Workshop on experimental and theoretical aspects of NN and NNN forces

INT, Seattle, October 7-10, 2003

Present Status of the Nucleon-Deuteron Elastic Scattering at Intermediate Energy

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RIKEN

Are there three-nucleon forces(3NF)?

- 3NF is much weaker than 2NF.

  →3NF effects are easily masked by 2NF effects.

- Equations of motion must be solved exactly.

  →Faddeev eq.

  →2NF must be reliable.

However, numerical calc. are extremely difficult.

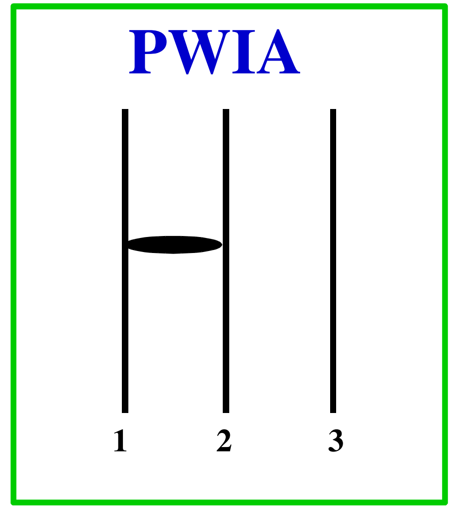
Three-Body Problems in Quantum Mechanics

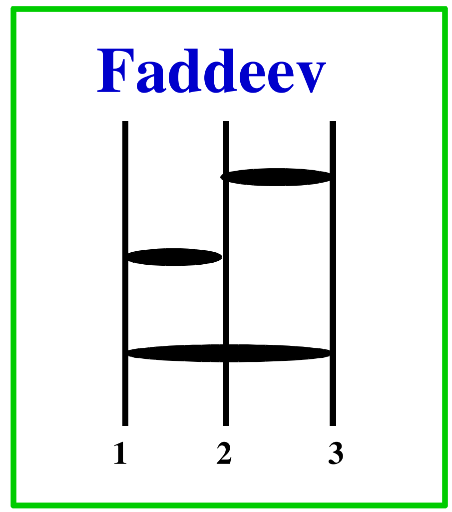
L.D. Faddeev, Sov. Phys. JETP 12(1961)1014

Faddeev Equation

$$H = H_0 + V_{12}^{NN} + V_{23}^{NN} + V_{31}^{NN} + V_{123}$$

→ **can be solved exactly!**





Characteristics

nuclear force (2NF, 3NF) input

↓↑

Faddeev equation

↓↑

numerical results

↓↑

experimental results of 3NS

1. **Independent of reaction models**
2. **Direct comparison possible between data and inputs**

Two nucleon force   NF)

One π Exchange (OPE) model by Hideki Yukawa

(Proc. Phys. Math. Soc. Jpn 17(1935) 48.)

$m_\pi c^2 = 140$ **MeV** **(J^π, T)=(0^-, 1)**

$$V^{OPE}_{(1,2)} = \frac{1}{3}\frac{f^{\ \ 2}}{\hbar c} m\ \ c^2 (\vec{\ }_1 \vec{\ }_2)\{\vec{\ }_1 \vec{\ }_2 + \left(1 + \frac{3}{x} + \frac{3}{x^2}\right) S_{12}\} \frac{\exp^{-x}}{x}$$

$$S_{12} = \frac{3(\vec{\ }_1 \vec{r})(\vec{\ }_2 \vec{r})}{r^2} - (\vec{\ }_1 \vec{\ }_2)$$

$$x \equiv \frac{m\ \ c}{\hbar} r$$

Realistic modern 2 nucleon forces available now.

reproduces more than 3,500 exp. NN data with $\boldsymbol{x^2 \cong 1}$.

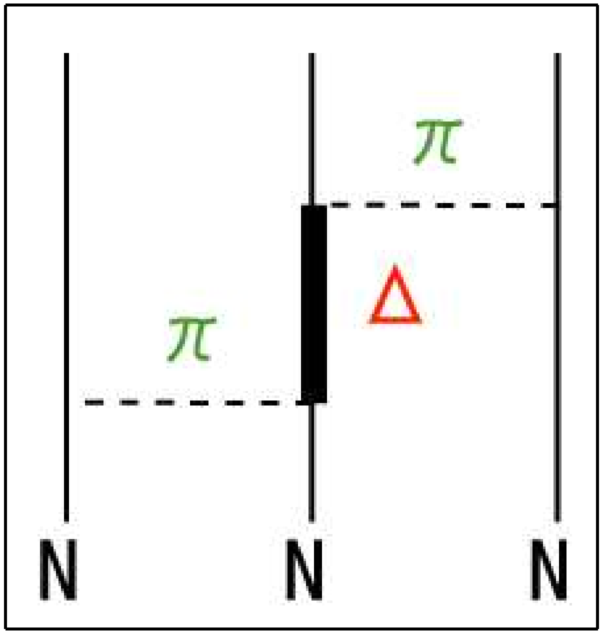
- **CD Bonn pot.** : strong non-locality
- **AV18 pot.** : OPE + phenom.
- **Nijmegen I/II/93 pot.** : one boson exch.

Main differences are of-shell properties

Three nucleon force　NF)

2.Fujita • Miyazawa type 3NF

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



2π exchange type 3NF

N: proton / neutron

$$m_N c^2 = 940\text{MeV}$$

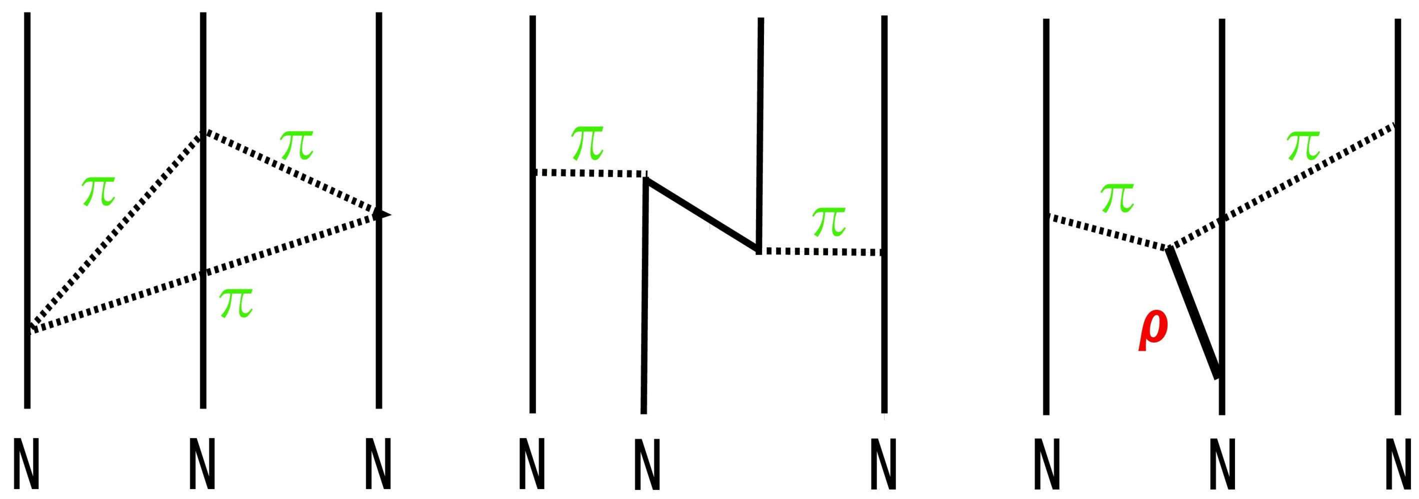
$$\left(J \;, \mathrm{T}\right) = \left(\frac{1}{2}^+ , \frac{1}{2}\right)$$

Δ　excited state of nucleon

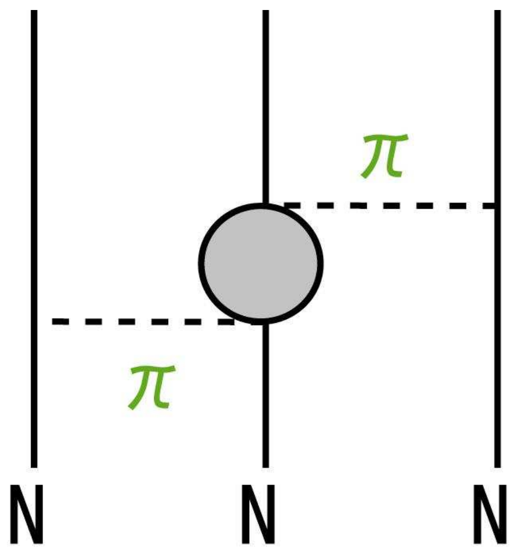
$$m_\Delta c^2 = 1232\ \text{MeV}$$

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

other type of 3NF



3NF based on 2π exchange model



TM-3NF

S.A.Coon *et al.*, Nucl. Phys. A317(1979)242.

current algebra

4. UR-3NF

J.Carlson *et al.*, Nucl. Phys. A401(1983)59.

FM+phenomenological SR term

7. BR-3NF

H.T. Coelho *et al.*, Phys. Rev. C28(1983)1812.

chiral Lagrangian + current algebra

10. Texas-3NF

U.van. Kolck *et al.*, Phys. Rev. C49(1994)2932.

chiral perturbation theory

Three-Nucleon Force

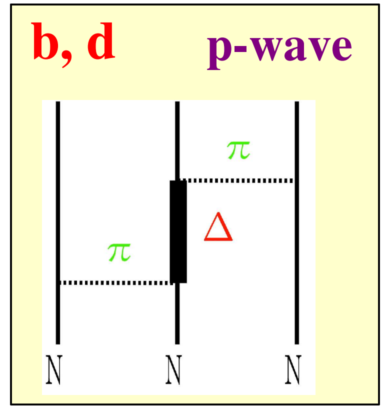
$$V^{(3)} = \frac{1}{(2\pi)^6}\frac{g^2_{\pi NN}}{4m^2}\frac{F^2_{\pi NN}(q^2)}{(q^2+m_\pi^2)}\frac{F^2_{\pi NN}(q'^2)}{(q'^2+m_\pi^2)}\vec{\sigma}_1\cdot\vec{q}\,\vec{\sigma}_2\cdot\vec{q}'\left[O^{\alpha\beta}\tau_\alpha\tau_\beta\right]$$

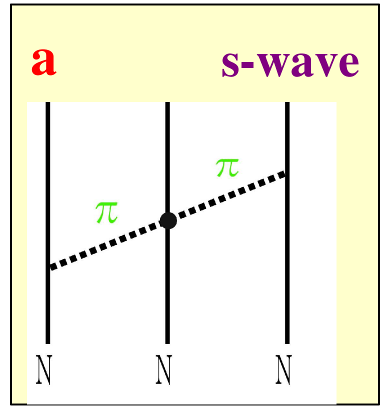
$$O^{\alpha\beta} = \delta^{\alpha\beta}\left[a + b\vec{q}\vec{q}' + c(q^2+q'^2)\right] - d(\tau_3^\gamma\varepsilon^{\alpha\beta\gamma}\vec{\sigma}_3\cdot\vec{q}\times\vec{q}')$$

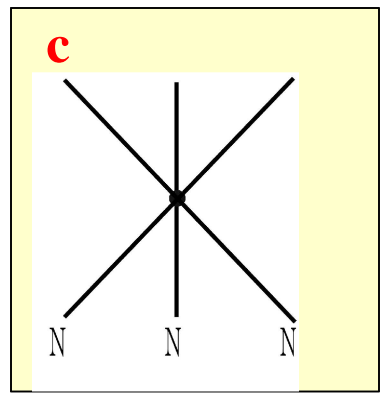
$$F^{2}{}_{NN}(q^2) = \frac{{}^2 - m^2}{{}^2 + q^2}$$ NN form factor

: cut – off parameter

3NF model	a	b	c	d
FM	0.0	-1.15	0.0	-0.29
TM	1.13	-2.62	1.05	-0.60
Urbana IX	0.0	-1.20	0.0	-0.30
Brazil	1.05	-2.29	1.05	-0.77
Texas	1.87	-3.82	0.0	-1.12
Ruhr	0.51	-1.82	0.0	-0.48
TM’	-0.87	-2.62	0.0	-0.60







Faddeev type calculations

1 Bochum-Cracow-KIT group calculation

→ **H. Witała, H. Kamada, W. Glöckle,**

E. Epelbaum

Input data

NN	3NF
CD Bonn	Tucson-Melbourne
AV18	Urbana IX
Nijmegen	

2 Hannover group calculation

→ **P.U. Sauer, D.Deltuva**

Input data

NN	3NF
CD Bonn	Δ – isobar

N and Δ on an equal footing!

dispersive two-body effects exist.

Both calc., *nd* scattering assumed.

→No Coulomb force effects included.

First Evidence of 3NF Effects

- **B.E. of ^{3}H: 8.48 MeV**

Faddeev calculations

Bochum-Cracow-KIT group calc.

NN pot.	NN only	NN+3NF(TM)	Λ
CD Bonn	8.00	8.483	4.86
AV18	7.65	8.479	5.22
Nijm93	7.66	8.480	5.10
Ruhr	7.64	8.459	5.31

Hannover group C.C. calc.

CDBonn	8.00	8.29 (CDBonn + Δ)	–

- **NN force only calc. is underboud by 0.5-1.0 MeV.**
- **3NF fills this gap.(but with Λ)**

→ put constraint on overall strength of 3NF.

- **to study dynamical properties of 3NF**

→ scattering

→ No adjustable parameter in Faddeev calc.

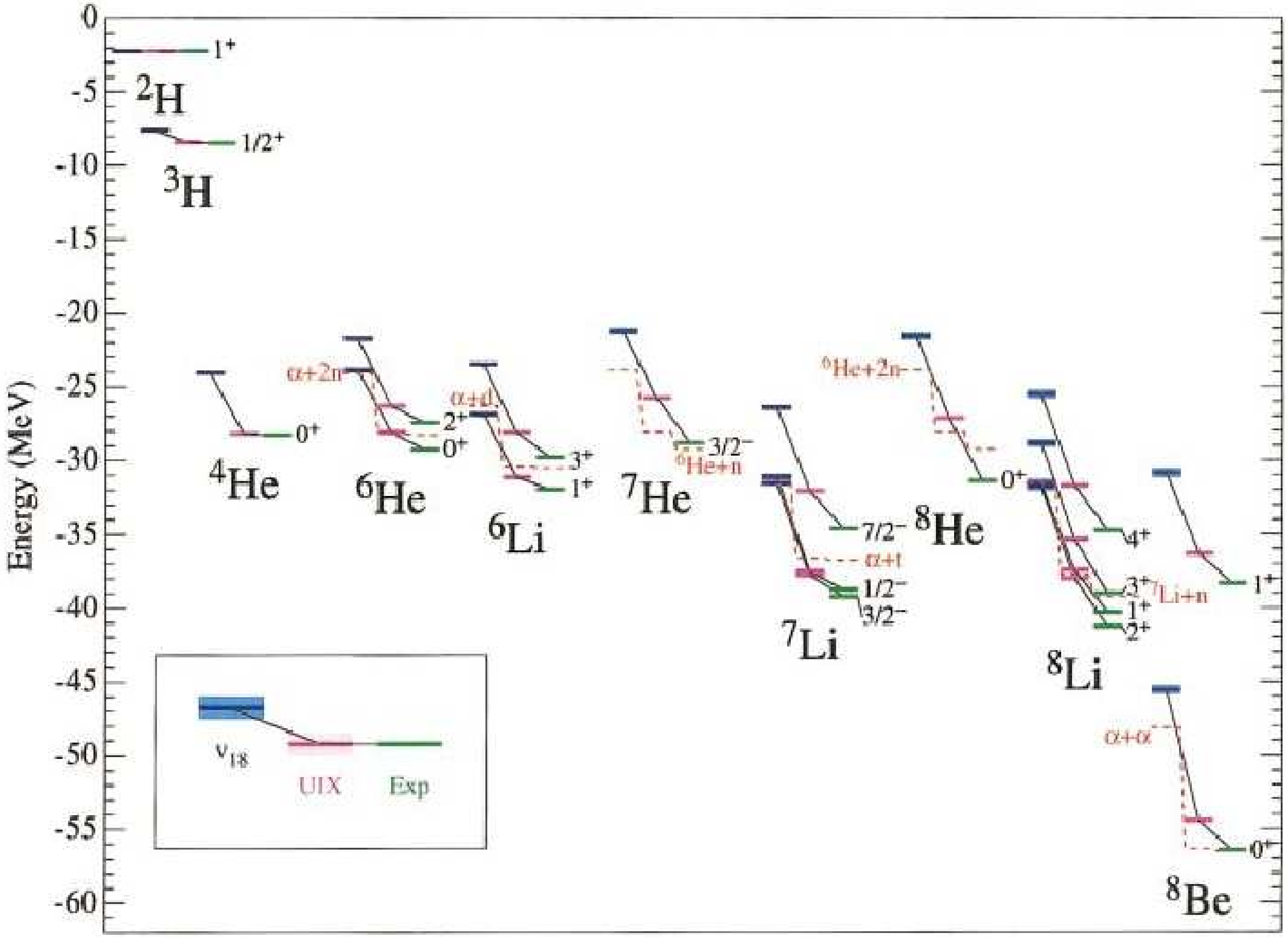
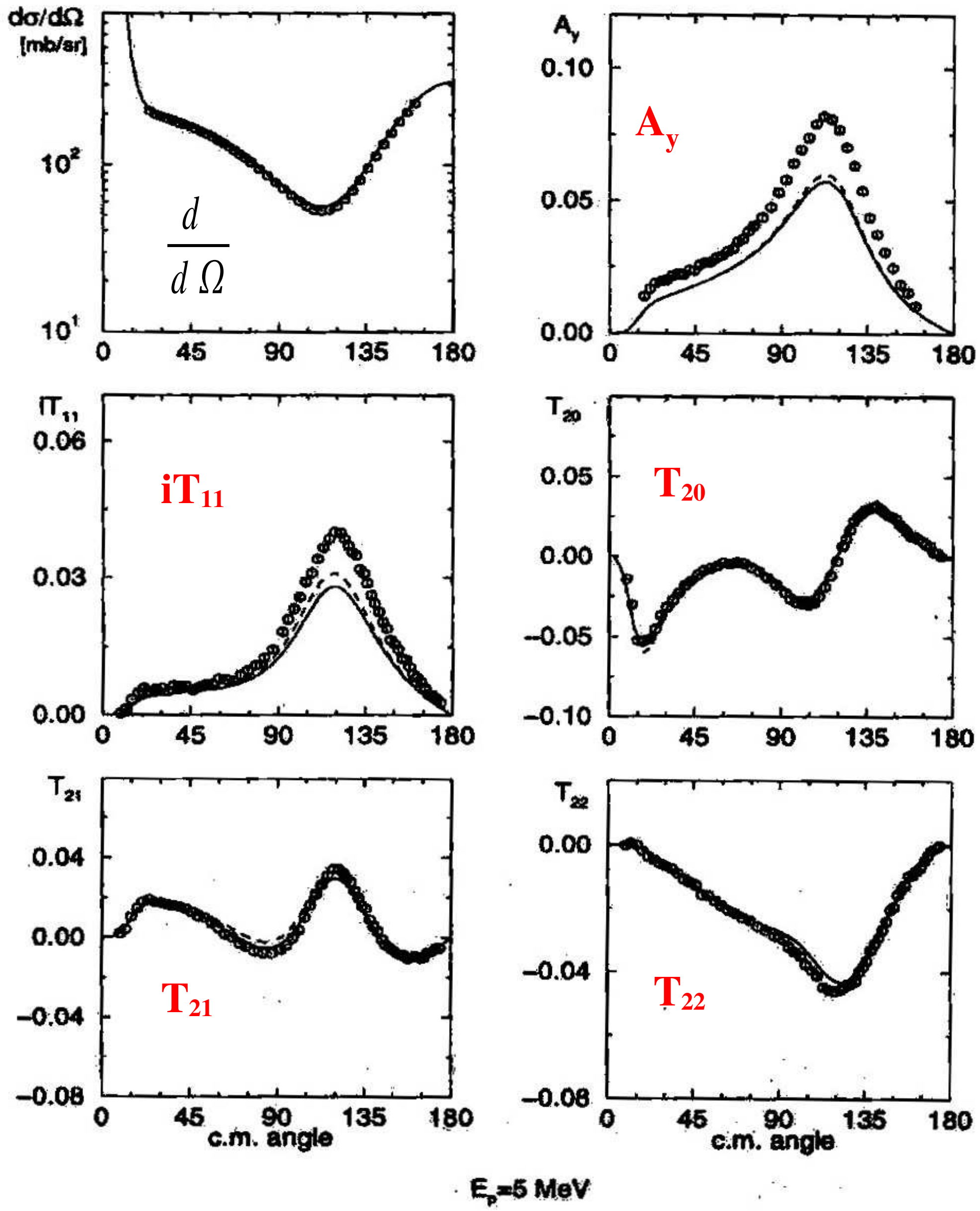


FIG. 1. (Color) Energies of ground or low-lying excited states of light nuclei computed with the AV18 and AV18/UIX interactions, compared to experiment. The light shading shows the Monte Carlo statistical errors. The dashed lines indicate the thresholds against breakup for each model or experiment.

To where should we look for 3NF effects?

N*d* elastic scattering is very attractive since it is simple and offers a rich set of spin observables.

Low energy *pd* scattering



Faddeev calc.

No parameter !

No need of 3NF !

***A_y* (iT_{11})discrepancy**

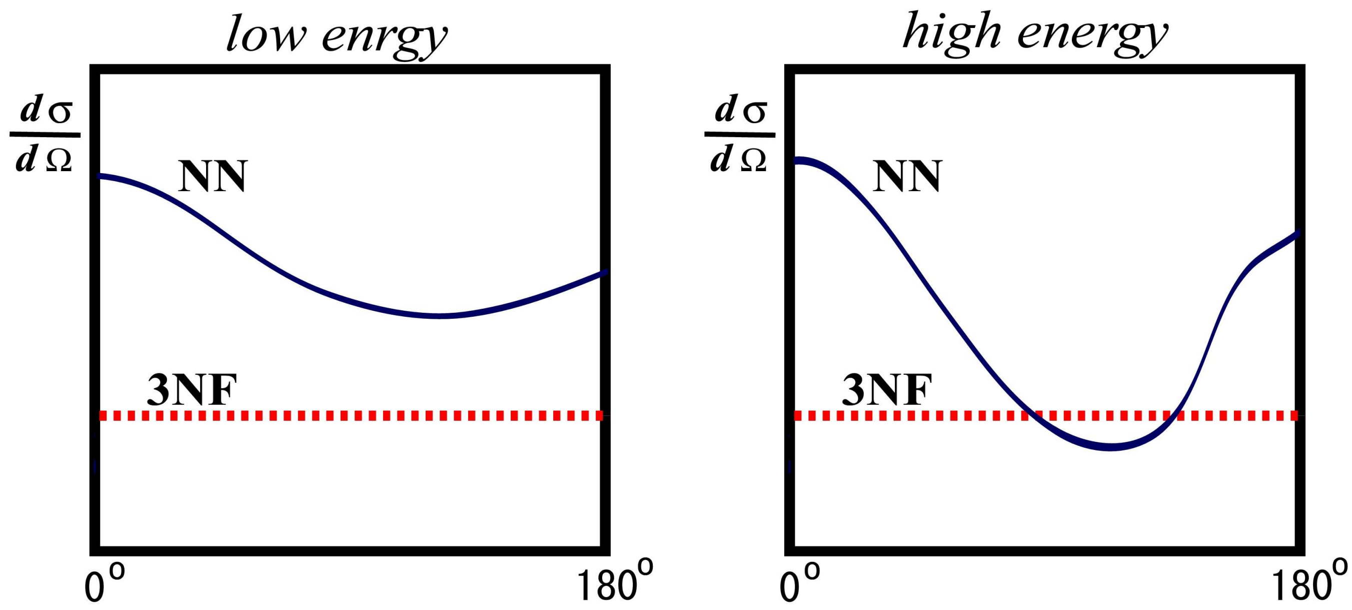
→ 3NF ?

Probably due to deficiency in ^3P_J phase shifts of NN.

To where should we look for 3NF effects?

Prediction by H.Witała. PRL **81**('98) 1183.

