東北大学

Experimental approach to three-nucleon forces via three- and four-nucleon scattering

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Three-Nucleon Forces in Nucleus

Three-Nucleon Force (3NF)

key element to fully understand properties of nucleus.

- First evidence of 3NF : Binding Energies of Triton (^3H)

’90〜

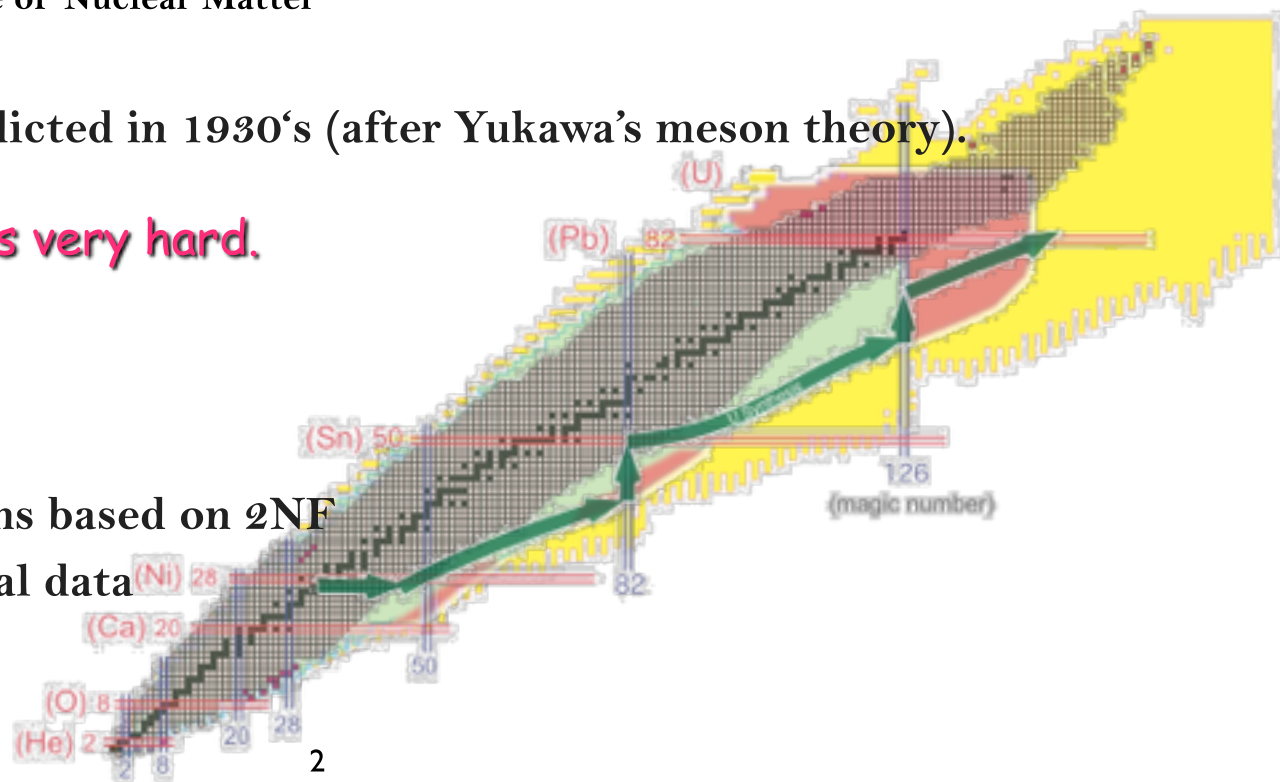
- Nucleon-Deuteron Elastic Scattering at Intermediate Energies
- Biding Energies / Levels of Light Mass Nuclei
- Equation of State of Nuclear Matter

etc ...

Existence of 3NF was predicted in 1930‘s (after Yukawa’s meson theory).

To find Evidence of 3NF is very hard.

- 3NF < 2NF
- One needs,
  1. Reliable 2NF
  2. *Ab* initio calculations based on 2NF
  3. Precise experimental data

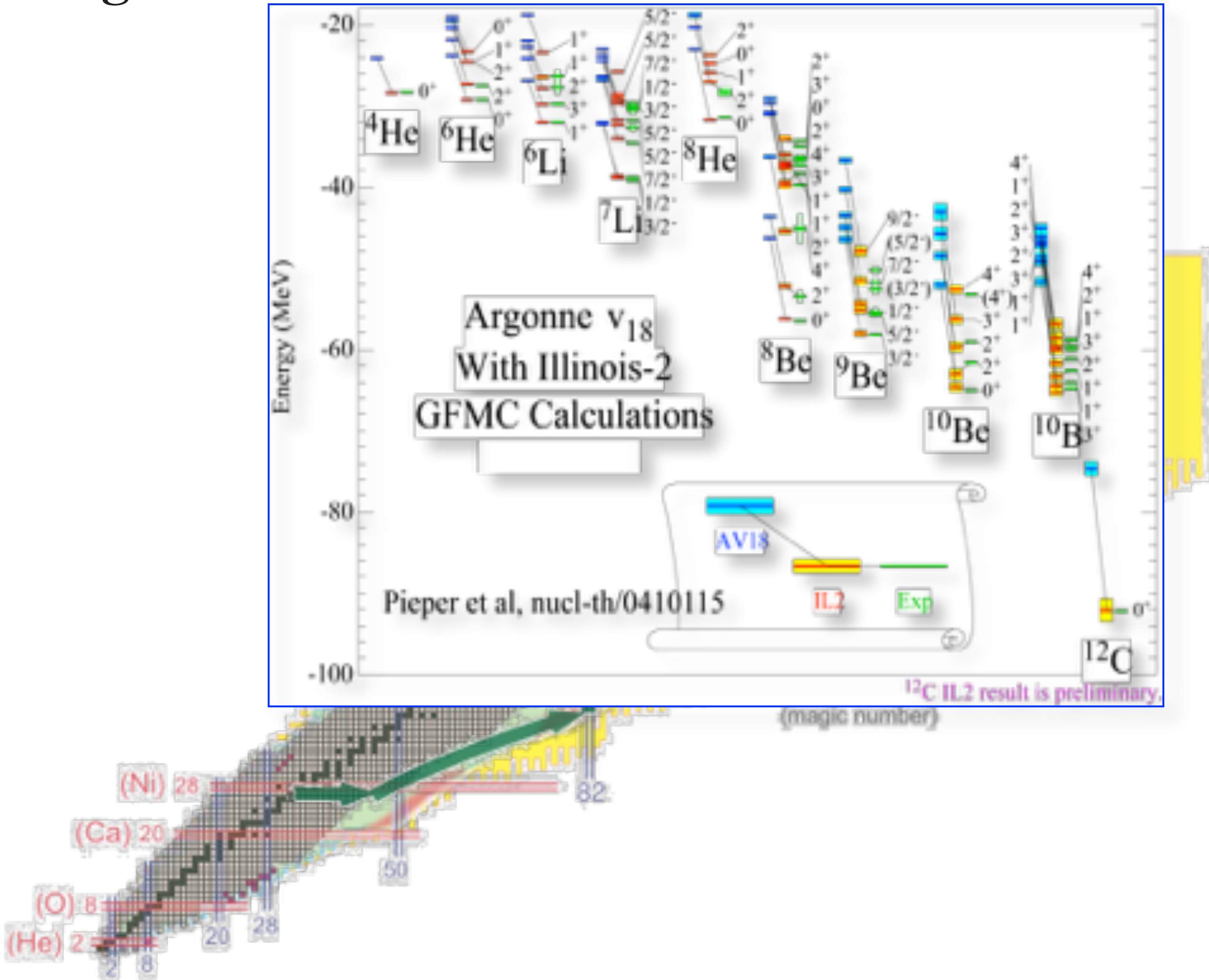


Where can we find 3NF effects ? - I -

3NFs in Finite Nuclei

Ab Initio Calculations for Light Nuclei

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



Where can we find 3NF effects ? - I -

3NFs in Finite Nuclei

Ab Initio Calculations for Light Nuclei

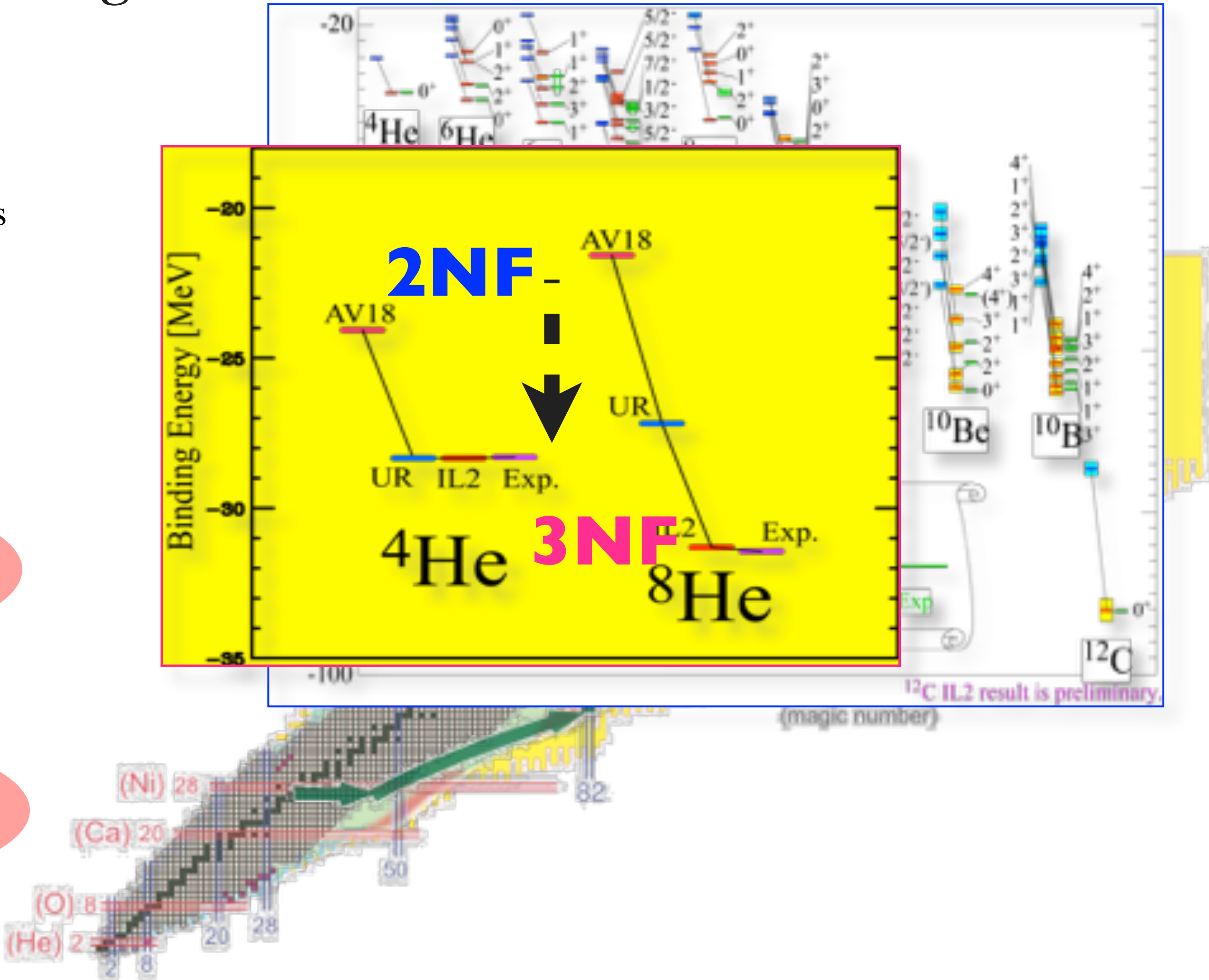
- ***Green's Function Monte Carlo***
- ***No-Core Shell Model*** etc..

