INTRODUCTION TO EFFECTIVE FIELD THEORIES OF QCD

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Outline

- ☐ Effective Field Theories
- ☐ QCD at Low Energies
- ☐ Towards Nuclear Structure
  - ▶ Contact Nuclear EFT
  - ▶ Few-Body Systems
  - ▶ No-Core Shell Model
  - ▶ Halo/Cluster EFT
  - ▶ Conclusions and Outlook

References:

U. van Kolck,
Effective field theory of short-range forces,
Nucl.Phys.A645:273-302,1999, **nucl-th/9808007**

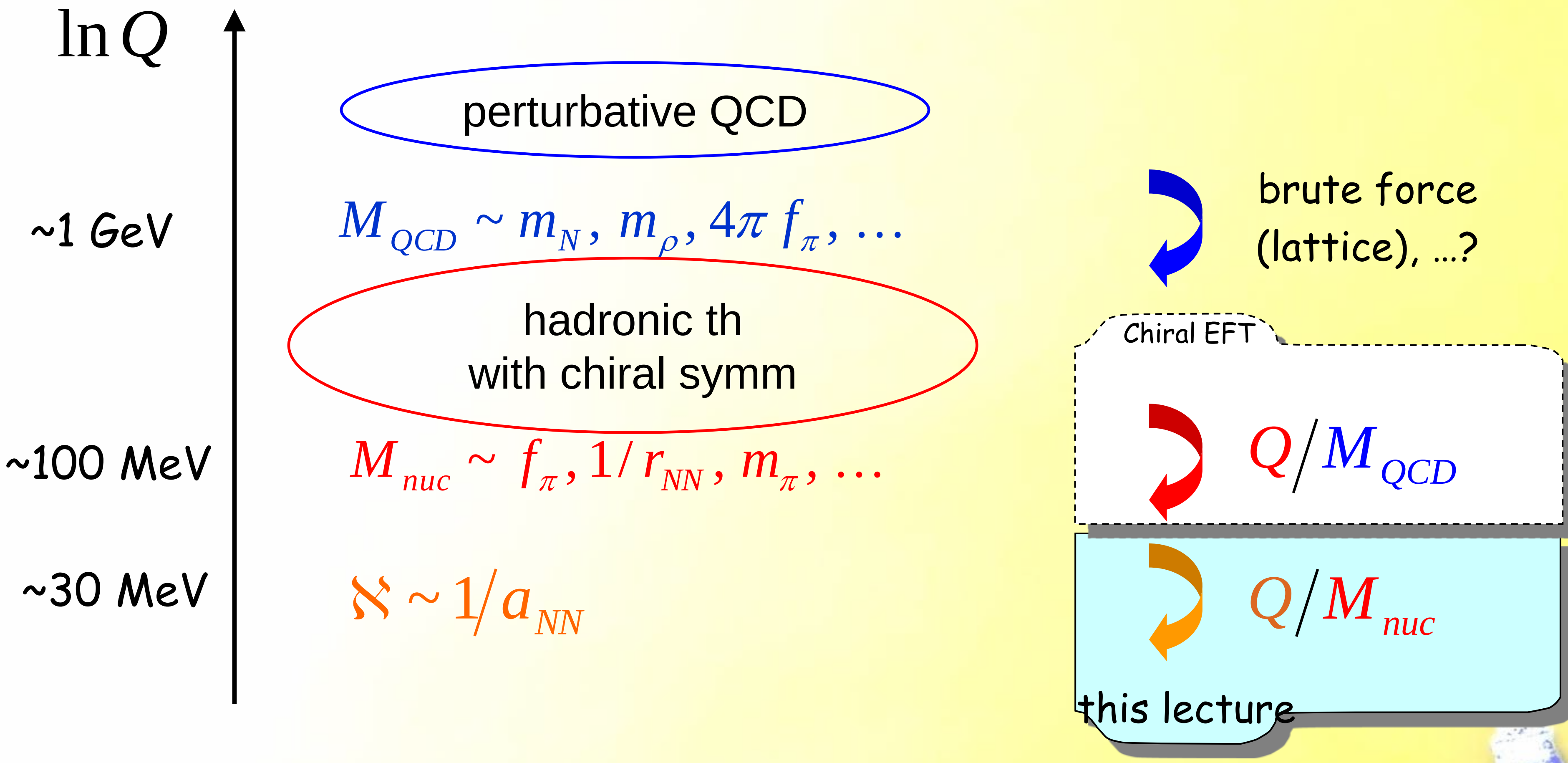
P.F. Bedaque, H.-W. Hammer, and U. van Kolck,
The three-boson system with short-range interactions,
Nucl.Phys.A646:444-466,1999, **nucl-th/9811046**

