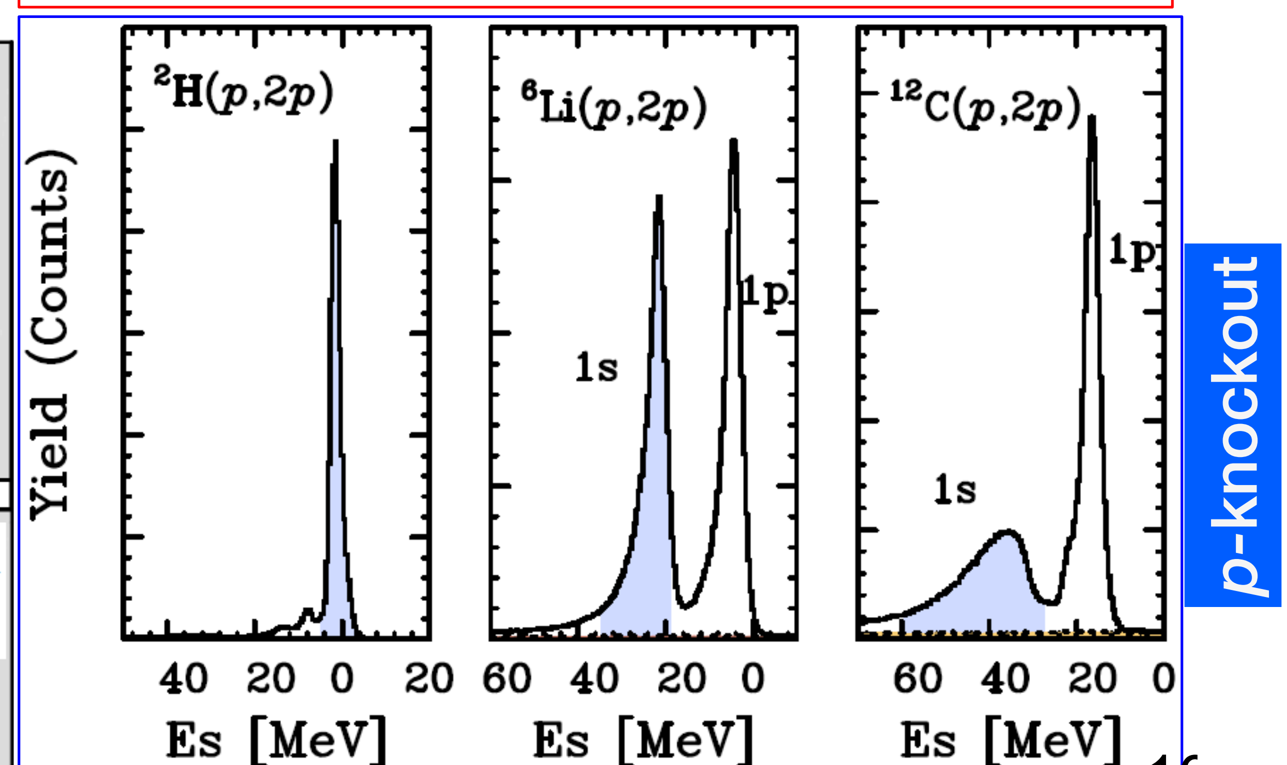




(p,pn) and (p,2p) are measured *simultaneously*







Y. Yamada, Ph.D. thesis, Kyushu University (2010).
TW, K.Ogata, and T.Noro, PPNP 96, 32 (2017).

A_y data for $1s_{1/2}$ knockout (p,pN) at k_{recoil}=0

Y. Yamada, Ph.D. thesis, Kyushu University (2010).
TW, K.Ogata, and T.Noro, PPNP 96, 32 (2017).

(p,2p) data are consistent with the previous results

- Data with this new setup for (p,pN) are reliable

(p,pn) data with the p-forward emission

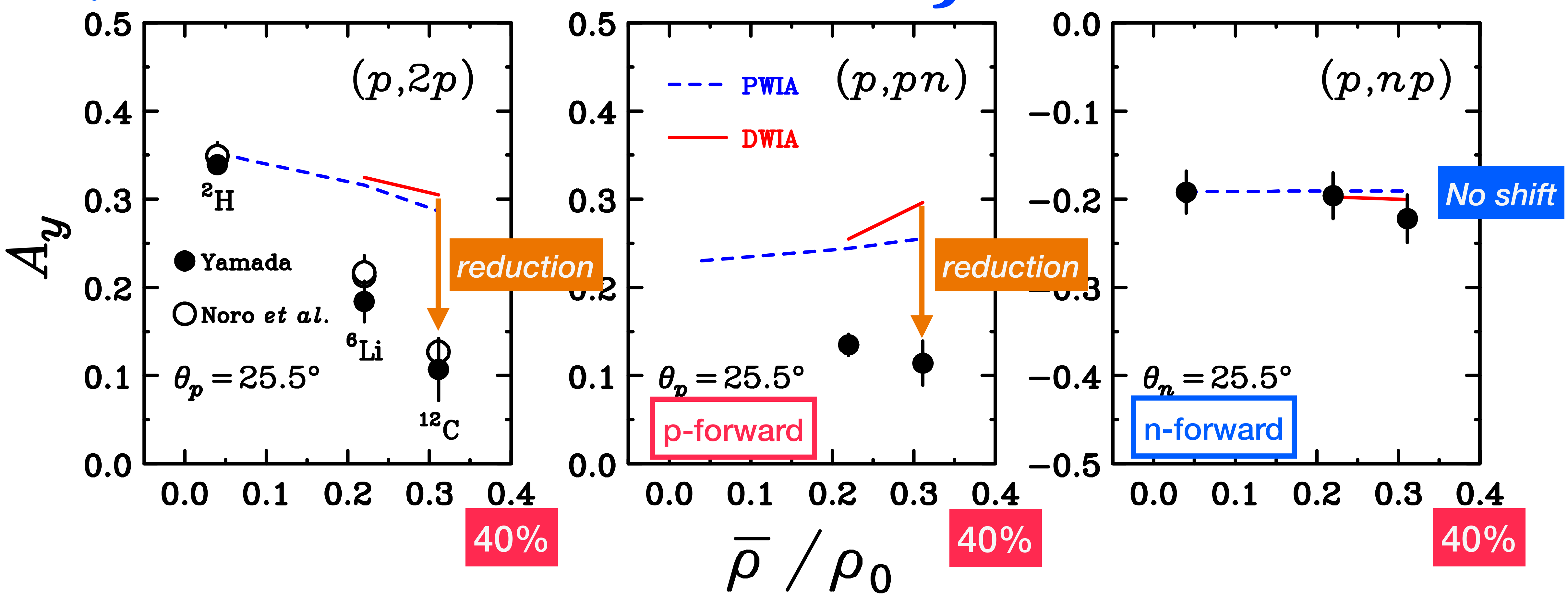
- Ay-reduction similar to (p,2p)

ΔT=0 and 1
(no charge transfer)

(p,np) data with the n-forward emission

- NO Ay-reduction

ΔT=1 only
(charge transfer)



Nuclear medium effects on 2NF depend on isospin (charge) transfer
✤ *Suggest the modification in isoscalar meson exchange → Can we model these effects?*

Medium effects on A_y for (p,np) and (p,2p)

TW et al., Phys. Rev. C 96, 014604 (2017).

Spinor distortion (3NF effects)

Effective mass M_N^* correction:

$$M_N^* = \left[1 - C\left(\frac{\bar{\rho}}{\rho_0}\right)\right] M_N$$

(C=0.18 from QCD sum-rule)

- (p,2p) : M_N^*-corr. is ***significant***
- (p,np) : M_N^*-corr. is ***negligible***

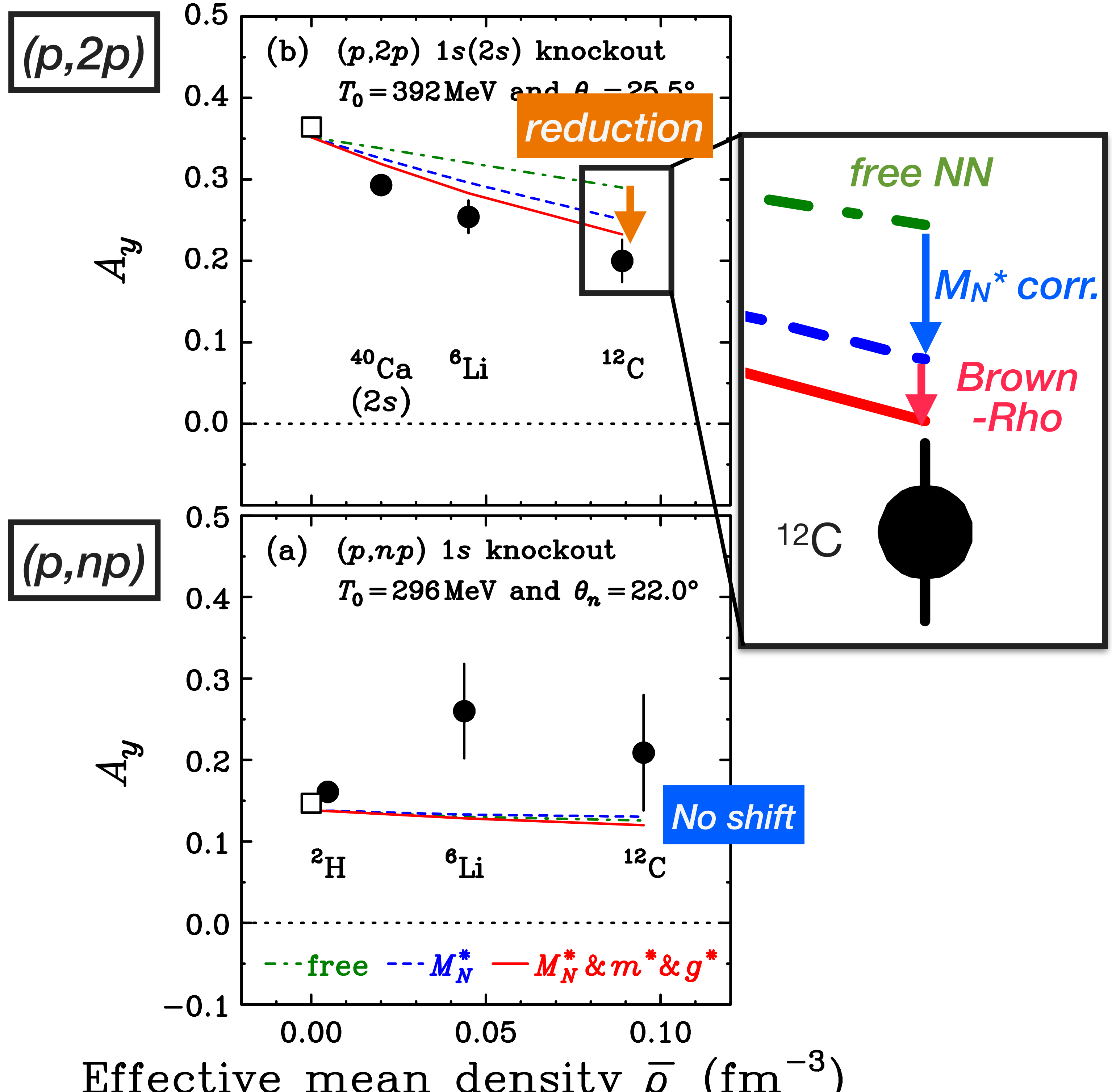
Non-conventional medium effects

Brown-Rho scaling conjecture:

$$\overbrace{\frac{m^*}{m} = \frac{g^*}{g}}^{\text{in-medium meson mass/coupling}} = \frac{M_N^*}{M_N} = 1 - C\left(\frac{\bar{\rho}}{\rho_0}\right)$$

$$\underbrace{\frac{m^*}{m} = \frac{g^*}{g}}_{\text{free meson mass/coupling}}$$

- (p,2p) : ***Significant*** effect
- (p,np) : ***Negligible*** effect



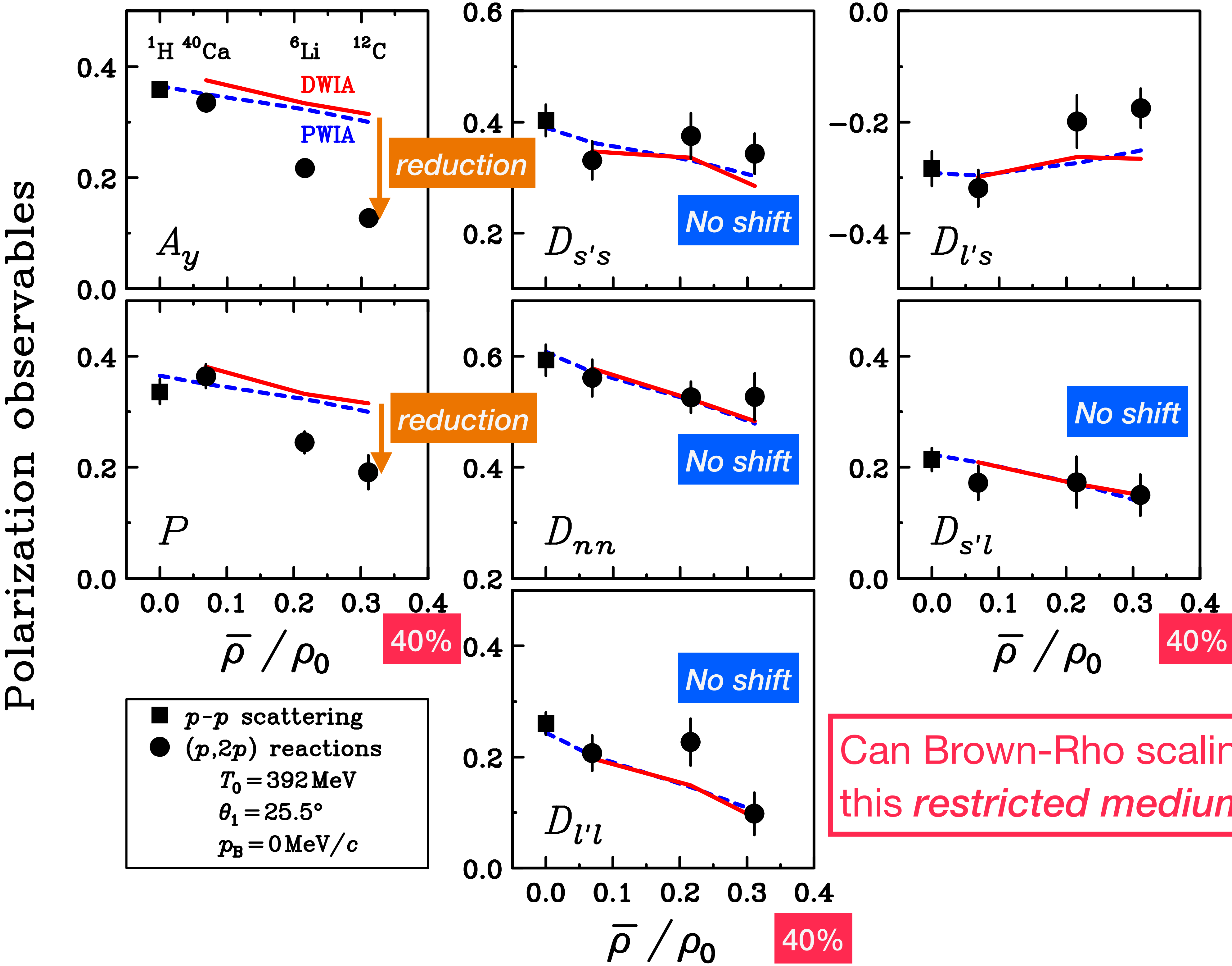
Isospin and density dependences of nuclear medium effects are reasonably explained.
→ *How about other spin observables ?*

Medium effects on D_{ij} for (p,2p)

T. Noro et al., Phys. Rev. C 77, 044604 (2008).

Complete measurements of D_{ij} of (p,2p) at 392 MeV

No shift (reduction) from PWIA/DWIA predictions (***Reduction is restricted to A_y/P***)



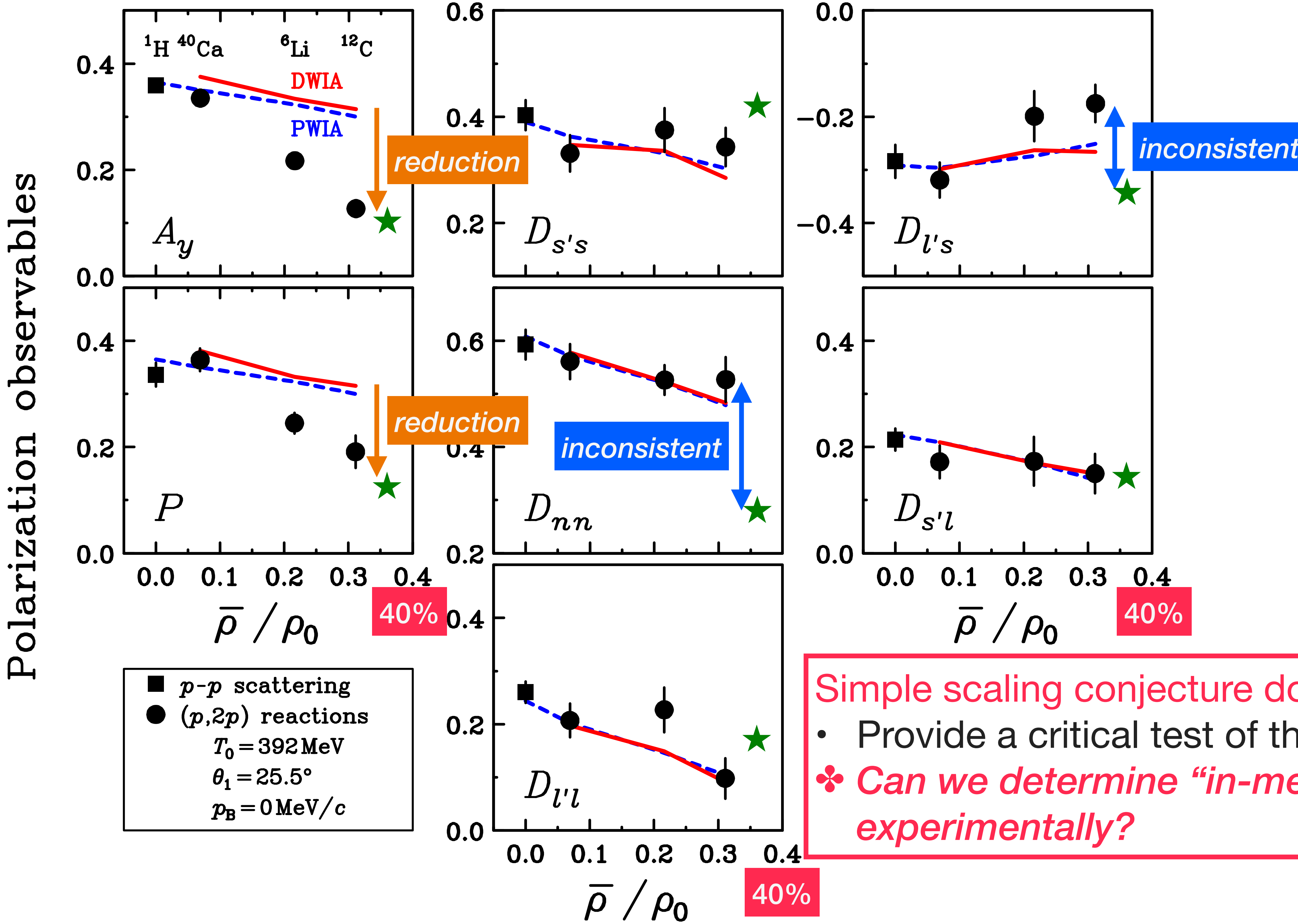
Can Brown-Rho scaling conjecture explain this ***restricted medium effects on A_y and P*** ?

