International Conference
Nuclear Theory in the Supercomputing Era -2016
September 19th, 2016

Experiments of Few-Nucleon Scattering and Three-Nucleon Forces

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東北大学

Tohoku University

- Location : **Sendai**
- Established in 1907, the third oldest Imperial University in Japan
  (1st: Univ. of Tokyo in 1877, 2nd: Kyoto Univ. in 1897)
  - 10 schools, including Science, Engineering, Medicine, Law, Arts and Letters, Agriculture etc...
- Students : 10,000 (undergraduate), 7700 (graduate)

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〜

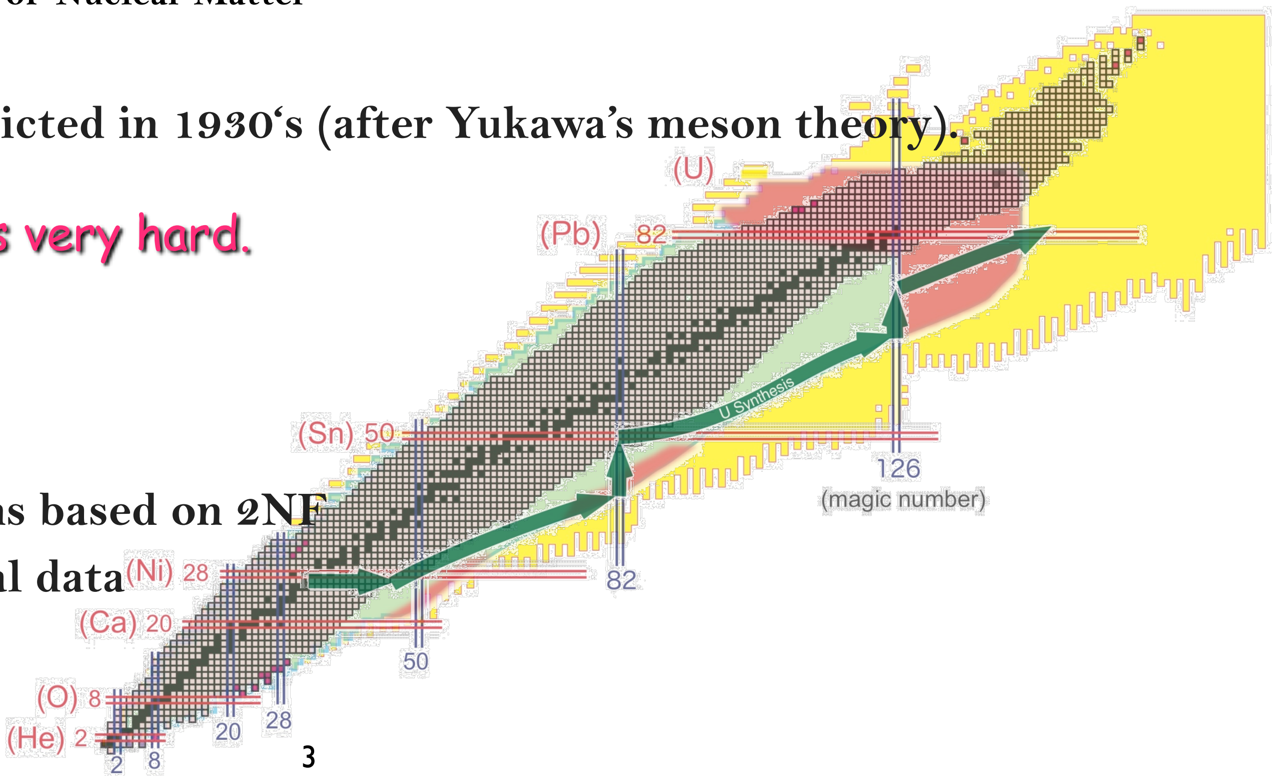
- Nucleon-Deuteron Elastic Scattering at Intermediate Energies
- Biding Energies / Levels of Light Mass Nuclei
- Equation of State of Nuclear Matter

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

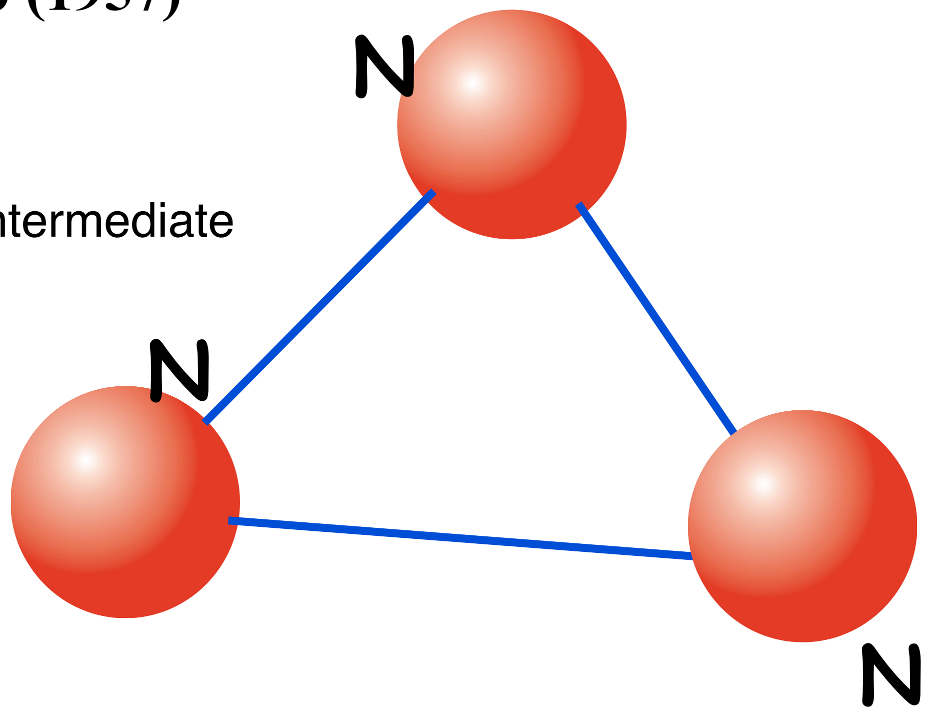


Three Nucleon Force (3NF)

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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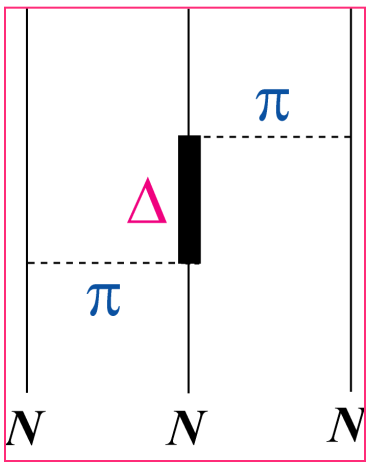

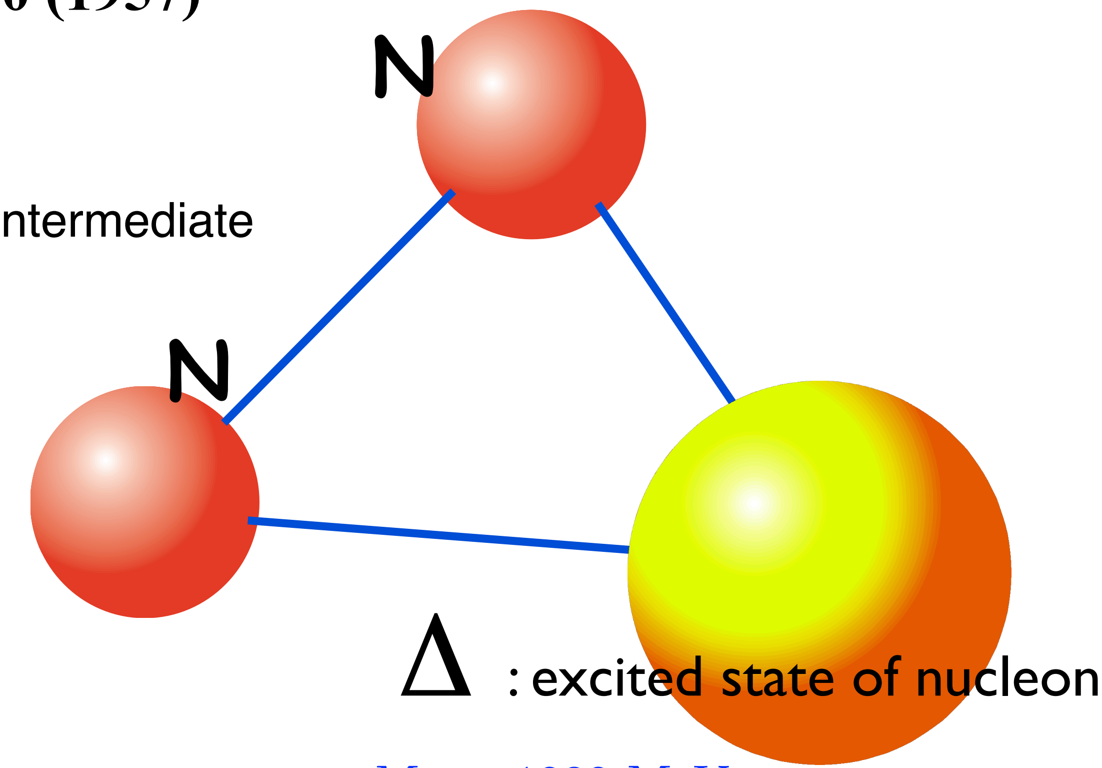

$$M_\Delta = 1232 \text{ MeV}$$

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

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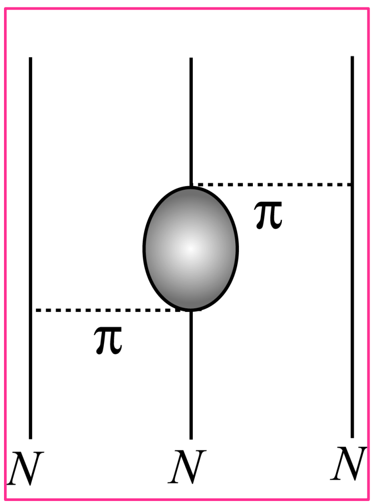

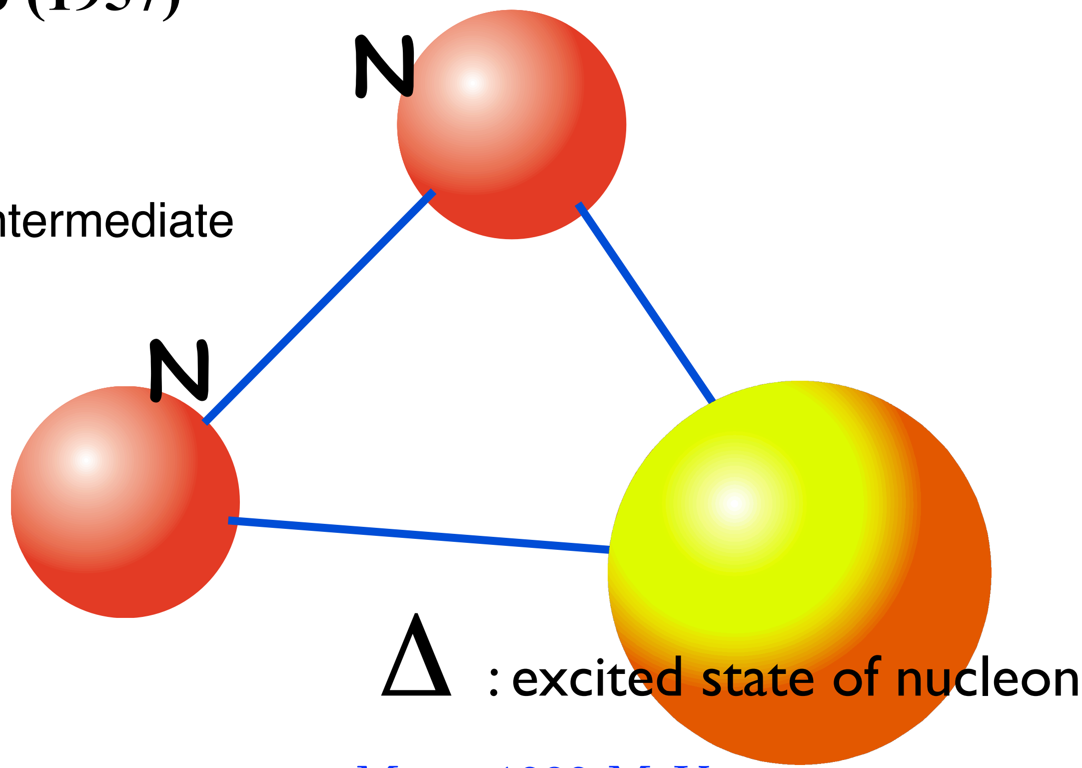

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- Tucson-Melbourne (TM)
- Urbana IX
- Brazil, Texas etc…

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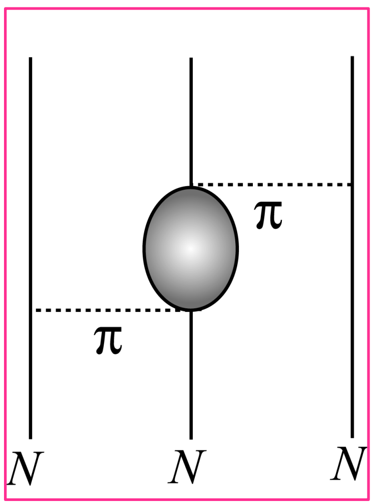

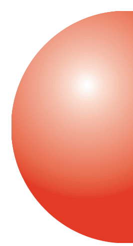

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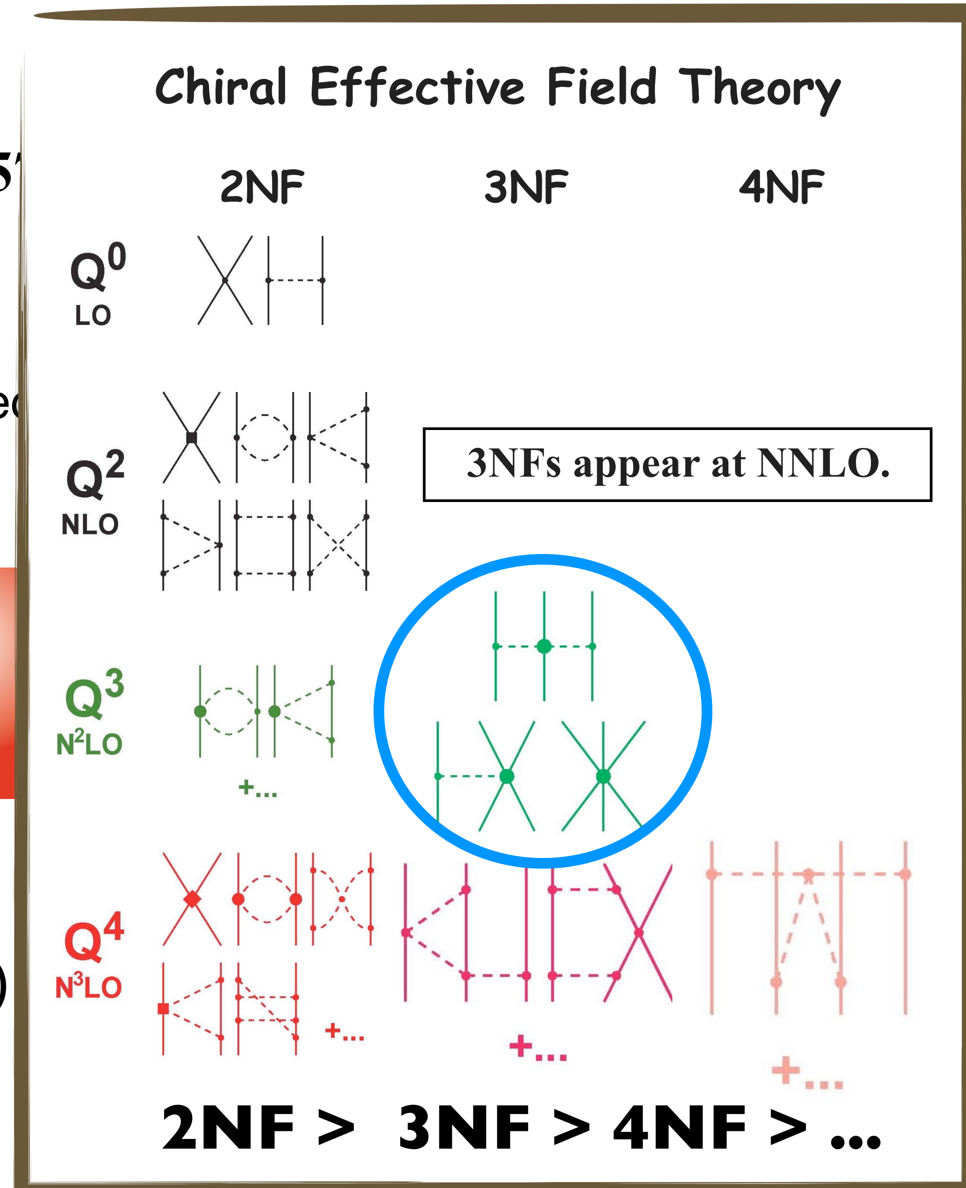
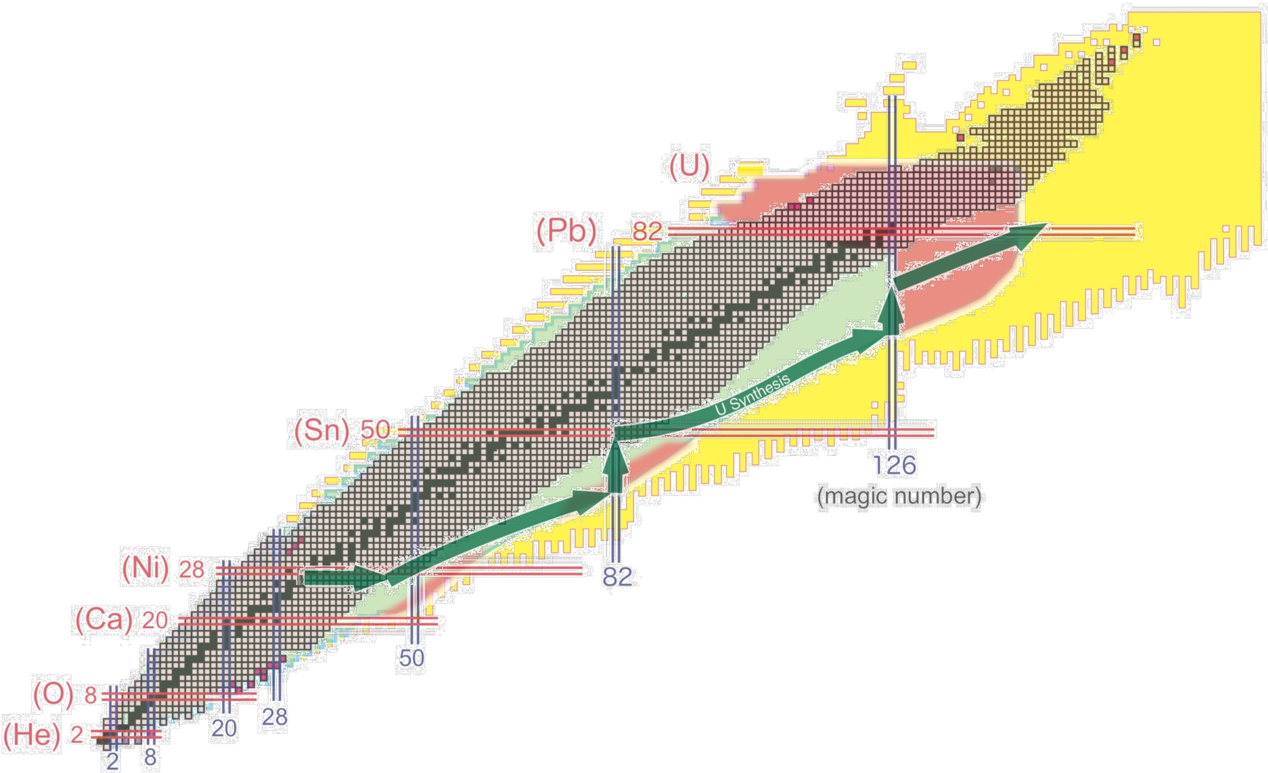


