2022/11/03

International Symposium on Clustering as a Window on the Hierarchical Structure of Quantum Systems (CLUSHIQ2022)

Study of three nucleon force via proton-^{3}He scattering

1. Introduction
2. Measurement of p-^{3}He Scattering
3. Experimental Results
4. Future Plan
5. Summary

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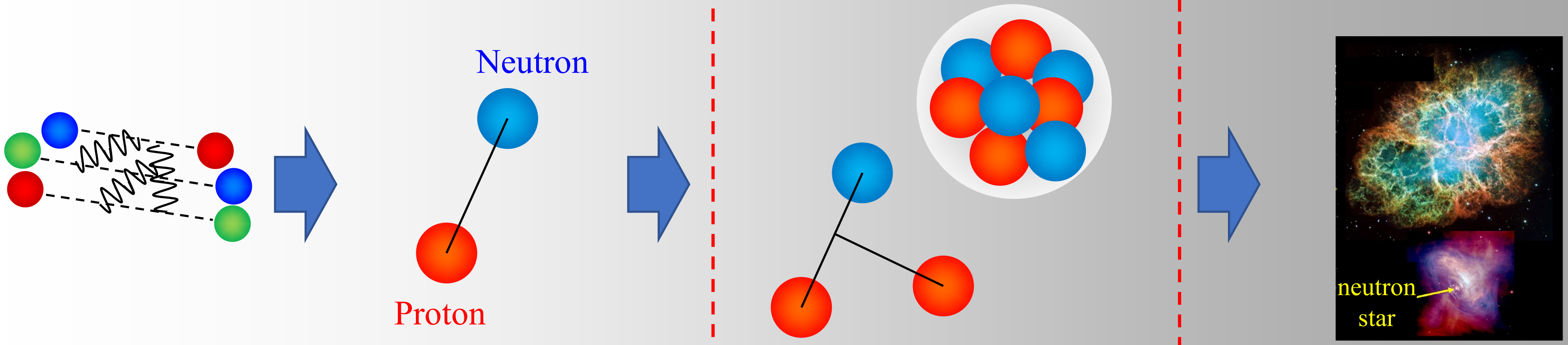
Department of physics

Atomu Watanabe

Study of Nuclear Forces *–from quark to universe–*

Quark | **Nucleon** | **Nucleus** | **Universe**



Quark-gluon interactions

Nucleon-nucleon interactions

Many-nucleon interactions (**Three nucleon forces**)

Supernovae, neutron star, etc…

Consistent understanding from quarks to the universe

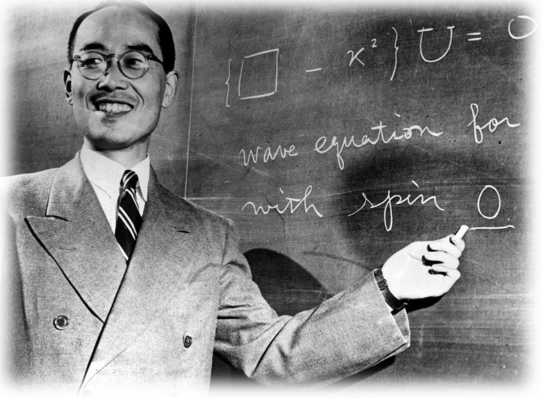
2 & 3 Nucleon Force

Theoretical Description of Nucleon-Nucleon (NN) Force

1935 **Meson exchange picture** by H. Yukawa   Proc. Phys. Math. Soc. Jpn **17**, 48.

1990's **Realistic NN potentials**

→ precisely reproduce 3000–4000 NN scattering data (χ^2/datum$\sim$1)



Hideki Yukawa

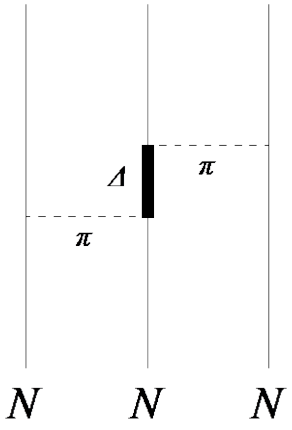
Three-Nucleon Force (3NF)

First theoretical insight by **Fujita** & **Miyazawa** → 2π-exchange 3NF

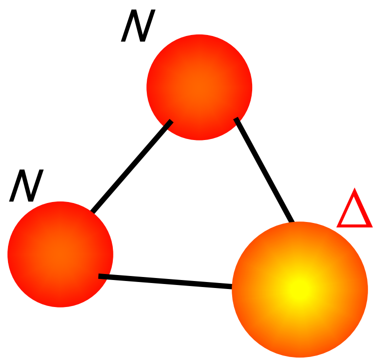
Prog. Theor. Phys. **17**, 360 (1957).

- ✓ Δ-isobar excitation in the intermediate state.
- ✓ 3NFs play important roles in various nuclear properties (e.g., few-nucleon scattering, B.E. of light nuclei, and nuclear matter).

3NF is a key to understand nuclear phenomena



2π-exchange 3NF diagram



Δ : exited state of N

Few-Nucleon Scattering

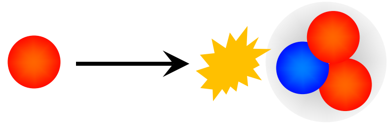
A **good probe** to study the dynamical aspects of 3NFs.
- ✓Momentum dependence
- ✓Spin & Iso-spin dependence

Direct Comparison

Theory : Faddeev (-Yakubovsky) eq., etc…

Rigorous numerical calc. for 3, 4N system

with 2NF, 3NF inputs



Exp. : Precise Data

Cross section, Spin observables ($\boldsymbol{A_i}$, $\boldsymbol{C_{ij}}$, $\boldsymbol{K_{ij}}$)

We can extract **fundamental information of Nuclear Forces !**

Where can we find 3NFs?

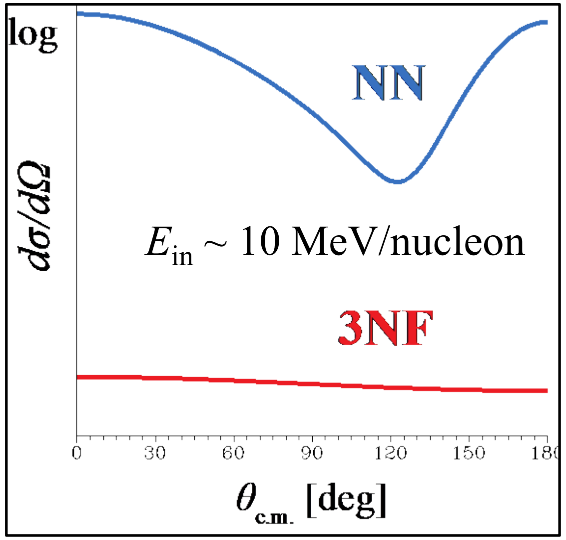
Nucleon-Deuteron Scattering

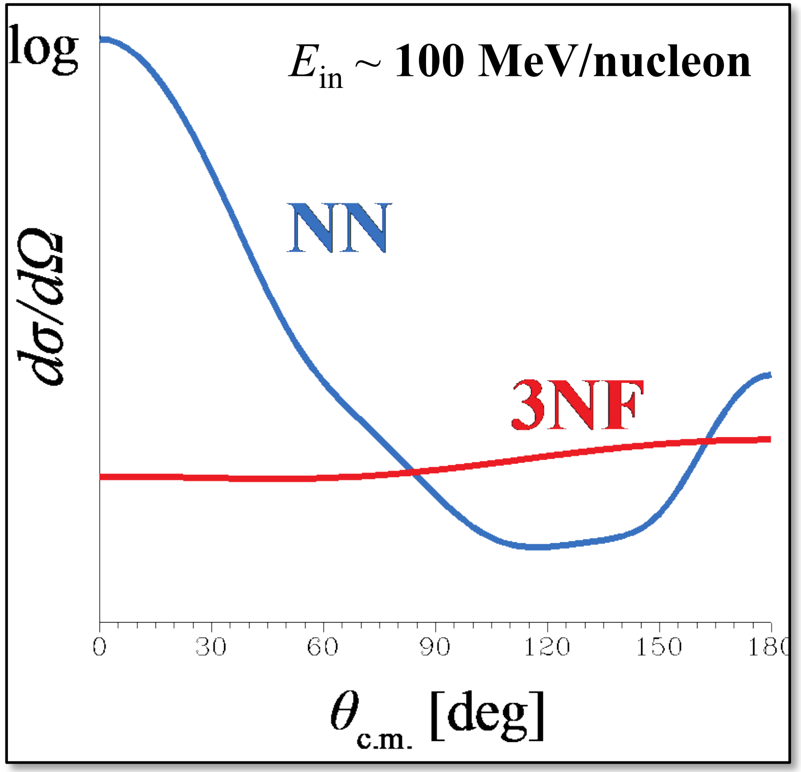
H. Witala *et al*., Phys. Rev. Lett. **81**, 1183 (1998).

