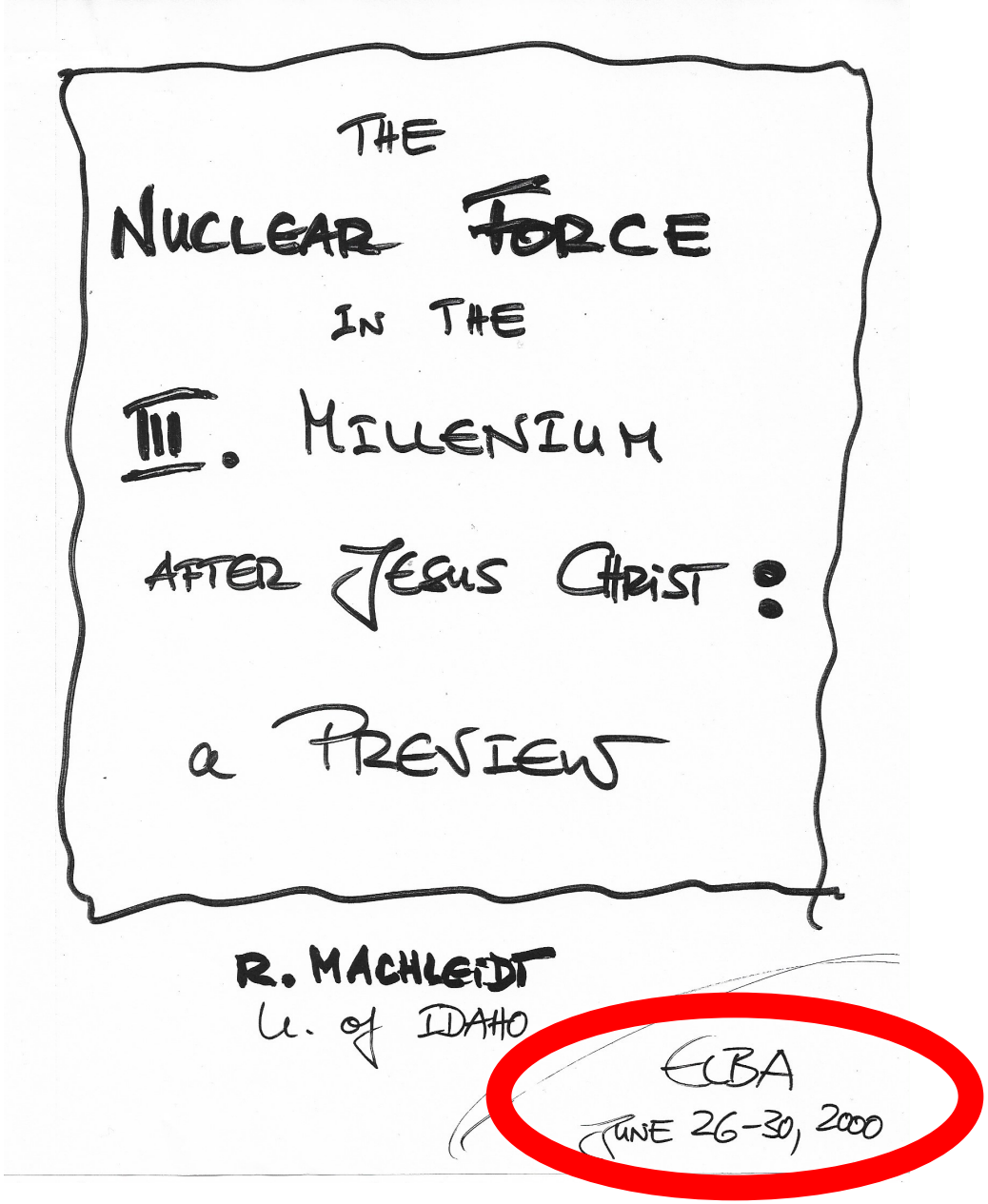
Elba 2019 – Lepton Interactions with Nucleons and Nuclei

