Exploring Three-Nucleon Forces
via
Three- and Four-Nucleon Scattering

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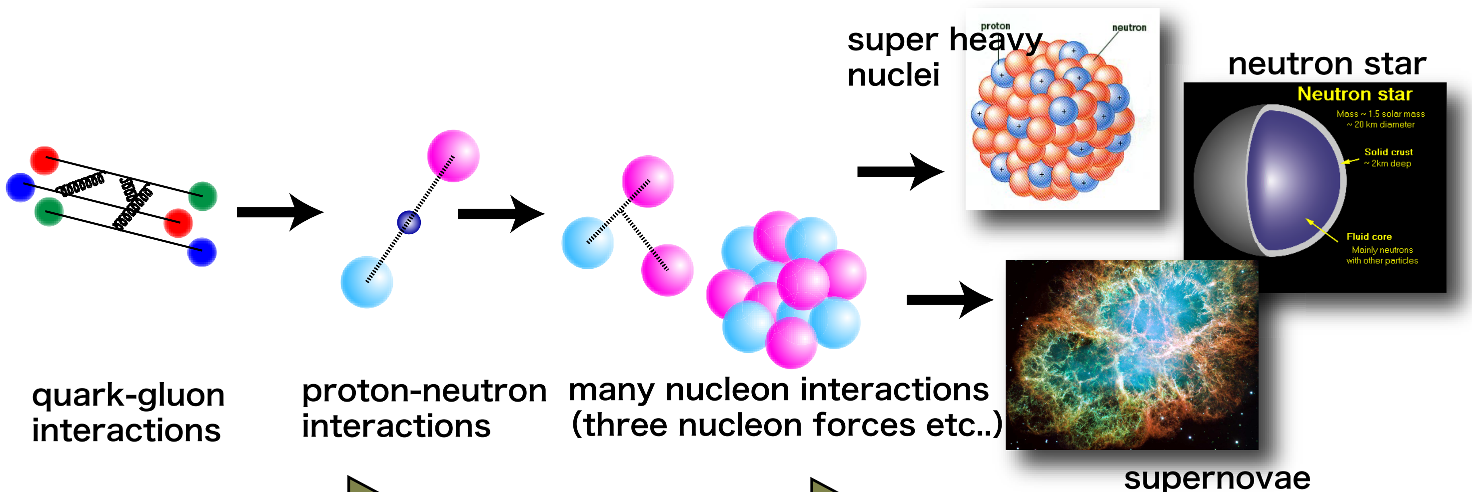
Frontier of Nuclear Force Study

- To understand Nuclear Forces from Quarks (elementary particles)
- To understand Nuclei and Nuclear Matter from bare Nuclear Forces
  ～ 2NF & 3NF ～



Consistent Understanding from quarks to the Universe

Three-Nucleon Force in Nucleus

Three-Nucleon Force (3NF)

key element to fully understand properties of nucleus.

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

'90〜

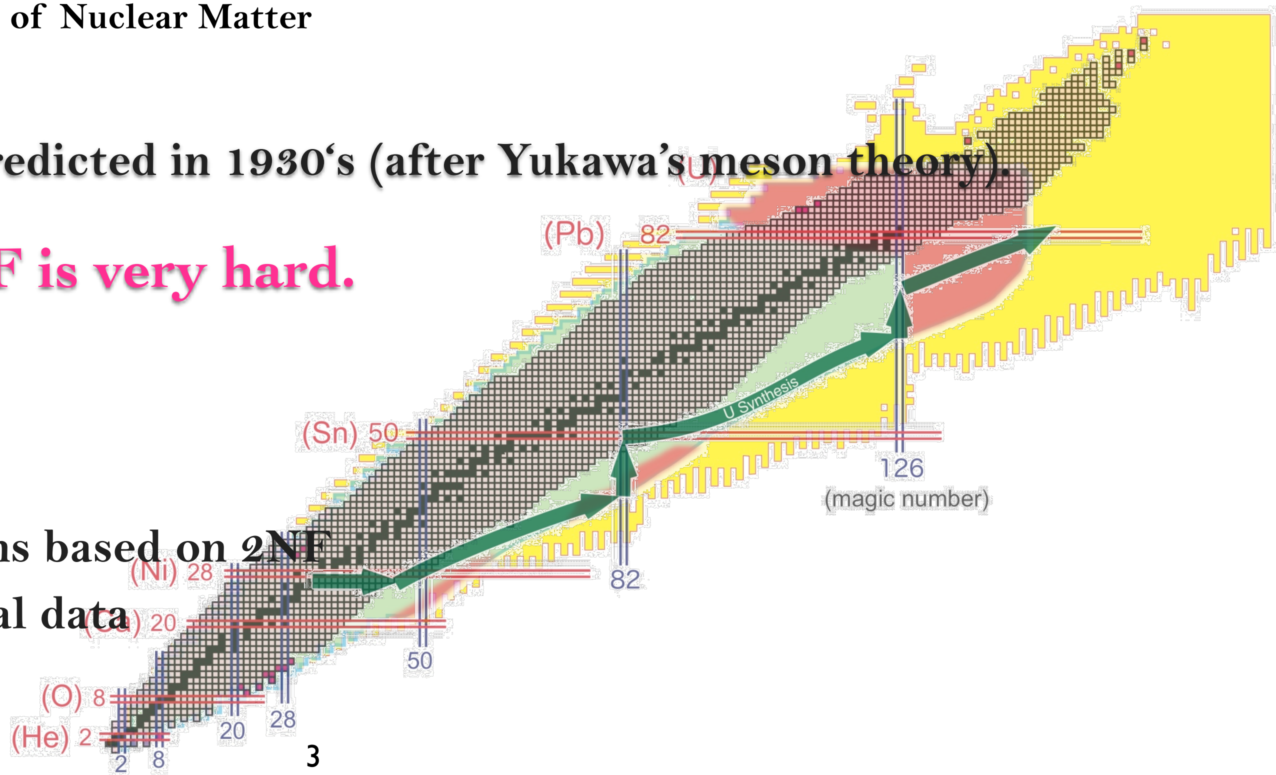
- Nucleon-Deuteron Elastic Scattering at Intermediate Energies
- Biding Energies / Levels of Light Mass Nuclei
- Equation of State of Nuclear Matter

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

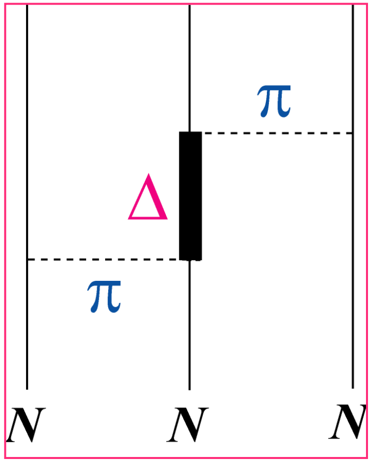


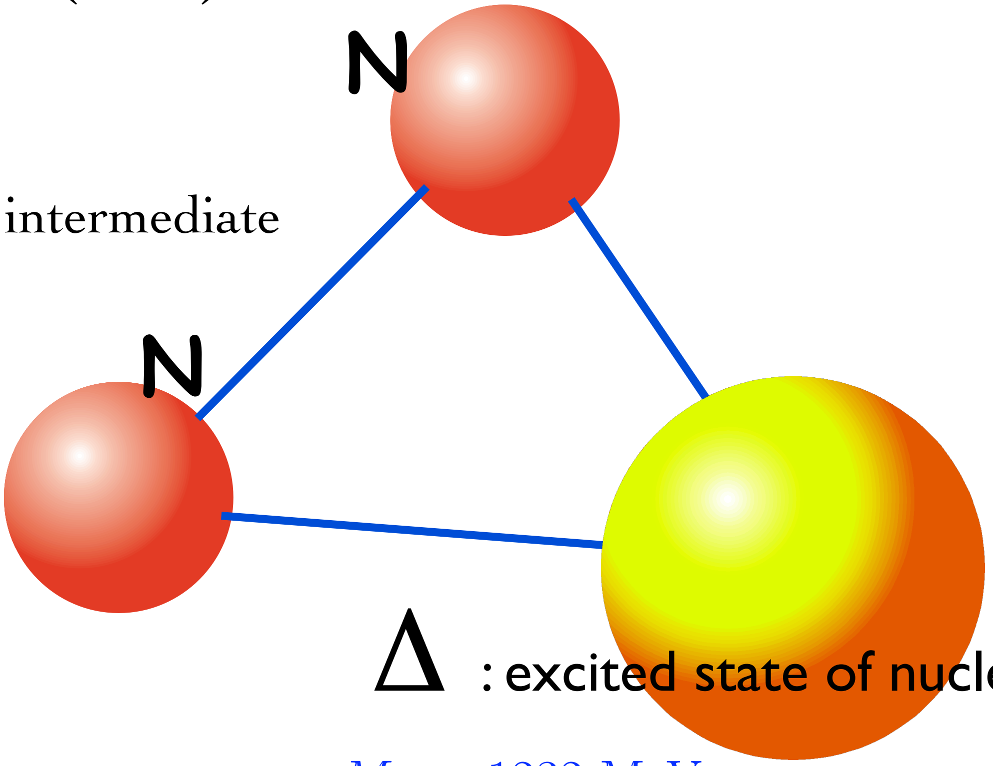
Three-Nucleon Force (3NF)

1957 Fujita-Miyazawa 3NF

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

- 2π-exchange 3NF :
  - Main Ingredients :
    Δ-isobar excitations in the intermediate





Δ : excited state of nucleon

$M_\Delta = 1232$ MeV

$(J^\pi, T) = \left(\frac{3}{2}^+, \frac{3}{2}\right)$

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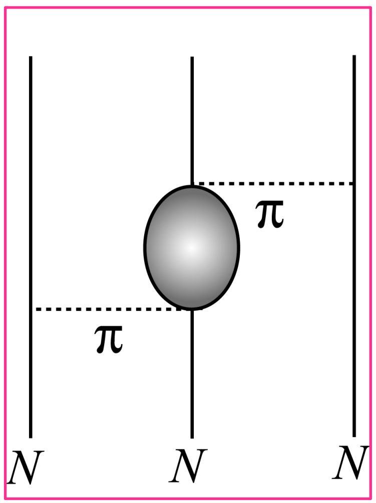
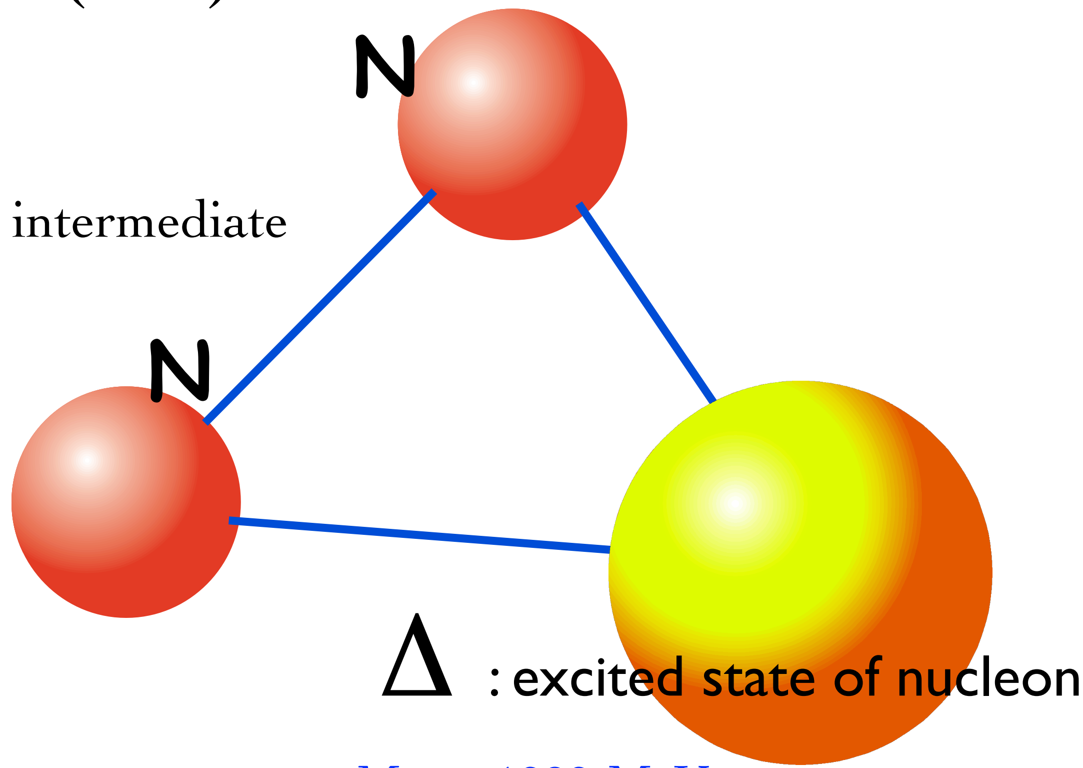


- Tucson-Melbourne (TM)
- Urbana IX
- Brazil, Texas etc…



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Prog. Theor. Phys. 17, 360 (1

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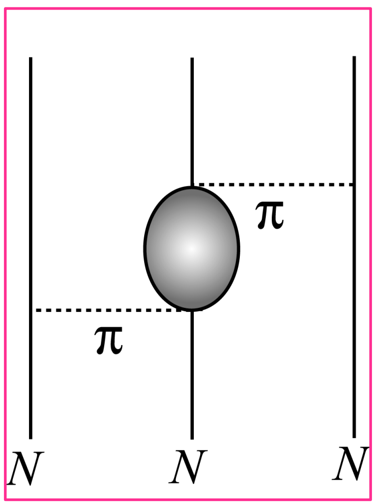

