Nuclear Two- and Many-Body Forces from Chiral EFT:

Current Status and Open Issues

R. Machleidt
University of Idaho

From the Program's web site

The program would address the following issues, among others:
1. Potentials:
The nature of the NN potential: CPT potentials vs empirical potentials.
Three-nucleon interactions, particularly those based on CPT.
The application of these NN and NNN potentials to nuclear-structure calculations.
Evidence for or against the need for higher-rank potentials, and, in particular, the possible importance of NNNN correlations in nuclei.
The modification of these potentials inside the nuclear medium, *i.e.*, what is the structure of the renormalized or effective interaction needed for nuclear-structure calculations, particularly for heavier nuclei?
2. Theoretical Issues:
Linkages among QCD, lattice gauge calculations, EFT/CPT and nuclear structure calculations.
Consistent treatment of regulators/cutoffs between the 2/3-body systems and the many-body systems.

Outline

- **History of microscopic nuclear structure**
- **Analyzing history: Where are we and what's left to do?**
- **QCD and nuclear physics**
- **The effective field theory approach to nuclear forces: 2N, 3N, 4N forces**
- **Summary and open issues**

History of microscopic nuclear structure

1958	Brueckner, Gammel Eden, Emery	Brueckner Theory	Gammel-Thaler potential	Nuclear matter Finite nuclei 16O

History of microscopic nuclear structure

1958	Brueckner, Gammel Eden, Emery	Brueckner Theory	Gammel-Thaler potential	Nuclear matter Finite nuclei ^{16}O
1966	Kuo, Brown	Brueckner Theory	Hamada-Johnston pot	Spectra of ^{18}O, ^{18}F
1965-1968	Becker, MacKellar; Davies, Baranger, …	Brueckner Hartree-Fock	Hamada-Johnston potential	^{16}O

Oak Ridge

History
of microscopic

1958	Brueckner, Gammel Eden, Emery	Brueckner Theory	Gammel-Thaler potential	Nuclear matter Finite nuclei 16O
1966	Kuo, Brown	Brueckner Theory	Hamada-Johnston pot	Spectra of 18O, 18F
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1973	Kuemmel, Zabolizky	Coupled Cluster	Reid pot.	4He, 16O
1970's	Decline in microscopic nuclear structure			

Oak Ridge

History

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1970's	Decline in microscopic nuclear structure			
1980's 1990's	Pandharipande, Pieper, Wiringa, Carlson	Variational, GFMC	Argonne V14, V18 pot., 3N forces	A<=10
1990's	Barrett, Vary, Navratil, …	No-Core Shell Model	High-precision pots.	A<=48
2000	Dean, Hjort-Jensen, Papenbrock,…	Coupled Cluster	High-precision pots.	A=16, A>16

Oak Ridge

Analyze history

Microscopic nuclear structure has two ingredients:

- many-body theory/method

- bare nuclear forces

Analyze history under these two aspects.

1958	Brueckner, Gammel Eden, Emery	Brueckner Theory	Gammel-Thaler potential	Nuclear matter Finite nuclei 16O
1966	…wn	Brueckner Theory	Hamada-Johnston pot	Spectra of 18O, 18F
1965- 1968	…r; …, …	Brueckner Hartree-Fock	Hamada-Johnston potential	16O
1973	…l, …y	Coupled Cluster	Reid pot.	4He, 16O
1970's				
1980's 1990's	…ande,	Variational, GFMC	Argonne V14, V18 pot., 3N forces	A<=10
199…	…, …	No-Core Shell Model	High-precision pots.	A<=48
2000	…n, Hjort-Jensen, Papenbrock,…	Coupled Cluster	High-precision pots.	A=16, A>16

Progress in many-body methods

1958	**Brueckner, Gammel** **Eden, Emery**	**Brueckner Theory**	**Gammel-Thaler potential**	**Nuclear matter** **Finite nuclei** **16**
1966	**Kuo, Brown**	**Brueckner Theory**	**Hamada-Johnston pot**	**Sp** **18**
1965-1968	**Becker, MacKellar;** **Davies, Baranger, …**	**Brueckner Hartree-Fock**	**Hamada-Johnston potential**	**16**
1973	**Kuemmel, Zabolizky**	**Coupled Cluster**	**Reid pot.**	**4H**
1970's				
1980's 1990's	**Pandharipande, Pieper, Wiringa, Carlson**	**Variational, GFMC**	**Argonne V14, V18 pot., 3N forces**	**A<**
1990's	**Barrett, Vary, Navratil, …**	**No-Core Shell Model**	**High-precision pots.**	
2000	**Dean, Hjort-Jensen, Papenbrock,…**	**Coupled Cluster**	**High-precision pots.**	**A=16,** **A>16**

Progress in nuclear forces

1958	Brueckner, Gammel Eden, Emery	Brueckner Theory	Gammel-Thaler potential	Nuclear matter Finite 16
1966	Kuo, Brown	Brueckner Theory	Hamada-Johnston pot	Sp 18
1965-1968	Becker, MacKellar; Davies, Baranger, …	Brueckner Hartree-Fock	Hamada-Johnston potential	16
1973	Kuemmel, Zabolizky	Coupled Cluster	Reid pot.	4H
1970's				
1980's 1990's	Pandharipande, Pieper, Wiringa, Carlson	Variational, GFMC	Argonne V14, V18 pot., 3N forces	A<
1990's	Barrett, Vary, Navratil, …	No-Core Shell Model	High-precision pots.	A
2000	Dean, Hjort-Jensen, Papenbrock,…	Coupled Cluster	High-precision pots.	A=1 A>16

Pure pheno-menology

in nuclear

Meson models

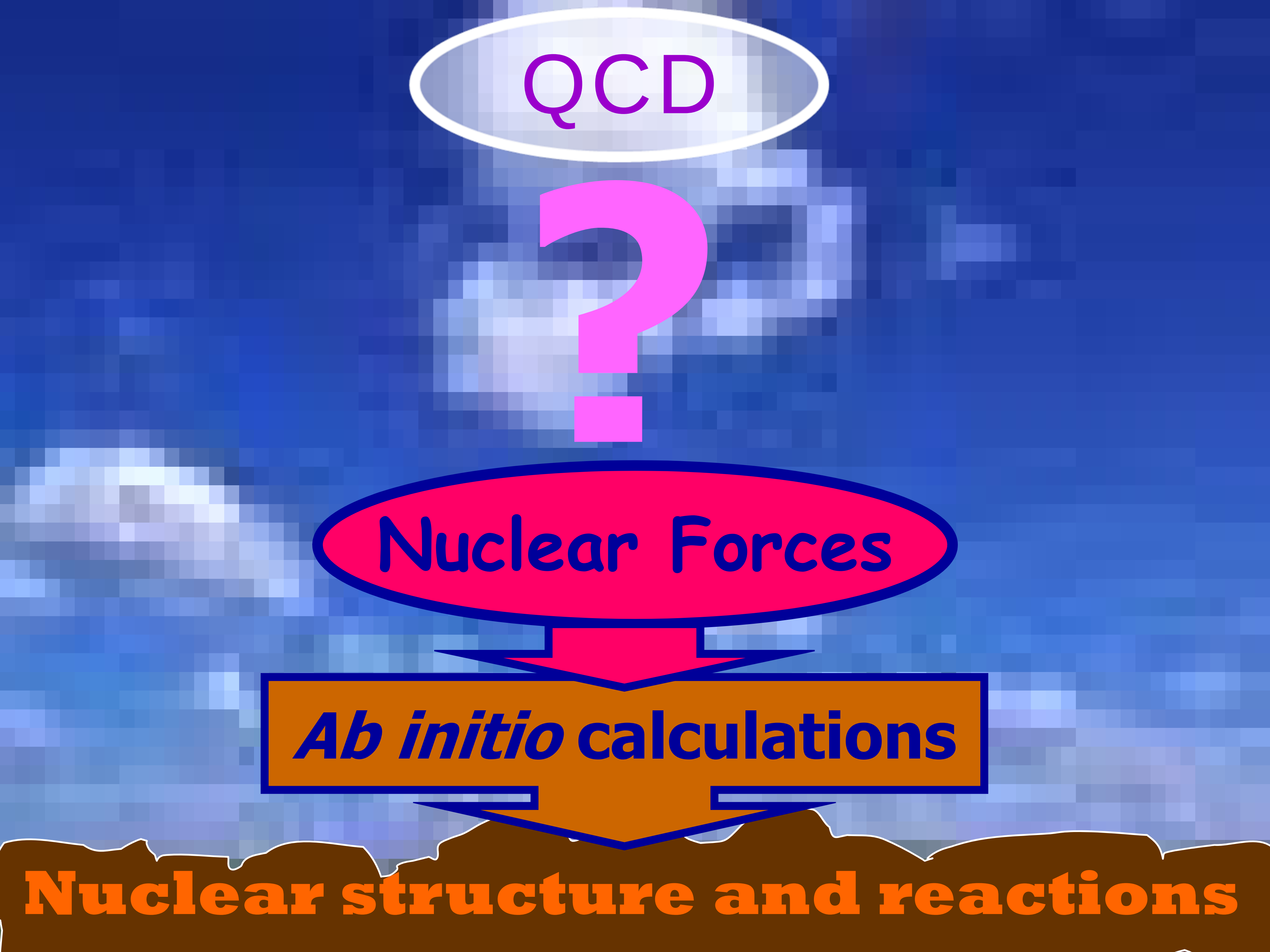
Was this good enough and are we done?

