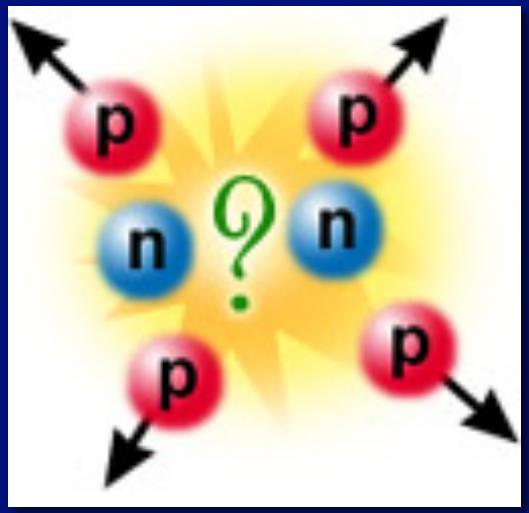
What have we learned about few-nucleon systems at intermediate energies?



Nasser Kalantar-Nayestanaki

KVI-Center for Advanced Radiation Technology,

University of Groningen

The Sixth Asia-Pacific Conference on Few-Body Problems in Physics

8 April, 2014, Hahndorf, Australia

道生一、一生二、二生三、三生萬物。

The Way(Tao) produces one,

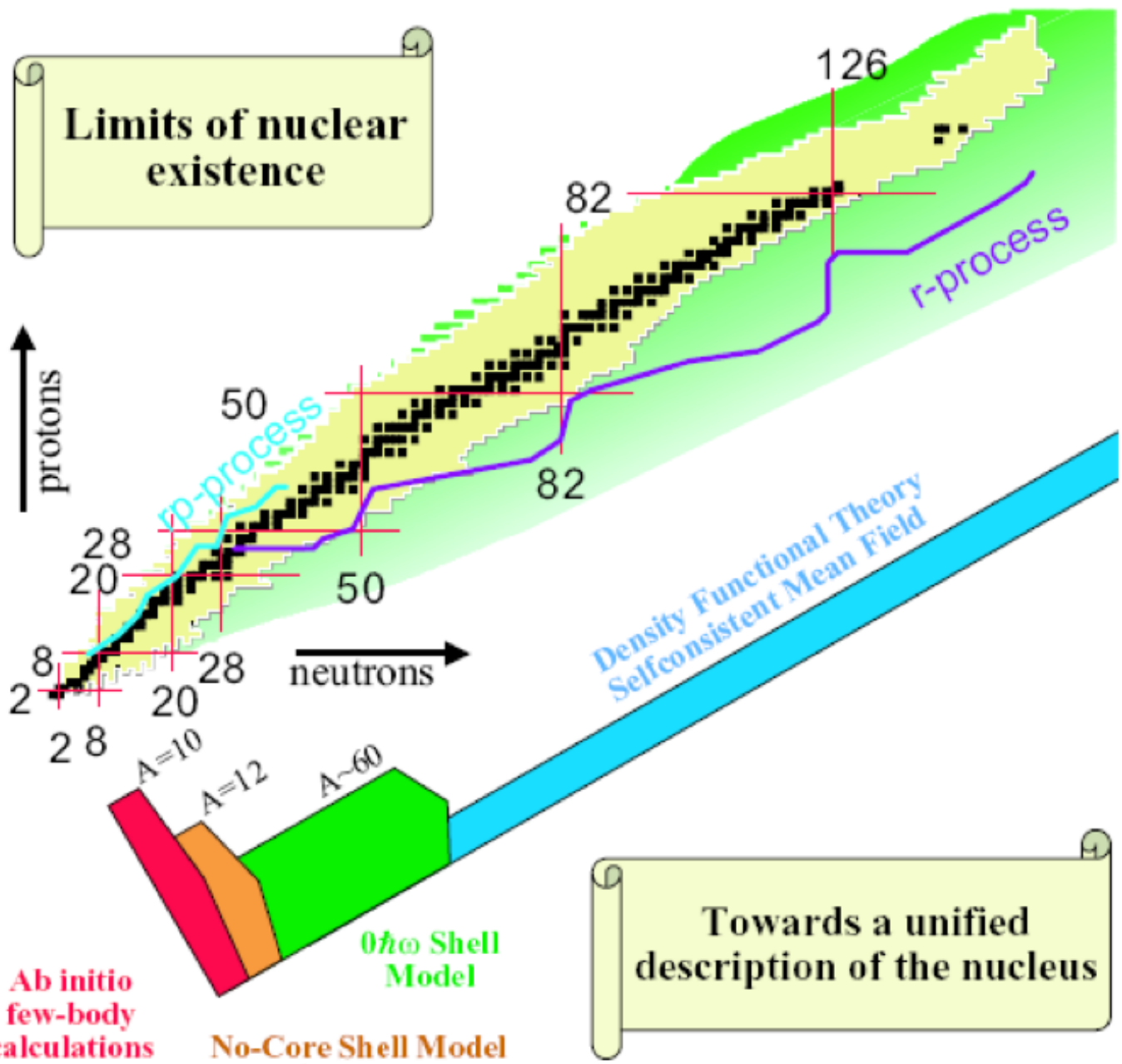
one produces two.

The two produces the three and

the three produces all things.

道徳経 "Tao-te Ching"
老子 by Lao Zi (Chinese philosopher, B.C. 400)

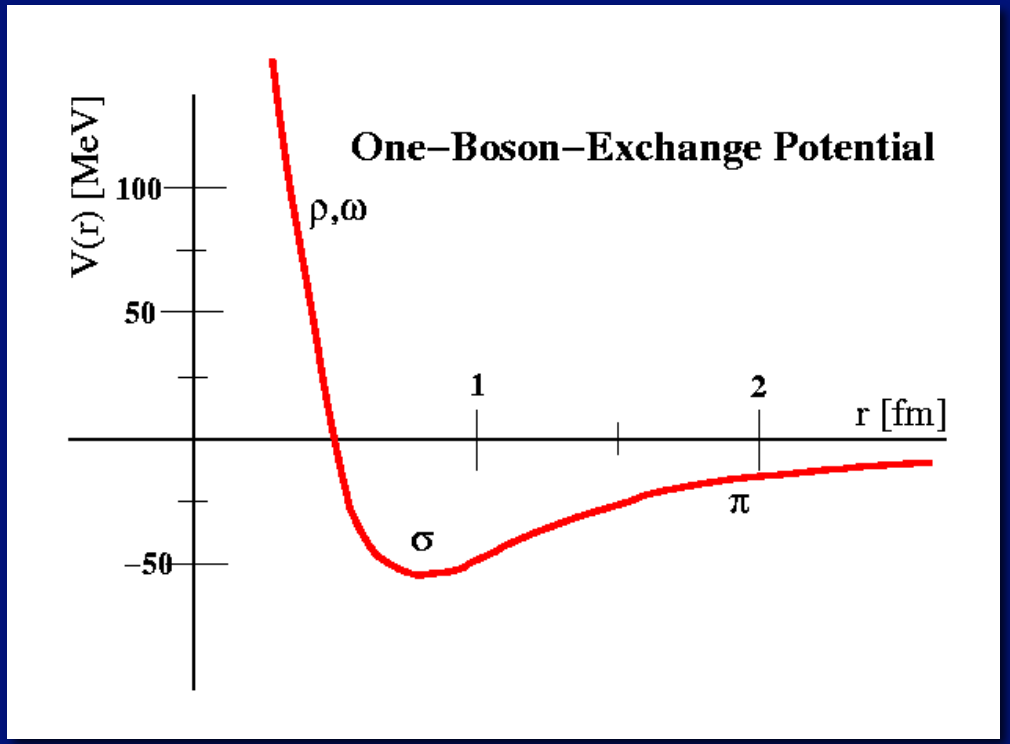
Courtesy: K. Sekiguchi


Limits of nuclear existence
126
82
50
82
28
20
50
8
2
28
20
2 8
protons
neutrons
rp-process
r-process
Density Functional Theory
Selfconsistent Mean Field
A=10
A=12
A~60
0ħω Shell Model
Ab initio few-body calculations
No-Core Shell Model
Towards a unified description of the nucleus

N-N Potentials

Modern phenomenological NN potentials:

- Nijmegen I
- Nijmegen II
- Reid 93
- CD-Bonn
- Argonne V18
- …



Comparison with experimental np&pp database gives:
χ^2/data ~ 1

Triton Binding Energy

Model	χ^2/data	^{3}H B.E. [MeV]
NIJM I	1.03	7.72
NIJM II	1.03	7.62
Reid93	1.03	7.63
Argonne V18	1.09	7.62

Triton Binding Energy

Model	χ^2/data	^{3}H B.E. [MeV]
NIJM I	1.03	7.72
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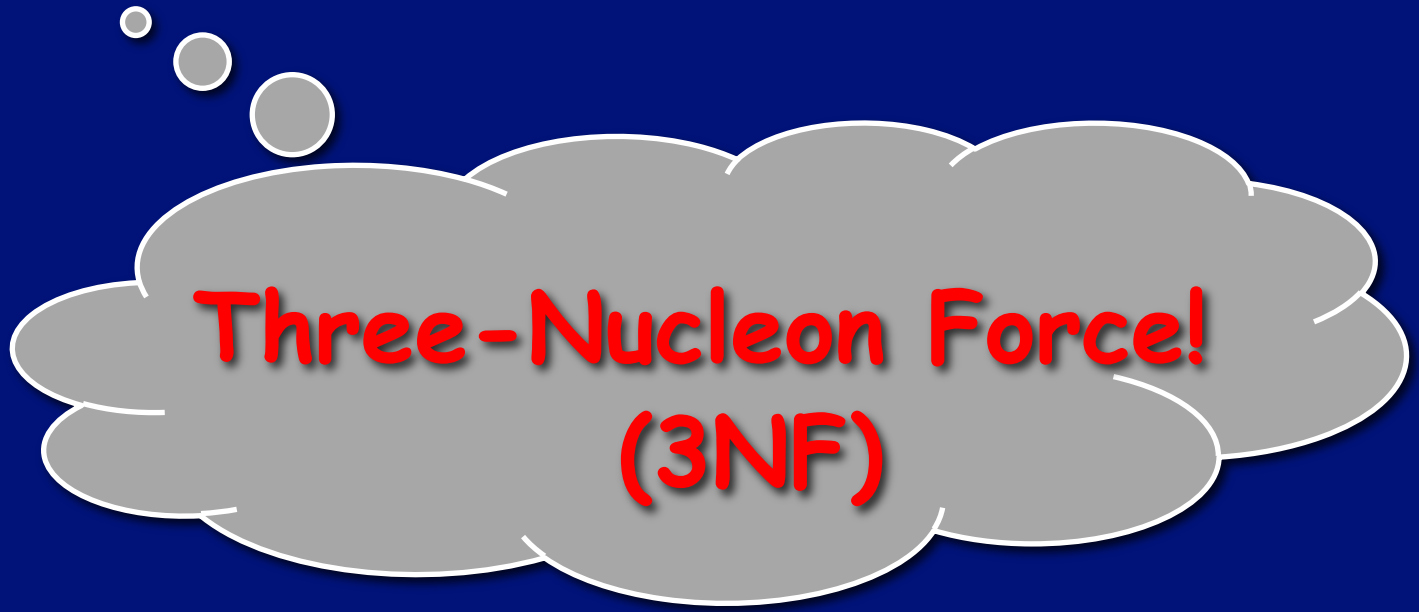
Reid93	1.03	7.63
Argonne V18	1.09	7.62
EXPERIMENT	-	8.48

Modern N-N potentials fail to describe triton B.E.

Beyond phenomenological N-N forces

Phenomenological N-N forces fail to describe A>2 systems! How to resolve?



Three-Body Forces in Nuclear Physics

JUNE 15, 1939 PHYSICAL REVIEW VOLUME 55

Many-Body Interactions in Atomic and Nuclear Systems

H. PRIMAKOFF, *Polytechnic Institute of Brooklyn, Brooklyn, New York*

AND

T. HOLSTEIN, *New York University, University Heights, New York, New York*

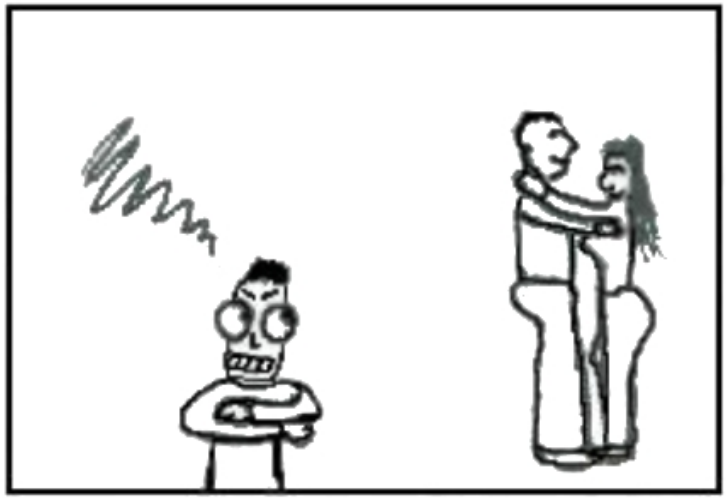
(Received March 28, 1938)

"...the replacement of field interactions by two-body action-at-a-distance potentials is a poor approximation in nuclear problems."

