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

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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

- CDBonn
- Argonne V18 (AV18)
- Nijmegen I, II, 93

3NF Input

- Tucson-Melbourne
- Urbana IX
- etc..

2NF & 3NF Input

- Chiral Effective Field Theory

- Experiment : Precise Data

- $d\sigma/d\Omega$ , Spin Observables ( $A_p, K_{ij}, C_{ij}$ )

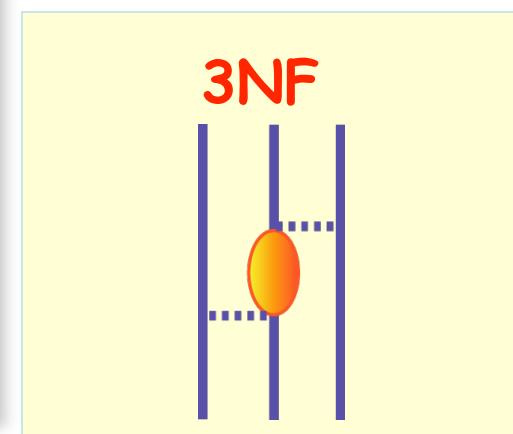
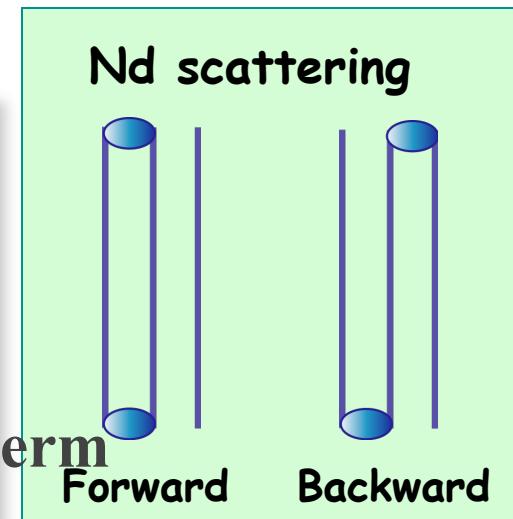
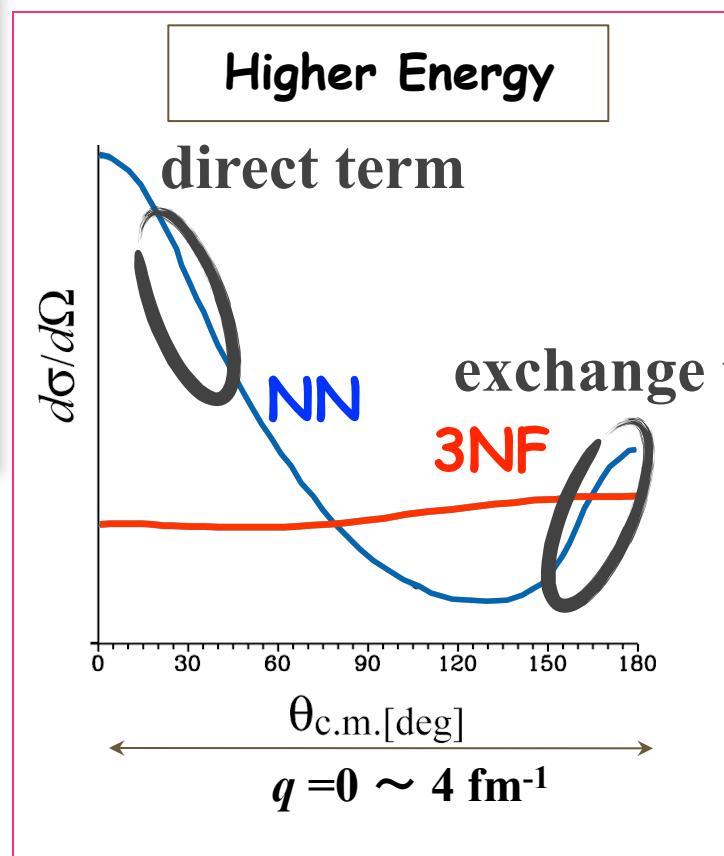
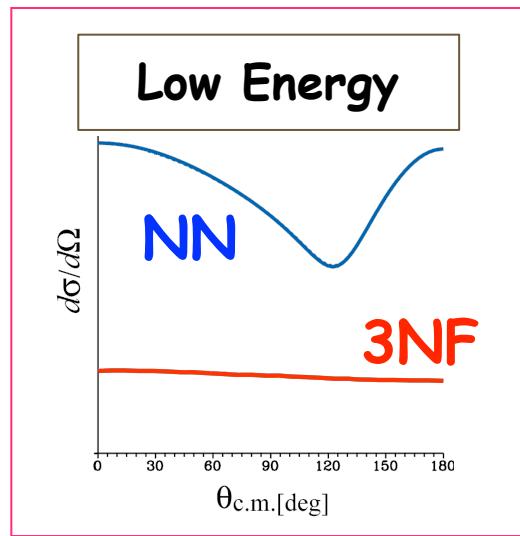


Extract information of Three Nucleon Forces.