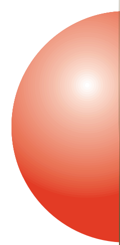

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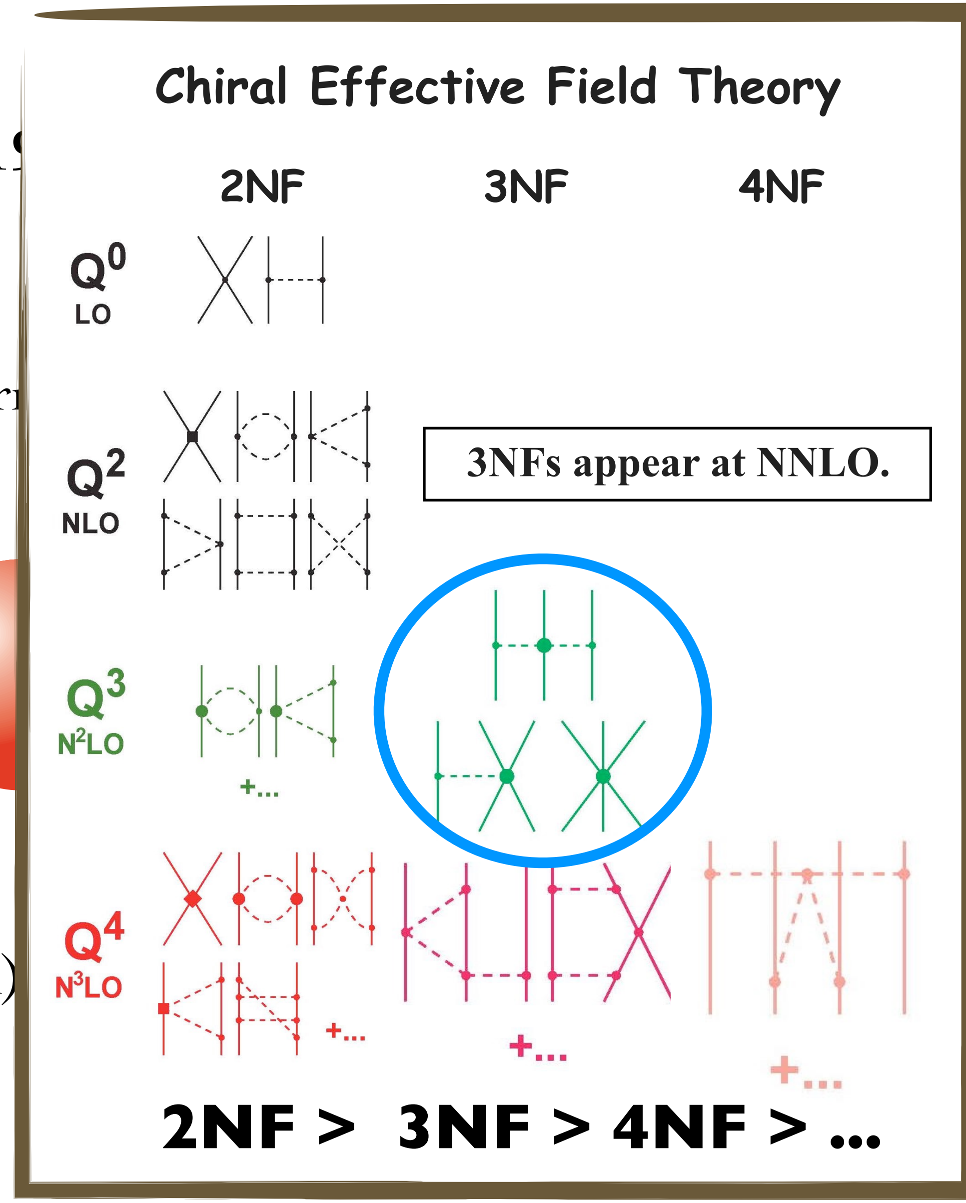
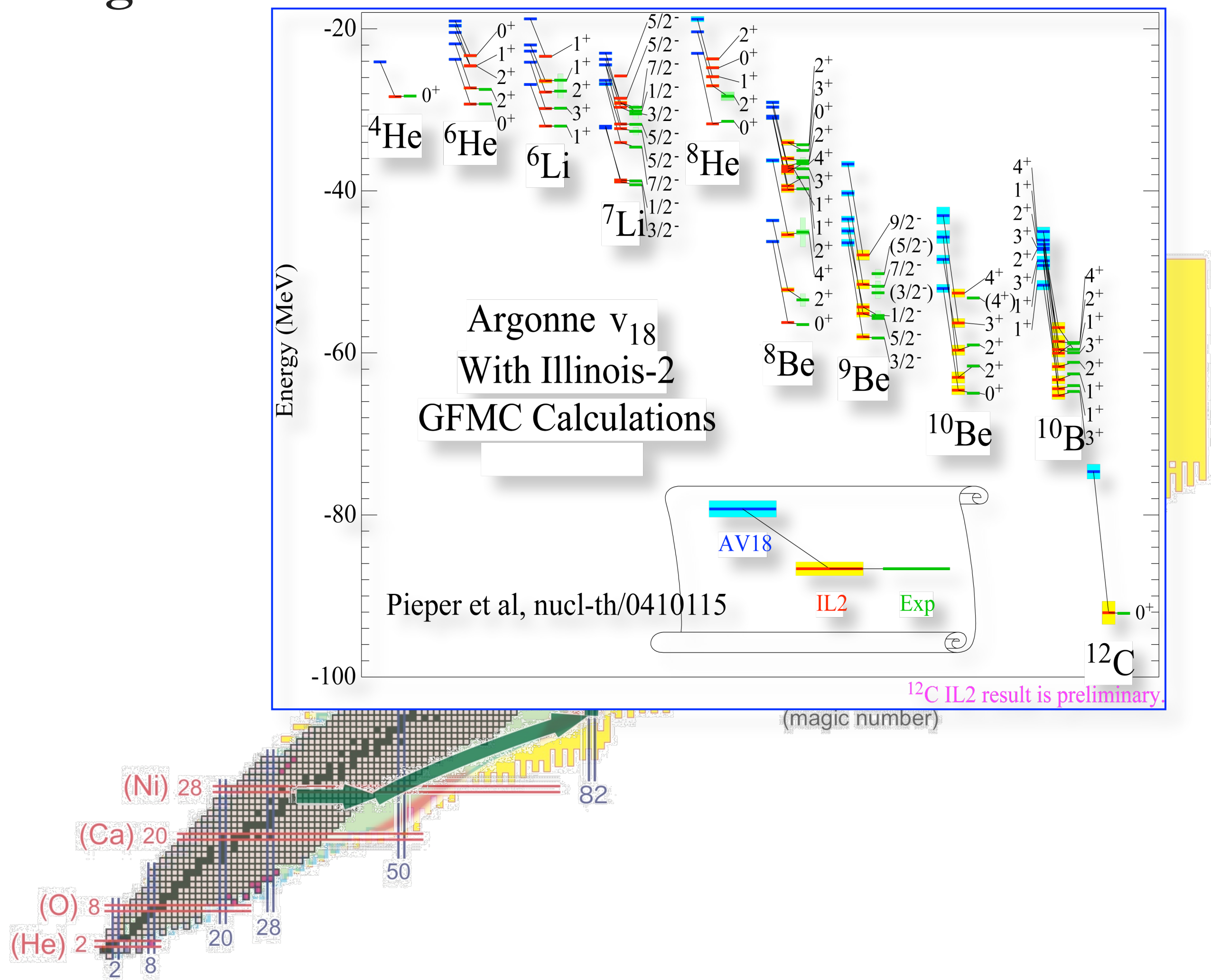


Where can we find 3NF effects ? - I -

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

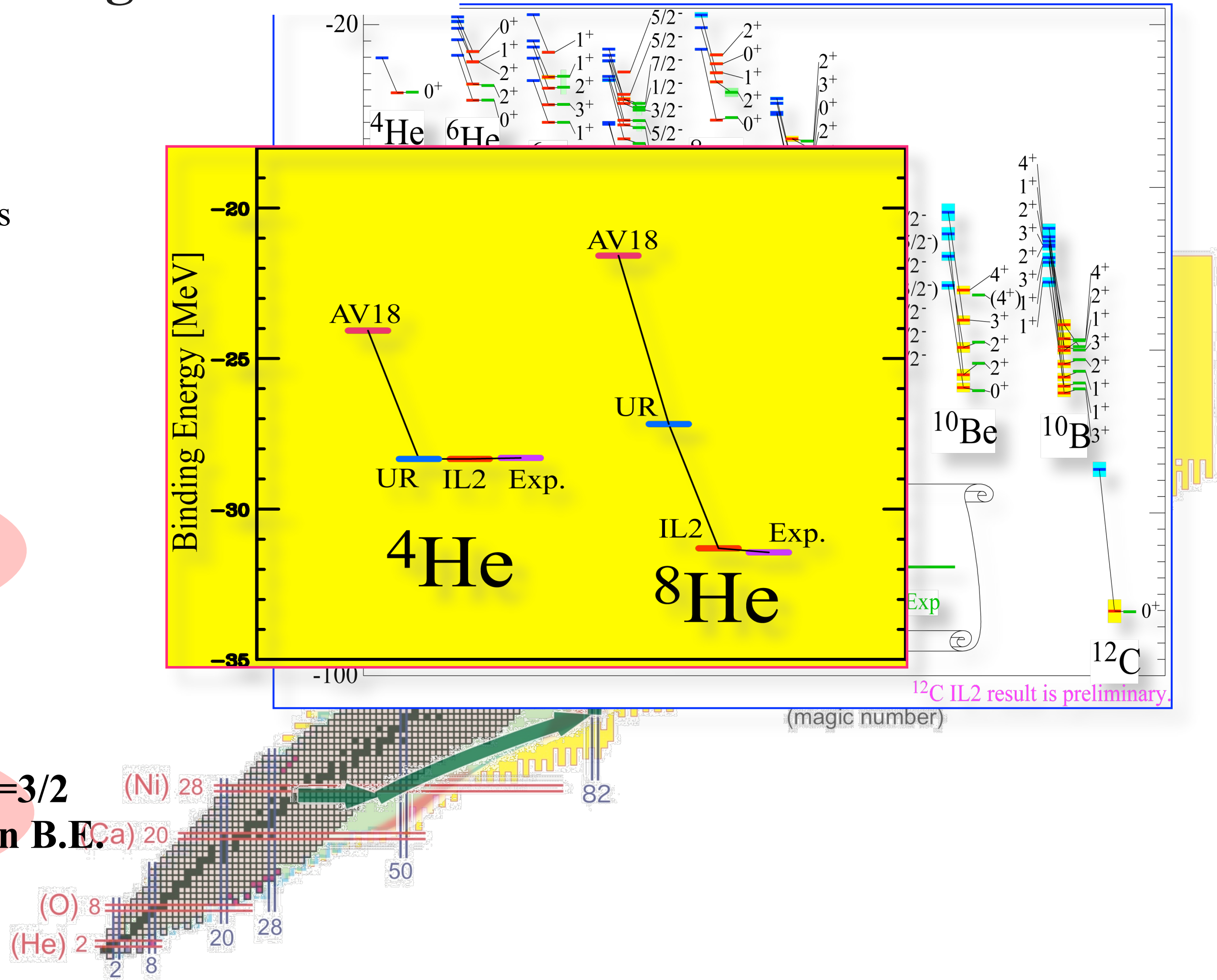
Ab Initio Calculations for Light Nuclei

- **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

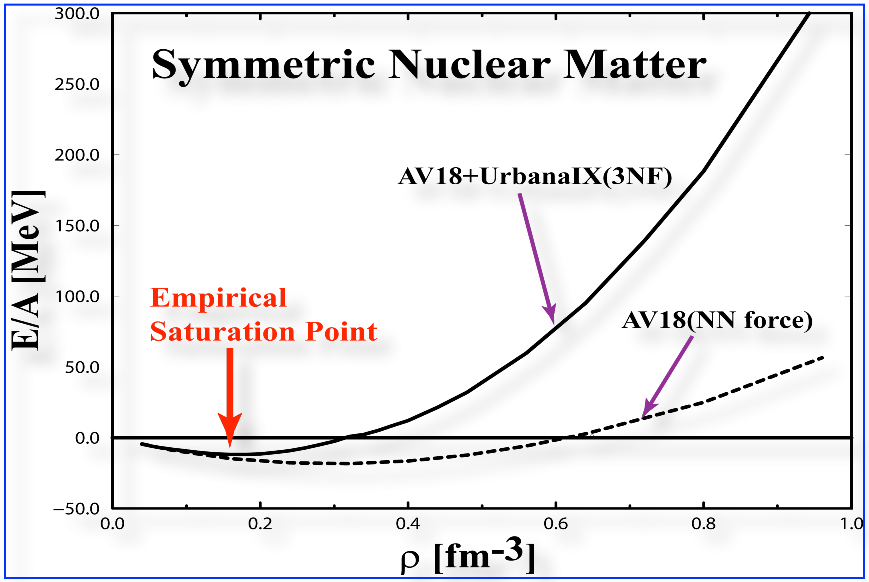
3NF effects in B.E.
- **10-25%**
- **Attractive**



Note :
3NFs with iso-spin states of T=3/2 play important roles to explain B.E. in neutron rich nuclei.

Where can we find 3NF effects ? - II -

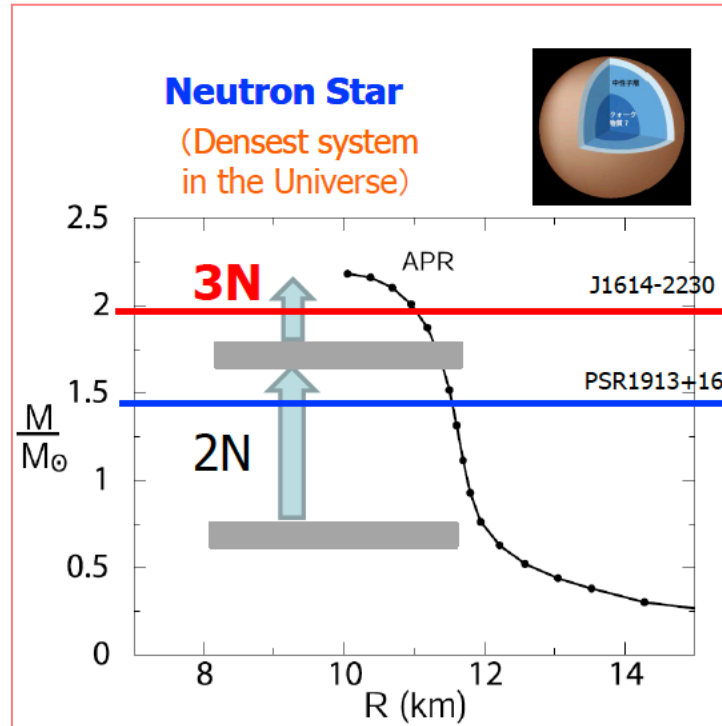
3NFs in Infinite Nuclei



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

Short-range 3NFs play important roles at high density.