✎ H. Witala *et al*. predicted that 3NF effects are seen in the cross section minimum at around **100 MeV/nucleon**.

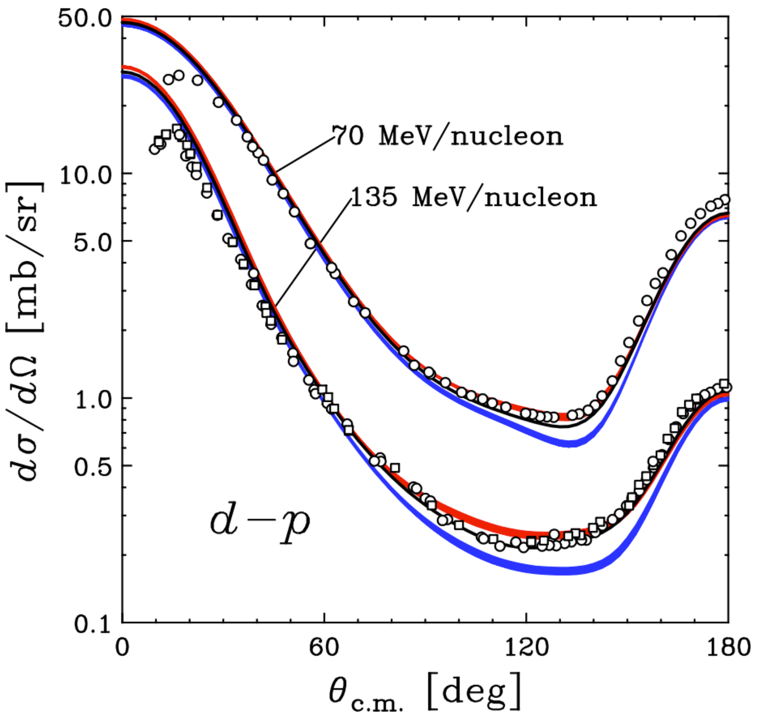
@Higher energy

@Low energy

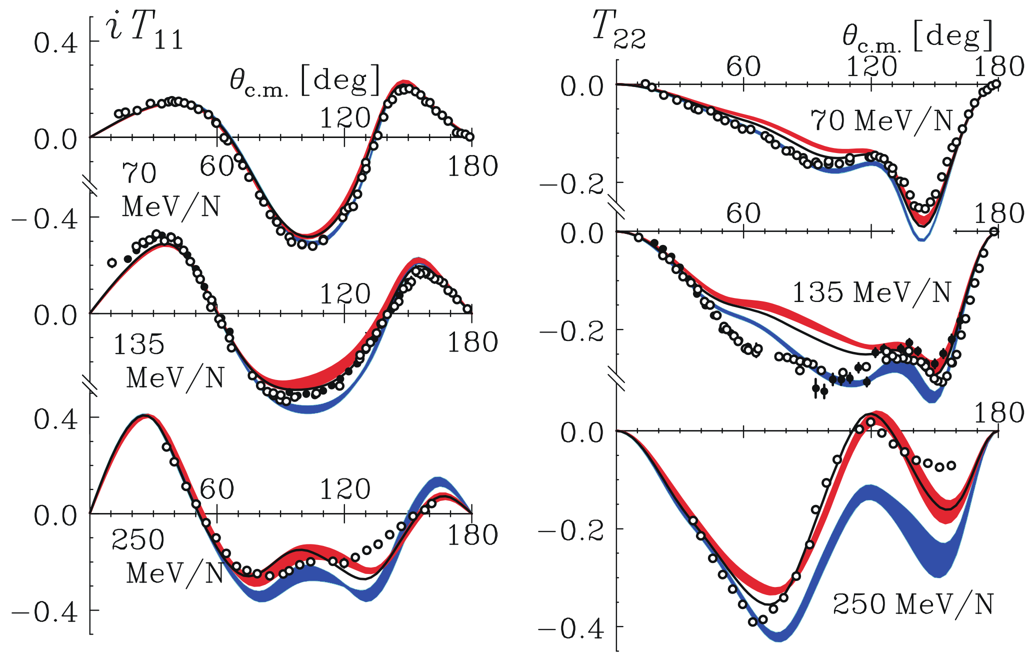




3NF Study via ***d+p* Elastic Scattering** at 70–300 MeV/u



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



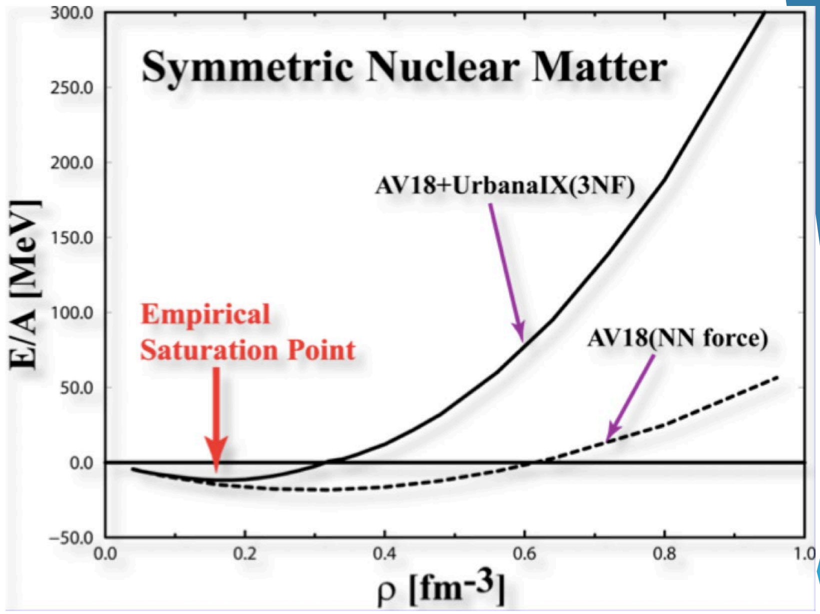
2NF (AV18, CDB, Nijm I,II)
2NF + 3NF (TM'99)
Urbana IX + AV18

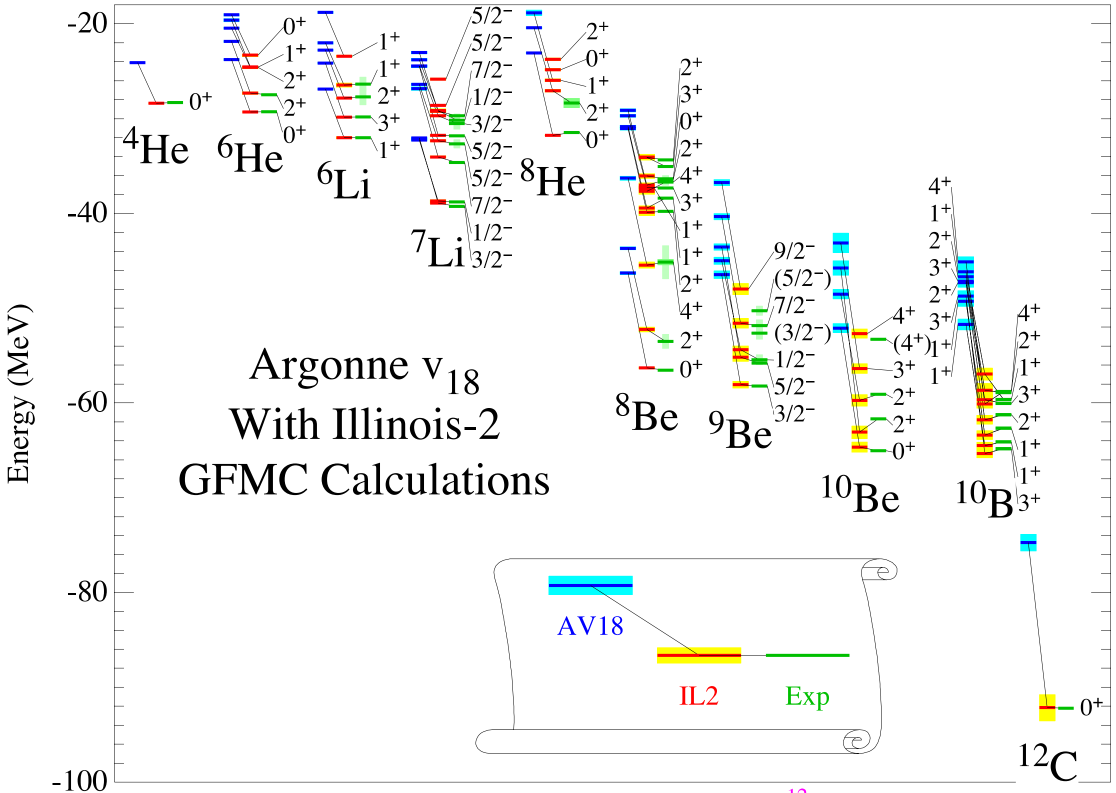
- Differential Cross Section ***dσ/dΩ***
  - 3NFs are clearly needed.
- Spin Observables (iT_{11}, T_{20}, T_{21}, T_{22}, $K_{ij}^{l'}$)
  - The data are partially reproduced by including 3NFs.

