International Conference
Nuclear Theory in the Supercomputing Era -2014
June 23-27th, 2014

Approach to Three Nucleon Forces from Experiment

Kimiko Sekiguchi
Department of Physics, Tohoku University

東北大学

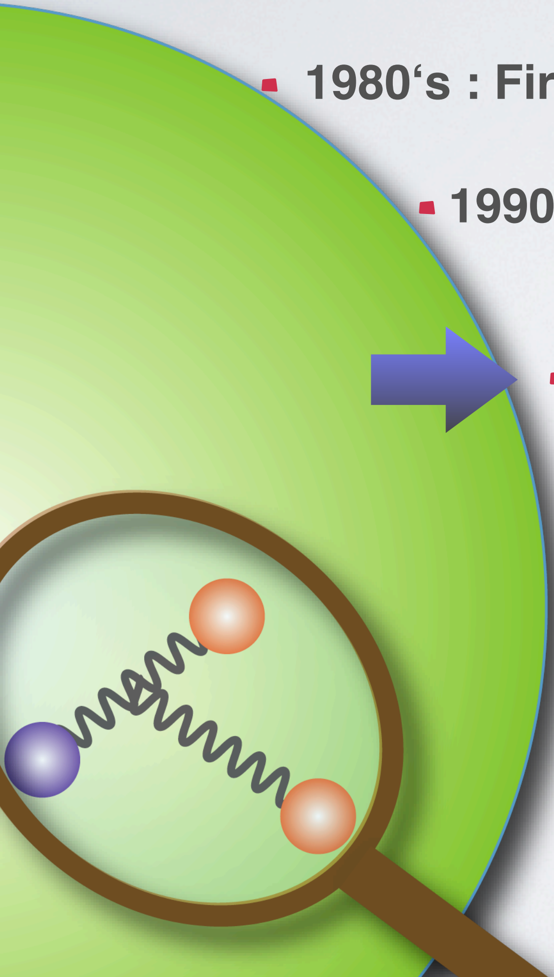
Three Nucleon Forces in Nucleus

Three Nucleon Force (3NF)

a key element to fully understand properties of nucleus

- Existence of 3NF : predicted in 1930's (after Yukawa's meson theory)
- 1980's : First evidence of 3NF : Binding Energies of Triton (^{3}H)
- 1990's Realistic Nucleon-Nucleon Potential
  (CD Bonn, AV18, Nijmegen I, II)
- Evidence / Candidates of 3NF Effects
  - Nucleon-Deuteron Scattering at Intermediate Energies
  - Biding Energies / Levels of Light Mass Nuclei
  - Equation of State of Nuclear Matter

  etc ...



How to attack Three Body Forces ?

1. **Exact Solution of $N \geq 3$ Body System**
2. **Establishment of Two Body Force**
3. **High Precision Experiment**

Earth-Moon-Satellite Gravitational Interactions

～ Three Body Problem in Classical Mechanics ～

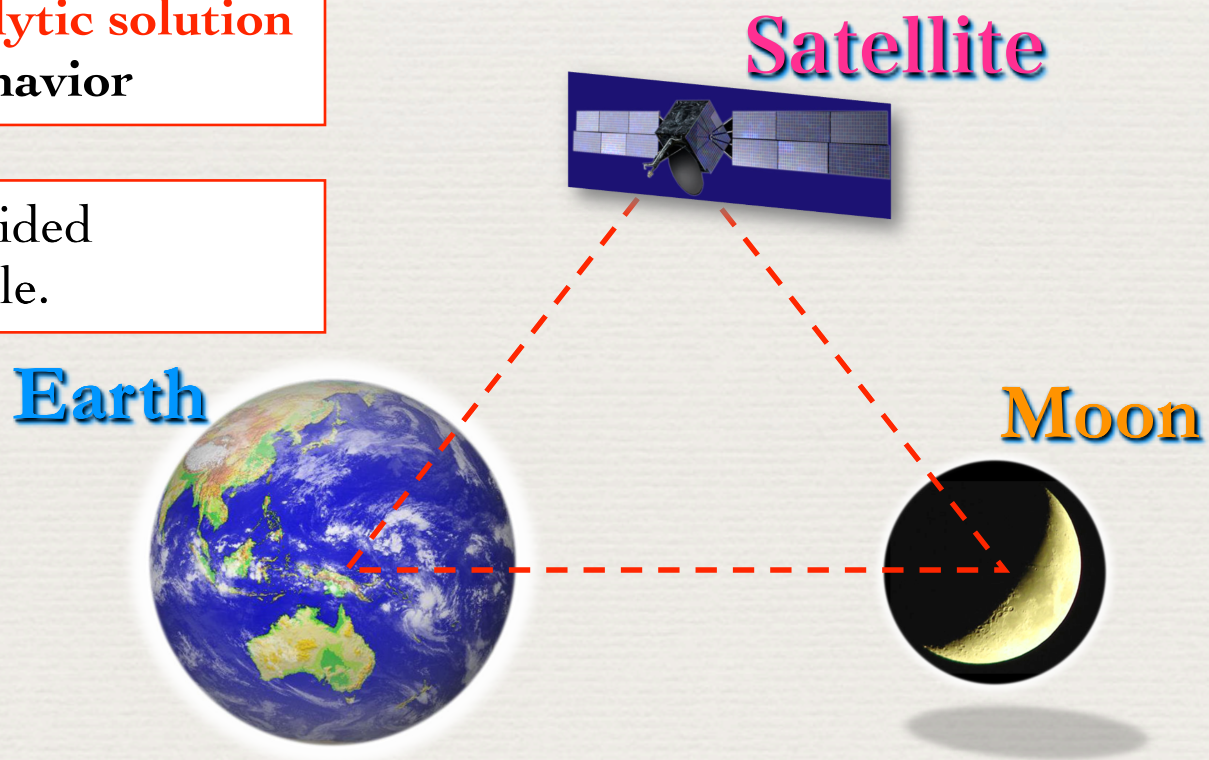
$$H = \frac{1}{2}\left(\frac{P_E^2}{m_E} + \frac{P_M^2}{m_M} + \frac{P_G^2}{m_G}\right) - G\frac{m_E m_M}{r_{EM}} - G\frac{m_E m_G}{r_{EG}} - G\frac{m_M m_G}{r_{MG}} + V(r_E, r_M, r_G)$$

by the polarizations of the ocean water of the earth by the moon's gravity

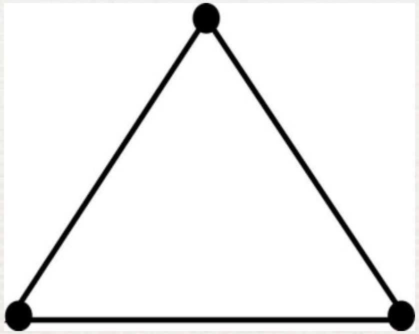
H. Poincaré (1892)

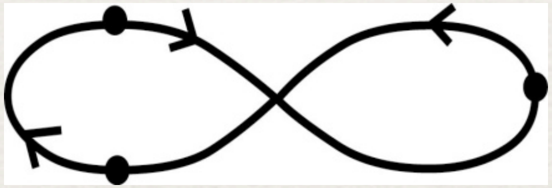
- **non-existence of analytic solution**
- **sometime chaotic behavior**

Now super computer-aided calculations are available.



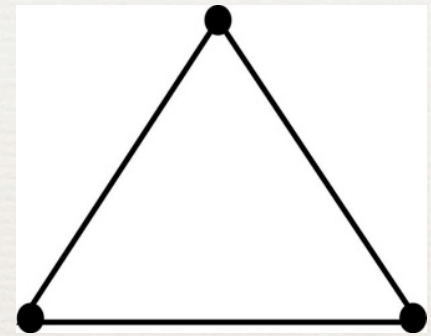
Special Solutions

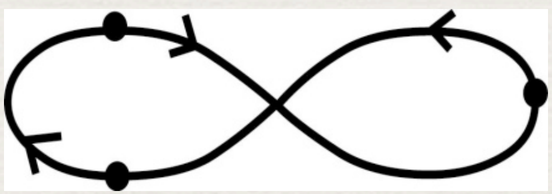




Chenciner-Montgomery,
Ann. Math. 152(2000)881

Special Solutions





Chenciner-Montgomery, Ann. Math. 152(2000)881

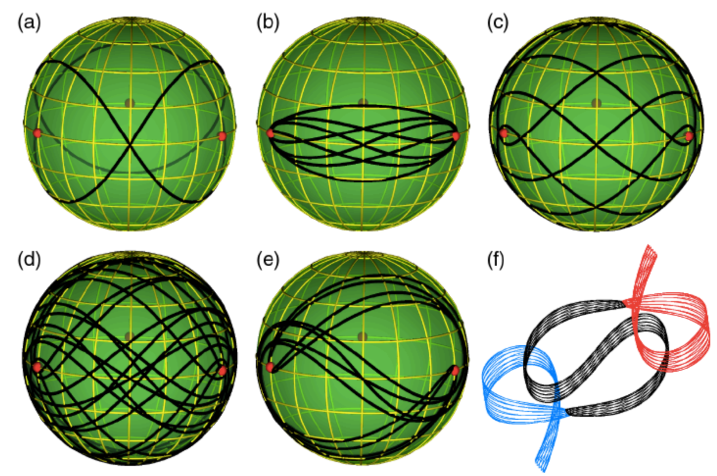


FIG. 1 (color online). The (translucent) shape-space sphere, with its back side also visible here. Three two-body collision points (bold red circles)—punctures in the sphere—lie on the equator. (a) The solid black line encircling the shape sphere twice is the figure-8 orbit. (b) Class I.A butterfly I orbit (I.A.1). Note the two reflection symmetry axes. (c) Class I.B moth I orbit (I.B.1) on the shape-space sphere. Note the two reflection symmetry axes. (d) Class II.B yarn orbit (II.B.1) on the shape-space sphere. Note the single-point reflection symmetry. (e) Class II.C yin-yang I orbit (II.C.2) on the shape-space sphere. Note the single-point reflection symmetry. (f) An illustration of a real space orbit, the yin-yang II orbit (II.C.3a).

Milovan Suvakov and V. Dmitrasinovic
Phys. Rev. Lett. 110, 114301 (2013)

Triplets of Atoms
Van der Waals Type Three Body Force

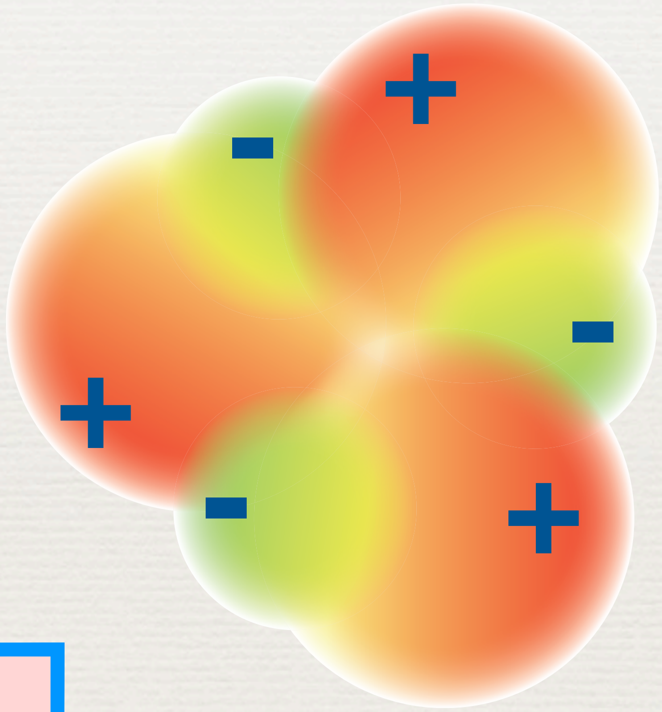
- Two Body Electro-Magnetic Interactions

$$V_{12} = \frac{C\alpha^3}{r_{12}^6}$$

- Three Body Interactions

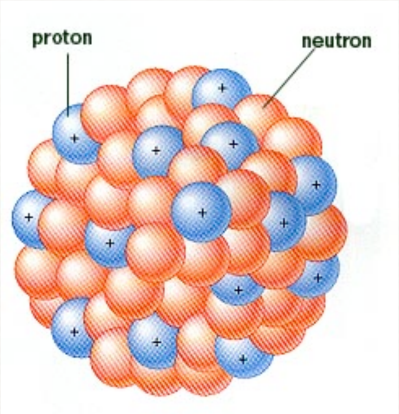
$$V_{123} = C\frac{3\cos\gamma_1\cos\gamma_2\cos\gamma_3 + 1}{r_{12}^3\, r_{23}^3\, r_{31}^3}$$

Effects of the polarizations of
the electron density distribution



How About Three Nucleon Forces in Nuclei ?

- **Nucleus : a compact system of nucleons**
- **Nuclear Force : Strong Interactions**
- **Effects of Three Nucleon Forces**



	Solar System	Atom	Nucleus
Length	10^8 m	10^{-10} m	10^{-15}m
Interaction	Gravity	Electro-Magnetic	Strong
Coupling Constant	10^{-38}	10^{-2}	1
$\frac{V(3BF)}{V(2BF)}$	0.001%	< 0.1%	?

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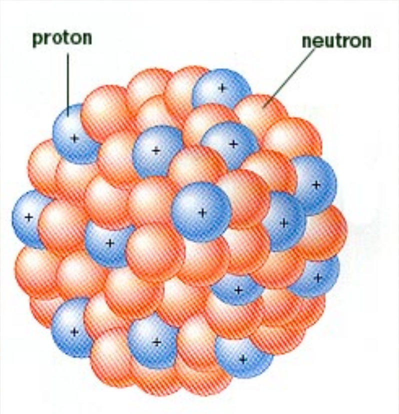

Where and How to attack ?

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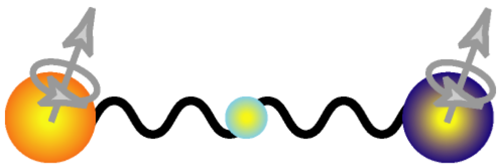
Before Three Nucleon Force …

Two Nucleon Force (2NF)



π, ρ, ω

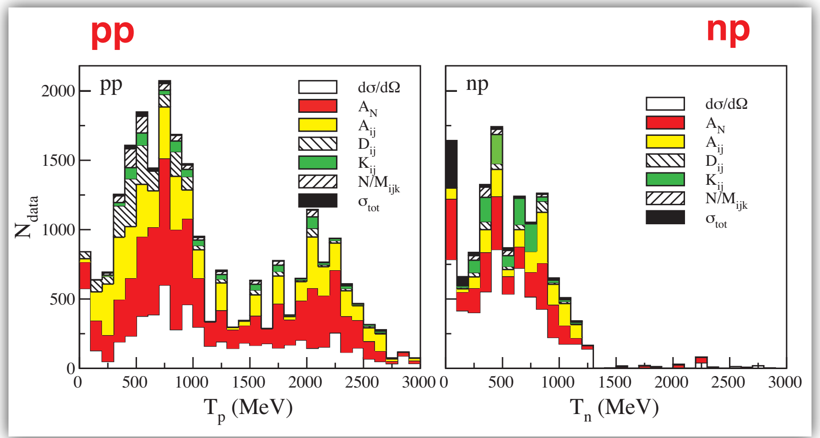
1935 Yukawa's meson theory (2NF)

Theory :

- One Pion Exchange Model
- One Boson Exchange Model
  Heavier Meson Exchange
  e.g. ρ, ω

Experiment :

- Nucleon-Nucleon (NN) Scattering Data Set ($d\sigma/d\Omega$ and Spin Observables)
- Deuteron Properties



1990's Realistic Modern NN Force

CDBonn, AV18, Nijmegen I,II,93

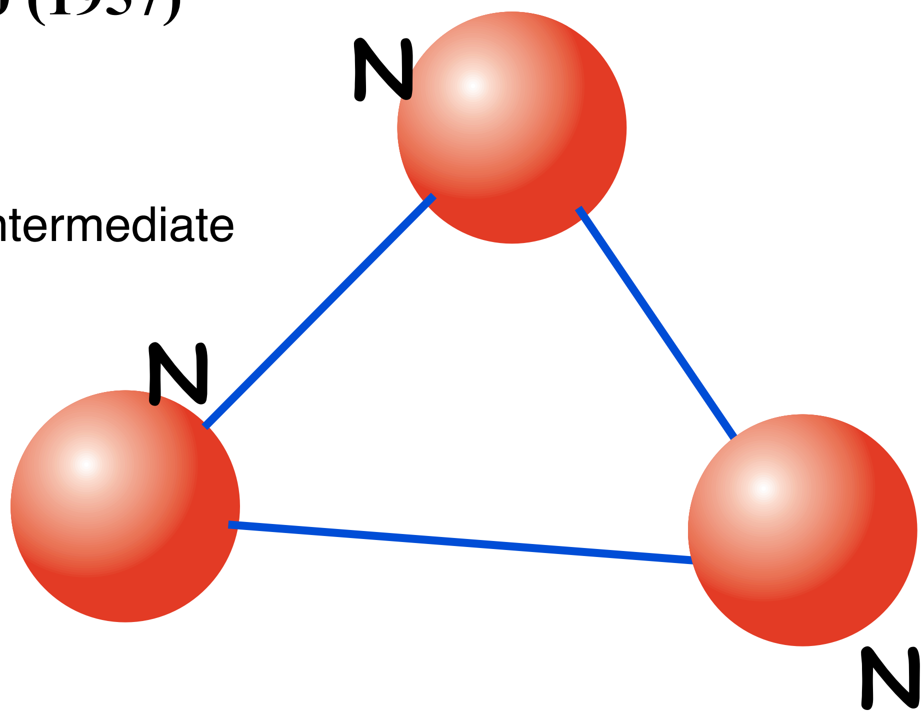
reproduce 3500 exp. NN scattering data with high precision, $\chi^2 \sim 1$

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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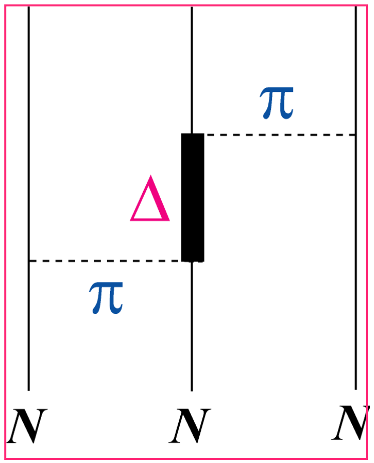

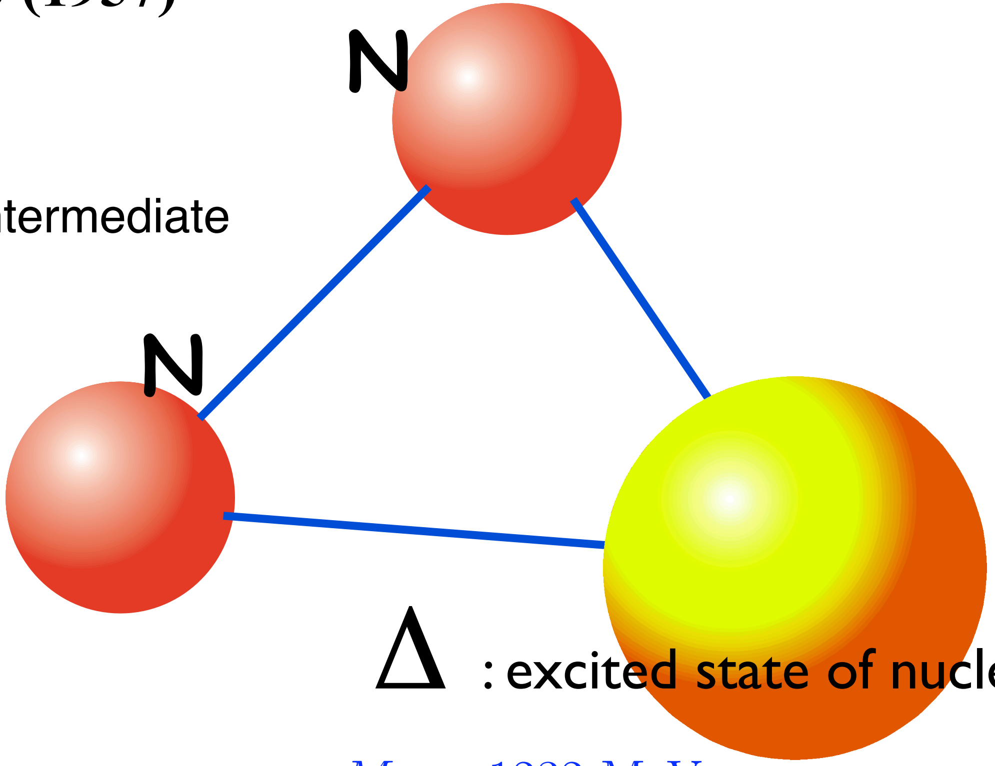

Δ : excited state of nucleon

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

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

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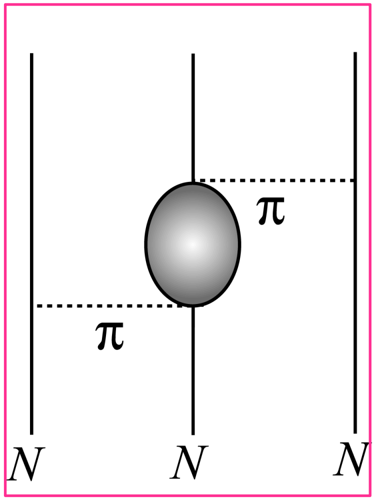

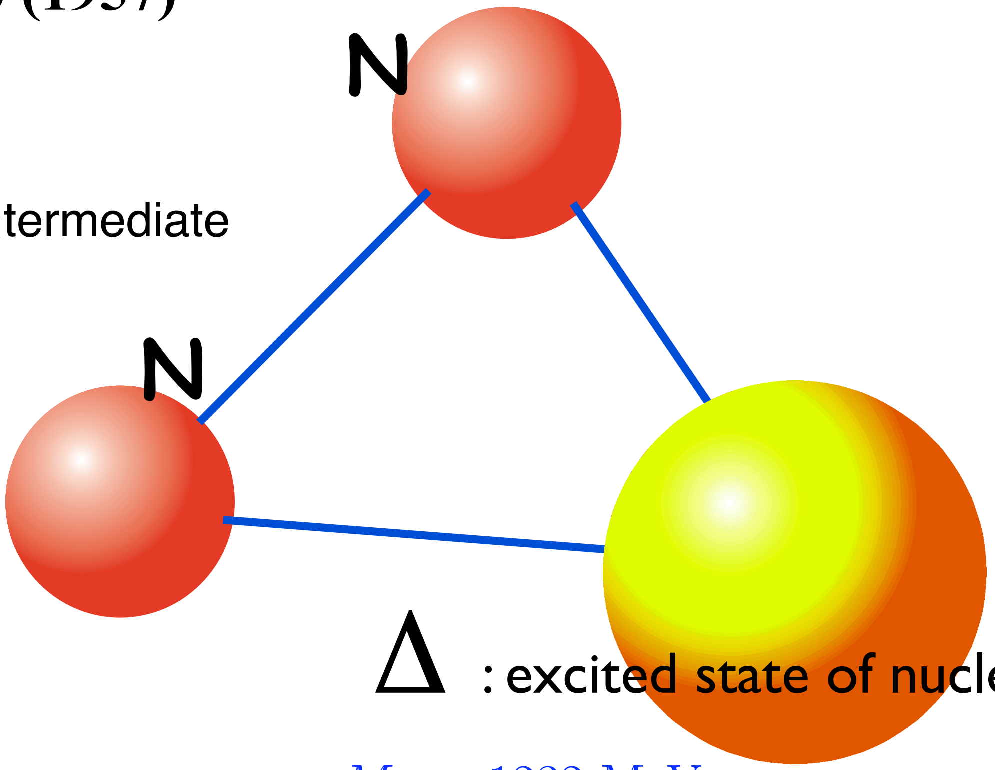

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- Tucson-Melbourne (TM)
- Urbana IX
- Brazil, Texas etc…

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Prog. Theor. Phys. 17, 360 (195

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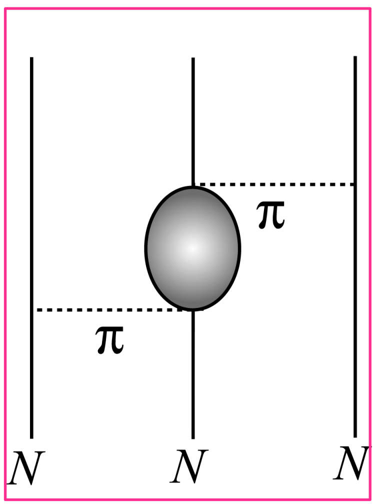

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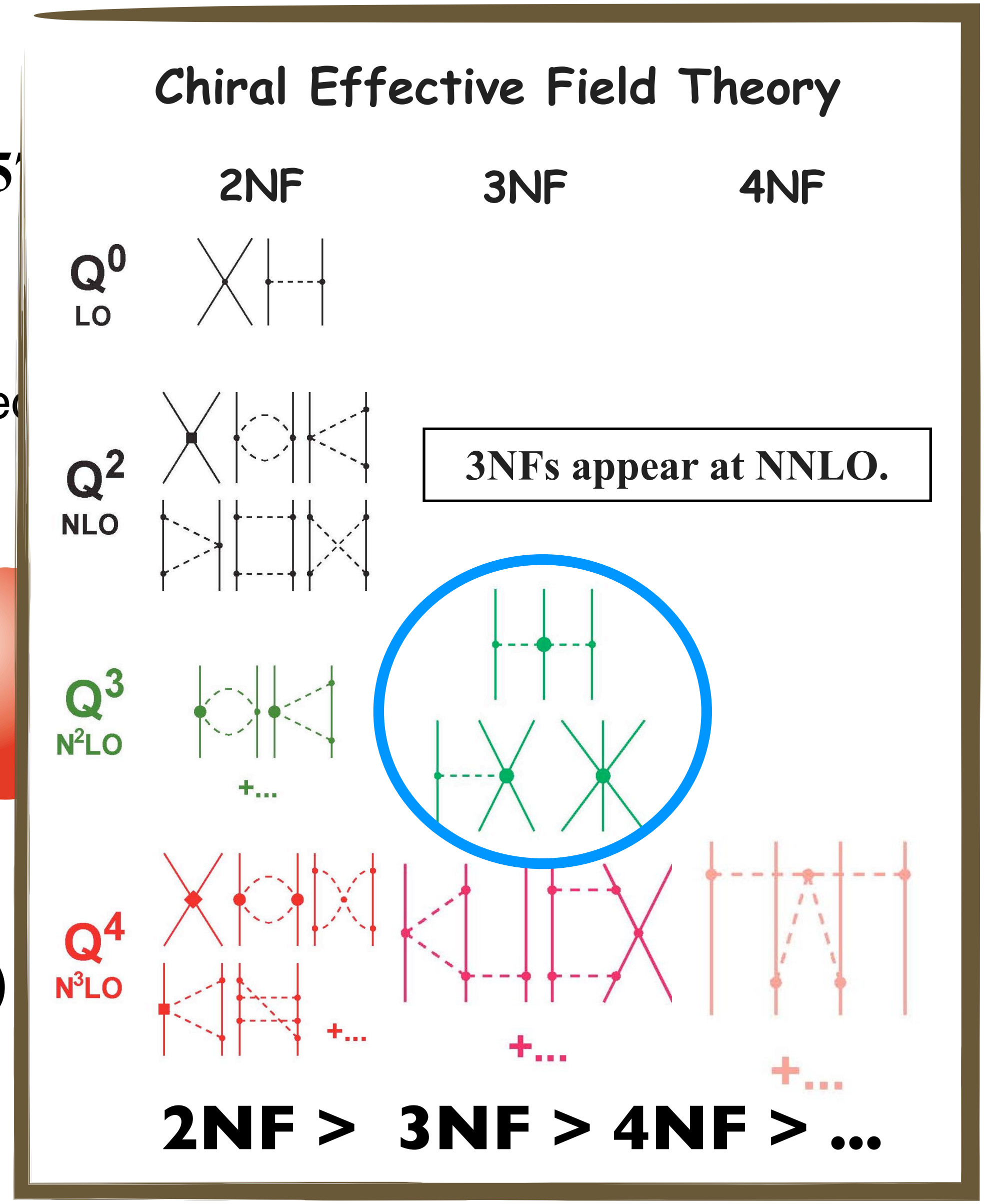
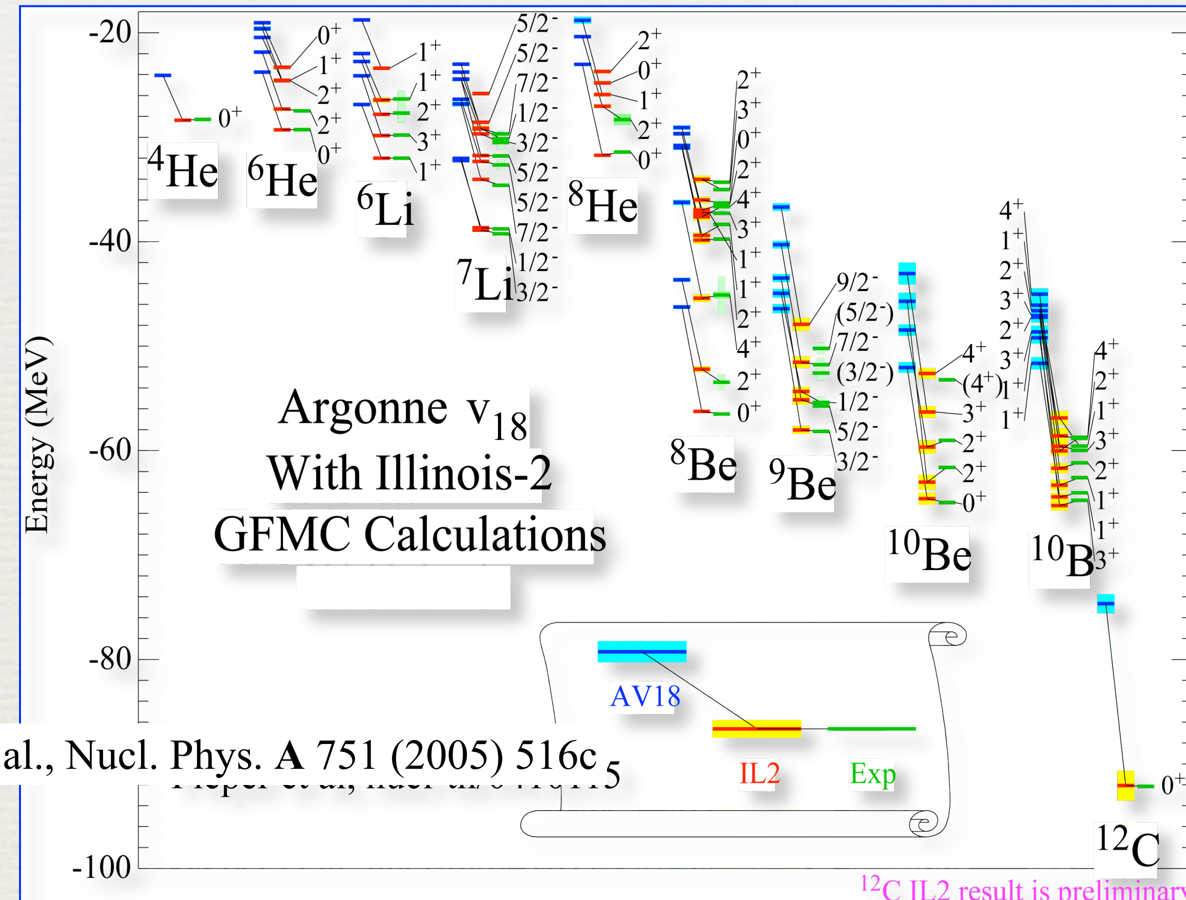


