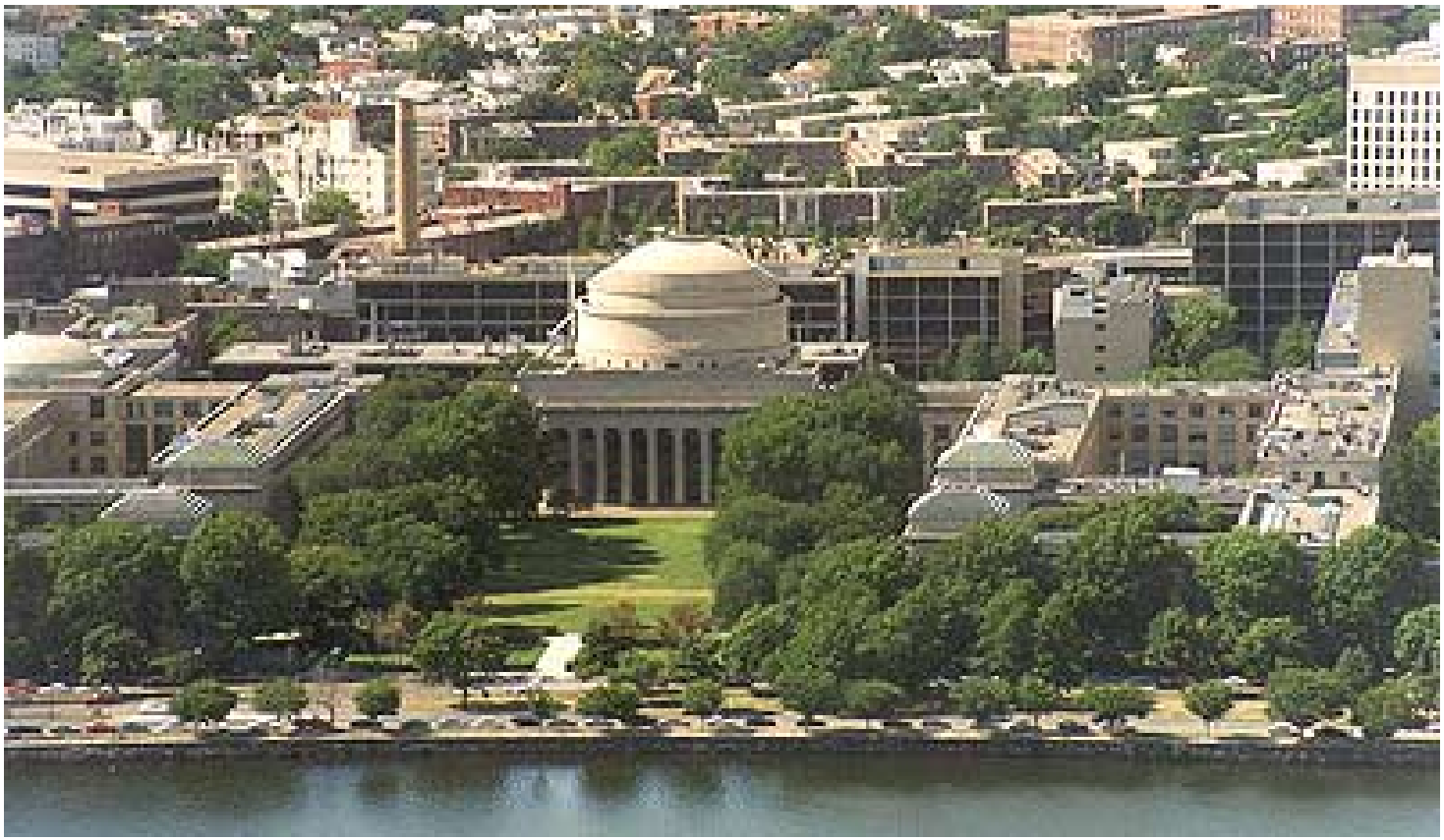
The Three-Nucleon Force - Revisited

Some Historical Thoughts

Peter U. Sauer

Leibniz University Hannover



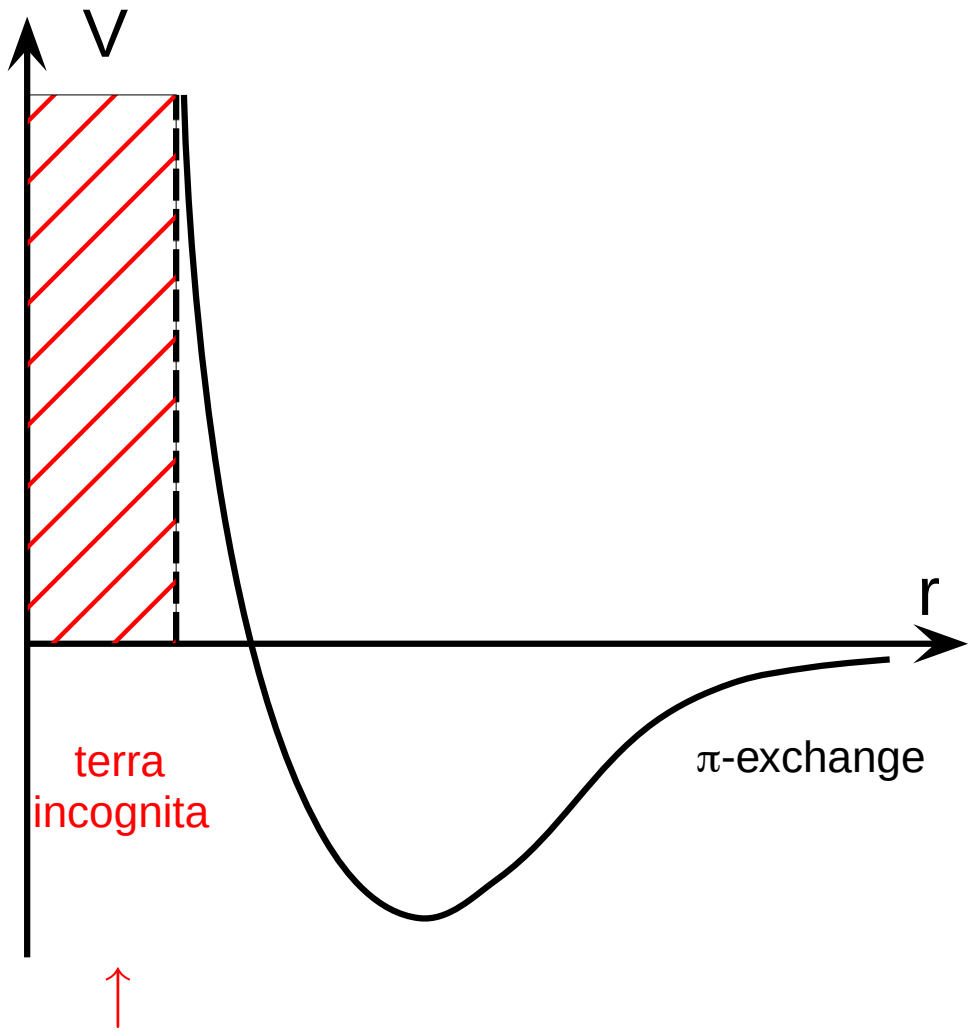
MIT 1970/71

Nuclear Structure in Terms of Realistic Two-Nucleon Potential

Outline

- Shell Model of Nuclear Structure - Distant Past
- Few-Nucleon Systems - Test of Nuclear Dynamics
  - Choice of Hilbert Space and Hamiltonian
  - Technical Challenges
  - Celebrated Successes
  - Remaining Puzzles
- What Have We Learnt from all those Calculations?

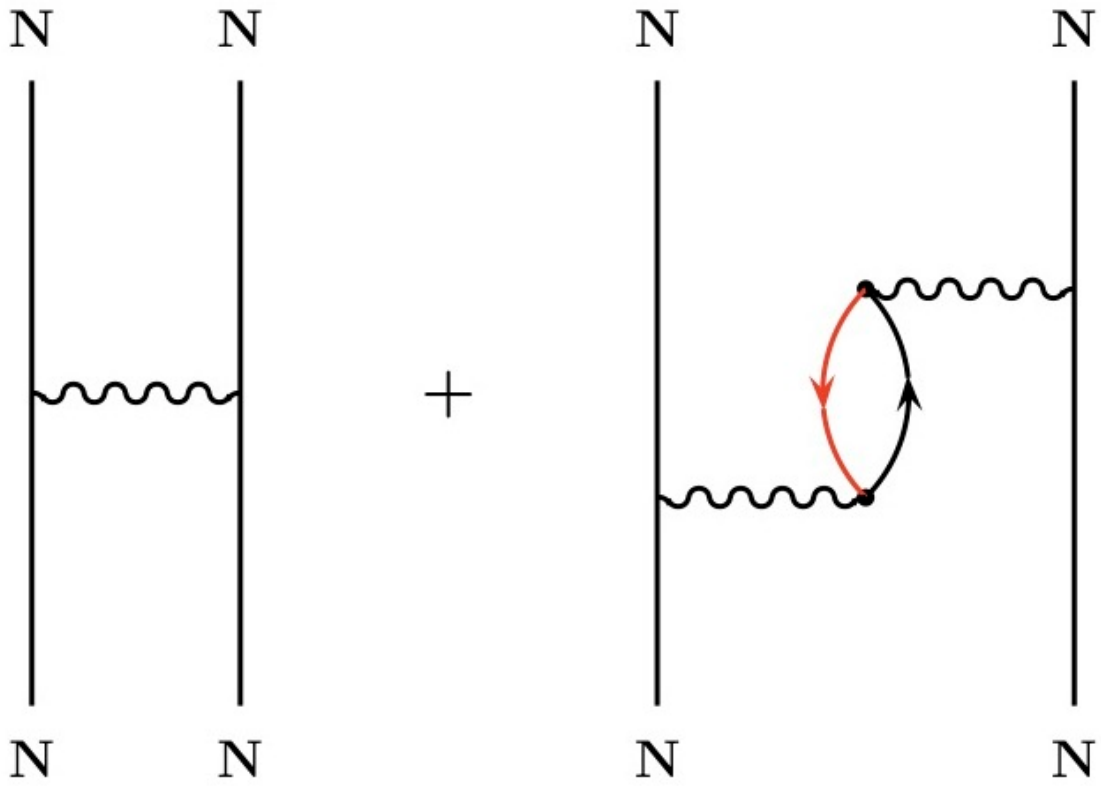
Two-Nucleon Potential a Terrifying Beast



strongly repulsive core

- softening into reaction matrix required
- super-soft core forbidden by
  MIT experimental theorem