→ Solid basis to explore the 3NF properties

$T = 3/2$ channel of 3NFs

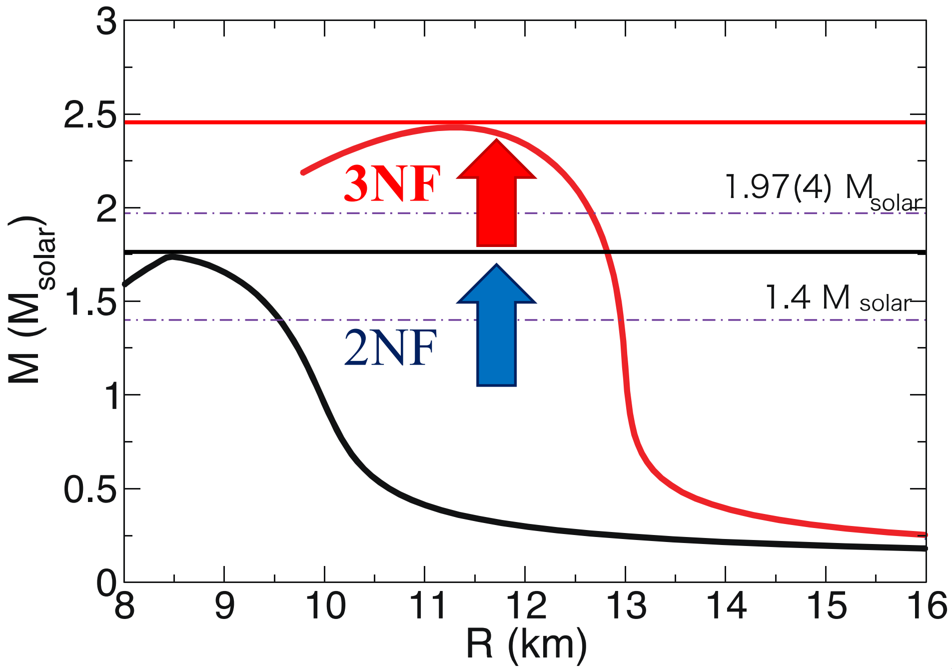
- Important roles for Neutron-rich nuclei, Neutron matter, etc. ...
- Total isospin channel of 3NFs is limited to $T = 1/2$ for $d + p$.





12C IL2 result is preliminary.

S. C. Pieper *et al.*, NPA **751**, 516 (2005).



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

3NF Study via p-^{3}He Scattering

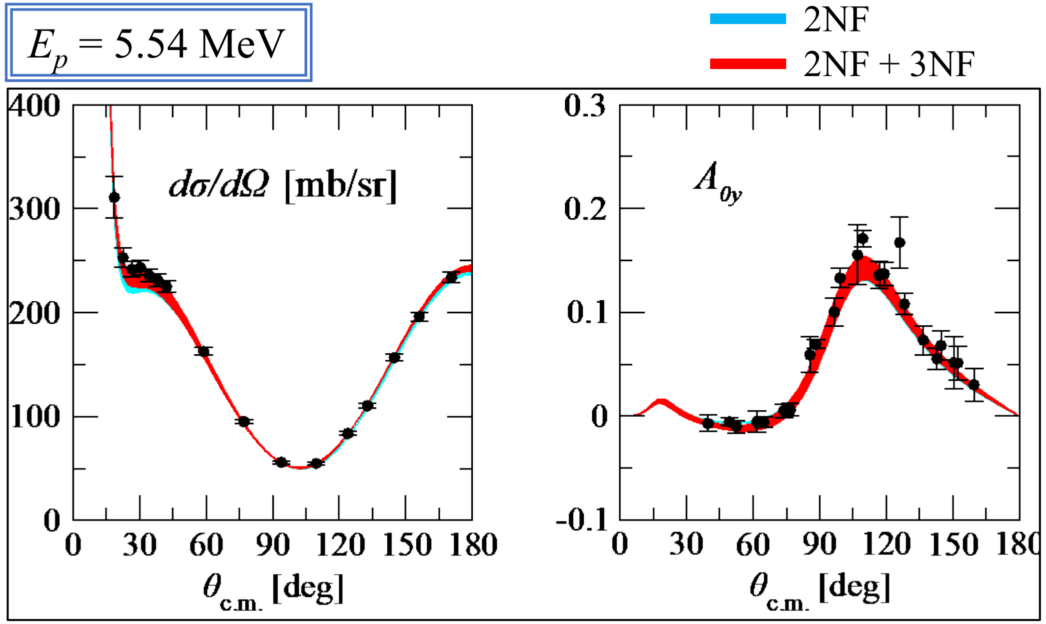
Measurement of p+^{3}He system ($E_p \geq 65$ MeV)

- First Step from few to many nucleon systems
- Approach to iso-spin dependence of 3NFs (T = 3/2 3NFs)
- Theory in progress…

Observables

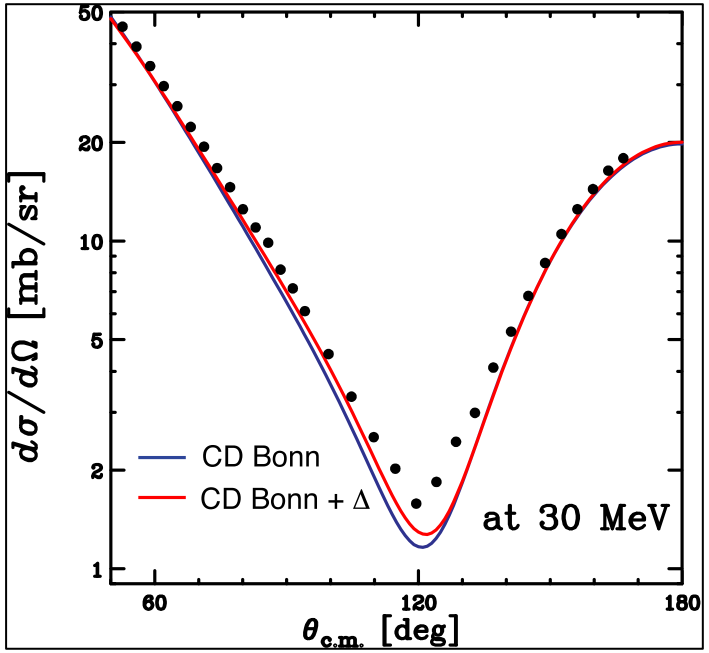
Cross section,
Analyzing powers,
Spin correlation coefficients.

