Why new power counting and does it give us more predictive power?

MITP workshop:
Uncertainty Quantification in Nuclear Physics

Chieh-Jen (Jerry) Yang

June. 25, 2024

The origin of coupling constants

Absolute theory or god-given-like fundamental theory
(Everything can be derived, none or very little fitting)

In reality/practice:
Some portion of details in the mother theory are **integrated out**, absorbed and encoded in the low energy constants (LECs).

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That‘s call renormalization, and it’s OK. But it will then be of importance to check whether the results after renormalization satisfies the renormalization group requirement.

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One should work on

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Current status: nuclear structure

- Most ab-initio calculations adopt chiral EFT potential organized under **Weinberg power counting** (WPC).
- Good results (w.r.t. exp. data) for light systems, if low-energy constants (LECs) are renormalized at NN/NNN-level.
- But not quite the same for ^{16}O (or heavier)➔ **need to refit** (optimize) the potential and **sacrifice** NN.

Why new PC (other than WPC)?

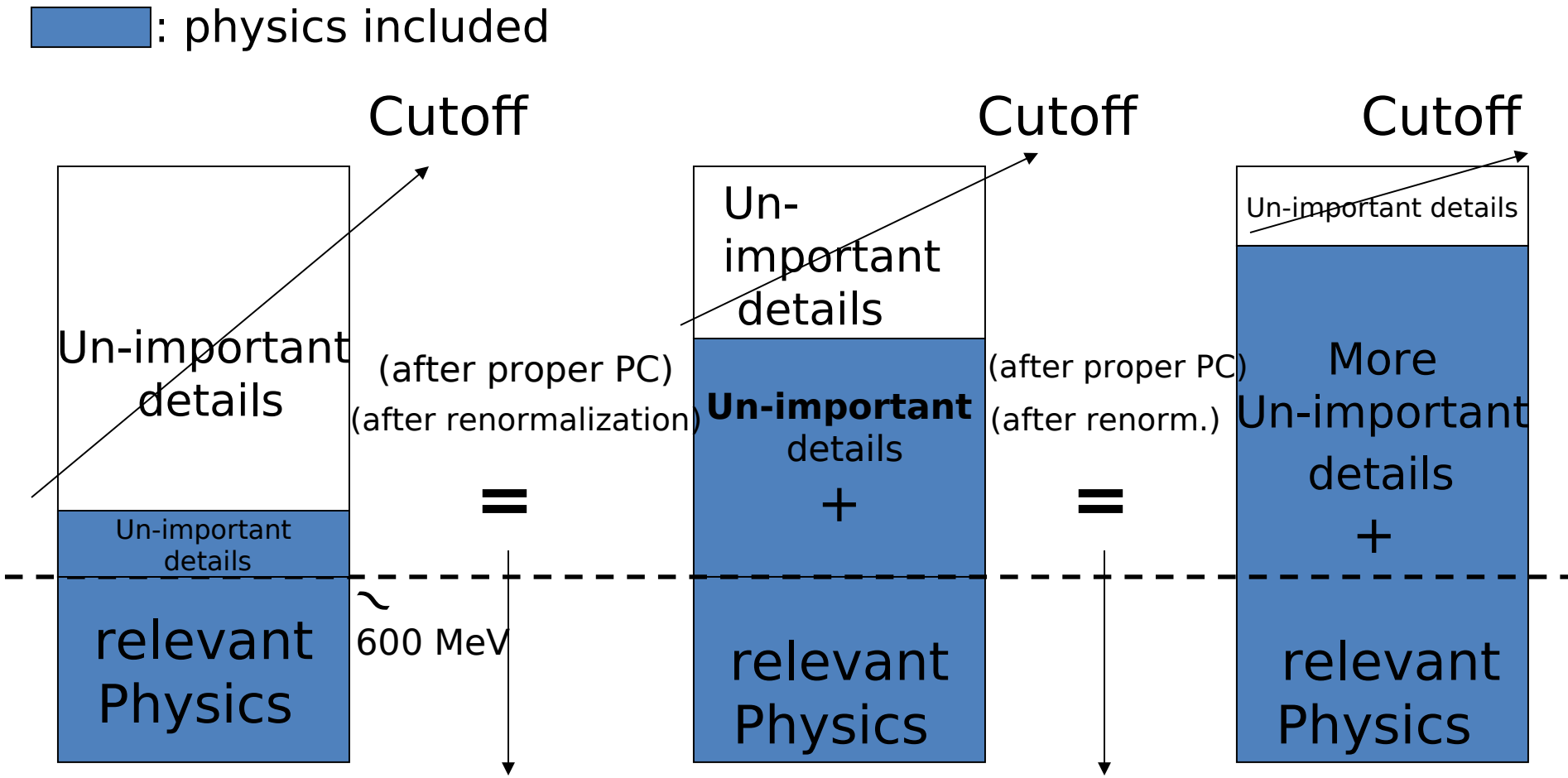
- The original proposal (WPC) is to **iterate all** chiral potentials **truncated** up to a certain order **non-perturbatively** (Weinberg 90', van Kolck, Epelbaum, Machleidt, etc.).

First problem: Once the pion-exchange is iterated, there's no way to properly renormalize the divergence caused by varying the pion mass.

Second problem: Even without varying m_π, there's still RG-issues (especially if Λ>600 MeV).

3rd problem (this applies to perturbative PC as well): The importance of many-body forces can grow with the number of nucleons.

Second problem (RG-related)



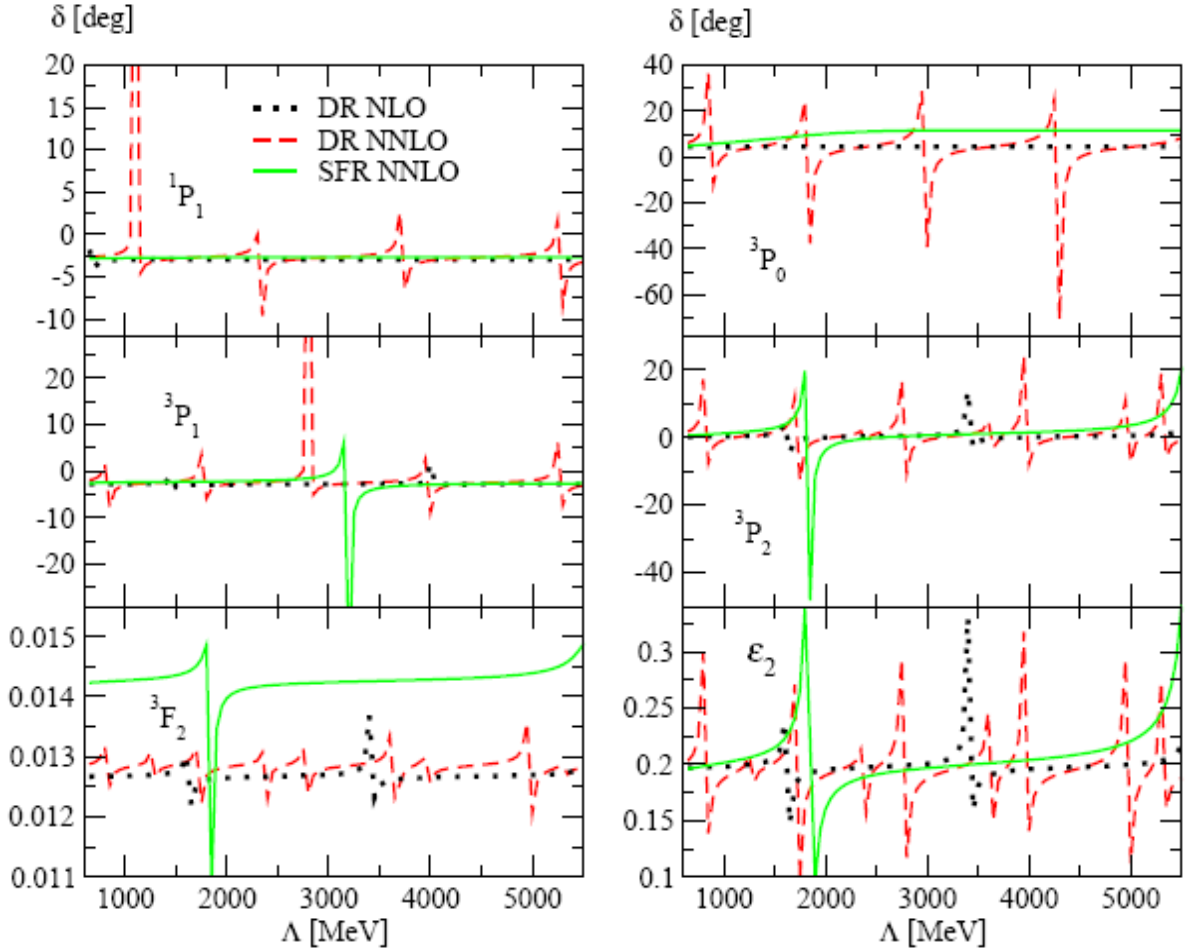
***Only source of error**: given by the high order terms.

If not so, ➡ **the power counting isn't completely correct!**

Problems of WPC

WPC is wrong at LO ! (Nogga, Timmermans, van Kolck, *PRC 72 (2005) 054006*)

- Beyond LO: (Yang, Elster, Phillips (2008-2010))



In short, WPC might be WPP (pragmatic proposal)
(many in-debate issues, but not the topic today)
More details/opinions could be found in:

Few Body Syst. 62 (2021) 4, 85 and Few Body Syst. 63, no.2, 44 (2022)

Nuclear Effective Field Theories: Reverberations of the early days

U. van Kolck

Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France
and
Department of Physics, University of Arizona, Tucson, AZ 85721, USA

July 27, 2021

What Can Possibly Go Wrong?

Harald. W. Grießhammer

Received: date / Accepted: date

Abstract A lot.

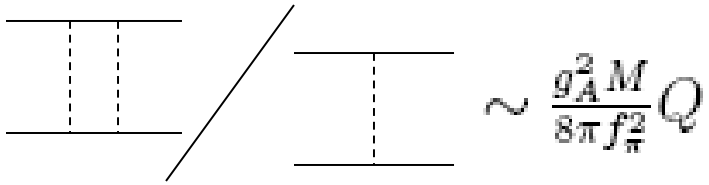
New power counting

Decided by RG

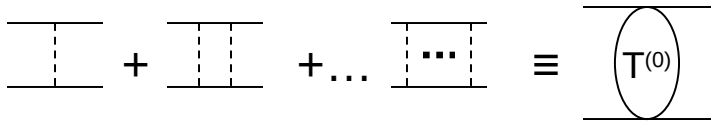
Long & Yang, (2010-2012)

LO: Still iterate to all order (at least for $l<2$).

Reason: van Kolck, Bedaque,… etc.