Shell Model in Early Days



O^{18}

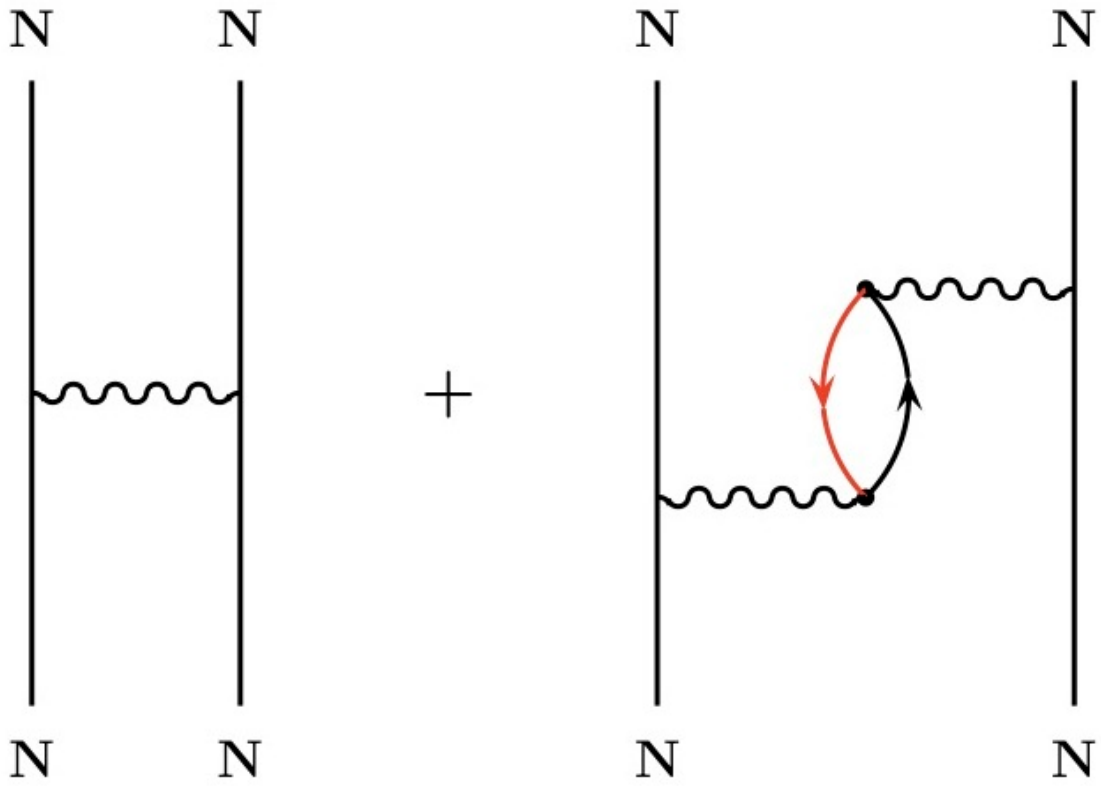
model space of
2N's in s-d shell

Effective Potential with *Core-Polarization*

Kuo, Brown and Bertsch:

"Theory correct, since agreement with data good!"

Shell Model in Early Days



O^{18}

model space of
2N's in s-d shell

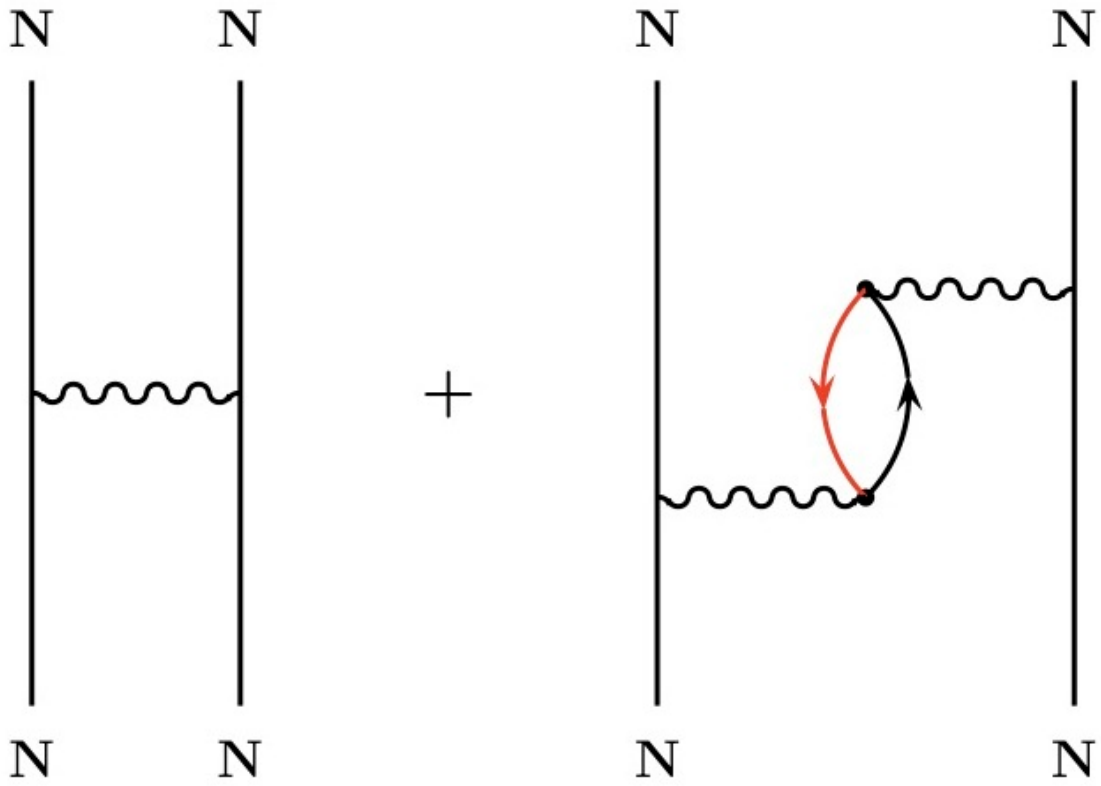
Effective Potential with *Core-Polarization*

Vary, Sauer, Wong:

"Calculation of core-polarization not converged"

Very sorry, wrong!

Shell Model in Early Days



O^{18}

model space of
2N's in s-d shell

Effective Potential with *Core-Polarization*

Barrett, Kirson - Schucan, Weidenmüller:

"Effective interaction not converging"

Shell Model Now - View of a Bystander

Core-Polarization Moved

from Effective Interaction to Model Space

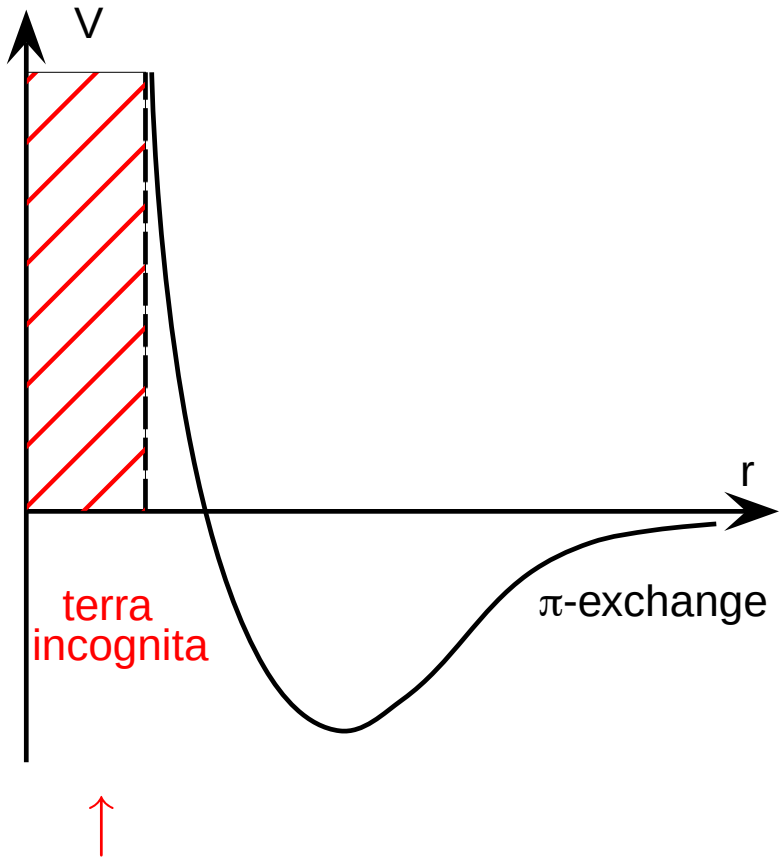
Strategy

- Efficient Balance between Model Space and Effective Interaction
- Hilbert Space Truncated:

  Many-Body Contributions to Effective Interaction

  Effective Three-Nucleon Interaction

Two-Nucleon Potential a Terrible Beast

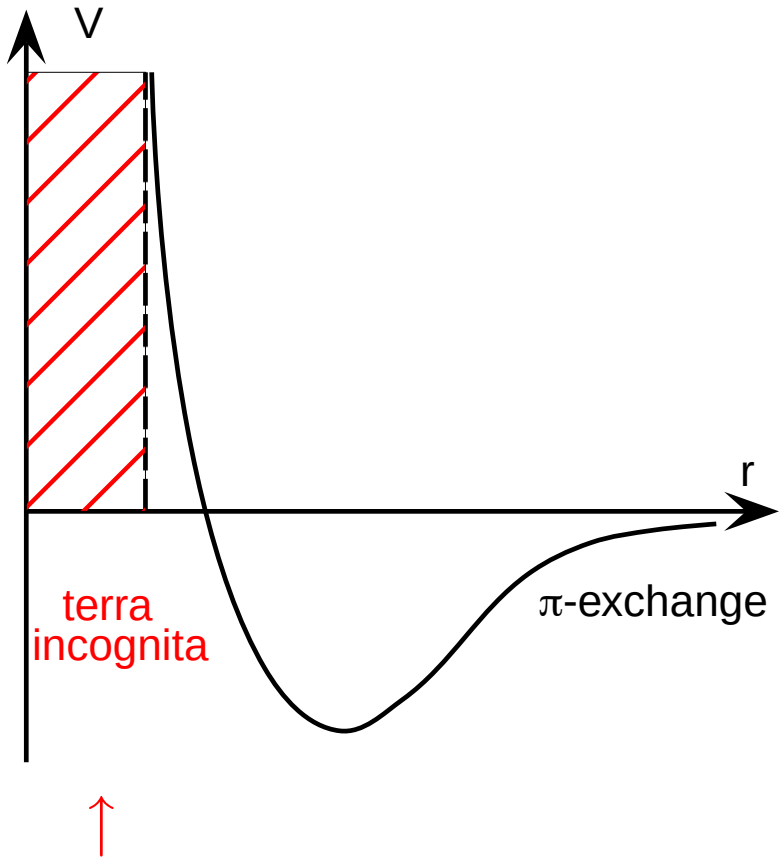


• realm of phase-equiv. off-shell variations

Hope: Off-shell information on 2N force from nuclear-structure results like O^{18}

Pradhan, PUS, Vary - no strategic exploration

Two-Nucleon Potential a Terrible Beast



- realm of phase-equiv. off-shell variations

Hope: Off-shell information on 2N force from nuclear-structure results like O^{18}

At that time an illusion - now *ab exitu* approach

Basic Assumption for Nuclear Structure and Reactions:

Rigid Nucleons Interact through 2N, 3N and ... Forces

Problems twofold and distinct:

- How to solve the many-nucleon problem for chosen forces? → shell model
- How to learn about nucleonic forces? How important is the genuine three-nucleon force? → few-body physics

Three- and Four-Nucleon Systems

Exactly Numerically Solvable - in Principle

Faddeev - Alt, Grassberger, Sandhas

3N and 4N Systems Theoretical Laboratories of Choice for Studying Properties of Interaction between Nucleons.