# 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 - 1<sup>st</sup> Step -

## d-p Elastic Scattering at 135 MeV/nucleon

### @ RIKEN Accelerator Research Facility (RARF)

**Cross Section** : Good description by  $2\pi$ -3NF

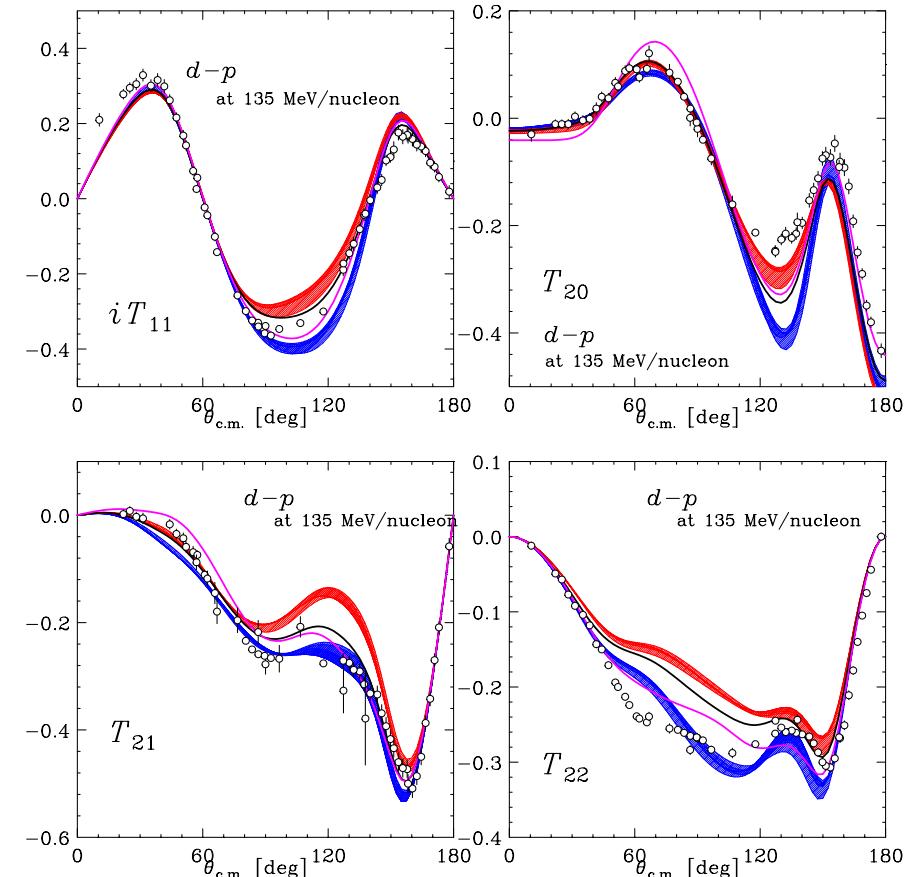
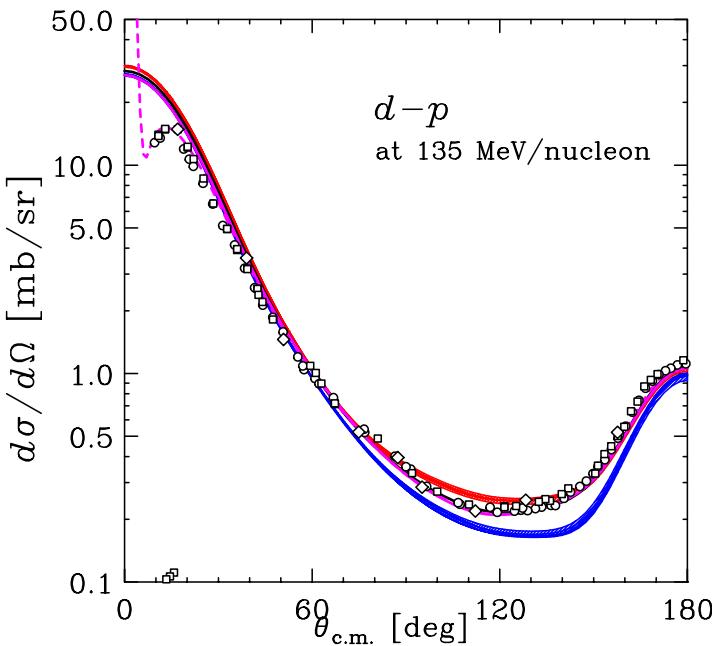
First Clear Signature of 3NFs in 3N Continuum

**Spin Observables** : Insufficient descriptions by  $2\pi$ -3NF

Defects of 3NF in Spin parts ??

K. S. et al., Phys. Rev. C 65, 034003 (2002).

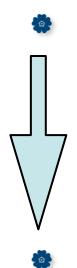
K. S. et al., Phys. Rev. Lett. 95, 162301 (2005).