Where can we find 3NF effects ? - 1 -

3NFs in Finite Nuclei

Ab Initio Calculations for Light Nuclei

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



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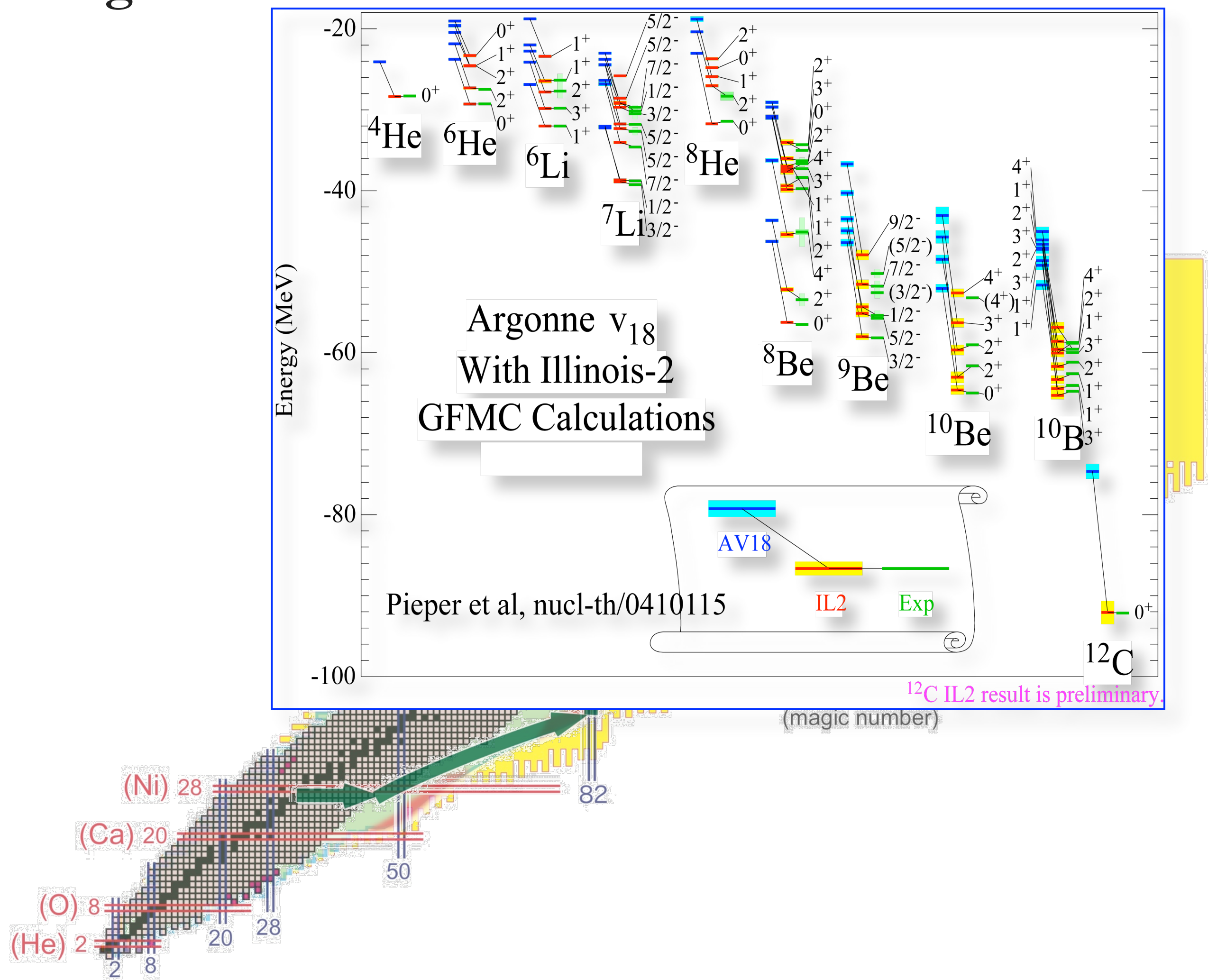

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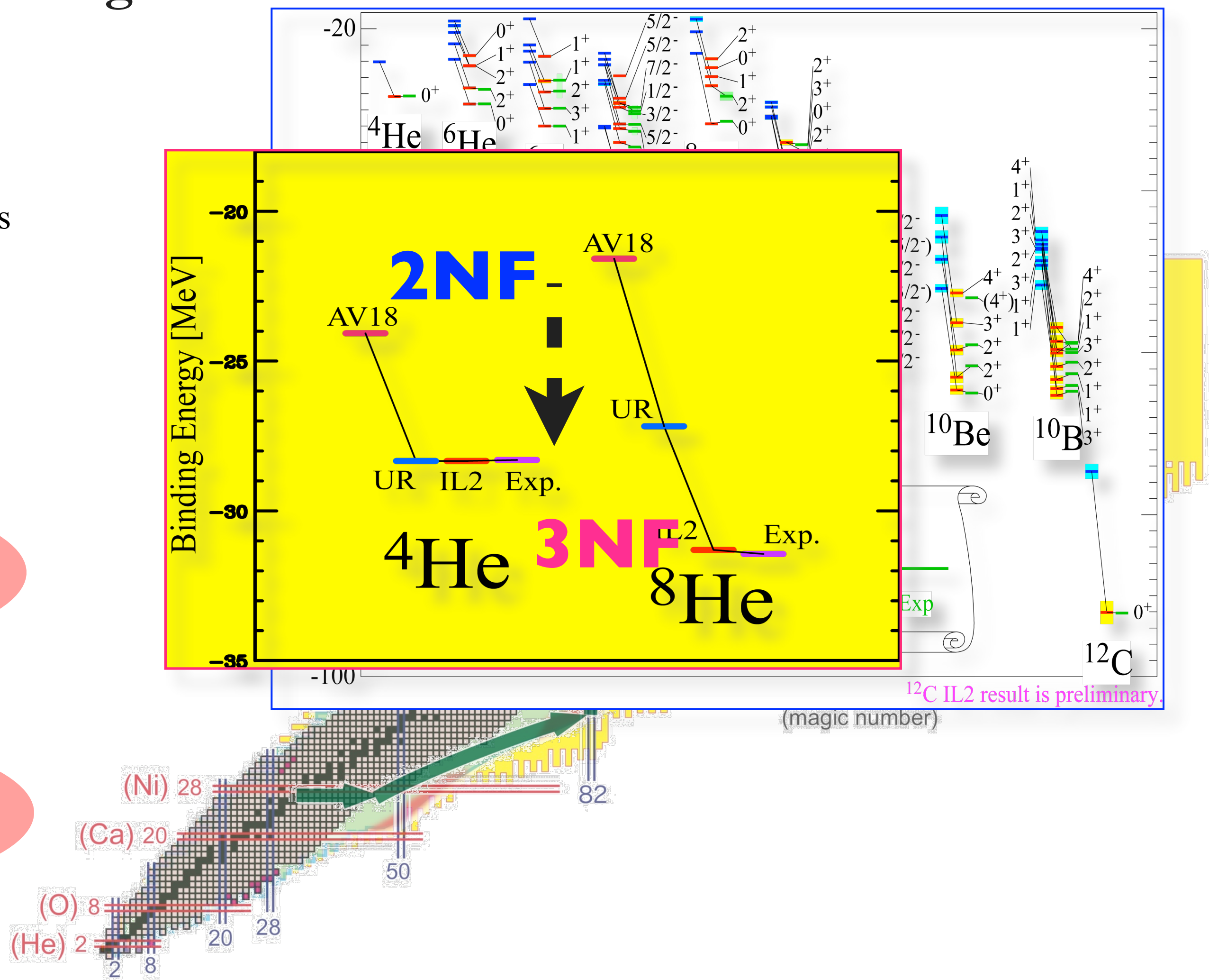
- 2NF provide less binding energies
- 3NF : well reproduce the data

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.



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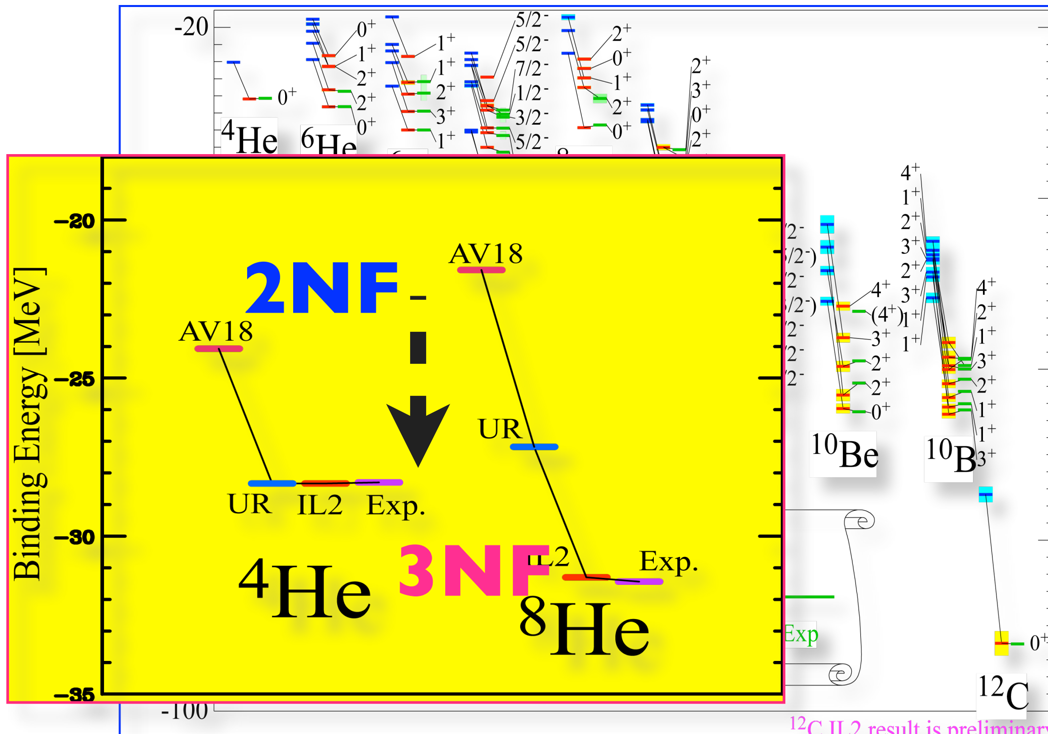

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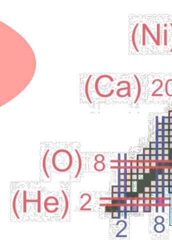
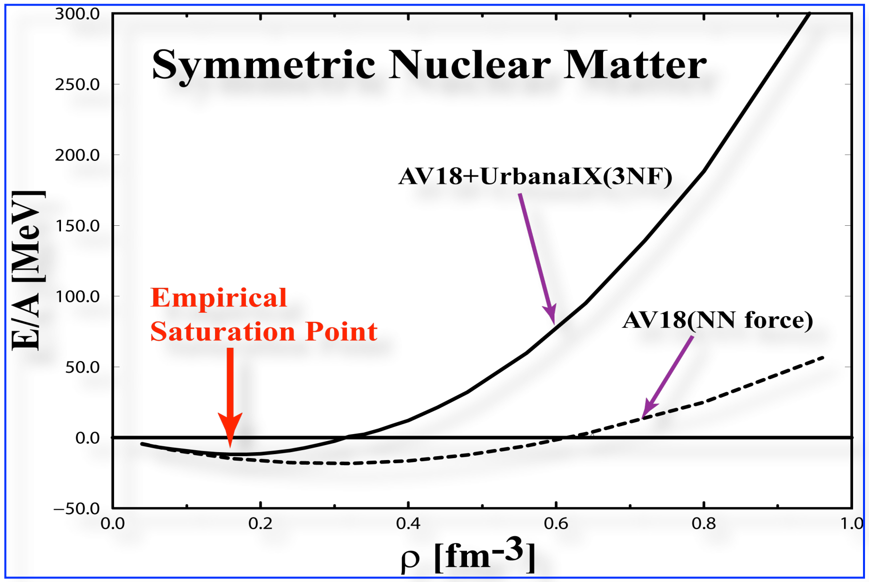


Recently extended to
- medium mass nuclei
- candidates of tetra-neutron state

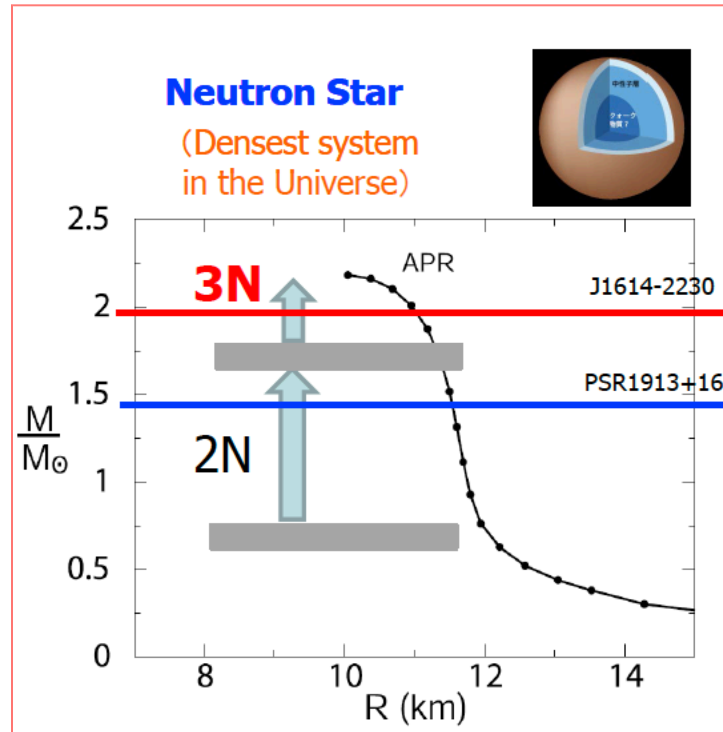
Where can we find 3NF effects ? - II -

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



- Short range repulsive terms of 3NFs
  (3-Baryon Fs) are taken as key elements
  to understand 2 M(sun) neutron star.

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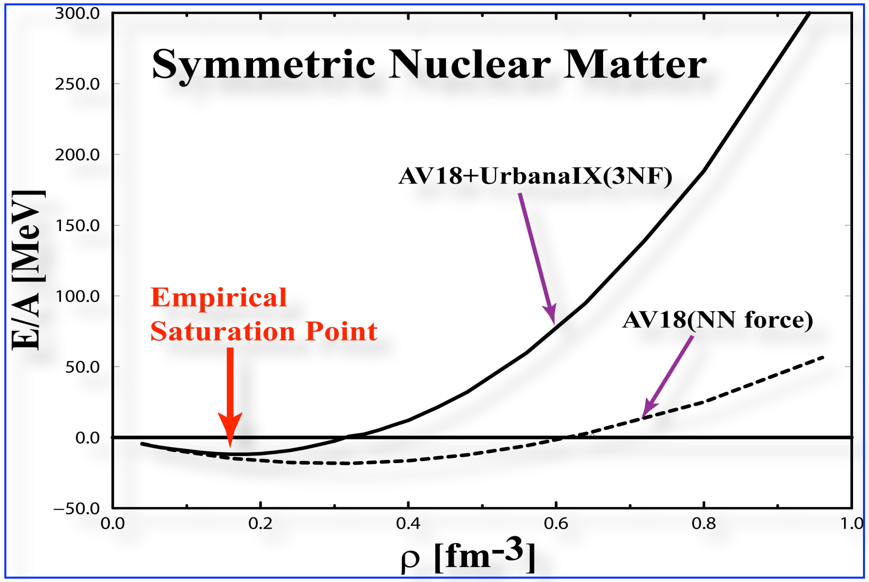

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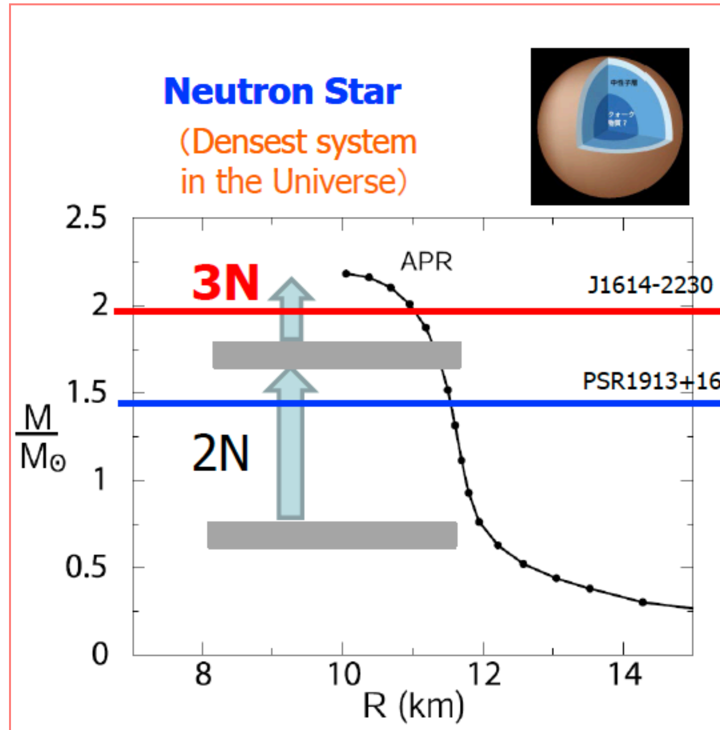
3NFs play important roles at high density



- Short range repulsive terms of 3NFs (3-Baryon Fs) are taken as key elements to understand 2 M(sun) neutron star.

- Understanding of 3NF is one key element to describe nuclear phenomena.
- How to constrain the properties of 3NF ?

Three-Nucleon Scattering is a good probe to study the dynamical aspects of 3NFs.

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

Three-Nucleon 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

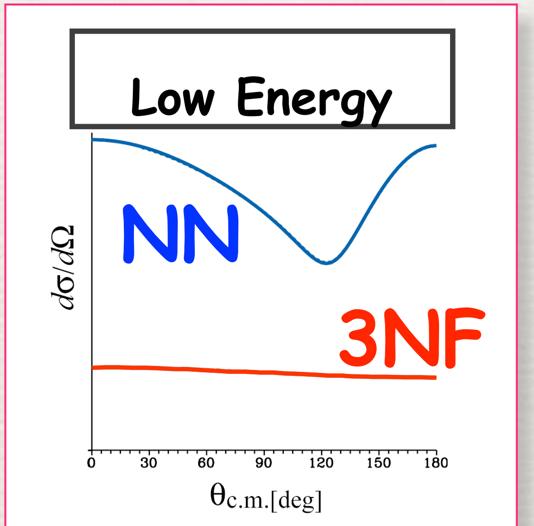
- Experiment : Precise Data
  - $d\sigma/d\Omega$, Spin Observables (A_i, K_{ij}, C_{ij})

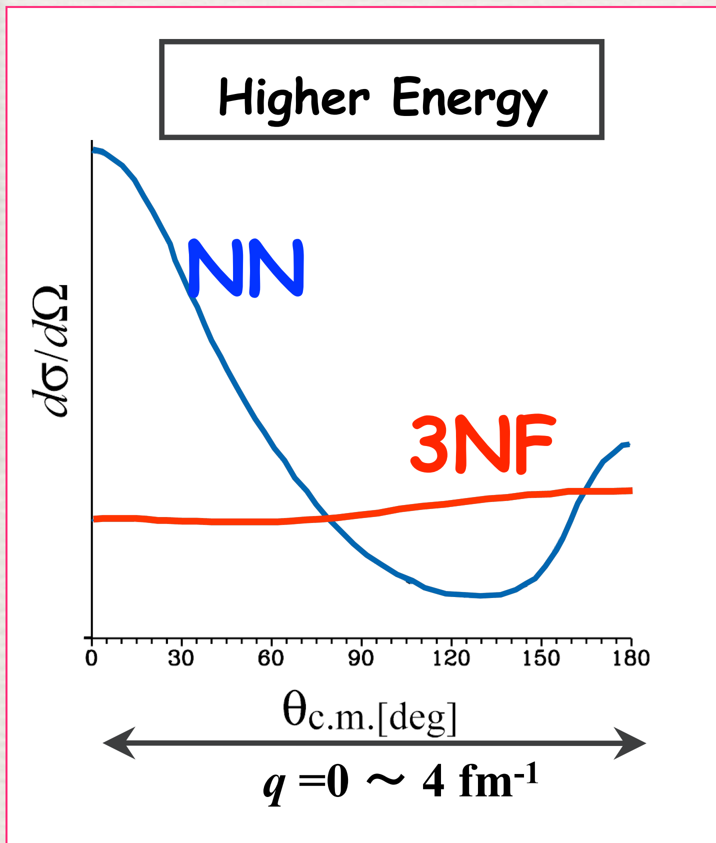
Extract fundamental information of Nuclear Forces.

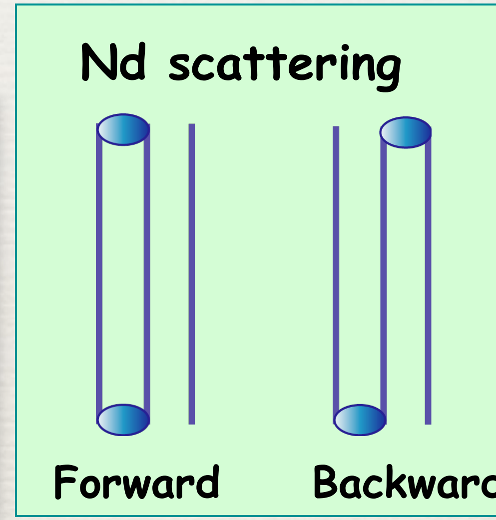
Where is the hot spot for 3NF ?

