東北大学

Deuteron Analyzing Powers for *dp* Elastic Scattering at Intermediate Energies and Three-Nucleon Forces

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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)

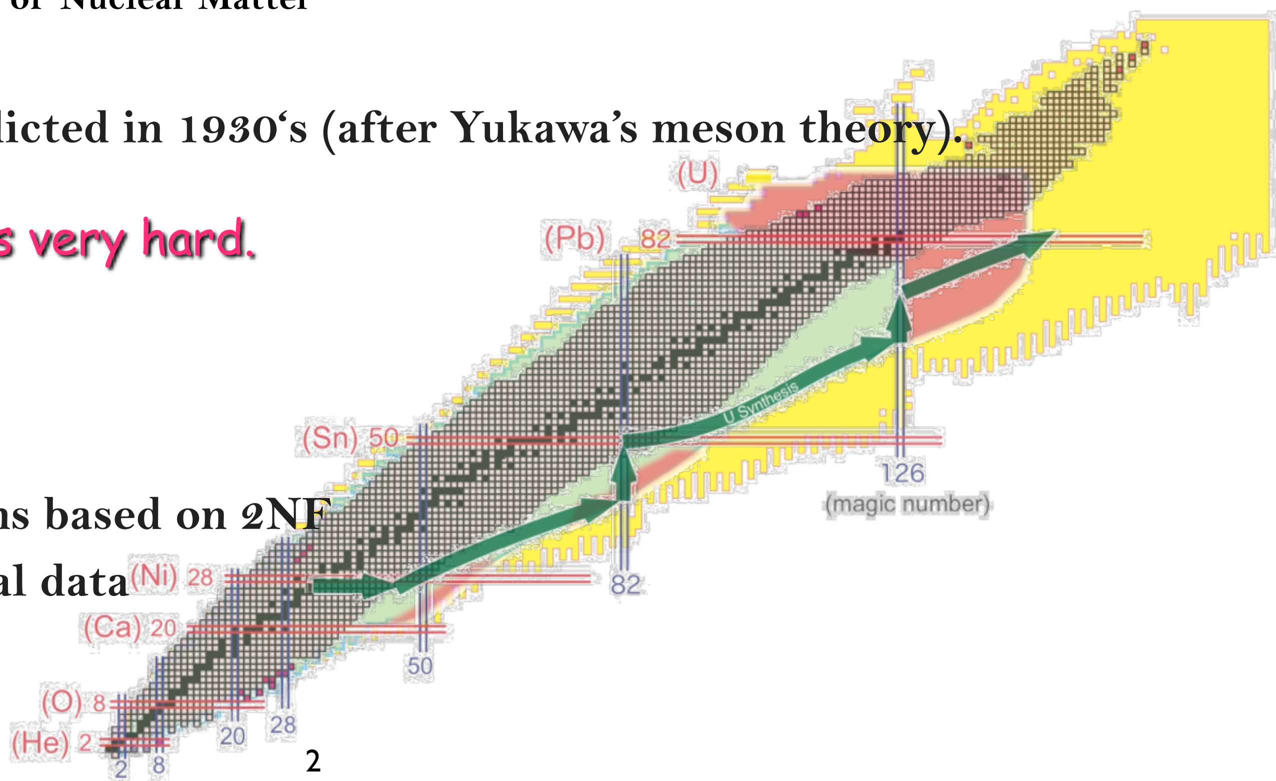
'90〜
- Nucleon-Deuteron Elastic Scattering at Intermediate Energies
- Biding Energies / Levels of Light Mass Nuclei
- Equation of State of Nuclear Matter

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

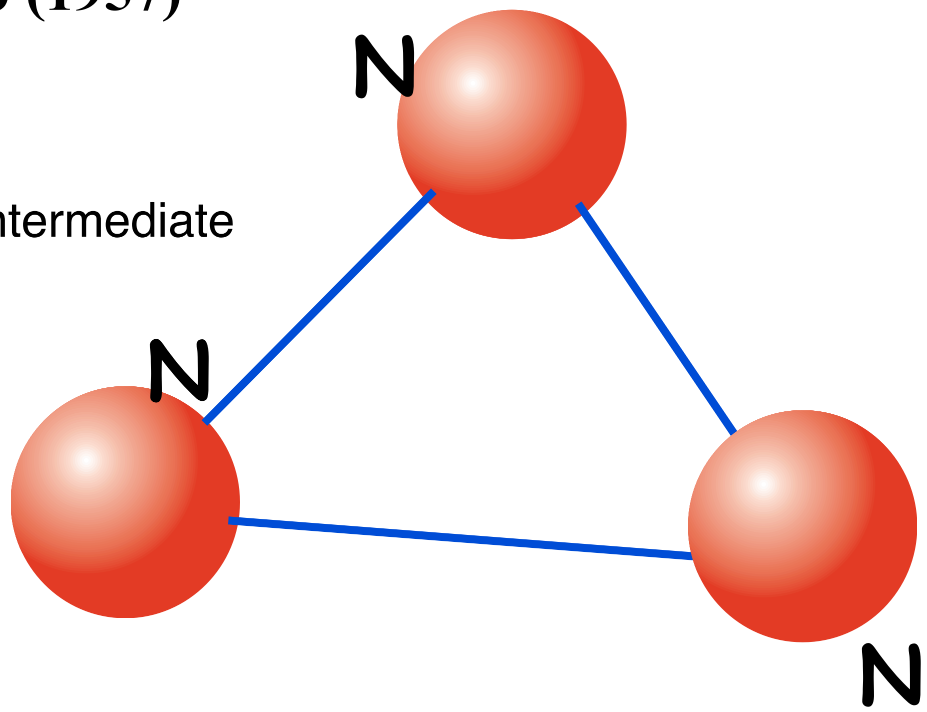


Three-Nucleon Force (3NF)

1957 Fujita-Miyazawa 3NF

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

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



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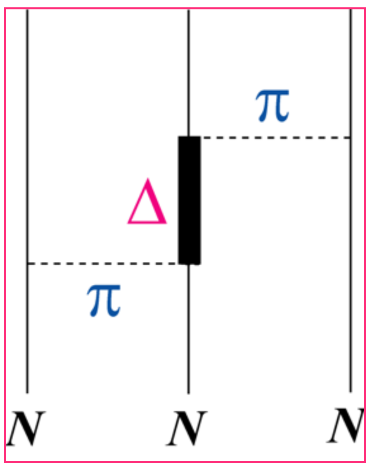

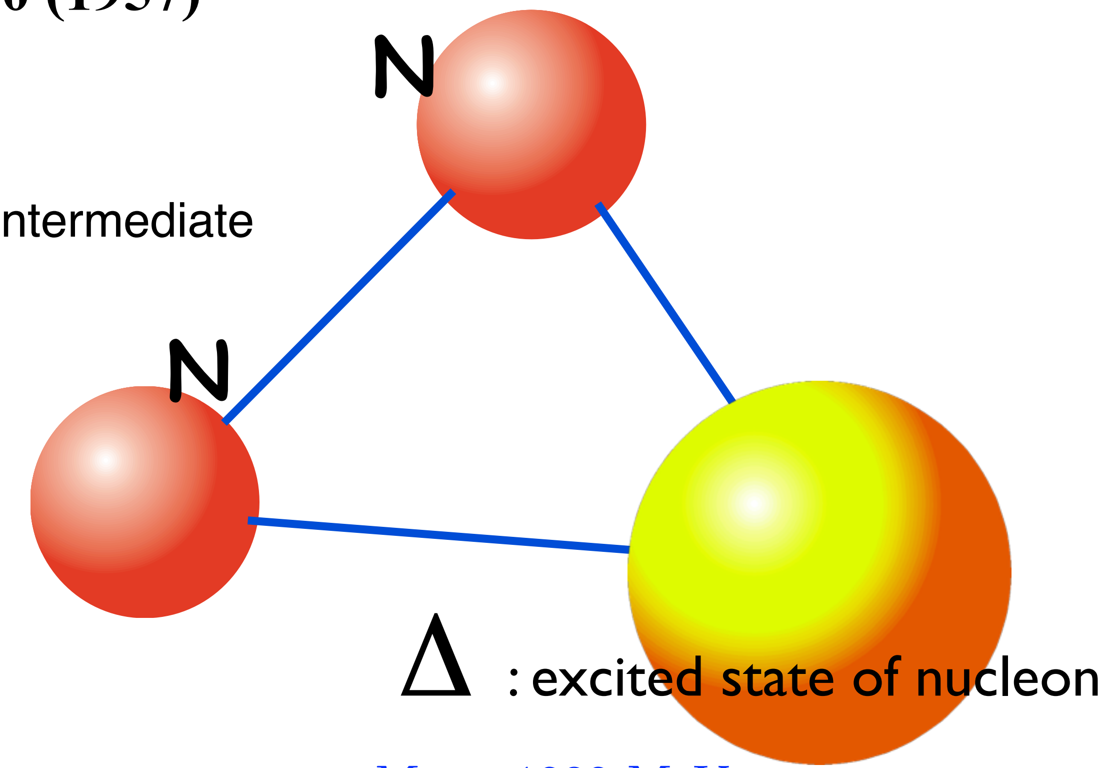

$$M_{\Delta} = 1232\ \mathrm{MeV}$$

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

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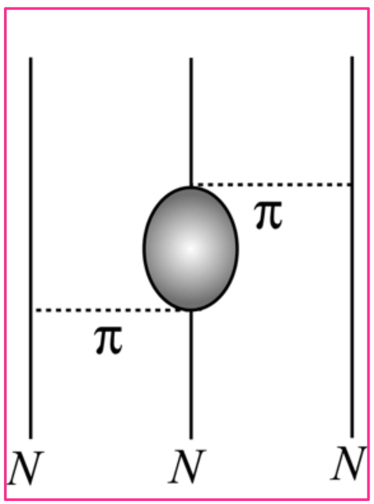

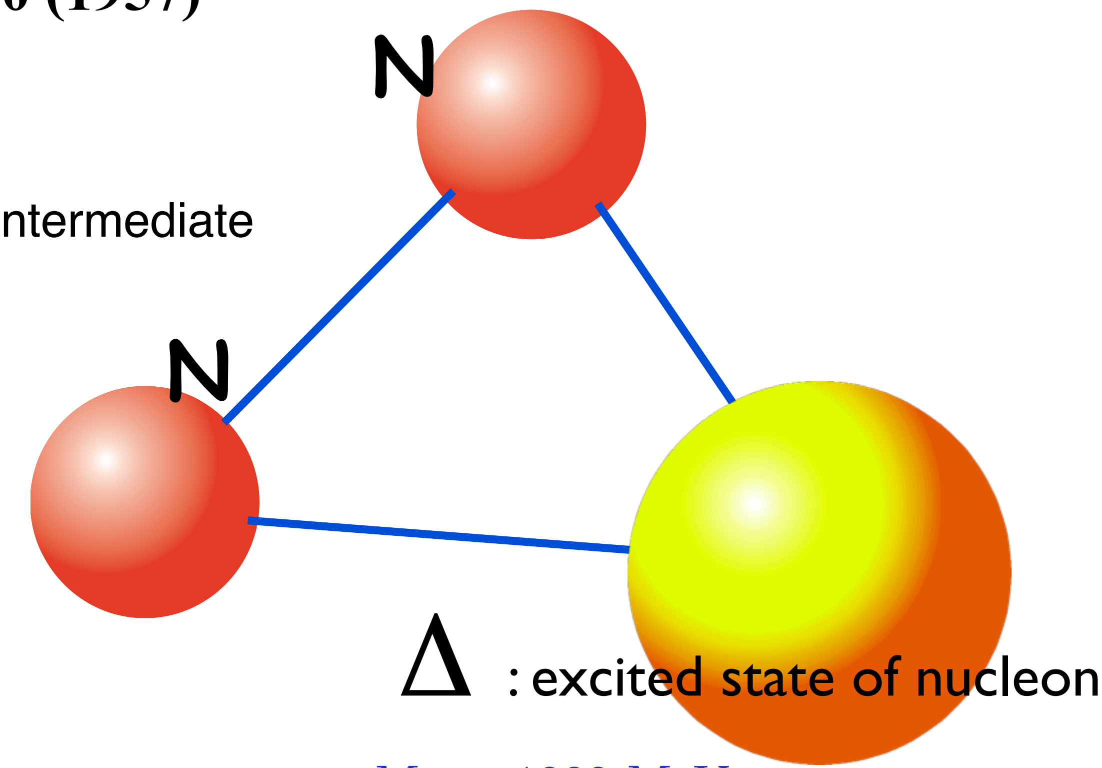

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- Tucson-Melbourne (TM)
- Urbana IX
- Brazil, Texas etc…