E_p = 5.54 MeV



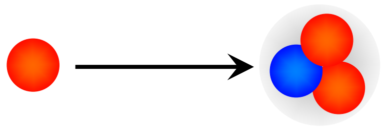
M. Viviani *et al.*, PRL **111**, 172302 (2013).

up to 30 MeV



A. Deltuva and A. C. Fonseca, PRC **87**, 054002 (2013).

Measurements of proton-^{3}He Scattering



E_p = 65, 70, 100 MeV

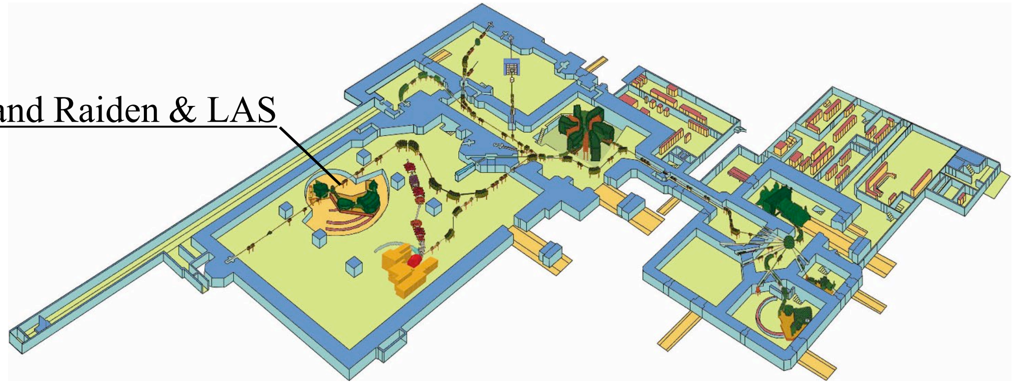
Reported in “AW *et al*., Phys. Rev. C **103**, 044001 (2021)” for 65, 70 MeV.

Paper of the measurement at 100 MeV has been accepted to PRC.

Summary of Measurement for p+^{3}He

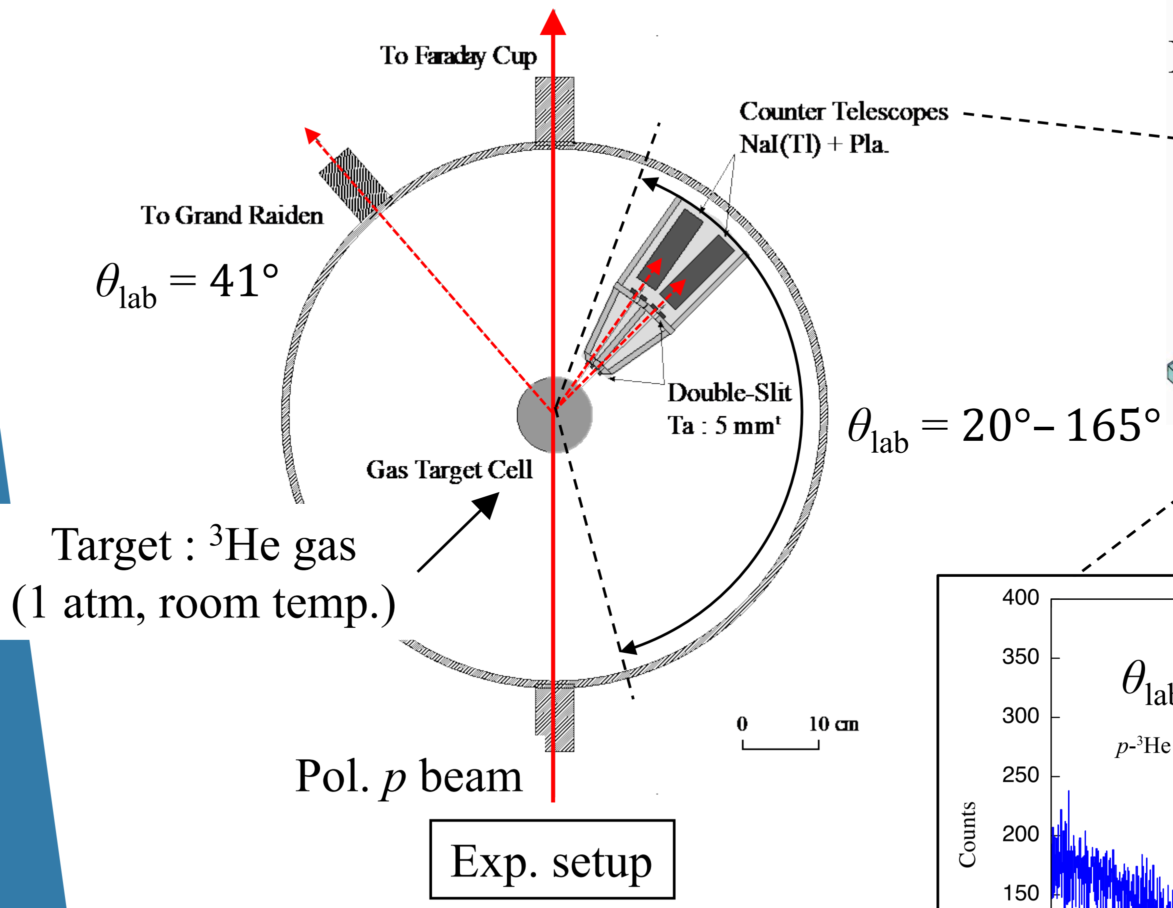
Incident Energy	70 MeV	65 MeV	65 MeV	100 MeV
Beam	p	pol. p	pol. p	pol. p
Observables	$A_y(^3\mathrm{He})$	$d\sigma/d\Omega$, $A_y(p)$	$A_y(p)$, $A_y(^3\mathrm{He})$, $C_{y,y}$	$A_y(p)$, $A_y(^3\mathrm{He})$, $C_{y,y}$
Measured Angles ($\theta_{\mathrm{c.m.}}$)	46°– 141°	27°– 170°	46°– 133°	47°– 149°
Facility	**CYRIC**, Tohoku Univ.	**RCNP**, Osaka Univ.	**RCNP**, Osaka Univ.	**RCNP**, Osaka Univ.
Exp. Course	41 course	WS course	ENN course	ENN course

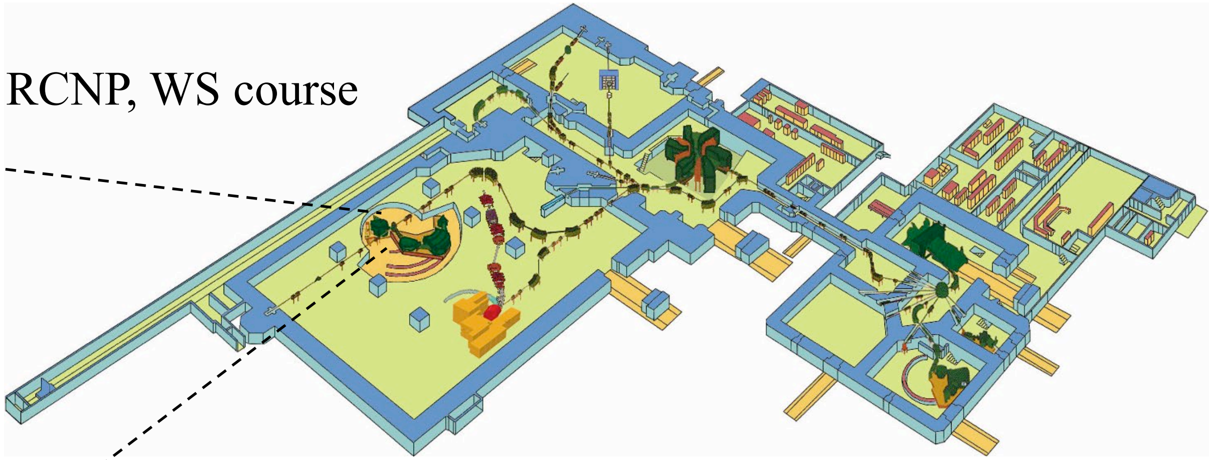
CYRIC (AVF cyclotron)