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

- 3NF is a key to understand nuclear phenomena quantitatively.
- 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})

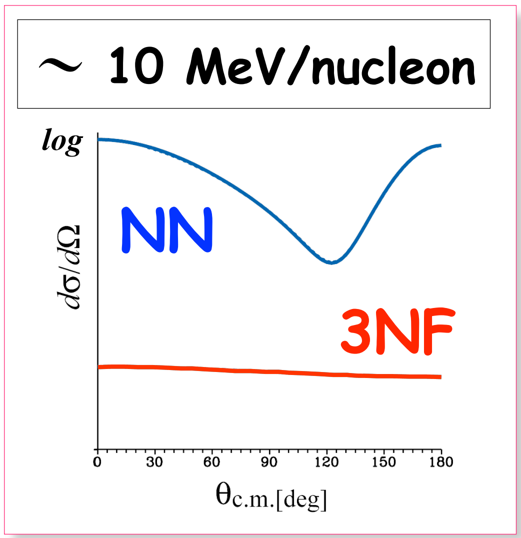
Extract fundamental information of Nuclear Forces

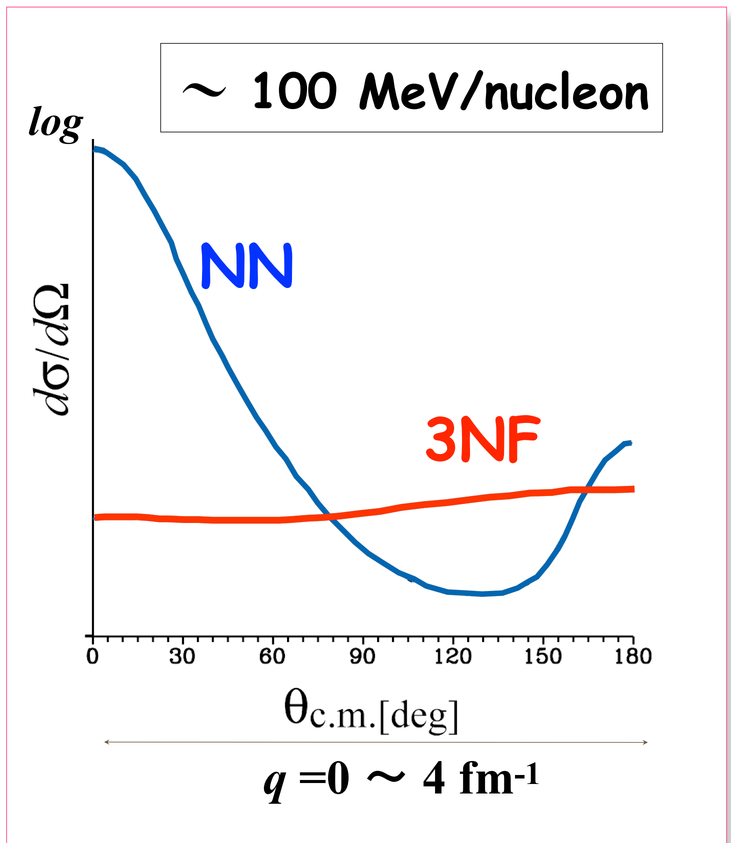
Where is the hot spot for 3NFs ?

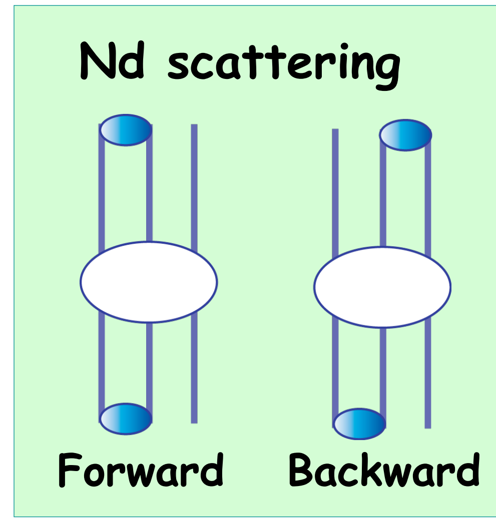
Nucleon-Deuteron Scattering - 3N Scattering -

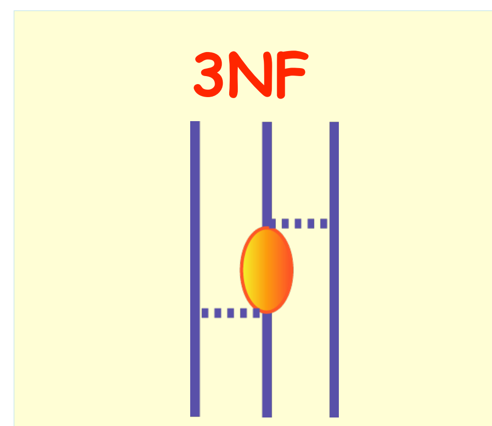
Predictions by H. Witala et al. (1998)

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

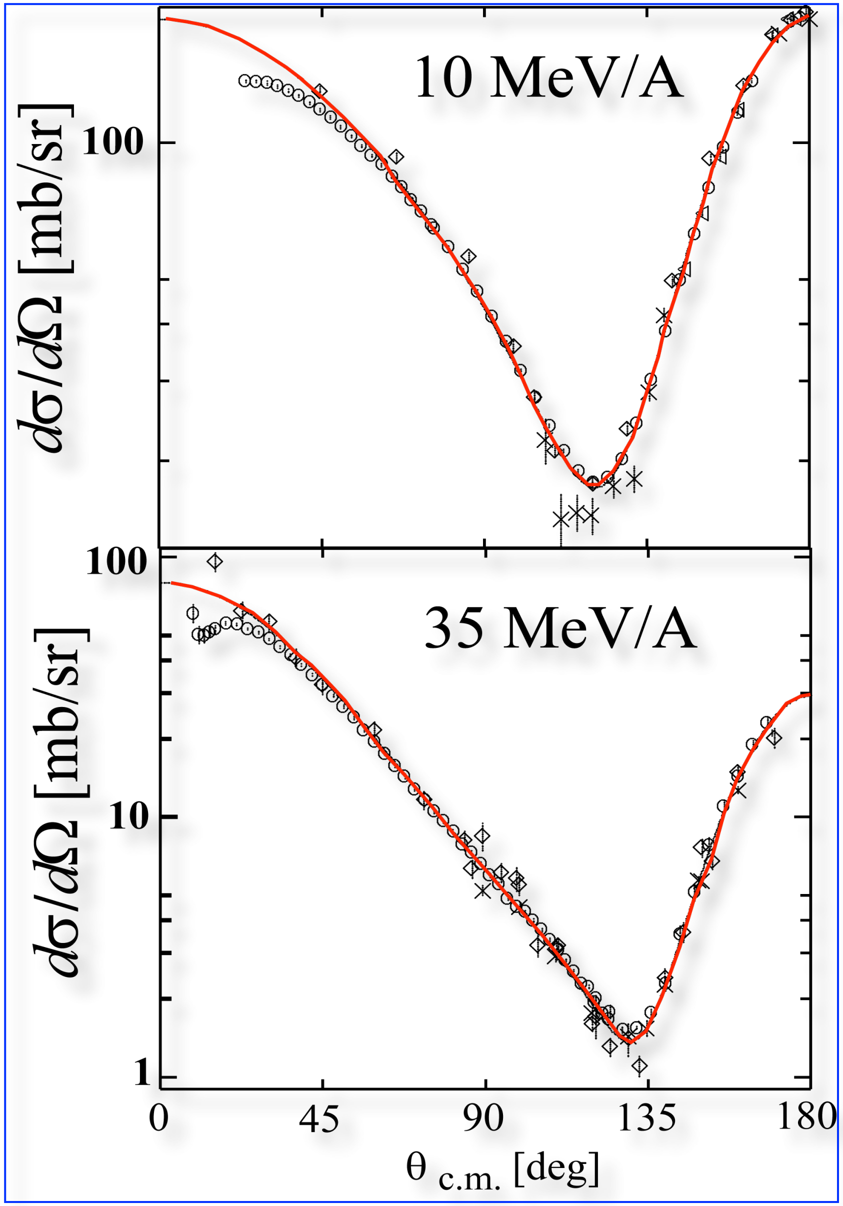








Nd Scattering at Low Energies ($E \leq 30$ MeV/A)



- High precision data are explained by Faddeev calculations based on 2NF.
  (Exception : A_y, $i T_{11}$)

No signatures of 3NF

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

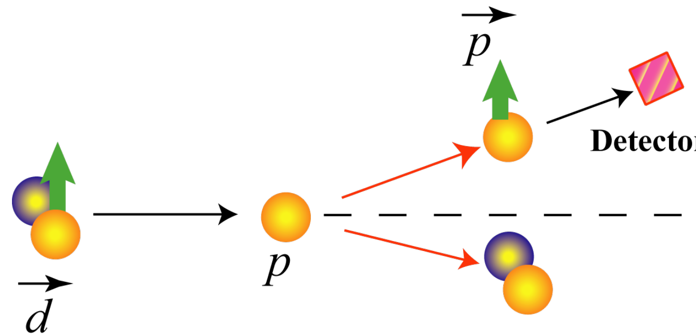
W. Glöckle et al., Phys. Rep. 274, 107 (1996).

Observables for *Nd* Scattering

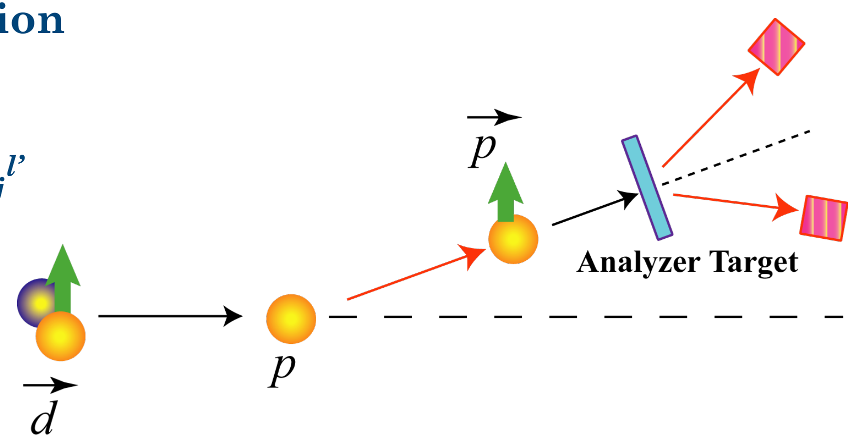
- **Differential Cross Section**
  - **Overall Strength**
  - **Absolute Quantity : normalization to *pp or np* data**

$$\frac{d\sigma}{d\Omega} = \frac{\text{yields}}{(\text{target thickness}) \times (\text{beam charge}) \times (\text{solid angle}) \times (\text{efficiency})}$$

- **Spin Observables :**
  - **Analyzing Powers**
    - **Vector Analyzing Power : iT_{11}**
      - **$(L \cdot S)$ interaction**
    - **Tensor Analyzing Power : T_{20}, T_{21}, T_{22}**
      - **Tensor interaction (D-state)**
      - **Higher order $(L \cdot S)$ interaction**

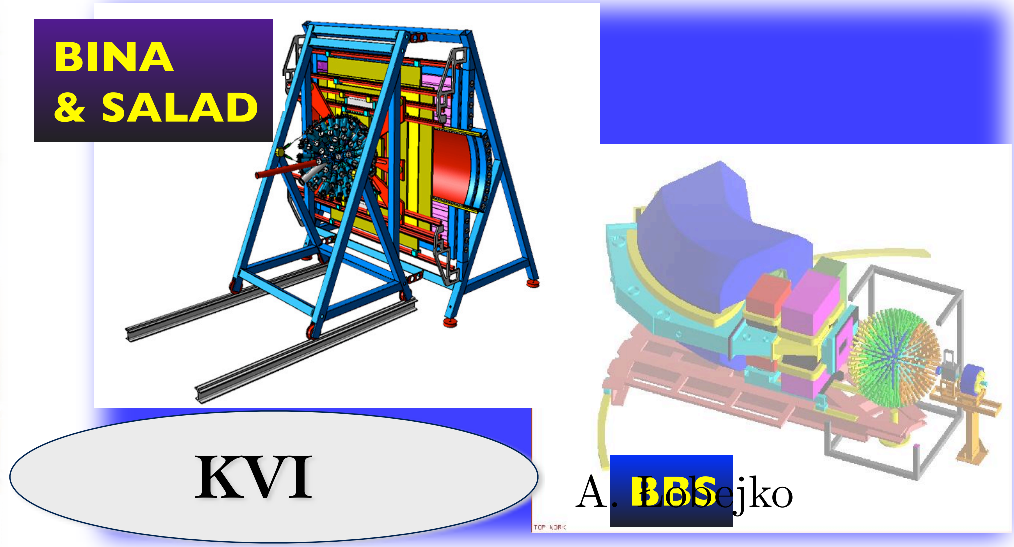


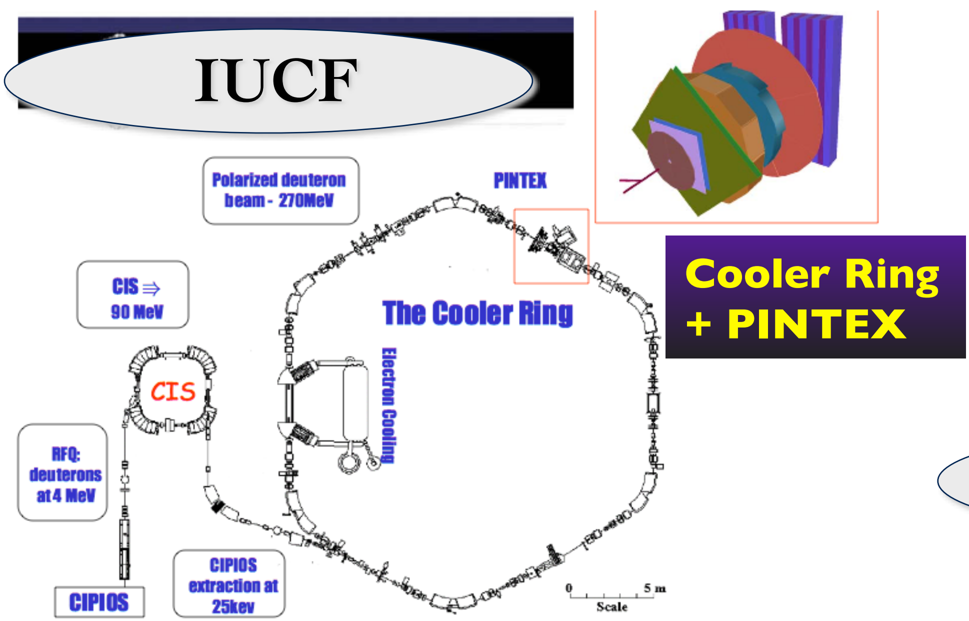
  - **Polarization Transfer Coefficient : $K_{ij}^{l'}$**
  - **Spin Correlation Coefficients C_{ij}**
    - **Spin-Spin interaction**