Three- and Four-Nucleon Systems

bound states: $^3\mathrm{H}, ^3\mathrm{He}, ^4\mathrm{He}$
3N reactions: $\mathrm{N} + \mathrm{d}$
4N reactions: $\mathrm{N} + {}^3\mathrm{H}$
$\mathrm{N} + {}^3\mathrm{He}$
$\mathrm{d} + \mathrm{d}$

multitude of hadronic reactions, coupled and with break-up, with polarization, and corresponding em reactions

shown results obtained with A. Deltuva and A. C. Fonseca, Lisboa
our approach momentum space - not all theory groups can do all needed calculations

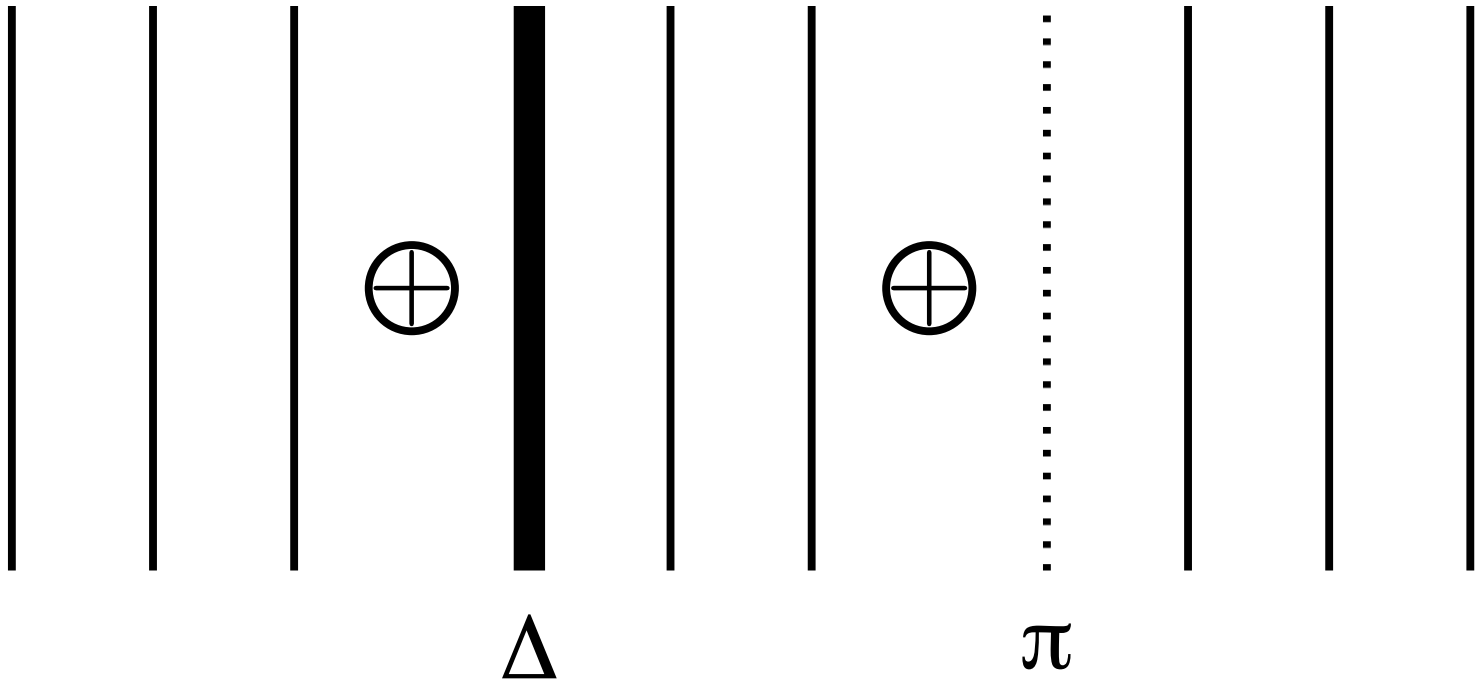
our historic choice of 2N and 3N forces

more ambitious than low energy

- what are the important degrees of freedom up to 0.5 GeV c.m. energy?
- how can consistency between the forces be achieved?

framework: old-fashioned meson theory

Hilbert space

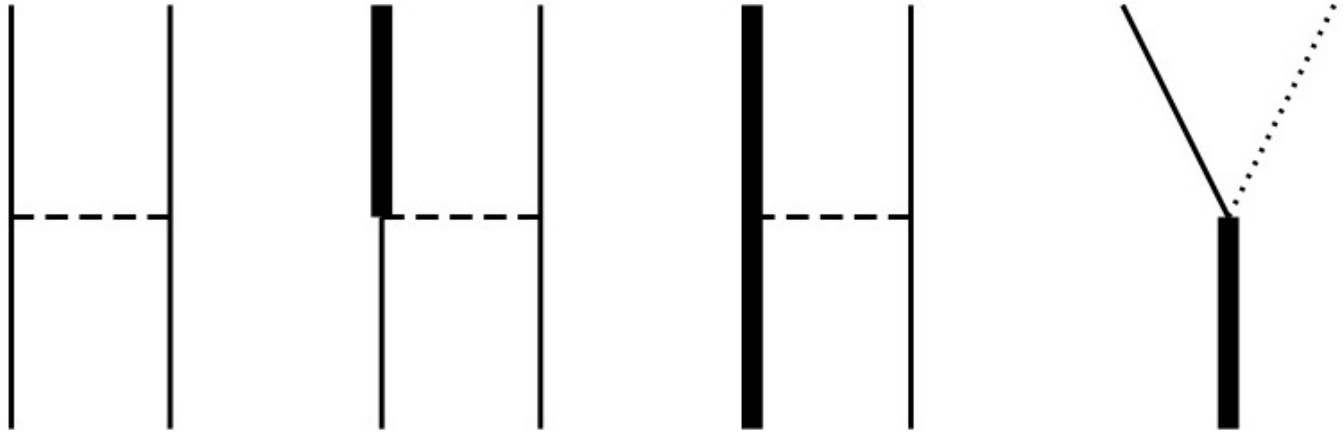


dynamics up to 0.5 GeV c.m. energy:

single Δ excitation

single π channels

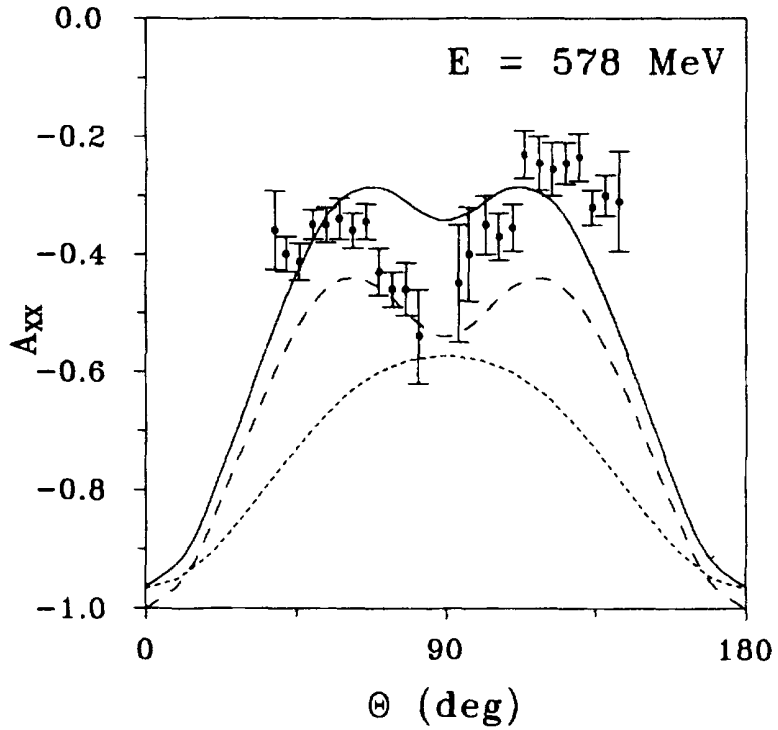
hamiltonian unifying nuclear phenomena at low and intermediate energies



novel scattering theory with particle production and absorption

- description of πN scattering
- unified description of NN and πNN dynamics
- nuclear structure with many-nucleon forces
- π-nucleus scattering with Δ-hole approach

unified description of NN and πNN dynamics



NN - πd scattering

Valcarce *et al* PRC 1994

test of NΔ potential

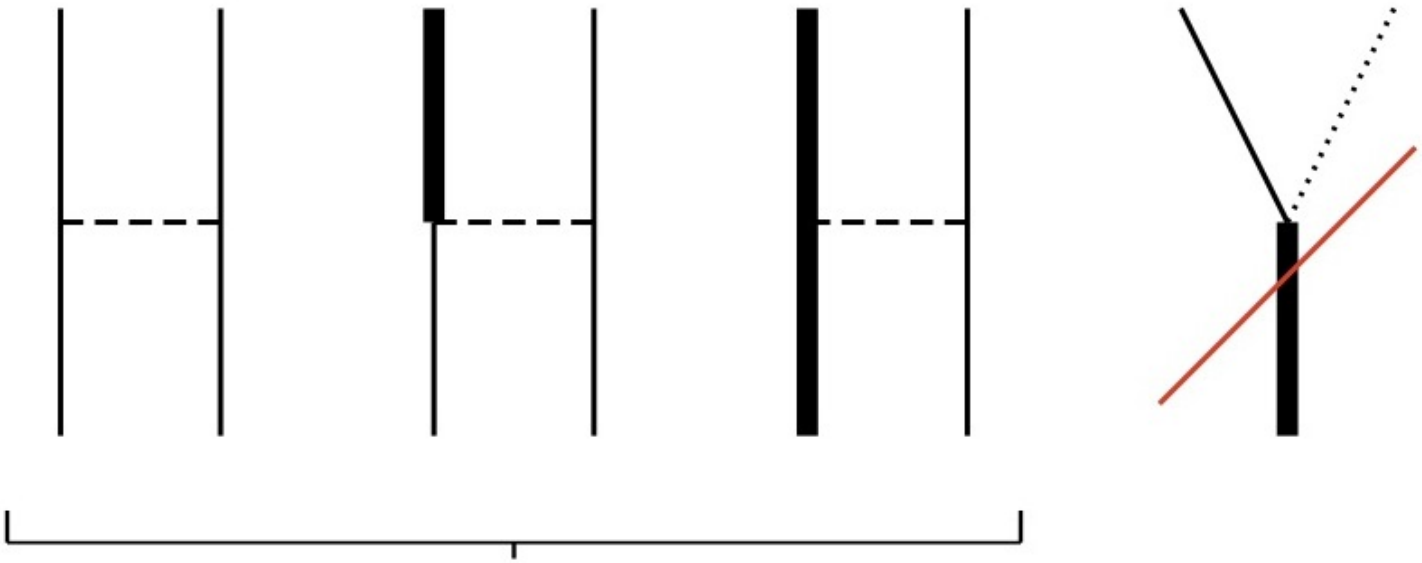
——— quarks

- - - - - - mesons

· · · · · · · · · NΔ = 0

dream of unifying low and intermediate energies ended with the end of pion factories - concentration on low-energy few-nucleon systems