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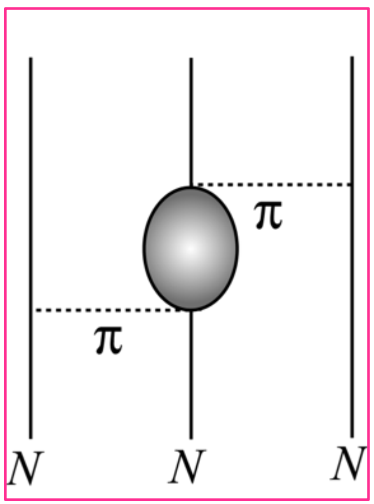

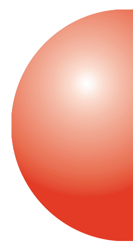

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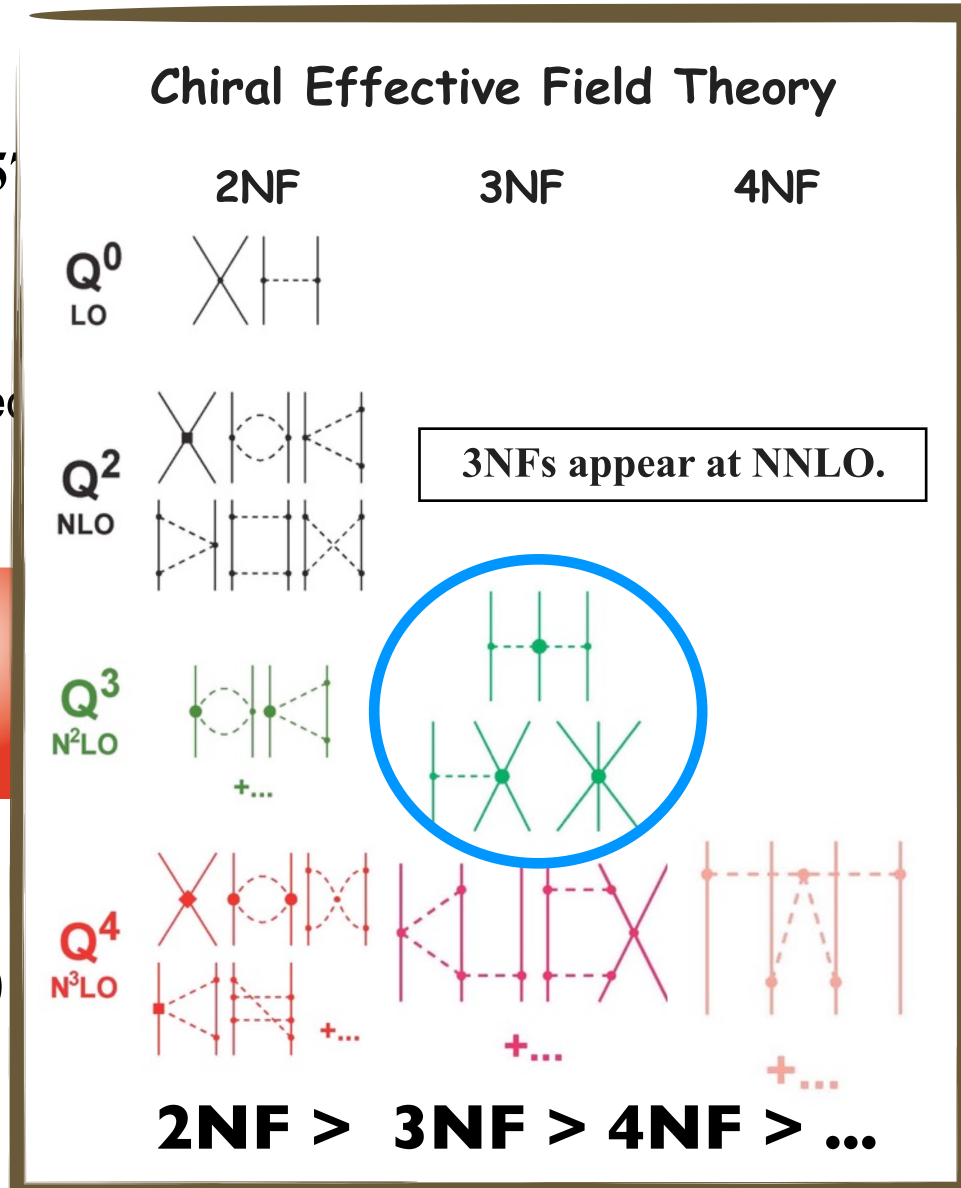
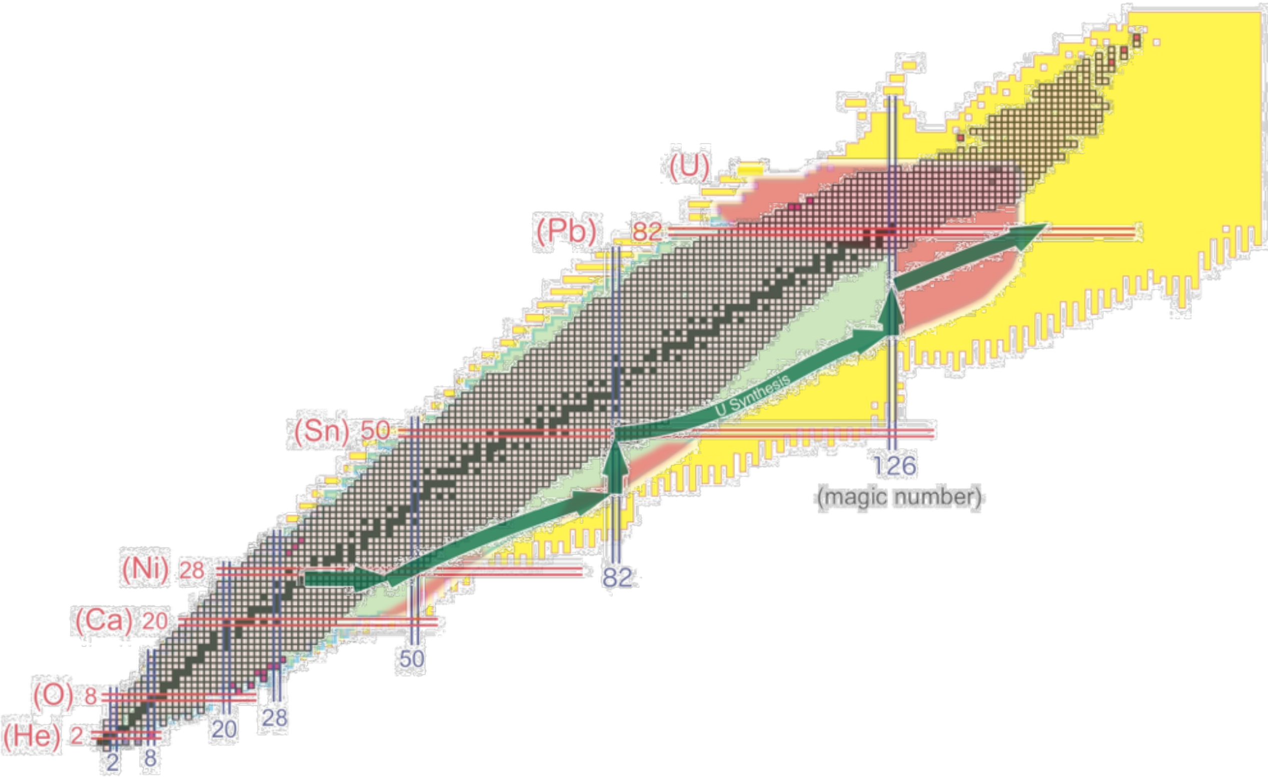


Where can we find 3NF effects ? - I -

3NFs in Finite Nuclei

Ab Initio Calculations for Light Nuclei

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



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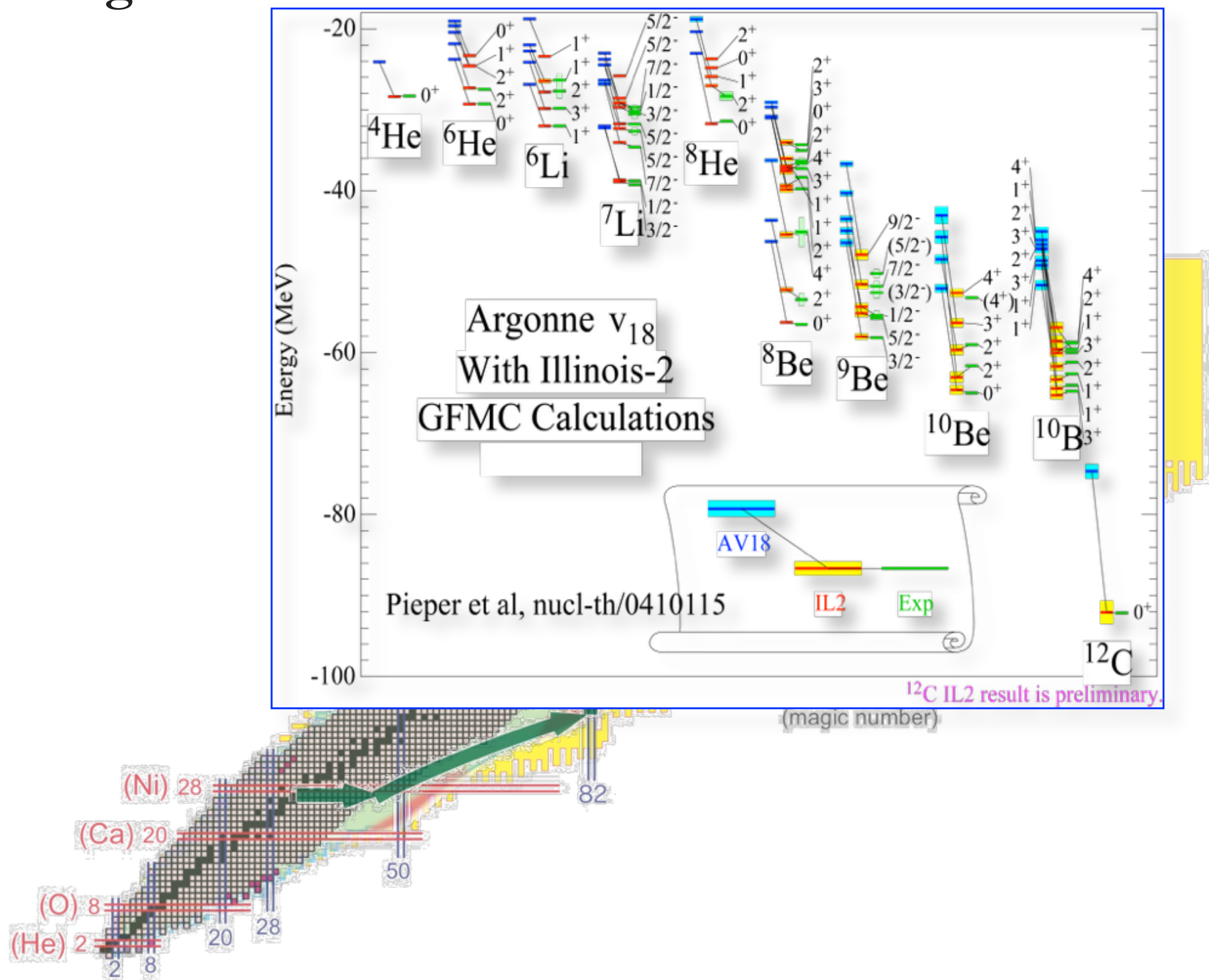

