重陽子ー陽子弾性散乱測定による三体力の研究

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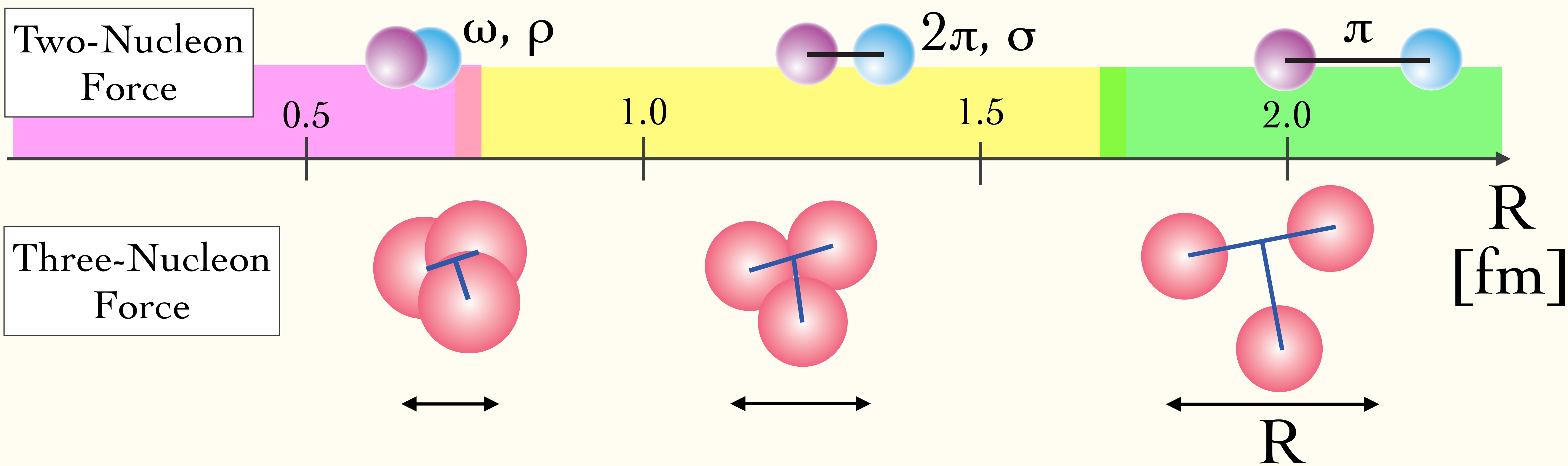
原子核の 力 - 2 & 3 Nucleon Force -

①. Repulsive
-Short Range-

②. Attractive (strong)
-Intermediate Range-

③. Attractive (weak)
- Long Range -



3NF は 2NFと同様に距離, スピン, 荷電スピン依存

Nuclear Matter Neutron Star

Nuclear Structure

Deuteron-Proton (*dp*) 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 Calculations**

  Rigorous Numerical Calculations of 3, 4N 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_i, K_{ij}, C_{ij})

Extract fundamental information of Nuclear Forces

Our interest is Three-Nucleon Force (3NF).

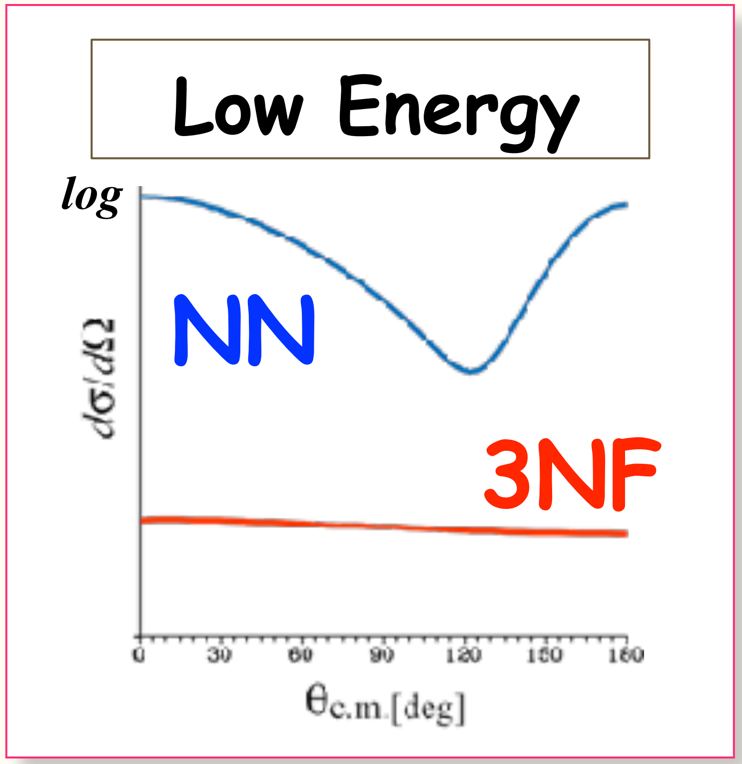
Where is the hot spot for study of 3NFs ?

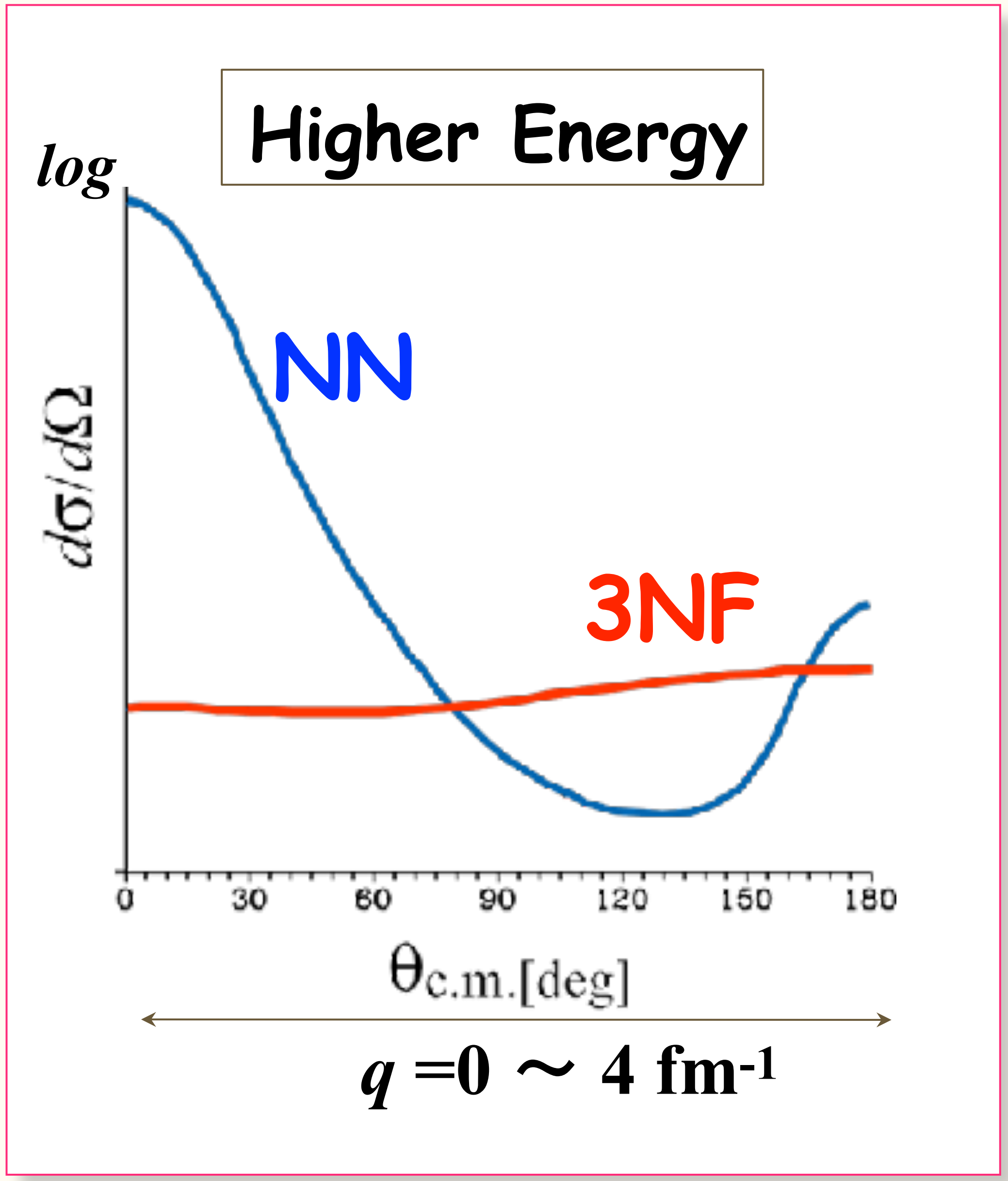
Nucleon-Deuteron Scattering

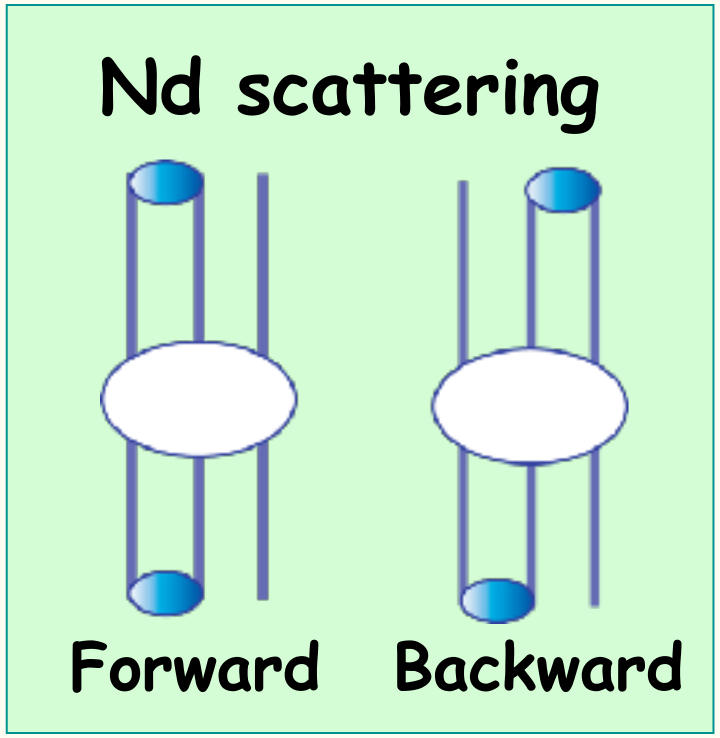
To study momentum & spin dependences
Iso-spin dependence : T=1/2 only

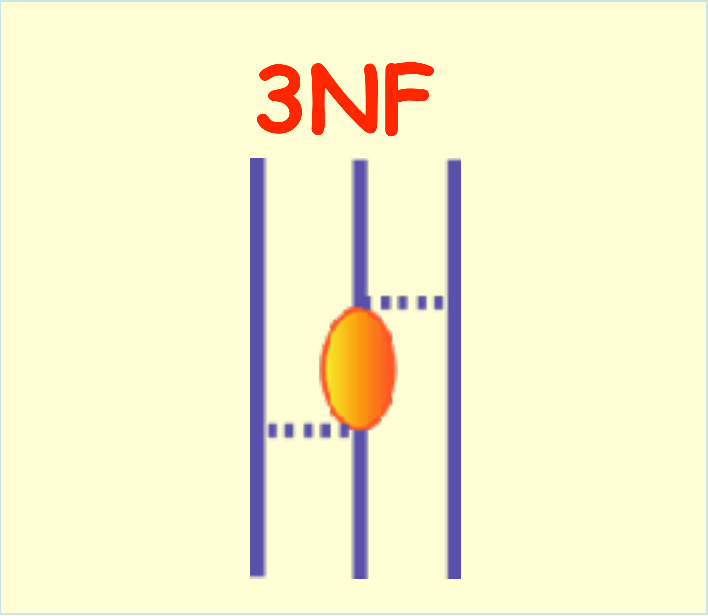
Predictions by H. Witala et al. (1998)