Hamiltonian for Low Energies

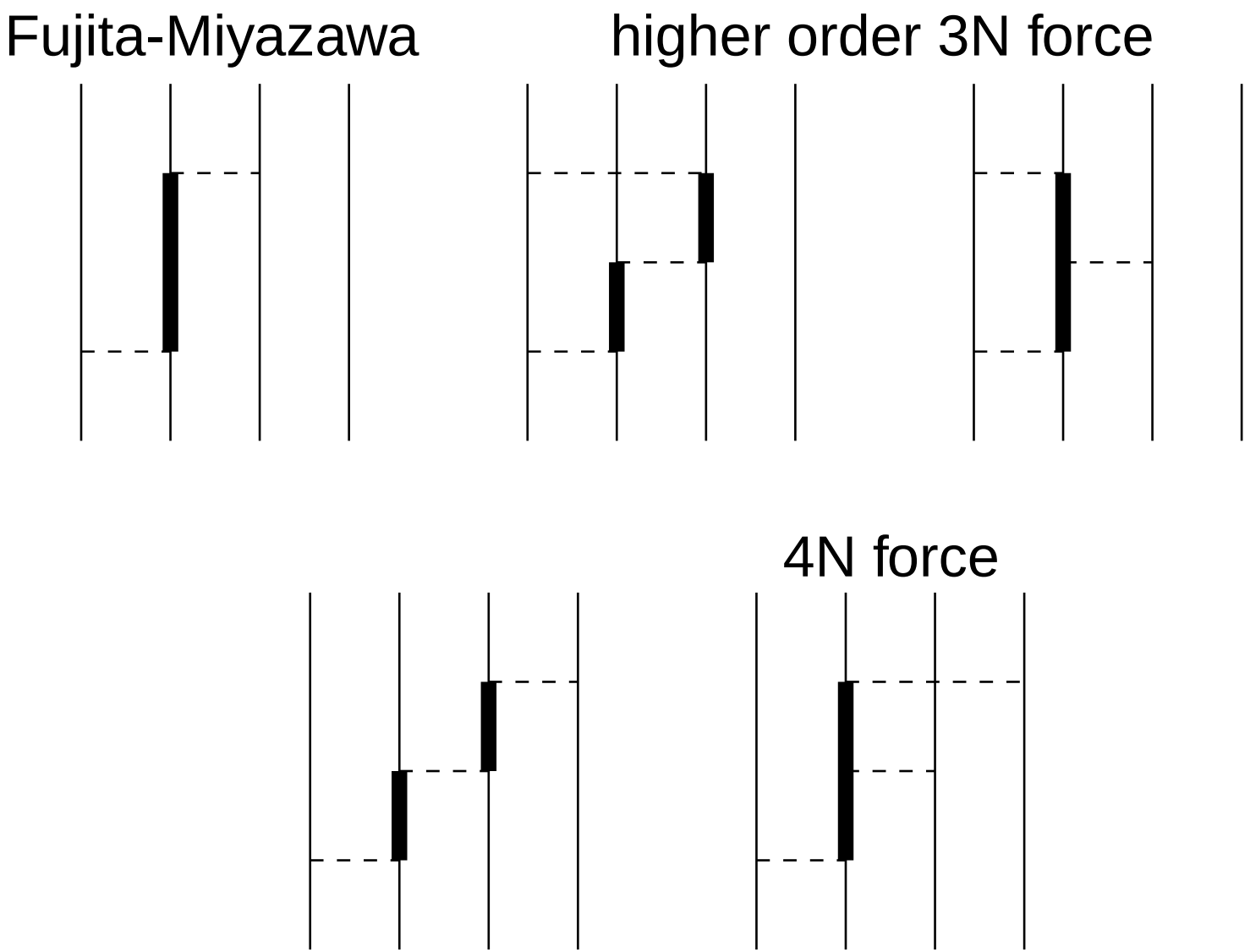


CD Bonn + Δ = 0

χ^2 / datum $= 1.02$ for NN scattering

dynamic assumption: no pionic channel, Δ without width
no irreducible many-baryon forces

effective and consistent 2N, 3N and 4N forces



interesting relation to shell model

- coupled-channel approach with Δ-isobar

  extension of nuclear Hilbert space yields effective many-nucleon interactions standing for genuine many-nucleon forces

- *ab initio* shell model

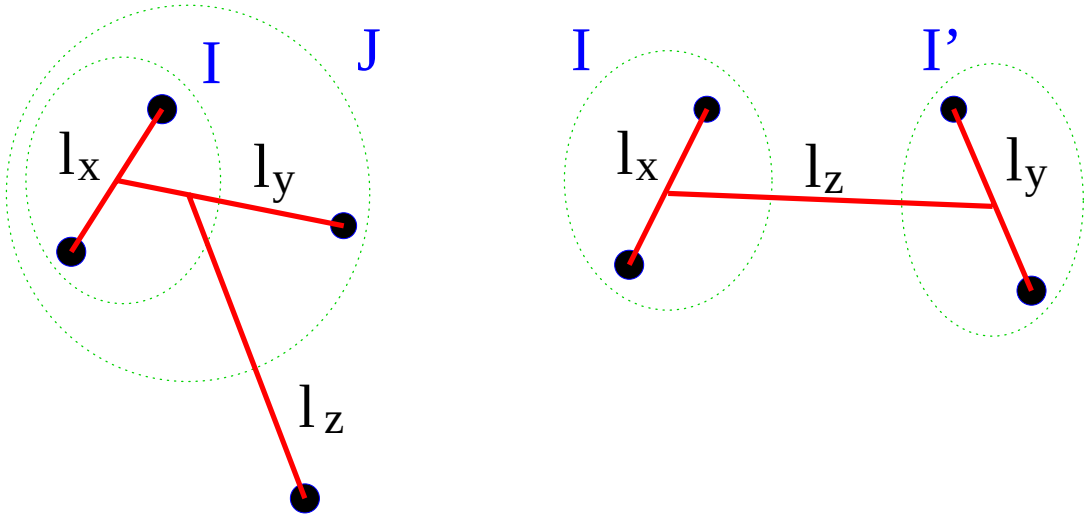
  truncation of nuclear Hilbert space yields effective many-nucleon interactions even without genuine many-nucleon forces

Technical Challenges

in Few-Body Calculations

Enormous

example 4N scattering



- momentum-space partial-wave basis
- set of coupled integral equations in 3 variables
- kernel full of singularities, though integrable

numerical methods

- Gaussian integration
- spline interpolation
- up to 20000 partial waves,
  20 Gaussian points for each momentum
  $\Rightarrow$ system of $> 10^8$ linear equations,
  size of the kernel $> 10^8$ GB
- summing up double Neumann series by Padé method
  [*Phys. Rev. C 75, 014005 (2007)*]

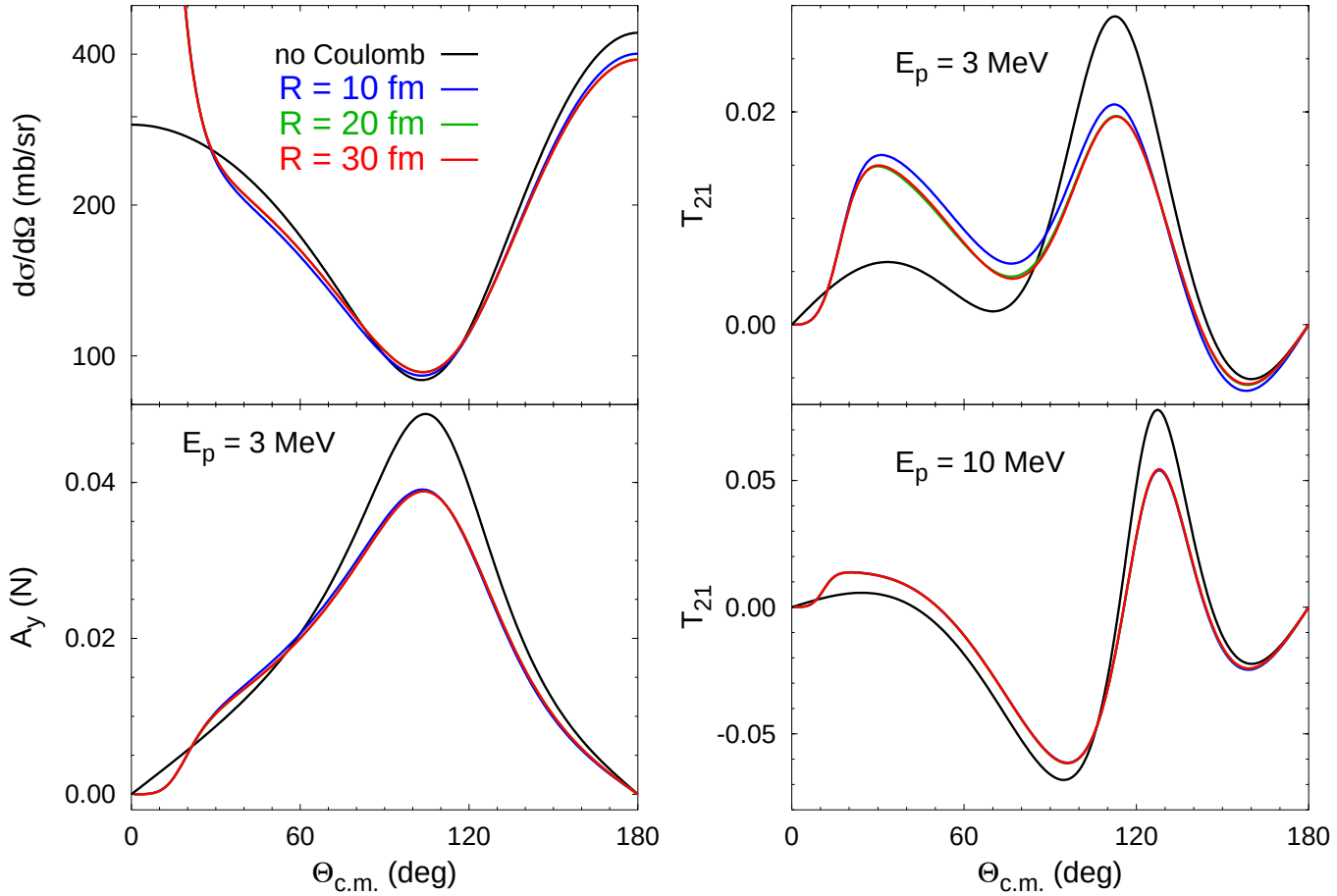
An Example for Nuclear Theory in the Supercomputing Era?

Coulomb Problem in Scattering

- experimentalists love reactions with charged particles - rich amount of accurate data
- Coulomb interaction hides nuclear dynamics and symmetries, e.g., charge asymmetry
- Coulomb interaction is nightmare for theorists

screening and renormalization works beautifully

example *pd* elastic: convergence with screening radius



our technical limitation: numerically too awkward in keV-neighbourhood of thresholds