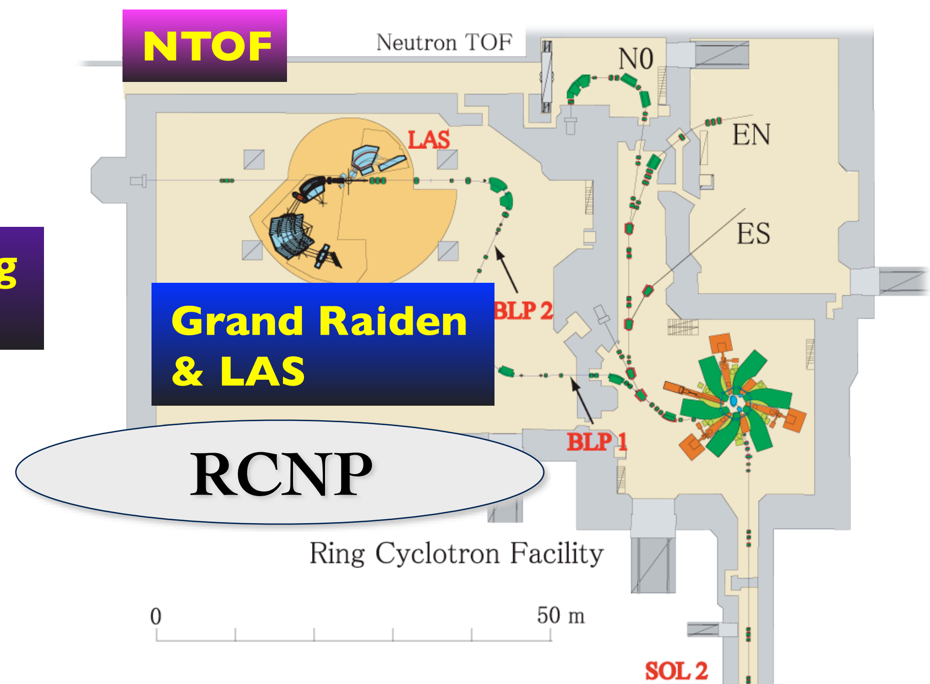


Facilities

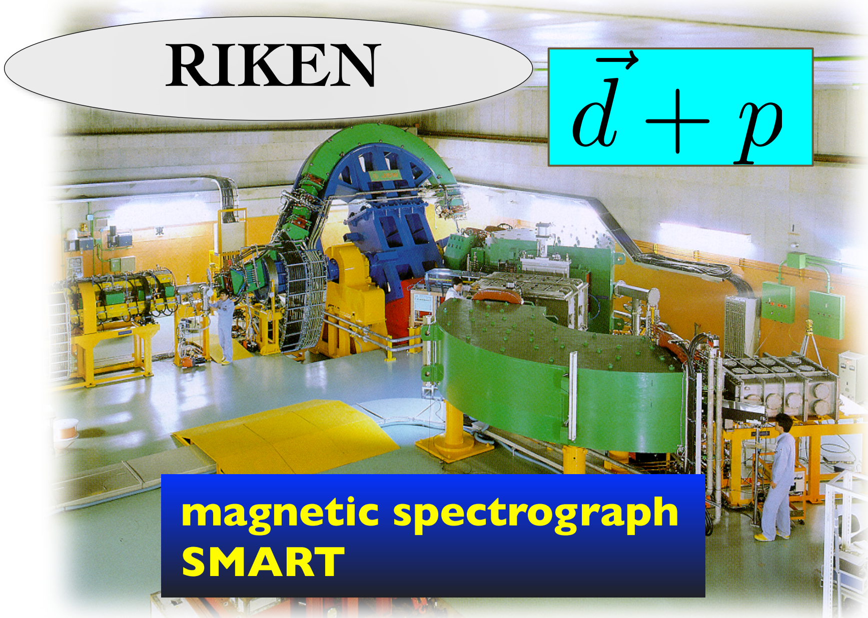

RIKEN
magnetic spectrograph
SMART


BINA
& SALAD
KVI
BBS

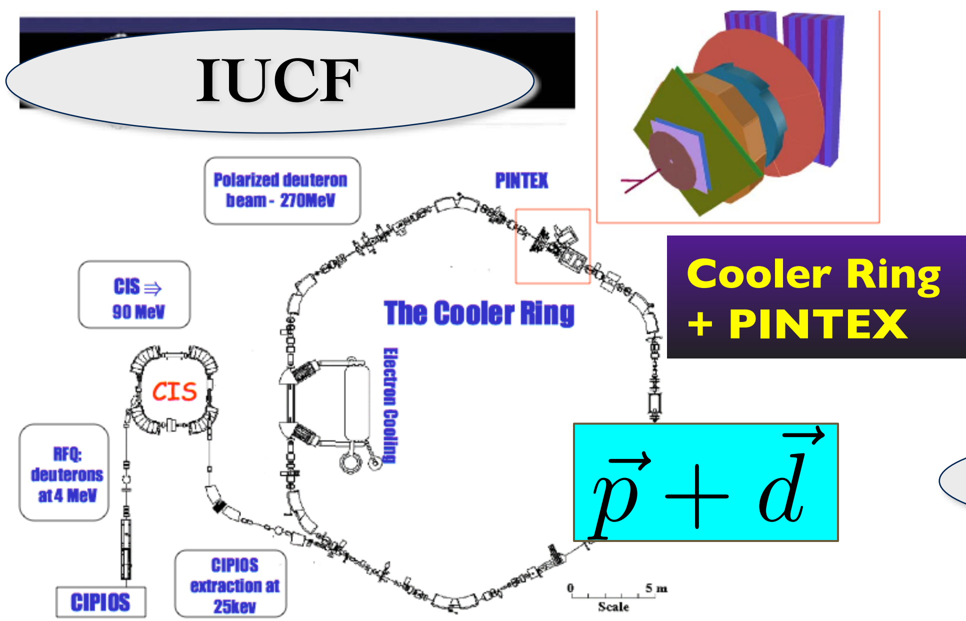

IUCF
Polarized deuteron
beam - 270MeV
PINTEX
CIS ⇒
90 MeV
CIS
The Cooler Ring
Electron Cooling
RFQ:
deuterons
at 4 MeV
CIPIOS
CIPIOS
extraction at
25kev
0
5 m
Scale
Cooler Ring
+ PINTEX

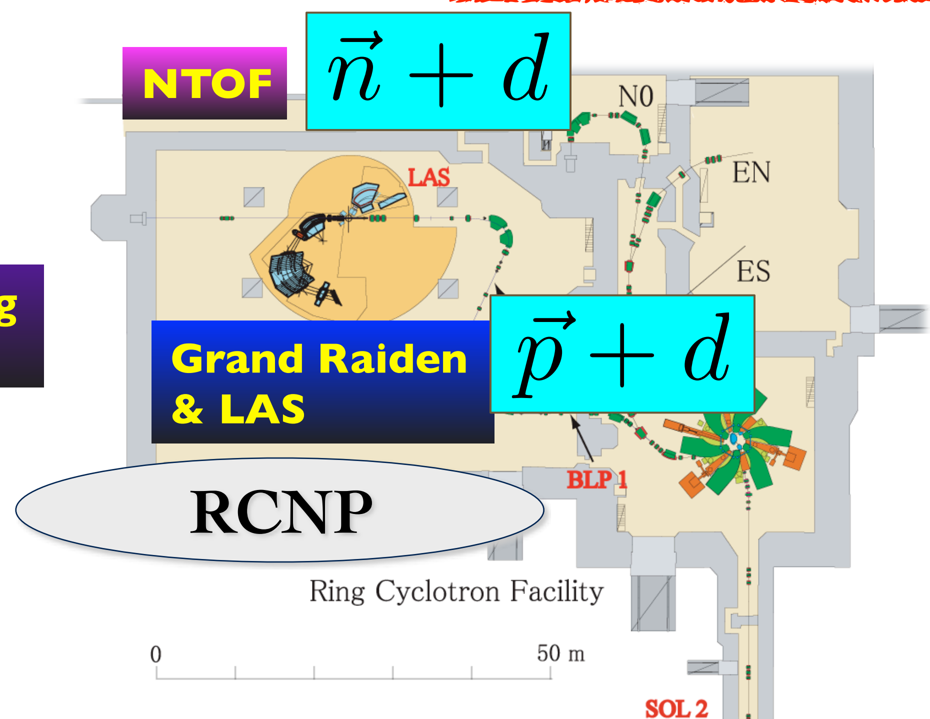

NTOF
Neutron TOF
N0
EN
ES
LAS
BLP 2
BLP 1
Grand Raiden
& LAS
RCNP
Ring Cyclotron Facility
0
50 m
SOL 2

Facilities



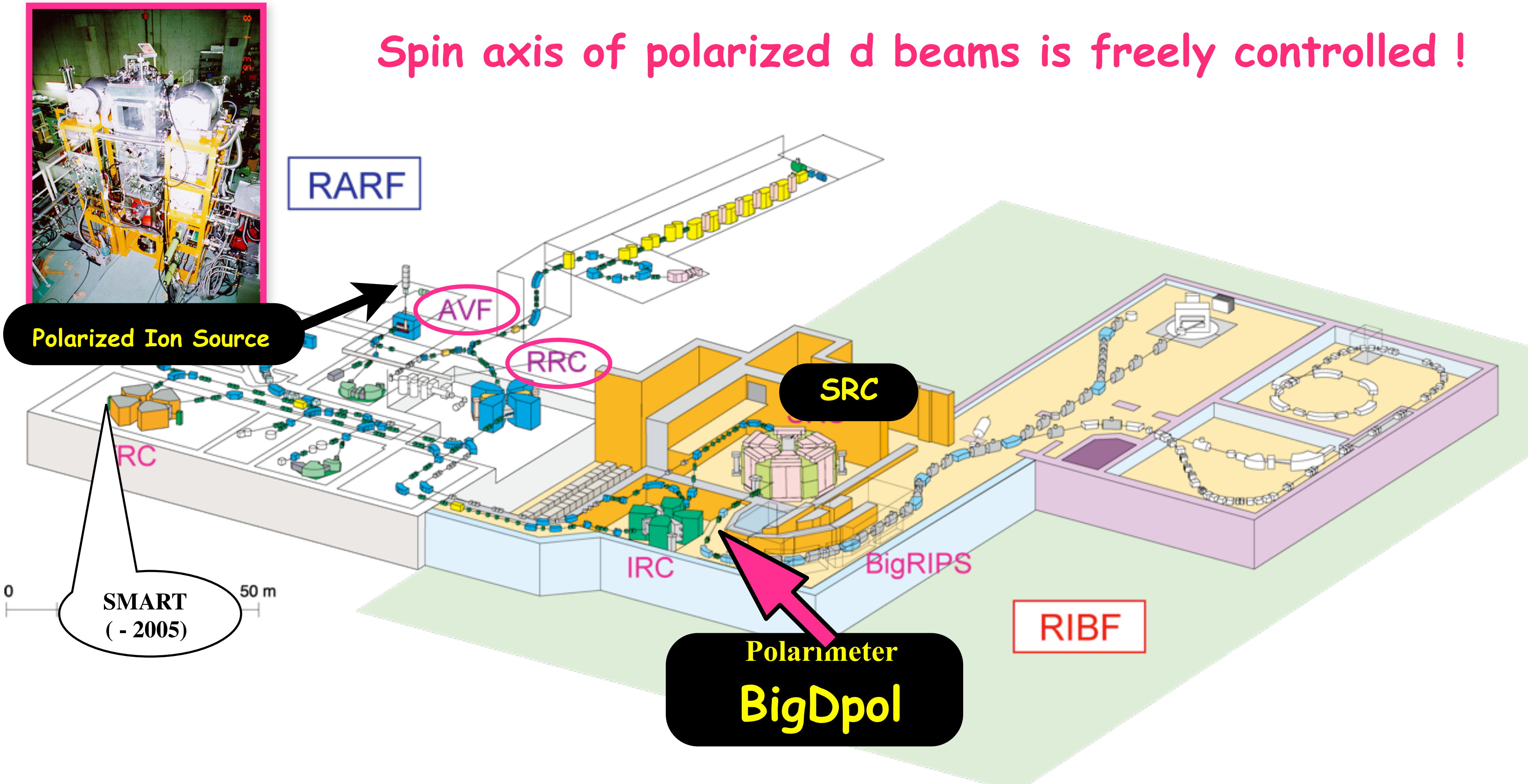
Talks by
A.G. Wilczek,
I. Skiwira-Chalot,
A. Łobejko
(Monday Afternoon)





RIKEN RI Beam Factory (RIBF)