Where can we find 3NF effects ? - I -

Ab Initio Calculations for Light Nuclei (A < 12)

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



Pieper et al., Nucl. Phys. **A** 751 (2005) 516c

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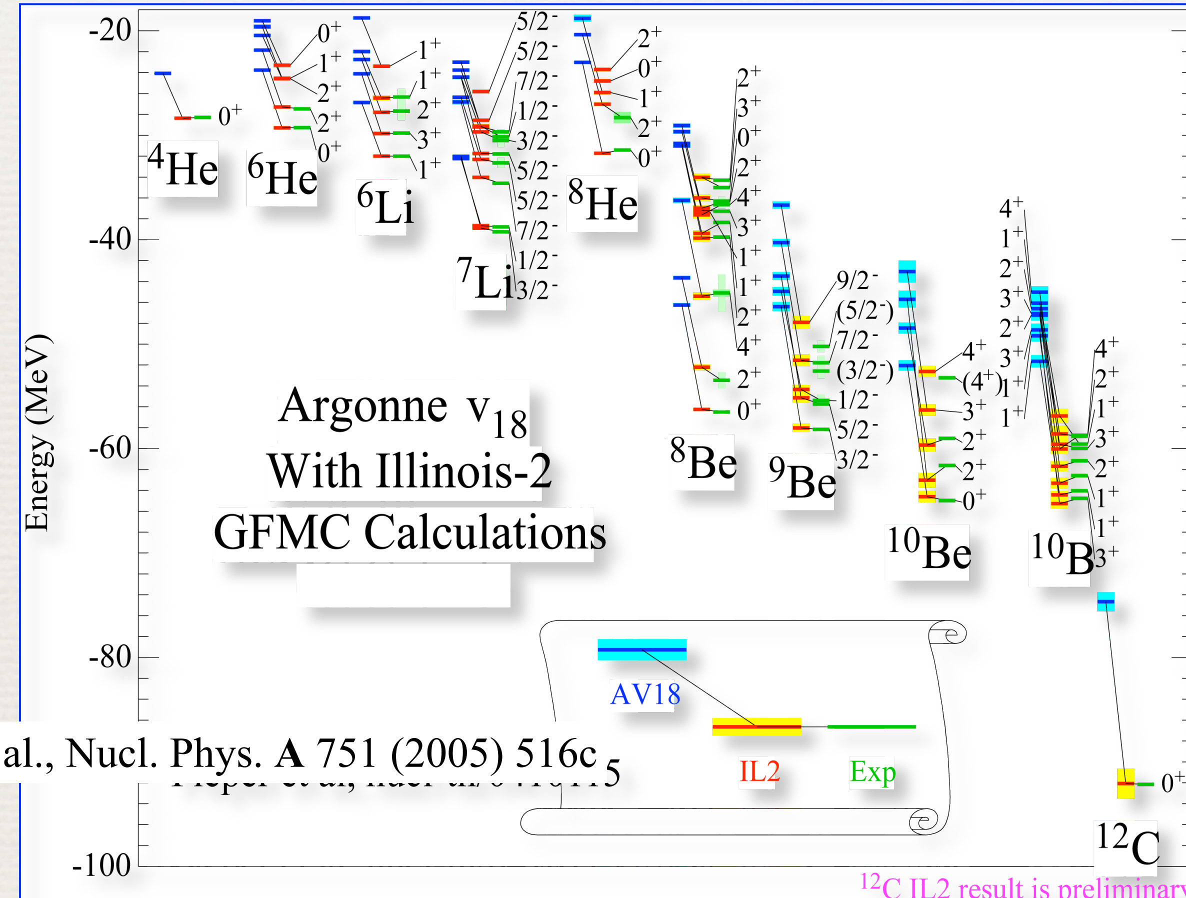
- 2NF provide less binding energies
- 3NF : well reproduce the data

IL2 3NF (Illinois-II 3NF) :
2π-exchange 3NF
+ 3π-ring with Δ-isobar



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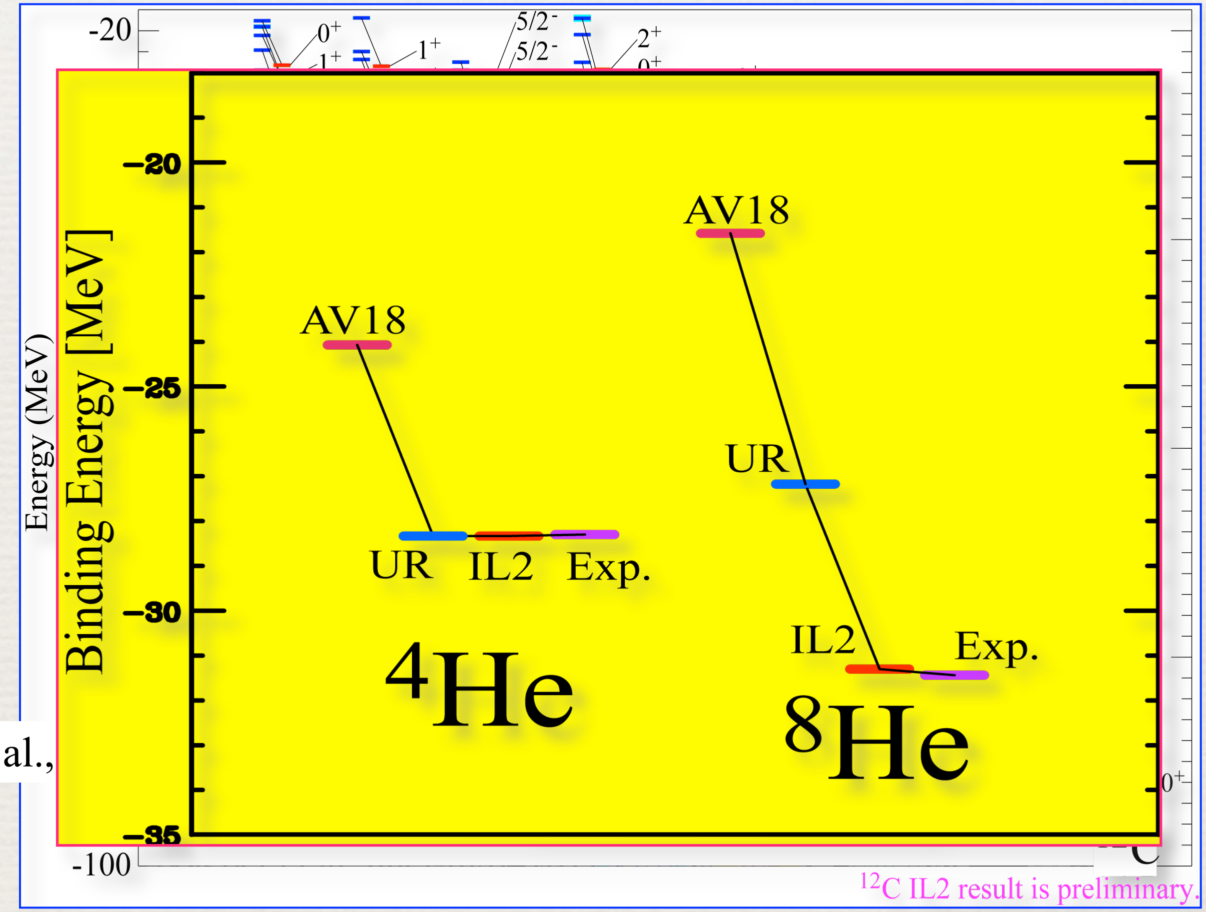
•Note :
T=3/2 3NFs plays important roles to explain B.E. in neutron rich nuclei.

Pieper et al.,



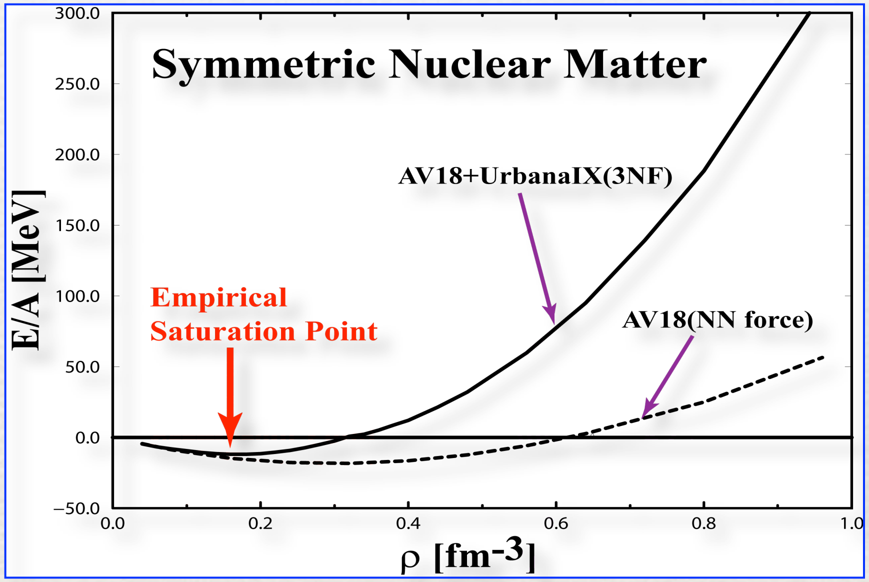
Where can we find 3NF effects ? - II -

A. Akmal et al., PRC 58, 1804('98)

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

Where can we find 3NF effects ? - II -

Equation of State for Nuclear Matter



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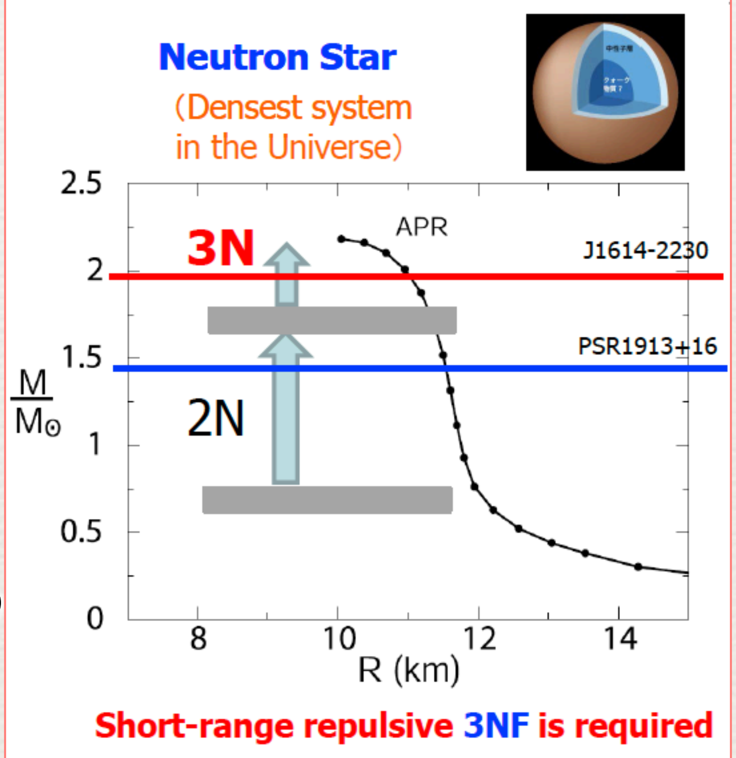


- All NN potentials
  (AV18, Nijmegen I,II, CD Bonn)
  provide larger saturation point
  of Nuclear Matter.
- 3NF
  - shift to the empirical
    saturation point
  - significant at higher density

- Note
  - Short range 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 ?

Nucleon-Deuteron 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

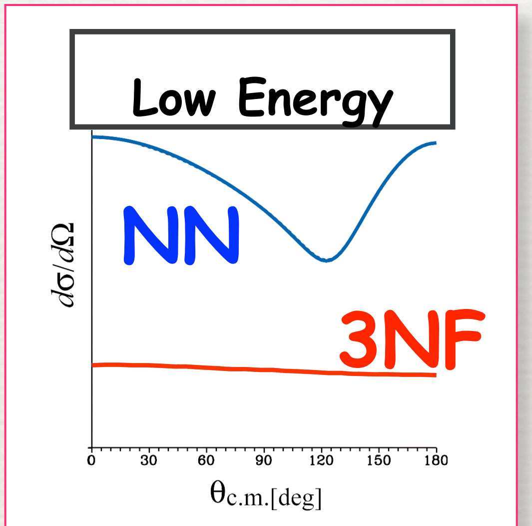
- **Experiment : Precise Data**
  - $d\sigma/d\Omega$, Spin Observables (A_i, K_{ij}, C_{ij})

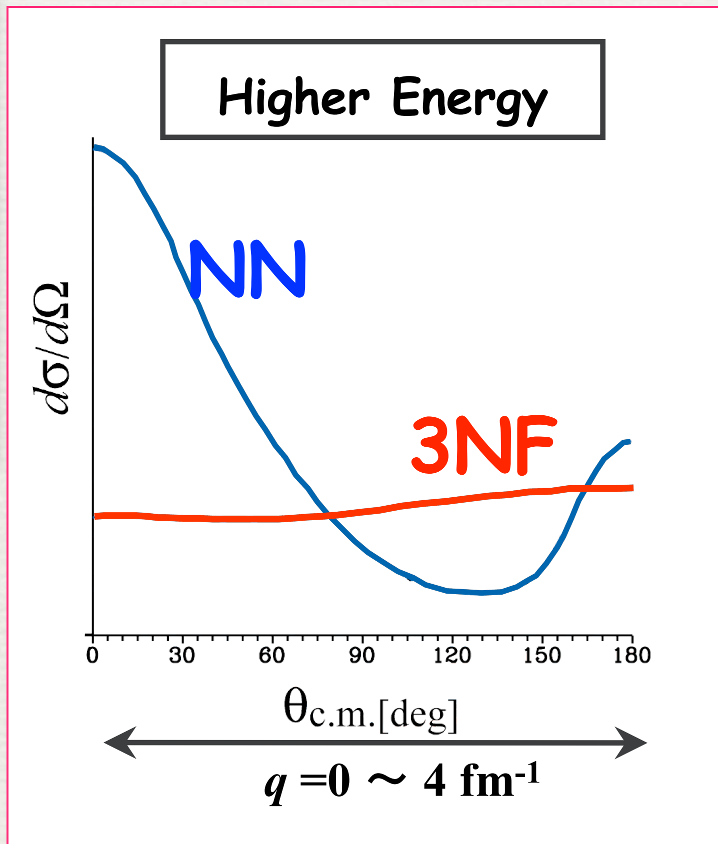
Extract fundamental information of Nuclear Forces.

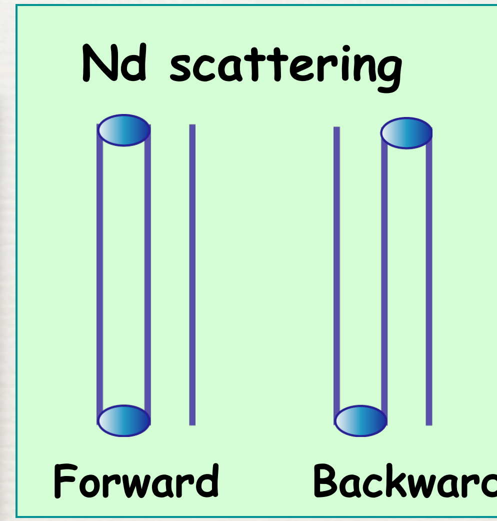
Where is the hot spot for 3NF ?

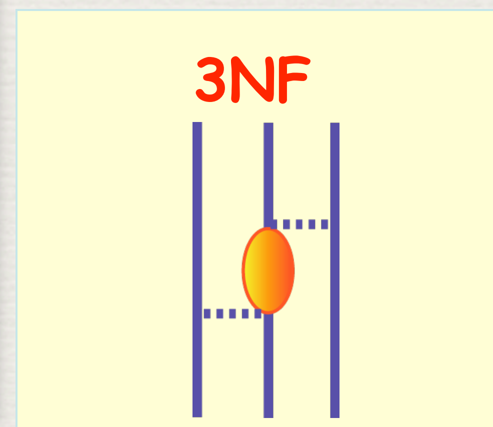
Predictions by H. Witala et al. (1998)

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

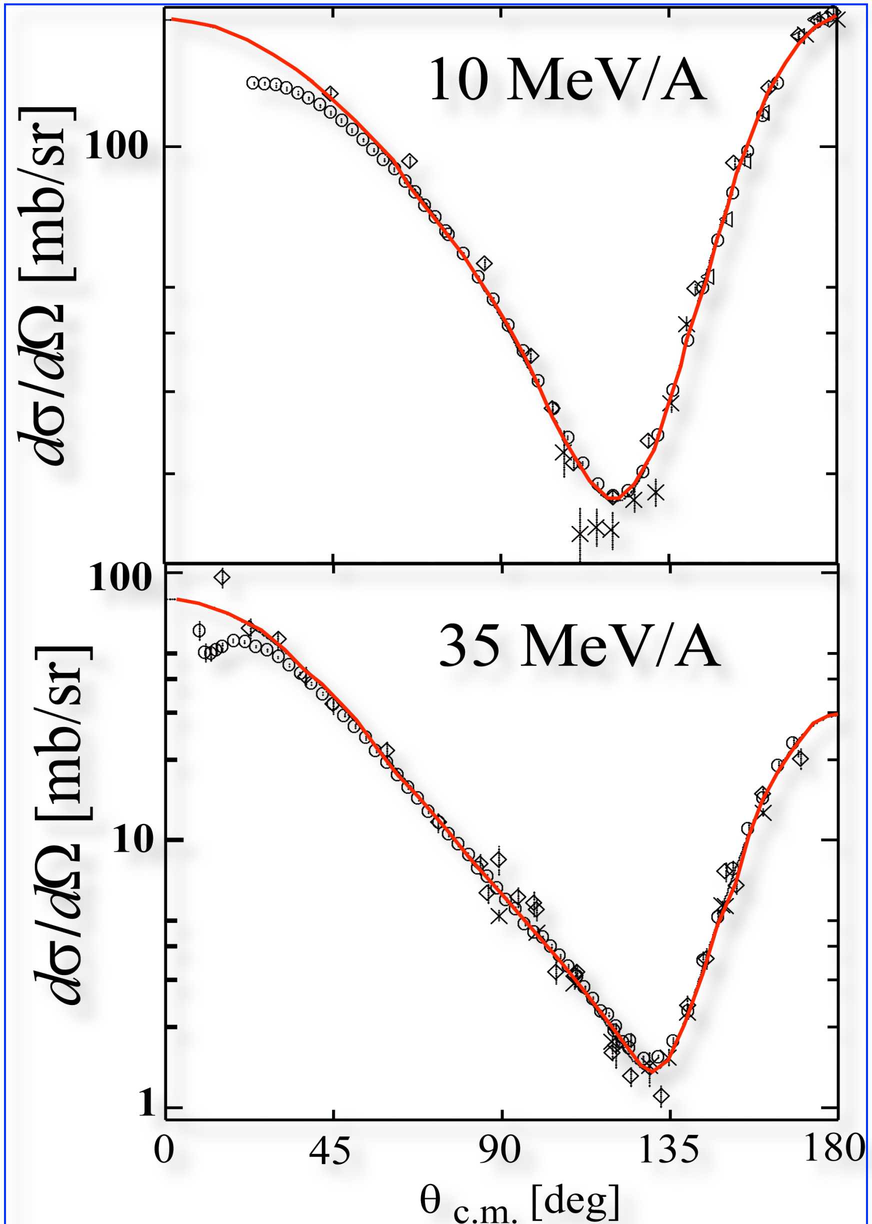








dp Scattering at Low Energies (E ≤ 30 MeV/A)



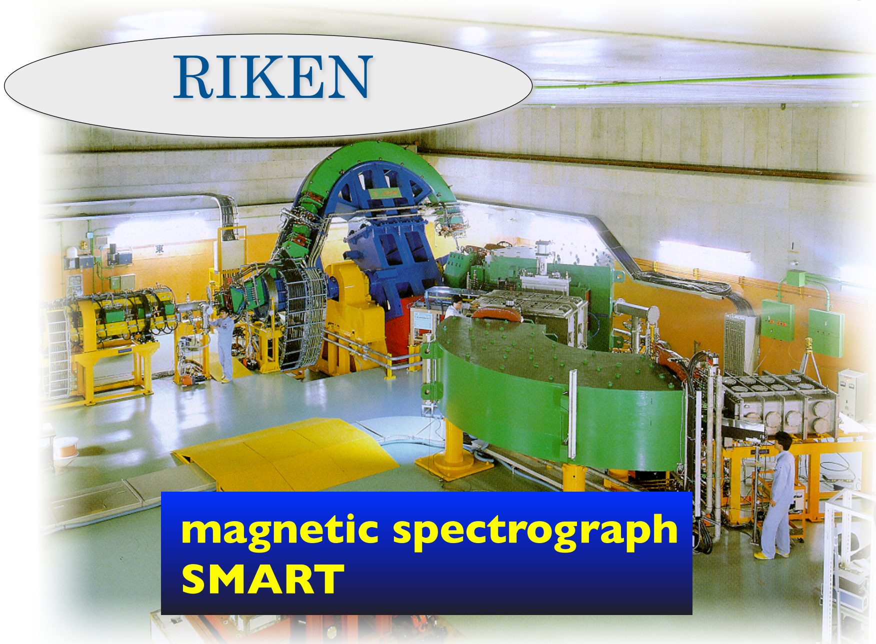
- High precision data are explained by Faddeev calculations based on 2NF.

No signatures of 3NF.

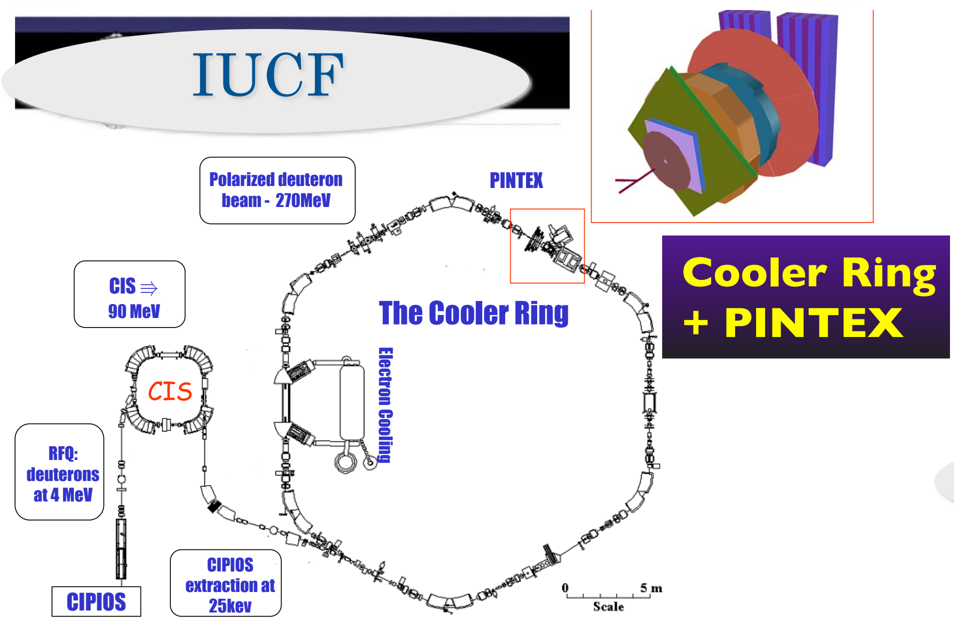
Exp. Data from
Kyushu, TUNL, Cologne etc..

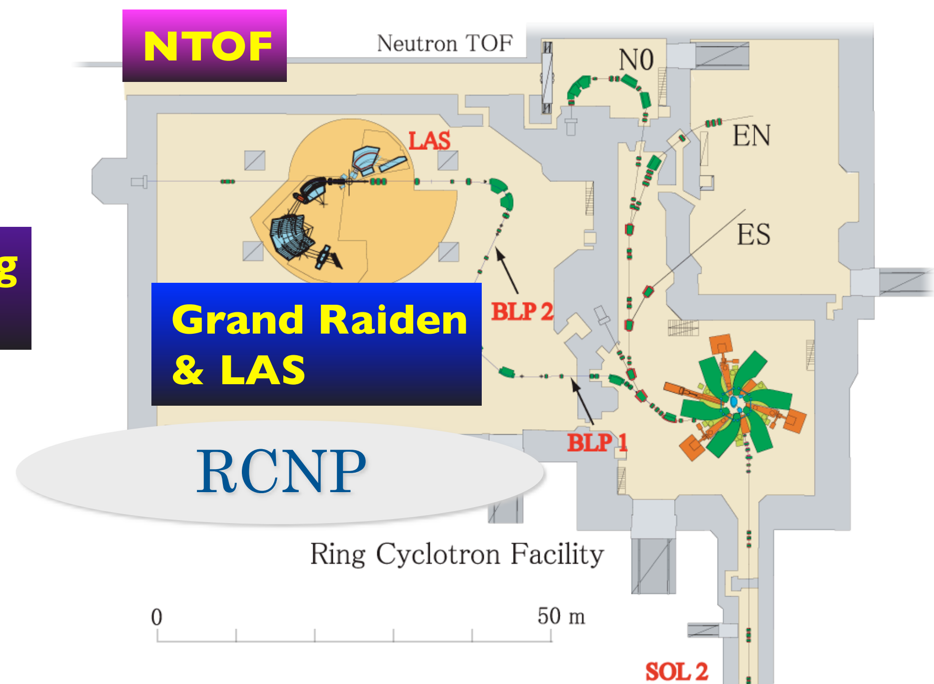
W. Glöckle et al., Phys. Rep. 274, 107 (1996).