→ **go to *nd* scatt. at intermediate energy.**



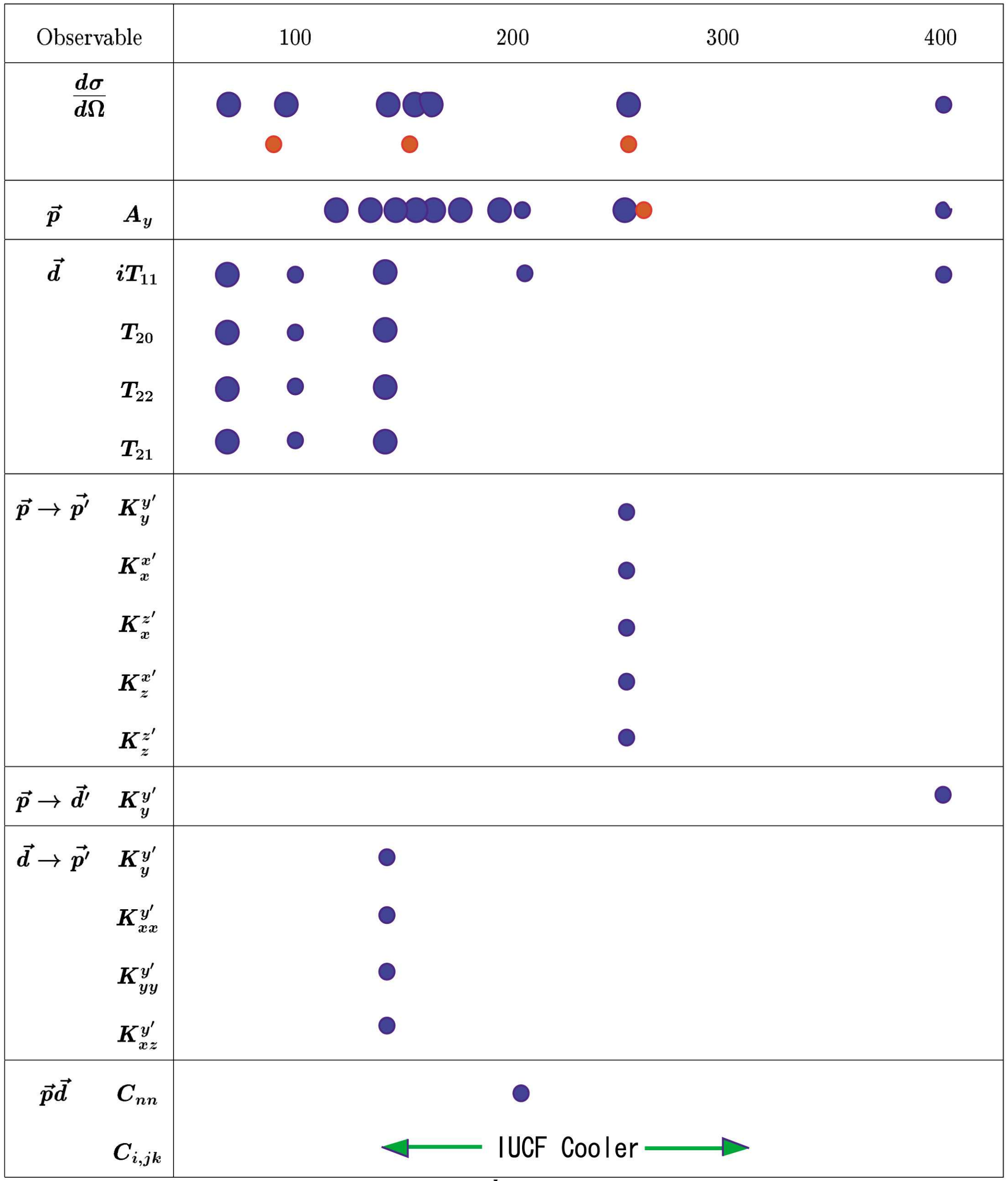
Look at *dσ/dΩ* minimum region.

Let's start with

135 MeV/u (E$_d$=270 MeV) data

at RIKEN by K. Sekiguchi

pd and *nd* scattering at 70–400 MeV/A



Other data : limited angular range $\frac{d\sigma}{d\Omega}$ and A_y.
T_{20}:0.15–1.15 GeV/A
$\sigma_{tot}(nd)$

$\vec{d} + p$ at 270 MeV (RIKEN)

$\vec{d}$: various spin(polarization) obs.

$d\sigma/d\Omega$, $P^{y'}(= -A_y^p)$, iT_{11}, T_{20}, T_{22}, T_{21}

K. Sekiguchi *et al*. Phys. Rev. C65 (2002) 034003.

Spin(polarization) transfer exp. by Sekiguchi

$\vec{d} + p \rightarrow \vec{p} + d$ at 270 MeV (135 MeV/u)

$K_{xx}^{y'}, K_{yy}^{y'}, K_{xz}^{y'}, K_{y}^{y'}$

$\longrightarrow$ K. Sekiguchi: to be published soon.

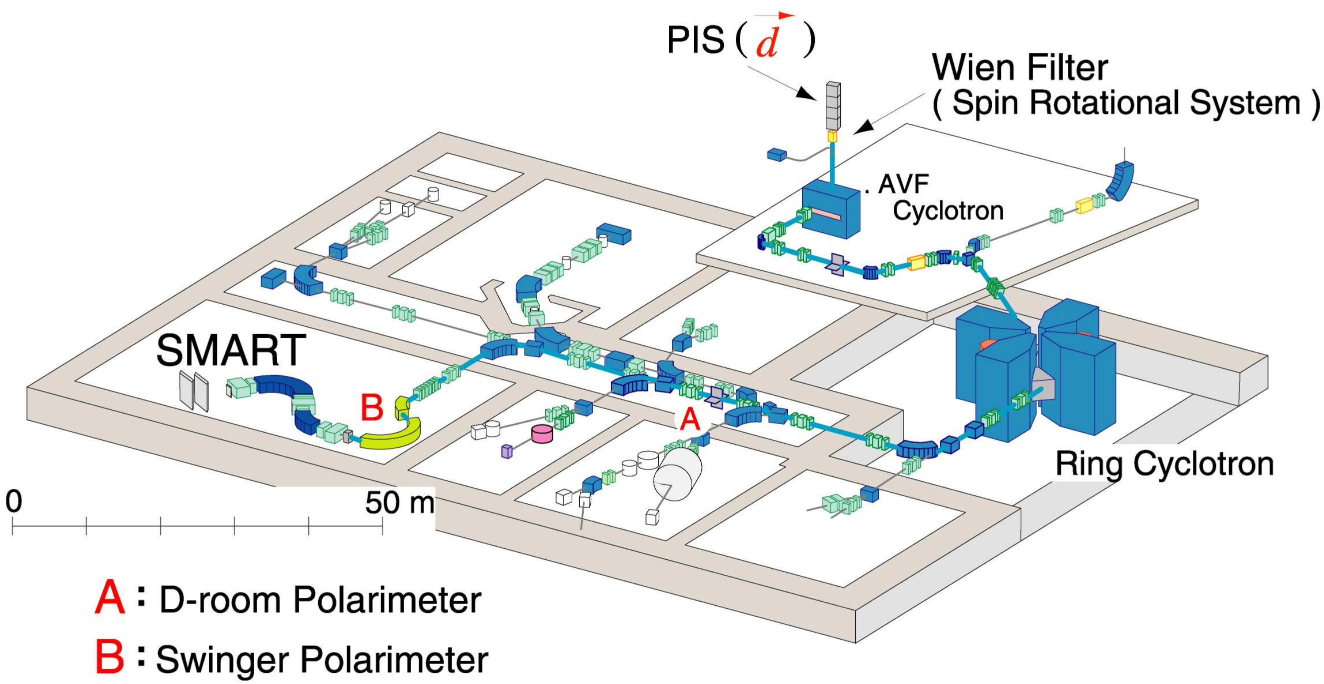
RIKEN Accelerator Research Facility (RARF)

Directions of polarization of *d* beams are freely controlled!

- **Vector** and **tensor** polarized deuteron beams are provided by the polarized ion source(**PIS**).
- The Spin axis is controlled by a **Wien Filter** prior to acceleration.
- Single-turn extraction is available both for the AVF and Ring cyclotrons.

Beam polarizations : 60-80% of the theoretical maximum values

at D-room polarimeter (**A**) and the Swinger polarimeter (**B**)



Method of spin rotation

magnetic moment $\mu = s\frac{e\hbar}{mc}(1+a)$

cyclotron frequency in magnetic field B $\quad {}_c = \frac{eB}{m}$

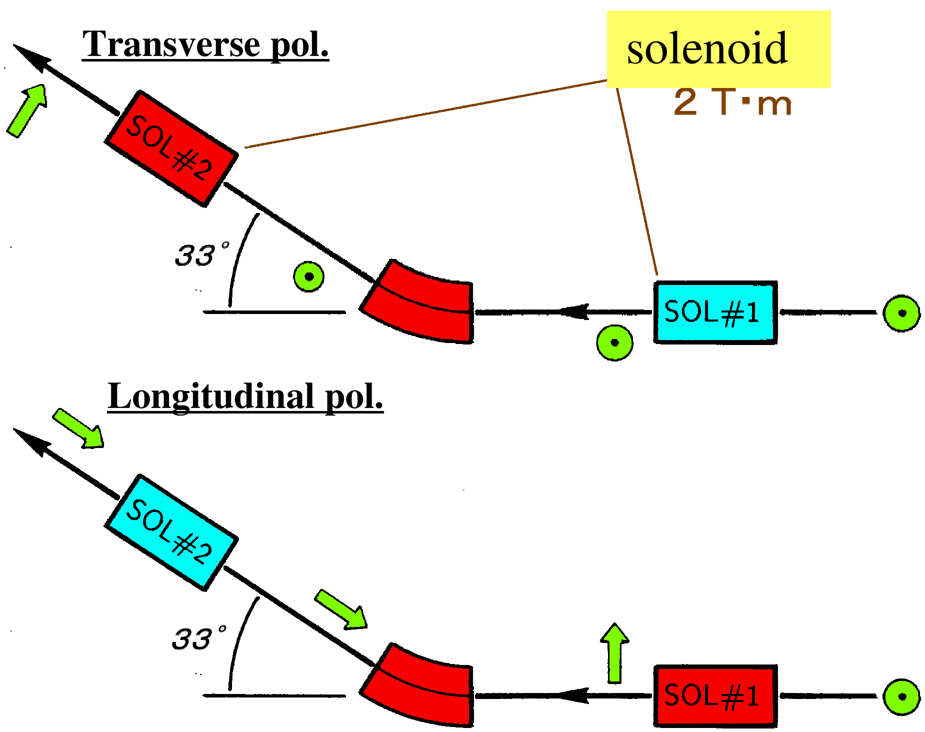
angular rotation frequency in B $\quad {}_s = \frac{eB}{m}(\ a+1)$

Larmor freq. + Thomas precession (rel. effects)

Dirac particle $(a=0) \Rightarrow {}_s = {}_c$

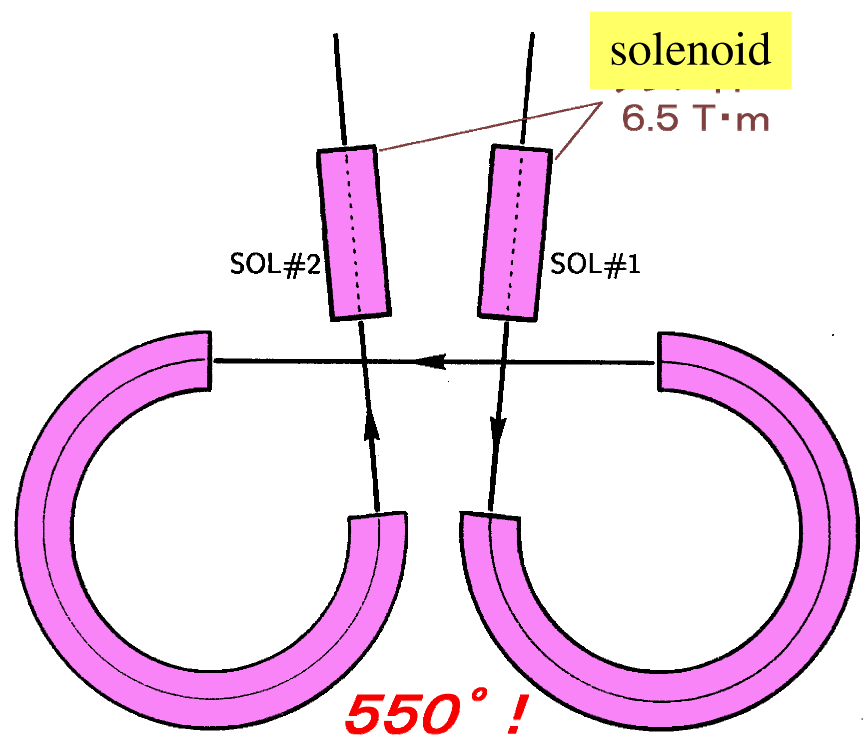
proton $\mu_p = \frac{1}{2}\frac{e\hbar}{m_p c} \times 2.793$

500 MeV proton



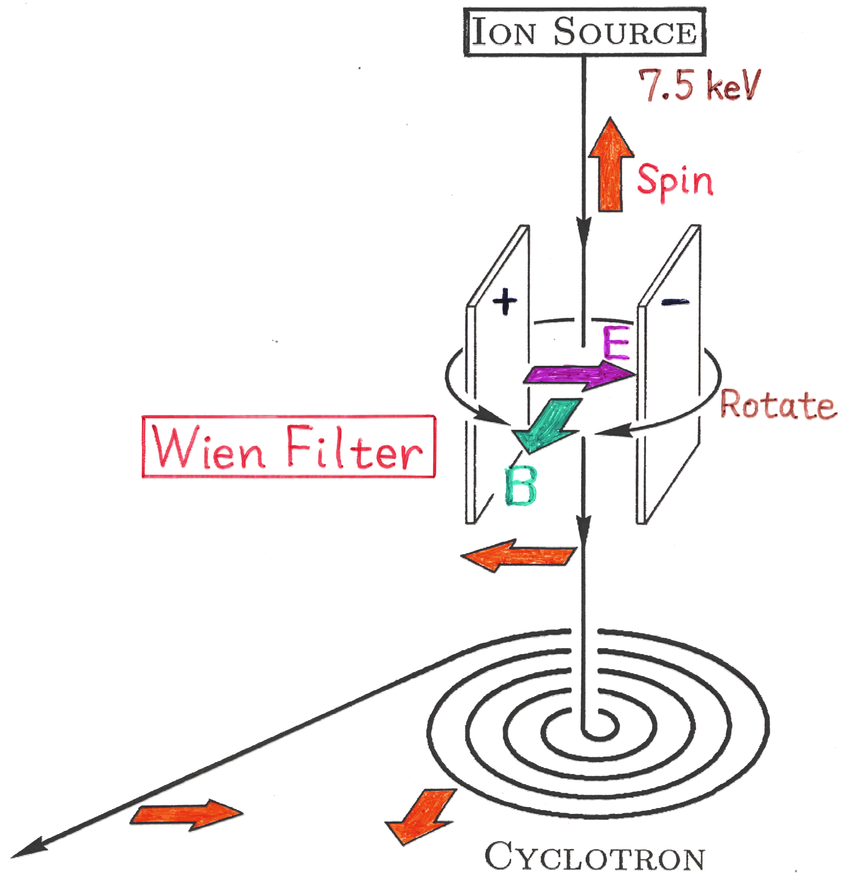
deuteron $\mu_d = \frac{e\hbar}{m_d c} \times 0.857$

270 MeV deuteron



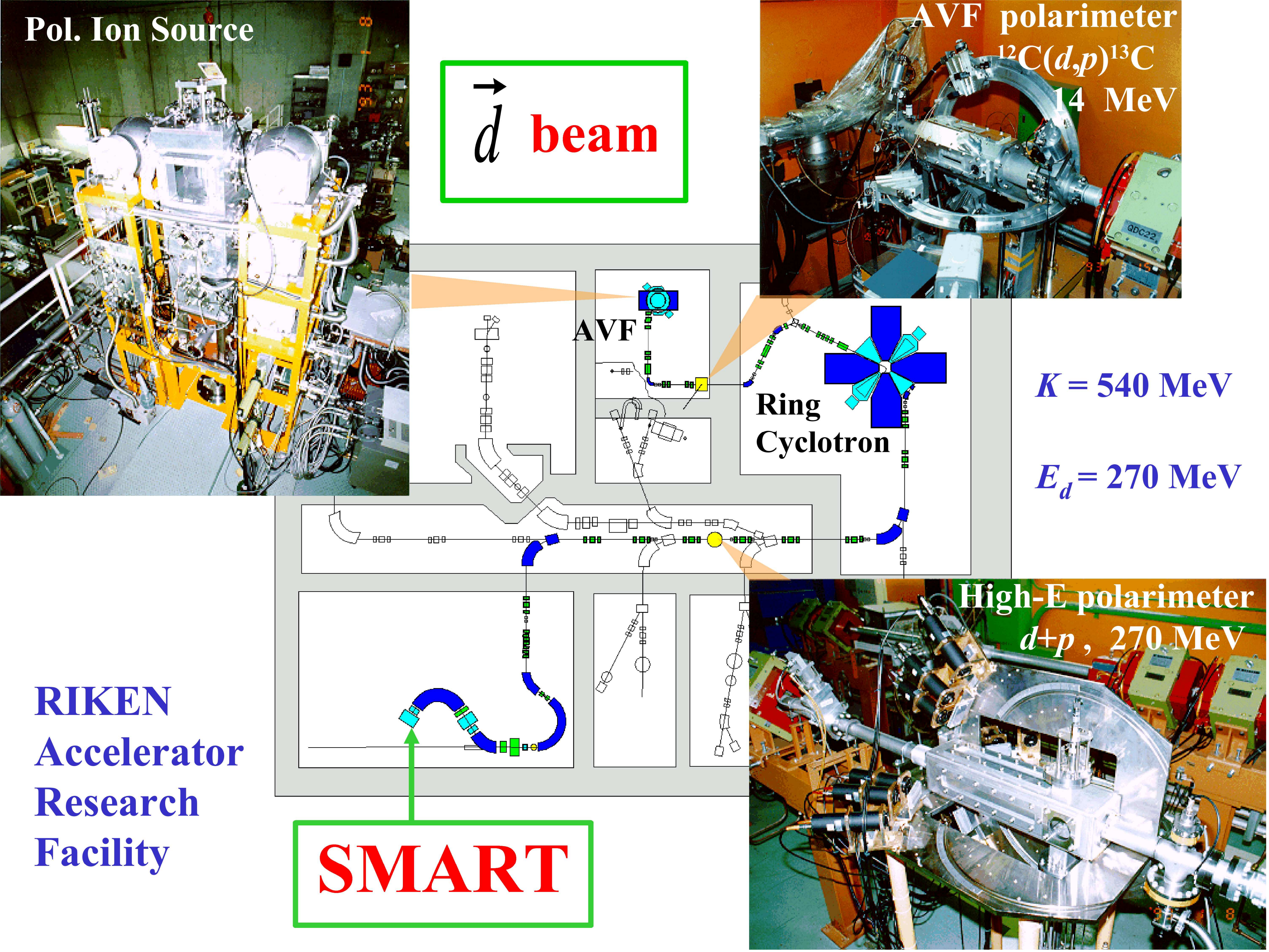
Method of spin rotation

Spin rotation before injection
into cyclotron at low energy
spin precession during accel.



Familiar at Tandem VdG accel…

- **single turn extraction needed at cyclotron**
  Thanks to RIKEN Accelerator Staff
- **spin direction moniter needed after accel. With high efficiency.**

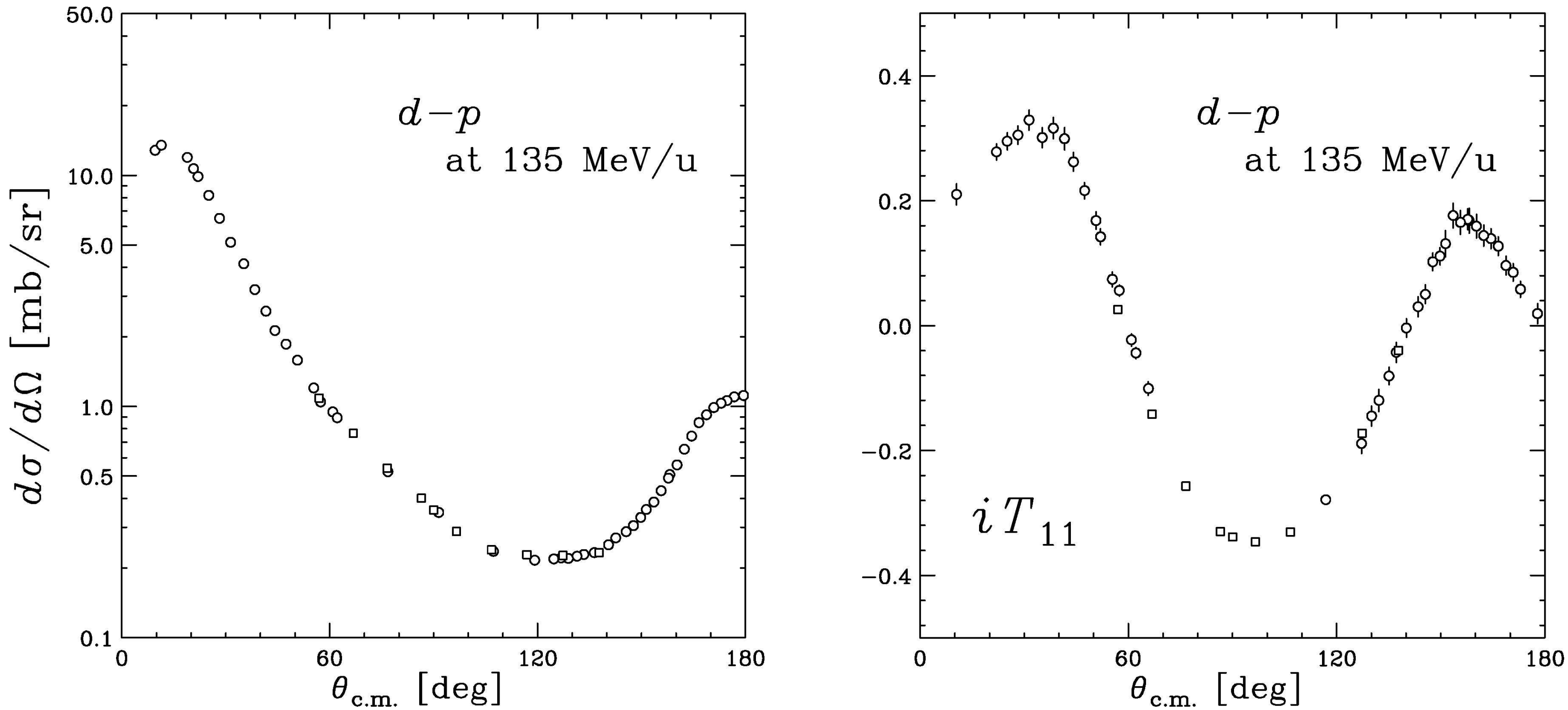


Pol. Ion Source
$\vec{d}$ beam
AVF polarimeter
$^{12}C(d,p)^{13}C$
14 MeV
AVF
Ring
Cyclotron
$K = 540$ MeV
$E_d = 270$ MeV
High-E polarimeter
$d+p$, 270 MeV
RIKEN
Accelerator
Research
Facility
SMART

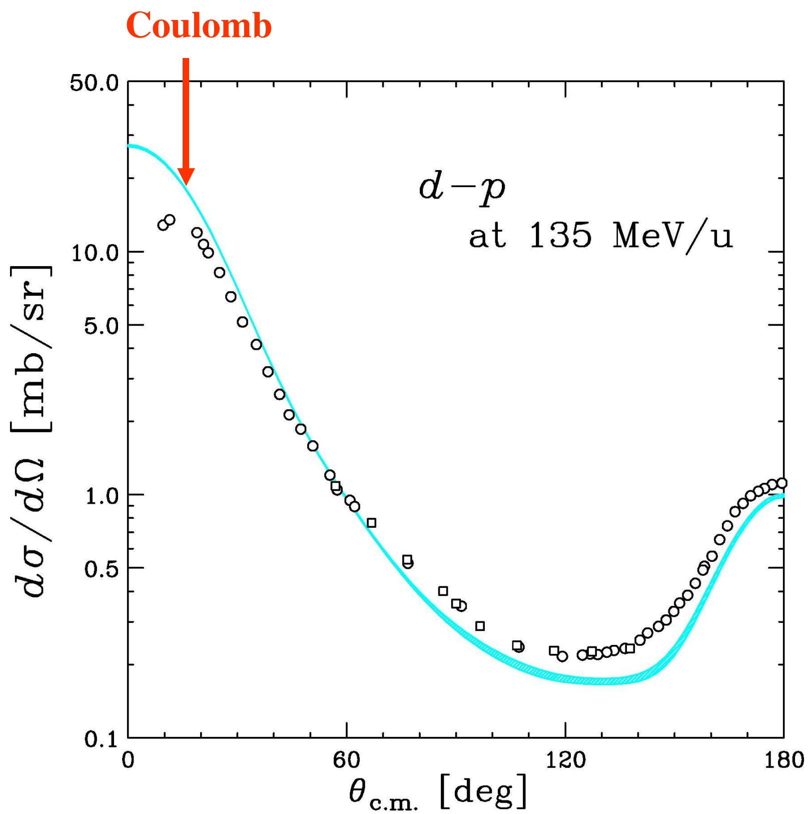
SMART: Swinger and Magnetic Analyzer with Rotator and Twister

