核力の媒質効果と３体核力を含む核力の精密化

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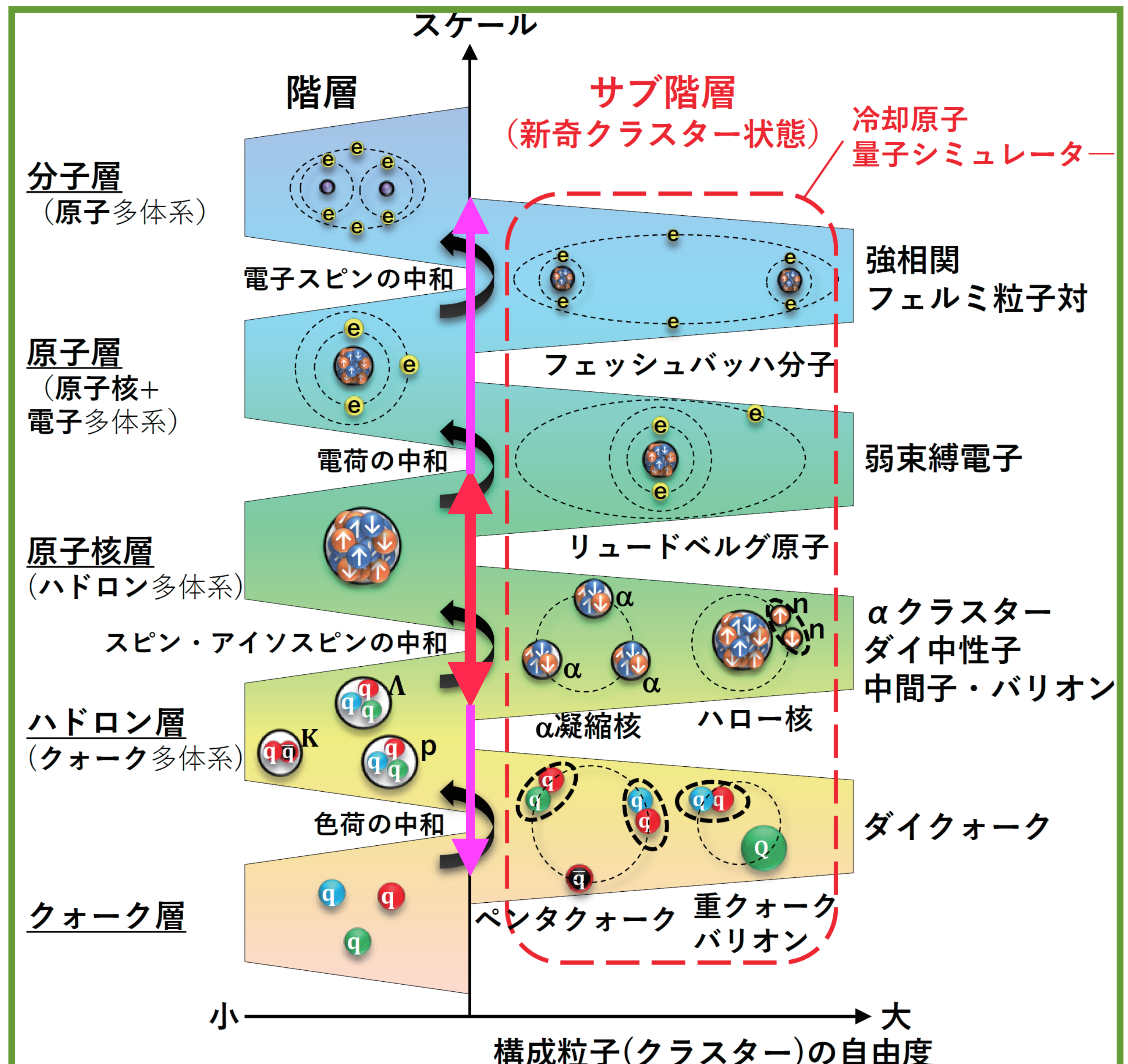
B02：エキゾチック核子多体系で紐解く物質の階層構造

原子核層の「サブ階層・多中性子クラスター」と階層をつなぐ鍵を握る「３体核力」の研究

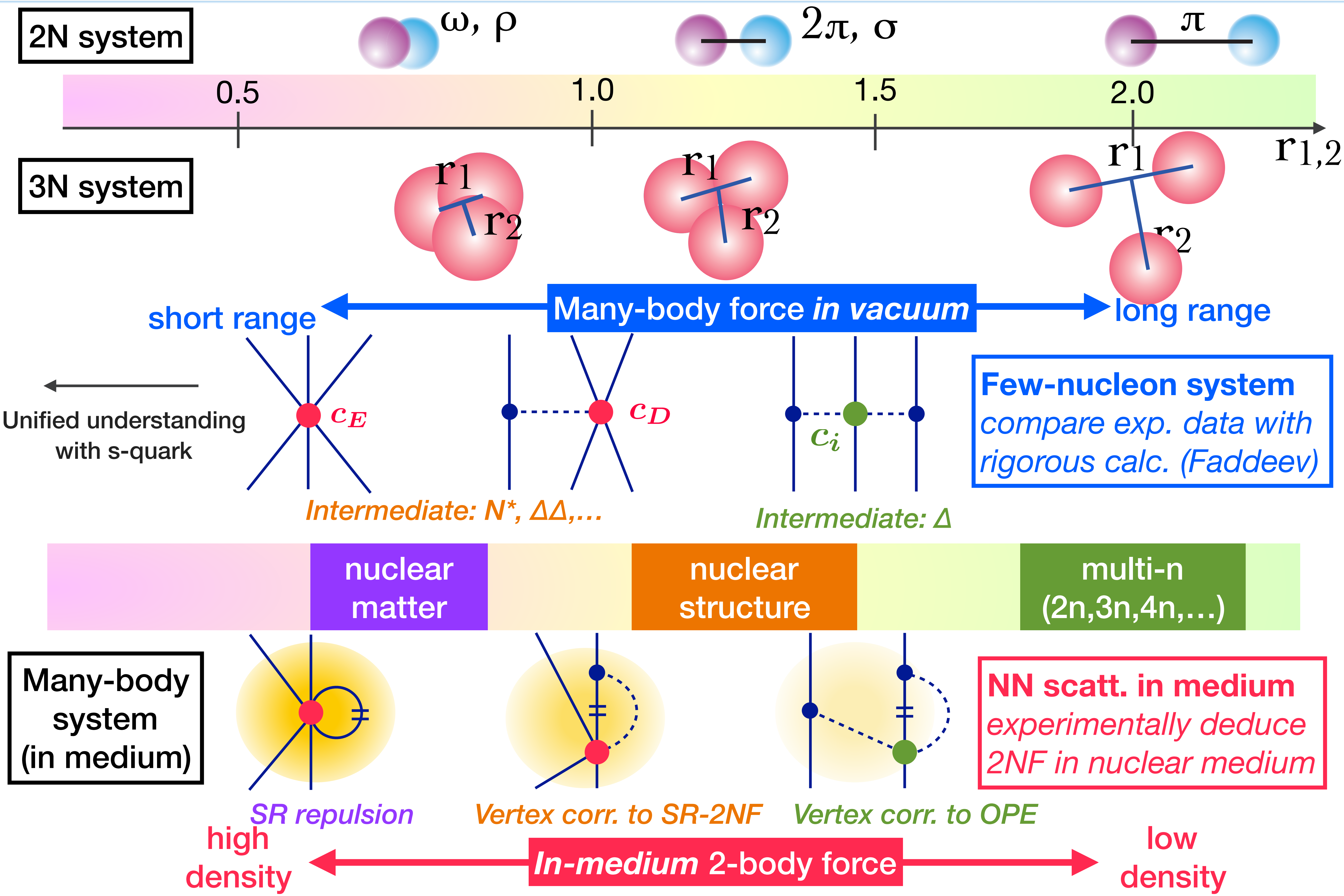
多中性子クラスターの研究（中村・近藤）

３体核力の研究（関口・若狭）⇒ **「力」の研究**

- 核子多体系における「多体力（３体核力）」「多体効果（核媒質効果）」
  - 多体系固有の力の理解の深化
    ⇒ 階層構造形成のメカニズム解明へ
  - ２つの視点（アプローチ）
    ⇒ 第一原理的・統一的理解、普遍性
- 核子自身がクラスター（色荷の中和）であることに起因
  - ハドロン層と原子核層を結ぶ
    ⇒ クォークから核力を理解する

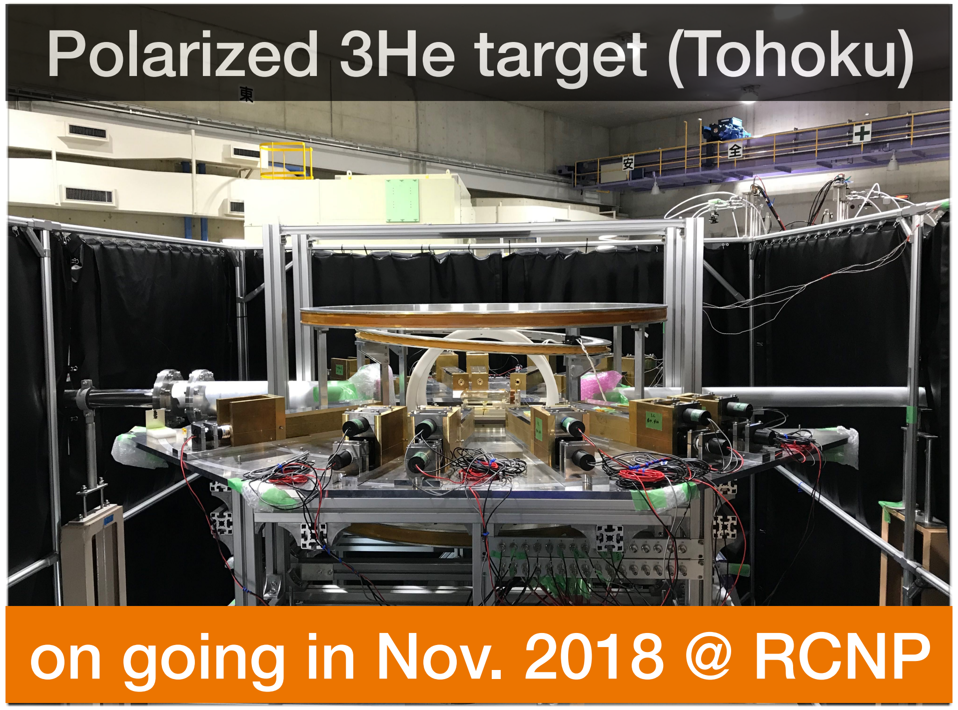


Bridge nuclear/hadron hierarchies &
Deeper understanding of nuclear system/hierarchy



Three nucleon force effects in few-nucleon systems

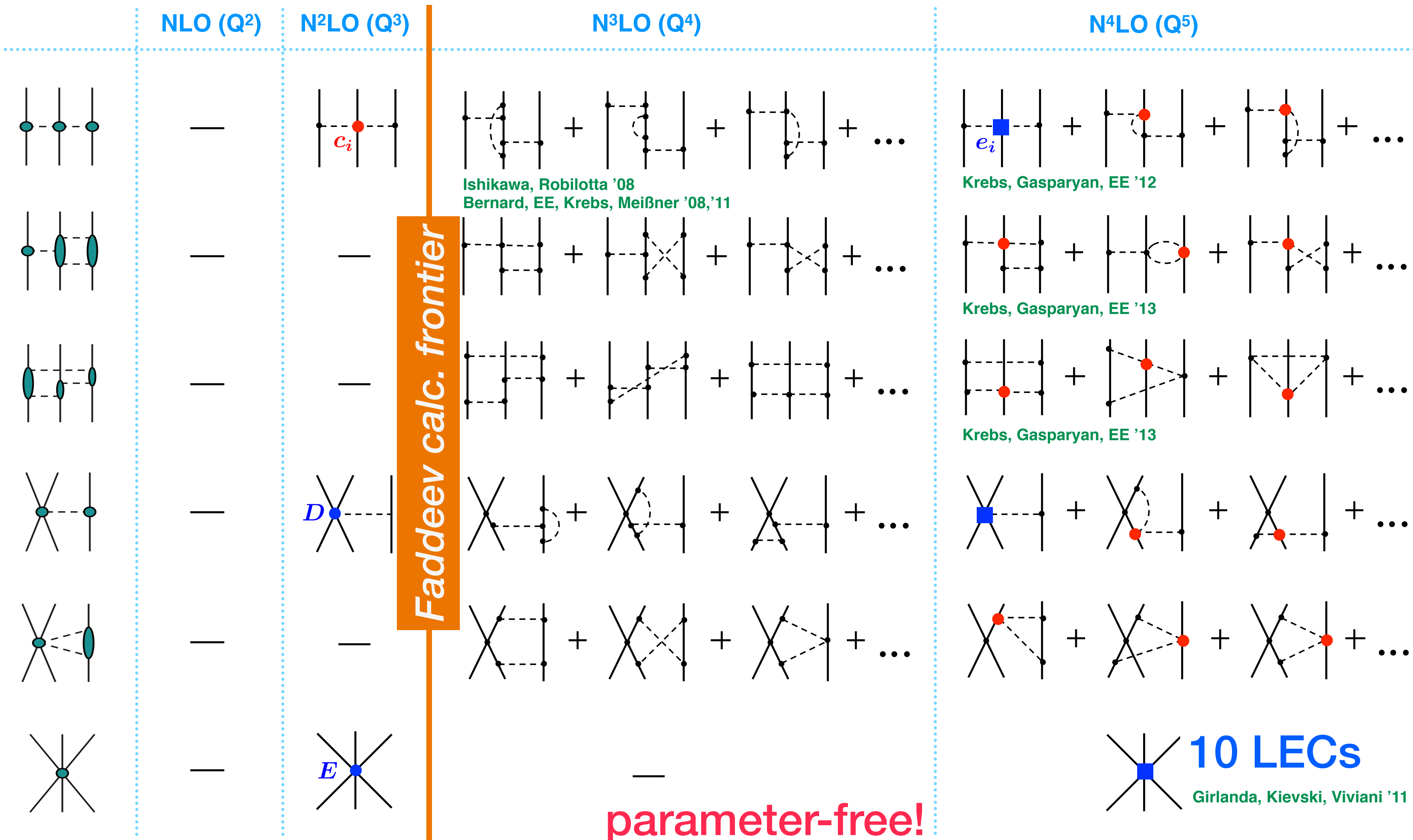
Current status and planning research



Frontiers & challenges for the future

Chiral expansion of 3NF

- N^2LO (Q^3): 2 LECs: ^3H B.E. and N-d c.s. at 70 MeV → Could not explain exp. data
- N^3LO (Q^4): parameter-free, but large N^4LO contributions by Δ is expected
- N^4LO (Q^5): new 10 LECs
  - Need *high-precision N-d scattering data* in wide energy region→T=1/2 only
  - ***Exp. data for T=3/2 3NF are highly required***