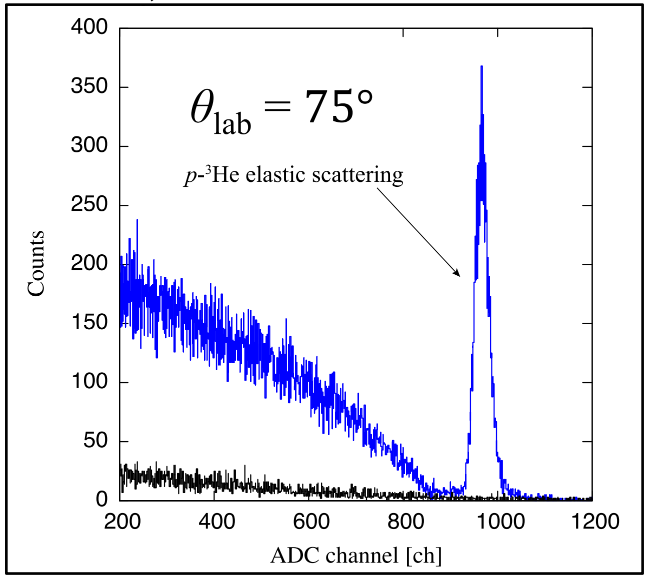


RCNP

Measurement of Differential Cross Section





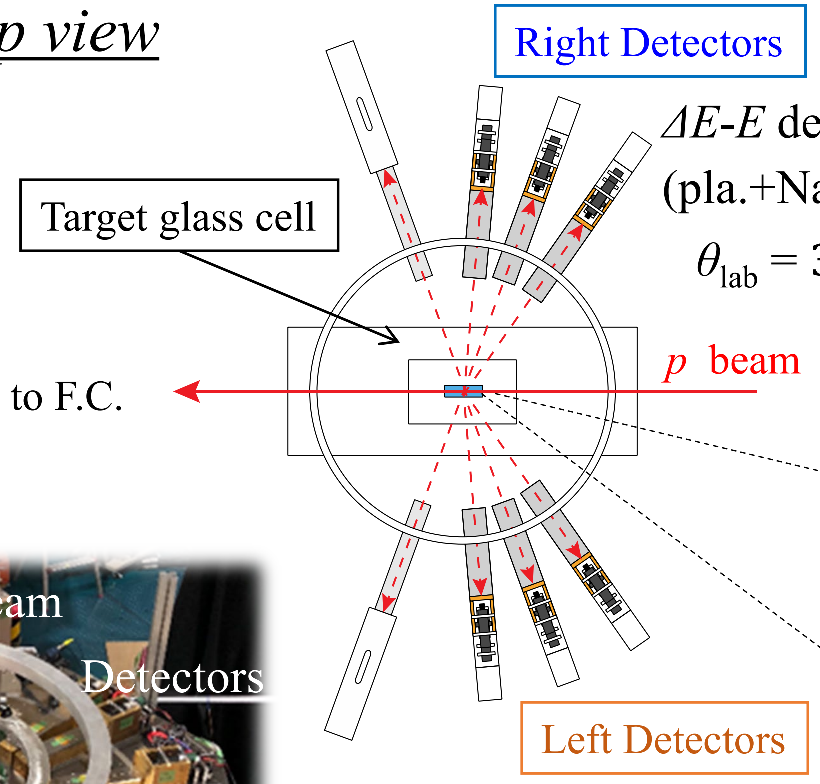


Grand Raiden & LAS

Experimental Setup with Pol. ^{3}He Target

@CYRIC, RCNP

Top view



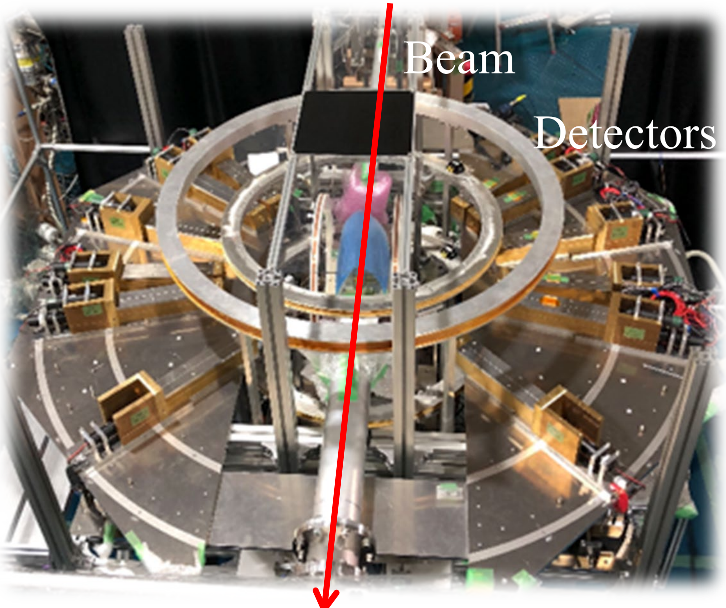
ΔE-E detectors
(pla.+NaI(Tl) scinti.)
θ_{lab} = 35°– 135°

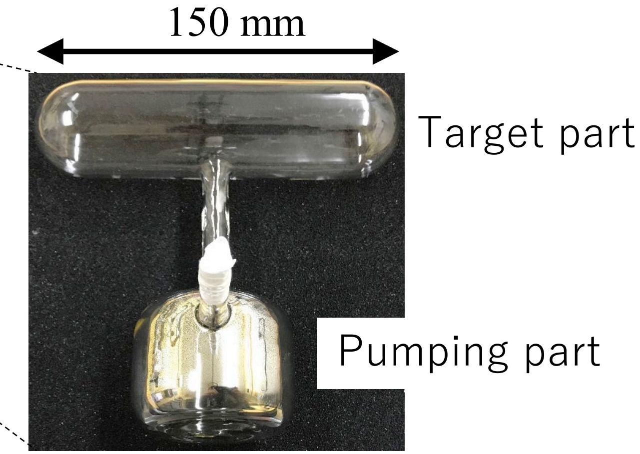
Pol. ^{3}He Target

Method: AH-SEOP

Target cell: GE180 glass

Typical pol.: ~40%



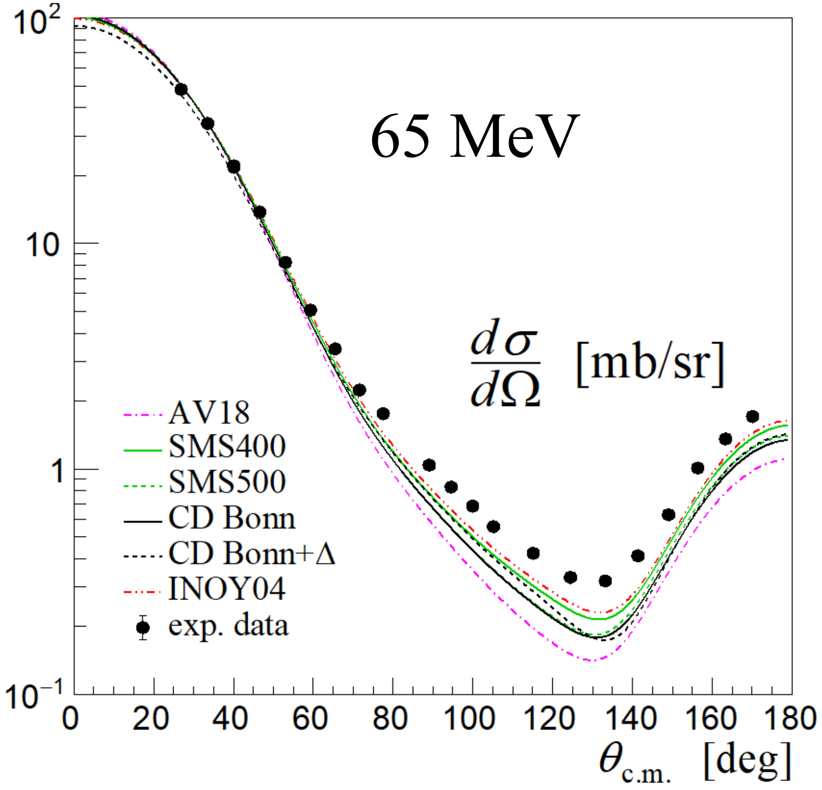


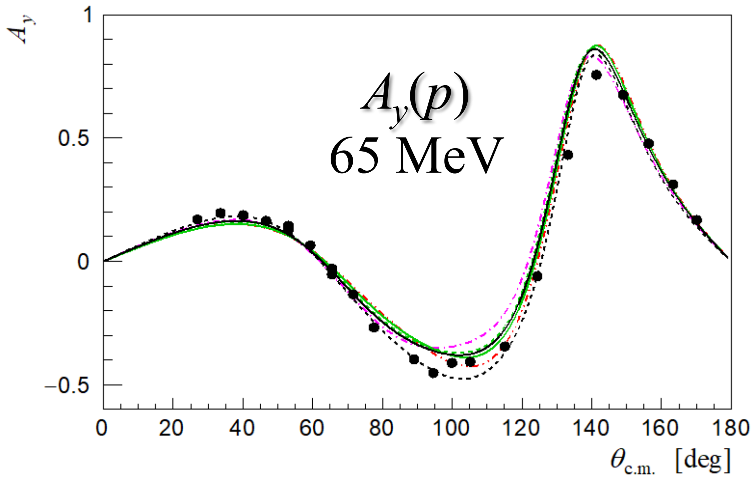
Target glass cell

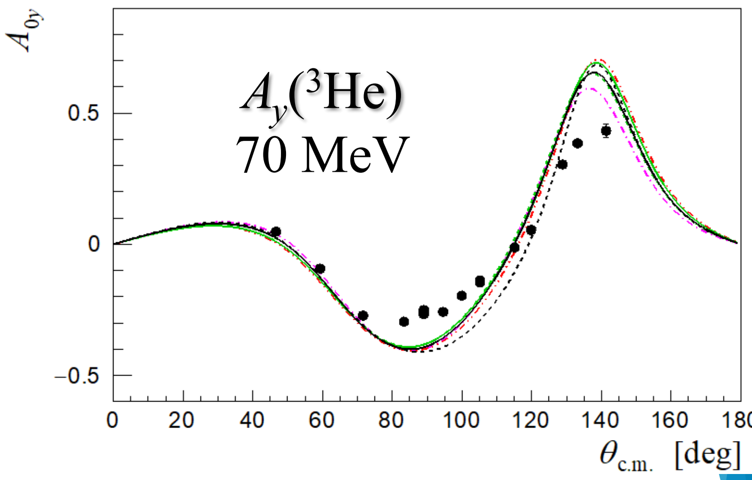
- ^{3}He gas : 3 atm, ~2 mg/cm^2
- N_2 gas : ~ 0.1 atm
- A small amount of Rb, K