- 2NF provide less binding energies
- 3NF : well reproduce the data

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

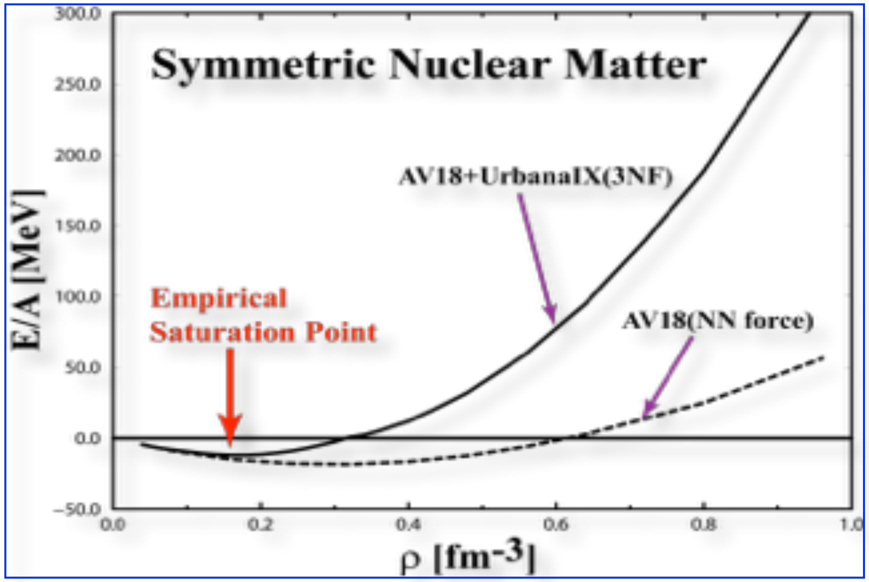
3NF effects in B.E.
- **10-25%**
- **Attractive**

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



Where can we find 3NF effects ? - II -

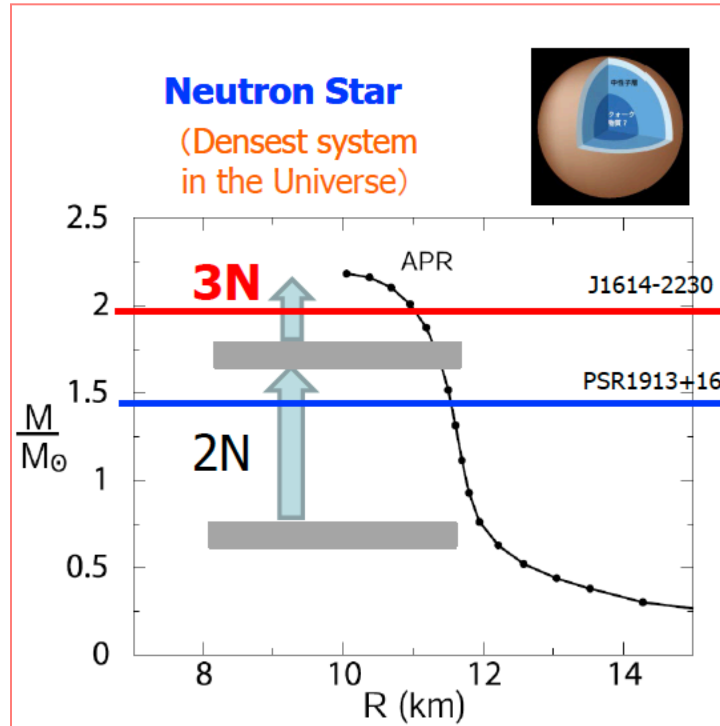
3NFs in Infinite Nuclei



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

- All NN potentials
 (AV18, Nijmegen I,II, CD Bonn)
 provide larger saturation point
 of Nuclear Matter.
- 3NF
 - shift to the empirical saturation point
 - significant at higher density

3NFs play important roles at high density



- Short range repulsive terms of 3NFs
 (3-Baryon Fs) are taken as key elements
 to understand 2 M(sun) neutron star.

- Understanding of 3NF is one key element to describe nuclear phenomena.
- How to constrain the properties of 3NF ?

Few-Nucleon Scattering is a good probe to study the dynamical aspects of 3NFs.

- ✓ Momentum dependence
- ✓ Spin dependence
- ✓ Iso-spin dependence

Few-Nucleon Scattering

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

- ✓ **Momentum dependence**
- ✓ **Spin & Iso-spin dependence**

Direct Comparison between Theory and Experiment

- Theory : Faddeev / Faddeev-Yakubovsky Calculations

  Rigorous Numerical Calculations of 3, 4N System

2NF Input	3NF Input	2NF & 3NF Input
• CDBonn • Argonne V18 (AV18) • Nijmegen I, II, 93	• Tucson-Melbourne • Urbana IX etc..	• Chiral Effective Field Theory

- Experiment : Precise Data
  - $d\sigma/d\Omega$, Spin Observables (A_i, K_{ij}, C_{ij})

Extract fundamental information of Nuclear Forces.

Where is the hot spot for study of 3NFs ?

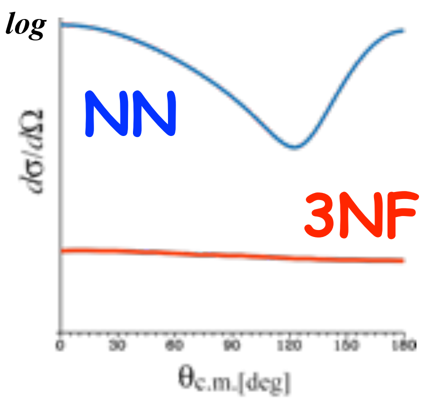
Nucleon-Deuteron Scattering

To study momentum & spin dependences
Iso-spin dependence : T=1/2 only

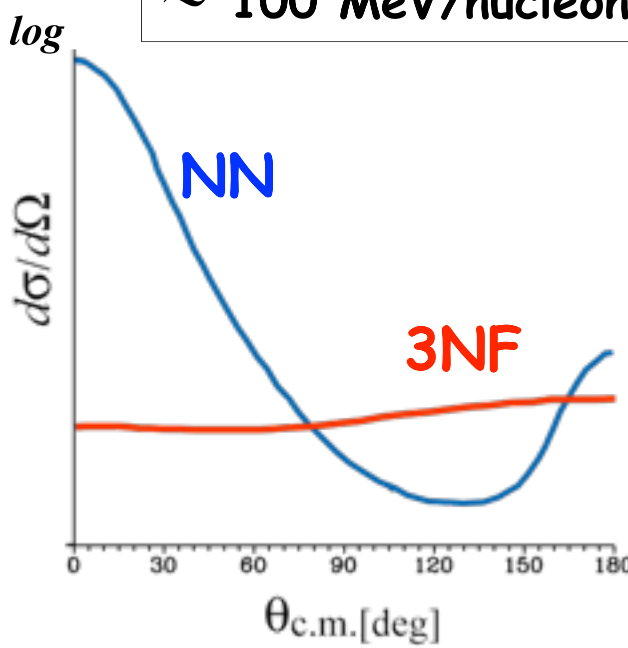
Predictions by H. Witala et al. (1998)