Faddeev calc. for scattering states is limited up to N^2LO

E. Epelbaum. presentation in IHEP, Peking (2014).

p+^{3}He scattering and T=3/2 3NFs

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

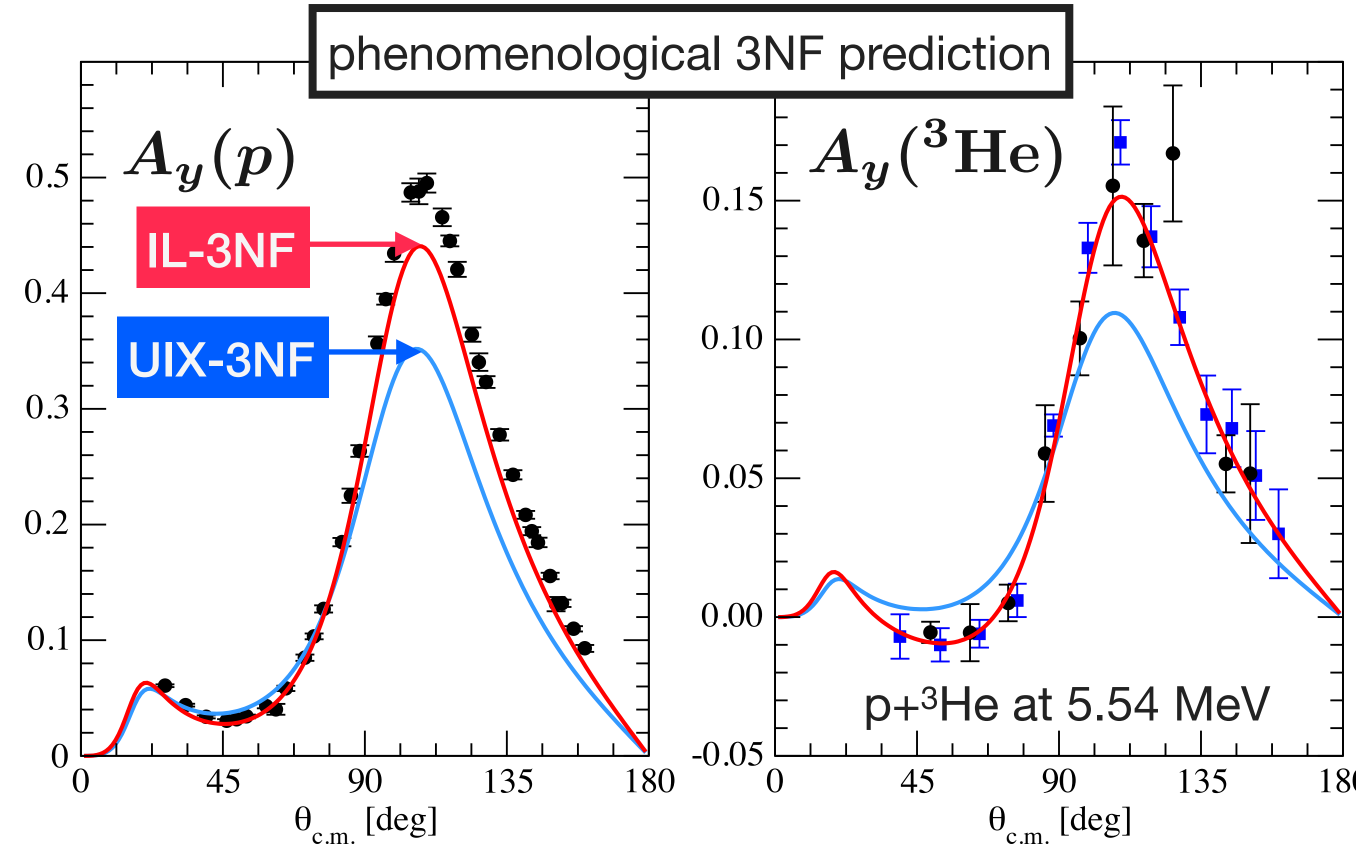
Pisa Gr. succeeds in 4-body calc.

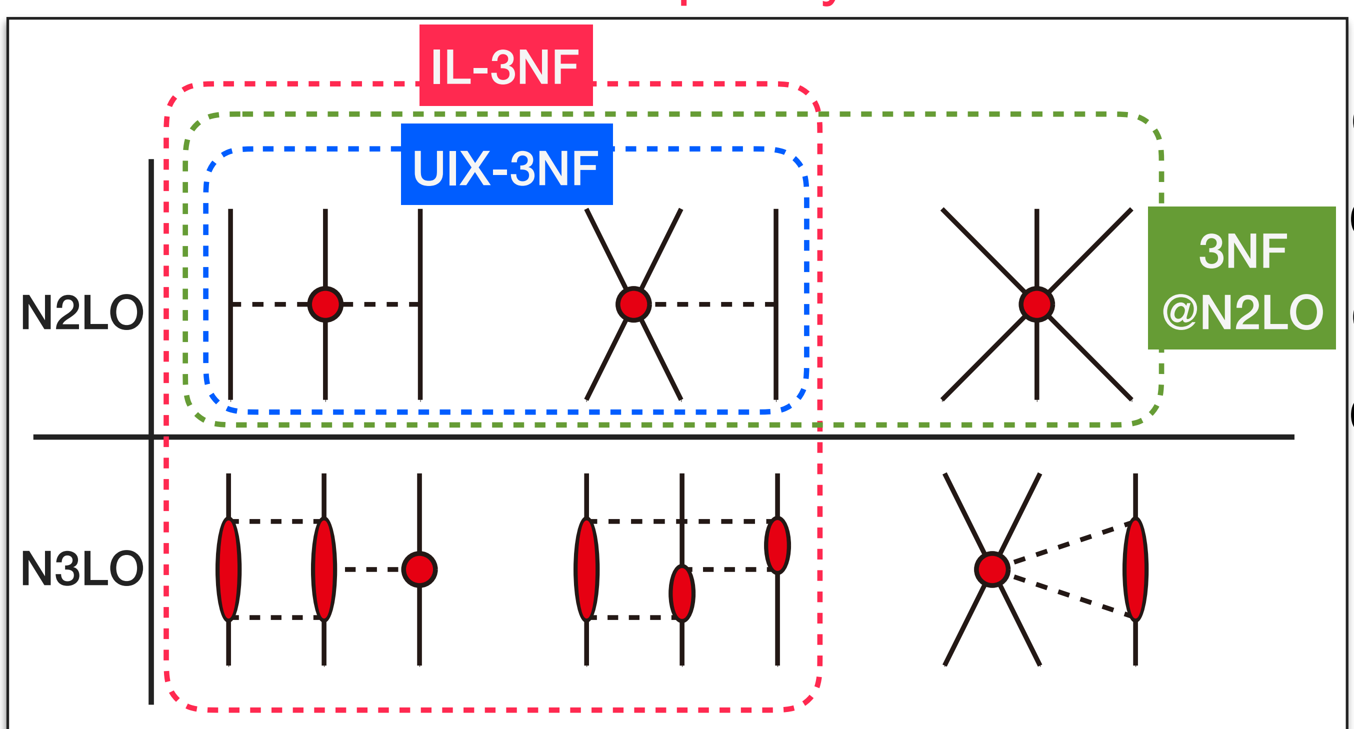
AV18 + UIX/IL 3NF

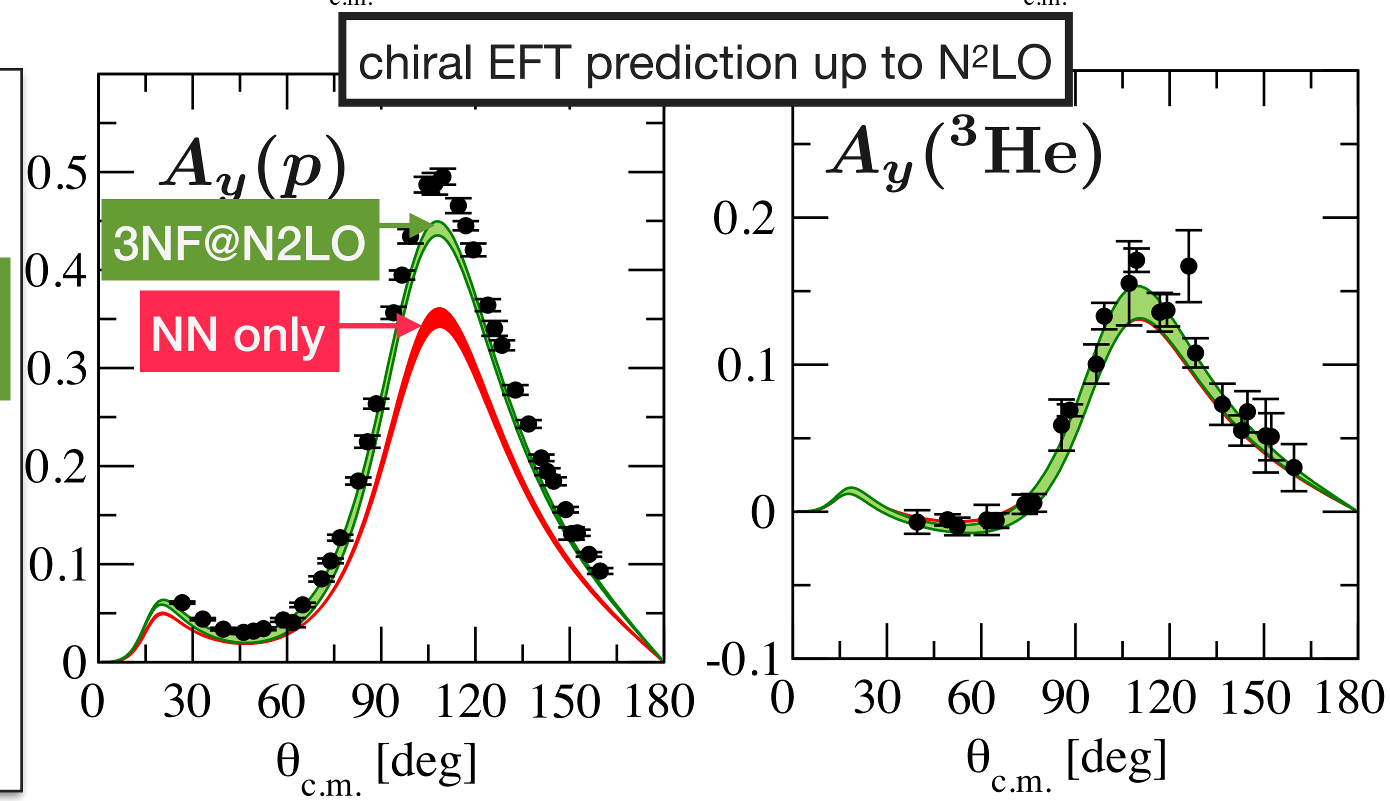
- Difference b/w UIX and IL predictions
- importance of 3π-ring with Δ in IL-3NF

chiEFT (3NF@N^{2}LO)

- 3NF plays an important role, but is insufficient
- 3π-ring terms @ N^{3}LO would resolve the discrepancy







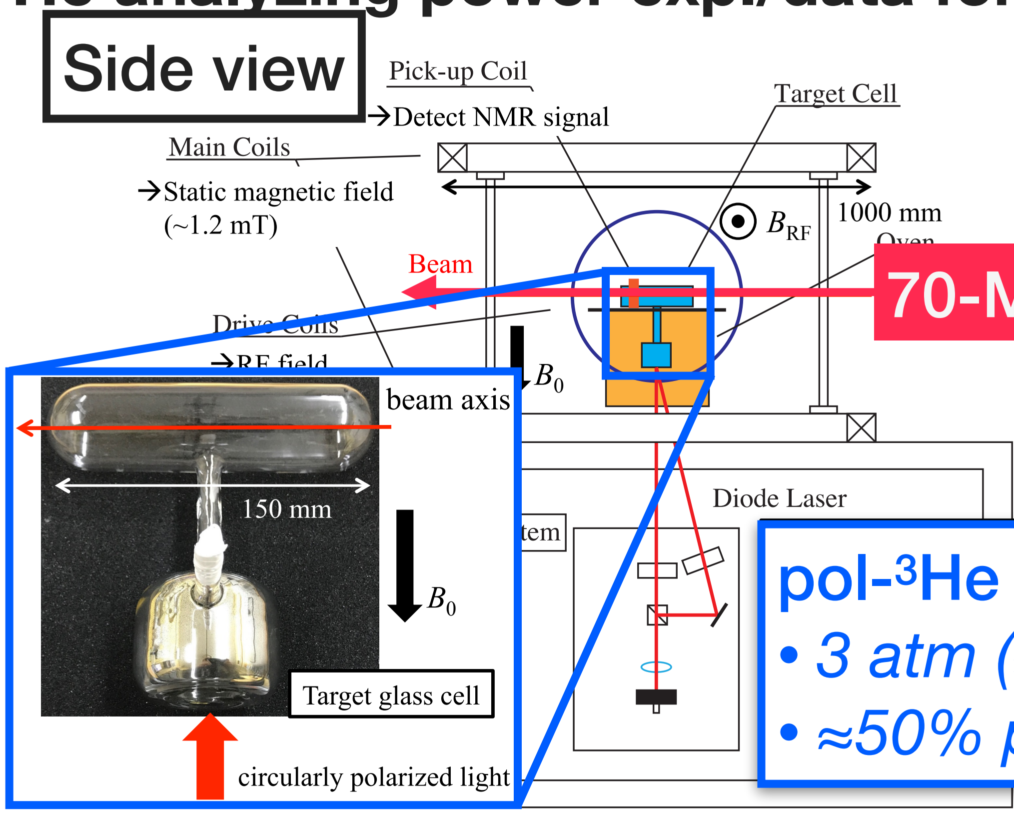
Now, it is interesting to study at higher energies for pol. observables with high accuracy!