Where can we find 3NF effects ? - I -

3NFs in Finite Nuclei

Ab Initio Calculations for Light Nuclei

- **Green's Function Monte Carlo**
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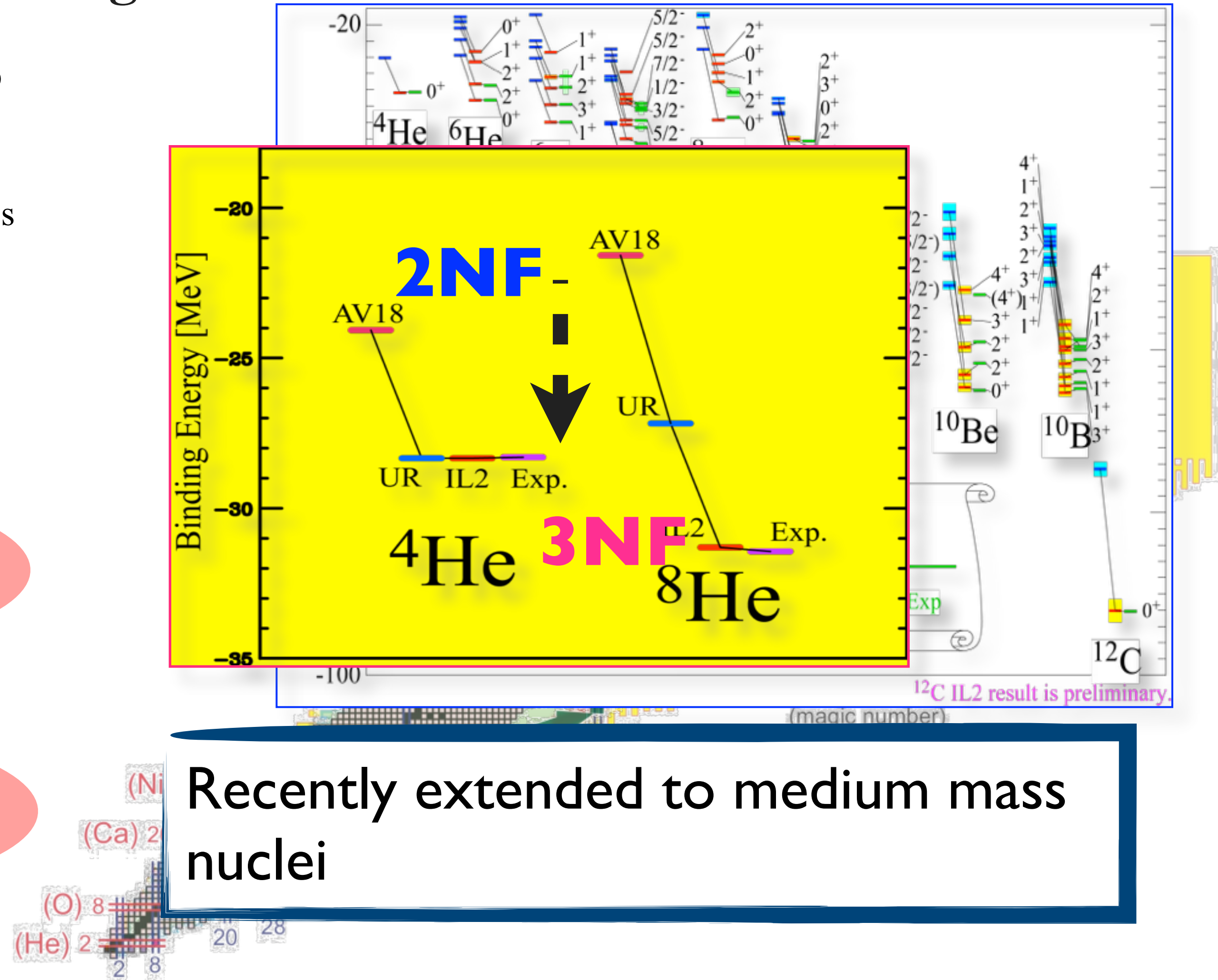
- 2NF provide less binding energies
- 3NF : well reproduce the data

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

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

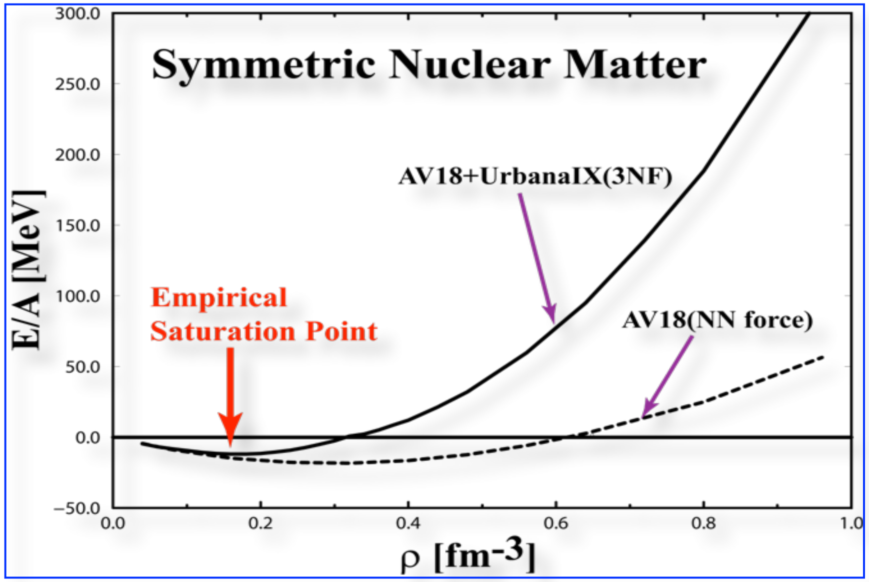
Note :
T=3/2 3NFs play important roles to explain B.E. in neutron rich nuclei.



Recently extended to medium mass nuclei

Where can we find 3NF effects ? - II -

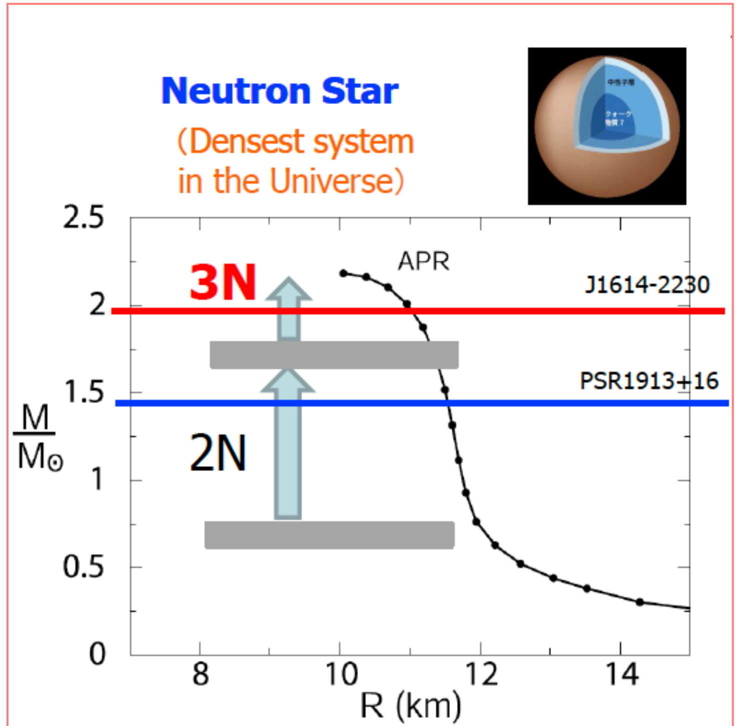
3NFs in Infinite Nuclei



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.

Nucleon-Deuteron Scattering

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

✓ Momentum & Spin dependence
✓ Iso-spin dependence : only T=1/2

Direct Comparison between Theory and Experiment

- Theory : Faddeev Calculations
  Rigorous Numerical Calculations of 3N 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

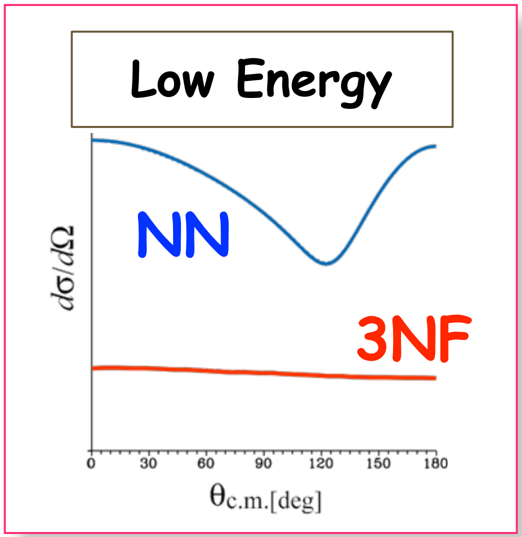
- Experiment : Precise Data
  - $d\sigma/d\Omega$, Spin Observables (A_i, K_{ij}, C_{ij})

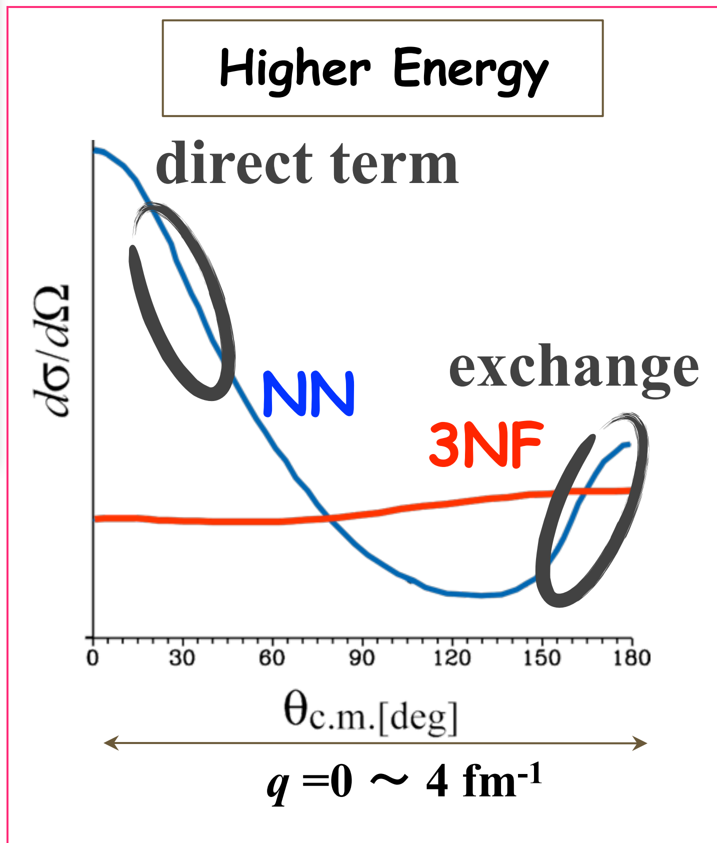
Extract information of Three Nucleon Forces.