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

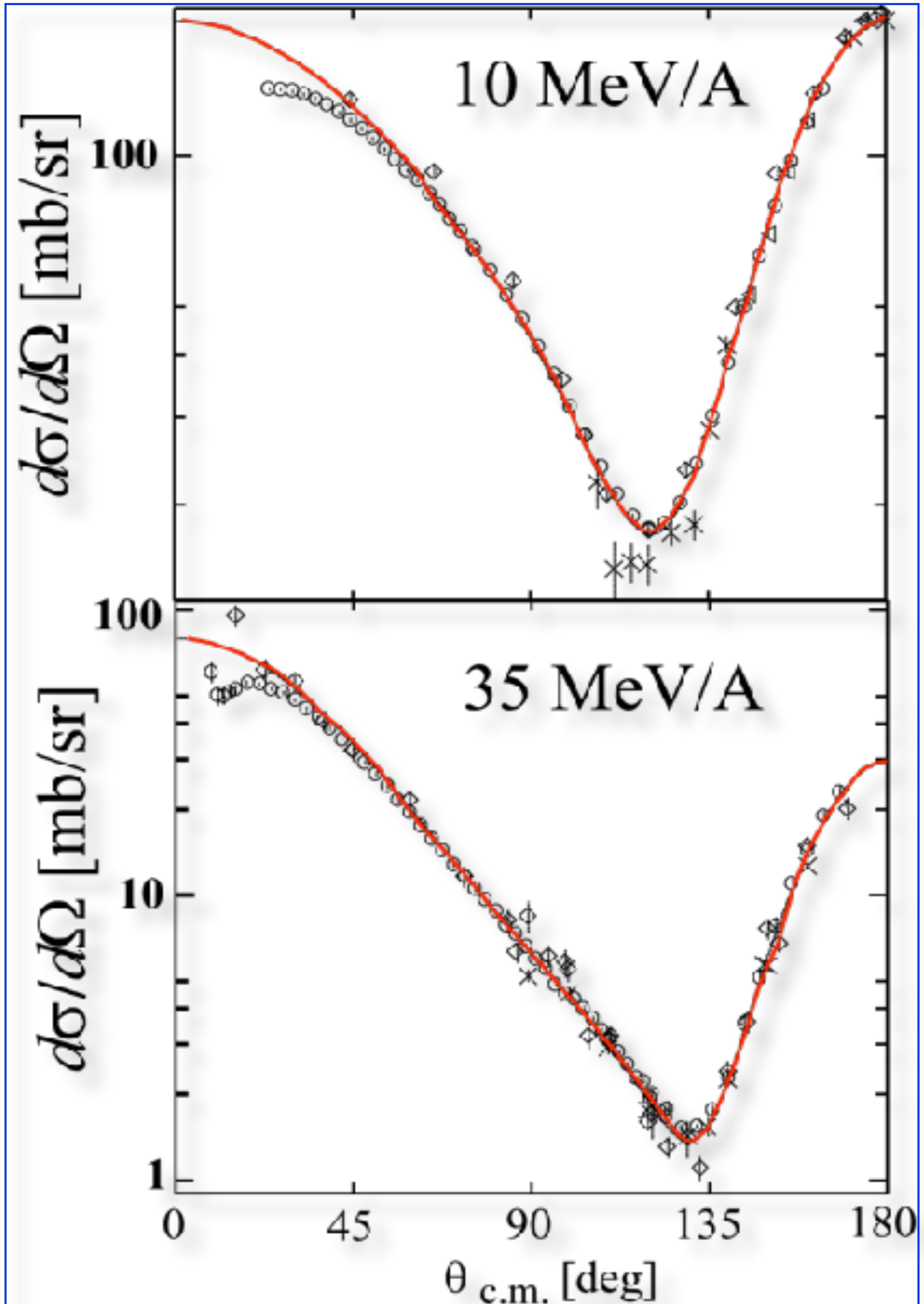








Nd Scattering at Low Energies ($E \leq 30$ MeV/A)



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

No signatures of 3NF

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

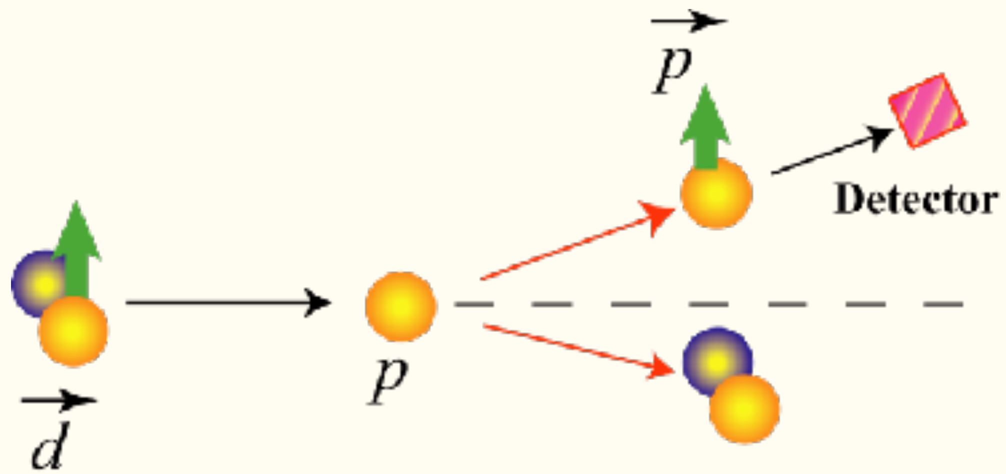
W. Glöckle et al., Phys. Rep. 274, 107 (1996).

Observables for *Nd* Scattering

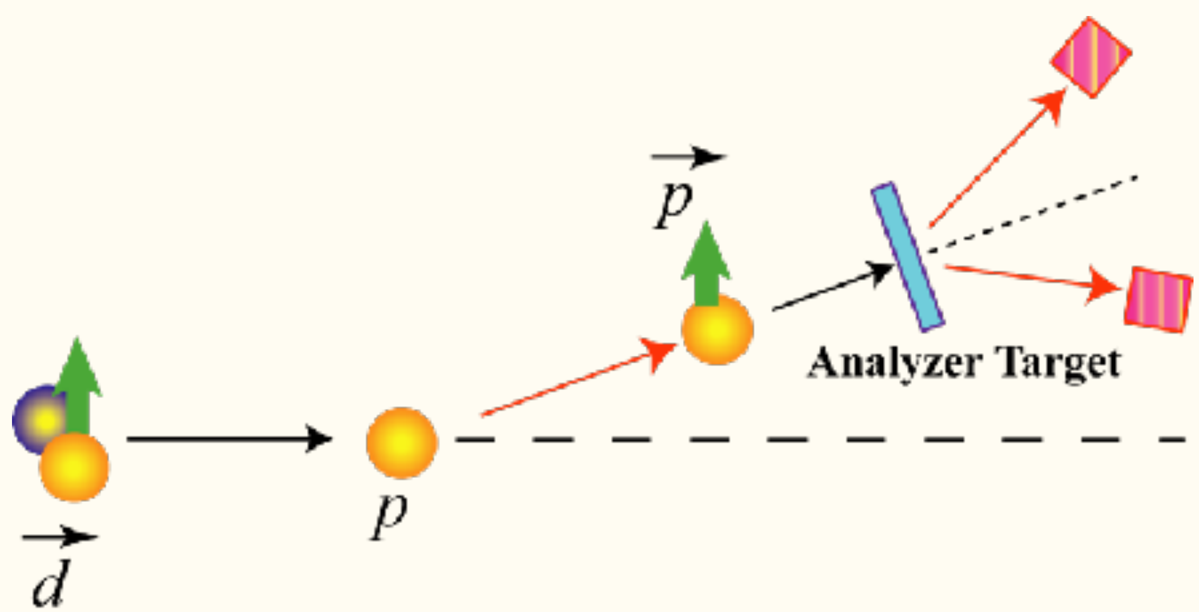
- **Differential Cross Section**
  - **Overall Strength**
  - ➢ **Absolute Quantity : normalization to *pp or np* data**

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

- **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**



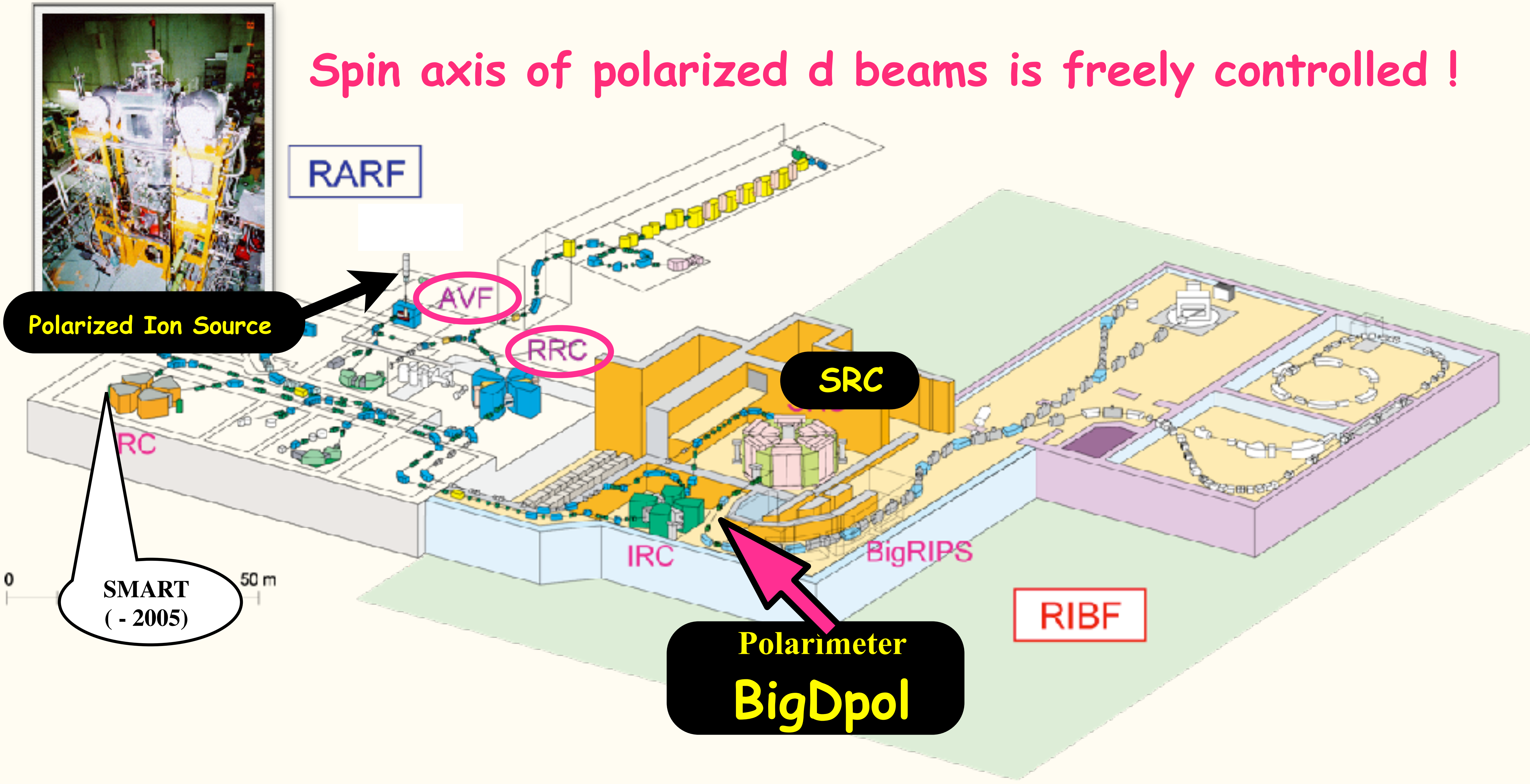
  - **Polarization Transfer Coefficient : $K_{ij}^{l'}$**
  - **Spin Correlation Coefficients : $C_{ij,k}$**
    - **Spin-Spin interaction**



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 !