p-^{3}He A_y data at 70 MeV

New exp. at 100 MeV is now in progress at RCNP

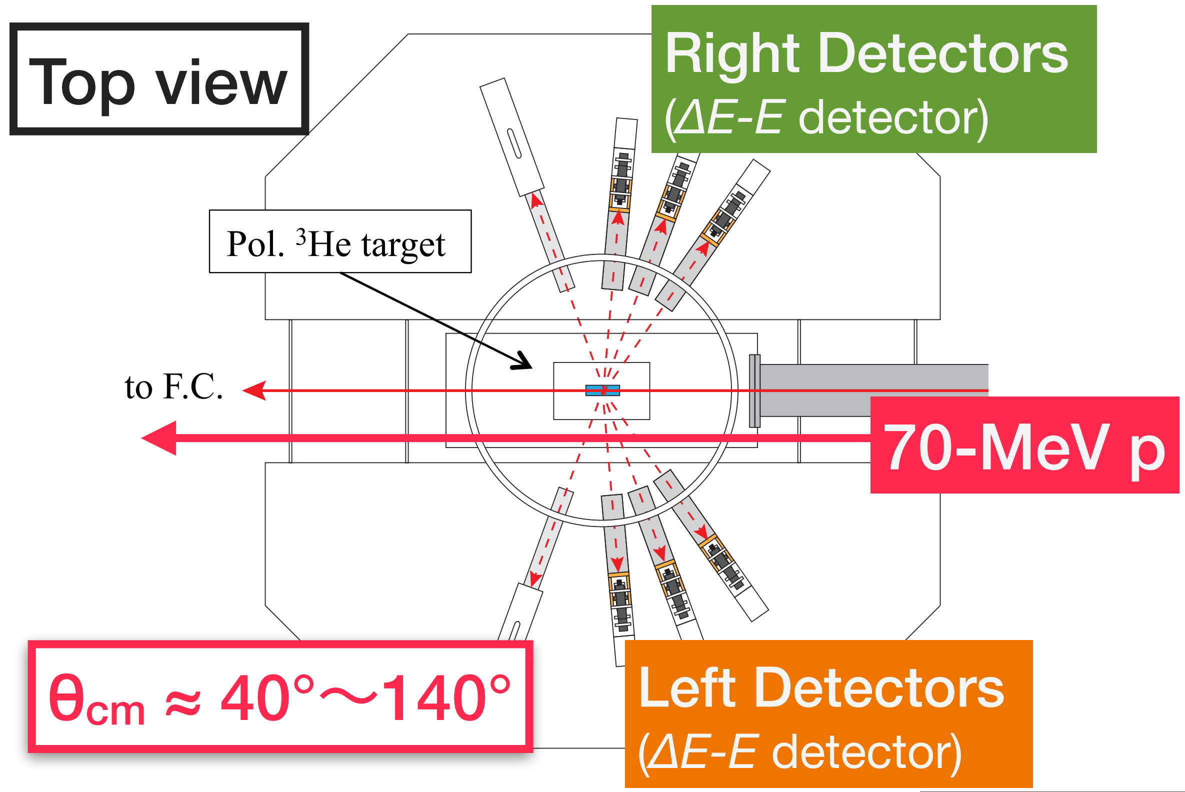
courtesy of A. Watanabe and K. Sekiguchi

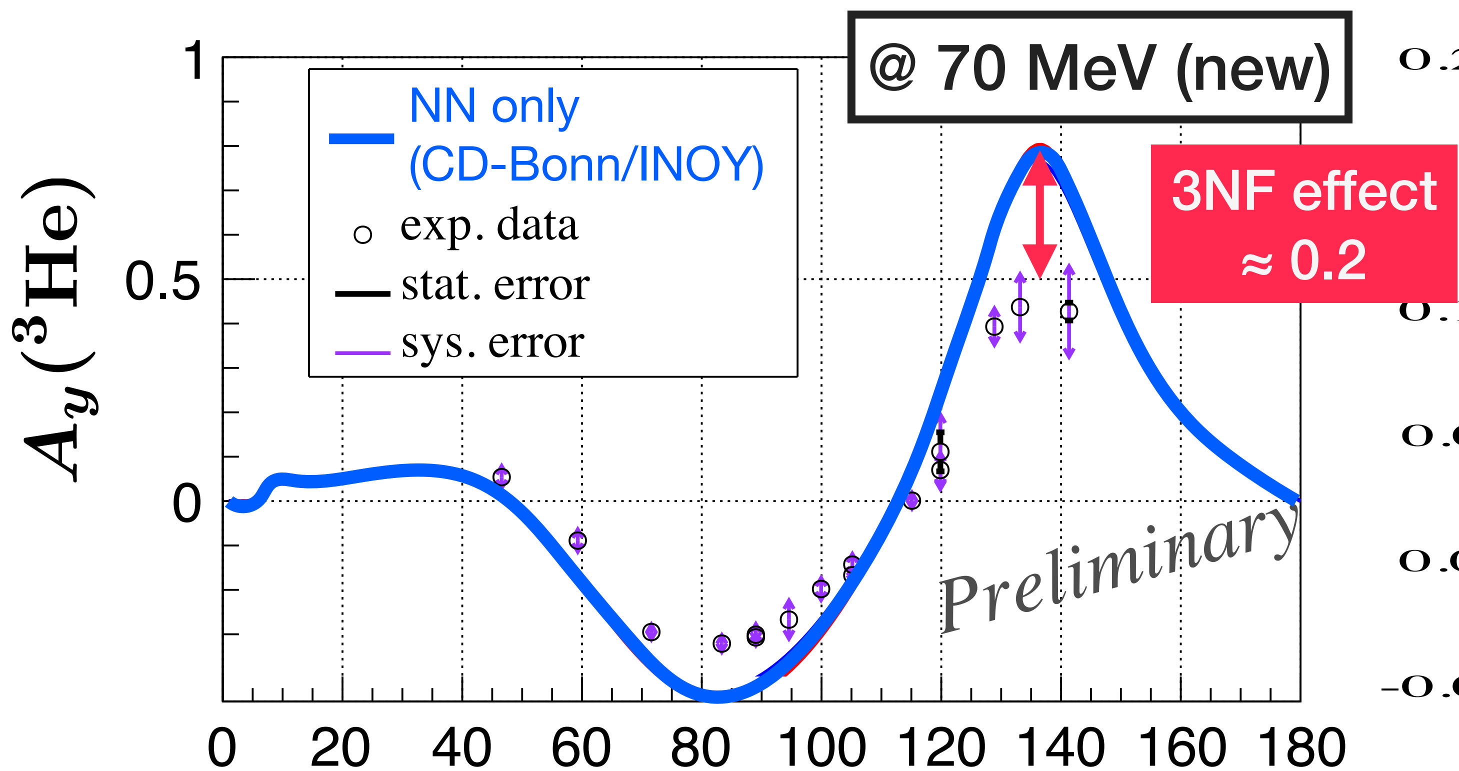
^{3}He analyzing power exp./data for p-^{3}He by Tohoku group (Sekiguchi-Gr.)

