# Complete Set of Deuteron Analyzing Powers for *dp* Elastic Scattering at Intermediate Energies and Three Nucleon Force

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# 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<br>• Argonne V18 (AV18)<br>• Nijmegen I, II, 93 | • Tucson-Melbourne<br>• Urbana IX<br>etc.. | • Chiral Effective Field Theory |

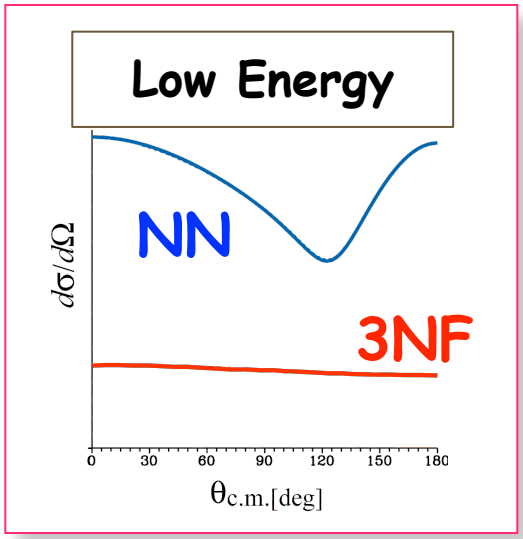
- Experiment : Precise Data
  - $d\sigma/d\Omega$, Spin Observables ($A_i$, $K_{ij}$, $C_{ij}$)

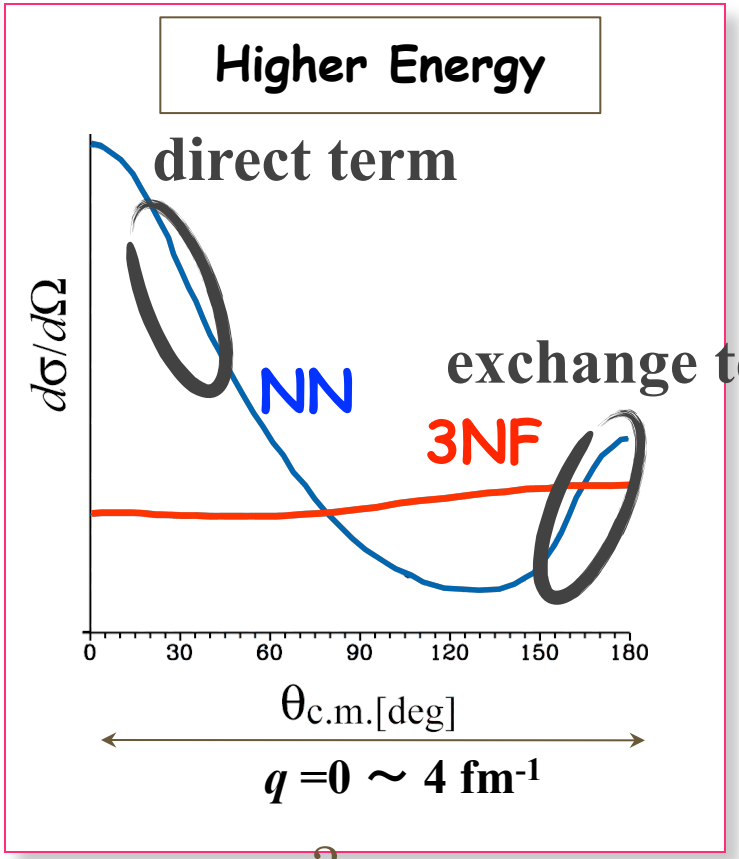
## Extract information of Three Nucleon Forces.

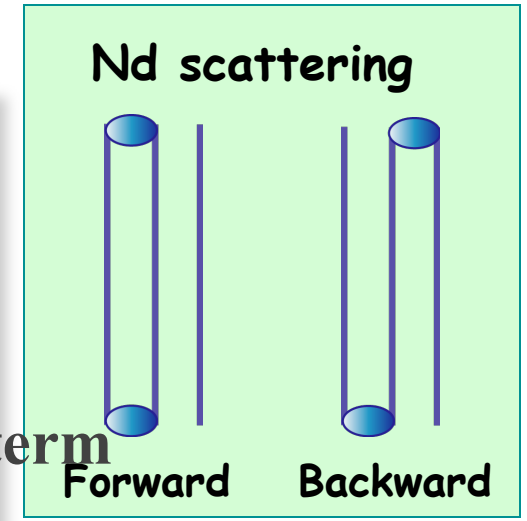
# Where is the Hot Spot for 3NF Effects in Three Nucleon Scattering?