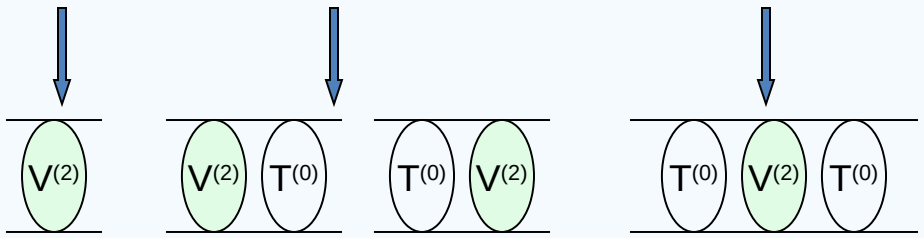
Thus, $O(Q^0)$:



Start at NLO, do perturbation. ($T = T^{(0)}+T^{(1)}+T^{(2)}+T^{(3)}+\ldots$)

If $V^{(1)}$ is absent:

$T^{(2)} = V^{(2)} + 2V^{(2)}GT^{(0)} + T^{(0)}GV^{(2)}GT^{(0)}.$



$$G \equiv \frac{2M_N}{\pi} \int^{\Lambda} \frac{p^2 dp}{p_0^2 - p^2 + i\varepsilon}$$

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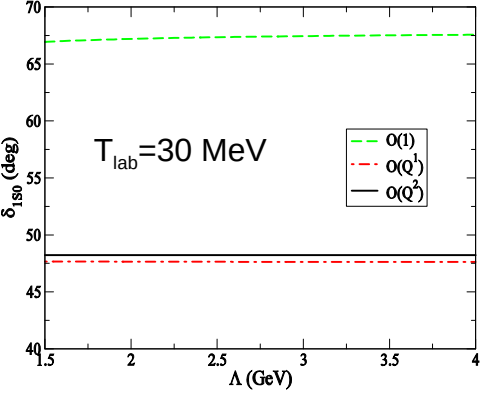
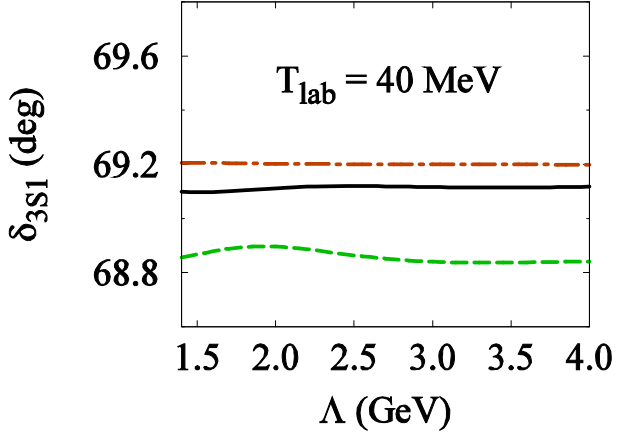
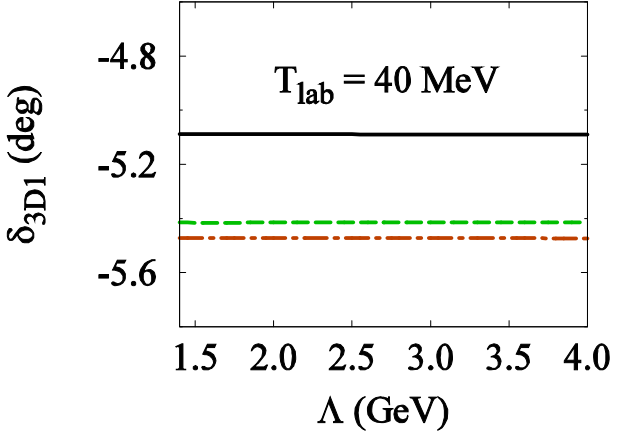
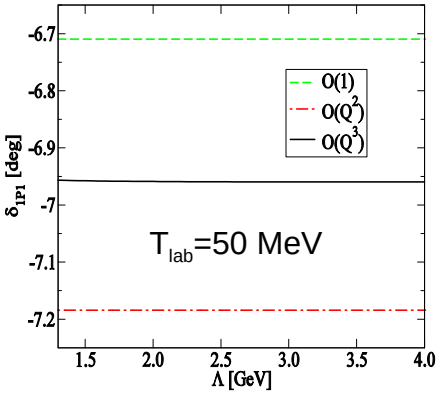
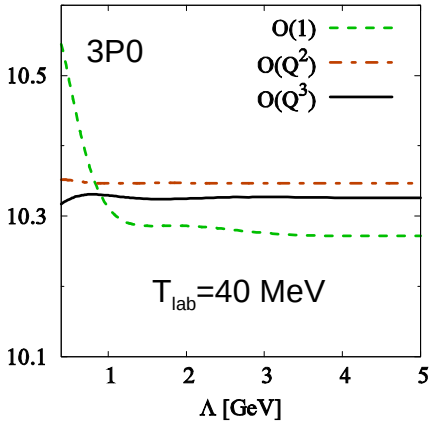
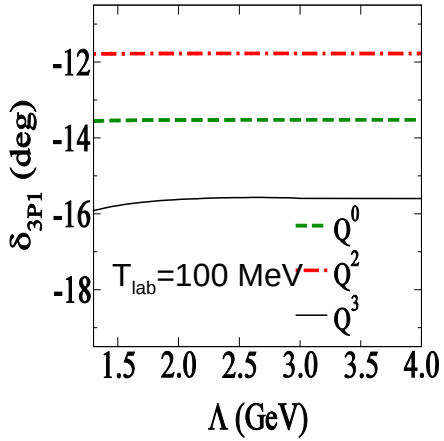

T_{lab}=30 MeV
O(1)
O(Q)
O(Q²)
δ_{1S0} (deg)
Λ (GeV)

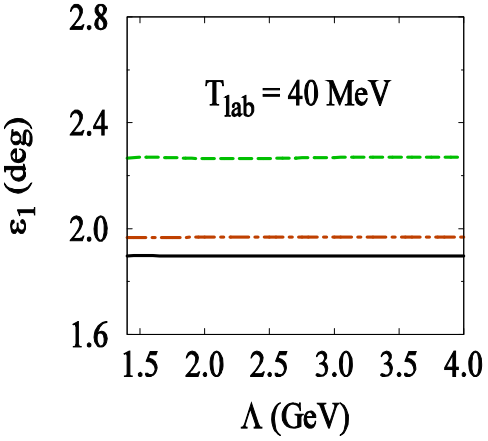

T_{lab} = 40 MeV
δ_{3S1} (deg)
Λ (GeV)

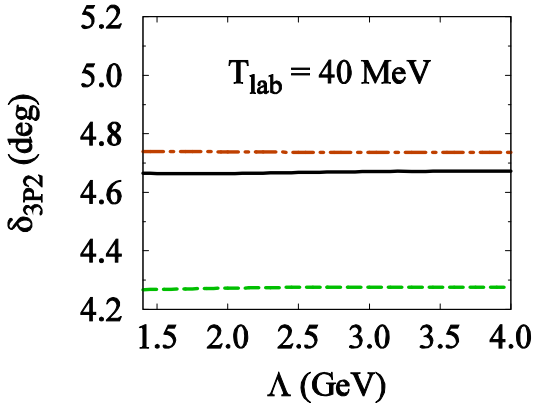

T_{lab} = 40 MeV
δ_{3D1} (deg)
Λ (GeV)

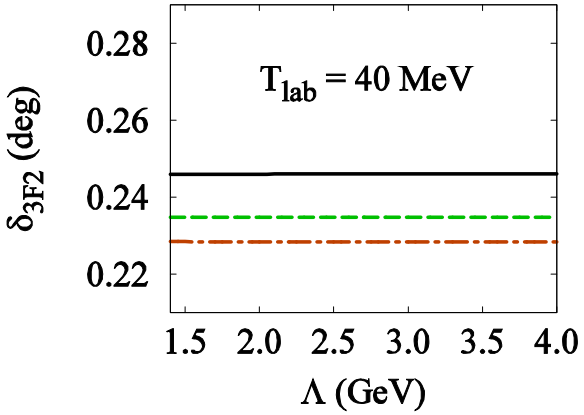

O(1)
O(Q²)
O(Q³)
T_{lab}=50 MeV
δ_{1P1} [deg]
Λ [GeV]

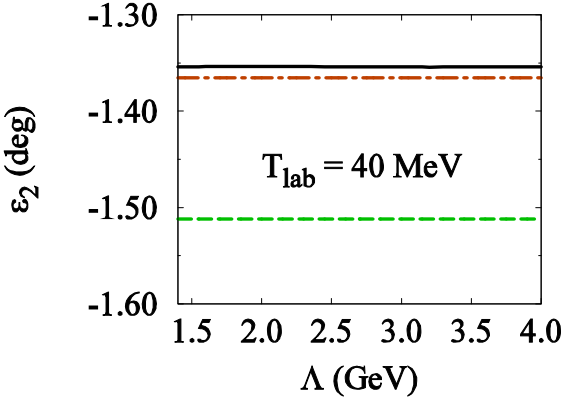

3P0
O(1)
O(Q²)
O(Q³)
T_{lab}=40 MeV
Λ [GeV]


T_{lab}=100 MeV
Q⁰
Q²
Q³
δ_{3P1} (deg)
Λ (GeV)


T_{lab} = 40 MeV
ε_1 (deg)
Λ (GeV)


T_{lab} = 40 MeV
δ_{3P2} (deg)
Λ (GeV)


T_{lab} = 40 MeV
δ_{3F2} (deg)
Λ (GeV)


T_{lab} = 40 MeV
ε_2 (deg)
Λ (GeV)

So, has conceptual problems (except the pion mass dep.) been basically solved !/?

If Yes: then the next step will be to refine the PC, push it to higher-orders, and apply the **Bayesian** analysis to test/optimize the fitting and arrange finer detail of the modified PCs (so far 3 versions under DWBA).

M. Birse, M.P. Valderrama, Long&Yang

Not so fast! → There are still (at least) 3 conceptual challenges.

1. Issue of “exceptional zero” (Gasparyan & Epelbaum).
2. Recovery of poles (e.g., bound states) beyond LO.
3. The importance of many-body forces.

Will be covered today

ECT* Aug.19-23.

1. Issue of “exceptional zero”

PHYSICAL REVIEW C **107**, 034001 (2023)

“Renormalization-group-invariant effective field theory” for few-nucleon systems is cutoff dependent

A. M. Gasparyan* and E. Epelbaum†
Ruhr-Universität Bochum, Fakultät für Physik und Astronomie, Institut für Theoretische Physik II, D-44780 Bochum, Germany

(Received 10 November 2022; accepted 10 March 2023; published 28 March 2023)

We consider nucleon-nucleon scattering using the formulation of chiral effective field theory which is claimed to be renormalization group invariant. The cornerstone of this framework is the existence of a well-defined infinite-cutoff limit for the scattering amplitude at each order of the expansion, which should not depend on a particular regulator form. Focusing on the $^3P_0$ partial wave as a representative example, we show that this requirement can in general not be fulfilled beyond the leading order, in spite of the perturbative treatment of subleading contributions to the amplitude. Several previous studies along these lines, including the next-to-leading order calculation by B. Long and C. J. Yang [Phys. Rev. C **84**, 057001 (2011)] and a toy model example with singular long-range potentials by B. Long and U. van Kolck [Ann. Phys. **323**, 1304 (2008)], are critically reviewed and scrutinized in detail.

DOI: 10.1103/PhysRevC.107.034001

RG-issue at NLO of long & Yang

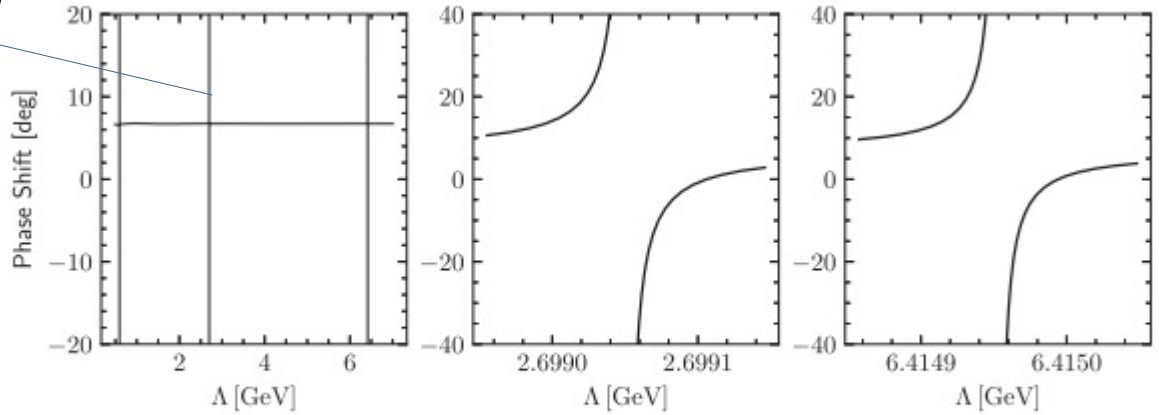


FIG. 5. Cutoff dependence of $^3P_0$ phase shift calculated at the fixed laboratory energy of $T_{\text{lab}} = 130$ MeV using the approach of Ref. [30] at NLO. The middle and right panels show zoomed regions in the vicinity of two exceptional cutoffs.