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

~ 10 MeV/nucleon

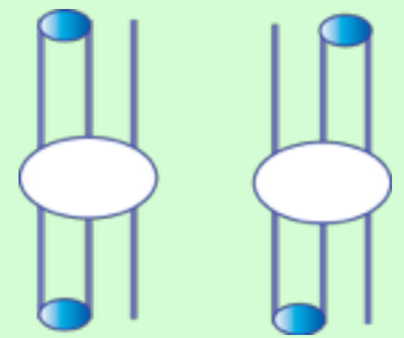


~ 100 MeV/nucleon



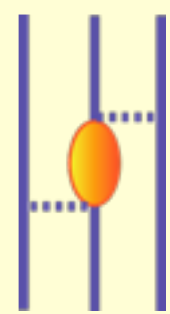
$q = 0 \sim 4\ \mathrm{fm}^{-1}$

Nd scattering

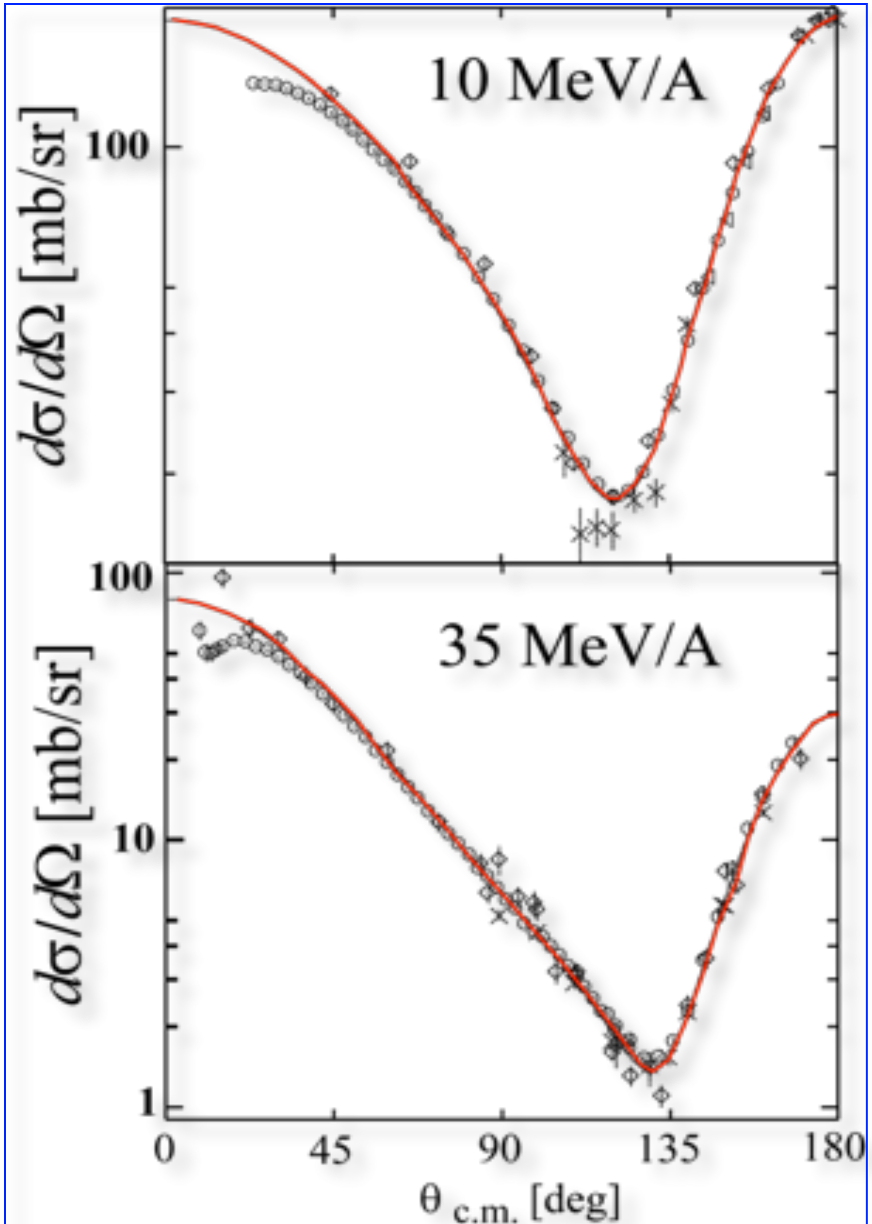


Forward Backward

3NF



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



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

No signatures of 3NF.

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

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

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. 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. C 89, 064007 (2014) etc…

$p + d$

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)

$n + d$

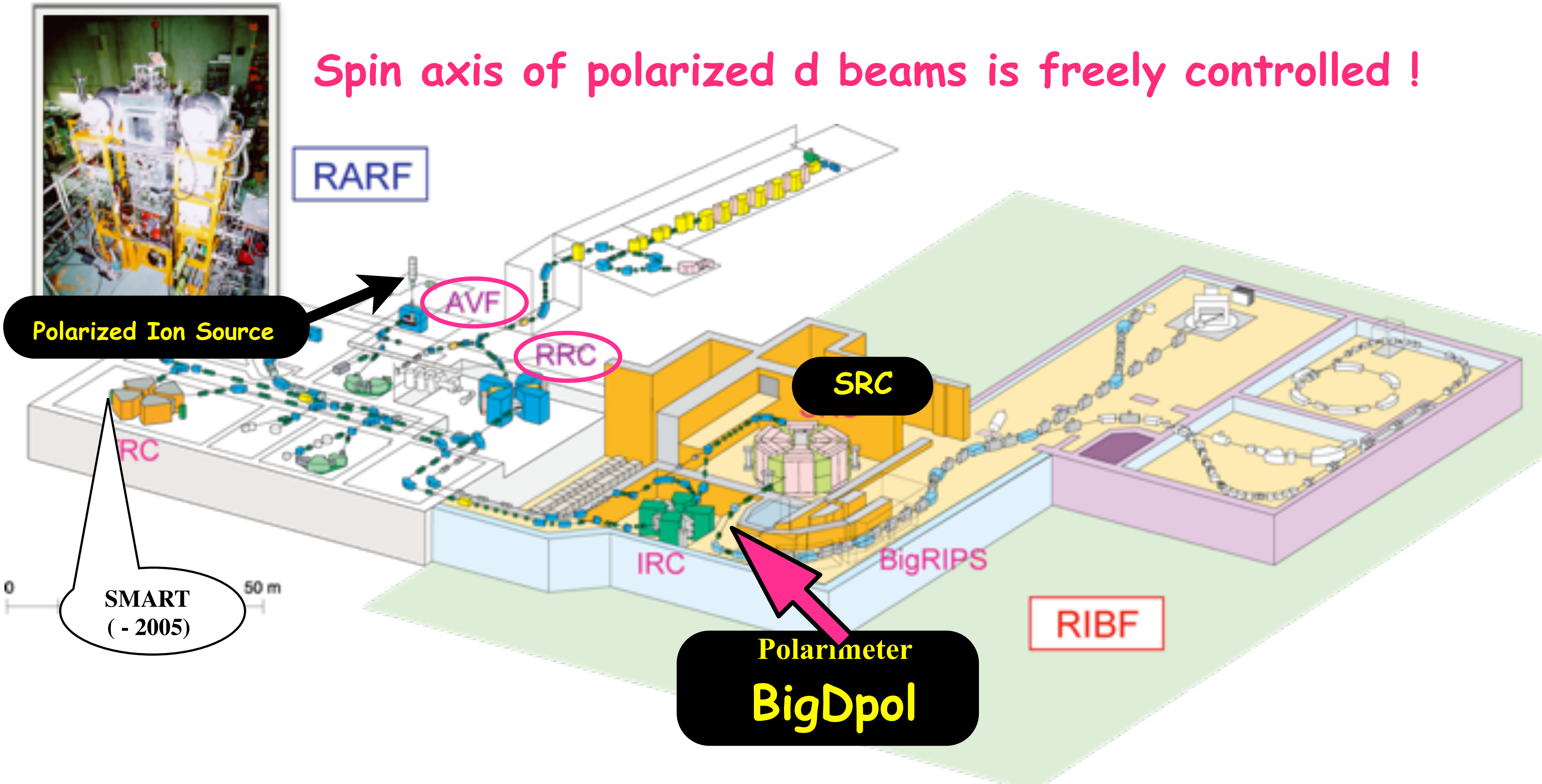
RCNP

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

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

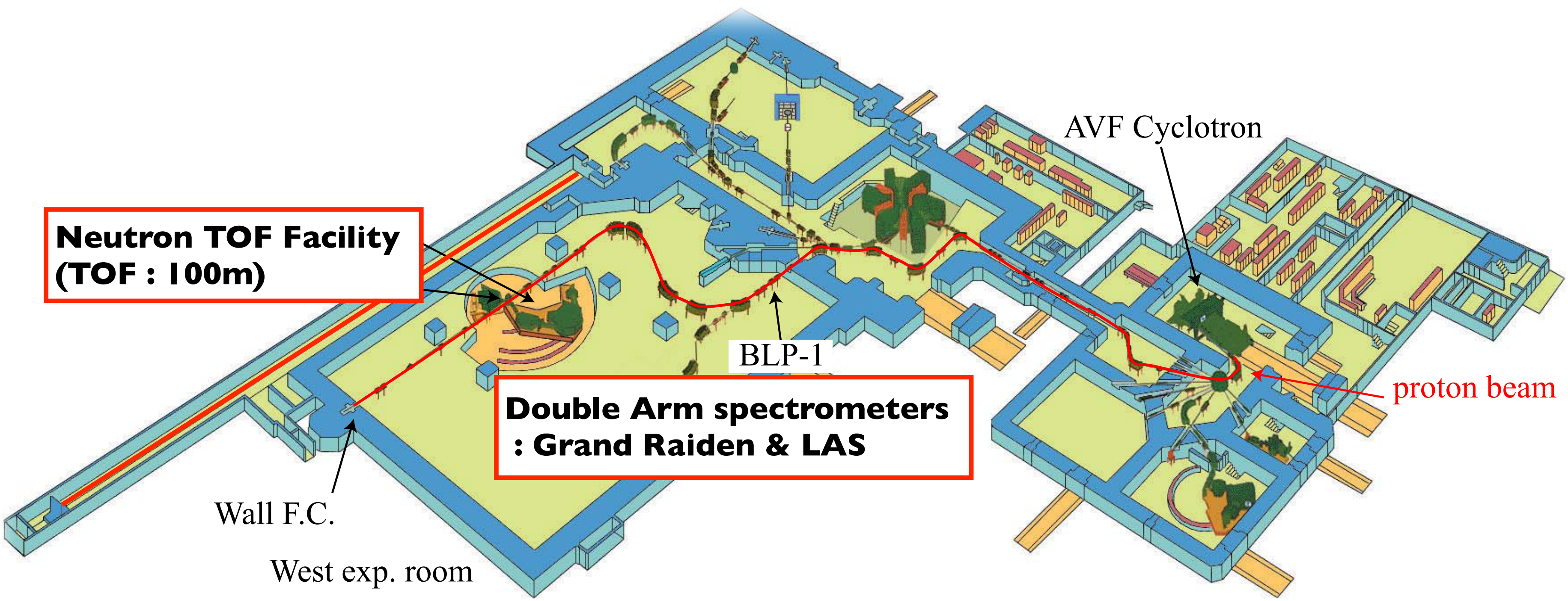
RIKEN RI Beam Factory (RIBF)