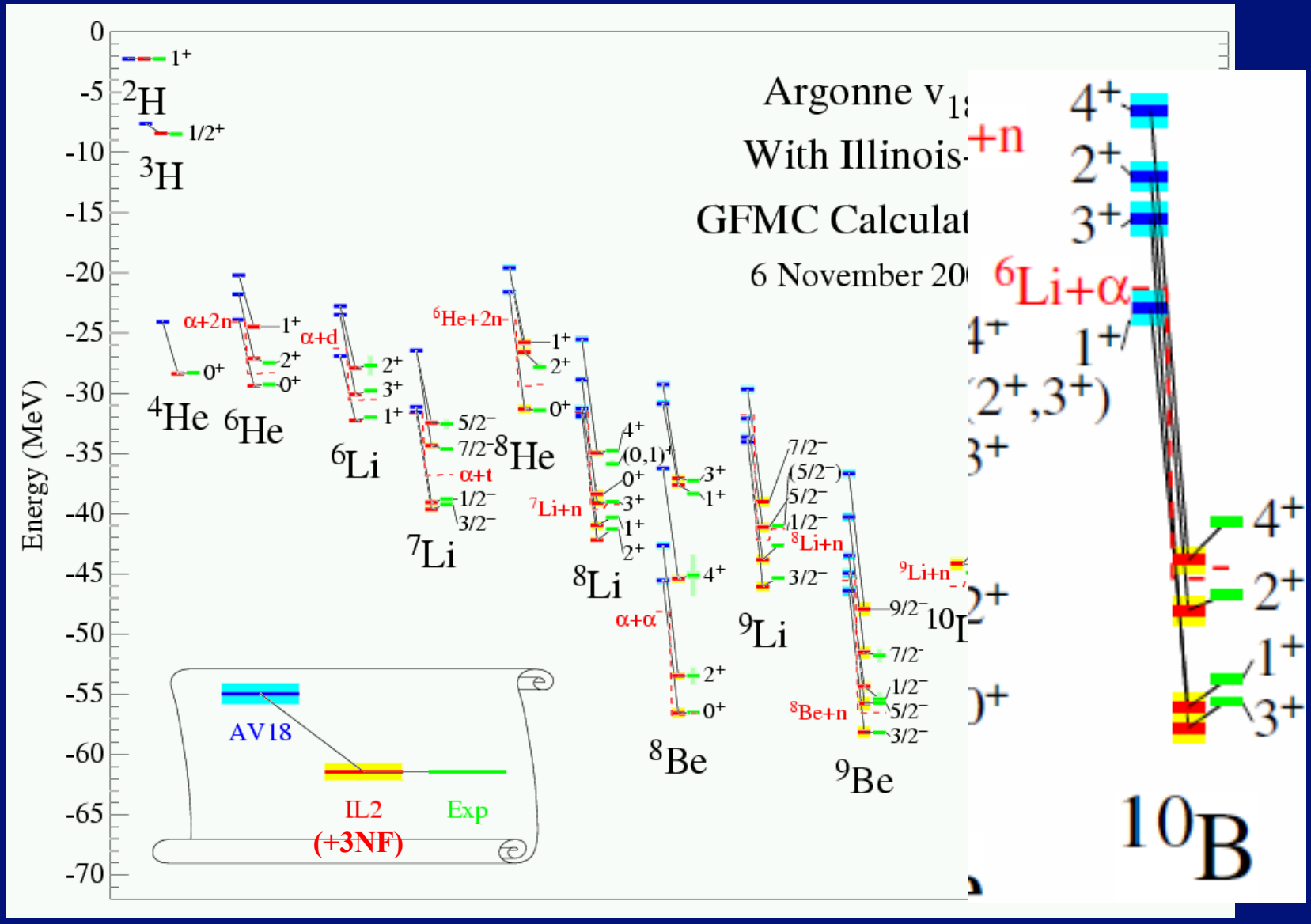
Three-body forces and Wikipedia

A three-body force is a force that does not exist in a system of two objects but appears in a system of three objects (three-body system like in Euler's three-body problem) or more. In physics, an intuitive example of a three-body force is the case of charged, metallic spheres: the charge distribution at the surface of two spheres placed close to each other will be modified, and thus the total force felt by a third sphere cannot be described by the sum of the forces from the two other spheres taken individually. The fundamental strong interaction seems to exhibits such behaviours. In particle physics, the interactions between the three quarks that compose baryons can be described in a diquark model which is equivalent to the hypothesis of a three-body force. There is growing evidence in the field of nuclear physics that three-body forces exist among the nucleons inside atomic nuclei (three-nucleon force).

As an analogy, if we identify bodies with human beings and forces with emotions, jealousy is a good example of three-body force: it is not felt as long as only two persons are acting, but it can show up as soon as a third person enters into the scene.

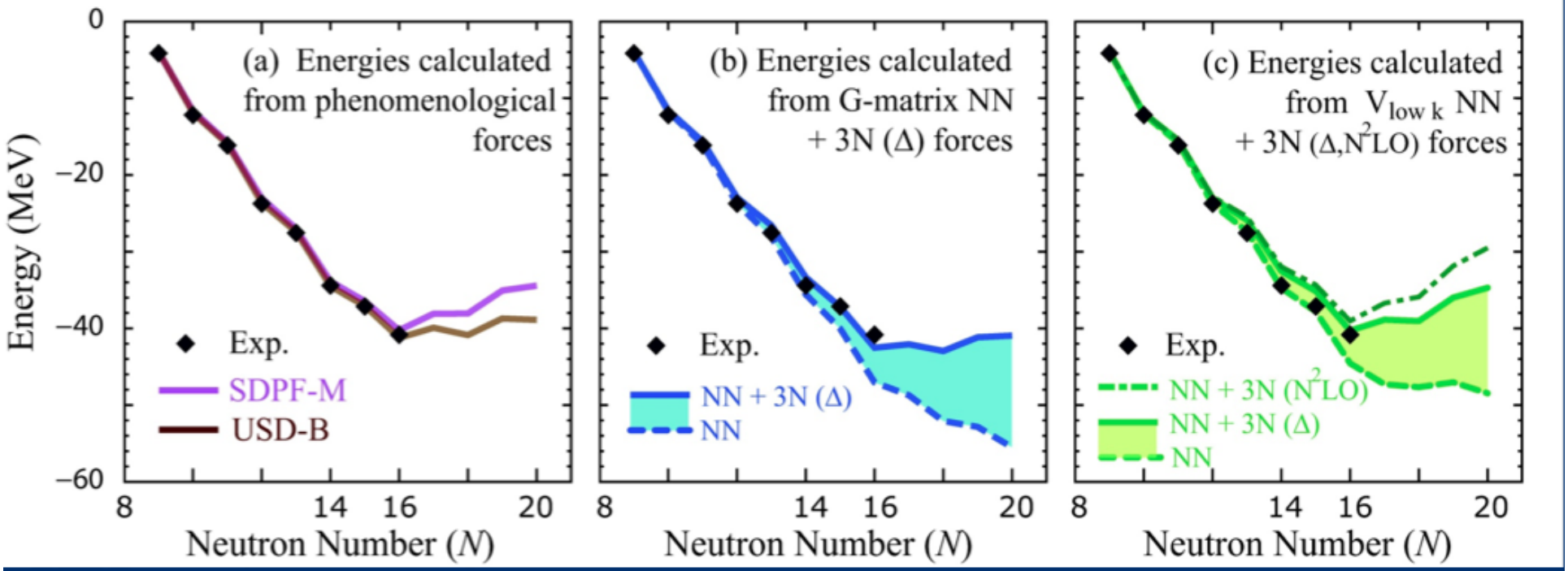


Ab-initio calculations for light nuclei



Courtesy S. Pieper, Argonne

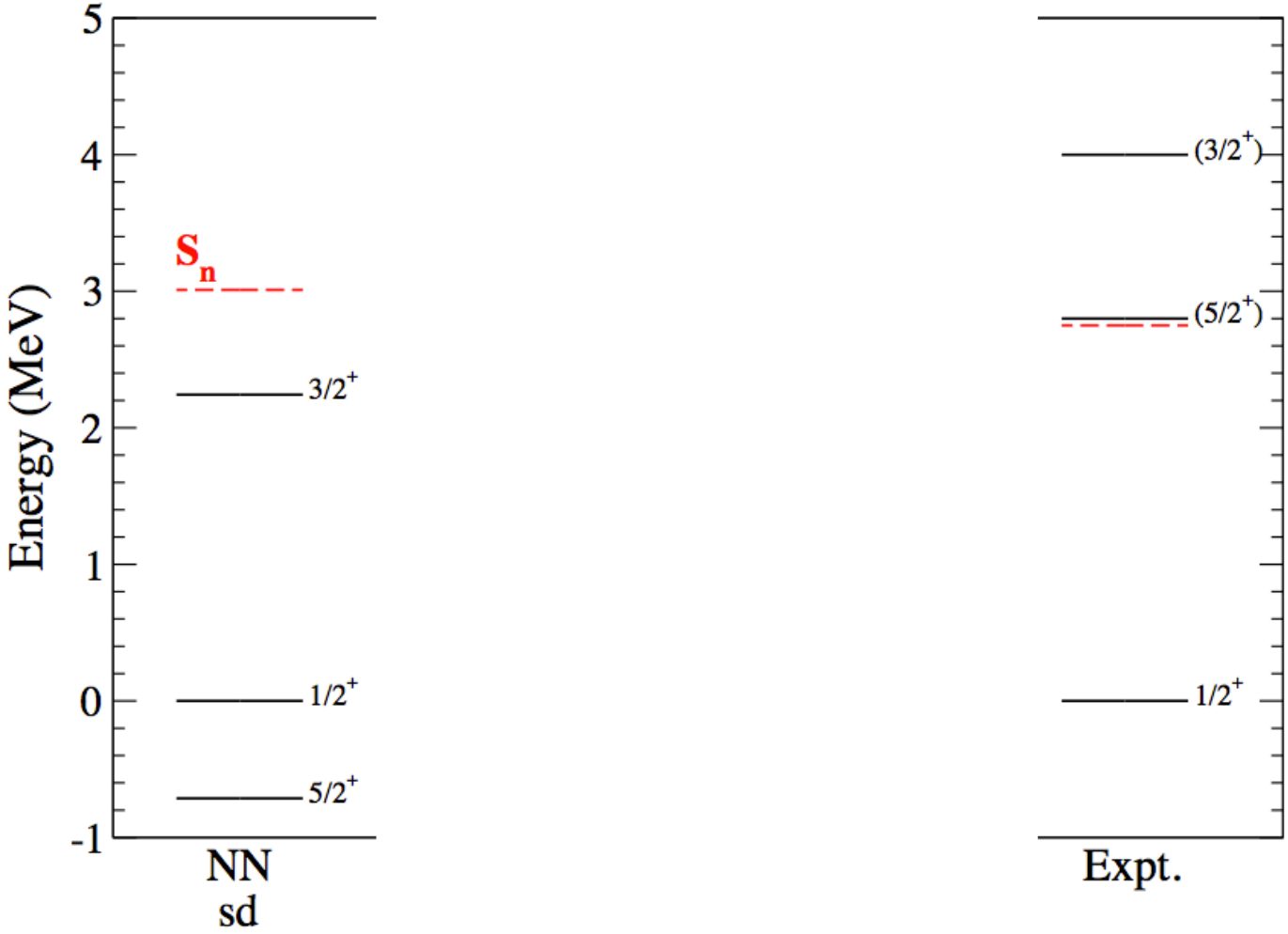
Binding Energies of Oxygen Isotopes



Otsuka, Suzuki, Holt, Schwenk, Akaishi, PRL 105, 032501 (2010)

^{23}O

$5/2^+$, $3/2^+$ indicate position of $d_{5/2}$ and $d_{3/2}$ orbits

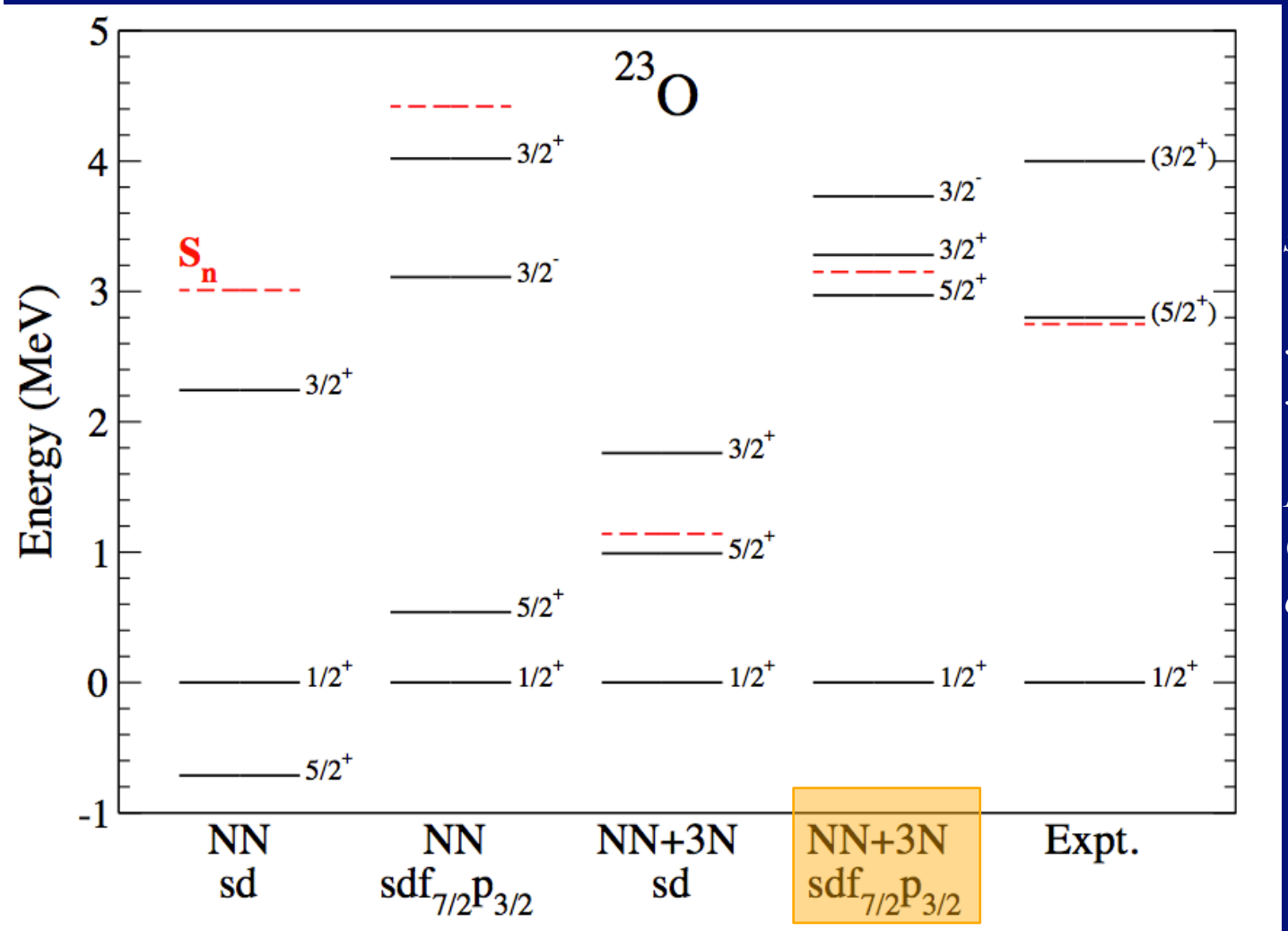


sd-shell NN-only
Wrong ground state!
$5/2^+$ much too low
$3/2^+$ bound

Holt et al., EPJ A49, 39 (2013)