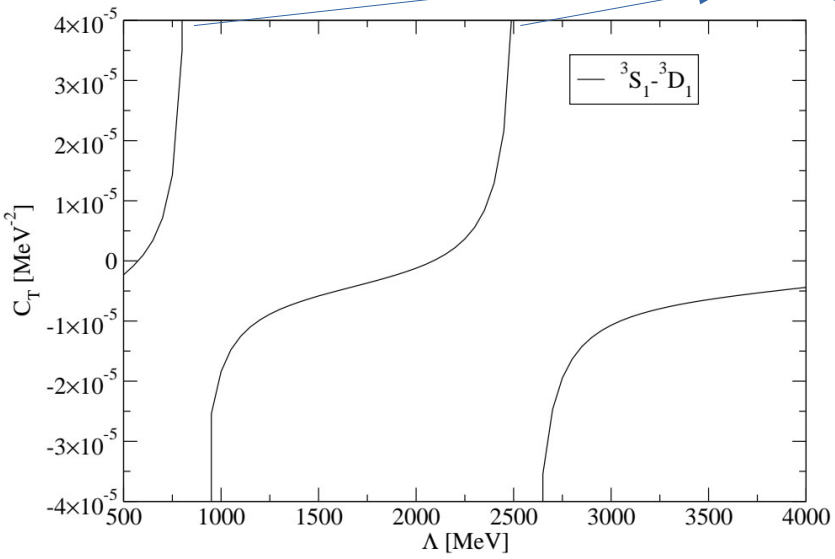
Origin of the issue

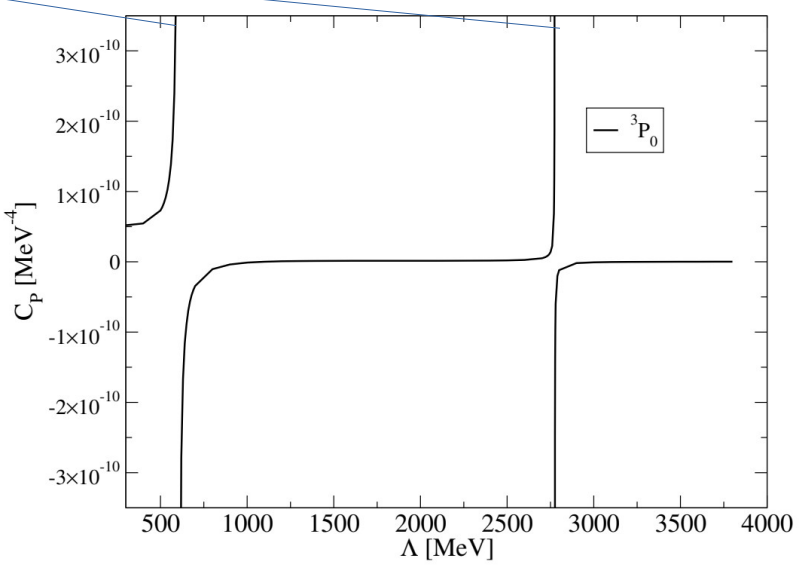
- LECs at LO (non-per. treatment) could have limit-cycle running.
- At LO, this is ok, even exactly at Λ_e where $c(\Lambda_e)=\infty$. Because: (non-per) = (matrix diagonalization), which guarantee that **each eigenvalue $\langle\Phi_{LO,i}|H_{LO}|\Phi_{LO,i}i\rangle=E_i$ is finite**.

  $\because$ <KE> and $\langle V_{LO}\rangle$ are finite, => $c(\Lambda_e)\langle\Phi_{LO,i}|\hat{O}_{ct}|\Phi_{LO,i}\rangle$=finite for all i.

∞ 0

You could perform subtraction to get δ at Λ_e.





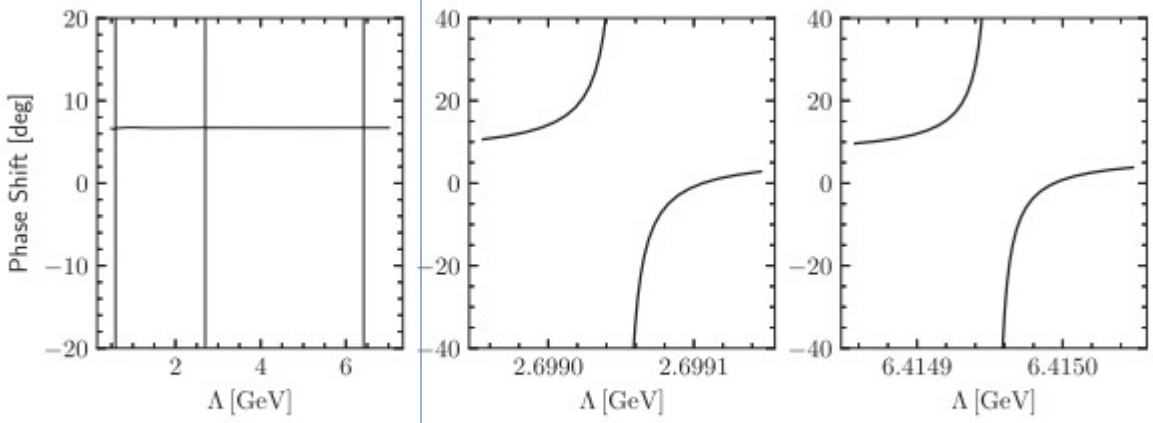
However, the same **won't hold** for NLO or higher-orders, if **DWBA** is adopted.

Origin of the issue

- At NLO (or higher), additional CT enters, but unlike LO, where $c(\Lambda_e)\langle\Phi_{LO,i}|\hat{O}_{LO,ct}|\Phi_{LO,i}\rangle$=finite for all i, the DWBA correction $d(\Lambda_*)\langle\Phi_{LO,i}|\hat{O}_{NLO,ct}|\Phi_{LO,i}\rangle\neq$finite for all i (as we are not protected by the eigenvalue feature).

  => At a certain i* (correspond to E*), $\langle\Phi_{LO,i}|\hat{O}_{NLO,ct}|\Phi_{LO,i}\rangle=0$, but for other i it's not!

- This means, if one **choose to renormalize** at E=E*, one faces the choice of using $d\to\infty$, in order to have a non-zero NLO correction. But then observable at other E blow up. On the other hand, using $d\neq\infty$ will make this CT have zero contribution (not good either).



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Allowed to choose anywhere below M_{hi}

In practice (on Long & Yang)

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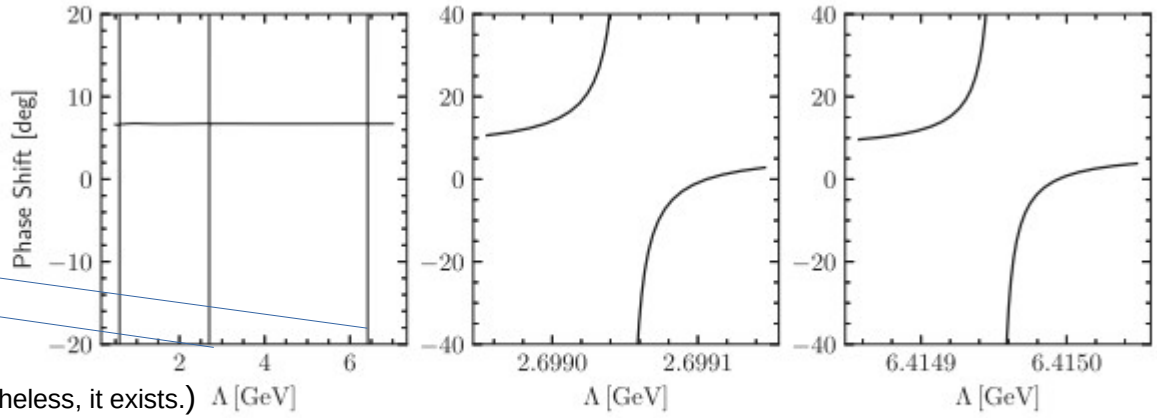
Problematic Λ_*, where $E^*\in p_{tye}$

(Extremely narrow, nevertheless, it exists.)



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Conditions of the breakdown (for the above case$_{Long\&Yang}$):

1. $\hat{O}_{NLO,ct}\neq\hat{O}_{LO,ct}$
2. Adopt Λ very close (>4 significant digits the same) to those problematic Λ_*.
3. Choose to renormalize **exactly** at E* (or exactly on a set of particular E_i, if number of LECs≥2).

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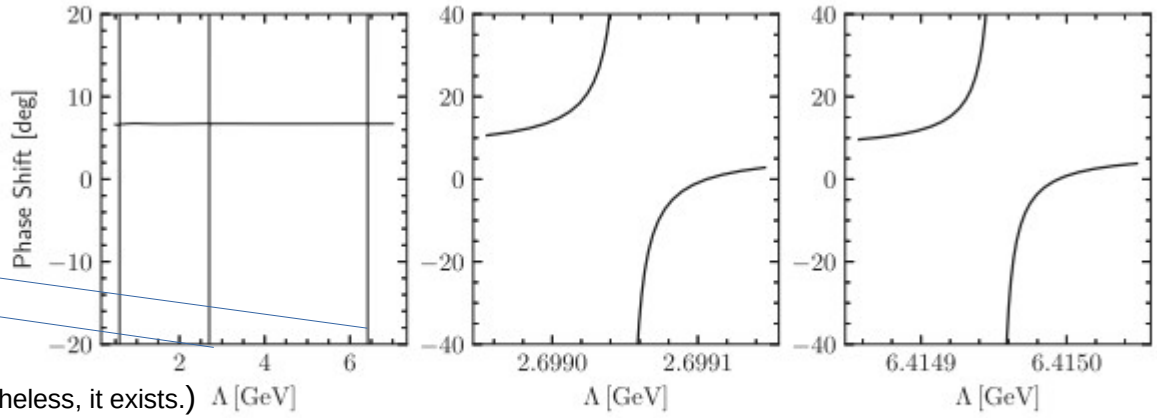

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Key word!

Origin of the issue

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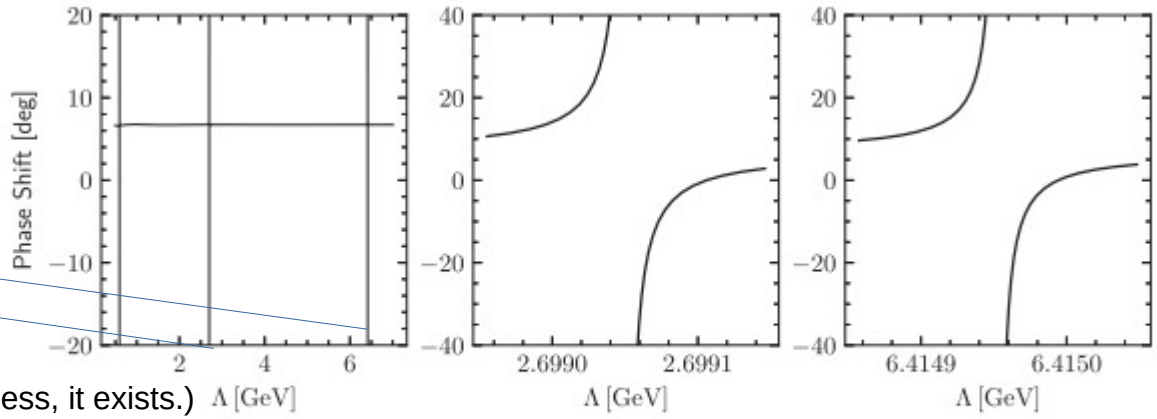

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However, the issue occurs only when one treats those incomplete, truncated amplitudes exactly or beyond the degree to which they should be trusted.

Root of the problem (**nothing to do with PC**, but a general feature of perturbative corrections)

The above has taken $\langle\Phi_{LO,i}|$ (and therefore the **NLO matrix element**) too **exact**.

Under EFT, it should always be accompanied by an uncertainty $\sim O(p/M_{hi})^n$.

Under EFT principles, one should always associate the result with an uncertainty which is adequate to its EFT order.

$$O_n(M_{lo};\Lambda;M_{hi})=\sum_i^n \left(\frac{M_{lo}}{M_{hi}}\right)^i \wp_i(M_{lo};M_{hi})+\Re_n(\Lambda;M_{lo};M_{hi})\left(\frac{M_{lo}}{M_{hi}}\right)^{n+1}$$

Trustable part — uncertainty

You are allowed to choose to fit anywhere below M_{hi}, but shouldn't ignore the EFT uncertainty associated with the observable you renormalize to.

In other words, you shouldn't ask what will happen if you choose to renormalize exactly at E*, if your result doesn't have this accuracy!

One way to accommodate this is to encode its effect into a more general form of contact terms, or, a slight change on the regulator.