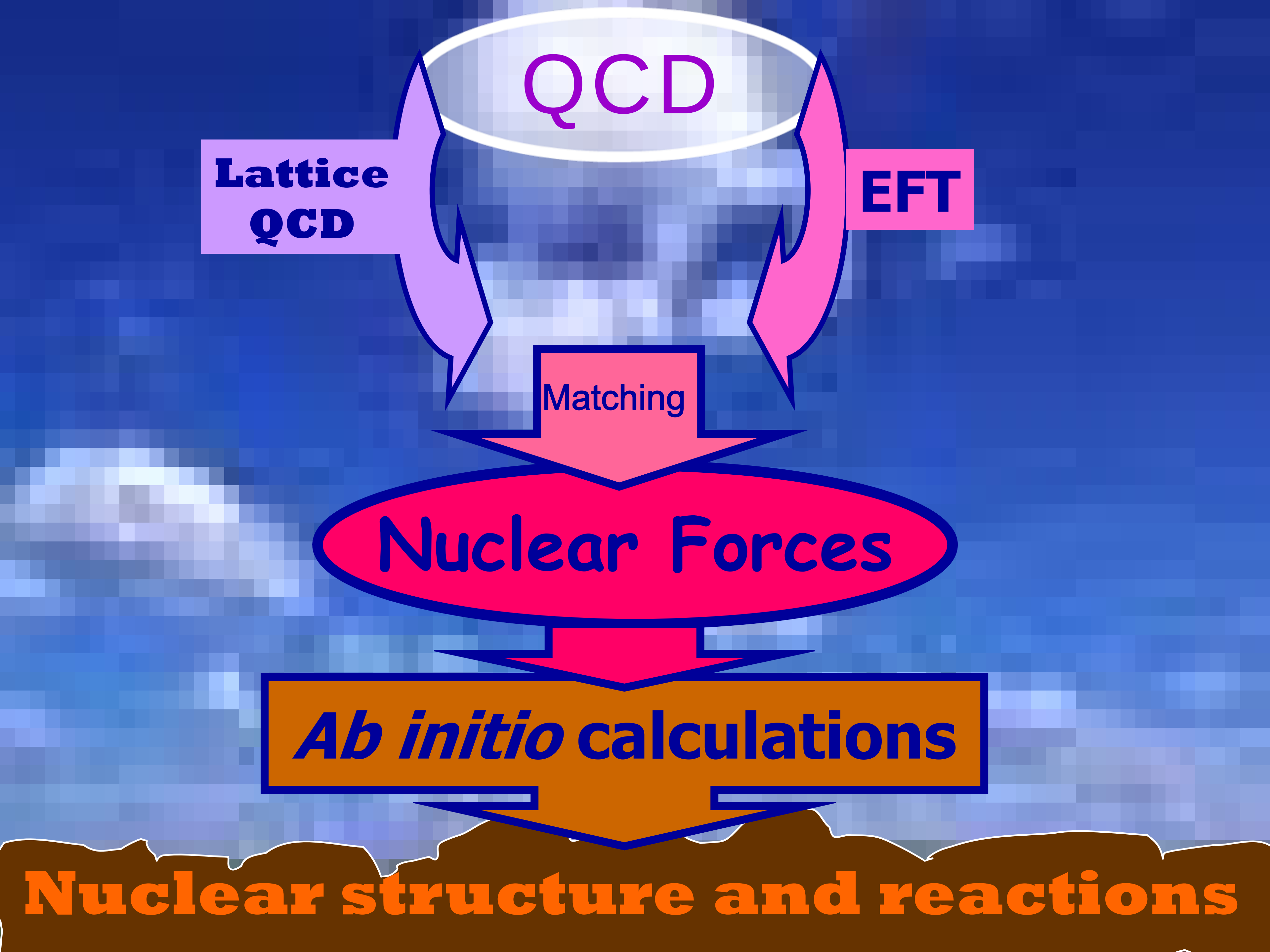
The most fundamental Physics question:

How does the world emerge from the Standard Model?

How does nuclear physics emerge from QCD?


QCD
?
Nuclear structure and reactions


QCD
?
Nuclear Forces
Ab initio calculations
Nuclear structure and reactions


QCD
Lattice QCD
EFT
Matching
Nuclear Forces
Ab initio calculations
Nuclear structure and reactions

Matching

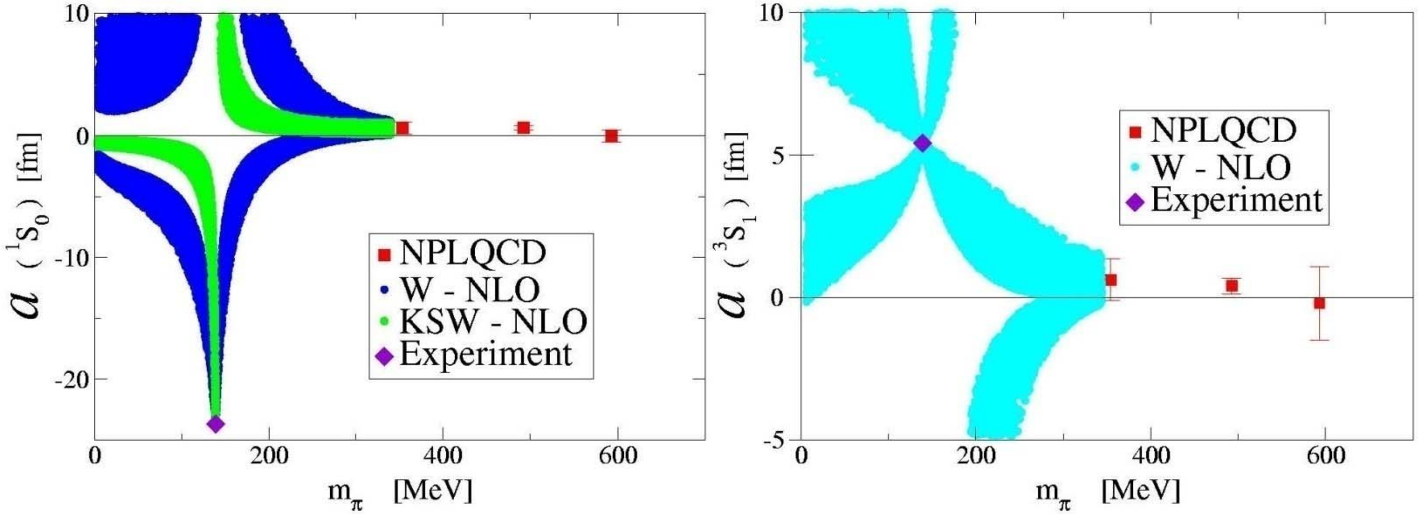


Fig. 4. Scattering lengths in the $^1S_0$ and $^3S_1 - ^3D_1$ NN channels as a function of pion mass. The experimental value of the scattering length and NDA have been used to constrain the extrapolation in both BBSvK [28,29,30] and W [31,32,33] power-countings at NLO.

The EFT approach

Notice first:
quarks and gluons are ineffective degrees of freedom at low energy.
Nuclear forces are residual forces between colorless objects.

- **Use the degrees which are relevant at nuclear physics energies: nucleons (and pions).**

- **Observe the symmetries of low-energy QCD and the patterns of their breaking: Symmetry generates and controls dynamics.**

The low-energy QCD scenario in the u- and d-quark sector is characterized by chiral symmetry; but this symmetry is broken in two ways:

- **explicitly broken,**

  because the u and d quark masses are not exactly zero;

- **spontaneously broken:**

  $$SU(2)_L \times SU(2)_R \simeq SU(2)_V \times SU(2)_A \longrightarrow SU(2)_V$$

  i.e., in the QCD ground state (hadron spectrum),
  axial symmetry is broken (no parity doublets),
  while isospin symmetry is intact (iso-spin multiplets).

- **There exist 3 Goldstone bosons: the pions**

The homework to be done:

- Write down the most general Lagrangian including **all** terms consistent with the assumed symmetries, particularly, spontaneously broken chiral symmetry. (Note: There will be infinitely many terms.)
- Calculate Feynman diagrams. (Note: There will be infinitely many diagrams.)
- Find a scheme for assessing the importance of the various diagrams (because we cannot calculate infinitely many diagrams).

The organizational scheme

"Power Counting"

Organize the contributions in terms of $\left(\frac{Q}{\Lambda}\right)^{\nu}$;

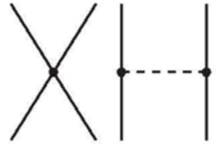
where Q denotes a momentum (derivative) or a pion mass (m_π);
Λ is the chiral symmetry breaking scale, $\Lambda \approx 1\,\text{GeV}$;
and $\nu \geq 0$.

⟷ **Chiral Perturbation Theory (ChPT)**

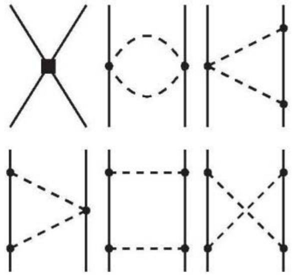
The Hierarchy of Nuclear Forces

		2N forces	3N forces	4N forces

Leading Order — Q^0 LO

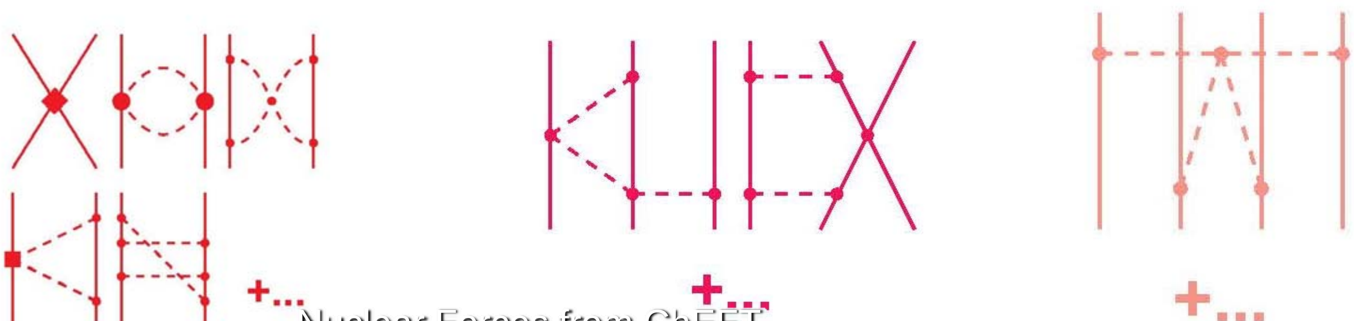


Next-to Leading Order — Q^2 NLO



Next-to-Next-to Leading Order — Q^3 N^{2}LO

Next-to-Next-to-Next-to Leading Order — Q^4 N^{3}LO



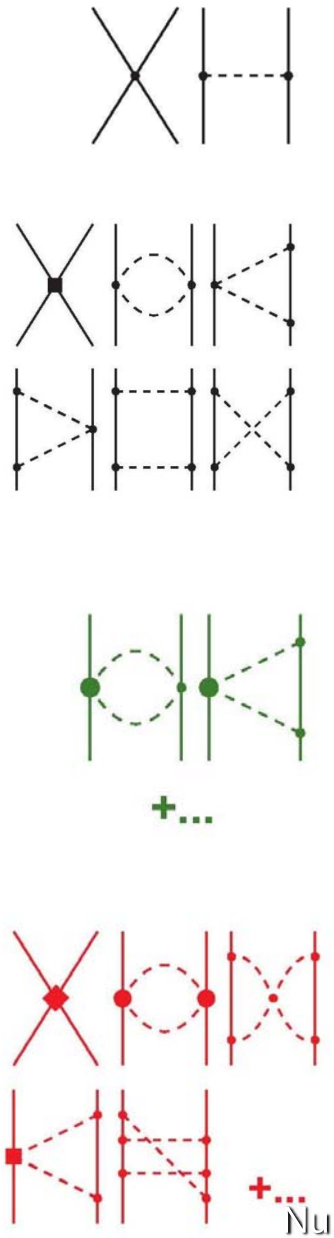
2N forces

Leading Order — Q^0 LO

Next-to Leading Order — Q^2 NLO

Next-to-Next-to Leading Order — Q^3 N^2LO

Next-to-Next-to-Next-to Leading Order — Q^4 N^3LO



The Hierarchy of Nuclear Forces

What order do we need for sufficient precision?