Facilities


RIKEN
magnetic spectrograph
SMART


BINA
& SALAD
KVI
to Krakow
BBS

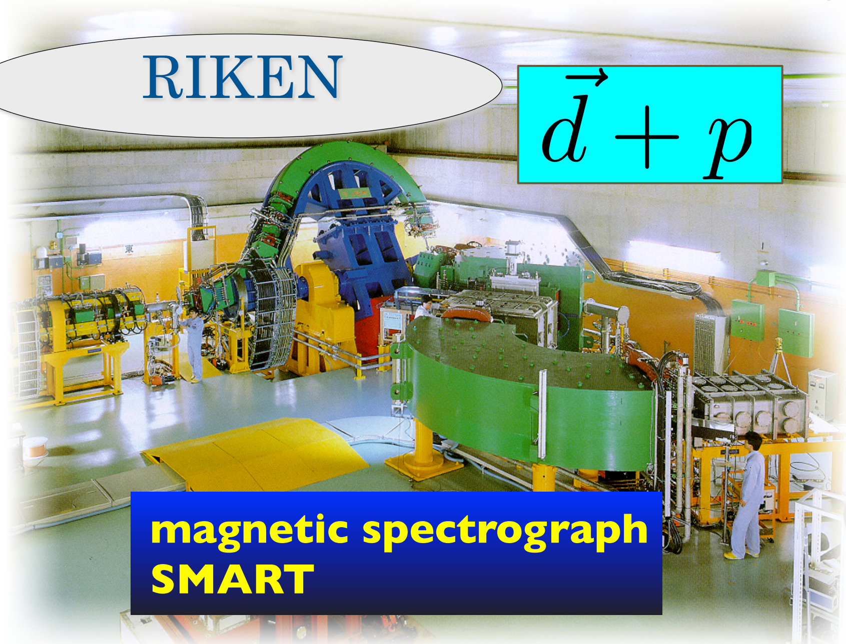

IUCF
Polarized deuteron
beam - 270MeV
PINTEX
CIS ⇒
90 MeV
CIS
The Cooler Ring
Electron Cooling
RFQ:
deuterons
at 4 MeV
CIPIOS
CIPIOS
extraction at
25kev
0
5 m
Scale
Cooler Ring
+ PINTEX


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

KVI to Krakow

BINA & SALAD

$\vec{p} + d$

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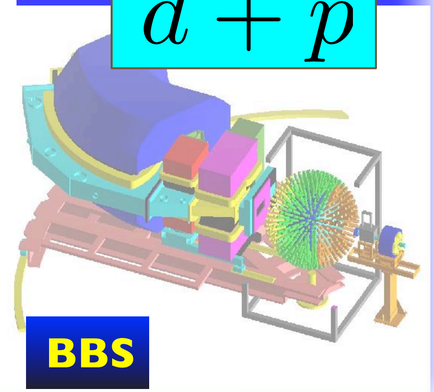

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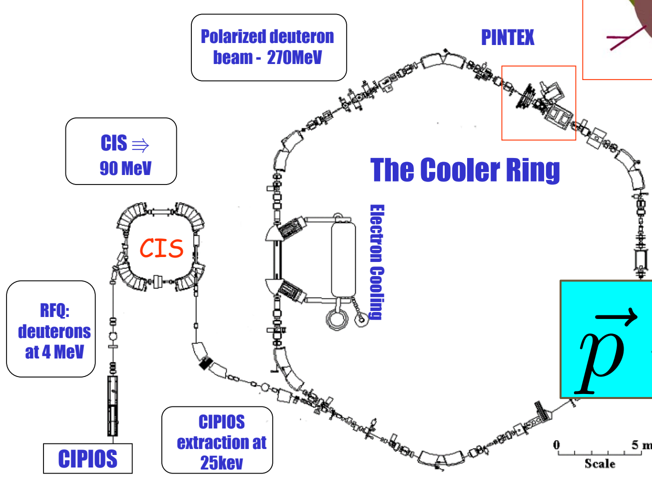
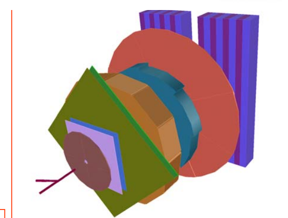


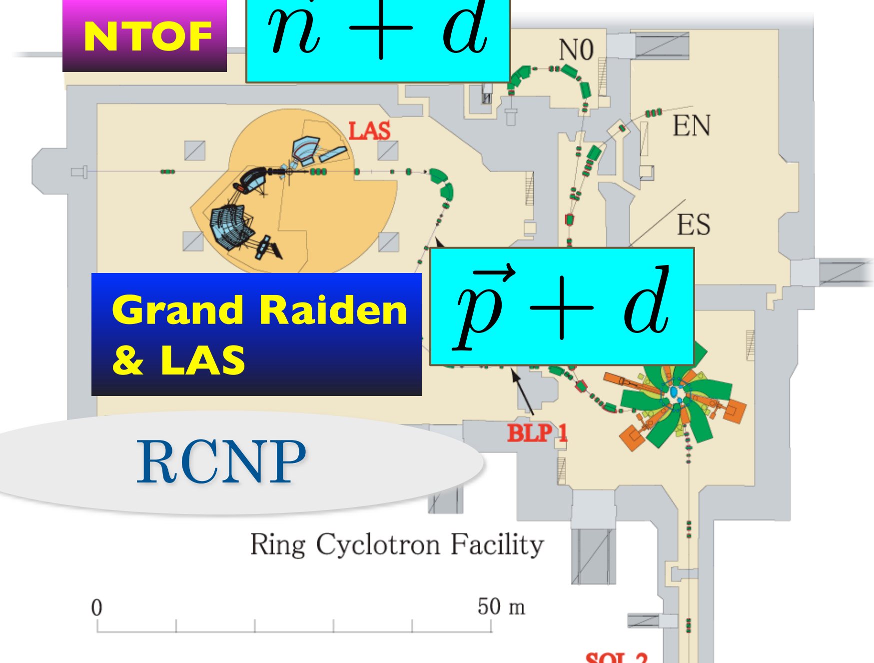


Cooler Ring + PINTEX

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

NTOF

$\vec{n} + d$



Grand Raiden & LAS

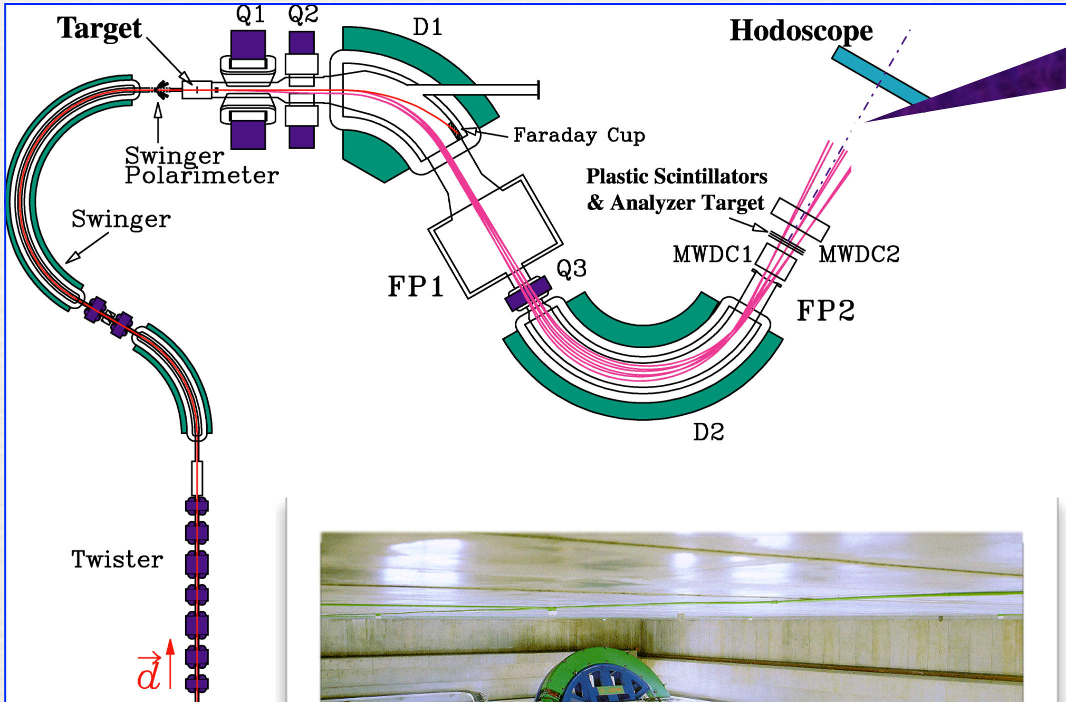
$\vec{p} + d$

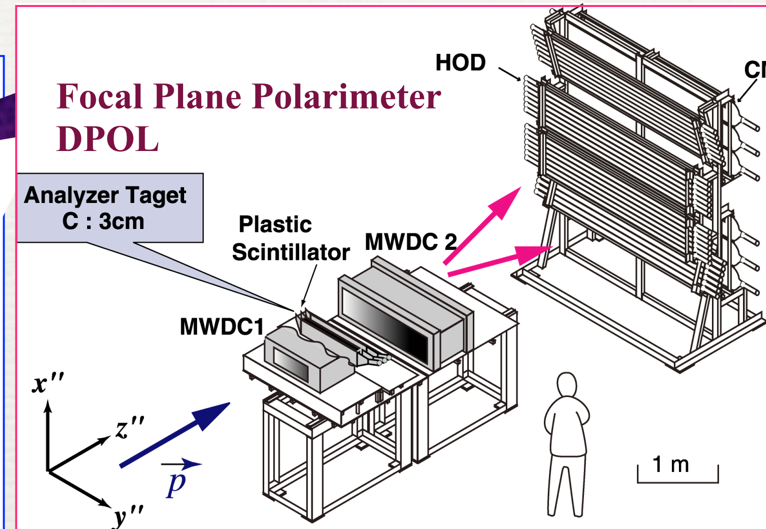
RCNP

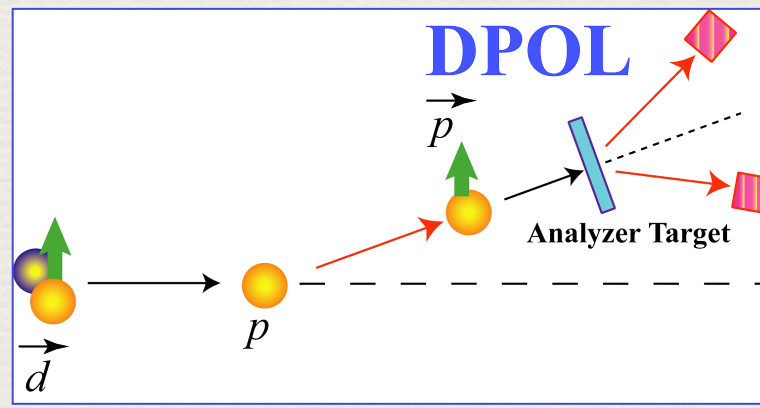
SMART at RIKEN (- 2005)

Swinger and Magnetic Analyzer with Rotator and Twister

$$\vec{d} + p$$





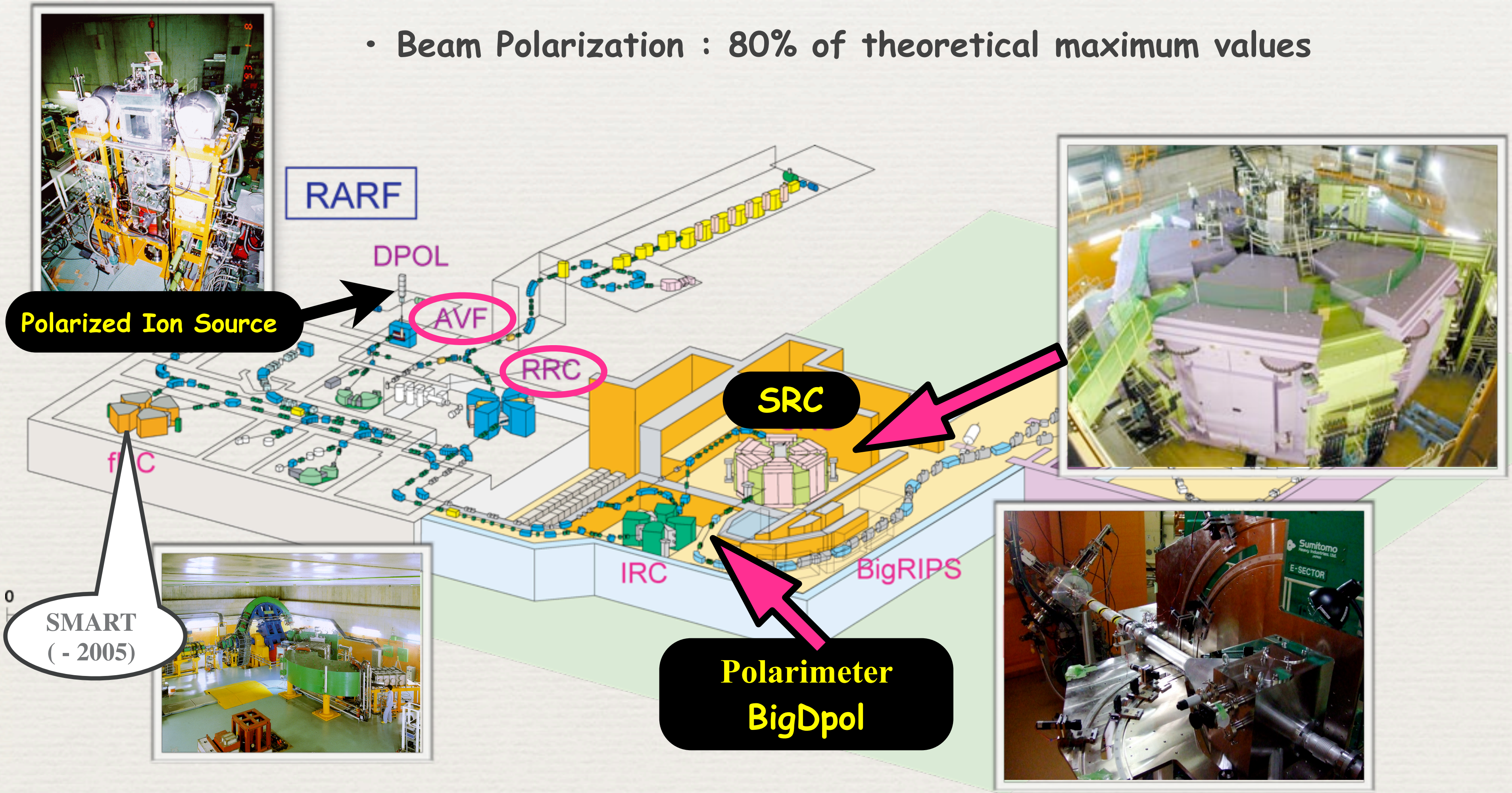


New Facility : RIKEN RI Beam Factory

$\vec{d} + p$

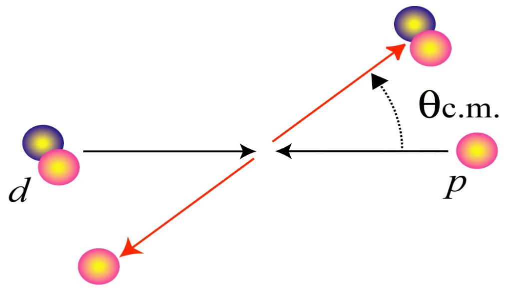
- RIBF : pol.d beams up to 400 MeV/nucleon are available by "AVF+RRC+ the new cyclotron SRC ".
  - First commissioning/experiment with pol.d beams at 250 MeV/nucleon was performed at the polarimeter BigDpol in 2009.

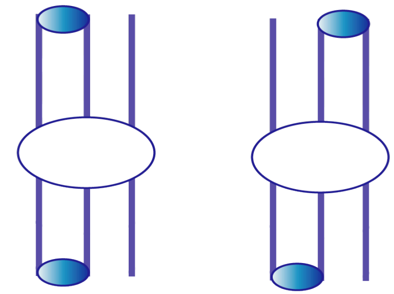
- Beam Polarization : 80% of theoretical maximum values



dp Scattering

- $d + p \longrightarrow d + p$





θc.m. = 0° ~ 180°

Momentum transfer

q =0 - 3.4 fm^{-1}

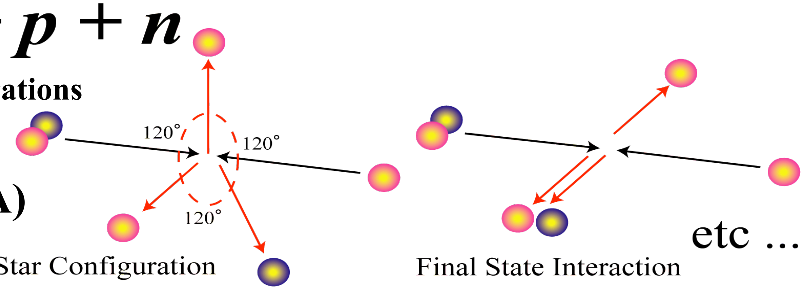
(at E = 135 MeV/A)

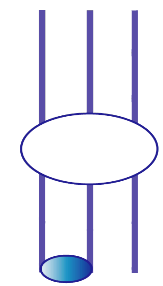
- $d + p \longrightarrow p + p + n$

Many kinematical configurations

q =0 - 3 fm^{-1}

(at E = 135 MeV/A)



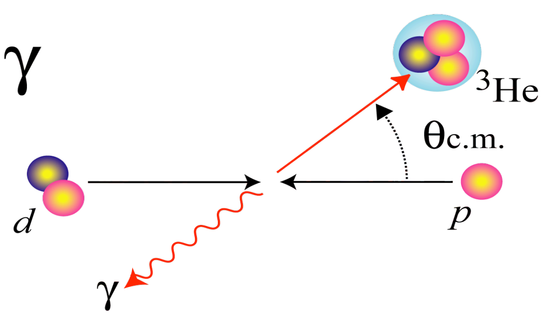


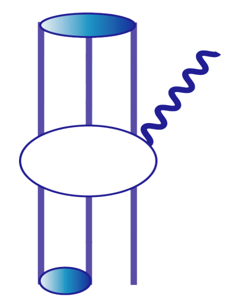
- $d + p \longrightarrow {}^3He + \gamma$

θc.m. = 0° ~ 180°

q =1.5 - 2.5 fm^{-1}

(at E = 135 MeV/A)



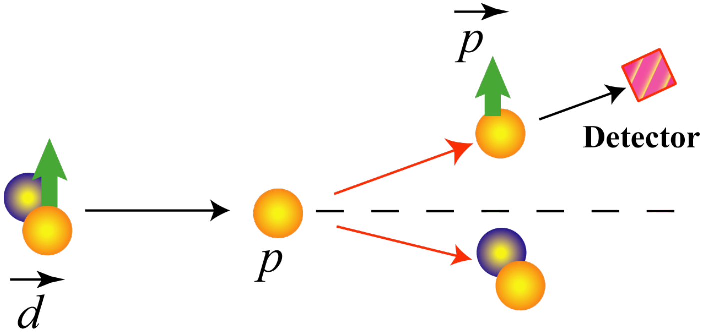


Observable for dp Scattering

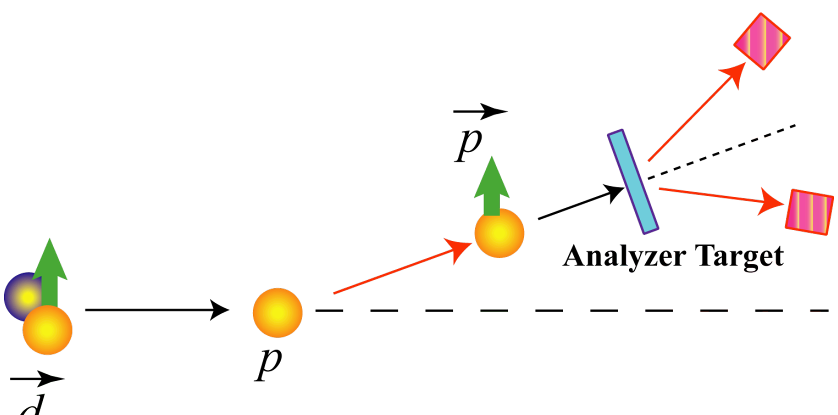
- **Differential Cross Section**
  - **Overall Strength**
  - **Absolute Quantity : normalization to *pp or np* data**

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

- **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**

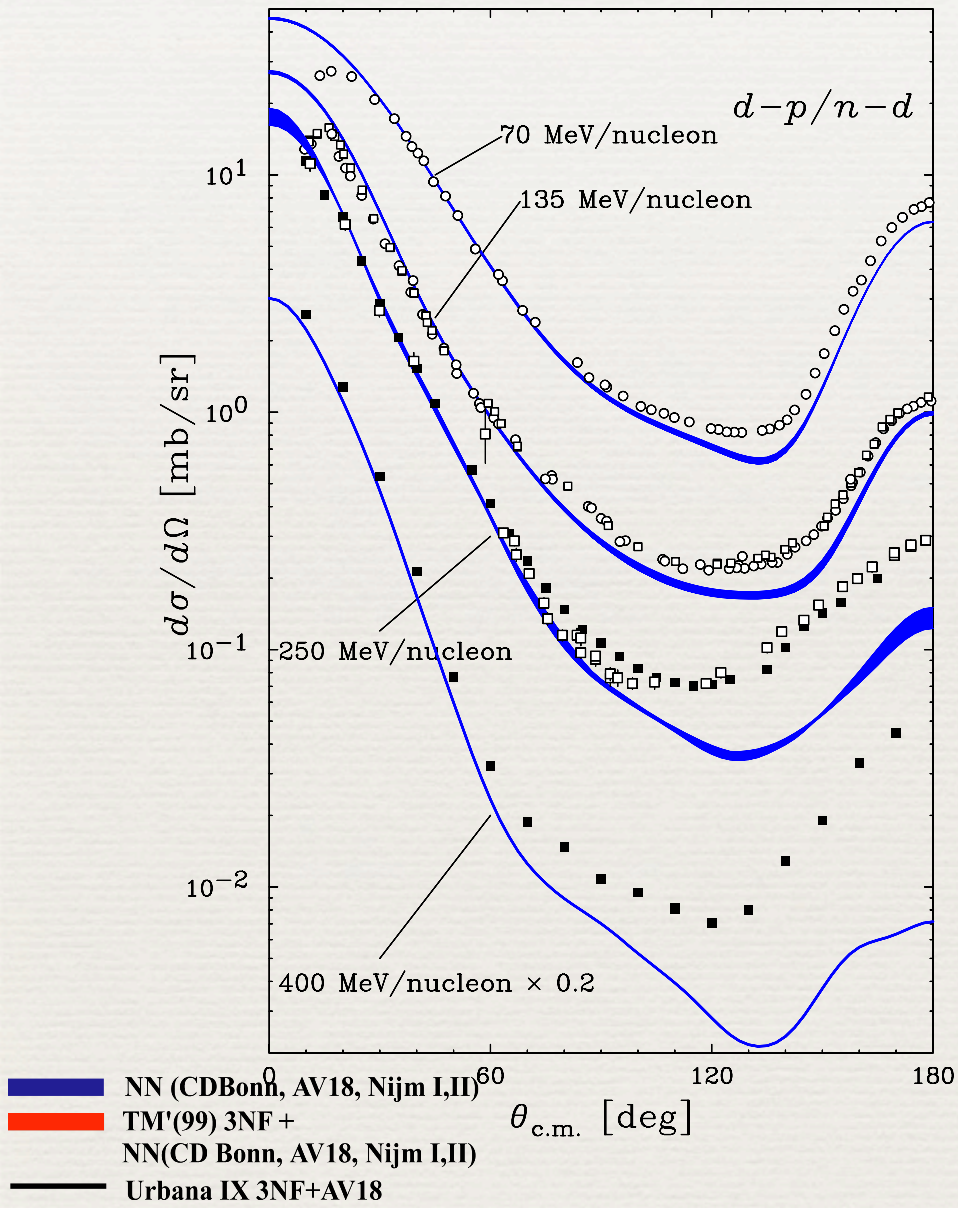


  - **Polarization Transfer Coefficient : $K_{ij}^{l'}$**
  - **Spin Correlation Coefficients C_{ij}**
    - **Spin-Spin interaction**



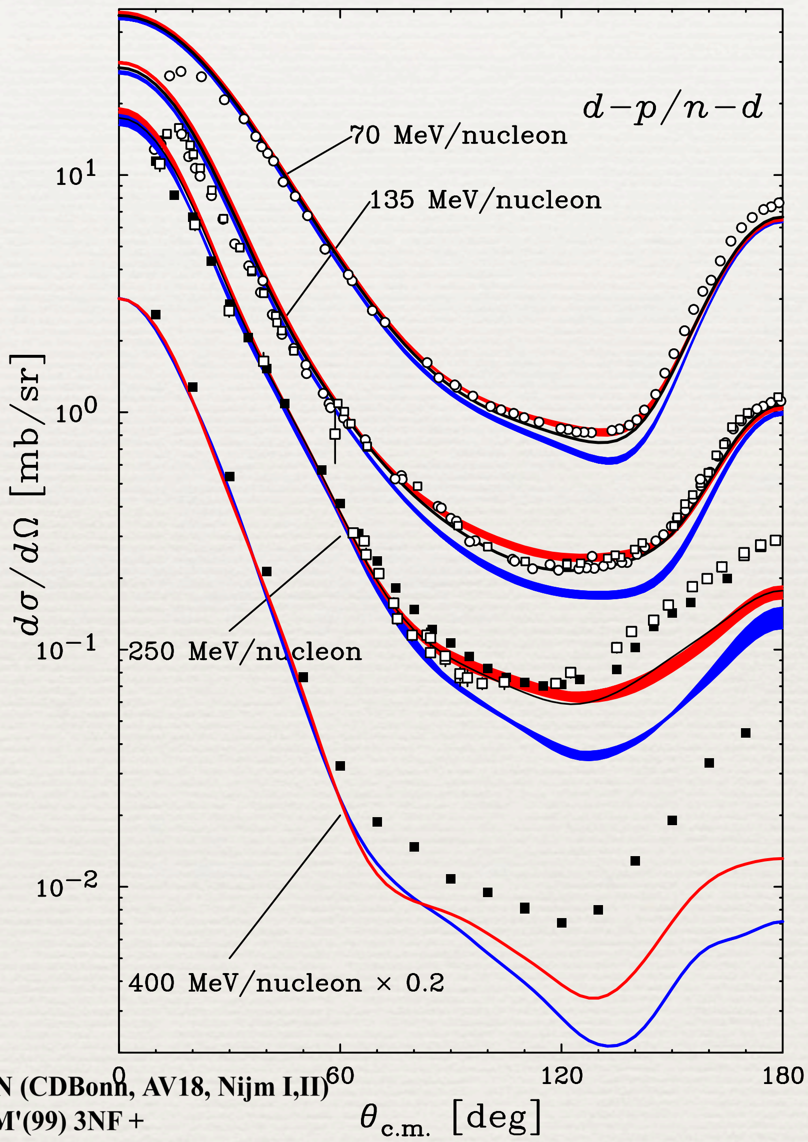
Nd Elastic Scattering

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)