^{23}O

$5/2^+$, $3/2^+$ indicate position of $d_{5/2}$ and $d_{3/2}$ orbits

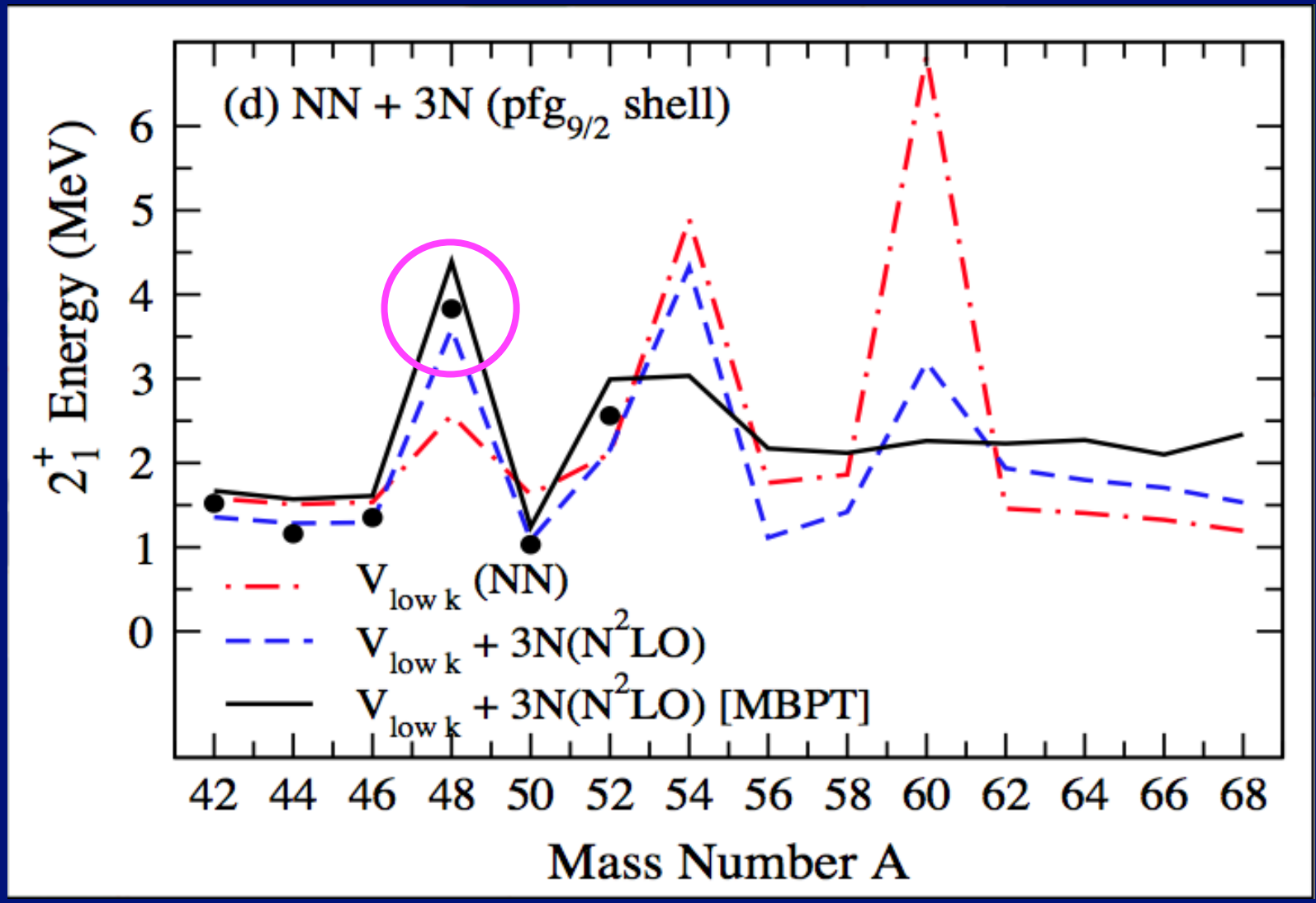


sd-shell NN-only
Wrong ground state!
$5/2^+$ much too low
$3/2^+$ bound

Microscopic NN+3N
Great improvements in extended valence space!

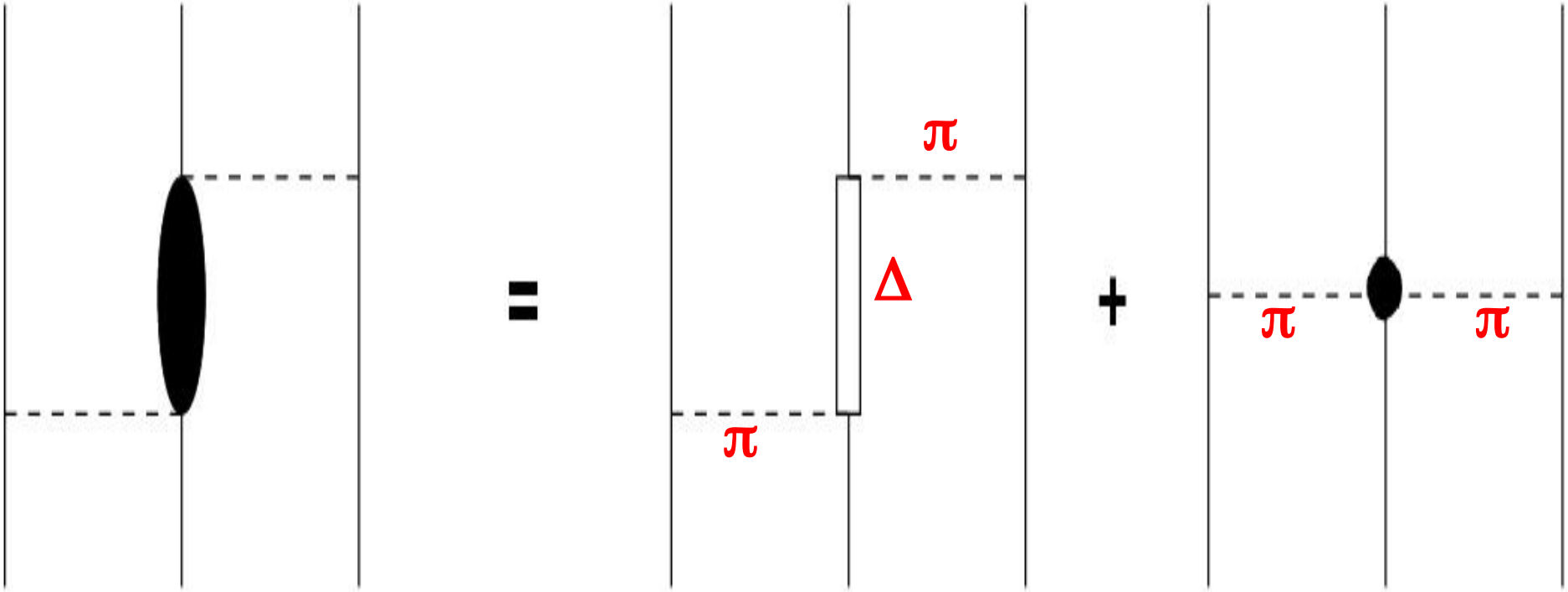
Holt et al., EPJ A49, 39 (2013)

N=28 magic number in Calcium



Holt, Otsuka, Schwenk and Suzuki, J. Phys. G39, 085111 (2012)

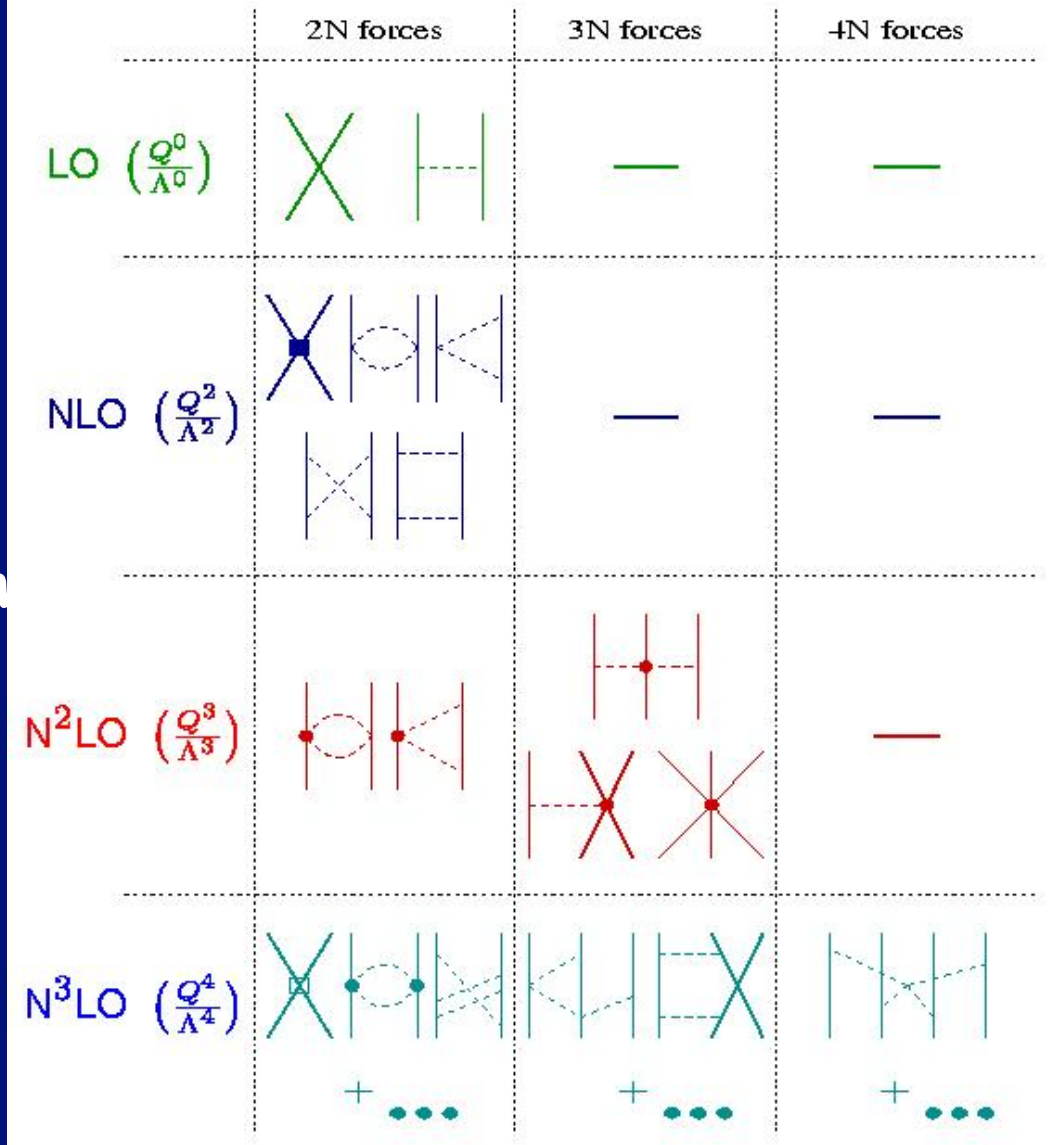
What is this three-nucelon force?



- parametrization of Fuijta-Miyazawa force + 2π rescattering + higher-order interactions
- Added to 2N potential as correction
- Tucson-Melbourne, Urbana IX, …

Effective-Field Theory Approach

- Developed by Weinberg
- Coupling of pions and nucleons in EFT
- Predicts structure of 3NF
- Self-consistent approach
- Only works at energies below pion-mass scale



Study of Three-Body Force

in Nuclear Physics

- Which reactions (and systems) to study?
  - Electromagnetic interaction on 3B systems
  - 3B (and more bodies?) Bound states
  - 3B Elastic scattering in large parts of phase space
  - 3B Break-up reaction in different kinematics
  - Many-body systems → Nuclear matter

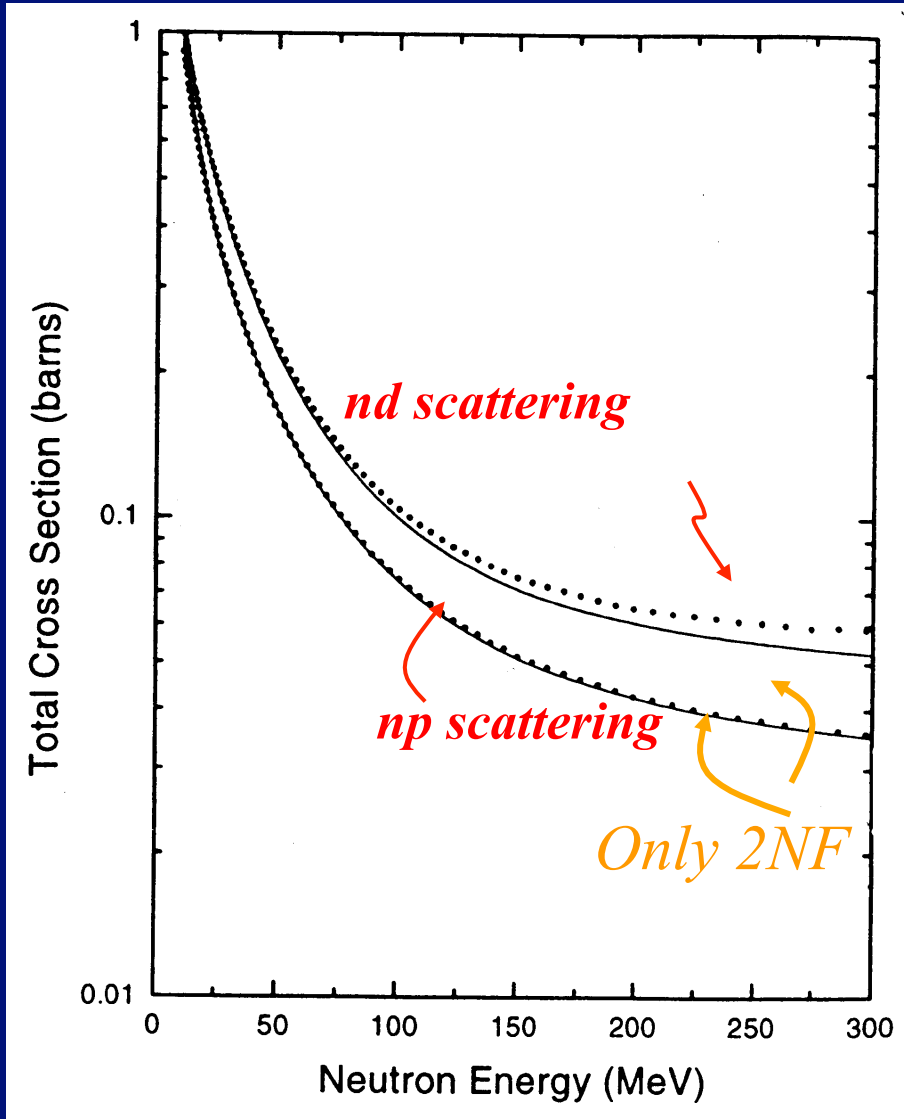
$$N + d \rightarrow N + d$$
$$N + d \rightarrow N + N + N$$
$$N + d \rightarrow {}^{3}He({}^{3}H) + \gamma^{(*)}$$
$$\gamma^{(*)} + {}^{3}He({}^{3}H) \rightarrow N + d$$
$$\gamma^{(*)} + {}^{3}He({}^{3}H) \rightarrow N + N + N$$