Failure of Brown-Rho scaling conjecture

T. Noro et al., Phys. Rev. C 77, 044604 (2008).

Calculations based on Brown-Rho scaling conjecture for $^{12}C(p,2p)$

- Significant medium effects are predicted especially D_{nn} → *Inconsistent with exp. data*



Simple scaling conjecture does not work.

- Provide a critical test of theoretical models.

✤ *Can we determine "in-medium 2NF" experimentally?*

Experimental determination of in-medium 2NF

A.K.Kerman, H.McManus, and R.M.Thaler, Ann. Phys. 8, 551 (1959).

For free NN scattering, the c.s. I and polarization transfer D_{ij} are defined as:

$$I \equiv \frac{d\sigma}{d\Omega} = \frac{1}{4}\mathrm{Tr}[MM^\dagger] \qquad D_{ij} = \frac{\mathrm{Tr}[M\sigma_j M^\dagger \sigma_i]}{\mathrm{Tr}[MM^\dagger]}$$

$$\left.\begin{aligned}\vec{q} &= \vec{k}_f - \vec{k}_i \\ \vec{n} &= \vec{k}_i \times \vec{k}_f\end{aligned}\right\} \rightarrow \boxed{\begin{aligned}\hat{q} &= \frac{\vec{q}}{|\vec{q}|} \\ \hat{n} &= \frac{\vec{n}}{|\vec{n}|} \\ \hat{p} &= \hat{q} \times \hat{n}\end{aligned}}$$

where M is the NN scattering amplitudes expressed as:

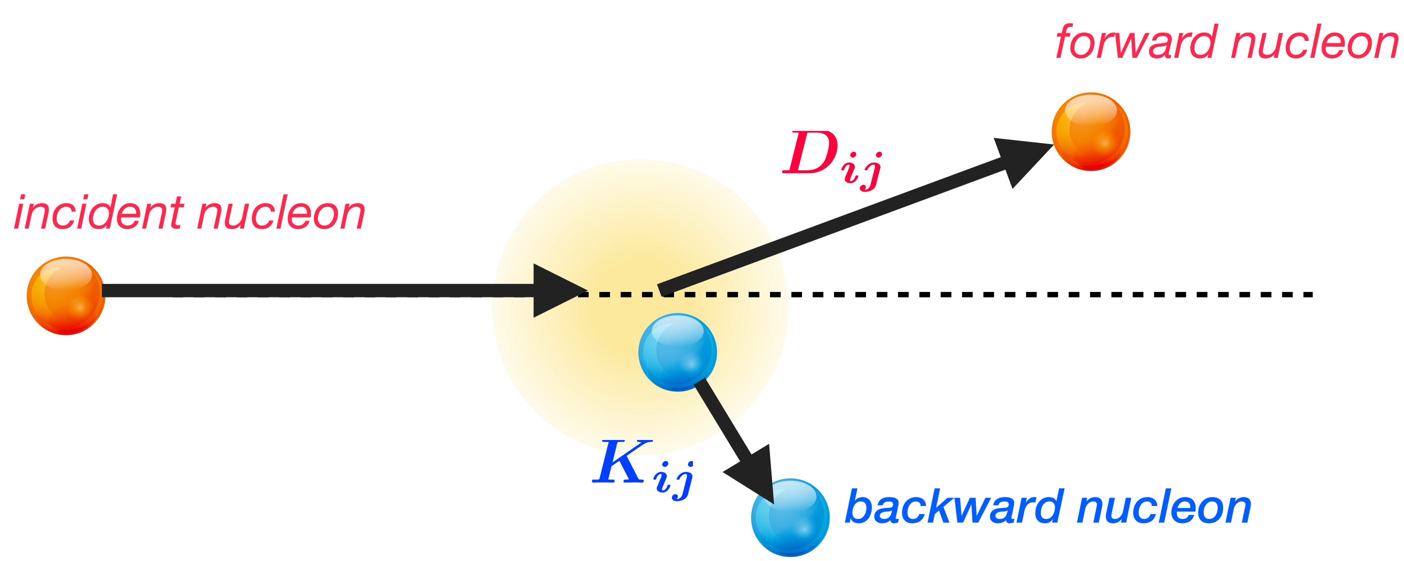
$$M(q) = A + B\sigma_{1\hat{n}}\sigma_{2\hat{n}} + C(\sigma_{1\hat{n}} + \sigma_{2\hat{n}}) + E\sigma_{1\hat{q}}\sigma_{2\hat{q}} + F\sigma_{1\hat{p}}\sigma_{2\hat{p}}$$

We neglect D-term for simplicity.

- 5 *complex* parameters
- 9 *real* parameters and 1 common phase → Need 9 independent observables
  - *We had only 6 observables (I, A_y=P, D_{qq}, D_{nn}, D_{pp}, D_{pq}=-D_{qp})*

We need another 3 observables

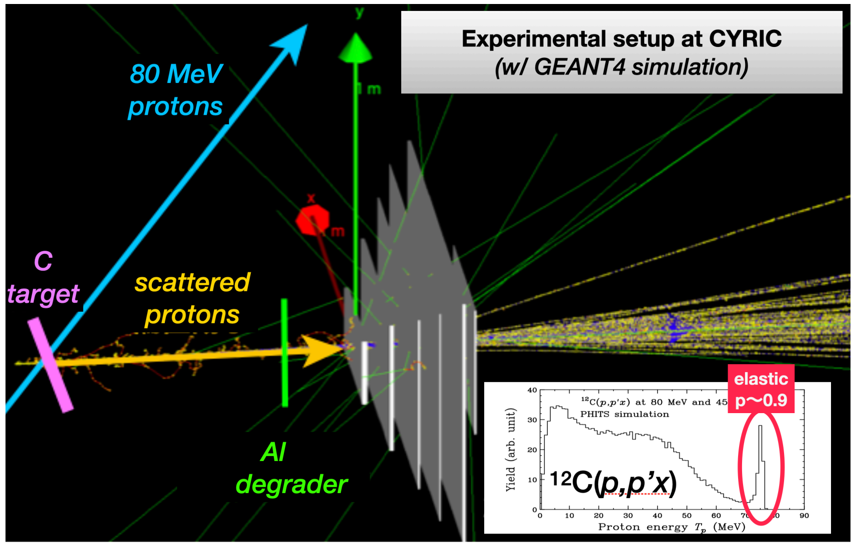
Spin transfer K_{ij} *to backward* particles



We can determine *in-medium 2NF (scatt. amps) experimentally* by measuring K_{ij} for (p,pN)

Towards an experimental determination of in-medium NN interactions

T. Noro, TW, et al., PTEP ptaa109 (2020).

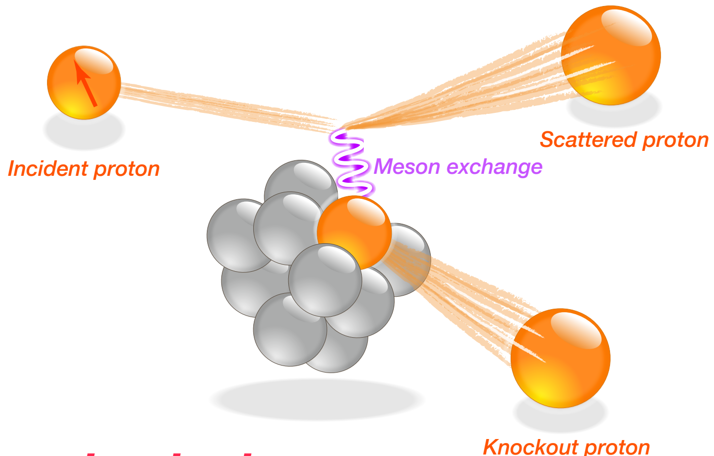


Development of the 2nd-FPP for K_{ij} measurements

- GEANT4 simulation with spin effects
- Improve the polarimeter efficiency with MWDCs

Testing the validity of theoretical treatments (DWIA)

High-quality exp. data at RCNP for *loosely-bound (ρ〜0) nucleons*



- Provide a solid basis to testing the validity of DWIA calculations
- We examined the reliability from two perspectives:

1. Reliability of the absolute values

- Spectroscopic factors (S-factors) are known from (e,e'p) data
  - *(p,pN) cross sections should be well reproduced by DWIA calculations*

2. Reliability of the spin observables

- Spin (Maris) effects are expected for l ≠ 0 orbits
  - *Ay data and j-dependence should be well reproduced with free NN interactions*

Low-energy proton polarimeter 2nd-FPP

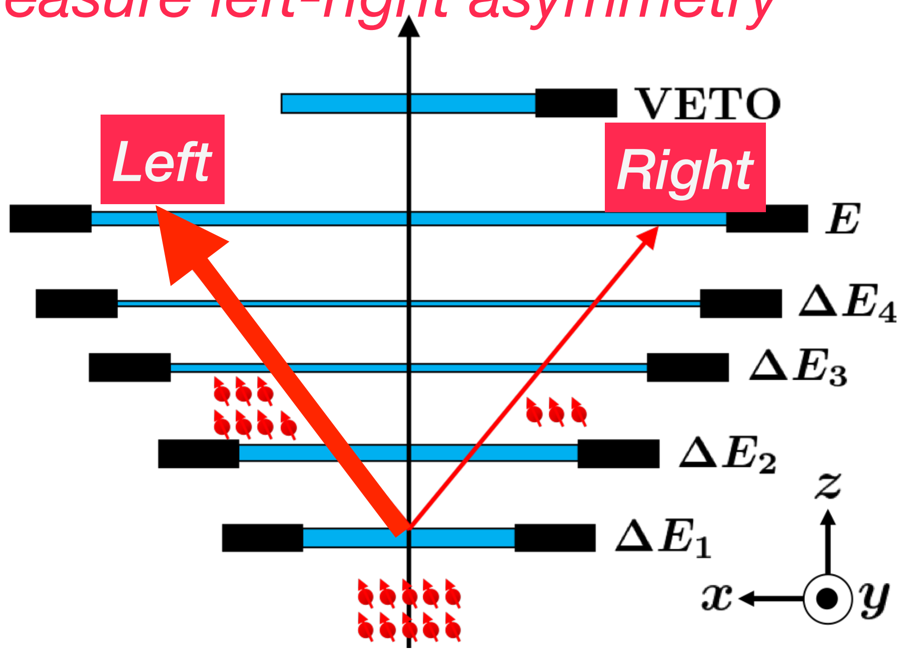
H,. Yoshida, Master thesis, Osaka Univ. (1998).