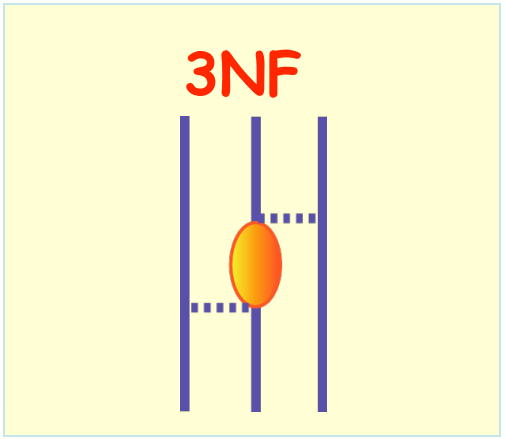
**Predictions by H. Witala et al. (1998)**

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



# Precise Measurement of dp scattering at RIKEN

## *RIKEN Accelerator Research Facility (RARF)*

$$d + p \longrightarrow d + p$$

**1.** **Cross Section** and **All Deuteron Analyzing Powers** at **70, 100, 135 MeV/A**

- **Whole Angular Range : θ c.m. = 10°－180°**

**2.** **Deuteron to Proton Polarization Transfer Coefficients at 135 MeV/A**

- **Double Scattering Experiment : Measurement of Polarizations of Recoil Protons**
- **Angular range : θ c.m. = 90°－180°**
- **Strong sensitivities to Three Nucleon Force**

$$d + p \longrightarrow p + p + n$$

**3.** **Extension from Elastic to Breakup**

- **Limited kinematical configurations : sensitive to 3NF**
- **First measurement of Polarization Transfer Coefficient**

## *RIKEN RI Beam Factory (RIBF)*

$$d + p \longrightarrow d + p$$

**4.** **Go to Higher Energies**

- **All Deuteron Analyzing Powers** $(A_y, A_{yy}, A_{xx}, A_{xz})$ **at 250, 294 MeV/A**

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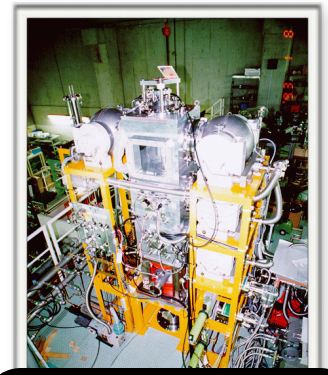
# *New Facility : RIKEN RI Beam Factory (RIBF)*

- **First commissioning/experiment** of pol.d beams at RIBF was performed with the **polarimeter BigDpol** **in April, 2009**.
- **Polarized *d* beam** was accelerated by the AVF+RRC+ **the new cyclotron SRC** up to **250 MeV/nucleon**.
- 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

from RRC

STH14
STH15
H16(TMP, FC, PF)
DMH6
STH60
H60(TMP, PF)
QDH61
GV-H61
H61(PF)
QSH17
QSH18
QSH62
QDH63
DMH7
QDH71
QDH72
DMH8
GV-H80
QTH81
DMK9
QTK91
GV-K91
STK91ab
QTG92
D-Polarimetar
QDG93
GV-G93
STH70
H70 (PF)
H72 (TMP, FC, PF)
STH72
H80 (PF)
H81 (PF)
STH81
K90 (TMP, FC, PF)
K91 (TMP, PF)
G93 (TMP, FC, PF)

