Pionful EFT & the long-forgotten lore of...

... Renormalization

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Beihang University

The nuclear interaction: post-modern developments
ECT*, August 2024, Trento

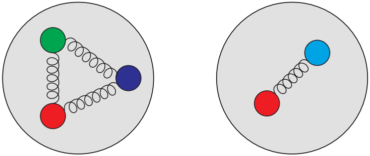
Contents

Effective field theories

& Renormalization

What is an effective field theory?

- Hadrons are particles composed of quarks and gluons.



- What is the problem with this?
  - We know pretty well the dynamics of quarks and gluons: **Quantum Chromodynamics**
  - But explaining hadrons in terms of quarks and gluons is **not exactly trivial**

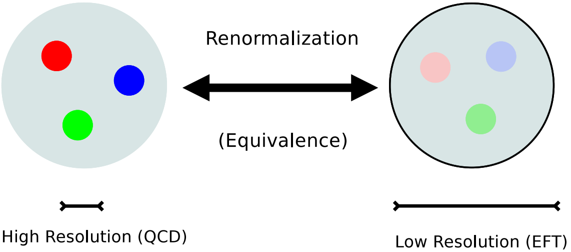
Why?: **Asymptotic Freedom**

What is an effective field theory

The right tool for this problem is Effective Field Theory:

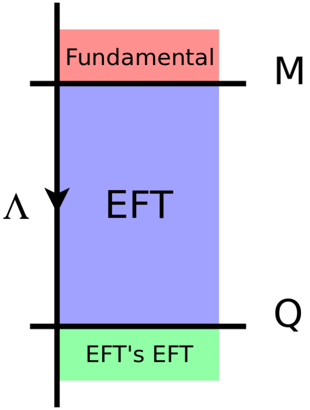
> Physics at long distances does not depend on the short distance details

Rigorous implementation of this principle: renormalization



The actual problem is how to implement this idea

Renormalization Group & EFT: Cutoff



Physics is unique, but choice of theory depends on resolution Λ:

- $\Lambda \geq M$: Fundamental
- $M \geq \Lambda \geq Q$: EFT

For equivalent descriptions:

$$\boxed{\frac{d}{d\,\Lambda}\langle\Psi|\mathcal{O}|\Psi\rangle = 0}$$

Renormalization group invariance

Renormalization Group & EFT: Ingredients

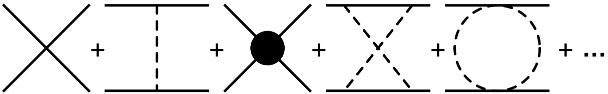
Begin at $\Lambda = M$, two equivalent descriptions

$$\underbrace{\text{quarks \& gluons}}_{\text{high energy}} \qquad \Longleftrightarrow \qquad \underbrace{\text{hadrons } (N,\, \Delta,\, \pi)}_{\text{low energy}}$$

The hadron description equivalent if and only if

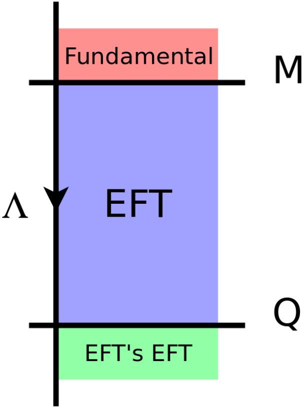
(1) Include low energy symmetries (particularly **chiral symmetry**)

(2) Consider infinite set of Feynman diagrams consistent with (1)

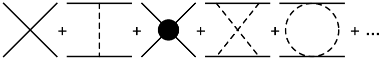


Problem: **infinite diagrams imply no predictive power**

Renormalization Group & EFT: Power Counting

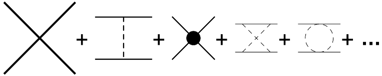


(1) At $\Lambda \sim M$ there is no order



$$\boxed{\frac{d}{d\Lambda}\langle\Psi|\mathcal{O}|\Psi\rangle = 0}$$

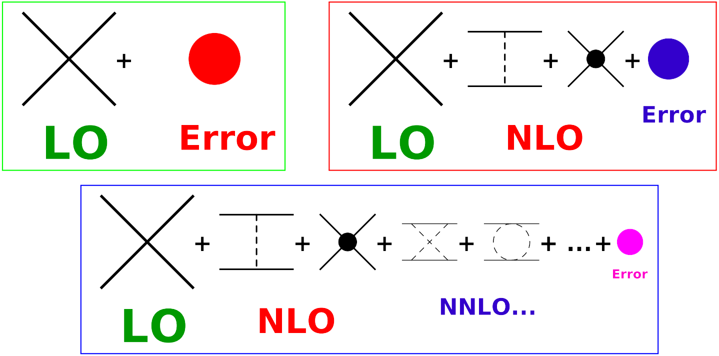
(2) while at $\Lambda \sim Q$ there is order



LO **NLO** **NNLO...**

Renormalization Group & EFT: Error Estimations

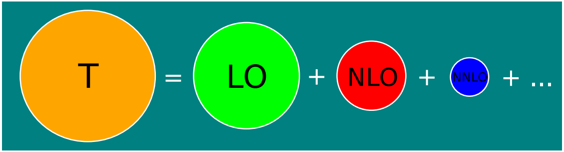
Predictive power: cut the expansion $\Rightarrow$ systematic error estimations



Caveat: Power counting is not unique. Example above: KSW

Renormalization Group & EFT: Summary

- EFT: generic low energy descriptions of physical phenomena
- **Renormalization:**
  - Theory: equivalence to the fundamental theory
  - Practice: derivation of a power counting (error estimations)
- Everything within EFT is an expansion (power counting):



$\Rightarrow$ **Error estimations** (expected size of the next blob)

- **Requires subleading corrections to be perturbative**
  (otherwise error estimations **might** not be possible)

Power counting wars

& the missing thought ecosystem

Nuclear physics: are you a fox or a hedgehog?