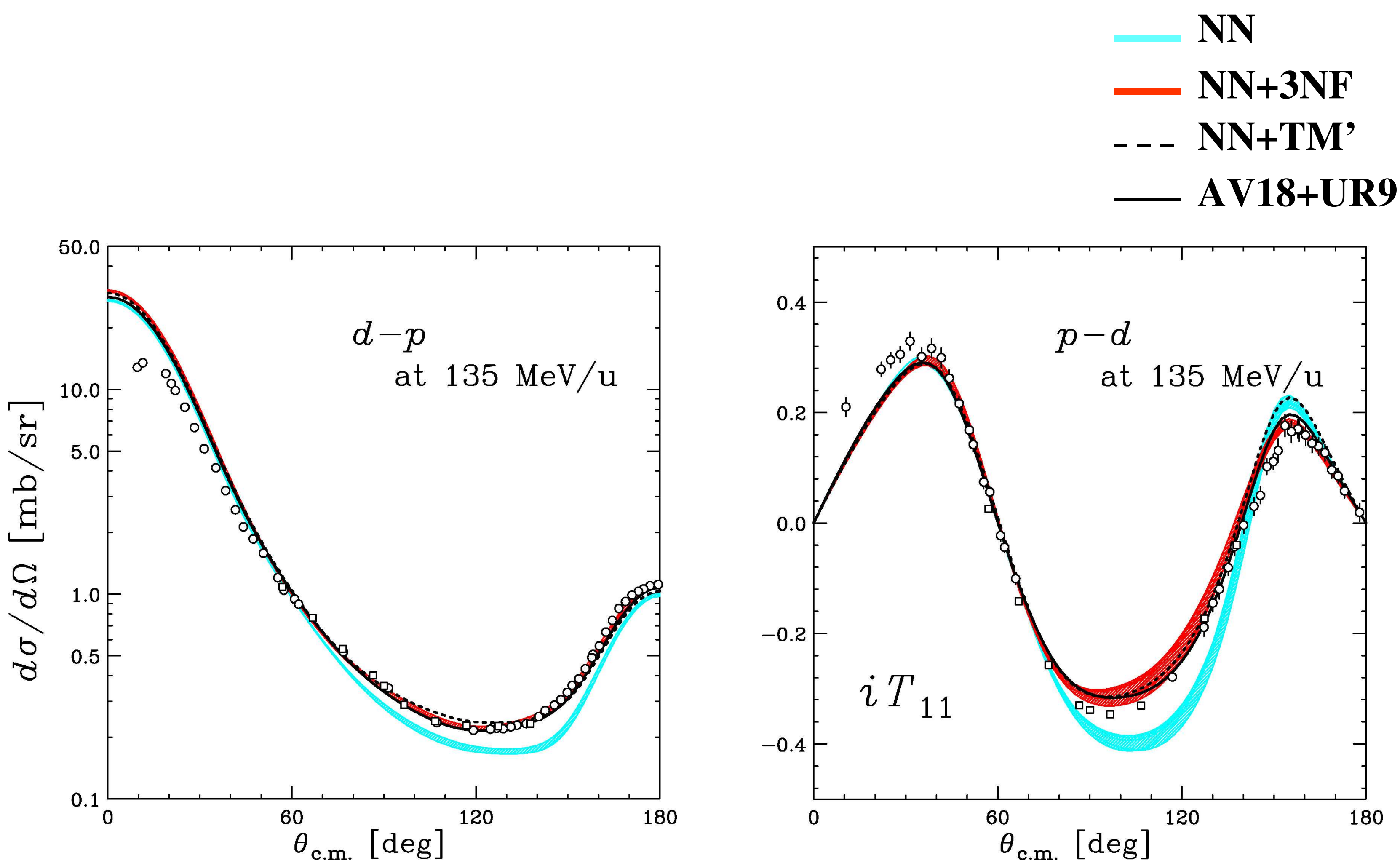
RIKEN data

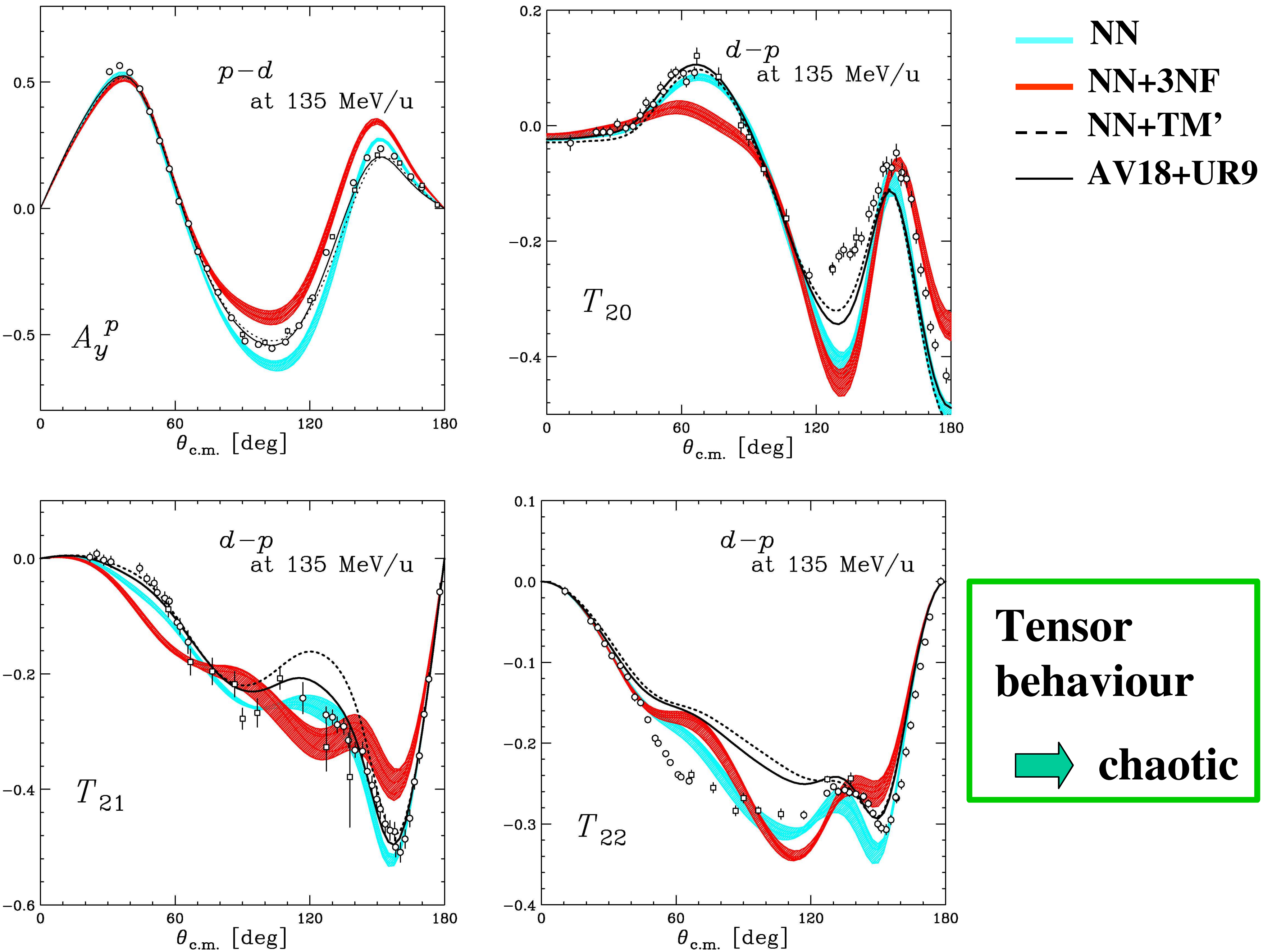
270 MeV (135 MeV/u)



Bochum calc. NN



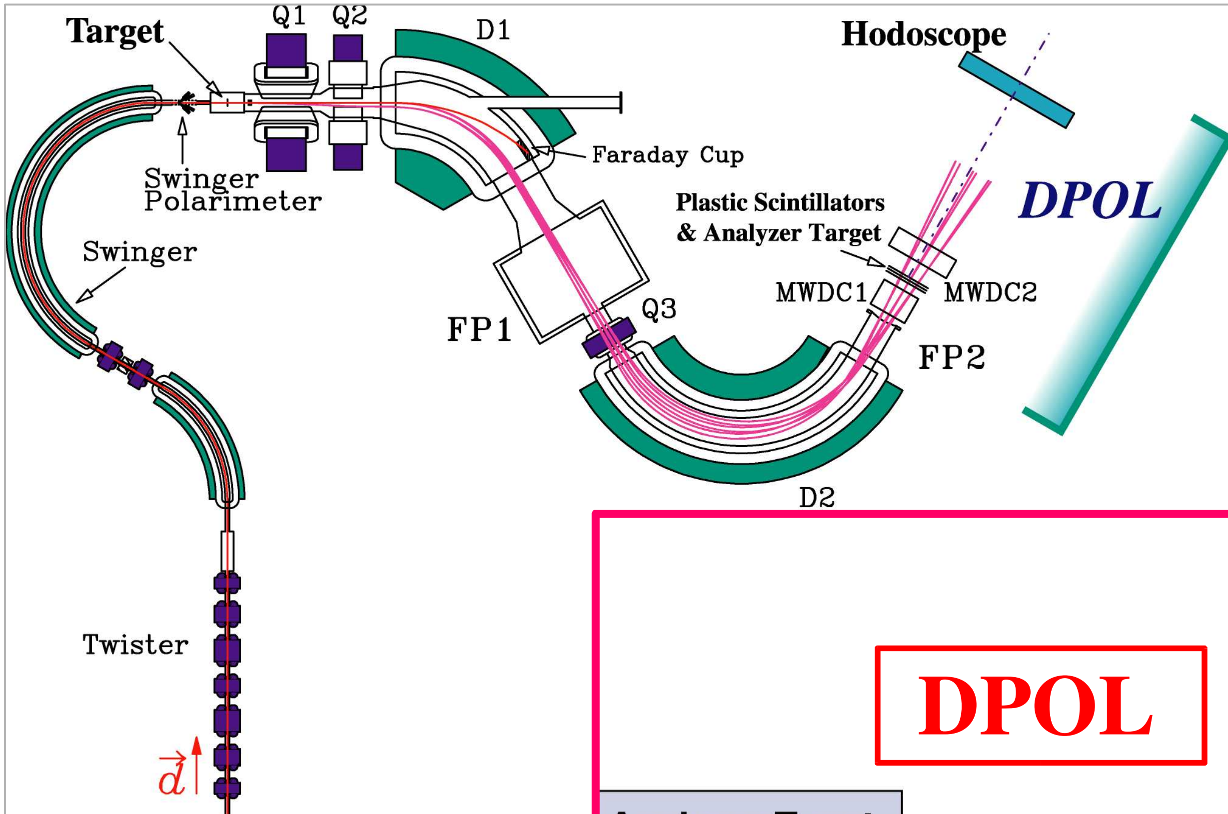

NN
NN+3NF
NN+TM'
AV18+UR9
d−p
at 135 MeV/u
dσ/dΩ [mb/sr]
θc.m. [deg]
p−d
at 135 MeV/u
iT11
θc.m. [deg]

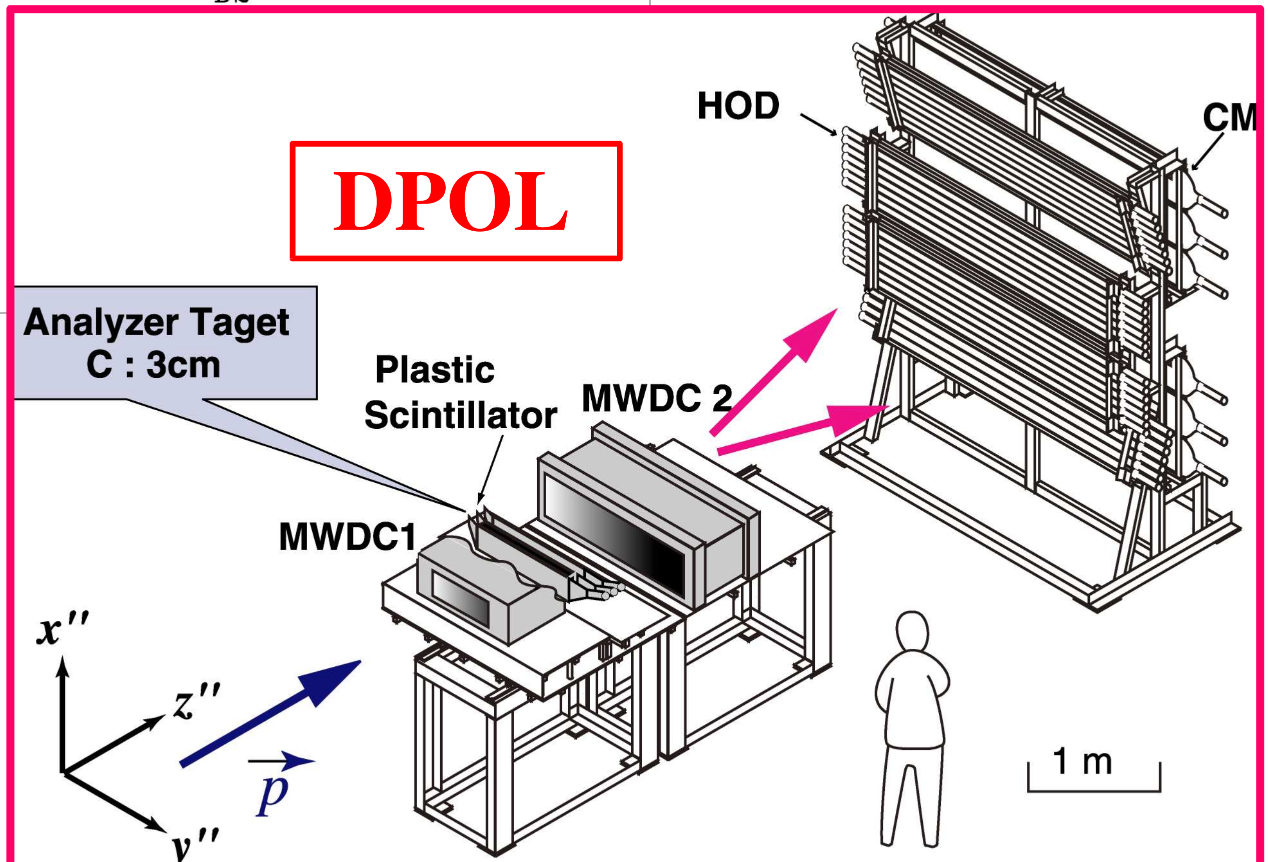


Tensor behaviour

➡ **chaotic**

Polarimeter





Measurement Conditions

Parameter

- Beam energy : E_d = 270 MeV
- Target : Liq. H (19.8 mg/cm^2) , CH_2 (93.4 mg/cm^2)
- Beam intensity : 10 - 60 nA
- Vector and tensor beam polarizations
  : 60 - 80 % of the theoretical maximum values

Measured Observables

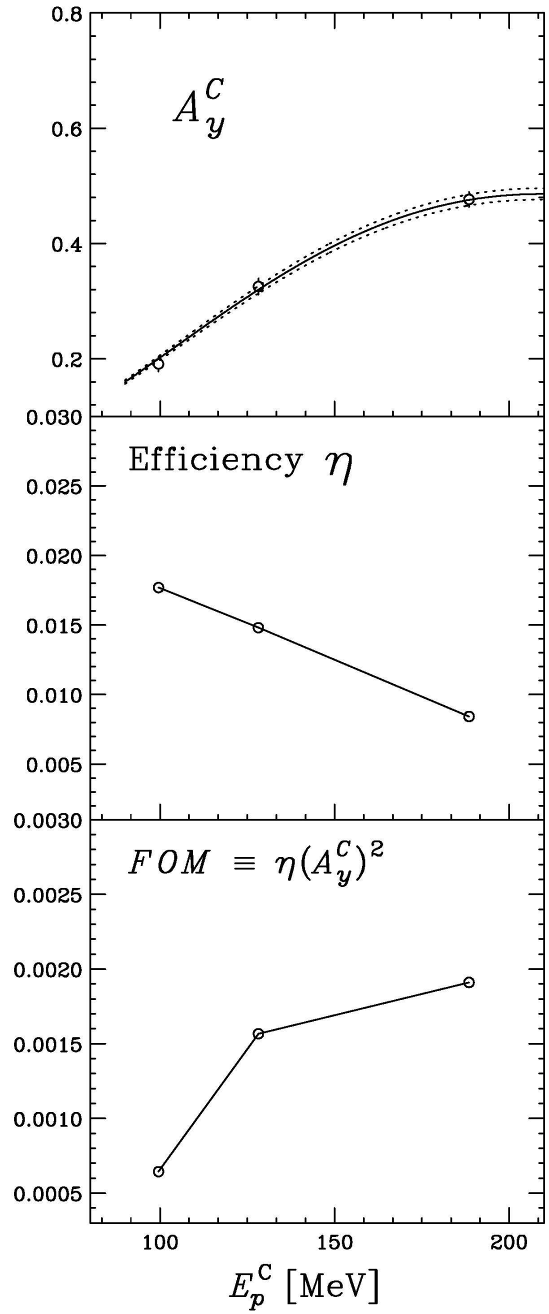
- $K_{xz}^{y'},\ K_{xx}^{y'} - K_{yy}^{y'}\ (K_{xx}^{y'}, K_{yy}^{y'}),\ K_{y}^{y'}$
- $P^{y'}$ —— Induced Polarization

Angular Range : $\theta_{\mathrm{c.m.}} = 90^\circ - 180^\circ$

DPOL calibration :

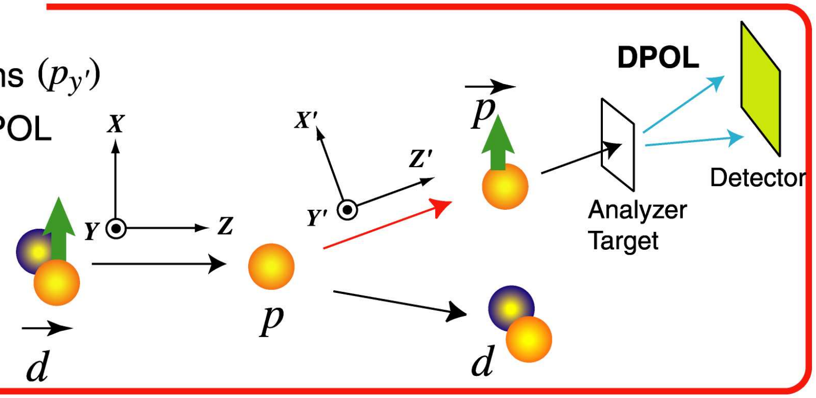
induced polarization of $^{12}C(\vec{p},p_0)\,^{12}C$

$|\delta\phi| \leqq 60^\circ$
$5^\circ \leqq \theta \leqq 15^\circ$



How to extract d to p polarization transfer coefficients?

- Control of Polarized Deuteron Beam Direction
- Measurement of Polarization of Scattered Protons $(p_{y'})$
  - ⇨ Calibration of effecitive analyzing power for DPOL



Polarized Cross Section

$$p_{y'}\,\sigma/\sigma_0 = P^{y'} + \frac{3}{2}p_y K_y^{y'} + \frac{2}{3}p_{xz}K_{xz}^{y'} + \frac{1}{3}\left(p_{xx}K_{xx}^{y'} + p_{yy}K_{yy}^{y'} + p_{zz}K_{zz}^{y'}\right)$$

→ Polarized d beam $(p_y, p_{yy}, p_{xx}, p_{xz})$ by **PIS & Wien Filter**

d beam spin mode

	P_Z	P_{ZZ}
#0	0	0
#1	0	-2
#2	$-2/3$	0
#3	$1/3$	1

$K_y^{y'}$ & $K_{yy}^{y'}$: $\quad p_{y'}\,\sigma/\sigma_0 = P^{y'} + \frac{3}{2}p_y K_y^{y'} + \frac{1}{2}p_{yy}K_{yy}^{y'}$

$K_{xx}^{y'}$: $\quad p_{y'}\,\sigma/\sigma_0 = P^{y'} + \frac{1}{2}p_{xx}K_{xx}^{y'}$

$K_{xz}^{y'}$: $\quad p_{y'}\,\sigma/\sigma_0 = P^{y'} + \frac{2}{3}p_{xz}K_{xz}^{y'} + \frac{1}{3}\left(p_{xx}K_{xx}^{y'} + p_{yy}K_{yy}^{y'} + p_{zz}K_{zz}^{y'}\right)$

Induced Polarization

Polarization Transfer Meas. @270MeV(135MeV/u)