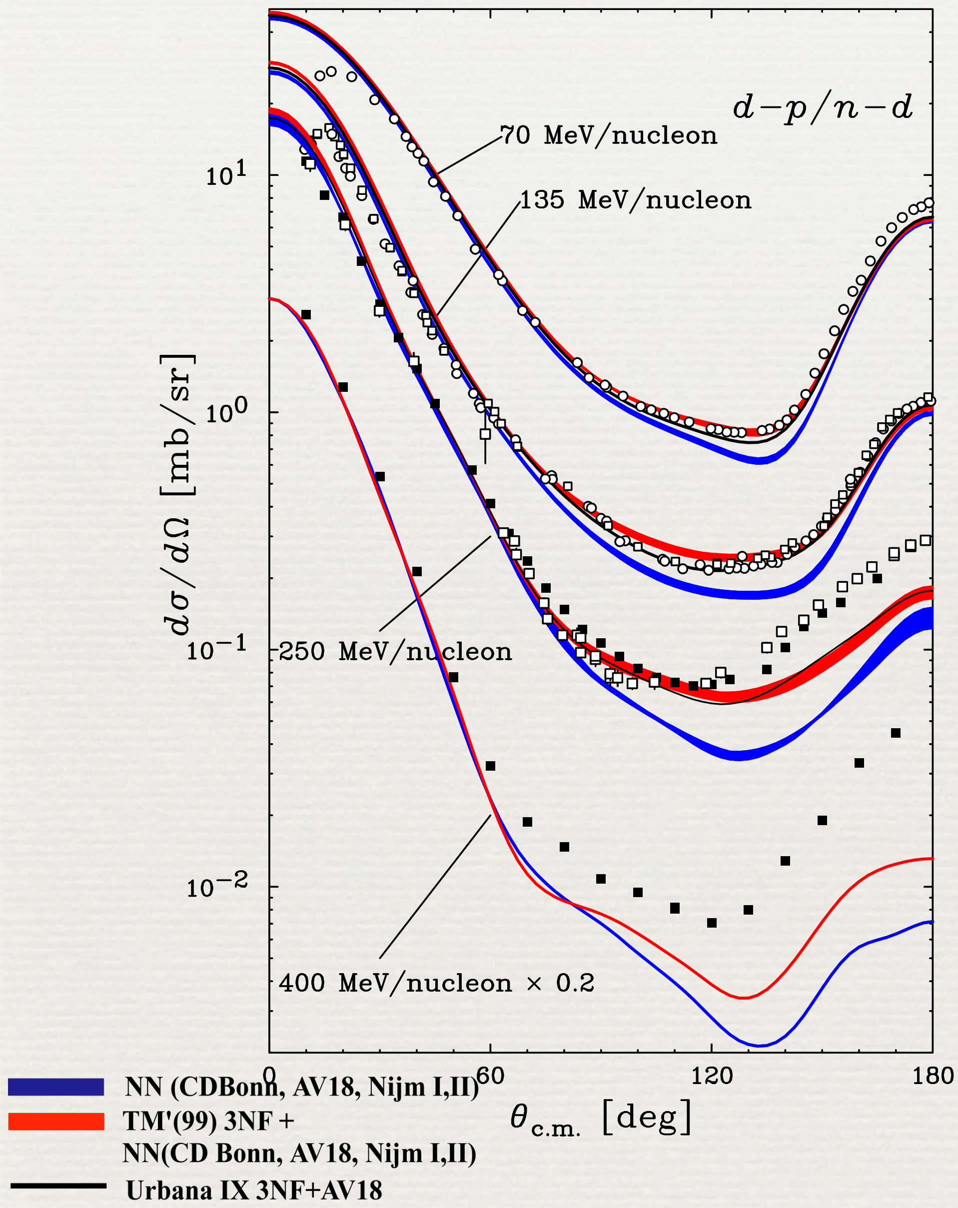
TM'(99) 3NF + NN(CD Bonn, AV18, Nijm I,II)

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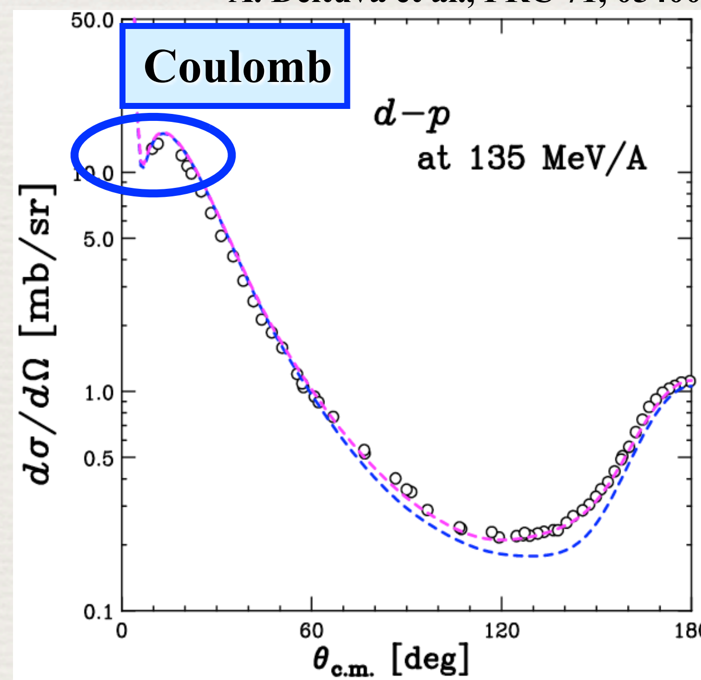
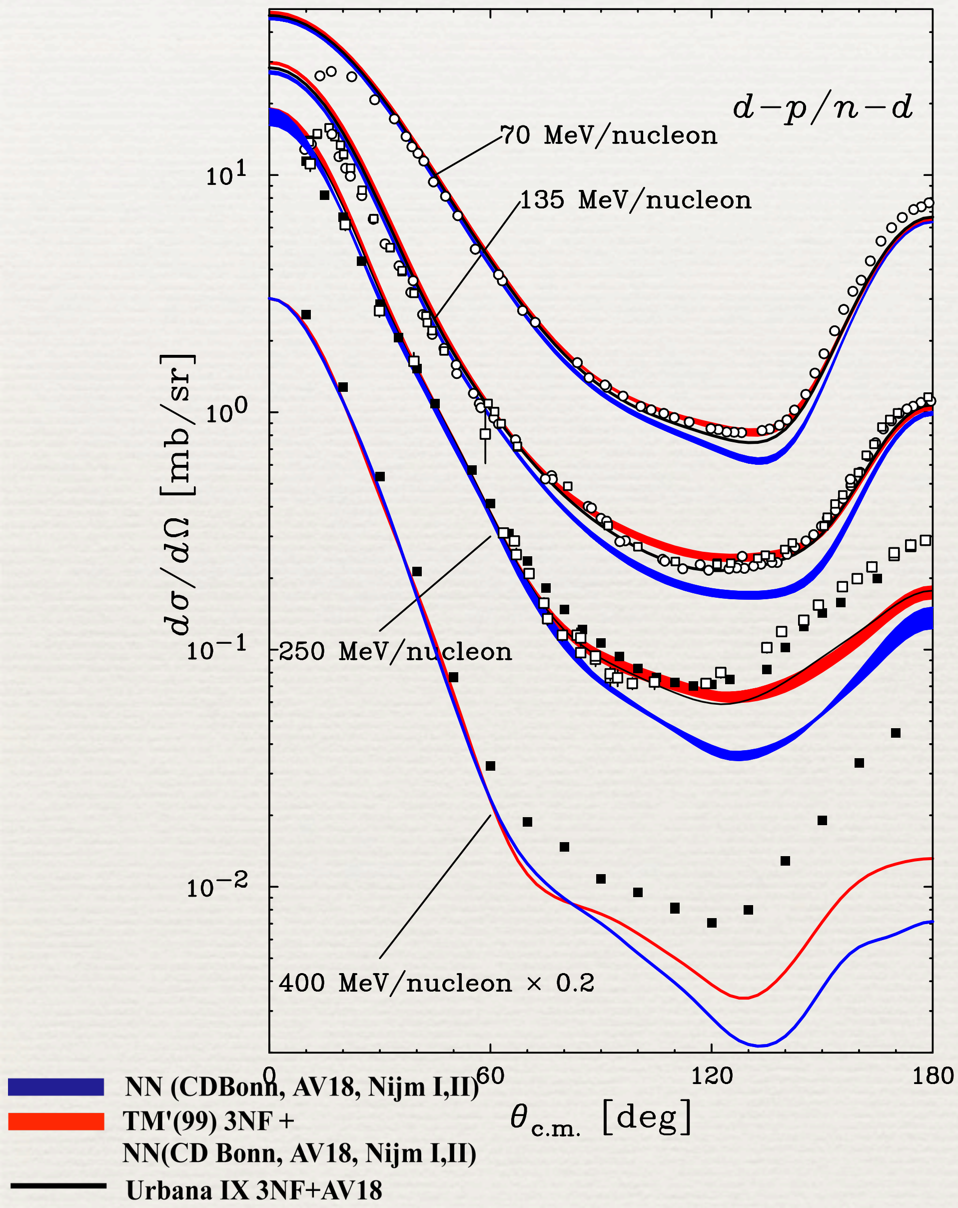
A. Deltuva et al., PRC 68, 024005 (2003)
A. Deltuva et al., PRC 71, 054005 (2005)



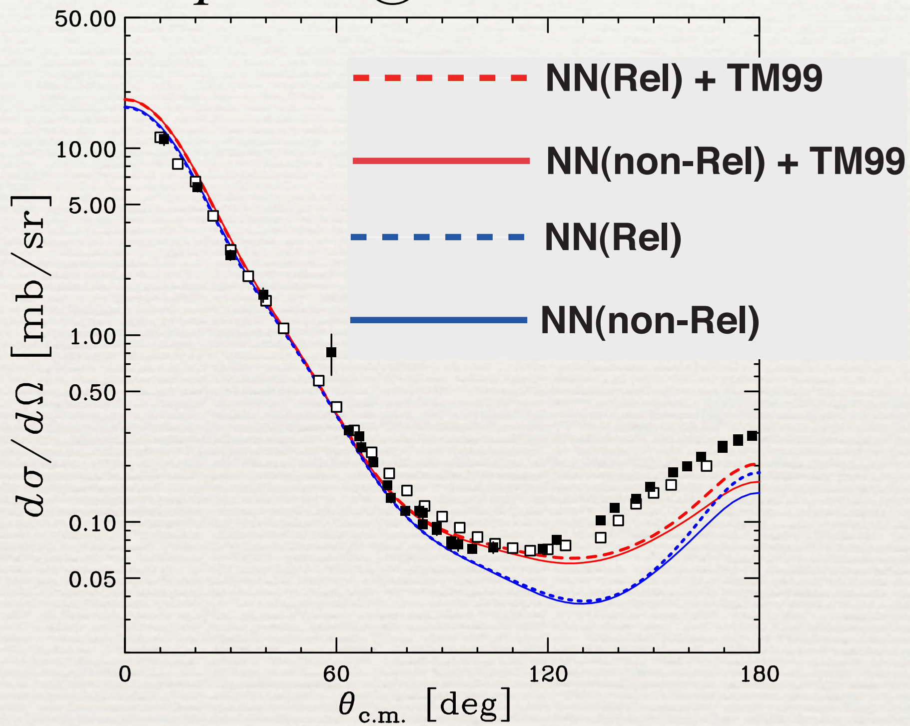
Differential Cross Section at 70 - 400 MeV/nucleon



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

H. Witala et al, private communications

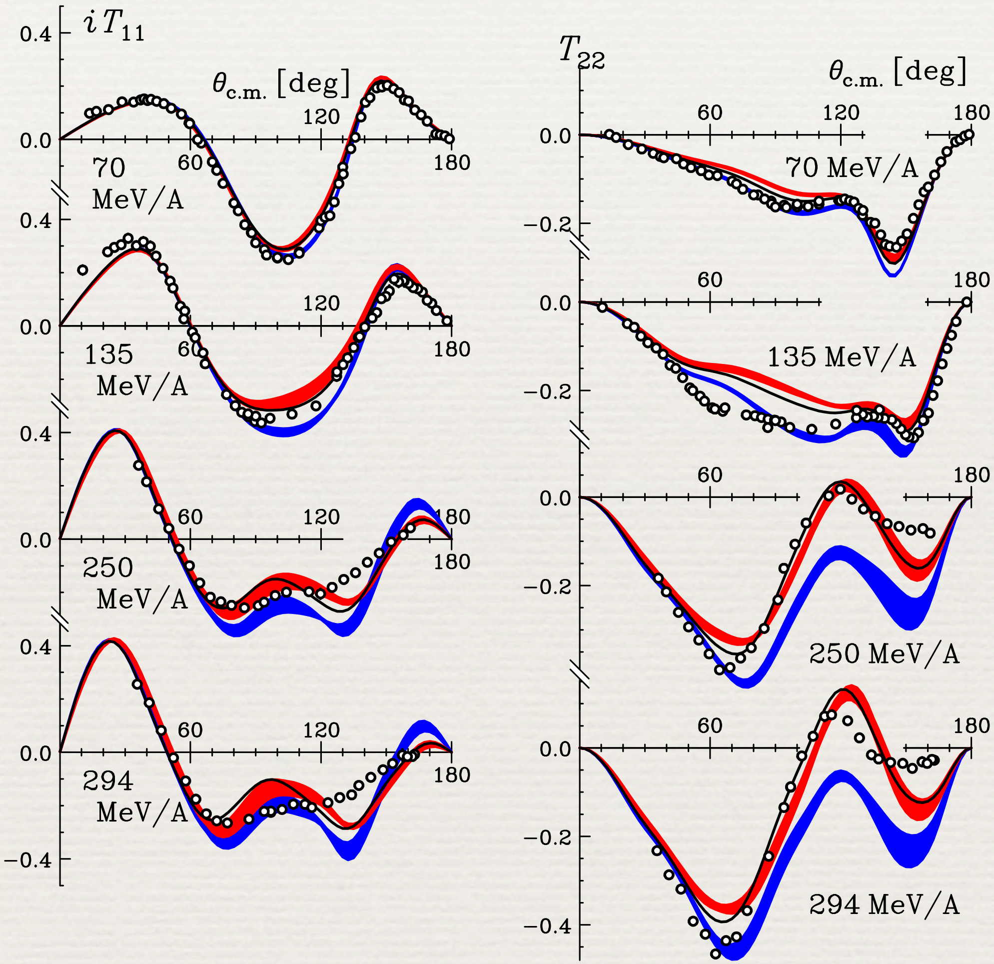
pd/nd @ 250 MeV



Relativistic effects are visible at backward angles, but small.

Deuteron Analyzing Powers at 70 - 300 MeV/nucleon

iT_{11} $\quad$ T_{22}

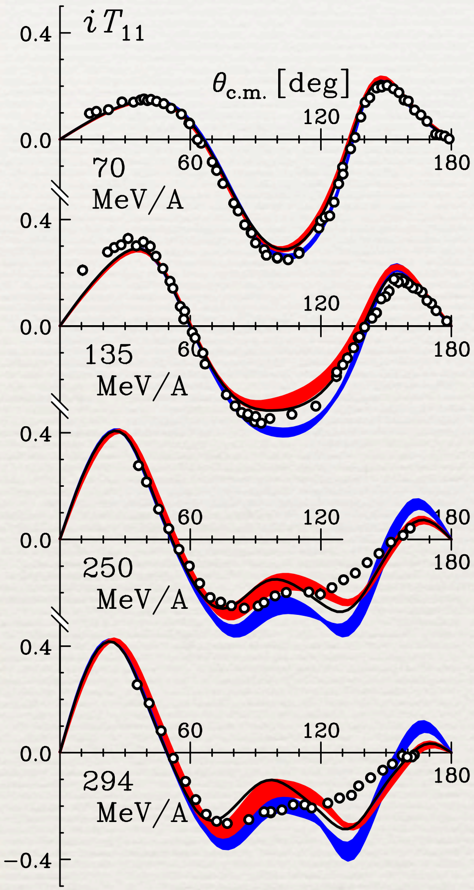


K.S. et al., Phys. Rev. C 83,061001 (2011)

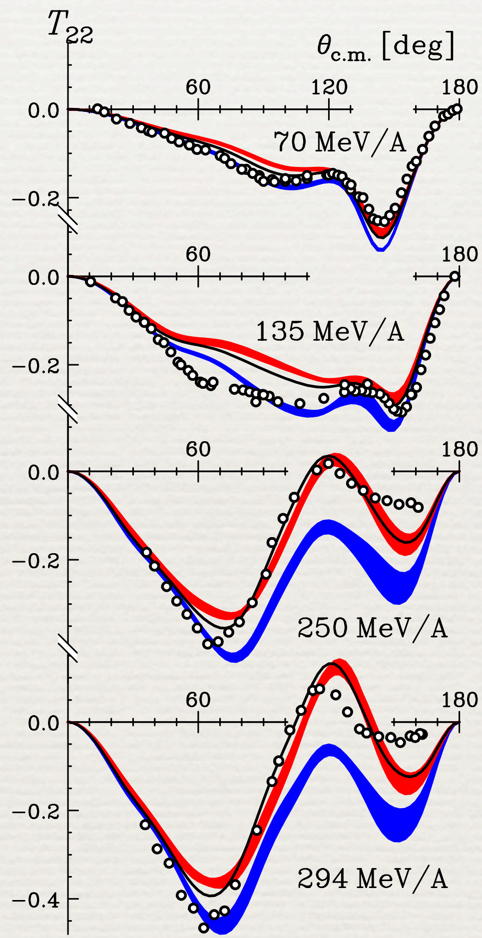
K.S. et al., Phys. Rev. C 89,064007 (2014)

Deuteron Analyzing Powers at 70 - 300 MeV/nucleon

iT_{11}



T_{22}



- **NN only**
  Large discrepancy
  in the backward region

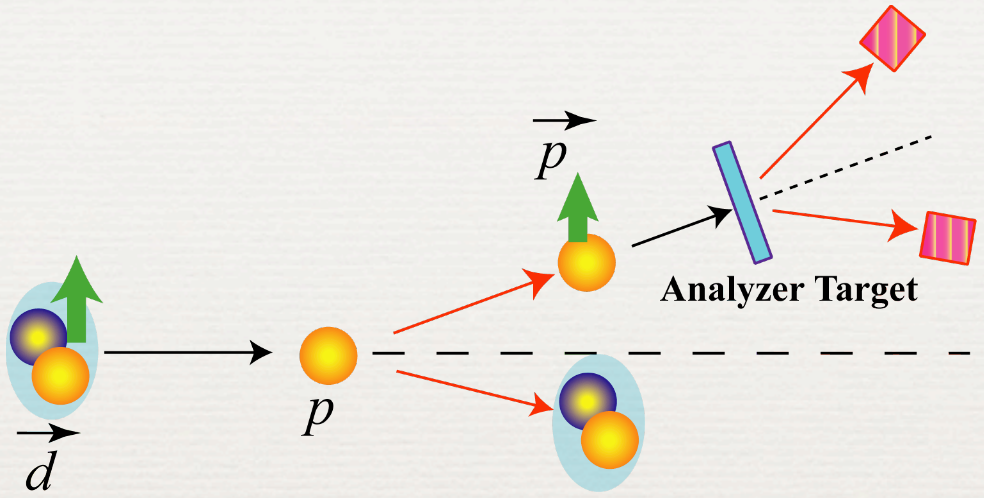
- **3NF at ~ 100 MeV/A**
  Results are NOT always
  similar to the cross section.

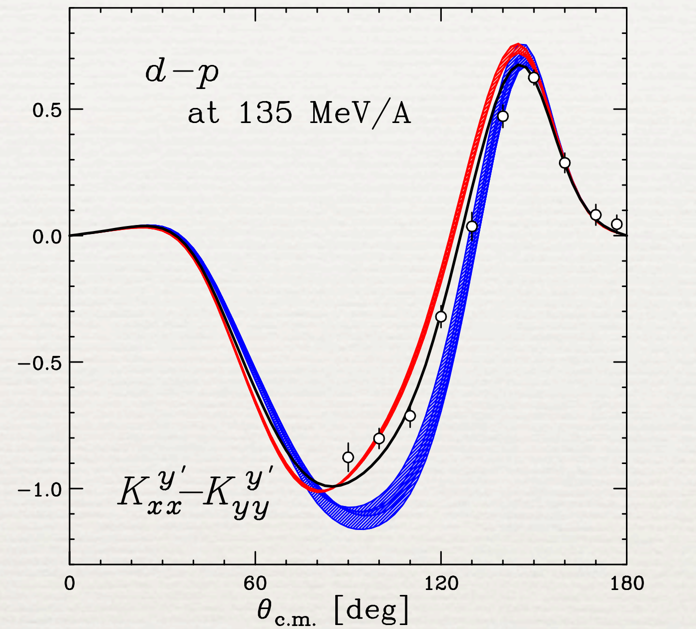
- **+ 2π3NF at ~ 250 MeV/A**
  - improve the agreement
  - not enough
    at very backward angles
    →similar to the cross section

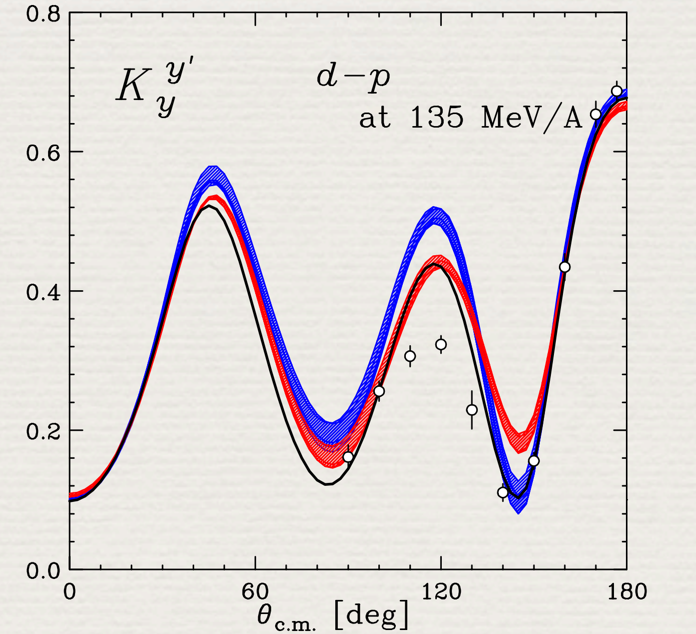
K.S. et al., Phys. Rev. C 83,061001 (2011)
K.S. et al., Phys. Rev. C 89,064007 (2014)

Polarization Transfer at 135 MeV/nucleon

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







3NF :

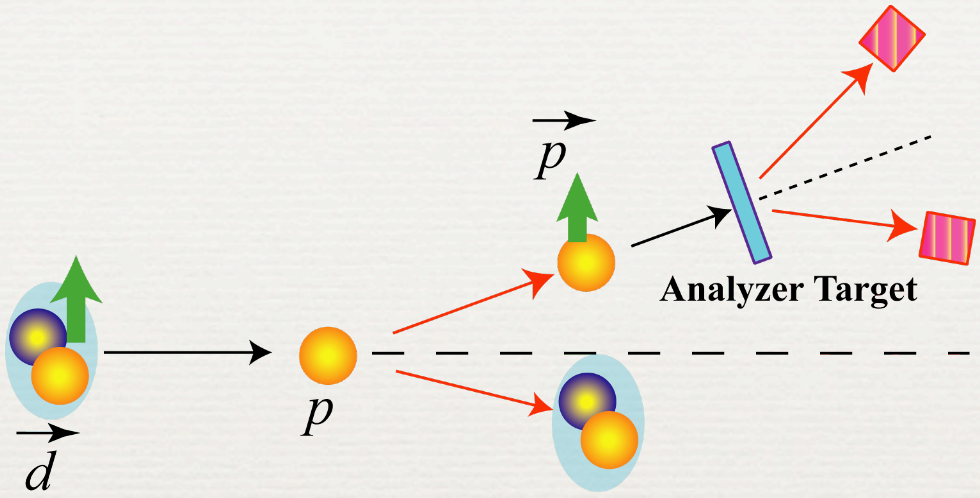
$K_{xx}^{y'}-K_{yy}^{y'}$: **Good Agreement**

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

Magnitude : not enough

Polarization Transfer at 135 MeV/nucleon

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



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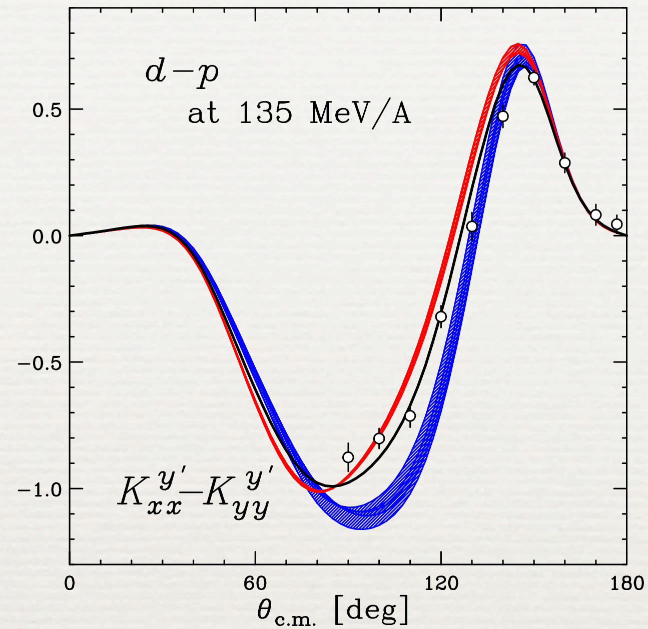
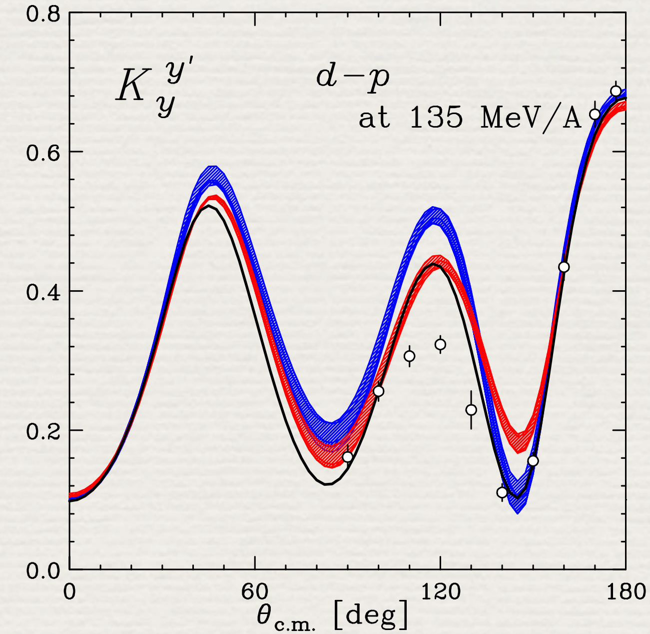




- **Around 100 MeV/nucleon**

  Cross Section : 3NFs are clearly needed.

  Spin Observables : Defects of spin dependent parts of 3NF

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

- **"What" we are missing ?**

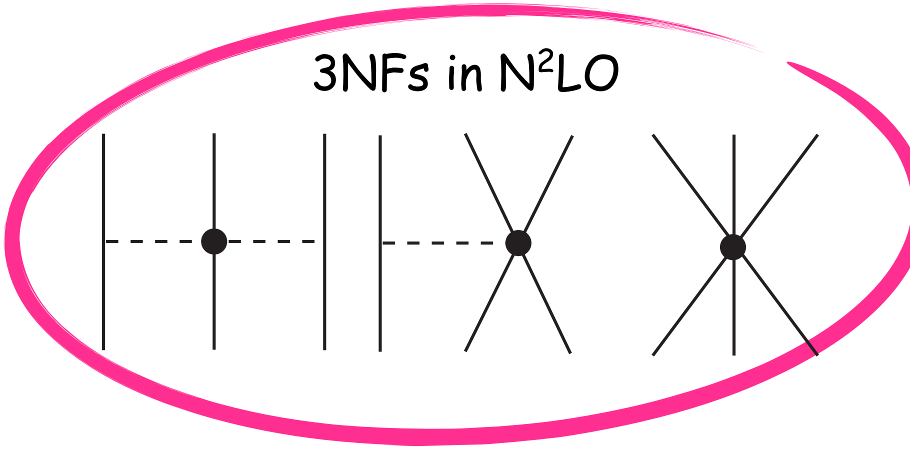
  Components other than 2π3NF;

  e.g. heavier meson exchange 3NFs .