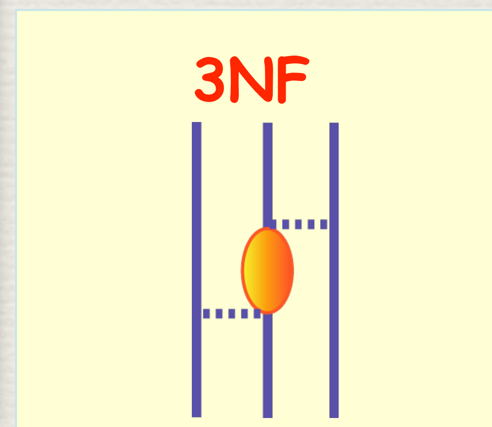
Predictions by H. Witala et al. (1998)

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

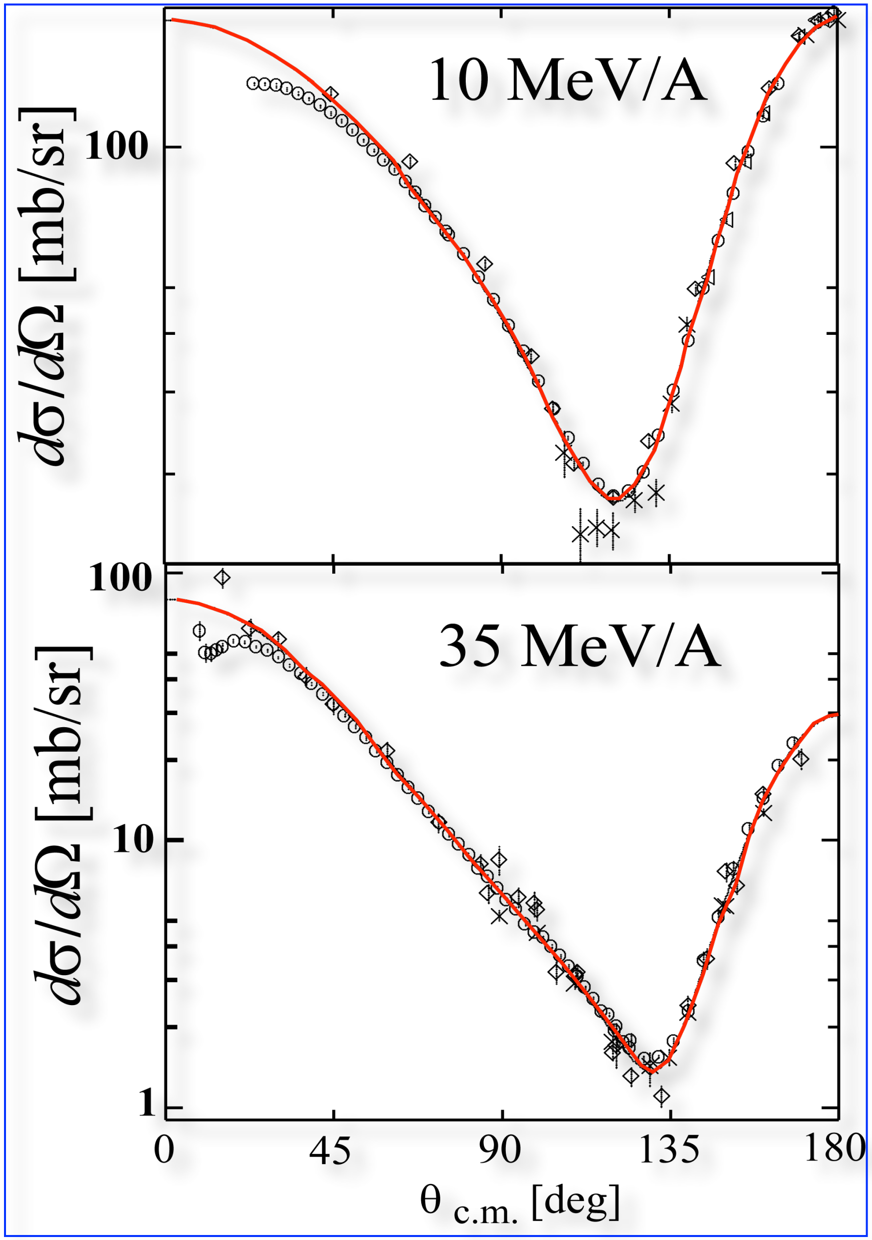








dp Scattering at Low Energies (E ≤ 30 MeV/A)



- High precision data are explained by Faddeev calculations based on 2NF.

No signatures of 3NF.

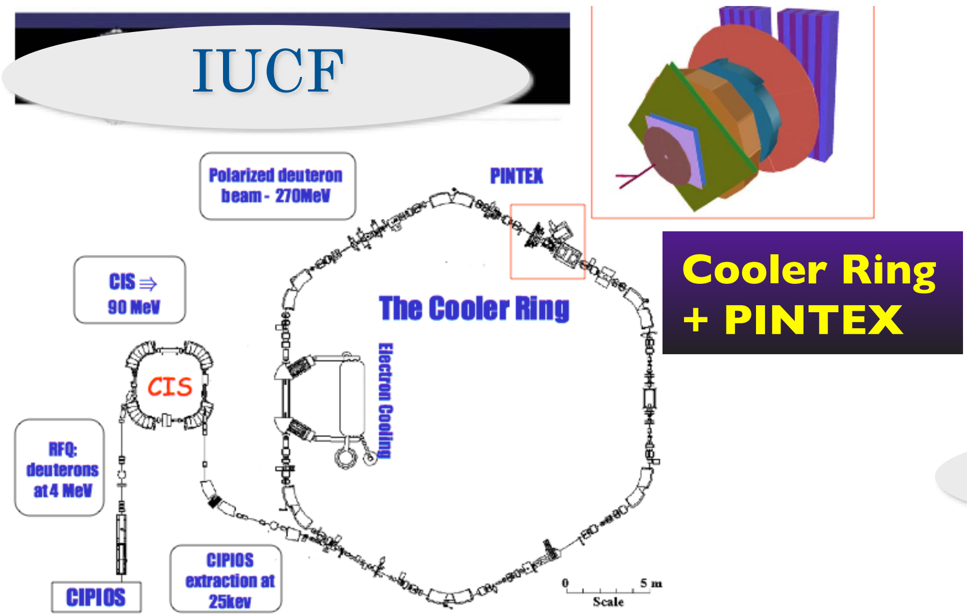
Exp. Data from
Kyushu, TUNL, Cologne etc..

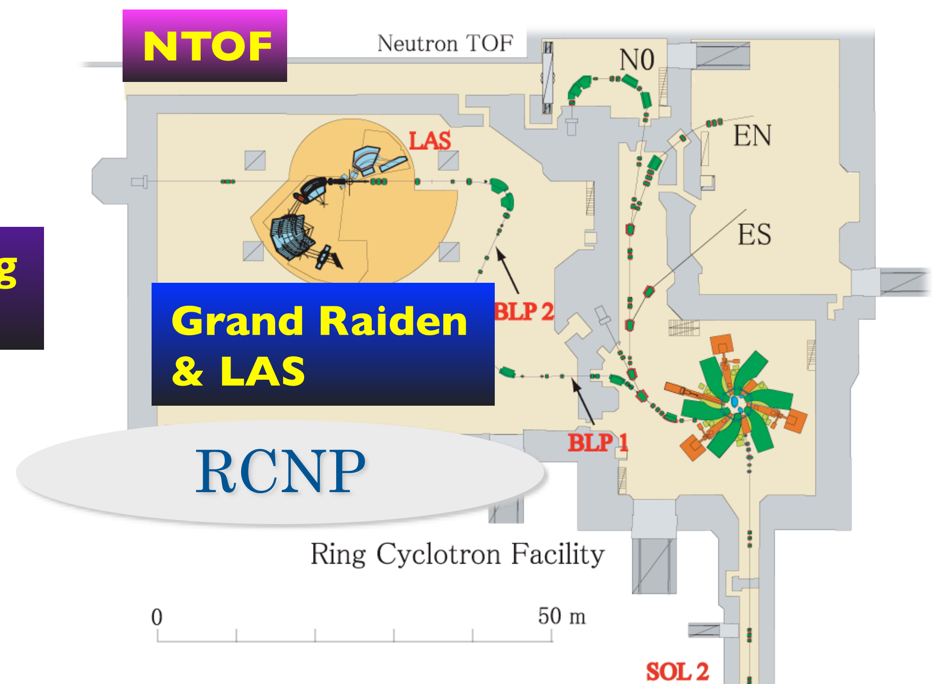
W. Glöckle et al., Phys. Rep. 274, 107 (1996).

Facilities

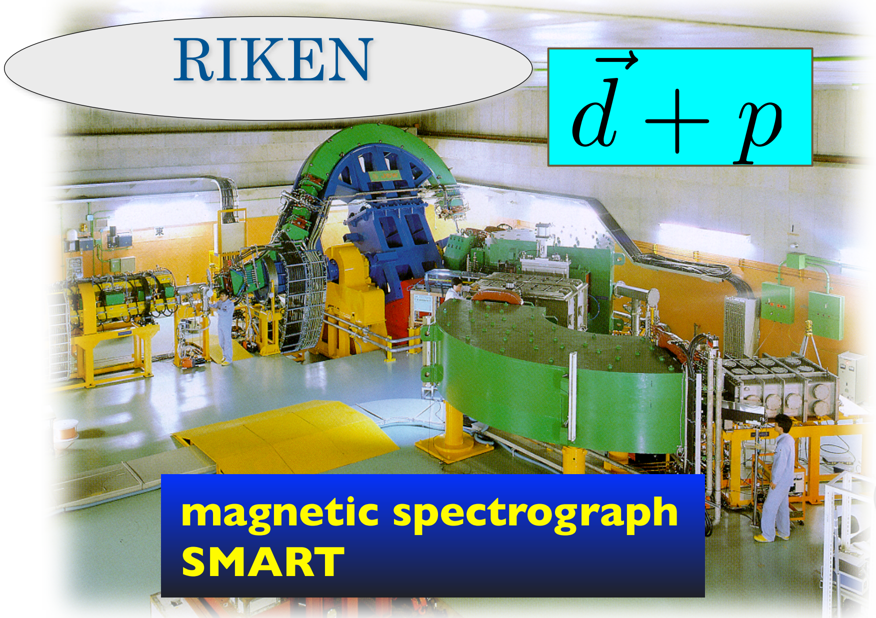

RIKEN
magnetic spectrograph
SMART


BINA
& SALAD
KVI
to Krakow
BBS

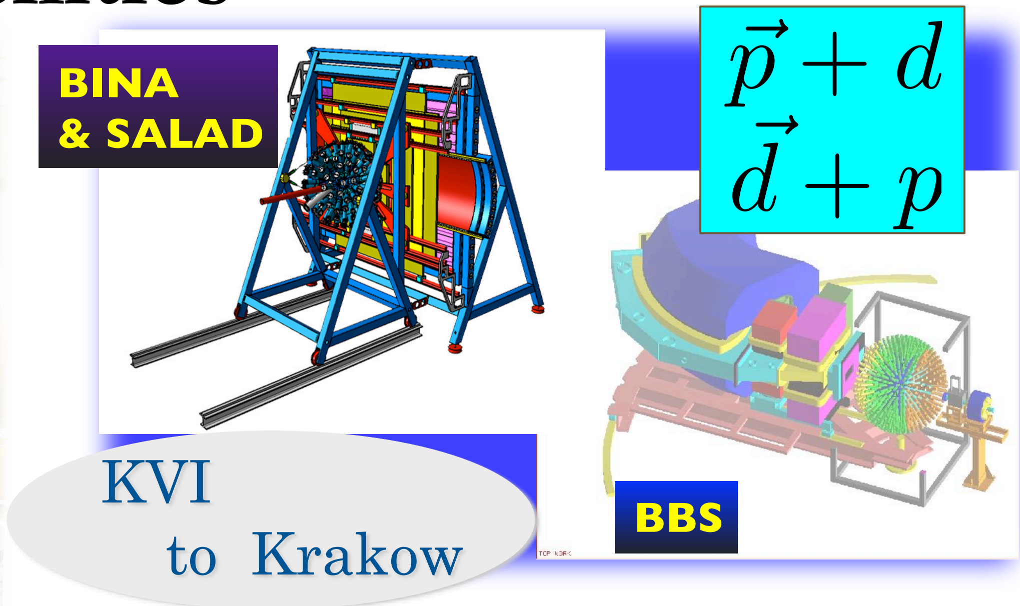

IUCF
Polarized deuteron
beam - 270MeV
PINTEX
CIS ⇒
90 MeV
CIS
The Cooler Ring
Electron Cooling
RFQ:
deuterons
at 4 MeV
CIPIOS
extraction at
25kev
CIPIOS
0
5 m
Scale
Cooler Ring
+ PINTEX


NTOF
Neutron TOF
N0
EN
ES
LAS
BLP 2
BLP 1
Grand Raiden
& LAS
RCNP
Ring Cyclotron Facility
0
50 m
SOL 2

Facilities



RIKEN
$\vec{d} + p$
magnetic spectrograph
SMART



BINA
& SALAD
$\vec{p} + d$
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KVI
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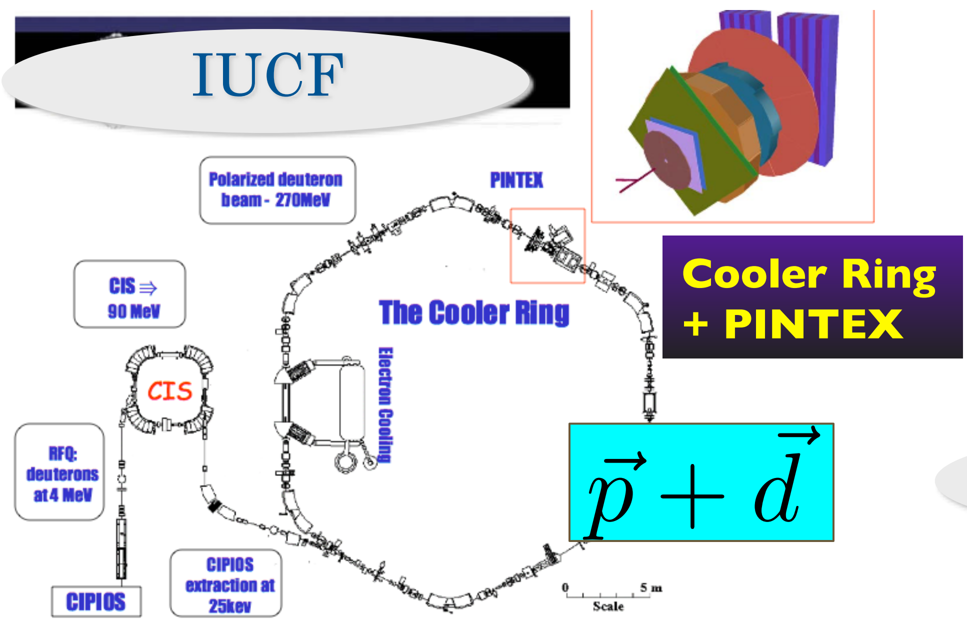
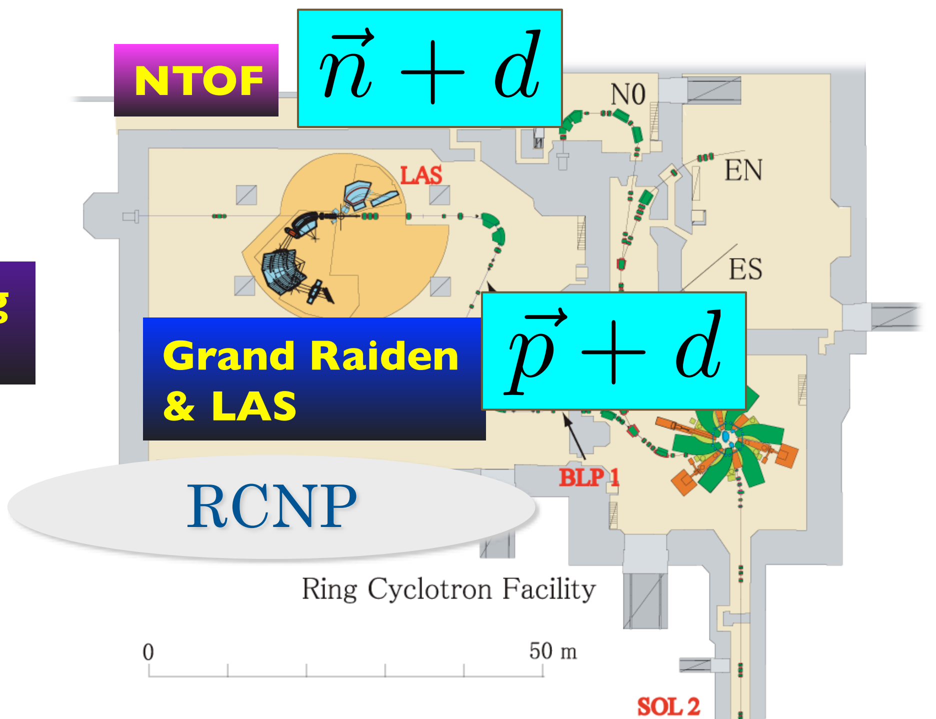


IUCF
Polarized deuteron beam - 270MeV
PINTEX
CIS ⇒ 90 MeV
The Cooler Ring
CIS
Electron Cooling
RFQ: deuterons at 4 MeV
CIPIOS
CIPIOS extraction at 25kev
Cooler Ring
+ PINTEX
$\vec{p} + \vec{d}$
0 5 m
Scale



NTOF
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BLP 1
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0
50 m
SOL 2

dp Scattering

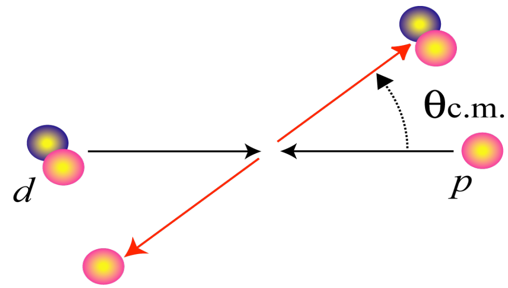
- $d + p \longrightarrow d + p$

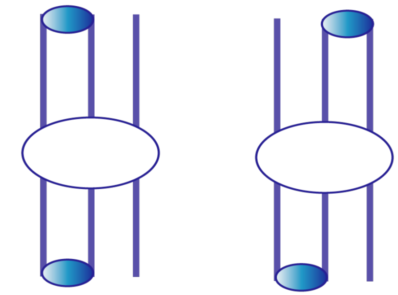
$\theta_{c.m.} = 0° \sim 180°$

Momentum transfer

q =0 - 3.4 fm^{-1}

(at E = 135 MeV/A)



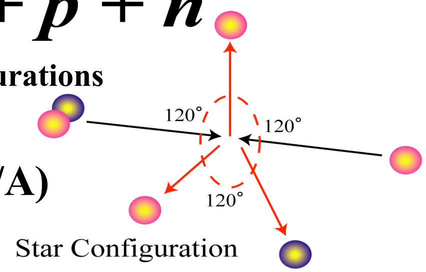


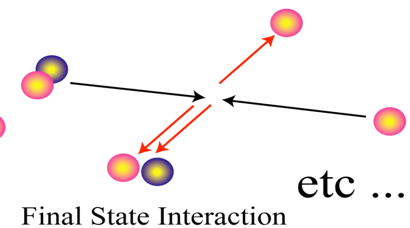
- $d + p \longrightarrow p + p + n$

Many kinematical configurations

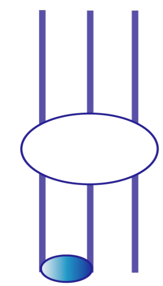
q =0 - 3 fm^{-1}

(at E = 135 MeV/A)





etc ...