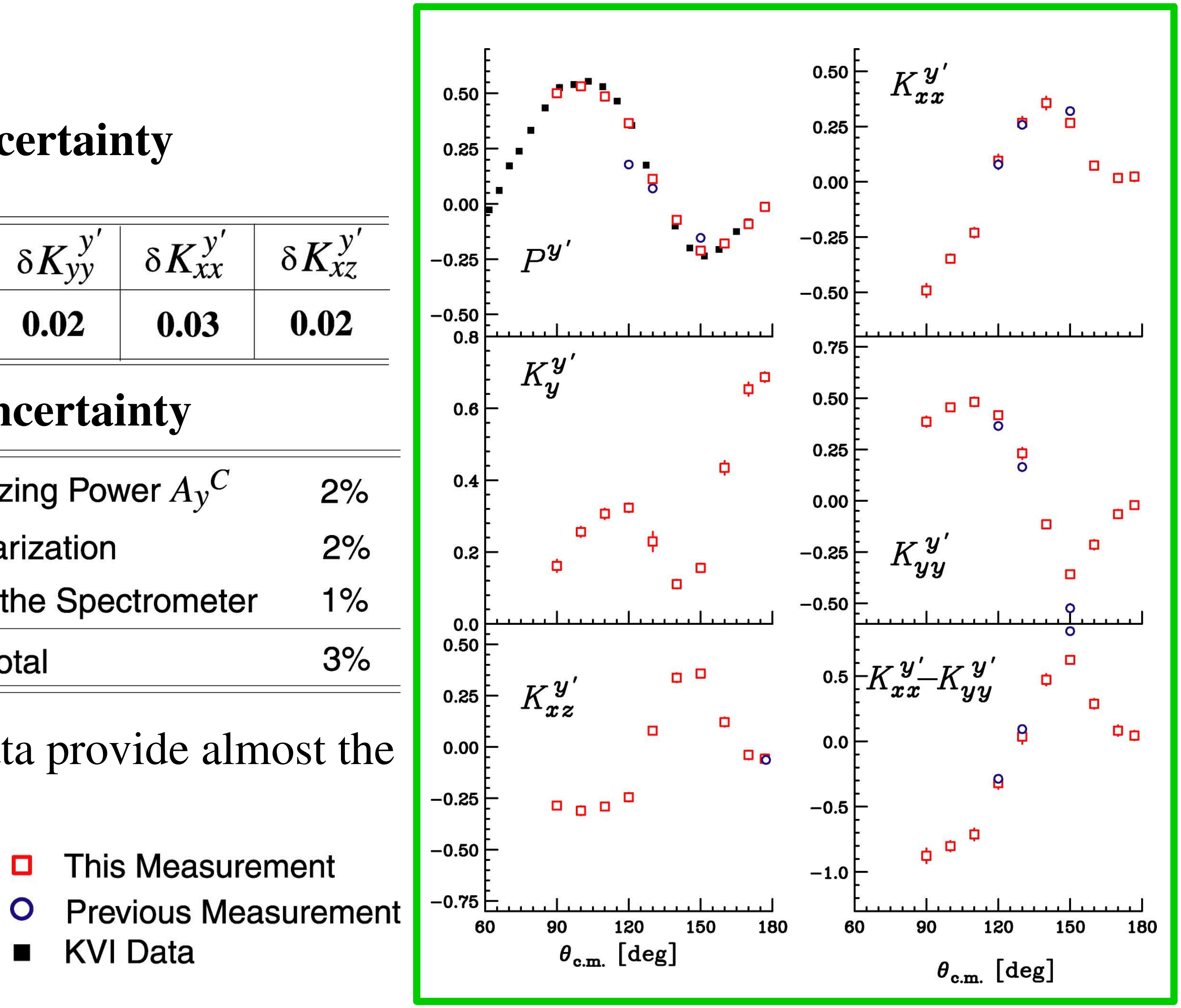
- **Statistical Uncertainty**

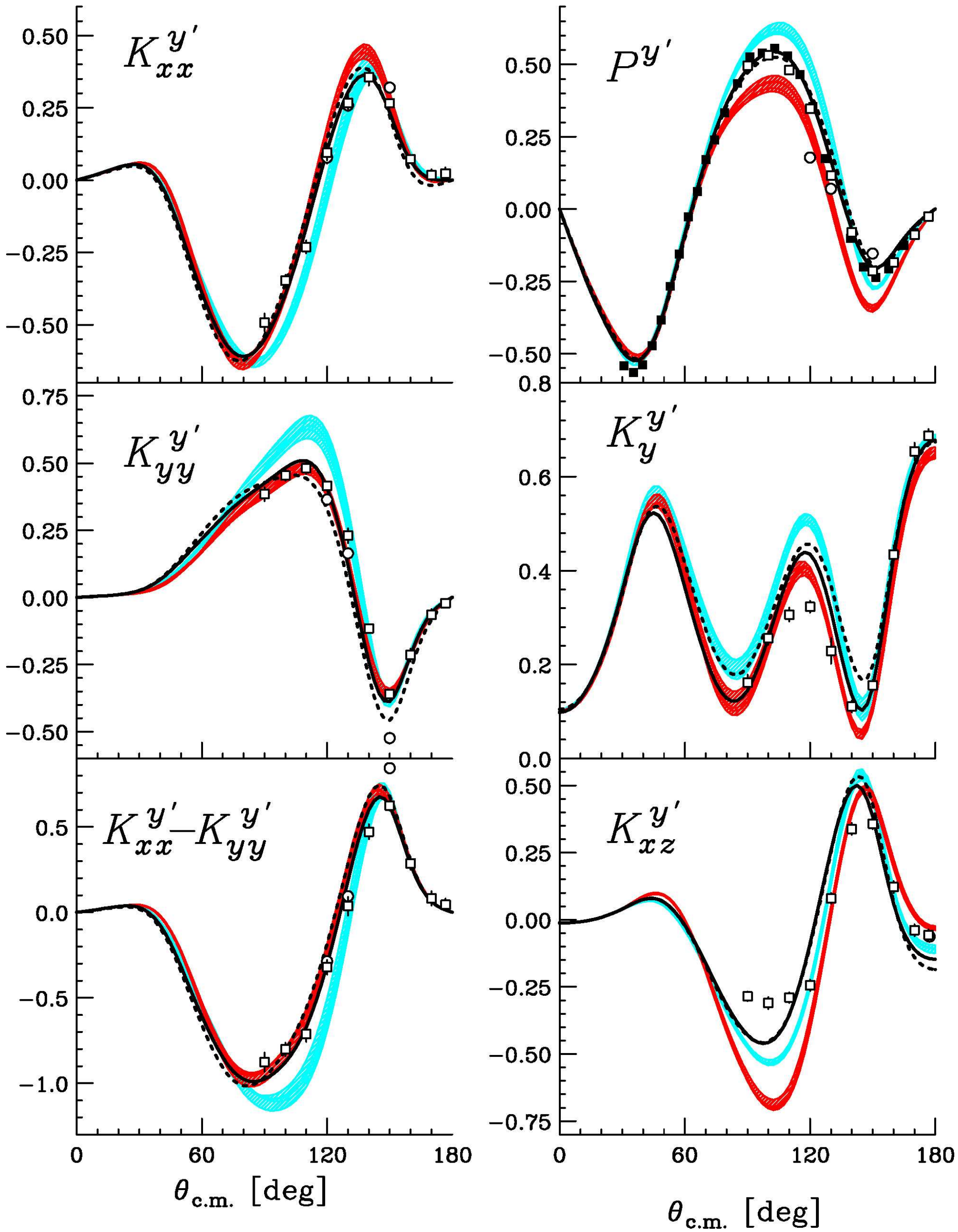
$\delta P^{y'}$	$\delta K_y^{y'}$	$\delta K_{yy}^{y'}$	$\delta K_{xx}^{y'}$	$\delta K_{xz}^{y'}$
0.01	0.02	0.02	0.03	0.02

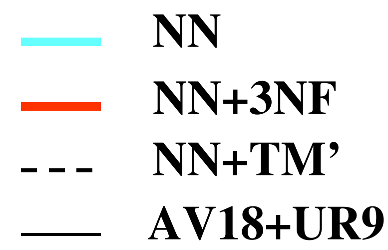
- **Systematic Uncertainty**

Effective Analyzing Power $A_y{}^C$	2%
Beam Polarization	2%
Bending Angle of the Spectrometer	1%
Total	3%

- $A_y{}^p$ (= $P_y{}'$) data provide almost the same results.





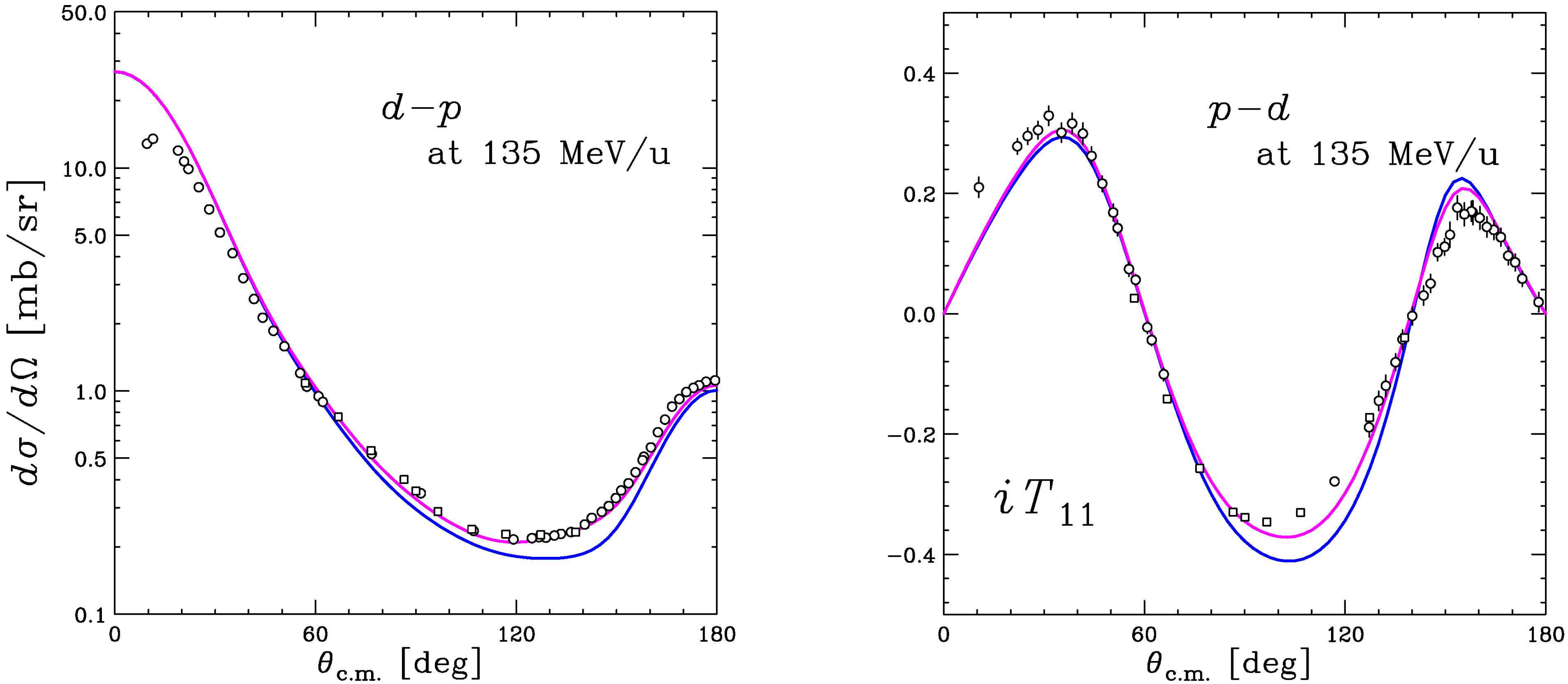


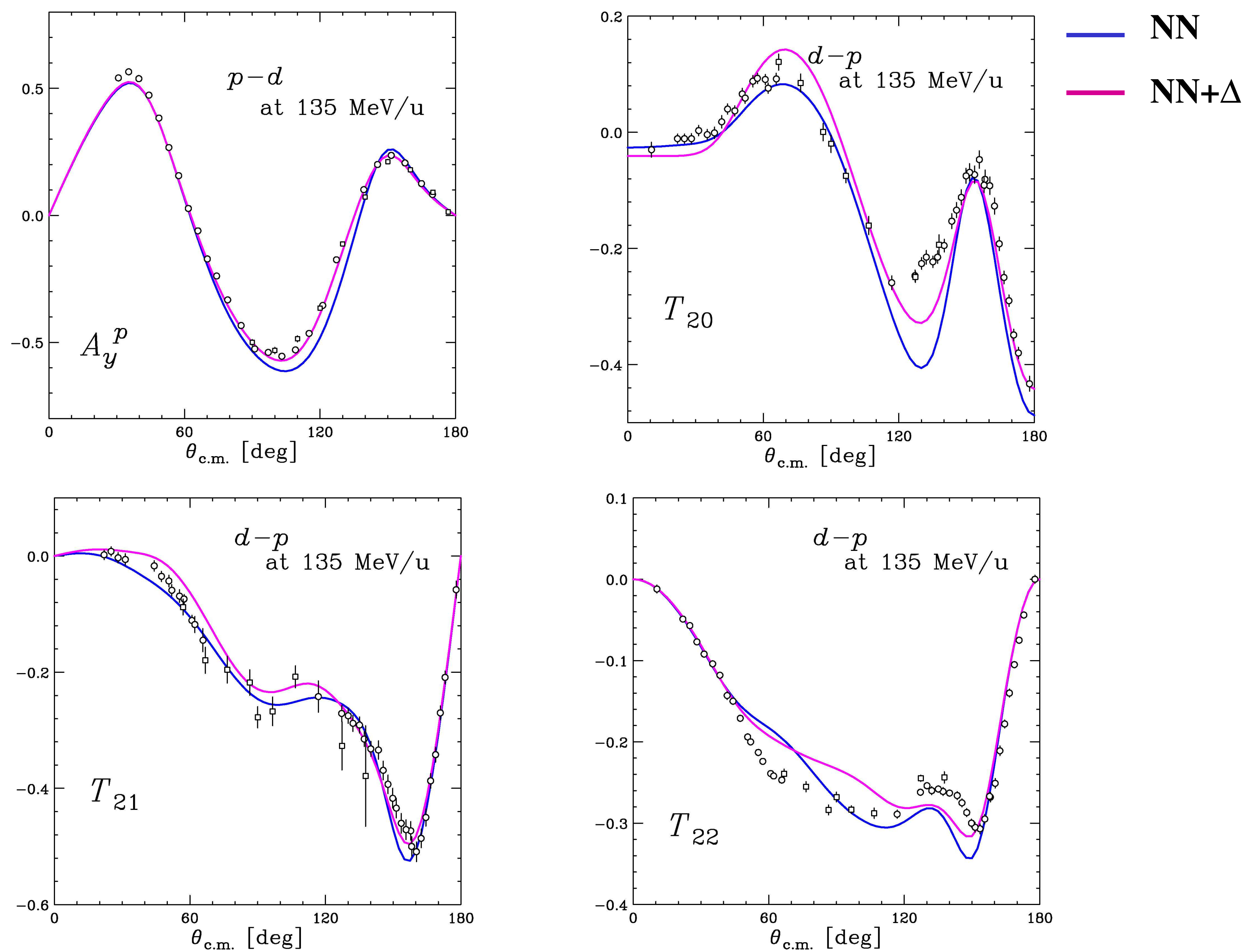
- **3NF is definitely needed.**
- **but $K_y^{y'}$ $K_{xz}^{y'}$?**

135 MeV/u

Hannover calc. NN

NN+Δ



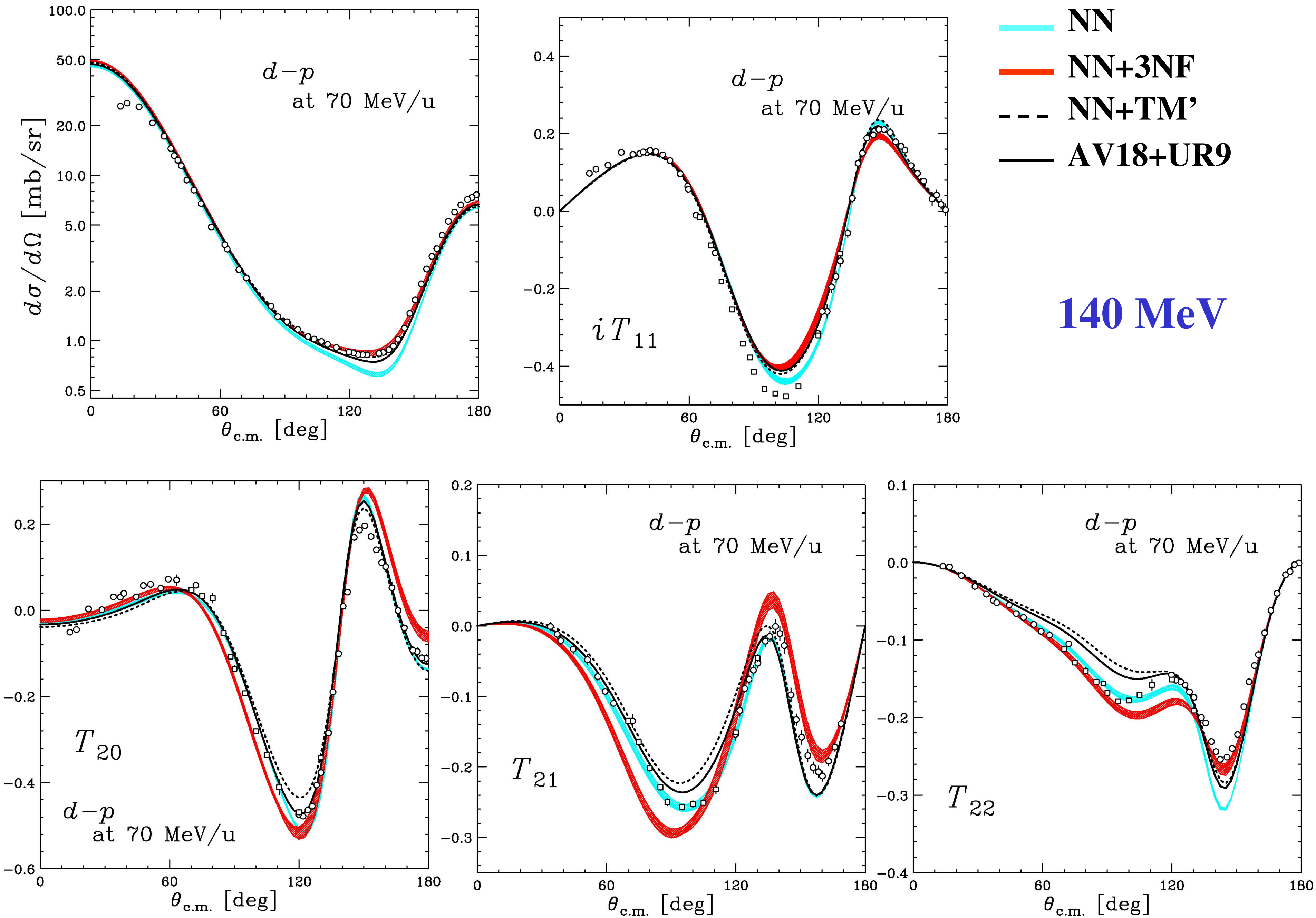


NN
NN+Δ
p−d
at 135 MeV/u
A_y^p
d−p
at 135 MeV/u
T_{20}
d−p
at 135 MeV/u
T_{21}
d−p
at 135 MeV/u
T_{22}
$\theta_{c.m.}$ [deg]

How they look like if the energy is halved ?

140 MeV(70 MeV/u) data

at RIKEN



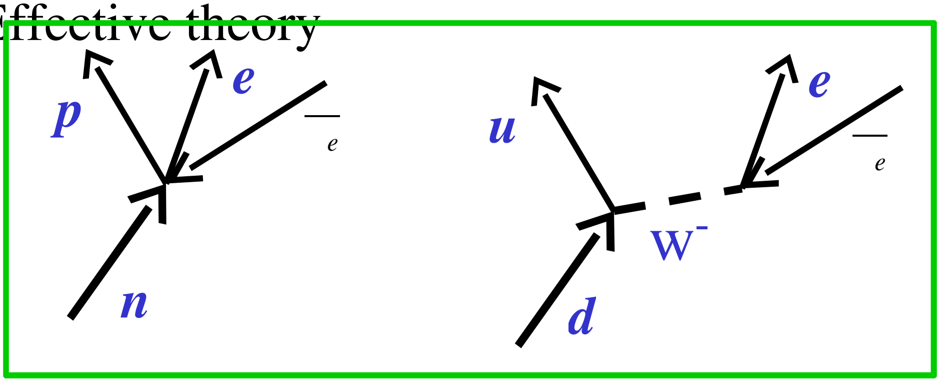
NN
NN+3NF
NN+TM'
AV18+UR9
140 MeV
$d\sigma/d\Omega$ [mb/sr]
$d-p$ at 70 MeV/u
iT_{11}
T_{20}
T_{21}
T_{22}
$\theta_{c.m.}$ [deg]

Chiral Effective Field Theory

- Relation with QCD

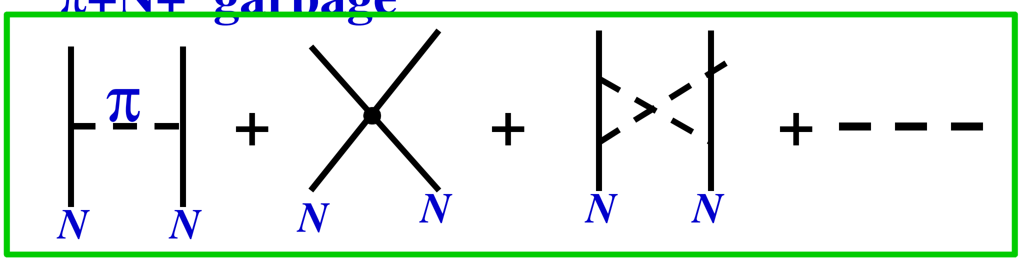
  Lagrangian L=. . . .
- Scale parameter Λ

  expand in power of Q/ Λ (Q=nucl. mom.)
- Chiral symmetry
- Effective theory



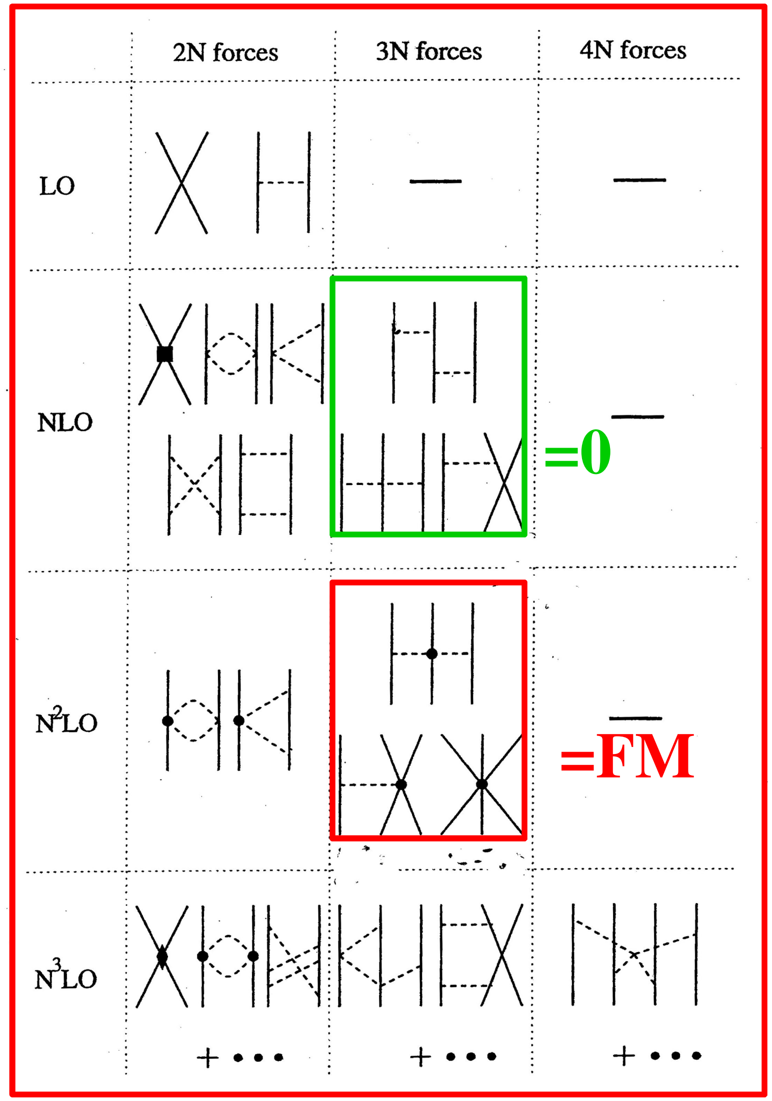
Chiral perturbation theory

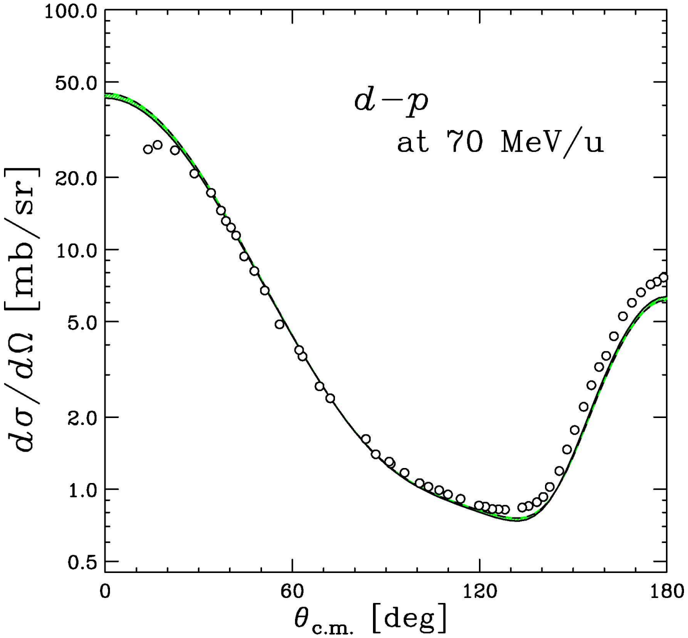
π+N+"garbage"

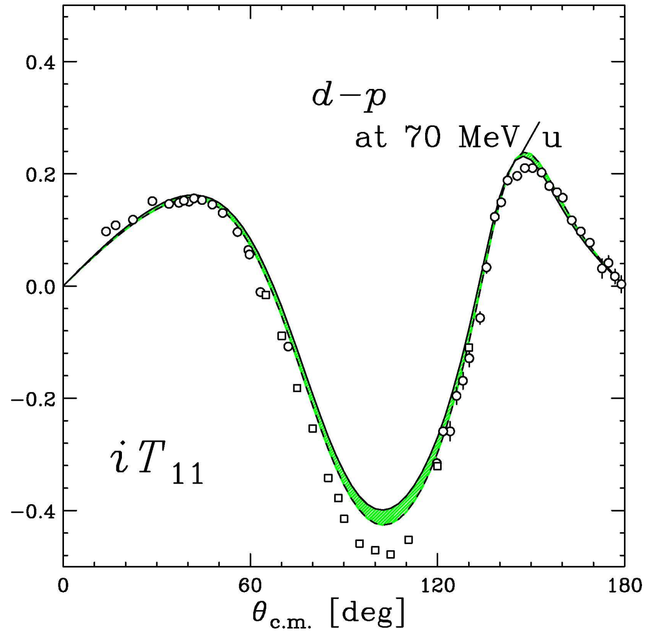


"garbage"=heavy meson, Δ

2N+3N on the same footing !