1. $f_R(\Lambda)\rightarrow F_R=xf_a(\Lambda)+(1-x)f_b(\Lambda)$

Choose two regulators have only slight difference

$0\le x\le 1$, *x accounts for uncertainty ,not an LEC !*

2. *Requirement*: *for* $0\le x\le 1$, *the variation of* $\left|\langle\phi|(V_{NLO}F_R)|\phi\rangle_i\right|\le\Re_n(M_{lo};\Lambda;M_{hi})\left(\frac{M_{lo}}{M_{hi}}\right)^{n+1}$ *holds for all* $p_i\le M_{hi}$.

⬇ If yes

Then you are allow to adjust *x* to whatever value ∈[0,1], and see if this avoid the aforementioned issue. => E.g., if the original issue occurs at x=1 with f_a, see if x=0.5 it still persists

For PC of Long & Yang

- Adopting $xf_a(\Lambda)+(1-x)f_b(\Lambda+\Lambda/1000)$ (or: f_a sharp cutoff, f_b as a super-gaussian) solves the issue.

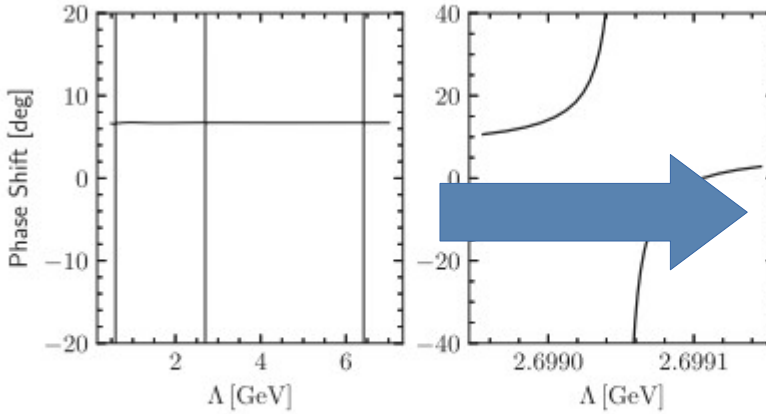
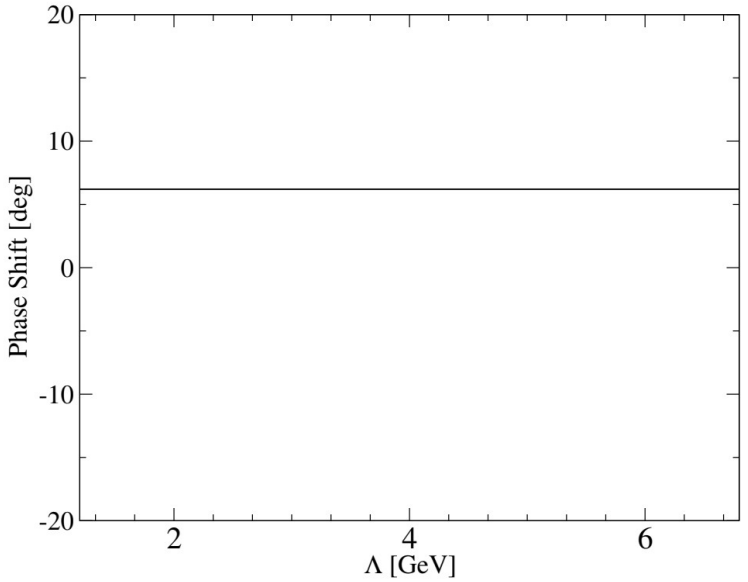


FIG. 5. Cutoff dependence of $^3P_0$ phase shift calculated at the fixed laboratory energy
at NLO. The middle and right panels show zoomed regions in the vicinity of two exceptior



C.-J. Yang et al, in preparation.

For the toy model

$\Lambda_{NLO}=2\Lambda_{LO}$ or $\Lambda_{LO}/2$ of Gasparyan & Epelbaum

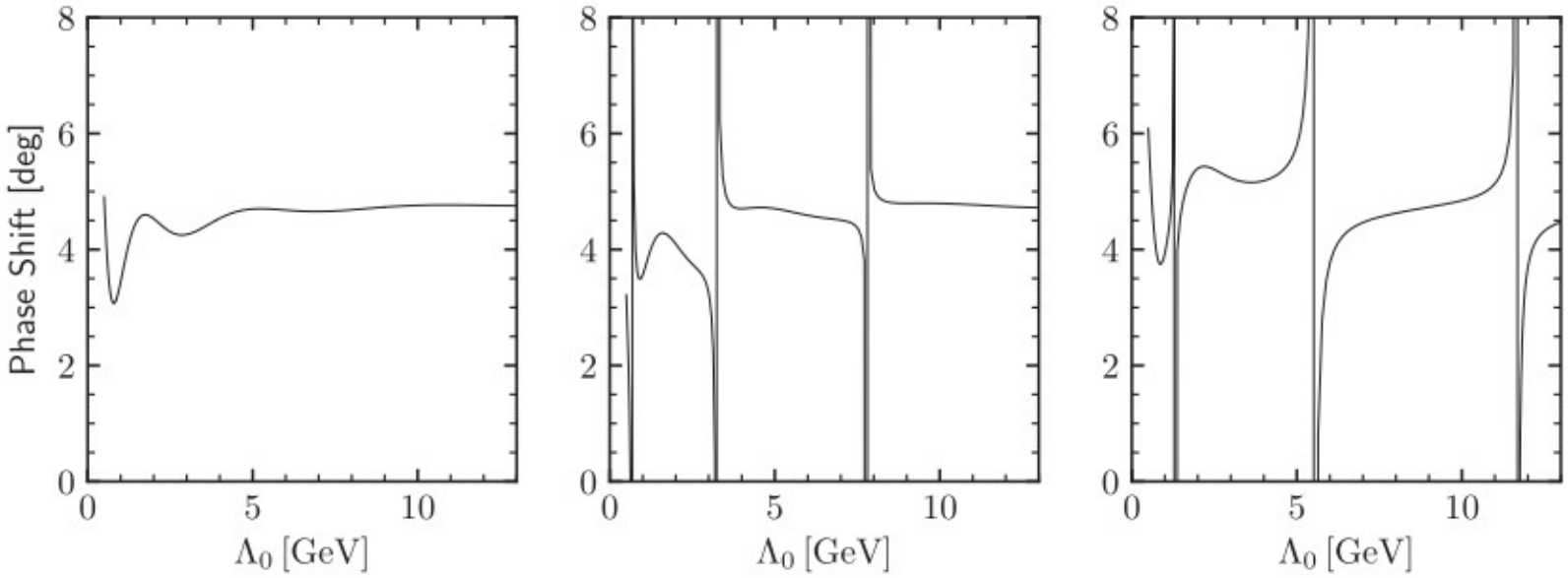
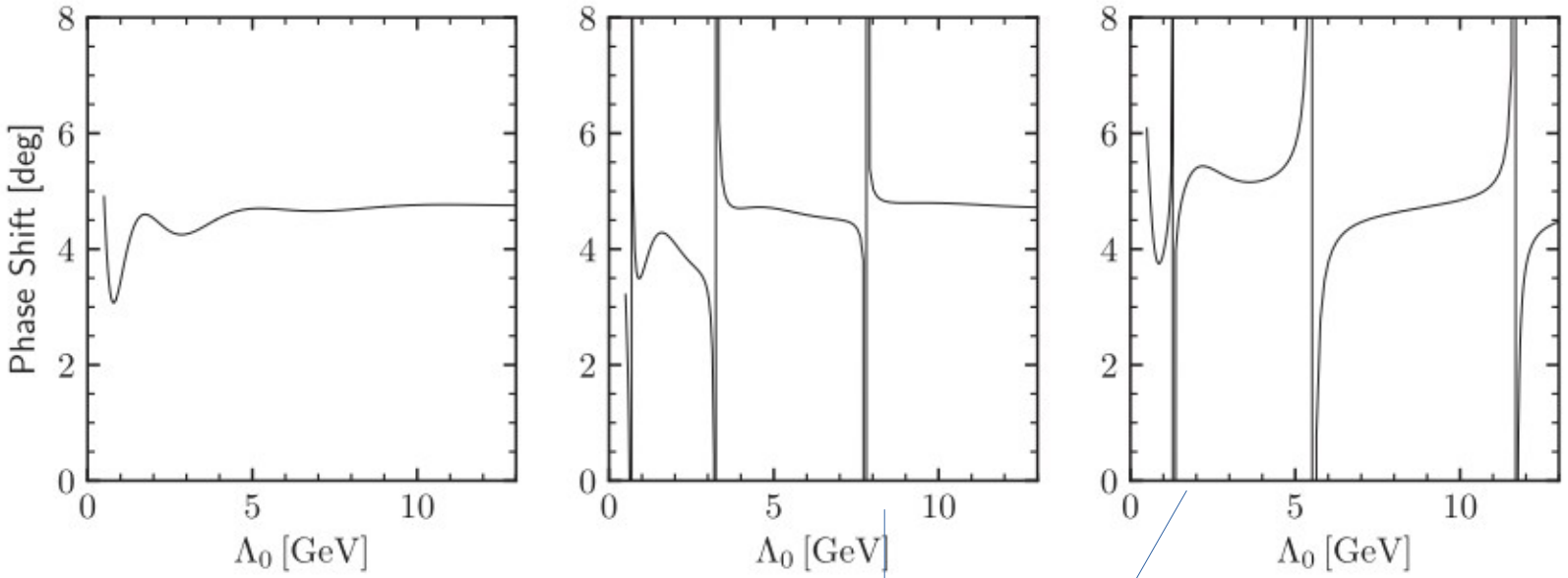


FIG. 2. The $^3P_0$ phase shift at the fixed laboratory energy of $T_{\rm lab} = 130$ MeV calculated in the simplified model at NLO as a function of the cutoff for $\Lambda_2 = \Lambda_0$ (left panel), $\Lambda_2 = 2\Lambda_0$ (middle panel), and $\Lambda_2 = \Lambda_0/2$ (right panel).

This is equivalent to imposing $F_R=xf_a+(1-x)f_b$, where $f_b=f_a(2\Lambda)$ or $f_b=f_a(\Lambda/2)$.

$$\textit{The variation of } \left|\langle\phi|(V_{NLO}F_R)|\phi\rangle_i\right| (\textit{for } 0\le x\le 1) \gg \Re_n(M_{lo};\Lambda;M_{hi})\left(\frac{M_{lo}}{M_{hi}}\right)^{n+1} > 200\,\% \times \left|\langle H_{LO}\rangle_i\right|.$$

For the toy model $\Lambda_{NLO}=2\Lambda_{LO}$ or $\Lambda_{LO}/2$ of Gasparyan & Epelbaum



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This means, the problem **cannot** be cured by taking uncertainty into account.

→ It's a real problem.

In other words, DWBA-based PC really doesn't work for the prescribed potentials.

Restoration of bound-states

- Bound-states are poles in S-matrix, they cannot be generated perturbatively.
- If the H_{LO} misses that, you're in trouble!

Restoration of bound-states

- The problem is very real.

  E.g., ^{16}O is unbound w.r.t. 4α at LO, for XEFT under WPC or MWPC. Also, for pionless EFT.

IF the amplitude (e.g., T-matrix) is analytic, there are hopes
→ EFT-guided re-summation.
Performed extensively in pionless EFT at few-body level.

For A>3 or numerical solutions.
Q: whether one can shift resonances/virtual states to bound-states perturbatively.

PHYSICAL REVIEW C **109**, 054003 (2024)

Feasibility of perturbative generation of bound states from resonances or virtual states

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(Received 8 December 2023; revised 20 March 2024; accepted 7 May 2024; published 24 May 2024)

I investigate whether it is possible to generate bound states from resonances or virtual states through first-order perturbation theory. Using contact-type potentials as those appeared in pionless effective field theory, I show that it is possible to obtain negative-energy states by sandwiching a next-to-leading order interaction with the leading-order (LO) wave functions, under the presence of LO resonances or virtual states. However, at least under the framework of time-independent Schrödinger equation and Hermitian Hamiltonian, there is an inability to create bound states with structure similar to those formed by the nonperturbative treatments.

DOI: 10.1103/PhysRevC.109.054003

Conclusion: Not very feasible!

Method

- Solve the LO non-per.,→ obtain $\Phi_{LO,i}$ and E_i^{LO}.
- Straightly apply 1st order perturbation theory to get E_i^{NLO}, then see if $E_i^{LO}+E_i^{NLO}<0$.
- Evaluate using HO-basis, with $\hbar w=1$ MeV and $N_{max}>150$ (increase until uncertainty <1%).