RECENT PROGRESS IN NUCLEAR INTERACTIONS FROM CHIRAL EFFECTIVE FIELD THEORY

R. Machleidt

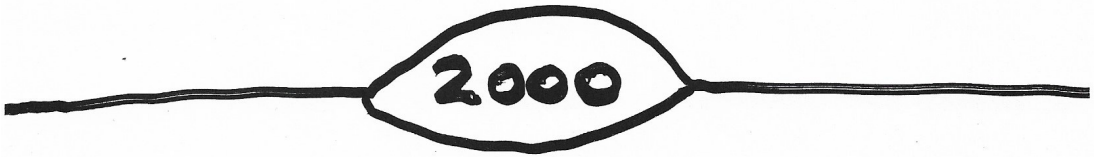
University of Idaho

Research supported by the US Department of Energy

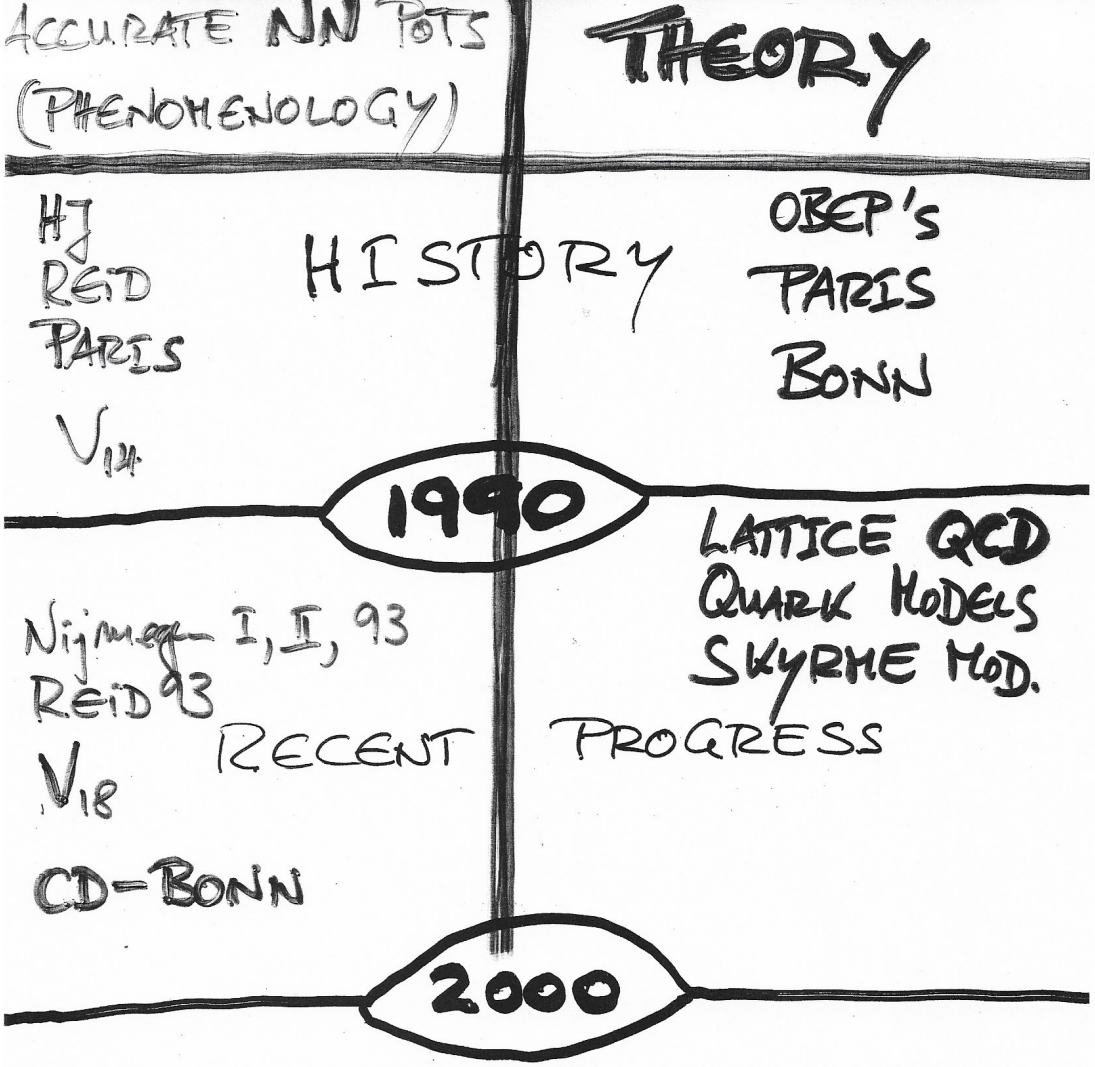

THE
NUCLEAR FORCE
IN THE
III. MILLENIUM
AFTER JESUS CHRIST:
a PREVIEW
R. MACHLEIDT
U. of IDAHO
ELBA
JUNE 26-30, 2000

HISTORY

RECENT PROGRESS



FUTURE


ACCURATE NN POTS
(PHENOMENOLOGY)
THEORY
HJ
REID
PARIS
V14
HISTORY
OBEP's
PARIS
BONN
1990
LATTICE QCD
QUARK MODELS
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Nijmegen I, II, 93
REID 93
V18
RECENT
PROGRESS
CD-BONN
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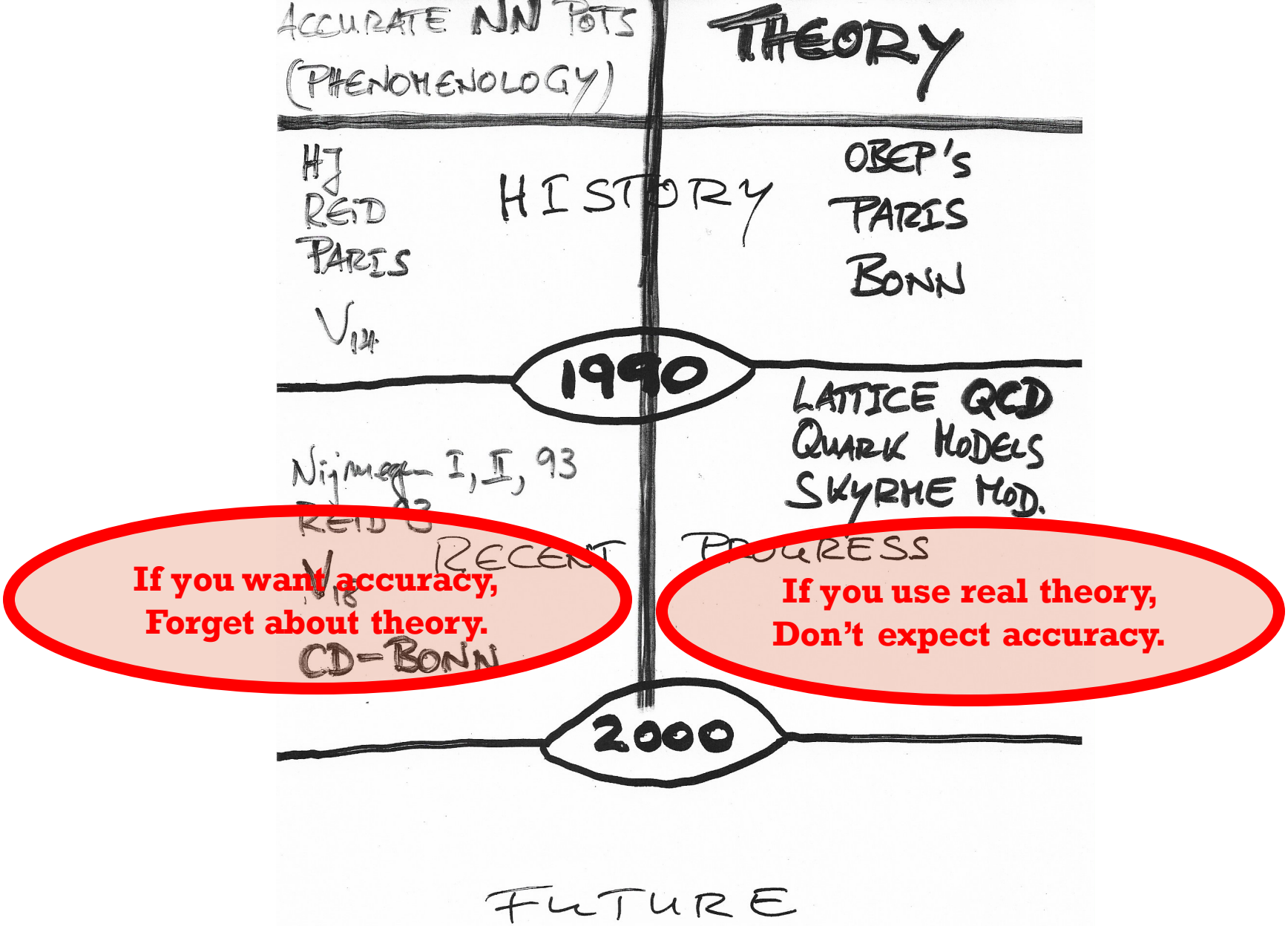
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If you want accuracy,
Forget about theory.
If you use real theory,
Don't expect accuracy.
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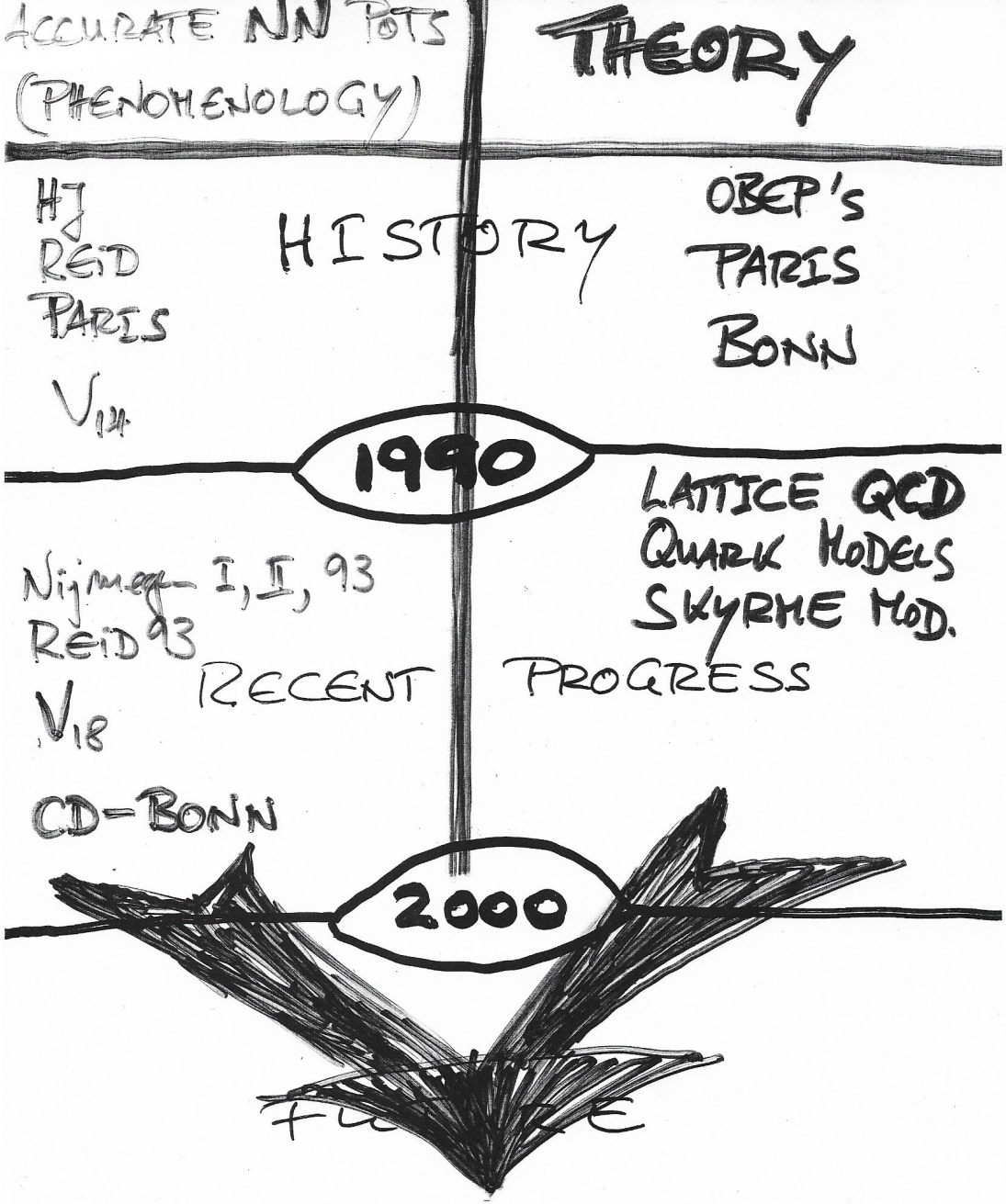
2000
FUTURE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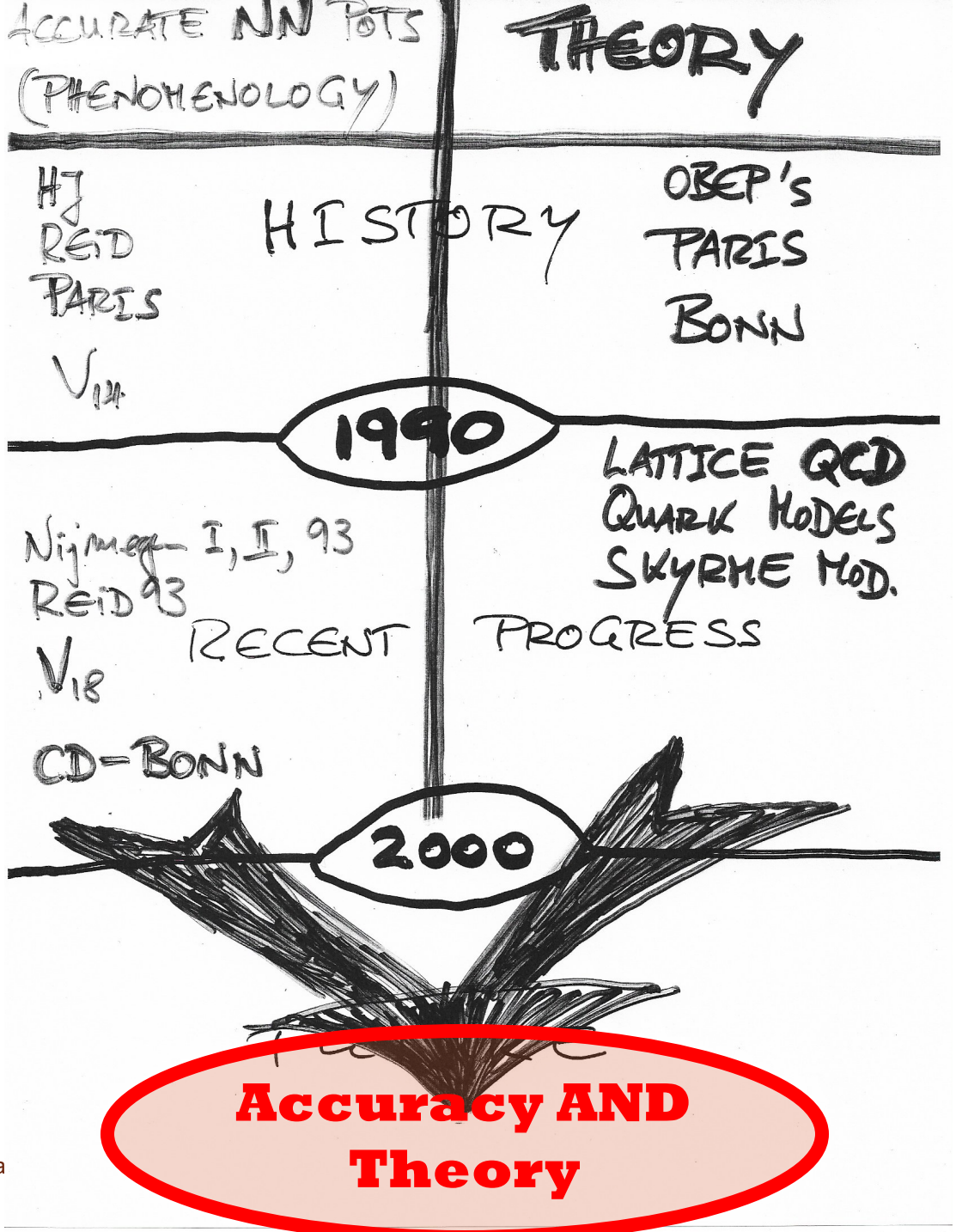
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Accuracy AND
Theory

THE PROGRAM FOR THE NEW MILLENIUM

For a reliable derivation of nuclear forces, we need

- a basic theory
- that is amenable to calculations
- yields quantitative results.

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For a reliable derivation of nuclear forces, we need