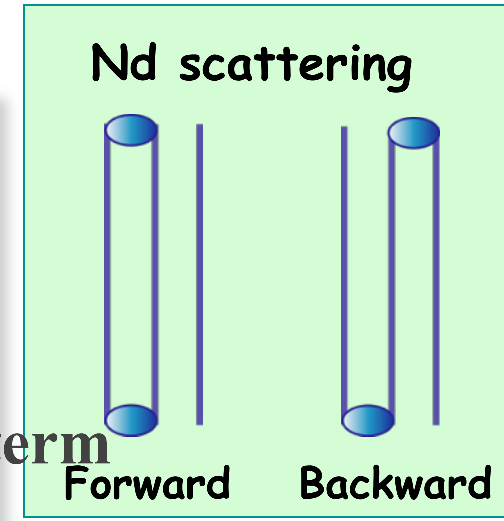
Where is the Hot Spot for 3NF Effects in Three Nucleon Scattering?

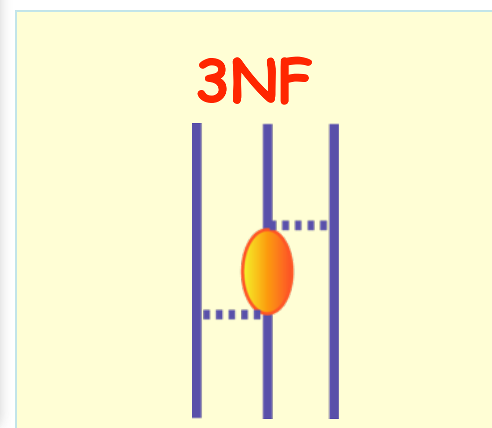
Predictions by H. Witala et al. (1998)

Cross Section minimum for Nd Scattering at 100-200 MeV/A









How to attack 3NF – 1st Step – d-p Elastic Scattering at 135 MeV/nucleon @ RIKEN Accelerator Research Facility (RARF)

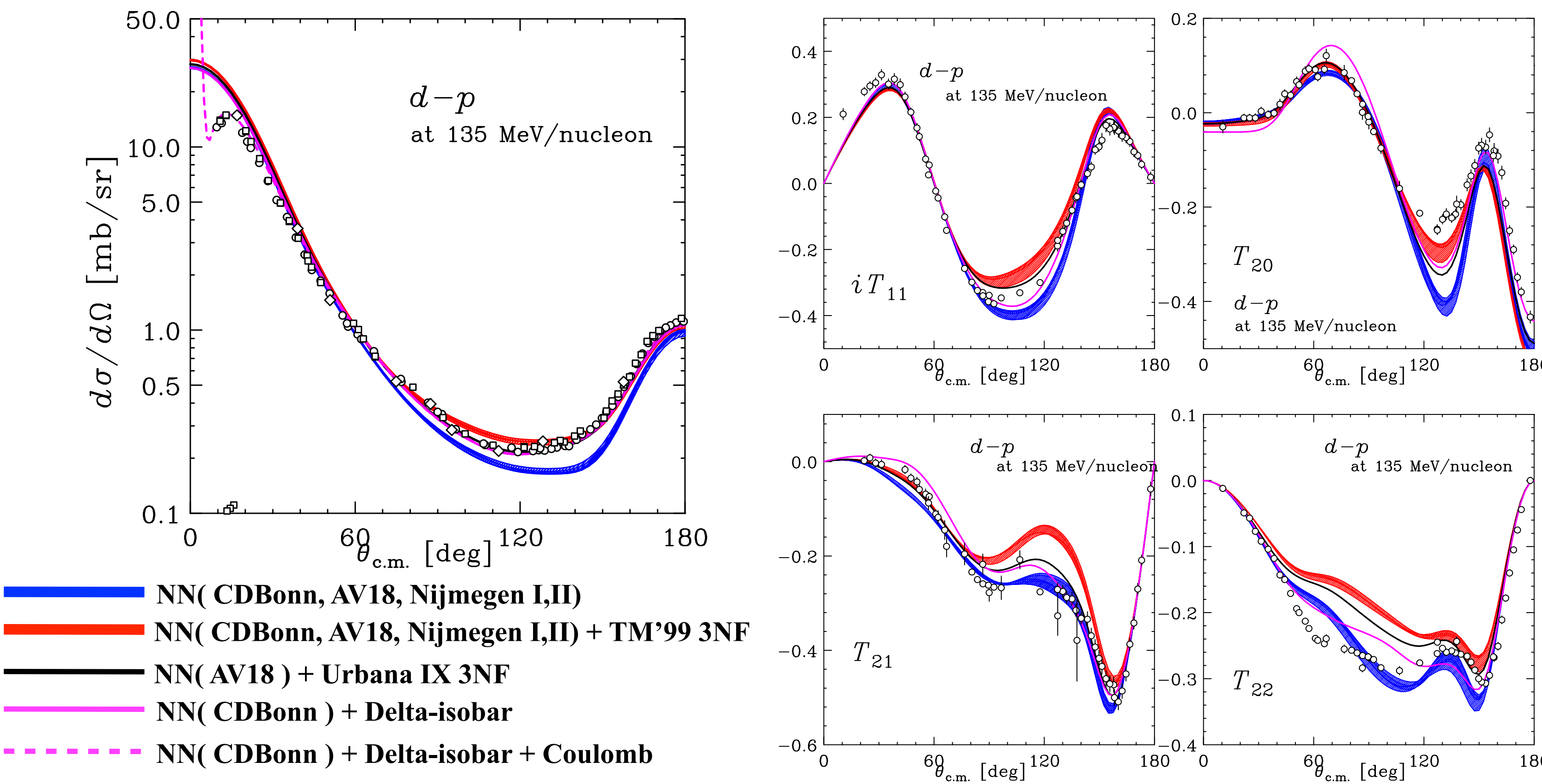
Cross Section : Good description by 2π-3NF

First Clear Signature of 3NFs in 3N Continuum

Spin Observables : Insufficient descriptions by 2π-3NF

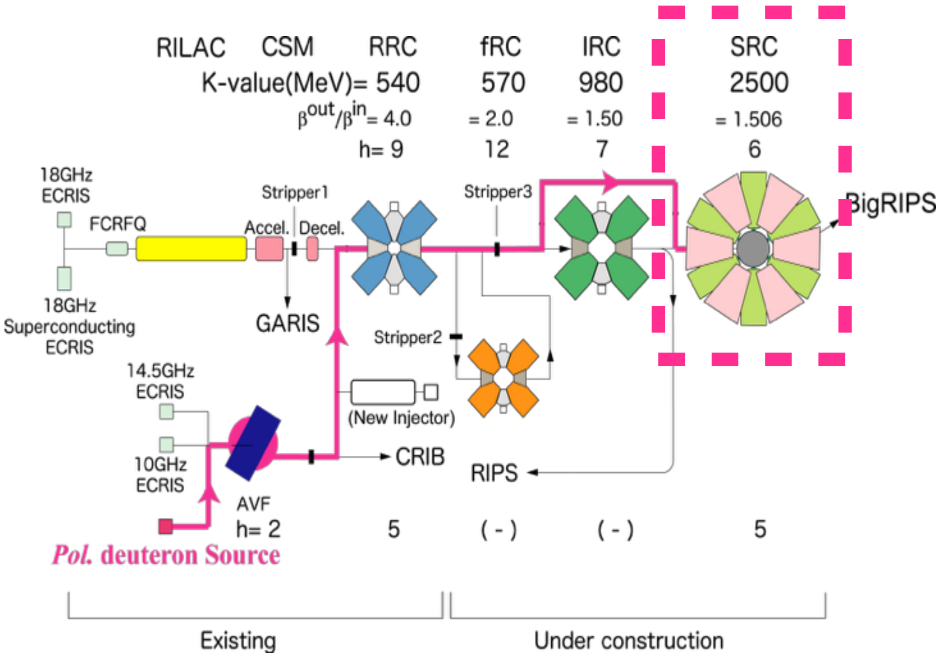
Defects of 3NF in Spin parts ??

K. S. et al., Phys. Rev. C 65, 034003 (2002).
K. S. et al., Phys. Rev. Lett. 95, 162301 (2005).



How to attack 3NF – Next Step –
Few Nucleon Scattering with pol.d beams
@ RIKEN RI Beam Factory (RIBF)

- **RARF : AVF+RRC**
  - **Incident energy of deuteron :**
    - **65 – 135 MeV/nucleon**
- **RIBF : AVF+RRC + SRC**
  - **Incident energy of deuteron :**
    - **190 - 400MeV/nucleon**



Experiment at RIBF

***dp* Elastic Scattering**

250 MeV/nucleon : in 2009
294 MeV/nucleon : in 2012
190 MeV/nucleon : in 2015

- **All deuteron analyzing powers**

$$A_y^d, A_{yy}, A_{xx}, A_{xz}(iT_{11}, T_{20}, T_{21}, T_{22})$$

- **Wide Angular Range**

$$\theta_{\rm c.m.} = 35^\circ - 160^\circ$$

- **High accuracy**

Go to higher energies

- Effects of 3NFs are relatively enhanced.
- Theory : harder

Polarized Deuterons

- rich set of spin observables

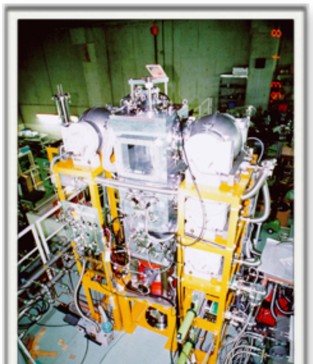
RIKEN RI Beam Factory (RIBF)