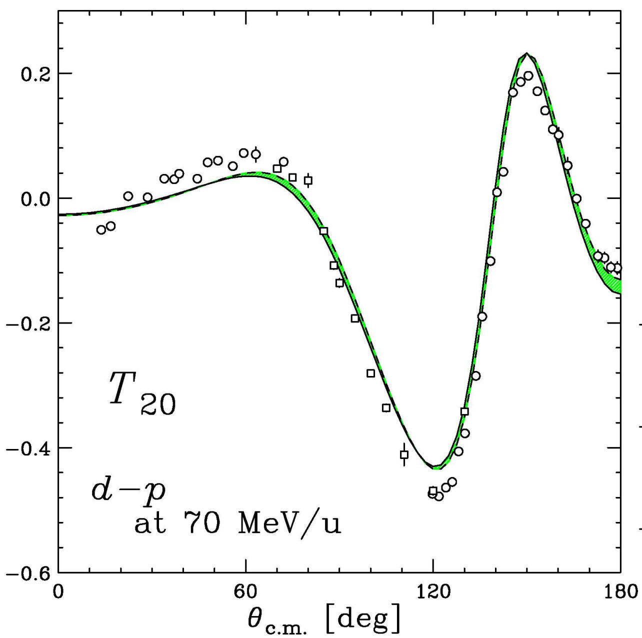


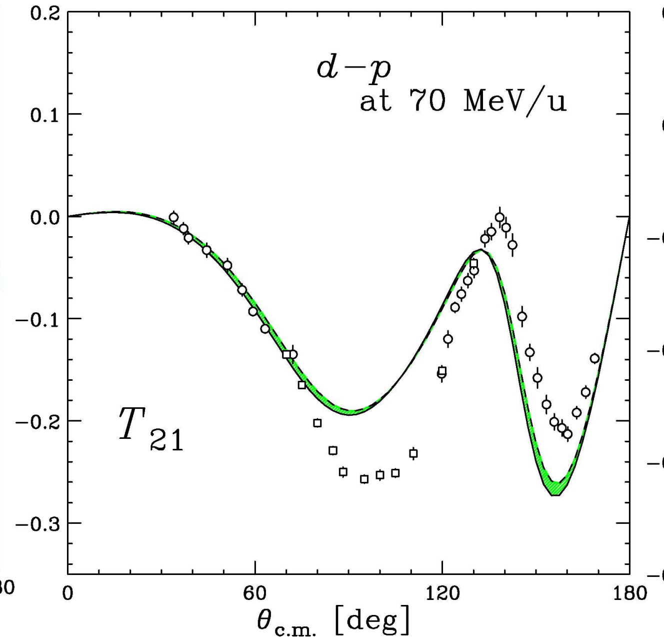
Chiral Eff. Field Theory Calc. NNLO

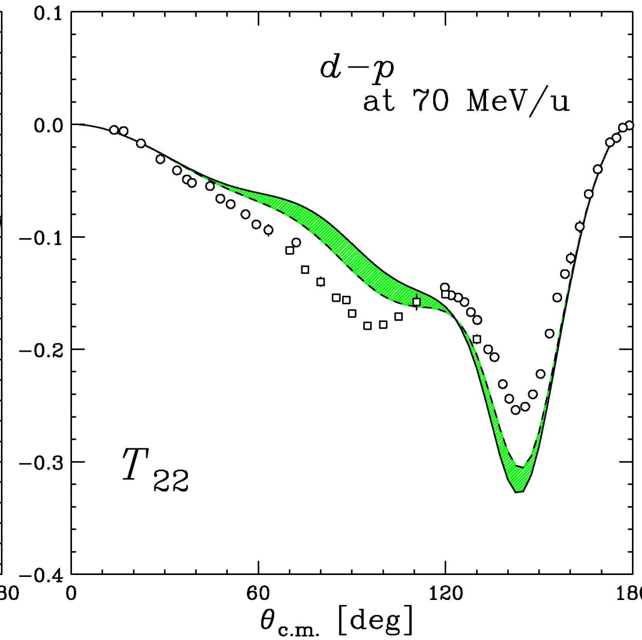
E. Epelbaum et al.

Phys. Rev. C66 (2002) 64001.

Λ = 500-600 MeV/c







Results of 270 and 140 MeV

$d\sigma/d\Omega$, iT_{11}: **Excellent fits!**

→ clear **3NF** effects in **N*d*** scatt.

→ magnitudes of 3NF seem to be O.K.

4. $A_y(= - p^{y'})$, T_{20}, T_{22}, T_{21}: Poor fits!

→ defects in spin dependent part of 3NF.

6. $K_{xx}^{y'}$, $K_{yy}^{y'}$: reasonable fits! $K_y^{y'}$, $K_{xz}^{y'}$: poor.

→ spin-spin interaction of 3NF is reasonable?

9. 3NF: TM'/ Urbana IX does better job.

→ chiral symmetry requires: The *c* term should be zero.

12. **Chiral Eff. Field Theory calc. does reasonable job for** $d\sigma/d\Omega$ but not much analyzing powers.

How they look like if the energy is doubled

from 135 MeV/u (E_d=270 MeV) ?

250 MeV/u data

at RCNP

$\vec{n}$ + d at 250 MeV (RCNP)

by Yukie Maeda

- Coulomb free
- direct comparison is possible:

  between ***nd*** data vs. Faddeev calc.

$\vec{n}$: secondary beam exp. → very difficult.

^{7}Li(p,n)^{7}Be reaction

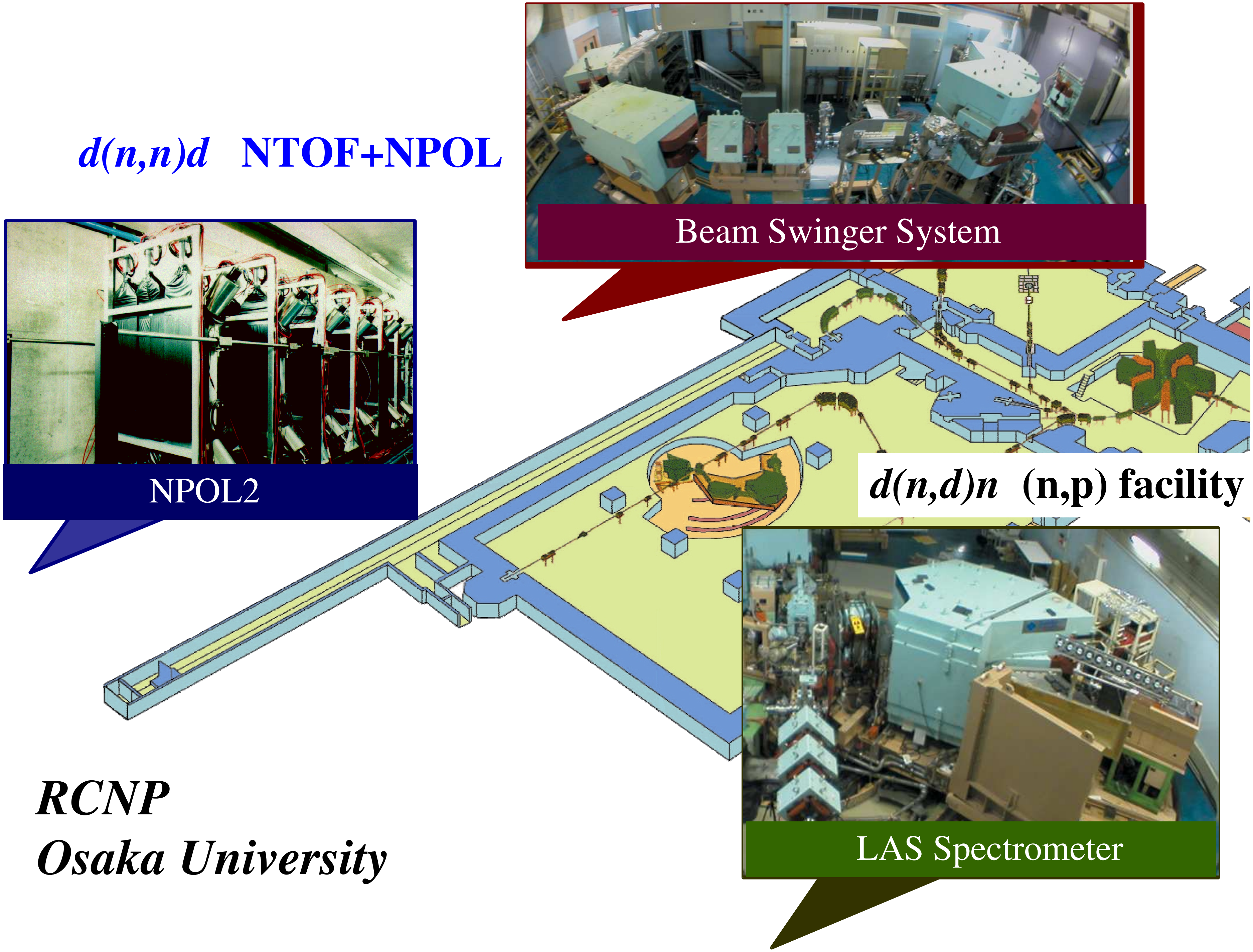
Forward angle : *d(n,n)d* NTOF+NPOL

D liq. Scintillator(active target)

Backward angle : *d(n,d)n* (n,p) facility

recoiled *d* dectected

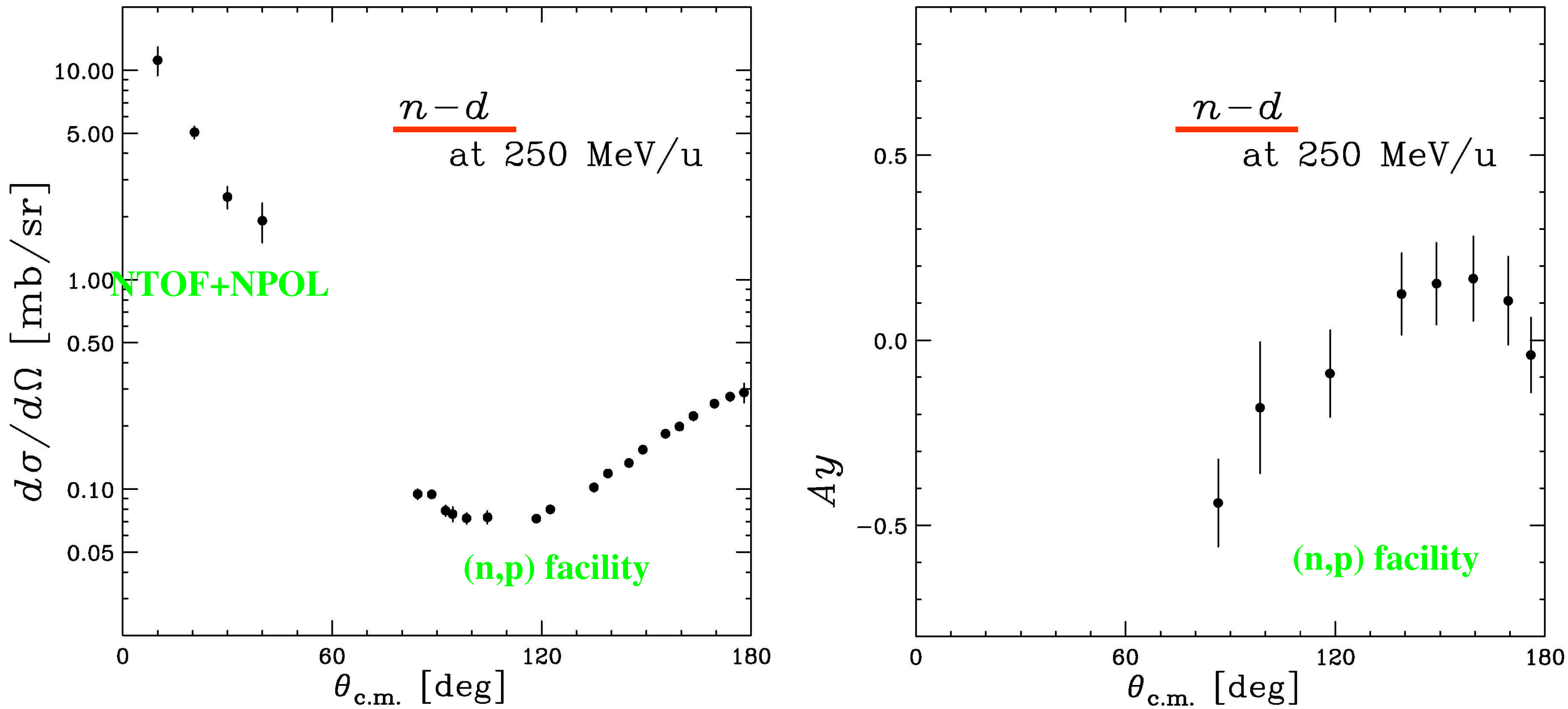
All data points are normalized by np scatt.



RCNP
Osaka University

$\vec{n}$ + d at 250 MeV

by Yukie Maeda



$\vec{p}$ + d at 250 MeV (RCNP)

by K. Hatanaka

- $d\sigma/d\Omega$, A_y
- complete pol. transfer meas.: $K_x^{x'}$, $K_y^{y'}$, $K_z^{z'}$, $K_z^{x'}$, $K_x^{z'}$

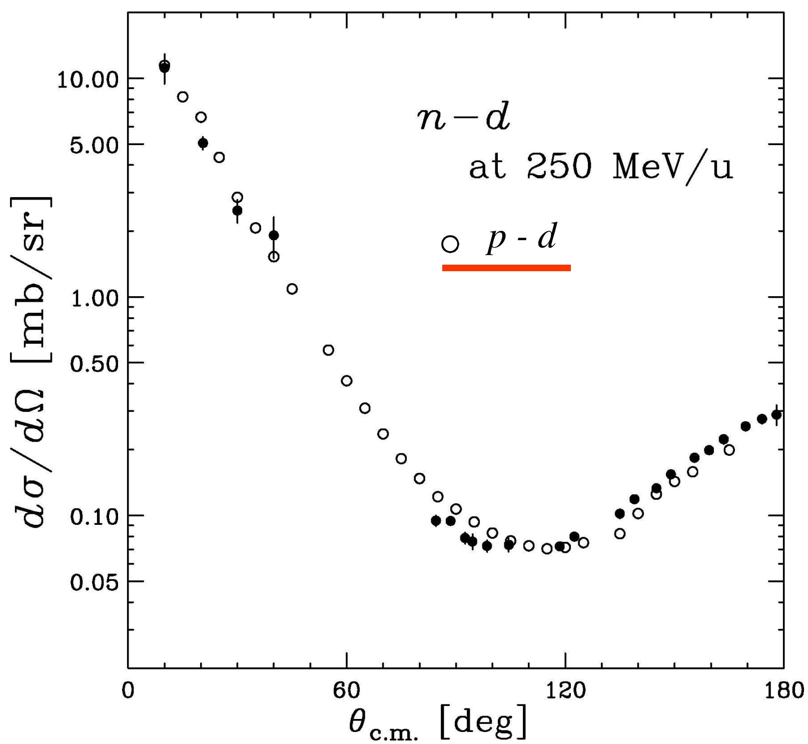
  proton to proton

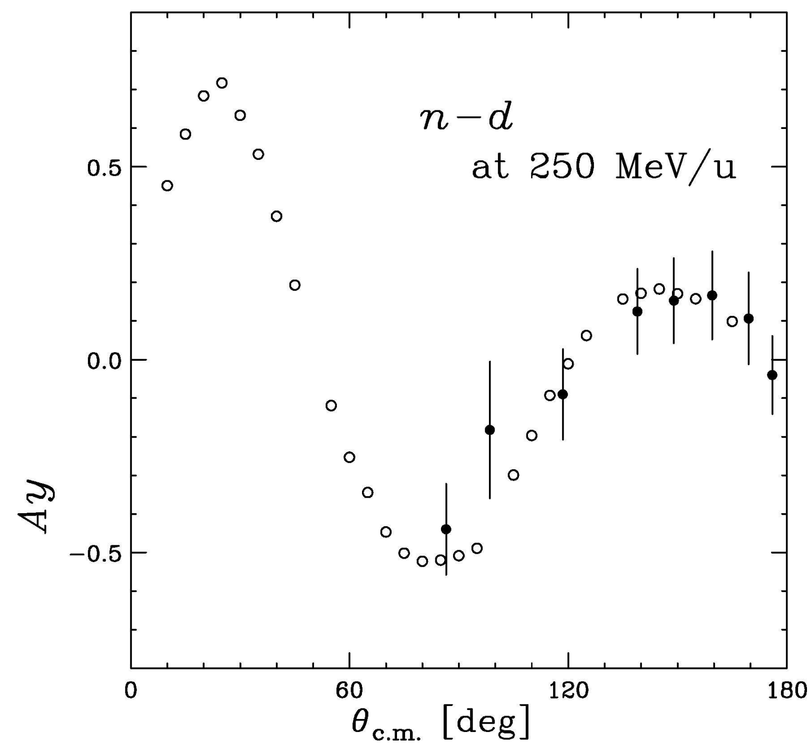
3. direct comparison possible: between ***nd*** *vs.* ***pd***

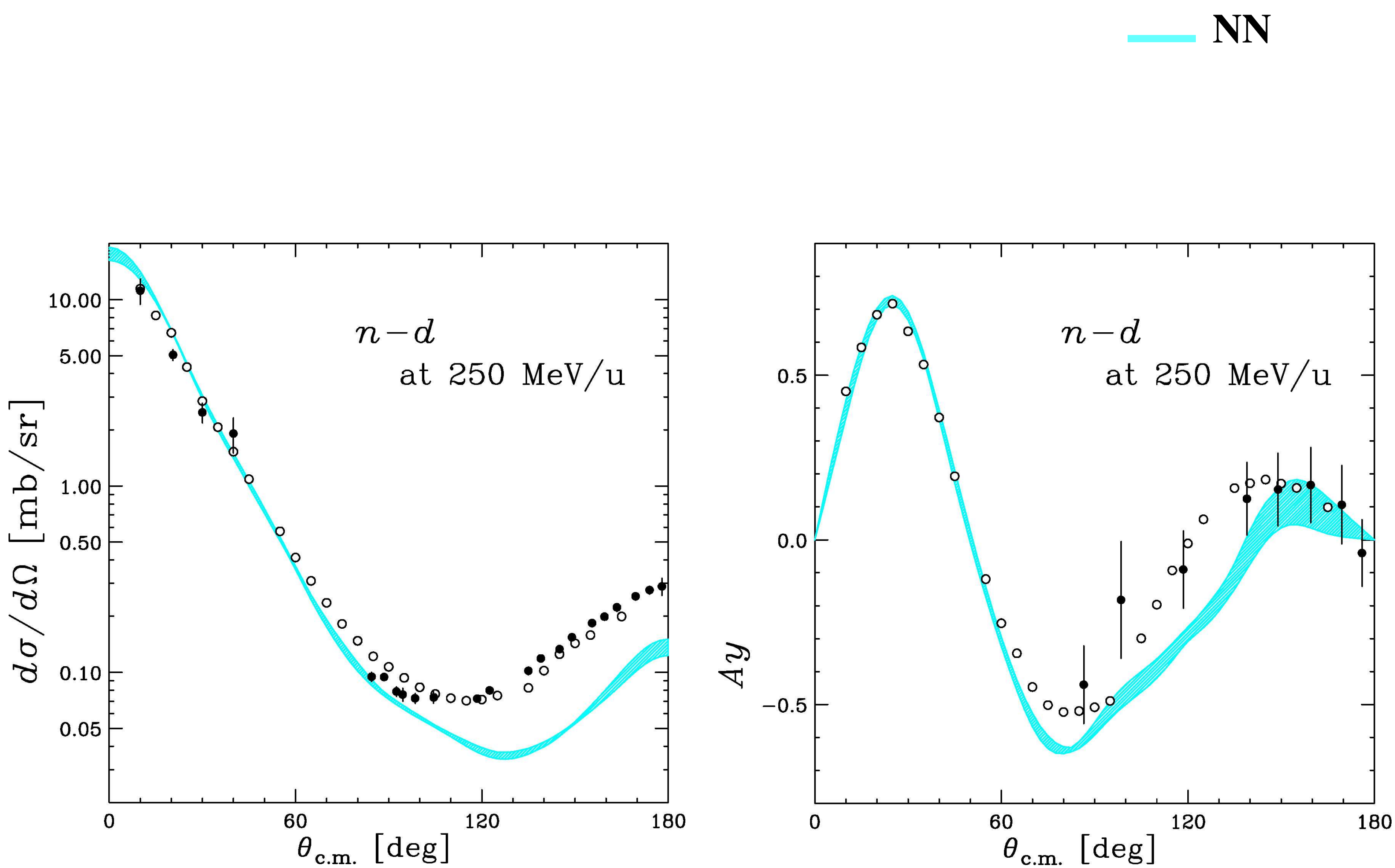
$\vec{p} + d \longrightarrow \vec{p} + d$ **at 250 MeV**

K. Hatanaka *et al*., Phys. Rev. C66 (2002) 044002.

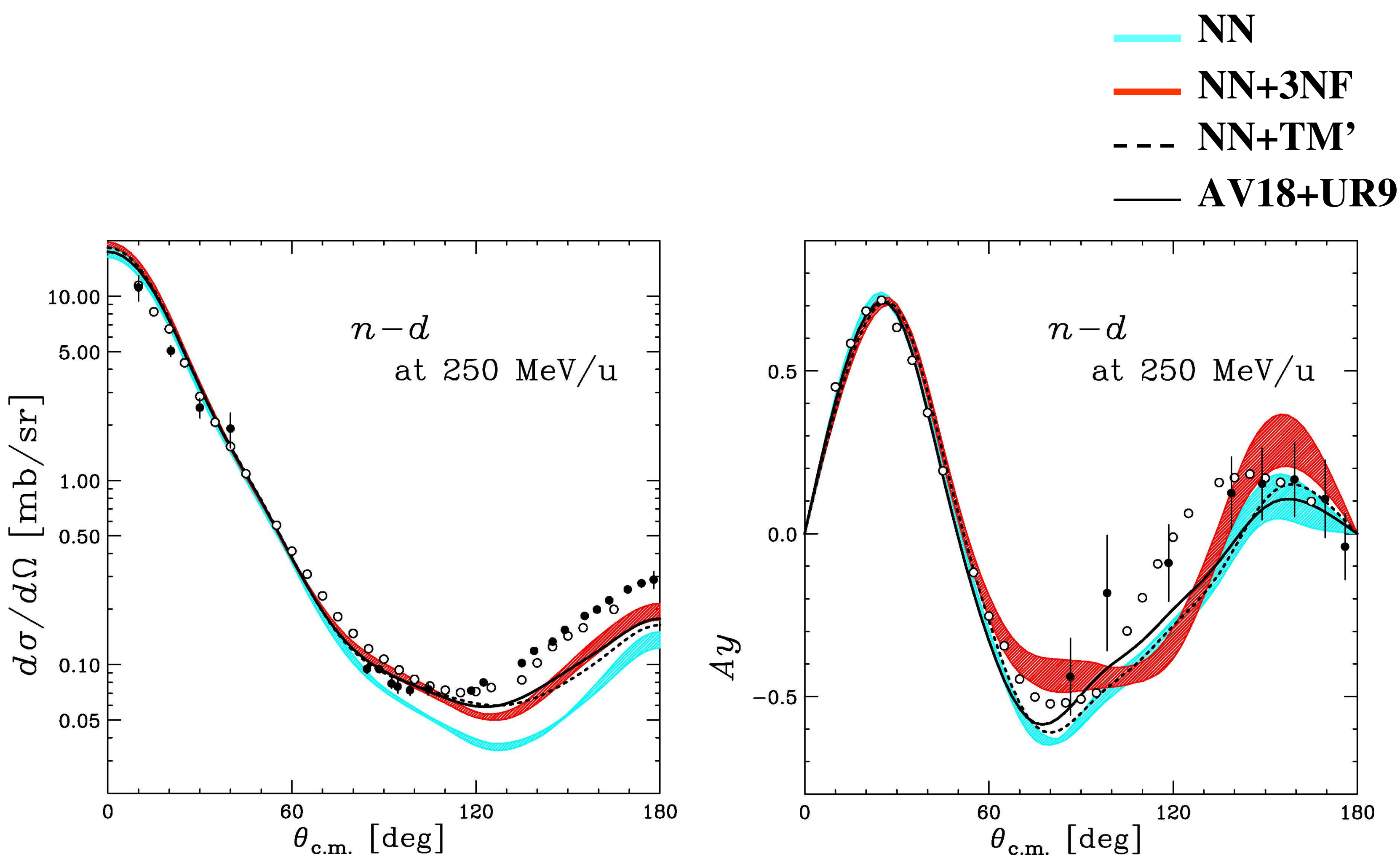
$\vec{n}$ + d and $\vec{p}$ + d at 250 MeV