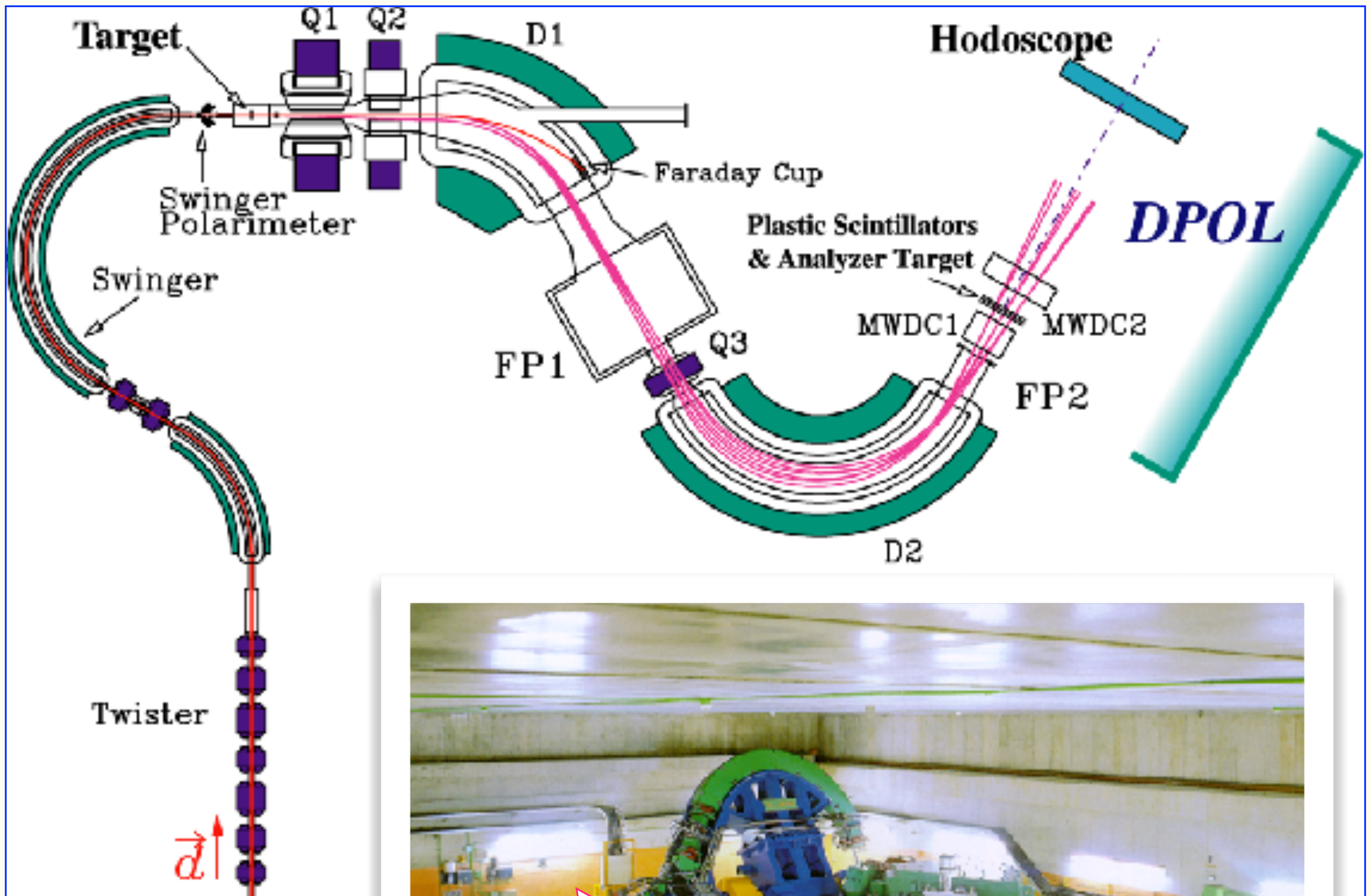


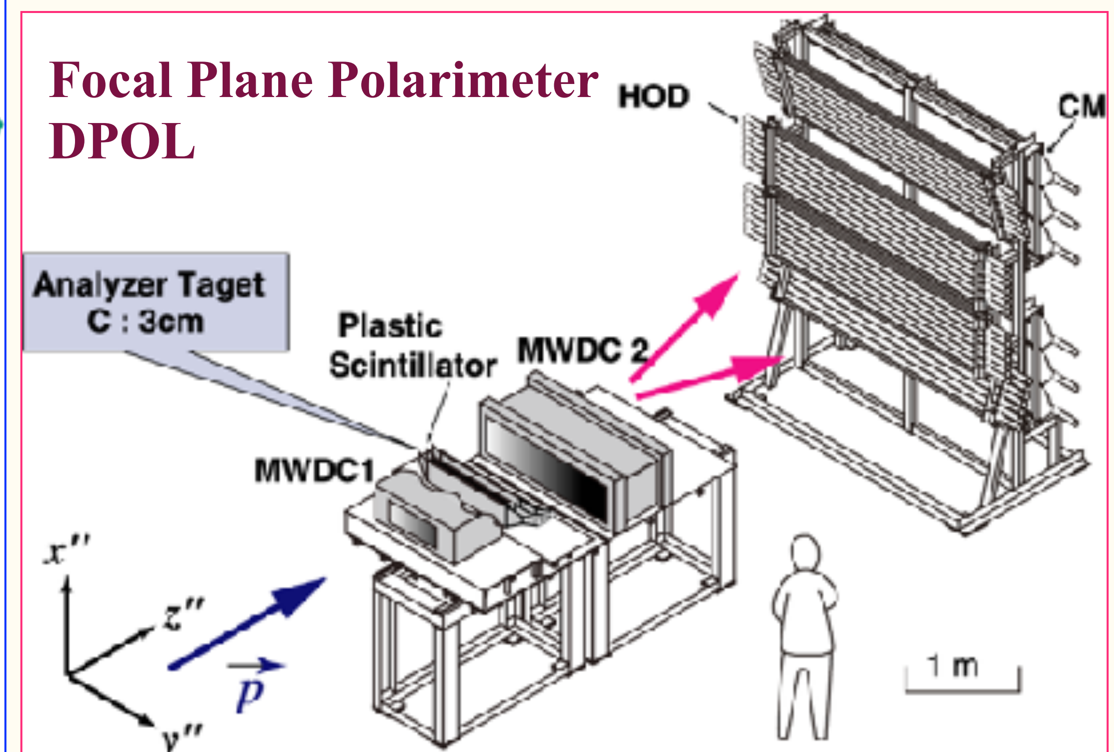
SMART at RIKEN (- 2005)

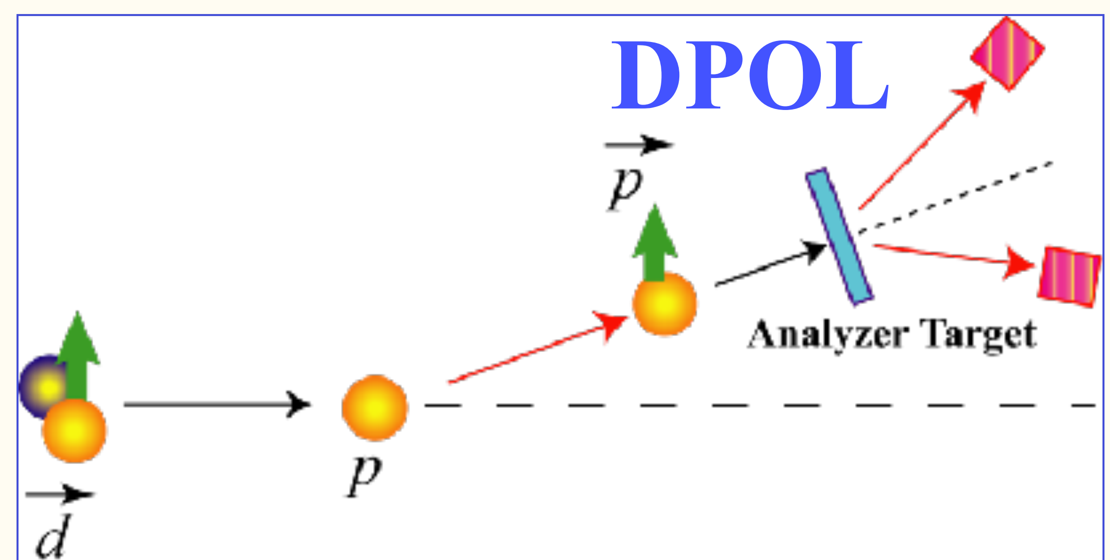
Swinger and Magnetic Analyzer with Rotator and Twister

N. Nakamoto 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. Lett. 95, 162301 (2005),
K. S. et al., Phys. Rev. C 79, 054008 (2009)

- Differential Cross Section at 70, 135 MeV/nucleon
- All Deuteron Analyzing Powers at 70, 100, 135 MeV/nucleon
- Deuteron to Proton Polarization Transfer Coefficients at 135 MeV/nucleon



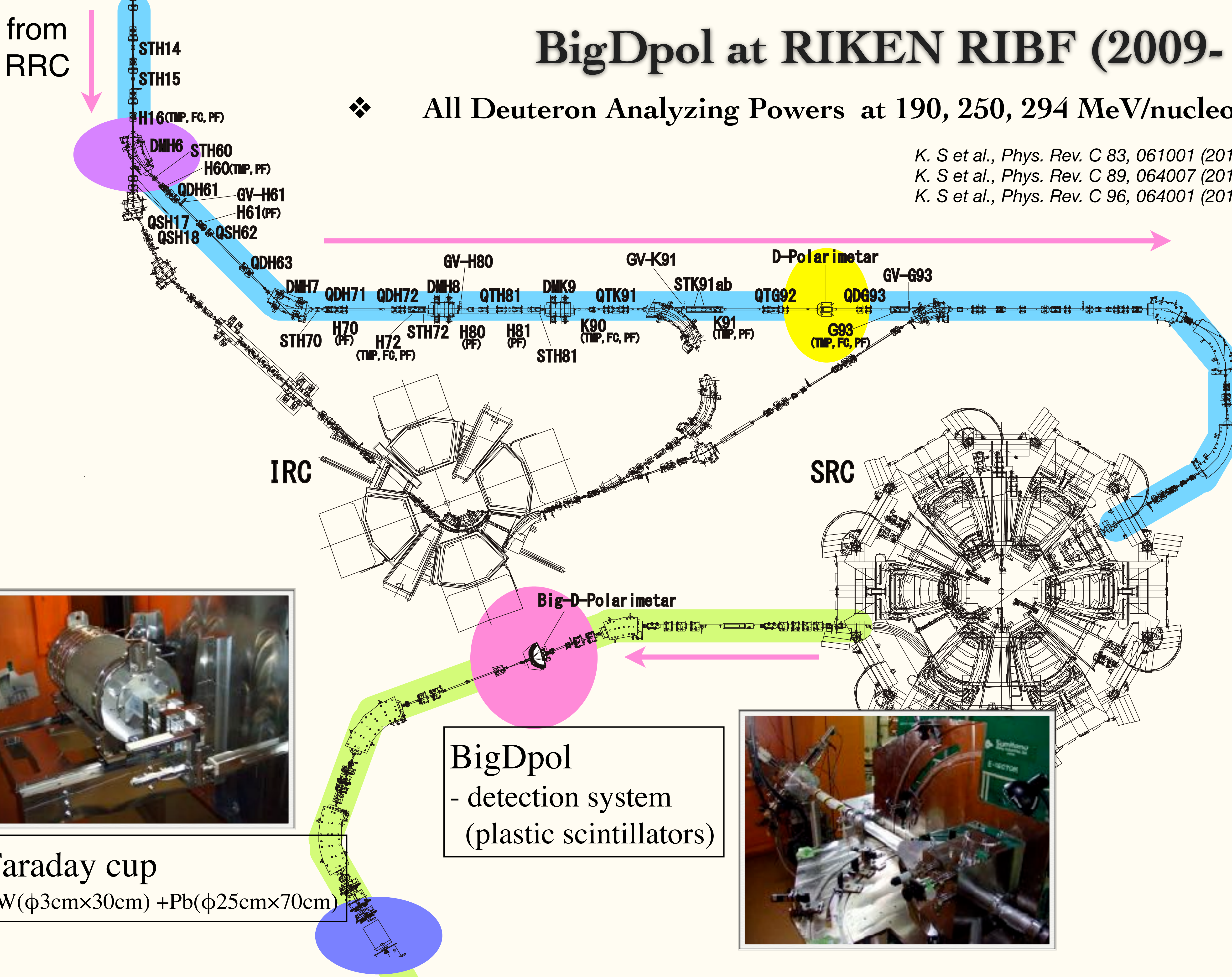




BigDpol at RIKEN RIBF (2009-)

❖ All Deuteron Analyzing Powers at 190, 250, 294 MeV/nucleon

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)