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

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

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



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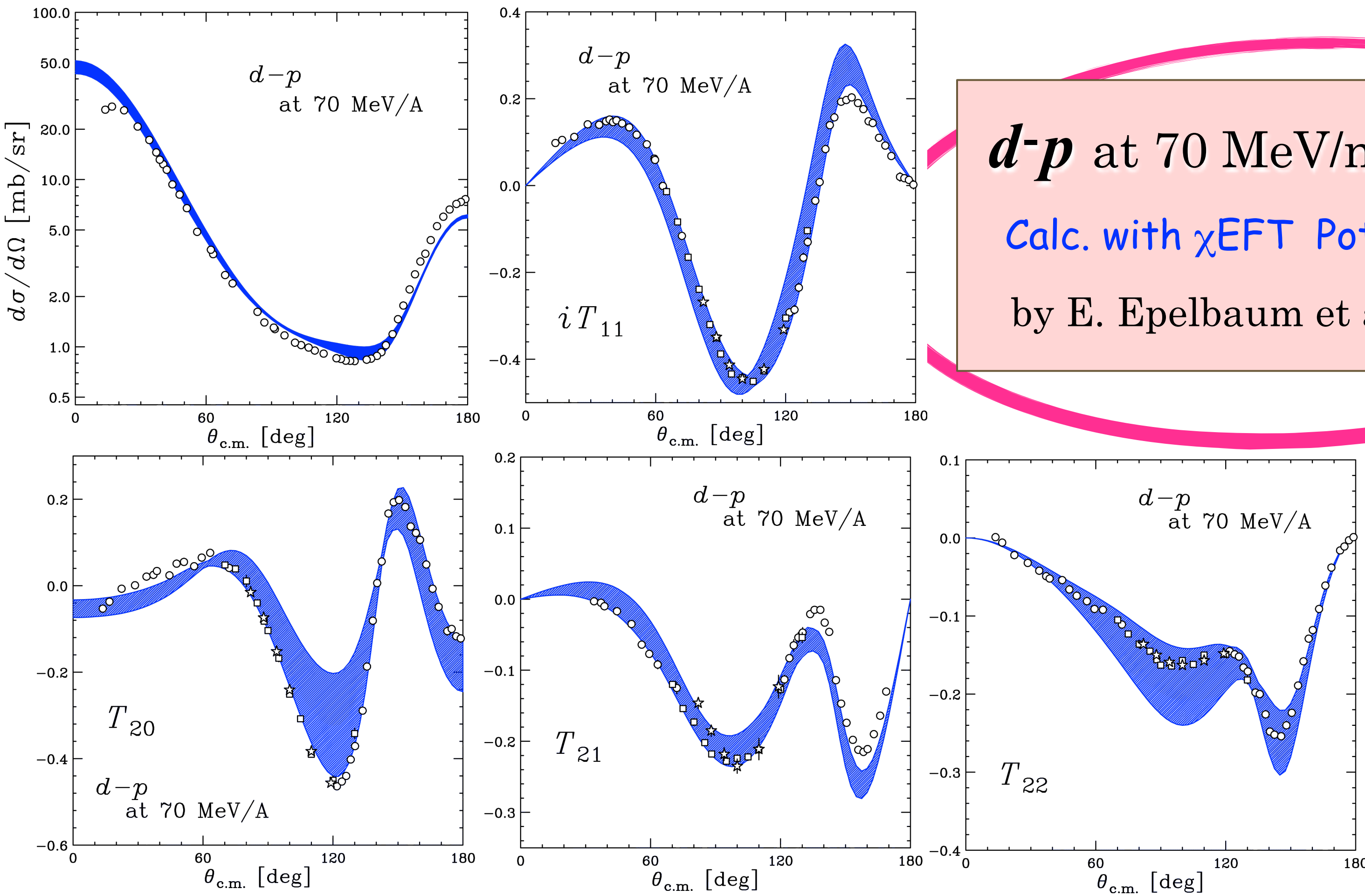


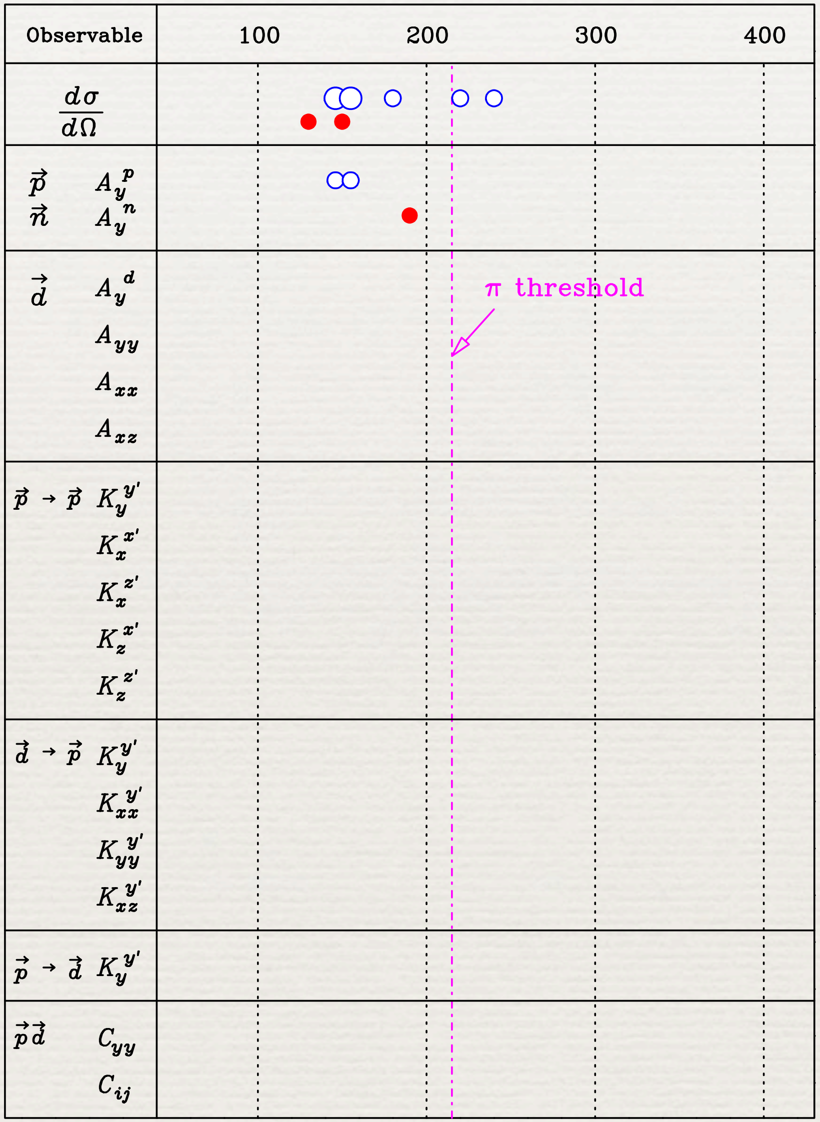
d-p **at 70 MeV/nucleon**

Calc. with χEFT Pot. (N2LO)

by E. Epelbaum et al.

Nd Elastic Scattering Data at Intermediate Energies

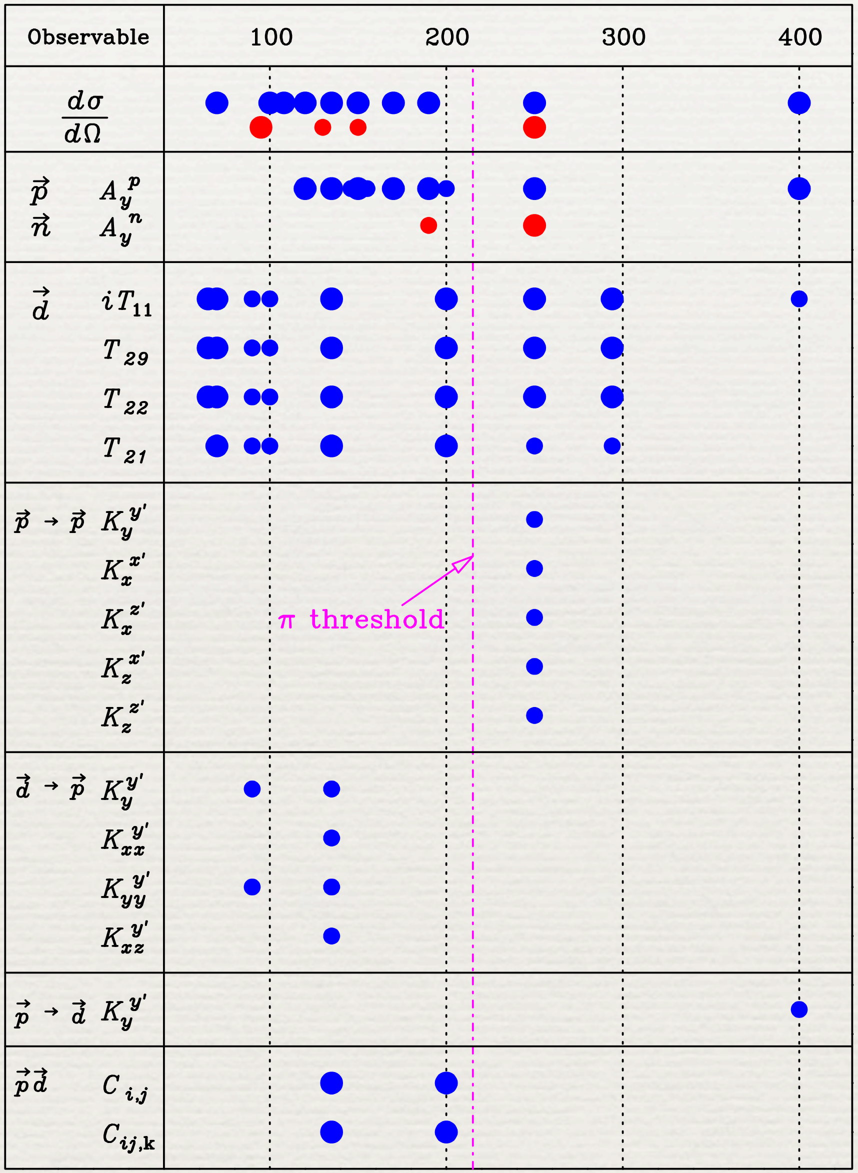
pd and nd Elastic Scattering at 70–400 MeV/A



~1998

Nd Elastic Scattering Data at Intermediate Energies

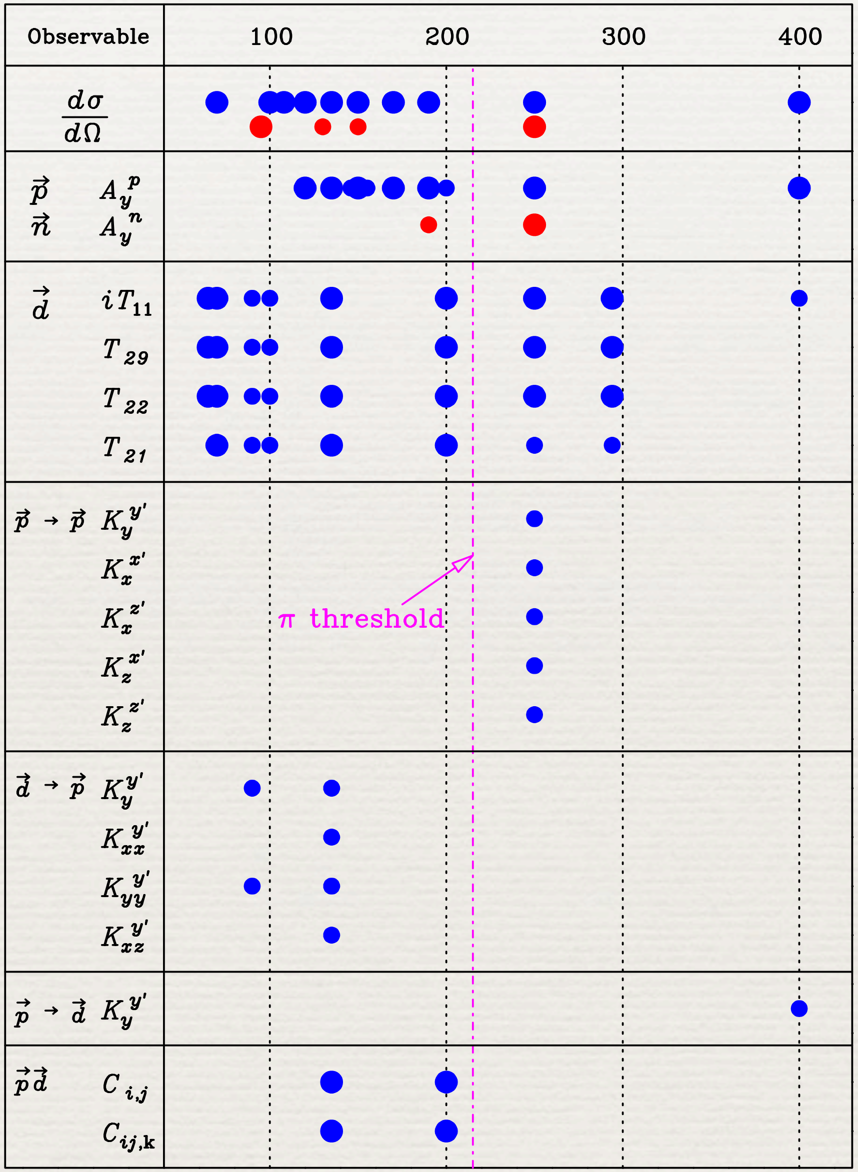
pd and *nd* Elastic Scattering at 70–400 MeV/nucleon



~2014

Nd Elastic Scattering Data at Intermediate Energies

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



~2014

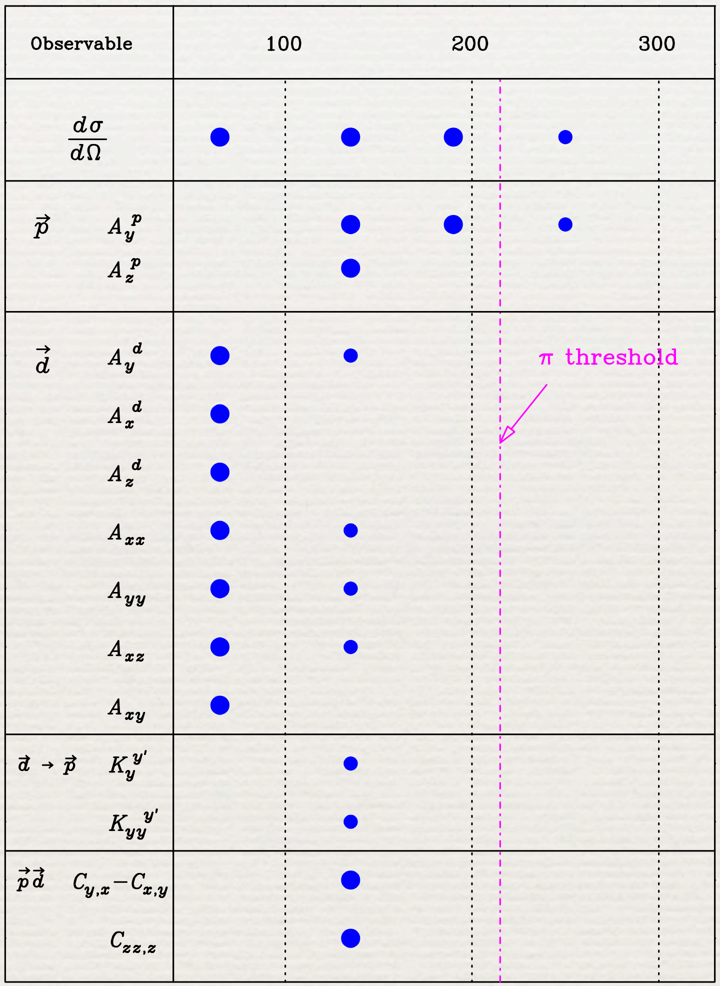
- **High precision data of**
  ***dσ/dΩ* & Spin Observables**
  from RIKEN, RCNP, KVI, IUCF

- **Energy dependent data**
  - √ ***dσ/dΩ***
  - √ **Proton Analyzing Power**
  - √ **Deuteron Analyzing Powers**

Nd Breakup Reaction

Nd Breakup Data at Intermediate Energies

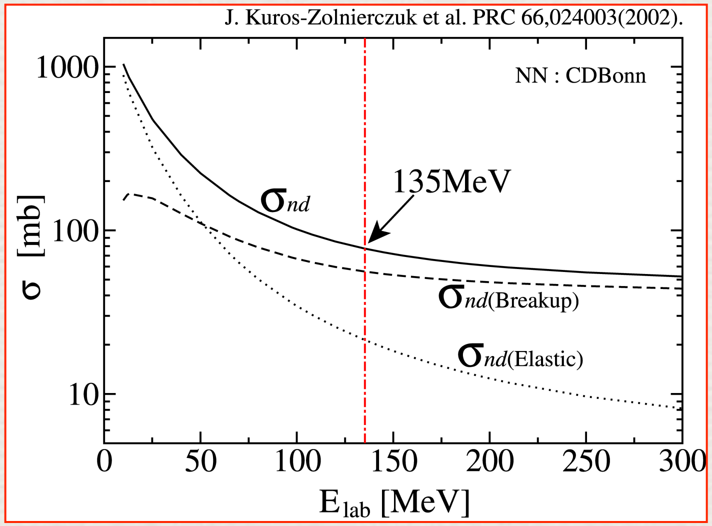
pd Breakup Reaction at 65−250 MeV/A



1st Step : ***Nd*** Elastic Scattering at Intermediate Energies

2nd Step : ***Nd*** Breakup Reactions at Intermediate Energies

- Leading Channel at Intermediate Energies
  - ***nd*** total cross section
    - $\sigma_{br} > \sigma_{el}$
    - e.g. $\sigma_{br} \sim 2.5\ \sigma_{el}$ at 135MeV/A

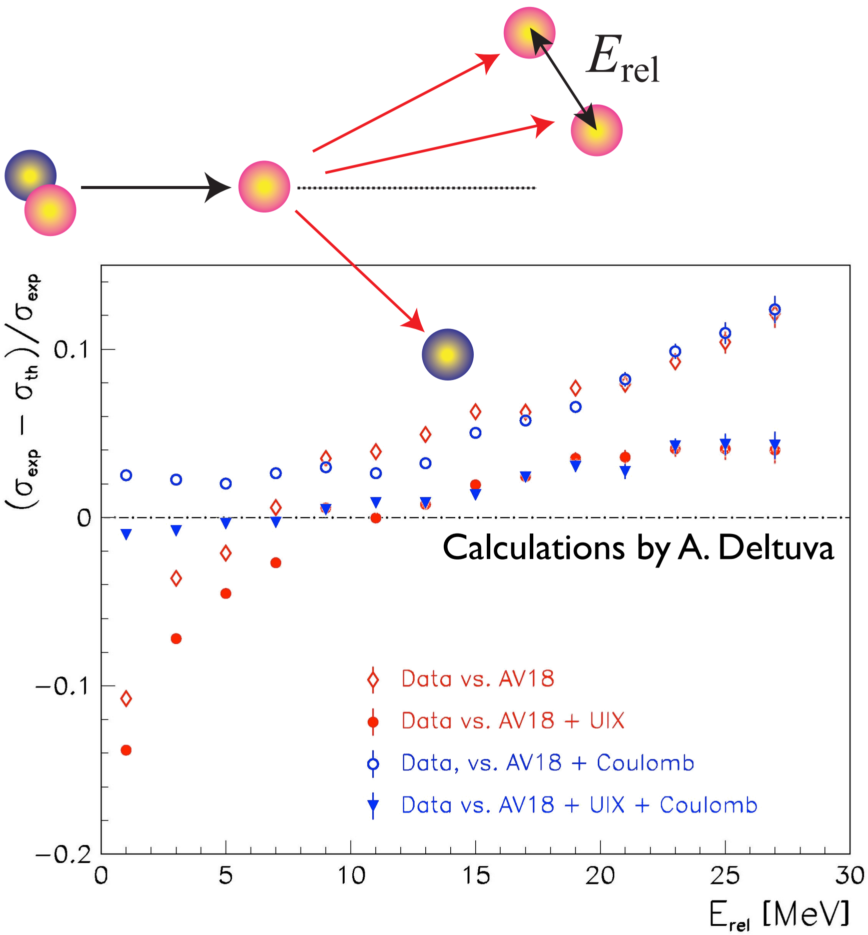


- Rich Phase-Spaces
  - a large amount of kinematical configurations
  - Selectivity

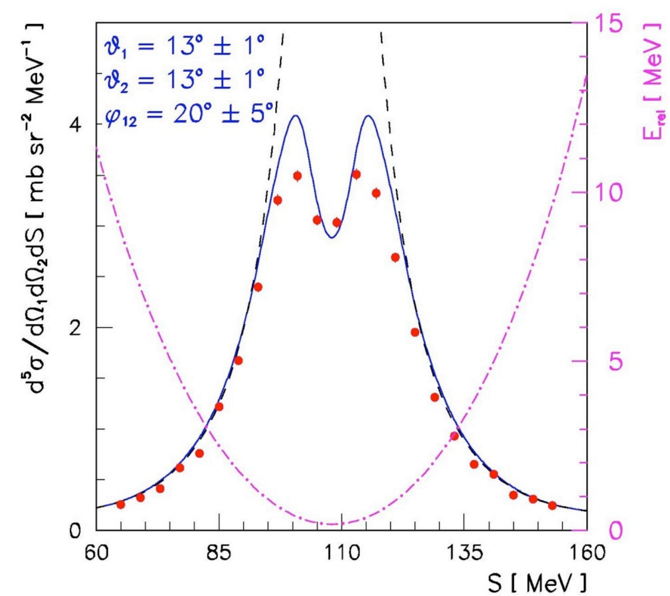
^{1}H(d,pp)n breakup Reaction at 65 MeV/nucleon from KVI

✓ Nearly 1800 data points of cross section

Courtesy by St. Kistryn



- **Small 3NF effects**
- Relative energies of the scattered two protons $E_{\rm rel}$
  - $E_{\rm rel} \lesssim 10 {\rm MeV}$
    : Clear signature of Coulomb Force effects
  - The best agreement is reached when the Coulomb and the 3NF (UrbanaIX) are taken into account.
- At lower polar angles (θ_1, θ_2)
  the data are explained by inclusion of Coulomb forces.



Coulomb Forces are needed.

St. Kistryn et al., Phys. Lett. B 641, 23(2006)

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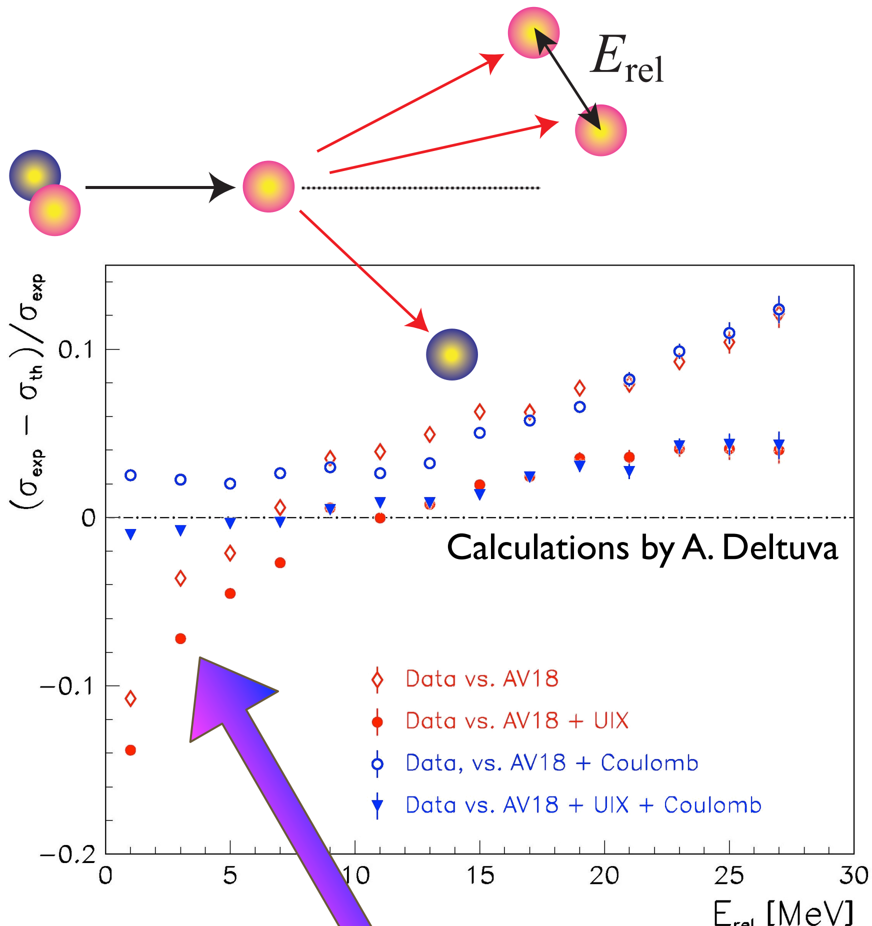

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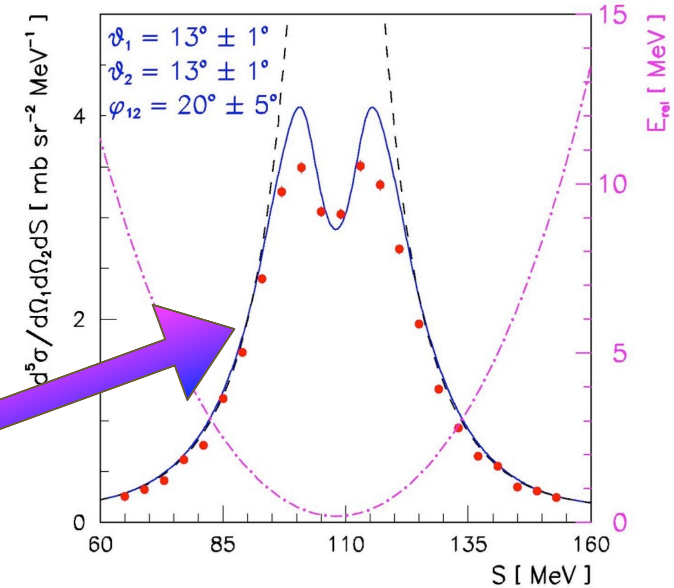


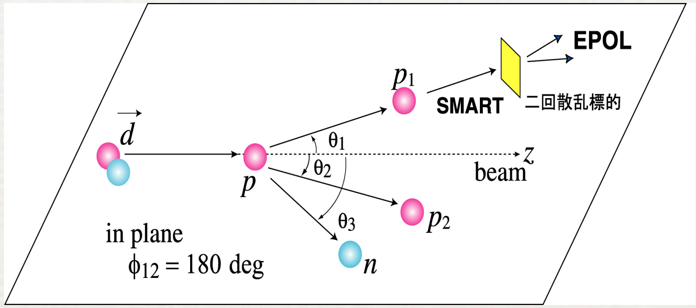
St. Kistryn et al., Phys. Lett. B 641, 23(2006)

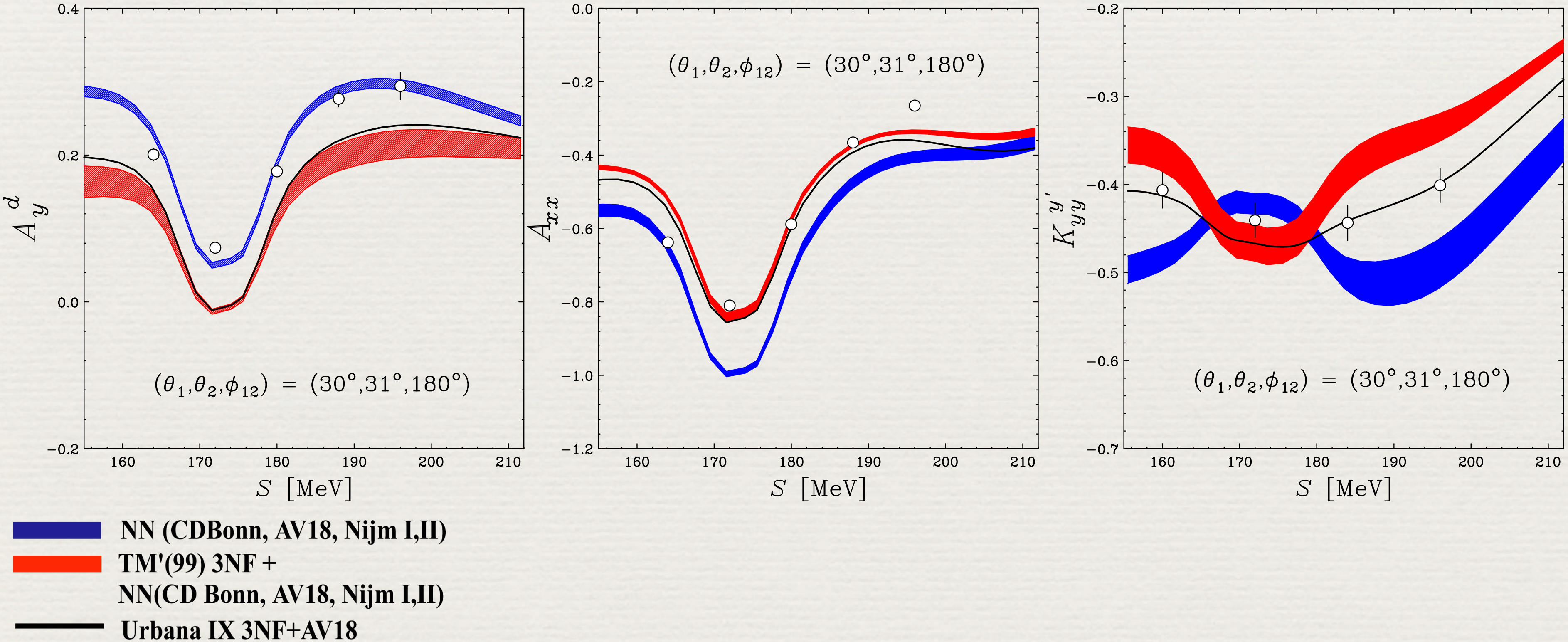
dp In-Plane Breakup Reaction at 135 MeV/nucleon from RIKEN

K.S. et al., Phys. Rev. C 78,054008 (2009)

Which is better, Tucson-Melbourne or Urbana IX ?