IRC

SRC

Big-D-Polarimetar

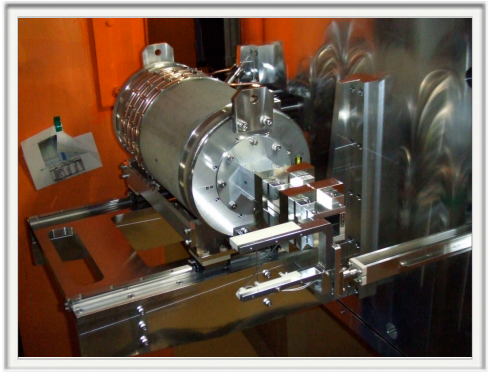
## IRC bypass beam transport line

- 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

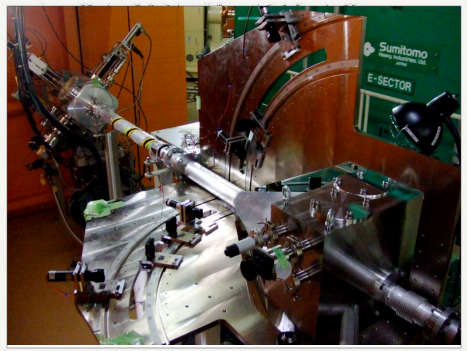


## Faraday cup @F0

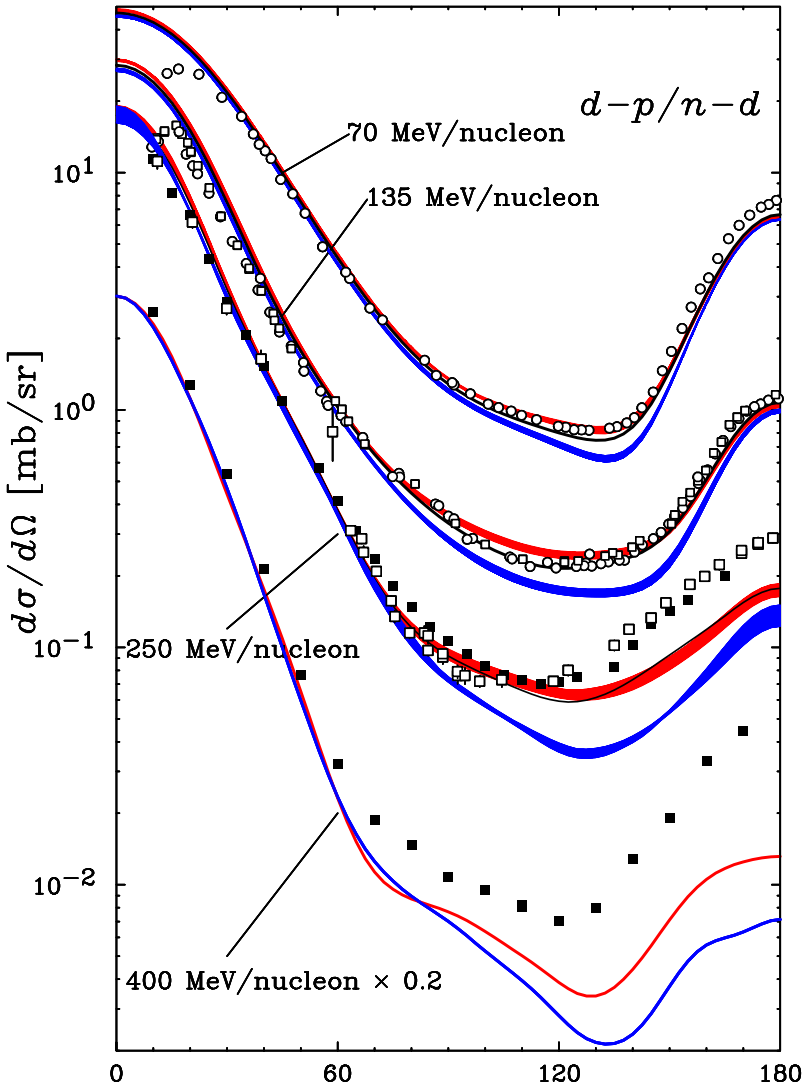
- W(ϕ3cm×30cm) +Pb(ϕ25cm×70cm)

## BigDpol

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



# 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
- With $2\pi$-3NF ?
  - improve the agreement
  - not enough at very backward angles at higher energies

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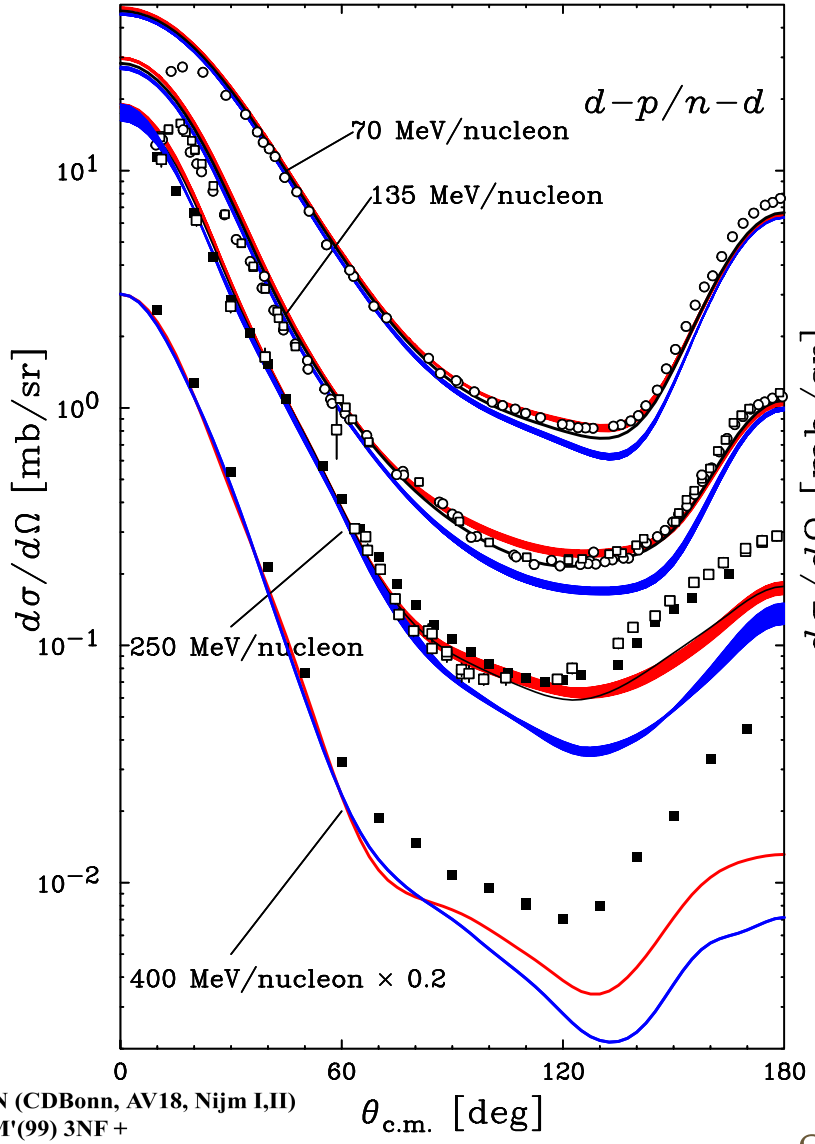