Total nd Cross sections

$$n + d \rightarrow n + d \,\&$$

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

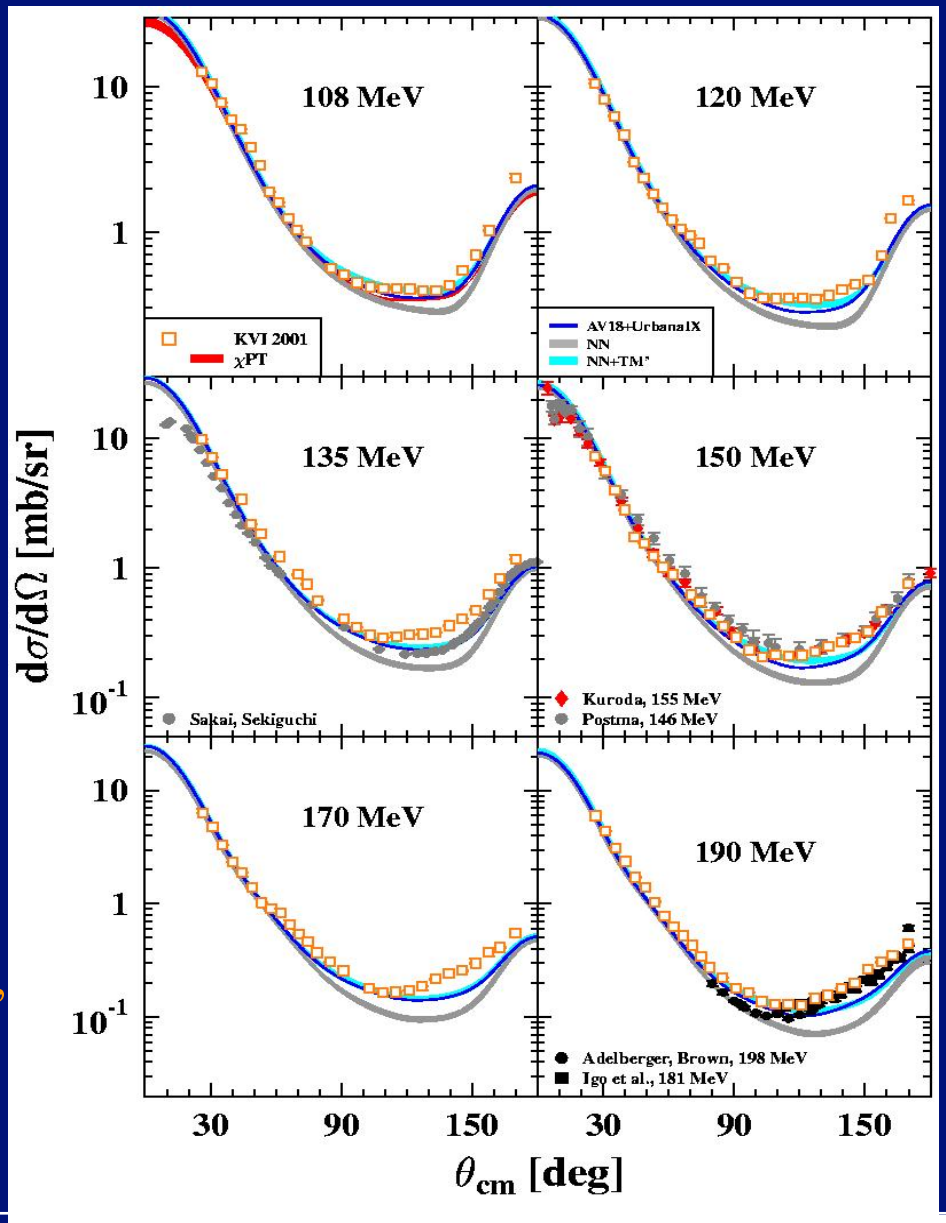
- Effect of 3NF small
- High-precision mandatory
- In addition, look for sensitivity:
  - ✓ exclusive channels
  - ✓ other observables



High precision data from Los Alamos
W.P. Abfalterer et al., PRL 81, 57 (1998)

pd elastic scattering cross sections

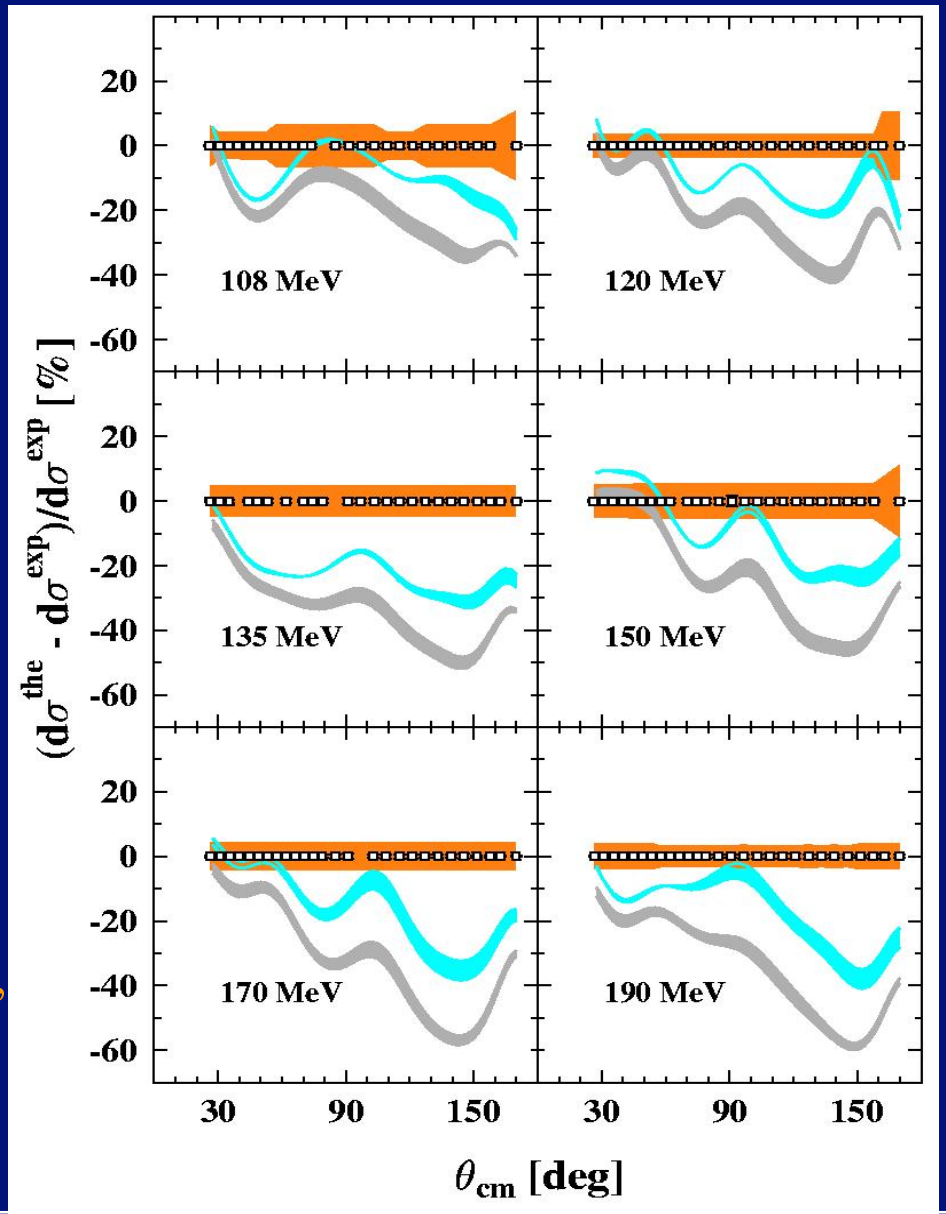
$$p + d \rightarrow p + d$$

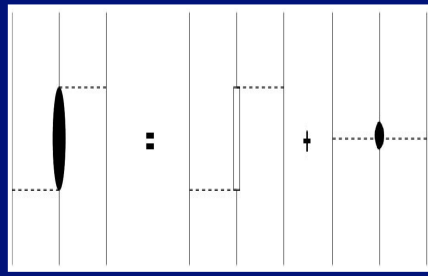


K. Ermisch et al.,
PRC 68, 054004 (2003),
PRC 71, 064004 (2005)

pd elastic scattering cross sections

(theory –data)/data





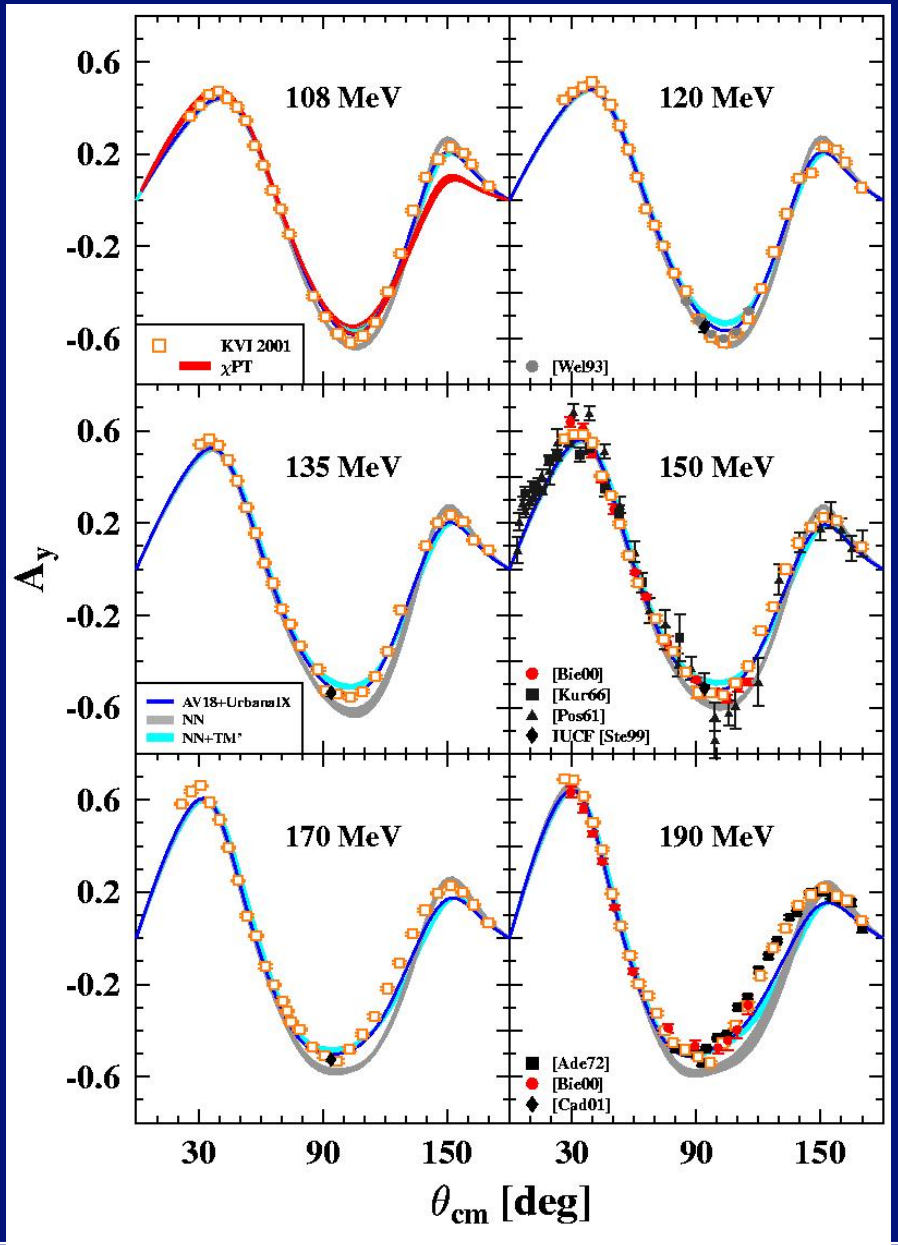
Hanover Approach of dynamical delta

K. Ermisch et al.,
PRC 68, 054004 (2003),
PRC 71, 064004 (2005)

p+d vector analyzing powers

Bieber et al.,
PRL84, 606 (2000)

Ermisch et al.,
PRL86, 5862 (2001)
PRC71, 064004 (2005)