- $(\theta_1,\theta_2) = (28 - 32$ deg, 31deg) , $\varphi_{12} = 180°$
  - Near Final State Interaction
- ***d*** **to** ***p*** **Pol. Transfer :** $K_{yy}^{y'}$
- **Analyzing Powers :** A_y^d, A_{yy}, A_{xx}, A_{xz}





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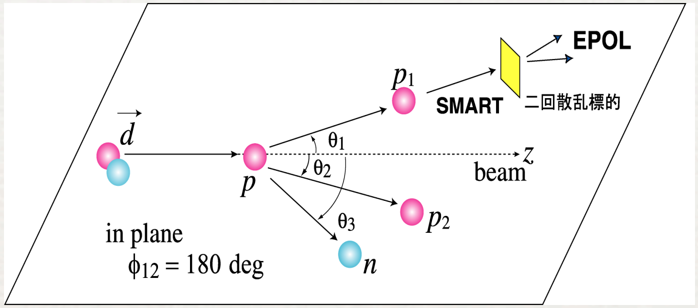

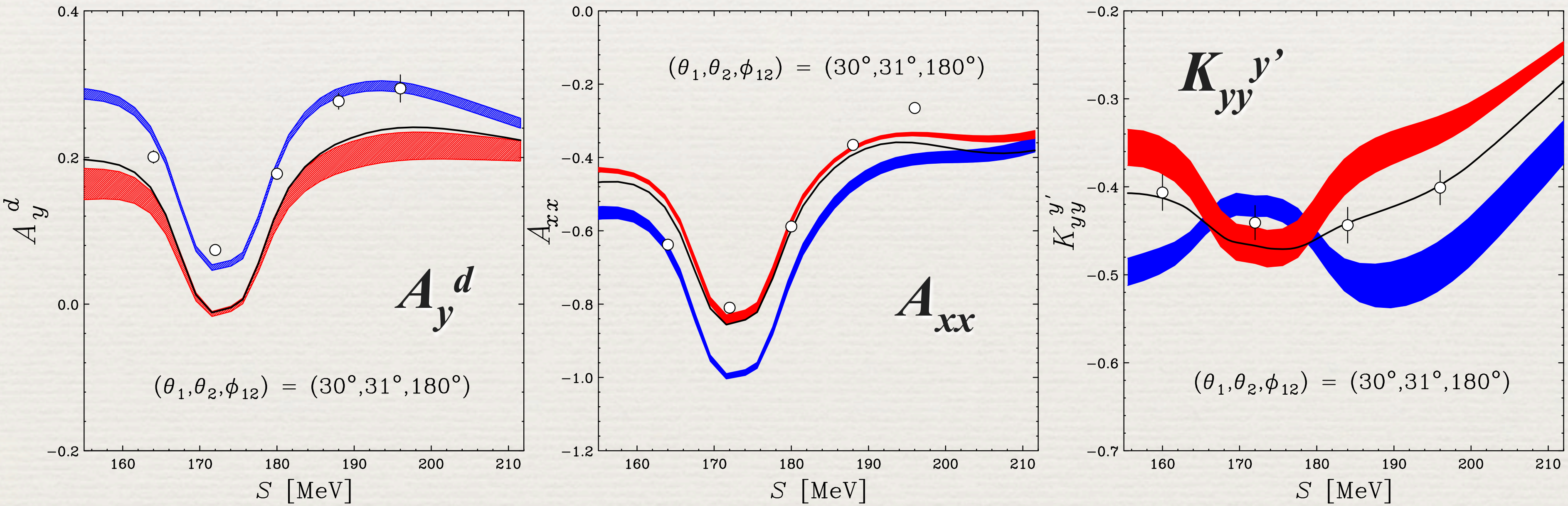

- **NN (CDBonn, AV18, Nijm I,II)**
- **TM'(99) 3NF + NN(CD Bonn, AV18, Nijm I,II)**
- **Urbana IX 3NF+AV18**

dp In-Plane Breakup Reaction at 135 MeV/nucleon from RIKEN

H. Witala et al, Phys. Rev. C **83**, 044001 (2011)

- (θ_1,θ_2) = (28 – 32 deg, 31deg) , φ_{12} = 180°
  - Near Final State Interaction
- *d* to *p* Pol. Transfer : $K_{yy}^{y'}$ (Double Scattering Measurement)
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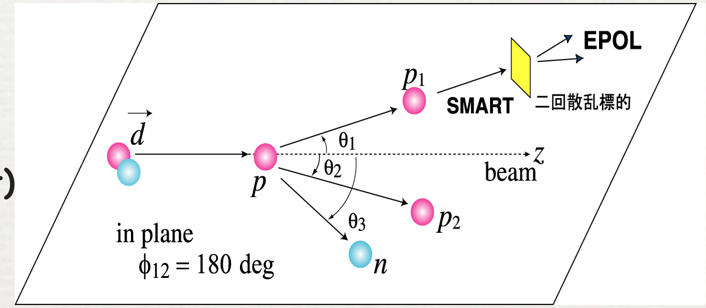
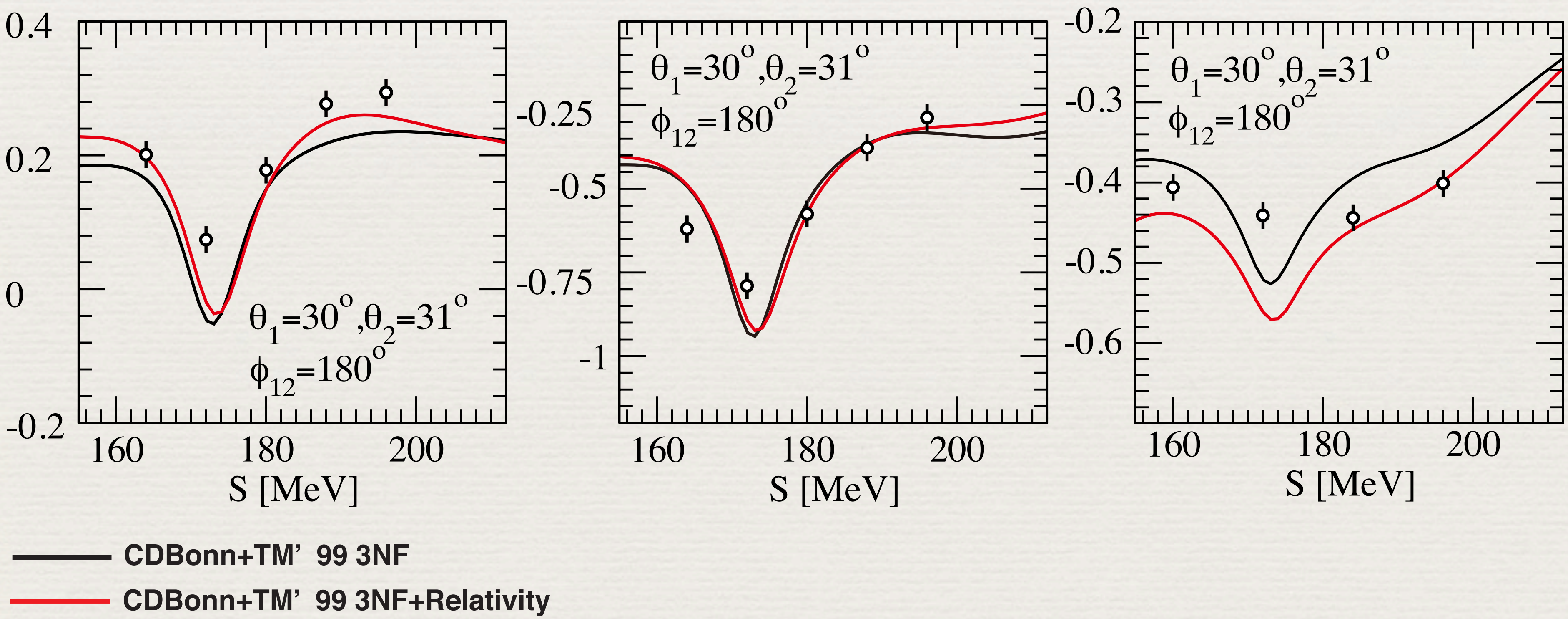


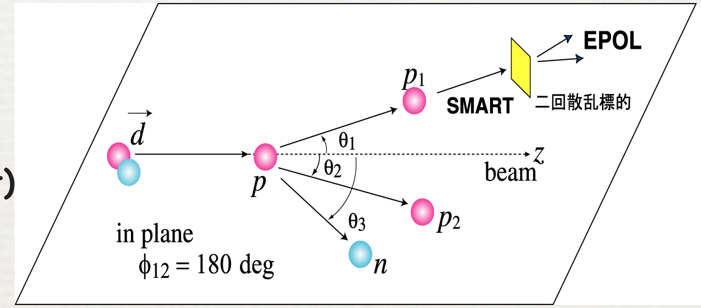


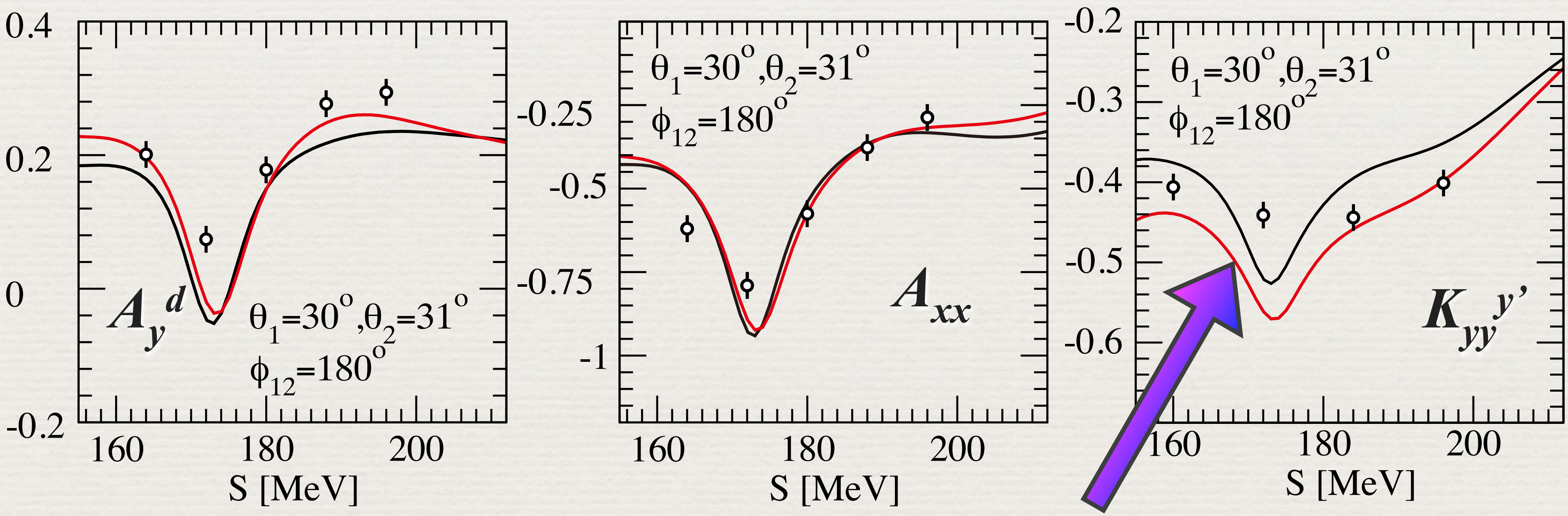
dp In-Plane Breakup Reaction at 135 MeV/nucleon from RIKEN

H. Witala et al, Phys. Rev. C **83**, 044001 (2011)

Relativistic Faddeev Calculations with TM'99 3NF

- (θ_1,θ_2) = (28 – 32 deg, 31deg) , φ_{12} = 180°
  - Near Final State Interaction
- *d* to *p* Pol. Transfer : $K_{yy}^{y'}$ (Double Scattering Measurement)
- Analyzing Powers : A_y^d, A_{yy}, A_{xx}, A_{xz}





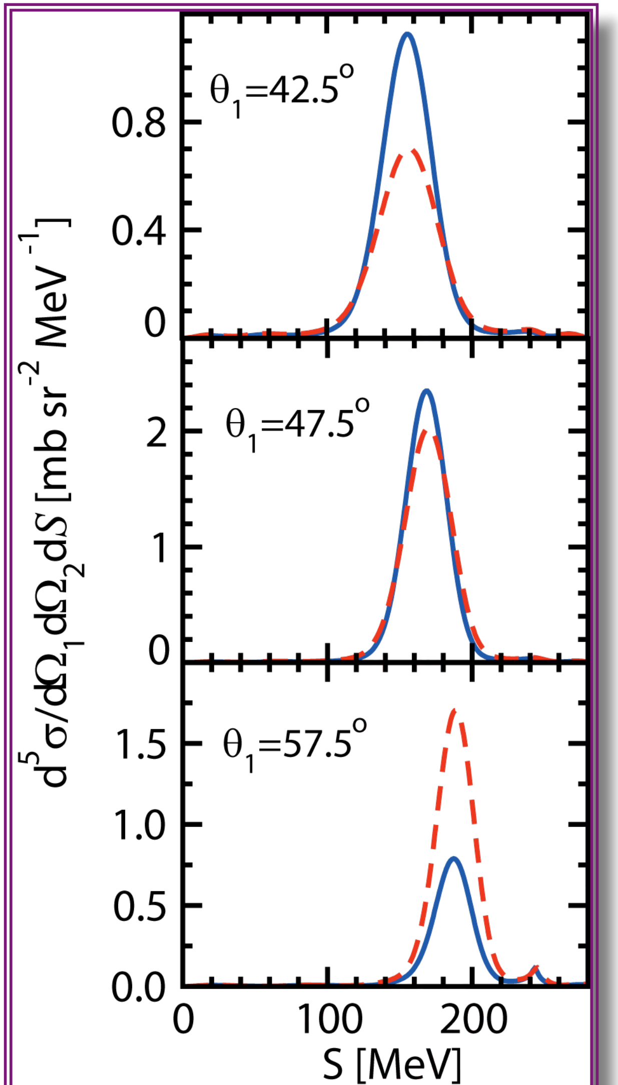
CDBonn+TM' 99 3NF
CDBonn+TM' 99 3NF+Relativity

Relativistic effects are NOT negligible.

Complementary effects in 3N Scattering

Relativistic Effects in ^{2}H(*p*,*pp*)*n* breakup Reaction

θ_2 = 37.5°, φ_{12}= 180°, at 200 MeV/nucleon

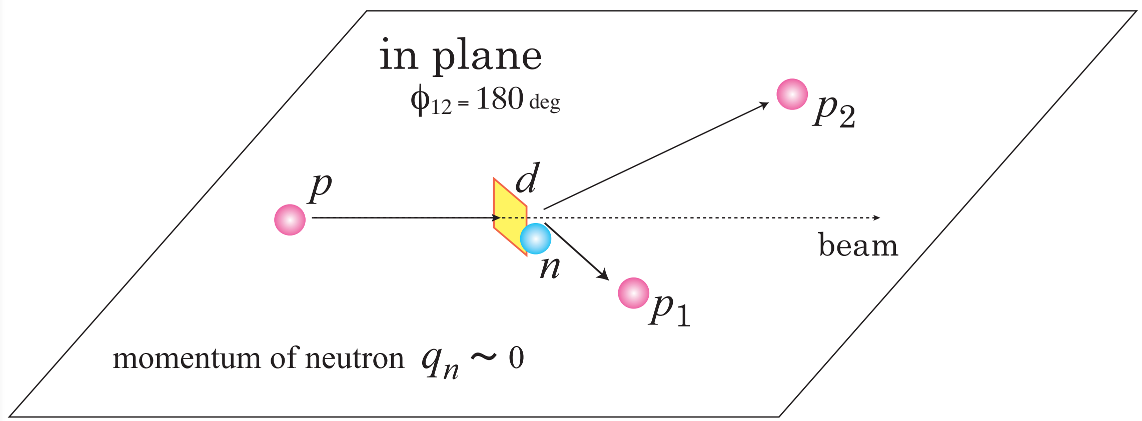


Large effects are predicted around Quasi Free Configuration.

Witala et al. Phys. Lett. B 634, 374 (2006)

Lorentz boosted NN pot.

non Lorentz boosted NN pot. (CD Bonn)



Summary of Current Status

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 65 - 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 250 & 300 MeV : serious discrepancy in backward angles
New Challenge to be solved

Complementary Effects, i.e. Effects of Relativity as well as Coulomb Forces, are NOT negligible in particular kinematical configurations of breakup.

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Next Step

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

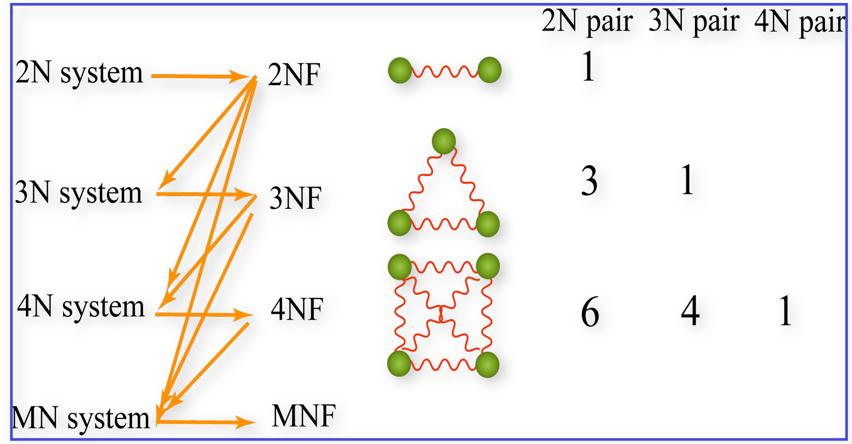
Nd Breakup Experiments : Study of Relativistic Effects

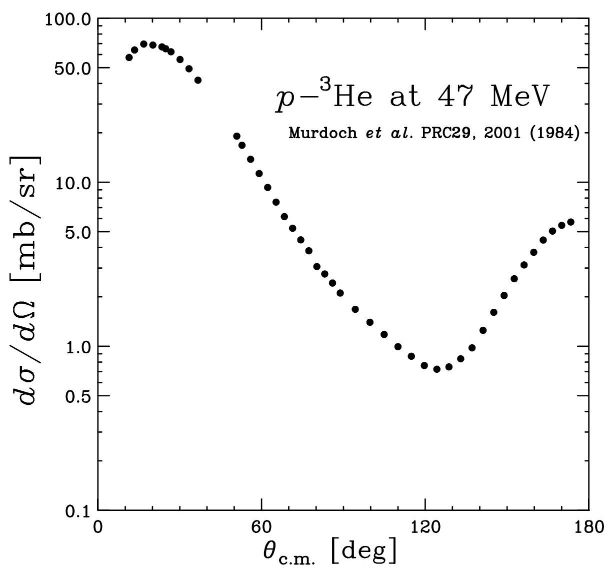
Four Nucleon Scattering, e.g. $p+{}^{3}He$: from Few to Many & Iso-spin dependence

Four Nucleon Scattering

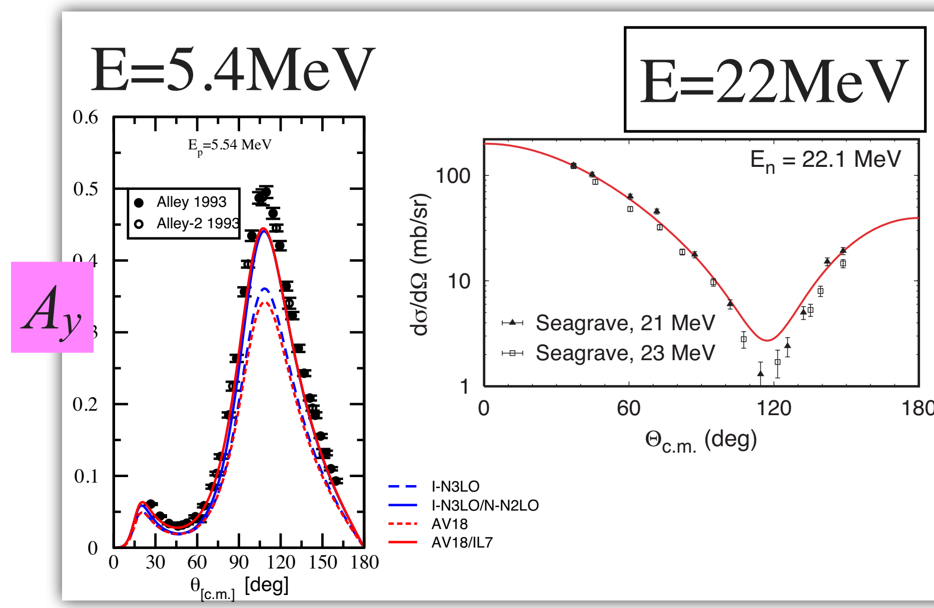
Four Nucleon Systems

- First Step from Few to Many
- Large 3NF effects in cross section minimum **(θc.m.～120°)** at Intermediate energies ?
- Isospin Dependence of 3NFs
- 4NFs ?



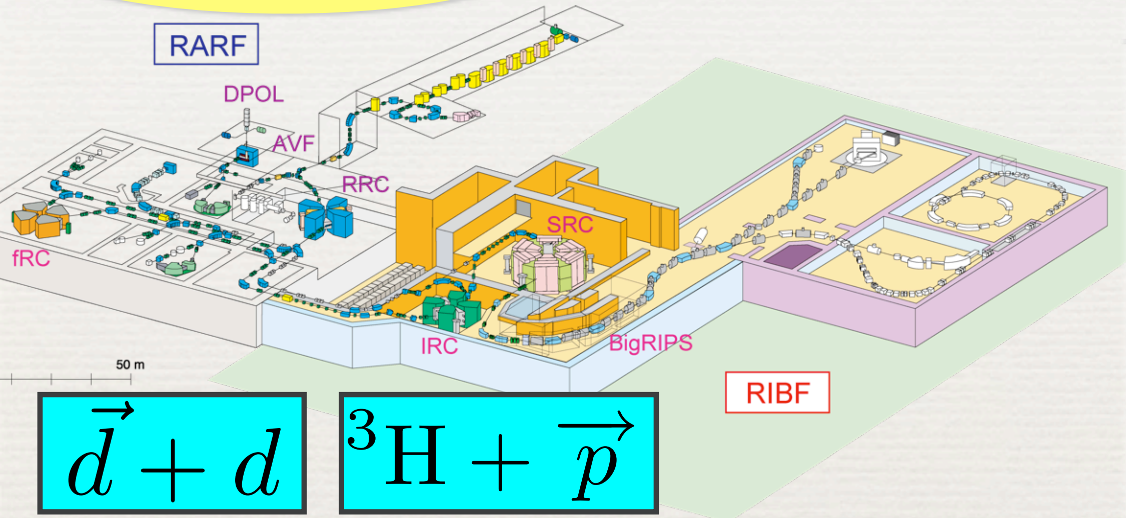


Murdoch et al., Phys. Rev. C 29, 2001 ('84)



Facilities

RIKEN RIBF

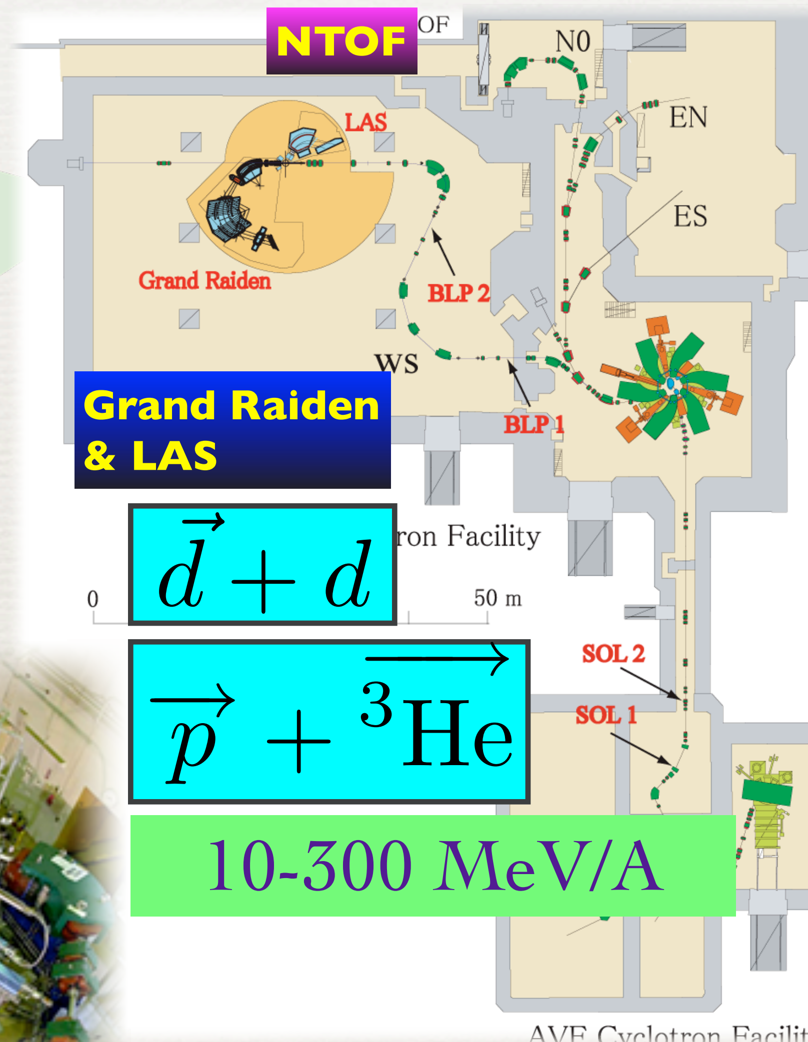


$\vec{d} + d$

${}^3\mathrm{H} + \vec{p}$

100-300 MeV/A

RCNP



$\vec{d} + d$

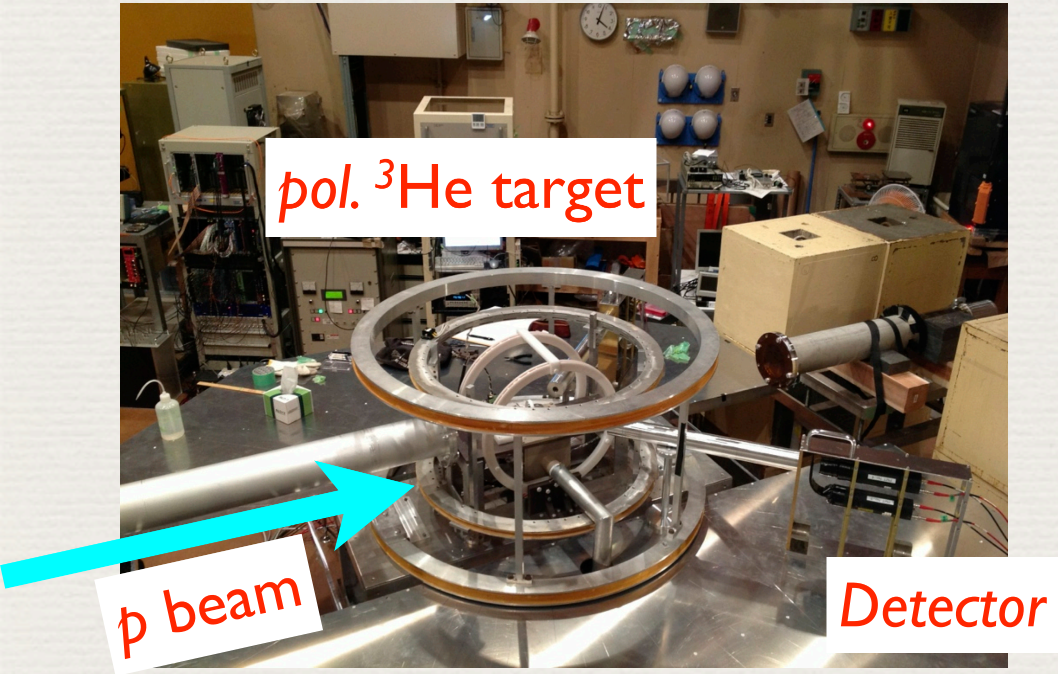
$\vec{p} + \overrightarrow{{}^3\mathrm{He}}$