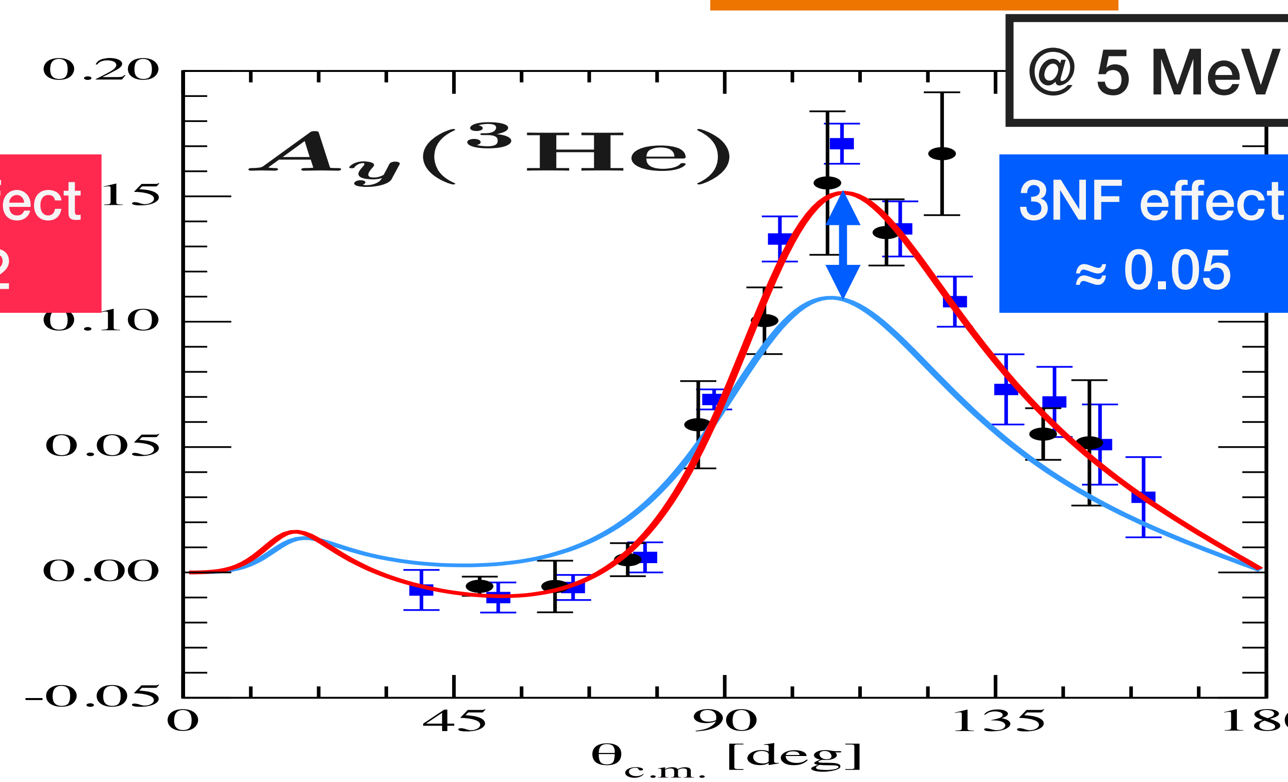


pol-^{3}He target

- *3 atm (≈2 mg/cm²)*
- *≈50% polarization*



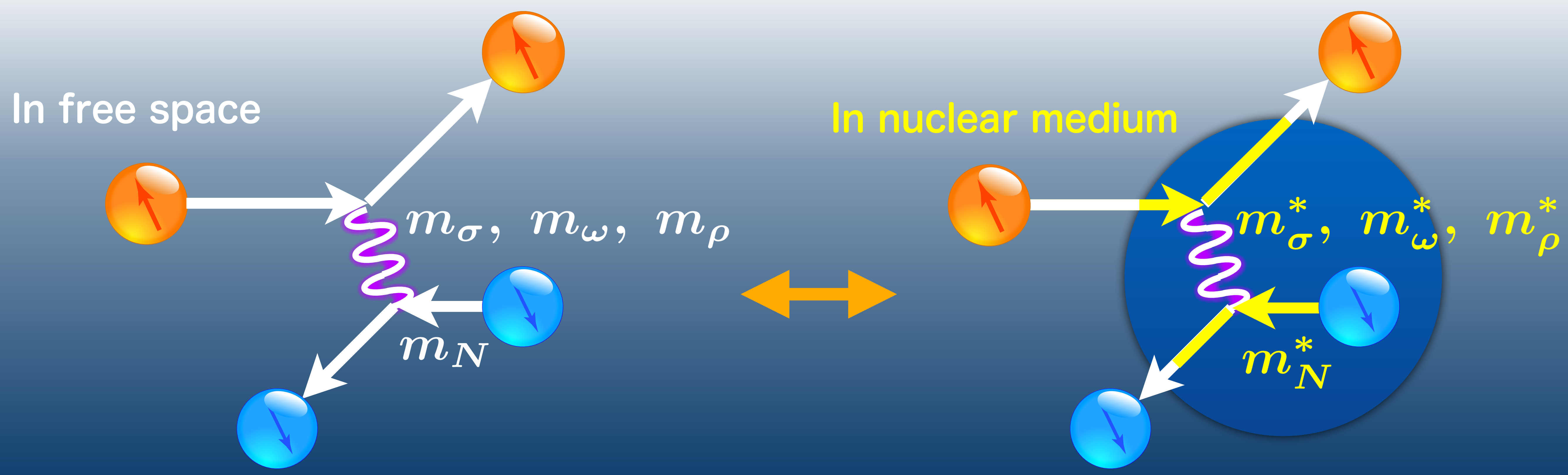




3NF effect at 70 MeV is large and is useful for understanding T=3/2 3NFs

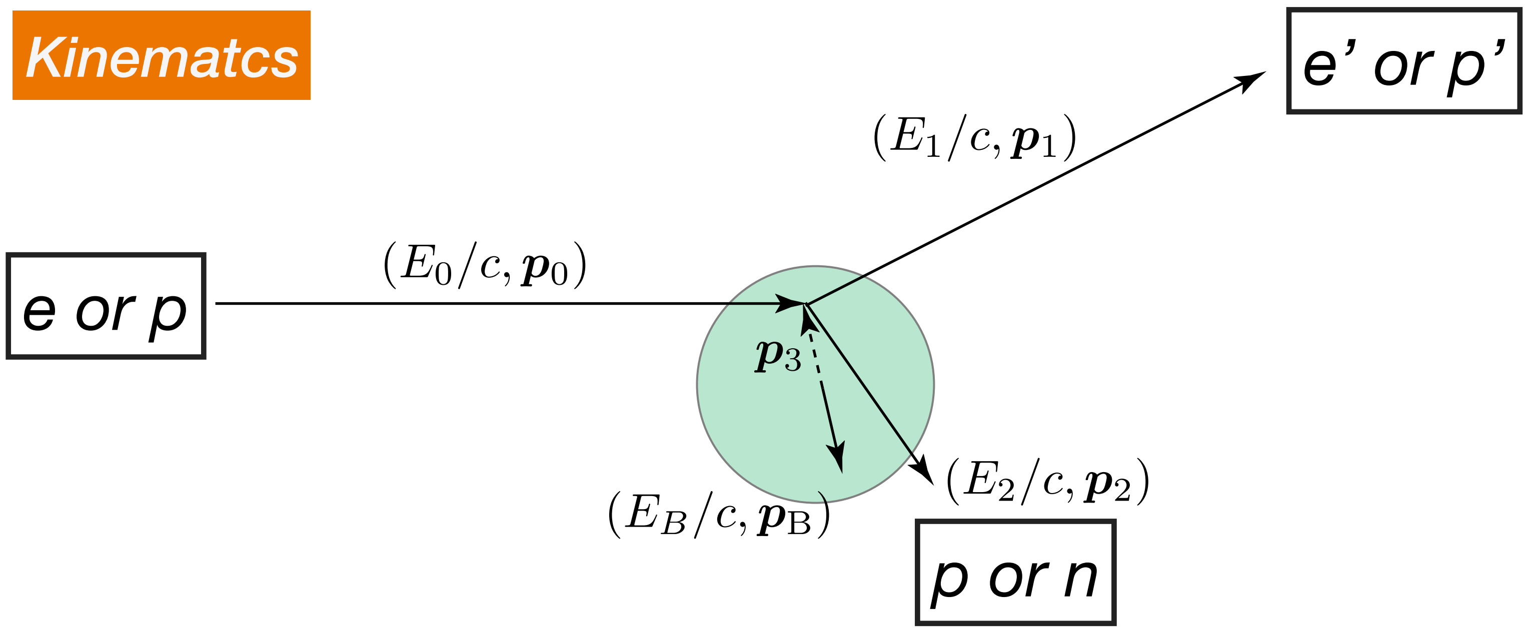
Investigation of nuclear medium effects on NN interactions

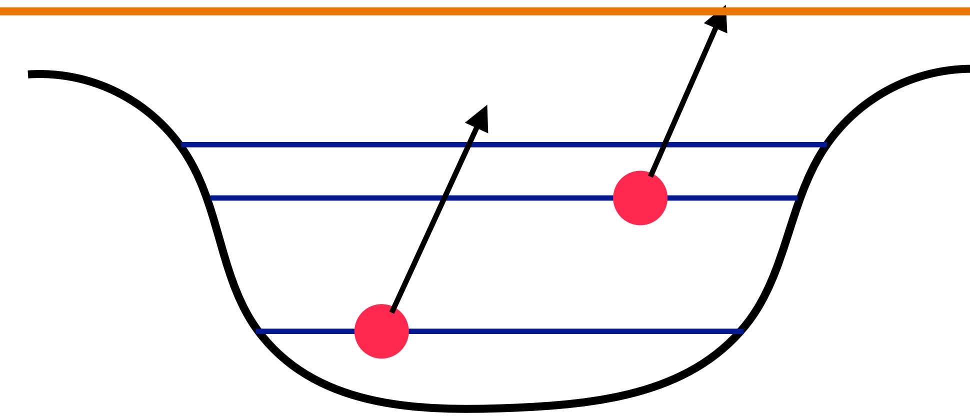
Current status



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, $\delta^{\mathrm{Tr}}(R)$**, can be defined as**

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

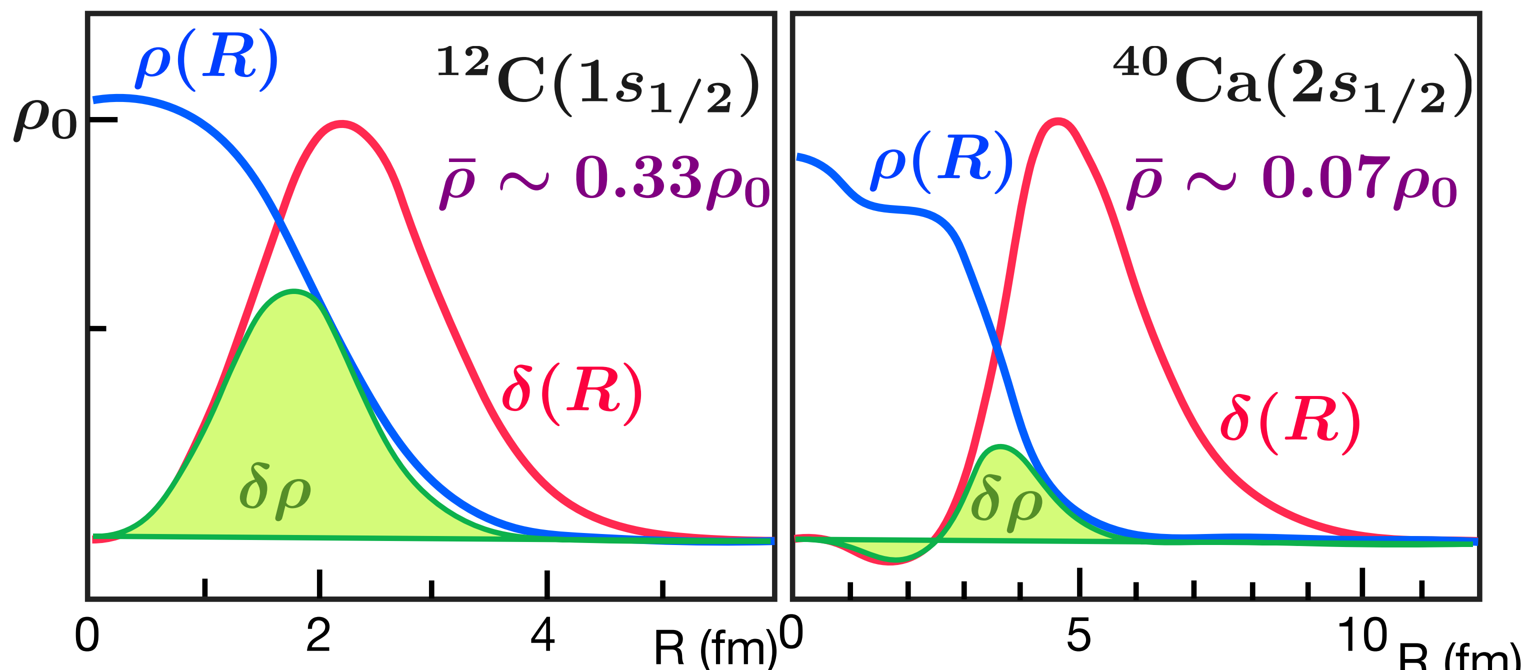
contribution to σ at R

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

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

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

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



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

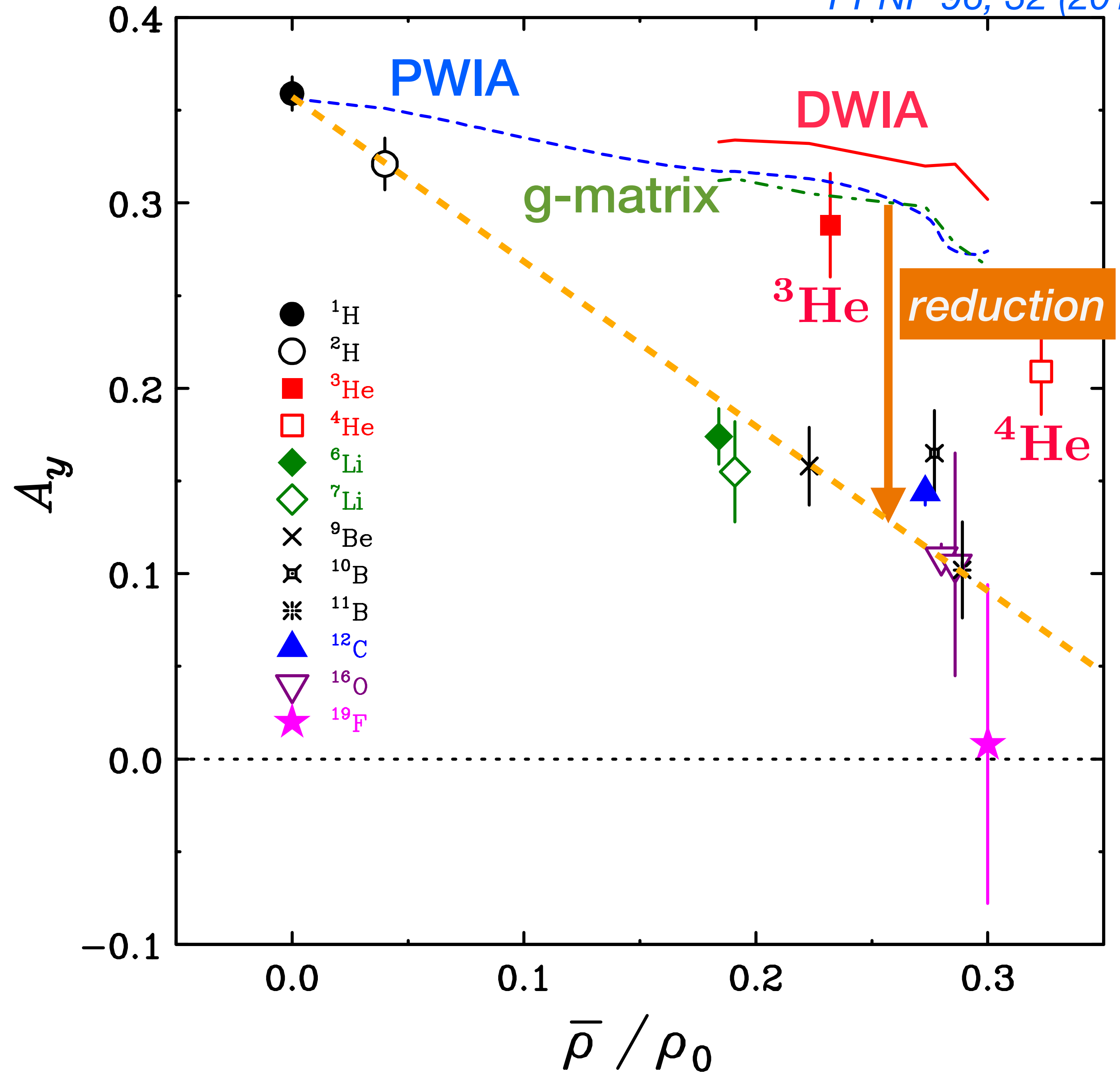
A_y reduction for p-p in nuclear medium

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?