Phillip Tetlock: Expert political judgement, how good it is? (2005)

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(hint: as good as dart-throwing chimps... except for the foxes)

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- **Hedgehog**: knows one big idea (intellectual economy)
  Resistance to update priors Convergence Fav word: Moreover
- **Fox**: knows many little ideas (intellectual scavenger)
  Bayesian operators Zigzagging Fav word: However

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  Bayesian operators Zigzagging Fav word: However

They form a "thought ecosystem".
Yet, nuclear physics is also messy: foxes may fare better (at getting it right, not at framing the discussion)

Nuclear physics: practicing your fox skills (I)

Contradictory/ambiguous information to be balanced:

Renormalization as cut-off independence (modulo corrections)

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- **Why:** connection to the underlying theory.
- **But:** underlying theory defines the breakdown scale M

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So what happens if renormalization broken for $\Lambda \gg M$?

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Renormalization as cut-off independence (modulo corrections)

- **Why:** connection to the underlying theory.
- **But:** underlying theory defines the breakdown scale M

So what happens if renormalization broken for $\Lambda \gg M$?

There might be grounds for disregarding a failure in renormalizing in this later case. The question to ask ourselves:

Is this happening at a fantastically hard cutoff? Or at a concerningly not-so-hard cutoff?

It might not be so bad...

Nuclear physics: practicing your fox skills (IIa)

Contradictory/ambiguous information to be balanced:

Power counting as an ordering principle

(Actually, the practical side of renormalization)

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Power counting as an ordering principle

(Actually, the practical side of renormalization)

- **It's something you want:** provides systematic errors.
- **But its practical implementation is tricky:**

  Requires treating subleading corrections as perturbations (DWBA), explicitly checking renormalizability, etc/

Nuclear physics: practicing your fox skills (IIa)

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Power counting as an ordering principle

(Actually, the practical side of renormalization)

- **It's something you want:** provides systematic errors.
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What happens if we want to save work? Is this possible?

Let's see with Weinberg counting as an example...

Nuclear physics: practicing your fox skills (IIb)

Weinberg counting is the power counting that appears from assuming either of these two things:

(a) that all interactions are perturbative,

(b) or that all two-nucleon (EFT) wave functions are regular.

Nuclear physics: practicing your fox skills (IIb)

Weinberg counting is the power counting that appears from assuming either of these two things:

(a) that all interactions are perturbative,

(b) or that all two-nucleon (EFT) wave functions are regular.

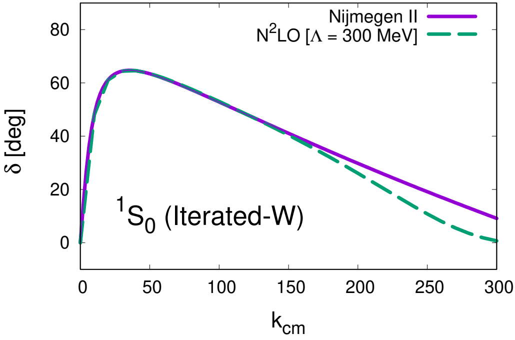
Neither (a) or (b) are true (for all cutoffs)...

...but (b) might hold for a sensible range of cutoffs

Maybe Weinberg counting could be a workable power counting.

Viability of Weinberg's counting: first approximation

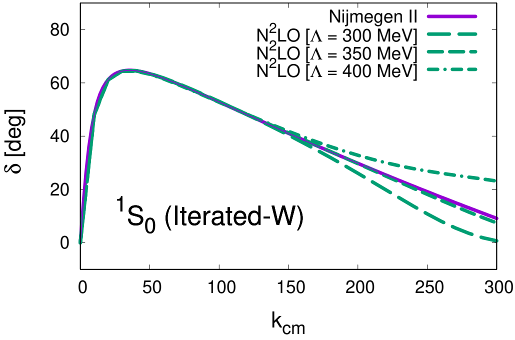
Calculate EFT potential, then fully iterate EFT potential: not the ideal procedure, but it's practical and it might work.



Not bad, let's try a few more cutoffs!

Viability of Weinberg's counting: first approximation

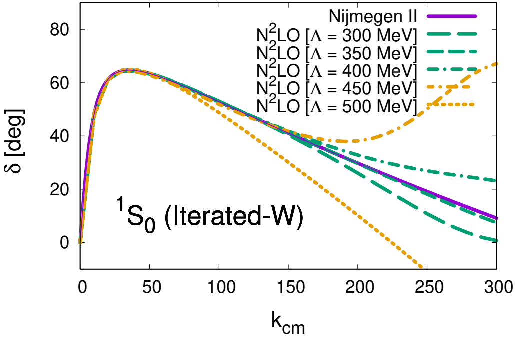
Calculate EFT potential, then fully iterate EFT potential: not the ideal procedure, but it's practical and it might work.