Believe it or not,
in answering this question,
the phenomenological
high-precision potentials
of the 1990's can help us here.

How many parameters do we need?

NUMBER OF PARAMETERS
for the np potential

	Nijmegen PWA93	CD-Bonn "high precision"	NLO Q^2 (NNLO)	N^3LO Q^4 (N^4LO)	N^5LO Q^6
$^1S_0$	3	4	2	4	6
$^3S_1$	3	4	2	4	6
$^3S_1$-$^3D_1$	2	2	1	3	6
$^1P_1$	3	3	1	2	4
$^3P_0$	3	2	1	2	4
$^3P_1$	2	2	1	2	4
$^3P_2$	3	3	1	2	4
$^3P_2$-$^3F_2$	2	1	0	1	3
$^1D_2$	2	3	0	1	2
$^3D_1$	2	1	0	1	2
$^3D_2$	2	2	0	1	2
$^3D_3$	1	2	0	1	2
$^3D_3$-$^3G_3$	1	0	0	0	1
$^1F_3$	1	1	0	0	1
$^3F_2$	1	2	0	0	1
$^3F_3$	1	2	0	0	1
$^3F_4$	2	1	0	0	1
$^3F_4$-$^3H_4$	0	0	0	0	0
$^1G_4$	1	0	0	0	0
$^3G_3$	0	1	0	0	0
$^3G_4$	0	1	0	0	0
$^3G_5$	0	1	0	0	0
Total	35	38	9	24	50

χ^2/datum for the reproduction of the 1999 *np* database

Energy range (MeV)	# of data	*Bochum/Juelich* NLO	NNLO
0–100	1058	4–5	1.4–1.9
100–190	501	77–121	12–32
190–290	843	140–220	25–69
0–290	2402	67–105	12–27

Conclusion:

At least, N3LO is needed

Entem & Machleidt, PLB **524, 93 (2002)**

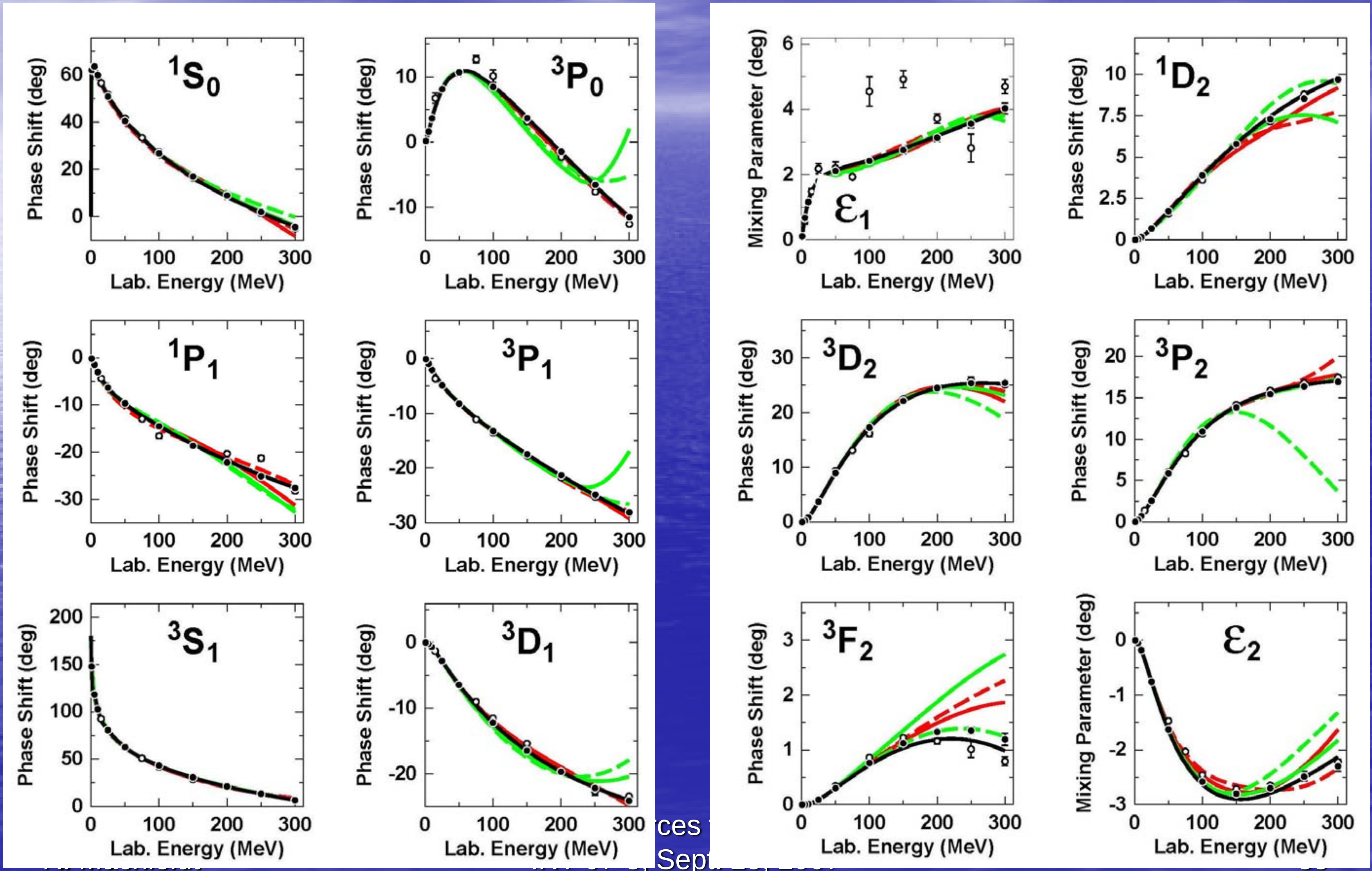
χ^2/datum for the reproduction of the 1999 *np* database

Energy range (MeV)	# of data	Idaho N^3LO (500–600)	Bochum/Juelich N^3LO (600/700–450/500)	Argonne V18
0–100	1058	1.0–1.1	1.0–1.1	0.95
100–190	501	1.1–1.2	1.3–1.8	1.10
190–290	843	1.2–1.4	2.8–20.0	1.11
0–290	2402	1.1–1.3	1.7–7.9	1.04

χ^2/datum for the reproduction of the 1999 *pp* database

Energy range (MeV)	# of data	Idaho N^{3}LO (500–600)	Bochum/Juelich N^{3}LO (600/700–450/500)	Argonne V18
0–100	795	1.0–1.7	1.0–3.8	0.96
100–190	411	1.5–1.9	3.5–11.6	1.31
190–290	851	1.9–2.7	4.3–44.4	1.82
0–290	2057	1.5–2.1	2.9–22.3	1.38

red = Idaho N3LO, green = Juelich N3LO, black = CD-Bonn



PHYSICAL REVIEW C **66**, 021303(R) (2002)

Microscopic nuclear structure based upon a chiral *NN* potential

L. Coraggio,[1] A. Covello,[1] A. Gargano,[1] N. Itaco,[1] T. T. S. Kuo,[2] D. R. Entem,[3,4] and R. Machleidt[3]
[1]*Dipartimento di Scienze Fisiche, Università di Napoli Federico II, Napoli, Italy*
and Istituto Nazionale di Fisica Nucleare, Complesso Universitario di Monte S. Angelo, Via Cintia, I-80126 Napoli, Italy

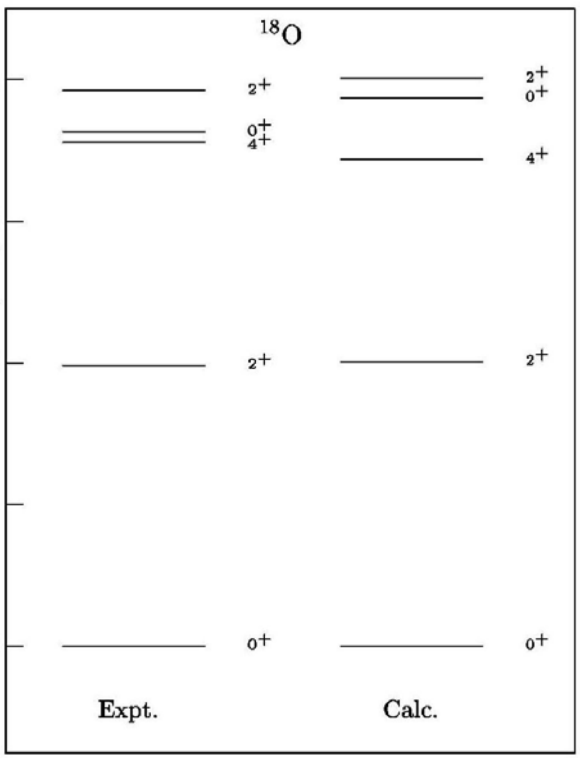


FIG. 1. Experimental and calculated spectra of ^{18}O.