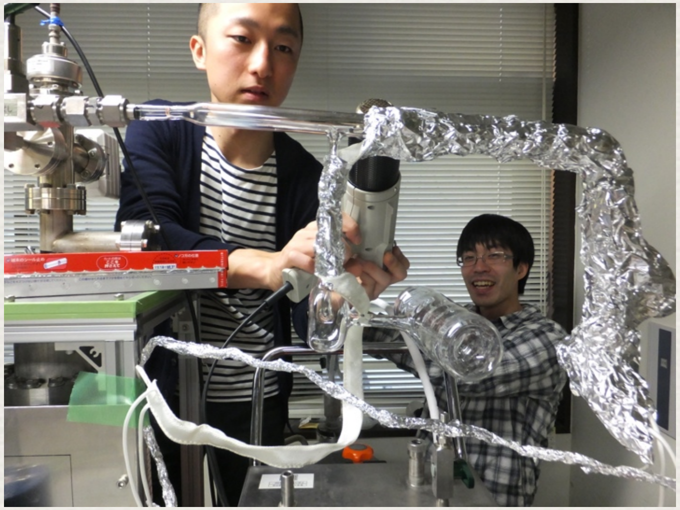
10-300 MeV/A

CYRIC
Tohoku Univ.

pol.^{3}He target is under construction at Tohoku University

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



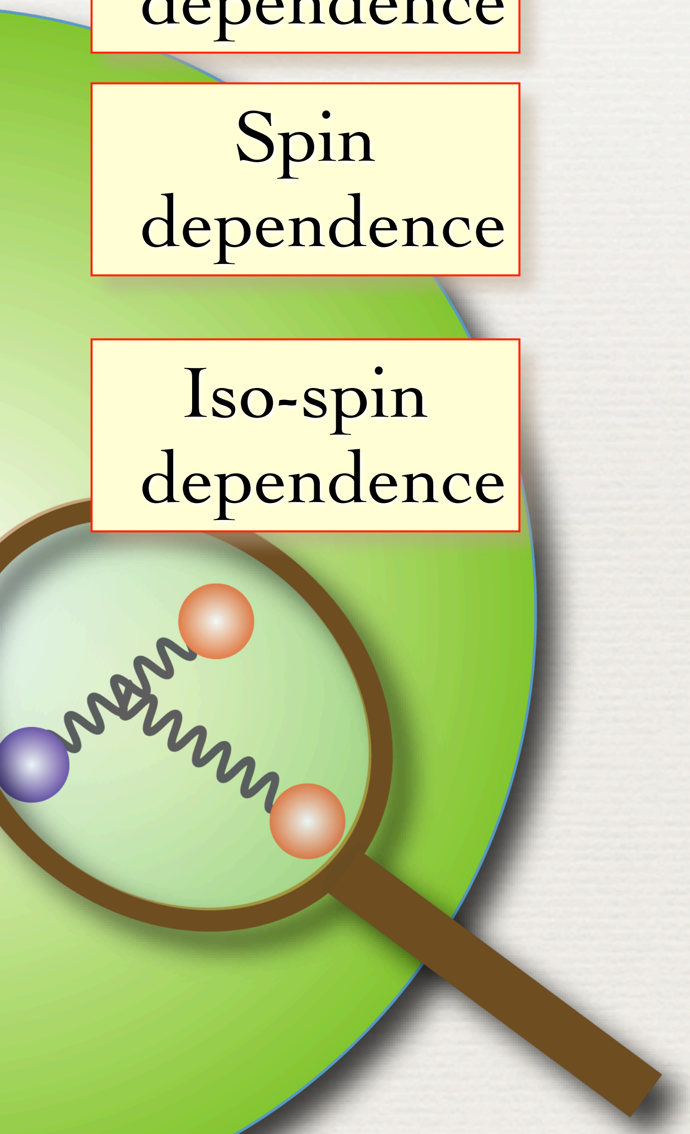


Perspective of 3NF Study

Momentum dependence

Spin dependence

Iso-spin dependence



Perspective of 3NF Study

Nd Scattering

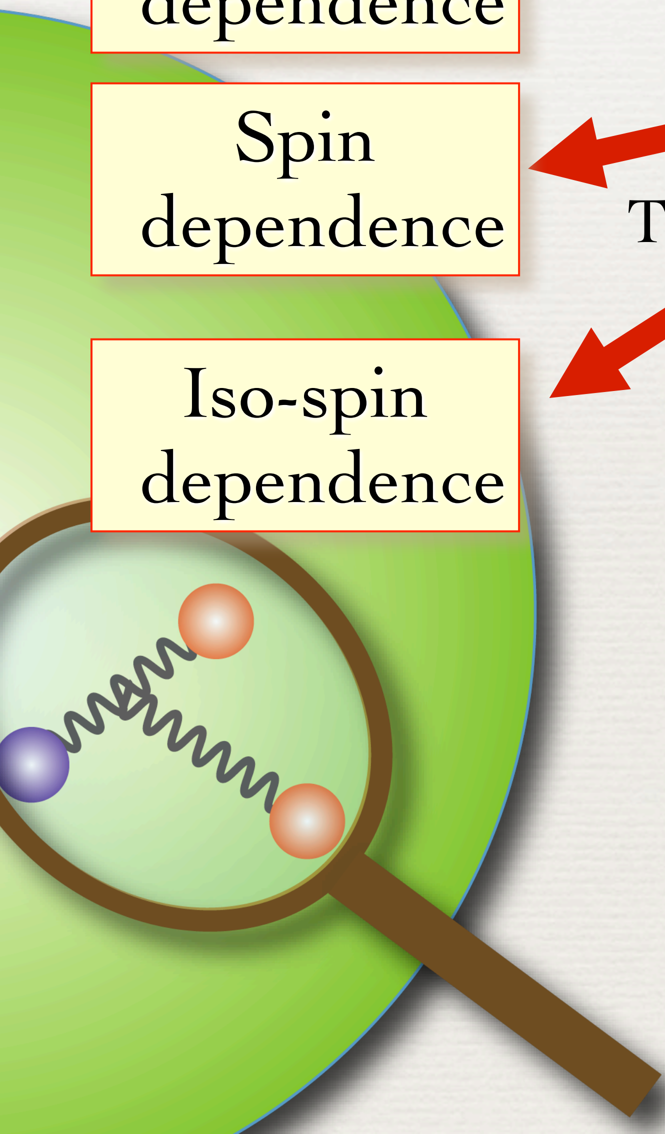
provide Fundamental Data/Theory of 3NF

Momentum dependence

Spin dependence

T=1/2

Iso-spin dependence



Perspective of 3NF Study

Momentum dependence

Spin dependence

Iso-spin dependence

T=1/2

Nd Scattering

provide Fundamental Data/Theory of 3NF

Higher Energies

Full treatment of ***dp*** Breakup Reactions

Perspective of 3NF Study

Momentum dependence

Spin dependence

Iso-spin dependence

Nd Scattering

provide Fundamental Data/Theory of 3NF

Higher Energies

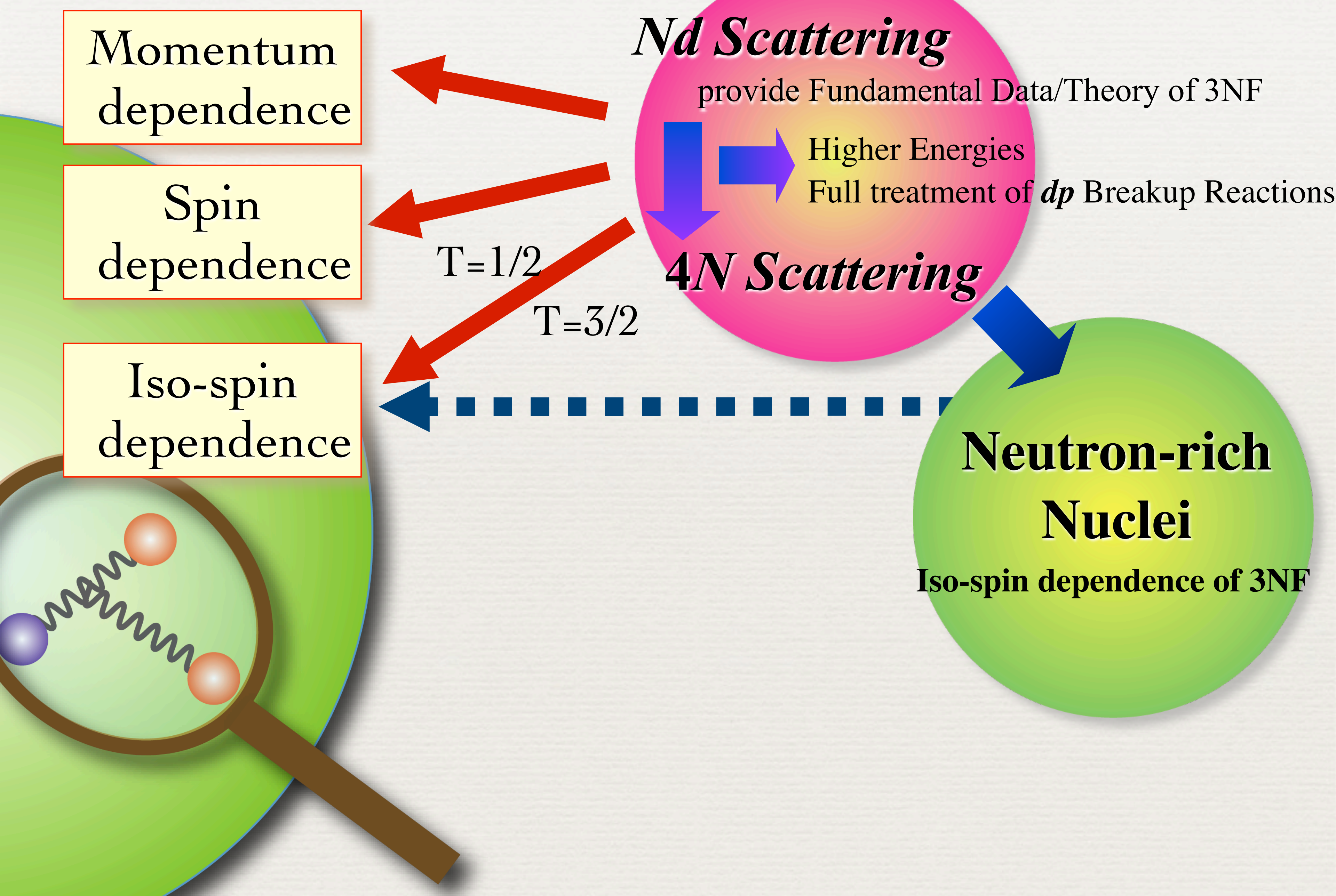
Full treatment of ***dp*** Breakup Reactions

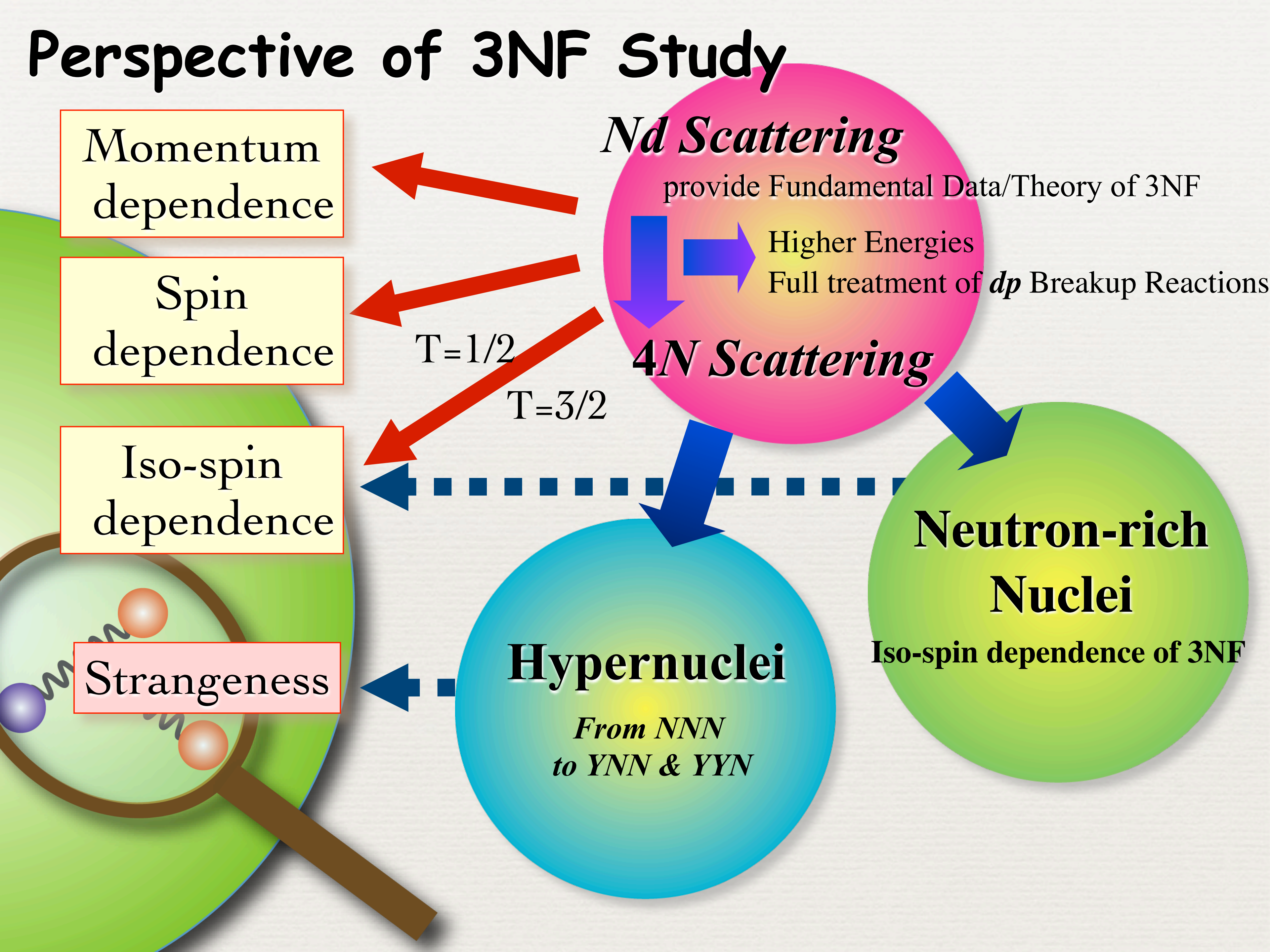
4*N* *Scattering*

T=1/2

T=3/2

Perspective of 3NF Study




Perspective of 3NF Study
Momentum dependence
Spin dependence
Iso-spin dependence
Strangeness
T=1/2
T=3/2
Nd Scattering
provide Fundamental Data/Theory of 3NF
Higher Energies
Full treatment of dp Breakup Reactions
4N Scattering
Neutron-rich Nuclei
Iso-spin dependence of 3NF
Hypernuclei
From NNN
to YNN & YYN

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

RIKEN Nishina Center

N. Sakamoto, T. Ohnishi, K. Sekiguchi

CNS, University of Tokyo

T. Uesaka, T. Kawabata, K. Suda, Y. Maeda, S. Sakaguchi, Y. Sasamoto

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～)

Collaboration

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

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

CNS, University of Tokyo
K. Yako, R. Tang, S. Kawase, Y. Kubota, C.S. Lee,

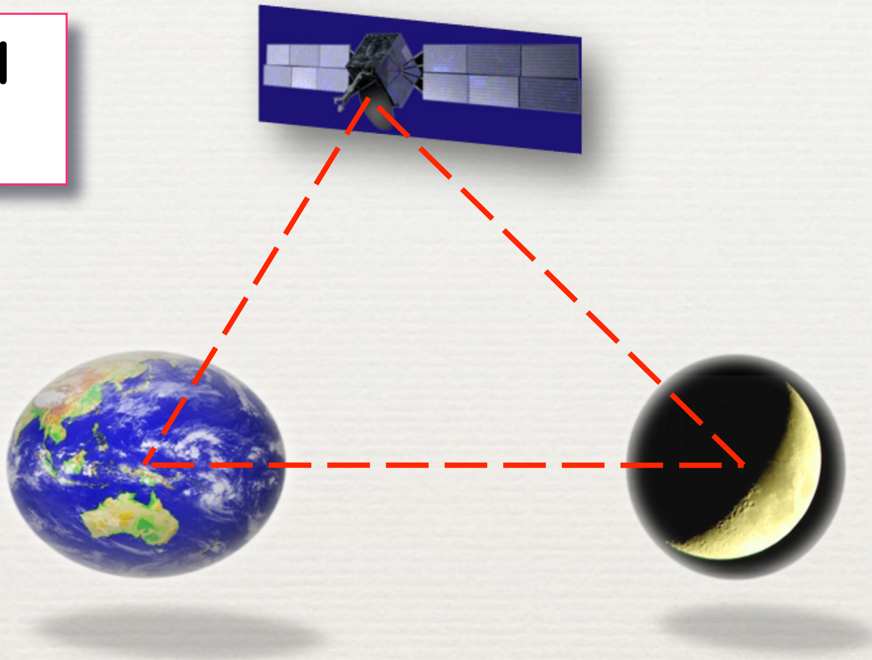
RCNP, Osaka University
H. Okamura, K. Miki

Kyushu University
T. Wakasa, S. Sakaguchi

Miyazaki University
Y. Maeda, T. Saito

To explore the laws of the nature, step in 1 → 2 → 3 .

Earth-Moon-Satellite Gravitational Interactions



- Two Body Interactions : Gravity

$$H = \frac{P_m^2}{2m} + \frac{P_M^2}{2M} + \frac{GMm}{r}$$

- Three Body Interactions

$$H = \frac{P_E^2}{2m_E} + \frac{P_M^2}{2m_M} + \frac{P_G^2}{2m_G} + \frac{Gm_E m_M}{r_{EM}} + \frac{Gm_E m_G}{r_{EG}} + \frac{Gm_M m_G}{r_{MG}}$$

$$+V(\vec{r}_E, \vec{r}_M, \vec{r}_G)$$

by the polarizations of the ocean water of the earth by the moon's gravity

To explore the laws of the nature, step in 1 → 2 → 3 .

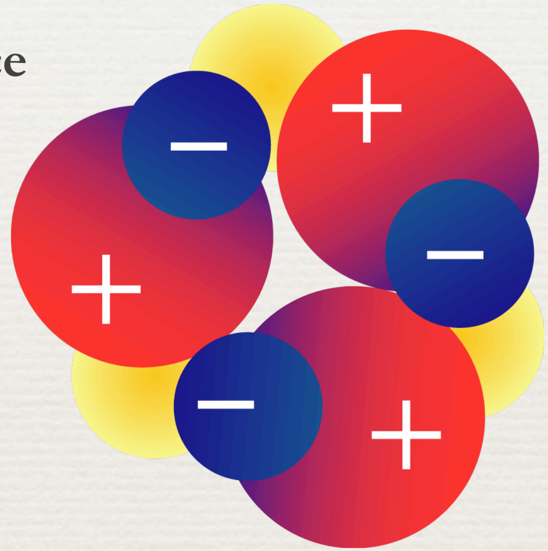
Triplets of Atoms
Van der Waals Type Three Body Force

- Two Body Interactions : Electro-Magnetic Force

$$V_{12} = \frac{C\alpha^3}{r_{12}^6}$$

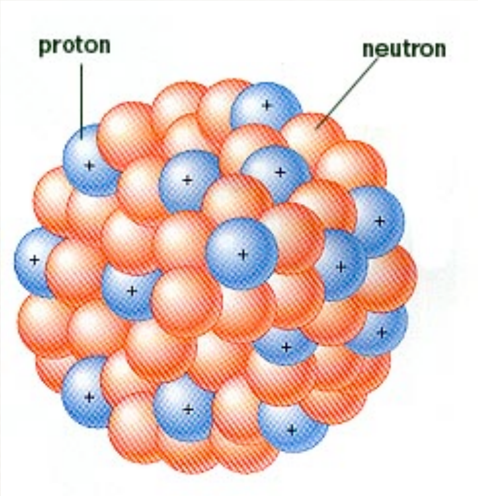
- Three Body Interactions

$$V_{123} = C\frac{3\cos\gamma_1\cos\gamma_2\cos\gamma_3+1}{r_{12}^3\, r_{23}^3\, r_{31}^3}$$



Effects of the polarizations of the electron density distribution

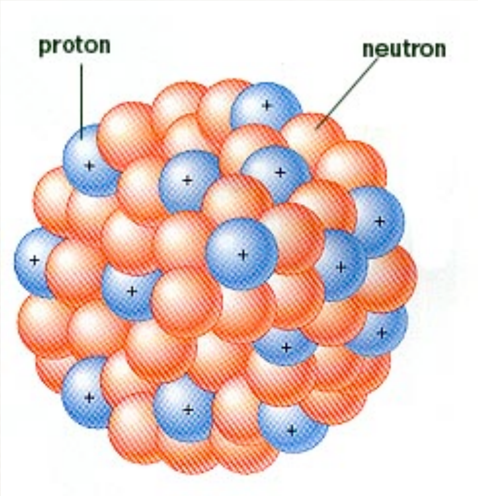
- Nucleus : a compact system of nucleons
- Nuclear Force : Strong Interactions
- Effects of Three Nucleon Forces
  – Where and How to attack- ?



	Solar System	Atom	Nucleus
Length	10^{8} m	10^{-10} m	10^{-15}m
Interaction	Gravity	Electro-Magnetic	Strong
Coupling Constant	10^{-38}	10^{-2}	1
$\frac{V(3BF)}{V(2BF)}$	0.001%	< 0.1%	?

Are there three nucleon forces in Nuclei ?

- Nucleus : a compact system of nucleons
- Nuclear Force : Strong Interactions
- Effects of Three Nucleon Forces
  – Where and How to attack- ?



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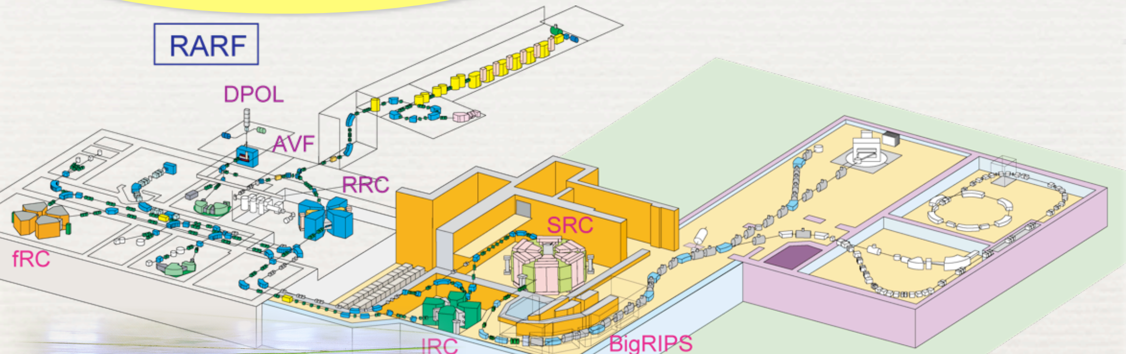
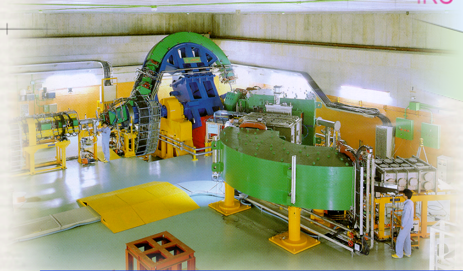
Facilities

RIKEN RIBF



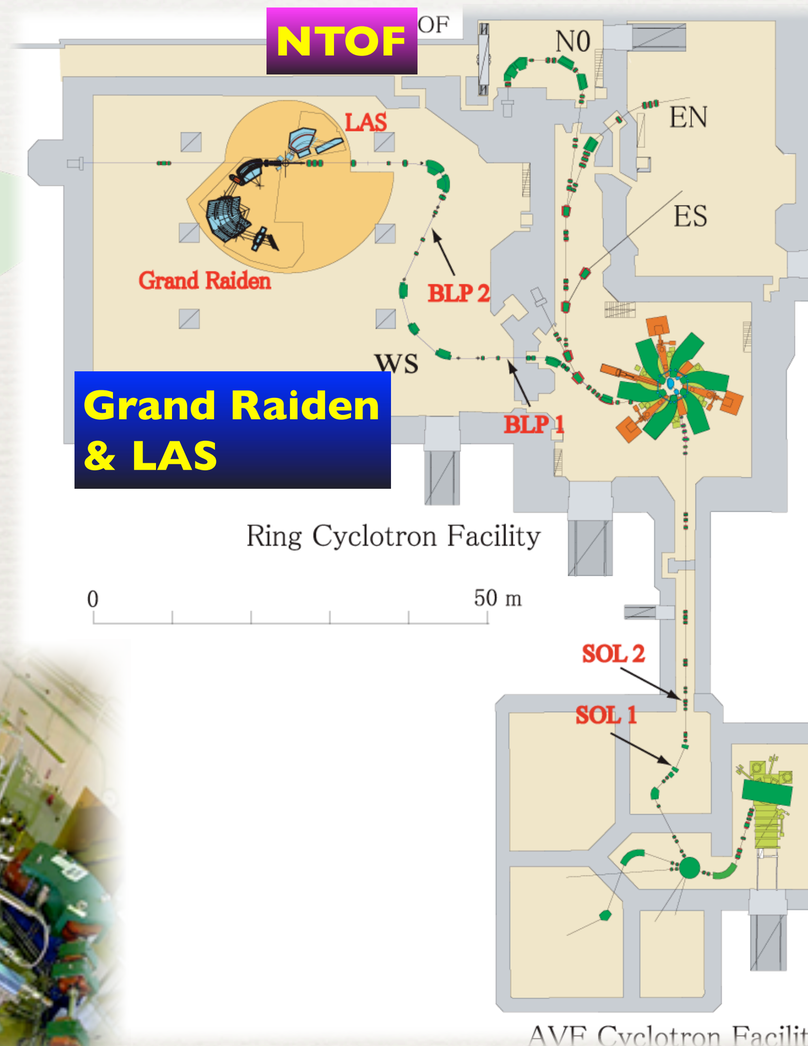
BigDpol



magnetic spectrograph SMART

RCNP

NTOF



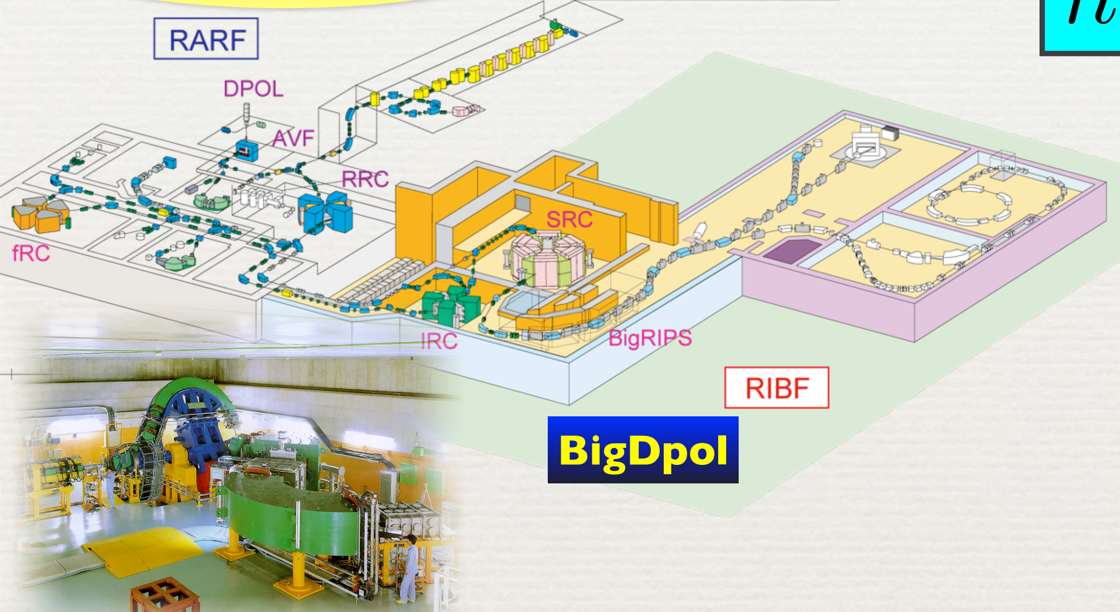
Grand Raiden & LAS

CYRIC Tohoku Univ.