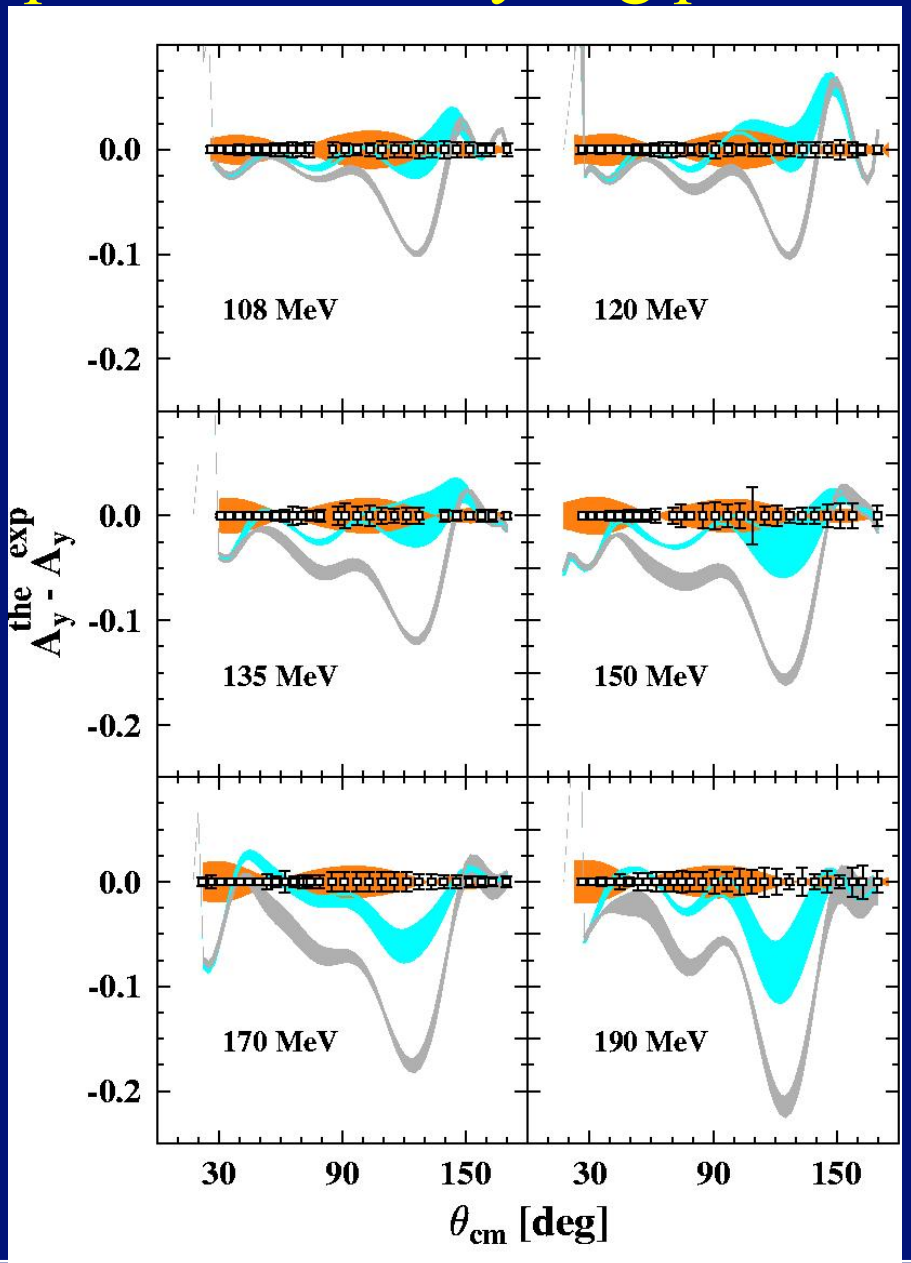
$$\vec{p} + d \rightarrow p + d$$

$$\sigma = \sigma_0 (1 + p A_y \cos\varphi)$$

$$\Rightarrow A_y = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

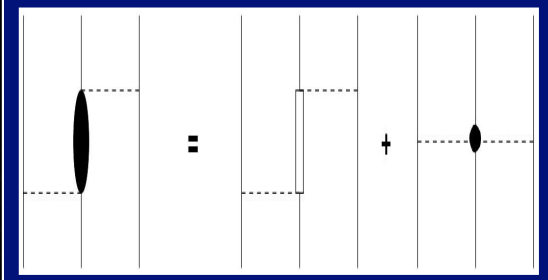
p+d vector analyzing powers

theory-data



Ermisch et al.,
PRC71, 064004 (2005)

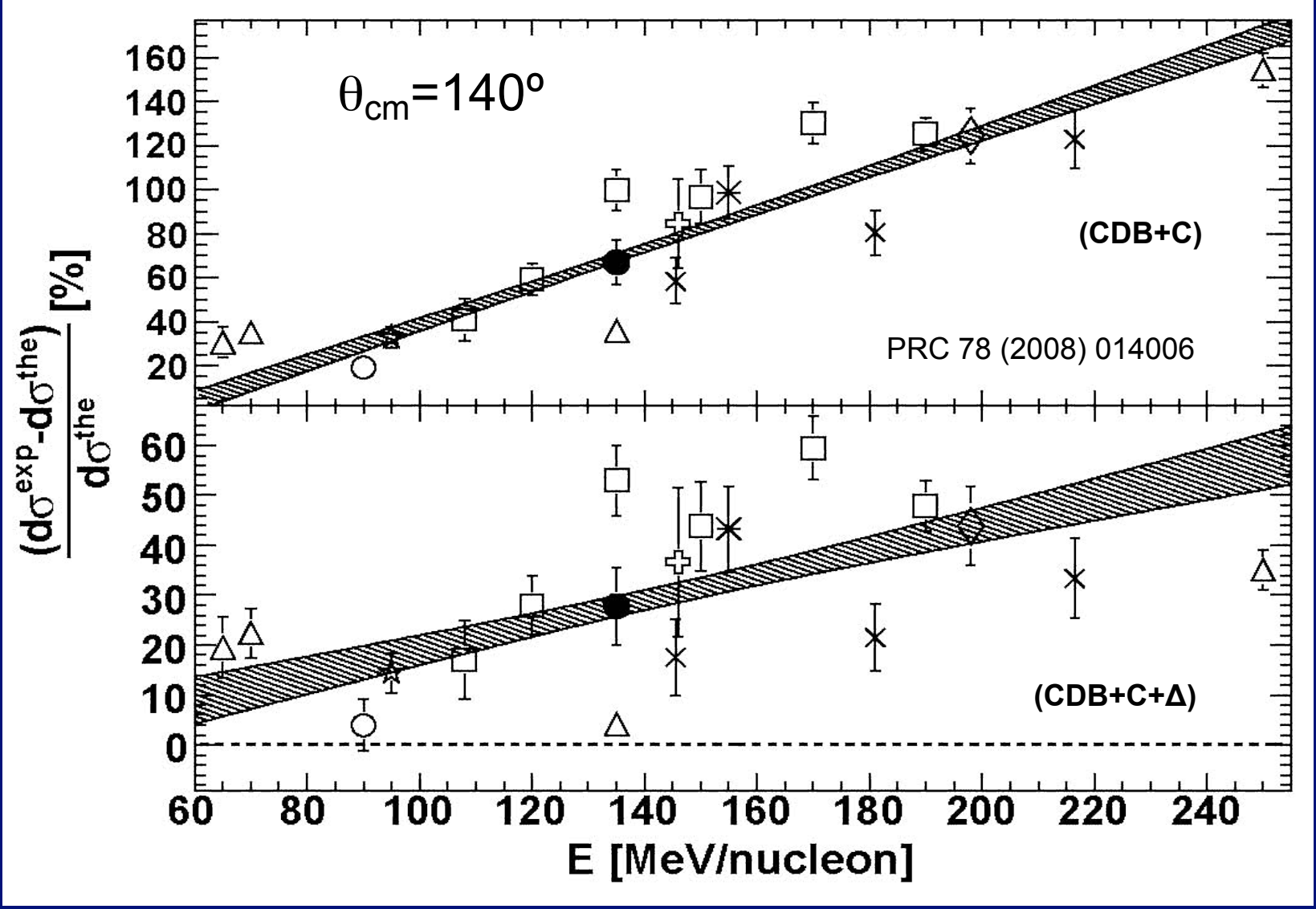
$$\vec{p} + d \rightarrow p + d$$



Hanover Approach of dynamical delta

Effect of 3NF as a function of Energy

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



A. Ramazani et al., Phys. Rev. C78, 014006 (2008)

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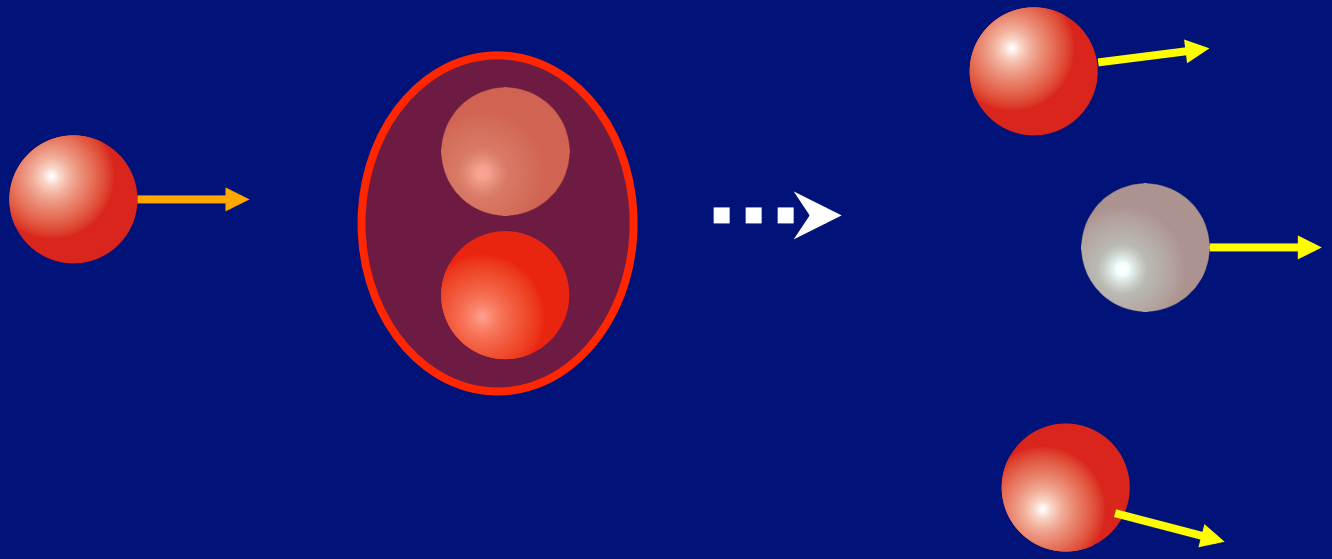
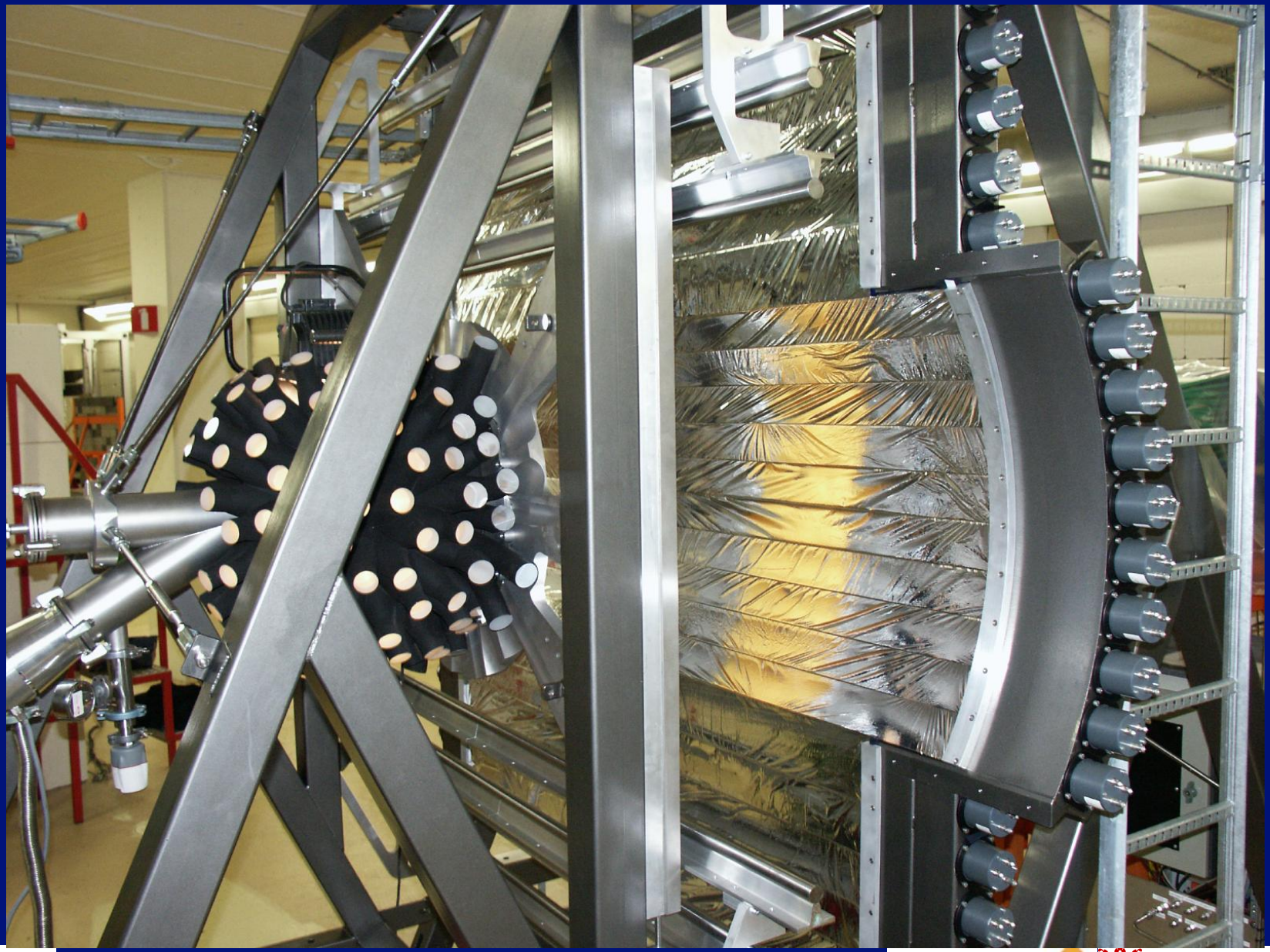
Break-up channel

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



- 5 dimensional phase space (θ_1, θ_2, E_1, E_2, ϕ_{12}) i.e. much larger than in the elastic channel (θ)
- Allows detailed road-map for the study of nuclear forces
- Requires a setup with large coverage

Big Instrument for Nuclear-Polarization Analysis (BINA)