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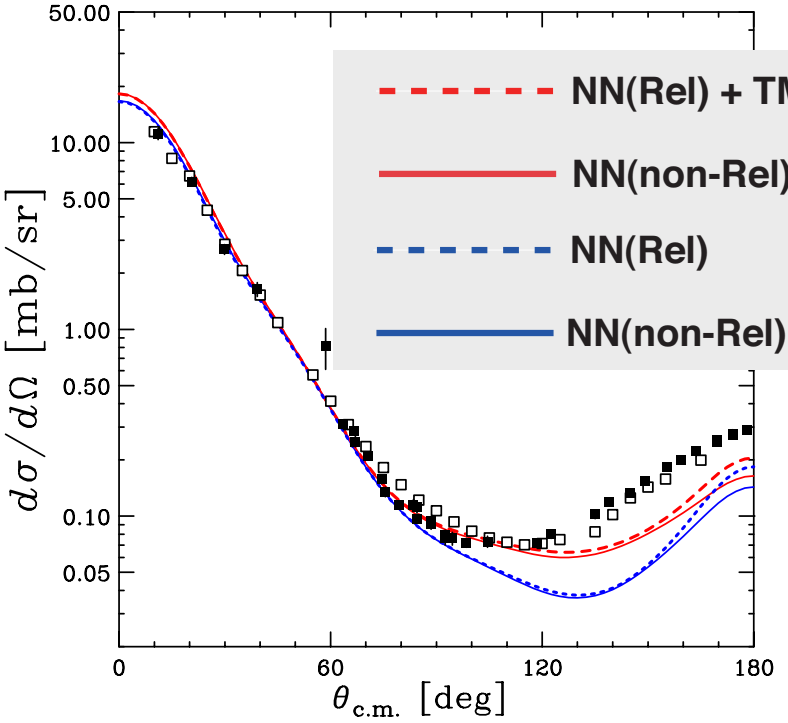
Relativistic Faddeev Calculations with TM'99 3NF