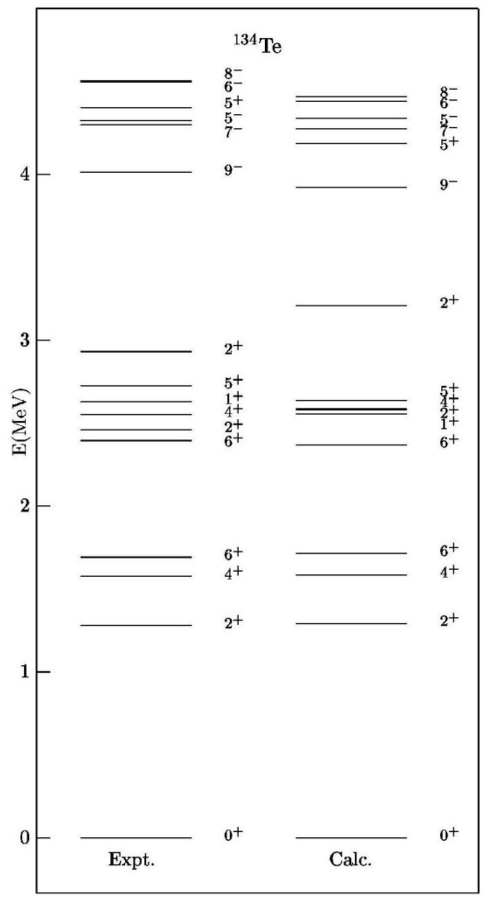


FIG. 2. Experimental and calculated spectra of ^{134}Te.

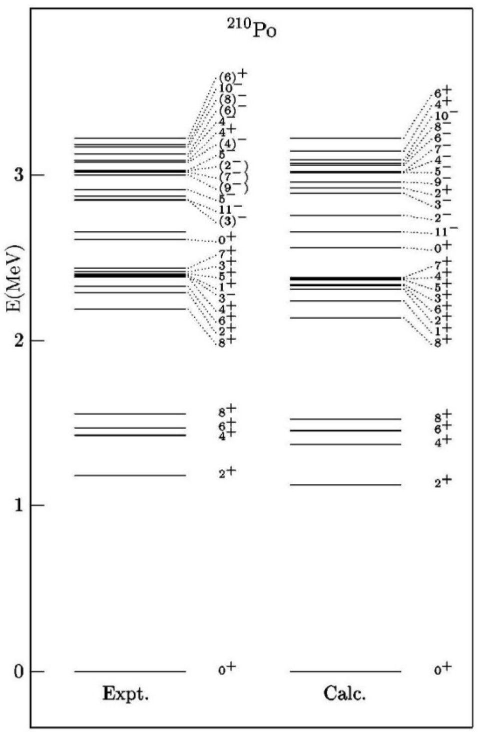


FIG. 3. Experimental and calculated spectra of ^{210}Po.

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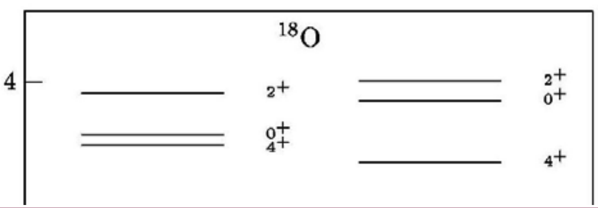
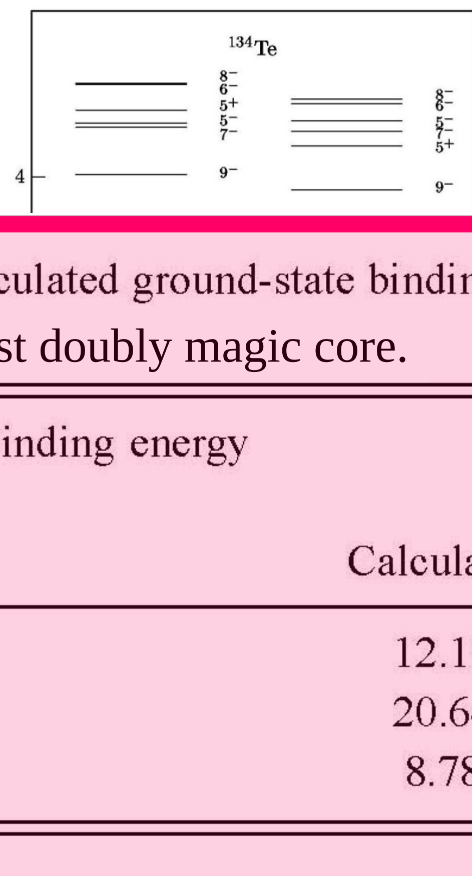




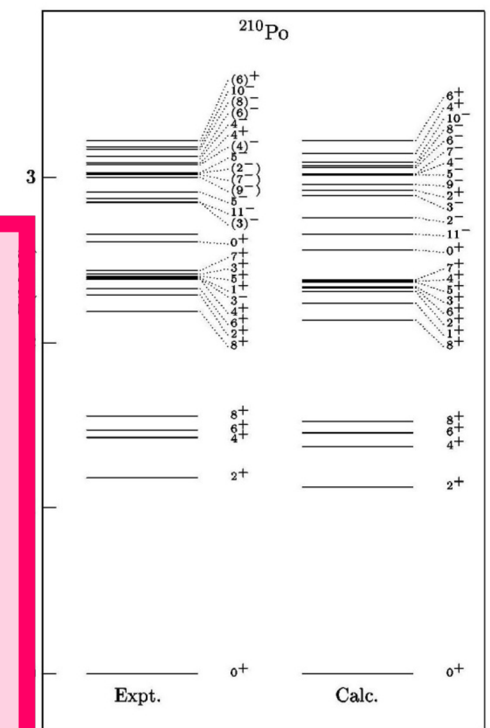


TABLE I. Experimental and calculated ground-state binding energies (MeV) relative to the closest doubly magic core.

Nucleus	Binding energy Experimental	Binding energy Calculated
^{18}O	12.19 ± 0.00	12.19
^{134}Te	20.56 ± 0.03	20.64
^{210}Po	8.78 ± 0.00	8.78

G. 3. Experimental and calculated spectra of ^{210}Po.

FIG. 2. Experimental and calculated spectra of ^{134}Te.