Analyzing power for break-up channel for E_p=190 MeV

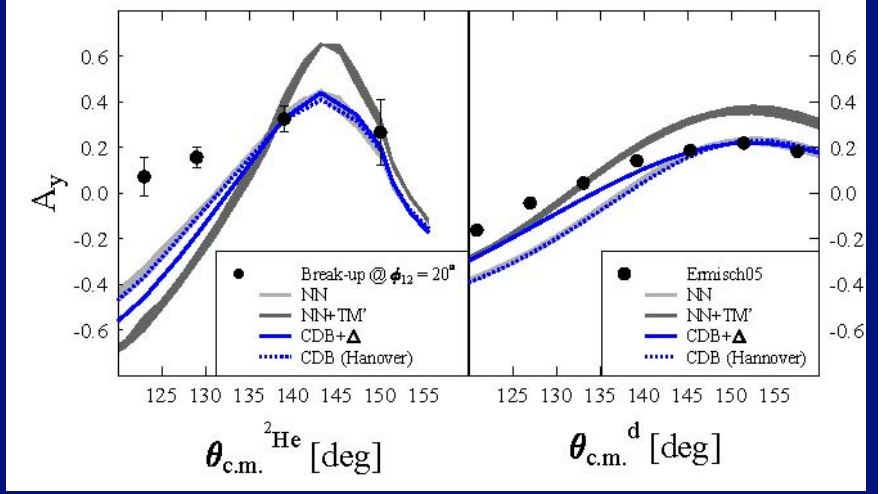
$$\vec{p} + d \rightarrow p + p + n$$

E_p = 190 MeV

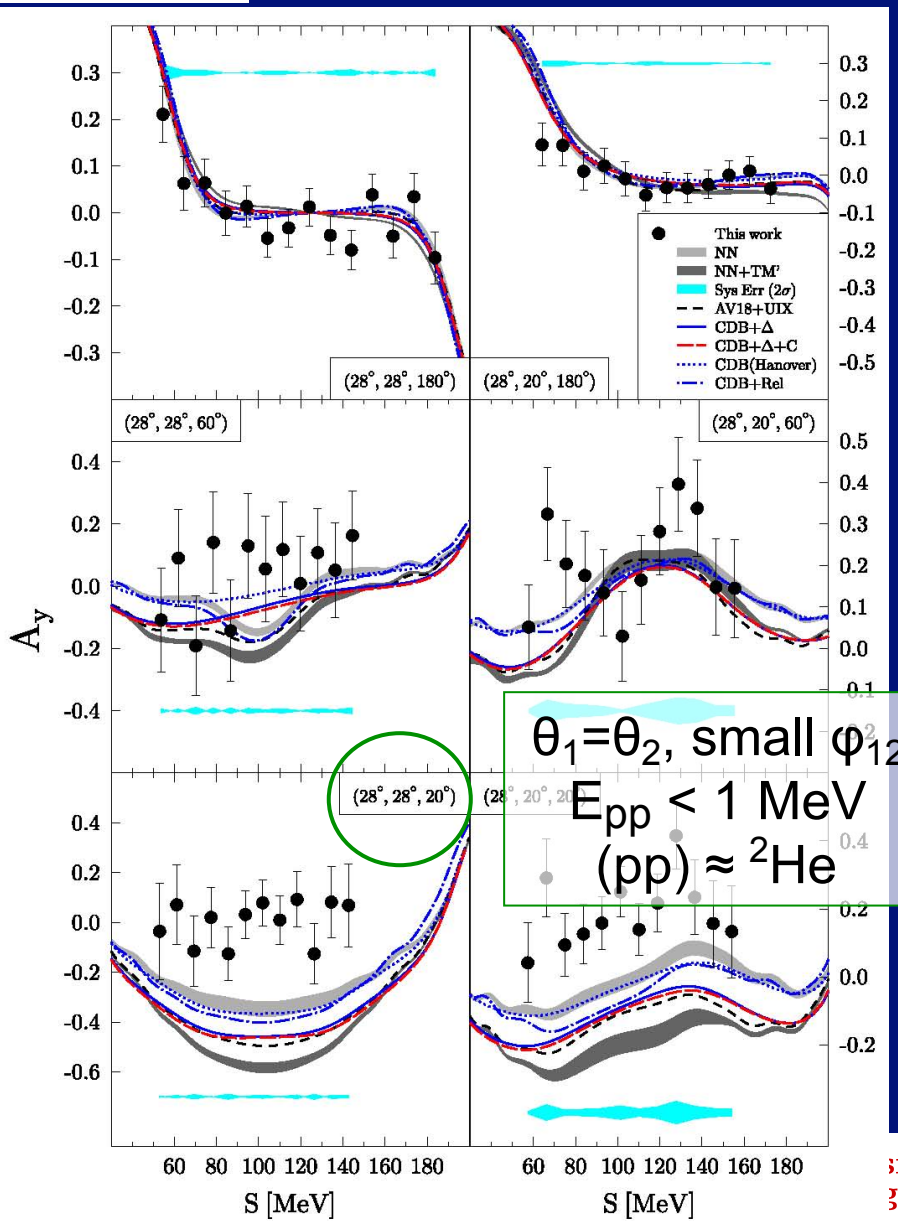
θ = 14° - 30°

H. Mardanpour *et al.*,
Phys. Lett. B687, 149 (2010)

$^2\mathrm{H}(\vec{p},^2\mathrm{He})n$ $^2\mathrm{H}(\vec{p},^2\mathrm{H})p$



I = 1/2, 3/2 I = 1/2



$\theta_1=\theta_2$, small φ_{12}
E_{pp} < 1 MeV
(pp) ≈ ^{2}He

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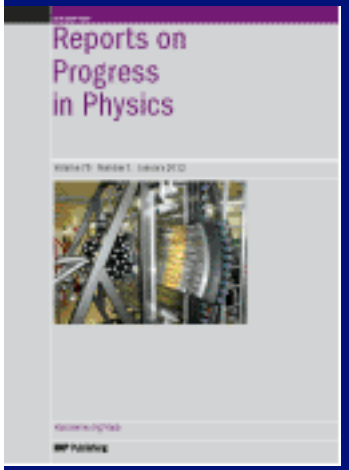
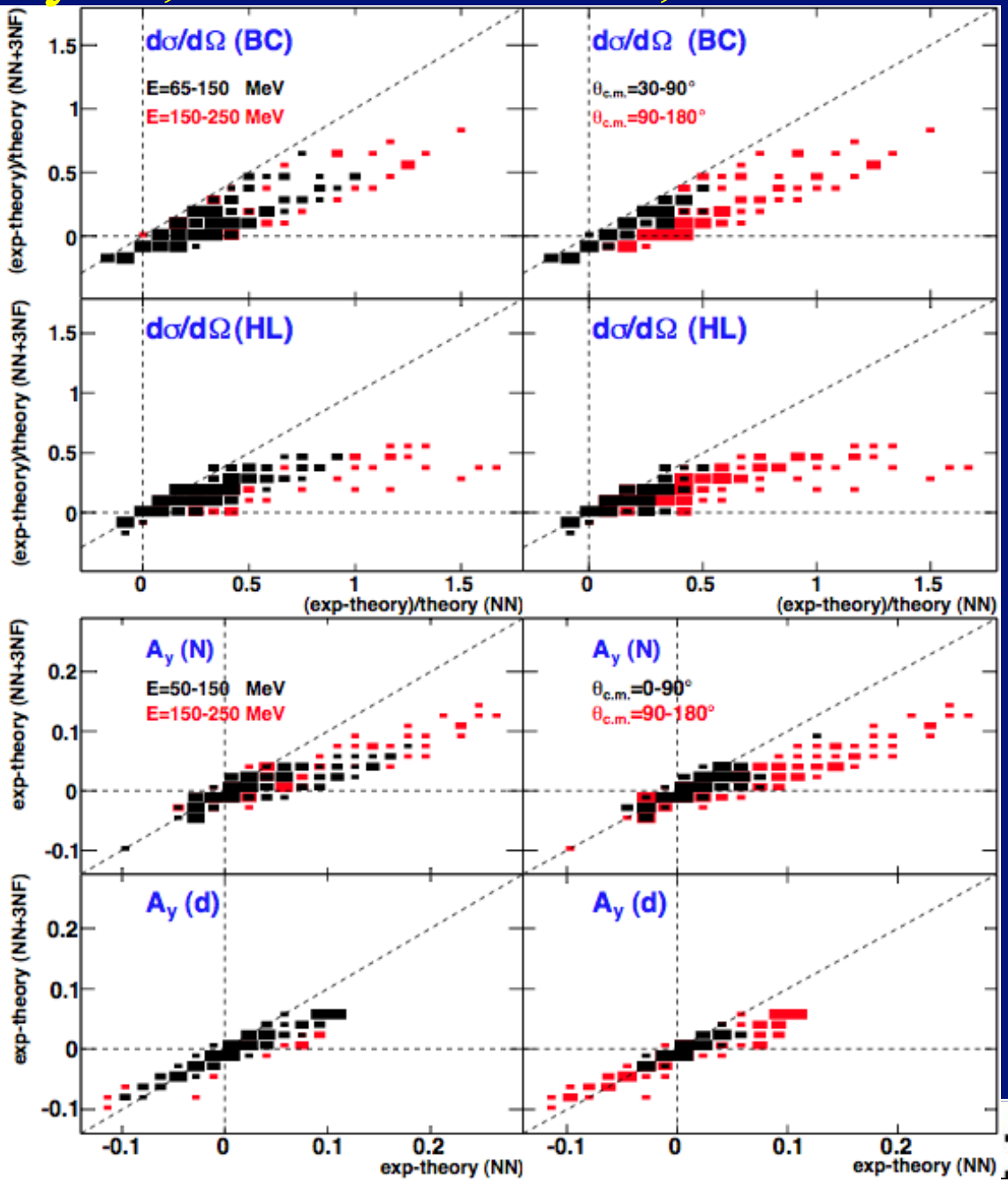
sity of
gen

Global Analysis, Elastic channel, 50-250 MeV/nucleon

Reports on Progress in Physics 75, 016301 (2012)





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

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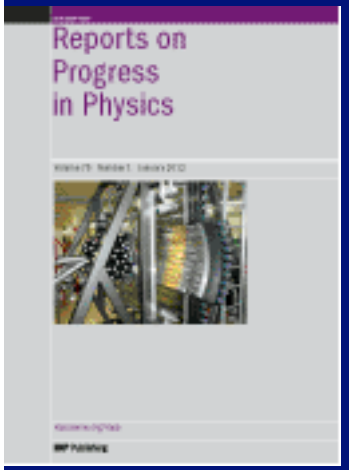
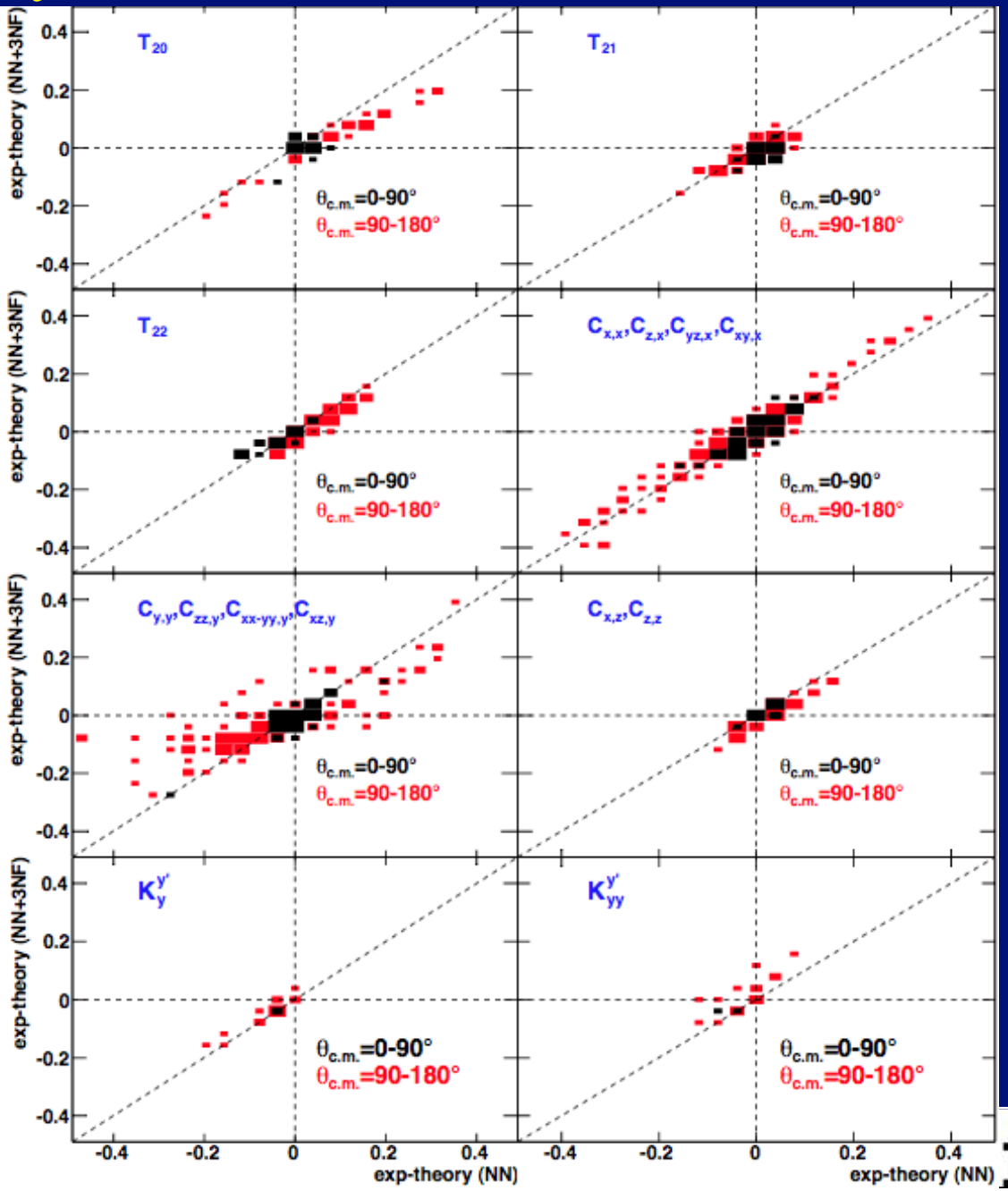
Global Analysis, Elastic channel, 50-250 MeV/nucleon

Reports on Progress in Physics 75, 016301 (2012)