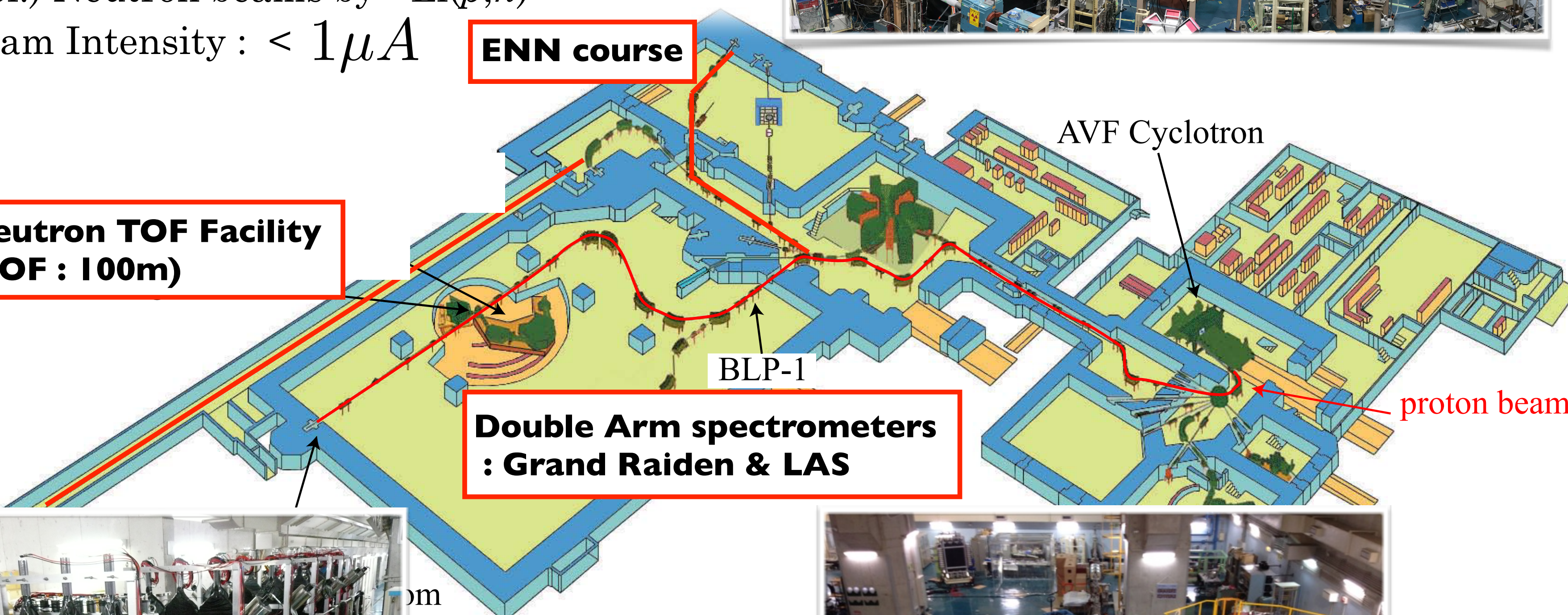
- Polarized d beam
  - acceleration by AVF+RRC : 65-135 MeV/nucleon
  - acceleration by AVF+RRC+SRC : 190-300 MeV/nucleon
  - polarization : 60-80% of theoretical maximum values
- Beam Intensity : < 100 nA



Spin axis of polarized d beams is freely controlled !

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 : $< 1\mu A$



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. Sakamoto 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 83, 061001 (2011), K. S. et al., Phys. Rev. C 89, 064007 (2014), K.S. et al., Phys. Rev. C 96, 064001 (2017).

$p + d$

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)

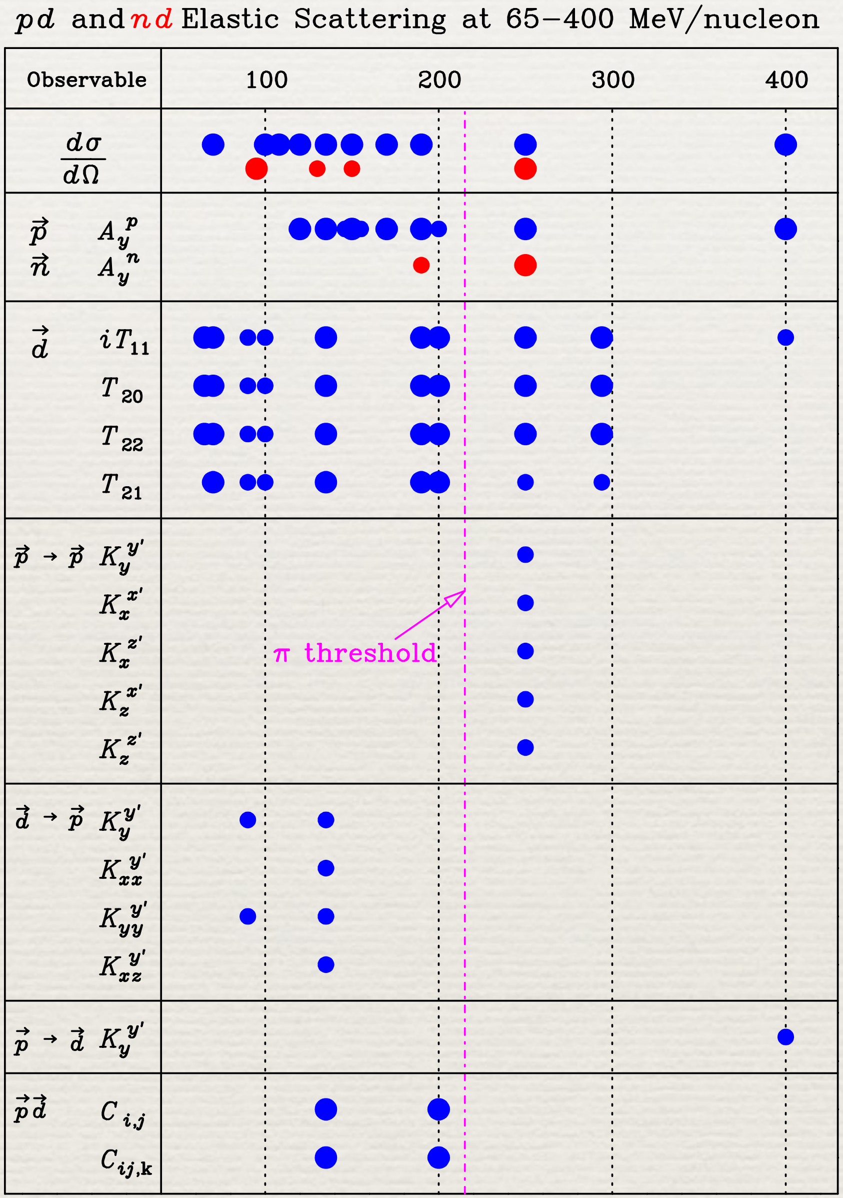
$n + d$

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)

Nd Elastic Scattering Data at Intermediate Energies



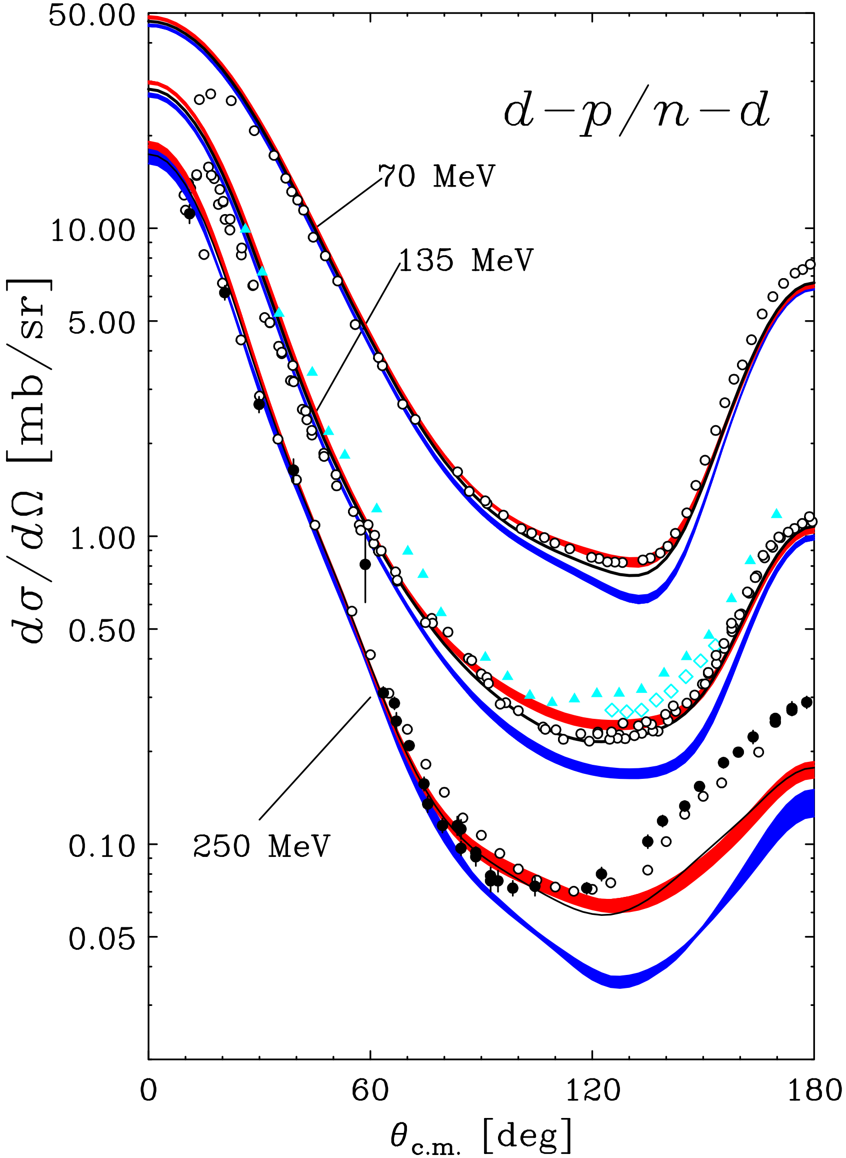
~2019

- **High precision data of $\frac{d\sigma}{d\Omega}$ & spin observables**

  from RIKEN, RCNP, KVI, IUCF

- **Energy dependent data**
  - ✓ ***dσ/dΩ***
  - ✓ **Proton Analyzing Power**
  - ✓ **Deuteron Analyzing Powers**

Differential Cross Section at 70 - 250 MeV/nucleon



NN only
- Large discrepancy at the backward angles

NN + 2π-3NF (TM'99, Urbana-IX) :
- Agreement is improved.
- Still discrepancy exits at very backward angles at higher energies

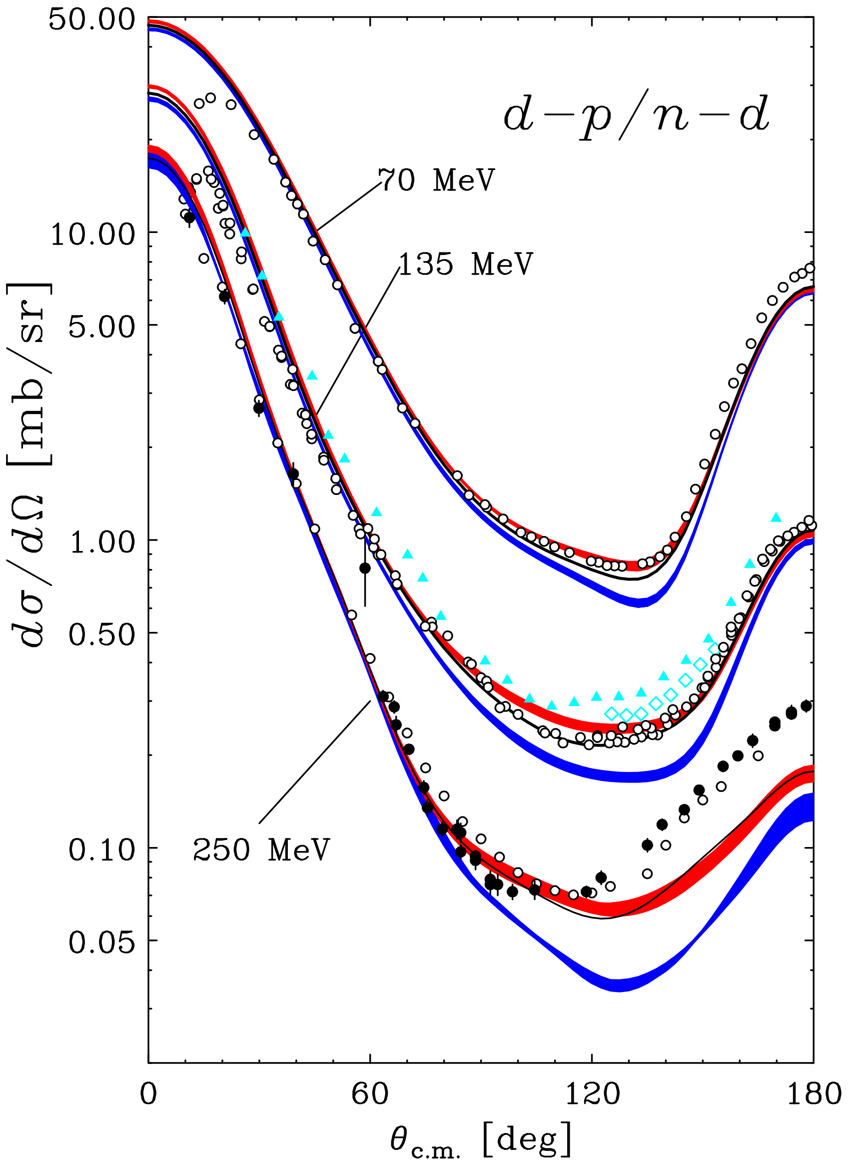
→
- *shorter range 3NFs ?*
- *other dynamics ?*

NN (CDBonn, AV18, Nijm I,II)

TM'(99) 3NF + NN(CD Bonn, AV18, Nijm I,II)