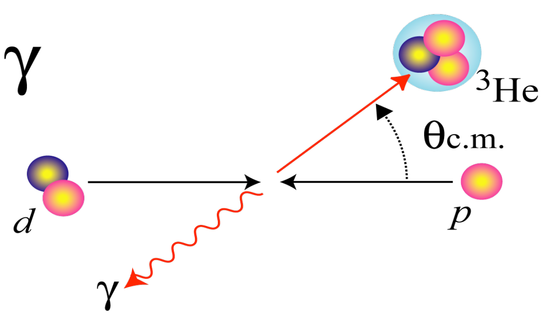


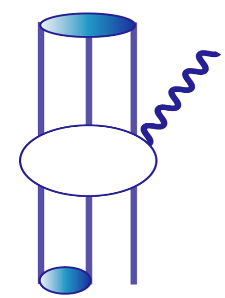
- $d + p \longrightarrow {}^3He + \gamma$

$\theta_{c.m.} = 0° \sim 180°$

q =1.5 - 2.5 fm^{-1}

(at E = 135 MeV/A)





dp Scattering

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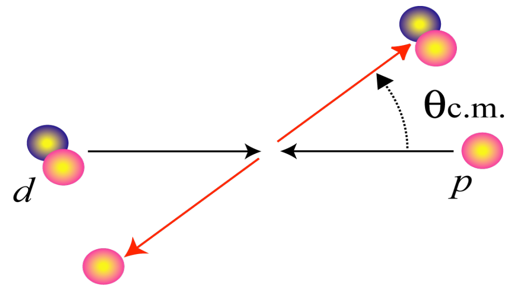
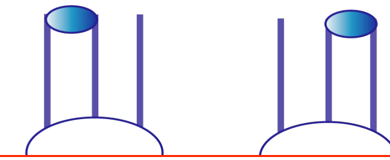
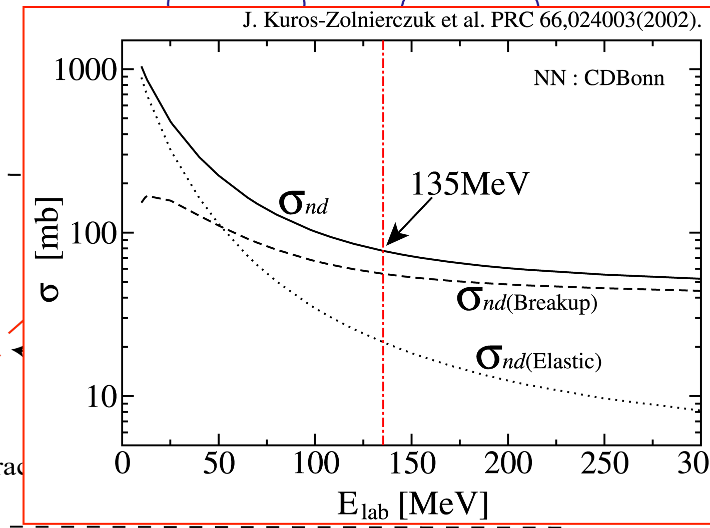
Momentum transfer

***q* =0 - 3.4 fm^{-1}**

(at *E* = 135 MeV/A)







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Many kinematical configurations

***q* =0 - 3 fm^{-1}**

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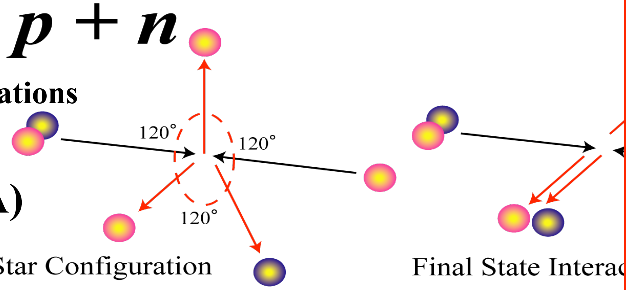

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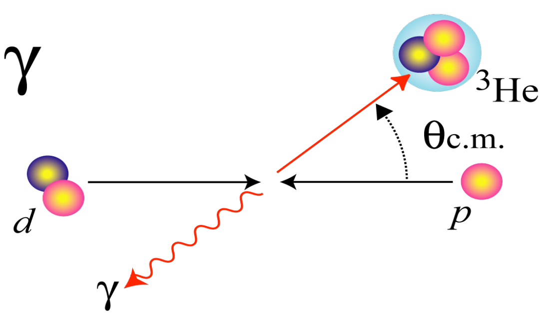

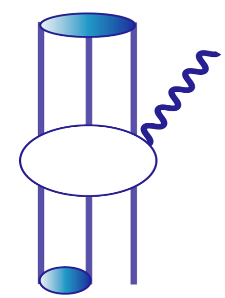

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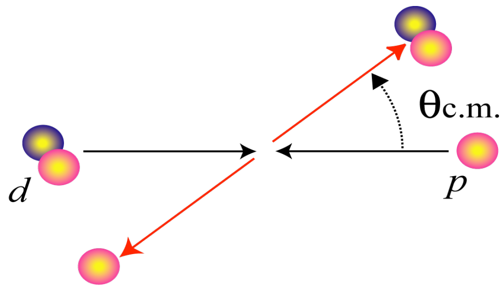

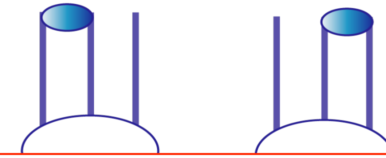

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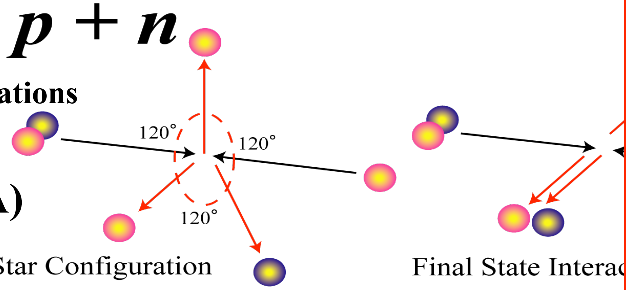

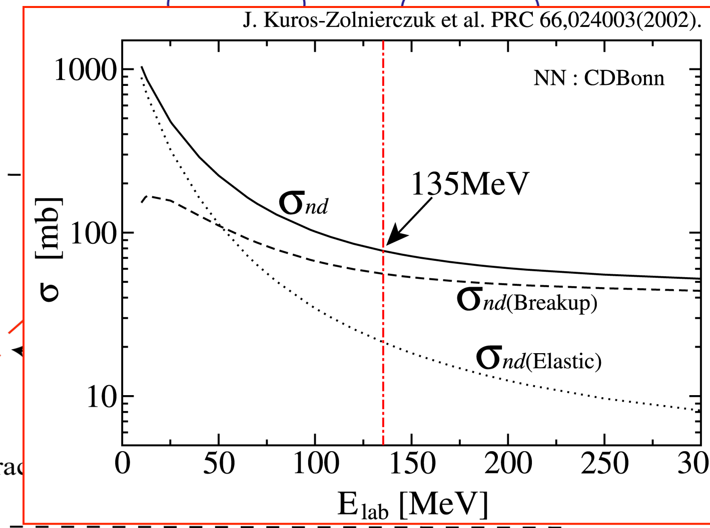

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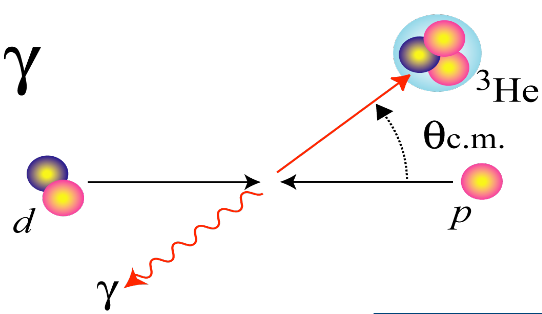
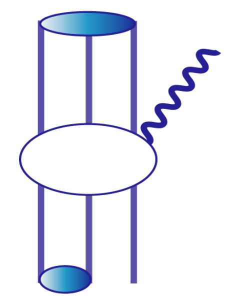




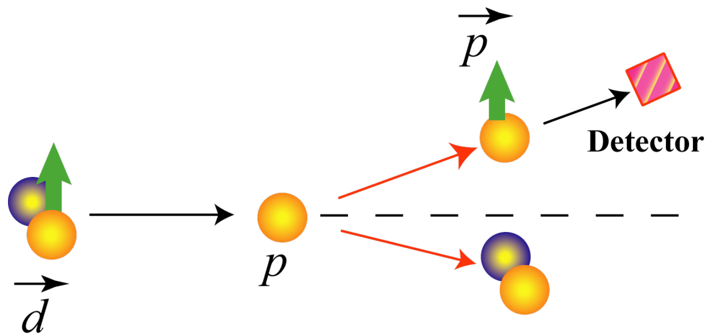
+ meson exchange currents

Observable for dp Scattering

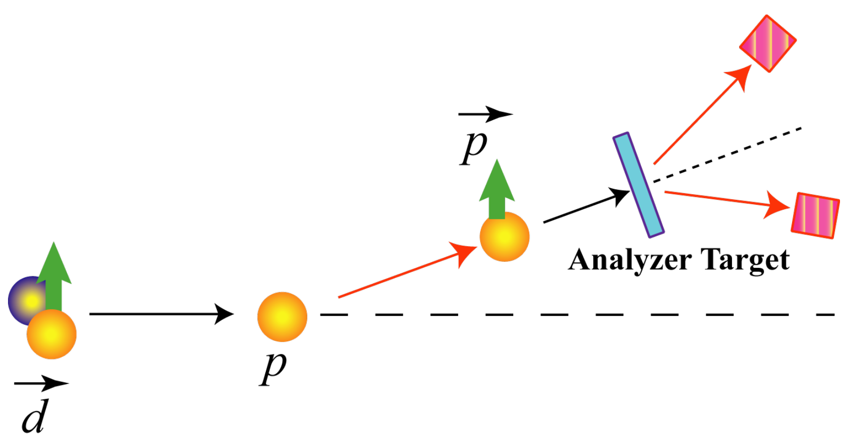
- **Differential Cross Section**
  - Overall Strength
  - ➢ Absolute Quantity : normalization to *pp or np* data

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

- **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}
    - Spin-Spin interaction



Precise Measurement of *d-p* scattering at RIKEN

$$d + p \rightarrow d + p$$

1 **Differential Cross Section** **and** **All Deuteron Analyzing Powers**

(iT_{11} , T_{20}, T_{21} , T_{22}) at 70, 100, 135, 190, 250, 300 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**

$$d + p \rightarrow p + p + n$$

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

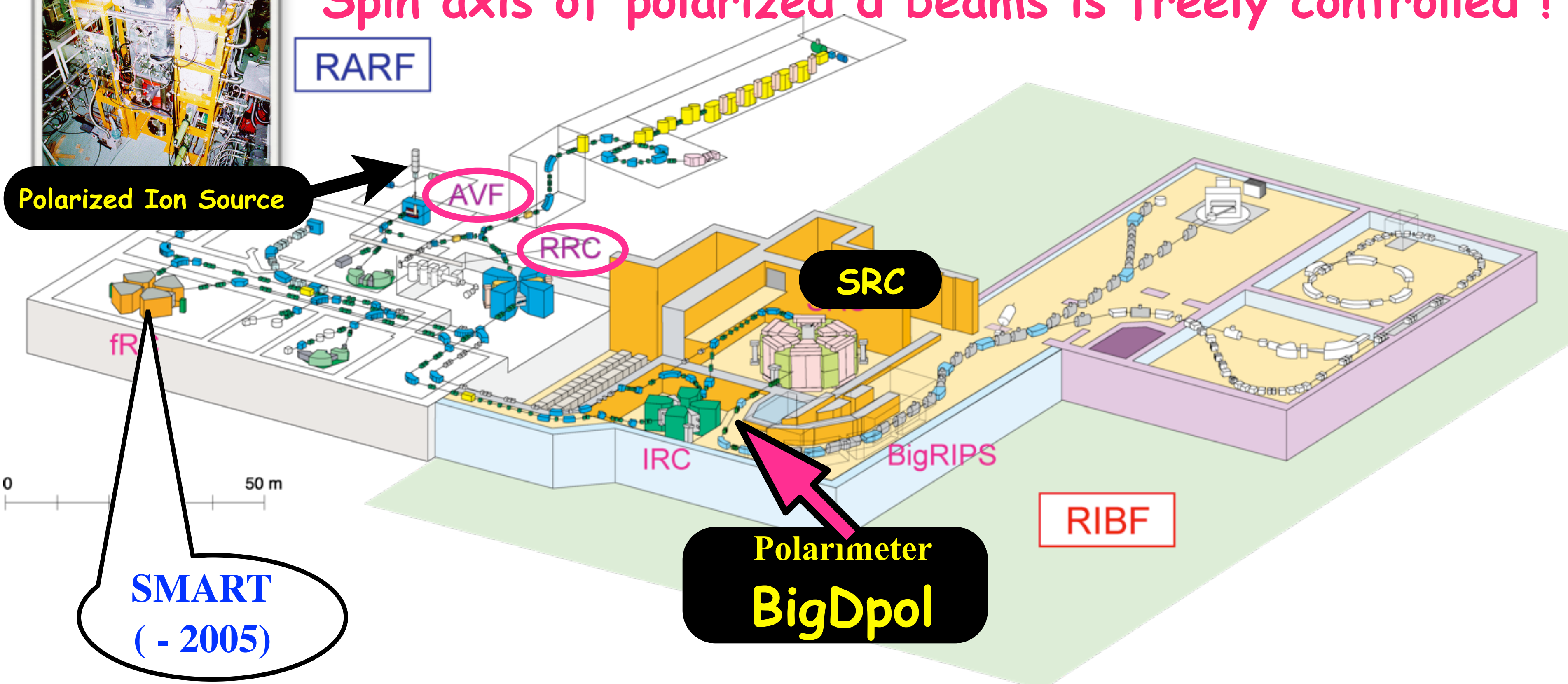
RIKEN RI Beam Factory (RIBF)

- **Polarized *d* beam : 70 - 300 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.**

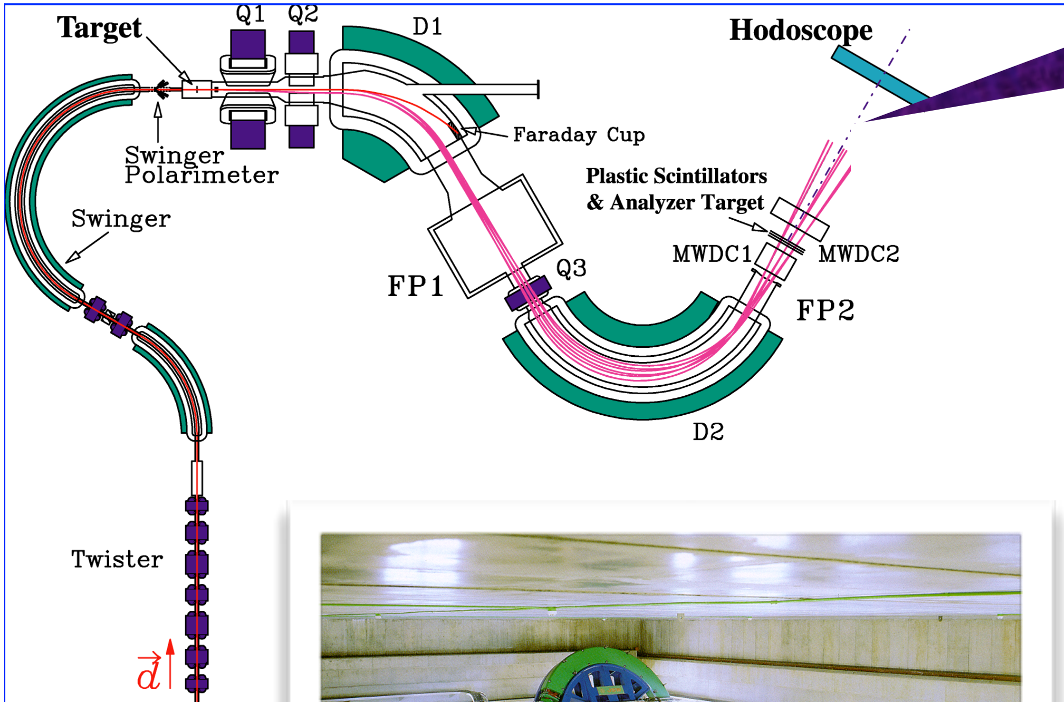
- **Beam Polarization : 80% of theoretical maximum values**

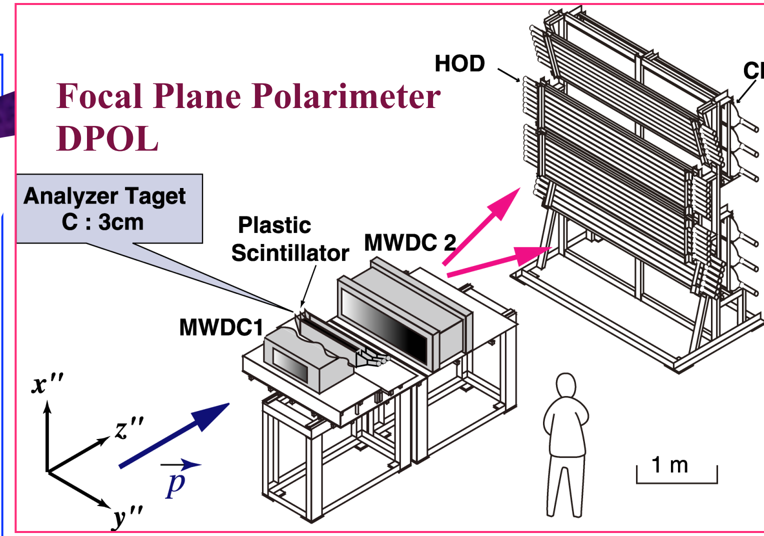
Spin axis of polarized d beams is freely controlled !

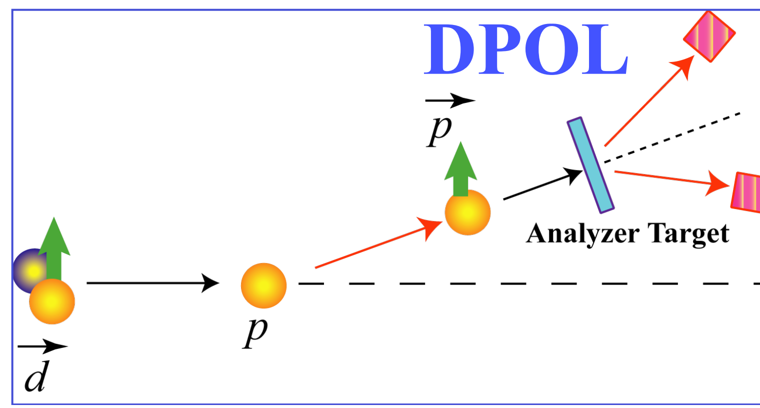


SMART at RIKEN (- 2005)

Swinger and Magnetic Analyzer with Rotator and Twister



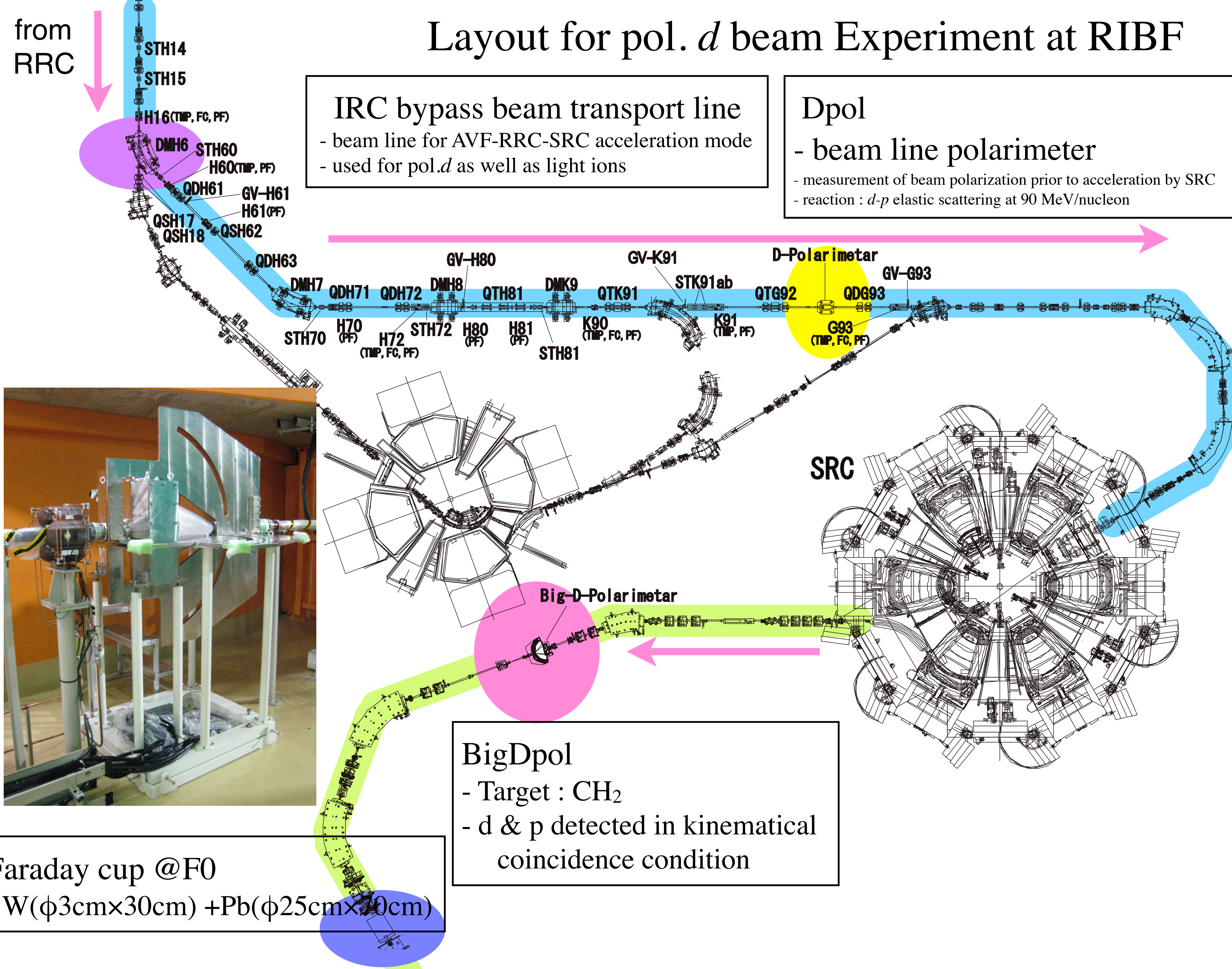




Layout for pol. *d* beam Experiment at RIBF

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)