3N Forces

The Hierarchy of Nuclear Forces

2N forces

3N forces

Leading Order

Q^0
LO

Next-to Leading Order

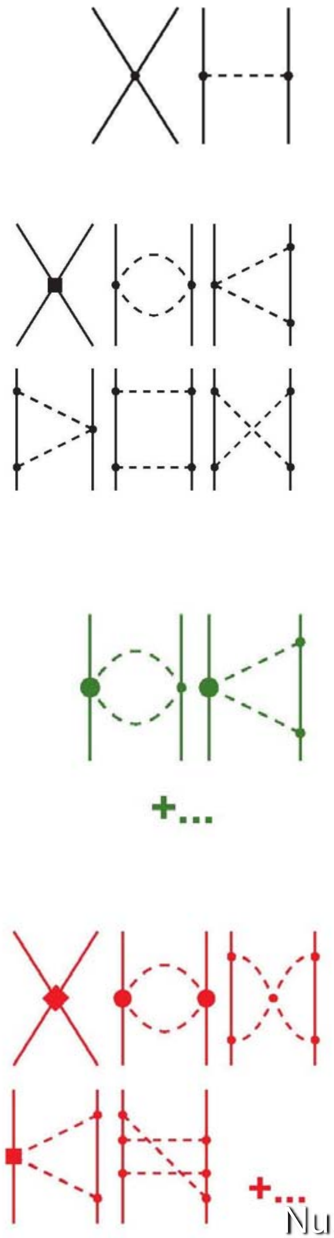
Q^2
NLO

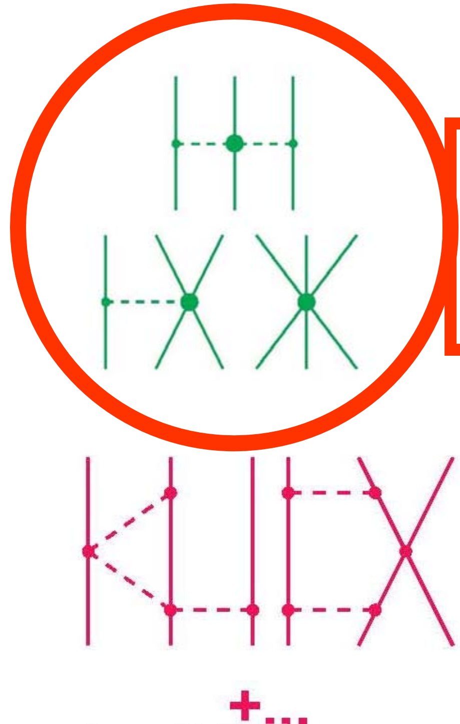
Next-to-Next-to Leading Order

Q^3
N^2LO

Next-to-Next-to-Next-to Leading Order

Q^4
N^3LO

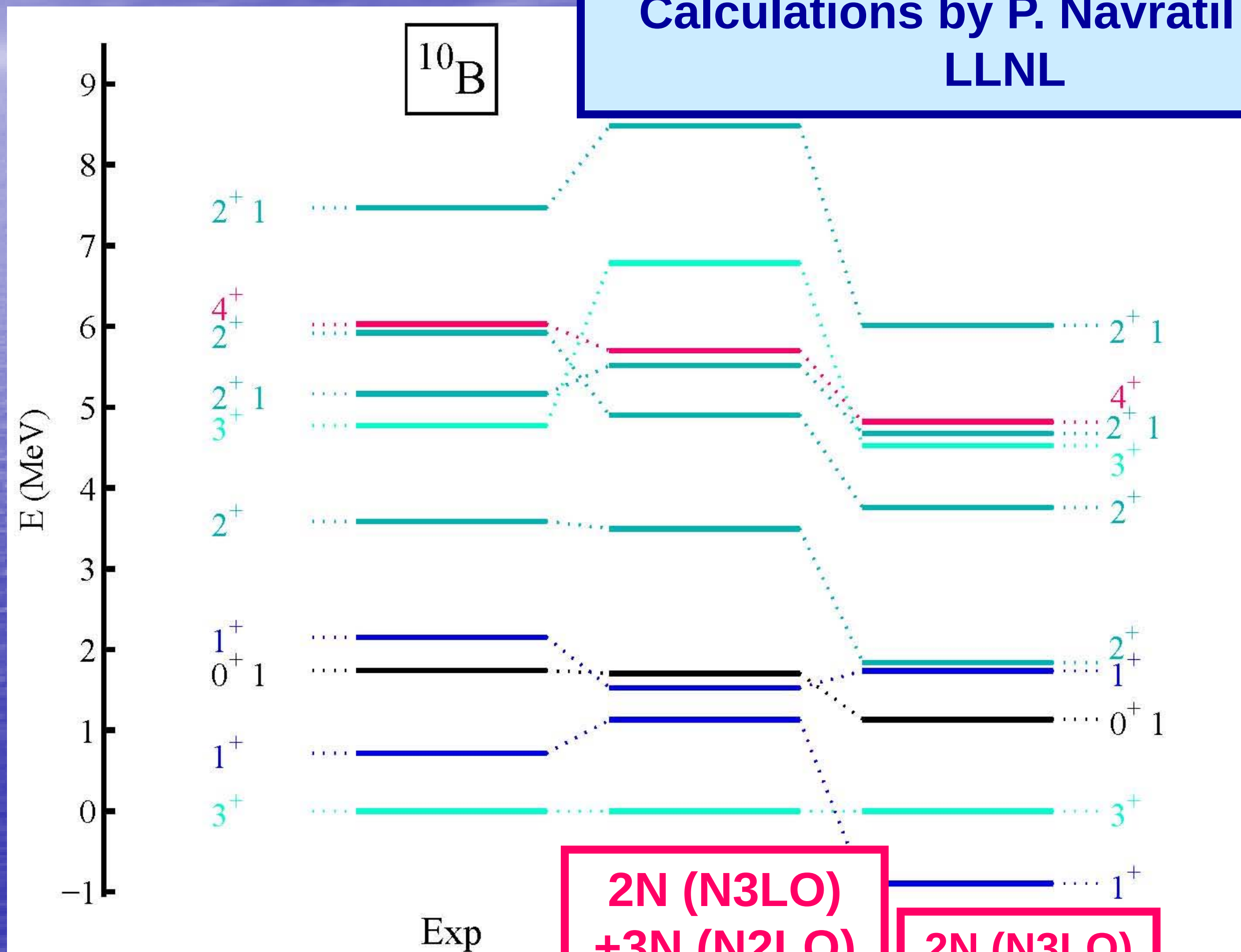




3NF at NNLO

Calculating the properties of light nuclei using chiral 2N and 3N forces

"No-Core Shell Model " Calculations by P. Navratil et al., LLNL

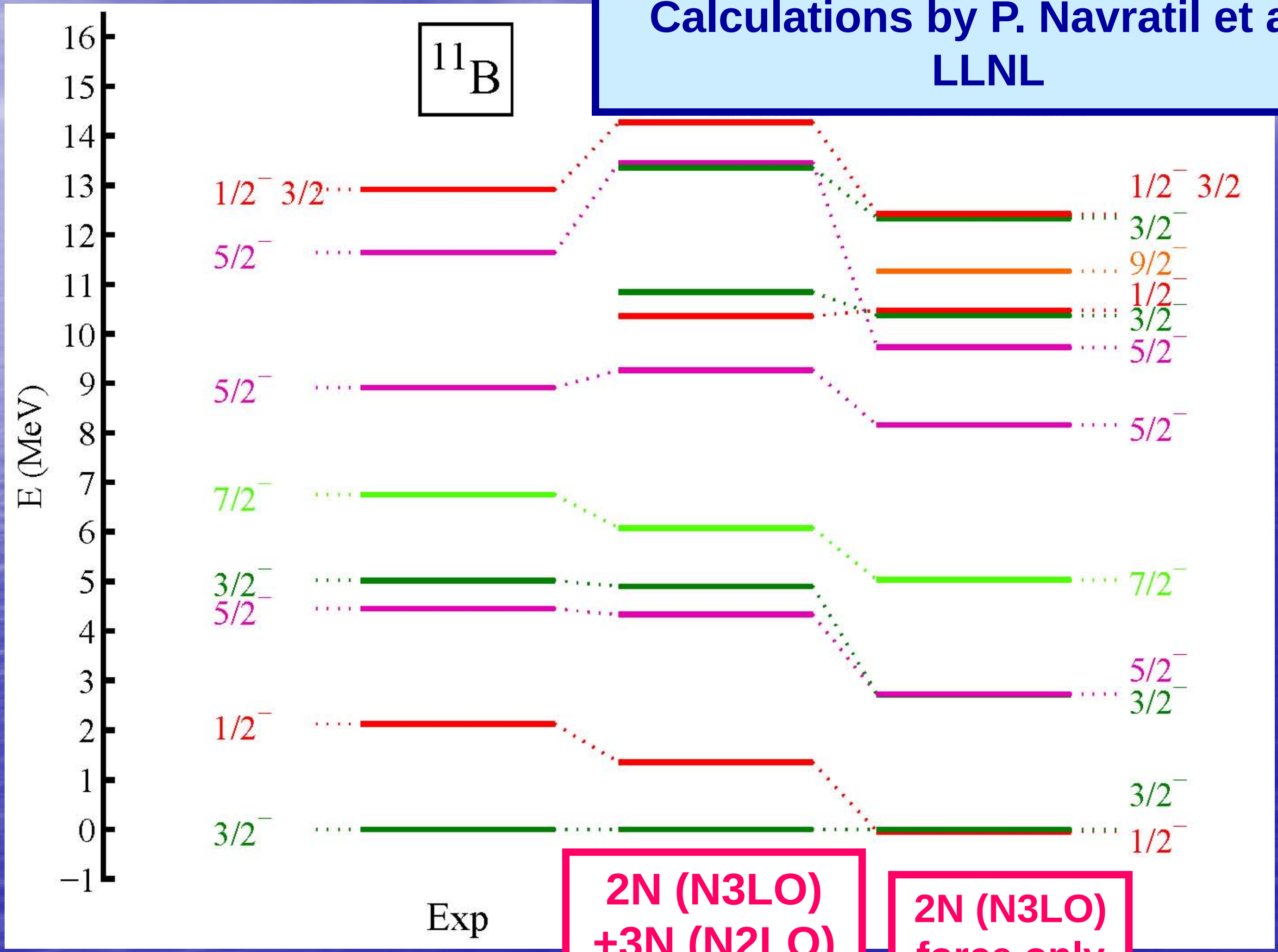


2N (N3LO) +3N (N2LO) forces

2N (N3LO) force only

Microscopic nuclear structure, cont’d

“No-Core Shell Model “ Calculations by P. Navratil et al., LLNL