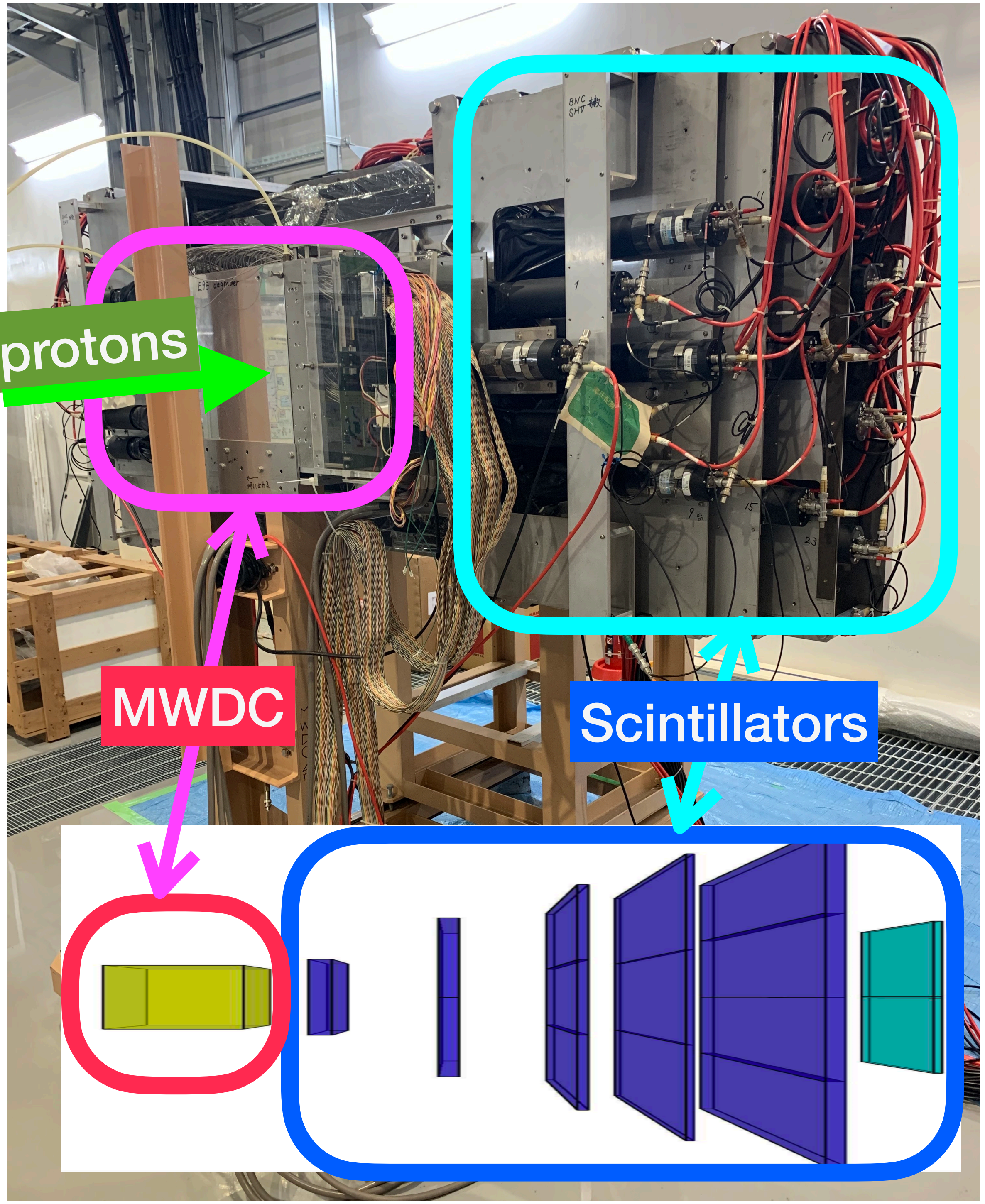
Focal Plane Polarimeter (FPP) for LAS; proton polarimeter for recoil protons

Use p-C scattering for polarimetry → ***suitable for K_{ij} at ∼80 MeV***

Configuration of 2nd-FPP

- MWDC
  - *Ray-tracking for incident proton*
- Scintillators (5 planes)
  - *Proton scatterer (Use p-C Ay for polarimetry)*
  - *Measure scattered proton energy*
    - *Select p-C events*
  - *Ray-tracking for scattered proton*
    - *Measure left-right asymmetry*





Upgrade of 2nd-FPP: ***Add MWDCs for better resolution and higher FOM (efficiency)***

GEANT4 simulation with spin effects

D. Inomoto, Master thesis, Kyushu Univ. (2020).
H. Jeong et al., PoS(PSTP2017)027.

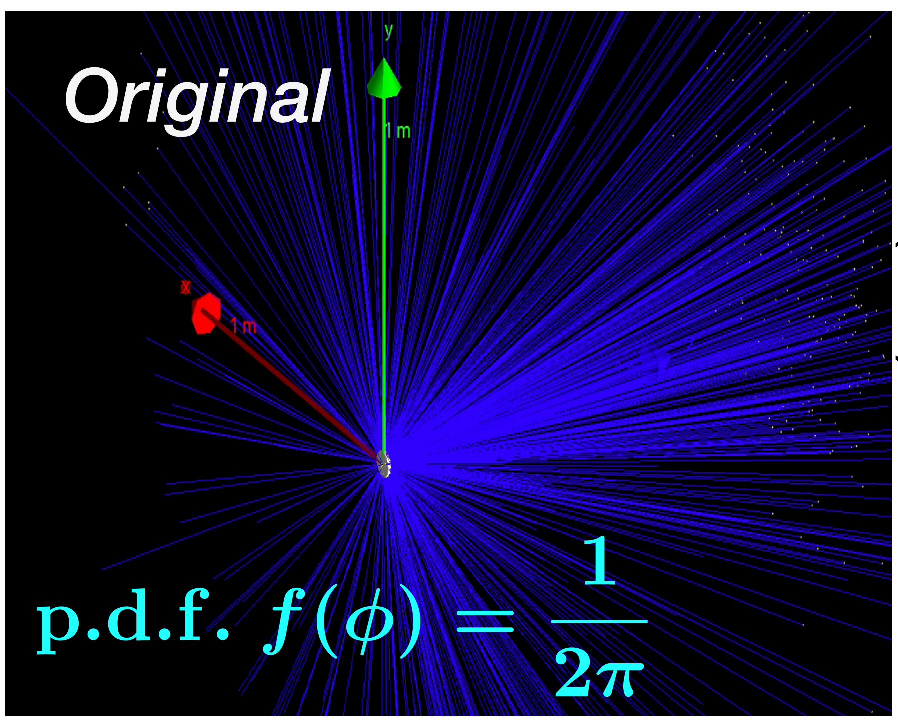
Original GEANT4 (10.5) :

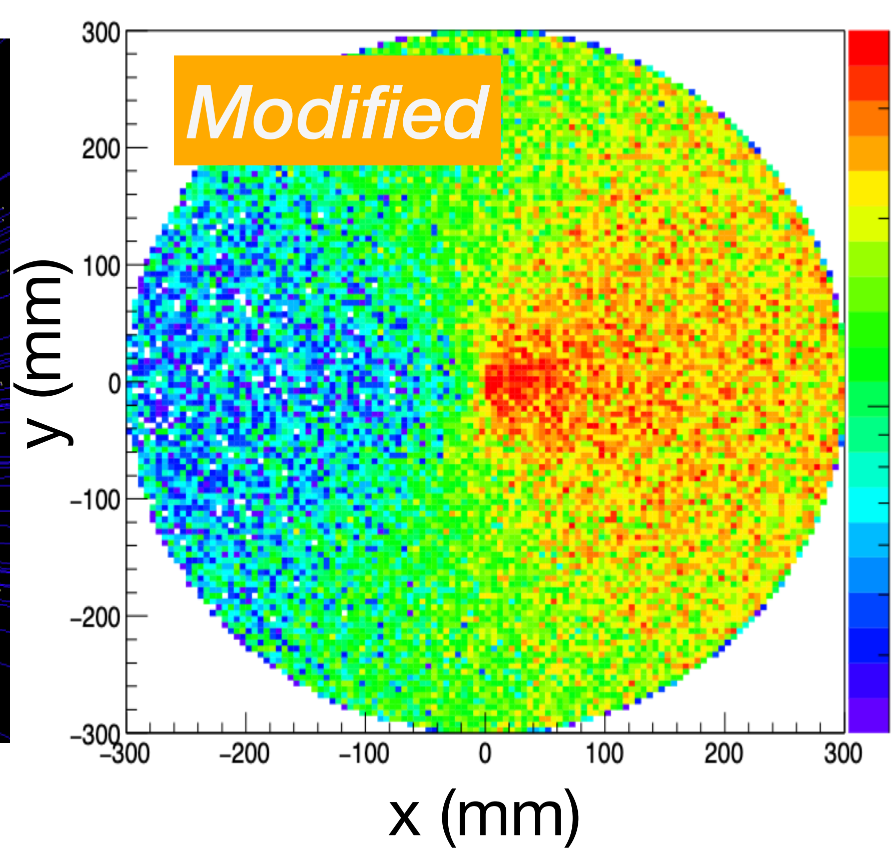
- The cross section of p-C scattering : Comparable with experimental data
- NOT consider spin effects in hadronic interactions. → **NO spin effects**
  - ***Azimuth angle ϕ : Uniformly distributed random number in [0,2π]***