- **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**



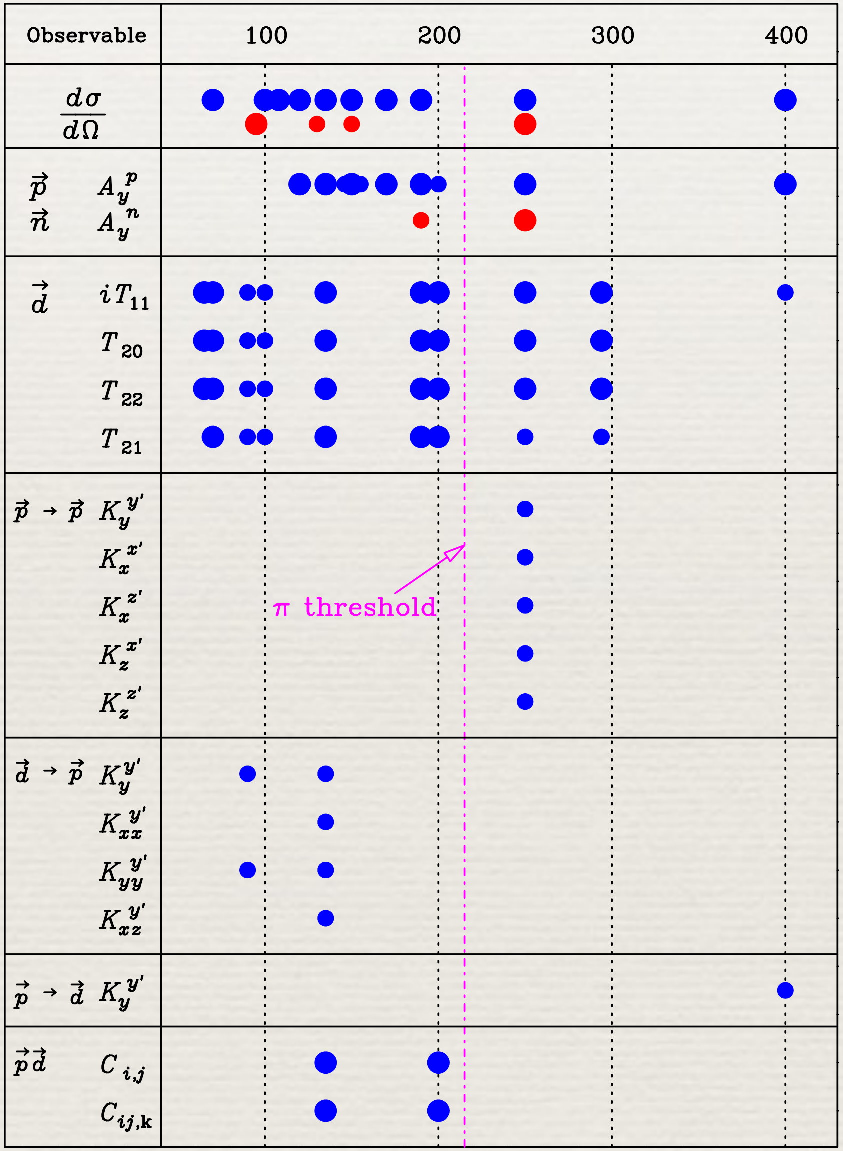
RCNP, Osaka University

- 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 : < $1\mu A$



Nd Elastic Scattering Data at Intermediate Energies

pd and *nd* Elastic Scattering at 65−400 MeV/nucleon



~2018

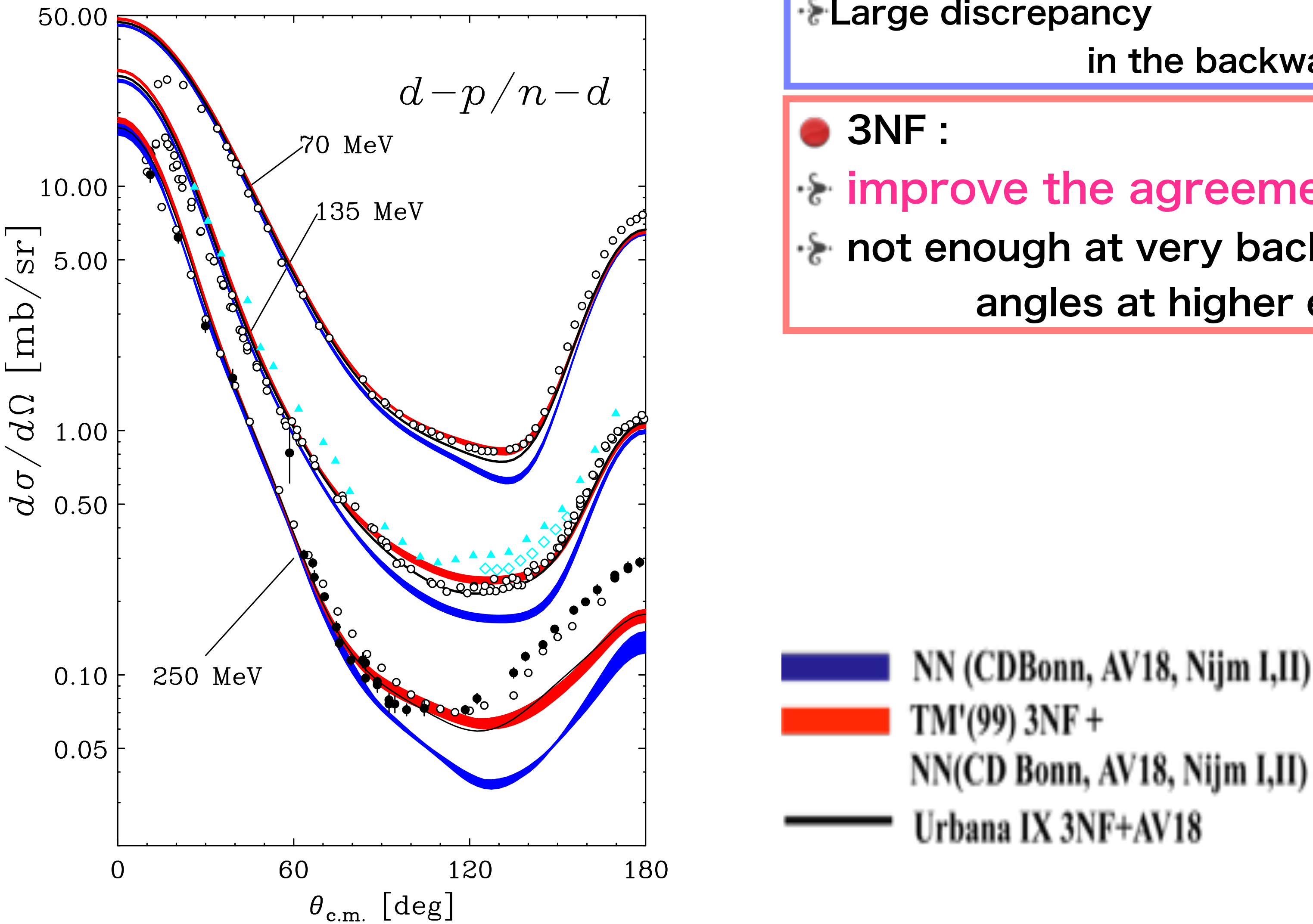
- High precision data of
  - *dσ/dΩ* & Spin Observables
    - from RIKEN, RCNP, KVI, IUCF
- Energy dependent data
  - ✓ *dσ/dΩ*
  - ✓ Proton Analyzing Power
  - ✓ Deuteron Analyzing Powers

dp elastic scattering

Cross Section

K.S. et al., Phys. Rev. C. 65,034003 (2002)
K.Hatanaka et al., Phys. Rev. C 66,044002 (2002)
K.S. et al., Phys. Rev. Lett. 95,162301 (2005)
Y. Maeda et al., Phys. Rev. C 76,014004 (2007)

Differential Cross Section at 70 - 250 MeV/nucleon

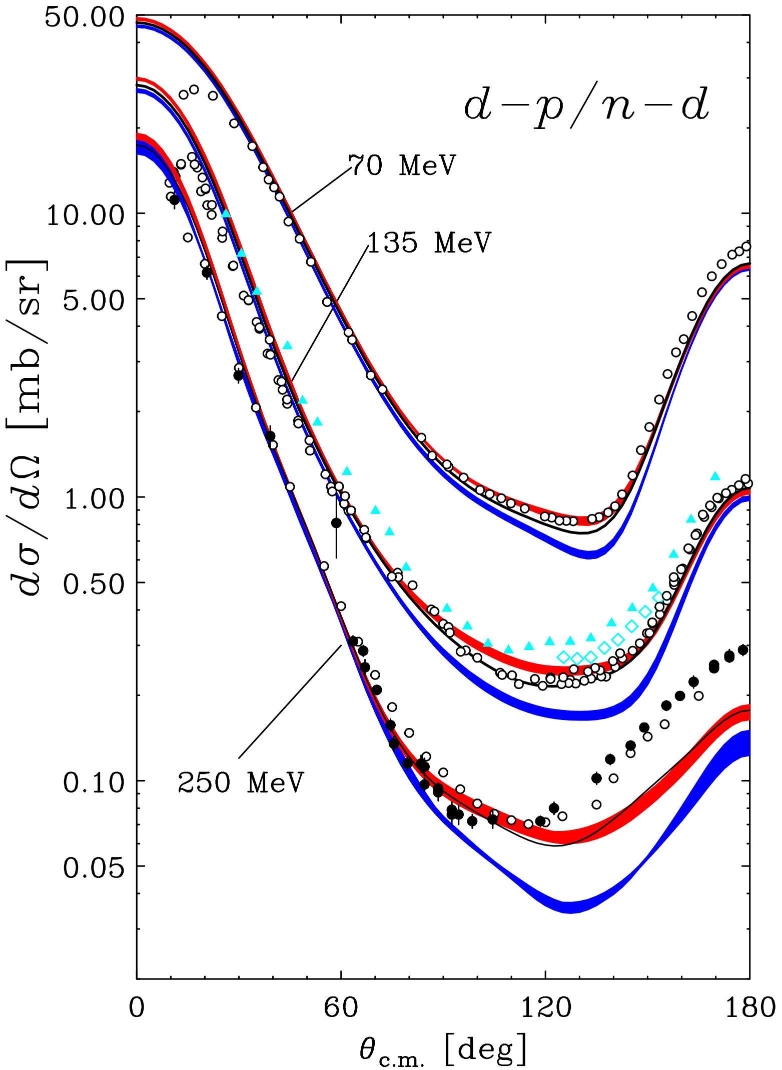


- NN only
  - Large discrepancy in the backward region

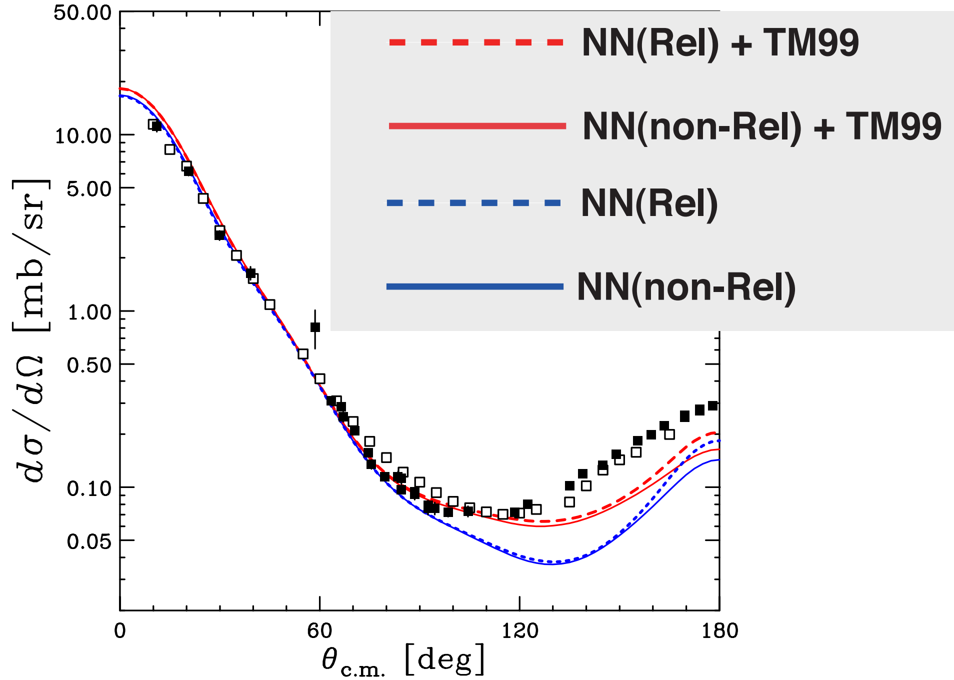
- 3NF :
  - improve the agreement
  - not enough at very backward angles at higher energies

Differential Cross Section at 70 - 250 MeV/nucleon

Relativistic Faddeev Calculations with TM'99 3NF



pd/nd @ 250 MeV



Relativistic effects are visible at backward angles, but small.