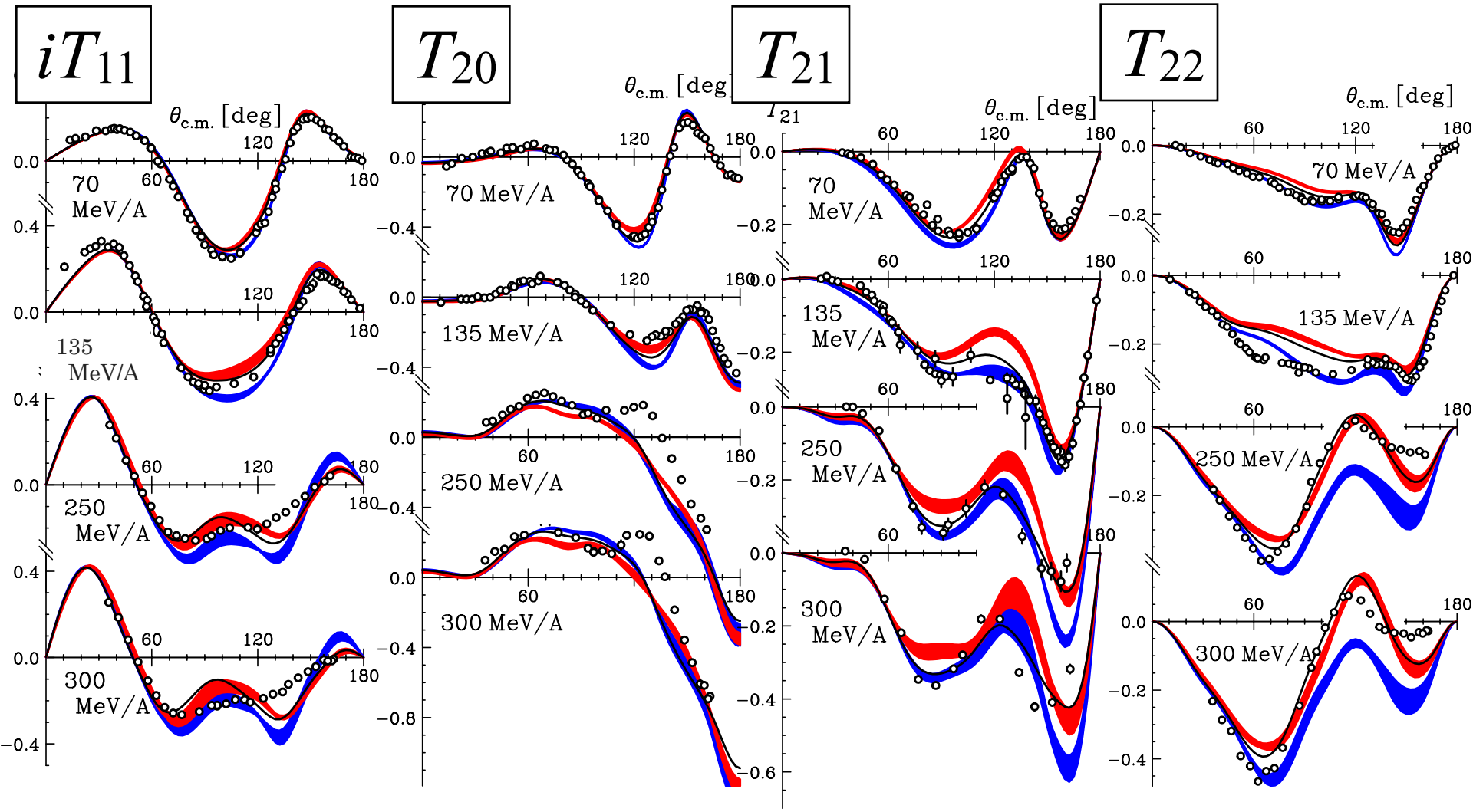
H. Witala et al, private communications

*pd/nd* @ 250 MeV




**Relativistic effects are visible at backward angles, but small.**

# Deuteron Analyzing Powers at 70 - 300 MeV/nucleon