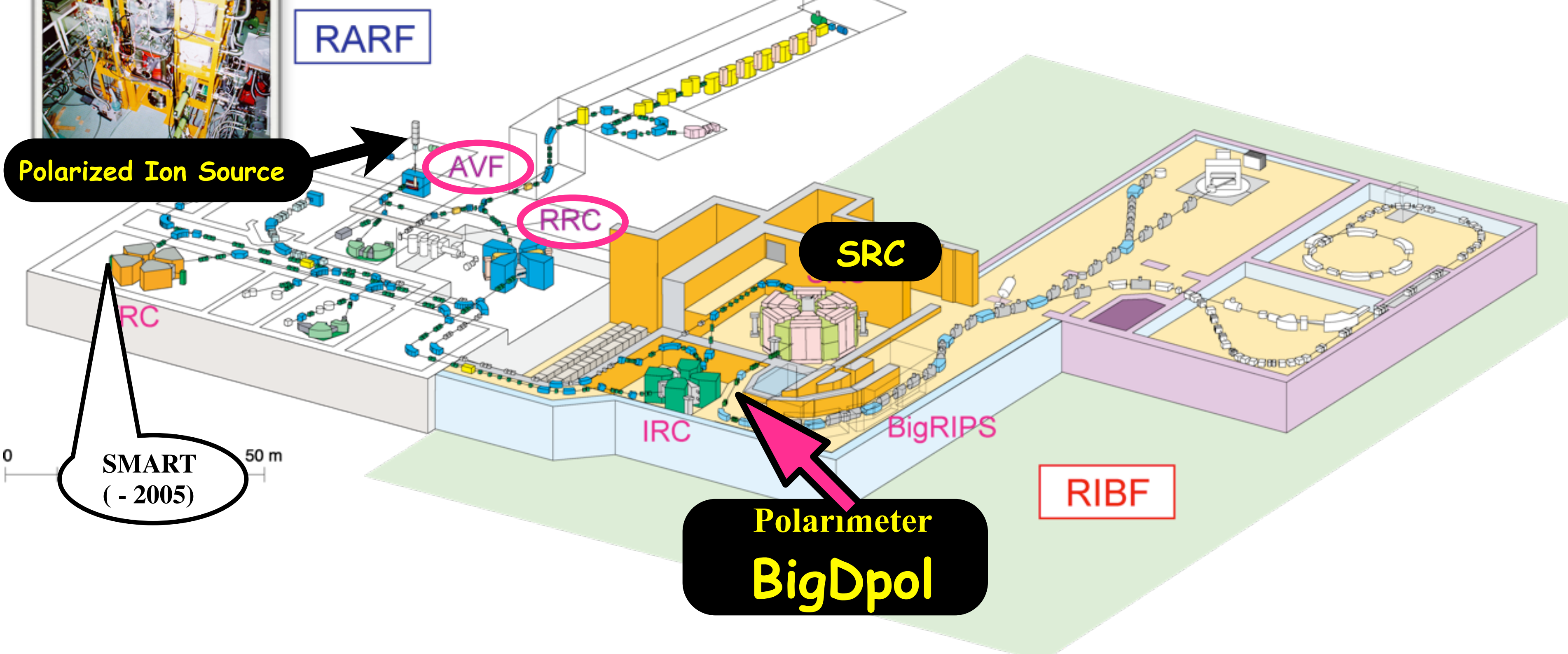
- **Polarized *d* beam was accelerated by the AVF+RRC+ SRC.**
- Spin axis of deuteron beam was rotated prior to acceleration.
- **Single turn extraction of beam was successfully obtained for all the cyclotrons.**

→ **Polarization amplitudes were maintained during acceleration.**

- **Beam Polarization : 80% of theoretical maximum values**

Spin axis of polarized d beams is freely controlled !

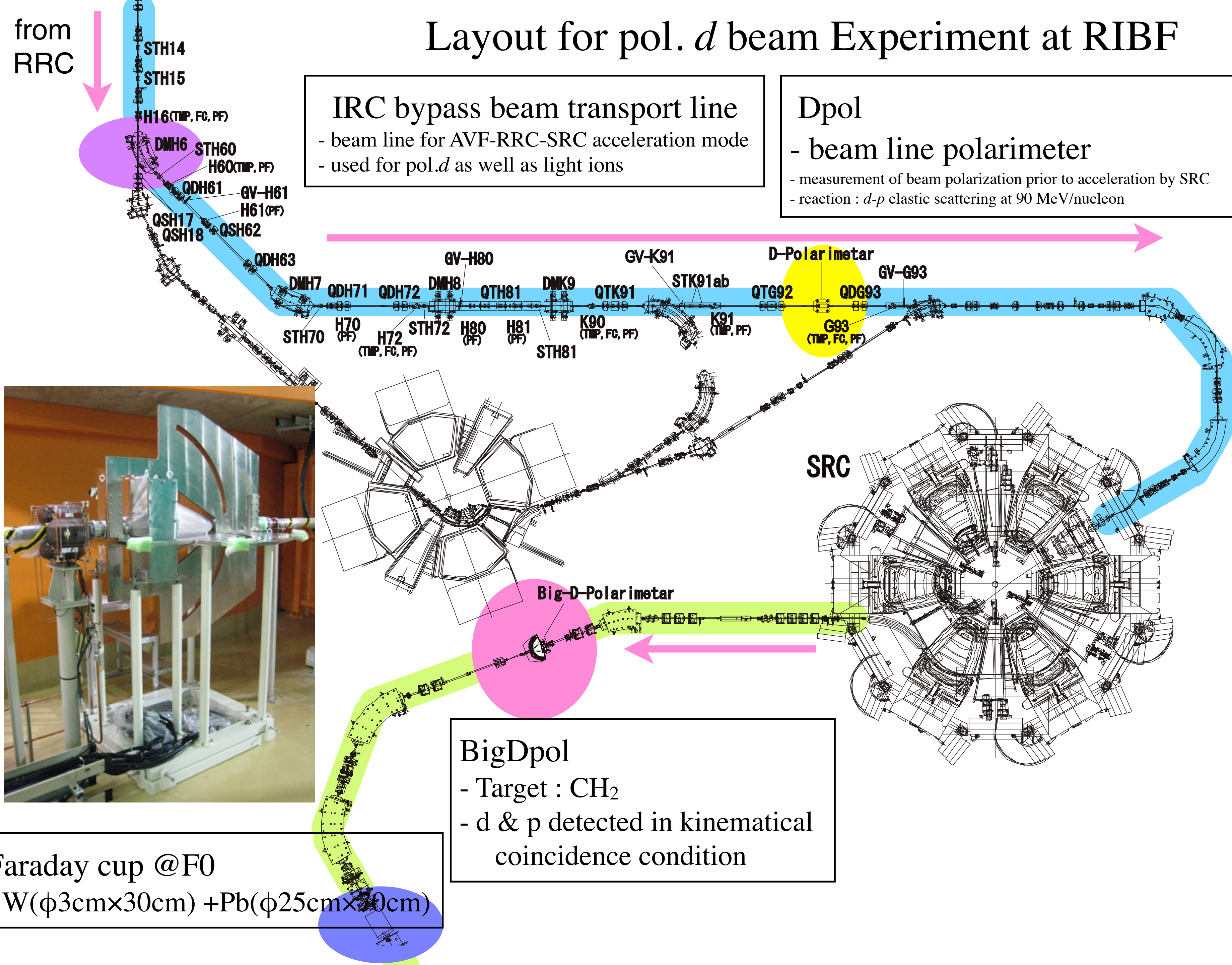




Layout for pol. *d* beam Experiment at RIBF

IRC bypass beam transport line
- beam line for AVF-RRC-SRC acceleration mode
- used for pol.*d* as well as light ions

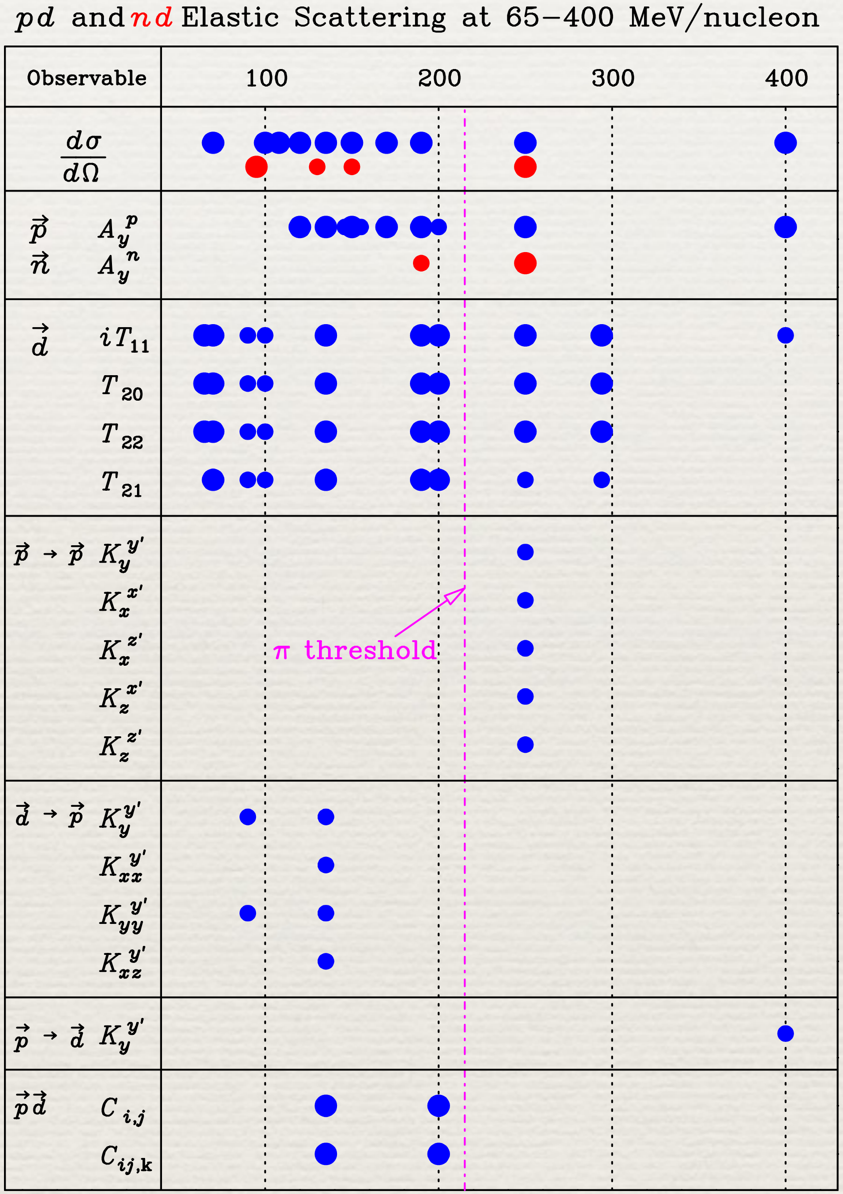
Dpol
- beam line polarimeter
  - measurement of beam polarization prior to acceleration by SRC
  - reaction : *d-p* elastic scattering at 90 MeV/nucleon



BigDpol
- Target : CH_2
- d & p detected in kinematical coincidence condition

Faraday cup @F0
- W(ϕ3cm×30cm) +Pb(ϕ25cm×40cm)