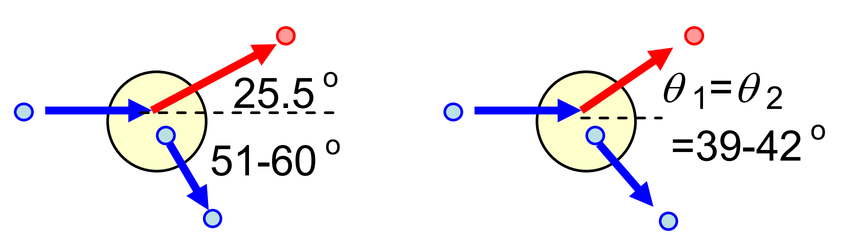


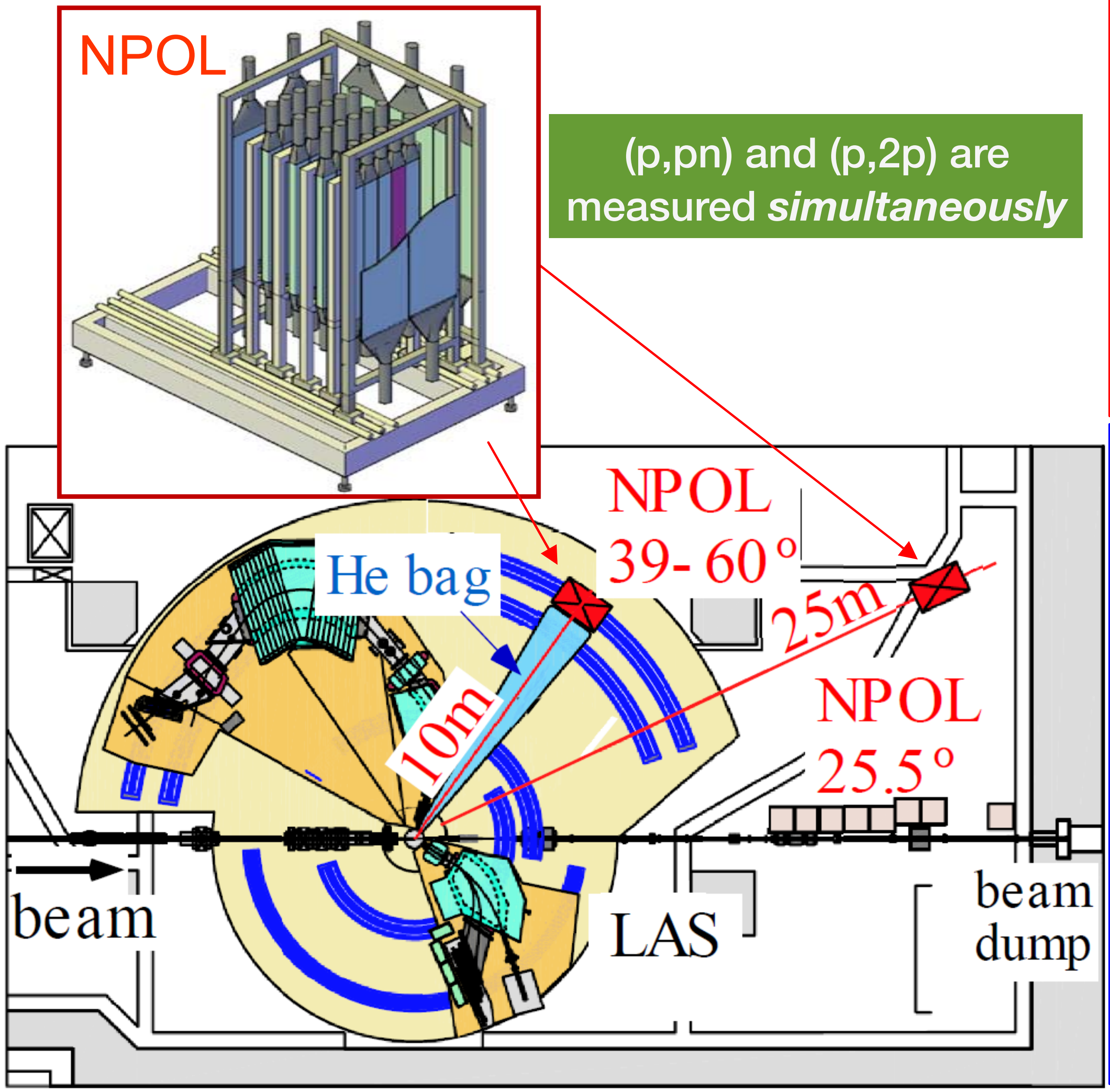
Ay of p-p in nuclear medium are reduced as a function of density.
・Distortion effect and conventional medium effect (g-matrix) could NOT explain.
→ *How about n-p in nuclear medium (isospin dependence) ?*

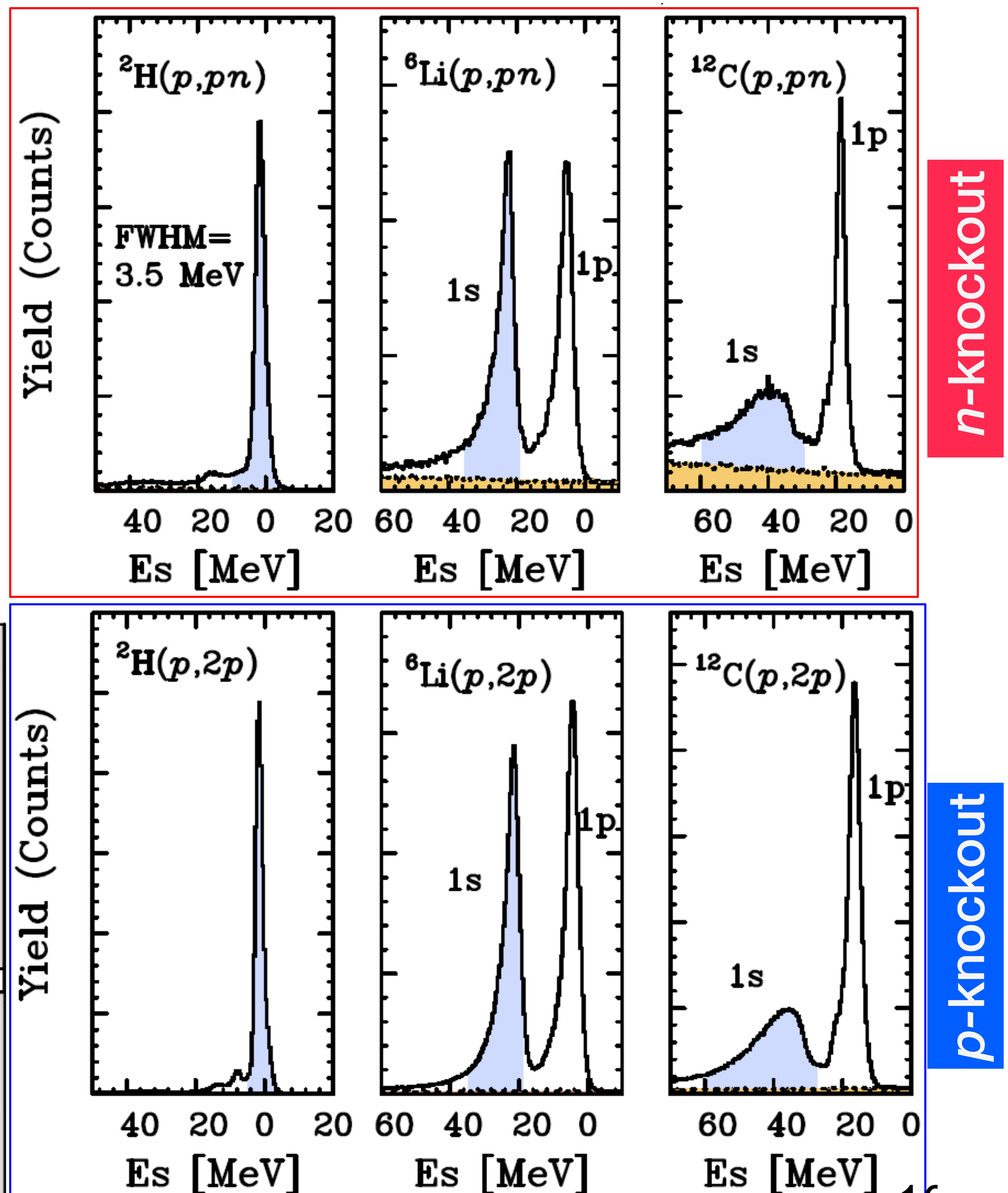
Extension to (p,pn) measurements

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.







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

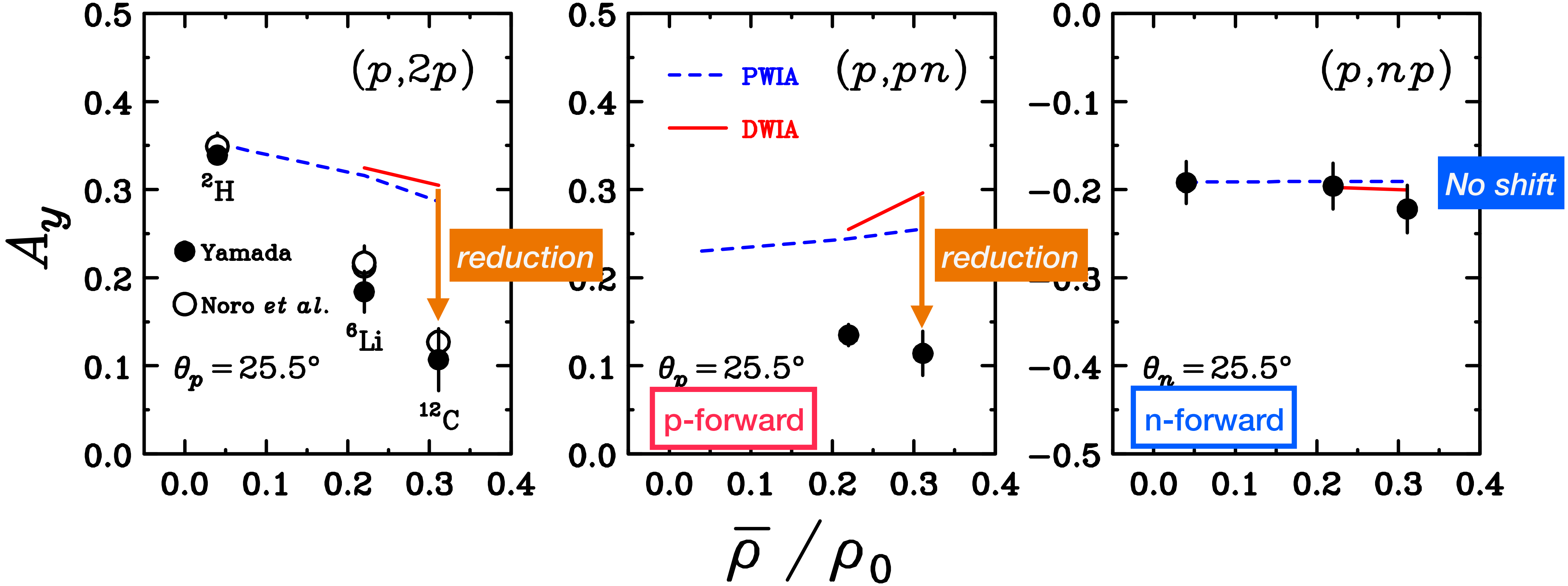
- Ay-reduction similar to (p,2p)

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***

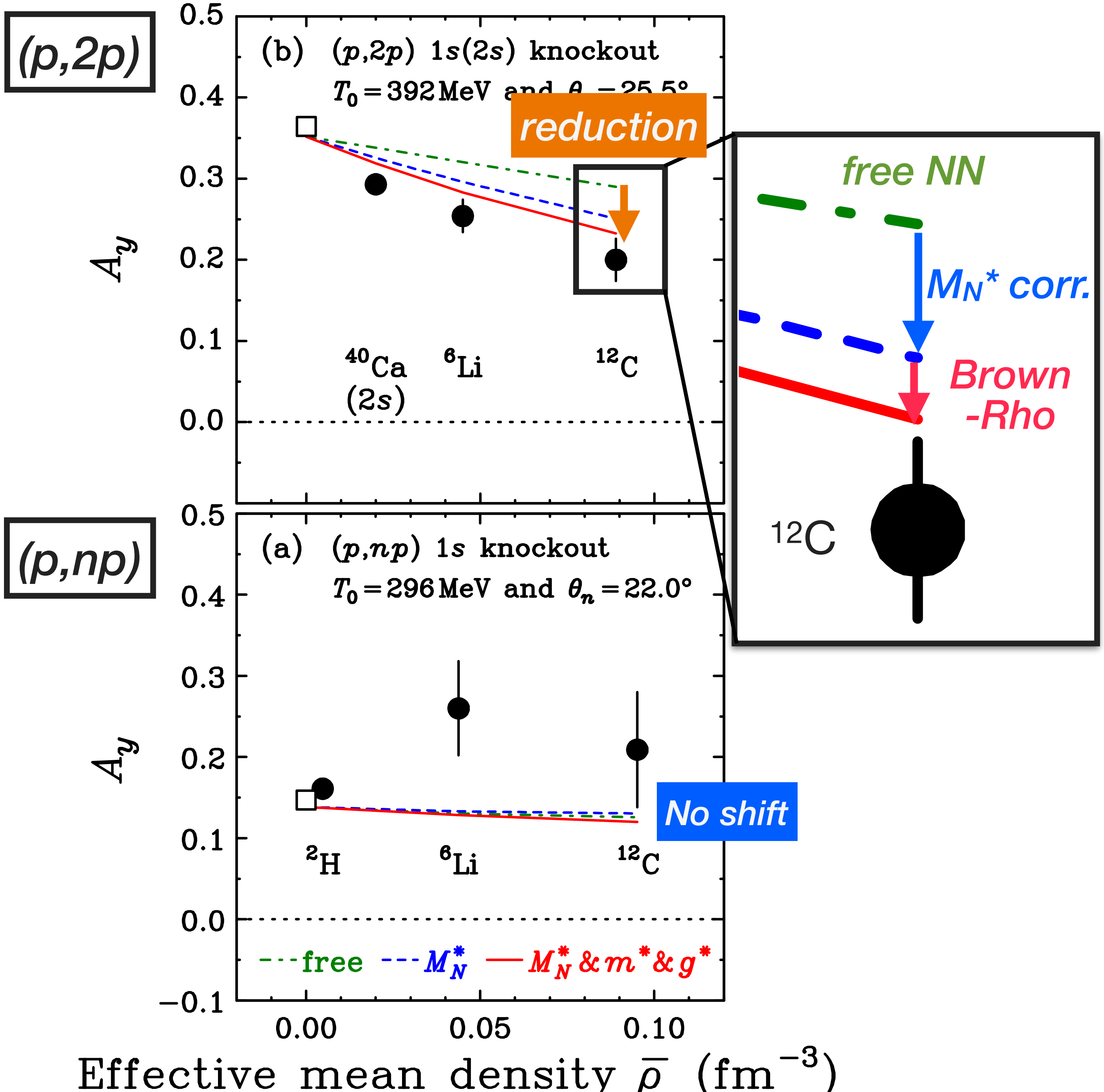
Non-conventional medium effects

Brown-Rho scaling conjecture:

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

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

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



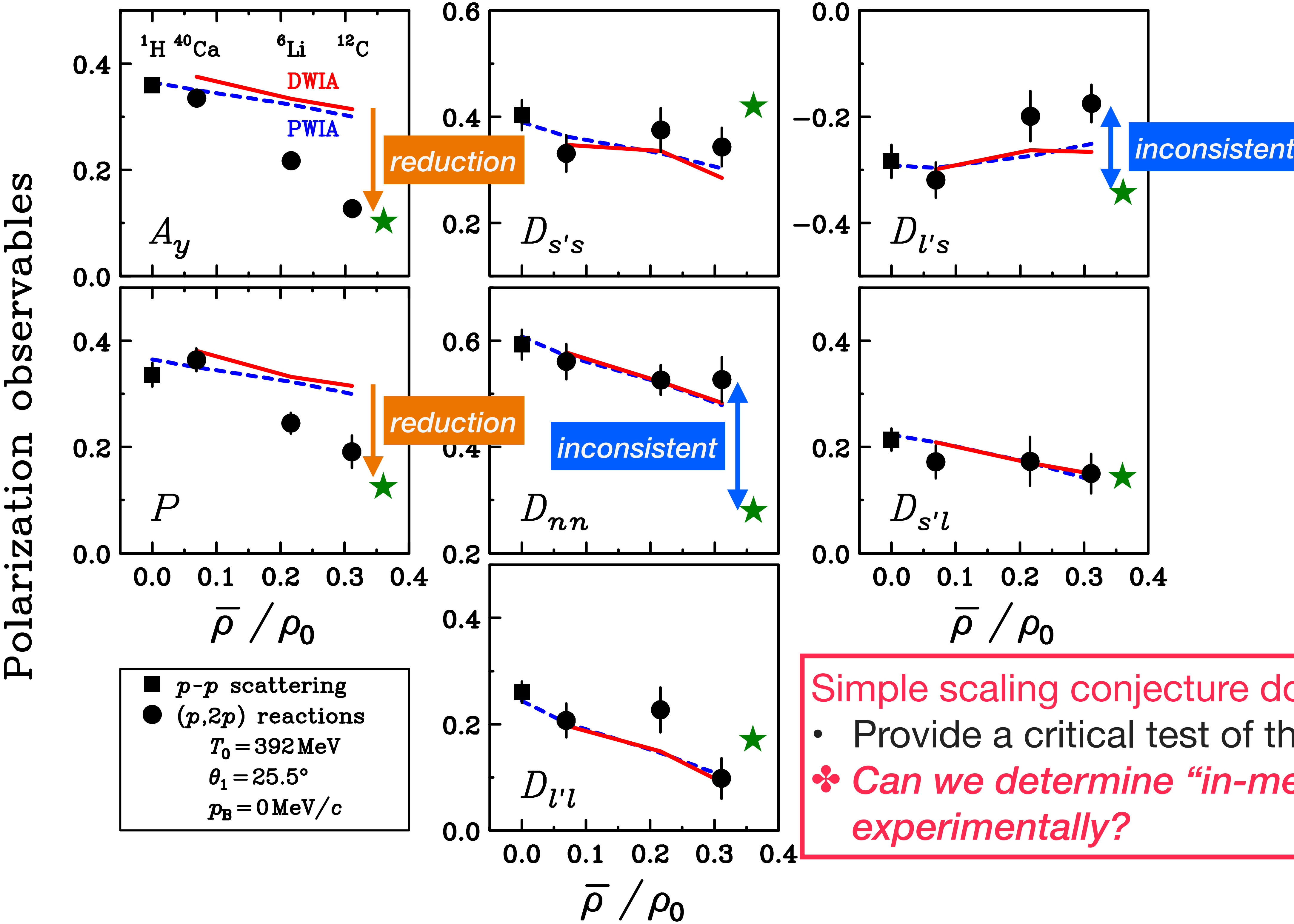
Isospin and density dependences of nuclear medium effects are reasonably explained.
→ *How about other spin observables ?*

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*



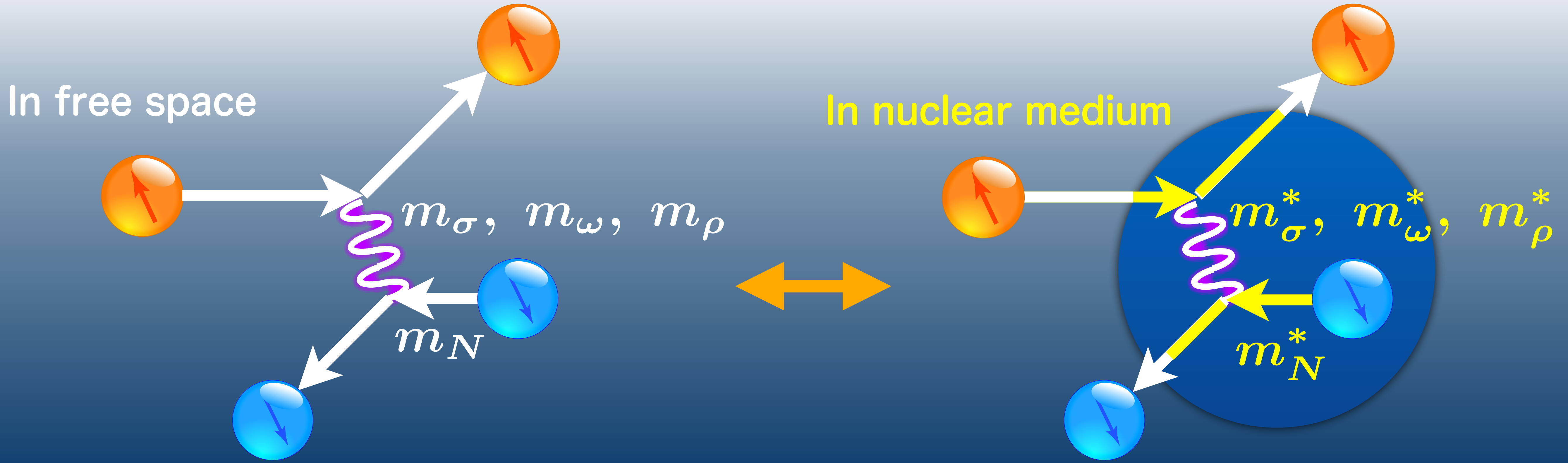
Simple scaling conjecture does not work.

- Provide a critical test of theoretical models.

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

Investigation of nuclear medium effects on NN interactions

Planning research



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:

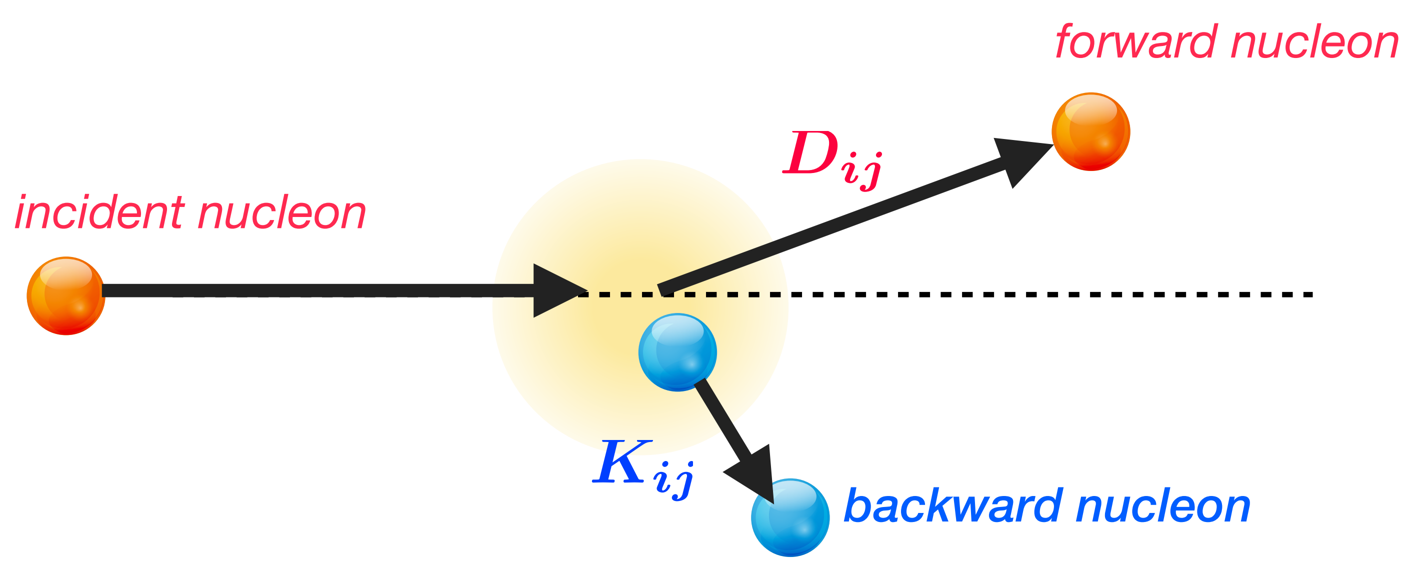
$$M(q) = A + B\sigma_{1\hat{n}}\sigma_{2\hat{n}} + C(\sigma_{1\hat{n}} + \sigma_{2\hat{n}}) + E\sigma_{1\hat{q}}\sigma_{2\hat{q}} + F\sigma_{1\hat{p}}\sigma_{2\hat{p}}$$

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)

Experimental setup for K_{ij}

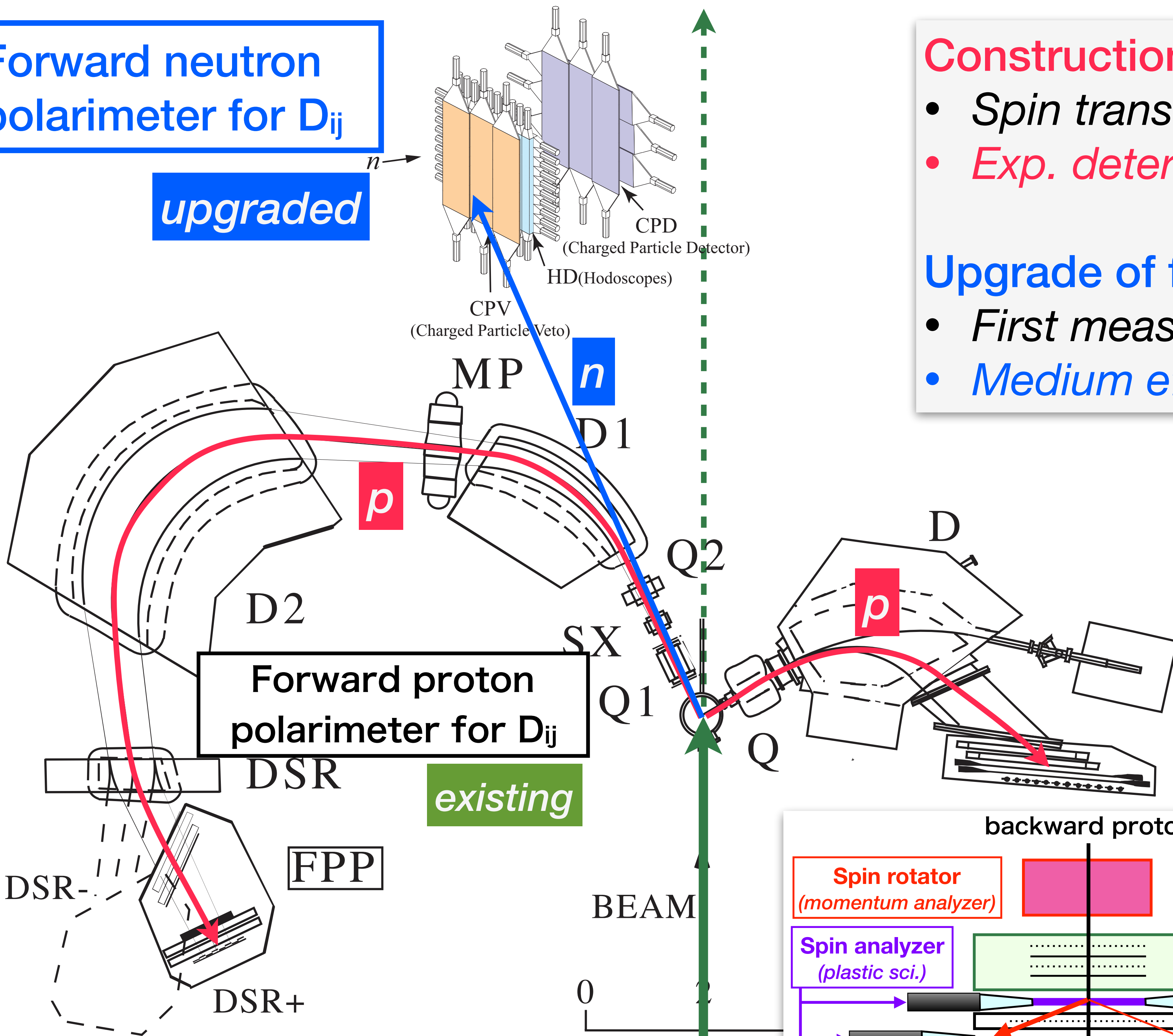
Construction of backward proton pol.
- *Spin transfer K_{ij} for A(p,2p)*
- *Exp. determination of in-medium 2NF*

Upgrade of forward neutron pol.
- *First measurement of D_{NN} for A(p,np)*
- *Medium effect on D_{NN} for np scattering*