Data are compared with

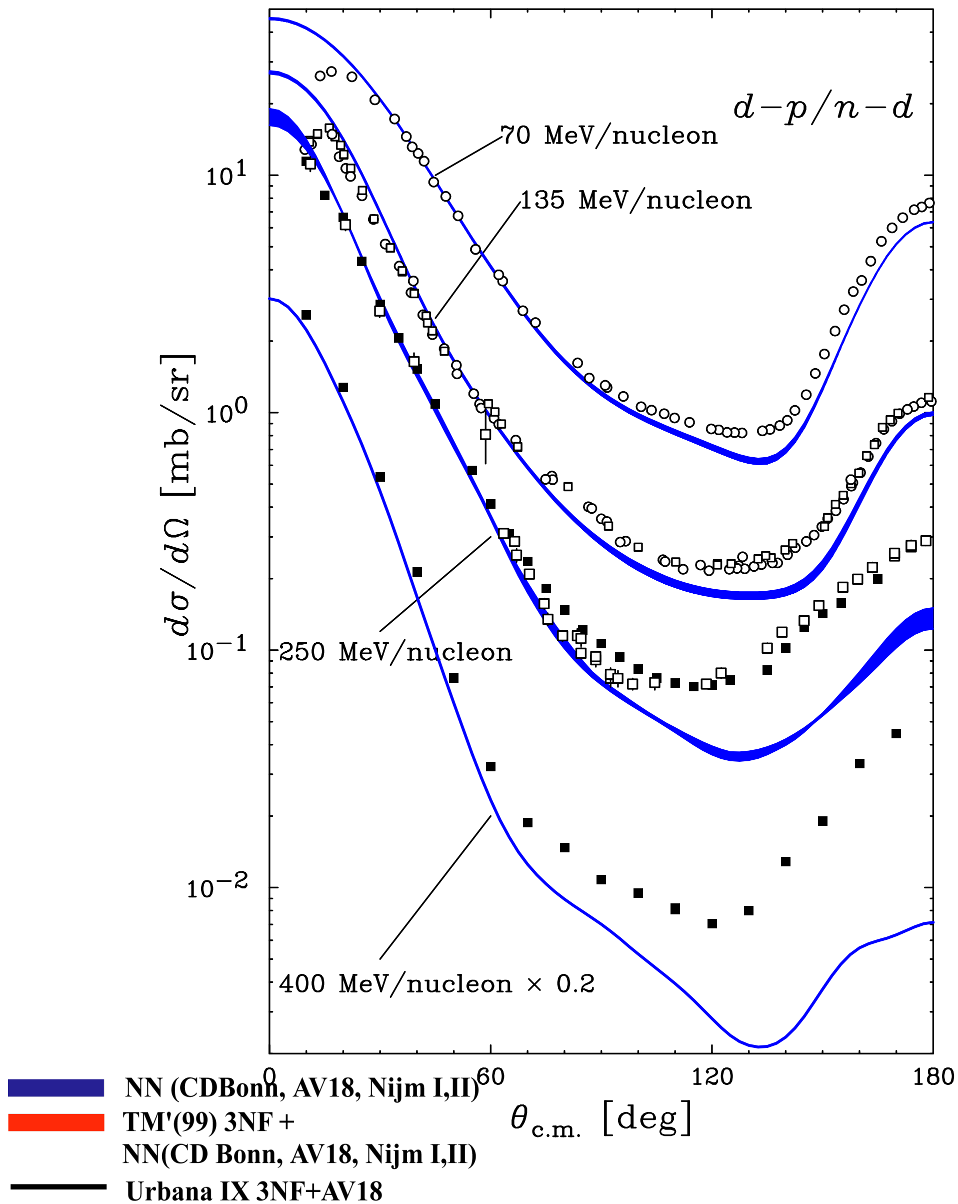
- CD Bonn, AV18, Nijmegen I, II
- CD Bonn, AV18, Nijmegen I, II + TM'99 3NF
- AV18 + Urbana IX 3NF
- Chiral EFT N4LO NN

dp elastic scattering

Cross Section

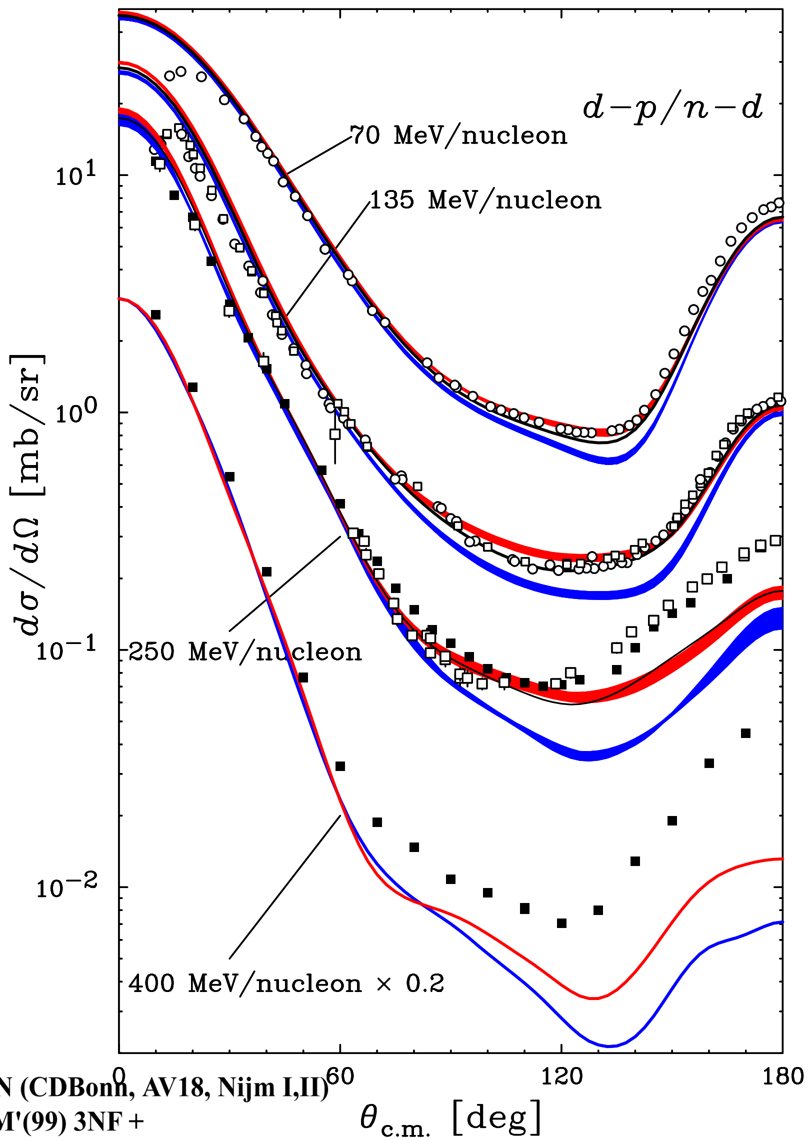
K.S. et al., Phys. Rev. C. 65,034003 (2002)
K.Hatanaka et al., Phys. Rev. C 66,044002 (2002)
K.S. et al., Phys. Rev. Lett. 95,162301 (2005)
Y. Maeda et al., Phys. Rev. C 76,014004 (2007)

Differential Cross Section at 70 - 400 MeV/nucleon



- NN only
- Large discrepancy in the backward region

Differential Cross Section at 70 - 400 MeV/nucleon

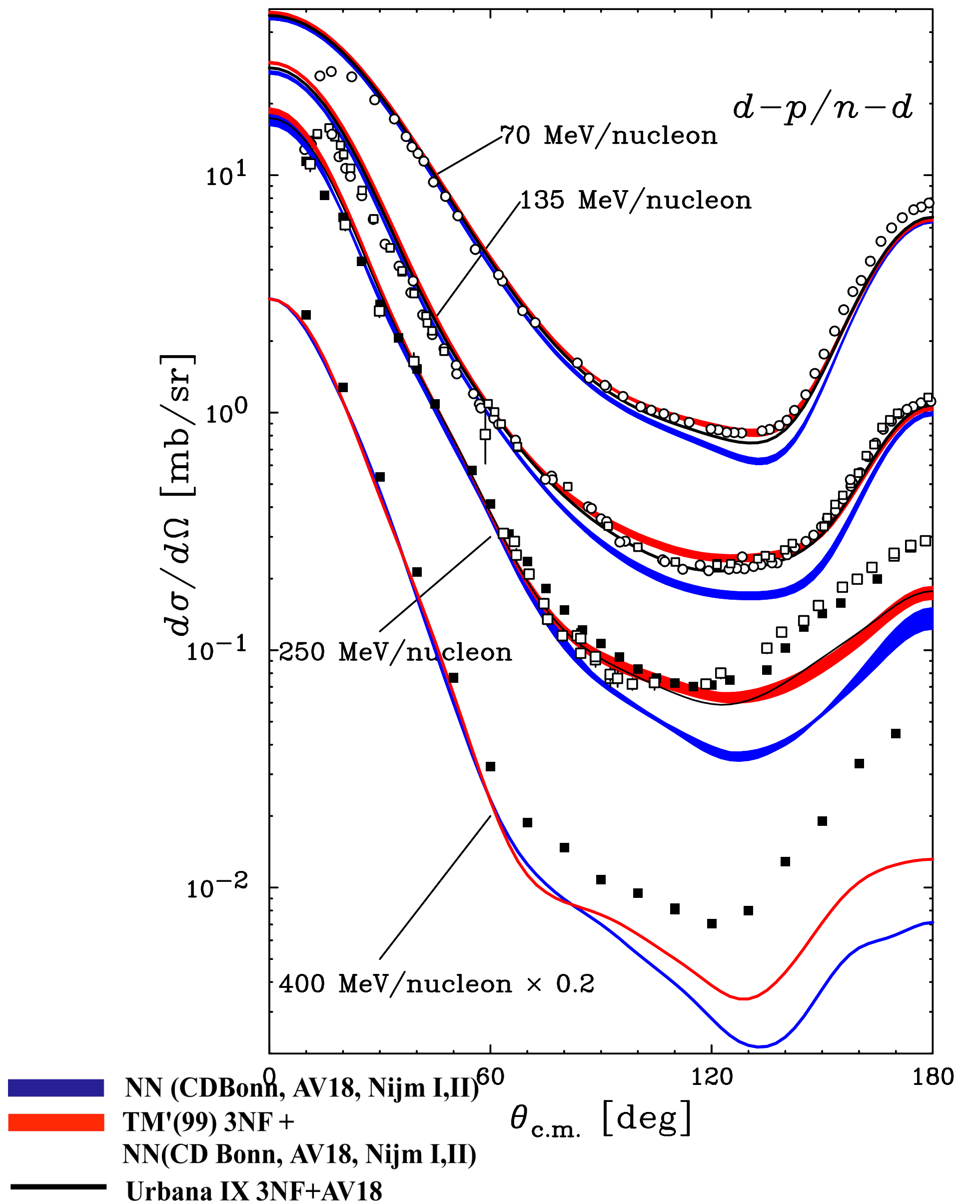


- NN (CDBonn, AV18, Nijm I,II)
- TM'(99) 3NF + NN(CD Bonn, AV18, Nijm I,II)
- Urbana IX 3NF+AV18

- 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



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  - improve the agreement
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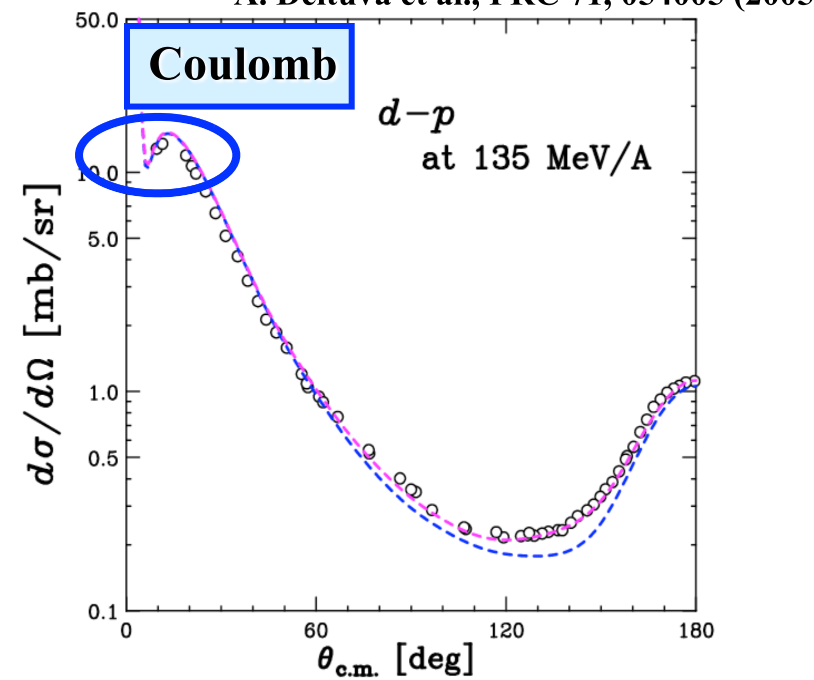
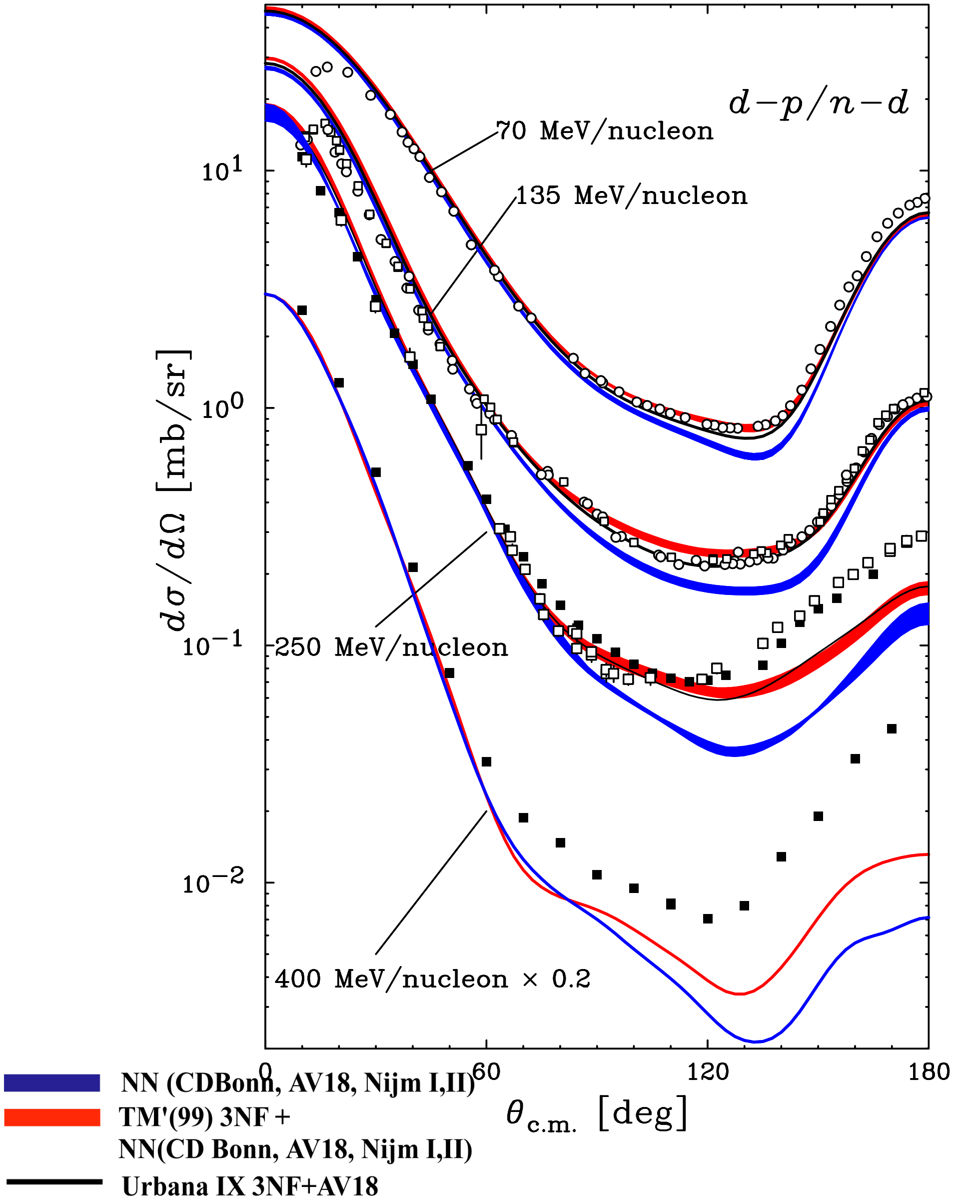
A. Deltuva et al., PRC 68, 024005 (2003)
A. Deltuva et al., PRC 71, 054005 (2005)