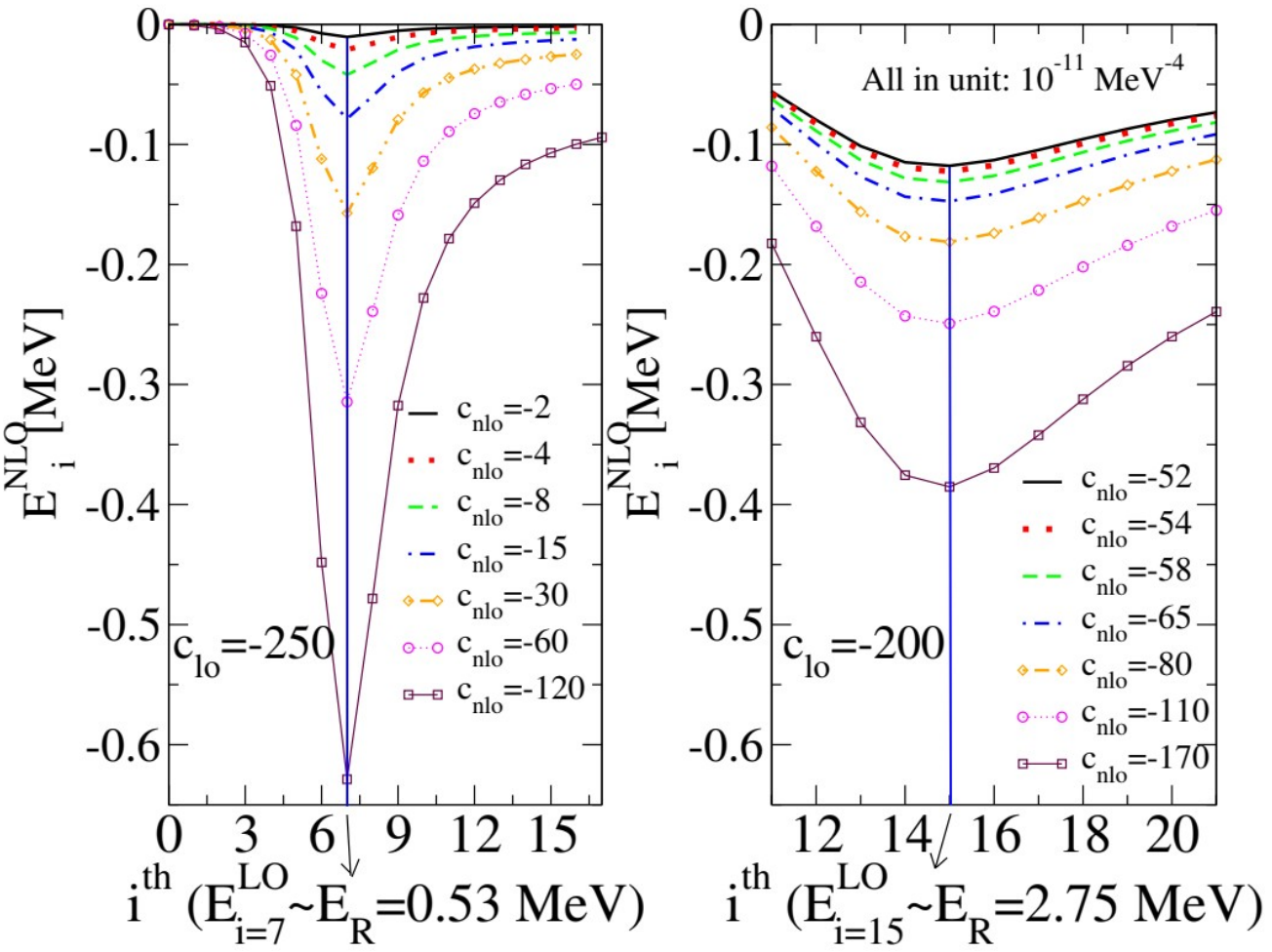
Example: NN 3P0 case with contact terms

$$V_{LO}=C_{lo}pp',$$
$$V_{NLO}=C_{nlo}pp'+D_{nlo}pp'(p^2+p'^2)$$

Tune C_{lo} and Λ, so that there's a resonance very near the threshold:

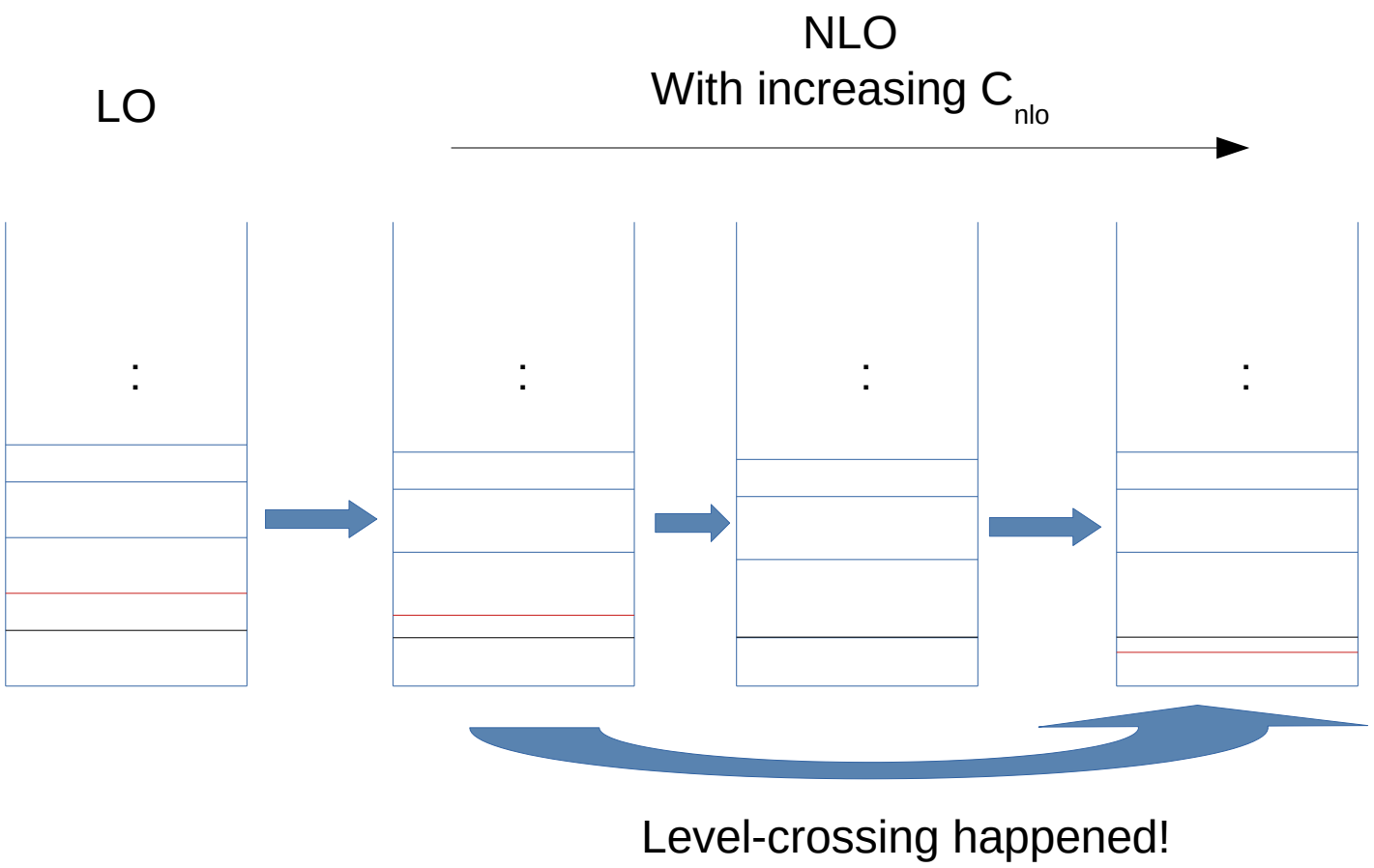
=> LO has a resonance at E_R=0.53 MeV, Γ=0.23 MeV.

$$E_i^{NLO}=\langle\Phi|V_{NLO}|\Phi\rangle_i$$



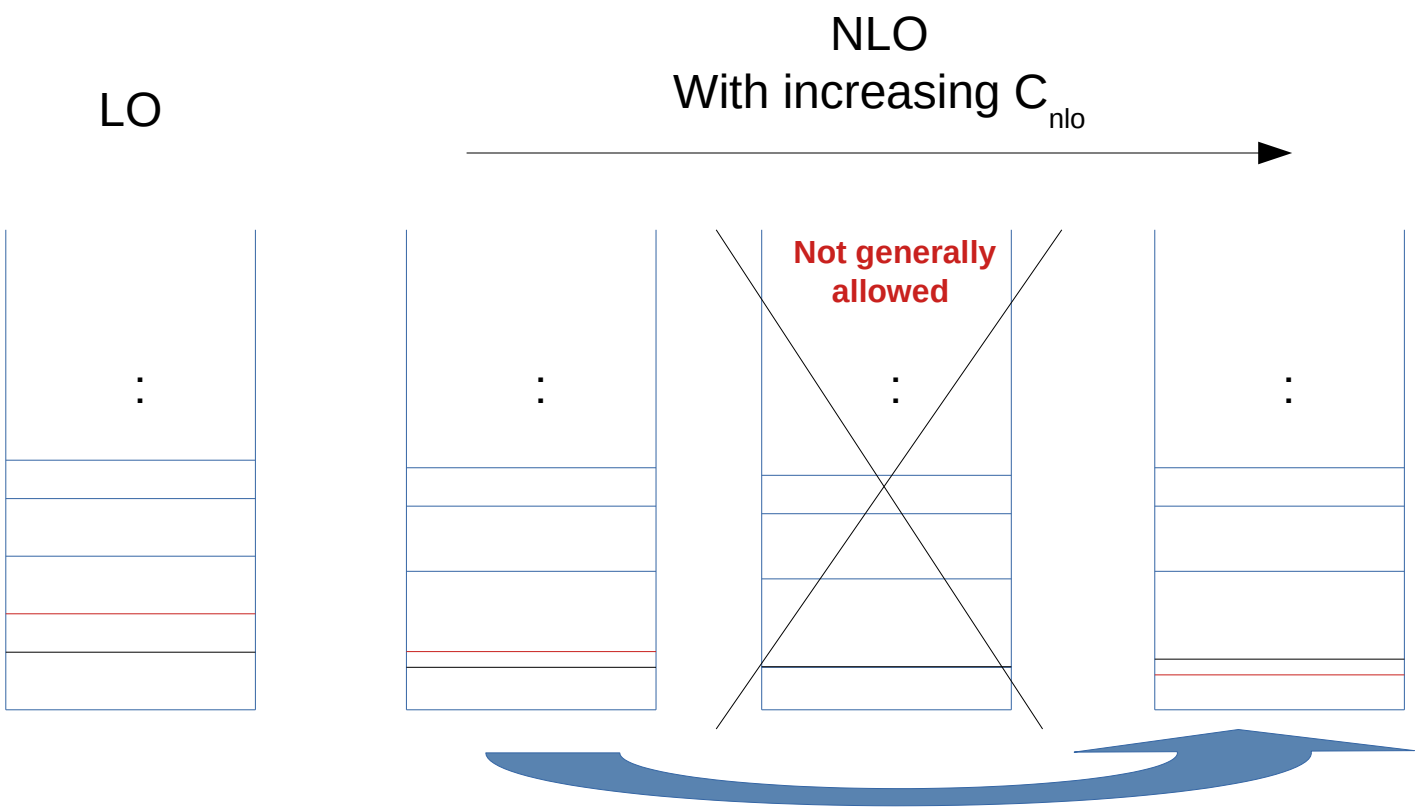
NLO receives more shifts at E~ER→ level-crossing happens
→negative E_i possible at NLO with per-treatment!