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  χ eff. field theory
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  χPTh
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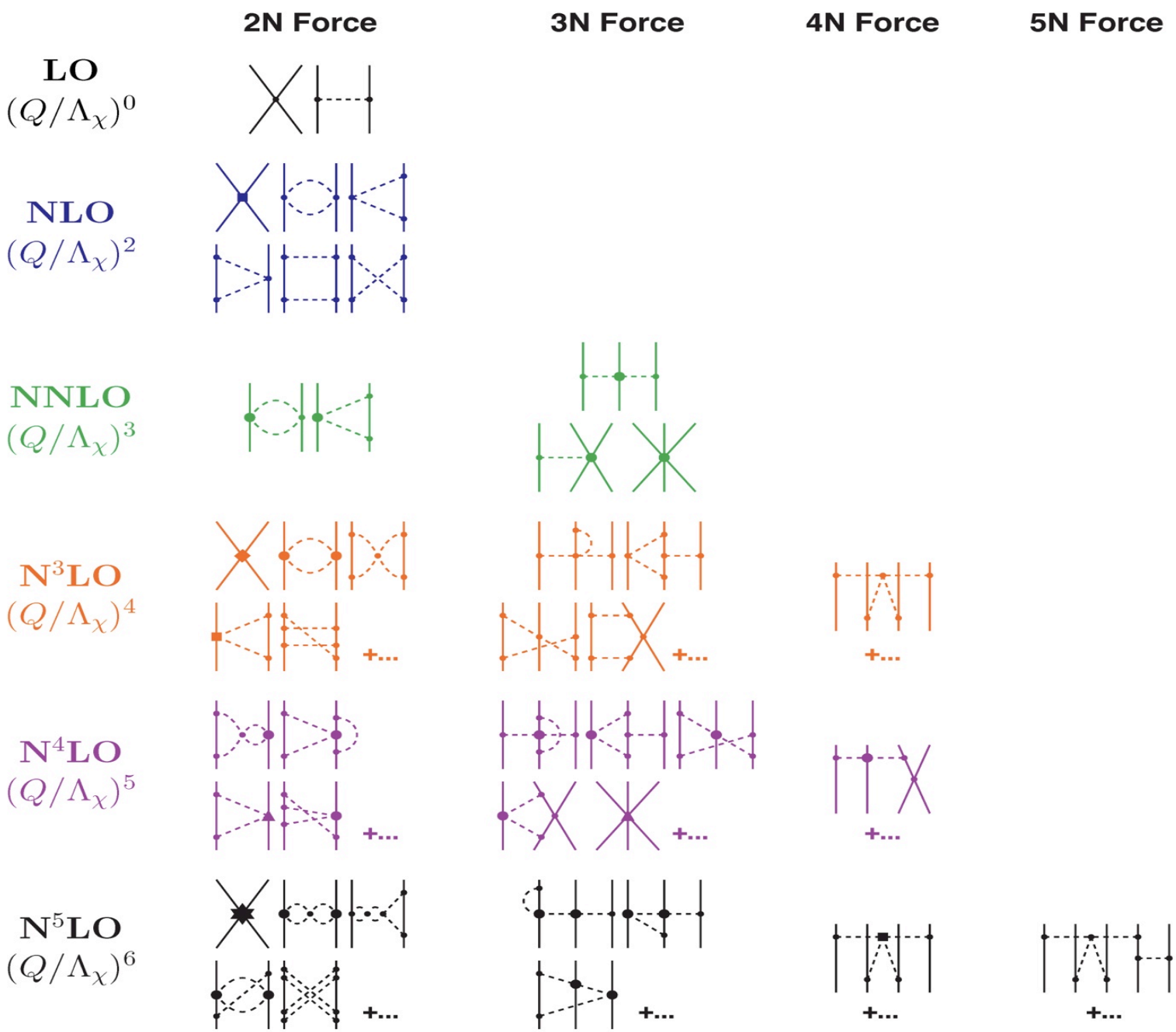
let's hope for it!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LO
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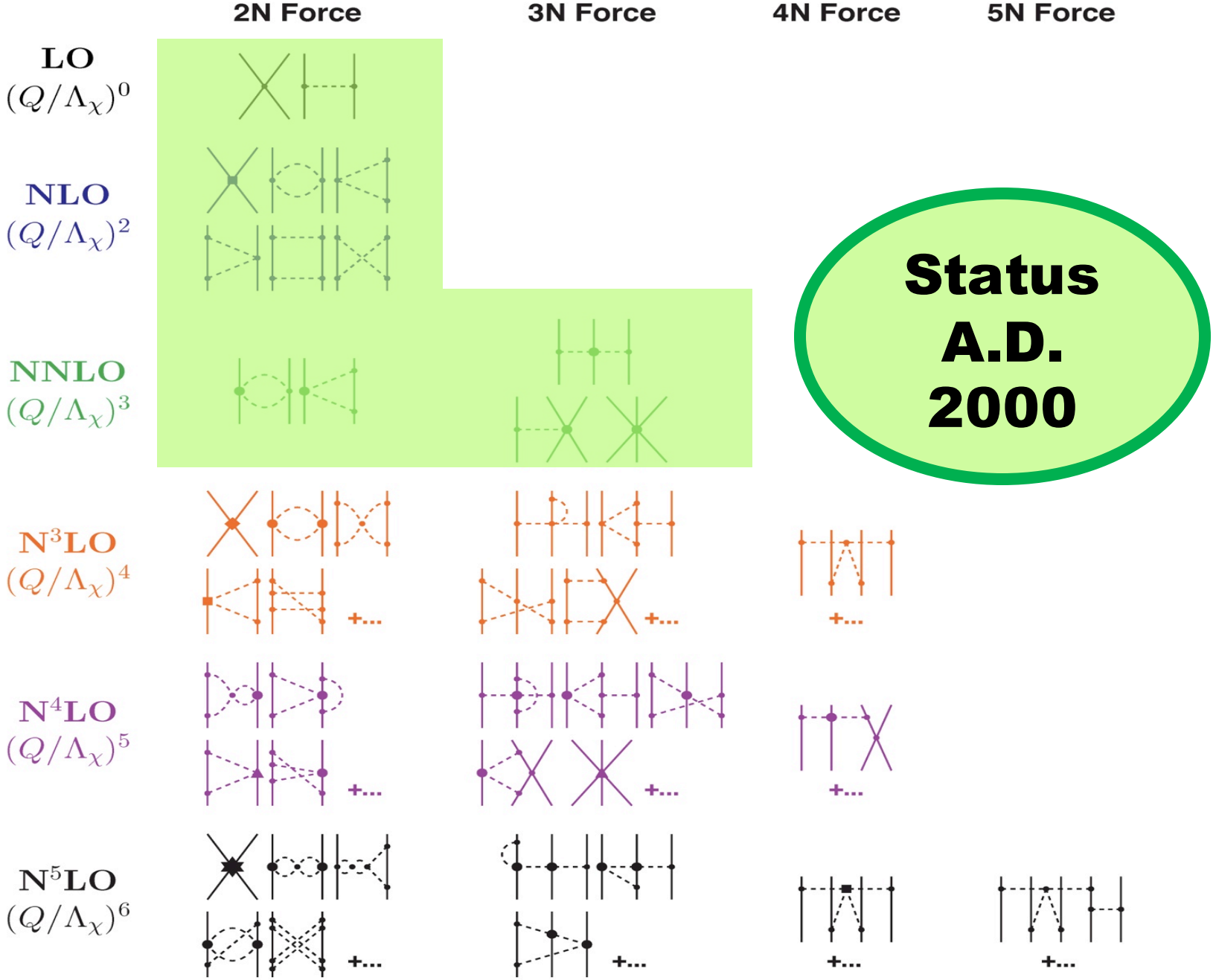
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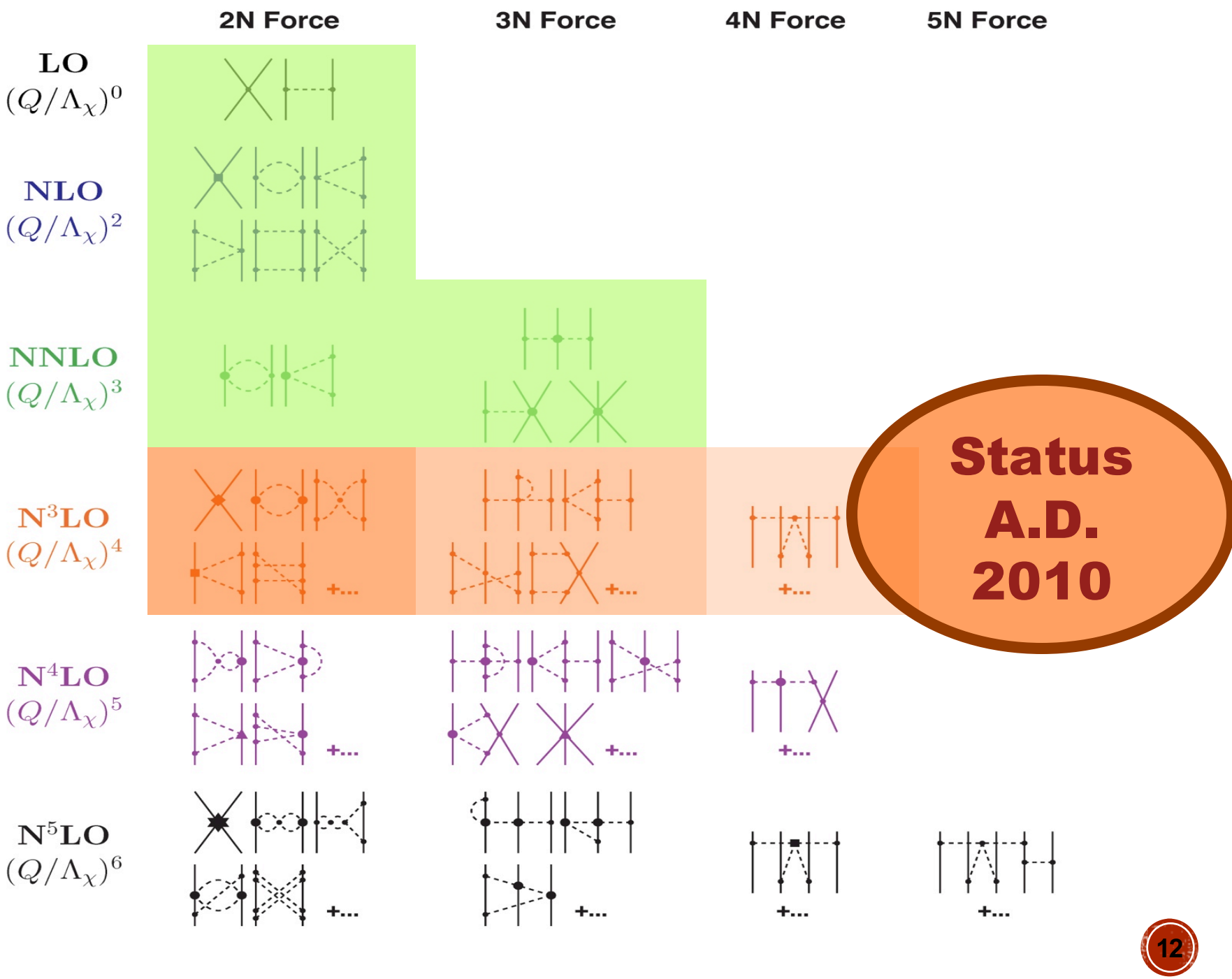
A.D.
2000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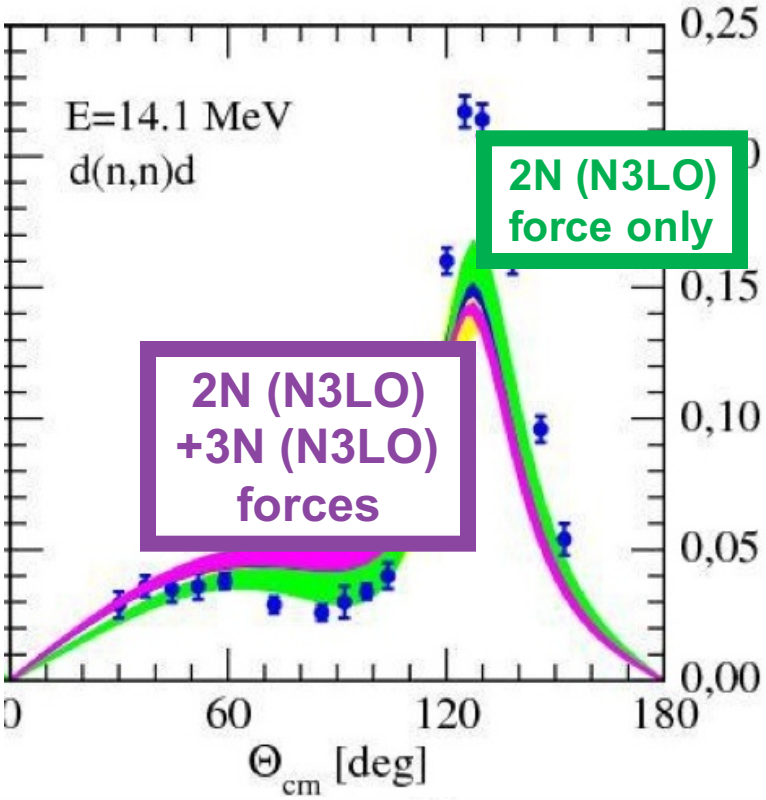
Status
A.D.
2010

WHAT HAVE WE ACHIEVED WITH THOSE FORCES?

- **There has been some success (ground state of 10B, drip lines, nuclear matter saturation, orbit evolution, etc.), but some persistent problems remain.**
- **In the few-body sector: Ay puzzle, N-d break-up, …**

N-d A_y calculations by Witala et al.



chiral N^{3}LO + 3NF N^{3}LO ($\pi\pi$+D+E)

chiral N^{3}LO + 3NF N^{3}LO ($\pi\pi$+2π1π+D+E)

chiral N^{3}LO

TUNL nd data

chiral N^{3}LO + 3NF N^{3}LO ($\pi\pi$+2π1π+ring+D+E)

CURRENT STATUS AND OPEN ISSUES

- **Current status: 2NFs and 3NFs up to N3LO are applied in nuclear few- and many-body systems.**
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Radii and Binding Energies in Oxygen Isotopes: A Challenge for Nuclear Forces

V. Lapoux,[1,*] V. Somà,[1] C. Barbieri,[2] H. Hergert,[3] J. D. Holt,[4] and S. R. Stroberg[4]
[1]CEA, Centre de Saclay, IRFU, Service de Physique Nucléaire, 91191 Gif-sur-Yvette, France
[2]Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom
[3]National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA
[4]TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3
(Received 29 April 2016; published 27 July 2016)

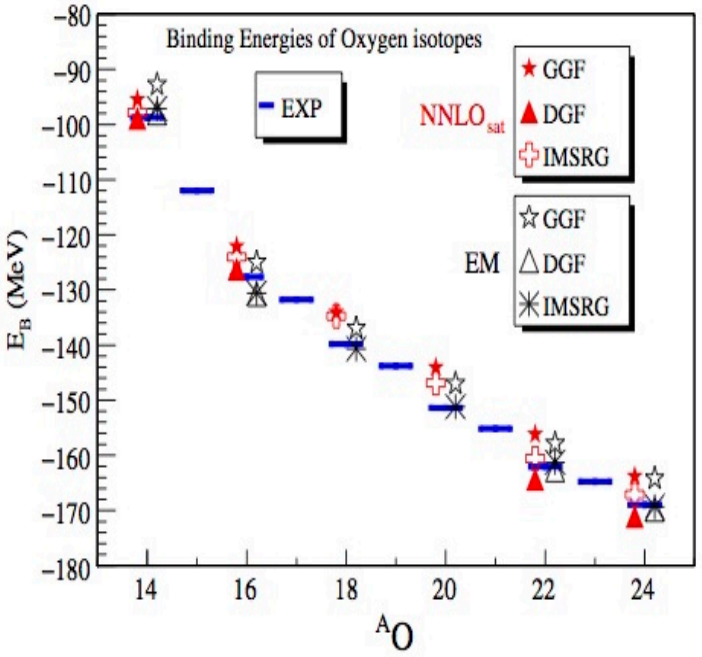

FIG. 1. Oxygen binding energies. Results from SCGF (DGF and GGF) and IMSRG calculations with EM and NNLO$_{sat}$ are displayed along with experimental data.

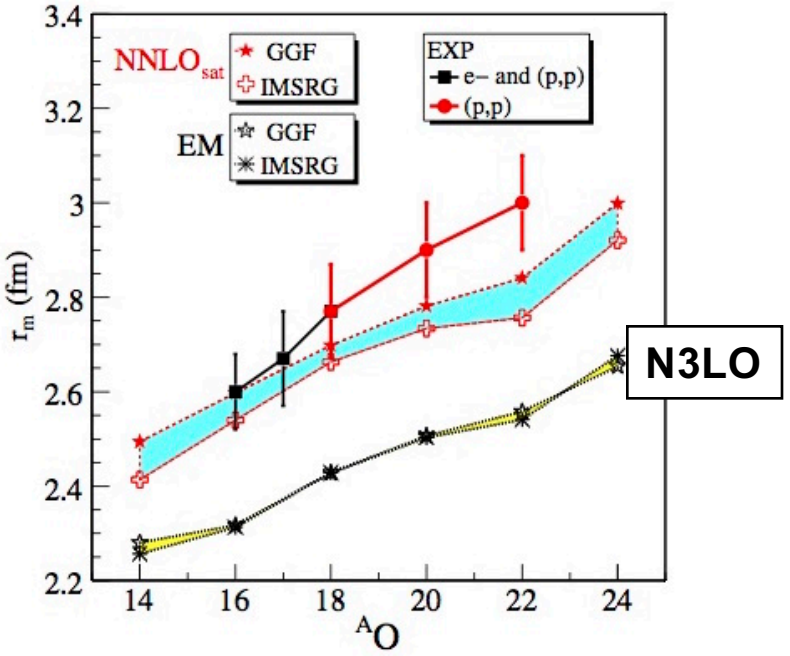

FIG. 5. Matter radii from our analysis and given in Table I, compared to calculations with EM [27–29] and NNLO$_{sat}$ [36]. Bands span results from GGF and MR-IMSRG schemes.