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

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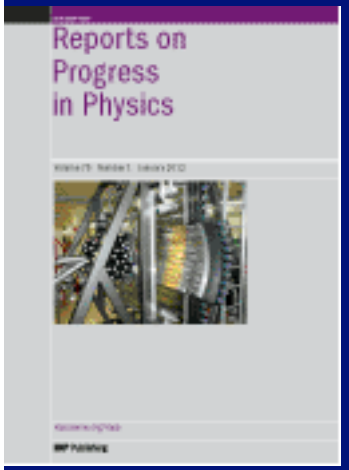
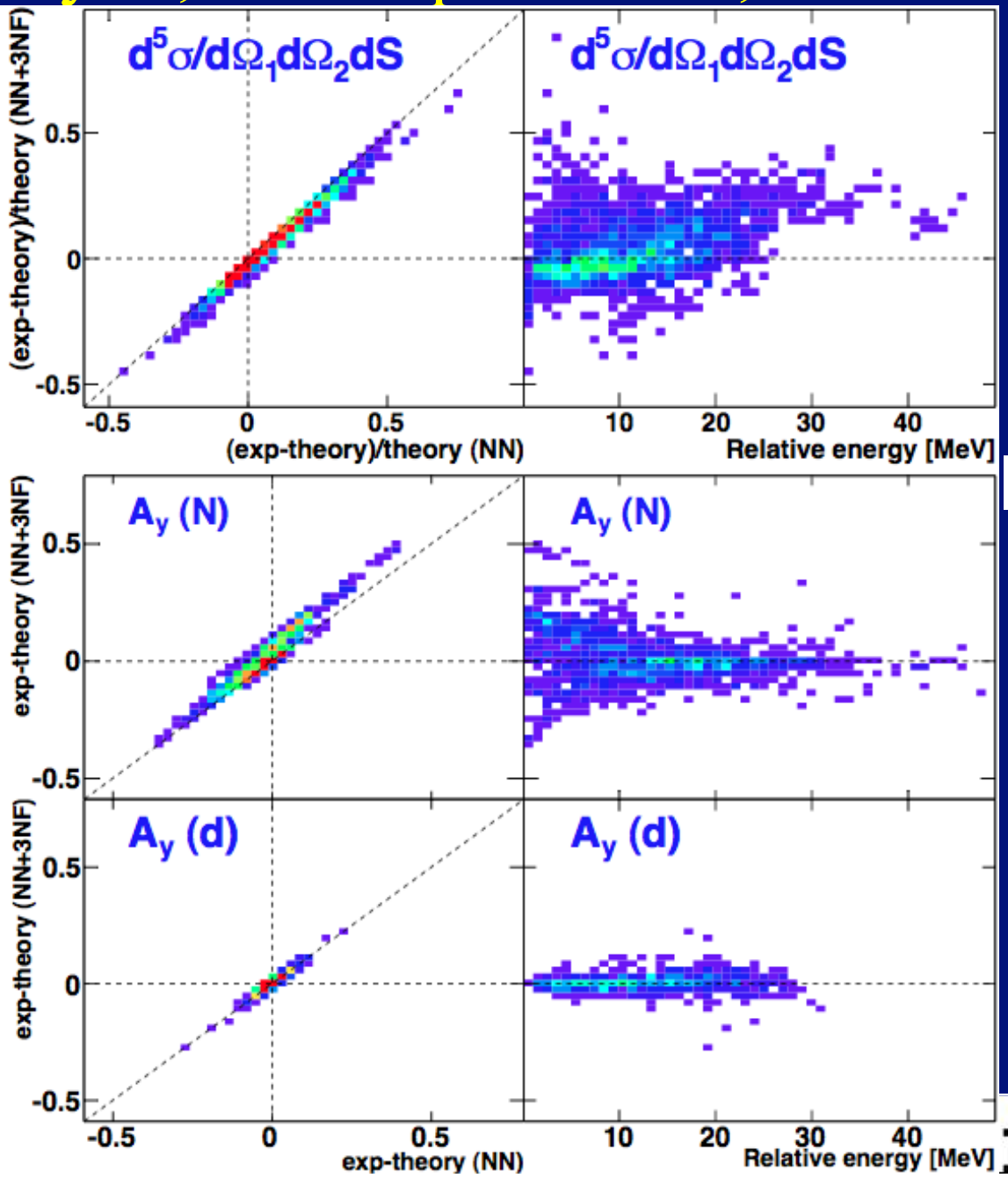
Global Analysis, Breakup Channel, 65-190 MeV/nucl.

Reports on Progress in Physics 75, 016301 (2012)



Also JPG 40, 063101 (2013)



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

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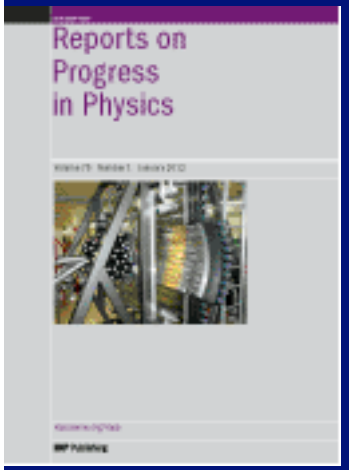
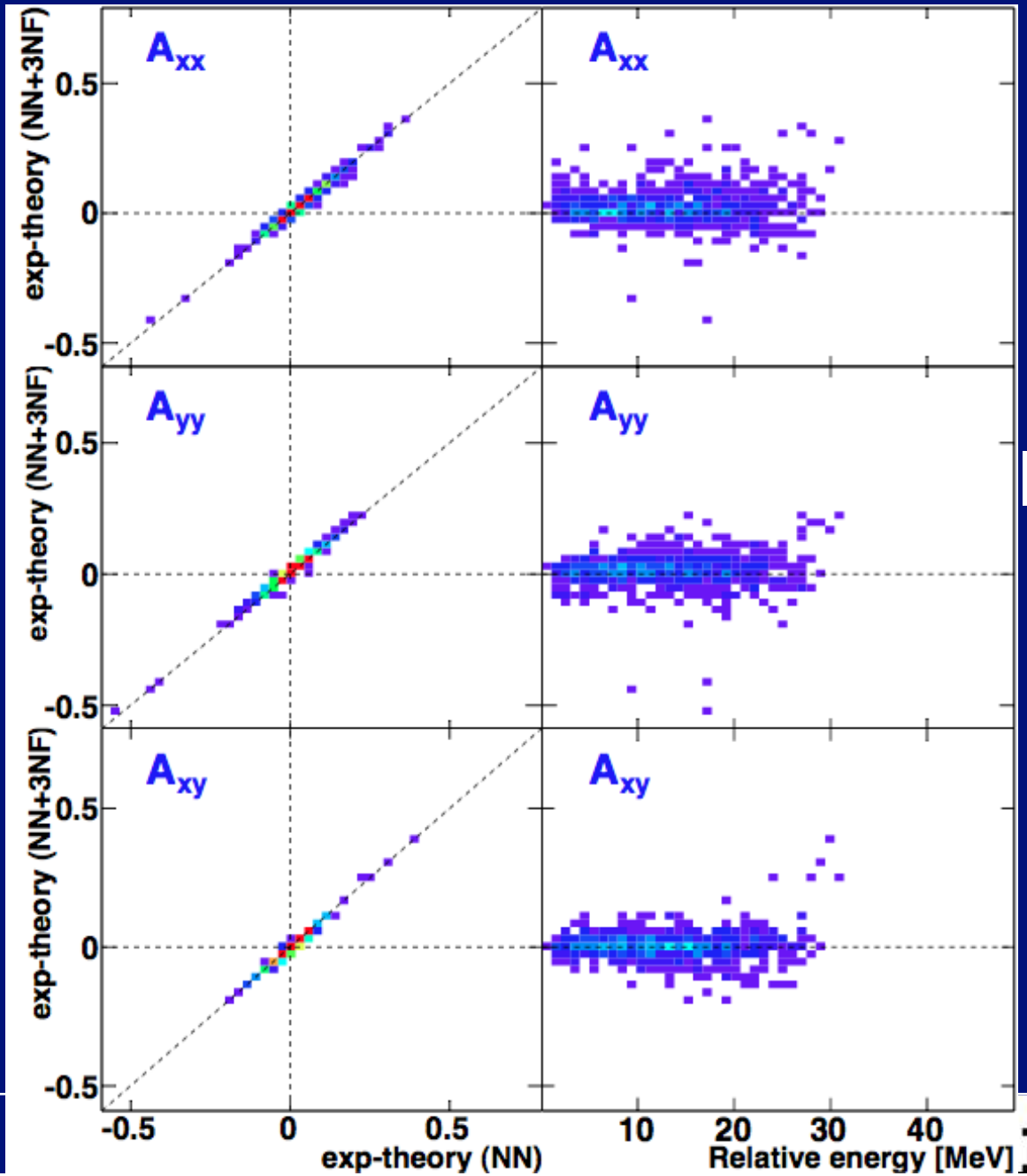
Global Analysis, Breakup Channel, 65-190 MeV/nucl.

Reports on Progress in Physics 75, 016301 (2012)



Also JPG 40, 063101 (2013)



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

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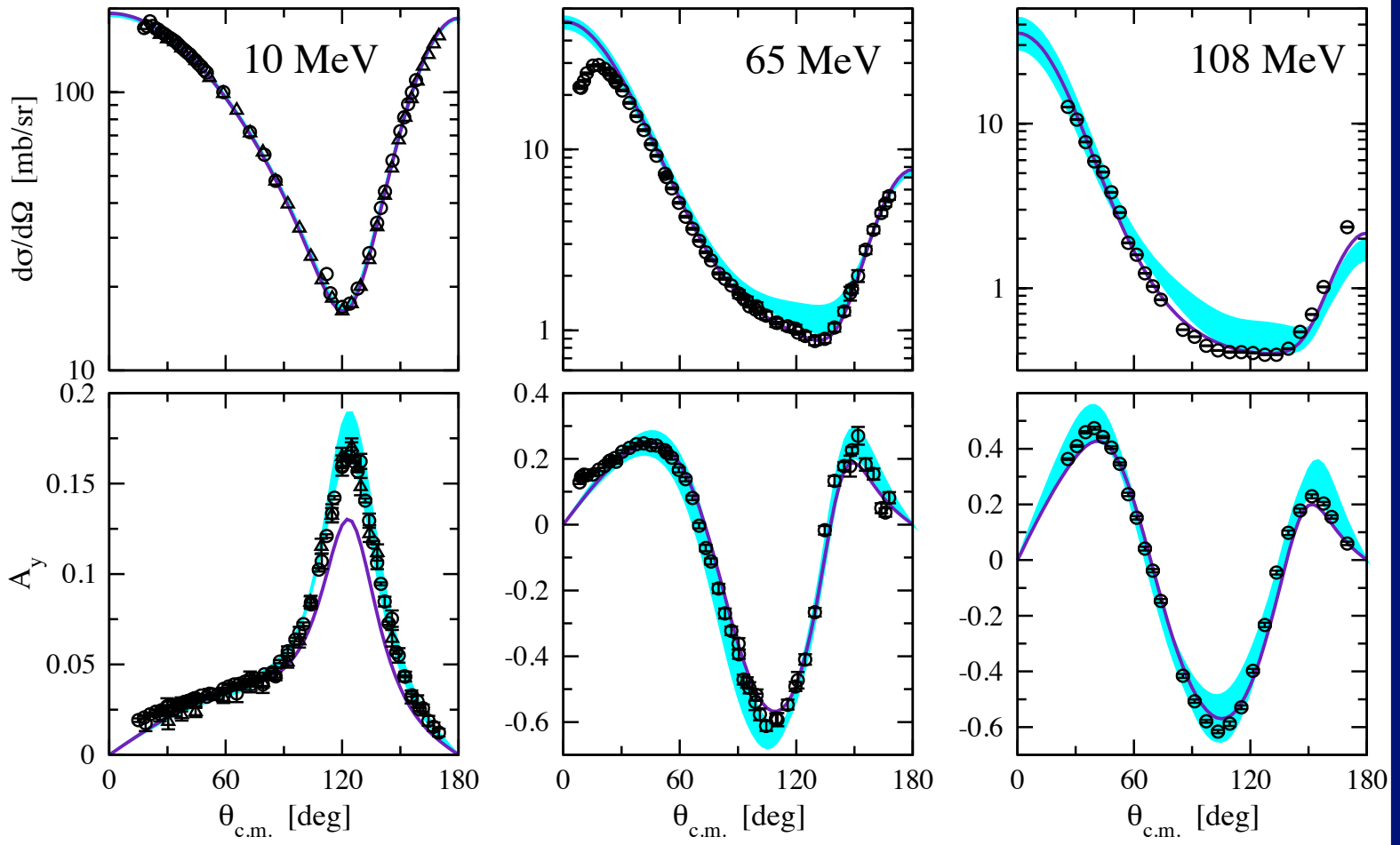
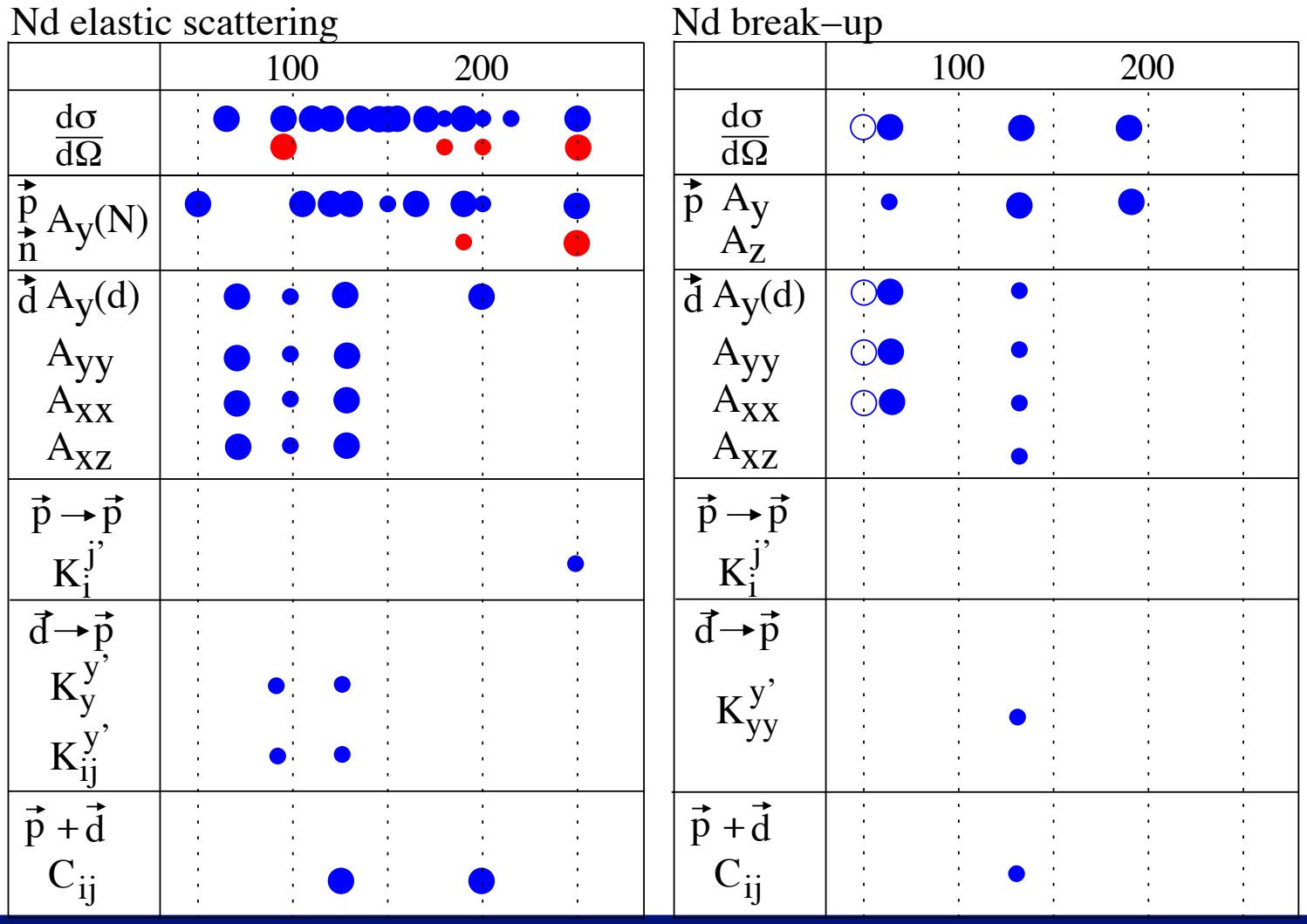
Limitations of effective field theories