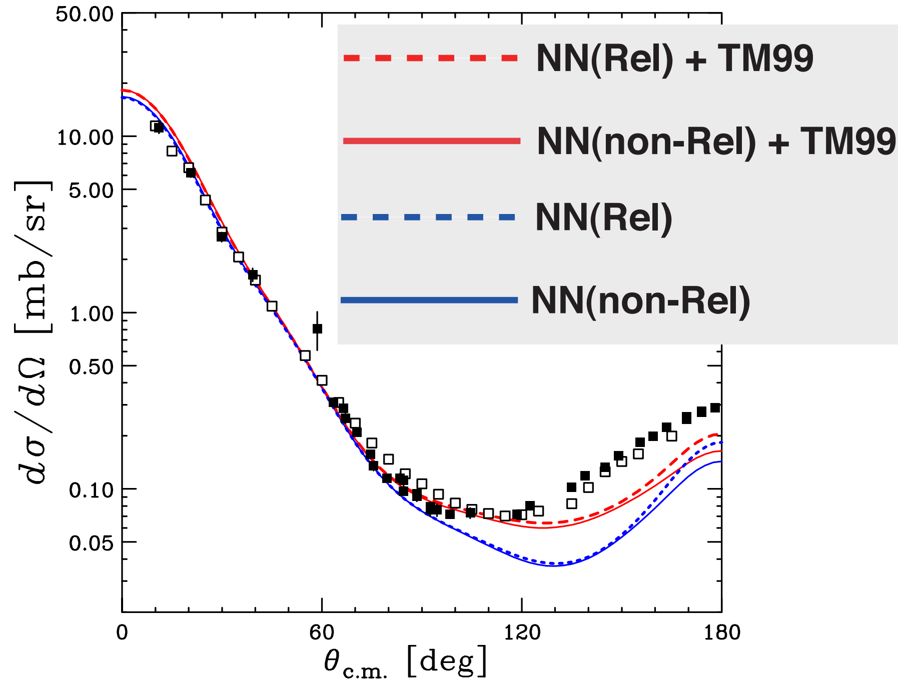
Urbana IX 3NF+AV18

Differential Cross Section at 70 - 250 MeV/nucleon



Relativistic Faddeev Calculations
with TM'99 3NF

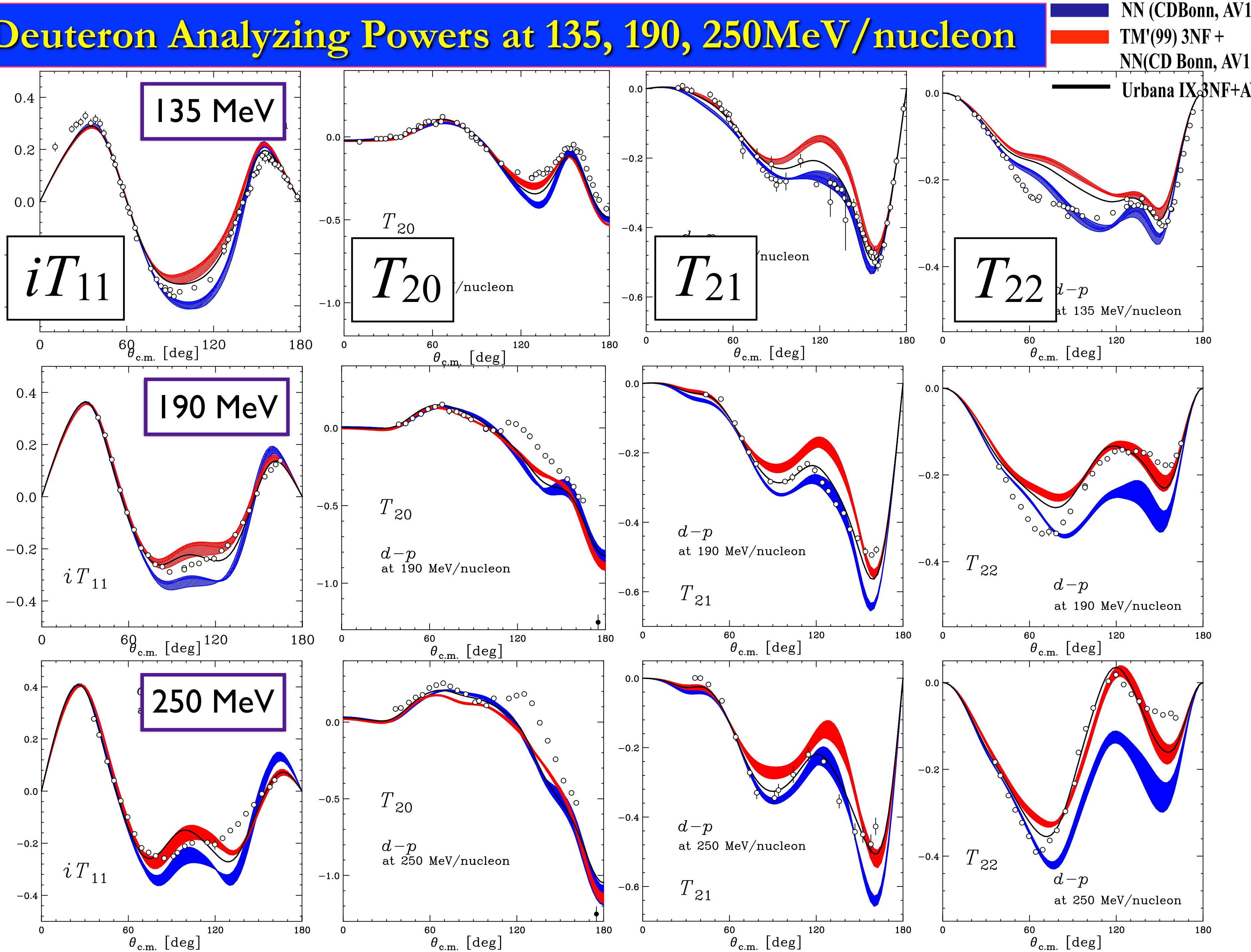
pd/nd @ 250 MeV



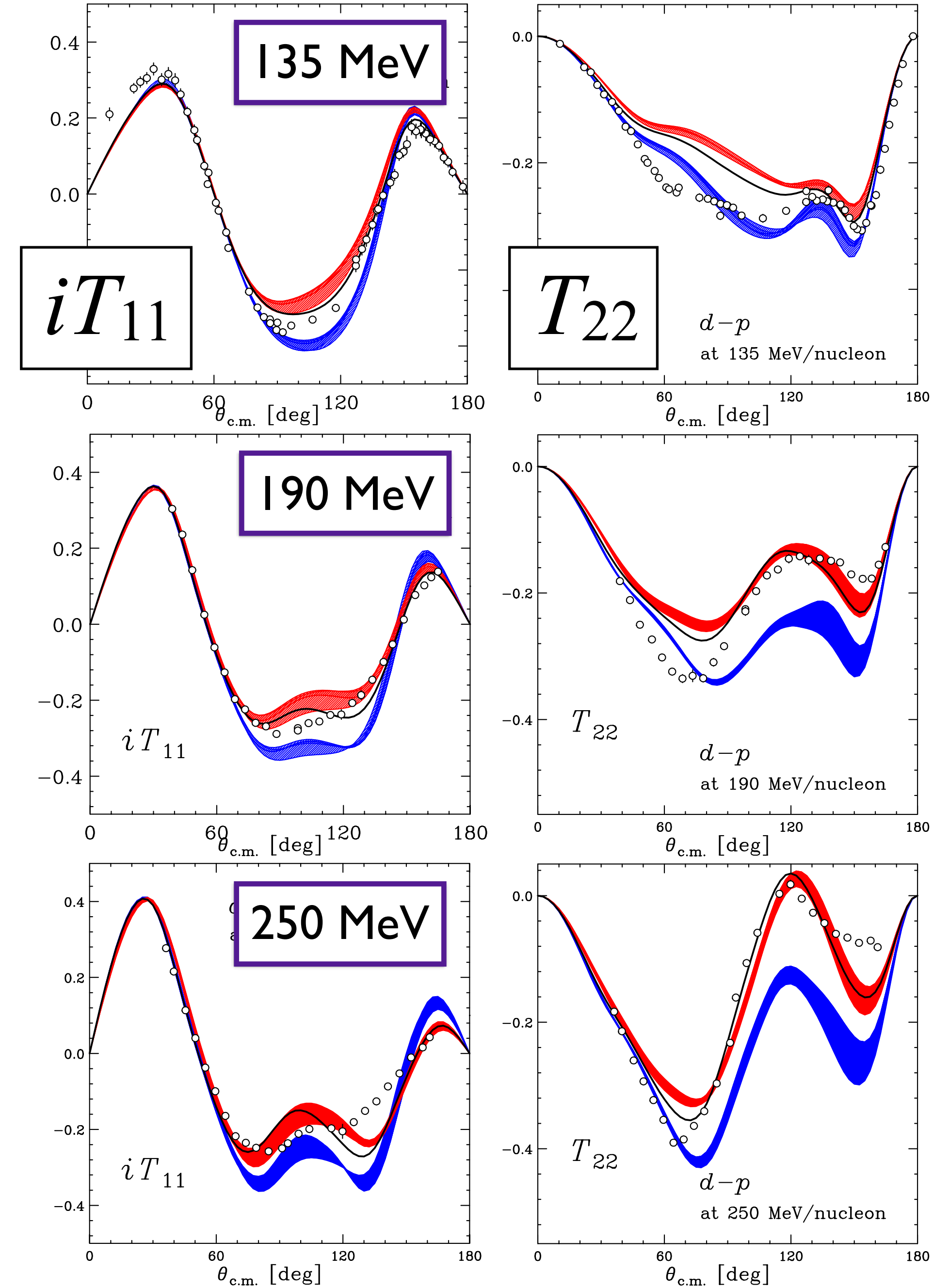
Relativistic effects are visible
at backward angles, but small.

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

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



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



- NN only
  - Large discrepancy at the backward angles

- NN + 2π-3NF (TM'99, Urbana-IX) :
  - Results are NOT always similar to the cross section.
  - Discrepancy exits at very backward angles at higher energies

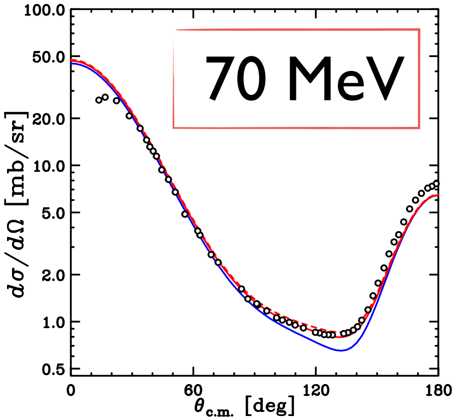
→ ***Insufficient knowledge of spin dependent parts of 3NFs***

NN (CDBonn, AV18, Nijm I,II)

TM'(99) 3NF + NN(CD Bonn, AV18, Nijm I,II)

Urbana IX 3NF+AV18

How does Chiral EFT Nuclear Potential work for Nd Elastic Scattering ?



N4LO⁺ NN pot. + N2LO 3NF Calculations (Preliminary)

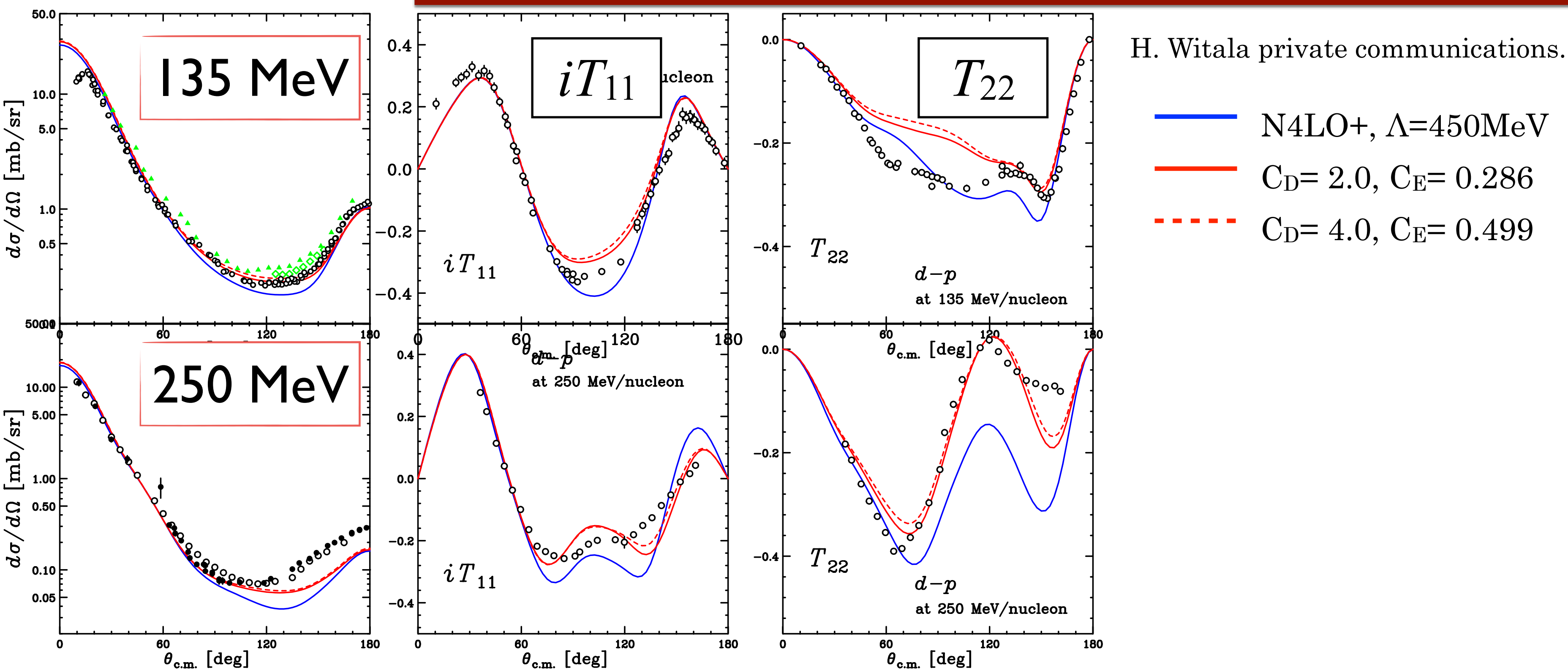
2NF: Semi-local Momentum-Space regularised Chiral NN potentials
P. Reinert, H. Krebs, E. Epelbaum EPJA 54, 86 (2018)

3NF: LECs of N2LO 3NF (D & E terms) are determined
by ^{3}H B.E. & cross section minimum for *Nd* @ 70MeV.

Calculated results are quite similar to phenomenological NN+3NF.

→ 3NFs of higher orders (N3LO & N4LO) are needed !

Nd data are useful to determine LECs of 3N sector.



Results of Comparison - *dp* elastic scattering -

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

- Spin Observables :
  - Not always described by adding 3NFs
  - Spin dependent parts of 3NFs are less known.