Backward angles :

Shorter range 3NFs ?

Other dynamics ?

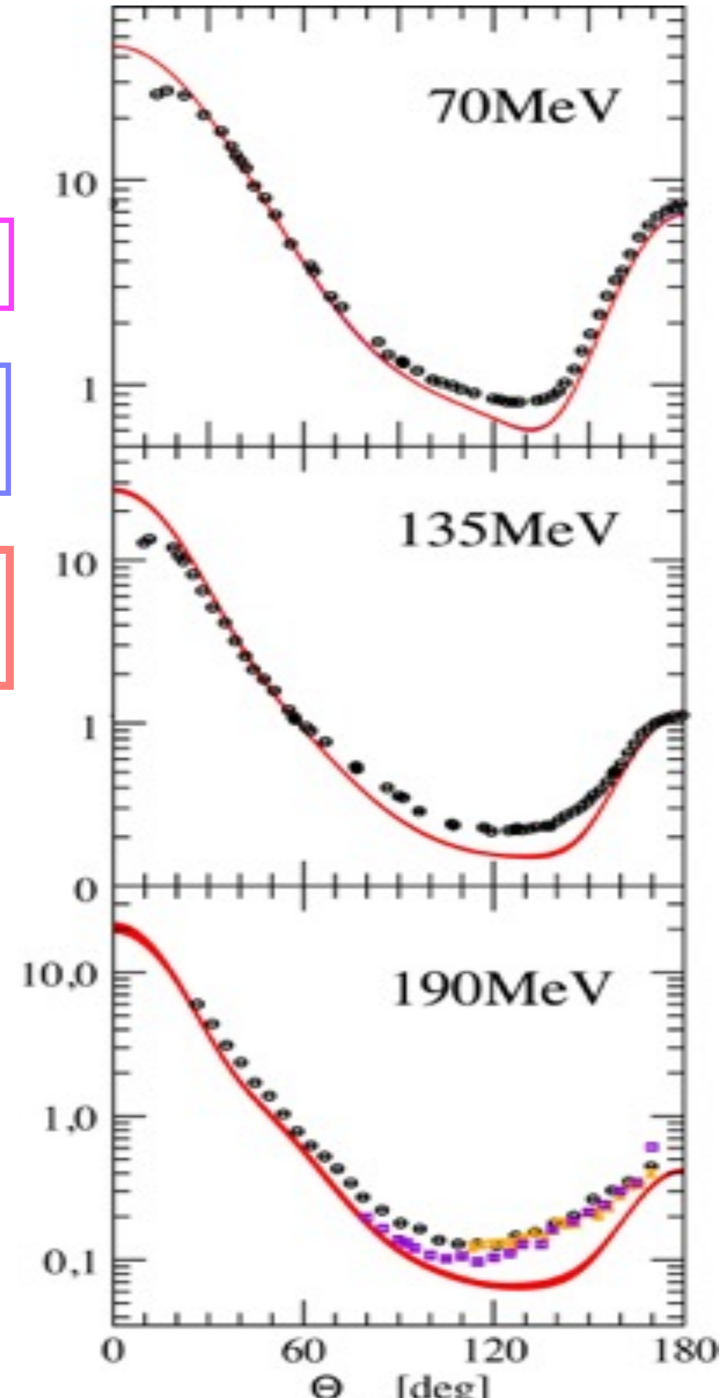
K. Sekiguchi et al., Phys. Rev. C89, 064007 (2014)

Differential Cross Section at 70 - 190 MeV/nucleon

Chiral EFT NN potential (N4LO)

● NN only
Large discrepancy in the backward region

● It is very interesting to see how χEFT 3NFs describe the cross section !



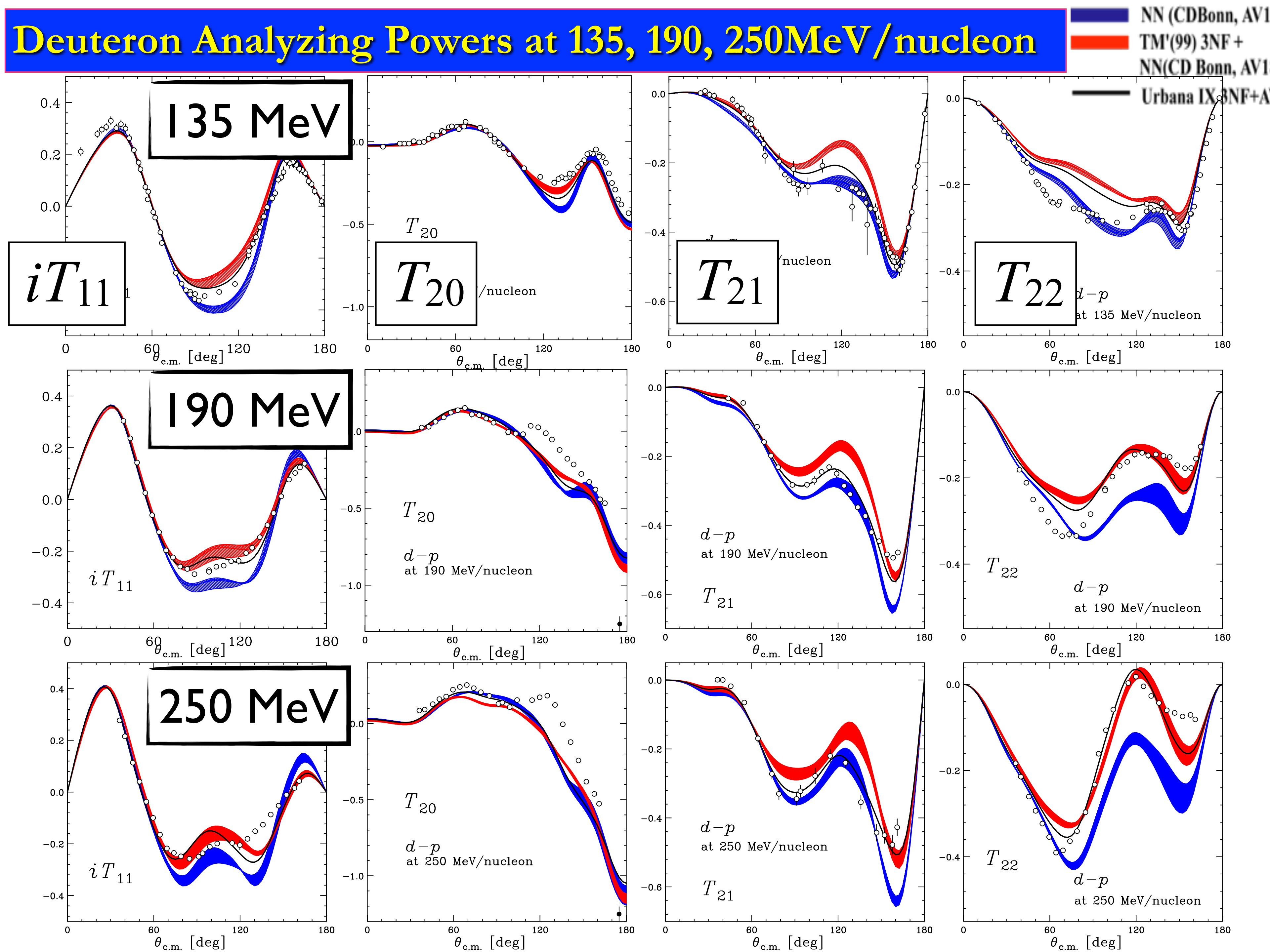
K. Sekiguchi et al., Phys. Rev. C96, 064001 (2017)

dp elastic scattering

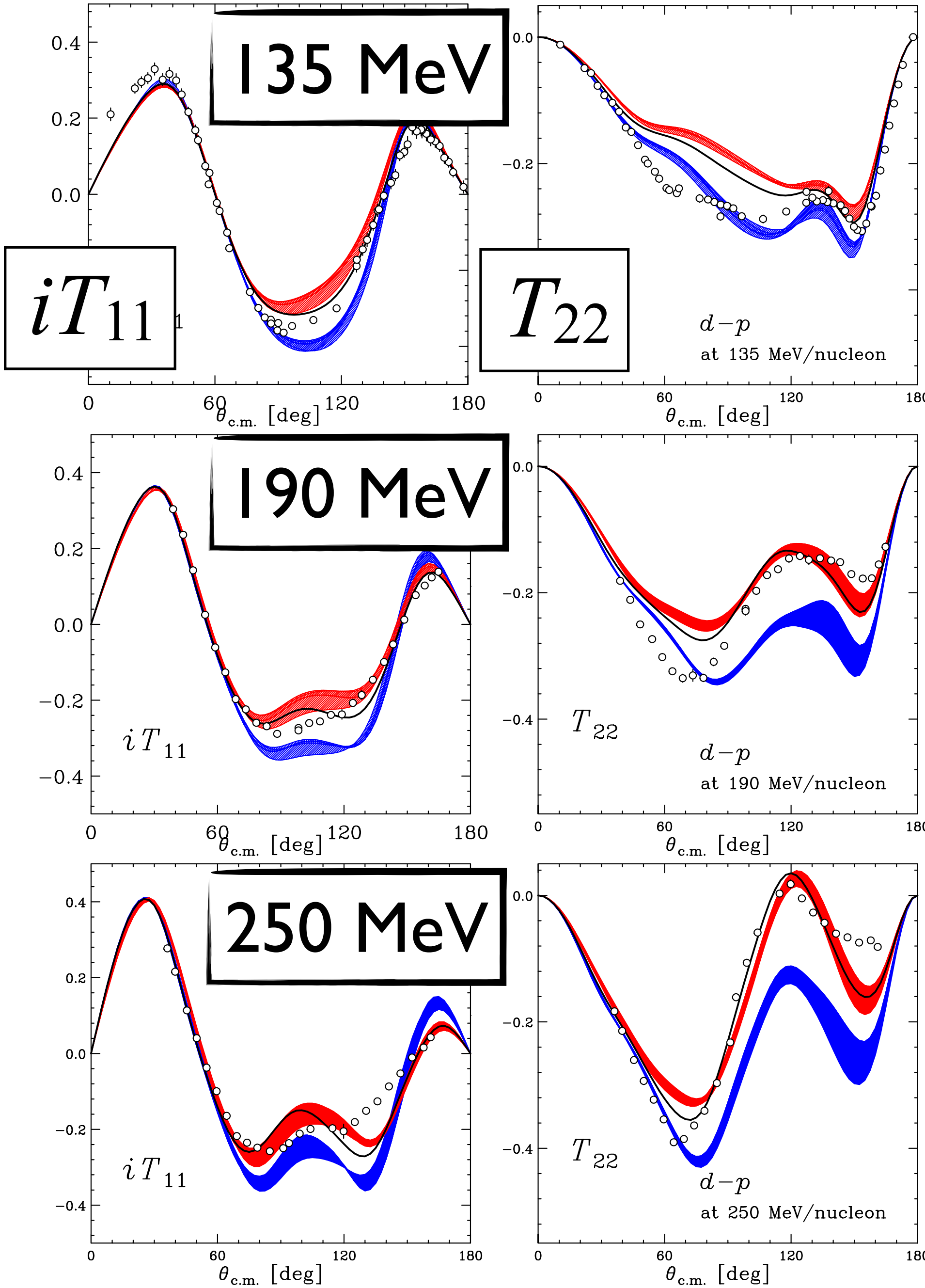
Spin Observables
(Analyzing Powers)

K.S. et al., Phys. Rev. C 89,064007 (2014) etc.