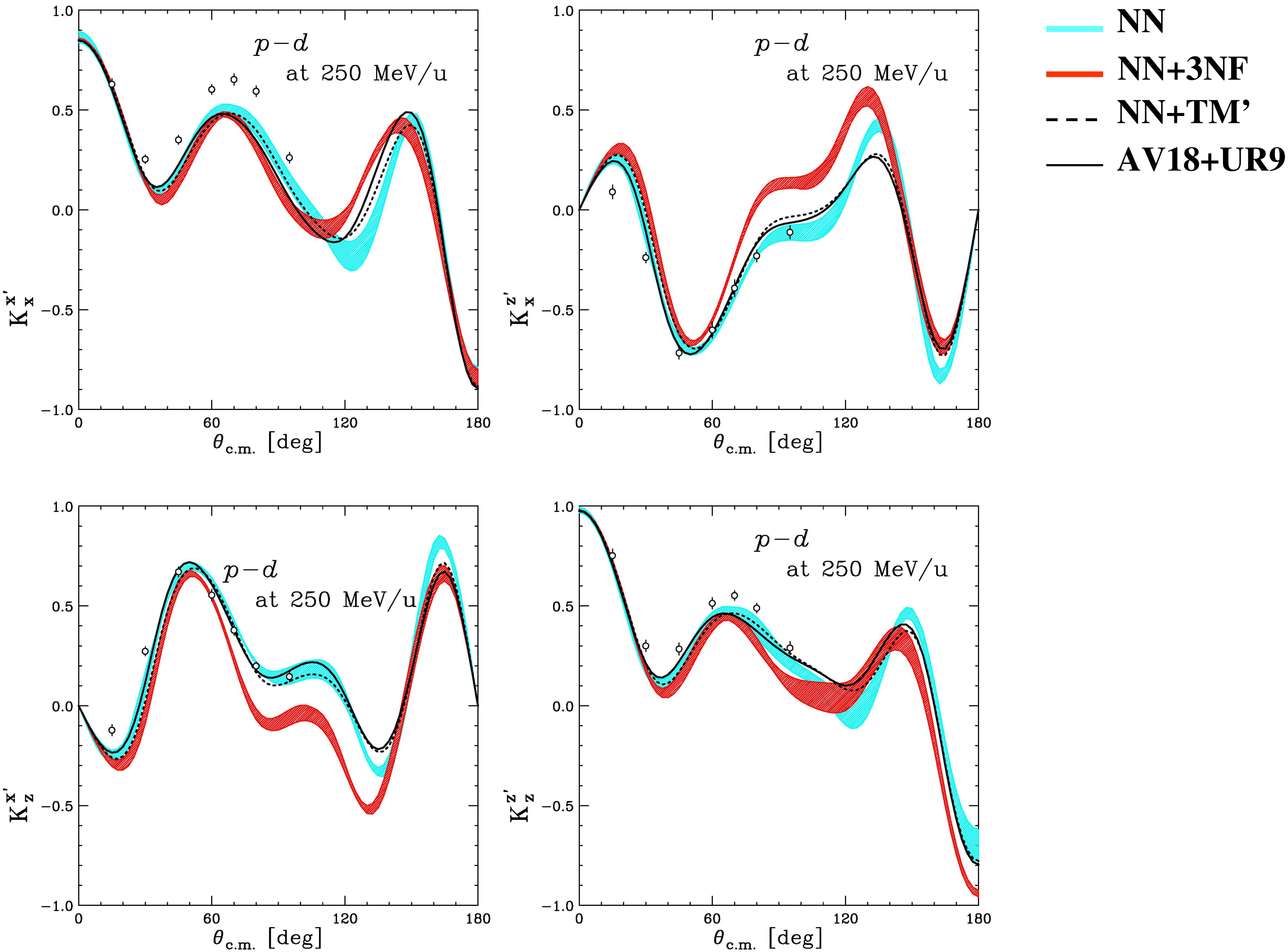




NN
n − d
at 250 MeV/u
dσ/dΩ [mb/sr]
θc.m. [deg]
Ay



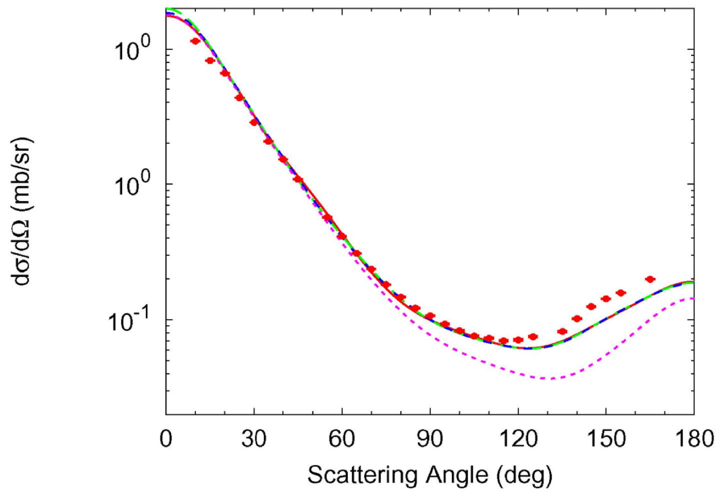
NN
NN+3NF
NN+TM'
AV18+UR9
$d\sigma/d\Omega$ [mb/sr]
$n-d$
at 250 MeV/u
10.00
5.00
1.00
0.50
0.10
0.05
0
60
120
180
$\theta_{\text{c.m.}}$ [deg]
Ay
0.5
0.0
−0.5

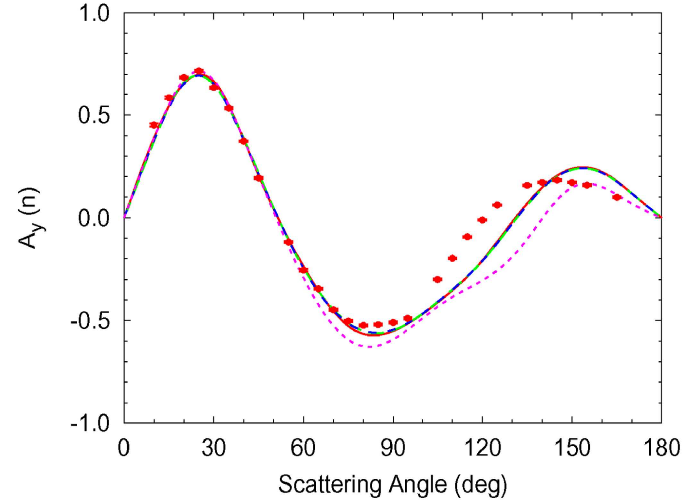


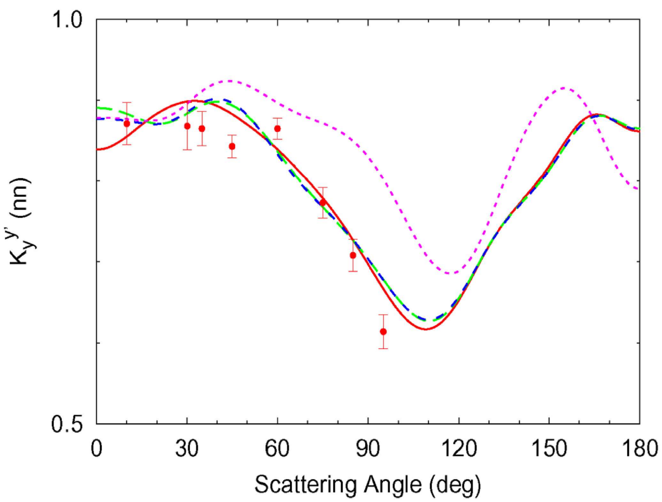
NN
NN+3NF
NN+TM'
AV18+UR9
p−d
at 250 MeV/u
$K_x^{x'}$
$K_x^{z'}$
$K_z^{x'}$
$K_z^{z'}$
$\theta_{c.m.}$ [deg]

pd elastic scattering at 250 MeV

Hannover calc.
by Arnas Deltuva







3 baryon total J = 35/2

CD Bonn (I=7)

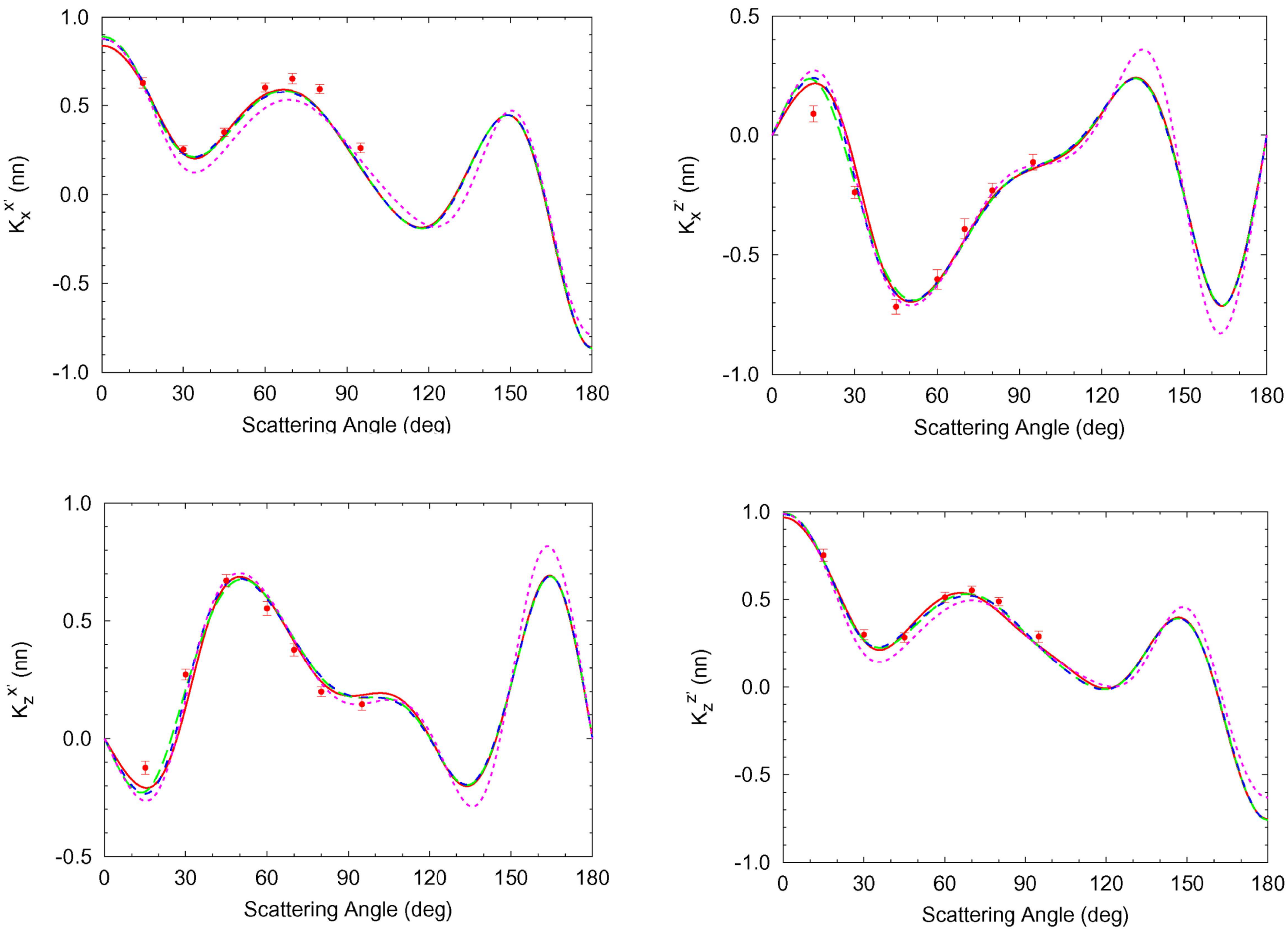
CDB + (I=5)

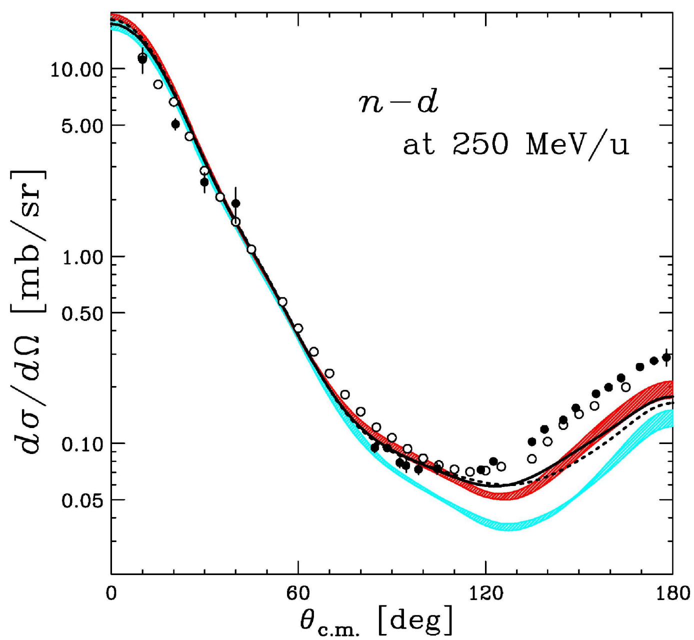
CDB + (I=6)

CDB + (I=7)

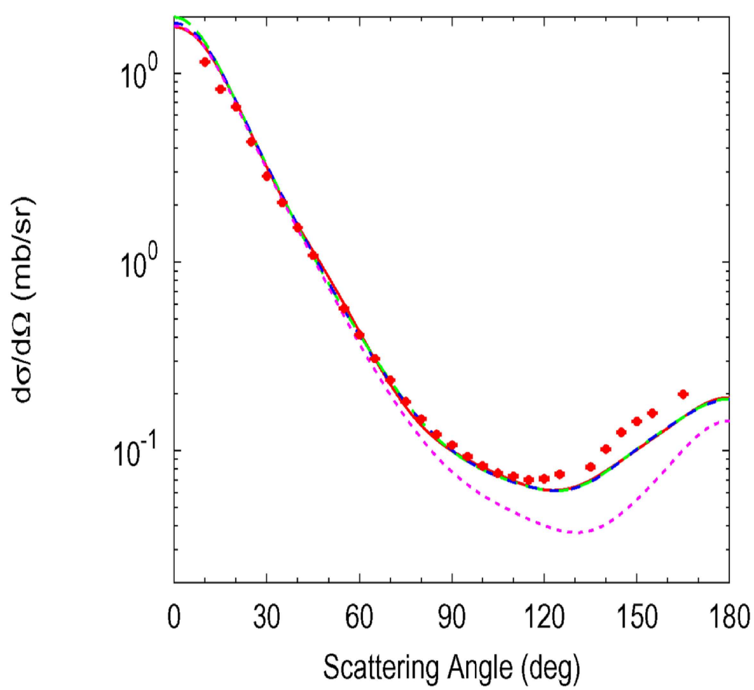
pd elastic scattering at 250 MeV

Hannover calc.
by Arnas Deltuva





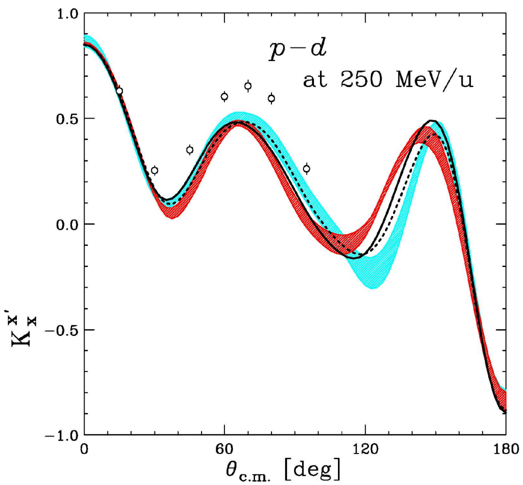
$n-d$
at 250 MeV/u
$d\sigma/d\Omega$ [mb/sr]
$\theta_{\text{c.m.}}$ [deg]

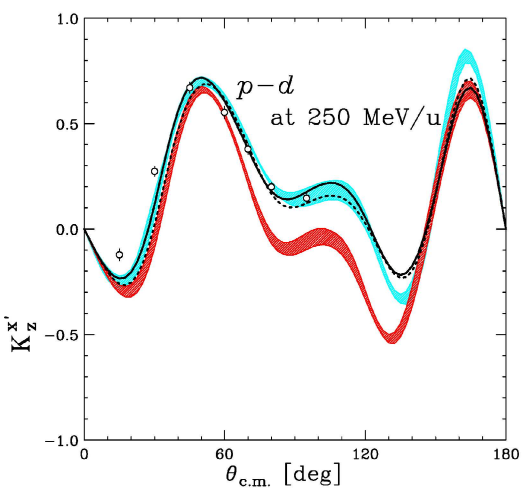


dσ/dΩ (mb/sr)
Scattering Angle (deg)

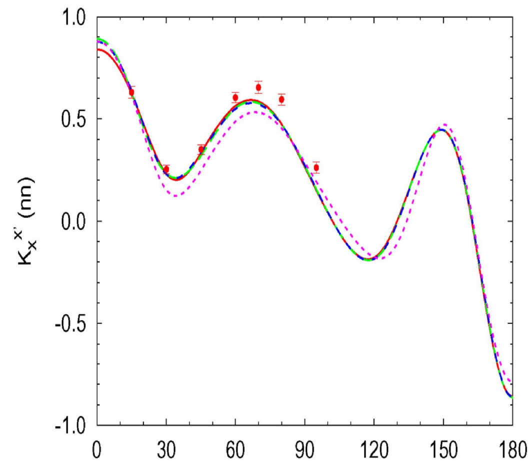
PT for *pd* elastic scattering at 250 MeV

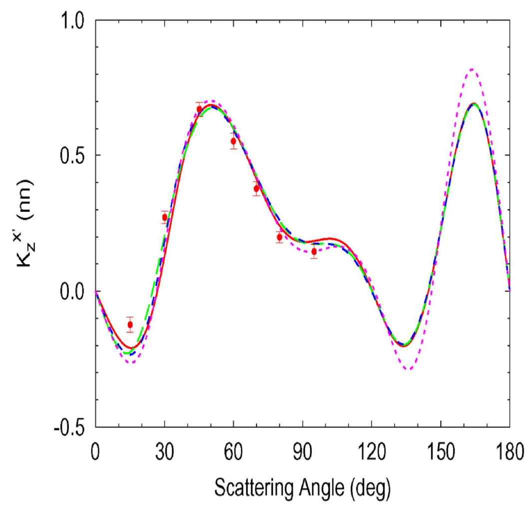
Bochum-Cracow-KIT calc.





Hannover calc.





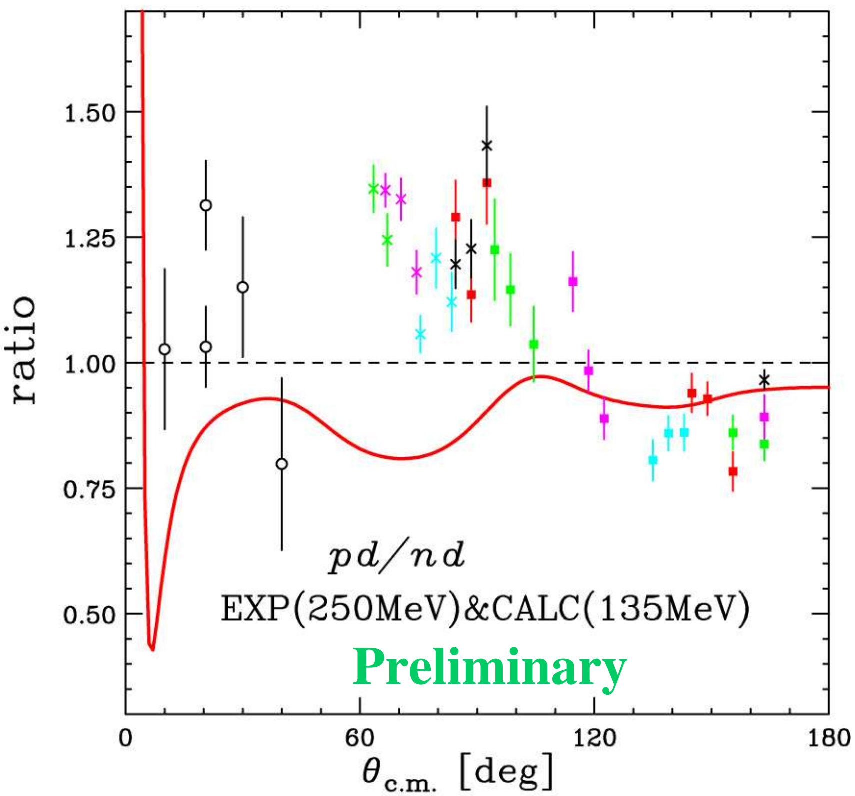
FM type(Δ) 3NF does not play a role in these spin obs.

Mostly due to c-term effects

Let's look at

- **Coulomb effects.**

Data-to-data comparison between *nd vs. pd*



$$\frac{\left(\frac{d}{d\ \Omega}\right)_{pd}}{\left(\frac{d}{d\ \Omega}\right)_{nd}}$$

Coulomb effect ! ?

Calculation by Y. Koike.

***Nd* at 135/u MeV**

Coulomb force is approx. included.

Results at 250 MeV

First $\vec{n}d$ and $\vec{p}d$ measurements at 250 MeV.

Data-to-data comparison was made: $\vec{n}d$ *vs*. $\vec{p}d$

→ **10-20 % variation in $d\sigma/d\Omega$**

→ **Coulomb effect ! ?**

direct comparison was made: ***nd***. data ***vs***. calc.

$d\sigma/d\Omega$: 50% disagreement in backward.

→ **irrespective of 3NF**

3. A_y **: large deviation in backward.**

→ **irrespective of 3NF**

5. $K_x^{x'}$, $K_y^{y'}$, $K_z^{z'}$, $K_z^{x'}$, $K_x^{z'}$ **(pd *vs*. calc.)**

→ **TM 3NF does poor job.**

→ **almost no FM 3NF(Δ) effects!**

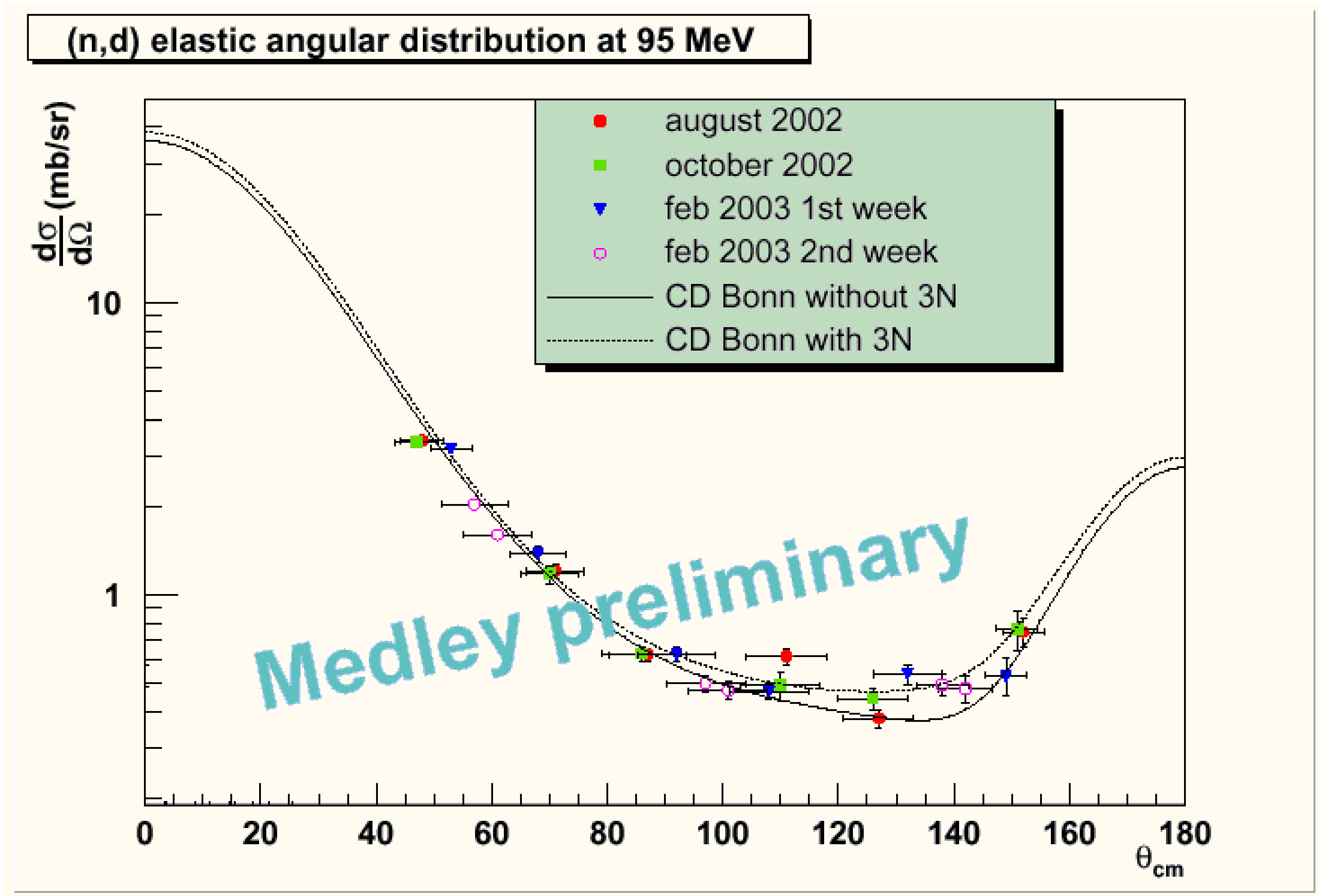
These results indicate :

→ **defects of 3NF or relativistic effects or both?**
OR

→ **defects of nucleon exchange process? OR**

defects of NN interactions?