Nd Elastic Scattering Data at Intermediate Energies



~2016

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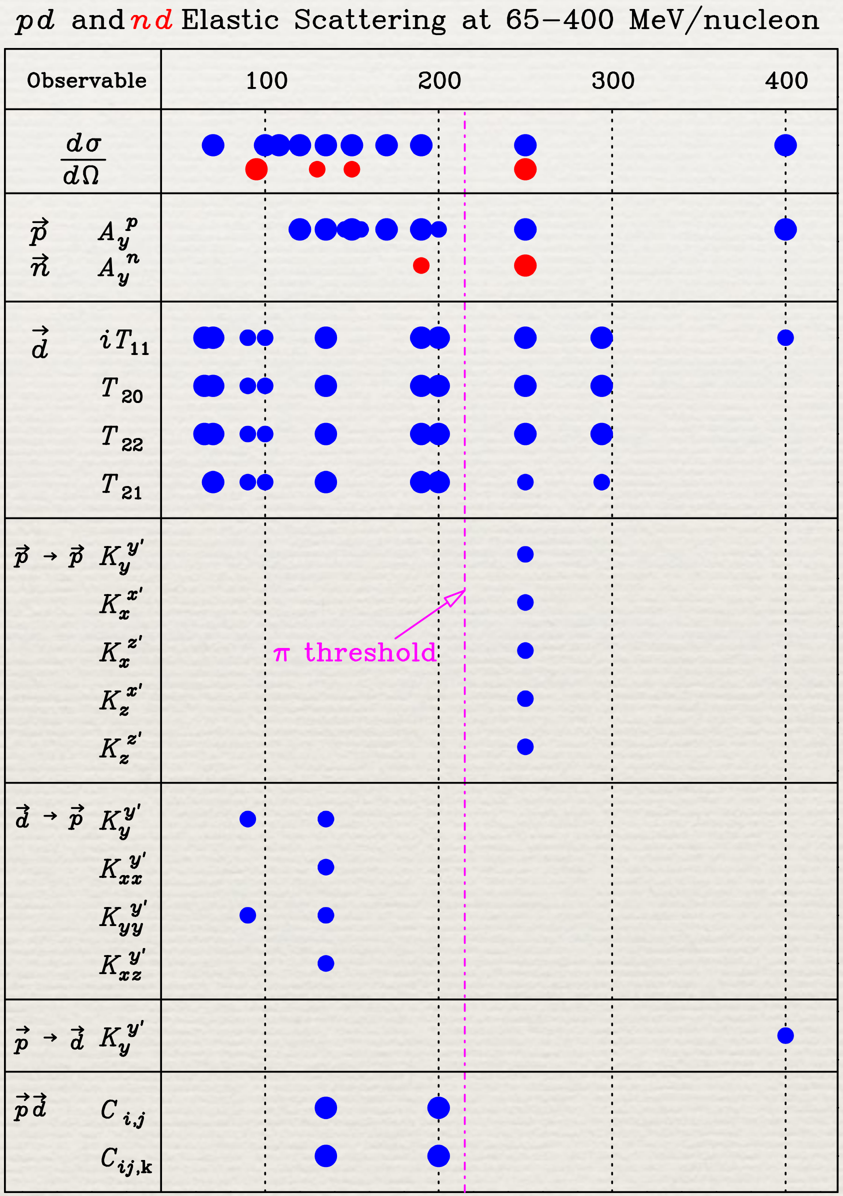


~2016

- **High precision data of**
  ***dσ/dΩ* & Spin Observables**
  from RIKEN, RCNP, KVI, IUCF

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

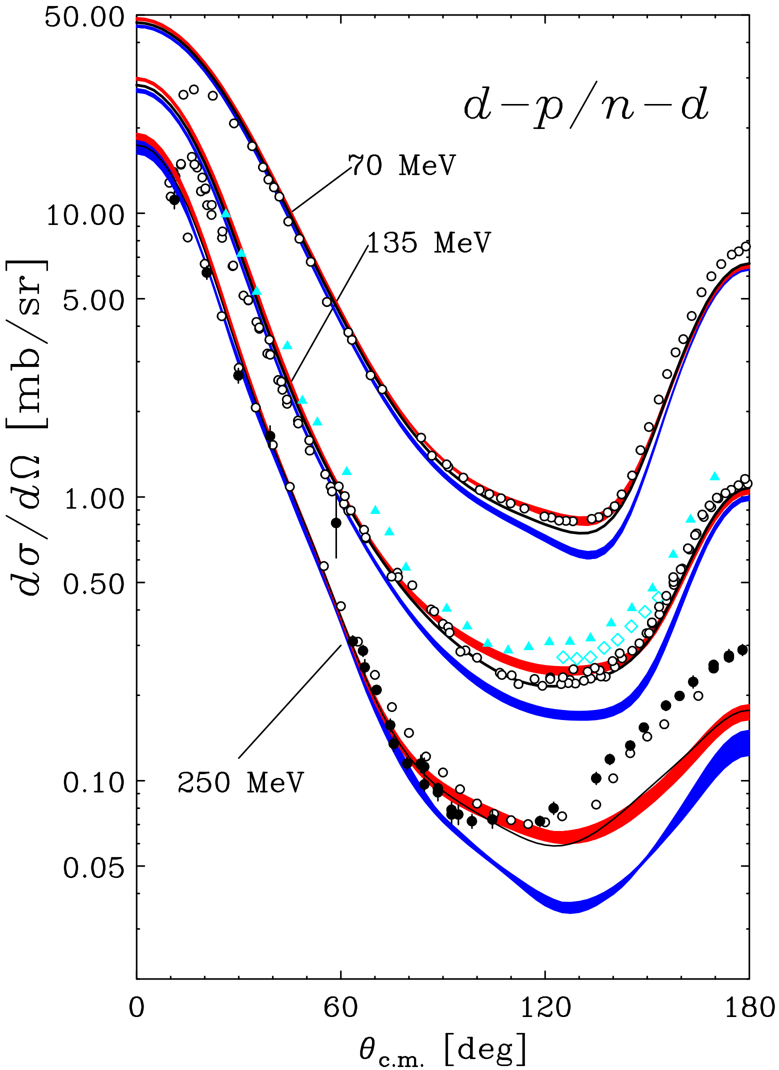
Data are compared with

- CD Bonn, AV18, Nijmegen I, II
- CD Bonn, AV18, Nijmegen I, II + TM'99 3NF
- AV18 + Urbana IX 3NF
- Chiral EFT N4LO NN

Differential Cross Section

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 - 400 MeV/nucleon

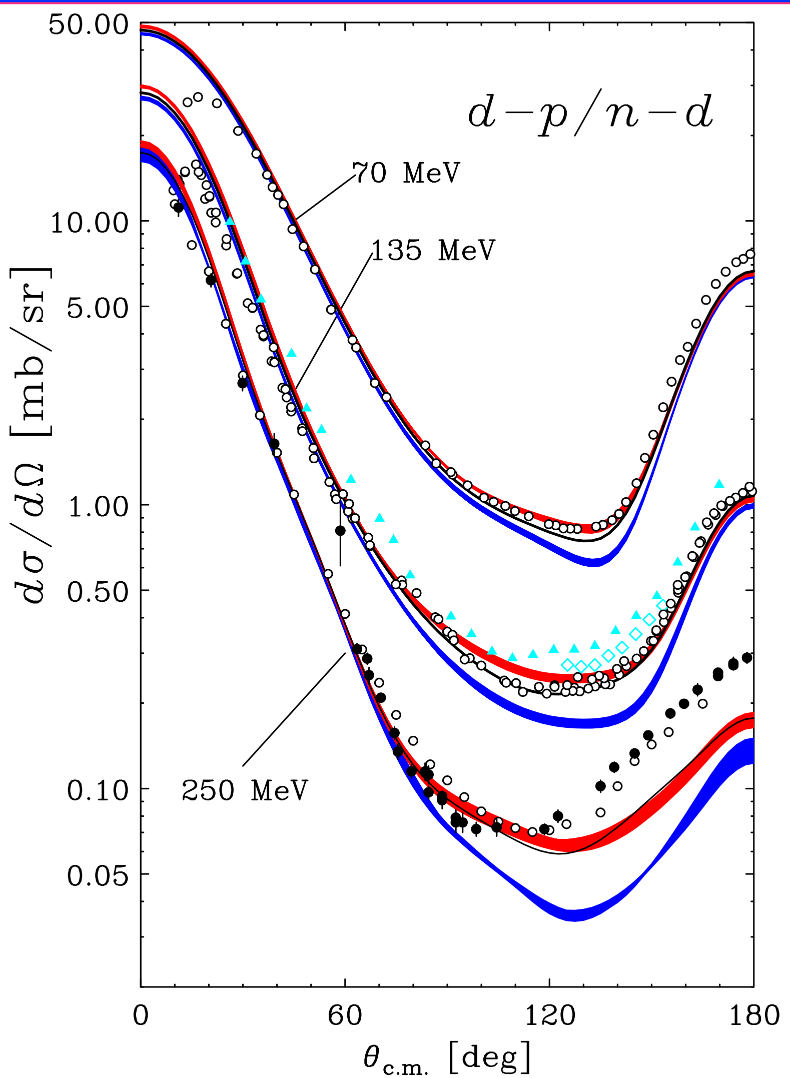


NN (CDBonn, AV18, Nijm I,II)
TM'(99) 3NF + NN(CD Bonn, AV18, Nijm I,II)
Urbana IX 3NF+AV18

- 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 - 400 MeV/nucleon



NN (CDBonn, AV18, Nijm I,II)
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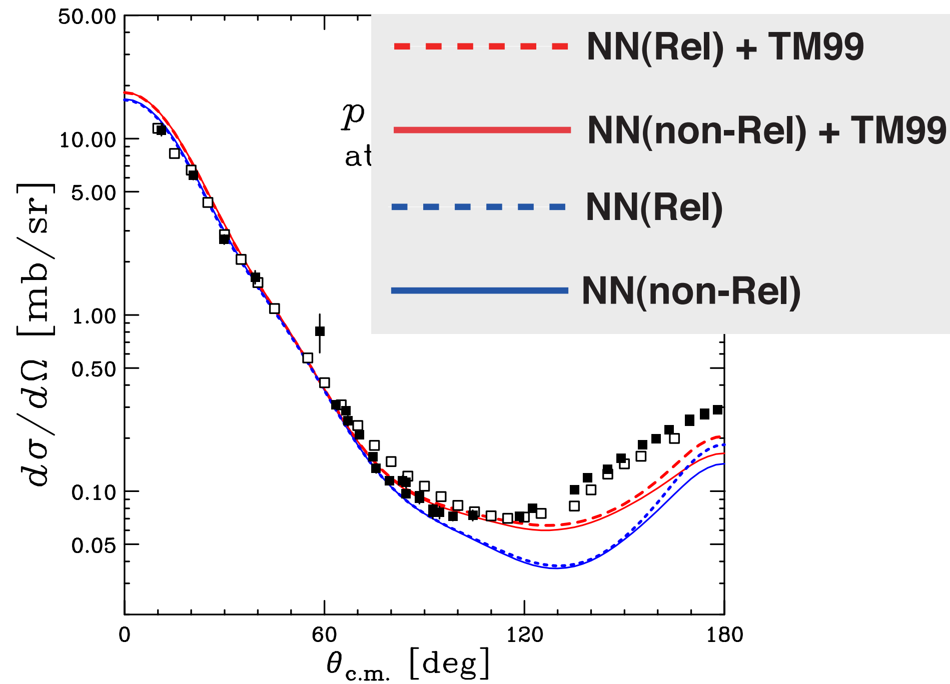
Relativistic Faddeev Calculations with TM'99 3NF

H. Witala et al, private communications

pd/nd @ 250 MeV



Relativistic effects are visible at backward angles, but small.

Backward angles :

Shorter range 3NFs ?

Other dynamics ?

