Removing the Wigner Bound in non-perturbative effective field theory

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arXiv:1907.11886

5.9.2019

Effective field theory (EFT) - A brief reminder

- Usually in physics we have an underlying theory with a typical scale M_{high} but we want to study it in a lower scale $M_{low} \ll M_{high}$.

- EFTs provides a framework to construct the interactions **systematically**.

- In EFT, the high energy degrees of freedom are integrated out and the details of the interactions are encoded in the coupling constants.

- In **pionless EFT ($\not\pi$EFT)** the degrees of freedom are baryons where the pions are integrated out. The interactions become contact.

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Structure-less bosonic fields

In the naïve power counting

- Non-relativistic fields count as $(M_{low}/M_{high})^{3/2}$.
- Derivatives count as (M_{low}/M_{high}).

The Lagrangian is expanded in (M_{low}/M_{high})

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_1 + \mathcal{L}_2 + \cdots.$$

For instance, the **LO** Lagrangian is

$$\mathcal{L}_0 = \psi^\dagger \left(i\partial_t + \frac{\nabla^2}{2m} \right) \psi - \frac{C_0}{4} \left(\psi^\dagger \psi \right)^2,$$

and the **NLO** Lagrangian is

$$\mathcal{L}_1 = -\frac{C_2}{4} \left[\left(\psi^\dagger \psi \right) \left(\psi^\dagger \nabla^2 \psi \right) + h.c. \right].$$

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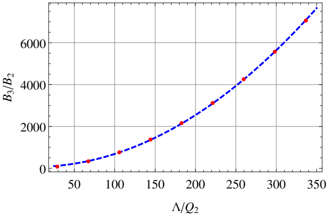
Naïve power counting in 3,4-body boson systems

Thomas collapse:

- When trying to calculate the 3-body binding energy we get, already in LO:

$$B_3 \propto \frac{\hbar \Lambda^2}{m}$$

In order to fix it, the 3-body force $D_0 \left(\psi^\dagger \psi\right)^3$ is **promoted from higher orders to the LO**.



- Again, the 4-body binding energy diverges in NLO and the 4-body force is **promoted to NLO** to fix it[1].

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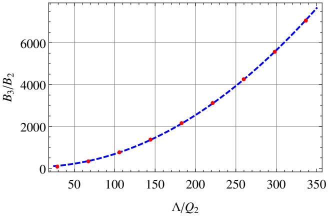

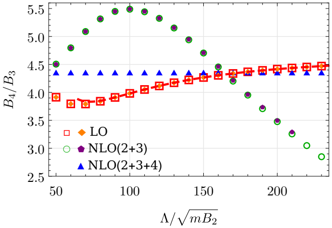

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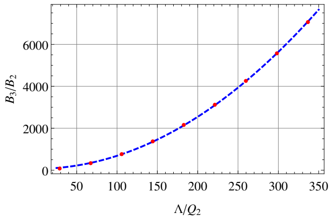

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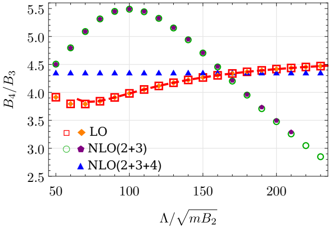

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Wigner bound

Phillips and Cohen showed that[2]:

$$r_{\text{eff}} \leq 2R\left(1 - \frac{R}{a_s} + \frac{R^2}{3a_s^2}\right)$$

In EFT, $R_{\text{EFT}} \sim \Lambda^{-1}$. Thus $r_{\text{eff}} \leq \frac{W}{\Lambda}$ as $\Lambda \to \infty$.

We can "reverse" this inequality to get

$$\boxed{\Lambda \leq \Lambda_{\text{max}} \equiv \frac{W}{r_{\text{eff}}}.}$$

Does Λ_{max} increase as more EFT orders are taken into accout? i.e. can we restore RG invariance order by order?

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Lippmann-Schwinger equation

In order to find r_{eff} we need to solve the Lippmann-Schwinger (LS) equation:

$$T = V + VGT,$$

where

$$V_{\text{N}^n\text{LO}} = C_0 + C_2\left(p^2 + p'^2\right) + C_4\left(p^4 + p'^4\right) + C_{22}p^2p'^2 + \cdots.$$

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Solving Lippmann-Schwinger equation

The potential can be written as

$$V = F\left(p^2/\Lambda^2\right)\left(\sum_{i,j=0}^{n} p^{2i}\lambda_{i,j}p'^{2j}\right)F\left(p'^2/\Lambda^2\right)$$

where

$$\lambda_{\mathrm{NLO}} = \begin{pmatrix} C_0 & C_2 \\ C_2 & 0 \end{pmatrix} \qquad \lambda_{\mathrm{N^2LO}} = \begin{pmatrix} C_0 & C_2 & C_4 \\ C_2 & C_{2,2} & 0 \\ C_4 & 0 & 0 \end{pmatrix} \qquad \cdots.$$