Results from TSL



How they look like if the energy is doubled ?

400 MeV/u data

at RCNP

$\vec{p}$ + d at 400 MeV (RCNP)

by Tamii

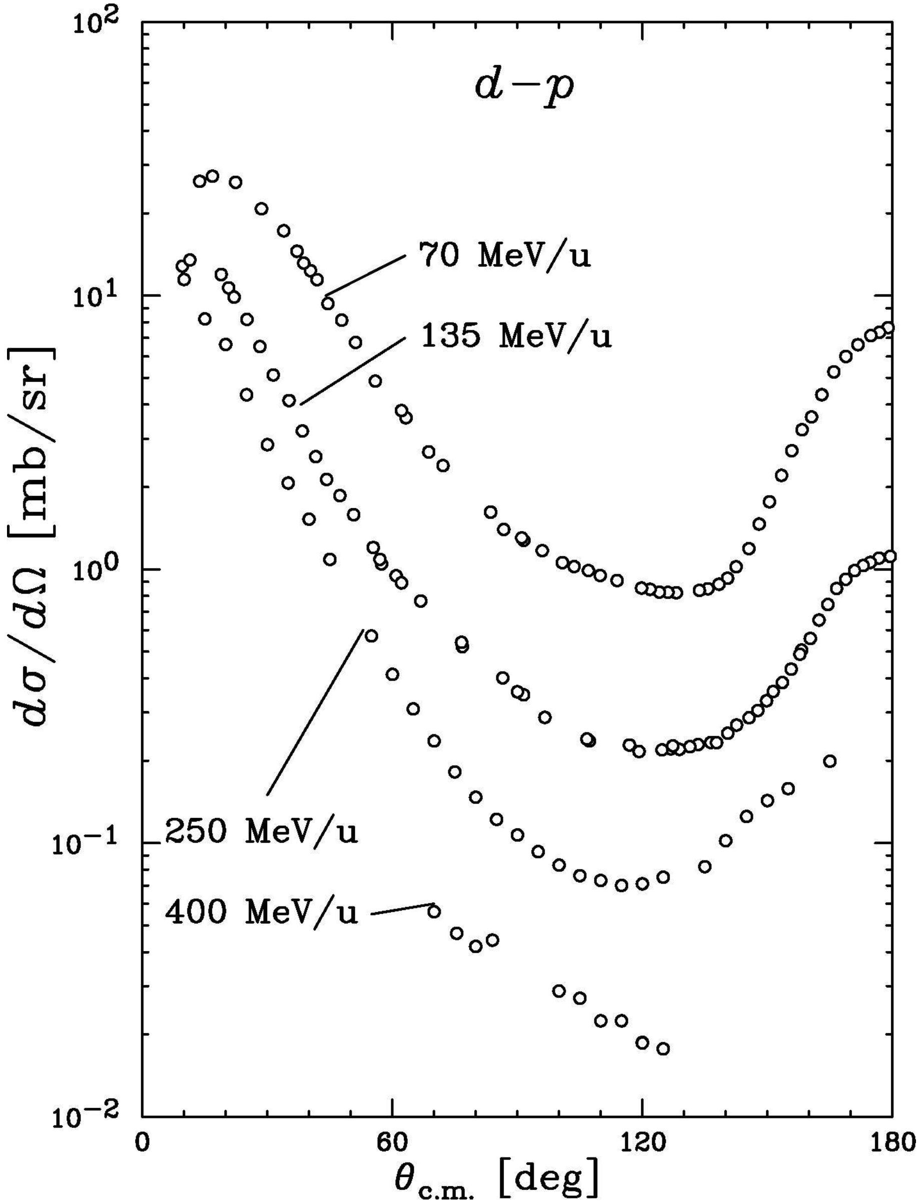
A.Tamii: $\vec{p} + d \rightarrow \vec{d} + p$ at 400 MeV

$d\sigma/d\Omega$, A_y^p, A_y^d $(= -P^{y'})$, $K_y^{y'}$

Limited angular range

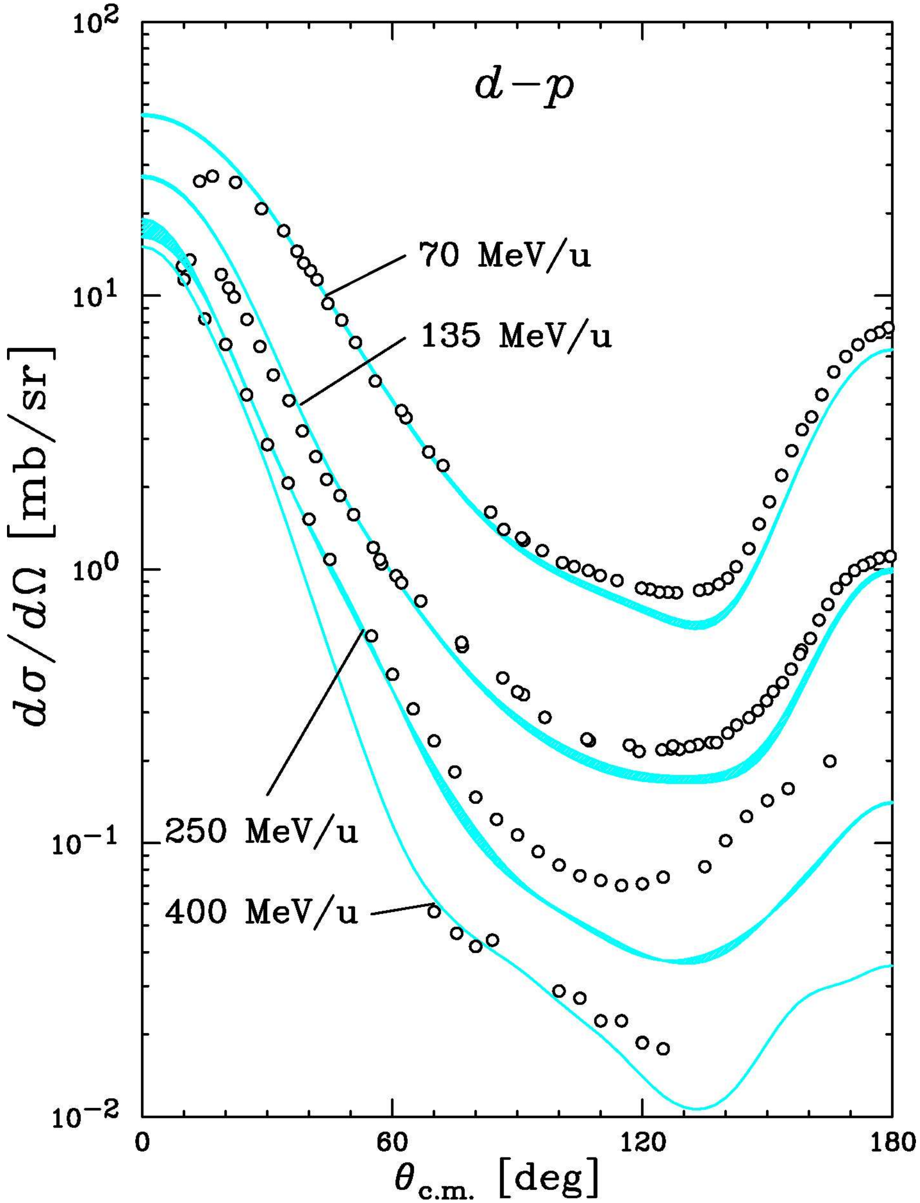
Very preliminary calc. by Kamada

- **2NF : CD Bonn**
- **3NF : TM**

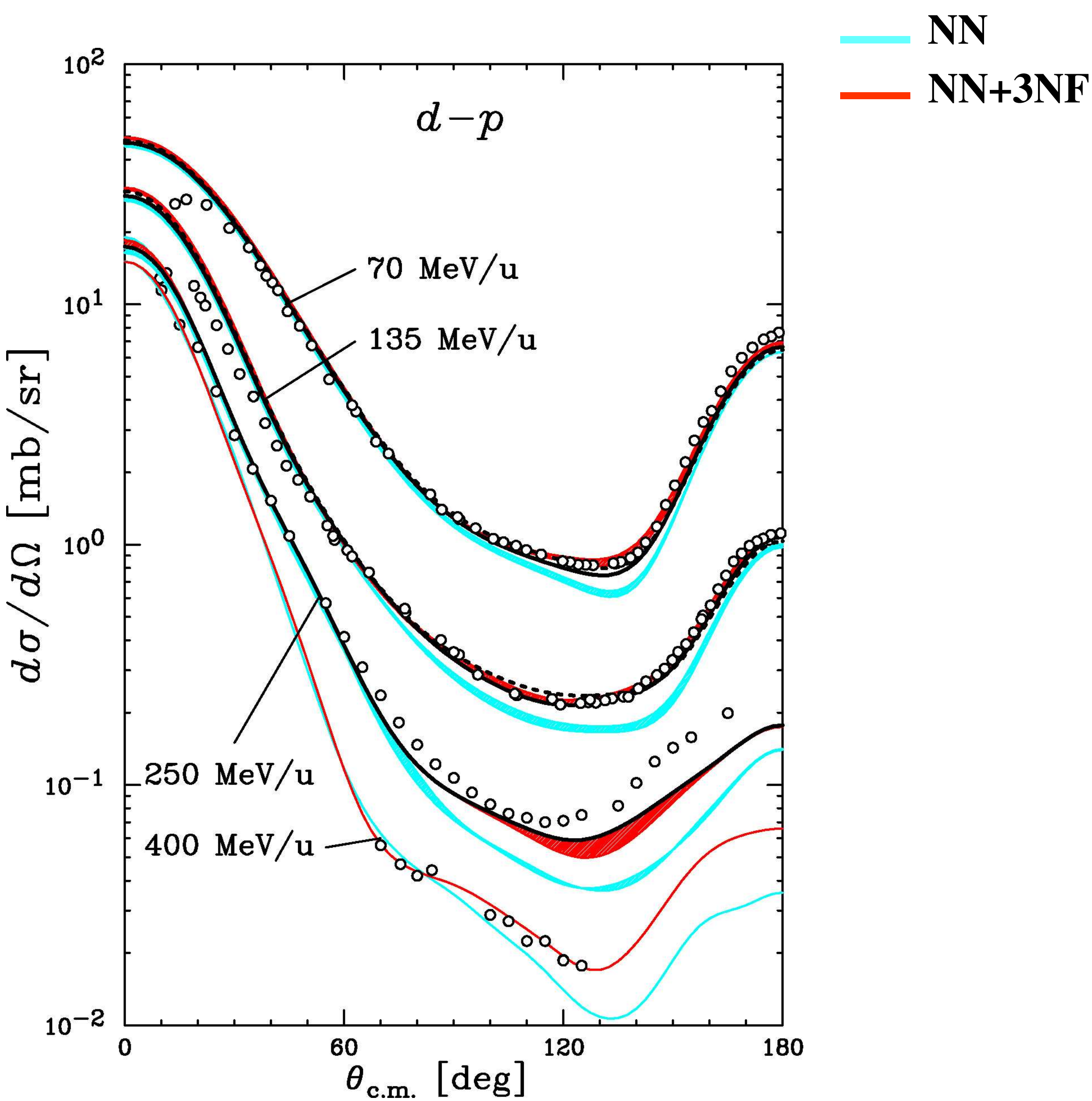


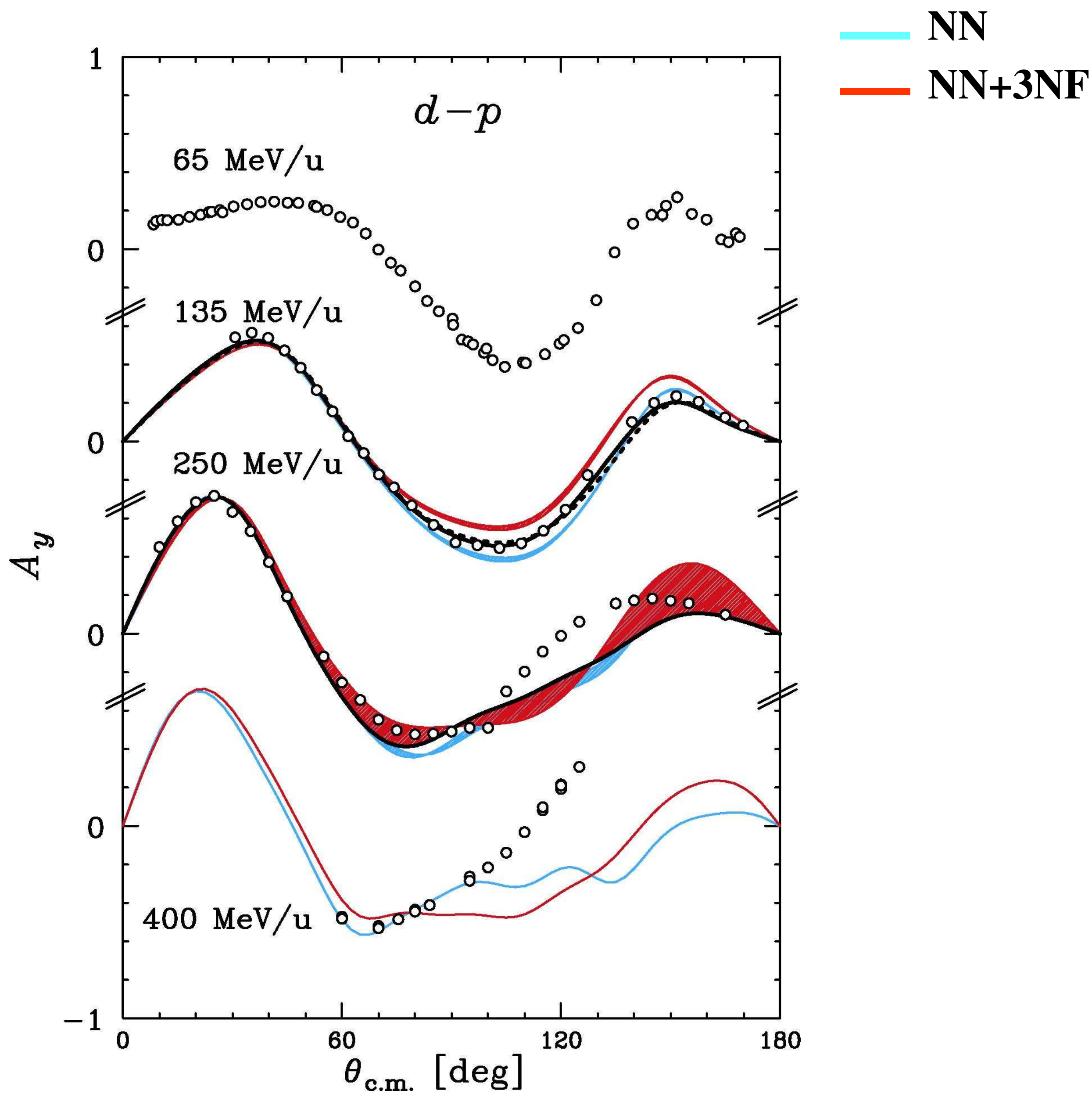
d−p
70 MeV/u
135 MeV/u
250 MeV/u
400 MeV/u
dσ/dΩ [mb/sr]
θc.m. [deg]

NN



d−p
70 MeV/u
135 MeV/u
250 MeV/u
400 MeV/u
$d\sigma/d\Omega$ [mb/sr]
$\theta_{c.m.}$ [deg]
10^2
10^1
10^0
10^{-1}
10^{-2}
0
60
120
180


NN
NN+3NF
d−p
70 MeV/u
135 MeV/u
250 MeV/u
400 MeV/u
dσ/dΩ [mb/sr]
θc.m. [deg]
10^2
10^1
10^0
10^−1
10^−2
0
60
120
180



NN
NN+3NF
d−p
65 MeV/u
135 MeV/u
250 MeV/u
400 MeV/u
1
0
0
0
0
−1
A_y
0
60
120
180
$\theta_{c.m.}$ [deg]

Results at 400 MeV

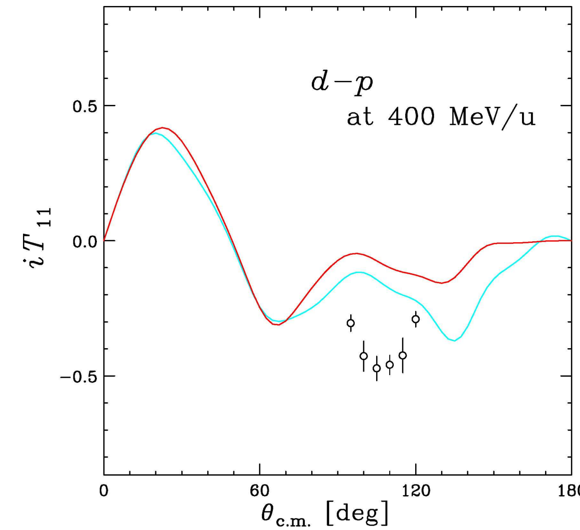
Calc. by H. Kamada are very preliminary!

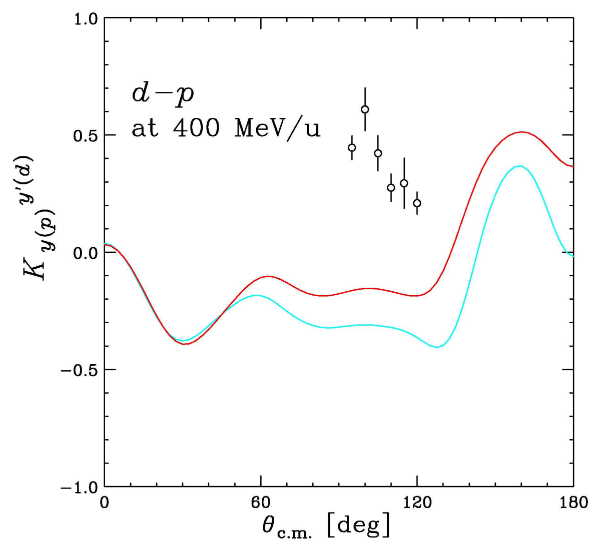
- $d\sigma/d\Omega$: agreement?

- $A_y^{\,p}$, $(= - P^{\,y'})$, iT_{11} : large deviation.

- $K_y^{\,y'}$: large disagreement(opposite sign!)

$$\vec{p} + d \to \vec{d} + p$$





Experimental Summary

- Precise data on $\boldsymbol{p + d}$ elastic scattering at $\mathbf{E_p = 70 - 400}$ **MeV** become available now, not only $d\sigma/d\Omega$, A_y^p, $(= - P^{y'})$, iT_{11}, T_{20}, T_{22}, T_{21} but also various **P**olarization **T**ransfer **O**bservables.

- **A lot of data expected at 135 MeV/u.**
  - *** Spin-correl. data from IUCF.**
  - *** Breakup data from KVI and may be from RIKEN**

→ 135 MeV/u will be the most extensive data set.

Present status of 3NF study

3NF established firmly ?

→Yes and No.

→Magnitudes seem to be O.K.

Spin dependence? Chaotic.

6. Defects of 3NF ?

→Yes, definitely in TM.

The *c* term violates chiral symmetry.

→Need to include, πρ and ρρ exch. 3NF and more.

11. New development of Chiral Eff. Field Theory calc. is extremely interesting.

13. Relativistic effects must be studied.

Are 2NFs reliable?

→Questionable in terms of off-shell properties.

No need of 3NF in BE(^{3}H) by Y. Fujiwara!

PHYSICAL REVIEW C **66**, 021001(R) (2002)

Triton binding energy calculated from the SU_6 quark-model nucleon-nucleon interaction

Y. Fujiwara,[1] K. Miyagawa,[2] M. Kohno,[3] Y. Suzuki,[4] and H. Nemura[5]
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[2]*Department of Applied Physics, Okayama Science University, Okayama 700-0005, Japan*
[3]*Physics Division, Kyushu Dental College, Kitakyushu 803-8580, Japan*
[4]*Department of Physics, Niigata University, Niigata 950-2181, Japan*
[5]*Institute of Particle and Nuclear Physics, KEK, Tsukuba 305-0801, Japan*

(Received 23 May 2002; published 2 August 2002)

Properties of the three-nucleon bound state are examined in the Faddeev formalism, in which the quark-model nucleon-nucleon interaction is explicitly incorporated to calculate the off-shell T matrix. The most recent version, fss2, of the Kyoto-Niigata quark-model potential yields the ground-state energy $E(^3\mathrm{H}) = -8.514$ MeV in the 34 channel calculation, when the np interaction is used for the nucleon-nucleon interaction. The charge root mean square radii of the ^{3}H and ^{3}He are 1.72 fm and 1.90 fm, respectively, including the finite size correction of the nucleons. These values are the closest to the experiments among many results obtained by detailed Faddeev calculations employing modern realistic nucleon-nucleon interaction models.

Are 2NFs reliable?

→Questionable in terms of off-shell properties.

No need of 3NF in BE(^{3}H) by Y. Fujiwara!

→ Should be tested by scatt. data.

→Exchange term might be problematic.