2018-2020: Construction
2020-2021: Commissioning
2021-2022: First data

Forward neutron polarimeter for D_{ij}

upgraded

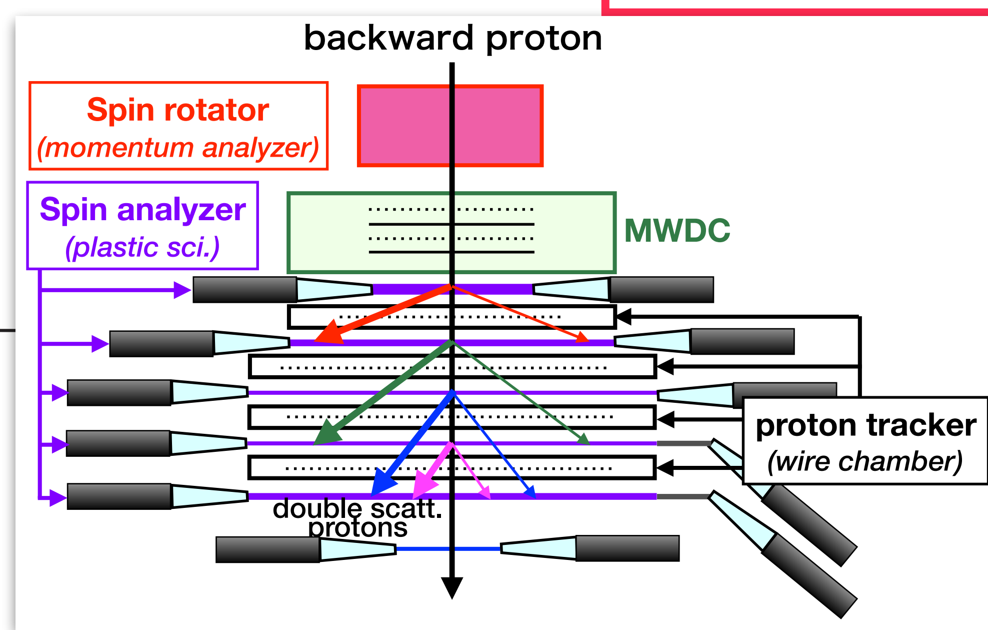


Forward proton polarimeter for D_{ij}

existing

Backward proton polarimeter for K_{ij}

new



High intensity&polarization
proton beam from
upgraded cyclotrons

最近の反応理論の進展

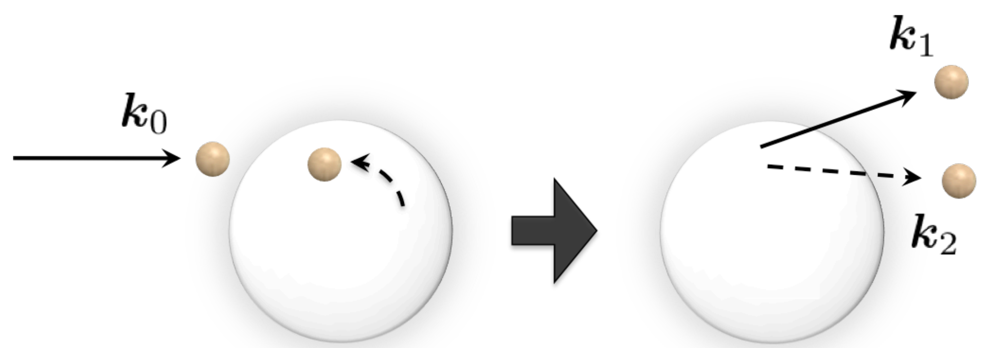
３体核力を取り込んだ、ノックアウト反応の理論予測

Theoretical progress for (p,2p) with 3NF

K.Minomo, M.Kohno, K.Yoshida, and K.Ogata, PRC 96, 024609 (2017).

Knockout from outer orbits

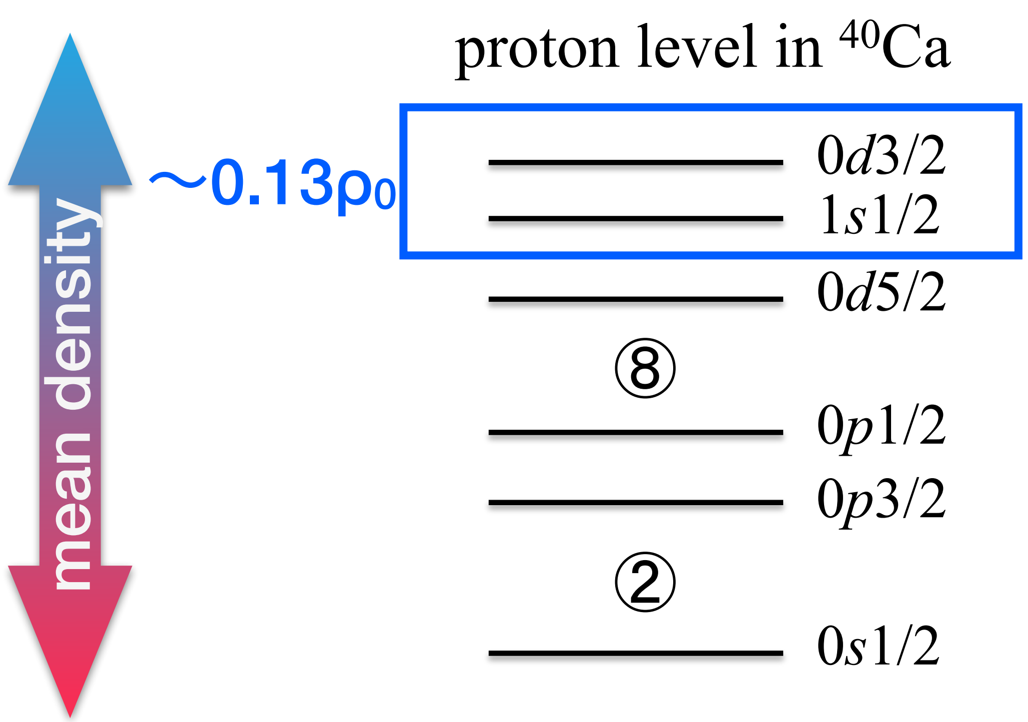
3NF effects are negligible at low density

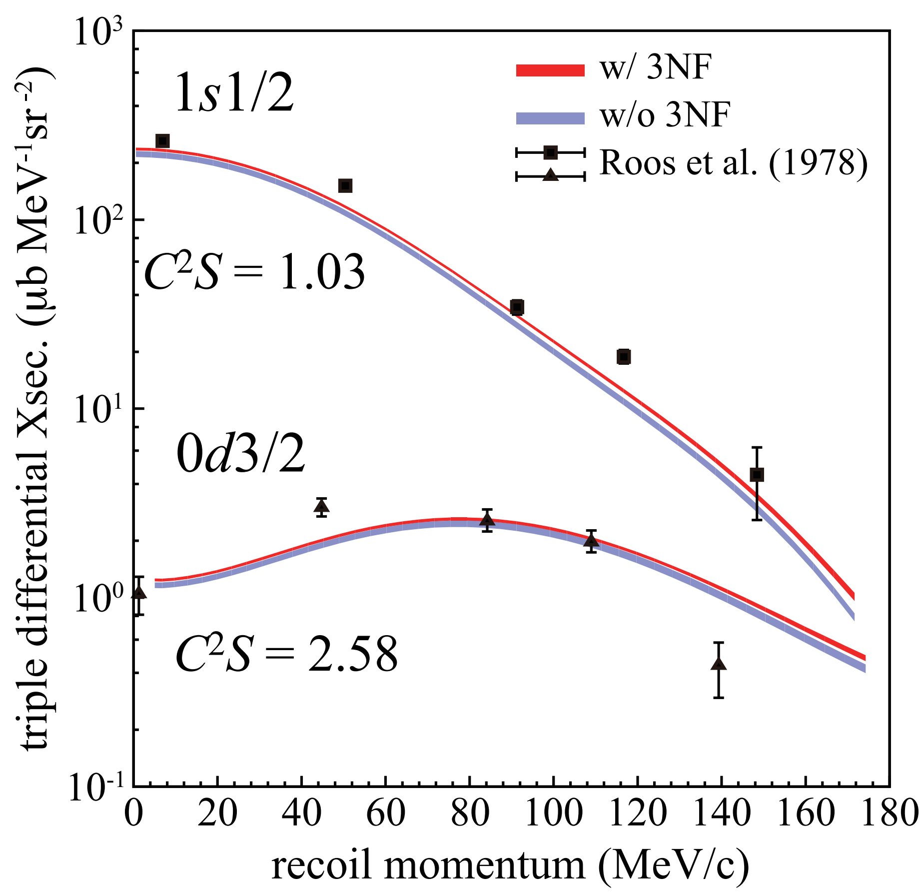


$\hat{\boldsymbol{k}}_1, \hat{\boldsymbol{k}}_2$: fixed

E_1 (E_2): changed

^{40}Ca(p,2p)^{39}K*@150MeV





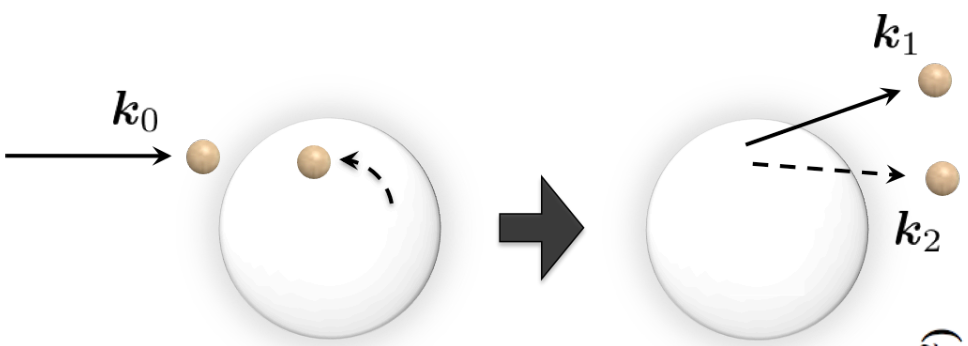
3NF effects are small for outer orbits

⇒ *Medium modifications for 2NF are small at low density (ρ=0.13ρ$_0$)*

Theoretical progress for (p,2p) with 3NF

K.Minomo, M.Kohno, K.Yoshida, and K.Ogata, PRC 96, 024609 (2017).