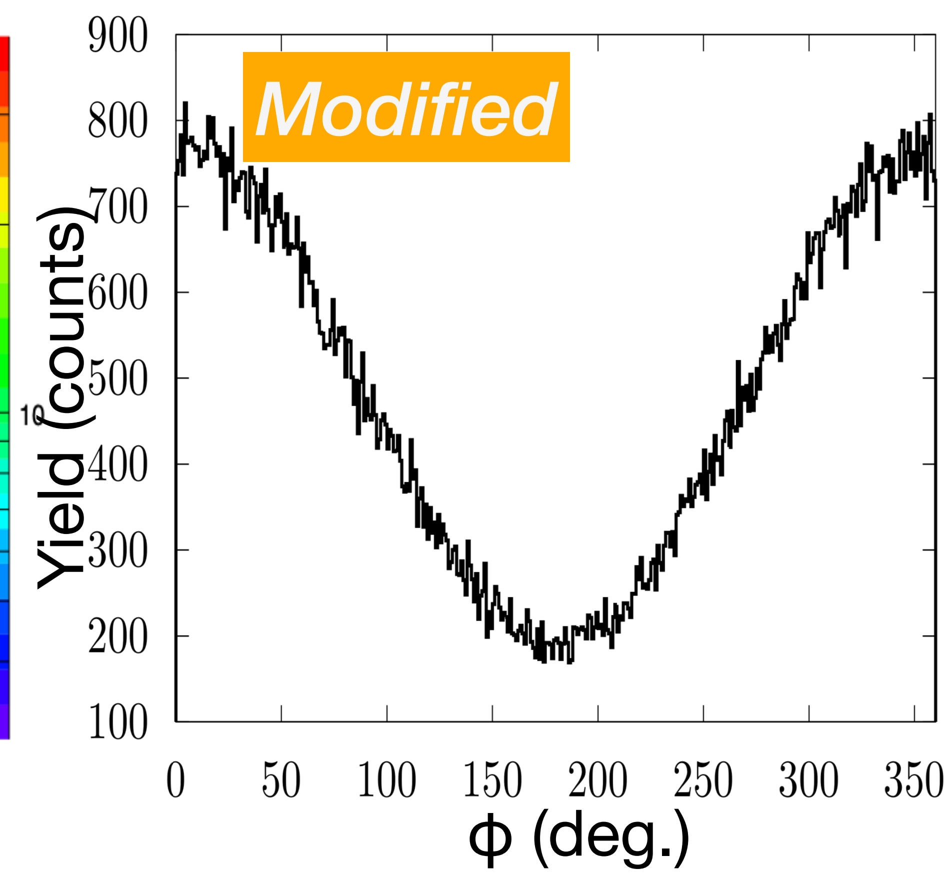
Modified ϕ generator with non-uniform spin effects

$$\mathrm{p.d.f.}\ f(\phi; p, A_y) \propto 1 + p\, A_y \cos\phi$$

p : *proton polarization*
A_y : *p-C analyzing power*







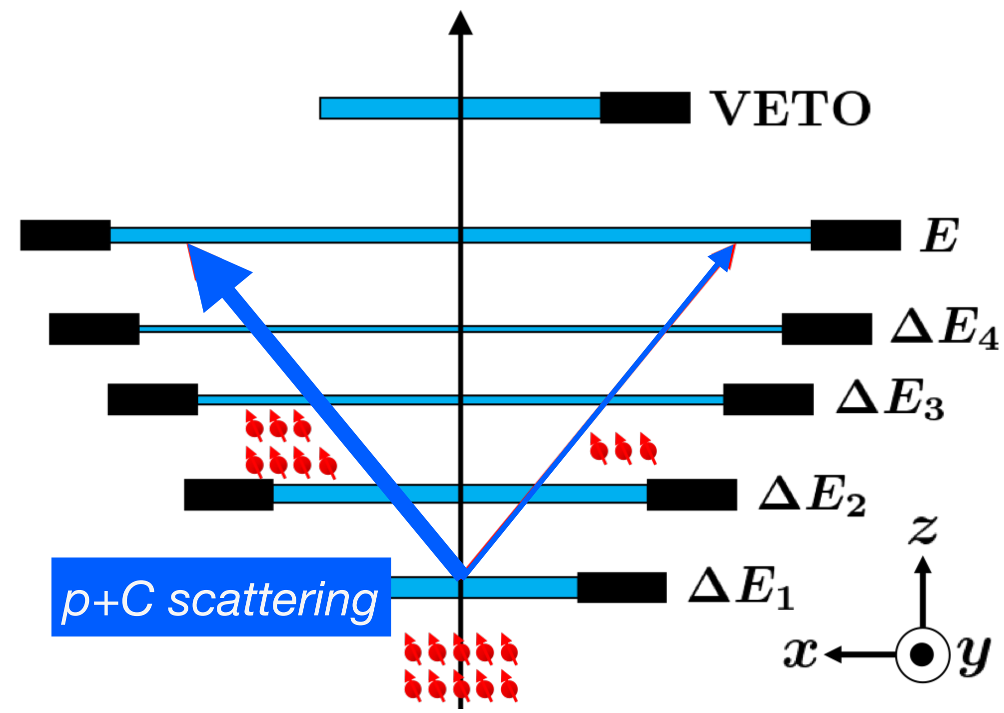
Left-right asymmetry and ϕ-dependence are successfully generated as spin effects.

Simulation for 2nd-FPP

GEANT4 simulation for 2nd-FPP with spin effects

D. Inomoto, Master thesis, Kyushu Univ. (2020).

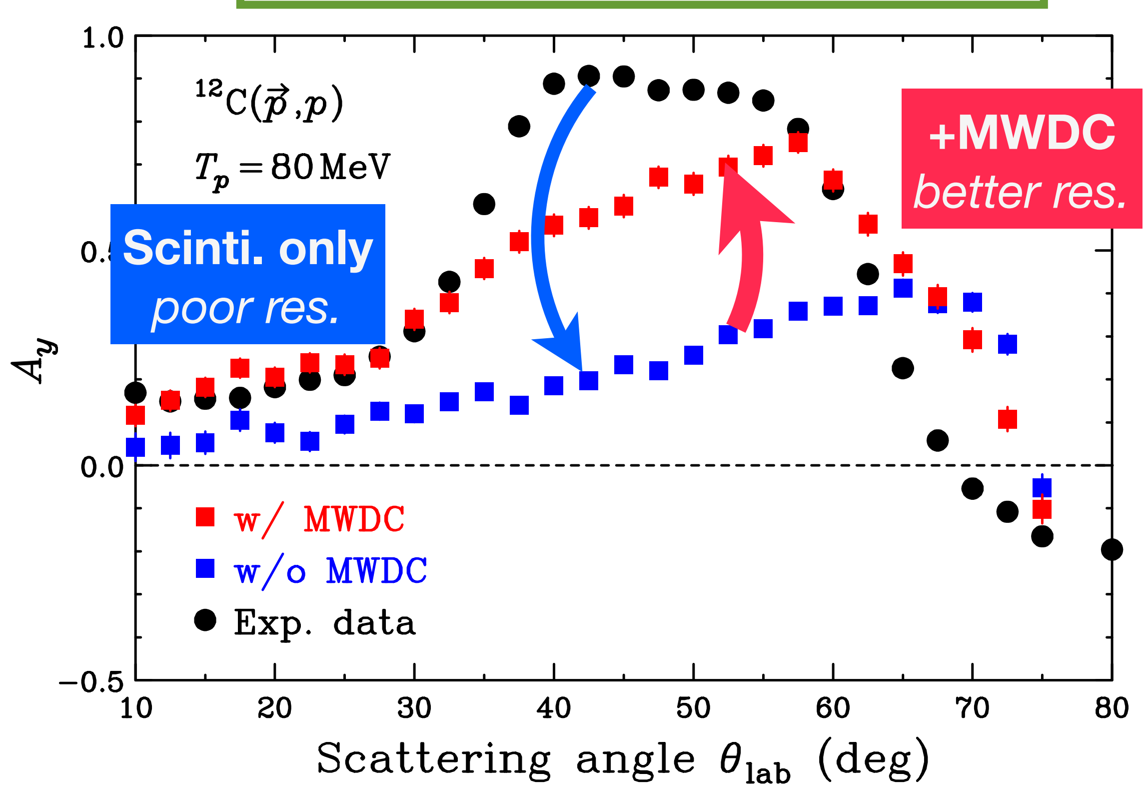
- Polarimetry : p-C scattering in a scintillator
- Implement exp. Ay data at 20-84 MeV
  - *M. Ieiri et al., NIMA 257, 253 (1987).*



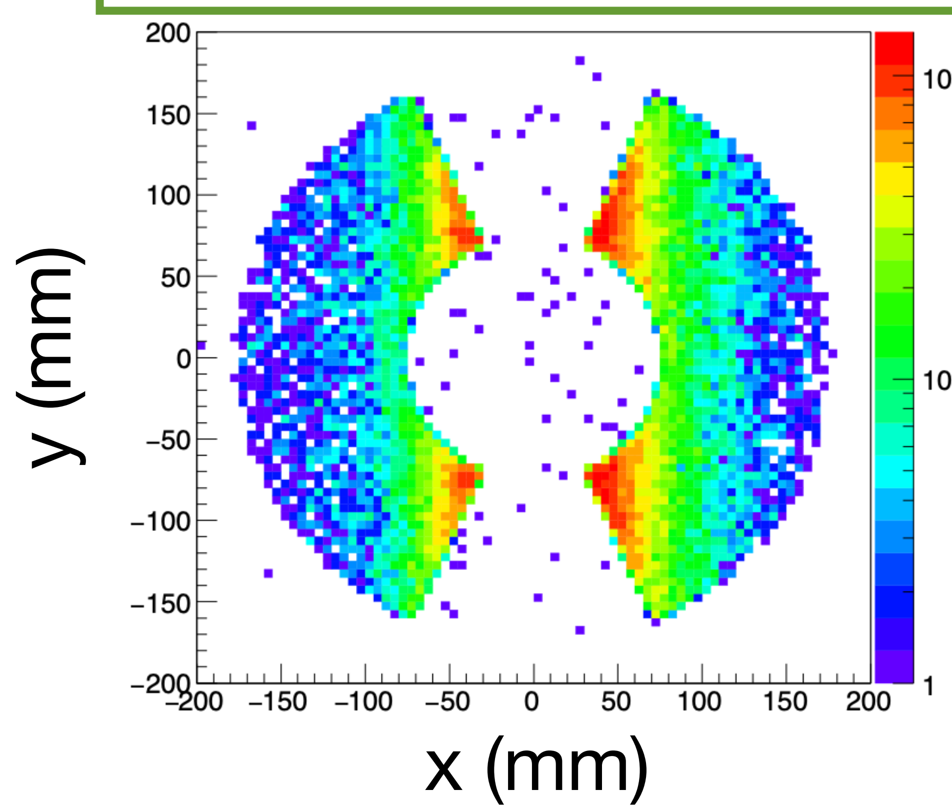
Results

- Better resolution with MWDC :
  - Increase the Ay by 100% (×2)
  - Increase the FOM by 200% (×3)