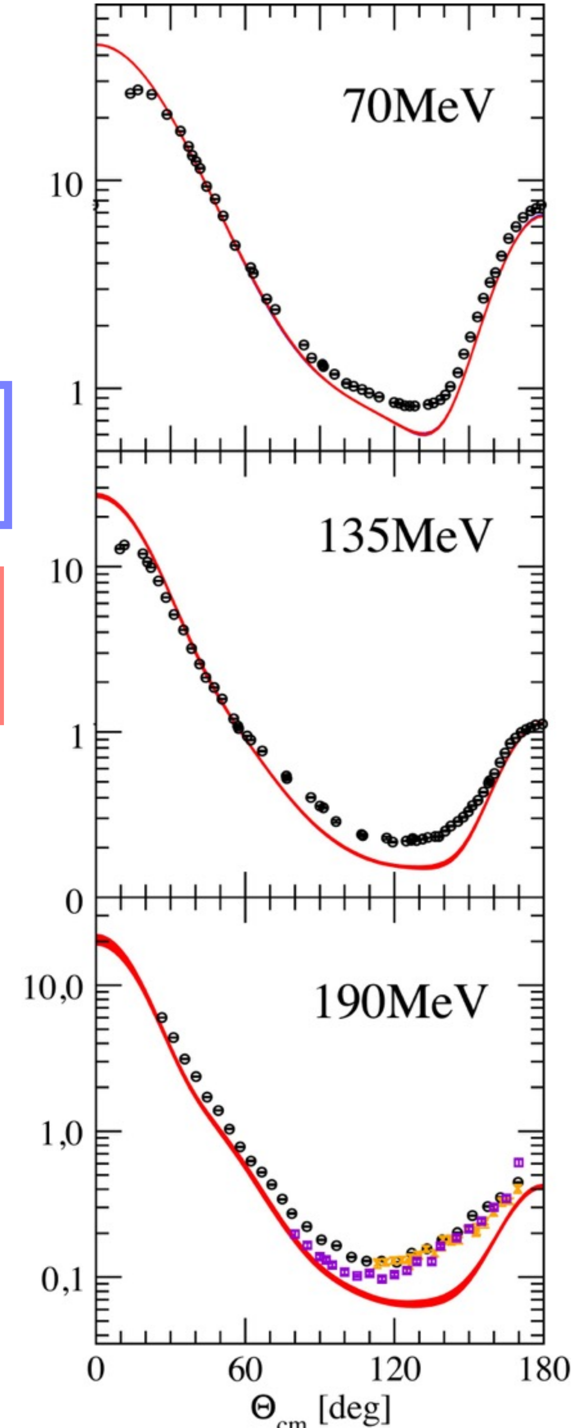
Differential Cross Section at 70 - 190 MeV/nucleon

Chiral EFT N4LO NN pot. by Cracow Gr.

NN only

Large discrepancy in the backward region

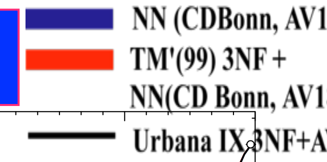
It is very interesting to see how χEFT 3NFs describe the cross section !

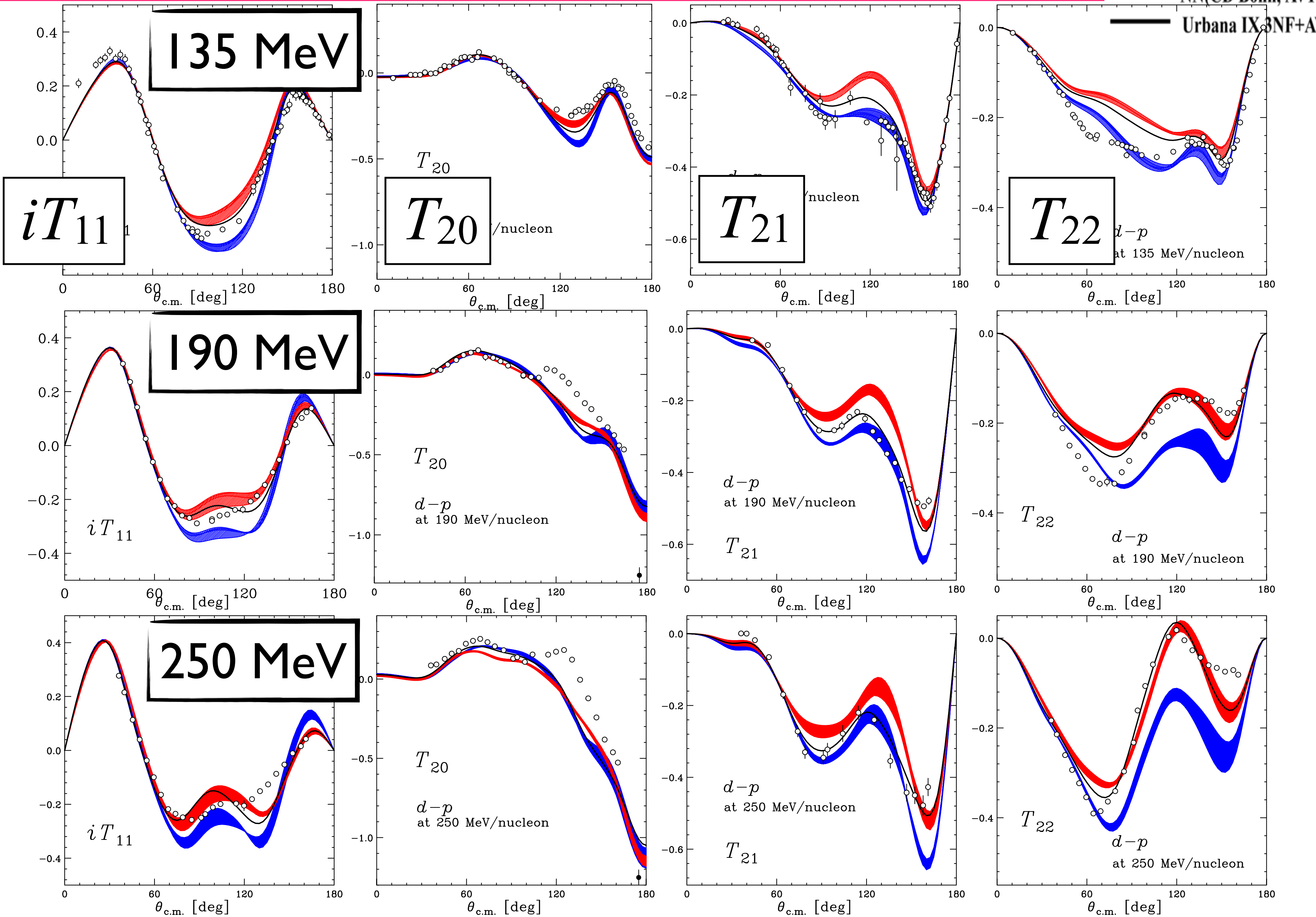


Deuteron Analyzing Powers

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

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TM'(99) 3NF +
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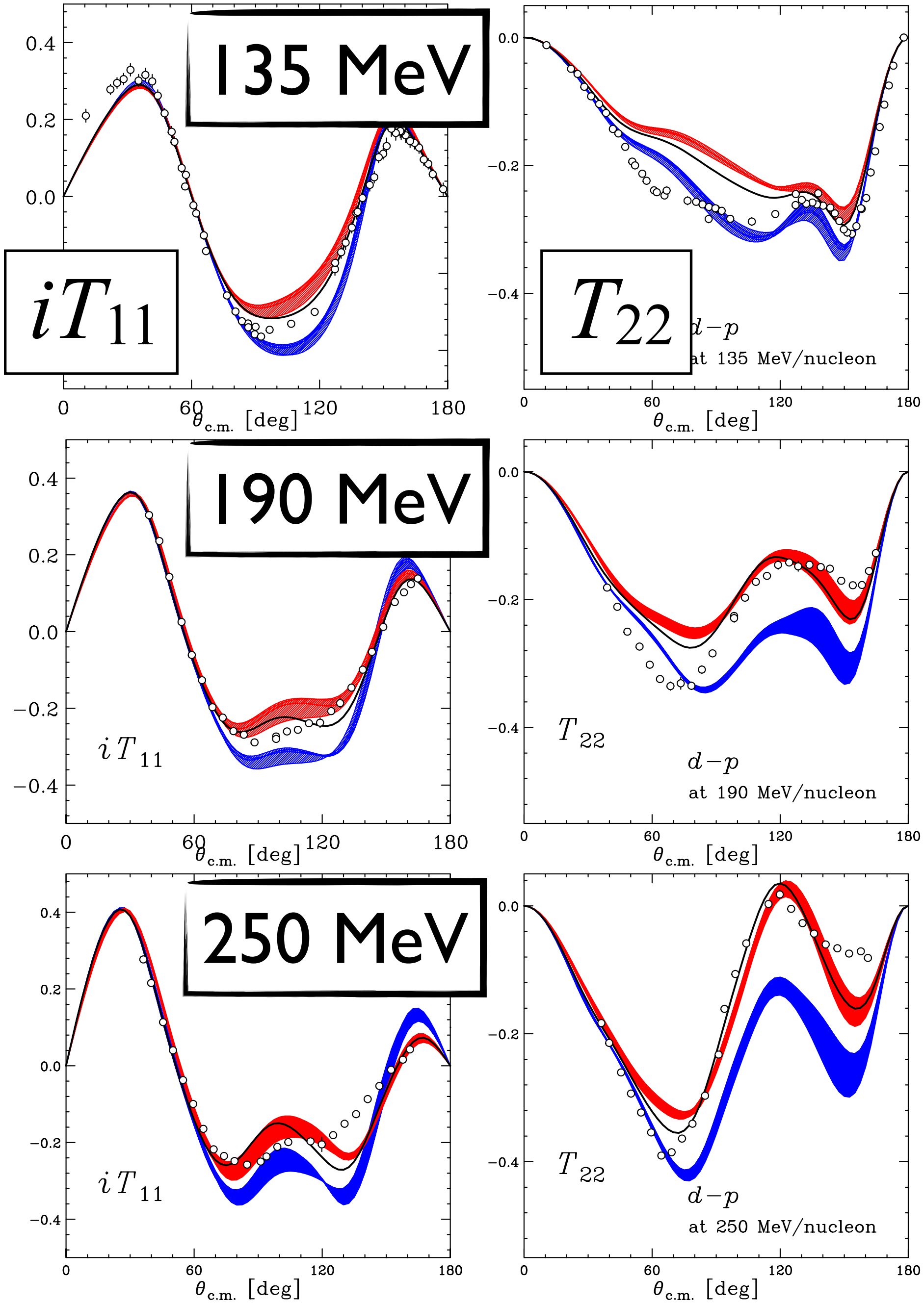