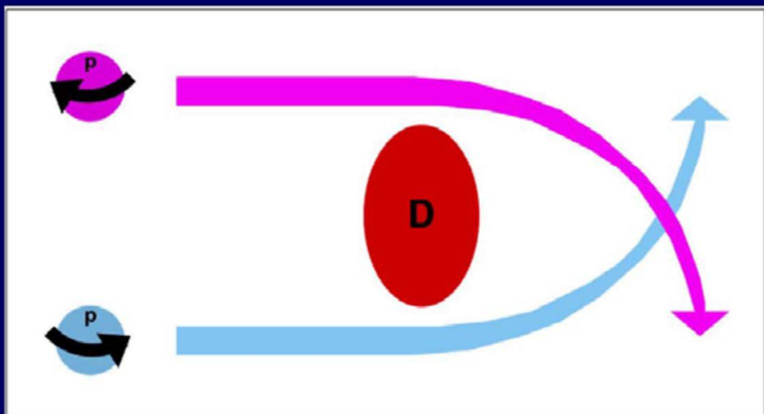


2N (N3LO) +3N (N2LO) forces

2N (N3LO) force only

The A_y puzzle at low energies

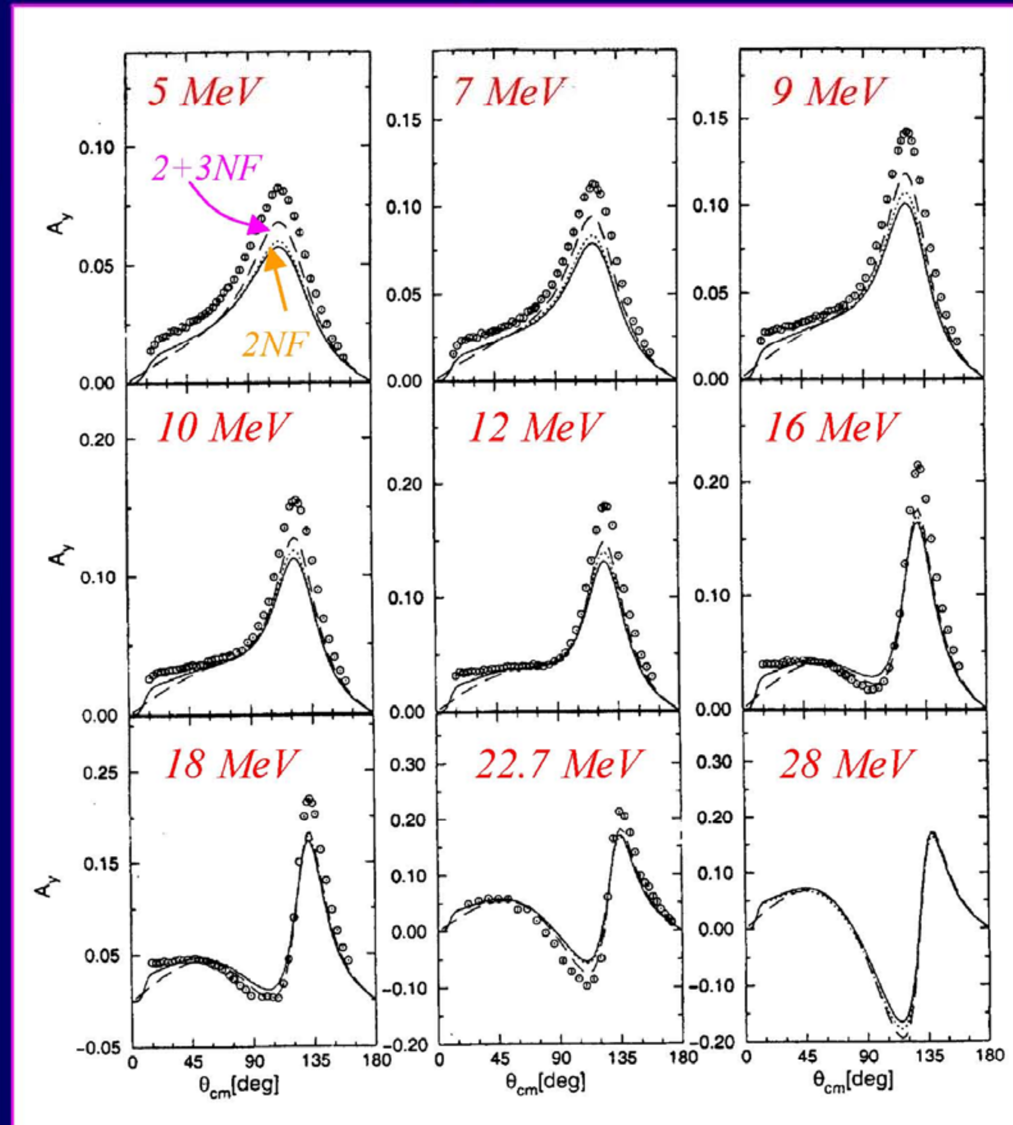
$$\vec{p} + d \rightarrow p + d$$



$$\sigma = \sigma_0(1 + pA_y\cos\phi)$$

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

Calculations by Pisa group

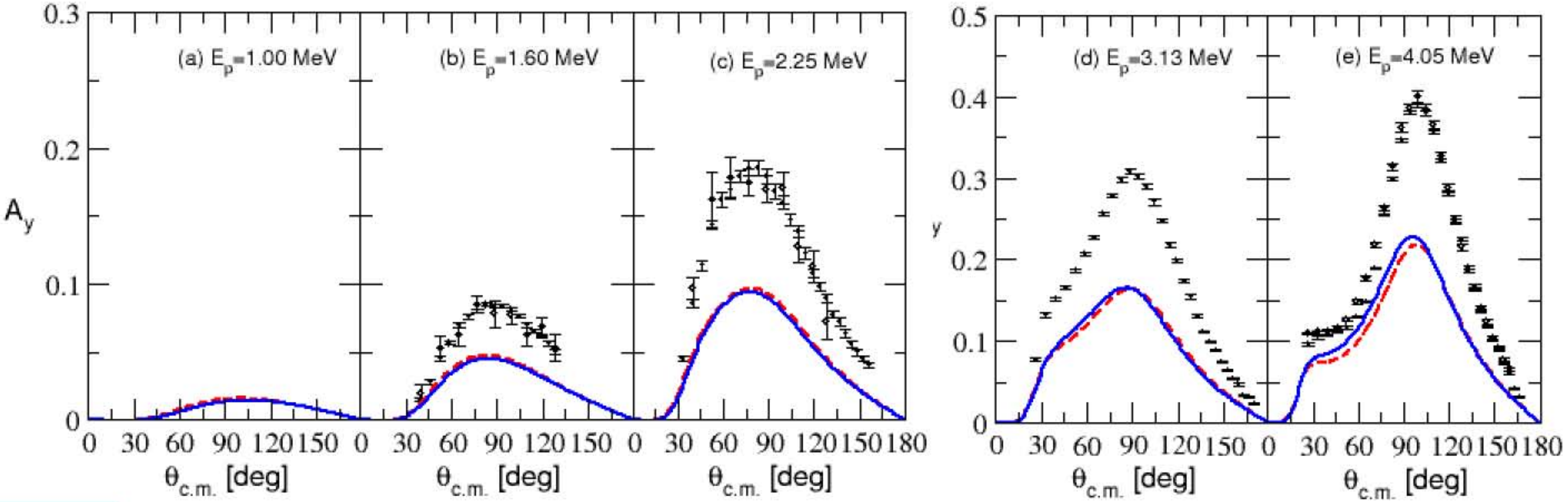


Very small effects from the (standard) 3N forces

p-^{3}He elastic scattering

$$\vec{p}+{}^3He \rightarrow p+{}^3He$$

Analyzing power



----- AV18

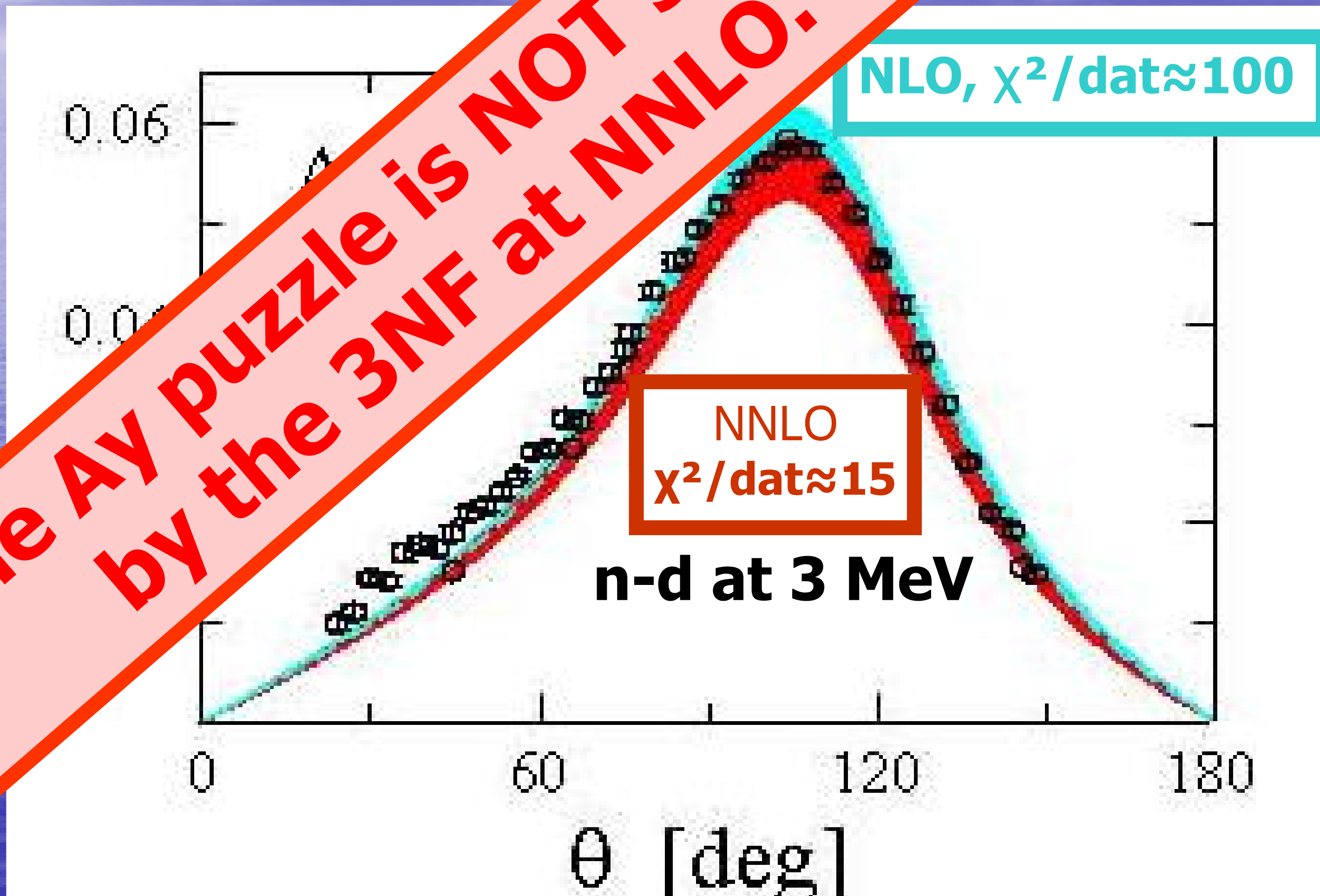
——— AV18+UIX

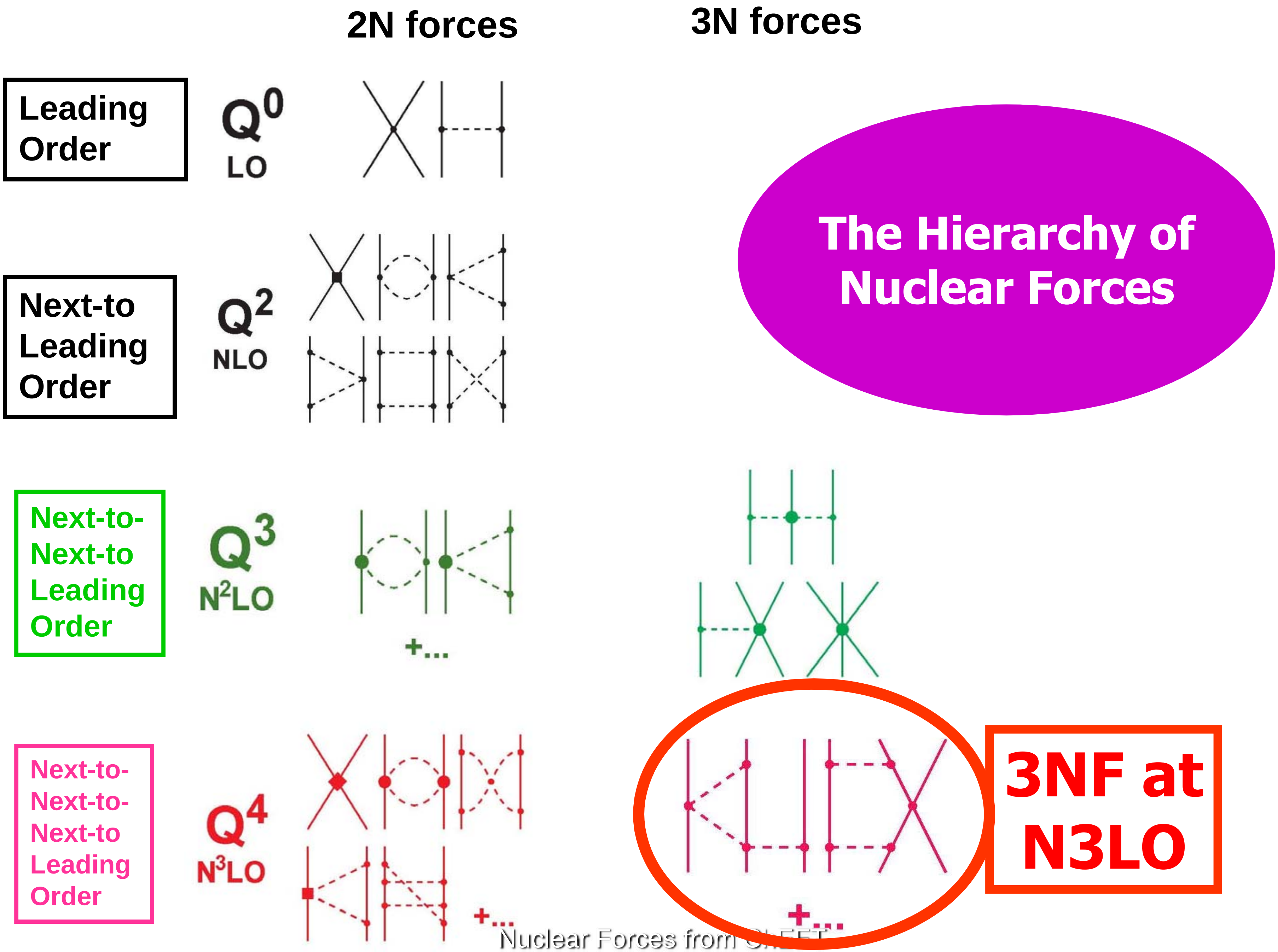
Courtesy of M. Viviani; latest data from TUNL.