Ay simulation for 2nd-FPP

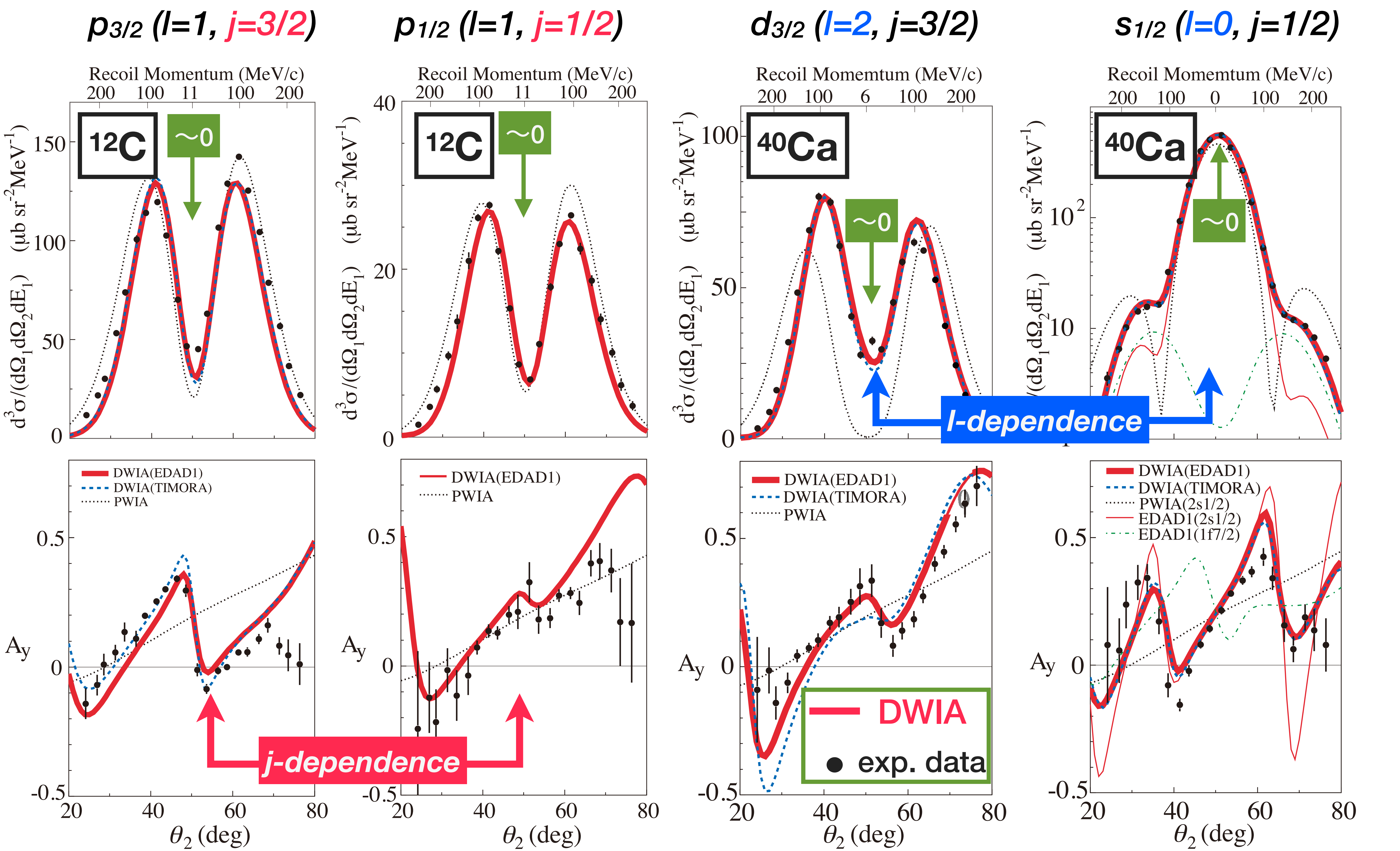


Left-right asymmetry for p-C



Experimental data for various targets/orbits

T. Noro, TW, et al., PTEP ptaa109 (2020).

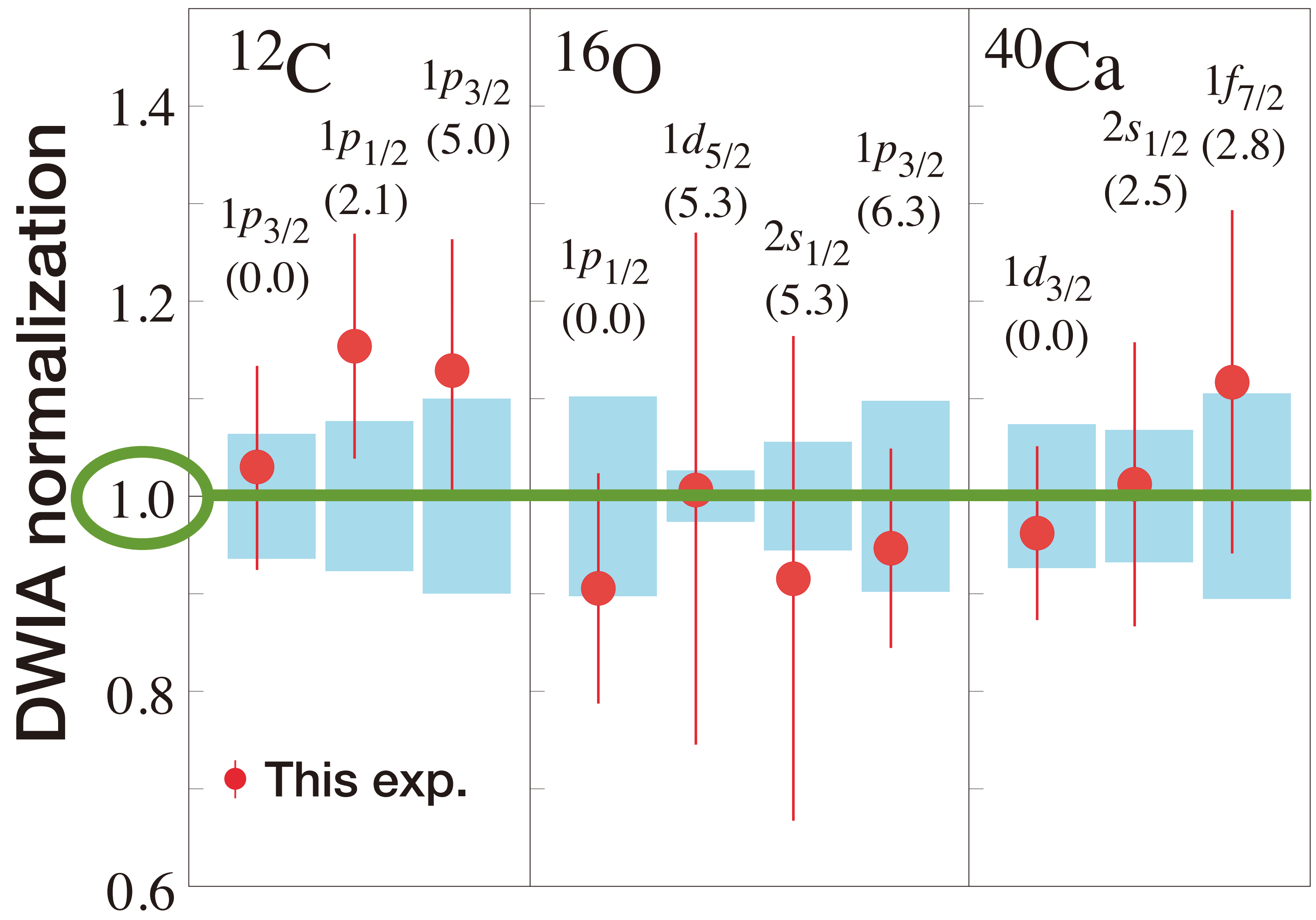


Both σ and Ay data are reasonably reproduced by DWIA with free NN interactions

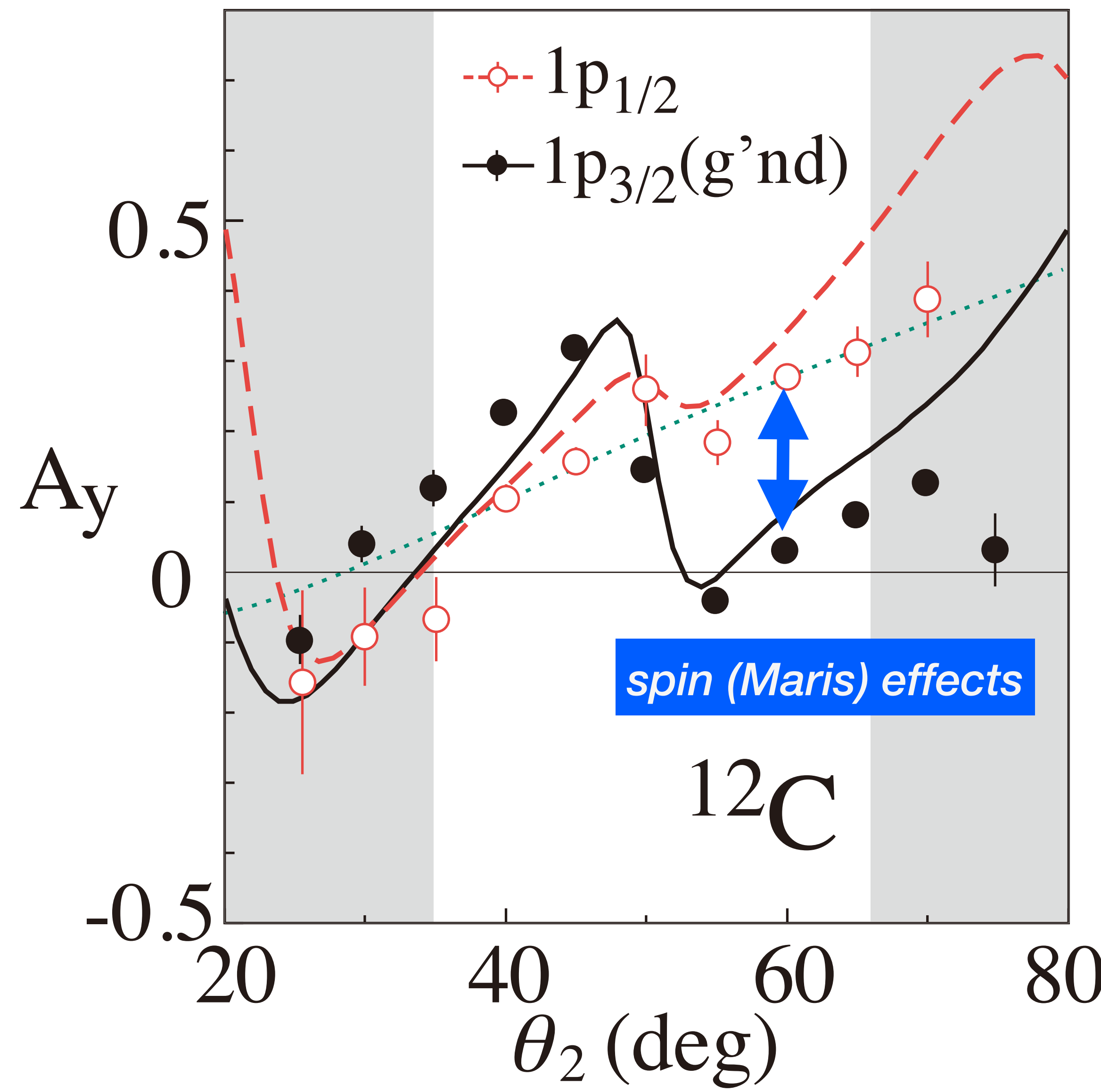
Reliability of DWIA calculations at 400 MeV

T. Noro, TW, et al., PTEP ptaa109 (2020).

Absolute values for cross sections



Spin effects on Ay



Reproduce the absolute values with 15% deviations
[(e,e'p) have similar uncertainties shown by blue.]