The T-matrix assumes the form

$$T = F\left(p^2/\Lambda^2\right)\sum_{i,j=0}^{n} p^{2i}\tau_{ij}(E)p'^{2j}F\left(p'^2/\Lambda^2\right).$$

The LS equation is reduced to the matrix equation

$$\boxed{\tau = \lambda + \lambda\mathcal{I}\tau} \quad , \quad \mathcal{I}_{ij} \equiv \int \frac{d^3q}{(2\pi)^3}\frac{F^2\left(q^2/\Lambda^2\right)q^{2(i+j)}}{E+i\varepsilon-\frac{q^2}{m}}.$$

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Solving Lippmann-Schwinger equation

The solution is easily found to be

$$\tau = \frac{1}{1-\lambda\mathcal{I}}\lambda$$

The matrix elements of $\mathcal{I}$ depend only on the sum of the indices $\mathcal{I}_{i,j} = \mathcal{I}_{2(i+j)}$ and admit the recursive relations

$$\mathcal{I}_{2k} = mE\mathcal{I}_{2(k-1)} + I_{2k+1}$$

where

$$I_{2k+1} = -m\int \frac{d^3q}{(2\pi)^3} F^2(q^2/\Lambda^2)q^{2k-2} \qquad \mathcal{I}_0(E) = \int \frac{d^3q}{(2\pi)^3}\frac{F^2(q)}{E+i\varepsilon-\frac{q^2}{2\mu}}.$$

For example, using Gaussian regulator in NLO:

$$\frac{1}{T} = e^{\frac{2mE}{\Lambda^2}}\left(\frac{(C_2 I_3-1)^2}{C_0+C_2^2 I_5+\frac{mE}{I_3}(1-(C_2 I_3-1)^2)} - \mathcal{I}_0(E)\right).$$

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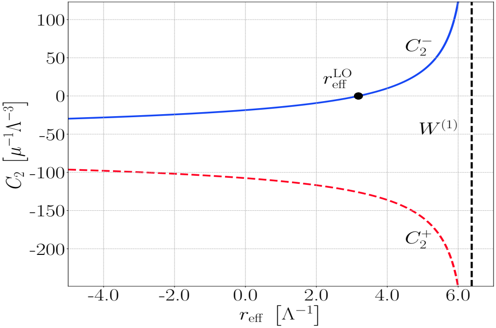
$$\frac{1}{T} \approx -\frac{m}{4\pi}\left(-\frac{1}{a_s} + \frac{1}{2} r_{\text{eff}} p^2 + \cdots - ip\right).$$

Match the LECs to the observables:

$$C_0,\ C_2 \longrightarrow a_s,\ r_{\text{eff}}$$

Two solutions for C_2 exist:



Black dot - r_{eff} obtained at LO for $a_s\Lambda = 10^3$.

$W^{(n)}$

The matching gives

$$r_{\text{eff}} = \frac{\tau'_{00}(0) + m(\tau_{01}(0) + \tau_{10}(0)) - \frac{8\pi a_s}{\Lambda^2}}{2\pi a_s^2}$$

To find $W^{(n)}$ we need to find its maximum using the parameter space $\{C_{pq}\}$ with the constraint $a_s = \frac{m}{4\pi}\tau_{00}(0)$.

$$\{C_0, C_2, C_4, C_{2,2}, \ldots\} \longrightarrow \{a_s, C_2, C_4, C_{2,2}, \ldots\}$$

Imposing the condition $C_{p,q} I_{p+q+1} \propto \Lambda$

$W^{(n)}$ as a function of the EFT order n:

Order	1	2	3	4	5	6
Gaussian	$8\sqrt{\frac{2}{\pi}}$	$\frac{32\sqrt{\frac{2}{\pi}}}{3}$	$\frac{64\sqrt{\frac{2}{\pi}}}{5}$	$\frac{512\sqrt{\frac{2}{\pi}}}{35}$	$\frac{1024\sqrt{\frac{2}{\pi}}}{63}$	$\frac{4096\sqrt{\frac{2}{\pi}}}{231}$
Sharp	$\frac{16}{\pi}$	$\frac{256}{9\pi}$	$\frac{1024}{25\pi}$	$\frac{65536}{1225\pi}$	$\frac{262144}{3969\pi}$	$\frac{4194304}{53361\pi}$