# How to attack 3NF - Next Step -

## Few Nucleon Scattering with pol.d beams

### @ RIKEN RI Beam Factory (RIBF)

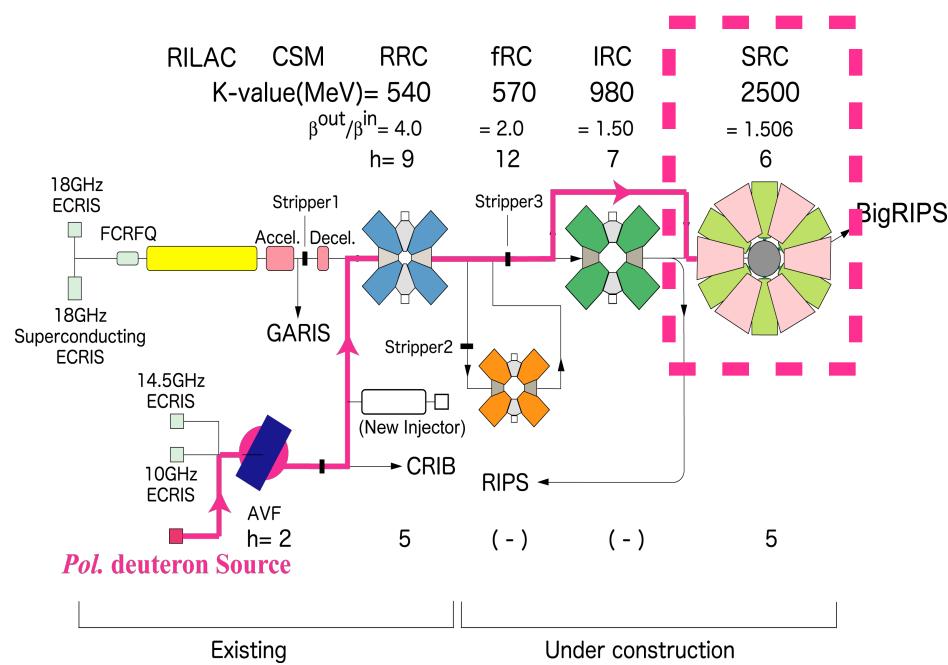


#### RARF : AVF+RRC

- Incident energy of deuteron :
  - 65 – 135 MeV/nucleon

#### RIBF : AVF+RRC + SRC

- Incident energy of deuteron :
  - 170 - 400MeV/nucleon



#### First Experiment at RIBF

##### *dp* Elastic Scattering at 250 MeV/nucleon

- All deuteron analyzing powers

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

- Wide Angular Range

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

- High accuracy



#### Go to higher energies

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



#### Polarized Deuterons

- rich set of spin observables

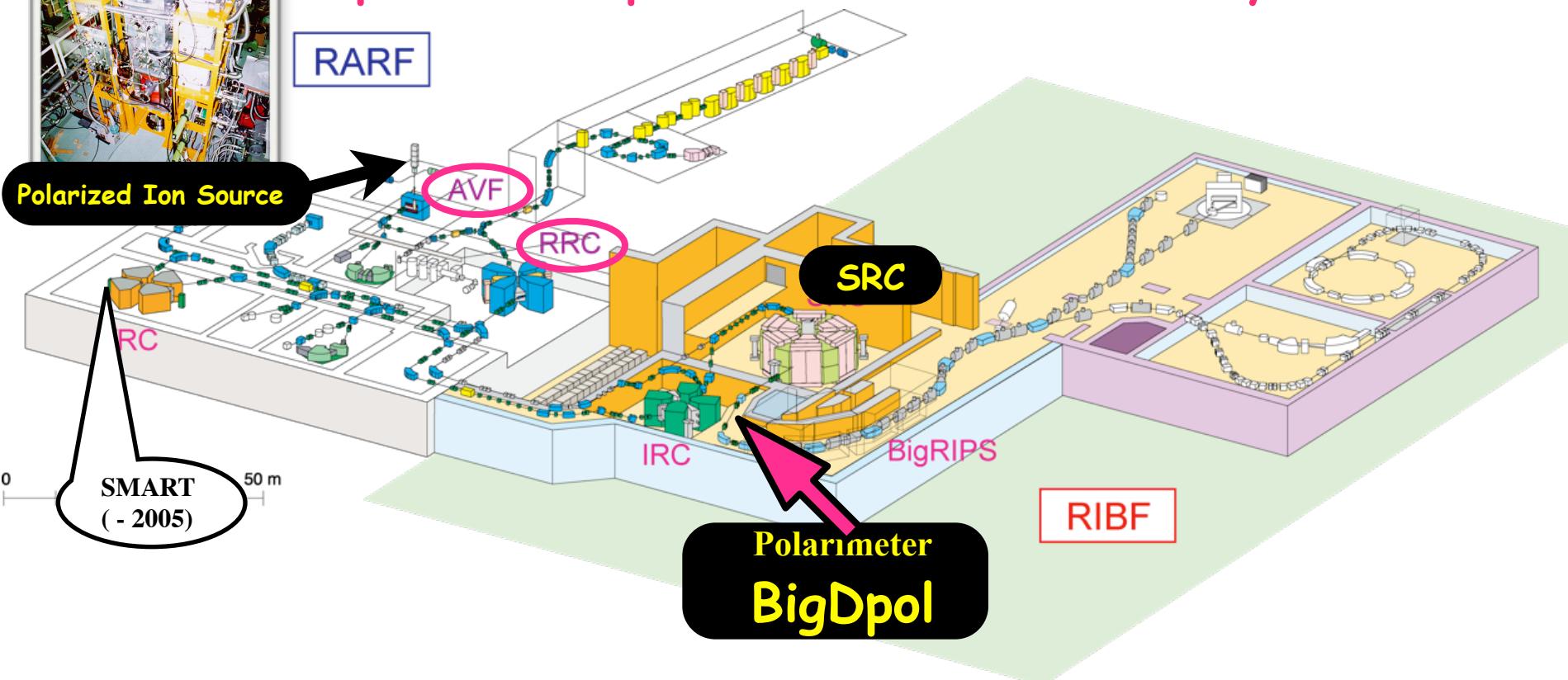
# *RIKEN RI Beam Factory (RIBF)*

- 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.

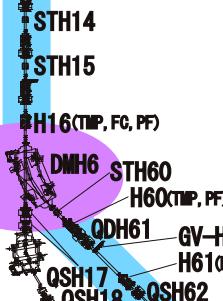
- Beam Polarization : 80% of theoretical maximum values

**Spin axis of polarized d beams is freely controlled !**



from  
RRC

# Layout for pol. $d$ beam Experiment at RIBF



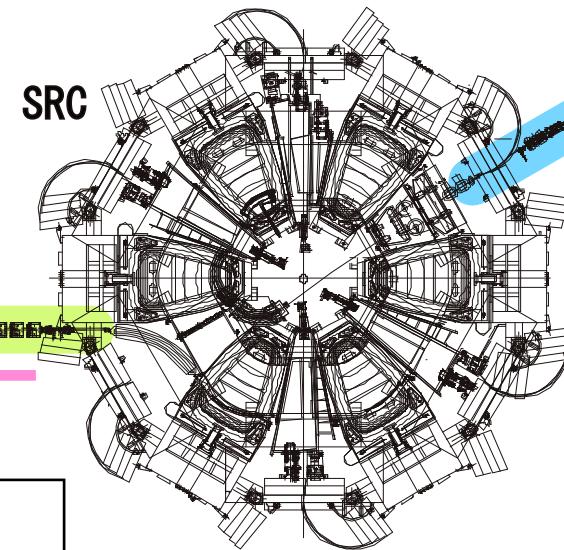
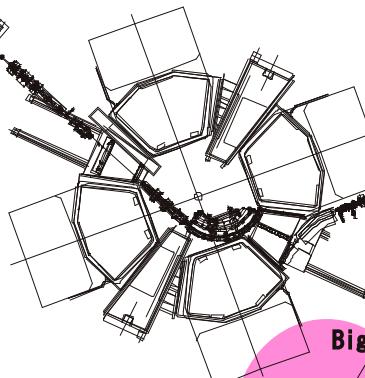
## IRC bypass beam transport line

- 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



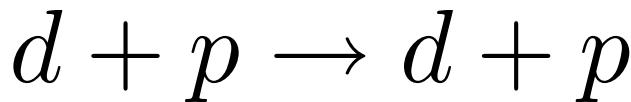
## BigDpol

- Target :  $\text{CH}_2$
- $d$  &  $p$  detected in kinematical coincidence condition

## Faraday cup @ F0

- $W(\phi 3\text{cm} \times 30\text{cm}) + Pb(\phi 25\text{cm} \times 20\text{cm})$