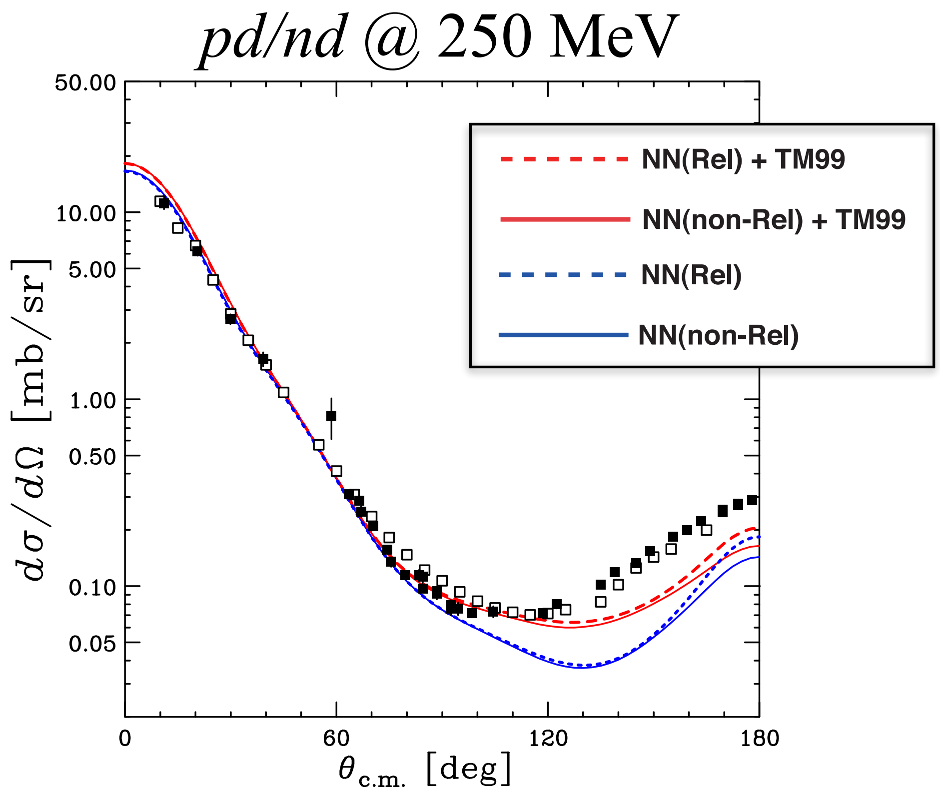


Differential Cross Section at 70 - 400 MeV/nucleon



Calculations with Lorentz boosted NN potentials with TM'99 3NF

H. Witala et al, private communications

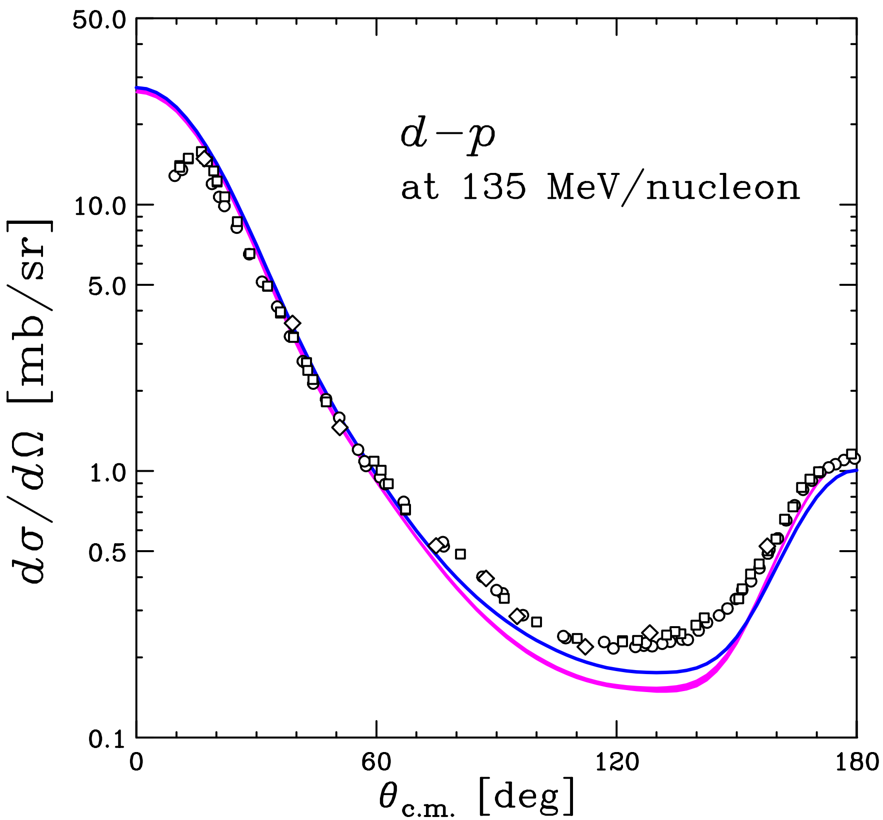


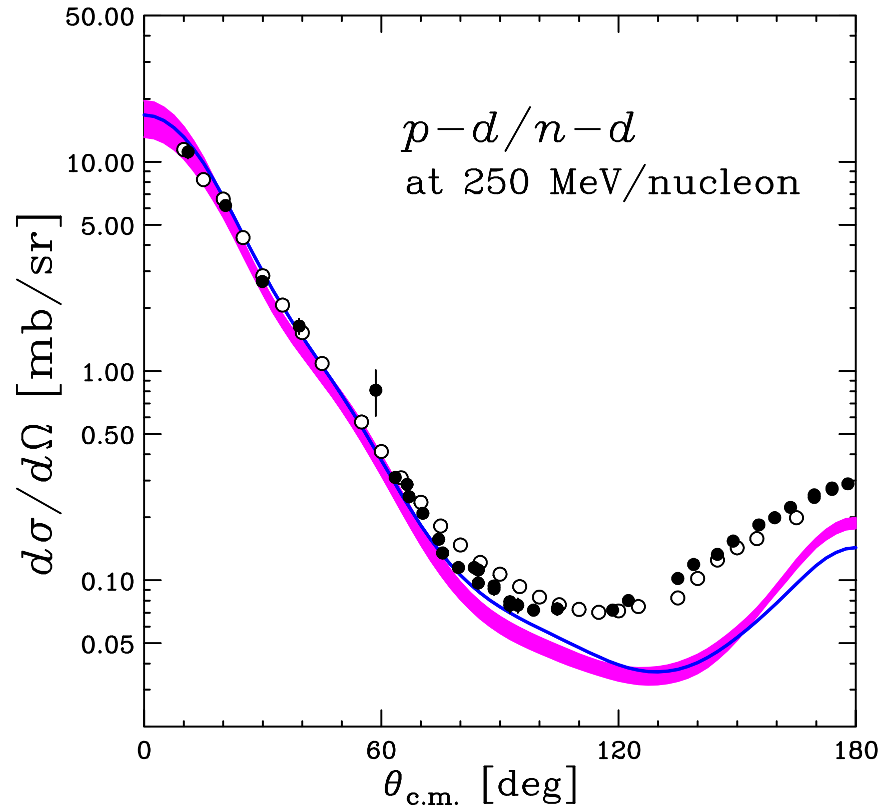
Relativistic effects are visible at backward angles, but small.

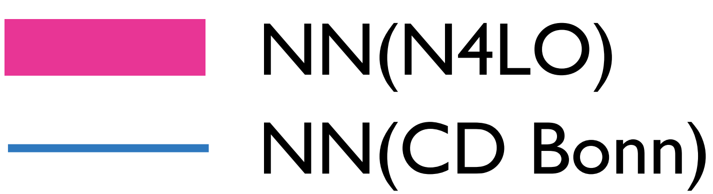
Differential Cross Section at 135 & 250 MeV/nucleon

Chiral EFT N4LO NN pot.

E. Epelbaum et al, private communications







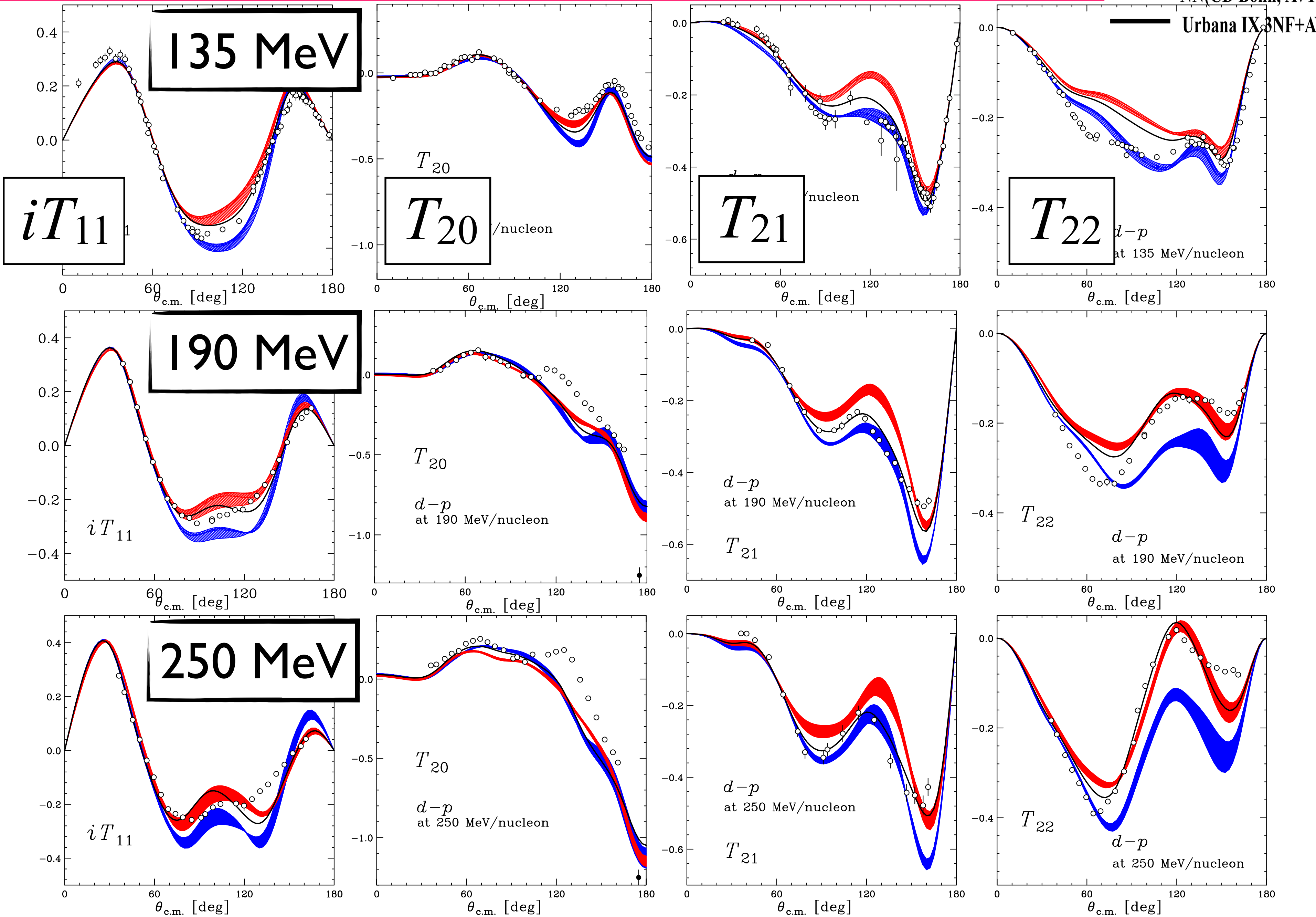
- It is very interesting to see how χEFT 3NFs explain the cross section data especially at very backward angles at 250 MeV/nucleon !

dp elastic scattering

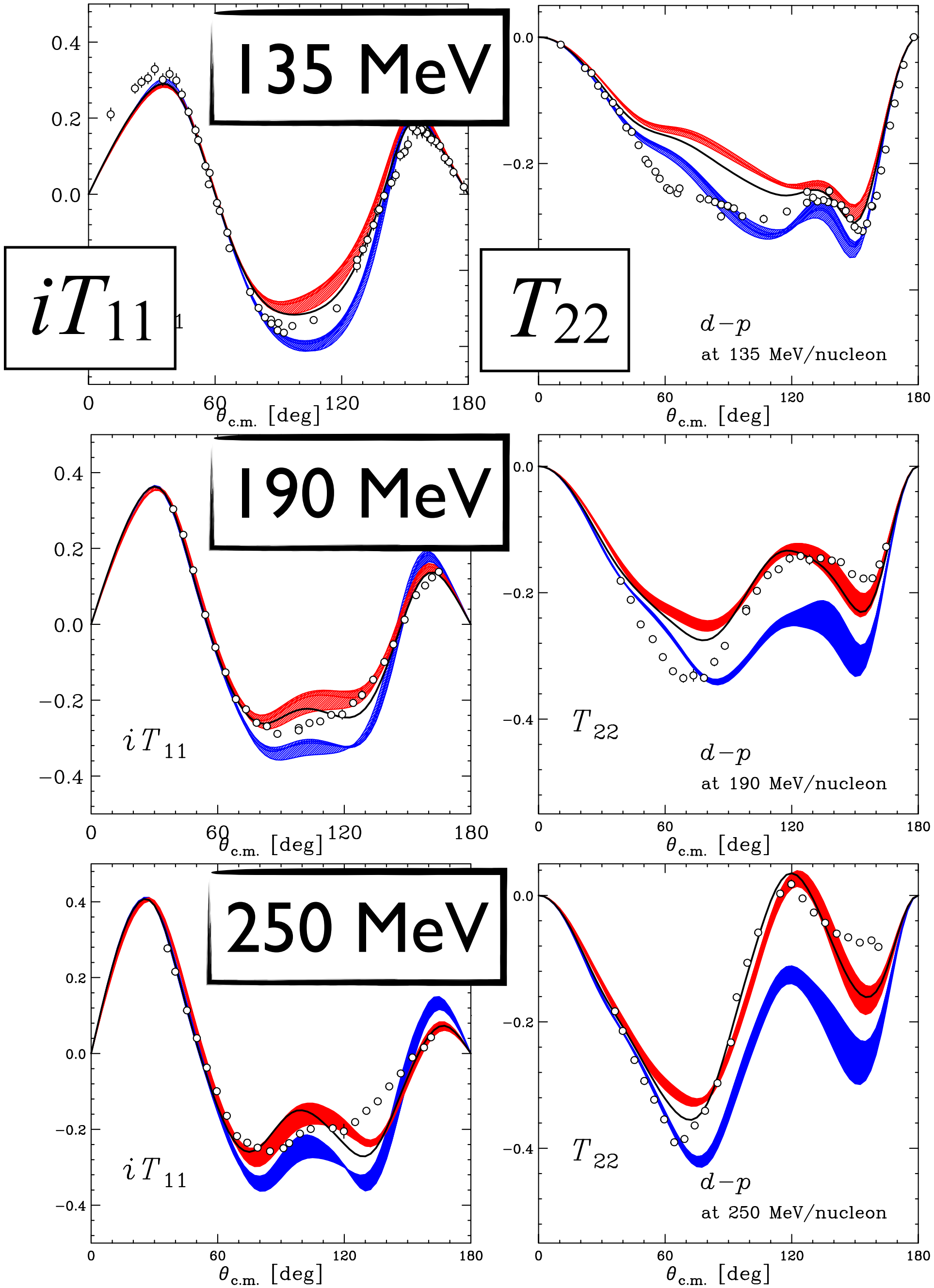
Spin Observables

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



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

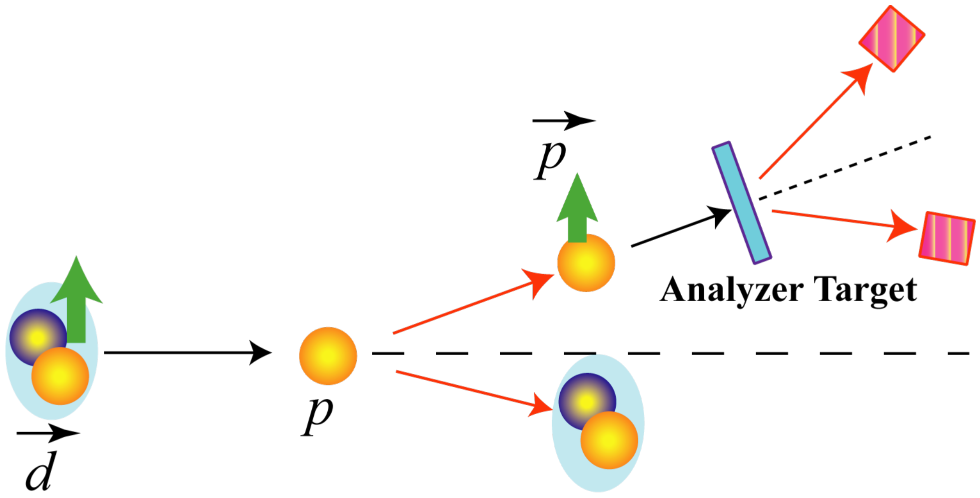
- NN only
- Large discrepancy in the backward angles

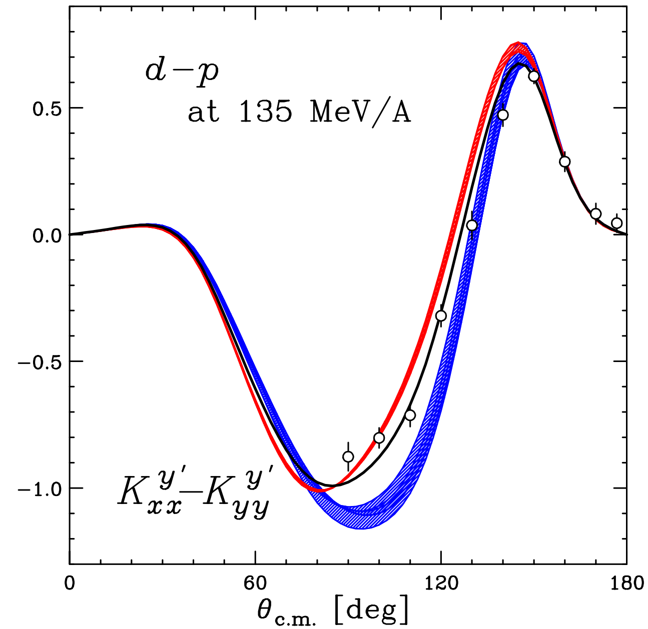
- + 2π3NF at 135 MeV
- results are NOT always similar to the cross section.

- + 2π3NF at 190, 250 MeV
- improve the agreement
- not enough at very backward angles

Polarization Transfer at 135 MeV/nucleon

K. S. et al. PRC 70, 014001(2004)



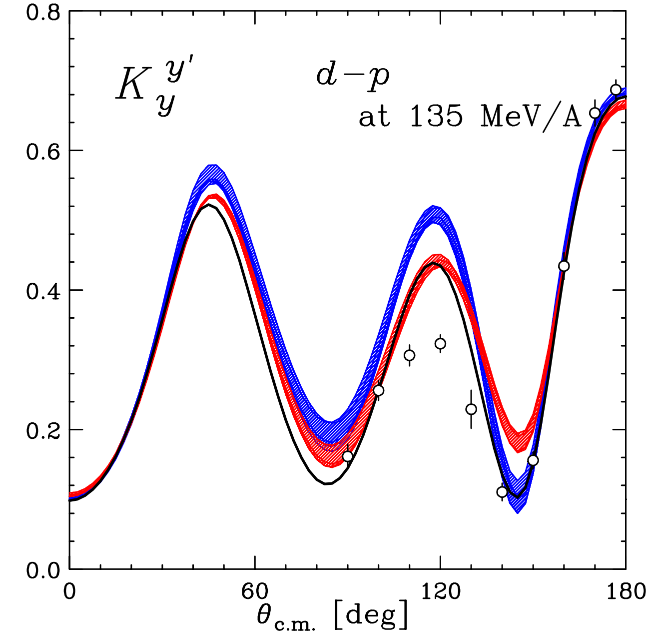


3NF :

$K_{xx}^{y'}-K_{yy}^{y'}$: **Good Agreement**

$K_{y}^{y'}$: **Direction : O.K.**

Magnitude : not enough



Polarization Transfer at 135 MeV/nucleon

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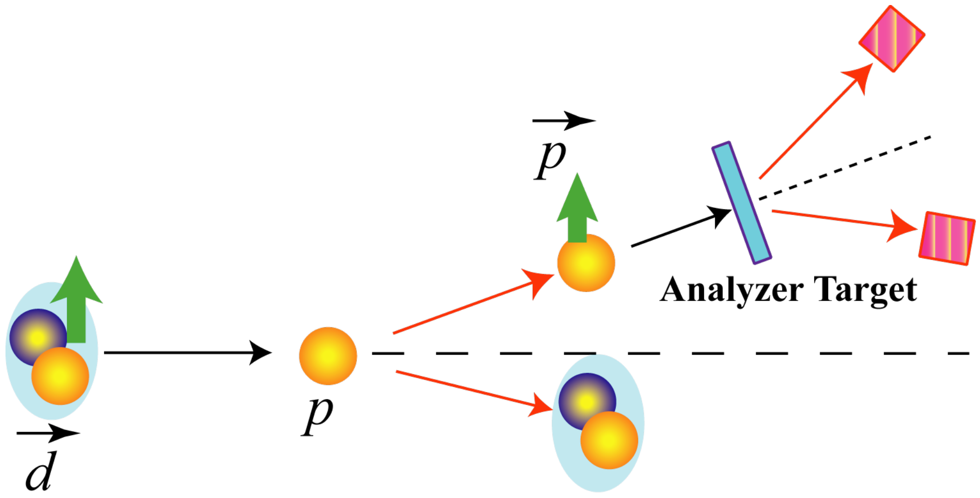