MV, Marcucci, Kievsky & Rosati, PRC in press

Ay puzzle at N… …nd NNLO (2N…

The Ay puzzle is NOT solved by the 3NF at NNLO.




2N forces
3N forces
Leading Order
Q0
LO
The Hierarchy of Nuclear Forces
Next-to Leading Order
Q2
NLO
Next-to-Next-to Leading Order
Q3
N2LO
+...
Next-to-Next-to-Next-to Leading Order
Q4
N3LO
+...
+...
3NF at N3LO

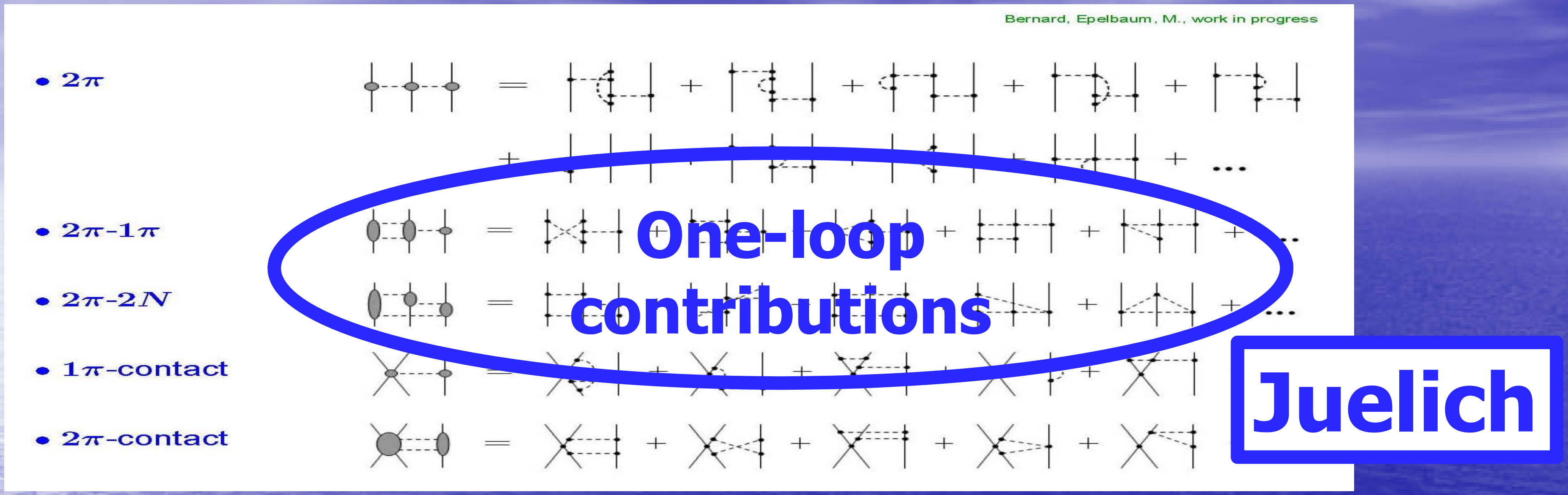
Why do we need the 3NF at N3LO?

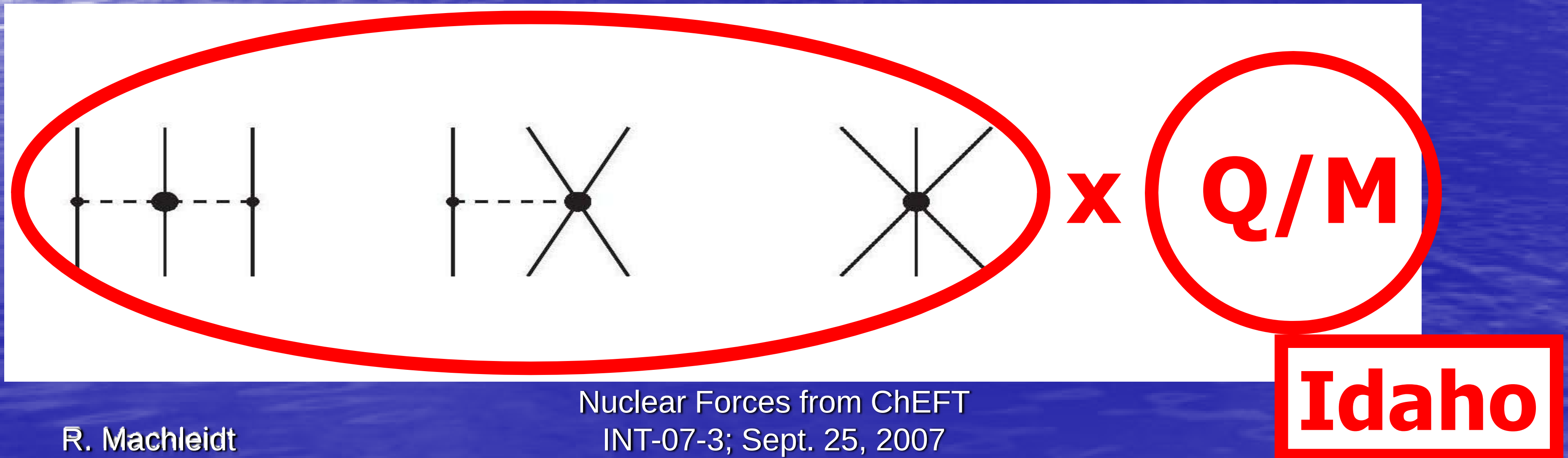
- The 2NF is N3LO;

  consistency requires that all contributions are at the same order.

- The are unresolved problems in 3N, 4N scattering and nuclear structure.

The 3NF at N3LO





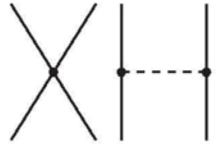
2N forces

3N forces

The Hierarchy of Nuclear Forces

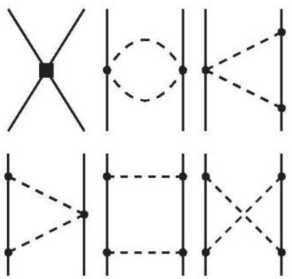
Leading Order

Q^0
LO



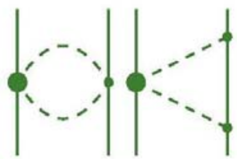
Next-to Leading Order

Q^2
NLO



Next-to-Next-to Leading Order

Q^3
N^2LO



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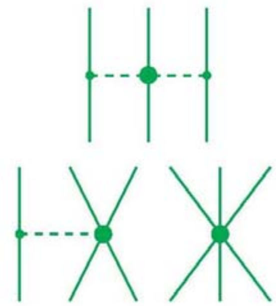
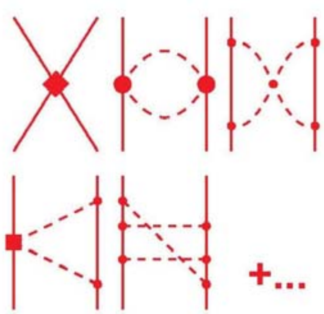
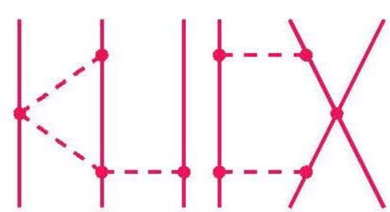


Next-to-Next-to-Next-to Leading Order

Q^4
N^3LO





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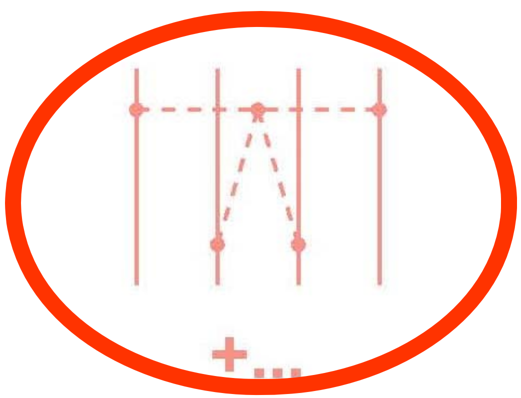
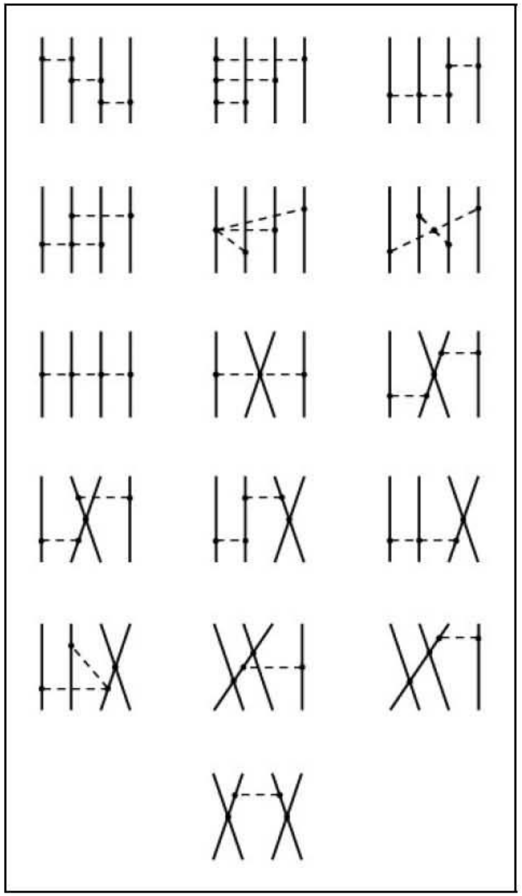


4NF at N3LO (leading order)

Epelbaum, Phys. Lett. **B639** (2006) 456 [nucl-th//0511025]



Note that only vertices from

$L^{(2)}_{\pi\pi}$, $L^{(1)}_{\pi N}$ and $L^{(0)}_{NN}$ are involved,

- no new parameters,
- weak.