Great, cutoff independence! Let's go further...

Viability of Weinberg's counting: first approximation

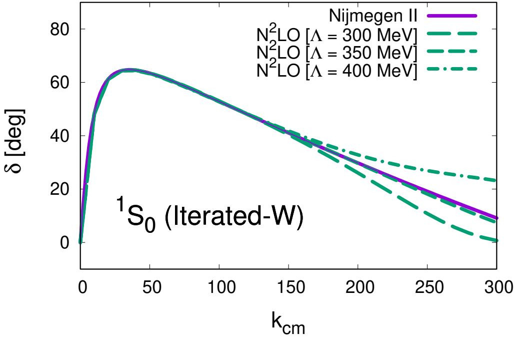
Calculate EFT potential, then fully iterate EFT potential: not the ideal procedure, but it's practical and it might work.



Nope, unreasonably high cutoff, let's go back!

Viability of Weinberg's counting: first approximation

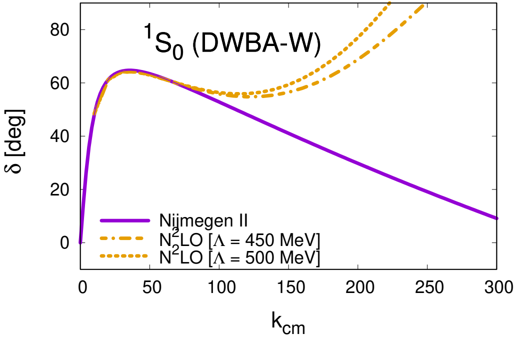
Calculate EFT potential, then fully iterate EFT potential: not the ideal procedure, but it's practical and it might work.



And this is simply perfect! Works great! (I guess...)

Viability of Weinberg's counting: doing it right

Perturbative treatment of subleading corrections: guarantees the counting by construction.



Not good, but unreasonable cutoffs, let's lower it.

Viability of Weinberg's counting: doing it right

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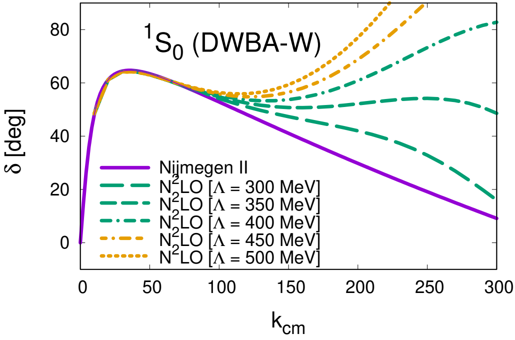
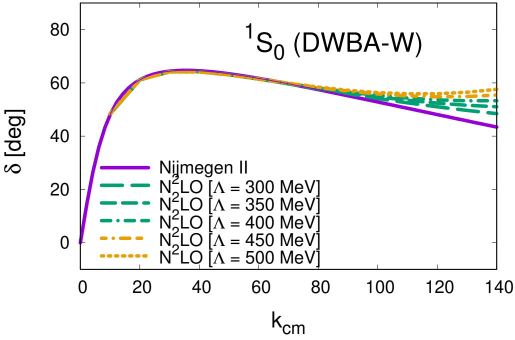


Not what I expected... maybe I'm seeing this in the wrong way.

Viability of Weinberg's counting: doing it right

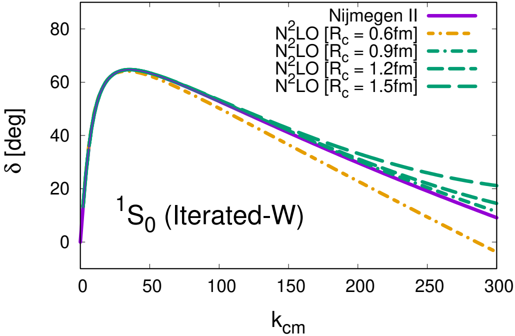
Perturbative treatment of subleading corrections: guarantees the counting by construction.



A perfectly good EFT for $k \leq 140\,\mathrm{MeV}$ and $\Lambda \leq 0.5\,\mathrm{GeV}$

Viability of Weinberg's counting: choice of regulator

But with a local regulator we arrive to a more nuanced conclusion:



If we iterate, it works perfectly.

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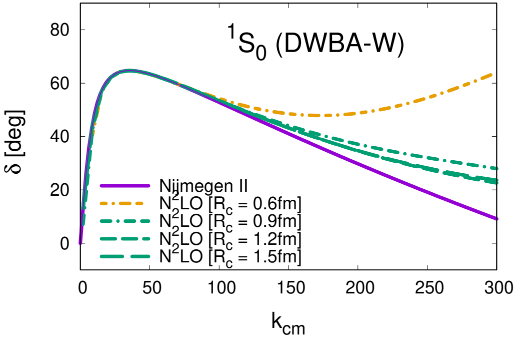

If we do DWBA, it still works pretty well (except for hard cutoffs)