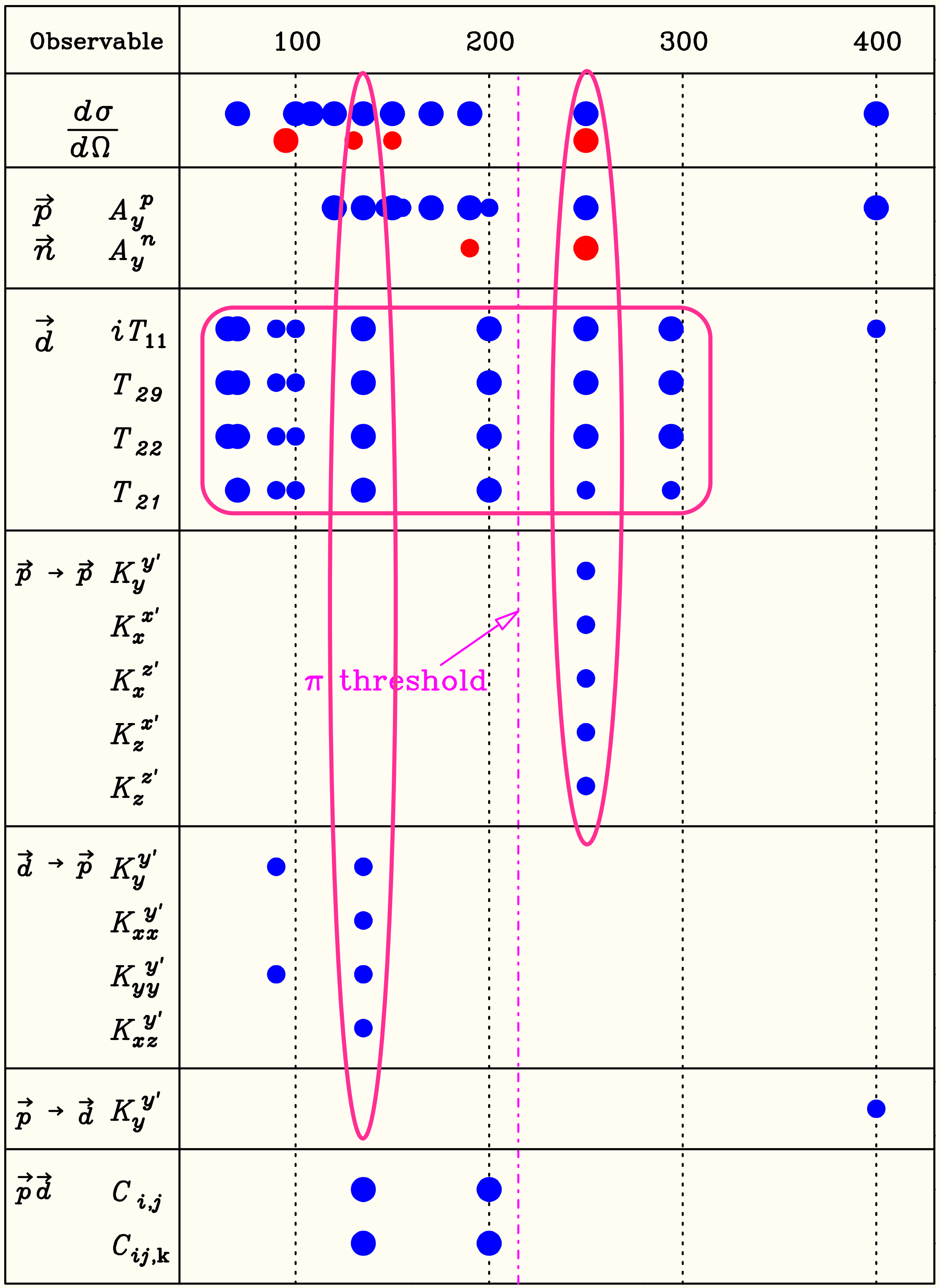


Faraday cup
- W(ϕ3cm×30cm) +Pb(ϕ25cm×70cm)

BigDpol
- detection system
(plastic scintillators)

Nd Elastic Scattering Data at Intermediate Energies

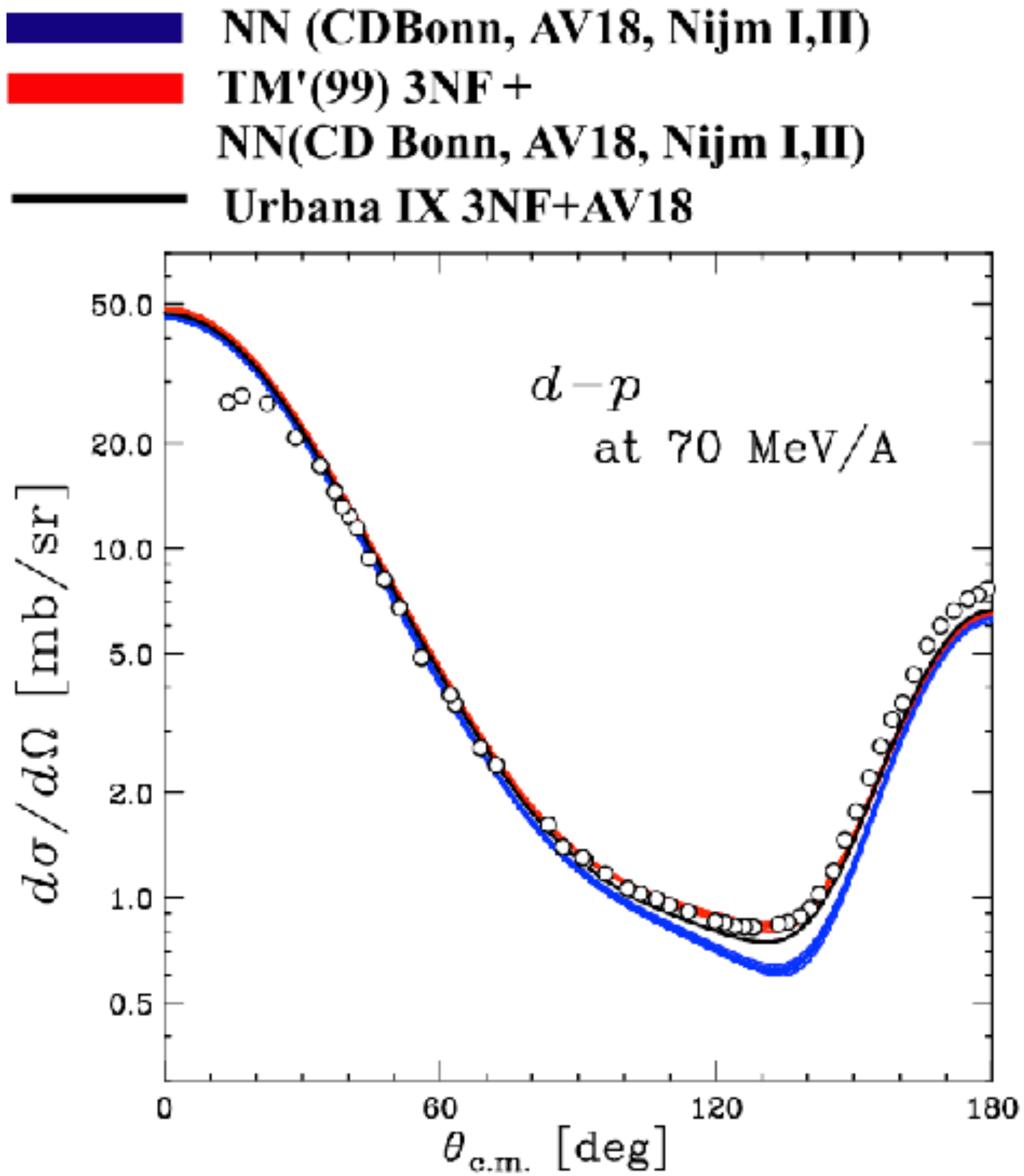
pd and *nd* Elastic Scattering at 70–400 MeV/nucleon

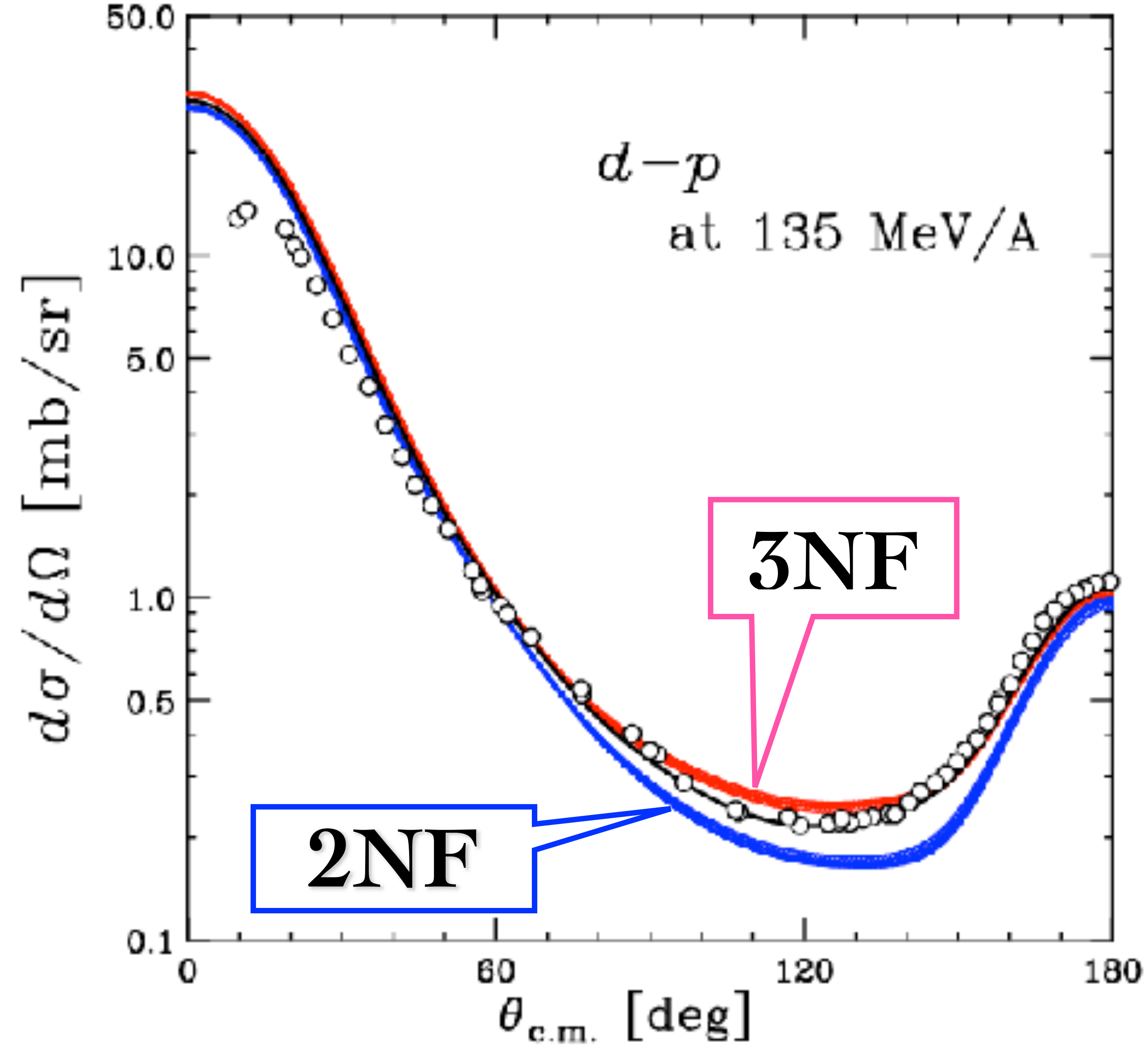


~2021

- **High precision data set of**
  ***dσ/dΩ* & Analyzing Powers**
  from RIKEN, RCNP, KVI, IUCF

Calculations by Bochum-Cracow Gr.