Facilities

RIKEN RIBF

$\vec{d}+p$



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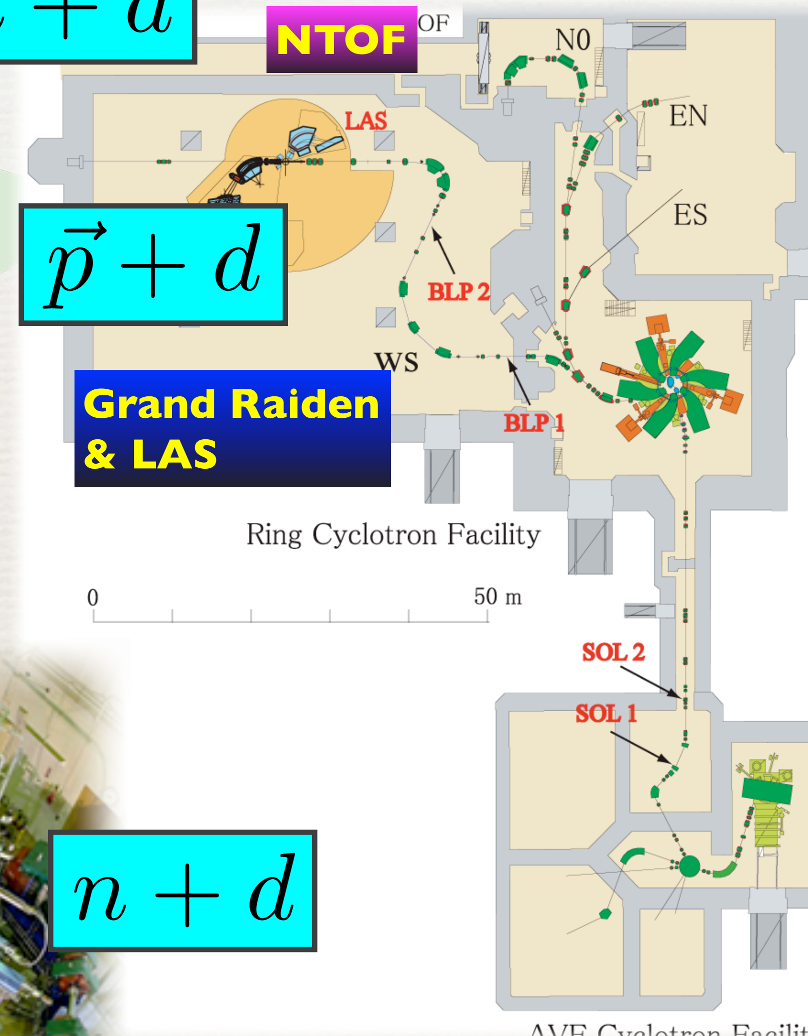
magnetic spectrograph SMART

RCNP

$\vec{n}+d$

NTOF



$\vec{p}+d$

Grand Raiden & LAS

$n+d$

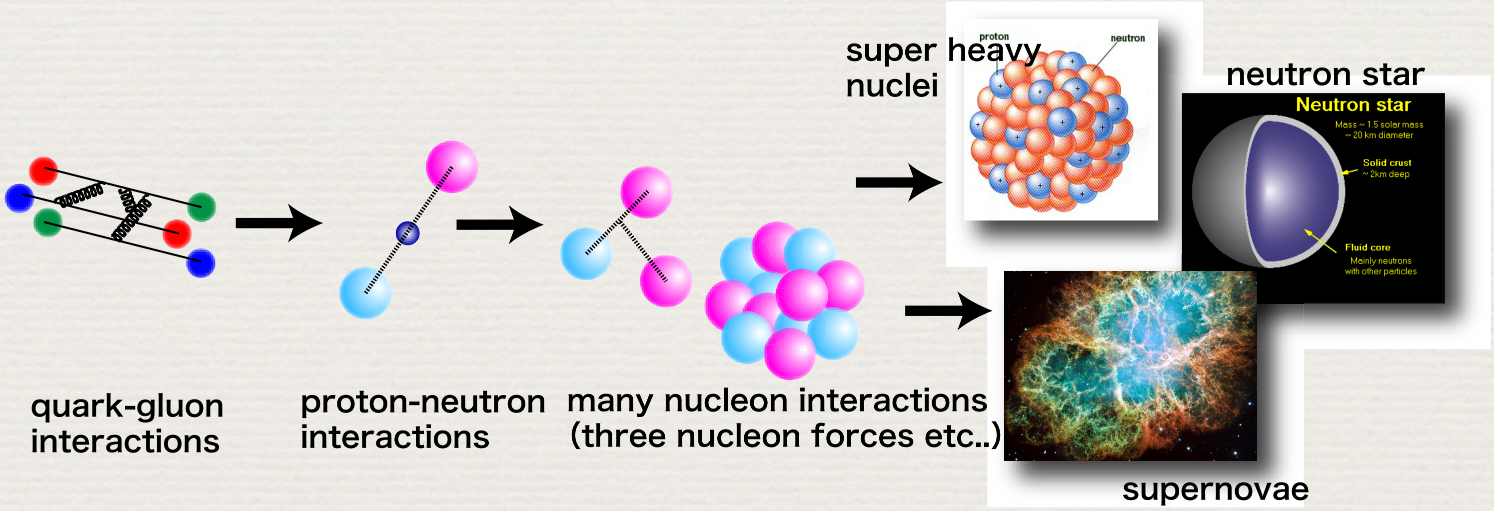
CYRIC Tohoku Univ.

Frontier of Nuclear Force Study

1990's Realistic Modern Nucleon-Nucleon Forces (2NFs)

→ **We have "reliable" two nucleon forces.**

- To describe Nuclear Forces from Quarks (elementary particles)
- To describe Nuclear Matter from bare Nuclear Forces ～ 2NF & 3NF ～



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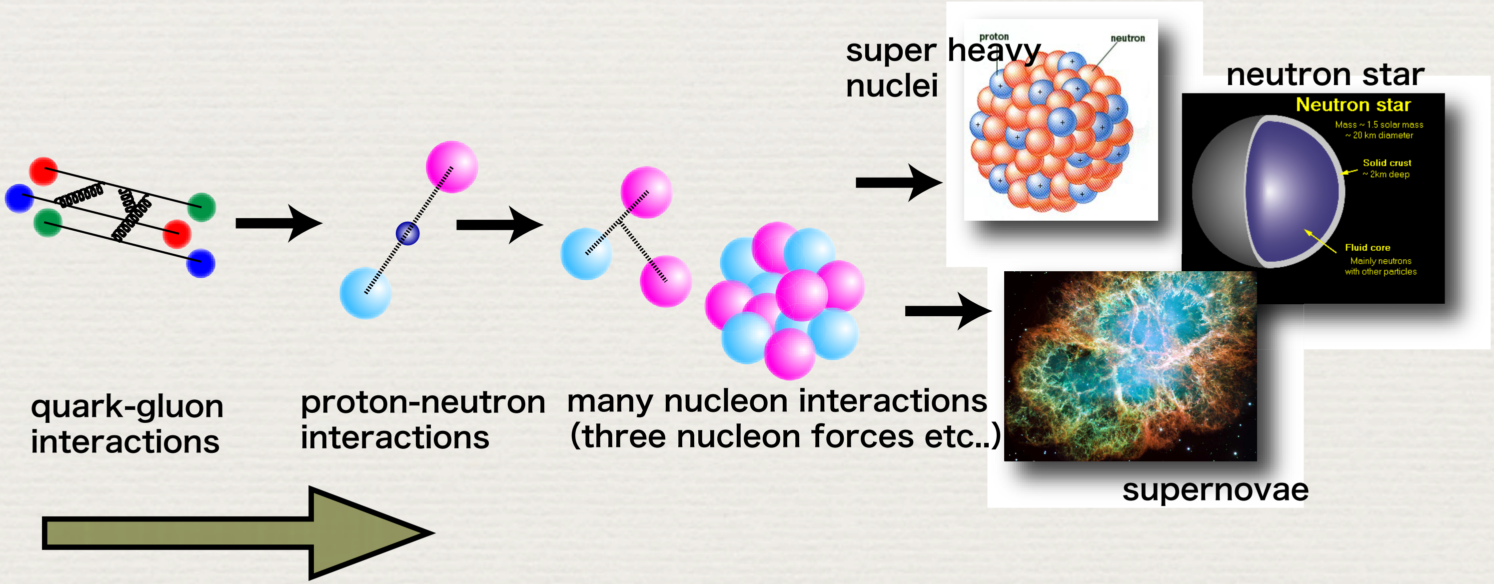

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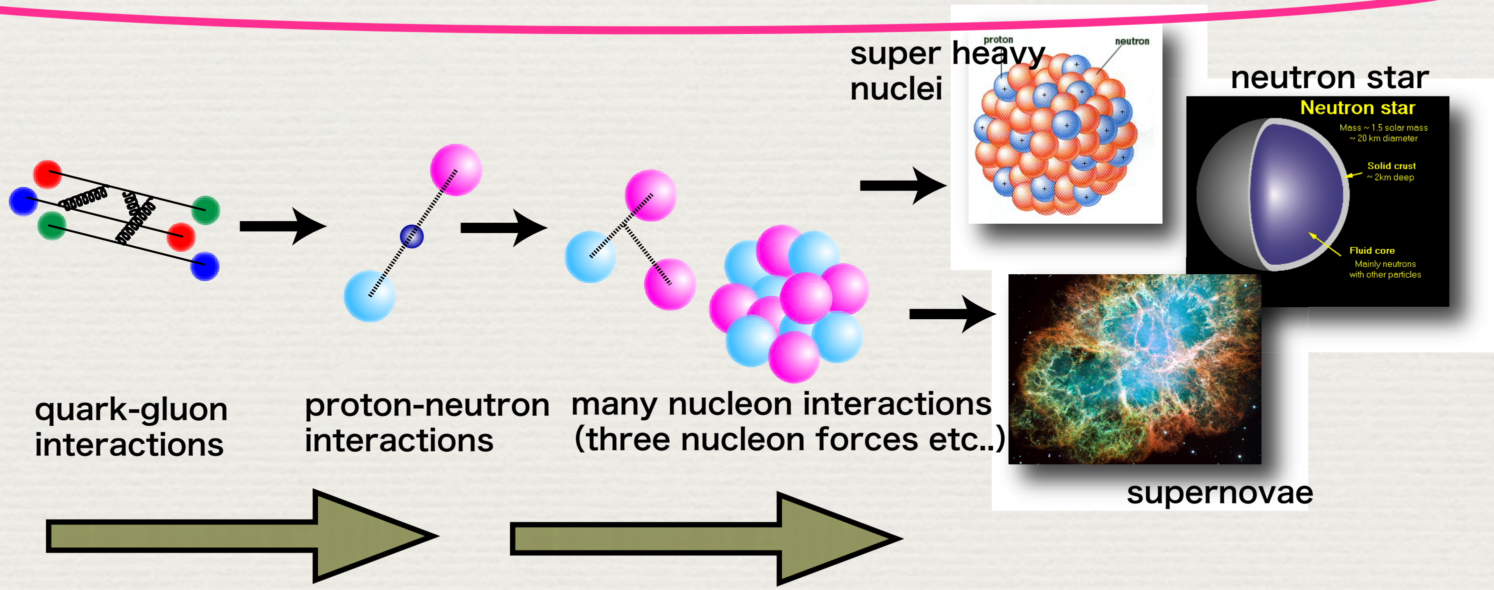

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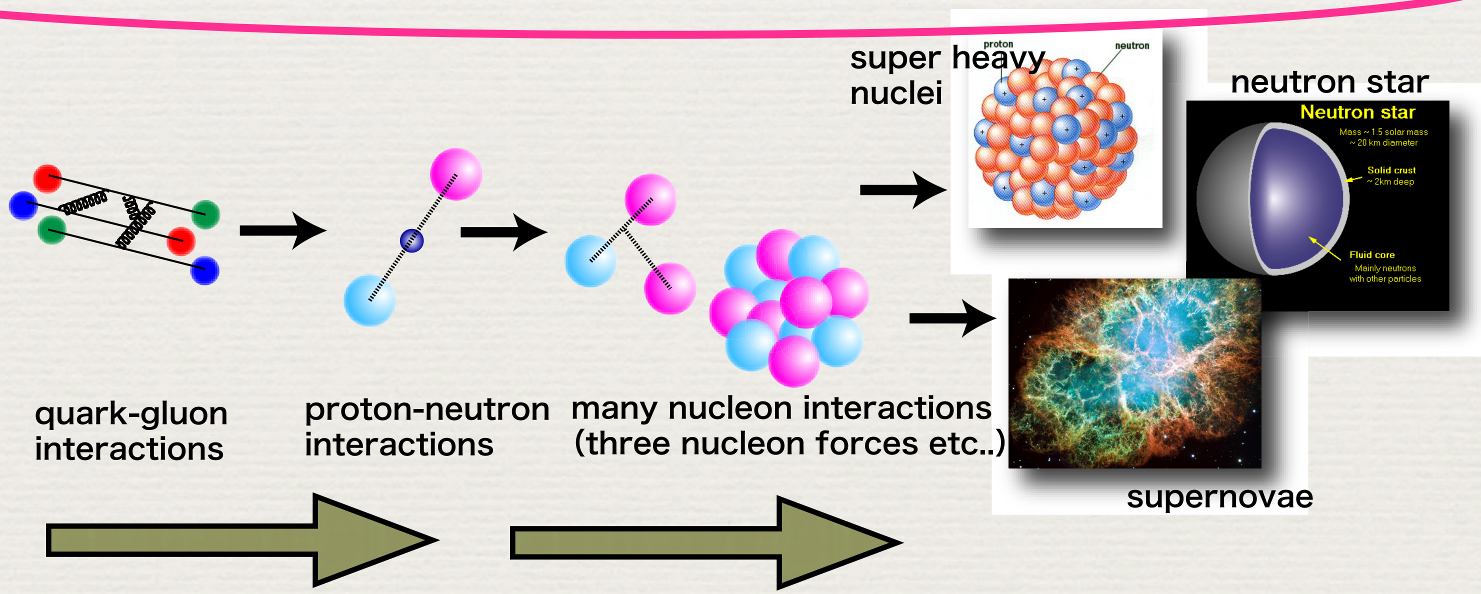
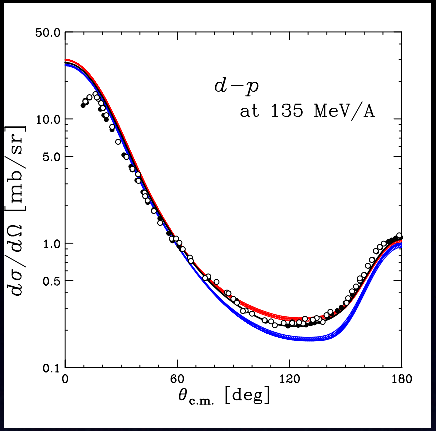
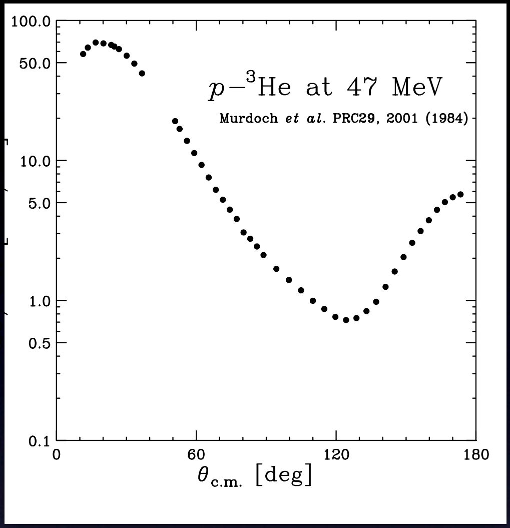


Understand from quarks to the Universe

核子+^{3}He 散乱系

- 系の大きさ
  - **First Step from Few to Many**
  - **Nd 散乱と同様に有限角度 (θc.m.〜120°) で三核子力の効果が現われると予想される**





Murdoch et al., Phys. Rev. C 29, 2001 ('84)

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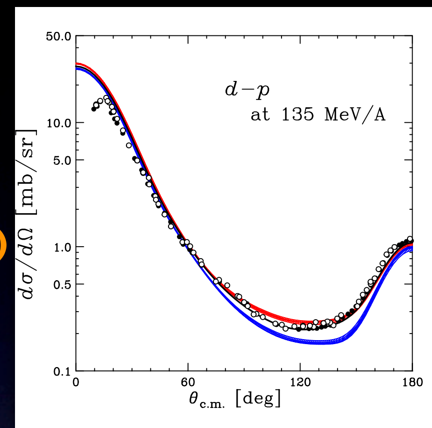

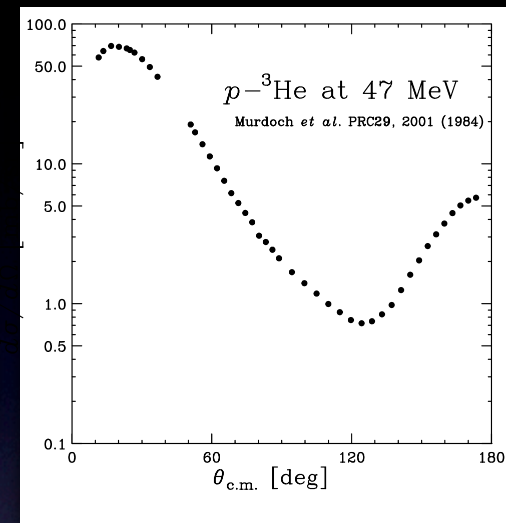

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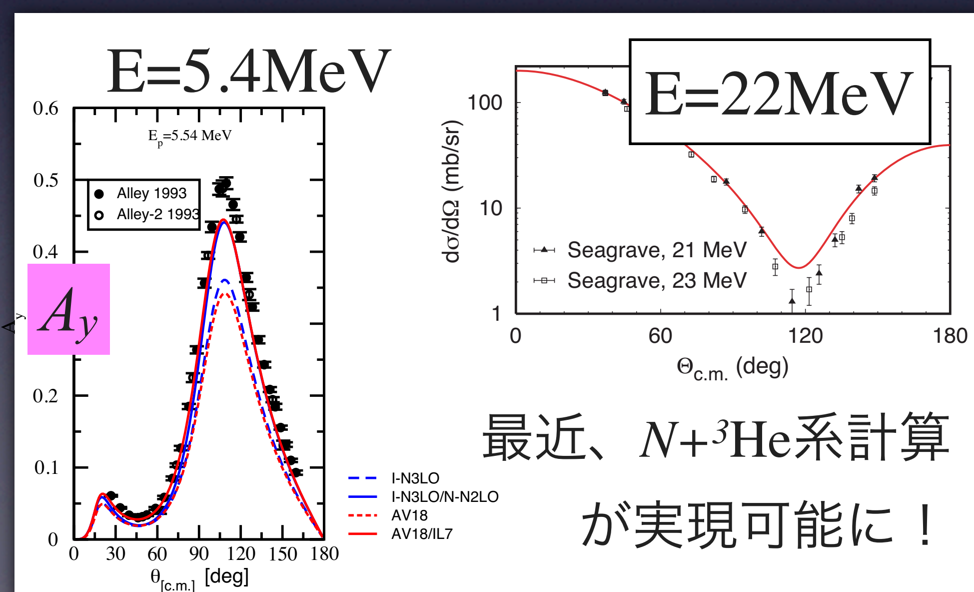

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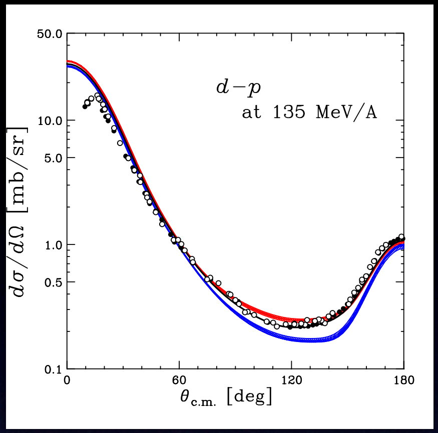
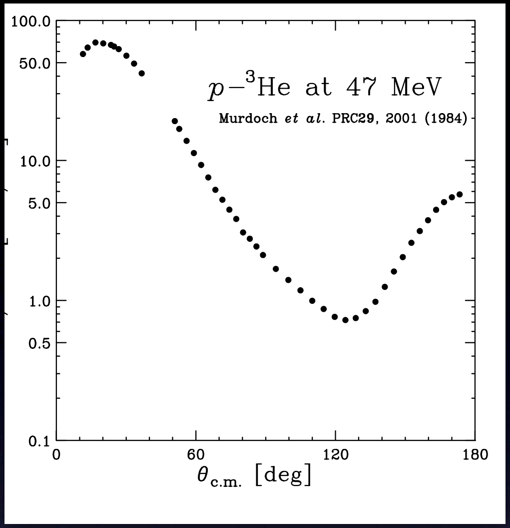
- 荷電スピン状態：
  - **三核子力の荷電スピン依存性が初めて現われる素過程**
  - **陽子／中性子過剰核の記述に大きな指標**





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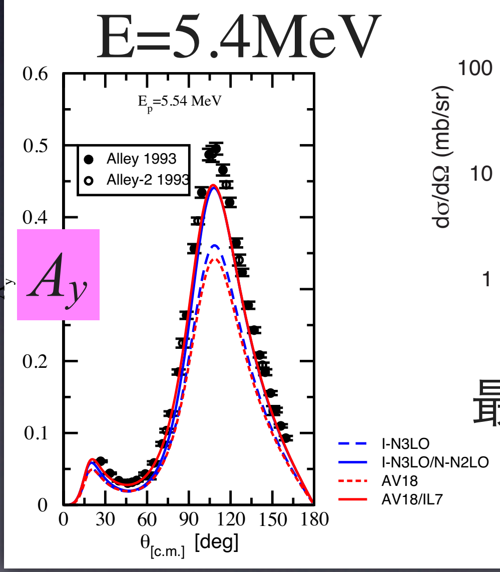
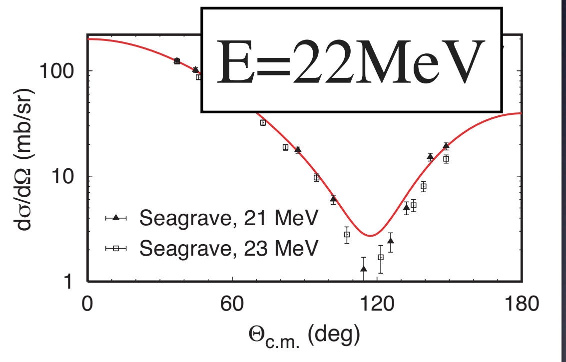




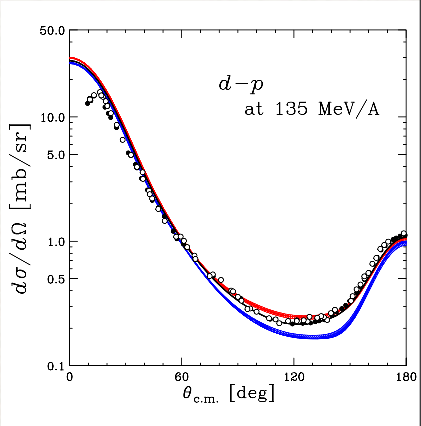
最近、N+^{3}He系計算が実現可能に！

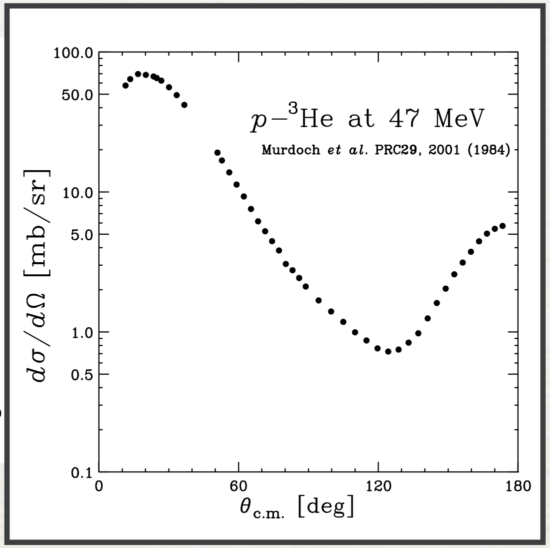
$N + {}^3$He Scattering

- **Four Nucleon System**
  - **First Step from Few to Many**
  - **Large 3NF effects**

    in DCS minimum ($\theta_{\rm c.m.} \sim 120^\circ$)

    at intermediate energies ?





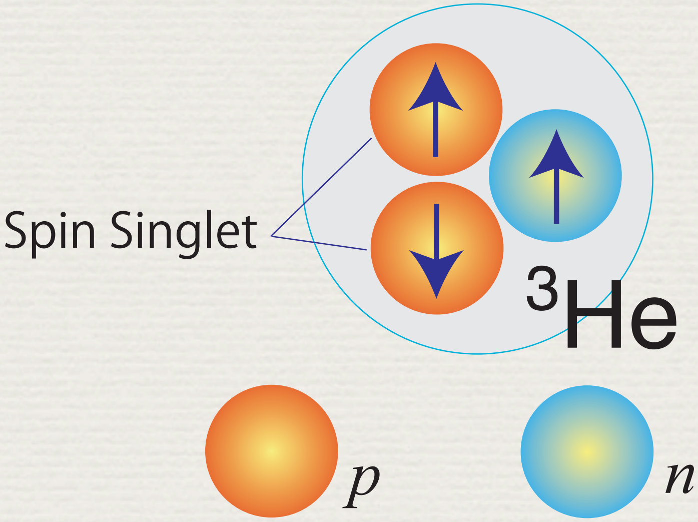
- **Iso-spin dependence of 3NFs in p+^{3}He**

Murdoch et al., Phys. Rev. C 29, 2001 ('84)

- **4NF effects ?**

- **pol. ^{3}He $\sim$ pol. n**

- **spin dependence of three proton systems via in p+^{3}He**
- **pol. $n + n$ by n+^{3}He ?**



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- **Four Nucleon System**
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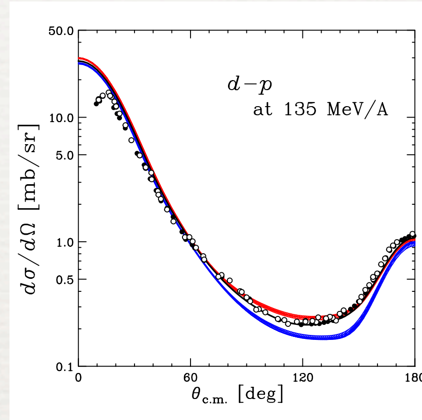

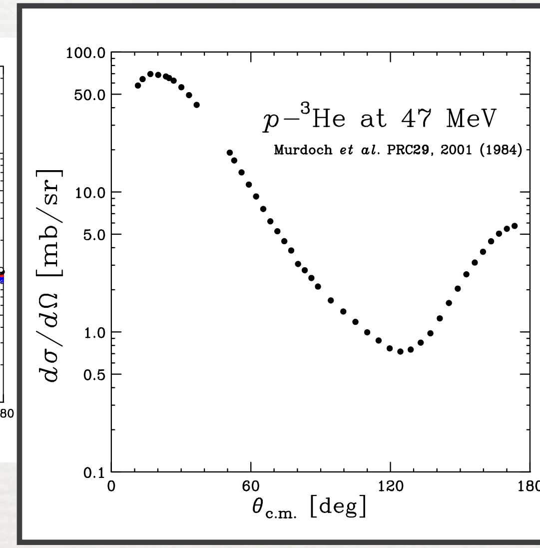

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- **4NF effects ?**

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  via in p+^{3}He
- pol. n + n by n+^{3}He ?