Level-crossing v.s. avoided level-crossing



Perturbative treatment of NLO

Level-crossing v.s. avoided level-crossing

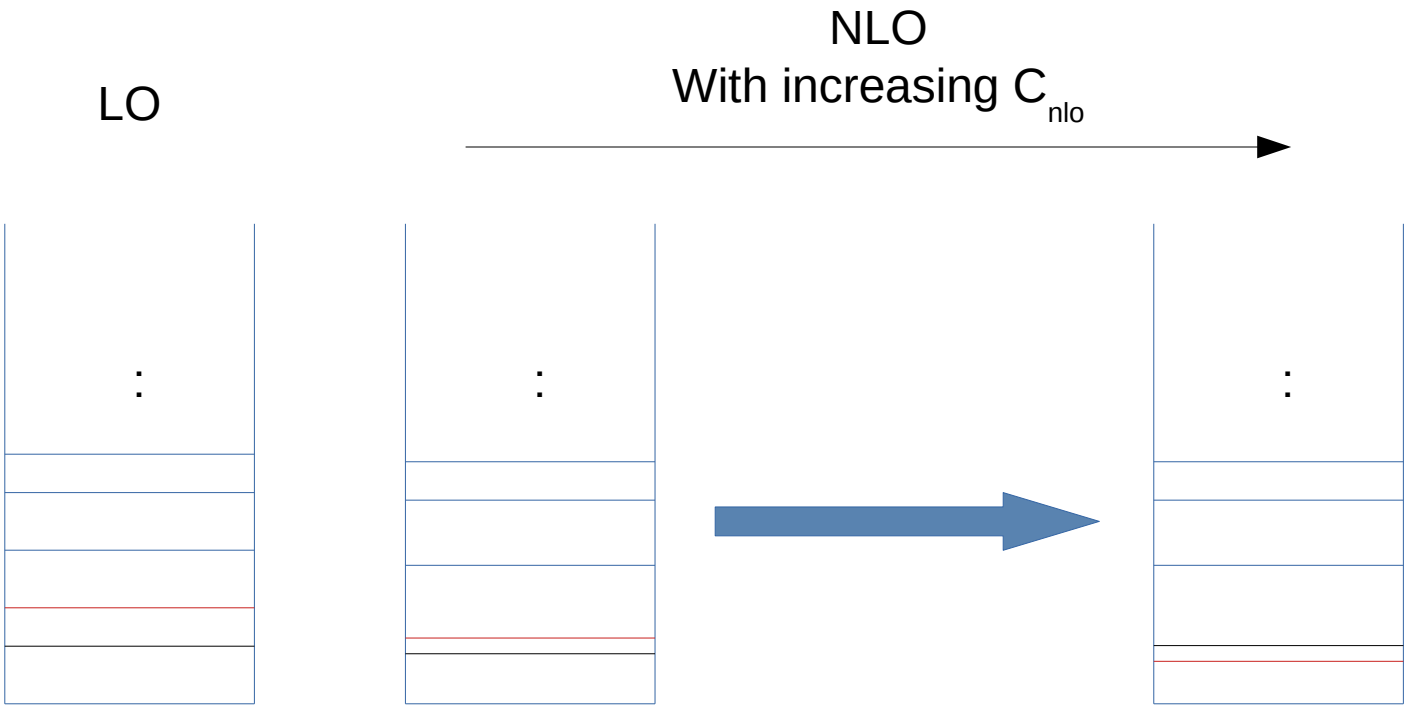


Avoided level-crossing !
There's a minimum and finite separation between levels!

A crucial difference w.r.t. per-treatment!

Non-perturbative treatment of NLO

Level-crossing v.s. avoided level-crossing



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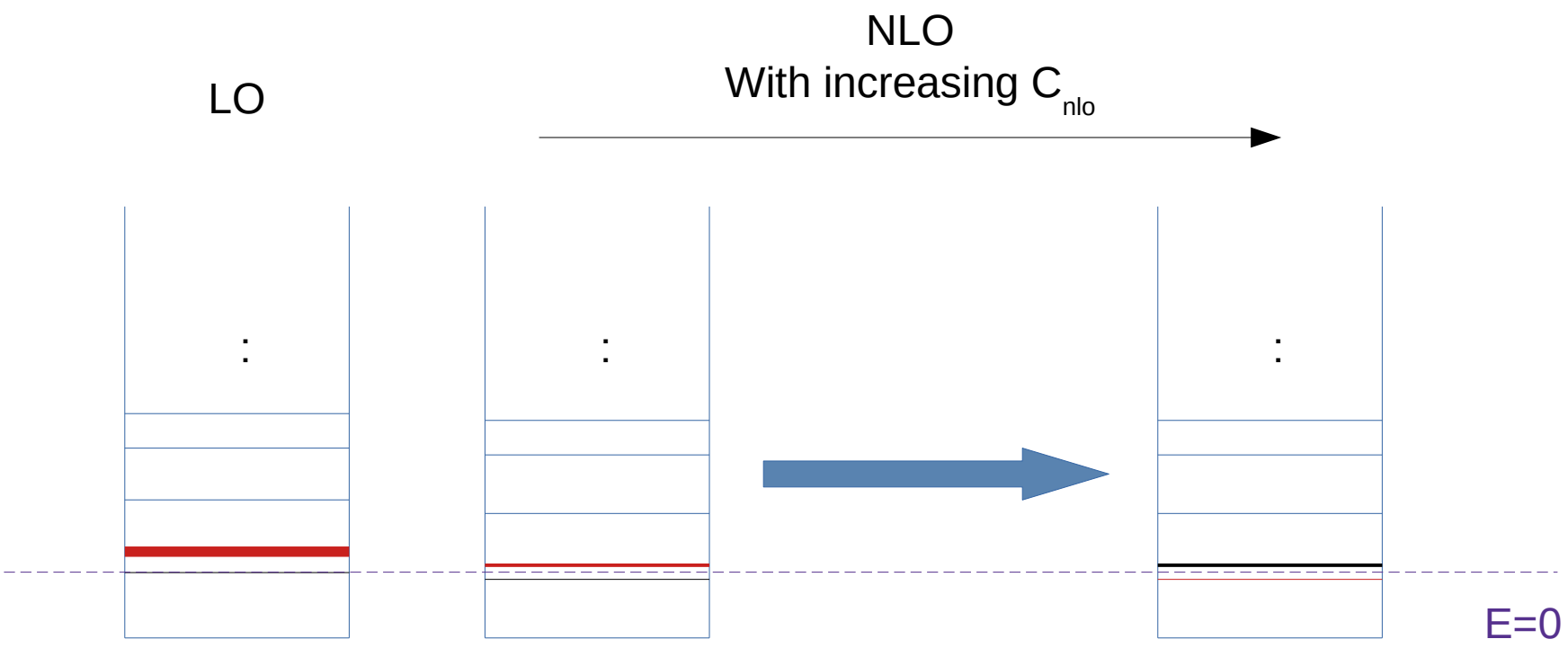
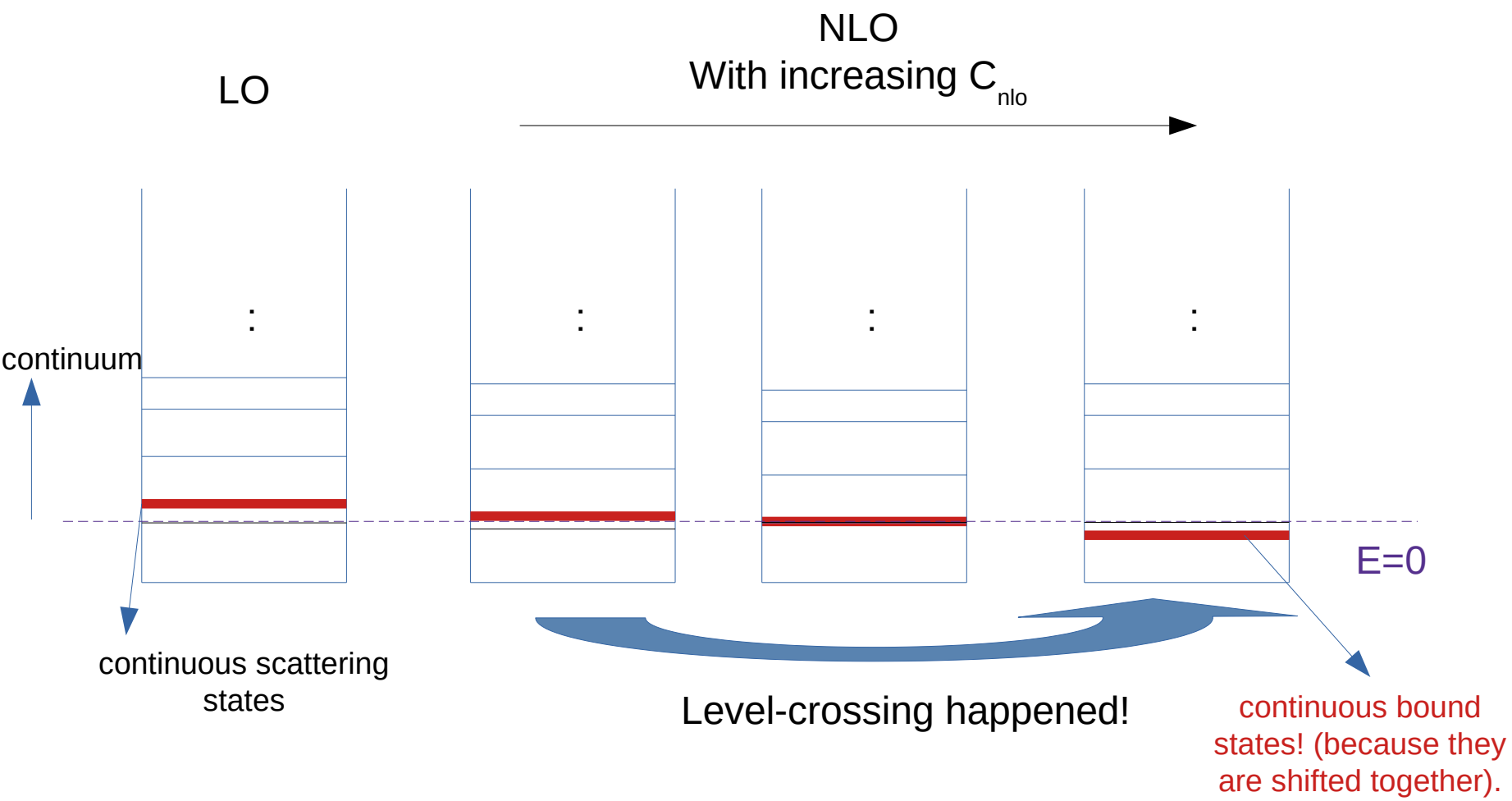