Results for 3N and 4N Systems

3N and 4N bound states: binding

	^{3}H	^{3}He	^{4}He
CD Bonn	8.00	7.26	26.18
CD Bonn + Δ	8.28	7.54	27.10
exp	8.48	7.72	28.30
ΔE_2	-0.51	-0.48	-2.80
ΔE_3(FM)	0.50	0.48	2.25
ΔE_3(h.o.)	0.29	0.28	1.30
ΔE_4			0.17

excited ^{4}He states seen as resonances in 4N scattering

3N and 4N bound states: binding

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ΔE_4			**0.17**

4N-force effect much smaller than 3N-force effect

3N and 4N reactions

colour coding of results

CD Bonn + Δ

CD Bonn + Δ + Coulomb

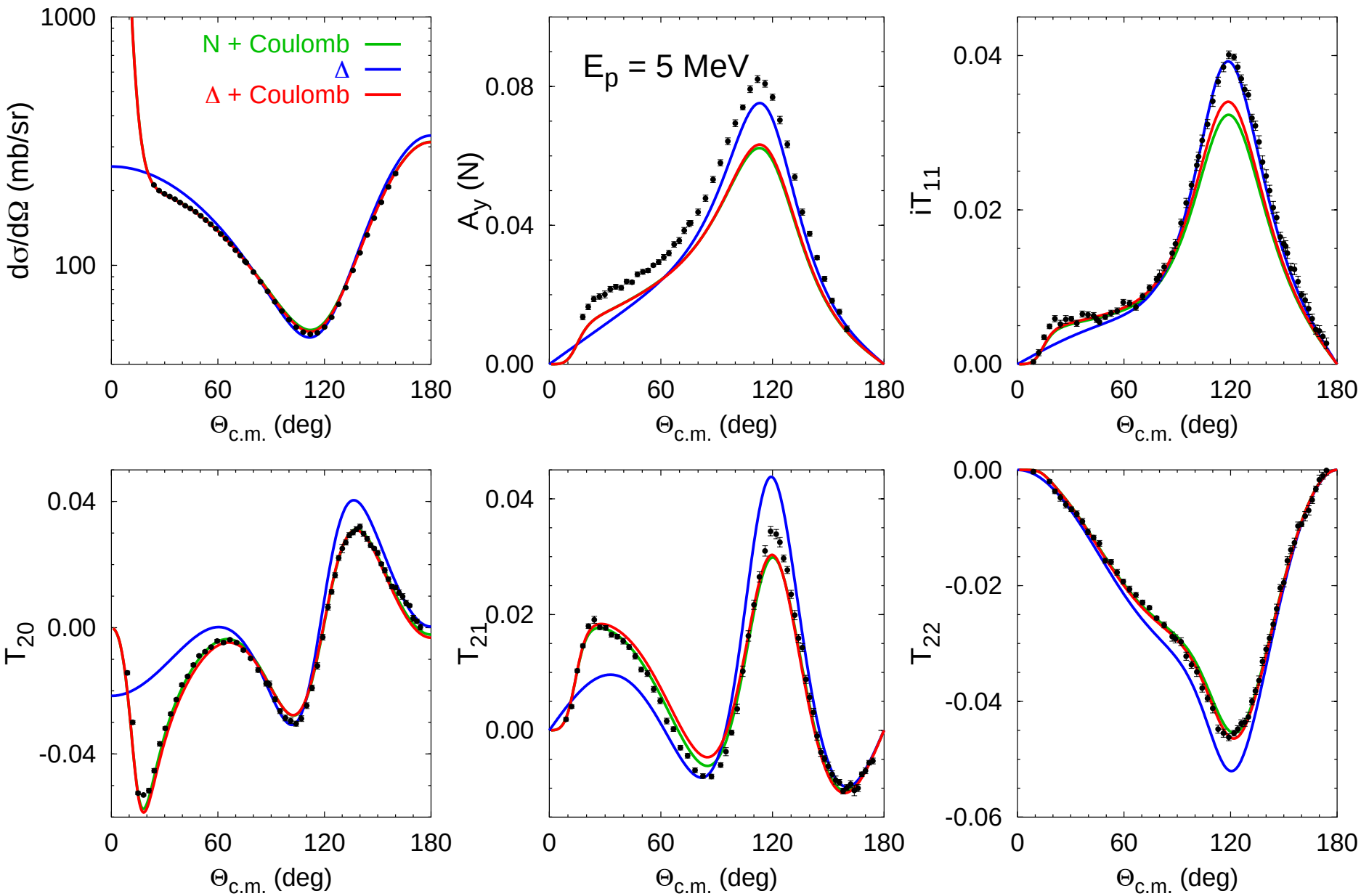
} Coulomb effect

CD Bonn + Coulomb

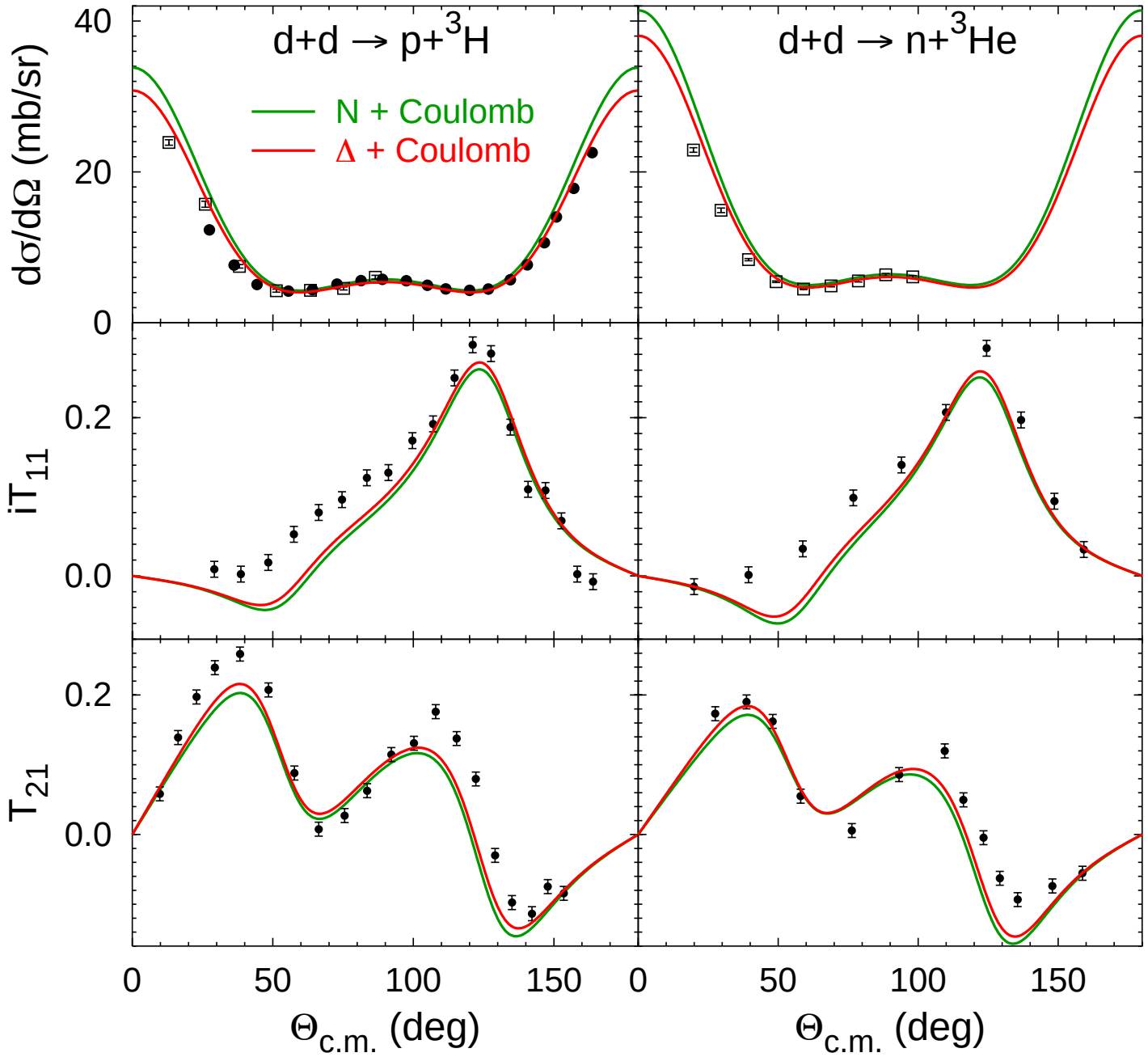
} 3N force effect

A. Deltuva, A.C. Fonseca and PUS, Annu.Rev.Nucl.Part.Sci. **58**, 27 (2008)

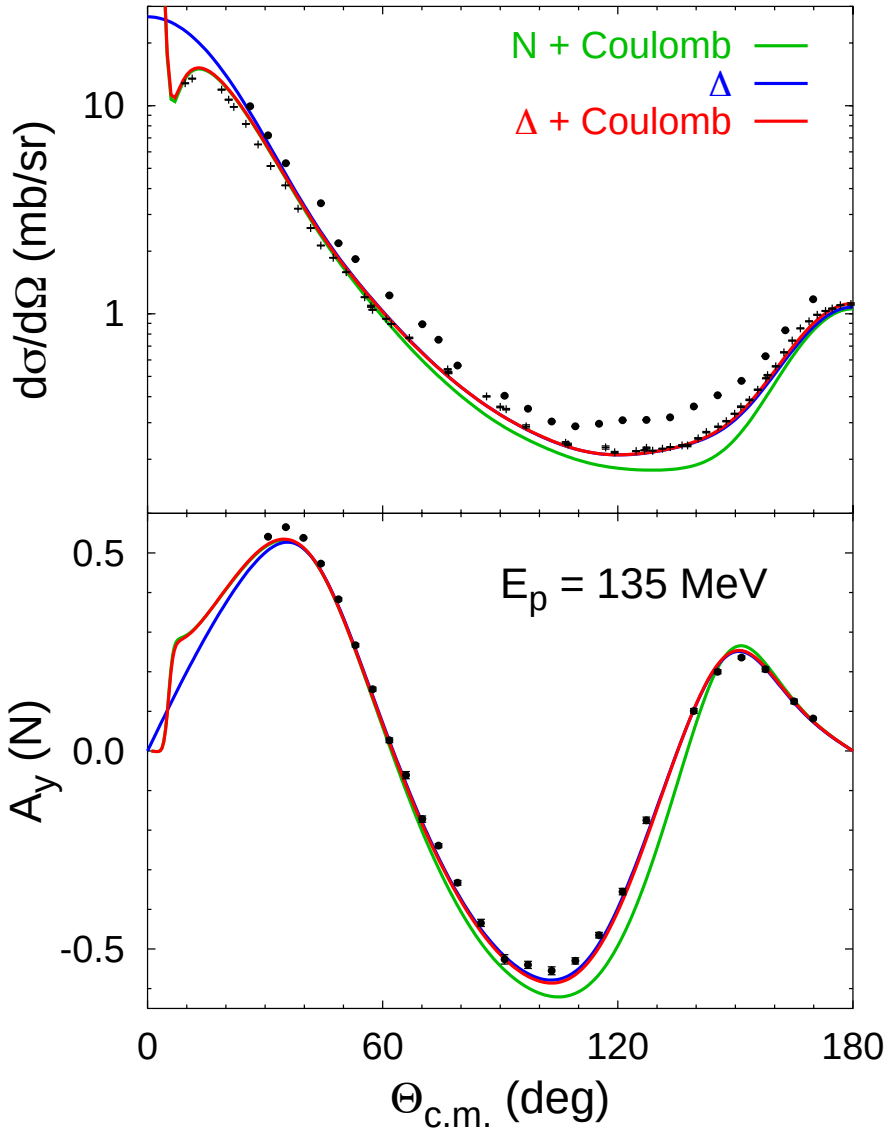
pd elastic scattering at low energies

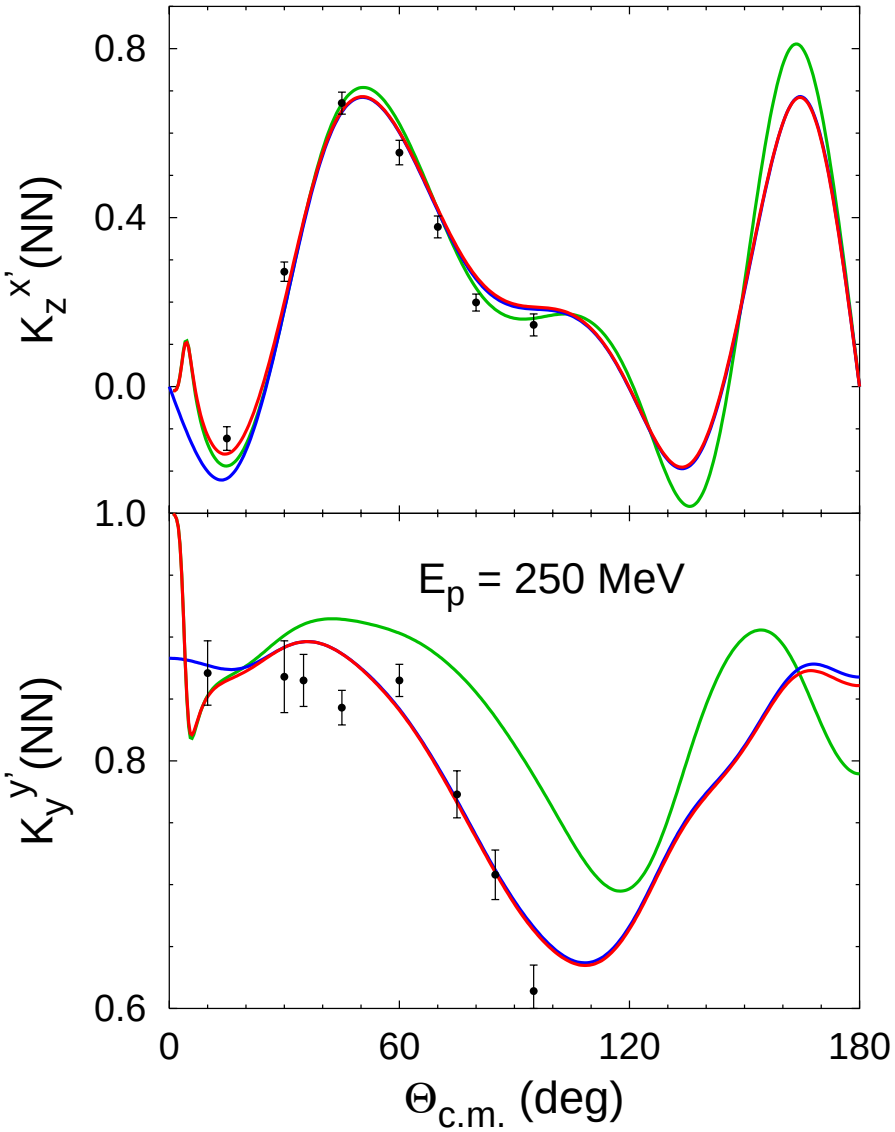


$d + d \rightarrow N + [3N]$ transfer at $E_d = 3$ MeV