Viability of Weinberg's counting: choice of regulator

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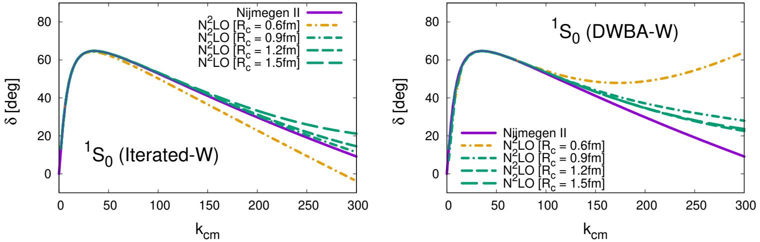
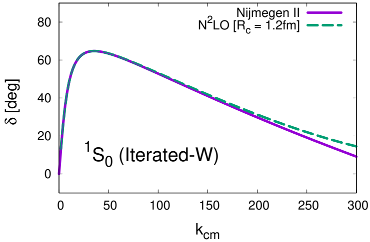


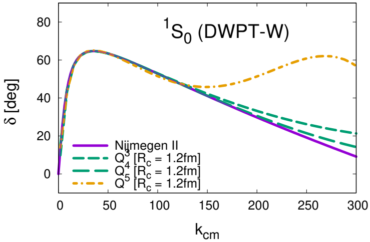
Both iterated and DWBA compare acceptably well:

The iterated amplitudes have good power counting properties (at least for the green cutoffs)

Viability of Weinberg's counting: beyond DWBA

Higher order perturbations, even w/ local regulators, problematic:



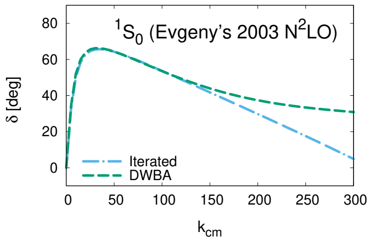


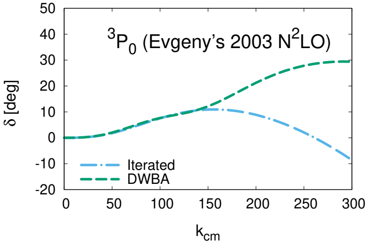
Up to Q^3: DWBA Q^4: $\mathrm{TPE}_L \times \mathrm{TPE}_L$ Q^5: $\mathrm{TPE}_{SL} \times \mathrm{TPE}_L$
(Like Q^4, Q^5 DW Weinberg but w/ $V_F = 0$ beyond Q^3)

It gets ugly as we approach the first iteration of subleading TPE

Viability of Weinberg's counting: other partial waves (I)

But problems likely limited to $^1S_0$ and $^3P_0$ (e.g. 2003 N^2LO):

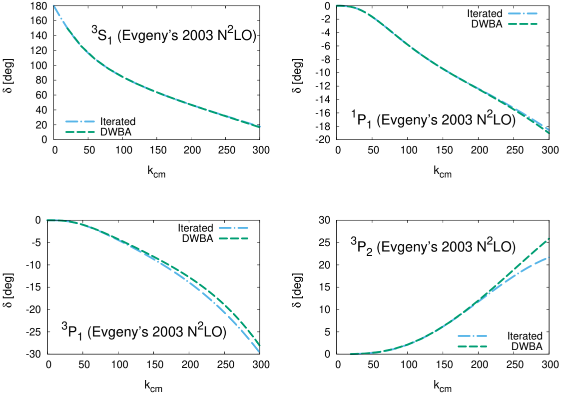




Better than bare N^2LO (bc/ spectral), but still not great.

Viability of Weinberg's counting: other partial waves (II)

As for $^3S_1$, $^1P_1$, $^3P_1$ and $^3P_2$ is **power counting perfect**



Viability of Weinberg's counting: foxes & hedgehogs (I)

Trying to balance the information we have so far:

Possible failure of power counting in $^1S_0$. But...

(i) Can be mitigated by choice of regulator.

Local potentials indeed do acceptably well:
many recent potentials are local or semilocal

(ii) Only affects two partial waves ($^1S_0$, $^3P_0$).

$^3S_1$-$^3D_1$, $^1P_1$, $^3P_1$ do relatively well.

(iii) Eventually, at higher orders the problem disappears.

The question is whether it is important to have all the terms in the EFT expansion (or whether nobody cares about LO).

But the question here is whether we are being honest in balancing this information, or lazy instead.

Viability of Weinberg's counting: foxes & hedgehogs (II)

Two ways to move forward here:

- **Fox move: update your beliefs**
- **Hedgehog move: double down**

Which brings us to a fourth consideration

(iv) Reinterpret renormalization, from which it follows that our previous amplitudes are "renormalized".

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Personally, I would naively agree if these problems where happening at really high cutoffs. **But they are happening at $\Lambda \sim M$!**

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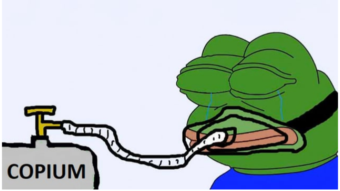

Which raises the question:

Is this legit? or...

Are we just trying to cope?

Viability of Weinberg's counting: discarding it

Instead of coping, we might as well **discard Weinberg's counting** entirely and use instead the counting deduced from RGA.

For the particular case of the ${}^1S_0$ partial wave:

- Weinberg: C_0 enters LO and C_2 at $\mathrm{N^2LO}$ (called NLO)
  LO is $(Q/M)^0$, NLO is $(Q/M)^2$, $\mathrm{N^2LO}$ is $(Q/M)^3$, etc.
- Pionful EFT: C_0 enters LO, C_2 at NLO, C_4 at $\mathrm{N^3LO}$
  LO is $(Q/M)^{-1}$, NLO is $(Q/M)^0$, $\mathrm{N^2LO}$ is $(Q/M)^1$, etc.