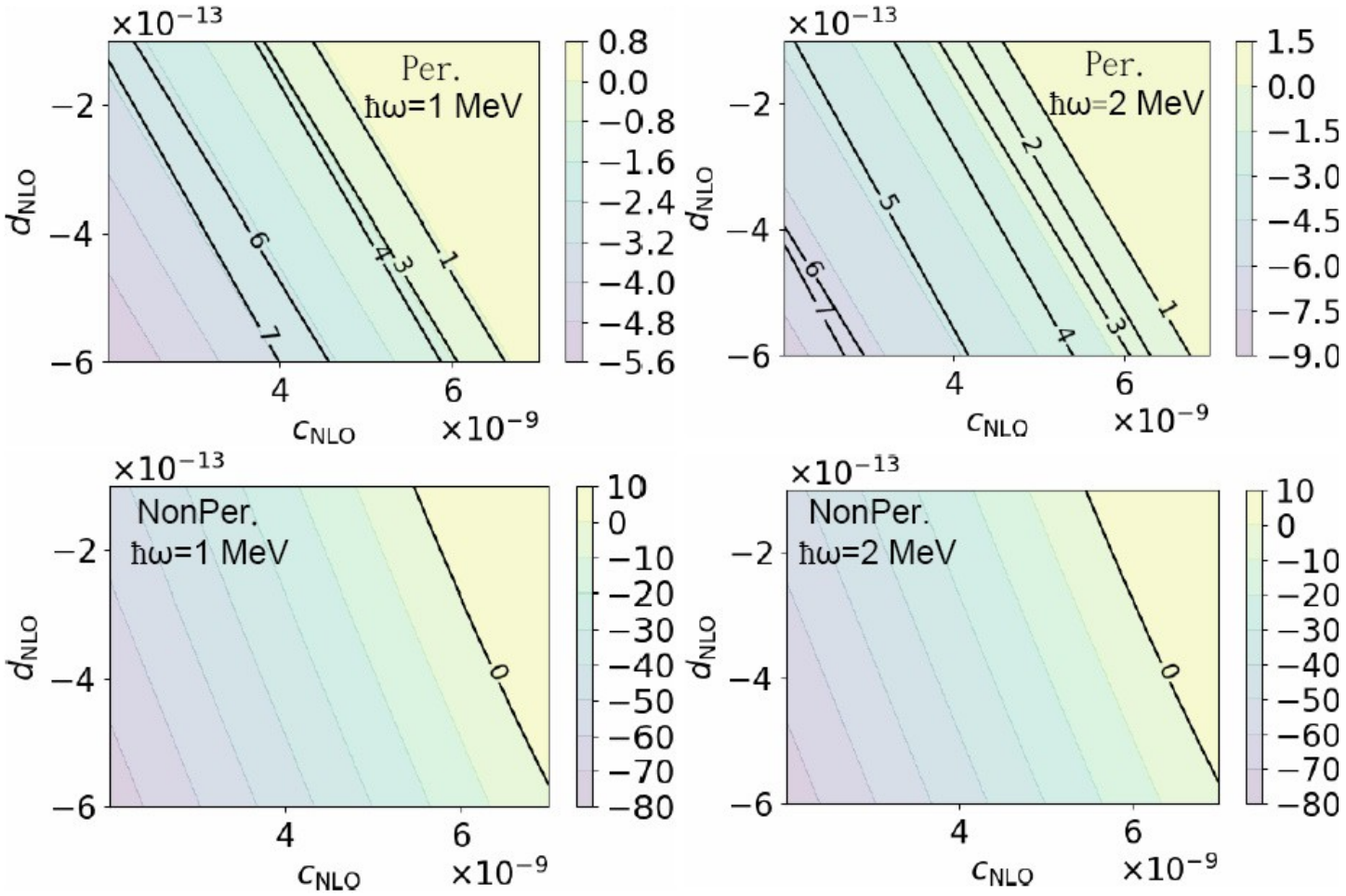
Avoided level-crossing !
There's a minimum and finite separation between levels!

Non-perturbative treatment allows stand-alone bound-states.

Level-crossing v.s. avoided level-crossing



Perturbative treatment of NLO



Lesson: Bound-states generated via straightforward perturbation theory in general have different structure as those are generated non-perturbatively.

What to do then (to restore the correct pole)?

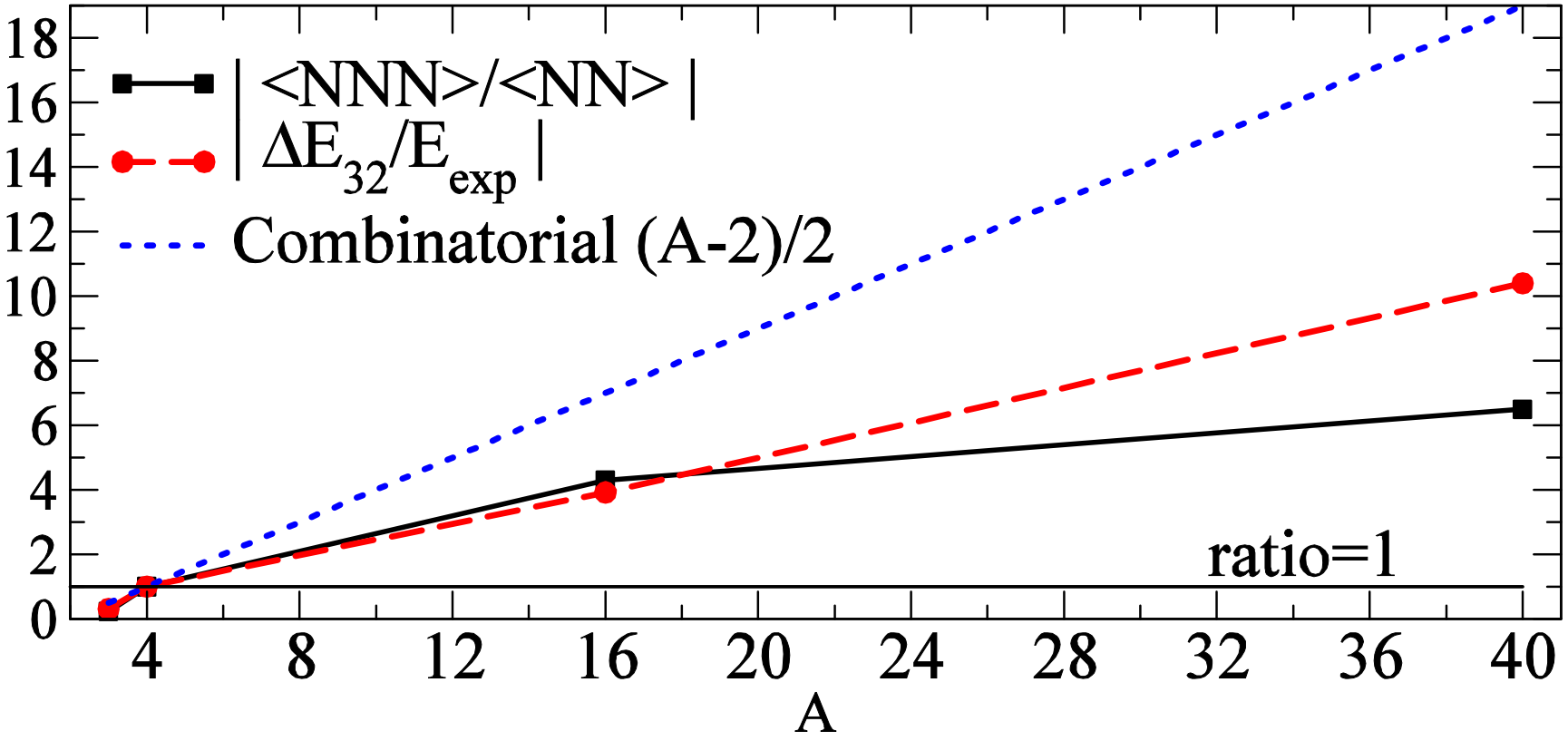
- “Improved action” applied to LO.

L. Contessi, M. Schäfer, U. van Kolck, Phys.Rev.A 109 (2024) 2, 022814
L. Contessi, M. Pavon Valderrama, and U. van Kolck, arXiv:2403.16596 [nucl-th]

- Seek if other ingredients should belong to LO is missing. PC works on NN and few-body level, but fails for A>10 →rethink the importance of 3NF.

C.J. Yang, A. Ekström, C. Forssén, G. Hagen, G. Rupak, U. van Kolck, Eur.Phys.J.A 59 (2023) 10, 233

Growth of 3NF/2NF with A



(Number of particles in the nuclei)

Summary

Why modified PC?

- Because it provides solutions/improvements of conceptual problem of WPC (allow RG to be o.k., or aka, a systematical control of the uncertainty).

Does it give us more predictive power?

- In principle yes (at least I cannot find a reason why not conceptually). But yet to be explored in detail (via Bayesian analysis and more).

O. Thim, E. May, A. Ekstrom, C. Forssen, Phys.Rev.C 108 (2023) 5, 054002

O. Thim, A. Ekstrom, C. Forssen, Phys. Rev. C 109, 064001 (2024)

A few thought-provoking questions

1. Why there's no Bayesian analysis on pionless EFT, to just check a known case (UQ with Λ as high as you like)?

So far people don't really vary this that much

2. Does the avoided-level-crossing feature in non-per PC put a limitation on the structure of excited state?

3. What to do if a well-organized per-PC contradicts with the requirement of the existence of bound-states.

4. Any doubt on 'the importance of many-body forces and it's dependence on the number of nucleons?

5. Any new frontier in nuclear physics?

ECT*

EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

ECT* workshop in Trento, Italy (next week, July 1-5, 2024)

Available for remote participation also. Contact me!

New opportunities and challenges in nuclear physics with high power lasers

Organizers:

C.J. Yang, K. Spohr, P. Tomassini, V. Horny, Y. Fukuda, D. Doria, L. Gizzi

Thank you!

S-wave (1S0), LO, pionless with a sharp cutoff (all analytic)

$$T_{LO} = \frac{1}{\frac{1}{c_{lo}} + \frac{2M}{\pi}\left[\Lambda + i\frac{\pi}{2}p_0 - \frac{p_0}{2}\ln(\frac{\Lambda+p_0}{\Lambda-p_0})\right]}.$$

If c_{lo} is slightly attractive, could be virtual state/resonance-poles for complex p_0

$$T_{NLO} = c_{nlo}\left[1 + F + \frac{F^2}{4}\right],$$

double-pole

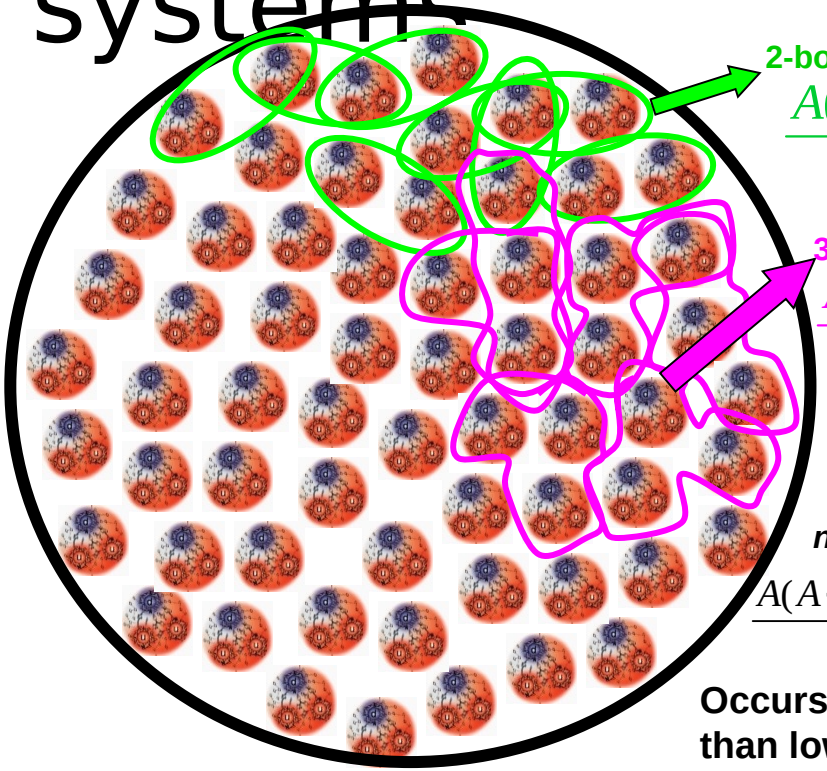
with

$$F = \frac{4M}{\pi}T_{LO}\left[-\Lambda - i\frac{\pi}{2}p_0 + \frac{p_0}{2}\ln(\frac{\Lambda+p_0}{\Lambda-p_0})\right].$$

If you want to know where the NLO pole is and its structure:
=> Need analytic continuation of LSE.

Many-body forces in complex systems

- Some of many-body couplings are genuine and unknown, i.e., cannot be derived from NN couplings.
- They are estimated to be weaker by naïve dimension analysis (NDA).
- However, their importance can grow in a large system.



2-body pairs

$$\frac{A(A-1)}{2!}$$

3-body subsets

$$\frac{A(A-1)(A-2)}{3!}$$

$$\vdots$$

$$\vdots$$

***n*-body subsets**

$$\frac{A(A-1)\cdots(A-n+1)}{n!} \equiv C_n^A$$

Occurs more frequently than lower-body forces !

A	number of doublets $\frac{A(A-1)}{2}$	number of triplets $\frac{A(A-1)(A-2)}{6}$
3	3	1
4	6	4
5	10	10
6	15	20

Explained in:

C.-J. Yang, Eur.Phys.J.A 56 (2020) 3, 96

“A choose n” enhancements

$$C_n^A = \frac{A(A-1)(A-2)\ldots(A-n+1)}{n!}$$

- In a self-bound system, the above enhancement won’t be fully counted. For example, an n-body subset will have nearly zero contribution if its constituents span a distance much larger than the range of the n-body forces.→ density saturates, not $\to \infty$.

- On the other hand, those small contributions could still add up to become sizable, due to the fact that there are many of them.