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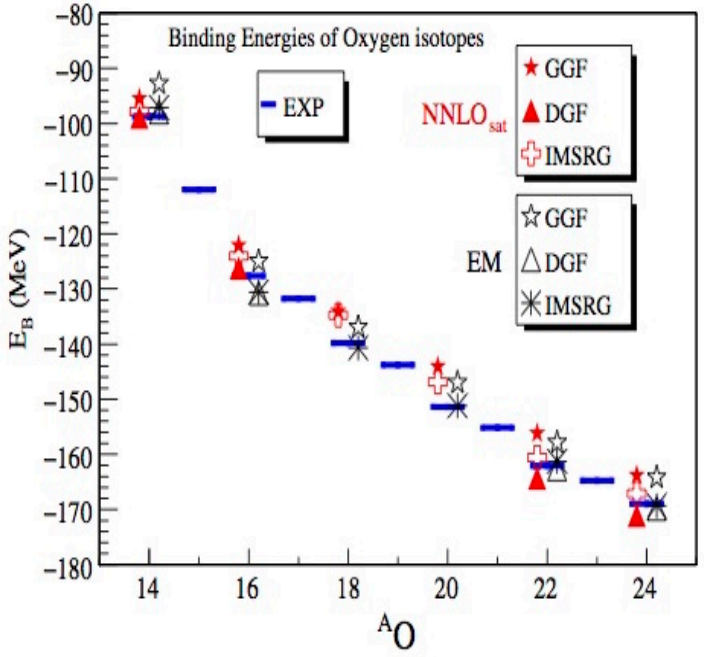
- **Overbinding of intermediate-mass nuclei**

Overbinding of intermediate-mass nuclei

Oxygen



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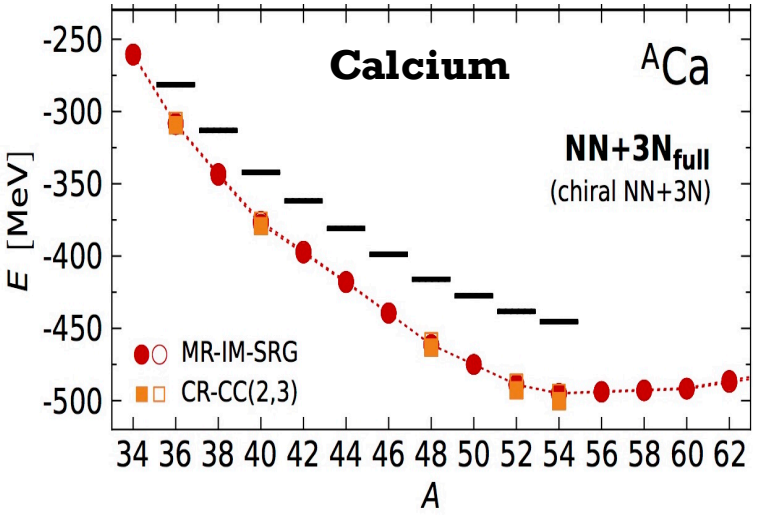

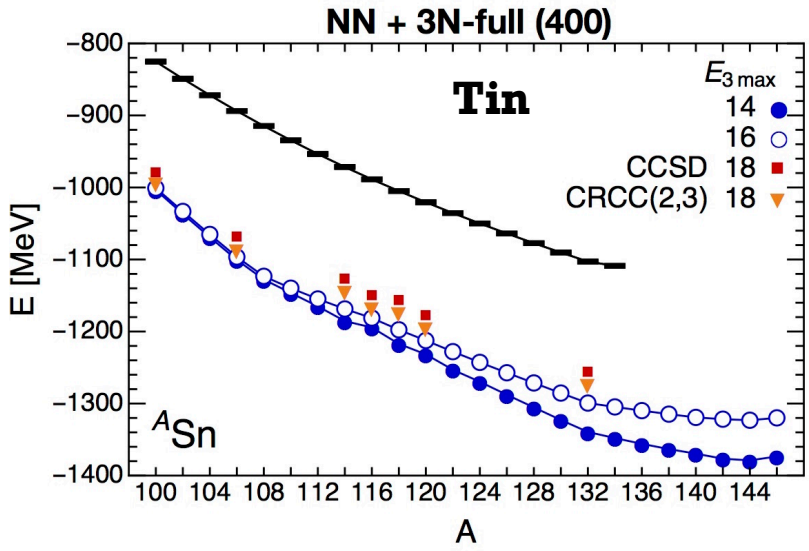

From Hergert et al., PRC 90, 041302 (2014).

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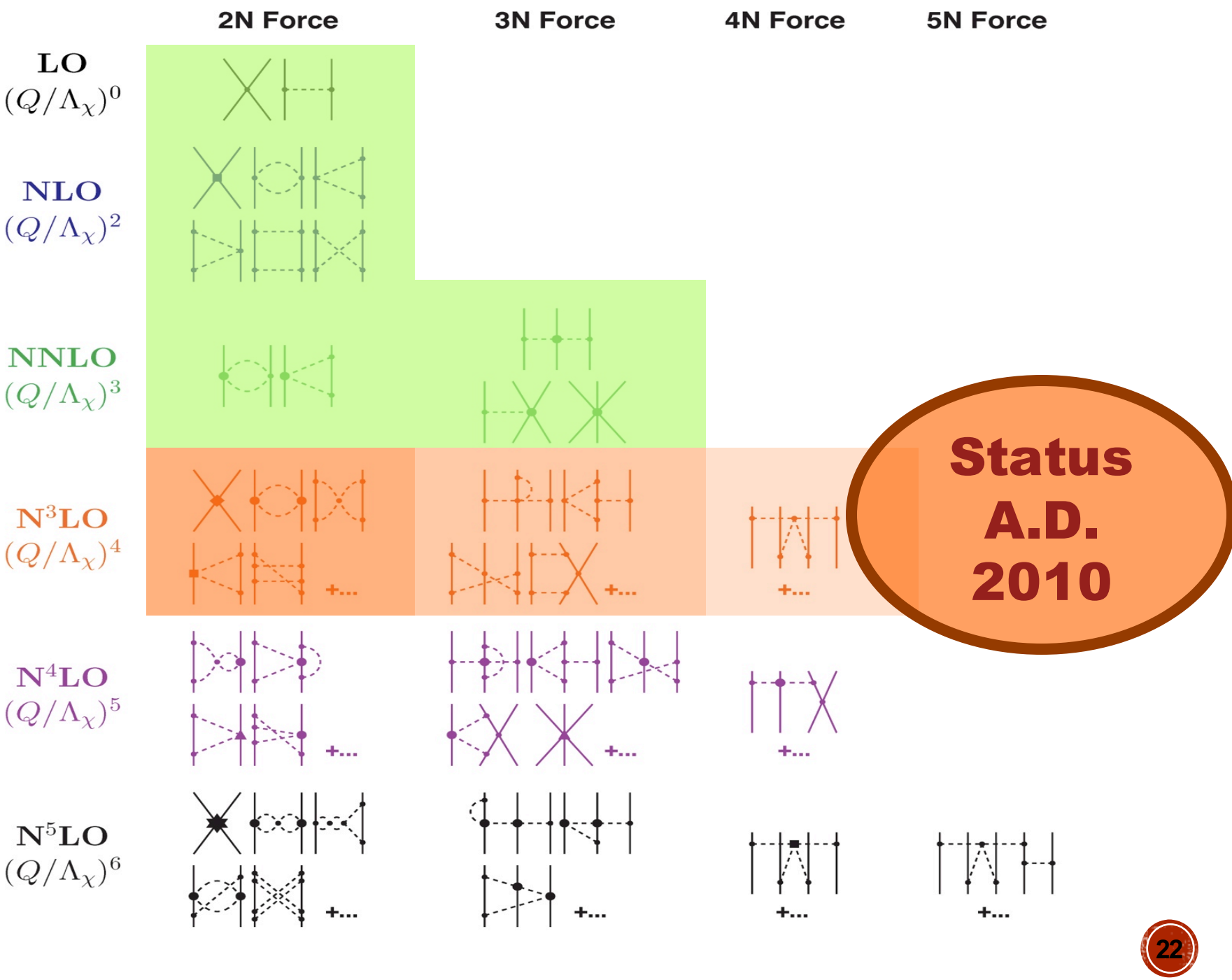
Because of the problems just pointed out, improvement of current nuclear forces is called for.

- **How?**
- **Revisit the lower orders**
- **Move on to higher orders**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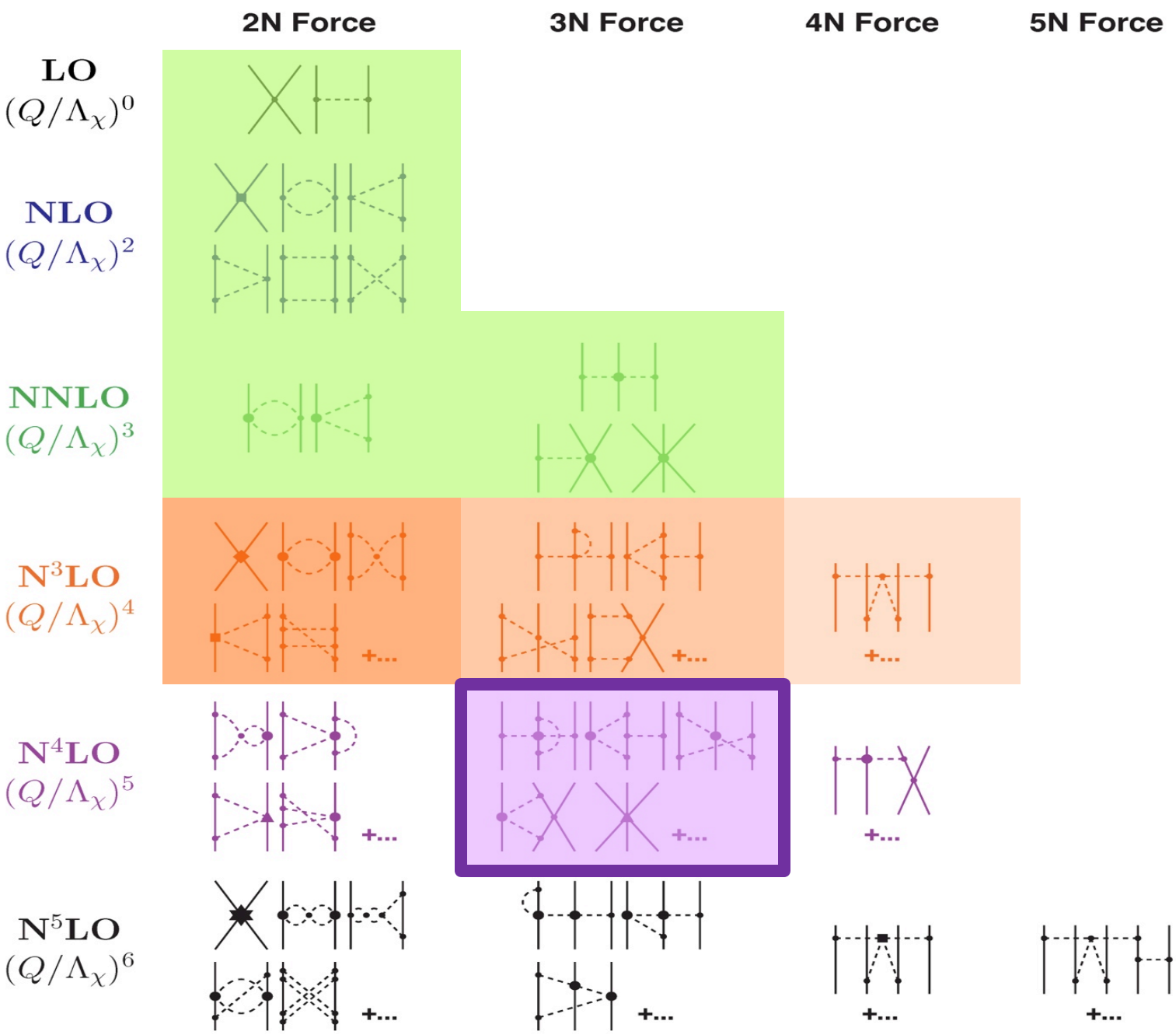
Status
A.D.
2010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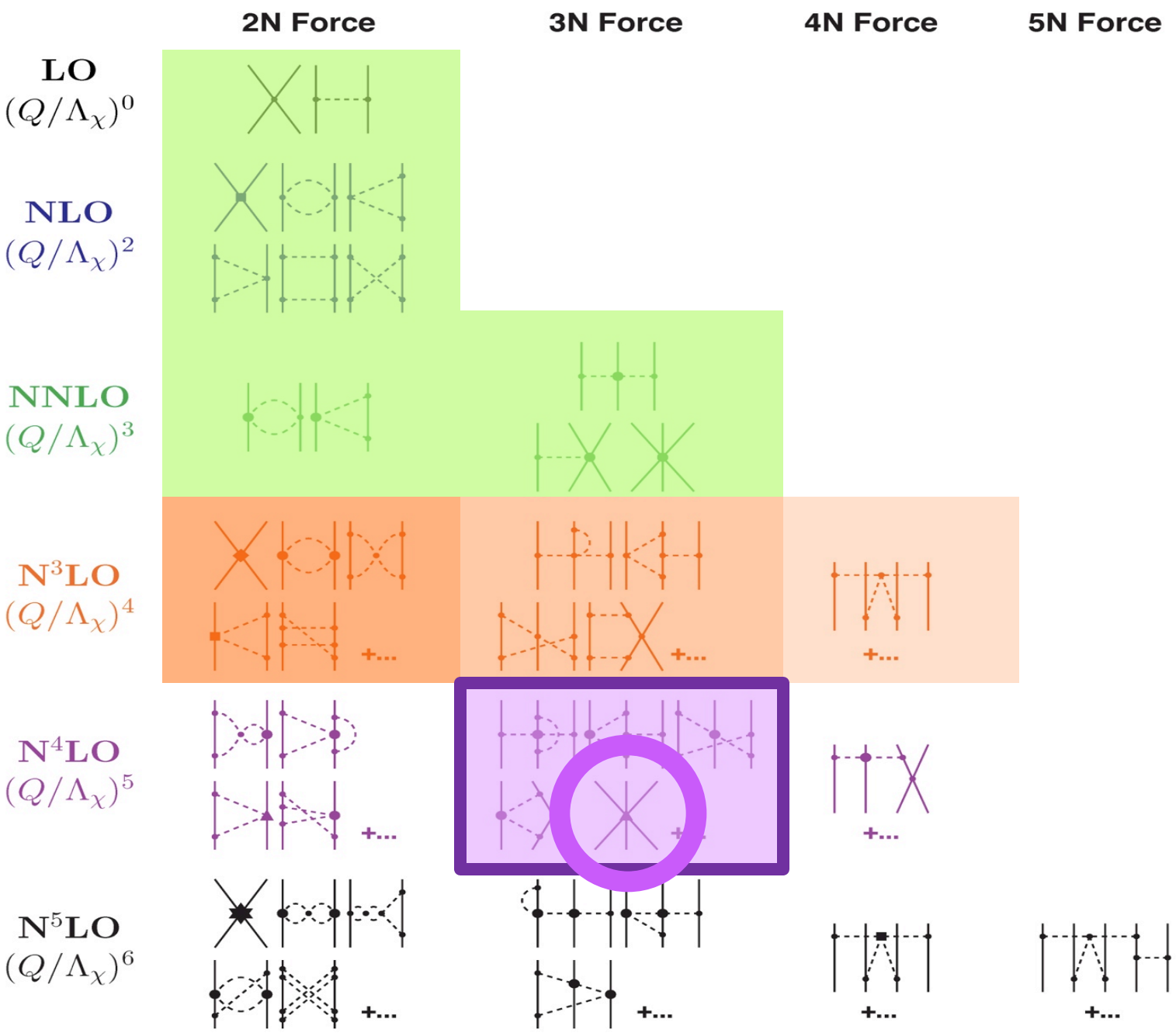
$(Q/\Lambda_\chi)^6$
+...