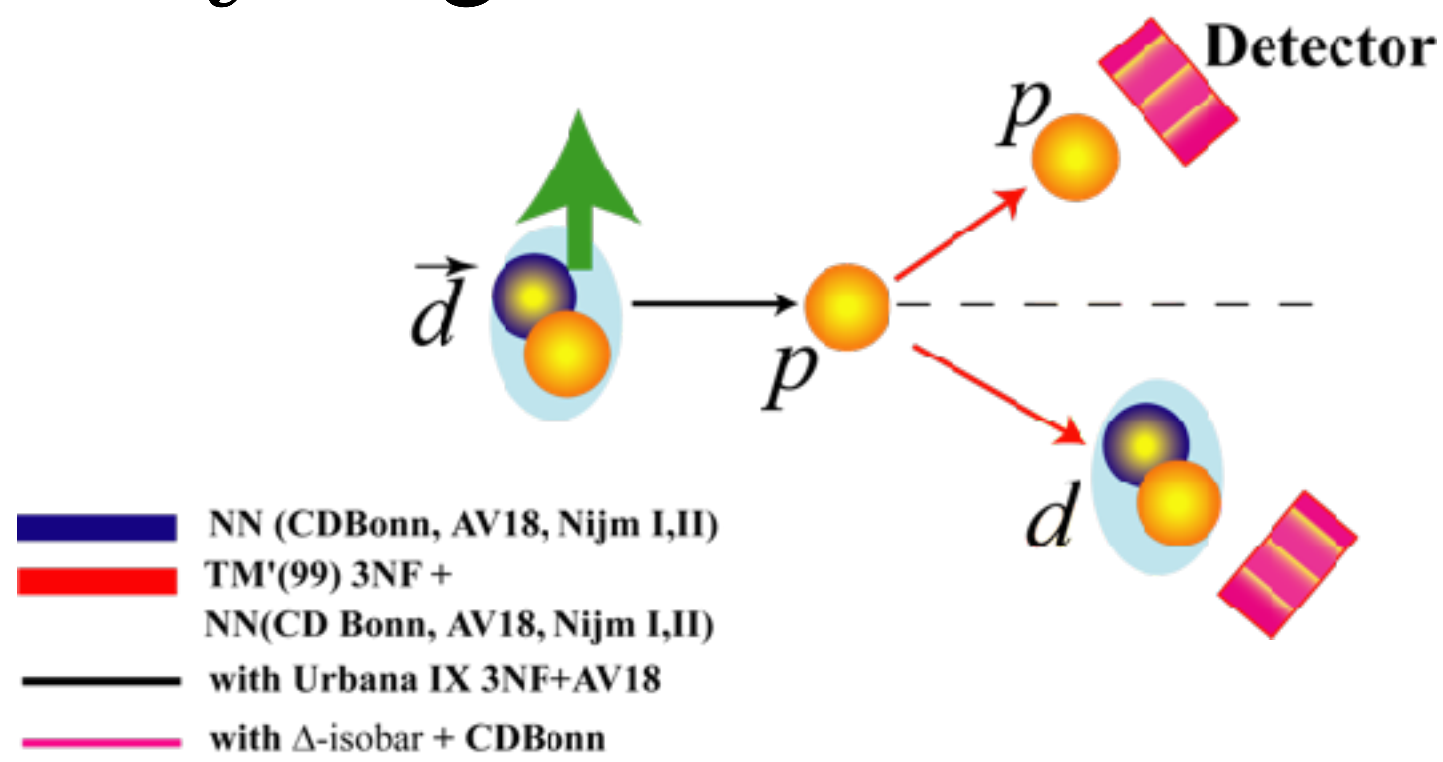




2NF (CDBonn, AV18, Nijmegen I,II)
: Large discrepancy in Cross Section Minimum (~ 30%)

2π-exchange 3NFs (Tucson-Melbourne, Urbana IX) : Good Agreement
: First Clear Signatures of 3NF effects in 3-Nucleon Scattering

Analyzing Powers

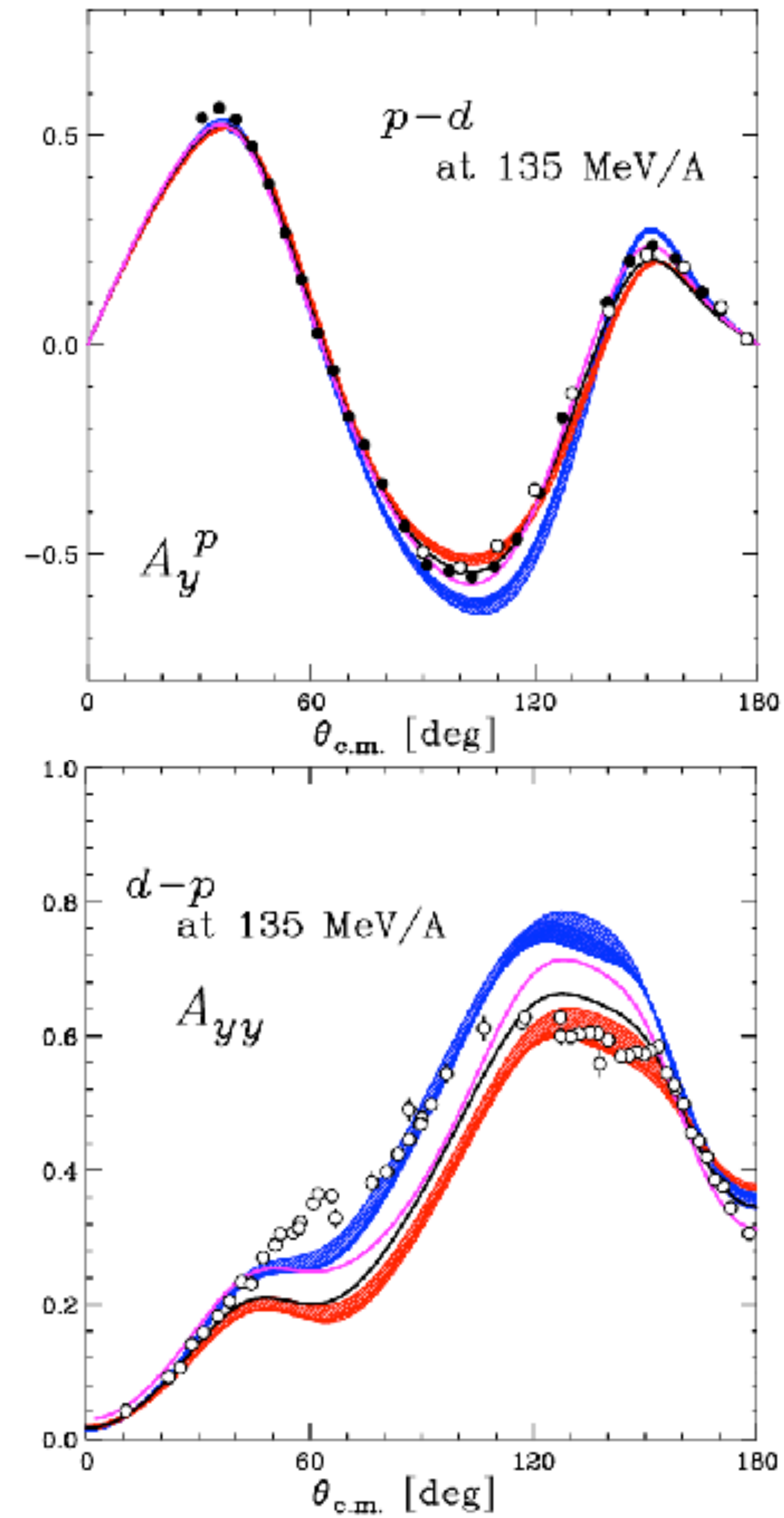


2NF (CDBonn, AV18, Nijmegen I,II) :
Large discrepancy
in Cross Section Minimum

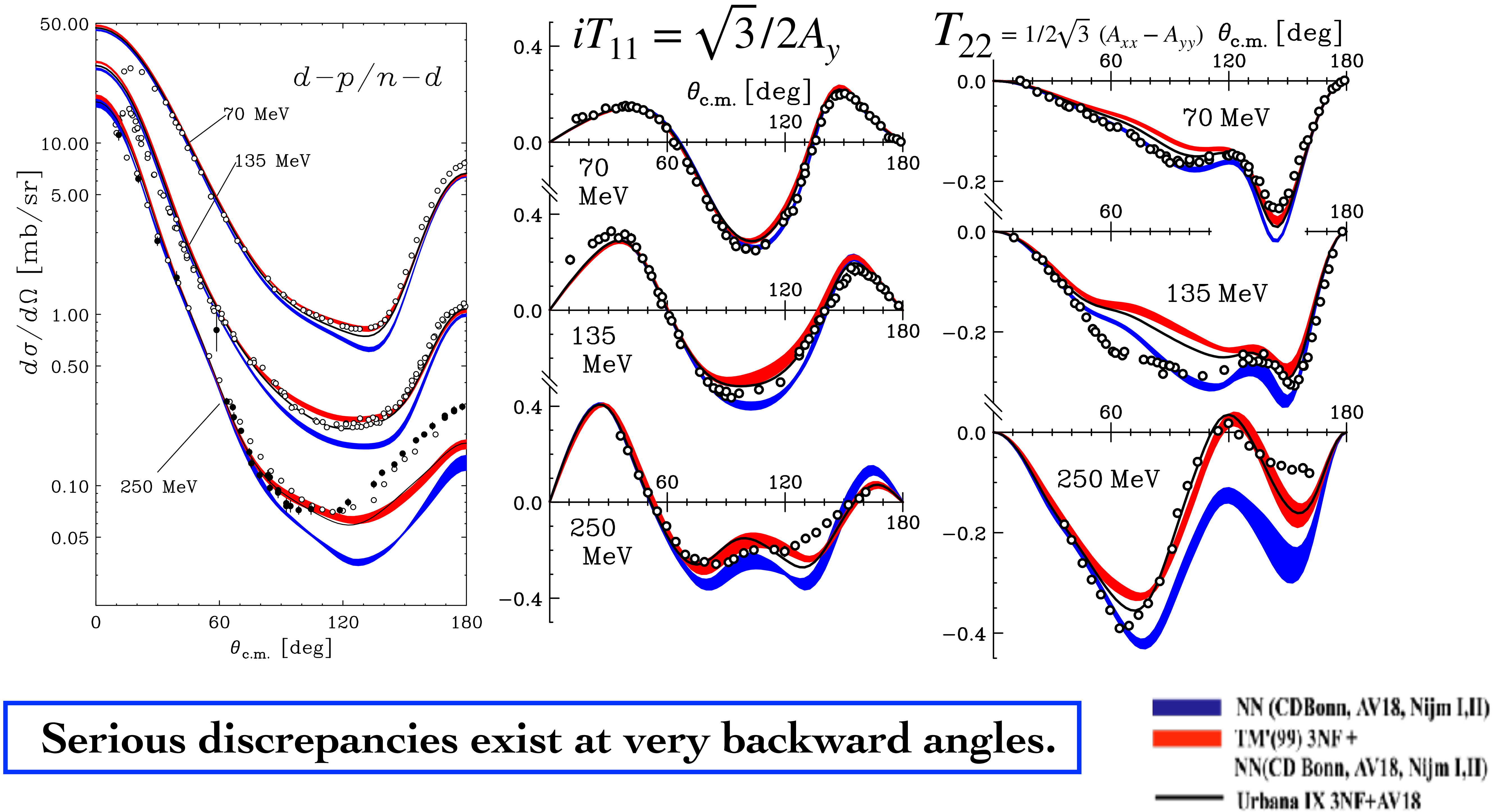
3NF (Tucson-Melbourne, Urbana IX, Δ-isobar) :

Vector Analyzing Power A_y^p
: Good Agreement

Tensor Analyzing Power A_{yy}
: No superiority



Energy Dependent Study for *dp* Scattering
- Cross Section & Analyzing Powers -



Serious discrepancies exist at very backward angles.