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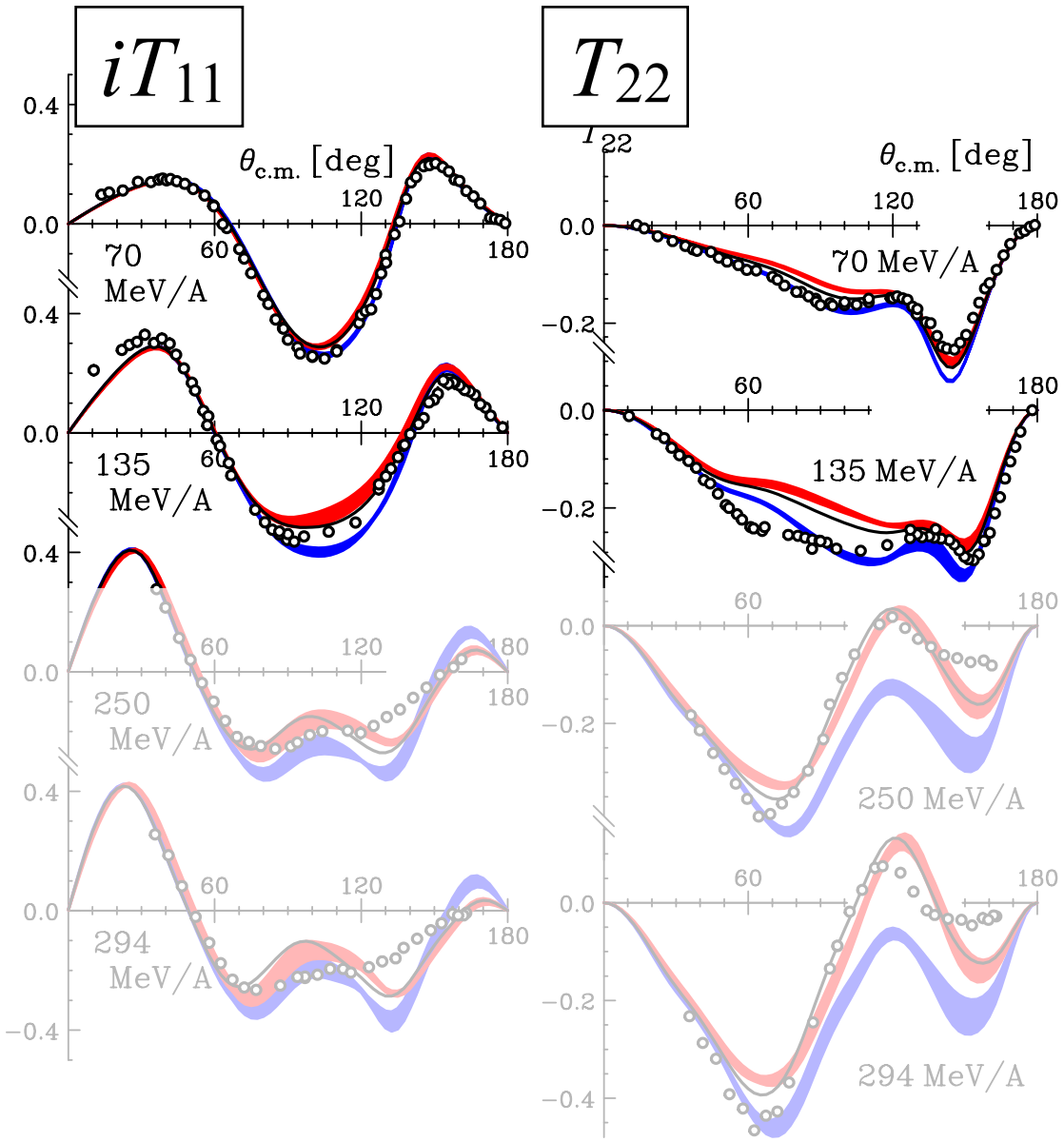
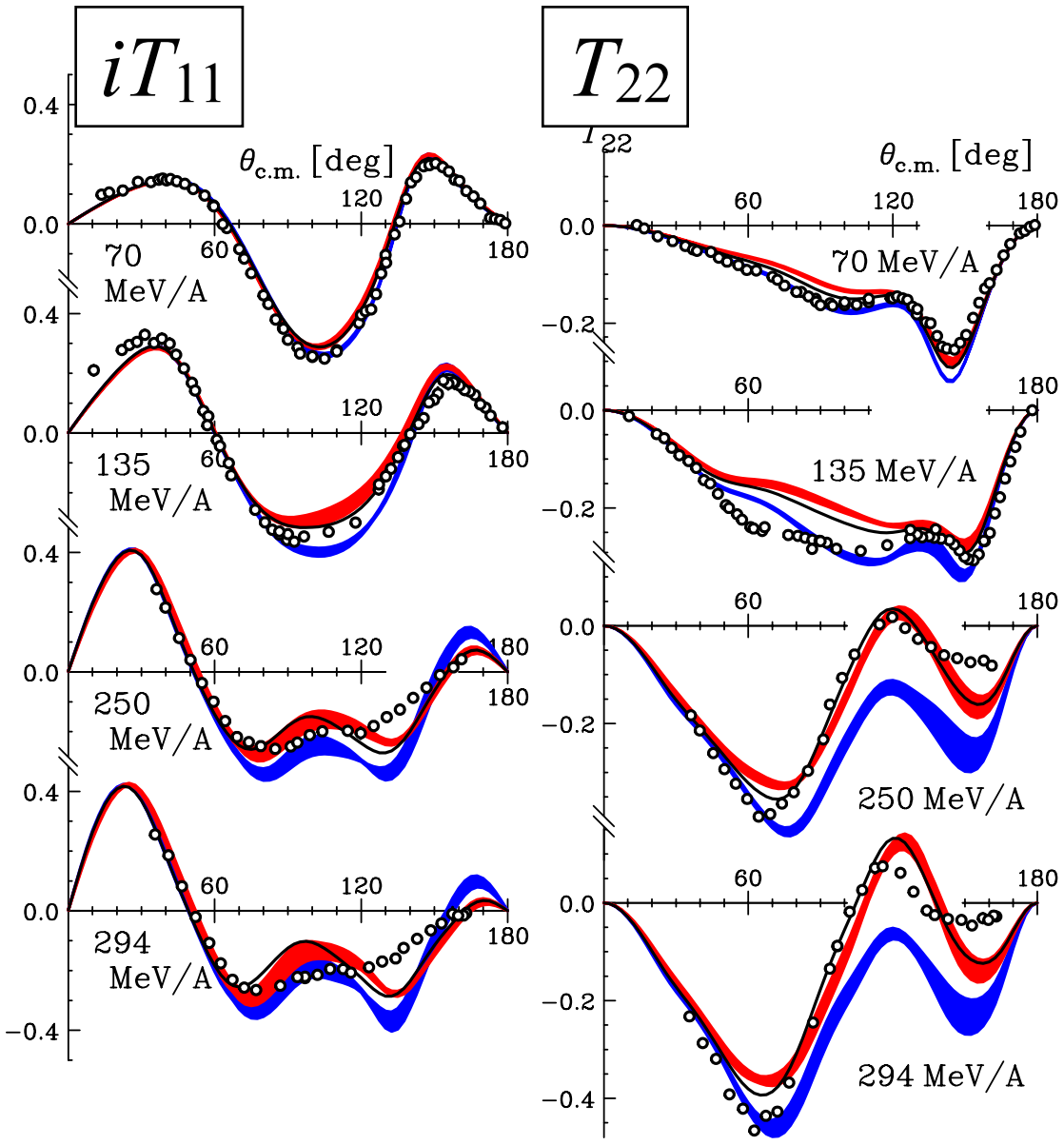



- NN only
  - Large discrepancy in the backward region
- + 2π3NF at ~ 100 MeV/A
  - results are NOT always similar to the cross section.