Deuteron Analyzing Powers at 135, 190, 250MeV/nucleon



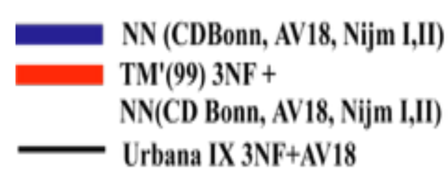
Deuteron Analyzing Powers at 135, 190, 250MeV/nucleon



NN only
- Large discrepancy in the backward angles

+ 2π 3NF at 135 MeV
- results are NOT always similar to the cross section.

+ 2π 3NF at 190, 250 MeV
- improve the agreement
- not enough at very backward angles



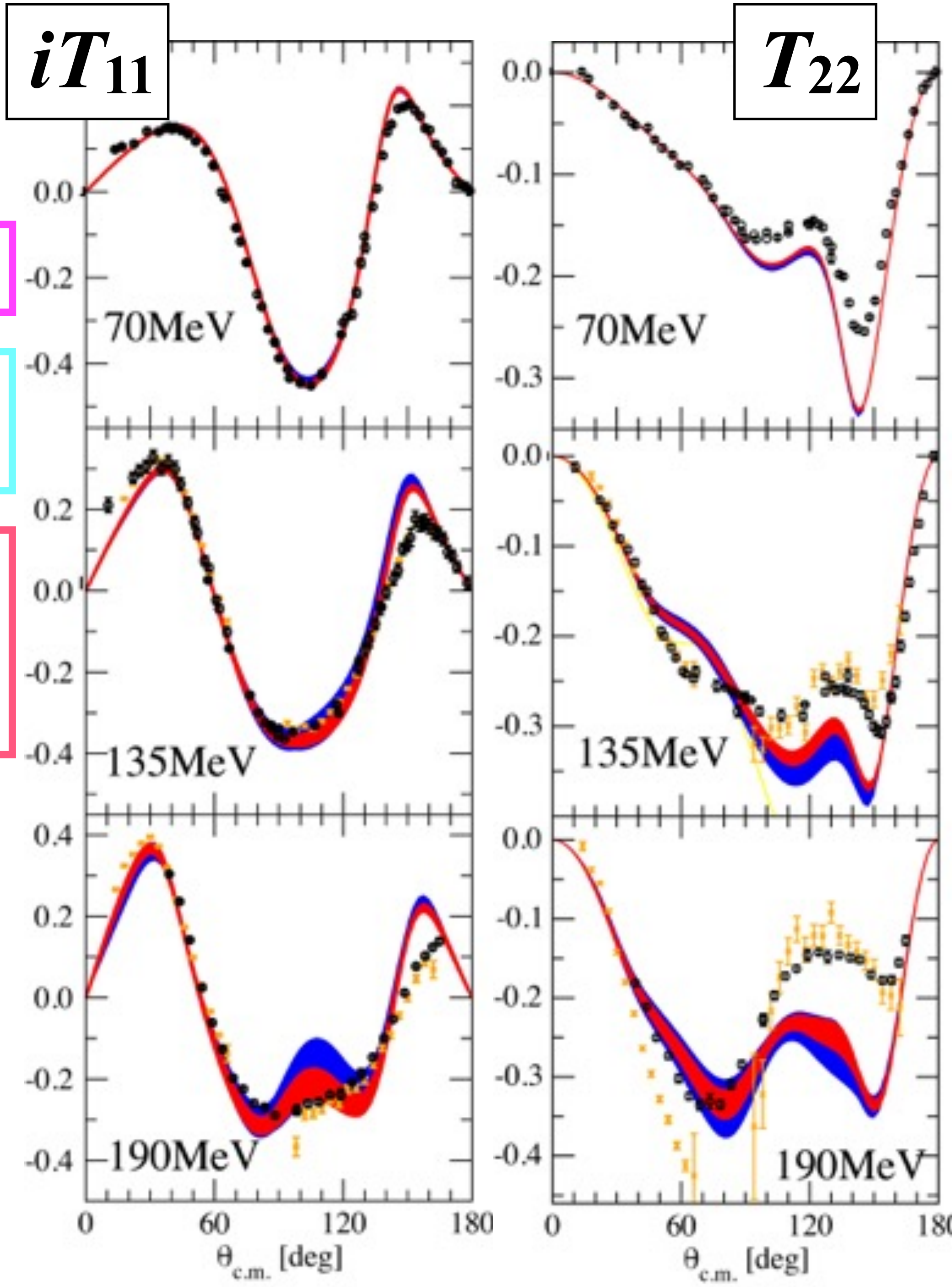
Analyzing Powers at 70 - 190 MeV/nucleon

Chiral EFT N3LO & N4LO NN pot.

Vector analyzing power (iT_{11}) :
Good agreements to NN forces

Large discrepancies
in Tensor analyzing powers (T_{22})

→ Rooms for 3NFs



Results of Comparison - dp elastic scattering -

- Cross Section :
  - **3NFs are clearly needed.**

- Spin Observables :
  - Not always described by adding 3NFs
  - 3NF effects are spin dependent.

- **Serious discrepancy at backward angles at higher energies**

  : Short-range terms of 3NFs ?

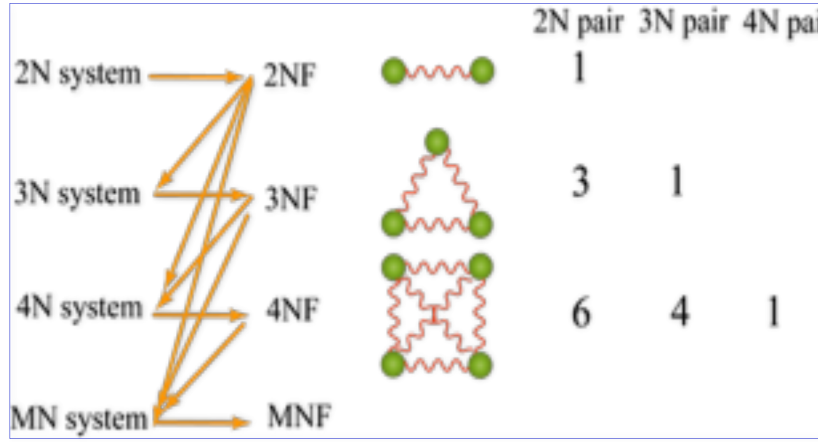
- **It is interesting to see how χEFT NN+NNN potentials explain the exp. data.**

$p + {}^3$He scattering

- Next Step -

$p+{}^3$He scattering

- **4-nucleon scattering**
  First Step from Few to Many



- **Approach to iso-spin dependence of 3NFs**
  T=3/2 3NFs

- **Large 3NF effects**
  in cross section minimum at intermediate energies

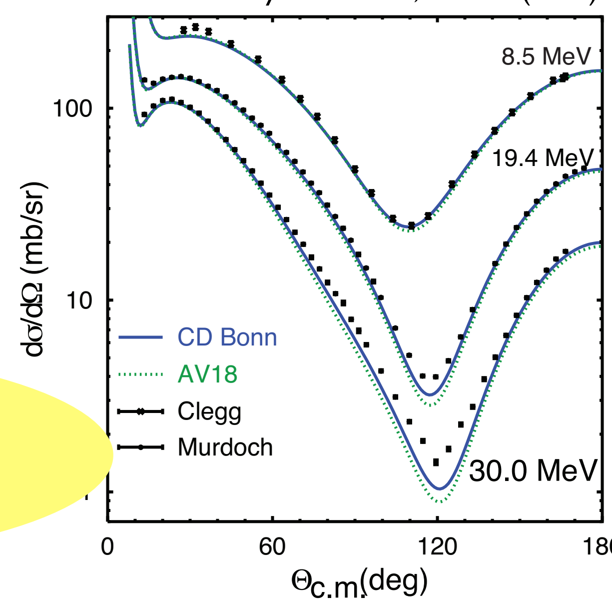
- **4NF effects**

Theory in Progress

Calculations above 4-body breakup threshold energy
open new possibilities of 3NF study in 4N scat.

Discrepancies in dcs minimum
at higher energies
New rooms for 3NF study

A. Deltuva and A.C. Fonseca
Phys. Rev. C 87, 054002 (2013)

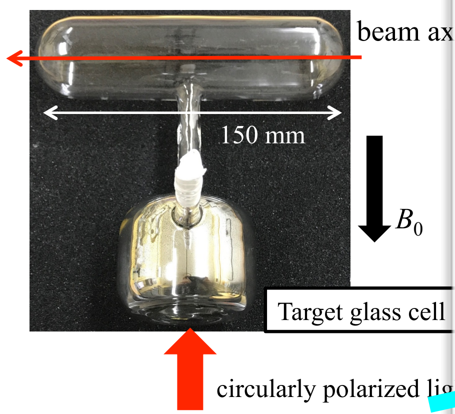


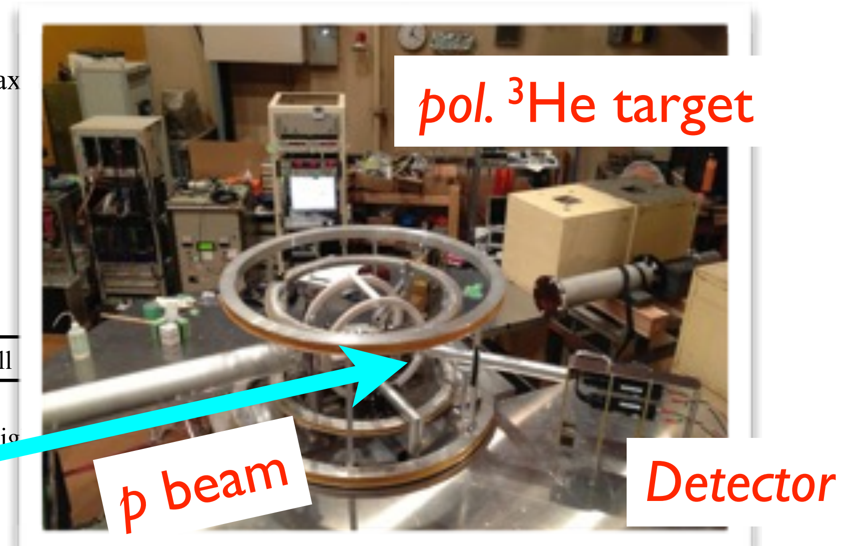
New ^{3}He Analyzing Power exp./data from CYRIC, Tohoku Univ.