Basically, Weinberg's $\mathrm{N^2LO}$ corresponds to pionful $\mathrm{N^4LO}$

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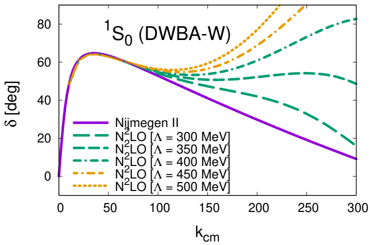
Basically, Weinberg's $\mathrm{N^2LO}$ corresponds to pionful $\mathrm{N^4LO}$

In the way I count (caveat): for a different prescription, Long & Yang have a one order counting offset as they promote TPE by one order.

This breaks a really beautiful correspondence between RGA and divergences, but it's a legit choice: power counting is not unique.

Viability of Weinberg's counting: embracing RGA

Discarding Weinberg's counting and embracing RGA $\Rightarrow$ **Robust**



Subleading perturbations work now.

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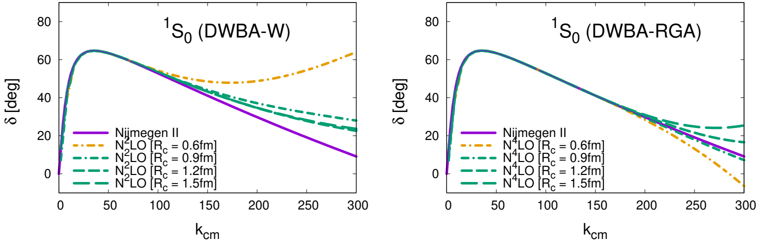

Subleading perturbations also work better for local regulators

Viability of Pionful RGA: being practical

Pionful RGA $+$ perturbative subleading corrections

$\Rightarrow$ Amplitudes w/ **RG Invariance** & **Power counting**

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But perturbative corrections are **difficult**! I don't want to do it!

Well, there is room for compromise if you still want to **iterate** (with a correct power counting: Weinberg does not count)

(i) Iteration breaks renormalizability at subleading orders

But what we lose is the theoretical connection with the underlying theory (yet, partially taken into account by RGA).

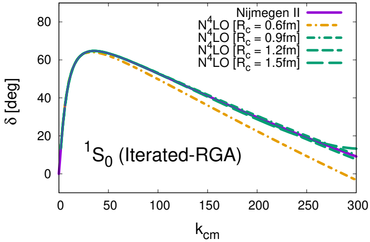
(ii) Iteration still preserves counting at cutoffs $\Lambda \sim M$

That is, systematic error estimations are possible: this is probably the most sought after feature of EFTs.

All in all, this is not such a bad deal!

Viability of Pionful RGA: compromises

By comparing the fully iterated and the DWBA phase shifts:



Very similar for the $R_c = (0.9 - 1.2)\,\mathrm{fm}$ cutoff range

No substantial difference (except difficulty of calculation).

Viability of Pionful RGA: accidental compromises

There are Weinberg-inspired $\mathrm{N^2LO}$ potentials w/ $\mathrm{N^3LO}$ contacts in the market $\Rightarrow$ not identical to RGA, but pretty close

Do they have good counting properties?

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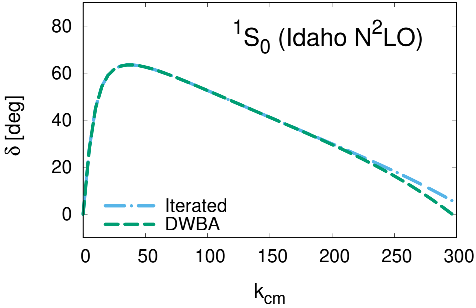
Do they have good counting properties?

Rup hit that nail on the head ;)



They do have (at least the good old Entem & Machleidt potential)

Probably the Piarulli et al. N^2LO/N^3LO potential will too.

Viability of Pionful RGA: foxes & hedgehogs

Two options to move forward:

- **Fox mindset: eternal beta, successive approximation**
- **Hedgehog mindset: no compromise on definite solution**

Viability of Pionful RGA: foxes & hedgehogs

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Which brings us to two possible strategies for the future:

- Build chiral potentials with RGA-derived countings (instead of Weinberg):
  - Absolutely trivial to implement right now
  - It represents a massive improvement **(good power counting)** even if not perfect **(no renormalizability yet)**
- Perfectly renormalized amplitudes or else:
  - Unlikely to work in the short or medium term
  - Not best intermediate strategy to eventually arrive to these amplitudes **(the perfect is the enemy of the good)**

Post-modernism and power counting:

power counting extravaganza

(or subverting your naive expectations)

What is post-modernism? (I)

Welcome to the world of smartassy! But what is post-modernism?

This is what happens when you read Heidegger instead of me.
– Ludwig.

Hodgepodge of disconnected ideas, including **"truth is not objective, but subjective (or even socially constructed)"**

- Usually associated with social sciences, just for them to by pwned by the sokal affair (but even this is debatable...)
- Yet, it is not like hard sciences are not passing by a post-modern phase (the replication crisis, Jan Hendrik Schön: pitty he didn't win the Nobel prize, would have been epic, Bogdanov affair: not sure what to say about this, etc.)