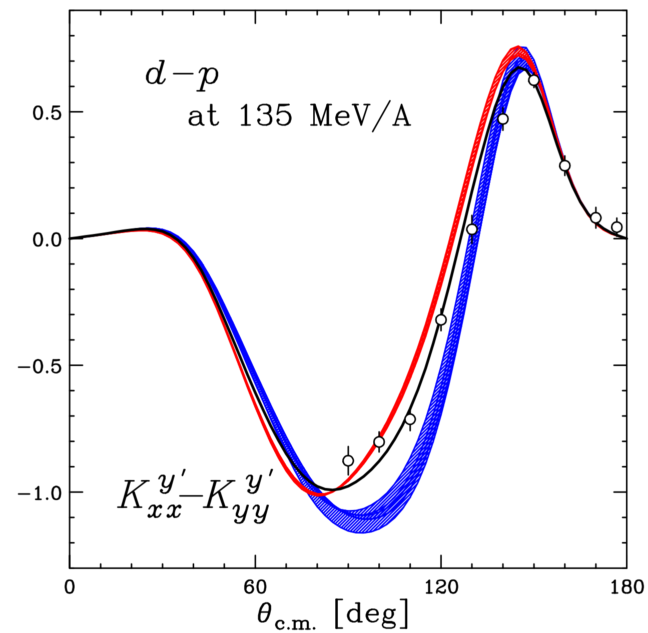

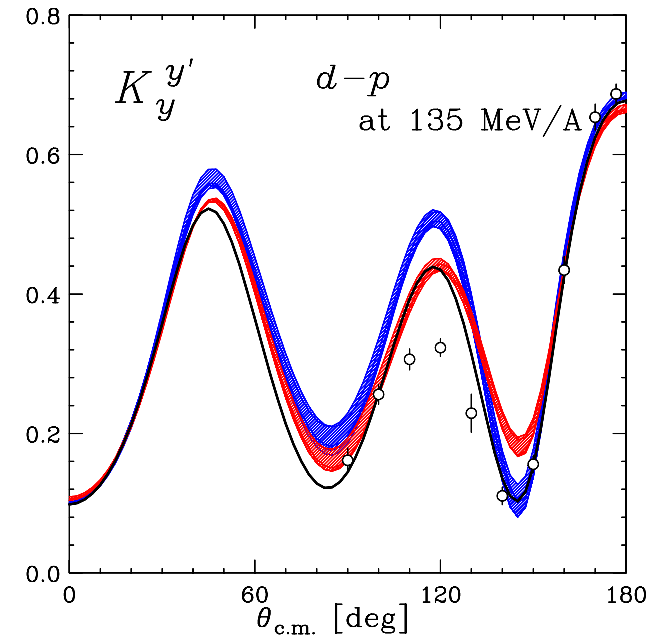

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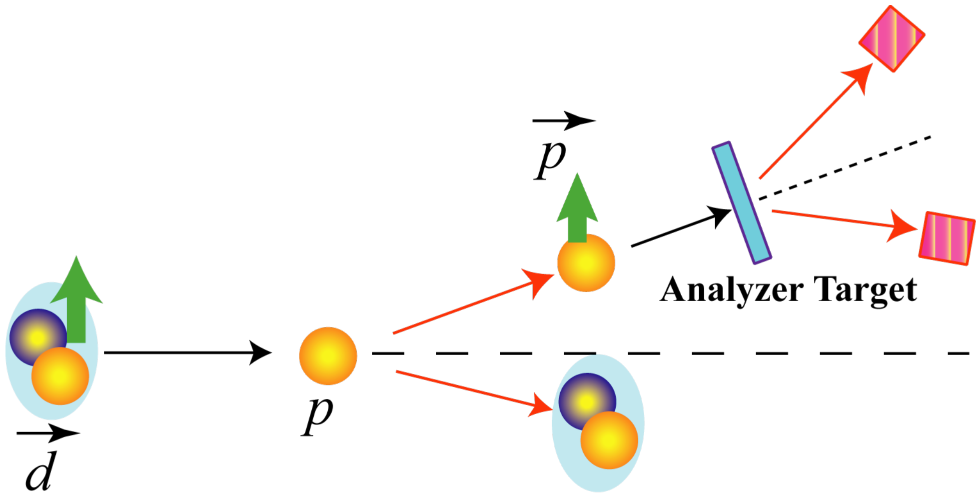
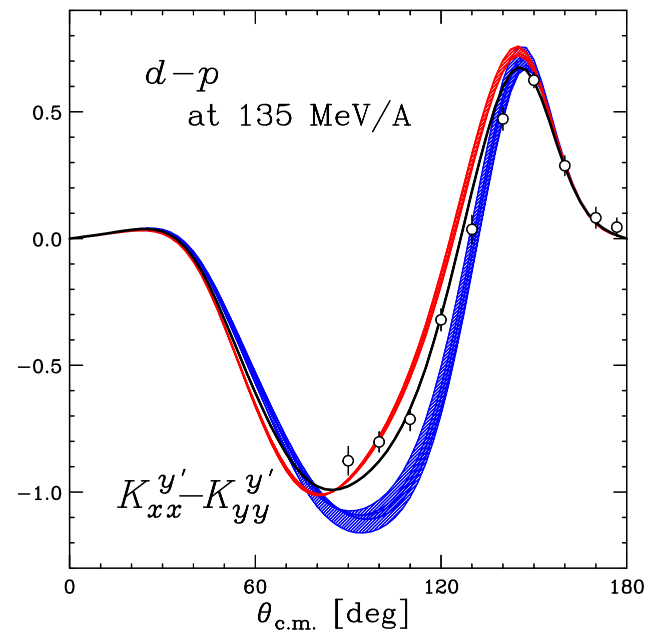
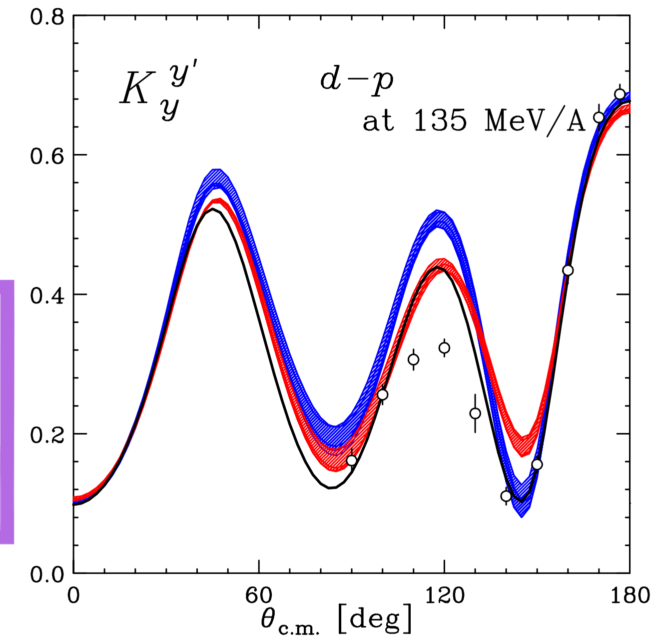






3NF :

$K_{xx}^{y'}-K_{yy}^{y'}$: Good Agreement

$K_y^{y'}$: Direction : O.K.

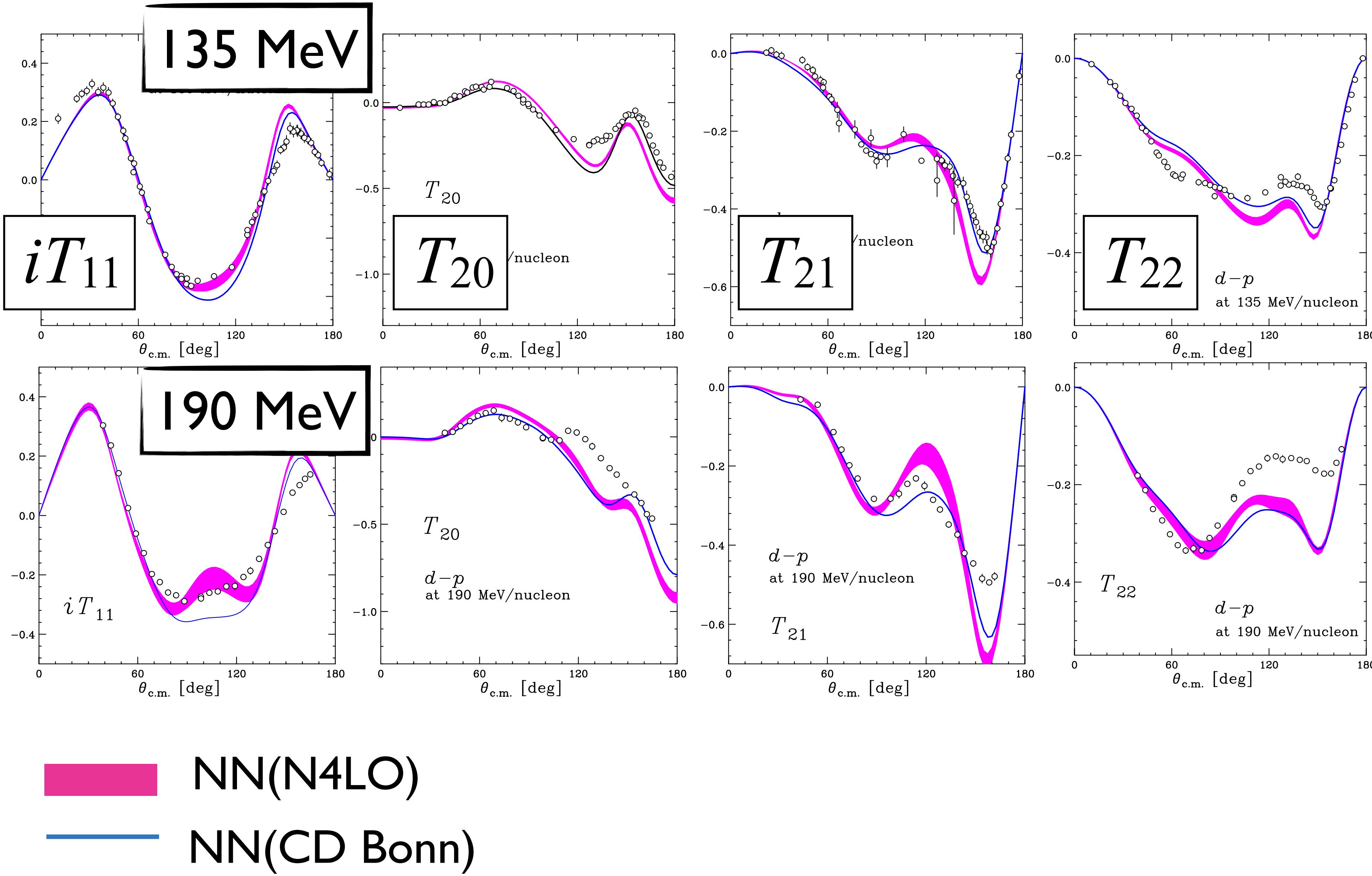
Magnitude : not enough

- Results of spin observables 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



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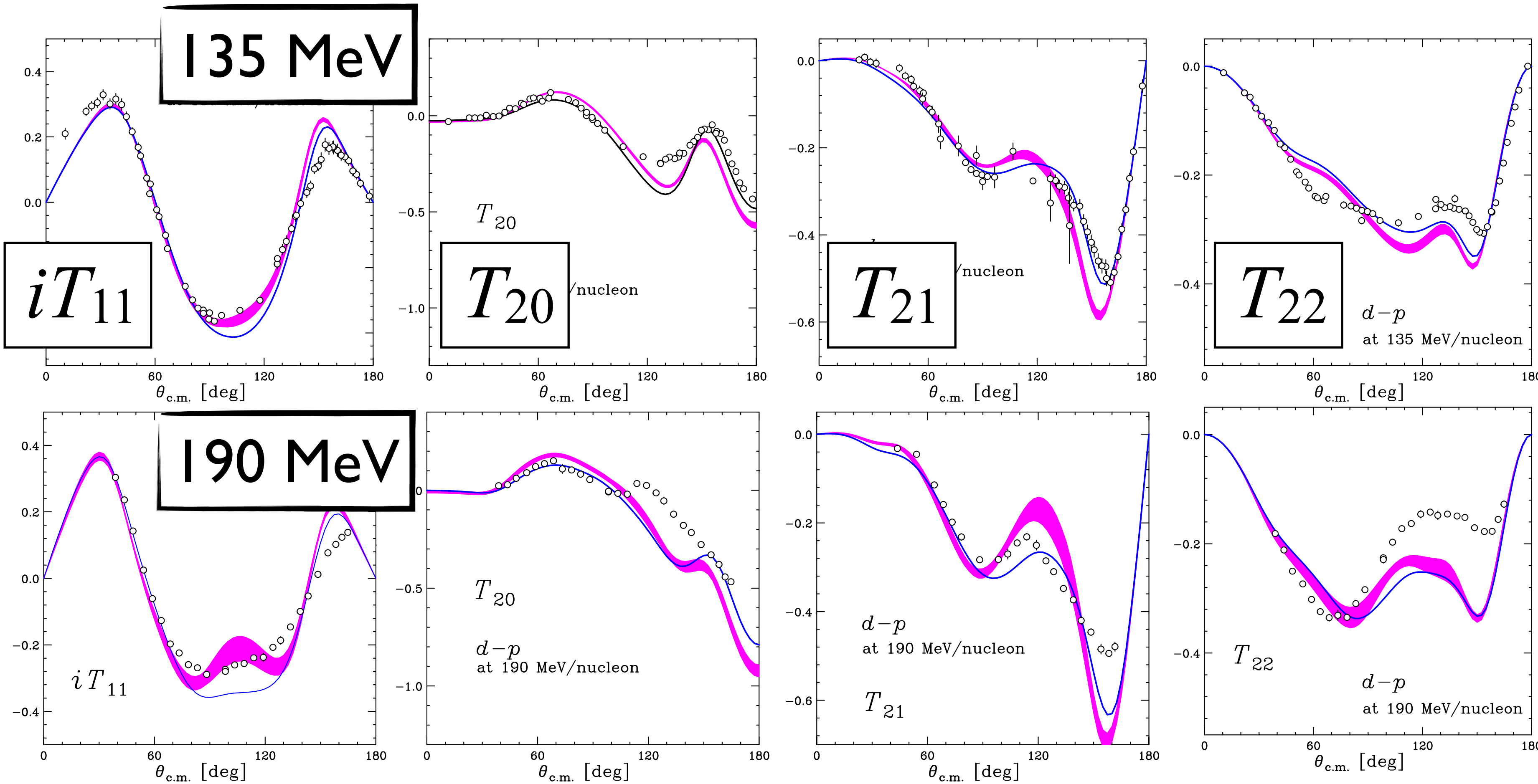


NN(N4LO)

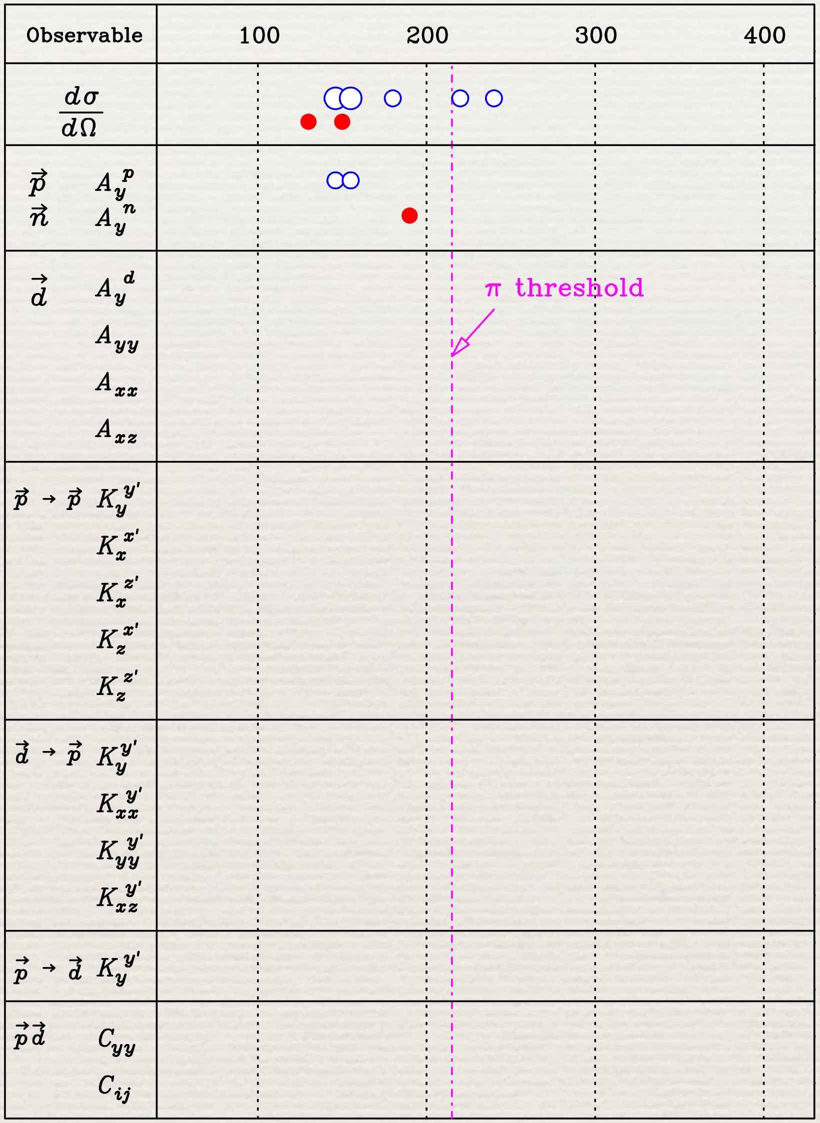
NN(CD Bonn)

Large discrepancies in Tensor analyzing powers T_{20} & T_{22}

→ Rooms for 3NFs ?

Nd Elastic Scattering Data at Intermediate Energies

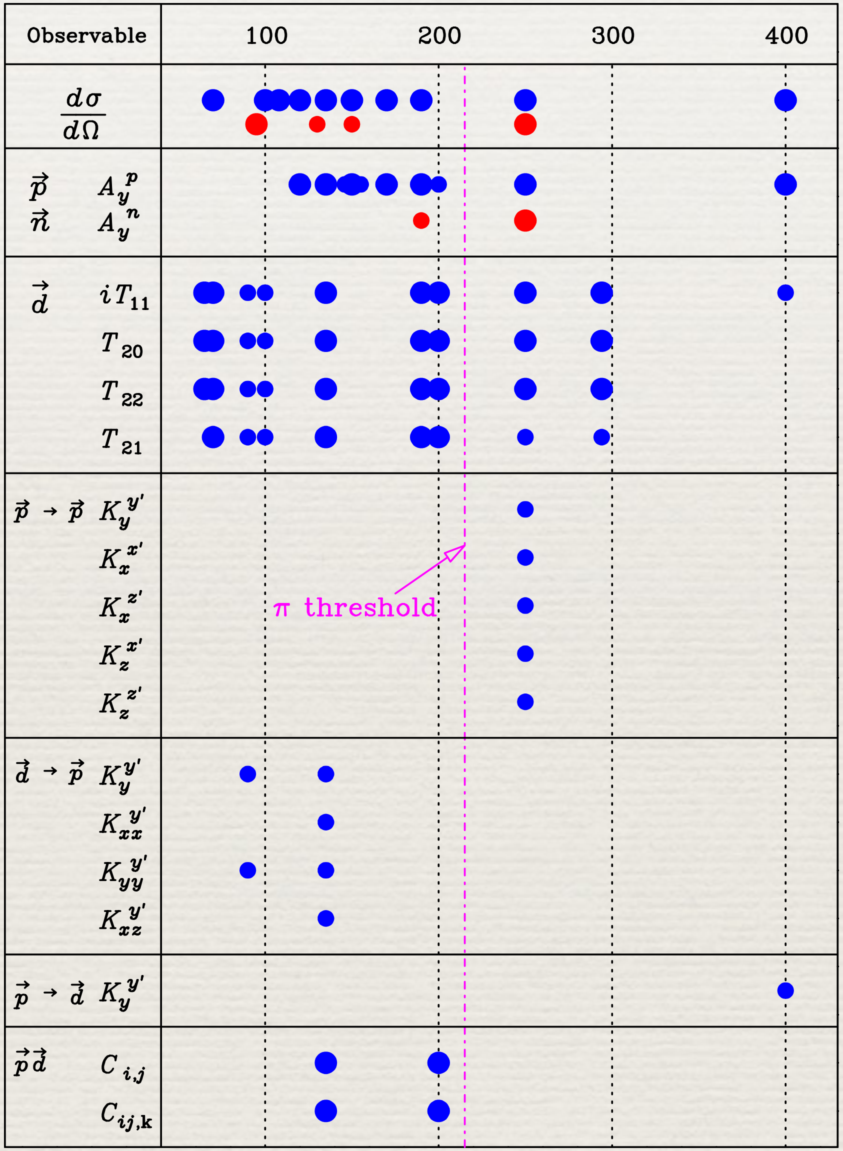
pd and nd Elastic Scattering at 70–400 MeV/A



~1998

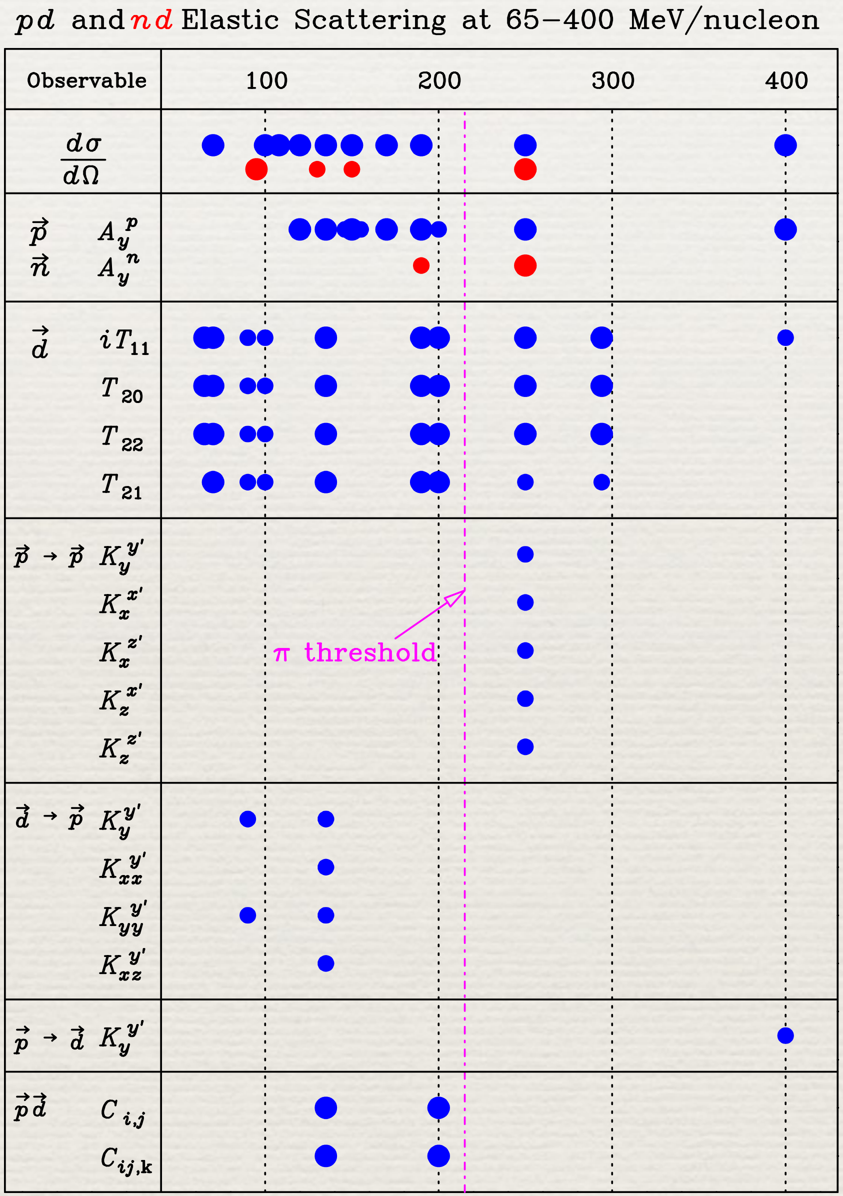
Nd Elastic Scattering Data at Intermediate Energies