First rough estimate:

$\approx$ 0.1 MeV to α binding.

Do not expect much for 4N scattering!

Summary

- Chiral EFT IS fundamental (QCD based) and quantitative.
- At N3LO, some accurate NN potentials have been developed (but, watch it, not all N3LO pots. are accurate!).
- Two- and many-forces are created on an equal footing.
- Current results in nuclear structure including the 3NF at N2LO are encouraging (however, the N-d A_y puzzle is not solved!).

Open issues, problems ...

- The 3NF at N3LO:

  Will it solve the N-d A_y puzzle, ... ,

  will it further improve the spectra of light nuclei, ... ?
- Do we need to go to N4LO, N5LO, ... ?

  - Not necessary for NN and if, then we have to go to N5LO - to get more contacts. Contacts at N5LO no problem, but the 2-pi, 3-pi, and 4-pi contributions will be a nightmare!

NUMBER OF PARAMETERS
for the np potential

	Nijmegen PWA93	CD-Bonn "high precision"	NLO Q^2 (NNLO)	N^{3}LO Q^4 (N^{4}LO)	N^{5}LO Q^6
$^1S_0$	3	4	2	4	6
$^3S_1$	3	4	2	4	6
$^3S_1$-$^3D_1$	2	2	1	3	6
$^1P_1$	3	3	1	2	4
$^3P_0$	3	2	1	2	4
$^3P_1$	2	2	1	2	4
$^3P_2$	3	3	1	2	4
$^3P_2$-$^3F_2$	2	1	0	1	3
$^1D_2$	2	3	0	1	2
$^3D_1$	2	1	0	1	2
$^3D_2$	2	2	0	1	2
$^3D_3$	1	2	0	1	2
$^3D_3$-$^3G_3$	1	0	0	0	1
$^1F_3$	1	1	0	0	1
$^3F_2$	1	2	0	0	1
$^3F_3$	1	2	0	0	1
$^3F_4$	2	1	0	0	1
$^3F_4$-$^3H_4$	0	0	0	0	0
$^1G_4$	1	0	0	0	0
$^3G_3$	0	1	0	0	0
$^3G_4$	0	1	0	0	0
$^3G_5$	0	1	0	0	0
Total	35	38	9	24	50

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  - Illinois 3NF contains N4LO and N5LO terms!

PHYSICAL REVIEW C, VOLUME 64, 014001

Realistic models of pion-exchange three-nucleon interactions

Steven C. Pieper,[1,*] V. R. Pandharipande,[2,†] R. B. Wiringa,[1,‡] and J. Carlson[3,§]
[1]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439*
[2]*Department of Physics, University of Illinois, Urbana, Illinois 61801*
[3]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545*
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"Illinois" 3NFs

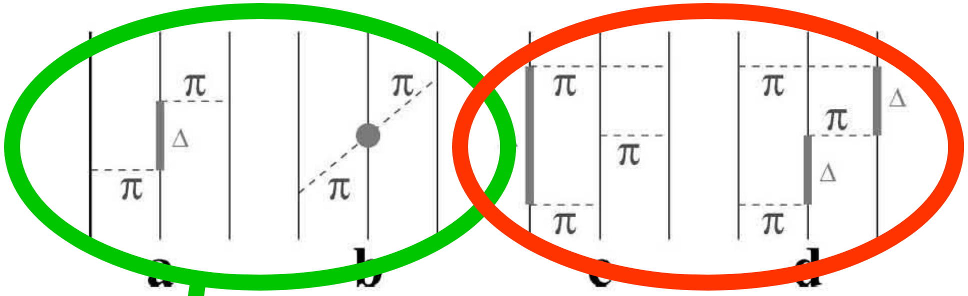
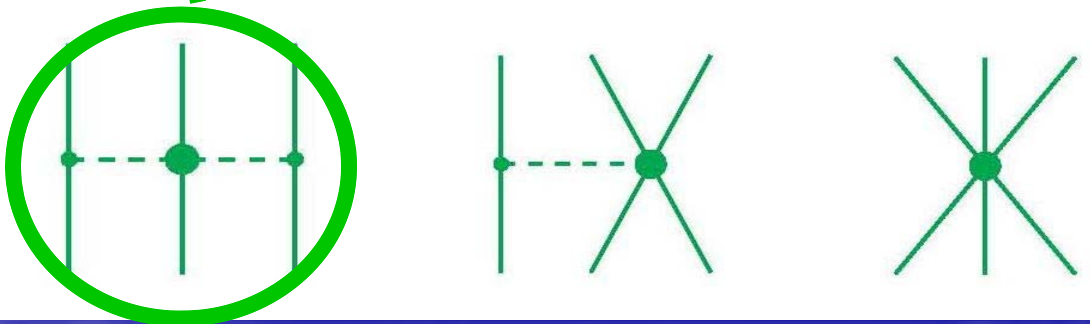


FIG. 2. T ree-body force Fey
Fujita-Miyaz awa, (b) is two-pion
rings wit one Δ in intermediate

N4LO and N5LO
(in a theory w/o explicit
Deltas)

N2LO 3NFs



Open issues, problems …

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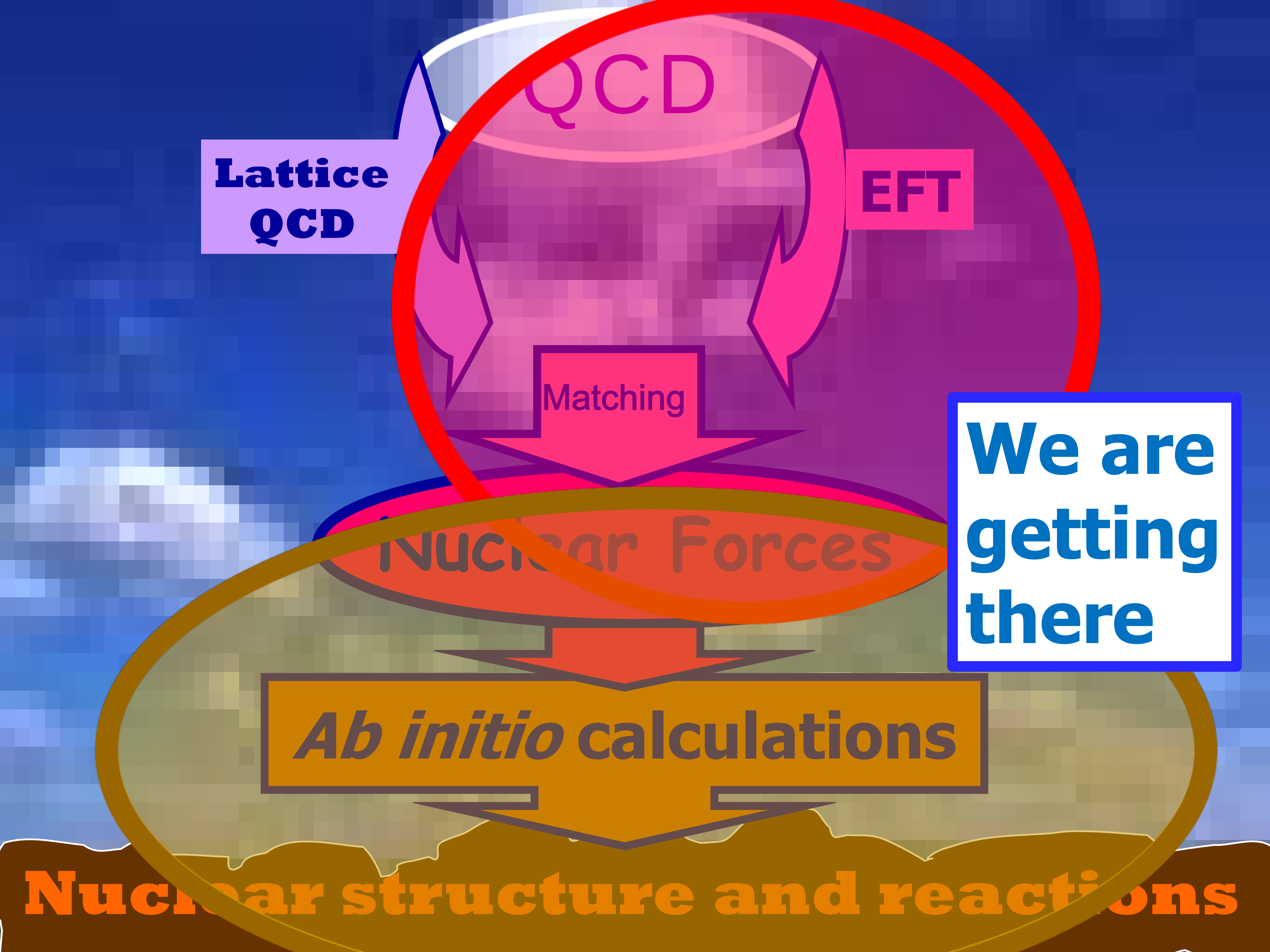
  - Illinois 3NF contains N4LO and N5LO terms!
- The renormalization of the chiral NN potemtial: What's the right power counting scheme? Weinberg counting has some problems!


QCD
?
Nuclear structure and reactions


QCD
Lattice QCD
EFT
Matching
Nuclear Forces
We are getting there
Ab initio calculations
Nuclear structure and reactions