What is post-modernism? (II)

On a more historical perspective, it has been remarked:

> Our own post-modern age has been inaugurated by the general ~~war of 1914–1918~~ power counting war of 2005-2010.
>
> – ~~Arnold J. Toynbee~~ Anonymous post-doc

that is, it began in the period between NTvK and peratization.

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that is, it began in the period between NTvK and peratization.

Post-modern developments characterized by the motto:

Renormalization is a social construct

(you better use the version helping you land a position)

What is post-modernism? (II)

On a more historical perspective, it has been remarked:

> Our own post-modern age has been inaugurated by the general ~~war of 1914–1918~~ power counting war of 2005-2010.
>
> – ~~Arnold J. Toynbee~~ Anonymous post-doc

that is, it began in the period between NTvK and peratization.

Post-modern developments characterized by the motto:

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Yet I remember a preprint ahead of its time in its post-modernism

It began in the mist of time...

About two decades ago I saw some interesting preprint in arxiv...

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Spectacular power counting extravaganza in two-nucleon scattering

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(Dated: April 1, 2005)

We uncover a previously unknown fixed point of the renormalisation group for two-nucleon scattering. Instead of expanding around the boring unstable fixed point associated with the exchange of single, lonely pions, we double down and expand around a wondrous fractal spiral RG-structure generated by the iteration of the two-pion exchange potential. The resulting power counting unironically realizes the intersectionality between the infrared and ultraviolet limits, clarifying the central importance of chiral van der Waals forces. The expansion works. Perfectly well, in fact. This, honestly, caught us by surprise.

PACS numbers: 03.65.Nk,11.10.Gh,13.75.Cs,21.30.-x,21.45.Bc
Keywords: Potential Scattering, Renormalization, Nuclear Forces, Two-Body System

Really inspiring! But afterwards I was unable to find it again.

The authors sound vaguely familiar though.

Post-modernism and power counting

Post-modern nuclear EFT is not all about renormalization.

It is also about deconstructing and subverting the power counting.

Power counting is a social construct

Which is what we are going to do now...

Fine tuning in the EFT expansion (I)

Post-modern approaches often rely on toy models, so...

Fine tuning in the EFT expansion (I)

Post-modern approaches often rely on toy models, so...

Toy EFT expansion: assume observable $\hat{\mathcal{O}}$ such that

$$\langle \hat{\mathcal{O}} \rangle = \sum_{\nu=\nu_{\rm min}}^{\infty} \langle \hat{\mathcal{O}}^{(\nu)} \rangle = \sum_{\nu=\nu_{\rm min}}^{\infty} c_\nu x^\nu \, .$$

We set $\nu_{\rm min} = 0$ and random coefficients within the range

$$c_\nu \in [0, \nu + 1] \quad \text{for } \nu \neq 1 \text{ (and } c_1 = 0) \, .$$

Then we set $x = 1/3$ for concreteness (probably close to the actual expansion parameter in nuclear physics).

Fine tuning in the EFT expansion (II)

A few things to take into account:

(i) Mathematically, the toy EFT expansion of $\hat{\mathcal{O}}$ is...
... always convergent (independently of the chosen c_ν values)

(ii) For randomly generated c_ν, the expected average contribution for each term (with $x = 1/3$) is:

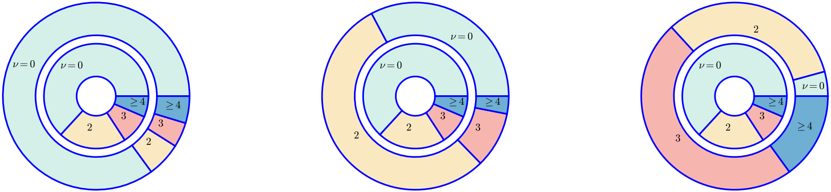
$$\overline{\langle\hat{\mathcal{O}}\rangle} = \overline{\langle\hat{\mathcal{O}}^{(0)}\rangle} + \overline{\langle\hat{\mathcal{O}}^{(1)}\rangle} + \overline{\langle\hat{\mathcal{O}}^{(2)}\rangle} + \overline{\langle\hat{\mathcal{O}}^{(3)}\rangle} + \sum_{\nu\geq 4}\overline{\langle\hat{\mathcal{O}}^{(\nu)}\rangle}$$
$$= \frac{1}{2} + 0 + \frac{1}{6} + \frac{2}{27} + \frac{11}{216}$$

(iii) But with random coefficients, we may run into surprises.

Fine tuning in the EFT expansion (III)

Three examples of randomly generated toy EFT expansions:

(a) Convergent expansion (b) N^{2}LO-dominated expansion (c) N^{3}LO-dominated expansion



Inner circle: average toy EFT expansion.

Outer circle: random toy EFT expansion.