# Precise Measurement of $d$ - $p$ scattering at RIKEN



## 1 Differential Cross Section at 70, 135 MeV/A

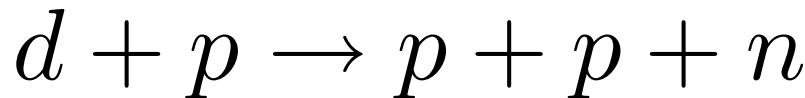
- Whole Angular Range :  $\theta$  c.m. =  $10^\circ - 180^\circ$

## 2 All Deuteron Analyzing Powers ( $iT_{11}$ , $T_{20}$ , $T_{21}$ , $T_{22}$ )

- at 70, 100, 135, 190, 250, 300 MeV/A
- Whole Angular Range :  $\theta$  c.m. =  $10^\circ - 180^\circ$

## 3 Deuteron to Proton Polarization Transfer Coefficients at 135 MeV/A

- Double Scattering Experiment : Measurement of Polarizations of Recoil Protons
- Angular range :  $\theta$  c.m. =  $90^\circ - 180^\circ$



- Extension from Elastic to Breakup
- Limited kinematical configurations : sensitive to 3NF
  - Polarization Transfer Coefficient at 135 MeV/A

# *Nd* Elastic Scattering Data at Intermediate Energies

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

Observable	100	200	300	400
$\frac{d\sigma}{d\Omega}$	Blue, Red	Blue, Red	Blue, Red	Blue, Red
$\vec{p}$	Blue	Blue	Blue	Blue
$A_y^p$	Blue	Blue	Blue	Blue
$\vec{n}$	Blue	Red	Blue, Red	Blue, Red
$A_y^n$	Blue	Blue	Blue	Blue
$\vec{d}$	Blue, Blue	Blue	Blue	Blue
$i T_{11}$	Blue, Blue	Blue	Blue	Blue
$T_{20}$	Blue, Blue	Blue	Blue	Blue
$T_{22}$	Blue, Blue	Blue	Blue	Blue
$T_{21}$	Blue, Blue	Blue	Blue	Blue
$\vec{p} \rightarrow \vec{p} K_y^{y'}$			Blue	Blue
$K_x^{x'}$			Blue	Blue
$K_x^{z'}$			Blue	Blue
$K_z^{x'}$			Blue	Blue
$K_z^{z'}$			Blue	Blue
$\vec{d} \rightarrow \vec{p} K_y^{y'}$	Blue	Blue		
$K_{xx}^{y'}$		Blue		
$K_{yy}^{y'}$	Blue	Blue		
$K_{xz}^{y'}$		Blue		
$\vec{p} \rightarrow \vec{d} K_y^{y'}$				Blue
$\vec{p} \vec{d}$		Blue	Blue	
$C_{i,j}$		Blue		
$C_{ij,k}$		Blue		

~2016

- High precision data of  $d\sigma/d\Omega$  & Spin Observables from RIKEN, RCNP, KVI, IUCF
  - Energy dependent data
    - ✓  $d\sigma/d\Omega$
    - ✓ Proton Analyzing Power
    - ✓ Deuteron Analyzing Powers

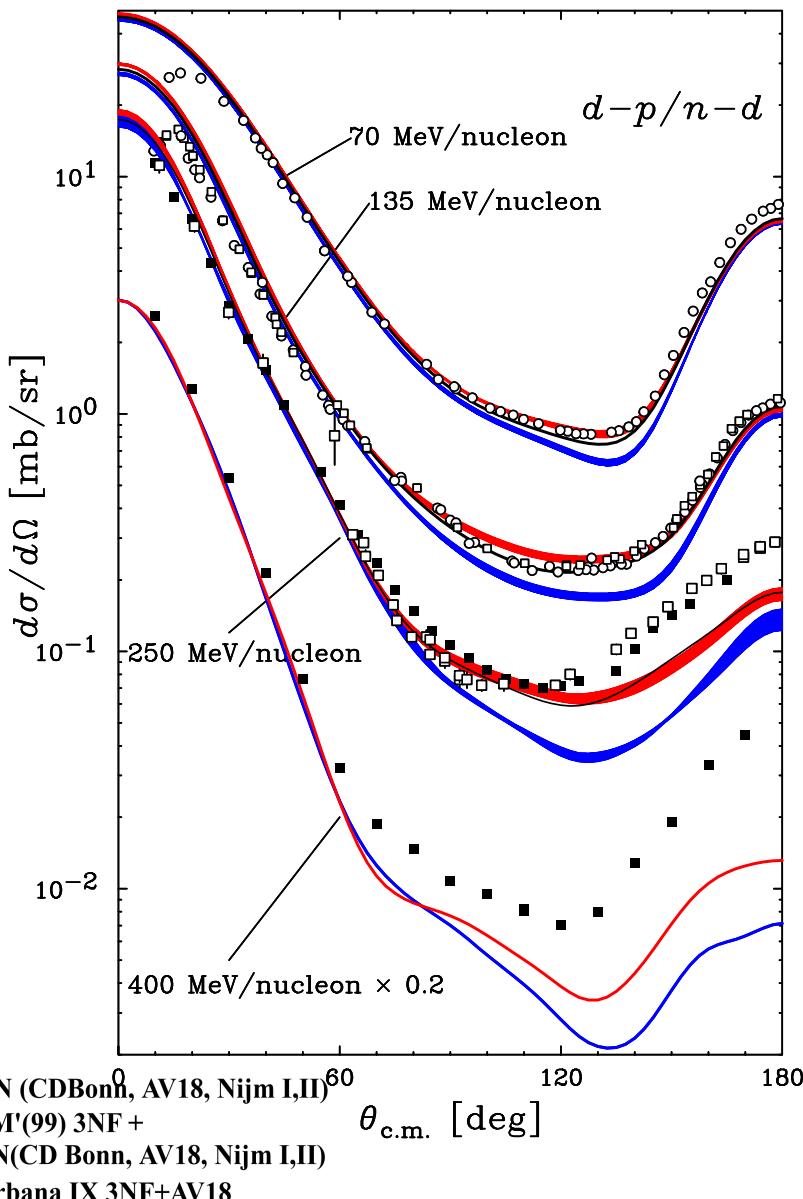
Data are compared with

- 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)