Summary of Results of Comparison for *dp* elastic scattering

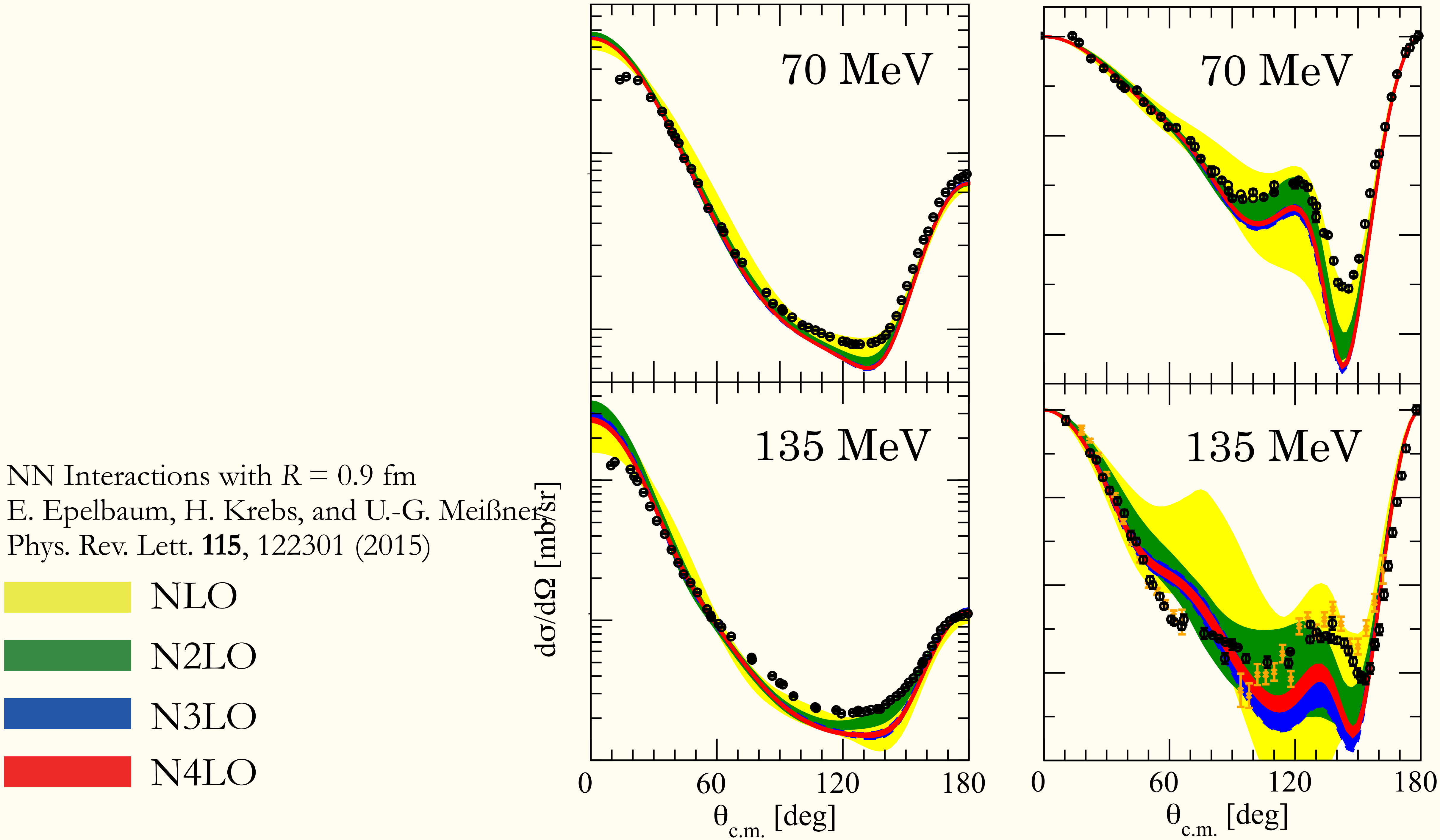
- Cross section at ~100 MeV/nucleon
  - First clear signature of 3NF effects in 3N scattering
    - Magnitudes of 3NFs is O.K. .
- Spin observables
  - Not always described by 2π-3NFs
    - Defects of spin-dependent parts of 3NFs
- At higher energies …
  - Serious discrepancy at backward angles
    - Short Range 3NFs are required.

χEFT & *dp* elastic scattering

- *dp* elastic scattering data are not explained by N4LO NN potentials.

PHYSICAL REVIEW C **96**, 064001 (2017)

NN Interactions with $R = 0.9$ fm
E. Epelbaum, H. Krebs, and U.-G. Meißner
Phys. Rev. Lett. **115**, 122301 (2015)

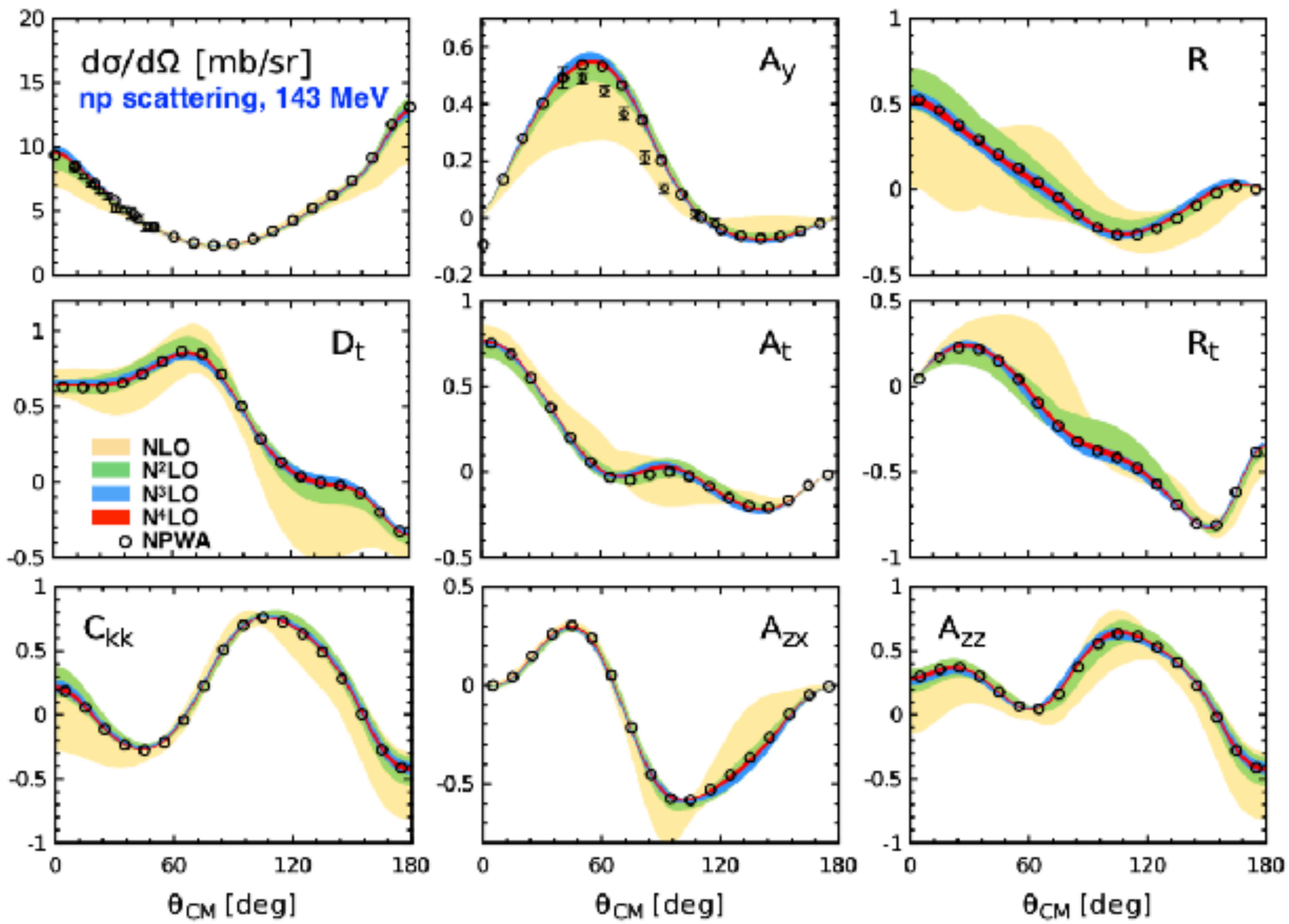


The 2N system

Experience in the 2N sector: how far should one go to obtain a precise description of data?

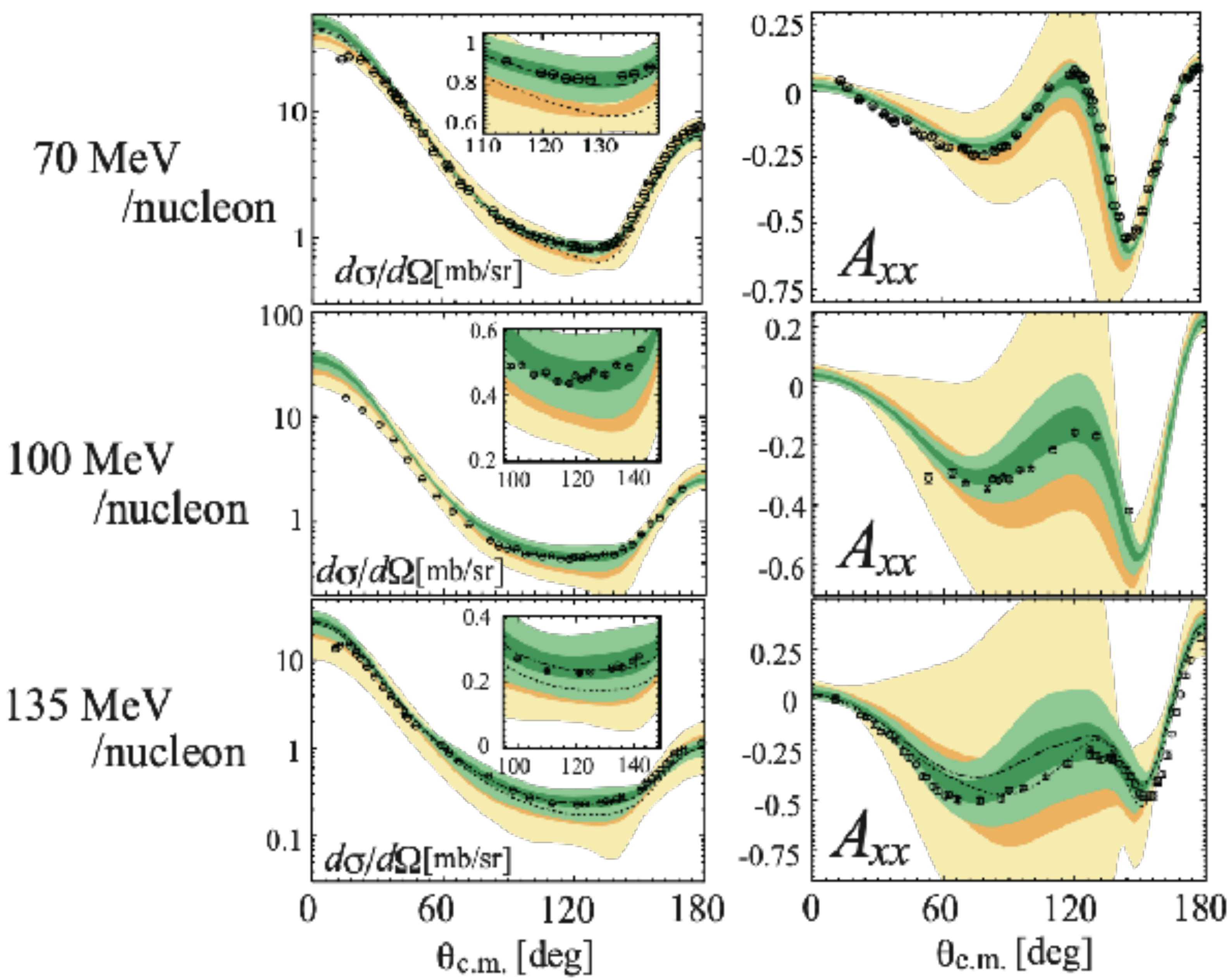
	LO	NLO	N^2LO	N^3LO	N^4LO^+
χ^2/datum (np, 0 – 300 MeV)	75	14	4.1	2.01	1.06
χ^2/datum (pp, 0 – 300 MeV)	1380	91	41	3.43	1.00

P. Reinert, H. Krebs, EE, EPJA 54 (2018) 88



χEFT N^4LO 2NF has achieved **high precision**.

dp scattering & χEFT **N2LO** 2NF+3NF (green bands)



- **LECs of N2LO 3NFs** (D and E terms) are determined by
  - Cross section of *dp* scattering at 70 MeV/nucleon
  - ^{3}He binding energy

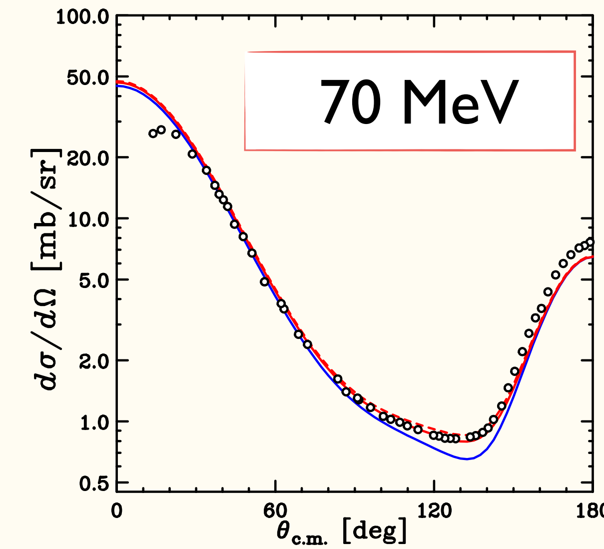
χEFT & *dp* elastic scattering

- Calculations of N4LO^{+} NN with N2LO 3NF (Preliminary)