All possible 20 isospin-spin-momentum/position structures occur in the 3NF at N4LO!

Epelbaum et al., Eur. Phys. J. A51, 26 (2015)

Generators $\mathcal{G}$ in momentum space	Generators $\tilde{\mathcal{G}}$ in coordinate space
$\mathcal{G}_1 = 1$	$\tilde{\mathcal{G}}_1 = 1$
$\mathcal{G}_2 = \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3$	$\tilde{\mathcal{G}}_2 = \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3$
$\mathcal{G}_3 = \vec{\sigma}_1 \cdot \vec{\sigma}_3$	$\tilde{\mathcal{G}}_3 = \vec{\sigma}_1 \cdot \vec{\sigma}_3$
$\mathcal{G}_4 = \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3 \vec{\sigma}_1 \cdot \vec{\sigma}_3$	$\tilde{\mathcal{G}}_4 = \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3 \, \vec{\sigma}_1 \cdot \vec{\sigma}_3$
$\mathcal{G}_5 = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{\sigma}_1 \cdot \vec{\sigma}_2$	$\tilde{\mathcal{G}}_5 = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \, \vec{\sigma}_1 \cdot \vec{\sigma}_2$
$\mathcal{G}_6 = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_1 \cdot (\vec{\sigma}_2 \times \vec{\sigma}_3)$	$\tilde{\mathcal{G}}_6 = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \, \vec{\sigma}_1 \cdot (\vec{\sigma}_2 \times \vec{\sigma}_3)$
$\mathcal{G}_7 = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_2 \cdot (\vec{q}_1 \times \vec{q}_3)$	$\tilde{\mathcal{G}}_7 = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \, \vec{\sigma}_2 \cdot (\hat{r}_{12} \times \hat{r}_{23})$
$\mathcal{G}_8 = \vec{q}_1 \cdot \vec{\sigma}_1 \vec{q}_1 \cdot \vec{\sigma}_3$	$\tilde{\mathcal{G}}_8 = \hat{r}_{23} \cdot \vec{\sigma}_1 \, \hat{r}_{23} \cdot \vec{\sigma}_3$
$\mathcal{G}_9 = \vec{q}_1 \cdot \vec{\sigma}_3 \vec{q}_3 \cdot \vec{\sigma}_1$	$\tilde{\mathcal{G}}_9 = \hat{r}_{23} \cdot \vec{\sigma}_3 \, \hat{r}_{12} \cdot \vec{\sigma}_1$
$\mathcal{G}_{10} = \vec{q}_1 \cdot \vec{\sigma}_1 \vec{q}_3 \cdot \vec{\sigma}_3$	$\tilde{\mathcal{G}}_{10} = \hat{r}_{23} \cdot \vec{\sigma}_1 \, \hat{r}_{12} \cdot \vec{\sigma}_3$
$\mathcal{G}_{11} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{q}_1 \cdot \vec{\sigma}_1 \vec{q}_1 \cdot \vec{\sigma}_2$	$\tilde{\mathcal{G}}_{11} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \, \hat{r}_{23} \cdot \vec{\sigma}_1 \, \hat{r}_{23} \cdot \vec{\sigma}_2$
$\mathcal{G}_{12} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{q}_1 \cdot \vec{\sigma}_1 \vec{q}_3 \cdot \vec{\sigma}_2$	$\tilde{\mathcal{G}}_{12} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \, \hat{r}_{23} \cdot \vec{\sigma}_1 \, \hat{r}_{12} \cdot \vec{\sigma}_2$
$\mathcal{G}_{13} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{q}_3 \cdot \vec{\sigma}_1 \vec{q}_1 \cdot \vec{\sigma}_2$	$\tilde{\mathcal{G}}_{13} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \, \hat{r}_{12} \cdot \vec{\sigma}_1 \, \hat{r}_{23} \cdot \vec{\sigma}_2$
$\mathcal{G}_{14} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{q}_3 \cdot \vec{\sigma}_1 \vec{q}_3 \cdot \vec{\sigma}_2$	$\tilde{\mathcal{G}}_{14} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \, \hat{r}_{12} \cdot \vec{\sigma}_1 \, \hat{r}_{12} \cdot \vec{\sigma}_2$
$\mathcal{G}_{15} = \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3 \vec{q}_2 \cdot \vec{\sigma}_1 \vec{q}_2 \cdot \vec{\sigma}_3$	$\tilde{\mathcal{G}}_{15} = \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3 \, \hat{r}_{13} \cdot \vec{\sigma}_1 \, \hat{r}_{13} \cdot \vec{\sigma}_3$
$\mathcal{G}_{16} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{q}_3 \cdot \vec{\sigma}_2 \vec{q}_3 \cdot \vec{\sigma}_3$	$\tilde{\mathcal{G}}_{16} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \, \hat{r}_{12} \cdot \vec{\sigma}_2 \, \hat{r}_{12} \cdot \vec{\sigma}_3$
$\mathcal{G}_{17} = \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3 \vec{q}_1 \cdot \vec{\sigma}_1 \vec{q}_3 \cdot \vec{\sigma}_3$	$\tilde{\mathcal{G}}_{17} = \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3 \, \hat{r}_{23} \cdot \vec{\sigma}_1 \, \hat{r}_{12} \cdot \vec{\sigma}_3$
$\mathcal{G}_{18} = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_1 \cdot \vec{\sigma}_3 \vec{\sigma}_2 \cdot (\vec{q}_1 \times \vec{q}_3)$	$\tilde{\mathcal{G}}_{18} = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \, \vec{\sigma}_1 \cdot \vec{\sigma}_3 \, \vec{\sigma}_2 \cdot (\hat{r}_{12} \times \hat{r}_{23})$
$\mathcal{G}_{19} = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_3 \cdot \vec{q}_1 \vec{q}_1 \cdot (\vec{\sigma}_1 \times \vec{\sigma}_2)$	$\tilde{\mathcal{G}}_{19} = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \, \vec{\sigma}_3 \cdot \hat{r}_{23} \, \hat{r}_{23} \cdot (\vec{\sigma}_1 \times \vec{\sigma}_2)$
$\mathcal{G}_{20} = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_1 \cdot \vec{q}_1 \vec{\sigma}_3 \cdot \vec{q}_3 \vec{\sigma}_2 \cdot (\vec{q}_1 \times \vec{q}_3)$	$\tilde{\mathcal{G}}_{20} = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \, \vec{\sigma}_1 \cdot \hat{r}_{23} \, \vec{\sigma}_3 \cdot \hat{r}_{12} \, \vec{\sigma}_2 \cdot (\hat{r}_{12} \times \hat{r}_{23})$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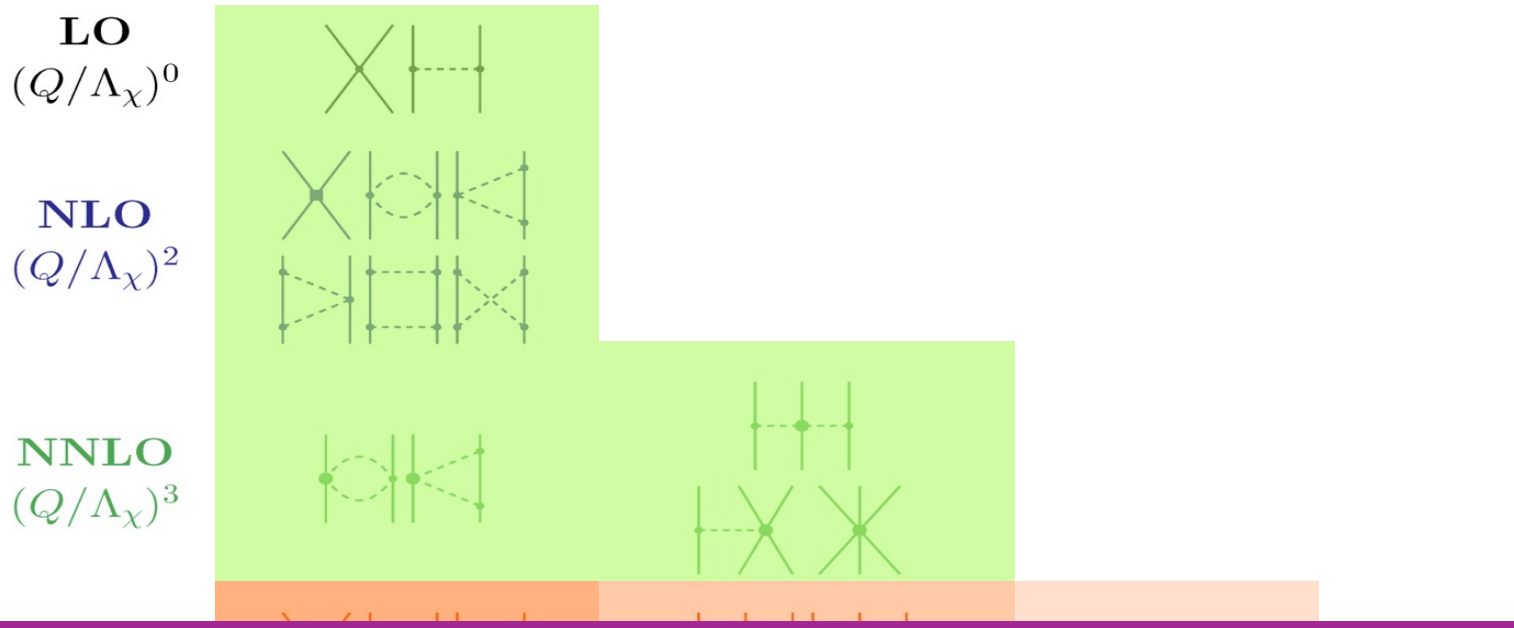


3NF contacts at N4LO

Girlanda, Kievsky, Viviani, PRC 84, 014001 (2011)

$\mathbf{k}_i = \mathbf{p}_i - \mathbf{p}'_i$ and $\mathbf{Q}_i = \mathbf{p}_i + \mathbf{p}'_i$, $\mathbf{p}_i$ and $\mathbf{p}'_i$ being the initial and final momenta of nucleon i, the potential in momentum space is found to be

$$
\begin{aligned}
V = \sum_{i\neq j\neq k} \Big[& -E_1\mathbf{k}_i^2 - E_2\mathbf{k}_i^2\boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j - E_3\mathbf{k}_i^2\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j - E_4\mathbf{k}_i^2\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j\boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j \\
& - E_5\left(3\mathbf{k}_i\cdot\boldsymbol{\sigma}_i\mathbf{k}_i\cdot\boldsymbol{\sigma}_j - \mathbf{k}_i^2\right) - E_6\left(3\mathbf{k}_i\cdot\boldsymbol{\sigma}_i\mathbf{k}_i\cdot\boldsymbol{\sigma}_j - \mathbf{k}_i^2\right))\boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j \\
& + \frac{i}{2}E_7\mathbf{k}_i\times(\mathbf{Q}_i - \mathbf{Q}_j)\cdot(\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j) + \frac{i}{2}E_8\mathbf{k}_i\times(\mathbf{Q}_i - \mathbf{Q}_j)\cdot(\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j)\boldsymbol{\tau}_j\cdot\boldsymbol{\tau}_k \\
& - E_9\mathbf{k}_i\cdot\boldsymbol{\sigma}_i\mathbf{k}_j\cdot\boldsymbol{\sigma}_j - E_{10}\mathbf{k}_i\cdot\boldsymbol{\sigma}_i\mathbf{k}_j\cdot\boldsymbol{\sigma}_j\boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j\Big], \qquad (15)
\end{aligned}
$$

Including N4LO 3NF contacts, Girlanda et al.