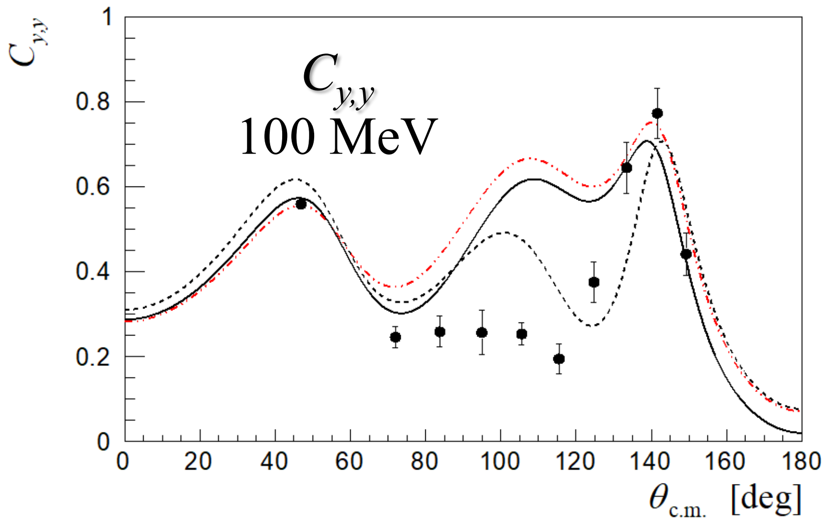
Experimental Results for p+^{3}He

*Calculations : A. Deltuva, private communications









AV18, CD-Bonn : Realistic NN potential

INOY04 : reproducing ^{3}H, ^{3}He B.E. w/o 3NFs

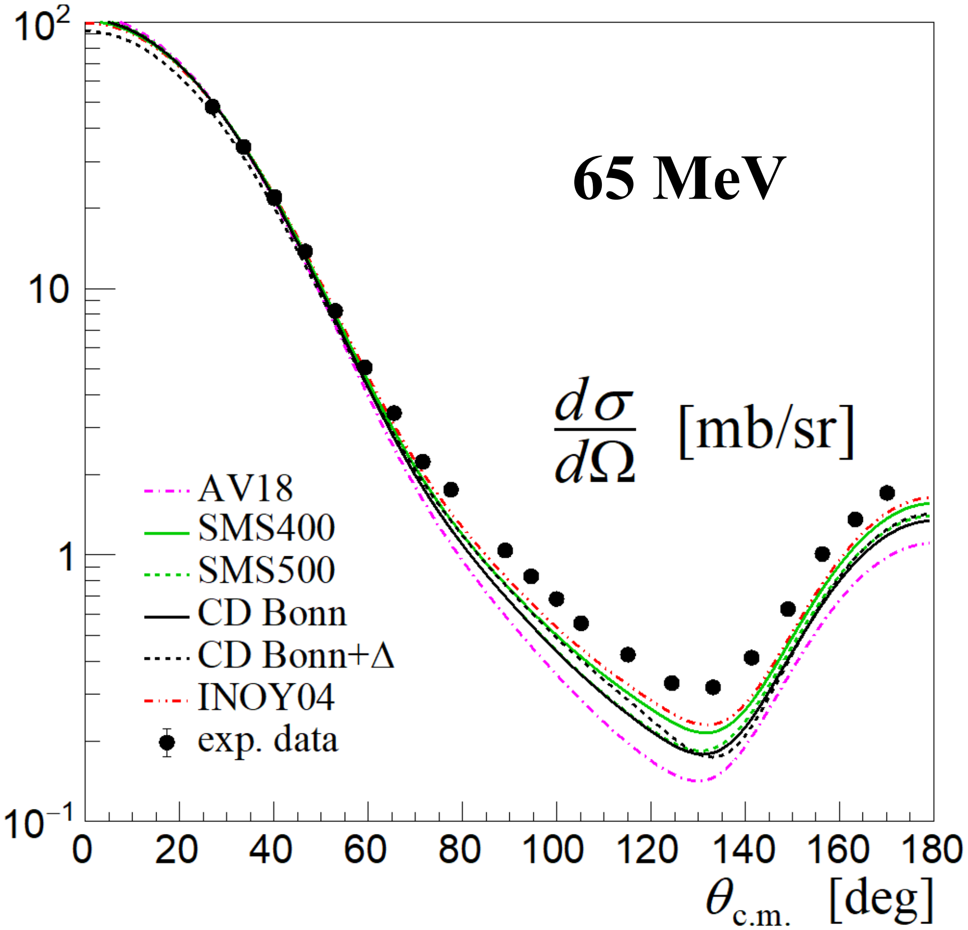
SMS : Chiral EFT (2NF, N^{4}LO+)

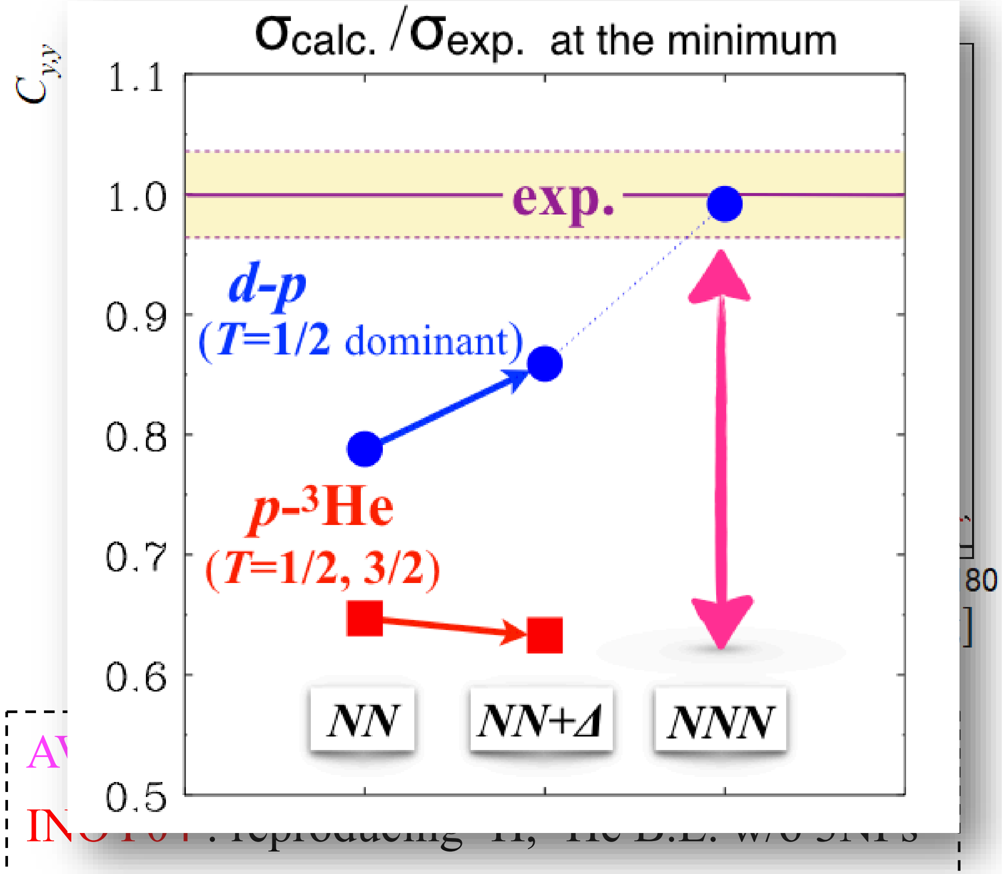
CD-Bonn+Δ : including Δ-isobar dof

*Coulomb force is omitted.