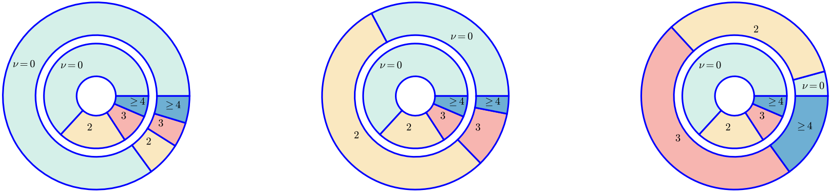
All convergent, but (b) and (c) seem problematic at lower orders

Fine tuning in the EFT expansion (IV)

(a) Convergent expansion

(b) N^{2}LO-dominated expansion

(c) N^{3}LO-dominated expansion

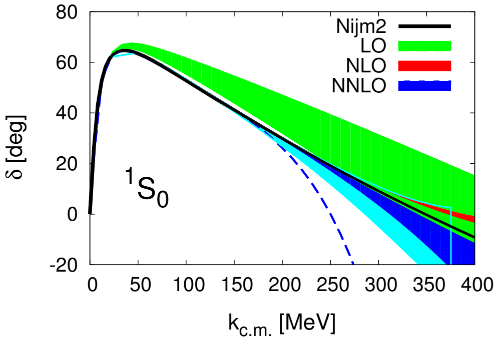


Nuclear EFT might very well be like (c) : subleading two-pion exchanges give a much larger contribution than expected.

Yet, this is merely an accident of the EFT expansion.

It the nuclear EFT expansion fine-tuned? (I)

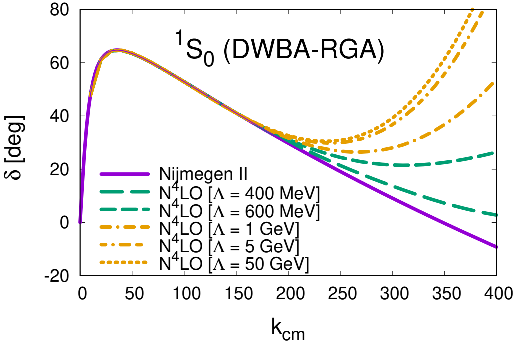
Reviewing my 2009 pionful EFT calculations of the singlet:



We have the dashed line ($R_c = 0.1\,\mathrm{fm}$): (i) calculations converge for $R_c \to 0$, (ii) but the later fails for $k_{\rm cm} > 200\,\mathrm{MeV}$

It the nuclear EFT expansion fine-tuned? (II)

Maybe artifact of the regulator choice? Let's go to p-space:



Exactly the same situation: (i) calculations converge for $\Lambda \to \infty$,
(ii) but the later fails for $k_{\rm cm} > 200\,\mathrm{MeV}$

It the nuclear EFT expansion fine-tuned? (III)

Why? Repetition of KSW's poor convergence: perturbative OPE converges only for $k < 100\,\mathrm{MeV}$ in the triplet (Mehen et al. 98)

Explained by Birse (05):

(i) Tensor OPE in chiral limit: $1/r^3$ potential

(ii) Gao 99: (secular) perturbative expansion of $1/r^3$ only valid below a certain critical momentum.

(iii) Ergo perturbative expansion of tensor OPE only valid below a certain critical momentum ($k < 70\,\mathrm{MeV}$ for triplet).

The argument requires a bit of abstraction and has thus been widely not understood by the community (yet Kaplan confirmed it by means of explicit perturbative calculations at high orders).

It the nuclear EFT expansion fine-tuned? (IV)

Why? How do this applies to subleading TPE?

Paraphrasing Birse:

(i) Subleading TPE in chiral limit: $1/r^6$ potential

(ii) Gao 99: (secular) perturbative expansion of $1/r^6$ only valid below a certain critical momentum.

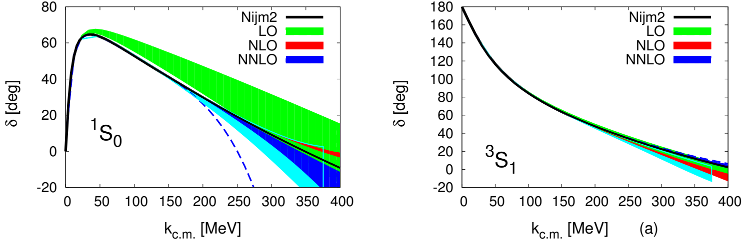
(iii) Ergo, provided that OPE is perturbative enough as not to upset the previous result, expansion of subleading TPE only valid below a critical momentum ($k < 160\,\mathrm{MeV}$ for singlet).

The proviso of perturbative OPE is important:

- In the singlet (OPE perturbative), failure at $k \sim 200\,\mathrm{MeV}$
- In the triplet (OPE non-perturbative), no failure for $k < M$

It the nuclear EFT expansion fine-tuned? (V)

Notice the singlet vs triplet (or any other partial wave) difference:



Except for the $^1S_0$, the convergence radius seems pretty typical ($k < 0.5\,\mathrm{GeV}$ give or take) even for $R_c \to 0$.

Expansion around subleading TPE (I)

Solution: **iterate subleading TPE**

A different way to think of this problem is to look at the S-wave potential in the chiral limit:

$$\lim_{m_\pi \to 0} V_{\rm NN}^{\rm EFT}(r) = -\frac{4\pi}{M_N}\left[\frac{1}{\Lambda^3_{\rm TPE(L)}}\frac{1}{r^5} + \frac{1}{\Lambda^4_{\rm TPE(SL)}}\frac{1}{r^6}\right] + \mathcal{O}\left(\left(\frac{Q}{M}\right)^4\right)$$

and checking the characteristic TPE scale:

$$\Lambda_{\rm TPE(L)}({}^1S_0) = +389\,{\rm MeV} \quad , \quad \Lambda_{\rm TPE(SL)}({}^1S_0) = +233\,{\rm MeV}\,,$$
$$\Lambda_{\rm TPE(L)}({}^3S_1) = -370\,{\rm MeV} \quad , \quad \Lambda_{\rm TPE(SL)}({}^3S_1) = +220\,{\rm MeV}\,,$$

from which it becomes apparent that $\Lambda_{\rm TPE(SL)}$ is pretty soft.