Finnaly,

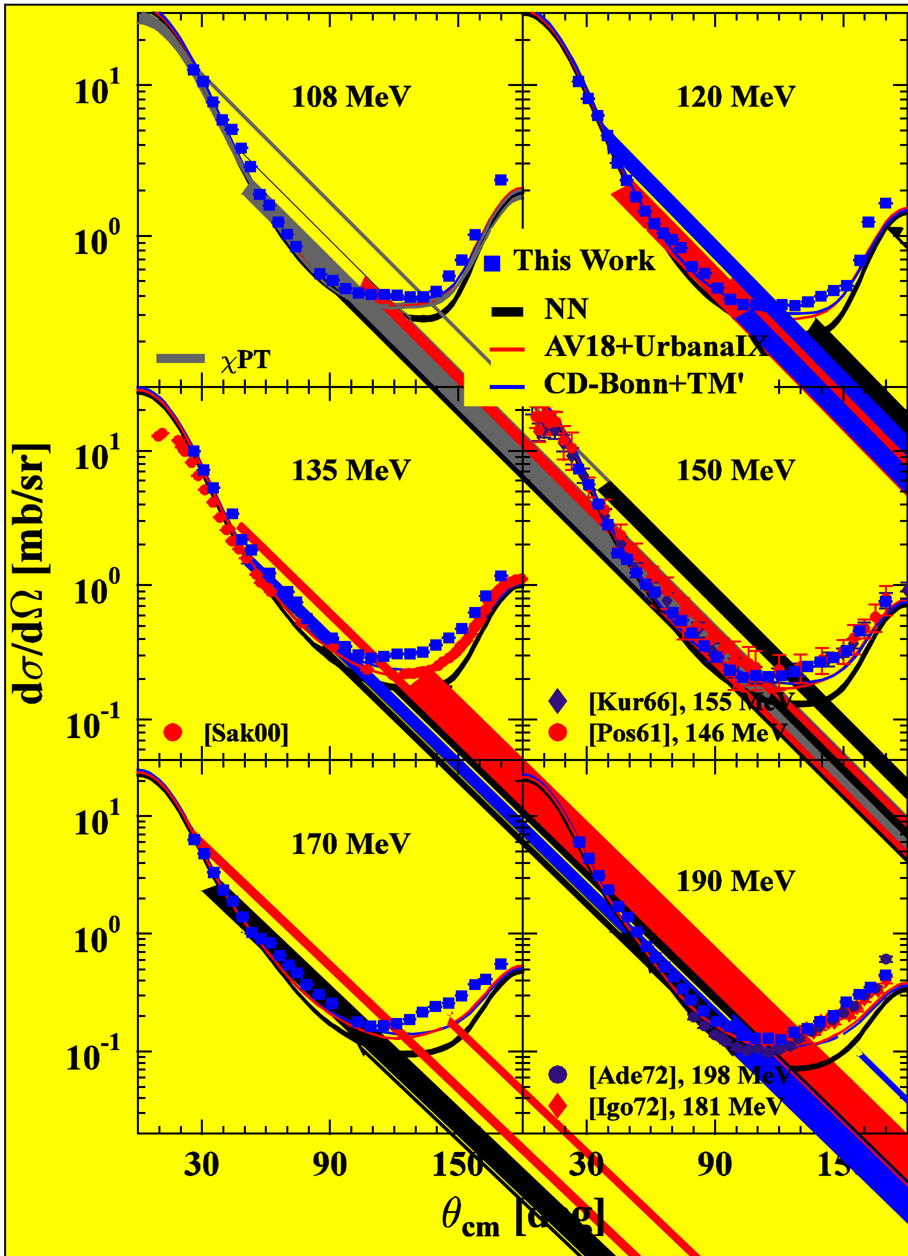
Recent 3NF studies have reached a new era of 'the Renaissance'.

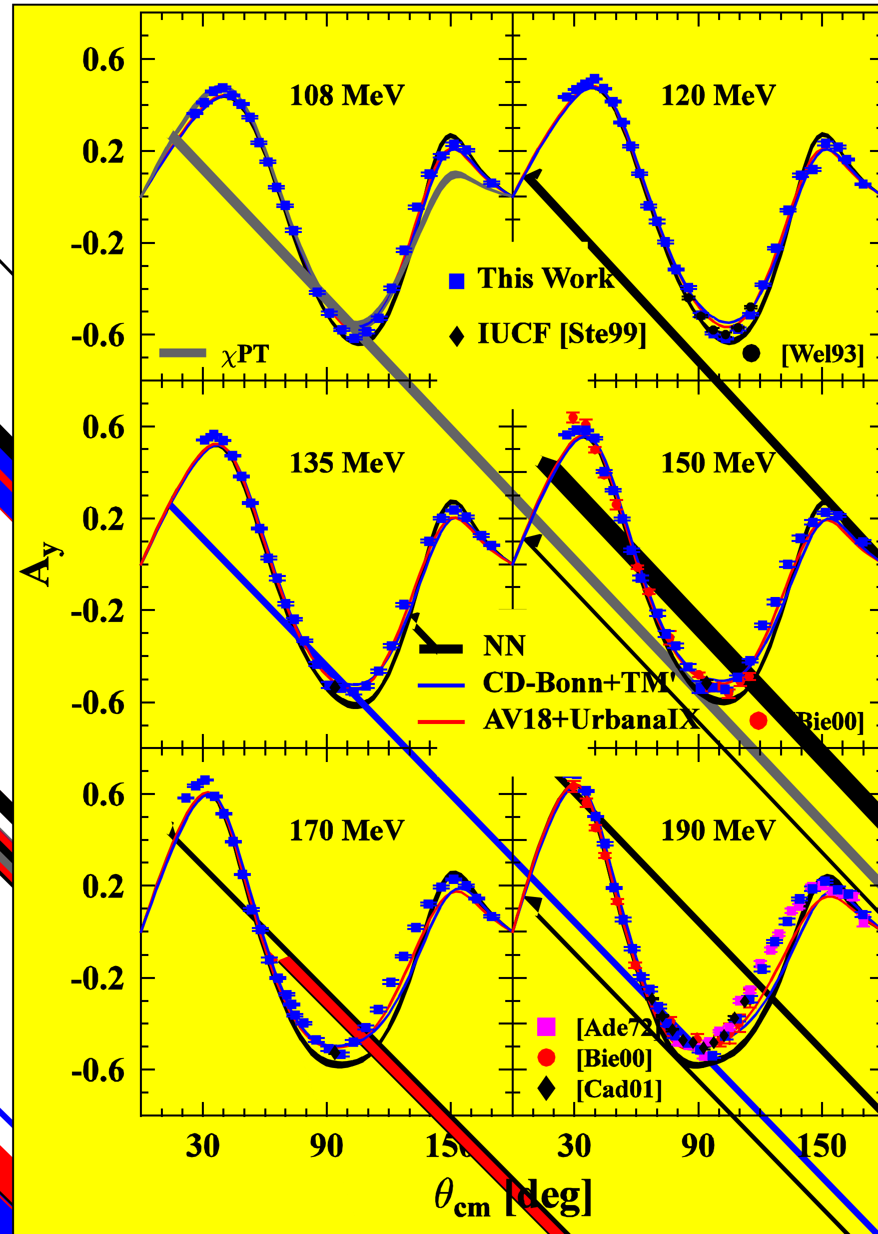
This is due to recent harmonious development of both experiments and theories.

But I think more theory inputs are needed.

Some experimental concern.

Results from KVI





Systematic Error of $d\sigma/d\Omega$

$\vec{d} + p$ 270 MeV

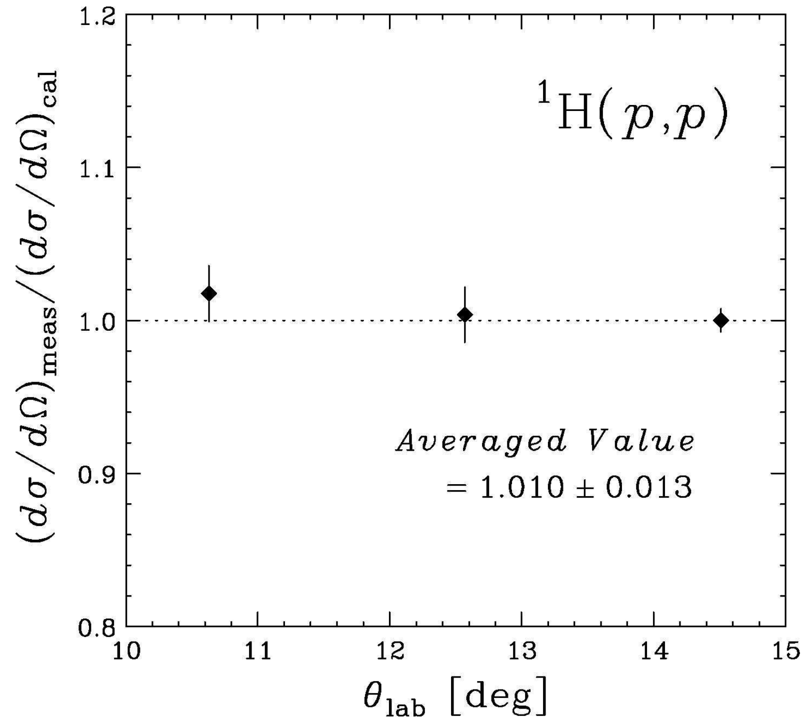
beam $d \to H_2^+$

3. measure $p + p$ 135 MeV

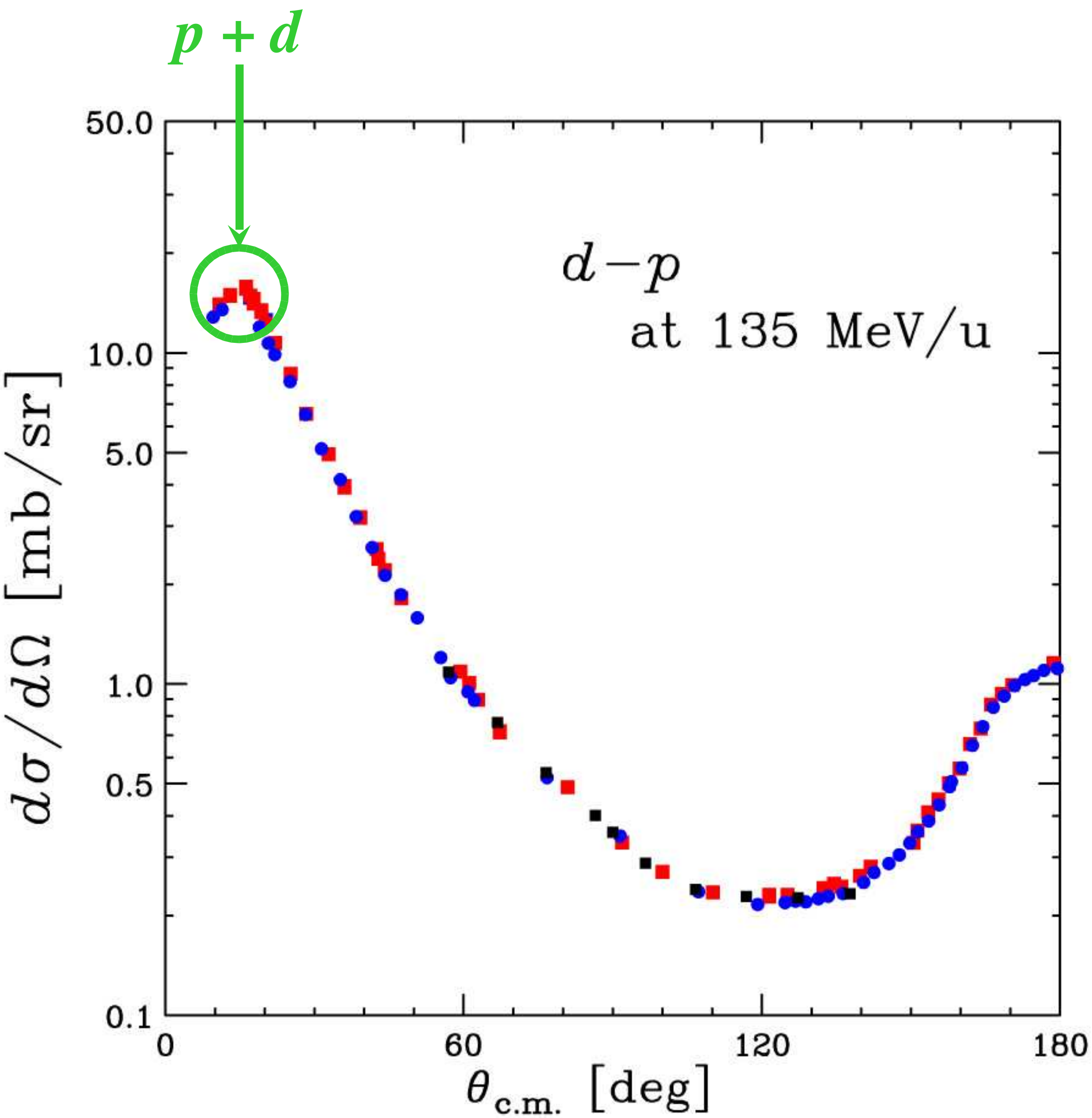
compare

6. *NN* phase-shift solution(SAID)

$$\frac{\left(\frac{d}{d\ \Omega}\right)_{\exp}}{\left(\frac{d}{d\ \Omega}\right)_{SAID}} = 1.01 \pm 0.015$$



$$\boxed{\Delta\left(\frac{d}{d\ \Omega}\right)_{\exp} \leq 2}$$



Sakamoto et al.,
Phys. Lett B367 (1996) 60

d+p : counter meas.

Sakai et al.,
Phys. Rev. Lett. 84 (2000) 5288

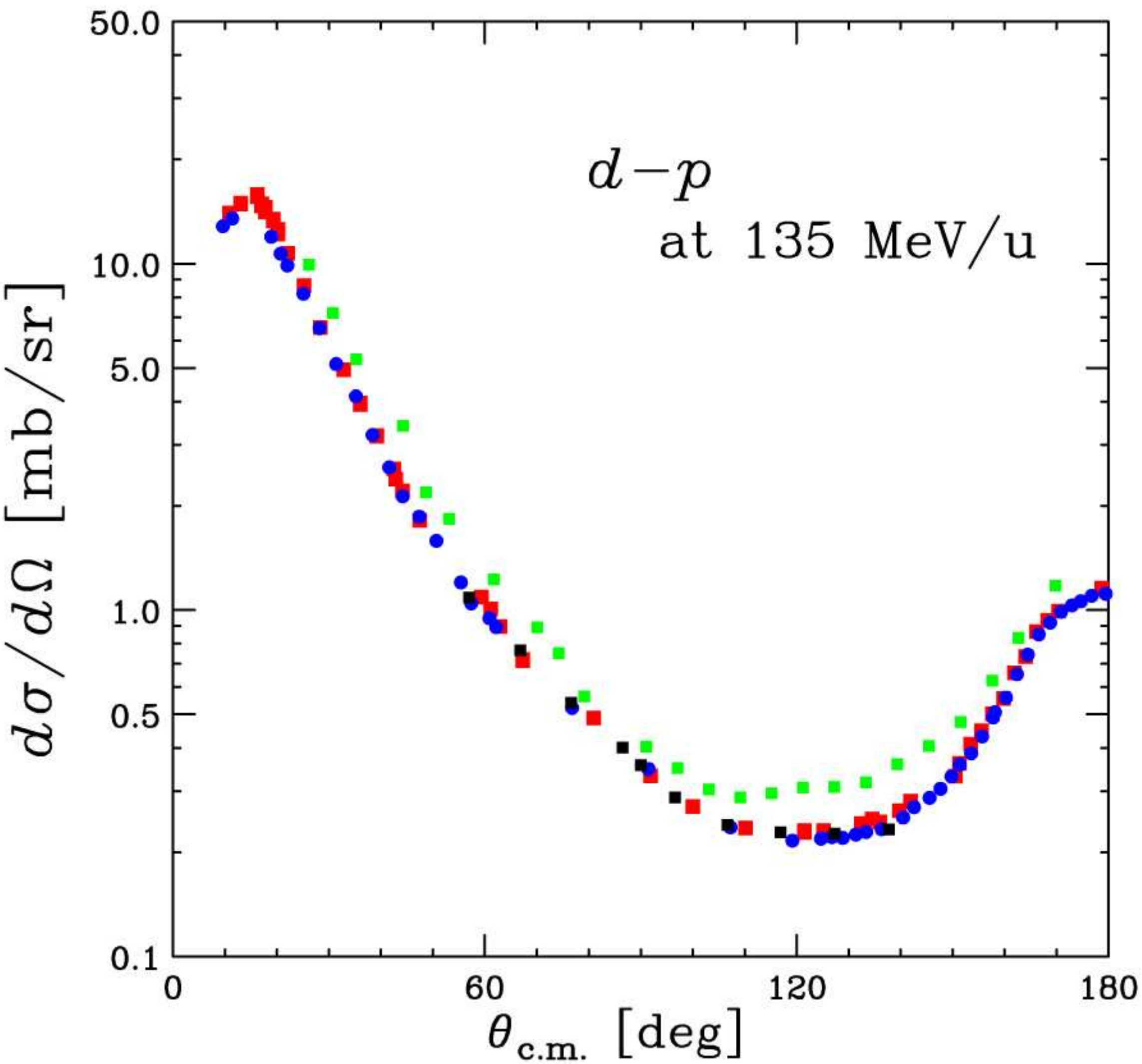
Sekiguchi et al.,
Phys. Rev. C65 (2002) 34002

d+p : SMART spectr.

Sekiguchi et al.,
to be published.

d+p & p+d :

SMART spectr.



Sakamoto et al.,
Phys. Lett B367 (1996)60

d+p : counter meas.

Sakai et al.,
Phys. Rev. Lett. 84(2000)5288

Sekiguchi et al.,
Phys. Rev. C65 (2002)34002

d+p : SMART spectr.

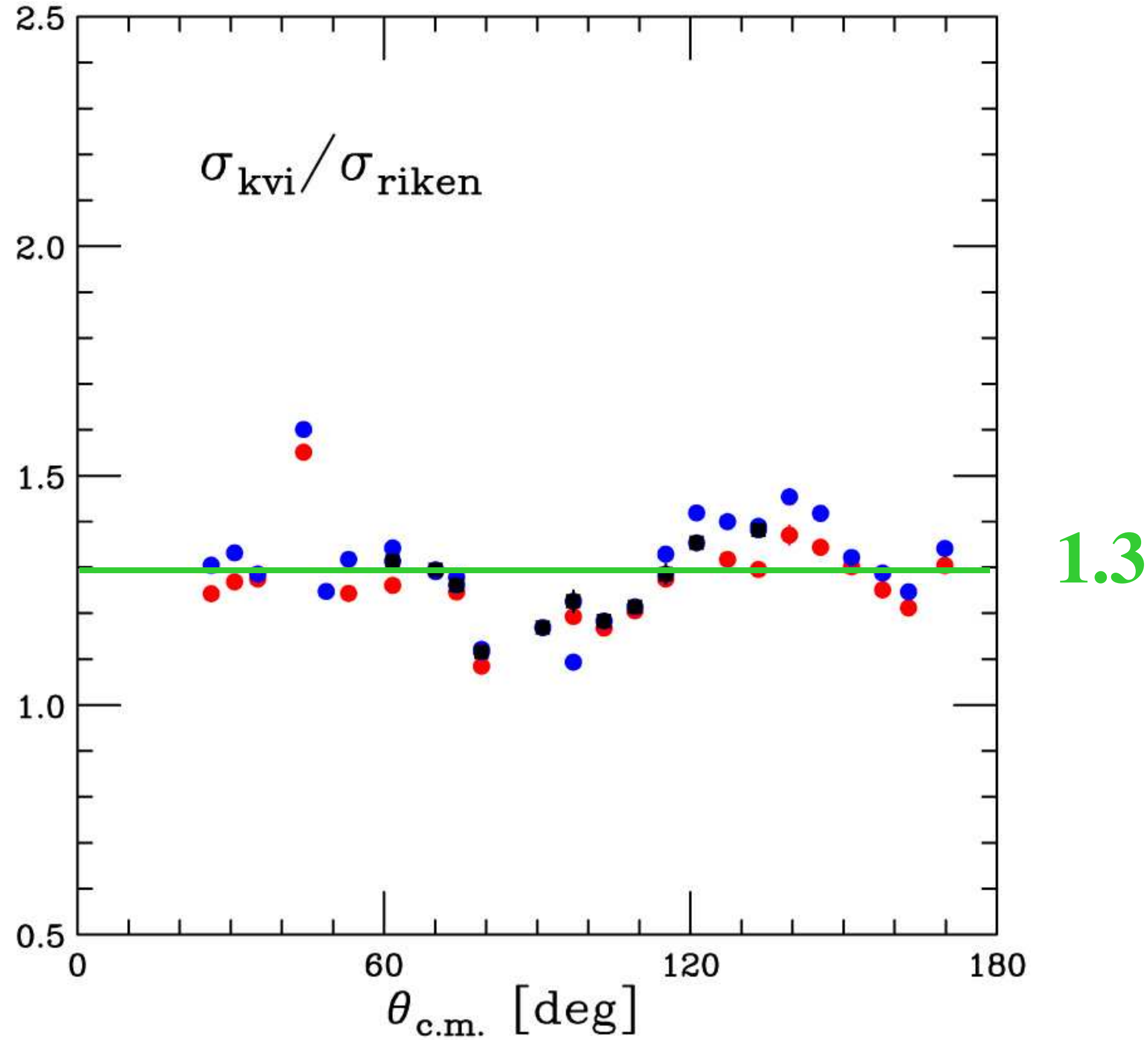
Sekiguchi et al.,
to be published.

d+p & p+d :

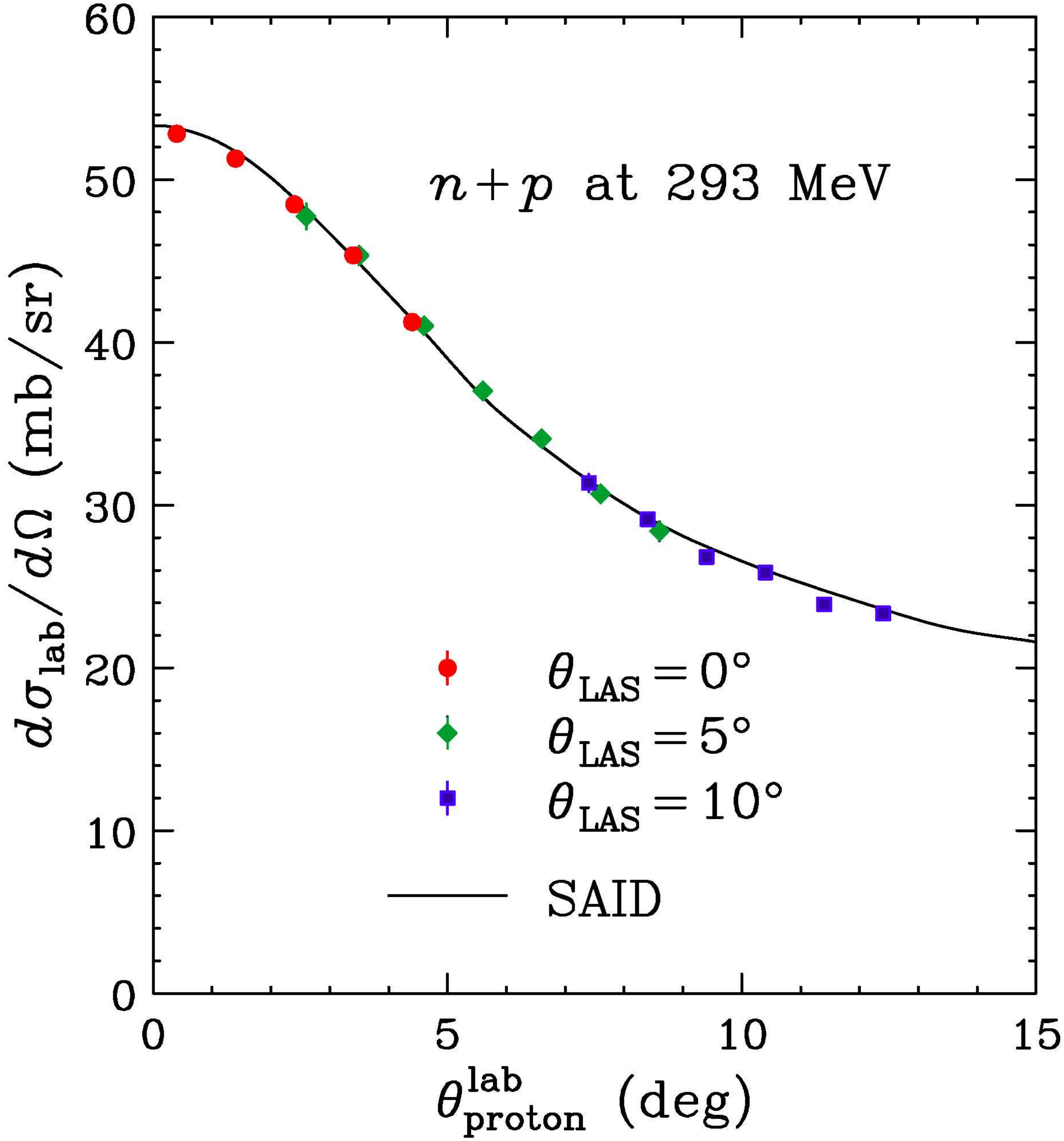
SMART spectr.

KVI data
to be published.

p+d : counter meas.



$\sigma_{kvi}/\sigma_{riken}$
2.5
2.0
1.5
1.0
0.5
0
60
120
180
$\theta_{c.m.}$ [deg]
1.3



n+p at 293 MeV
θ_LAS = 0°
θ_LAS = 5°
θ_LAS = 10°
SAID
dσ_lab/dΩ (mb/sr)
θ_proton^lab (deg)
0
10
20
30
40
50
60
0
5
10
15

Experiments were carried out under the collaboration of researchers from University of Tokyo, RIKEN, CNS, RCNP, Saitama University, CYRIC and TIT.

This talk is supported by

Kimiko Sekiguchi

Yukie Maeda

for preparing figures.