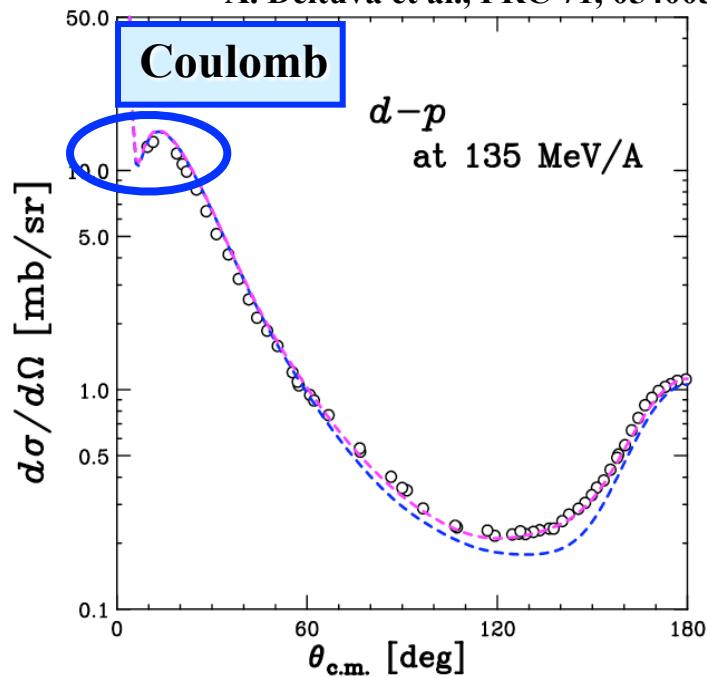
# Differential Cross Section at 70 - 400 MeV/nucleon



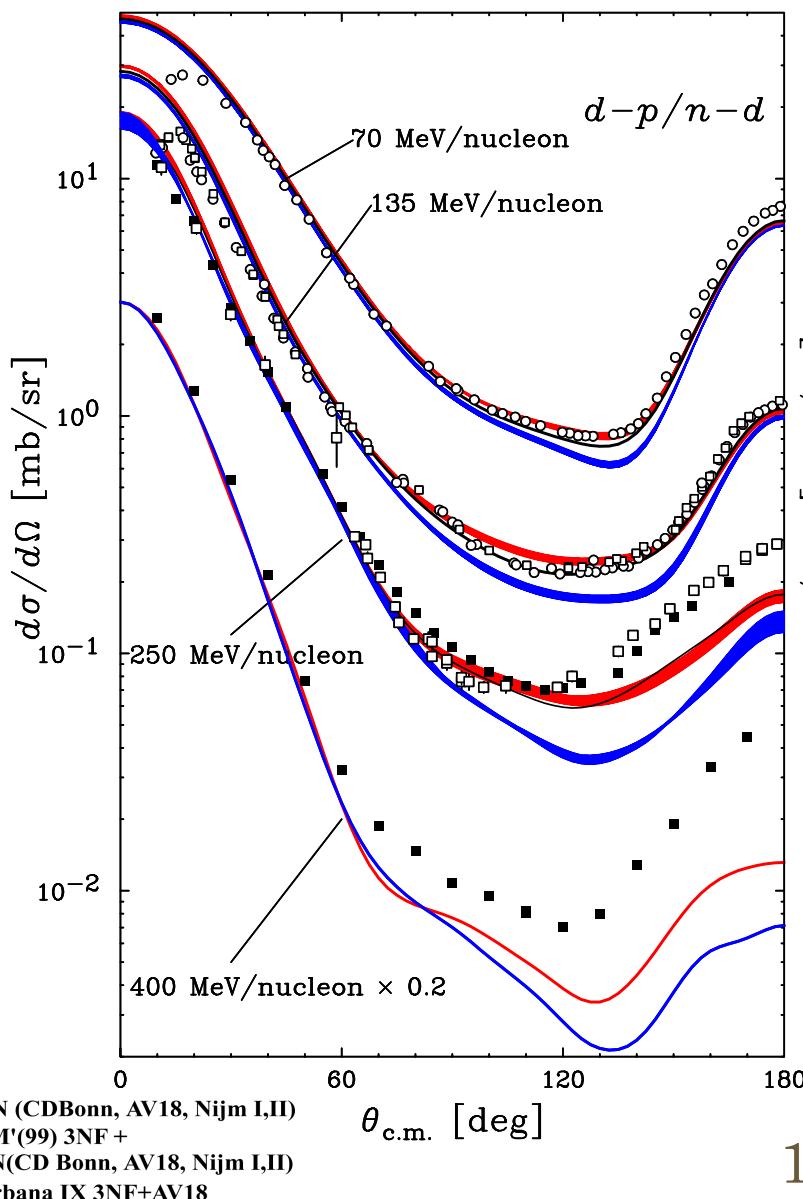
● NN only  
 ⚡ Large discrepancy  
 in the backward region

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

A. Deltuva et al., PRC 68, 024005 (2003)  
 A. Deltuva et al., PRC 71, 054005 (2005)



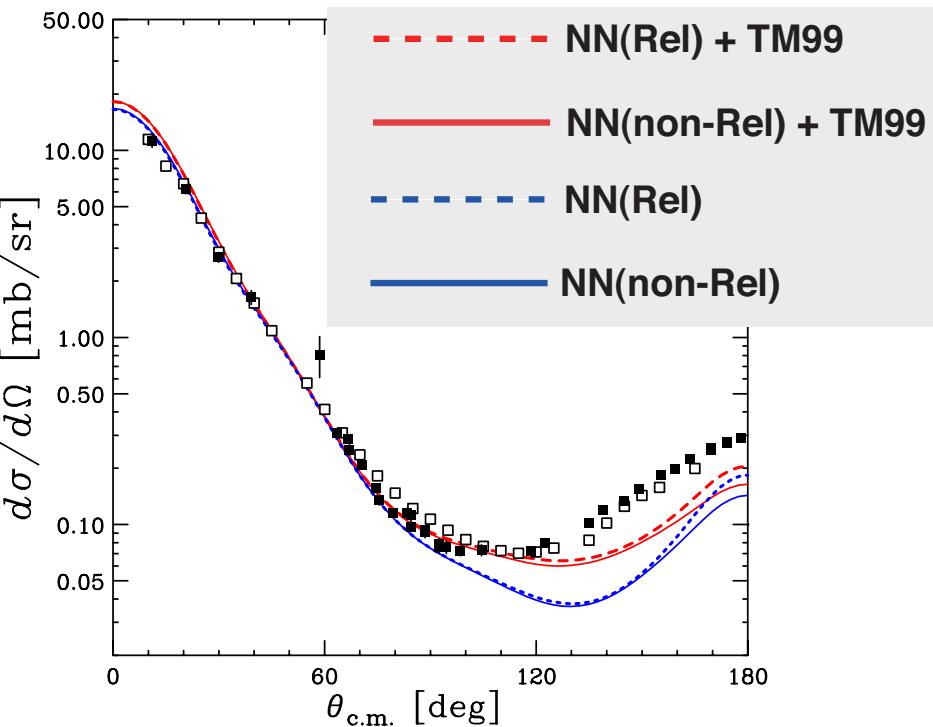
# Differential Cross Section at 70 - 400 MeV/nucleon