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

Overview world database elastic & breakup



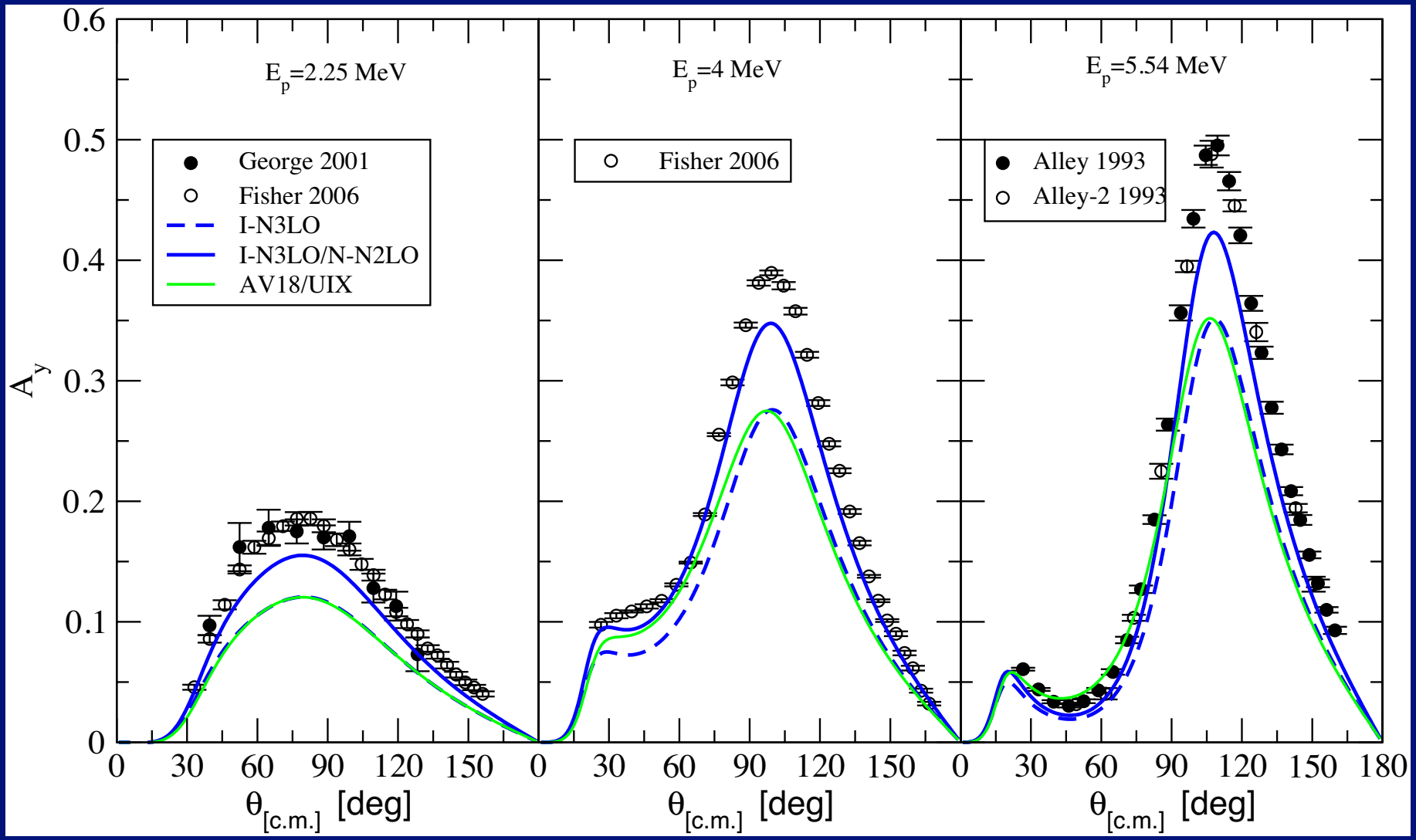
- rich set of observables, allowing a multi-dim. study of 3NF
- a sizable fraction has been measured accurately and systematically

(RIKEN/RCNP/IUCF/KVI,Jülich)

How about four-body systems?

$\vec{p} + \mathrm{He} \rightarrow p + \mathrm{He}$

Viviani, Kievsky et al., private communication



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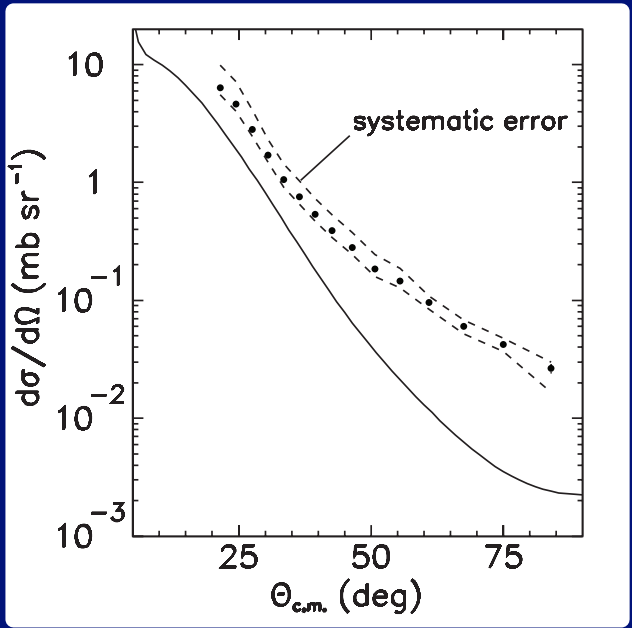
How about four-body systems?

Elastic dd



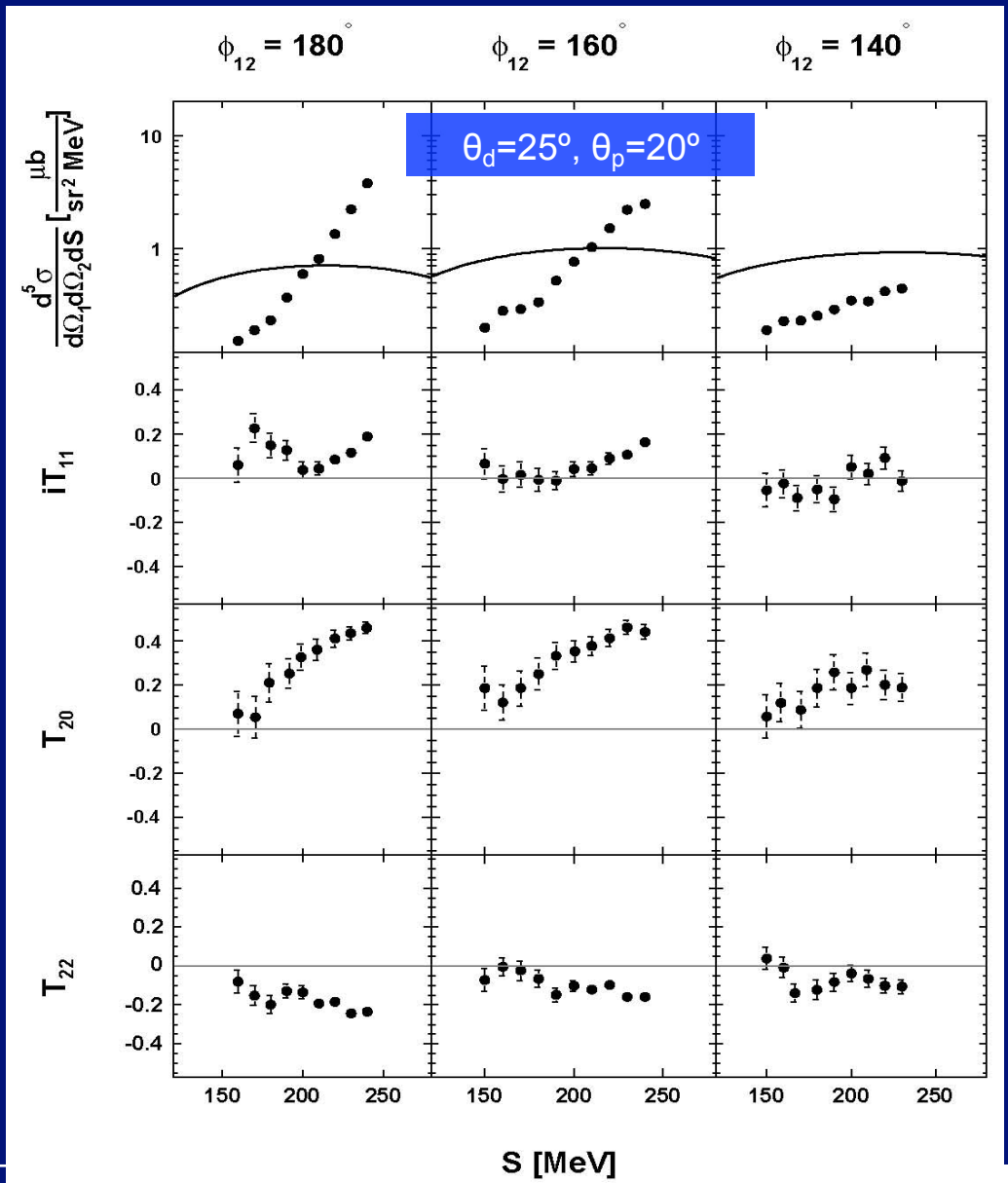
$$\vec{d} + d \longrightarrow p + n + d$$

Three-body break-up channel

E_d = 130 MeV

θ = 15° - 30°, Φ_{12} = 140° - 180°

A. Ramazani-Moghaddam-Arani et al., PRC ***83****, 024002 (2011)*



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BINA in Cracow

Concluding remarks

- Three-body hadronic reactions are the most promising tool for the study of 3NF effects.
- A large body of data has been gathered for cross sections and spin observables for elastic and break-up reactions at intermediate energies at KVI, RIKEN, RCNP, IUCF and Jülich. New measurements planned at RIKEN and Cracow.
- The Coulomb effect is now well under control.
- All data together show unambiguously the effect of 3NF.
- There are, however, still discrepancies indicating that the exact nature of 3NF is not yet known.
- Relativisitc corrections are coming but expected to be small.
- Four-body systems underway both exp. and theoretically.

STAY TUNED!

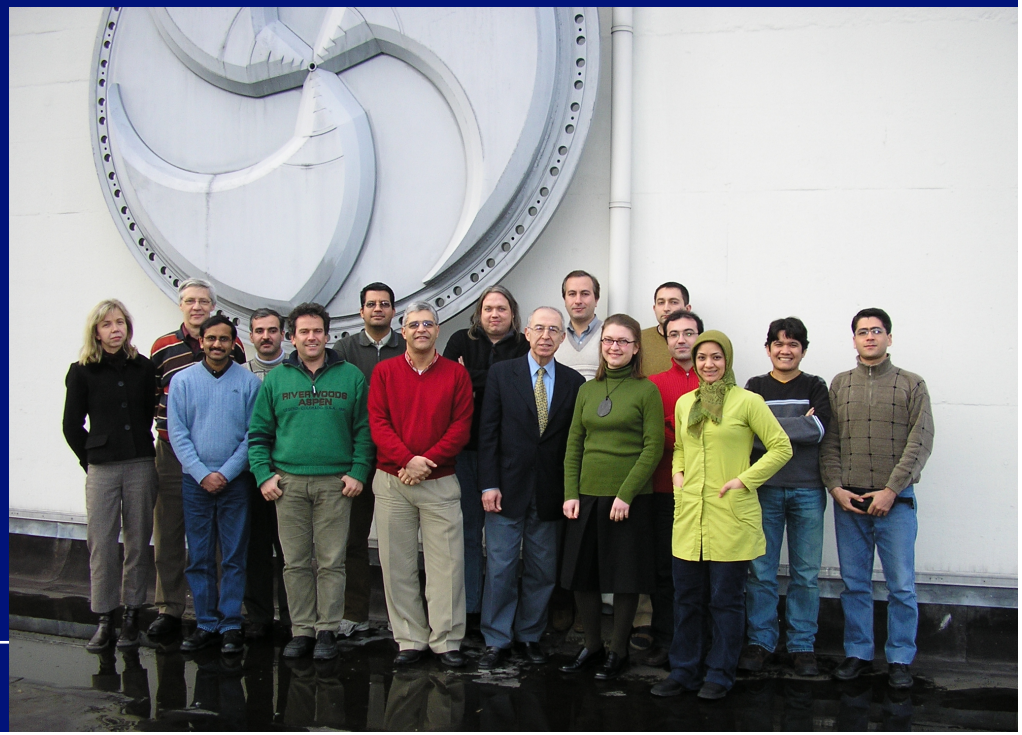
Acknowledgements

H.R. Amir Ahmadi, A.M. van den Berg, R. Bieber, K. Ermisch,
M. Elsami-Kalantari, M.N. Harakeh, H. Huisman, M. Kis, H. Mardanpour,
A. Mehmandoost, J.G. Messchendorp, M. Mahjour-Shafiei, A. Ramazani,
E. Van Garderen, M. Volkerts, S.Y. van der Werf, H. Woertche

+ Polish Experimental Group (O. Biegun, K. Bodek, St. Kistryn, A. Kozela,
A.Micherdzinska, E. Stephan, R. Sworst, J. Zejma and W. Zipper)

+IUCF group (E. Stehpenson, A. Bakker, and C. Bailey)

+ Theoretical support from
Bochum-Cracow
(Gloeckle, Golak, Kamada,
Kuros-Zolnierczuk,
Skibinski and Witala)
Hanover-Lisbonne
(Sauer, Deltuva and Fonseca)
Epelbaum, Nogga



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