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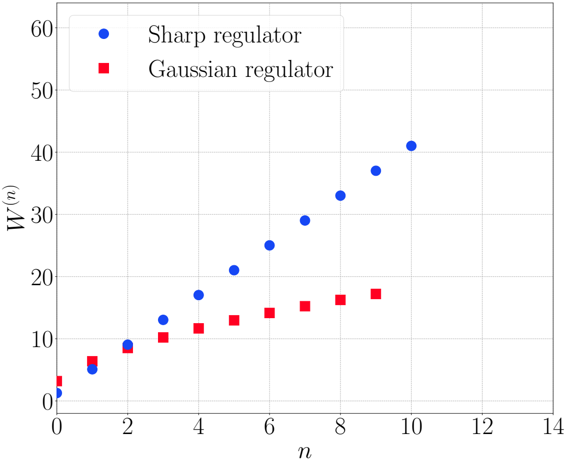
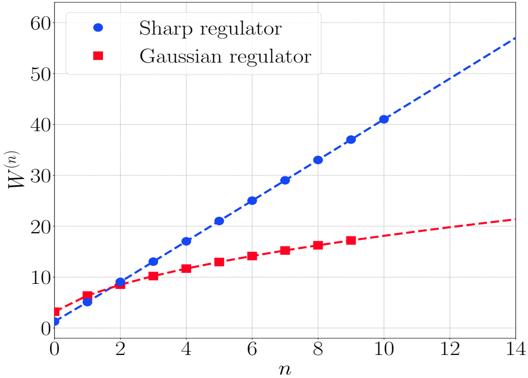

Sharp regulator
Gaussian regulator
$W^{(n)}$
n
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14

Conjecture for $W^{(n)}$



$$W^{(n)}_{Gauss} = 4\sqrt{2}\frac{\Gamma(n+1)}{\Gamma\left(n+\frac{1}{2}\right)} \qquad W^{(n)}_{Sharp} = 4\left(\frac{\Gamma(n+1)}{\Gamma\left(n+\frac{1}{2}\right)}\right)^2$$

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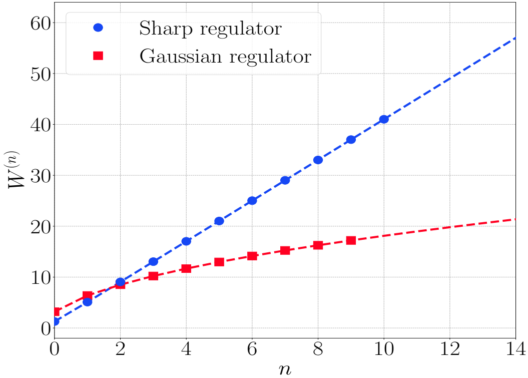

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$$\lim_{n\to\infty} W^{(n)}_{Gauss} = 4\sqrt{2n}$$

$$\lim_{n\to\infty} W^{(n)}_{Sharp} = 4n$$

Degeneracy of $C_{2,2}$

At NLO, two renormalization conditions were needed, i.e. a_s, r_{eff}.

Note, however, that the T-matrix provides **one** condition each order

$$\frac{1}{T} \approx -\frac{m}{4\pi}\left(-\frac{1}{a_s} + \frac{1}{2} r_{\text{eff}} p^2 + \sum_{n\geq 2} S_n p^2 - ip\right).$$

The potential, on the other hand, gives rise to more LECs. Already in **N^{2}LO** we get **2 more** coefficients: C_4, $C_{2,2}$

$$V_{\text{N}^n\text{LO}} = C_0 + C_2\left(p^2 + p'^2\right) + C_4\left(p^4 + p'^4\right) + C_{22} p^2 p'^2 + \cdots.$$

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The Volkov potential has the form

$$V(r) = V_R e^{-\frac{r^2}{R_1^2}} + V_A e^{-\frac{r^2}{R_2^2}}$$

with the effective range parameters

$$a_s = 10.08 \text{ fm} \qquad r_{\text{eff}} = 2.37 \text{ fm} \qquad S_2 = 0.43 \text{ fm}^3.$$

The **maximum** $\boldsymbol{r_{\text{eff}}}$ at different orders and cutoffs is

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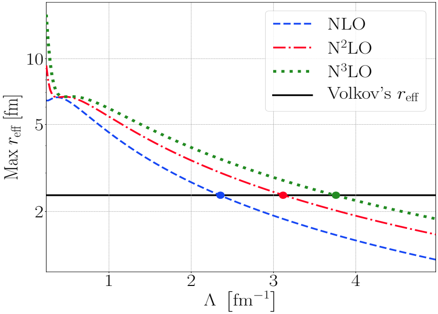
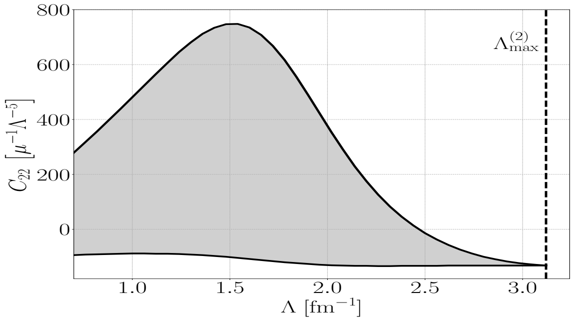


The freedom in C_{22}

Does fitting the LECs to the effective range expansion parameters constrain Λ_{max}?