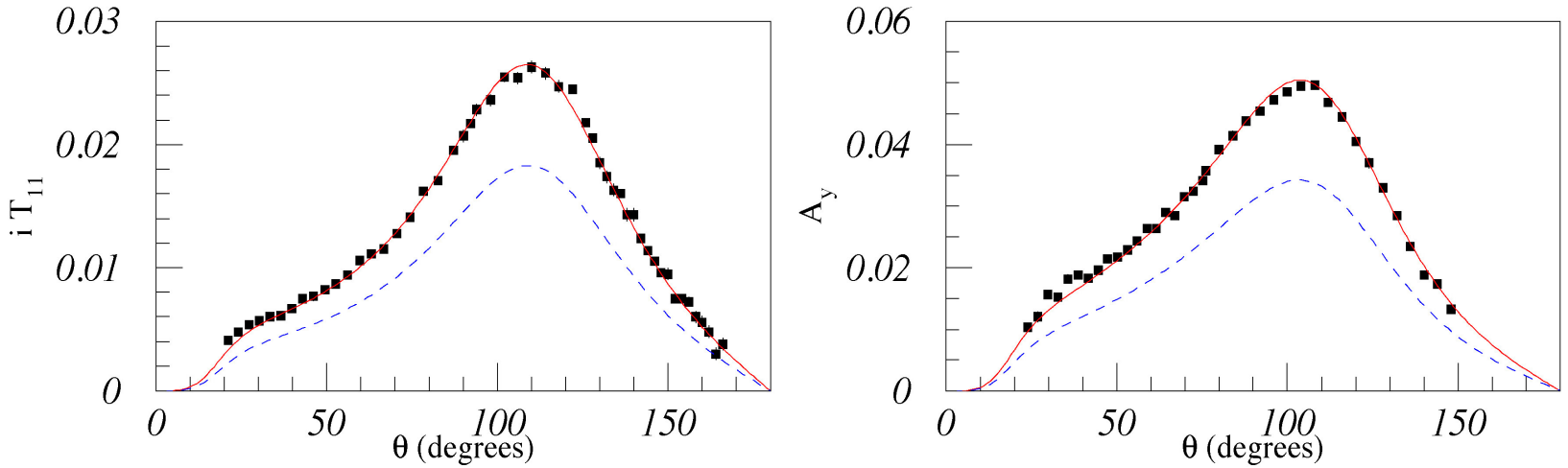
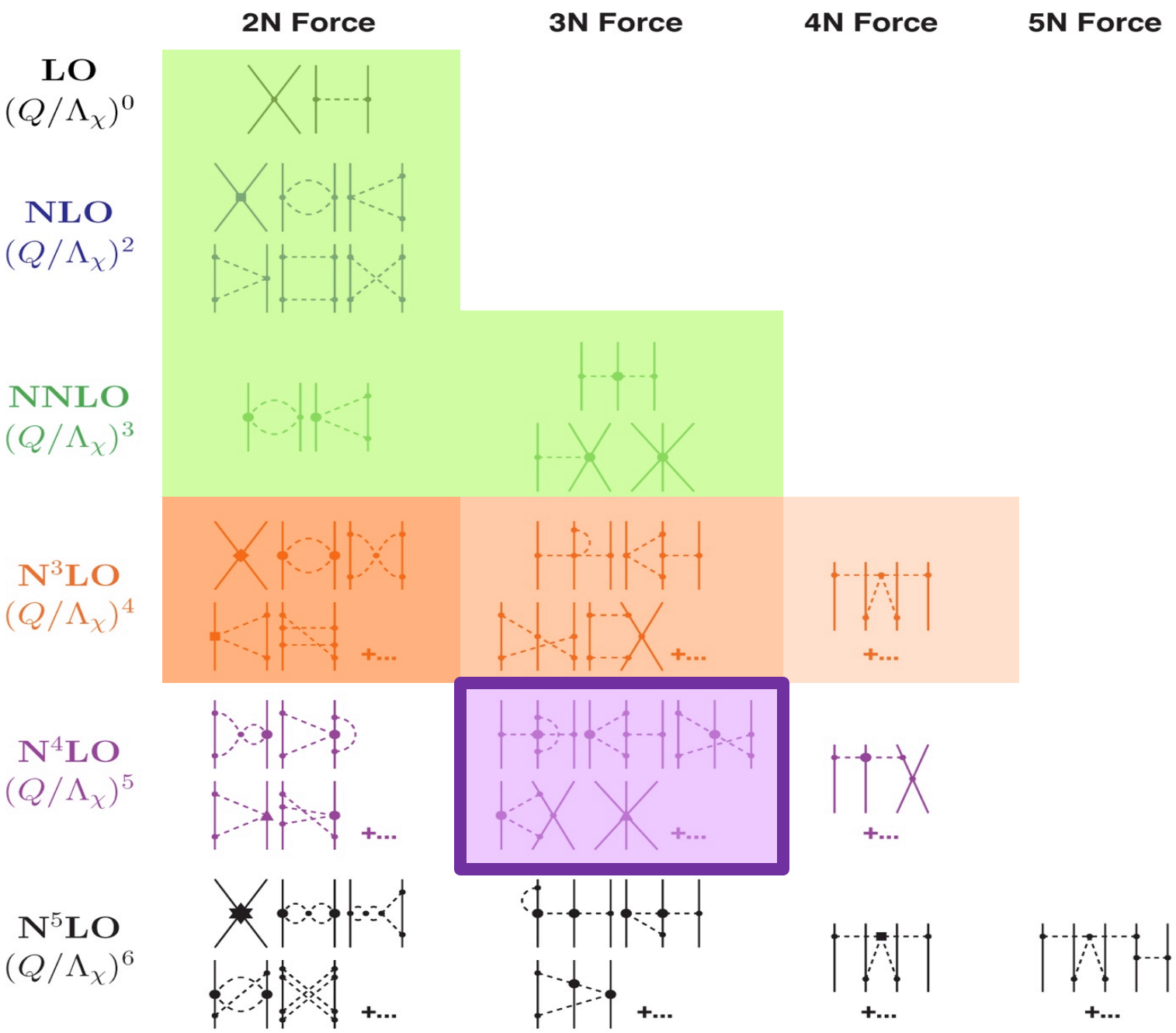


Figure 3: 8-parameter fit to $B(^3\mathrm{H})$, $^2a_{Nd}$ and all considered $p-d$ scattering observables at 3 MeV proton energy, for $\Lambda = 300$ MeV. Blue dashed curves corresponding to the AV18 *NN* interaction, while the red solid ones include the fitted TNI.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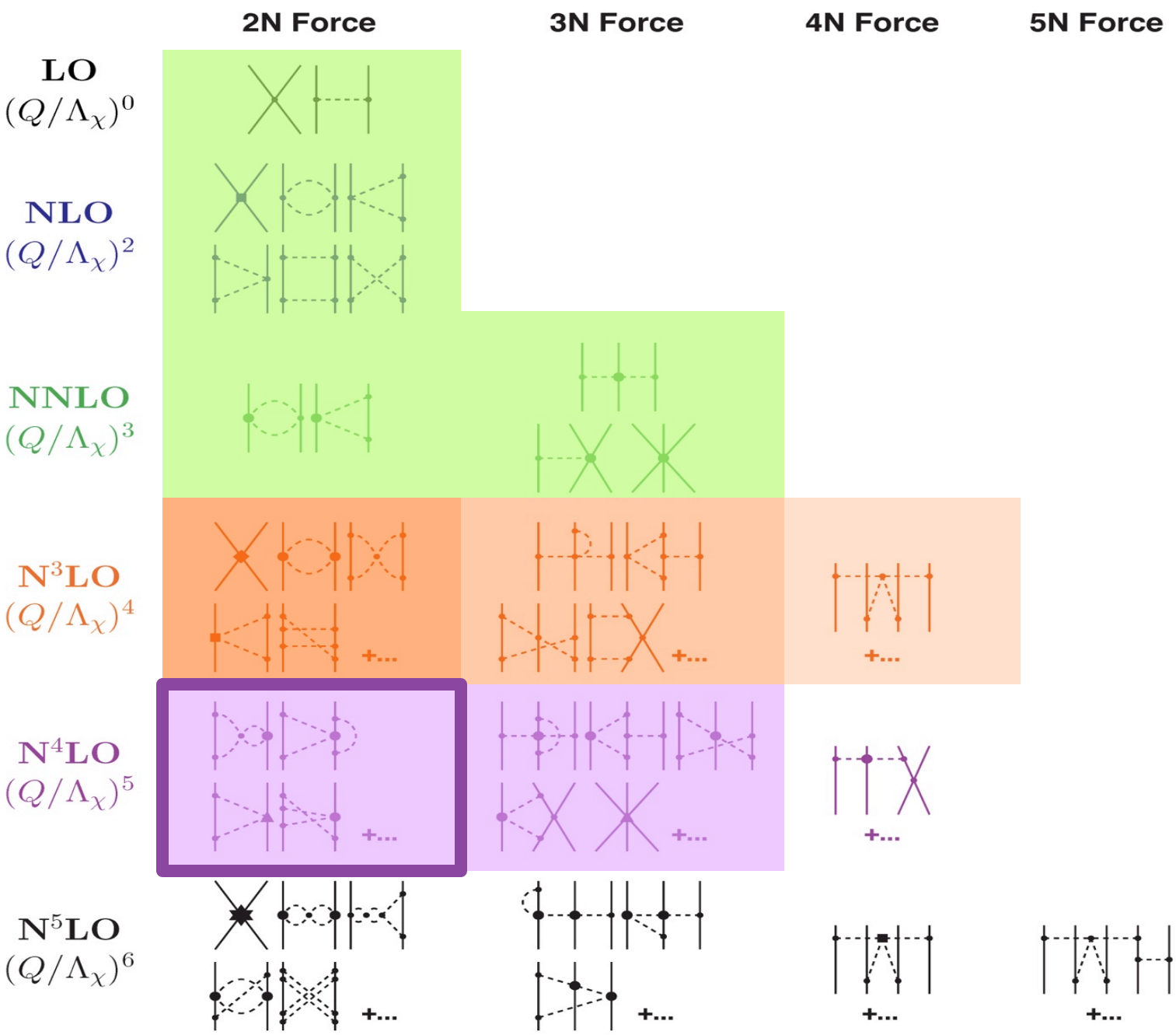
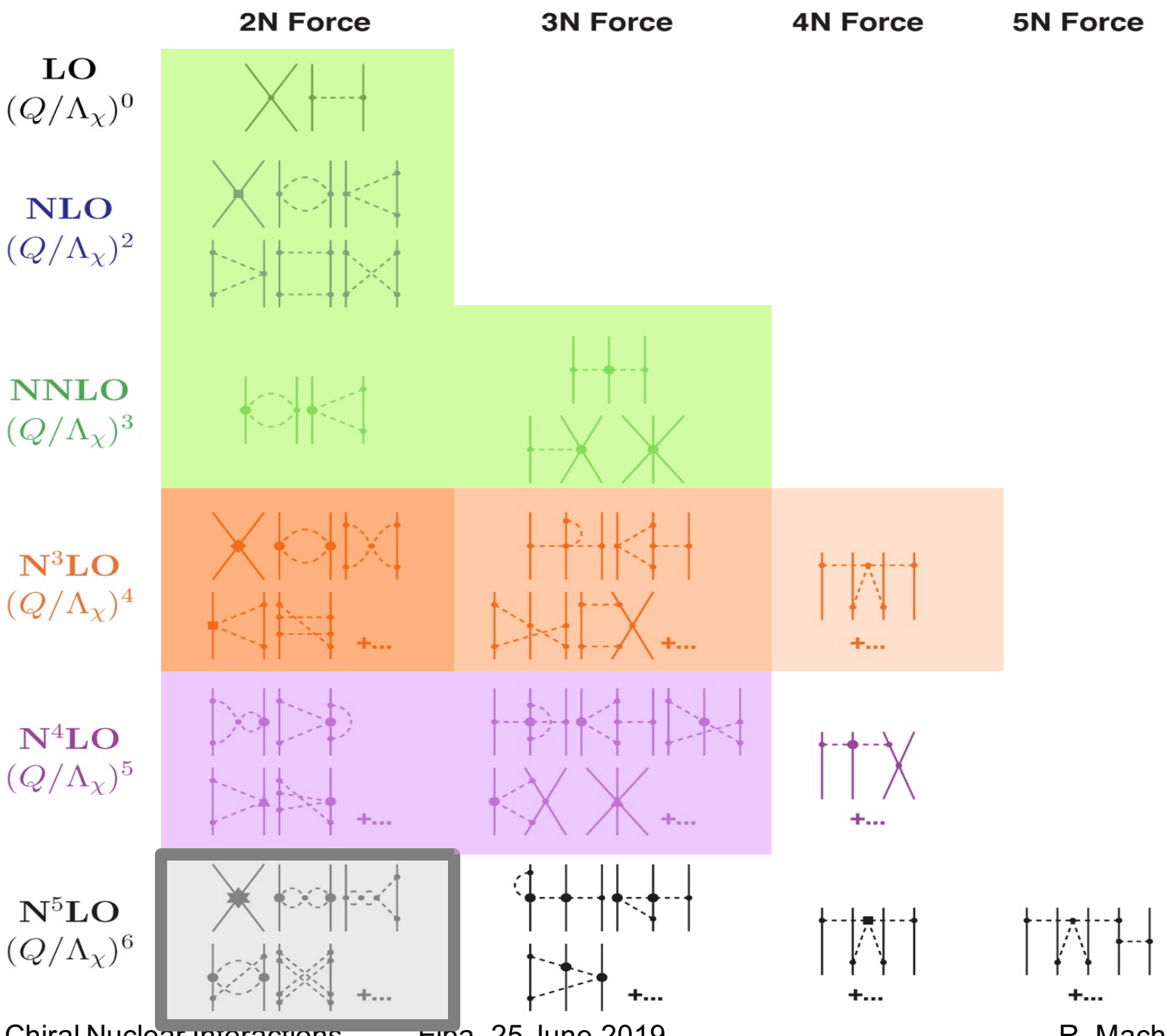
+...