K.S. et al., Phys. Rev. C 83,061001 (2011)

# Deuteron Analyzing Powers at 70 - 300 MeV/nucleon




- NN only
  - Large discrepancy in the backward region
- + 2π3NF at ~ 100 MeV/A
  - results are NOT always similar to the cross section.
- + 2π3NF at ~ 250 MeV/A
  - improve the agreement
  - not enough at very backward angles

→similar to the cross section

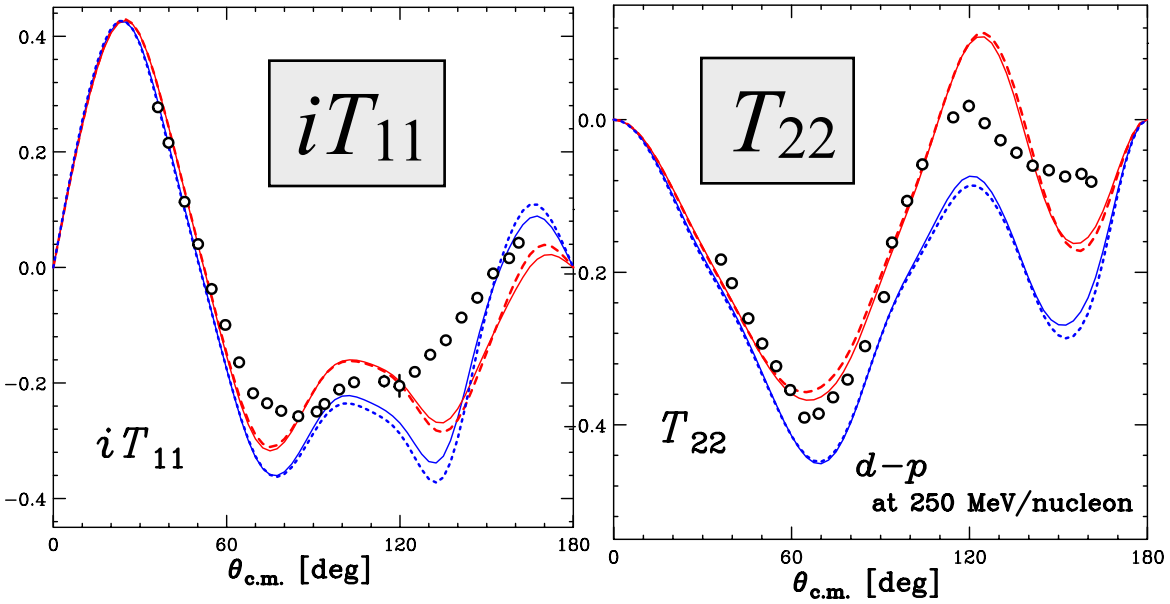
K.S. et al., Phys. Rev. C 83,061001 (2011)

# Deuteron Analyzing Powers

## Relativistic Faddeev Calculations with TM'99 3NF

H. Witala et al, private communications

### $dp$ @ 250 MeV




**Small relativistic effects**

# Deuteron Analyzing Powers

Relativistic Faddeev Calculations with TM'99 3NF

H. Witala et al, private communications

*dp* @ 250 MeV

- **Around 100 MeV/nucleon**
  elastic scattering data are mostly explained by adding 2π3NF, (though there are some exceptions, e.g. $T_{22}$).

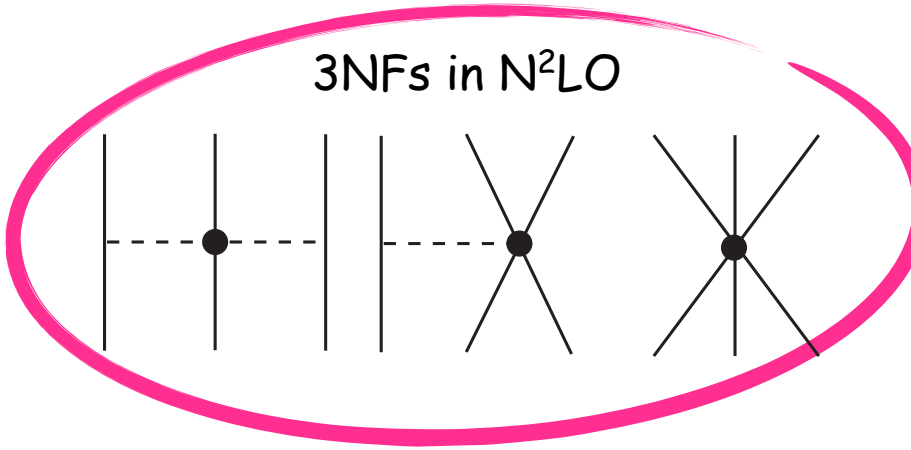
- **Serious discrepancies** exist at very backward angles at higher energies (250, 300 MeV/nucleon).

- **"What" we are missing ?**
  Components other than 2π3NF or relativistic effects; e.g. heavier meson exchange 3NFs .

# How does Chiral EFT pot. describe the Nd elastic scattering ?

Various types of 3NFs, including 2π3NF, appear in $N^2LO$, $N^3LO$.
Theory in Progress : up to $N^3LO$ (NN + NNN) for higher energies

So far calc. based on χEFT pot. is available below 100 MeV/nucleon.