# Relativistic Faddeev Calculations with TM'99 3NF

H. Witala et al, private communications

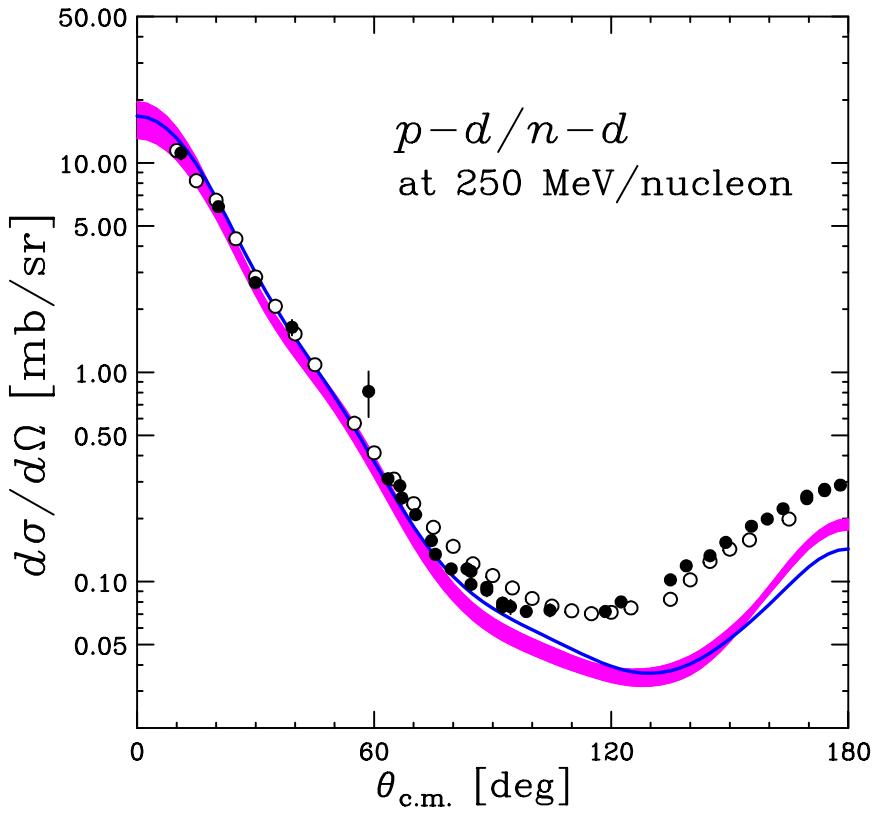
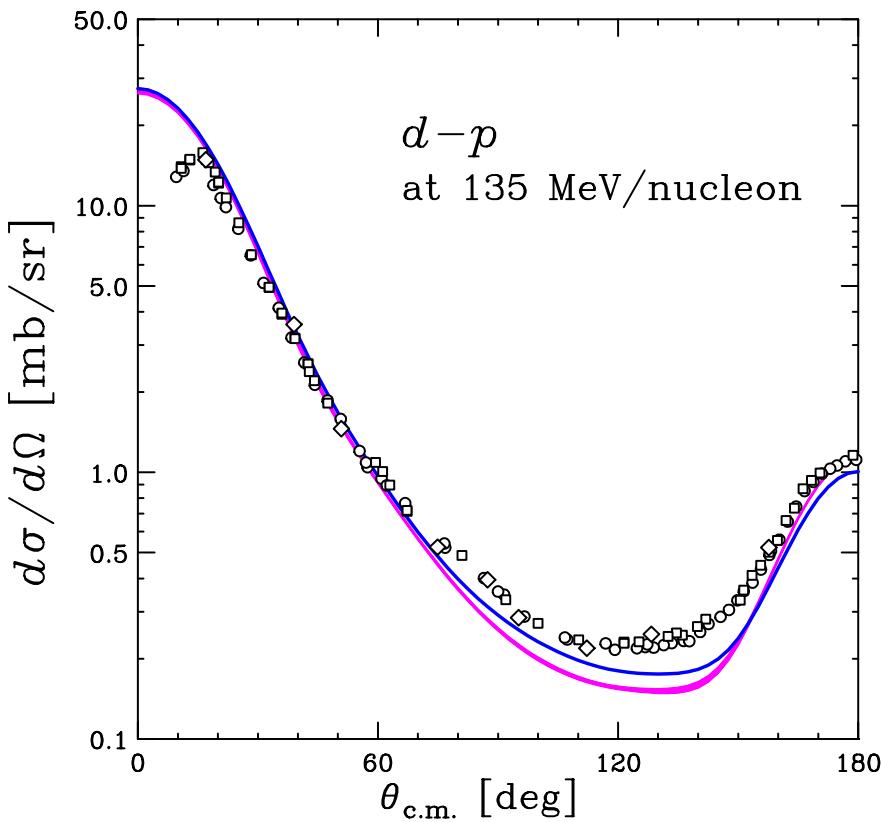
$pd/nd @ 250$  MeV



Relativistic effects are visible  
at backward angles, but small.