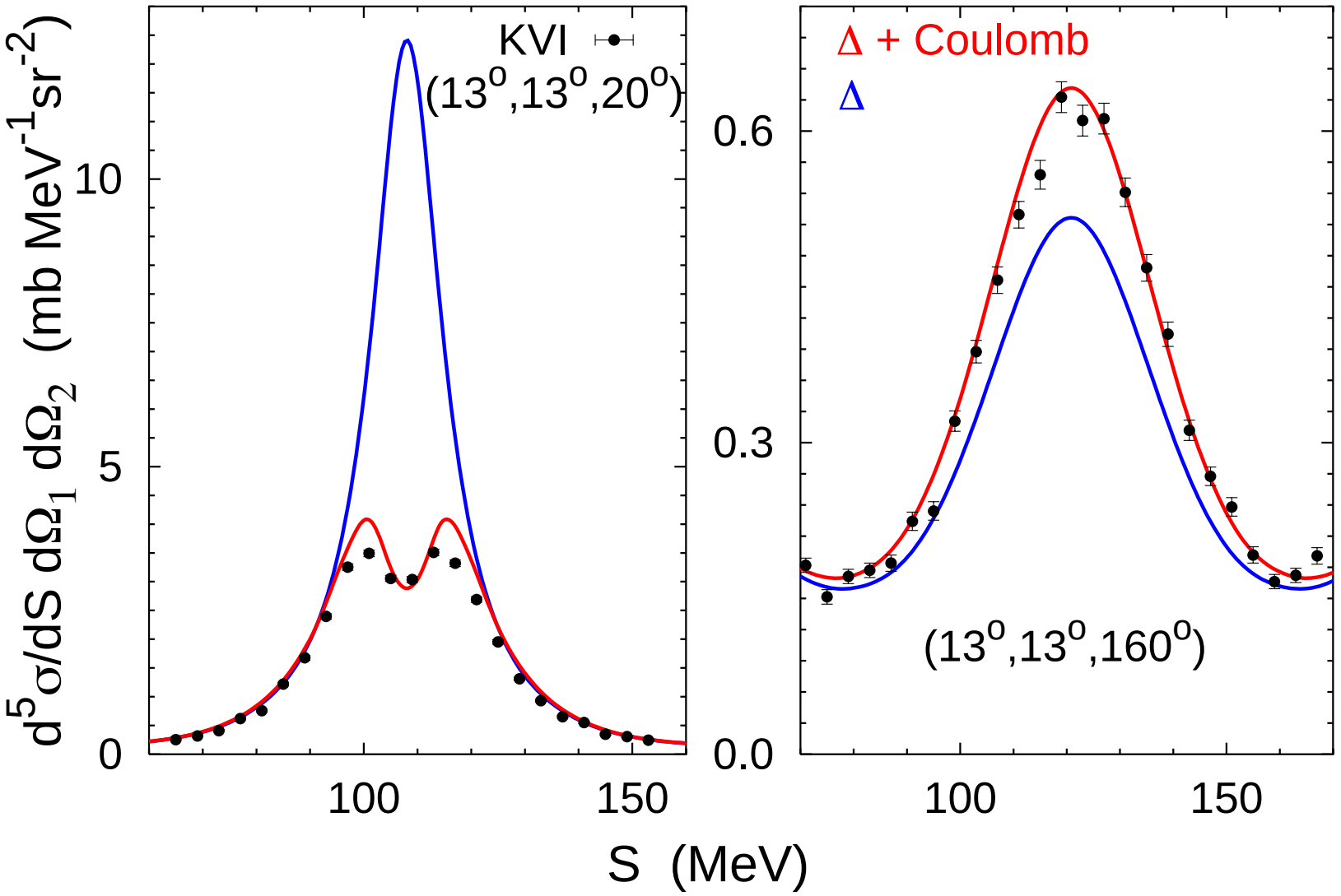


pd elastic scattering at higher energies





dp breakup at $E_d = 130$ MeV



What Have We Learnt?

Already 40 Years ago, before the Advent of Dedicated Research on Few-Nucleon Systems:

Bethe: *Never in history before was so much research energy ever spent on one scientific problem as on the two-nucleon interaction.*

What Have We Learnt?

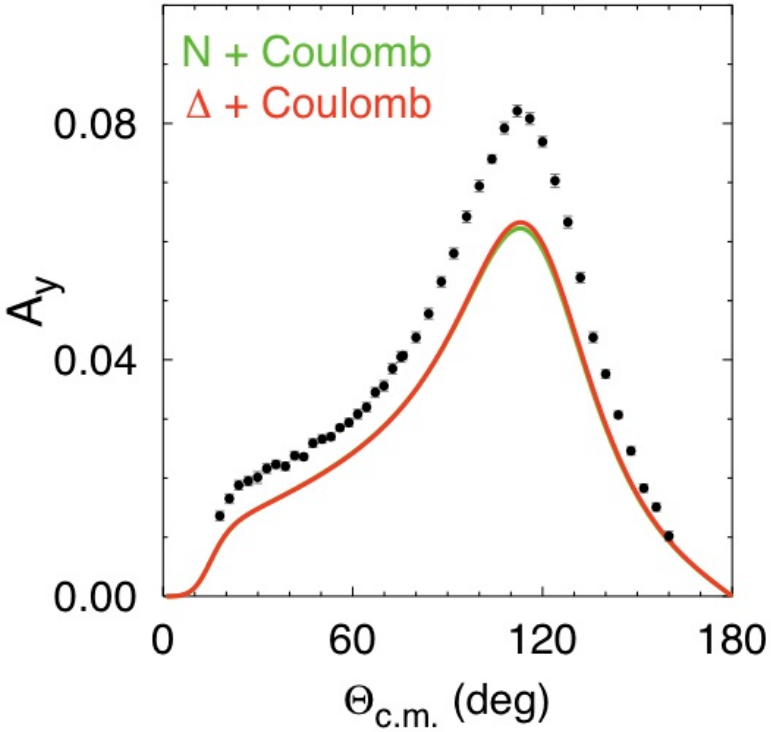
After 40 Years Research on Few-Nucleon Systems:

- large amount of 3N and 4N observables described well, Coulomb can be important
- 3N force needed for theoretical description of
  - bound states
  - thresholds and resonances in 4N scattering
  - 3N and 4N scattering at higher energies
- 4N force effects much smaller than 3N force effects
- despite successes, remaining questions

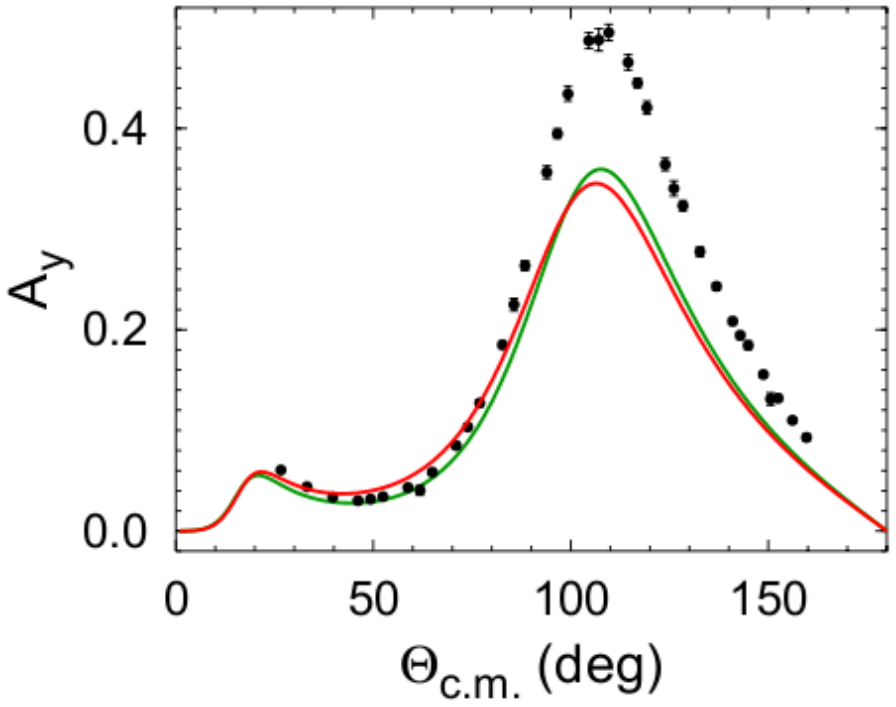
Remaining Questions

- discrepancies experiment/theory at low energies without clear hints for explanation: puzzles???