- **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.**
  - Quantitative understanding : 3NFs of higher orders are needed.
  - Nd data are useful to determine LECs of 3NFs (iso-spin states T=1/2).

p–^{3}He scattering

～ 4-Nucleon Scattering ～

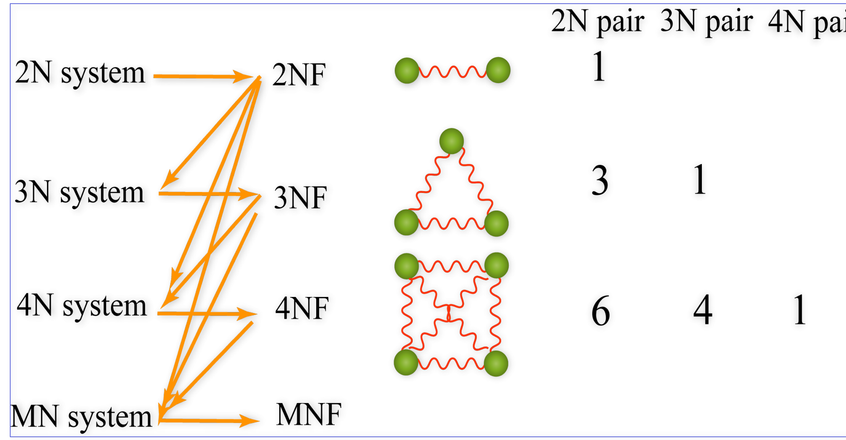
For *d+d* scattering Exp. & Analysis
talks by I. Ciepal, N. Kalantar-Nayestanaki, B. Włoch
(Tuesday Afternoon)

p-^{3}He scattering

- **4-nucleon scattering**
  - **First Step from Few to Many**
  - **Larger effects of 3NFs ?**

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

- **4NF effects**



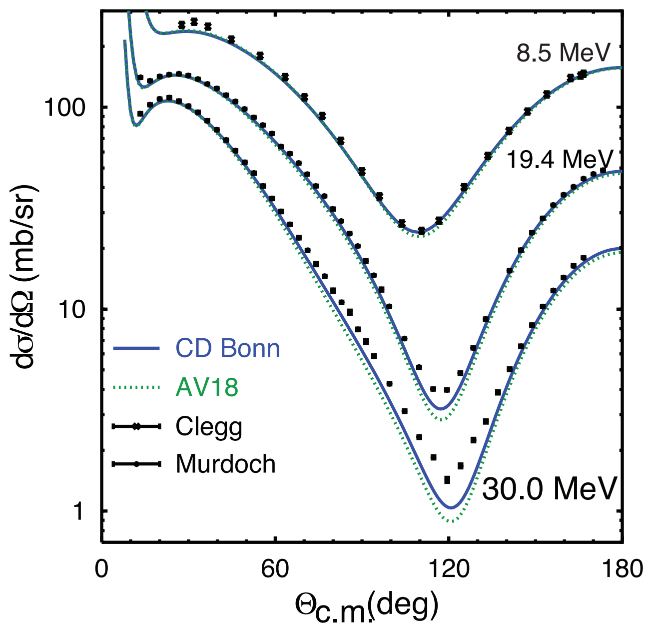
p-^{3}He scattering

Theory in Progress

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

up to 35 MeV

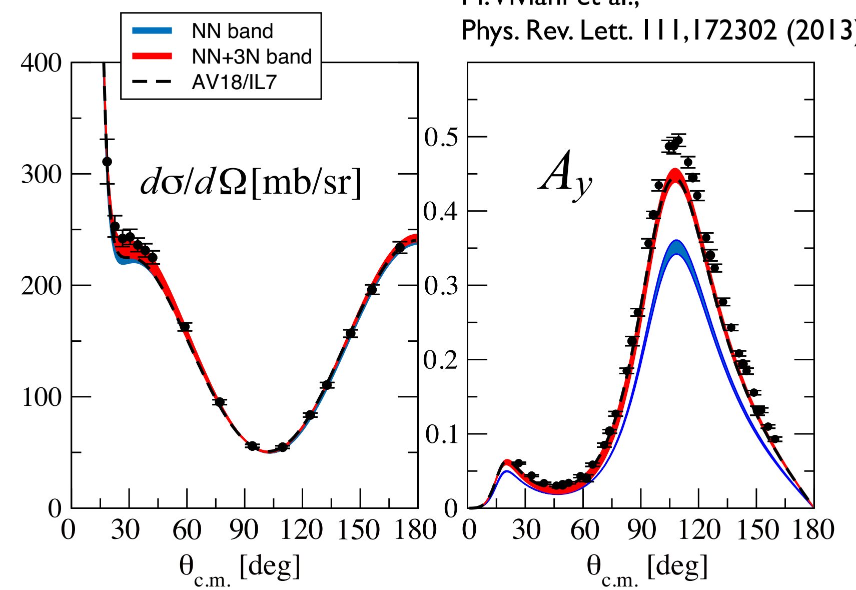
A. Deltuva and A.C. Fonseca
Phys. Rev. C 87, 054002 (2013)



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

at 5.54 MeV

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



- No signature of 3NFs in cross section
- *Ay*(*p*) puzzle : 3NFs sensitive to *p*-shell nuclei improve the agreement to the data.

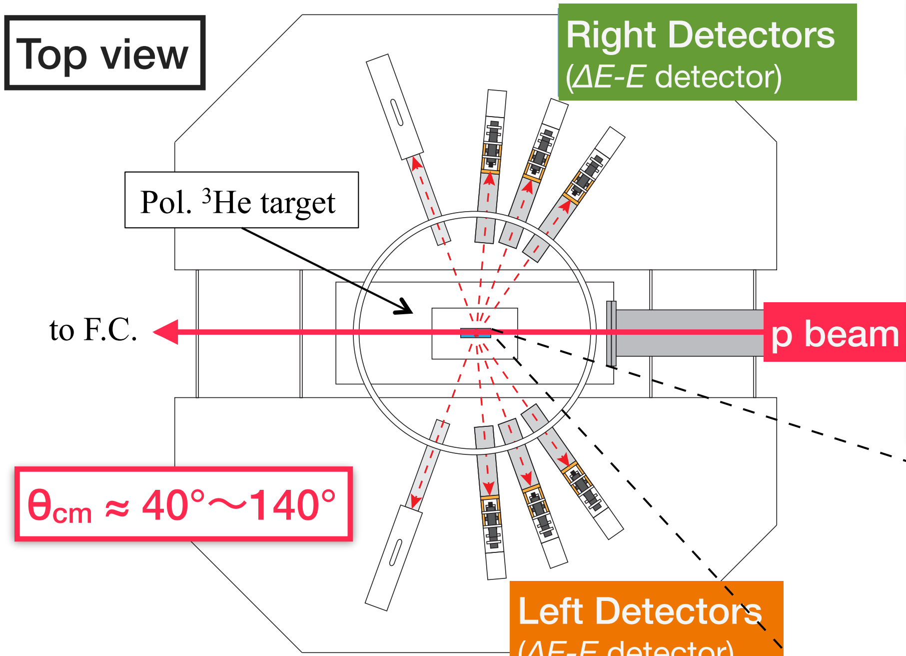
How about spin observables at higher energy?

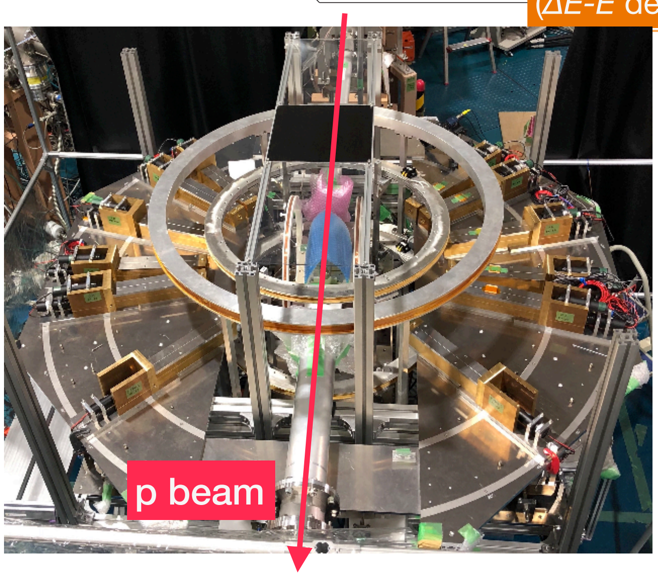
Summary of Measurement for p–^{3}He Elastic Scattering

Grand Raiden RCNP	65 MeV	Cross section & $A_y(p)$	$\theta_{c.m.} = 27° - 170°$
CYRIC Tohoku Univ.	70 MeV	$A_y(^3\mathrm{He})$	$\theta_{c.m.} = 46° - 141°$
ENN course RCNP	65 MeV	$C_{y,y}$, $A_y(p)$, $A_y(^3\mathrm{He})$	$\theta_{c.m.} = 47° - 156°$
ENN course RCNP	100 MeV	$C_{y,y}$, $A_y(p)$, $A_y(^3\mathrm{He})$	$\theta_{c.m.} = 47° - 156°$

Talks by M. Inoue, S. Nakai, A. Watanabe (Monday & Tuesday Afternoon)

Experiment with pol.^{3}He target (CYRIC/RCNP)

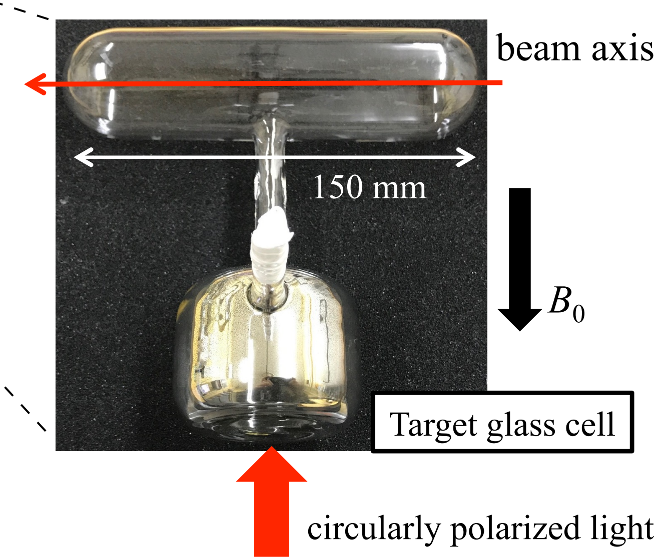




Measured Observables : $C_{y,y}$, $A_y(p)$, $A_y(^3\text{He})$

pol. ^{3}He target

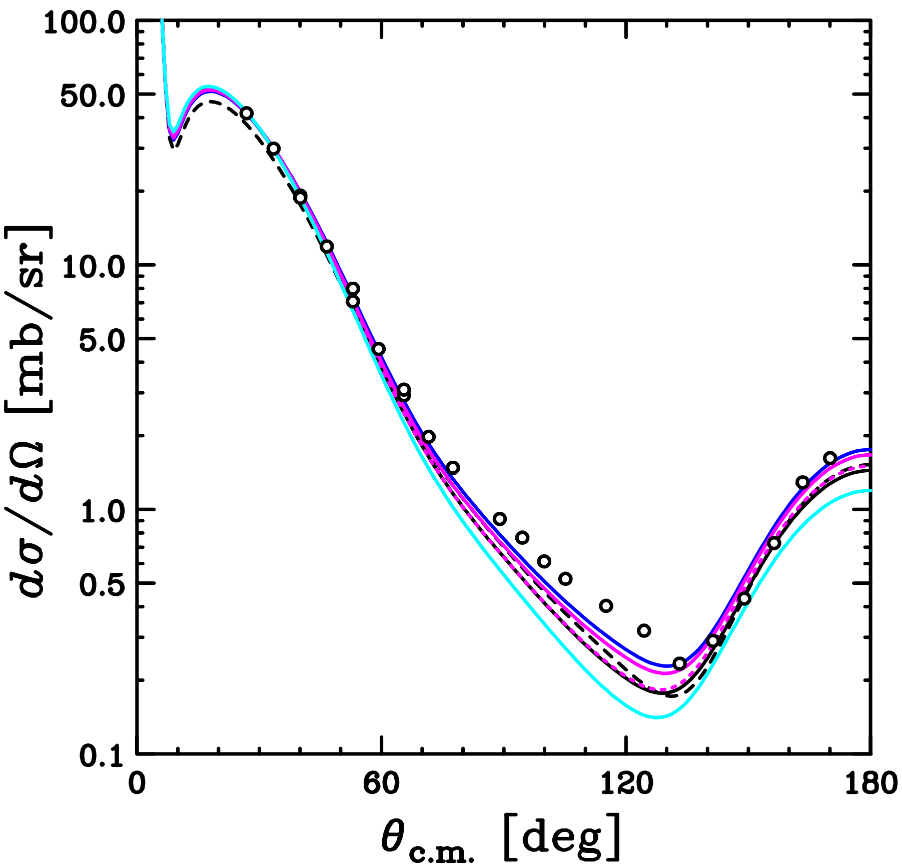
- *Method : AH-SEOP*
- *3 atm (≈2 mg/cm^2)*
- *Target Cell : GE180 (made in Tohoku Univ.)*
- *≈ 40% polarization*
  (calibration : EPR, neutron transmission)