2N Force
3N Force
4N Force
5N Force
LO
$(Q/\Lambda_\chi)^0$
NLO
$(Q/\Lambda_\chi)^2$
NNLO
$(Q/\Lambda_\chi)^3$
N^{3}LO
$(Q/\Lambda_\chi)^4$
N^{4}LO
$(Q/\Lambda_\chi)^5$
N^{5}LO
$(Q/\Lambda_\chi)^6$
+...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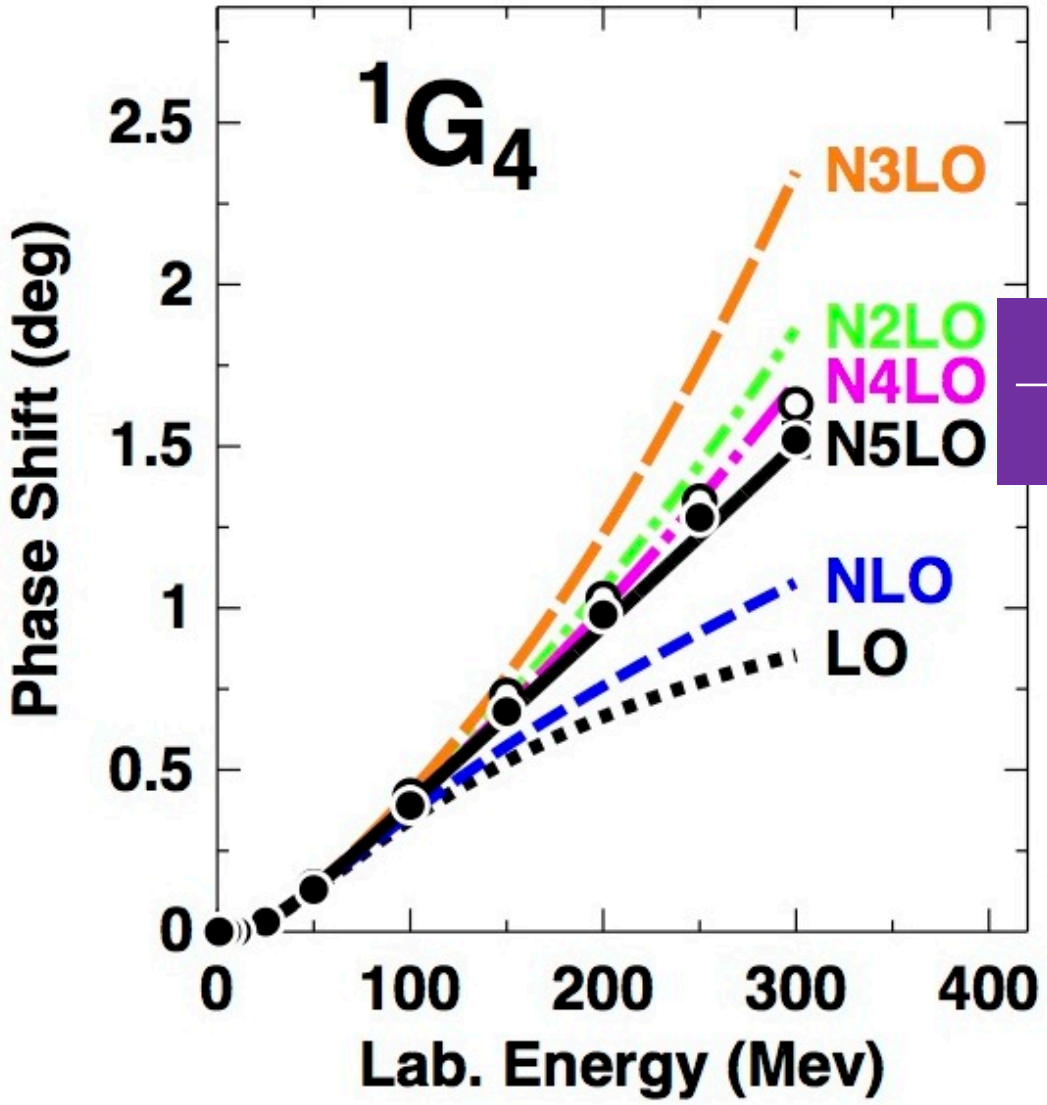
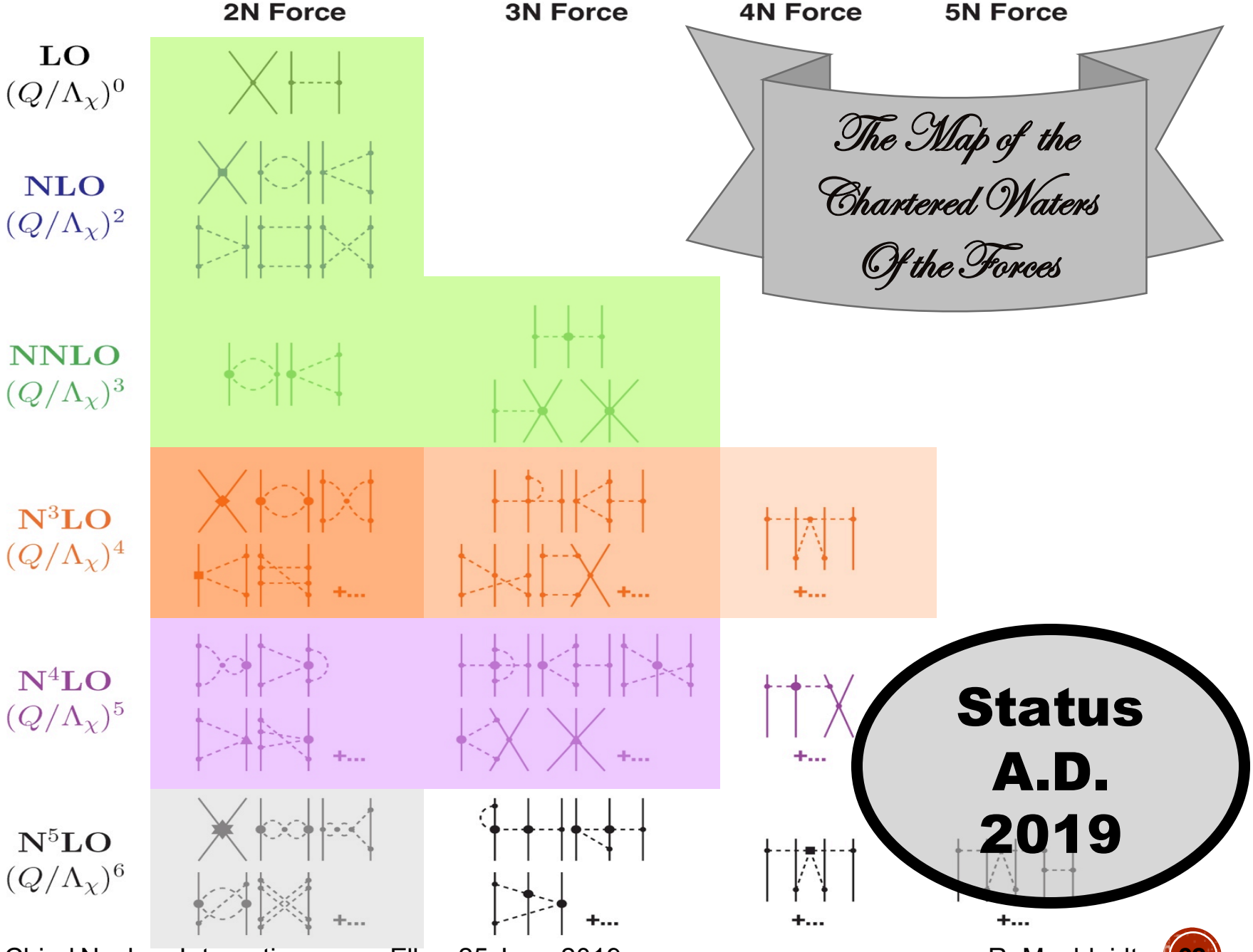


Converged at N4LO

From Entem, Kaiser, Machleidt, Nosyk, PRC 92, 064001 (2015)


2N Force
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LO
$(Q/\Lambda_\chi)^0$
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N^{4}LO
$(Q/\Lambda_\chi)^5$
N^{5}LO
$(Q/\Lambda_\chi)^6$
+...
The Map of the Chartered Waters Of the Forces
Status A.D. 2019

AND SO, RECENTLY, POTENTIALS HAVE BEEN CONSTRUCTED UP TO N4LO BY …

- Entem, Machleidt, Nosyk, PRC **96**, 024004 (2017); **non-local**.

- Reinert, Krebs, Epelbaum, Eur. Phys. J. A **54**, 86 (2018); **local**.

… with an excellent reproduction of the NN Data …

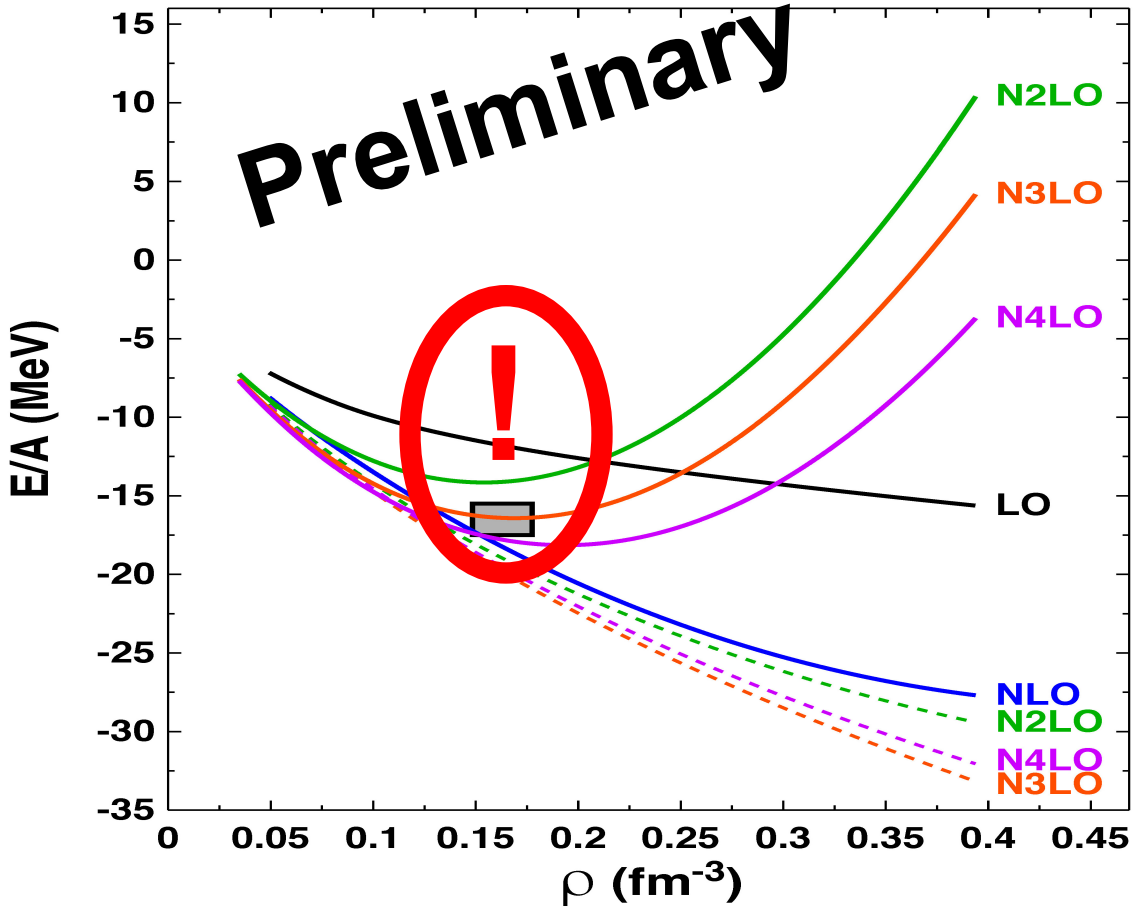
TABLE V: χ^2/datum for the fit of the 2016 NN data base y NN potentials at various orders of chiral EFT ($\Lambda = 500$ MeV in all cases).