Differences b/w $J_>=3/2$ and $J_<=1/2$ are reasonably reproduced.

Nuclear medium effects by (e,e')

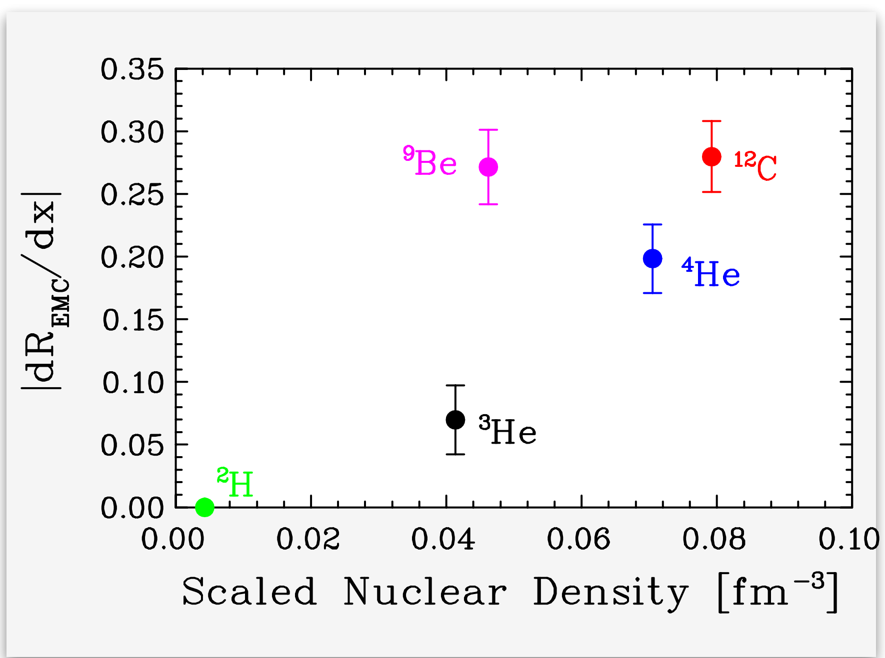
J. Seely et al., Phys. Rev. Lett. 103, 202301 (2009).
N. Famine et al., Phys. Rev. Lett. 108, 092502 (2012).

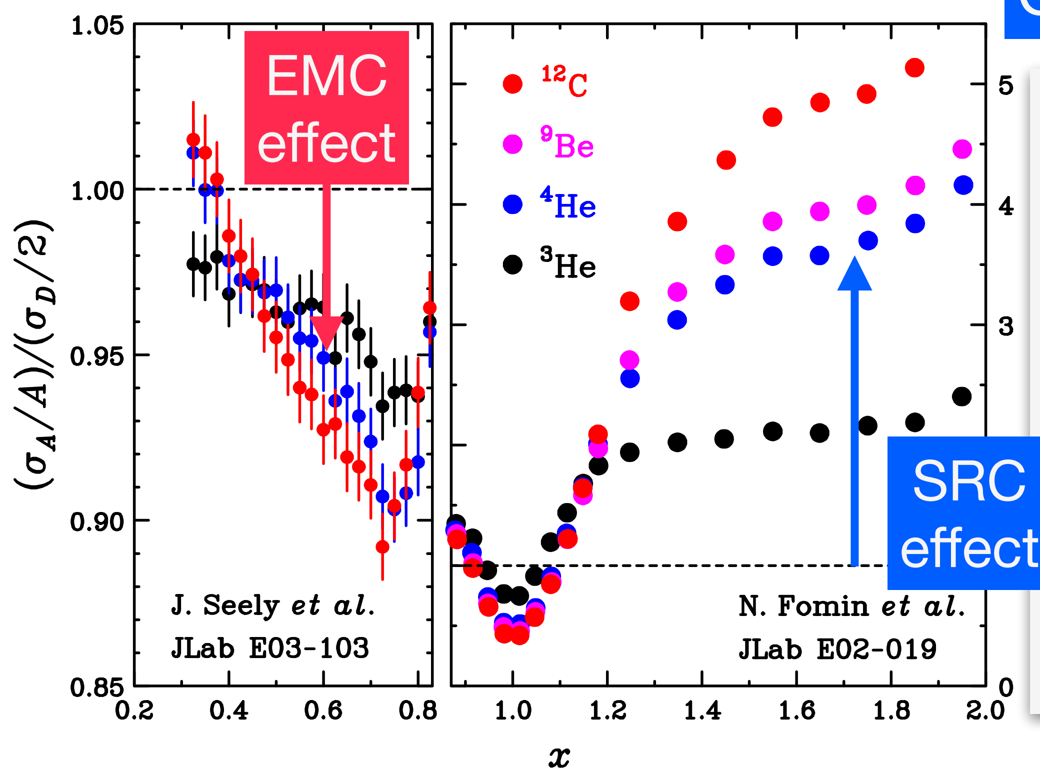
EMC and SRC effects observed by (e,e') at Lab

Cross section (per nucleon) ratio: $R_{EMC} = (\sigma_A/A)/(\sigma_D/2)$

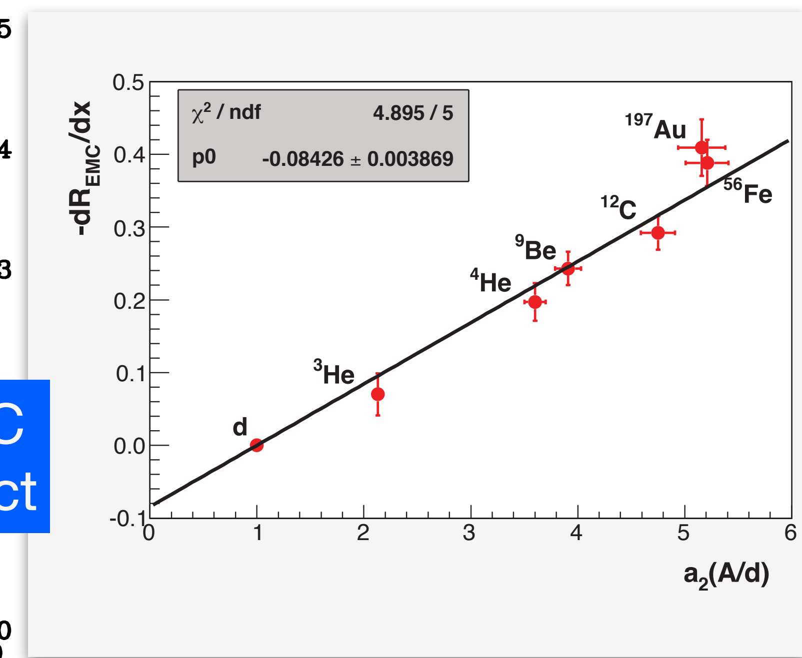
- EMC effect : Reduction from unity at x～0.6 (measured by slope $-dE_{EMC}/dx$)
- SRC effect : Enhancement from unity at x～1.7 (measured by ratio at plateau $a_2(A/d)$)