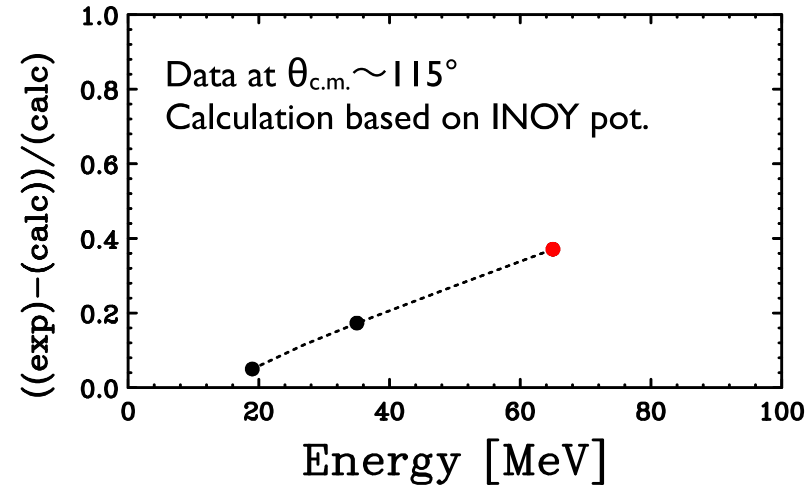


Differential Cross Section for $p-{}^3$He Elastic Scattering

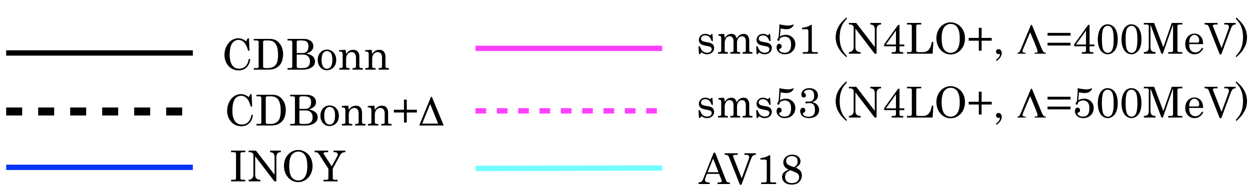
Calculations : A. Deltuva private communications

$p-{}^3$He at 65 MeV

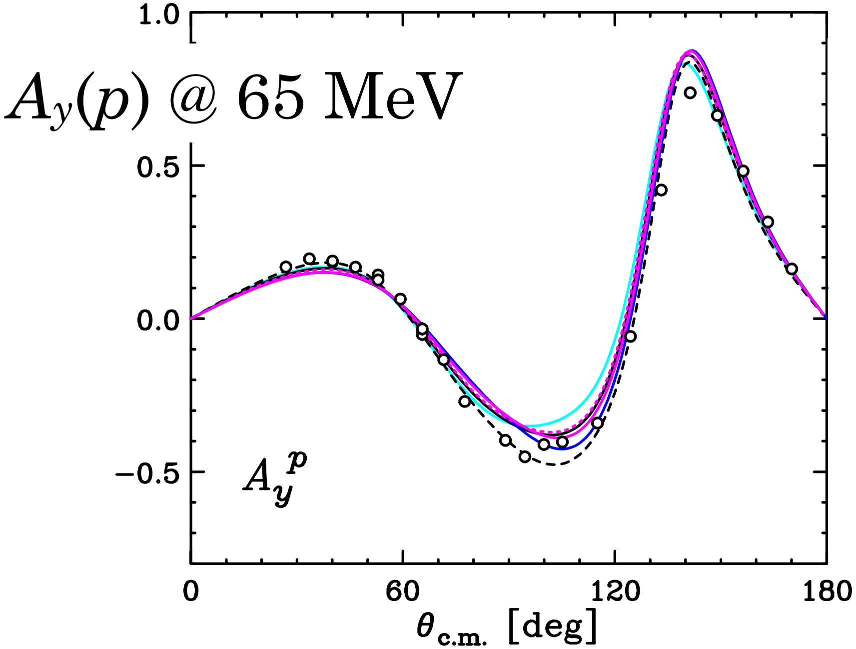


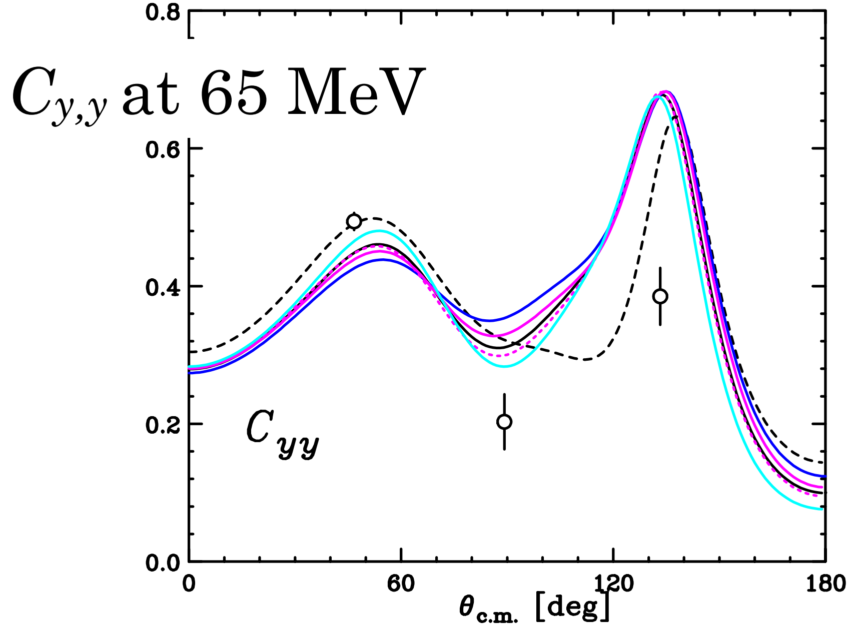


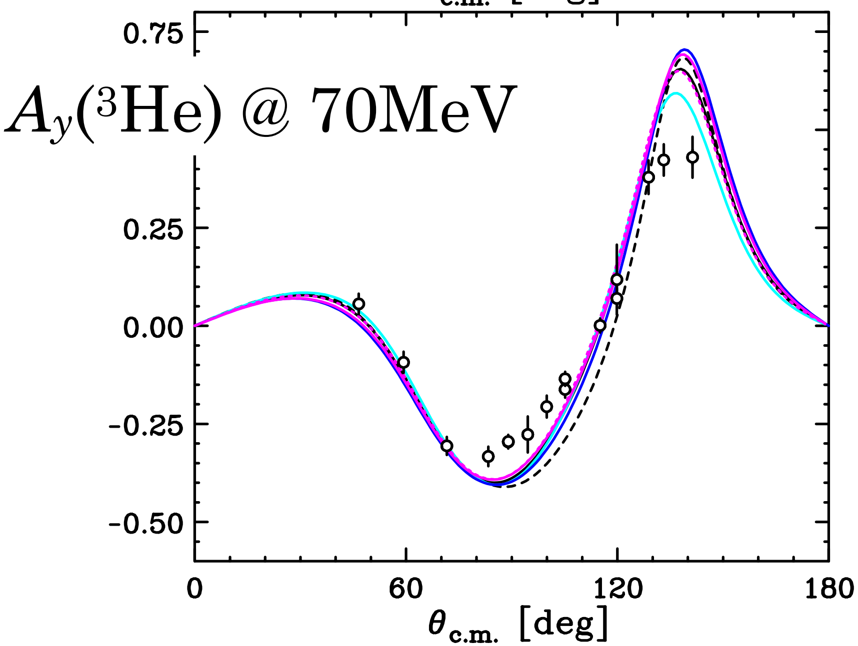
- Various NN potentials give similar results.
- Clear discrepancy is found around the minimum region.
- Predicted effects of Δ-isobar are small.



Spin Observables for p–^{3}He Elastic Scattering

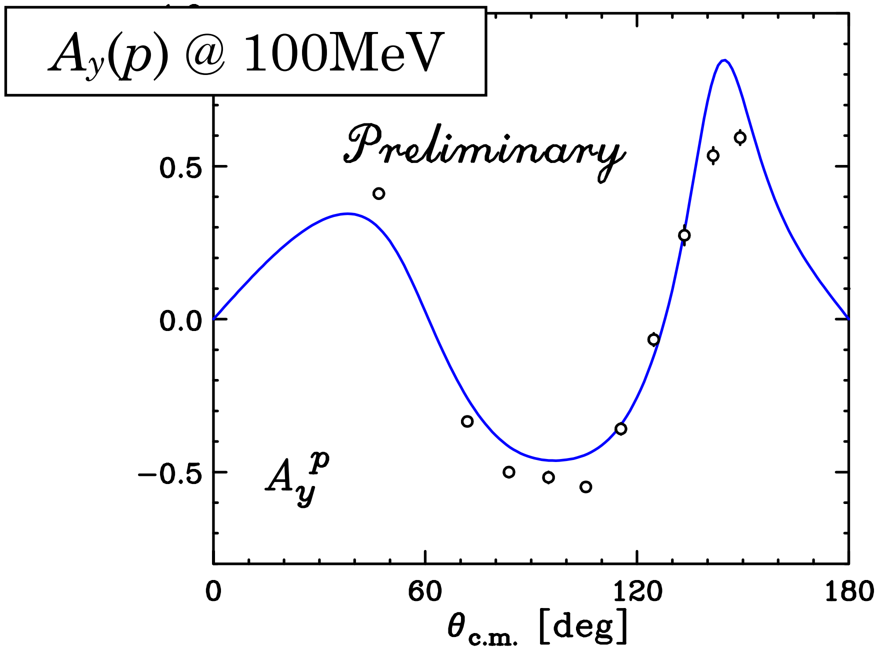


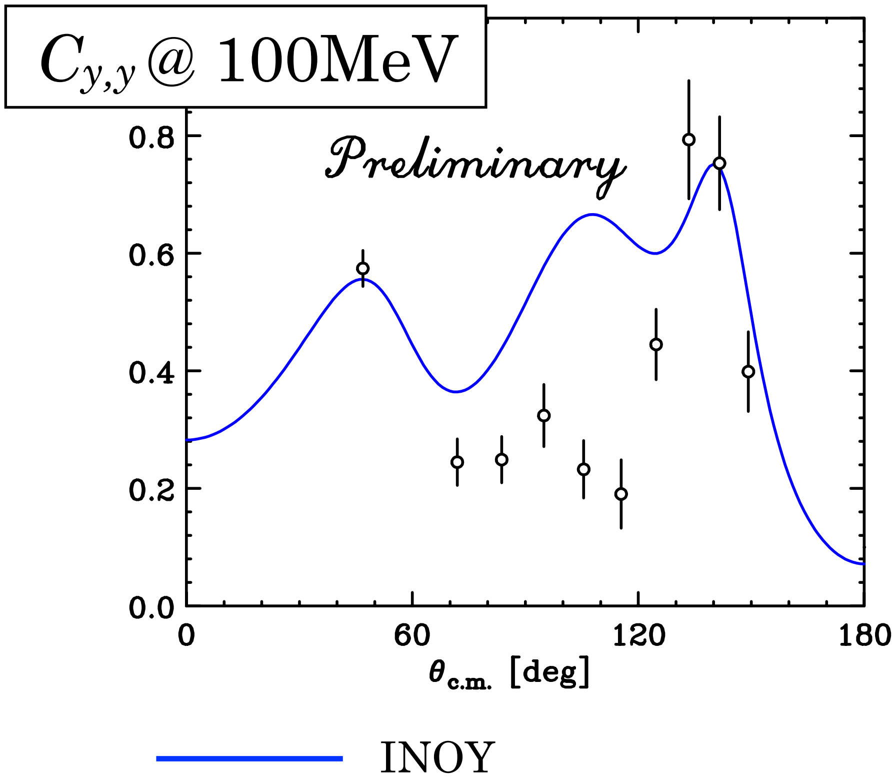


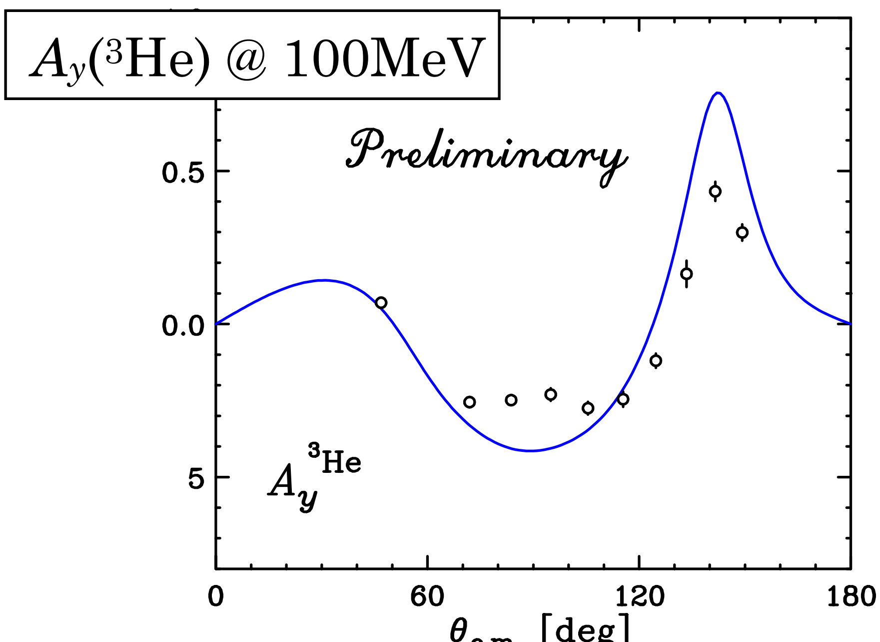


- $A_y(p)$: Good agreement to the calculations.
- $A_y(^3\mathrm{He})$: Small but clear difference is found.
- $C_{y,y}$: Large difference is found at backward angles. Sizable effects of Δ-isobar are predicted.
- These features are more enhanced at 100 MeV.

Spin Observables for p–^{3}He Elastic Scattering







Summary (1/2)

Three-Nucleon Forces

are key elements to fully understand nuclear properties.
e.g. nuclear binding energies, EOS of nuclear matter

Few-Nucleon Scattering

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

Nucleon-Deuteron Scattering - 3N 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.

Summary (2/2)

Proton-^{3}He Scattering - 4N Scattering -

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

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

Cross section minimum region at higher energies : Source of rich information of 3NFs

Spin correlation coefficient : Very sensitive to dynamics of Nuclear forces

Future Plan

Nucleon-Deuteron Scattering :
Energy dependent study of Spin Correlation Coefficients

p-^{3}He Scattering : Complete set of spin observables & Energy dependence

Study of T=3/2 three-nucleon systems (3p, 3n-states) (Spokesperson : K. Miki)

Study of 3NF effects in Nuclear Reaction

RIBF-*d*. Collaboration

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Yamada Conference LXXII

The 8th Asia-Pacific Conference on Few-Body Problems in Physics

August 19-23, 2020
Kanazawa, Japan

Organizers
E. Hiyama, A. Tamii, S. Ishikawa (co-chair)
Y. Ikeda, Y. Maeda (scientific secretariat)
K. Sekiguchi (chair of program committee)

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