# Differential Cross Section at 135 & 250 MeV/nucleon

Chiral EFT N4LO NN pot.  
E. Epelbaum et al, private communications



NN(N4LO)  
NN(CD Bonn)

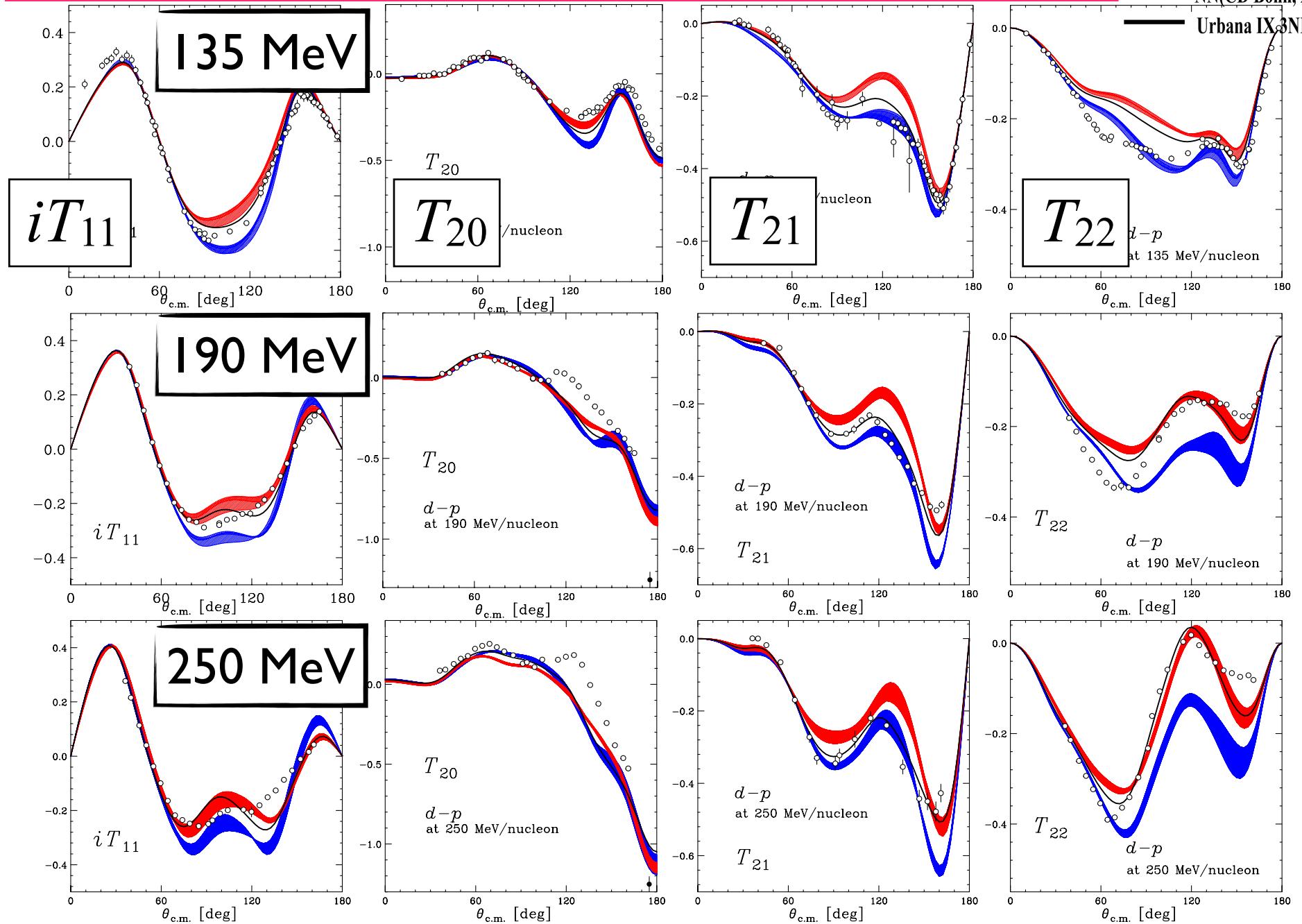
It is very interesting to see how  $\chi$ EFT  
3NFs describe the cross section !

# Deuteron Analyzing Powers

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

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

NN (CDBonn, AV1  
 TM'(99) 3NF+  
 NN(CD Bonn, AV1  
 Urbana IX 3NF+A

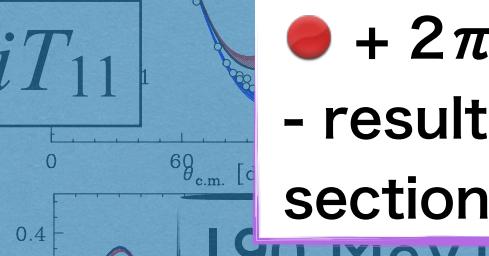


# Deuteron Analyzing Powers at 135, 190, 250MeV/nucleon



● NN only

- Large discrepancy in the backward angles



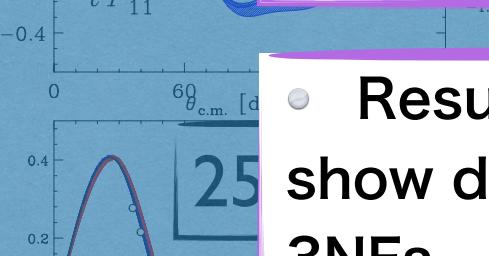
● +  $2\pi$  3NF at  $\sim 100$  MeV/nucleon

- results are NOT always similar to the cross section.