A_y problem in 3N and 4N scattering

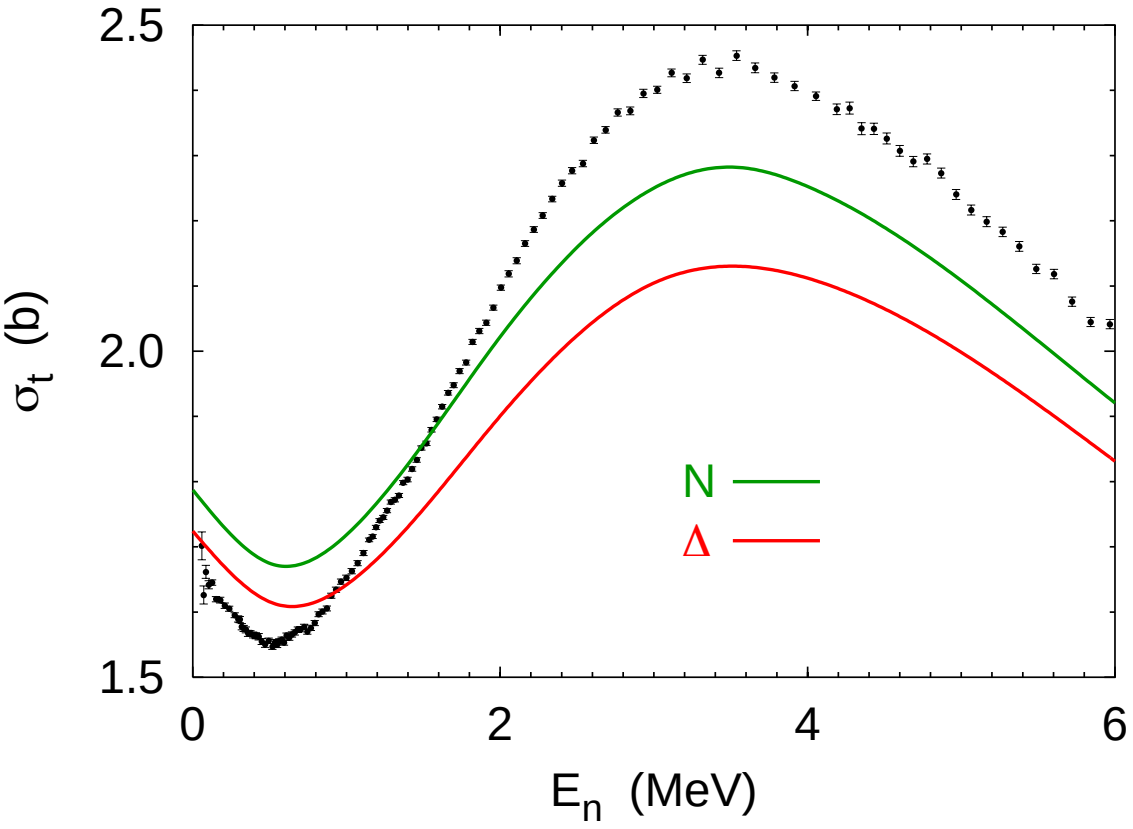


pd elastic scattering
E_p = 5 MeV



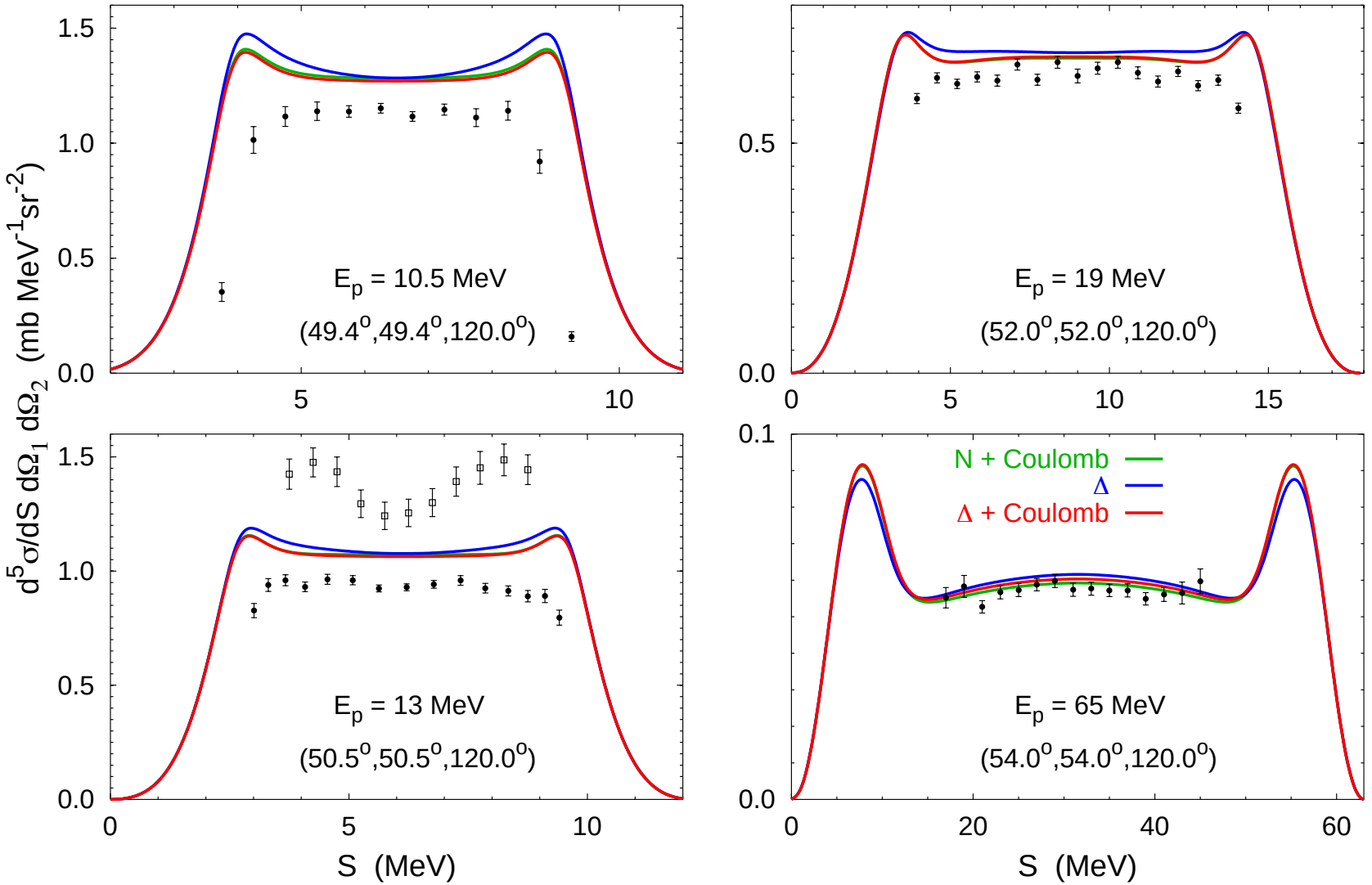
p^3He elastic scattering
E_p = 5.54 MeV

problem of total 4N cross sections



n^3H elastic scattering

problem of Nd breakup: space-star anomaly

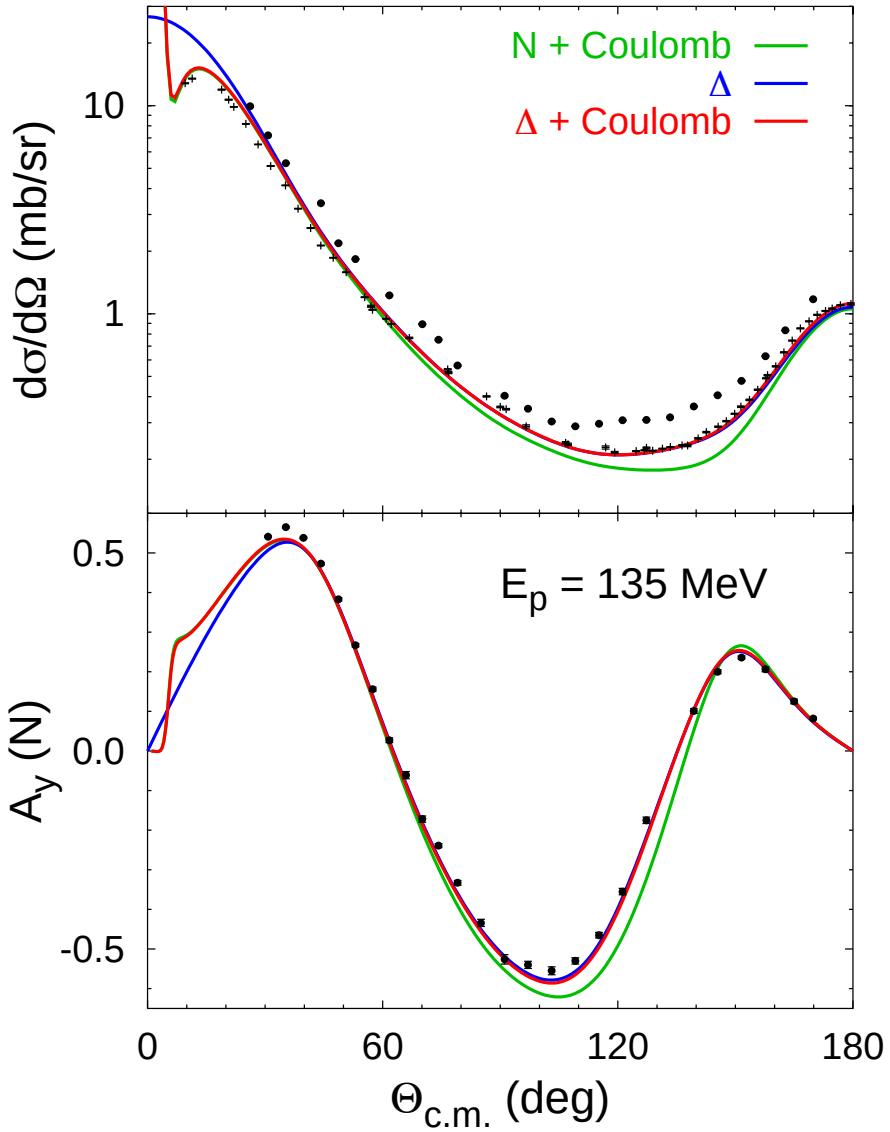


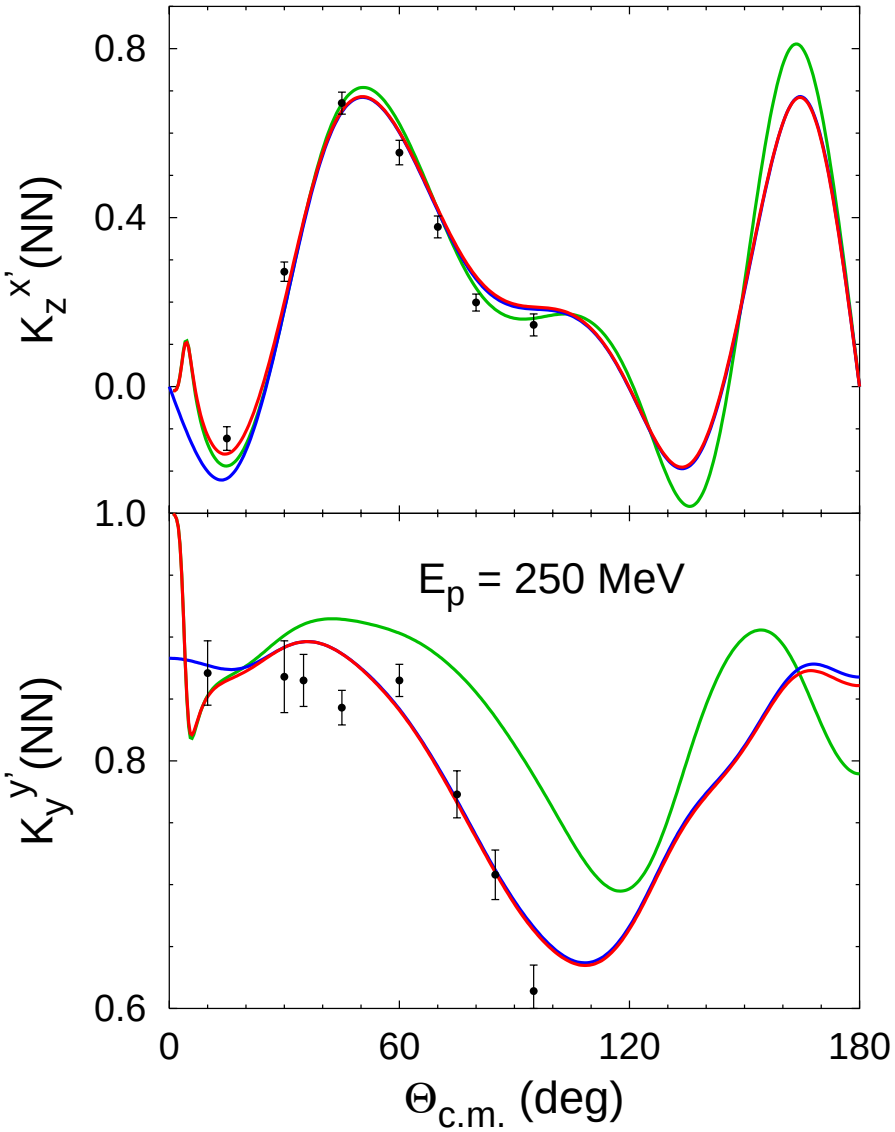
puzzle: large charge asymmetry?