$T_{\rm lab}$ bin (MeV)	No. of data	LO	NLO	NNLO	N^{3}LO	N^{4}LO
			proton-proton			
0–100	795	520	18.9	2.28	1.18	
0–190	1206	430	43.6	4.64	1.69	1.12
0–290	2132	360	70.8	7.60	2.09	1.21
			neutron-proton			
0–100	1180	114	7.2	1.38	0.93	0.94
0–190	1697	96	23.1	2.29	1.10	1.06
0–290	2721	94	36.7	5.28	1.27	1.10
			pp* plus *np			
0–100	1975	283	11.9	1.74	1.03	1.00
0–290	4853	206	51.5	6.30	1.63	1.15

(Includes ct's In F-waves.)

The above for Entem, Machleidt, Nosyk; Reinert, Krebs, Epelbaum similar.

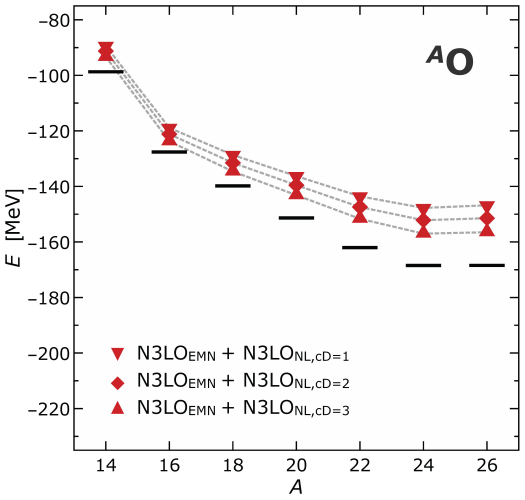
… and the following nuclear matter saturation properties …

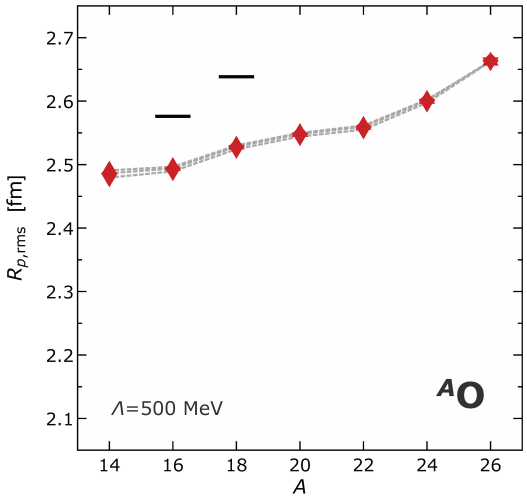


Applying the Entem, Machleidt, Nosyk potentials.
From F. Sammarruca *et al.*, to be published.

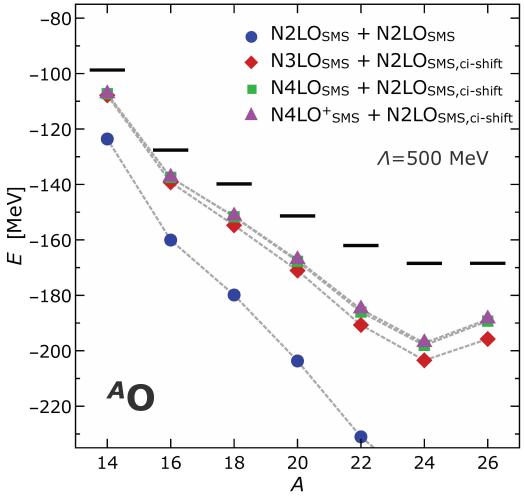
… and the following properties of finite nuclei …

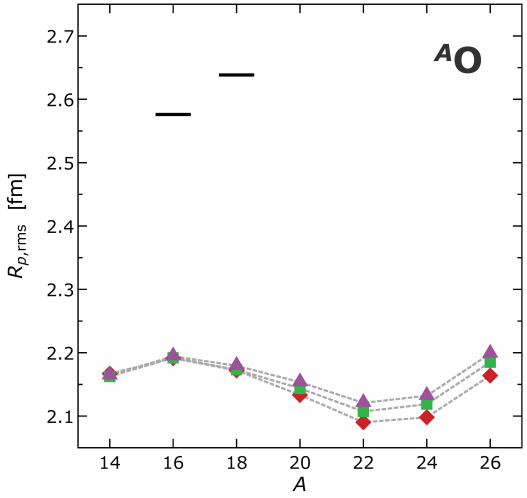
(Calculations by R. Roth et al., Darmstadt)





Applying the
Entem, Machleidt, Nosyk
Potentials which are
Non-local

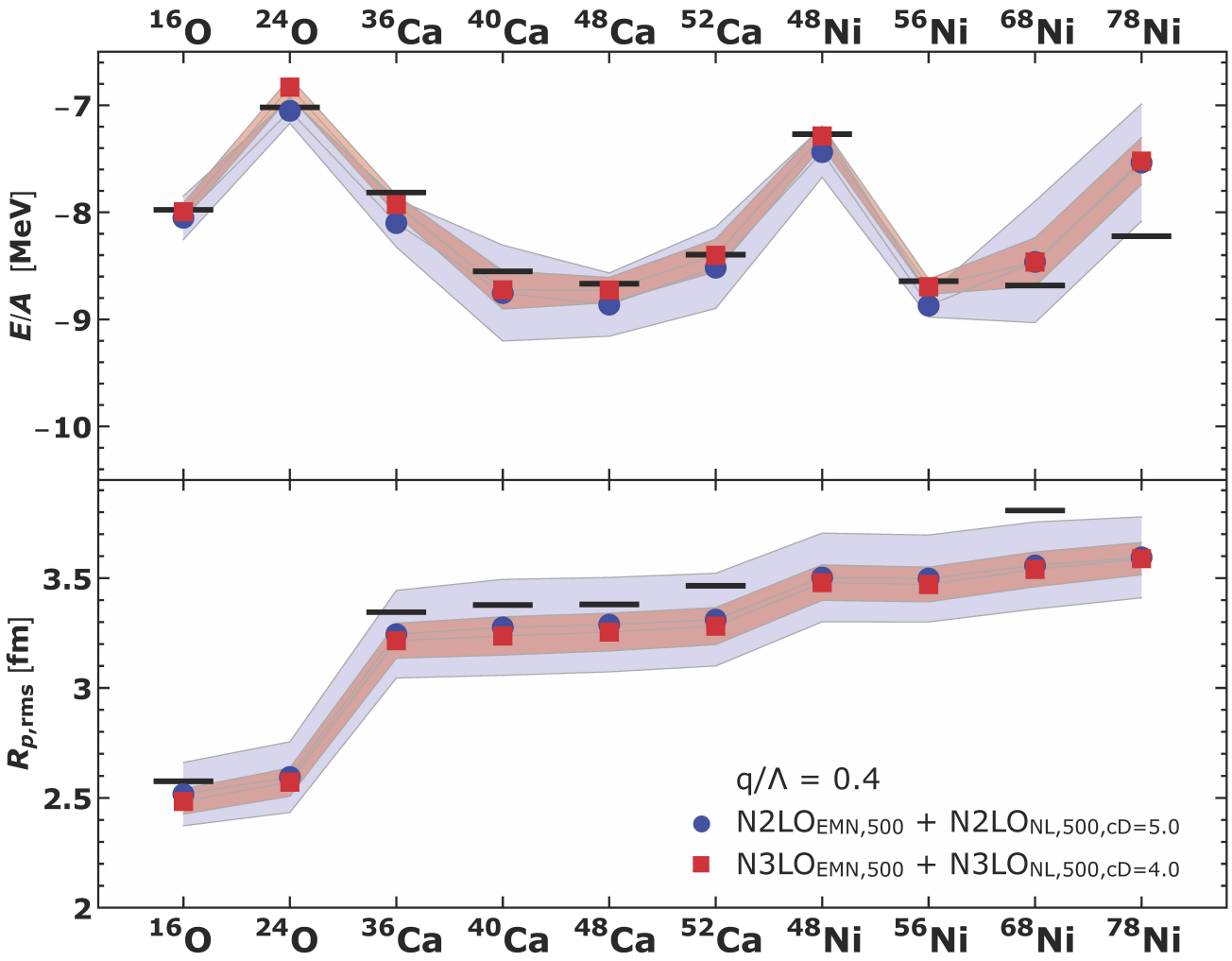




Applying the
Reinert, Krebs, Epelbaum
Potentials which are
Local

… and more properties of finite nuclei …

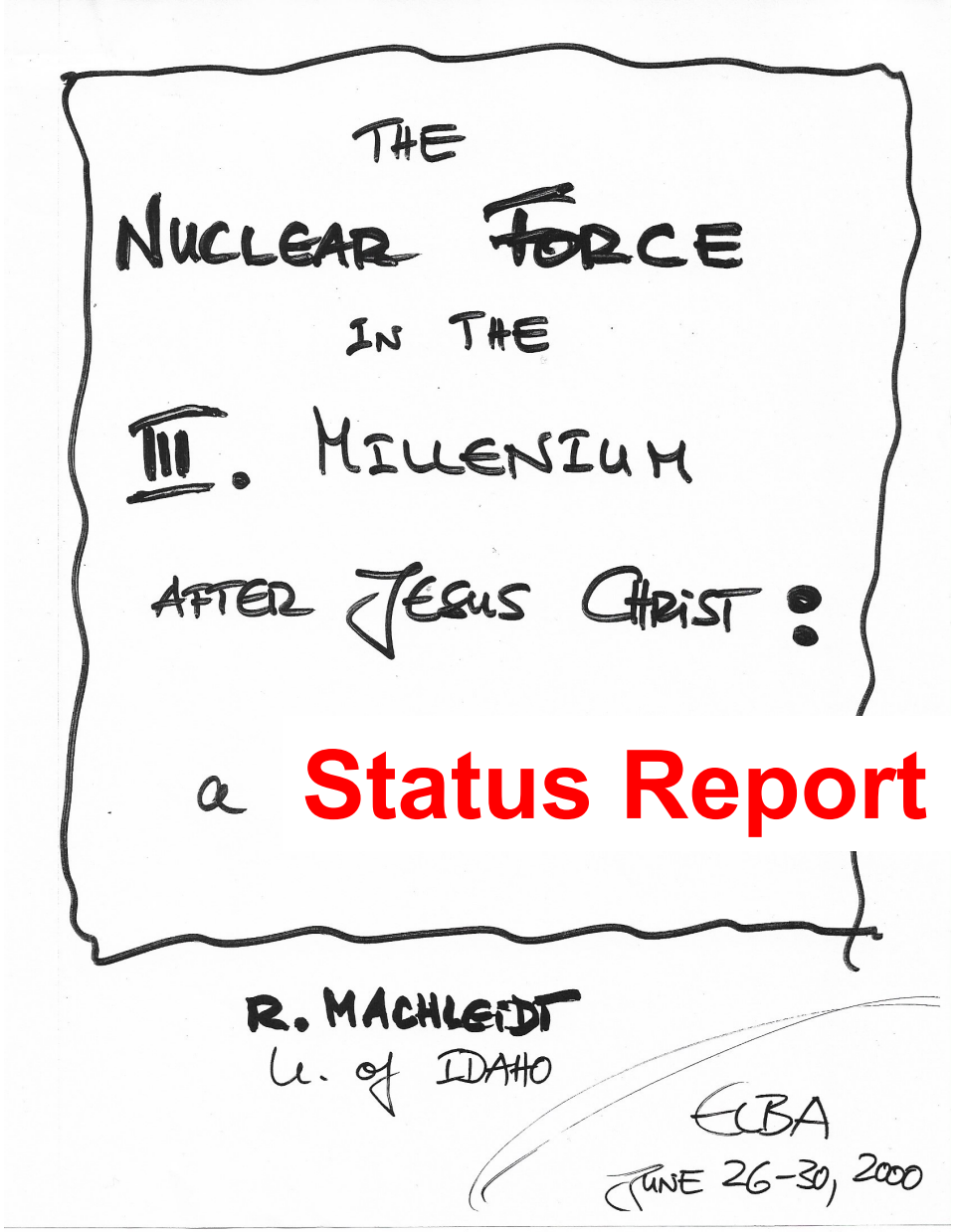
(Calculations by R. Roth et al., Darmstadt)



Applying the **Entem, Machleidt, Nosyk** Potentials which are **Non-local**

CONCLUSIONS

- Recently, there has been tremendous progress in the development of better nuclear forces based upon chiral EFT.
- Very quantitative NN potentials up to N4LO are available now.
- First applications in intermediate-mass nuclei show that the **non-local versions are very successful**, while the **local versions fail.**
- Further applications of the successfully tested potentials to issues like momentum distributions and short-range correlations (SRC) is now called for.


THE
NUCLEAR FORCE
IN THE
III. MILLENIUM
AFTER JESUS CHRIST:
a Status Report
R. MACHLEIDT
U. of IDAHO
ELBA
JUNE 26-30, 2000

THE PROGRAM FOR THE NEW MILLENIUM

For a reliable derivation of nuclear forces, we need

- a basic theory
  χ eff. field theory ✓
- that is amenable to calculations
  χPTh ✓
- yields quantitative results. ✓

~~Let's hope for it!~~

THE PROGRAM FOR THE NEW MILLENIUM

For a reliable derivation of nuclear forces, we need

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  ~~of~~ field theory
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~~Let's hope for it!~~

Mission accomplished