- Thus, the growth of n-body forces in large systems depends on multiple factors such as the **range** and the **form** of interactions, the mass of particles, etc., → **Require ab-initio calculations to know the PC.**

Estimations

- Combine NDA and “A choose n”:

Combine both:

Approx. with nuclear saturation density

$$\frac{C_n^A F_n}{C_m^A F_m} = \frac{A-m}{n}\left(\frac{\rho_0}{f_\pi^2 M_{\rm hi}}\right)^{n-m} = \frac{A-m}{n}\left(\frac{142({\rm MeV})}{M_{\rm hi}}\right)^{n-m}$$

~1

NN and NNN becomes the same important starting from A=13-26 (M_{hi}=500-1000 MeV)

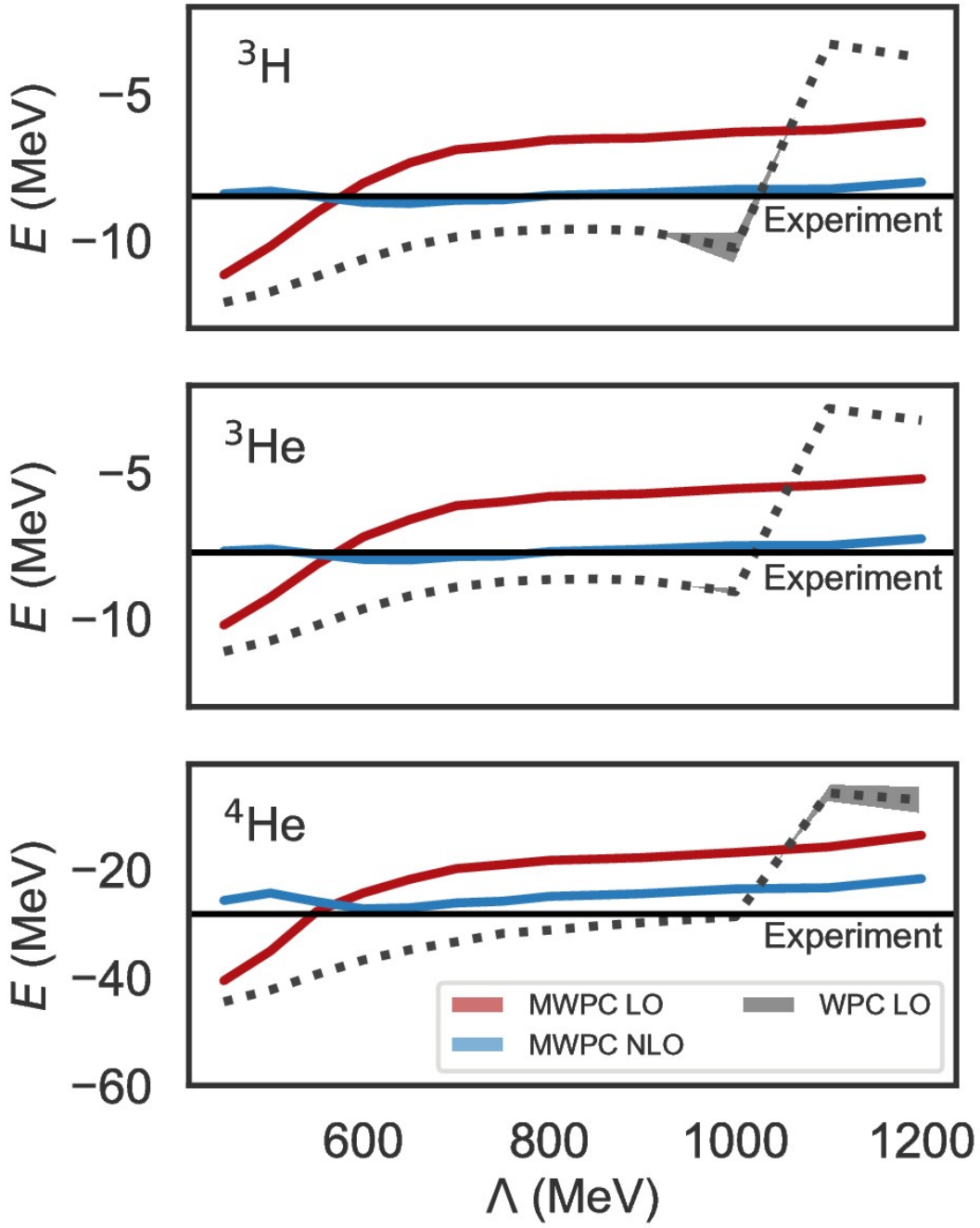
*NNN and NNNN becomes the same important starting from A=17-34.

*5^+-body force is more suppressed (s≥1), only equal to NNNN after A>500.

***Might be weaker due to the previous page’s argument.**

Let’s start from light systems: where 3NFs are small

Use only 2NF up to next-to leading order, do ^{3}H, ^{3}He, ^{4}He



Conclusion:
2NFs up to NLO works for A≤4 systems.

C.-J. Yang, A. Ekstrom, C. Forssen, G. Hagen, PRC 103 (2021) 5, 054304.

For A up to 3 see also:
Nogga et al, PRC 72 (2005), 054006
Song et al, PRC 96 (2017), 024002.

Wrong ^{16}O pole

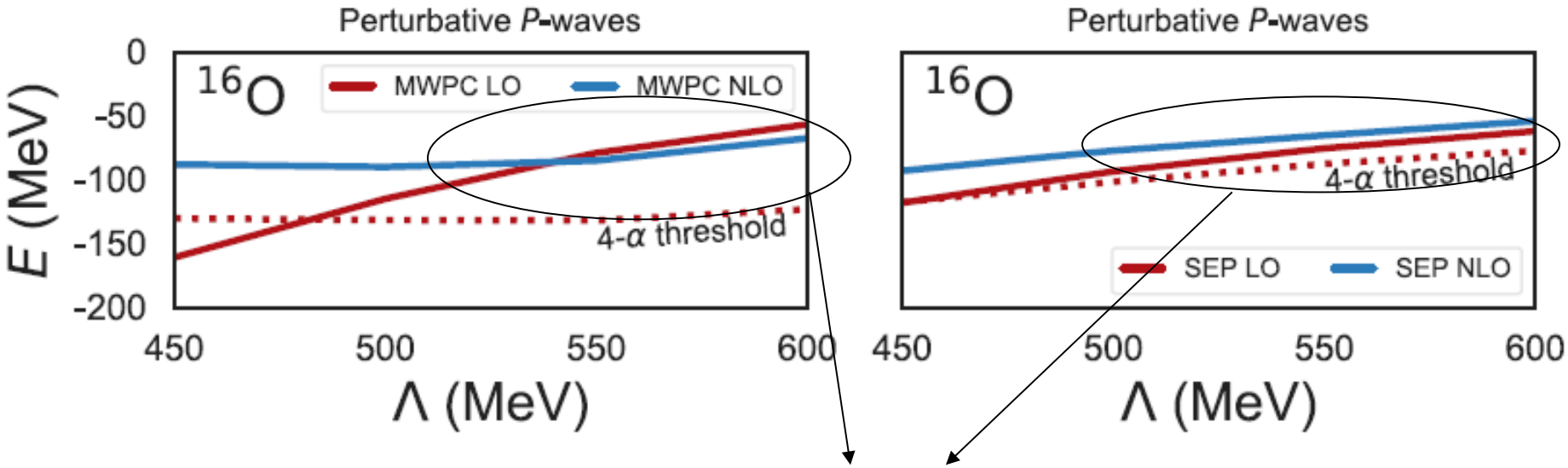
The same NN interaction generates ^{16}O with the *wrong* pole structure (not stable w.r.t. 4α decay) at LO. Also, deformed state becomes deeper than spherical state.

Same thing for PC improved with auxiliary dibaryon fields, Weinberg counting and pionless EFT.

M. S. Sánchez, C.-J. Yang, Bingwei Long, U. van Kolck, Phys.Rev. C97 (2018) no.2, 024001.

In fact, nobody got ^{16}O right at LO yet!

^{16}O results (LO, NN only)



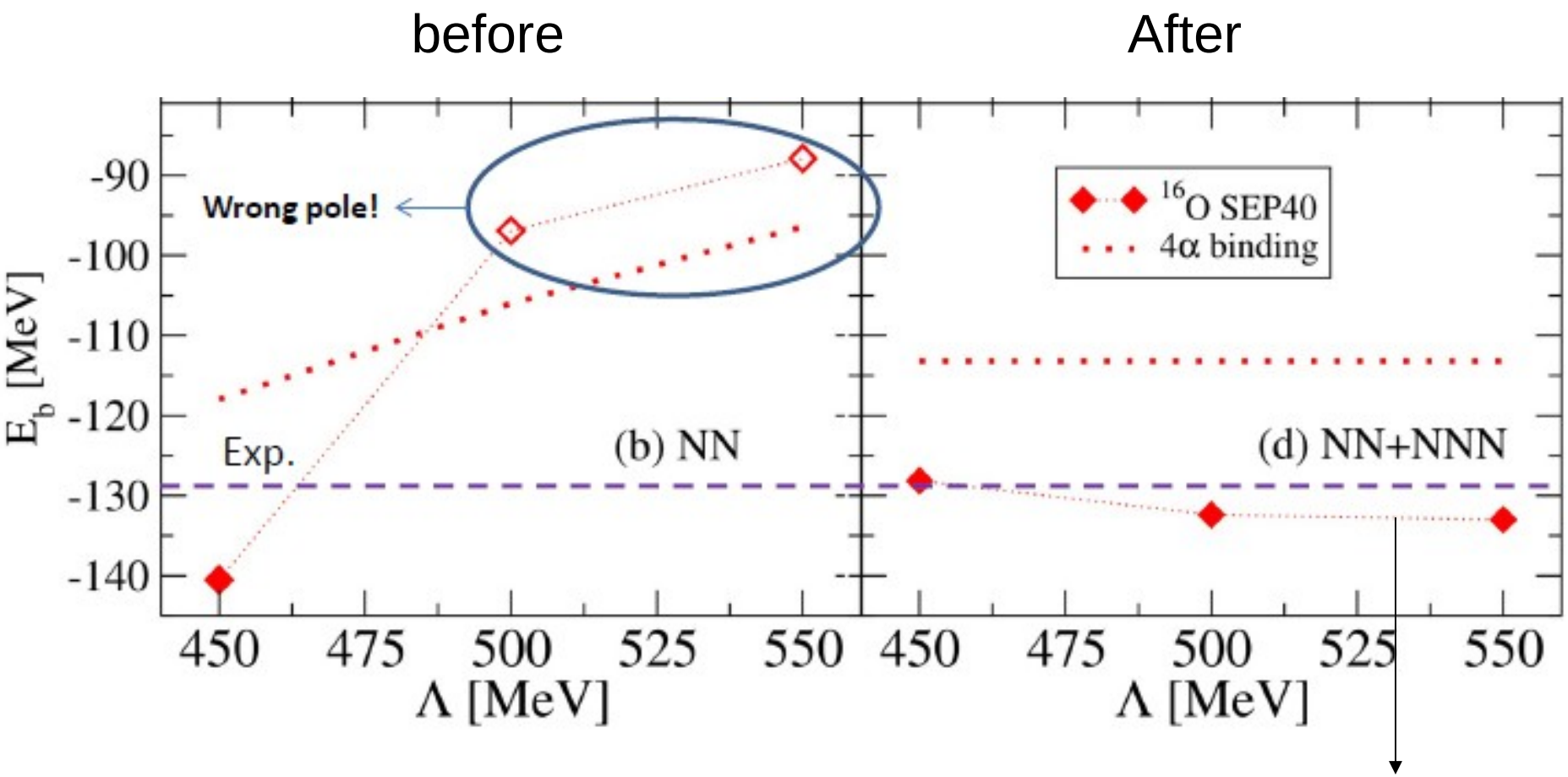
^{16}O non-physical !

MWPC:
At LO, Nogga, Timmerman, van Kolck PC
(*Phys.Rev.C 72 (2005) 054006)*
NLO, plus Long & Yang PC
(*Phys.Rev.C* 86 (2012) 024001)

SEP: NN 1s0 adopts dibaryon field
(Phys.Rev.C 97 (2018) 2, 024001)

Perturbative P-waves: PC by S. Wu & B. Long (*Phys.Rev.C* 99 (2019) 2, 024003)

With 3NFs' size limited to be NNLO on A≤4 systems



Problem solved! ^{16}O great already at LO!