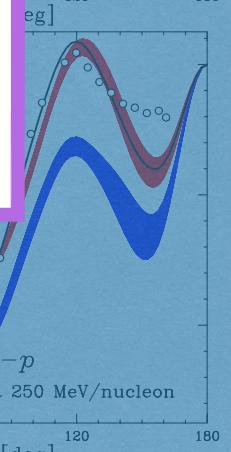
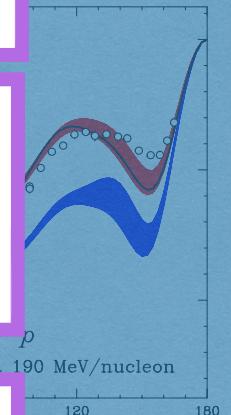
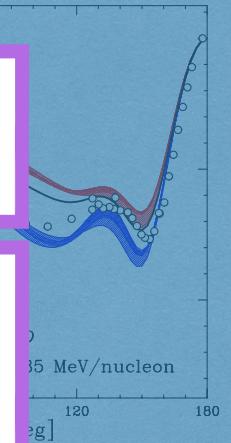
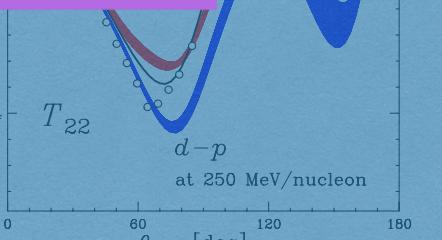
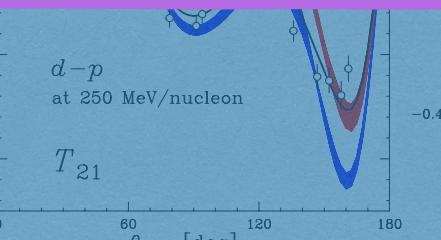
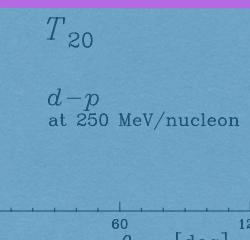
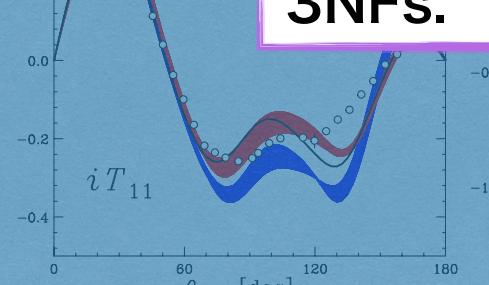


● +  $2\pi$  3NF at  $\sim 250$  MeV/nucleon

- improve the agreement
- not enough at very backward angles

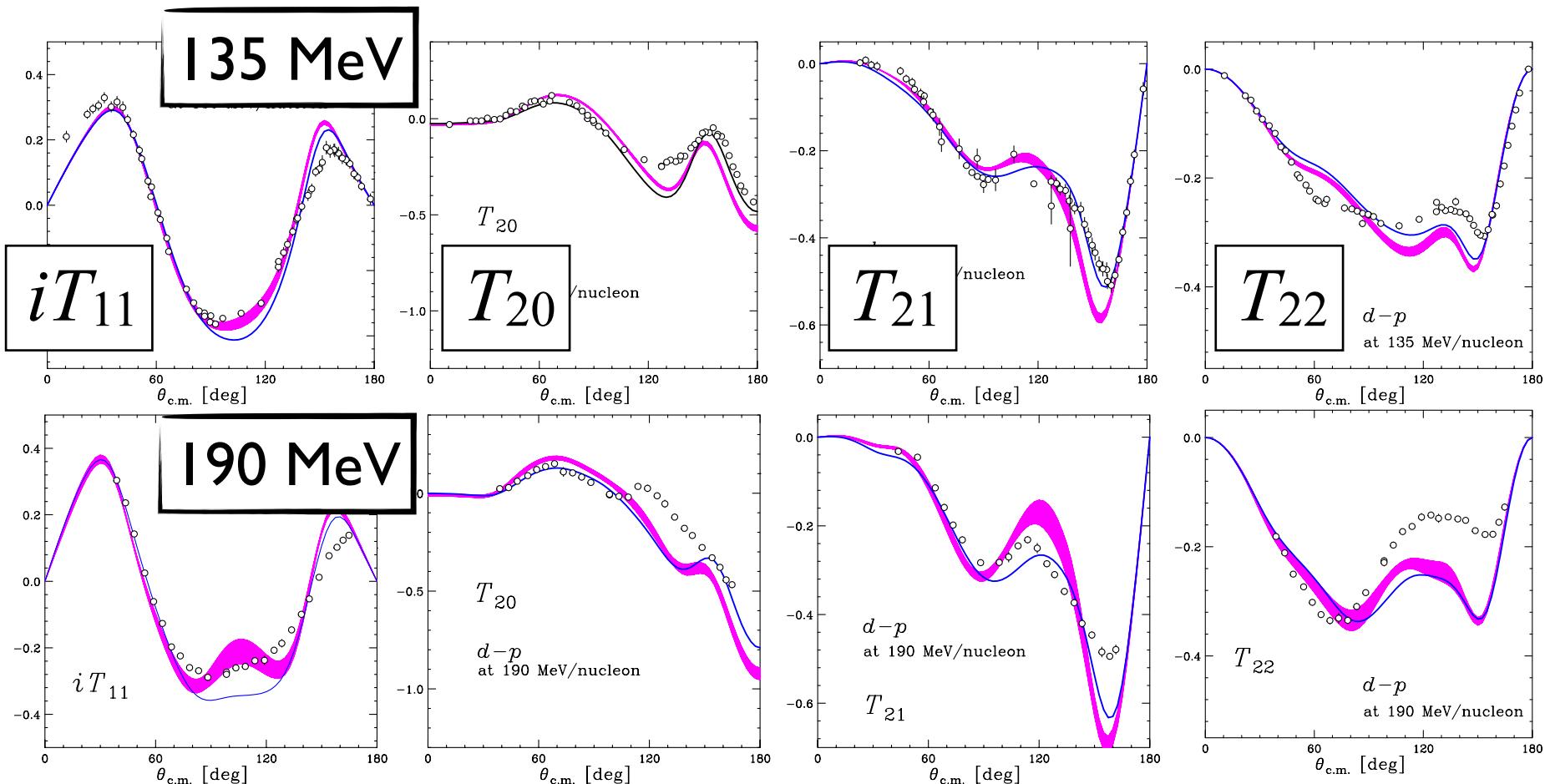


- Results of deuteron analyzing powers show deficiency of spin dependent parts of 3NFs.



# Deuteron Analyzing Powers at 135 & 190 MeV/nucleon

Chiral EFT N4LO NN pot.  
E. Epelbaum et al, private communications



NN(N4LO)  
NN(CD Bonn)

Large discrepancies in Tensor analyzing  
powers  $T_{20}$  &  $T_{22}$   
→ 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 many spin observables 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  $\chi$ EFT NN+NNN potentials explain the data.

## Next Step

Nd Breakup Experiments : Rich kinematical configurations

Four Nucleon Scattering, e.g. p+ $^3$ He : from Few to Many & Iso-spin dependence

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

**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



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