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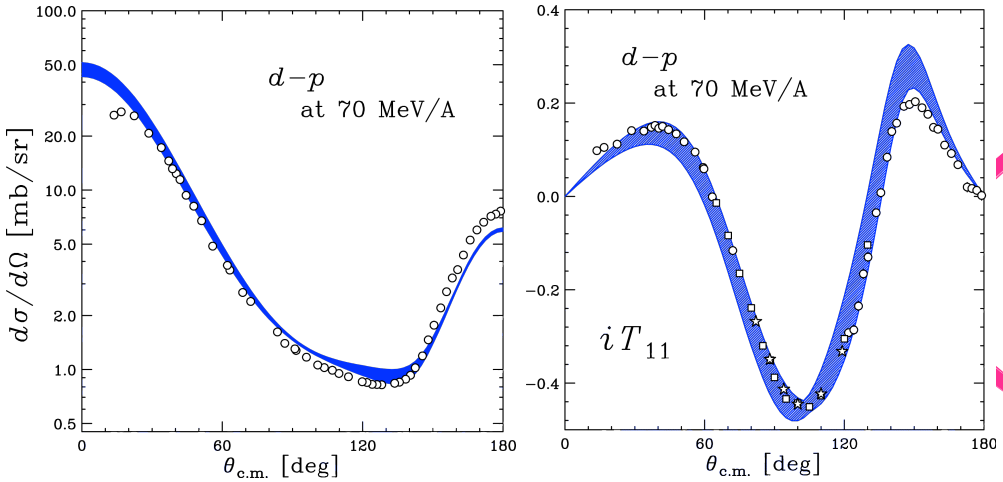


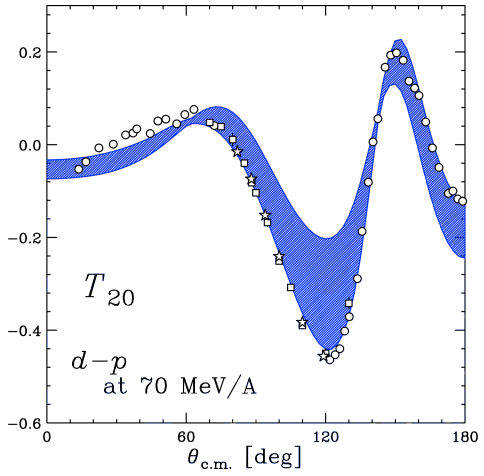


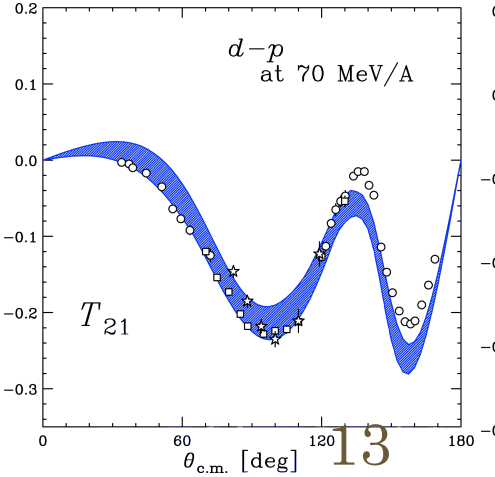


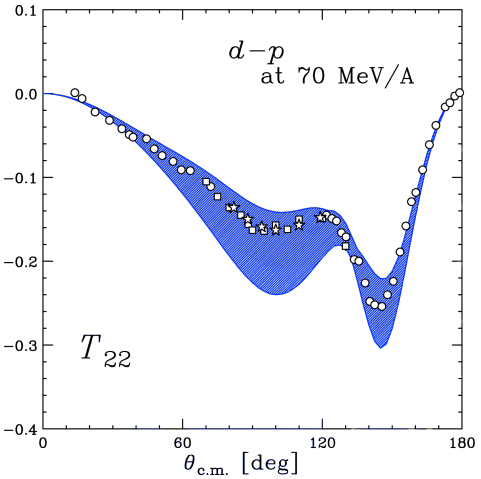
***d-p*** at 70 MeV/nucleon

Calc. with χEFT Pot. (N2LO)

by E. Epelbaum et al.



# Summary & Outlook

## 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 many spin observables at 70 - 300 MeV/nucleon**

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

**Spin Observables : not always described by adding 2π-exchange 3NFs**

**New Data from RIBF at 250 & 300 MeV : serious discrepancy in backward angles**
**New Challenge to be solved**

## Next Step

**Energy Dependence for Pol. Transfer and /or Spin Correlation Coefficients for Elastic Nd Scattering : Natural extension of 3NF study in Elastic scatt.**

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

# RIBF pol.d beam experiment Gr. (2009～)

**Collaboration**

**Tohoku University**

K. Sekiguchi, J. Miyazaki, Y. Wada, T. Taguchi, U. Gebauer, K. Takahashi, T. Mashiko

**RIKEN Nishina Center**

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

**CNS, University of Tokyo**

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

**RCNP, Osaka University**

H. Okamura, K. Miki

**Kyushu University**

T. Wakasa, S. Sakaguchi

**Miyazaki University**

Y. Maeda, T. Saito