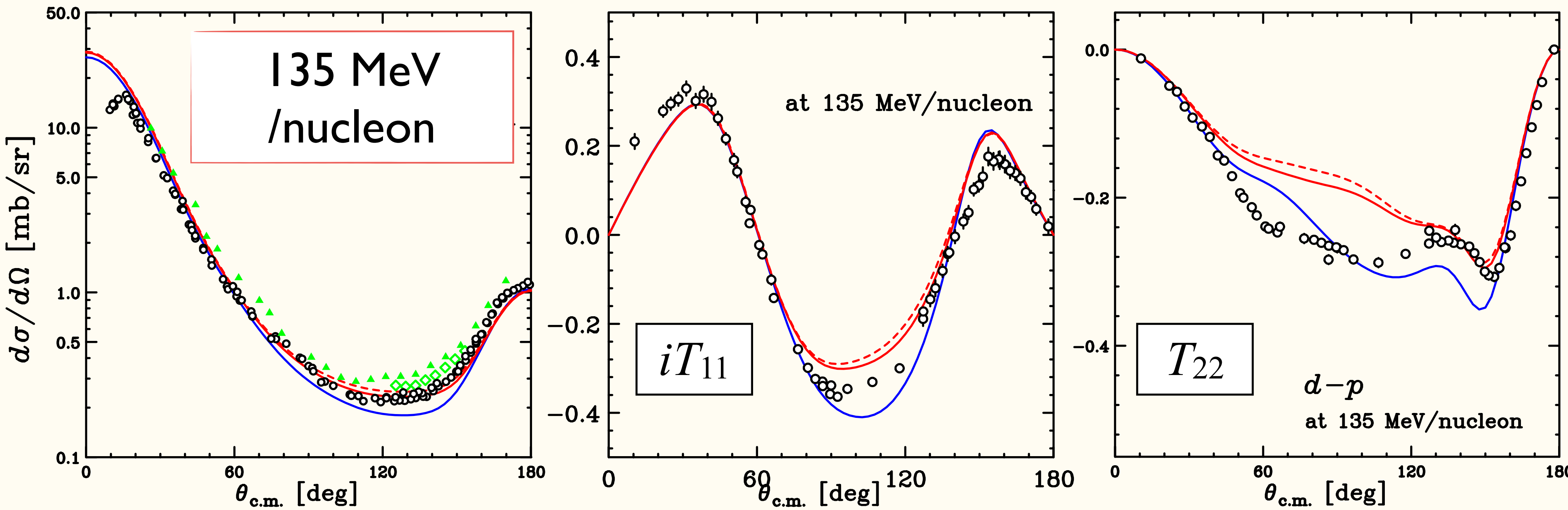
2NF : Semi-local Momentum-Space regularized Chiral NN potentials

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.



N4LO+, Λ=450MeV
C_D= 2.0, C_E= 0.286
C_D= 4.0, C_E= 0.499



calculations : H. Witala private communications.

- **Spin observables & C.S. at higher energies : N3LO&N4LO 3NFs are needed.**
- **Cross section minimum region : Golden Window for the higher-order 3NFs.**

c.f. E. Epelbaum et al., Eur. Phys. J. A (2020) 56, 92

Project

Determination of χEFT N4LO 3NFs from *dp* elastic scattering

➡ "High precision 2N+3N forces"

Project of Theory

(ERC Grant Project, PI : Evgeny Epelbaum, Term: 2021-2026)

✓ Partial Wave Analysis

✓ Low Energy Constants for N4LO 3NFs (short-range parts) are determined by 3N scattering data.

➡ High precision data set of *dp* scattering <u>at 100 MeV/nucleon and below</u> are highly demanded.

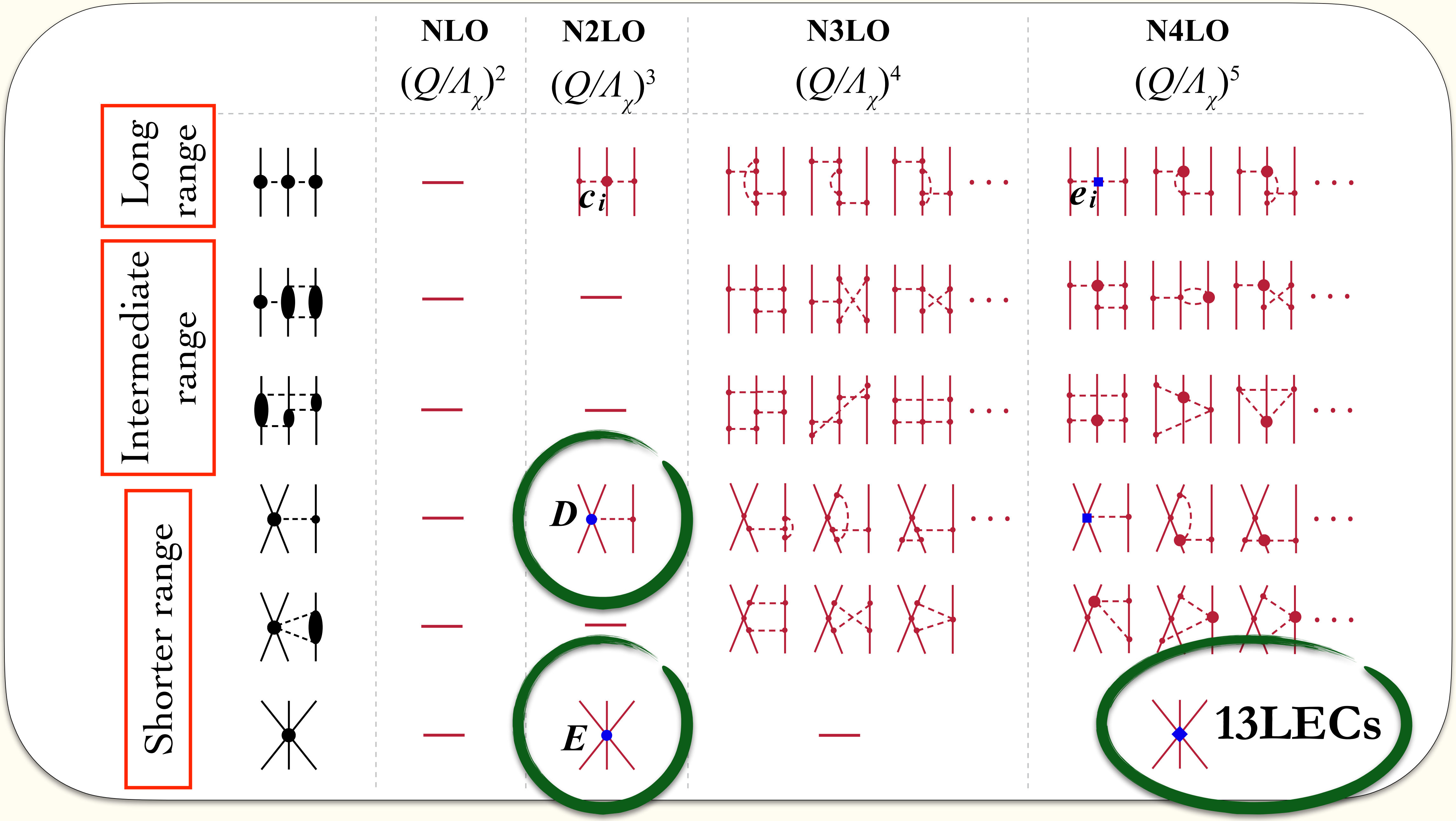
Project of Experiment

(KAKENHI Grant S Project, PI : Kimiko Sekiguchi, Term: FY2020-FY2024)

✓ Measurement of spin correlation coefficients for *dp* scattering at 100 MeV/nucleon

* Data sets are scarce for spin correlation coefficients.

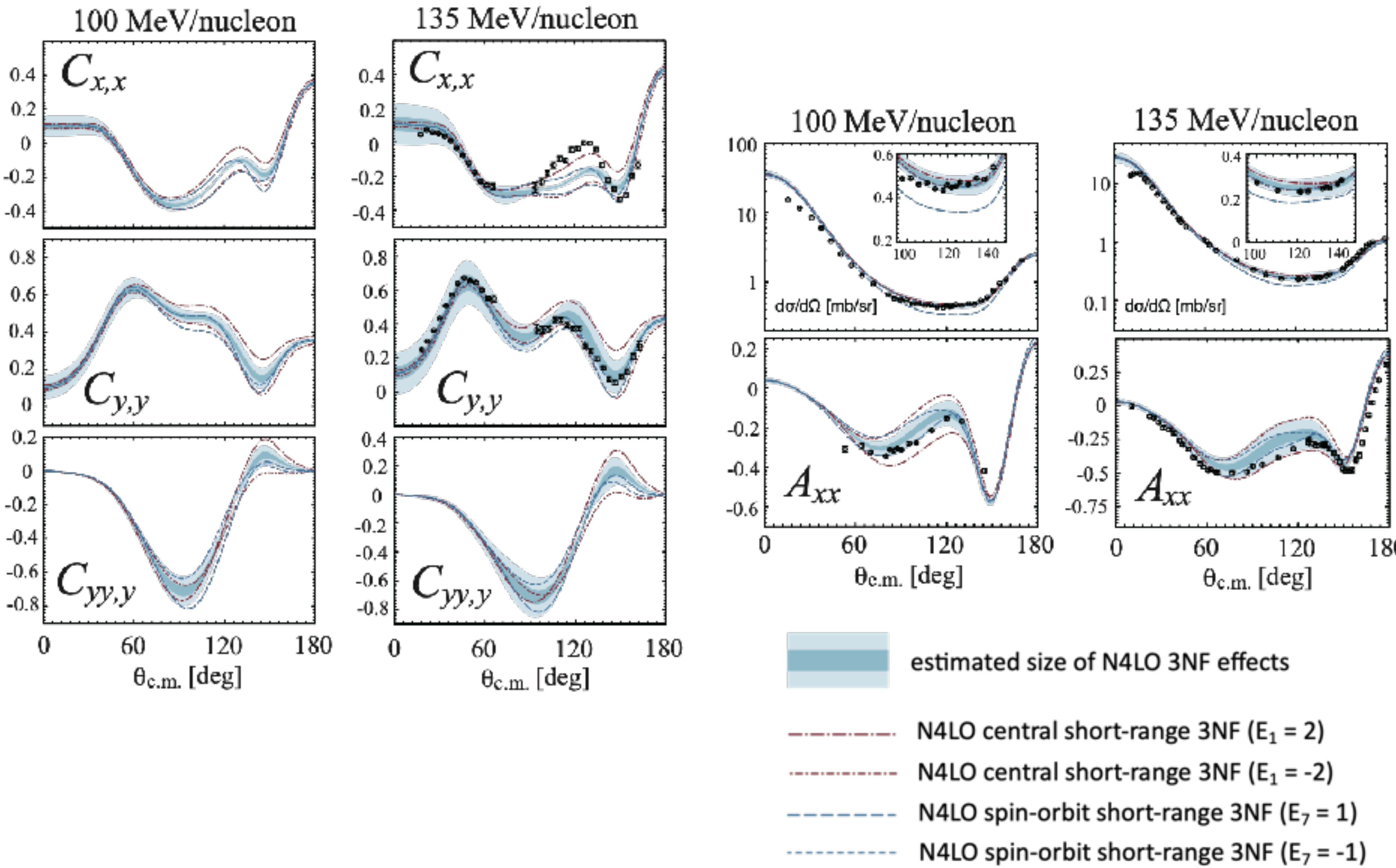
χEFT 3NF


NLO
$(Q/\Lambda_\chi)^2$
N2LO
$(Q/\Lambda_\chi)^3$
N3LO
$(Q/\Lambda_\chi)^4$
N4LO
$(Q/\Lambda_\chi)^5$
Long range
Intermediate range
Shorter range
c_i
e_i
D
E
13LECs