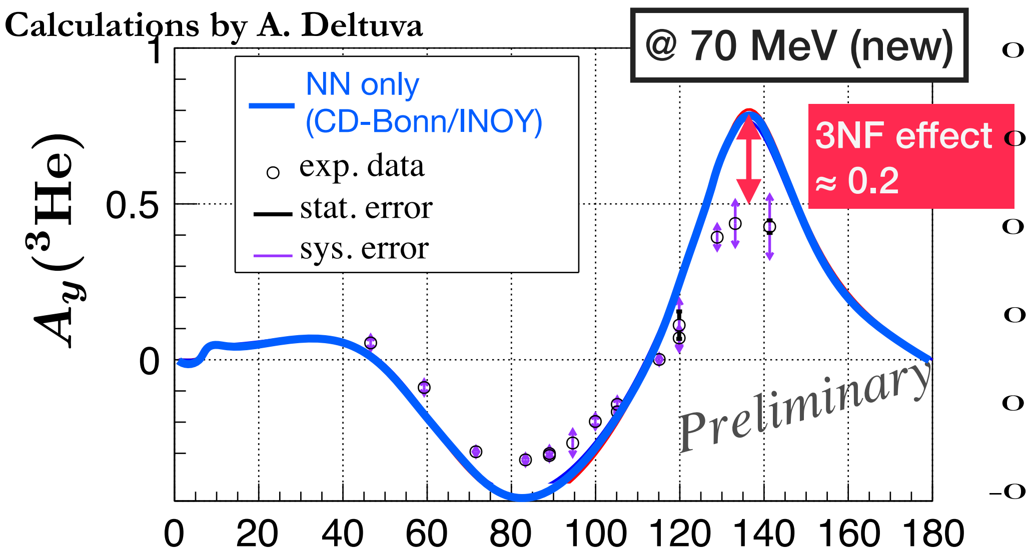
$p + \overrightarrow{^3\text{He}}$ at 70 MeV

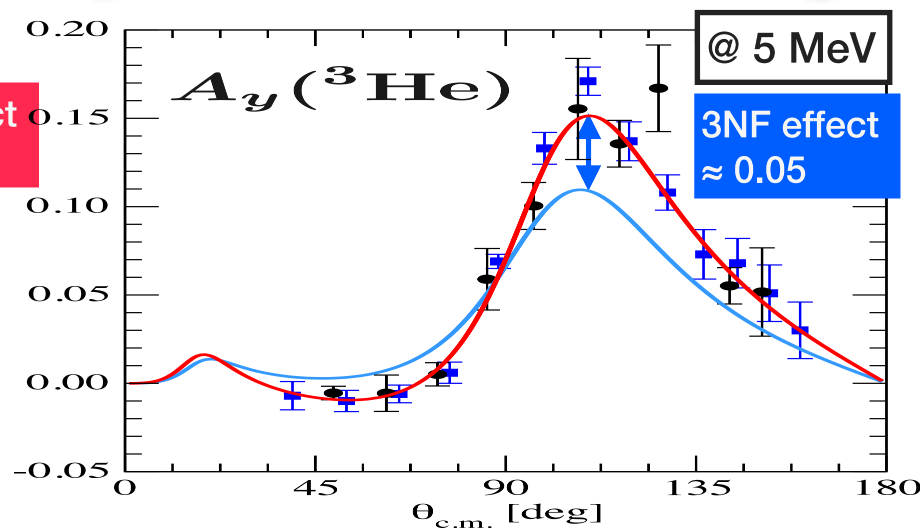
New pol-^{3}He target
- *3 atm (≈2 mg/cm2)*
- *≈50% polarization*

Thanks !
GE180 glass (Target cell)
was provided by
Prof. Wooyoung Kim,
Kyungpook National University, Korea.







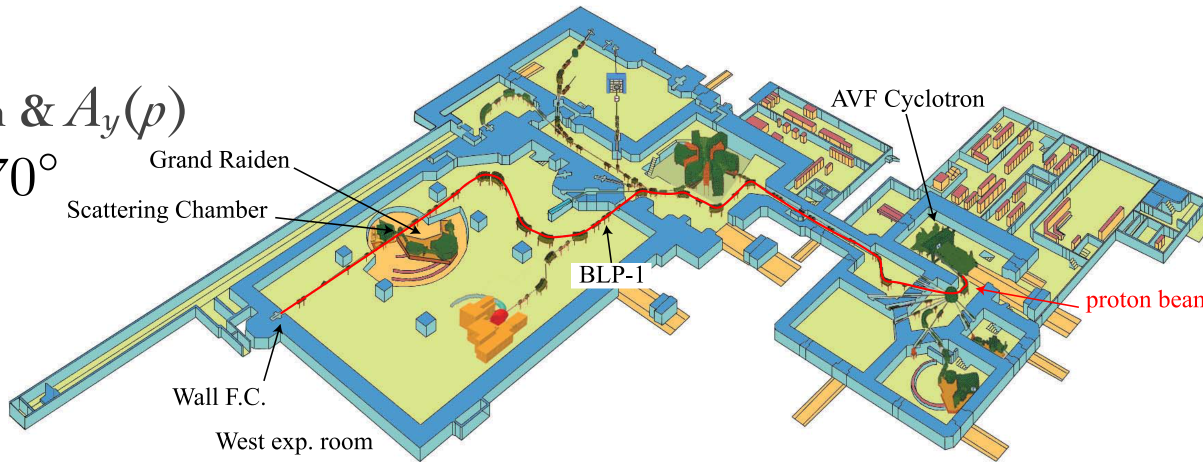


Large 3NF effects are indicated at 70 MeV.

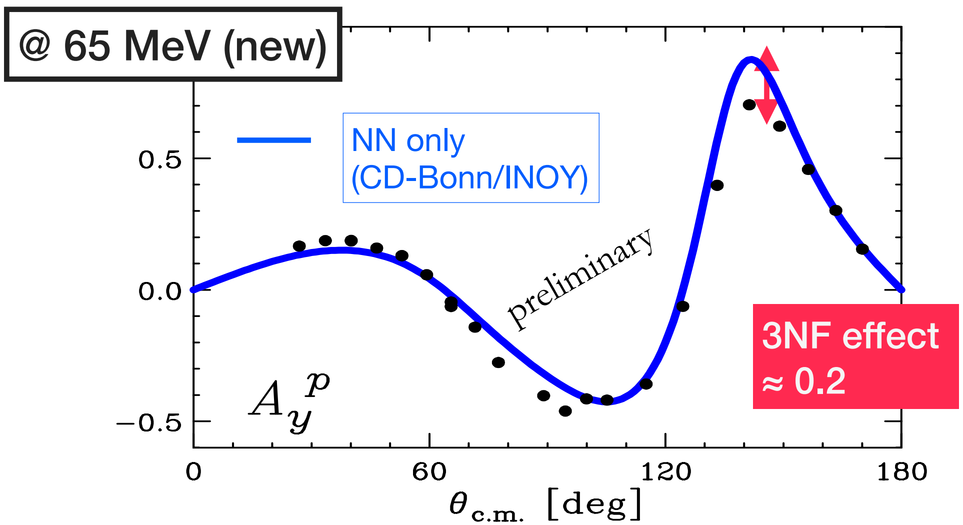
New Proton Analyzing Power exp./data from RCNP, Osaka Univ.

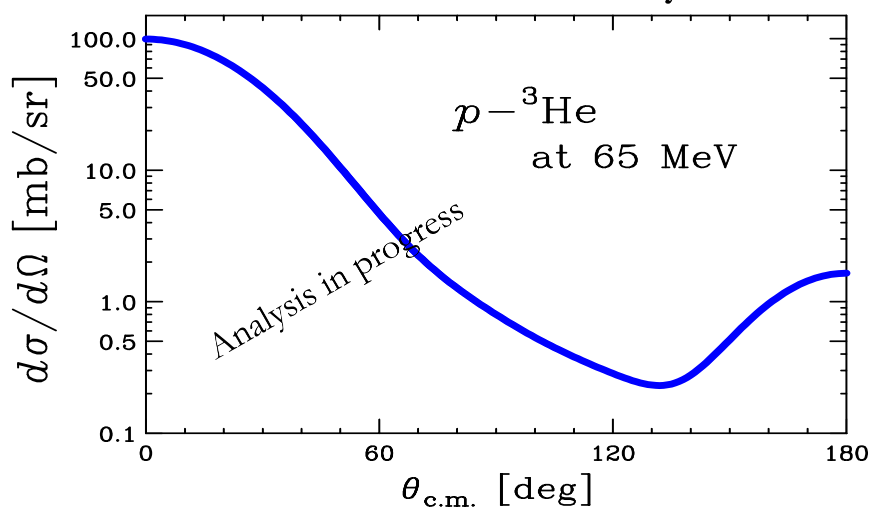
$\vec{p} + {}^3\text{He}$ at 65 MeV

- Observables : Cross section & $A_y(p)$
- Angles : $\theta_{\text{c.m.}} = 27^\circ - 170^\circ$