Experimental Results for p+^{3}He

*Calculations : A. Deltuva, private communications





SMS : Chiral EFT (2NF, N^{4}LO+)

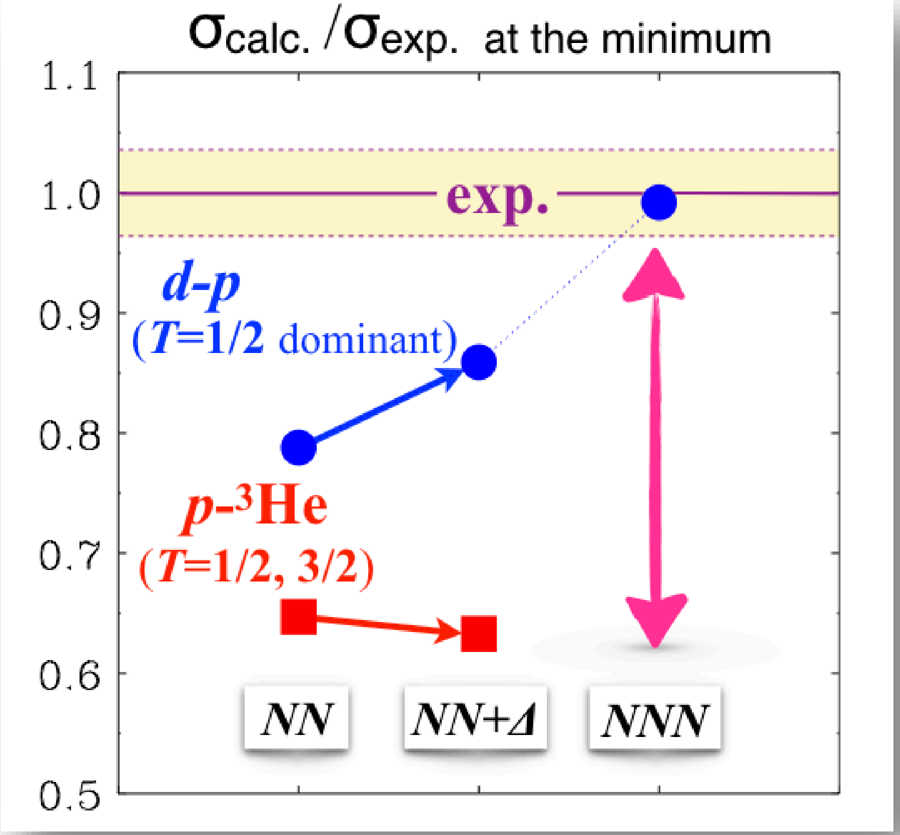
CD-Bonn+Δ : including Δ-isobar dof

*Coulomb force is omitted.

Conclusions

From comparison between the data and calculations...

- Clear discrepancies are found at $d\sigma/d\Omega$ minimum.
  → larger than *d-p* scattering
- Δ-isobar effects do **NOT** always remedy that situation.
- Spin correlation coefficient $C_{y,y}$ shows sizable effects of Δ-isobar.



p-³He elastic scattering at intermediate energies

An excellent tool to explore the 3NFs which could not be accessible in 3N scattering.

Further study in view of analysis of scattering amplitude is in progress...

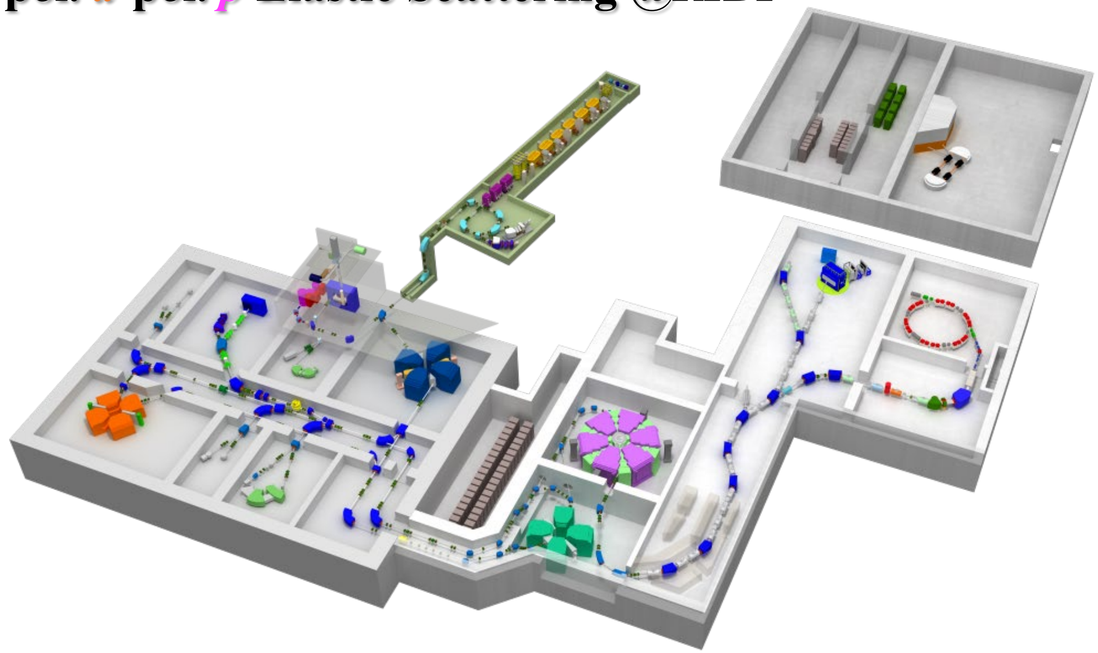
Future Plan for 3NF Study

Determination of χEFT 3NFs from *d*-*p* elastic scattering

Experiment:

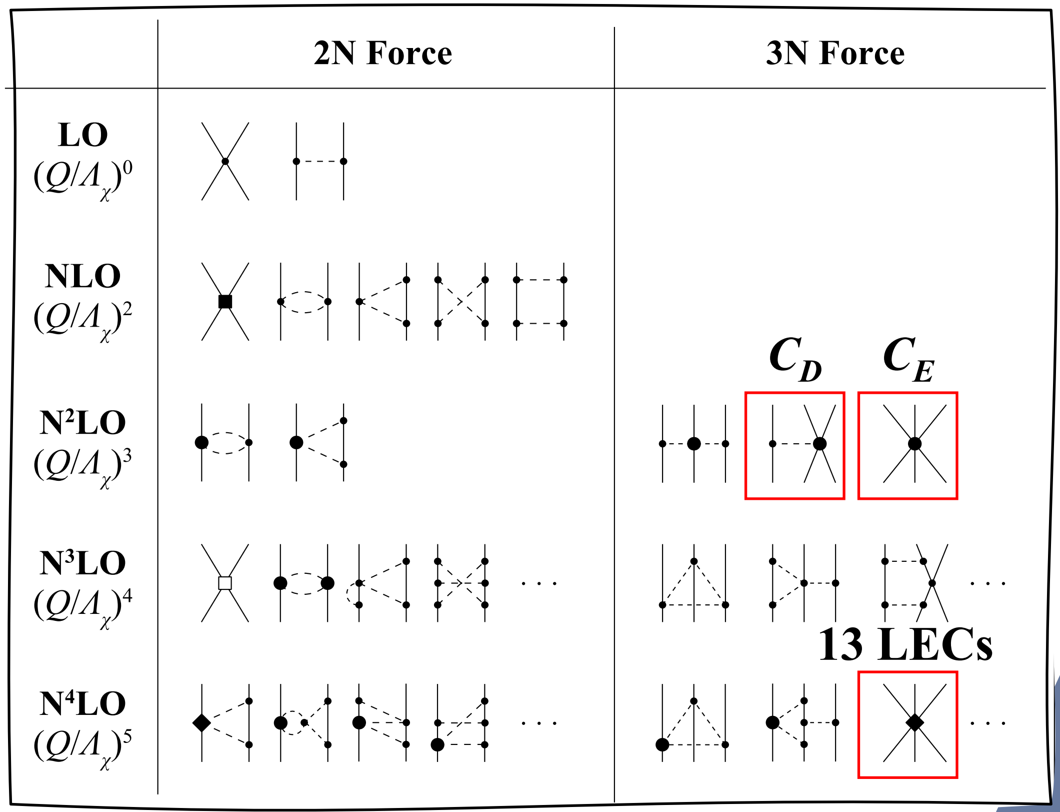
Measurement of spin correlation coefficients for *d*+*p*