Knockout from deeply-bound orbit

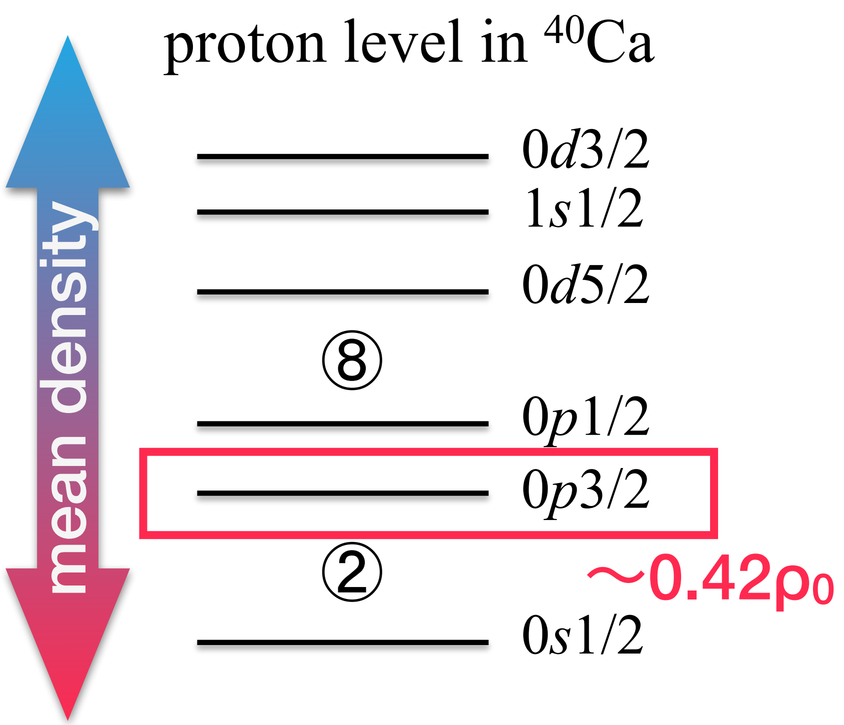


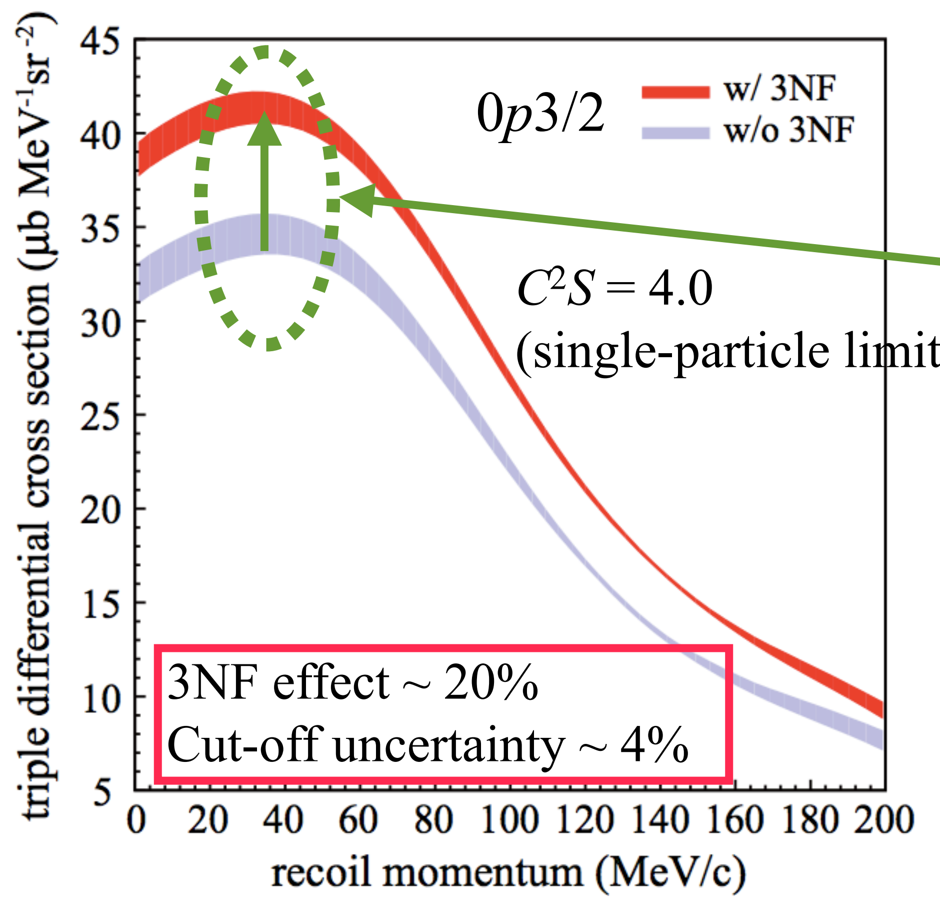
$\hat{k}_1, \hat{k}_2$: fixed

E_1 (E_2): changed

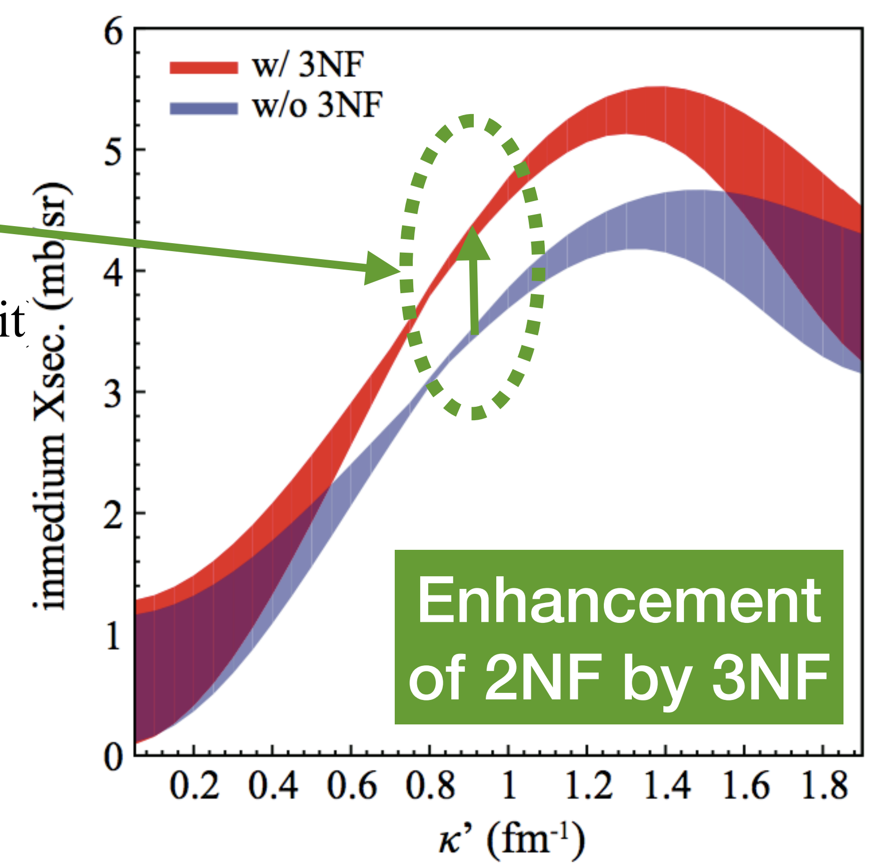
^{40}Ca(p,2p)^{39}K*@150MeV

3NF effects are enhanced at high density





In-medium p-p cross section



3NF effects are large for a deeply-bound orbit

⇒ *Medium modifications for 2NF are significant at high density (ρ=0.42ρ₀)*

Calculations for polarization observables (A_y, etc) are now in progress.

Recent progress for spin-isospin residual interaction

Key parameter, g'_{NN}, for π-condensation from GTGR in ^{132}Sn

理化学研究所

RIKEN

九州大学

参考資料配布

PRESS RELEASE

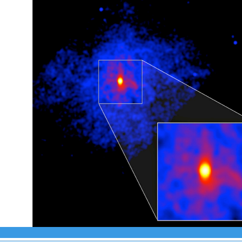
2018 年 10 月 19 日
理化学研究所
九州大学

中性子過剰なスズ同位体の巨大共鳴観測に成功

—パイ中間子凝縮から中性子星の構造解明に一歩近づく—

理化学研究所（理研）仁科加速器科学研究センタースピン・アイソスピン研究室笹野匡紀専任研究員、上坂友洋室長、九州大学理学府の安田淳平大学院生（研究当時）、理学研究院の若狭智嗣教授らの国際共同研究グループ[※]は、理研の重イオン[1]加速器施設「RI ビームファクトリー（RIBF）[2]」を用いて、二重魔法数[3]核「スズ-132（^{132}Sn）」に対する「巨大共鳴状態[4]」の観測に世界で初めて成功しました。

Nuclear force as residual interaction

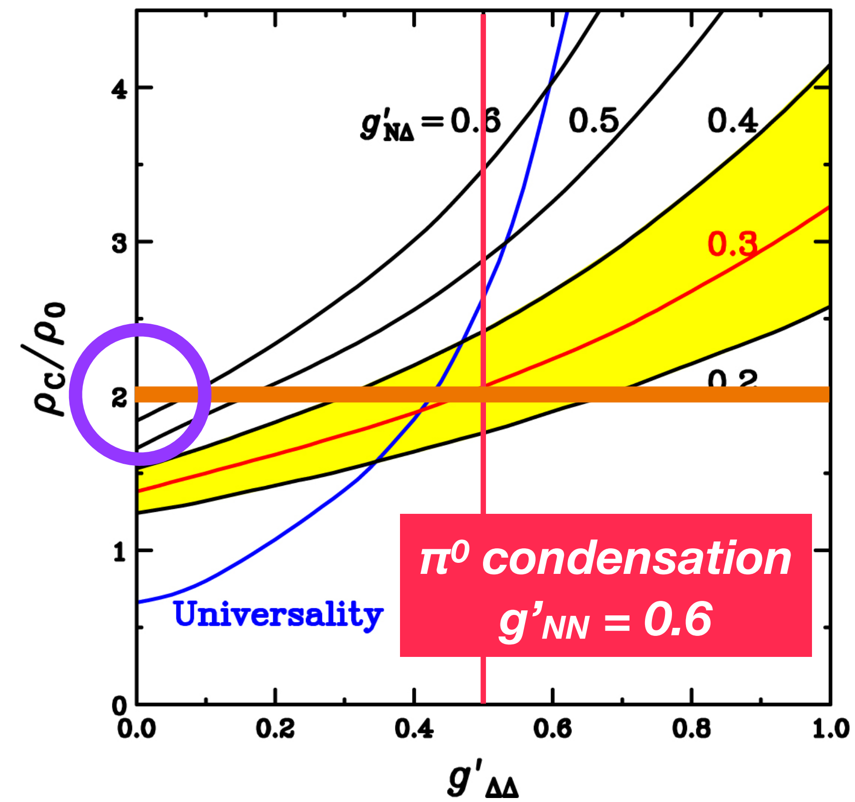


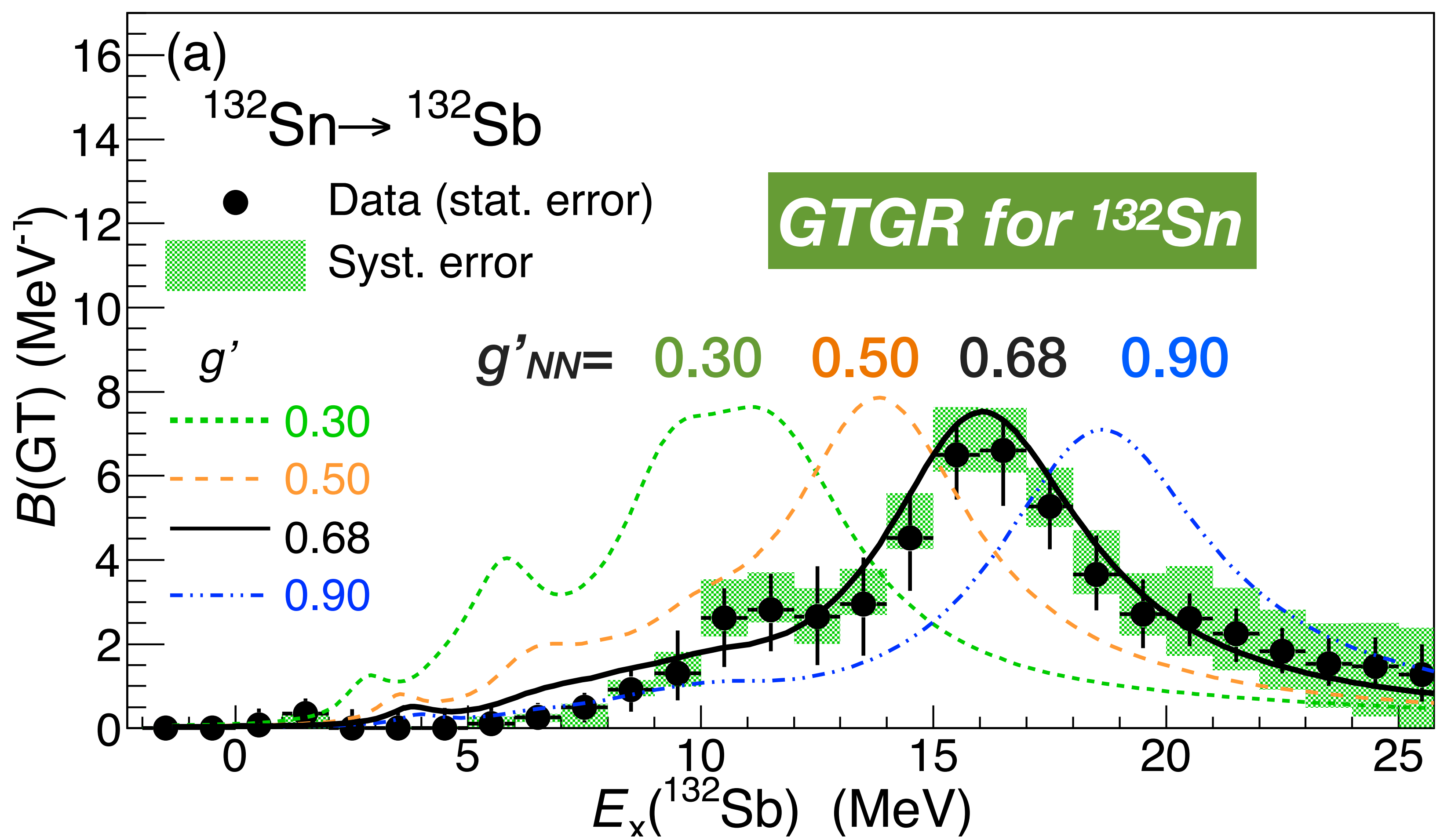
J. Yasuda(Kyushu), M. Sasano, R.G.T. Zegers, TW et al., PRL 121, 132501 (2018).

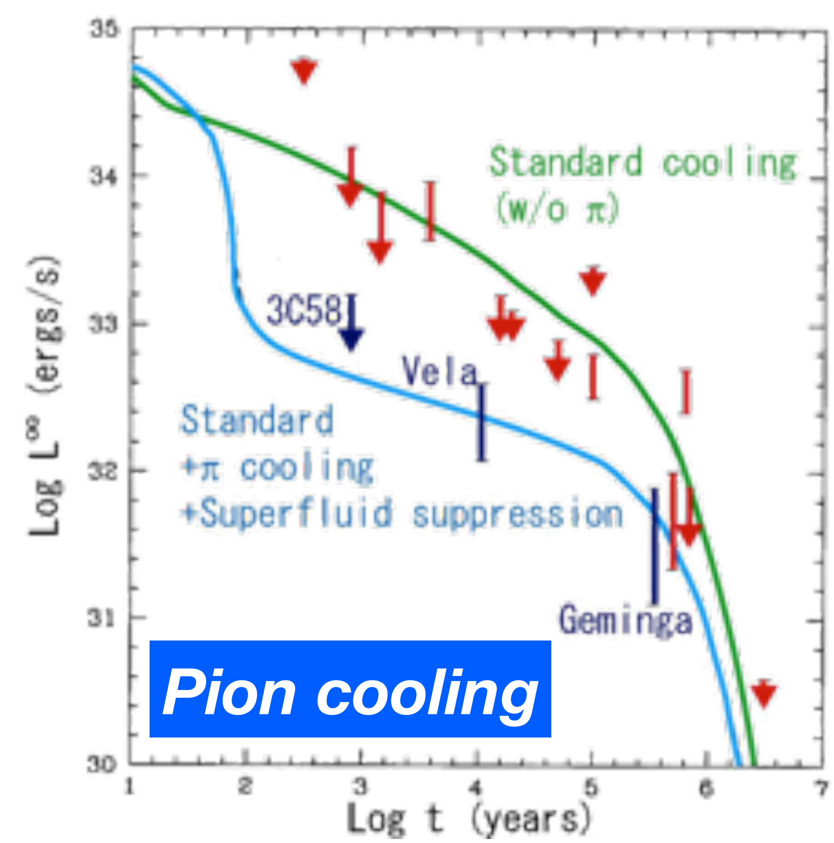
Gamow-Teller response of the doubly-magic neutron-rich nucleus ^{132}Sn

π+ρ+g' interaction as a spin-isospin residual interaction

- $g'_{NN} = 0.68 \pm 0.07$ for ^{132}Sn from GTGR
    - Consistent with 0.6 for ^{90}Zr and 0.64 for ^{208}Pb
- Constant g'_{NN} between (N-Z)/A = 0.11—0.24 (^{132}Sn)
- ***Pion condensation can occur for ～2ρ₀ (heavy NS) if constant g's hold for N/Z ≫ 1***







Summary and Outlook

Bridge nuclear/hadron hierarchies &
Deeper understanding of nuclear system/hierarchy