Calculations by A. Deltuva



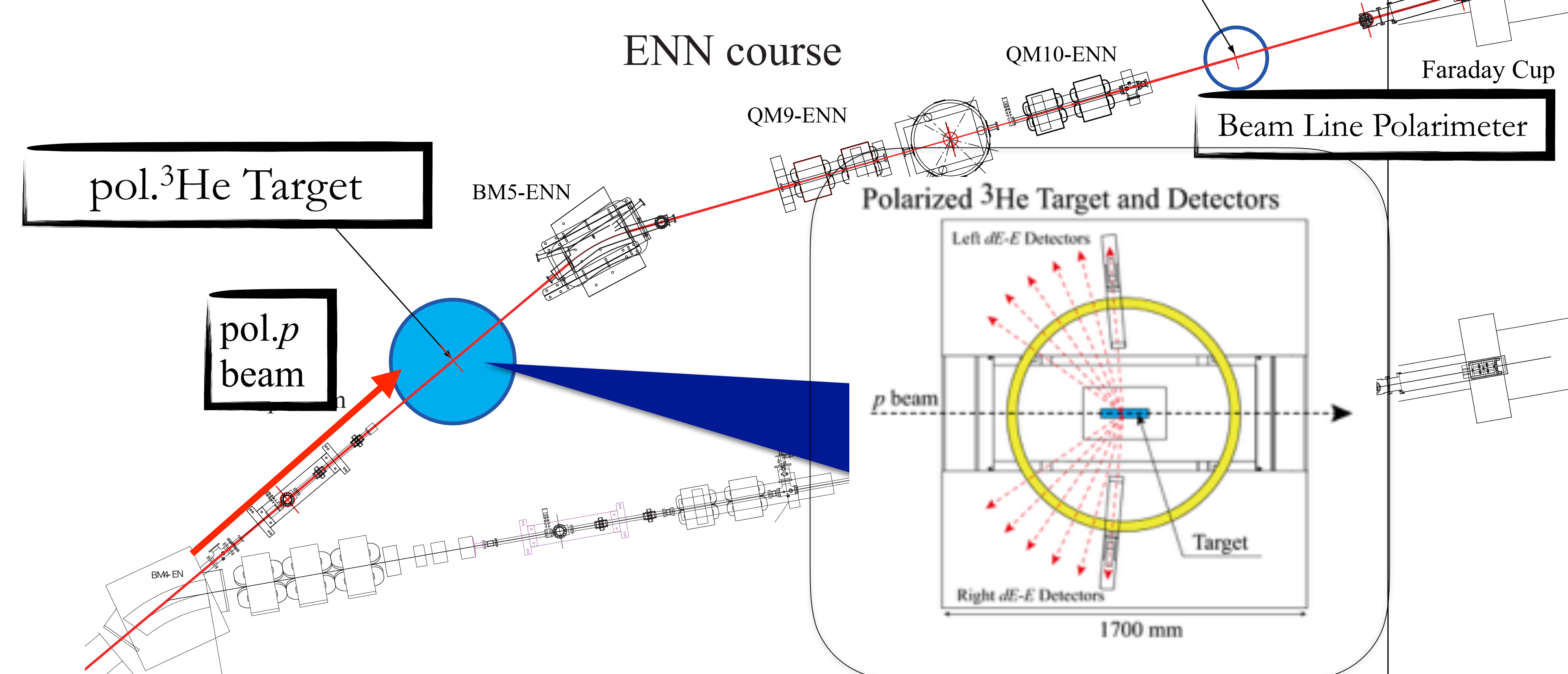


3NF effects can be seen in the cross section minimum.

New Experiment : pol.p+pol.^{3}He at RCNP

- First experiment : p+^{3}He at 135 MeV
  - Observables : $A_y(p)$, $A_y(^3\mathrm{He})$ & $C_{y,y}$
  - Angles : $\theta_{\mathrm{c.m.}} = 47^\circ - 156^\circ$
- Future Planning
  - Energy dependent study (65 - 200MeV)
  - Cross Section & Spin Correlation Coefficients

in preparation



Summary (1/2)

Few-Nucleon Scattering

is a good probe to investigate the dynamics of 3NFs.
- Momentum, Spin & Iso-spin dependence - .

Nucleon-Deuteron Elastic Scattering

Precise data of $d\sigma/d\Omega$ and spin observables at 70- 300 MeV/nucleon from RIKEN/RCNP

Cross Sections : Large discrepancy at backward angles. 3NFs are clearly needed.

Spin Observables : 3NF effects are spin dependent.

Serious discrepancy at backward angles at higher energies : short-range terms of 3NFs ?

It is interesting to see how ChEFT NN+NNN potentials explain the data.

p+^{3}He scattering

- Approach to Iso-spin states of T=3/2 3NF
- Faddeev-Yakubovsky calculations : New possibilities for 3NF study in 4N Scatt.

New Data from CYRIC & RCNP : ^{3}He & p Analyzing powers, & Spin Correlation Coefficient

Summary (2/2)

Future Plan

Nucleon-Deuteron Scattering :
Extend to Measurement of Spin Correlation Coefficients

$p+{}^3He$ Scattering : Energy dependent study
& Other reaction channels : e.g. ${}^3He(p,n)$

Study of 3NF effects in Nuclear Reaction

Study of T=3/2 three-nucleon systems (3p, 3n-states)

RIBF-d Collaboration

Tohoku University

K. Sekiguchi, K. Miki, Y. Wada, A. Watanabe, D. Eto, T. Akieda, H. Kon, J. Miyazaki, T. Taguchi, U. Gebauer, K. Takahashi, T. Mashiko

RIKEN Nishina Center

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

Kyushu University

T. Wakasa, S. Sakaguchi, J. Yasuda, A. Ohkura, S. Shindo, U. Tabata

Miyazaki University

Y. Maeda, T. Saito, S. Kawakami, T. Yamamoto

CNS, University of Tokyo

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

RCNP, Osaka University

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p+^{3}He Collaboration

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CYRIC, Tohoku University

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Kyushu University

T. Wakasa

Miyazaki University

Y. Maeda

RIKEN Nishina Center

H. Sakai, T. Uesaka

NIRS

T. Wakui

$p+{}^3$He scattering

at 5.54 MeV

Theory in Progress

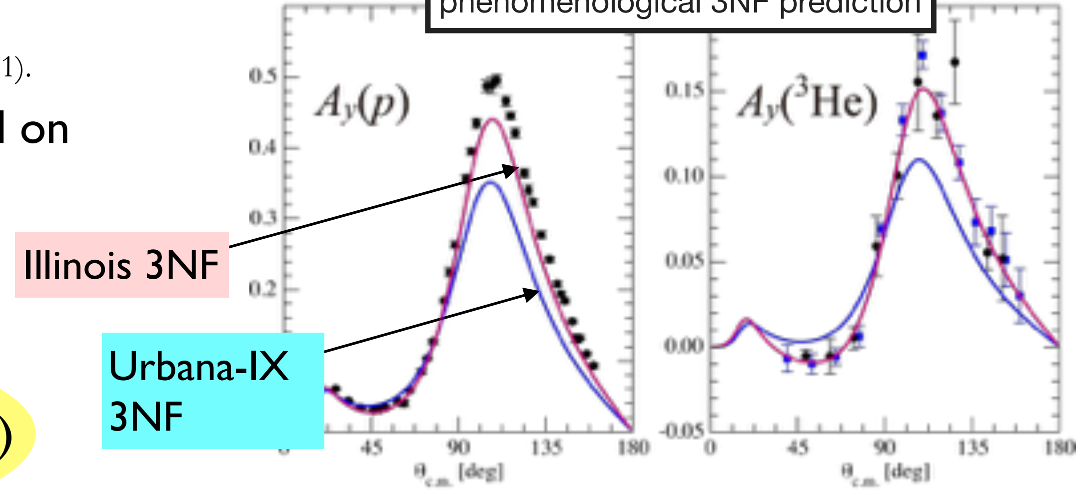
Viviani et al., Phys. Rev. Lett. 111, 172302(2011).

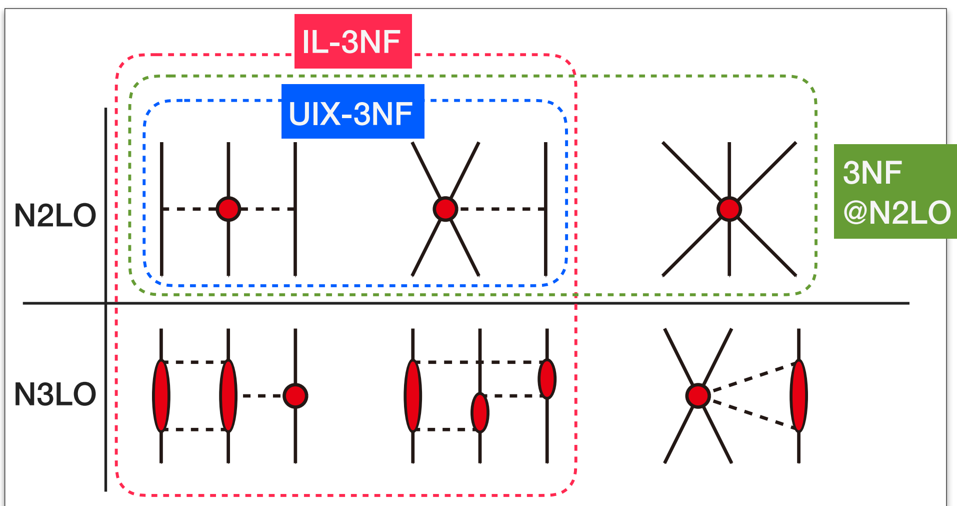
Pisa Gr. succeeds in calculations based on

- AV18 + Illinois 3NF
- χEFT (3NF : N2LO)

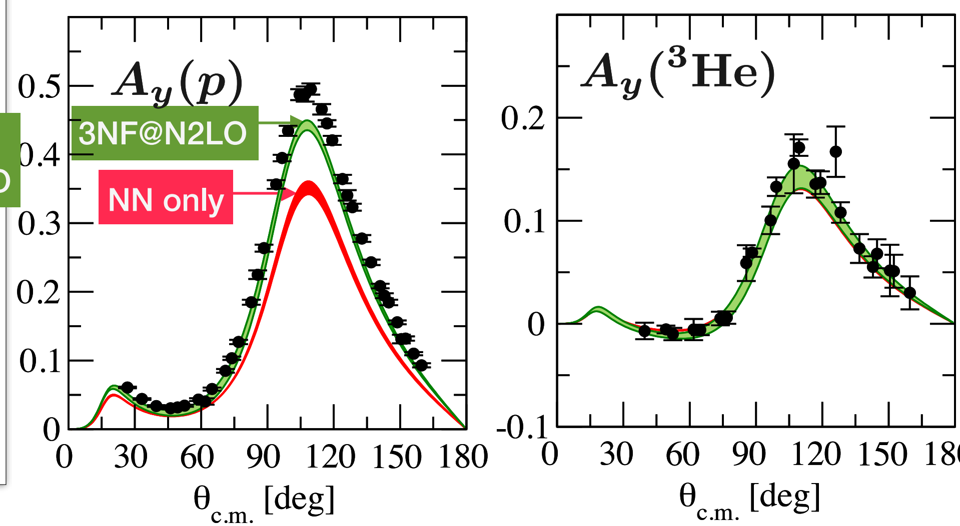
3π-ring with Δ 3NFs are significant for $A_y(p)$ & $A_y({}^3\mathrm{He})$ (Iso-spin dependence).

phenomenological 3NF prediction





chiral EFT prediction up to N²LO



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