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



~2016

Nd Elastic Scattering Data at Intermediate Energies



~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**

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

New Data from RIBF at 190 - 300 MeV : serious discrepancy in backward angles
New Challenge to be solved

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Next Step

Nd Breakup Experiments : Rich kinematical configurations

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

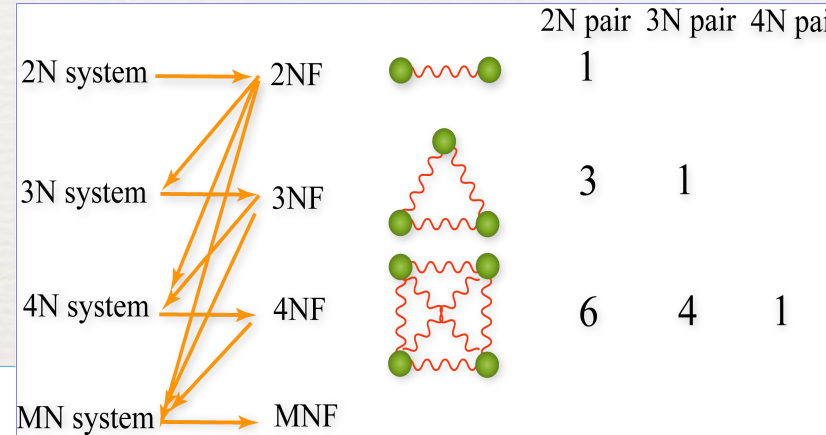
$p+{}^{3}$He scattering

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

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

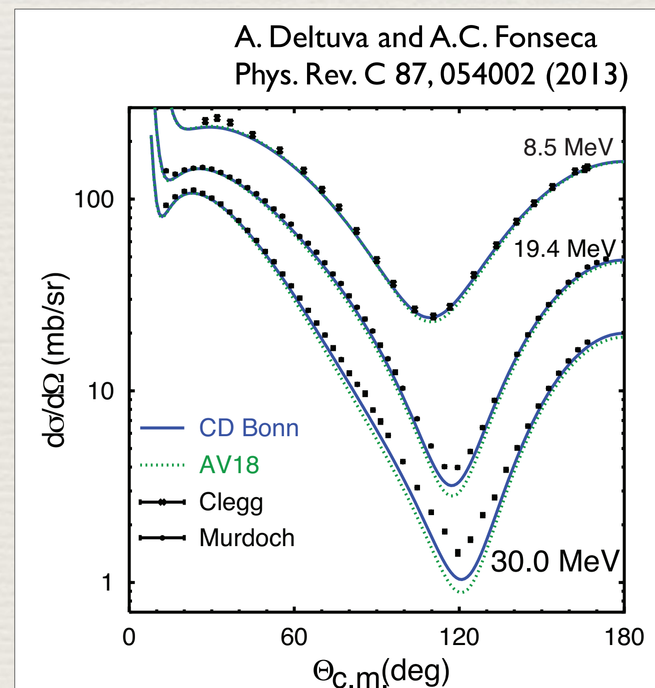
- **Large 3NF effects**
  in cross section minimum at intermediate energies

- **4NF ?**



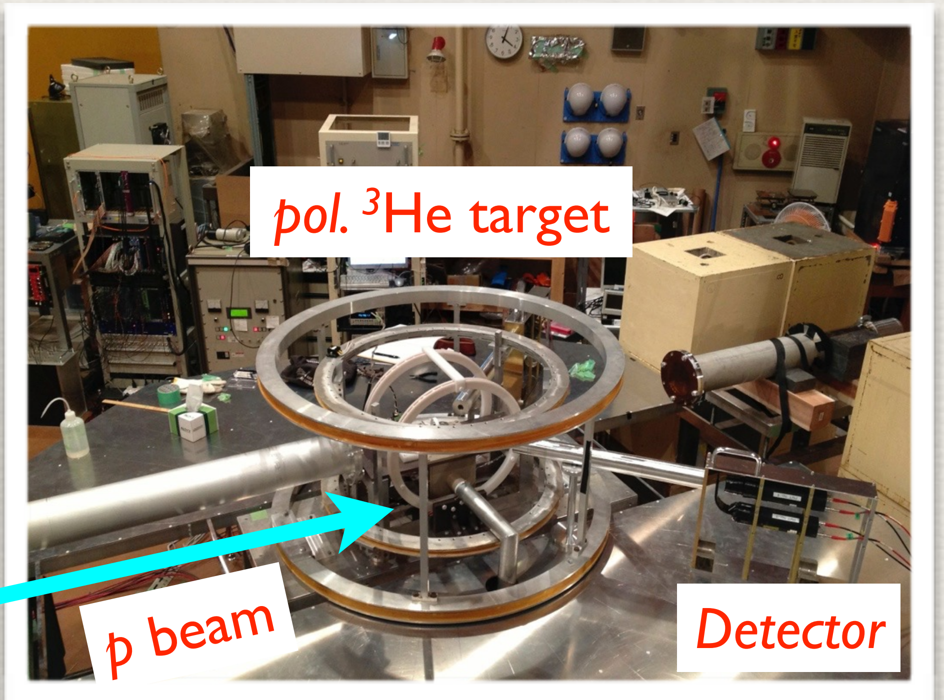
Theory in Progress

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



pol.^{3}He target for p+^{3}He scattering is under construction at CYRIC, Tohoku University

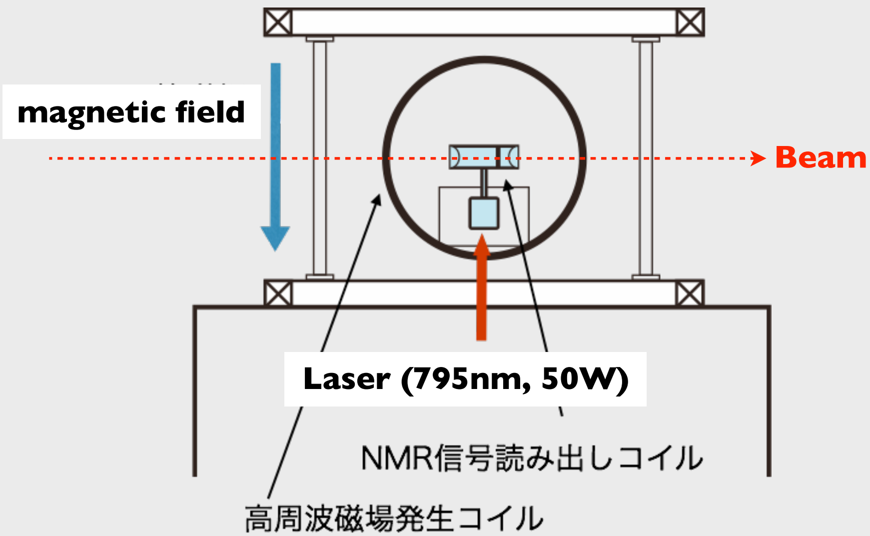
- Method : Spin Exchange Optical Pumping
- Polarization : about 10 % (current)
- Planning First Experiment : p+^{3}He at 70 MeV

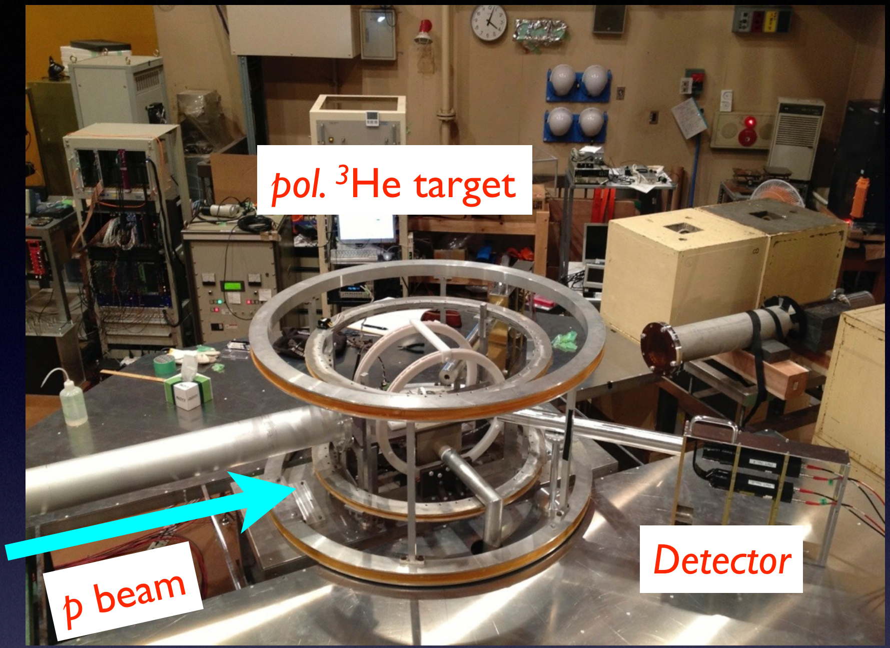


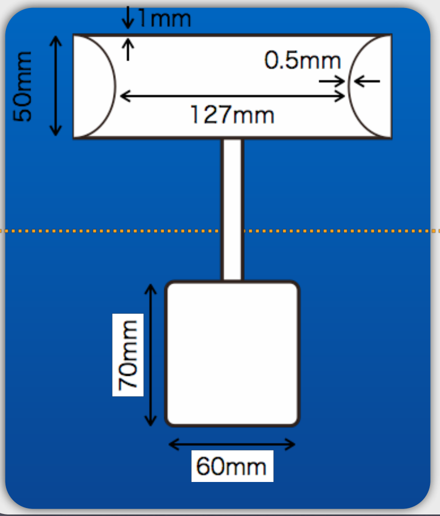
pol.^{3}He target for p+^{3}He

Method : Spin-Exchange Optical Pumping

High Pressure (3 atm)
Low Magnetic Field (~30gauss)







Target Cell

Pumping Cell

1. Polarization of Rb Atom
   by circularly pol. light
   +static mag. field
2. Polarization of ^{3}He Nucleus
   by spin exchange between
   Rb Atom & ^{3}He Nucleus

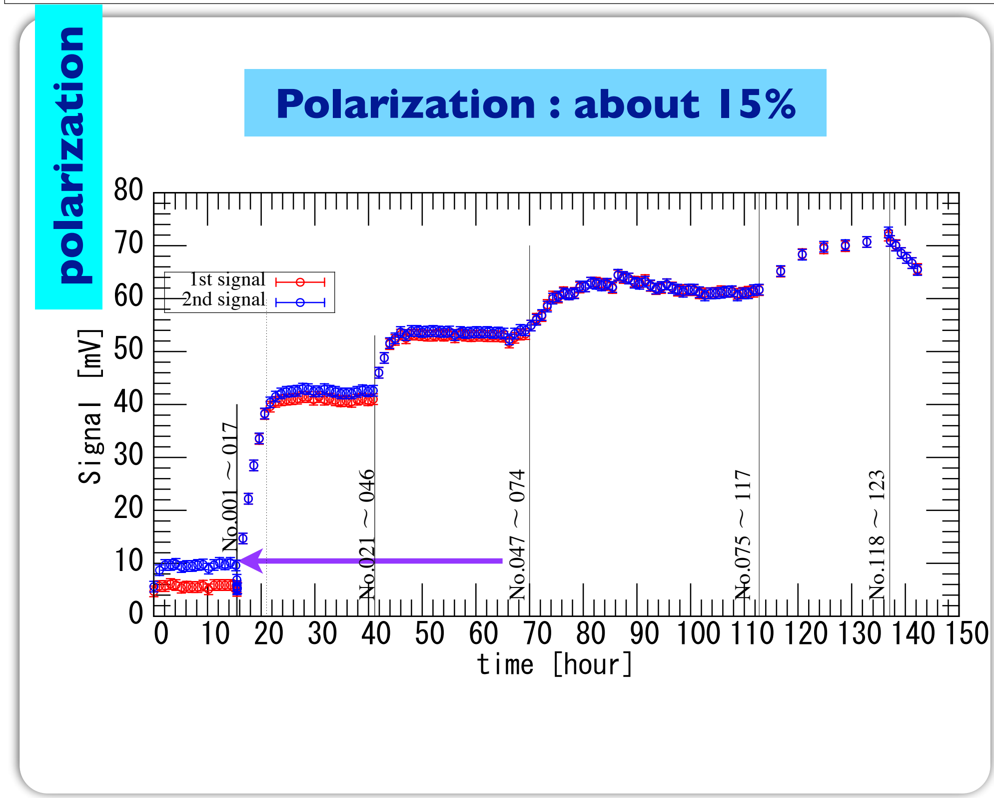
pol. ^{3}He target
gaseous cell (GE180)
by Tohoku Univ. Glass Workshop

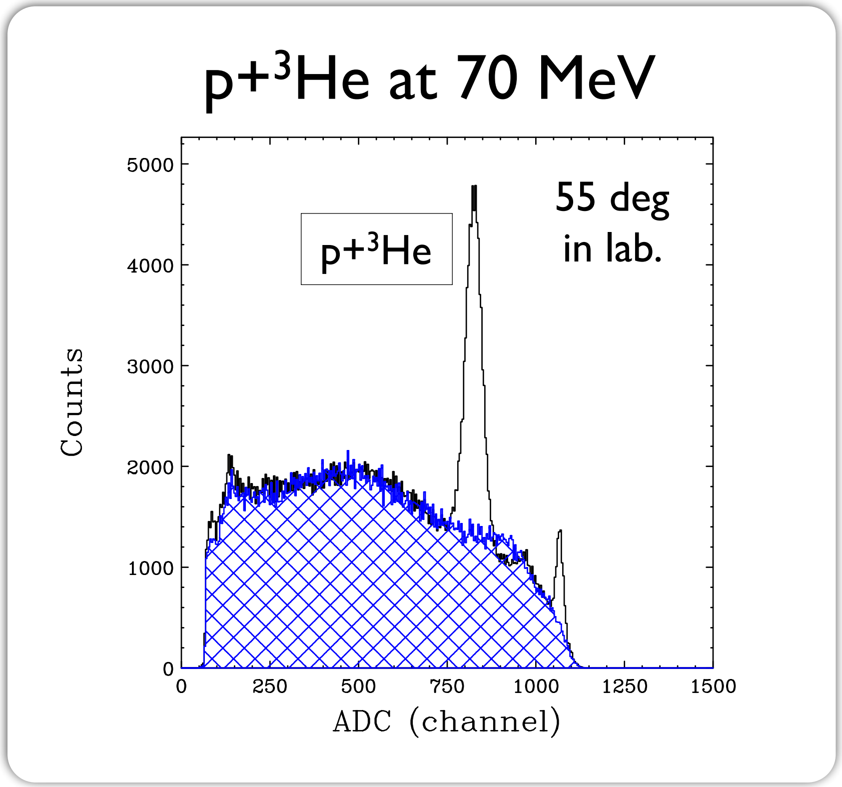
Current Status of pol.^{3}He target

- Polarization of Pol. 3He Target : 10 %
- Beam Test Experiment
  - ✓ depolarization effect : negligible
  - ✓ particle Identification of p+3He events : O.K.

In Progress

- Improvement of spin polarization
  : narrow band laser device etc...
- Determination of absolute values of polarization
- Measurement of analyzing powers at several angles (50deg-130deg in c.m.)





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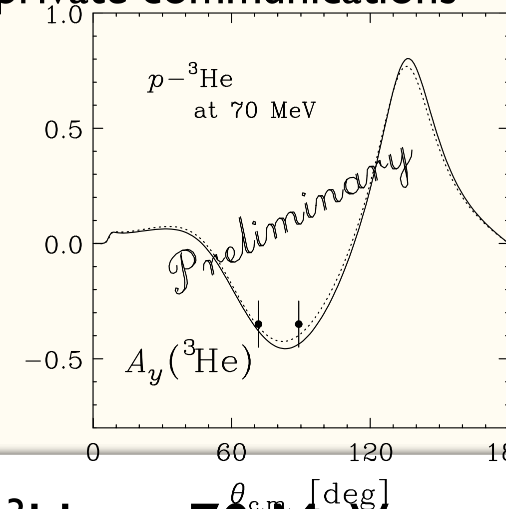
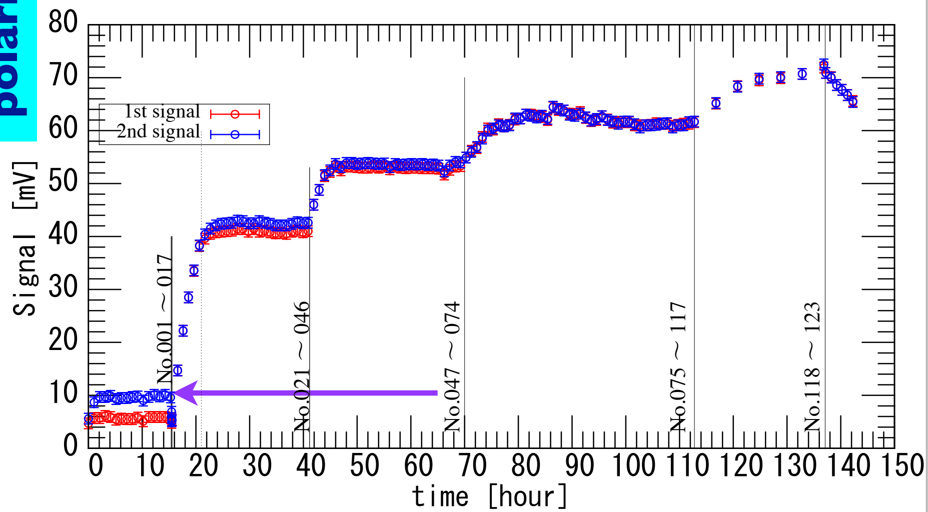
Calculations
based on CD Bonn
A. Deltuva, private communications

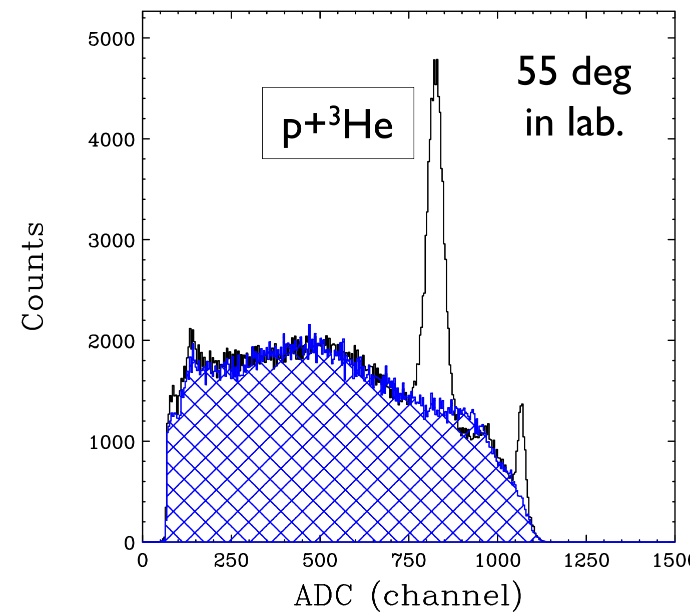


polarization

Polarization : about 15%



p+^{3}He at 70 MeV



SMART Gr. Collaboration (～ 2005)

School of Science, University of Tokyo

H. Sakai, K. Yako, S. Sakoda, H. Kato, M. Hatano, T. Saito, N. Uchigashima, H. Kuboki, M. Sasano, Y. Takahashi

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CYRIC, Tohoku Univ.

H. Okamura

RCNP, Osaka Univ.

A.Tamii

Tokyo Institute of Technology

Y. Satou

KVI

N. Kalantar-Nayestanaki

K. Ermisch

Kyushu University

T. Wakasa

Saitama University

J. Nishikawa, K. Itoh

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, E. , S.

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