dp scattering & χEFT N4LO 2NF + N2LO 3NF

E. Epelbaum et al., Eur. Phys. A 56:92 (2020)

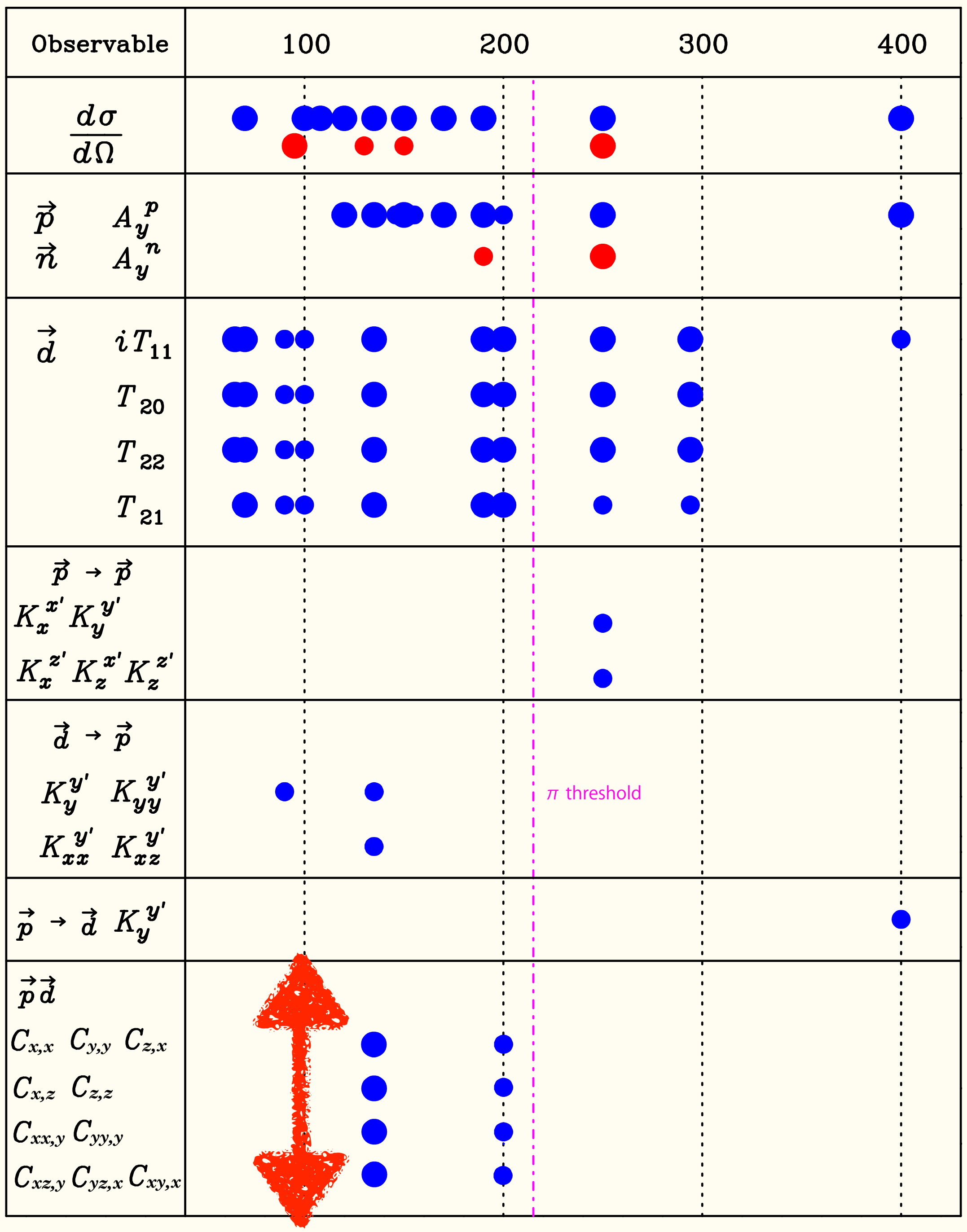
➢ **Blue bands in the figure** : Truncation uncertainty at N3LO → Expected size of **N4LO 3NFs**

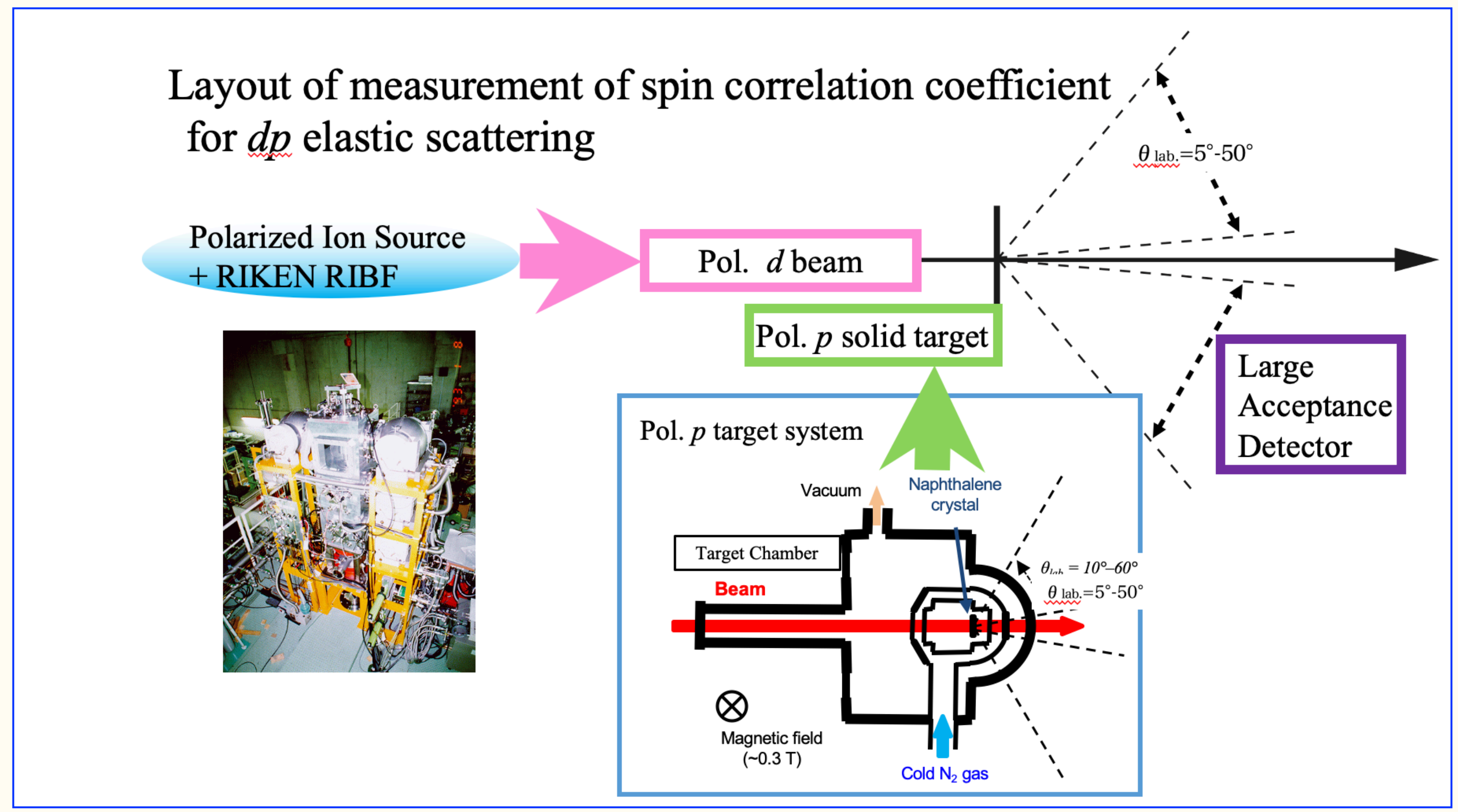


New Project :

Measurement of Spin Correlation Coefficients for *dp* elastic scattering at 100 MeV/nucleon

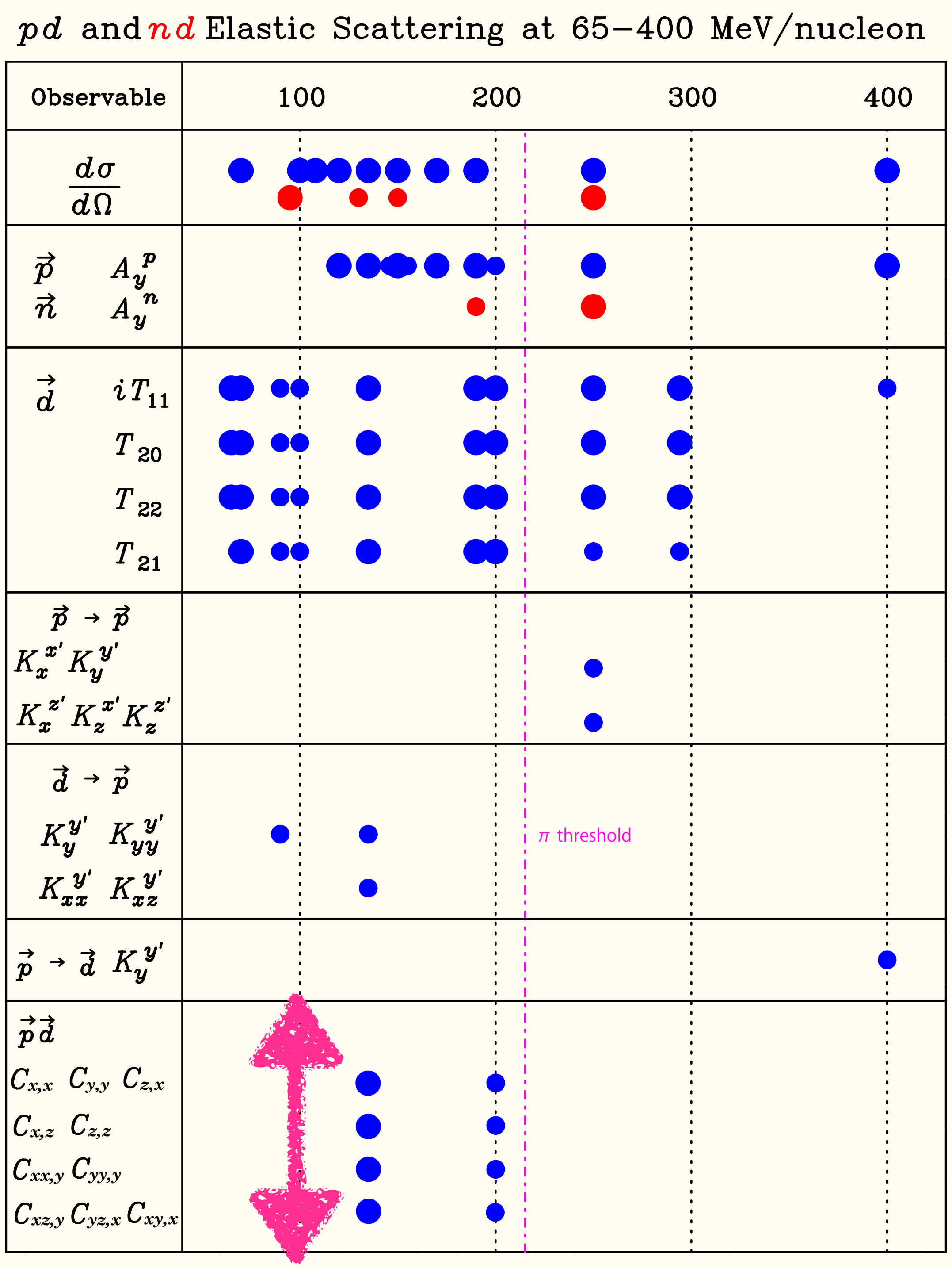
pd and *nd* Elastic Scattering at 65–400 MeV/nucleon





New Project :

Measurement of Spin Correlation Coefficients for *dp* elastic scattering at 100 MeV/nucleon



Test experiment will be performed at Tohoku University next week.

Summary

Few-Nucleon Scattering

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

Deuteron-Proton Elastic Scattering Experiment at RIKEN

Precise data of $d\sigma/d\Omega$ and spin observables at 70- 300 MeV/nucleon

Comparison with Faddeev calculations based on χEFT NN potential at N^4LO

Cross Section : Large discrepancy at backward angles. 3NFs are clearly needed.

Spin Observables : 3NF effects are spin dependent.

New Project :

- Measurement of spin correlation coefficients at 100 MeV/nucleon for investigation of N4LO 3NFs.

- Determination of LECs N4LO 3NFs from dp scattering data is about to start.

RIBF-*d.* Collaboration

Department of Physics, Tohoku University

K. Sekiguchi, A. Watanabe, K. Miki, Y. Saito, S. Kitayama, Y. Maruta, K. Kameya, T. Matsui, R. Urayama Y. Wada, D. Eto, T. Akieda, H. Kon, J. Miyazaki, T. Taguchi, U. Gebauer, K. Takahashi, T. Mashiko

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RCNP, Osaka University

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Kyungpook National University

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