pol. *d*-pol. *p* Elastic Scattering @*RIBF*



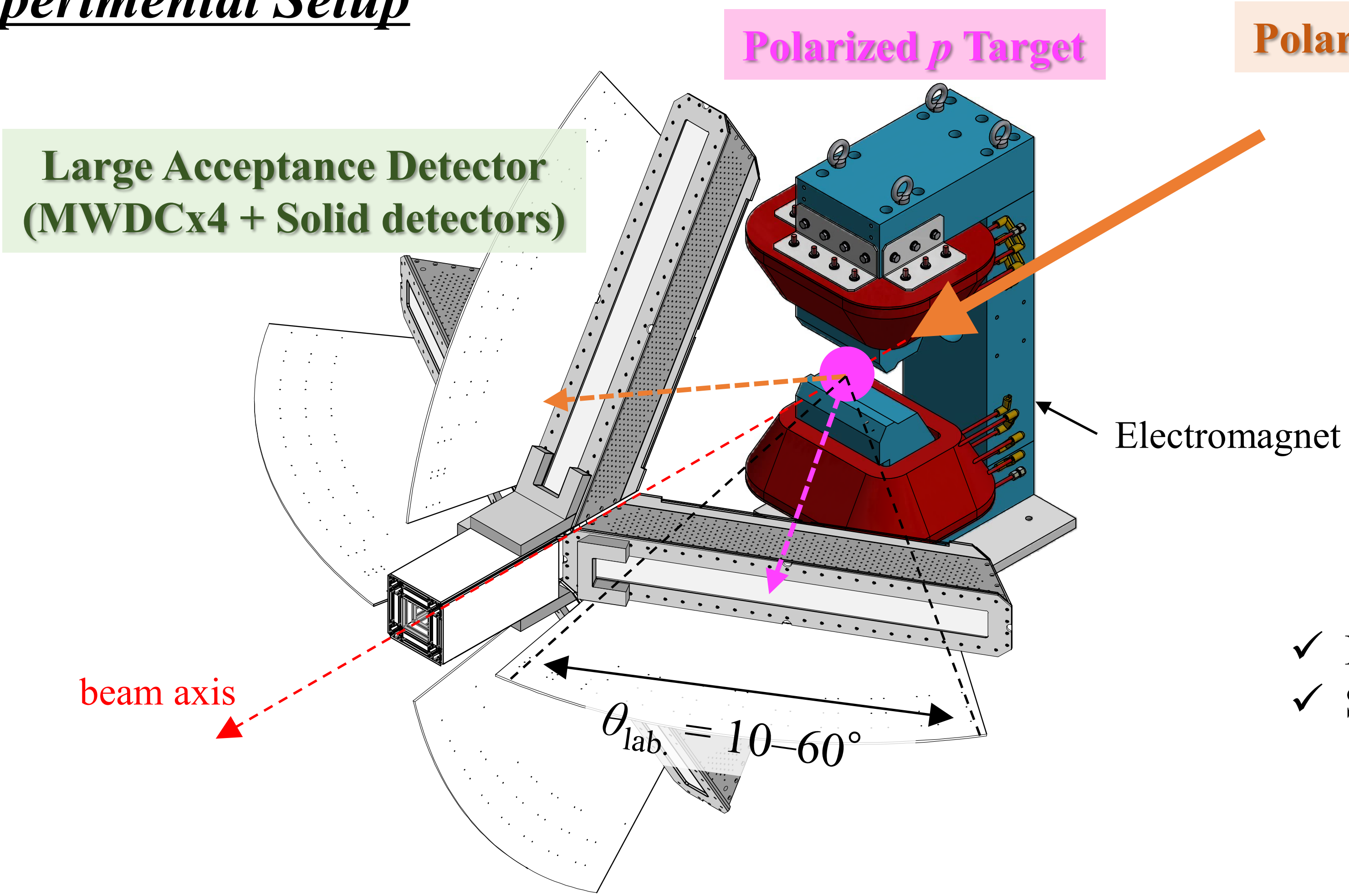
Theory:

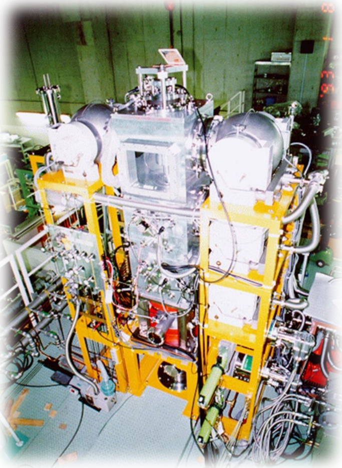
Chiral Effective Field Theory (EFT)



Measurement of Spin Correlation Coefficients for $d+p$

Experimental Setup





Polarized Ion Source

- ✓ High polarization: 60–80%
- ✓ Spin axis is freely controlled.

Beam test will be performed at HIMAC next month.

Summary

Study of 3NFs for *p*-^{3}He elastic scattering at intermediate energies ($E/A \geq 65$ MeV)

- First step from few-nucleons to many body
- Approach to total iso-spin $T = 3/2$ channel of 3NFs

Measurement of *p*-^{3}He elastic scattering for 65, 70 and 100 MeV @CYRIC, RCNP

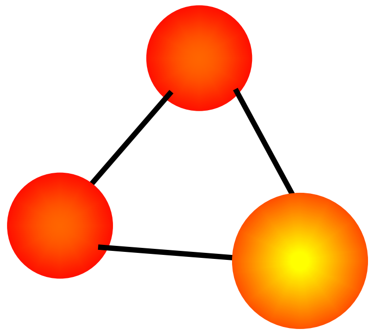
- Precise data of $d\sigma/d\Omega$, $A_y(p)$, $A_{0y}(^3\text{He})$, $C_{y,y}$
- Comparison the data with the predictions based on NN potential
  - ✓ Calculation (with Δ-dof.) **do NOT reproduce the data**
  - ✓ **Different properties from *d-p* scattering system**
  - ✓ $C_{y,y}$ shows sizable Δ-isobar effects

Excellent tool for 3NF study

Future Plan

***d-p* scattering** : Complete set of spin correlation coefficients

→ Determination of 3NFs based on χEFT from *d-p* scattering data



Collaborators

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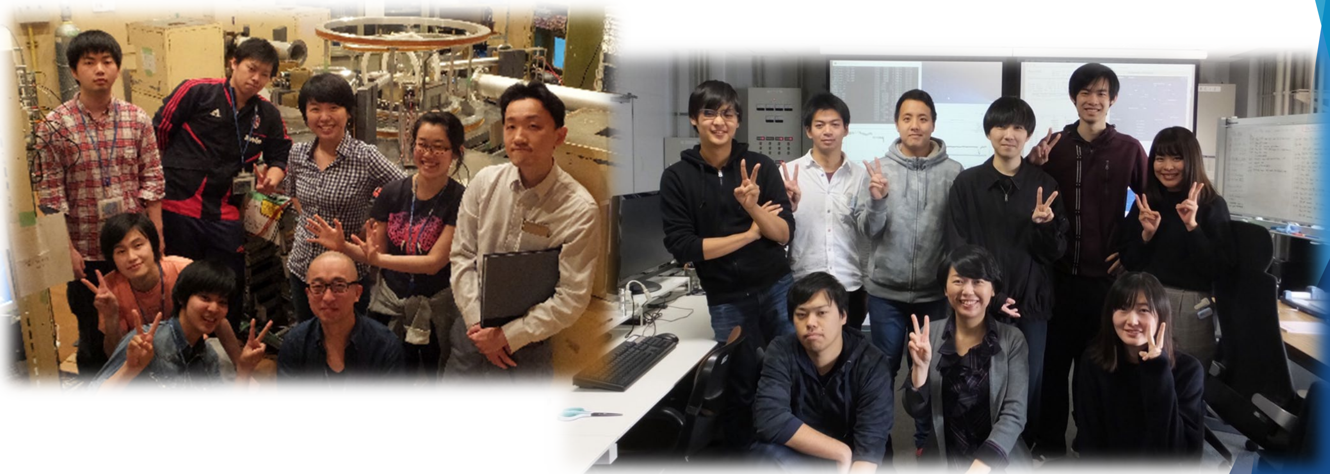

Thank you for your attention.