Remaining Questions

- discrepancies experiment/theory at low energies without clear hints for explanation: puzzles???
- what is kinematics, what dynamics in the structure of observables?

pd elastic scattering at higher energies





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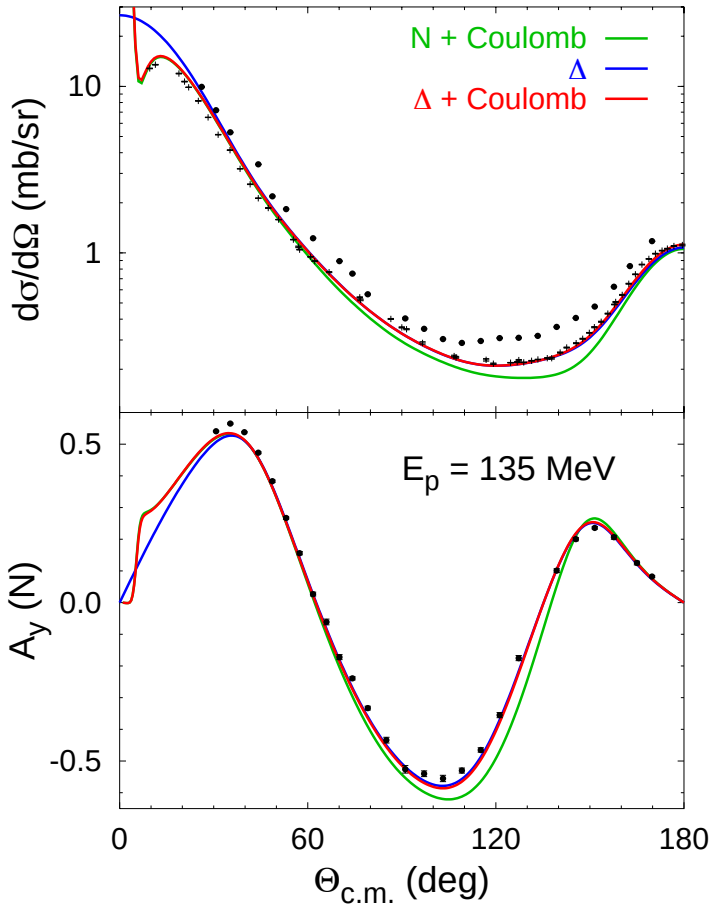
- how to ensure consistency of experimental data?

pd elastic scattering at higher energies



two inconsistent data sets in pd elastic scattering

in 2N scattering inconsistent data can be removed, NOT in 3N scattering

Remaining Questions

- discrepancies experiment/theory at low energies without clear hints for explanation: puzzles???
- what is kinematics, what dynamics in the structure of observables?
- how to ensure consistency of experimental data?
- how to extract detailed properties of many-nucleon forces from few-nucleon data?

Few-Nucleon Systems:

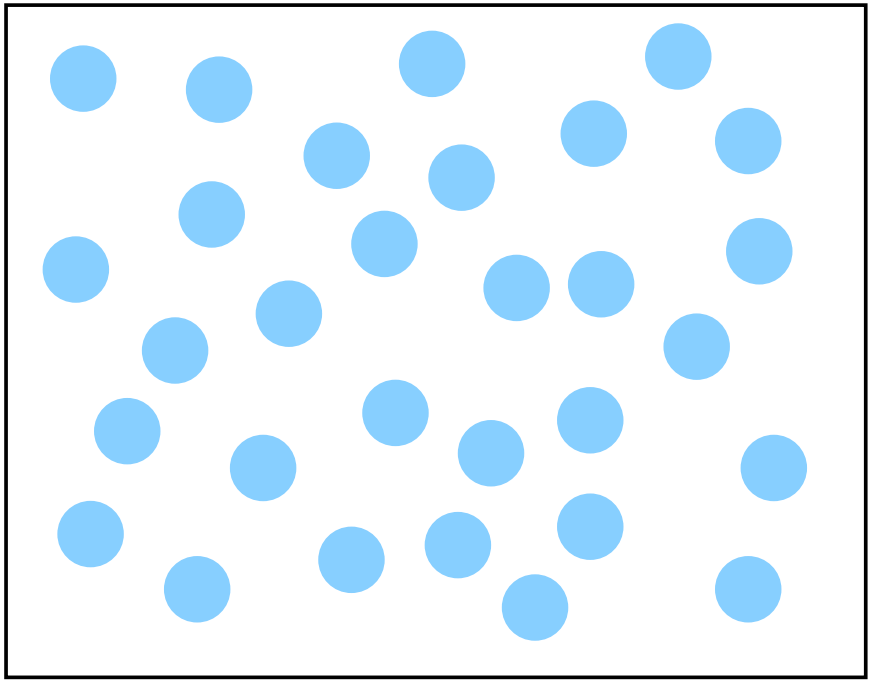
Testing OR Tuning Nuclear Dynamics?

ab initio OR *ab exitu?*

The Beautiful Bridges of Iowa

Bridge between Nuclear Structure and Few-Nucleon Systems?

Quantum Optics

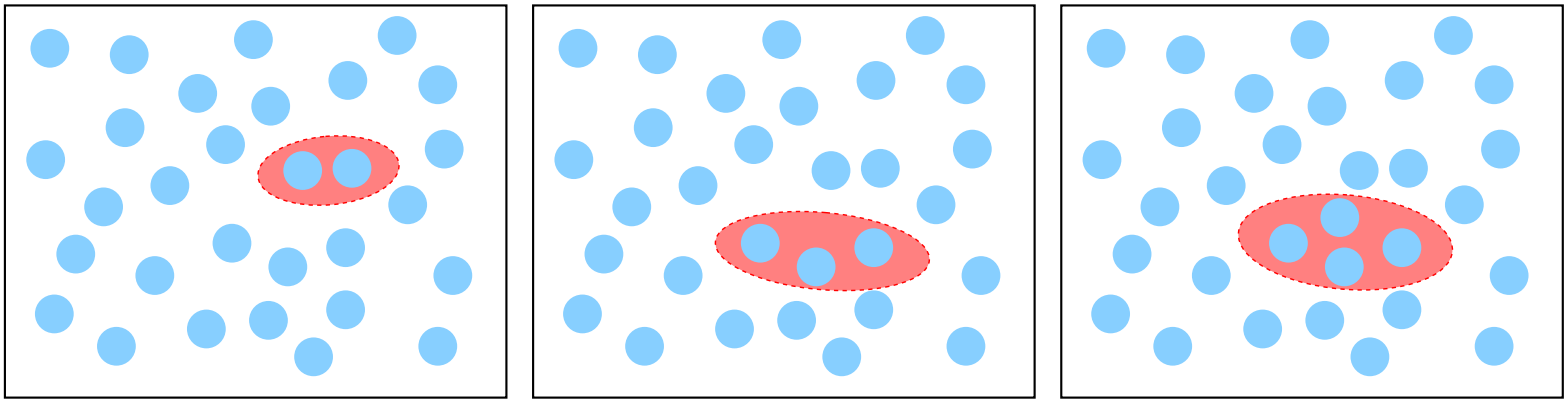


Atoms in Trap:

Atoms Move Freely Except for Trap Boundaries -

Reactions as in Free Space

Atoms in Trap

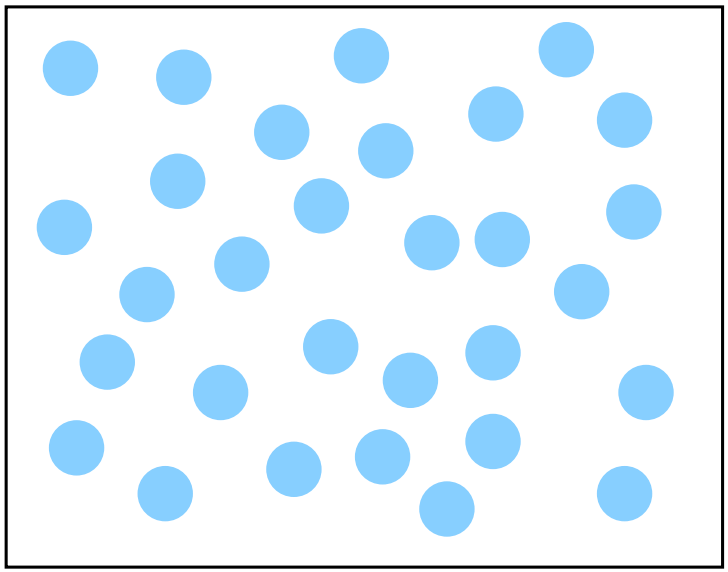


Reaction Rates: Loss of Atoms from Trap

2A Reaction 3A Reaction 4A Reaction + ?

Loss by Forming Bound States

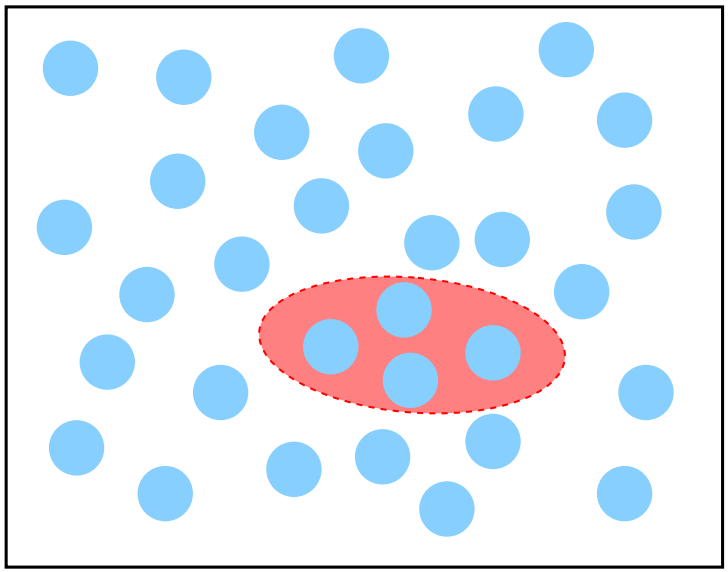
What is Special about Few-Body Reactions in Cold Atoms?



Interactions between

Atoms	Nucleons
Known and Tunable	Partially Unknown, but Fixed
Tunable to Efimov Regime	
Strong	Weak

What is Special about Few-Body Reactions in Cold Atoms?



Reactions with

Atoms

Nucleons

An Example - Time-Reversed Reactions - Calculations by Deltuva

$A + A + A + A \rightarrow t + A$

$N + {}^{3}H \rightarrow N + N + N + N$

Dear James, best wishes for a further successful future, wherever you may be!