- NN only
  - Large discrepancy in the backward angles

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

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

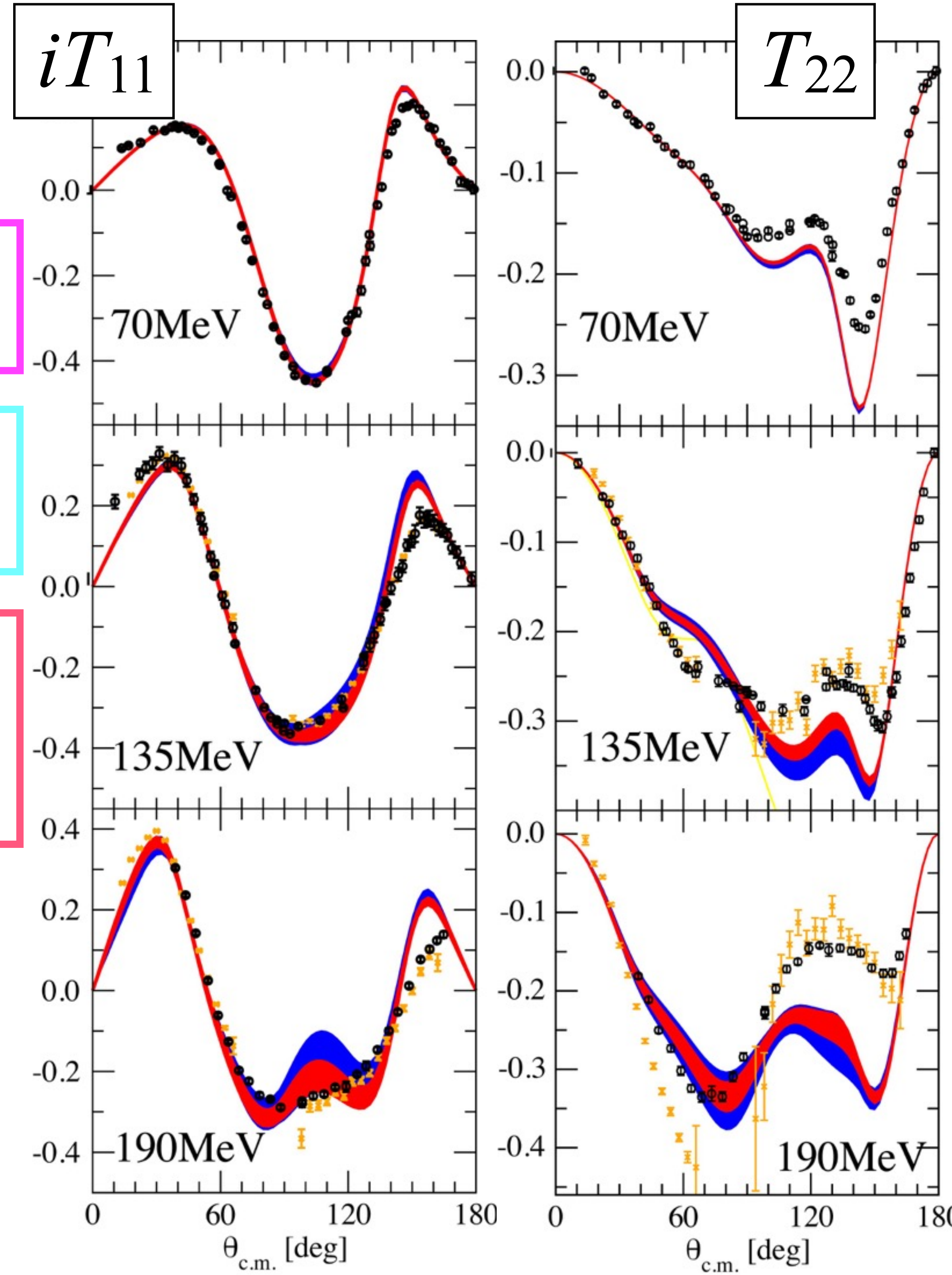
- Results of deuteron analyzing powers show deficiency of spin dependent parts of 3NFs.

Analyzing Powers at 70 - 190 MeV/nucleon

Chiral EFT N3LO & N4LO NN pot.
by Cracow Gr.

Vector analyzing power :
good agreements to NN forces

Large discrepancies
in Tensor analyzing powers
→ Rooms for 3NFs ?



Summary

Nucleon-Deuteron Scattering

is a good probe to investigate the dynamics of 3NFs.
- Momentum & Spin dependence - . For iso-spin, T=1/2 only.

Precise data of $d\sigma/d\Omega$ and deuteron analyzing powers at 70 - 300 MeV/nucleon

Cross Sections : 3NFs are clearly needed in Elastic Scattering.

Spin Observables : Defects of spin dependent parts of 3NFs

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

It is interesting to see how χEFT NN+NNN potentials describe the data.

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Next Step

Nd Breakup Experiments : Rich kinematical configurations

Four Nucleon Scattering : from Few to Many & Iso-spin dependence

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

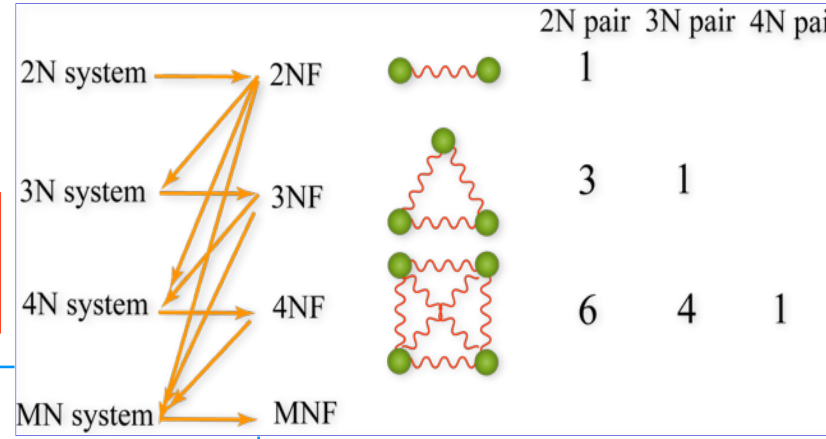
$p+^{3}$He scattering

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

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

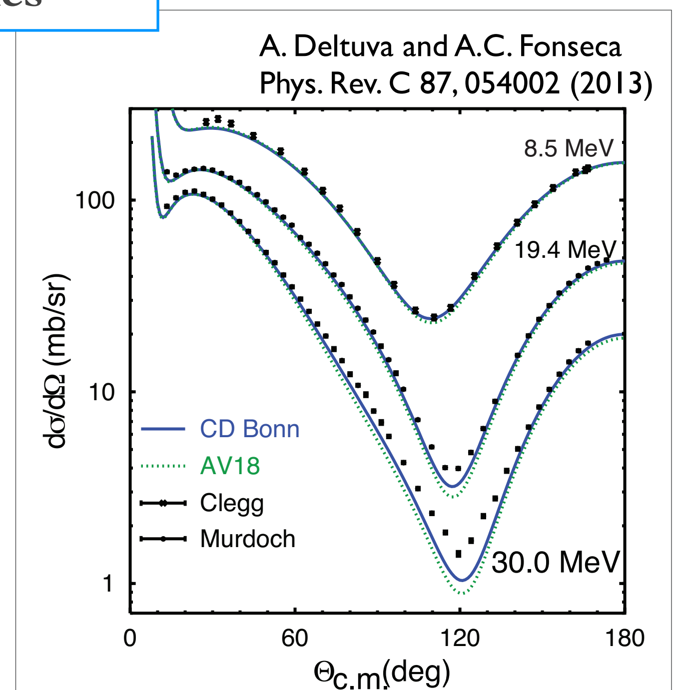
- **Large 3NF effects**
  in cross section minimum at intermediate energies

- **4NF effects**

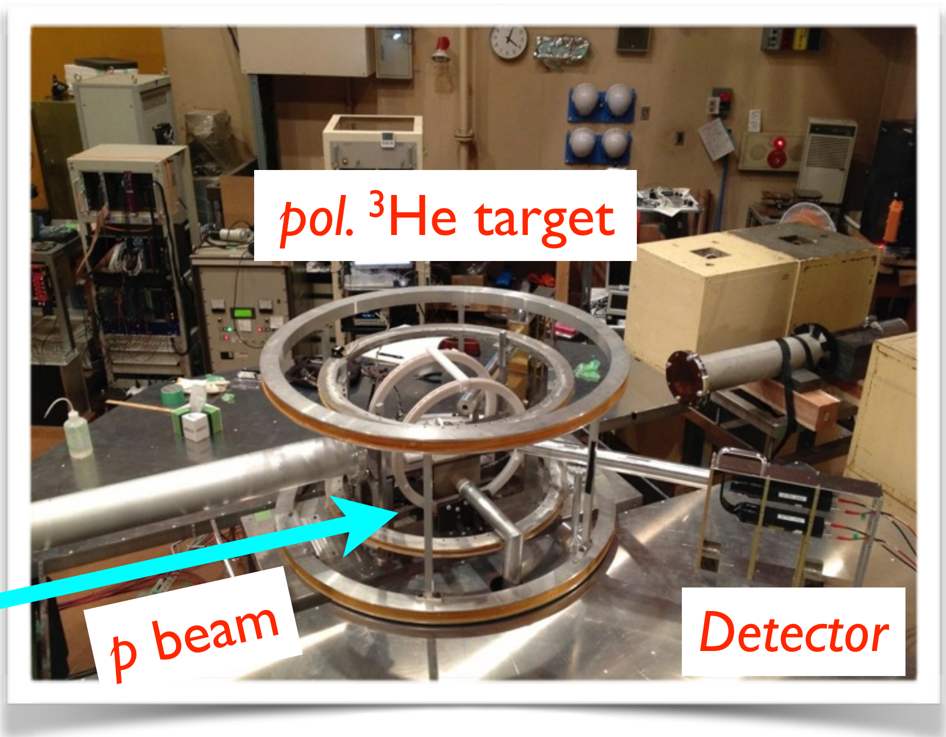


Theory in Progress

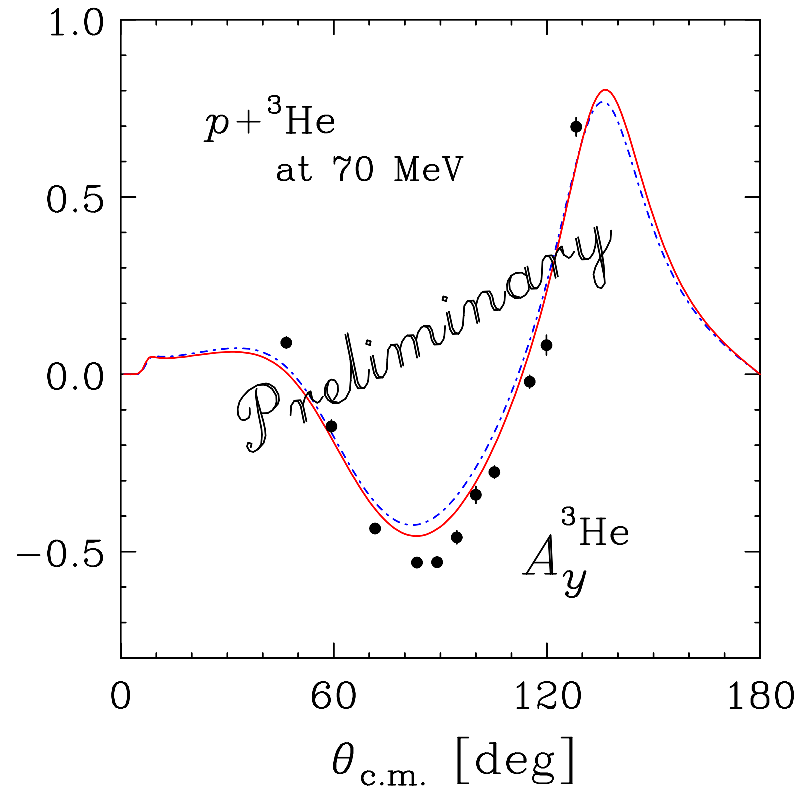
Calculations above 4-body breakup threshold energy open new possibilities for 3NF study in 4N scat.



Measurement of p+^{3}He scattering at 70 MeV with pol. ^{3}He target at Tohoku University



^{3}He Analyzing power at 70 MeV



Calculations by A. Deltuva et al.

(private communications)

RIBF pol.d beam experiment Gr.

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

H. Okamura

Kyungpook National University

S. Chebotaryov, E. Milman

May 2015