Density dep. of EMC effect





Corr. b/w EMC&SRC effects



O. Hen et al, PRC 85, 047301 (2012).

EMC effect is proportional to nuclear density ***except for ^{9}Be***

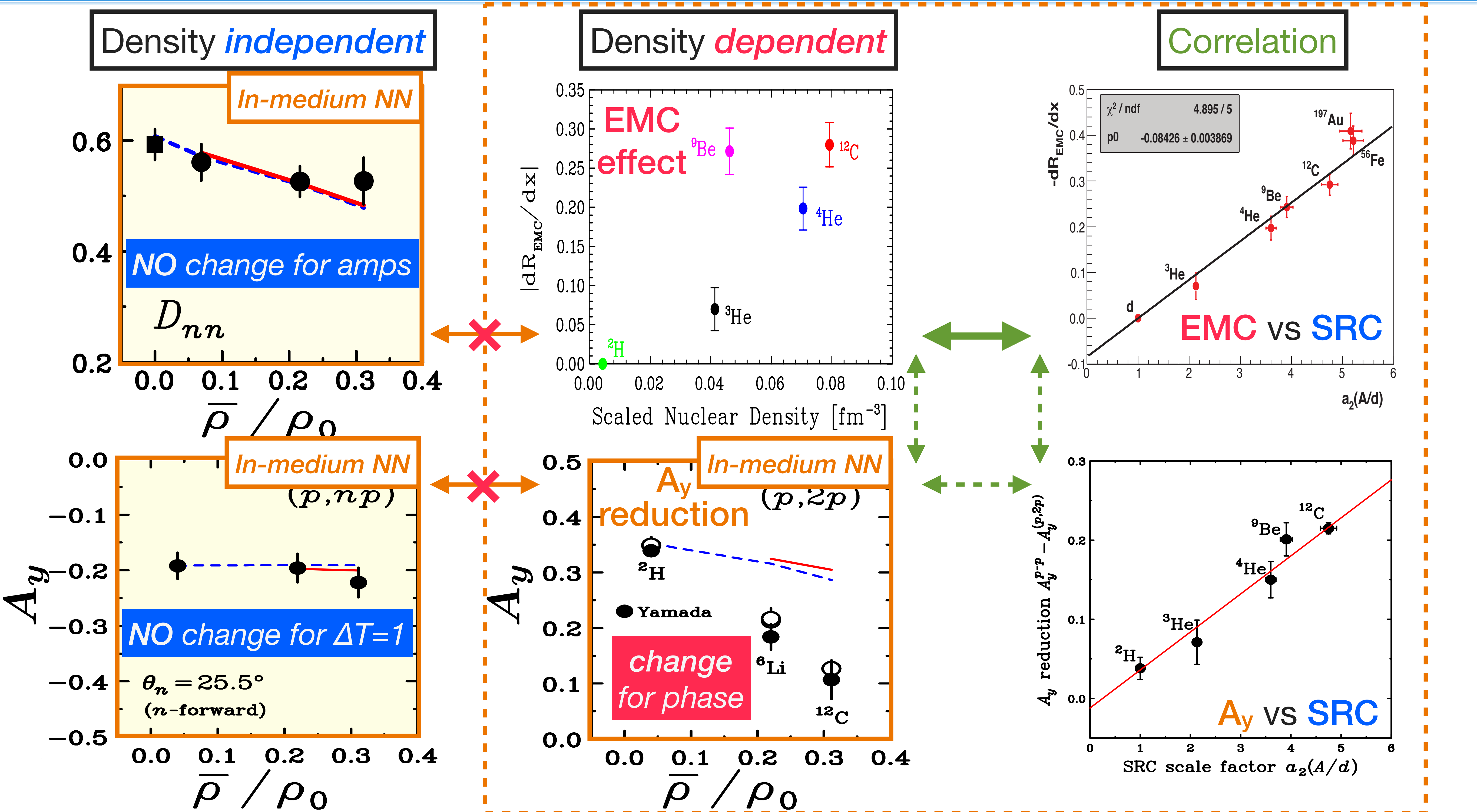
- EMC effect is proportional to "local" density (NOT average density)

SRC effect is proportional to EMC effect ***including ^{9}Be***

- SRC pairs (p-n by tensor force) are modified and cause EMC effects?

How about NN force? (mean-field N's)

Summary of nuclear medium effects



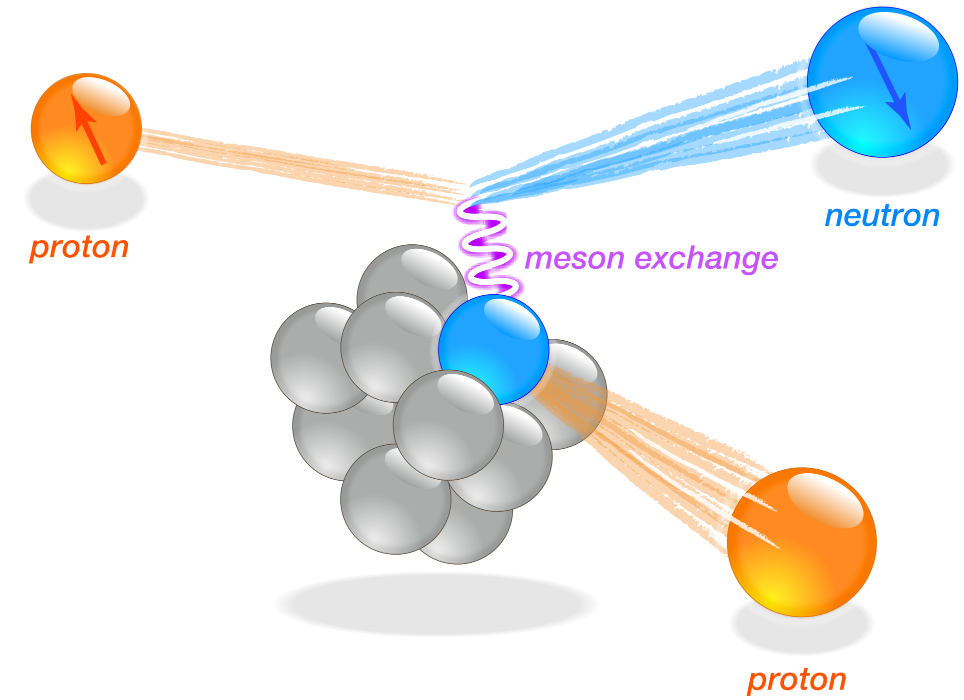
A_y reduction at p_B〜0 suggests ***"limited" nuclear medium effects for mean-field nucleons***

- NOT change the amplitudes but *affect the relative phase* (interference effects on A_y)
- NOT change for p-n (ΔT=1) but *affect for p-p (ΔT=0)*

model handling the effects consistently

Summary (1/2)

Nuclear medium effects on NN interaction



Nuclear interior can be seen through $1s_{1/2}$ knockout

- A_y for p-p : *density-dependent reduction*
- A_y for n-p : No effect → *isospin dependence*
- D_{ij} for p-p : No effect → *limited to relative phase*

Simple Brown-Rho scaling conjecture does not work

Spin-transfer K_{ij} are useful/important for experimental determination of in-medium 2NF

Testing the validity of theoretical treatments (DWIA) for loosely-bound orbits

Good-quality data including Ay have been measured at RCNP

- DWIA with free NN int. ***reproduce the absolute cross sections*** within 15% uncertainty
- ***Spin (Maris) effect has been well reproduced*** by DWIA

DWIA analyses are reliable to pin down the nuclear medium effects on NN interactions

Summary (2/2)

Development of the 2nd-FPP for K_{ij} measurements

Modified GEANT4 : *Realize the spin-dependent scattering*

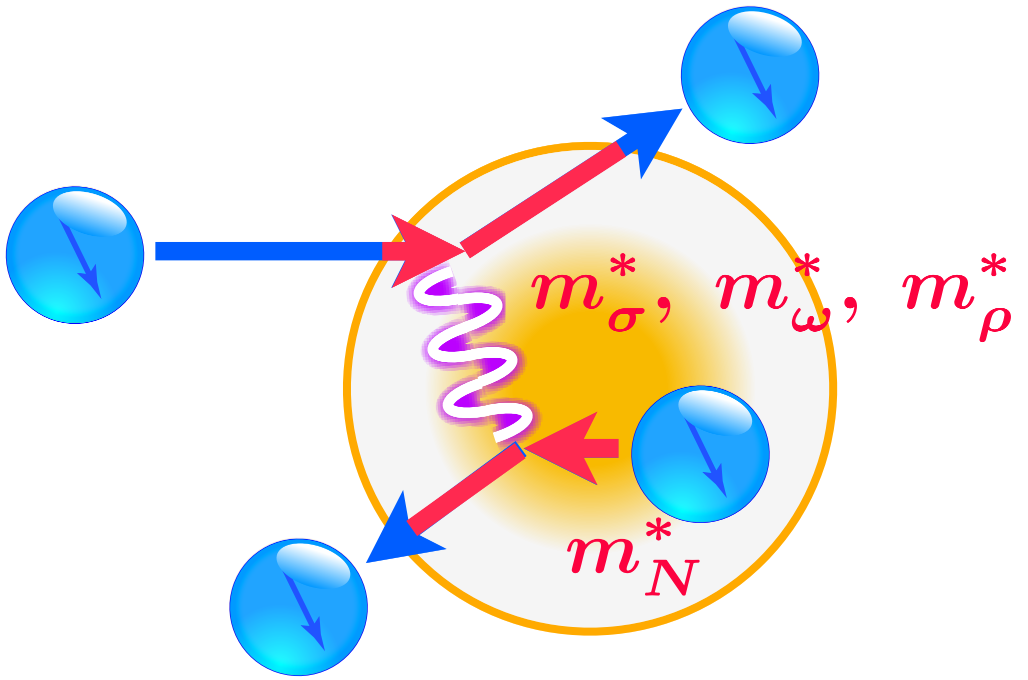
- Polarimeter performance ($A_{y;eff}$ and FOM) can be investigated by simulations
- Better resolution with MWDCs : ***Increase the FOM (performance) by 200% (×3)***

Calibration of 2nd-FPP : *Performed at CYRIC in this October*

Measurement of K_{ij}

Performed at RCNP after the accelerator upgrade

- In-medium 2NFs (scattering amplitudes) ***can be determined experimentally***



Theoretical/experimental challenges

Consistent understanding for 3NF and in-medium 2NF

- *4-body calculations for ^{3}He(p,2p) and ^{3}He(p,np) and their new data would be useful*

Unified understanding for medium effects on 2NF and EMC/SRC effects

D_{ij} and K_{ij} measurements for (p,pn) *for understanding isospin-dependence*