$\Longrightarrow$ **Further justification for the iteration of TPE**

Expansion around subleading TPE (II)

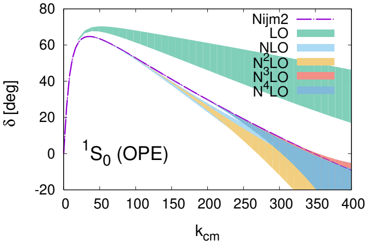
Simplification: iterate the full potential up to subleading TPE

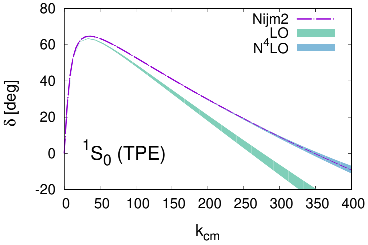
Contribution	NDA	EFT(OPE)	EFT(TPE)
$V_{\rm OPE}$	Q^0	Q^{-1}	Q^{-1}
$V_{\rm TPE(L)}$	Q^2	Q^2	Q^{-1}
$V_{\rm TPE(SL)}$	Q^3	Q^3	Q^{-1}
$C_0\,({}^1S_0)$	Q^0	Q^{-1}	Q^{-1}
$C_2\,({}^1S_0)$	Q^2	Q^0	Q^3
$C_4\,({}^1S_0)$	Q^4	Q^2	Q^5
$C_0\,({}^3S_1)$	Q^2	Q^{-1}	Q^{-1}
$C_0\,(E_1/{}^3D_1)$	Q^2	Q^2	Q^{-1}
$C_2\,({}^3S_1/E_1/{}^3D_1)$	Q^4	Q^2	Q^3
$C_0\,({}^3P_0)$	Q^0	Q^{-1}	Q^{-1}
$C_2\,({}^3P_0)$	Q^2	Q^2	Q^3

Power counting w/ demoted contacts entering at higher orders

Expansion around subleading TPE (III)

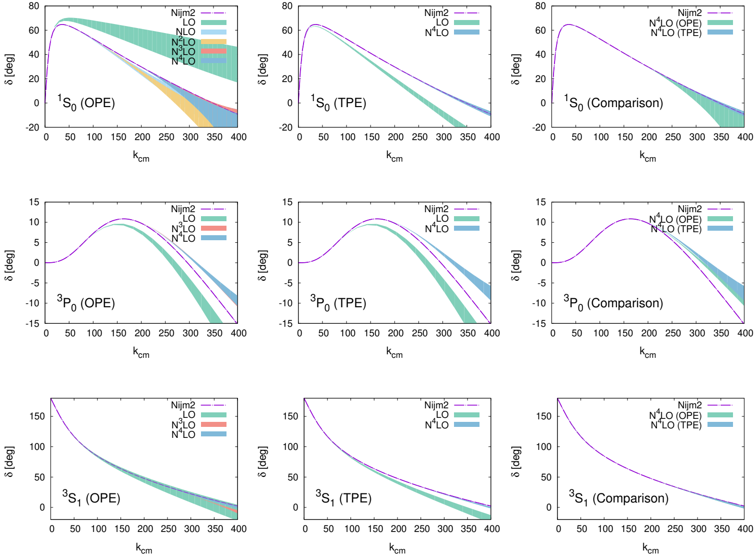
With this new expansion the singlet looks like:





Modest improvement for moderate cutoffs ($R_c = 0.5 - 1.0\,\mathrm{fm}$)

Expansion around subleading TPE (IV)



Expansion around subleading TPE (IV)

Comparison between the expansions around OPE and TPE

(i) EFT(TPE) works definitely better in the singlet
(ii) EFT(TPE) works as well as EFT(OPE) for other partial waves

The problem though is how subversive it feels: not expecting it to be taken seriously. However, the arguments behind it are legit.

(In fact I only considered this expansion ironically in 2010 and called it an "anti power counting"; Papenbrock et al. took it unironically in 2021)

And though power counting is not a social construct,

Power counting is still a theory construct,

a property of a particular type of theories (EFTs), but not a property of nature itself.

Conclusions

Conclusions (list)

- We want it all: **renormalization** & **power counting**
  But one is easier to get and more useful than the other
  - Renormalizable amplitudes are difficult to generate:
    bad news if you simply want to develop a chiral potential
- Compromises are possible (if you believe in compromises)
  Iterating the potential might generate amplitudes w/ good counting properties (for moderate cutoffs)
  - Could be applied to Weinberg, but highly inconsistent
    (and let's not talk about what will happen at $\mathrm{N^3LO}$)
  - But works significantly better for RGA-derived countings
- Post-modern developments: power counting can be subverted
  - Promoting subleading TPE to LO might sound deranged,
    but works surprisingly well (and is justifiable).

Thanks For Your Attention!