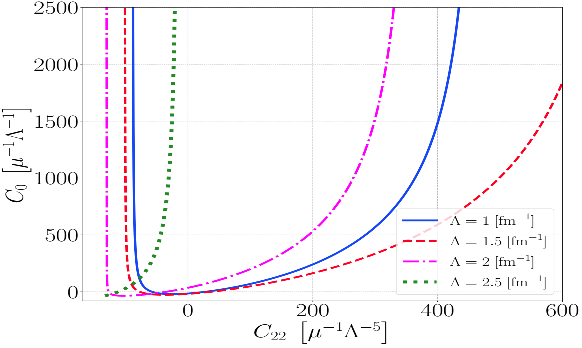
Match the LECs to the observables in N^{2}LO:

$$\begin{array}{cccc} C_0 & C_2 & C_4 & C_{22} \\ \downarrow & \downarrow & \downarrow & \downarrow \\ a_s & r_{\text{eff}} & S_2 & ? \end{array}$$



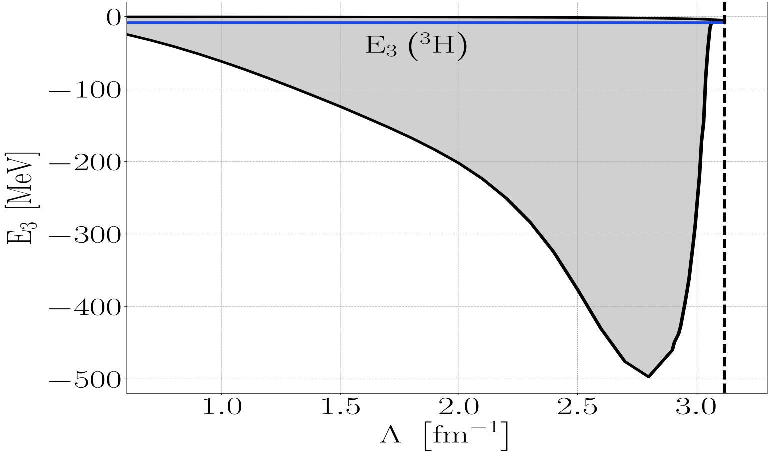
LECs dependence on the cutoff

The dependence of the LECs on the cutoff explodes near the extremal allowed values of C_{22}:

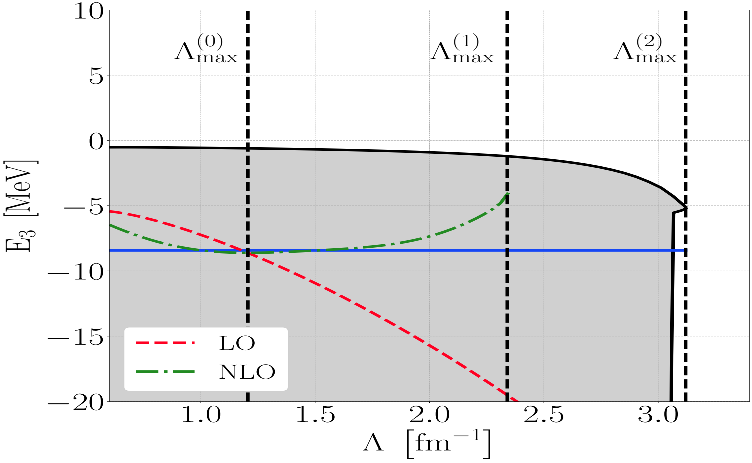


Unstable numerical results at high cutoff

3-body binding energy



3-body force



$\Lambda^{(0)}_{\max}$
$\Lambda^{(1)}_{\max}$
$\Lambda^{(2)}_{\max}$
10
5
0
−5
−10
−15
−20
E_3 [MeV]
1.0
1.5
2.0
2.5
3.0
Λ [fm^{-1}]
LO
NLO

Summary

- The Wigner bound on the effective range **increases** with the non-perturbative EFT orders.
- The number of possible solutions **increases** with increasing orders. Only one of them is physical.
- Numerical calculations become unstable at Λ_{max}.
- With the right choice of LECs, the promotion of the 3-body force may be suspended!

Saar Beck, Betzalel Bazak, and Nir Barnea, arXiv:1907.11886

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