I. Stetcu, B.R. Barrett, and U. van Kolck,
No-core shell model in an effective-field-theory framework,
Phys.Lett.B653:358-362,2007, **nucl-th/0609023**

P.F. Bedaque, H.-W. Hammer, and U. van Kolck,
Narrow resonances in effective field theory,
Phys.Lett.B569:159-167,2003, **nucl-th/0304007**

Nuclear physics scales

"His scales are His pride", Book of Job



$\ln Q$

perturbative QCD

~1 GeV

$M_{QCD} \sim m_N, m_\rho, 4\pi f_\pi, \ldots$

brute force (lattice), ...?

hadronic th with chiral symm

Chiral EFT

Q/M_{QCD}

~100 MeV

$M_{nuc} \sim f_\pi, 1/r_{NN}, m_\pi, \ldots$

~30 MeV

$\aleph \sim 1/a_{NN}$

Q/M_{nuc}

this lecture

no small coupling → expansion in ⬆

Lots of interesting nuclear physics at $E \sim 1\ \mathrm{MeV}$

instead of $E \sim 10\ \mathrm{MeV}$

within a few MeV of thresholds:

- many energy levels and resonances (cluster structures)
- most reactions of astrophysical interest

show universal features,

i.e. to a very good approximation are independent

of details of the short-range dynamics

bonus: same techniques can be used

for dilute atomic/molecular systems

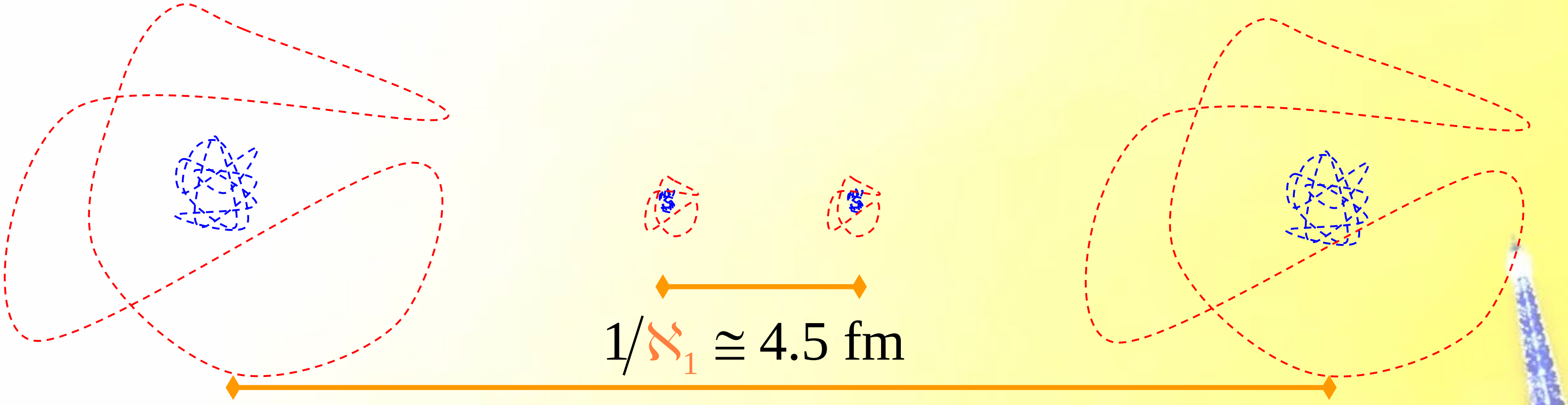
- pionful EFT an overkill at lower energies! cf. Bethe + Peierls '35

e.g. NN s_1 channel: | s_0 channel:

(real) bound state = deuteron | (virtual) bound state

$\aleph_1 \sim \sqrt{m_N B_d} \cong 45\ \mathrm{MeV} < m_\pi$

$\aleph_0 \sim \sqrt{m_N B_{d^*}} \cong 8\ \mathrm{MeV} \ll m_\pi$



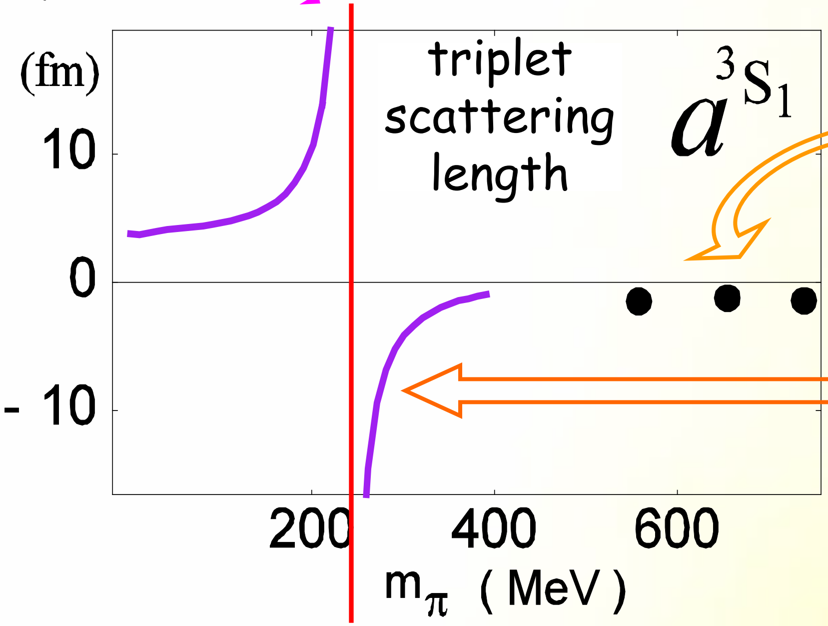
$1/\aleph_1 \cong 4.5\ \mathrm{fm}$

➡ multipole expansion of meson cloud:
contact interactions among local nucleon fields

Pion-mass dependence

unitarity limit

$|a_2| \to \infty$



$m_\pi^*\left(M_{QCD}\right)$

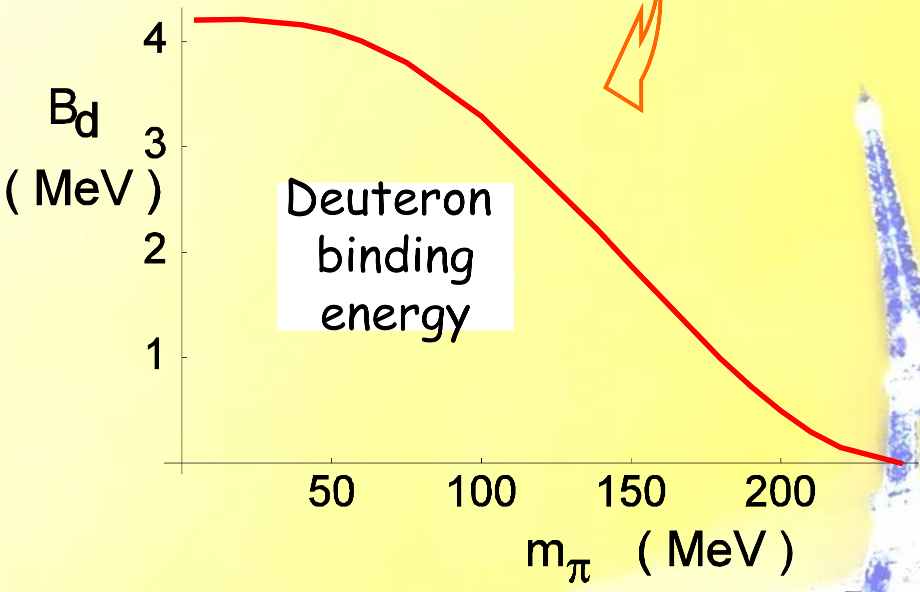
Lattice QCD: quenched Fukugita et al. '95

cf. Beane, Bedaque, Orginos + Savage '06

Beane, Bedaque, Savage + v.K. '02

EFT: (incomplete) NLO

…

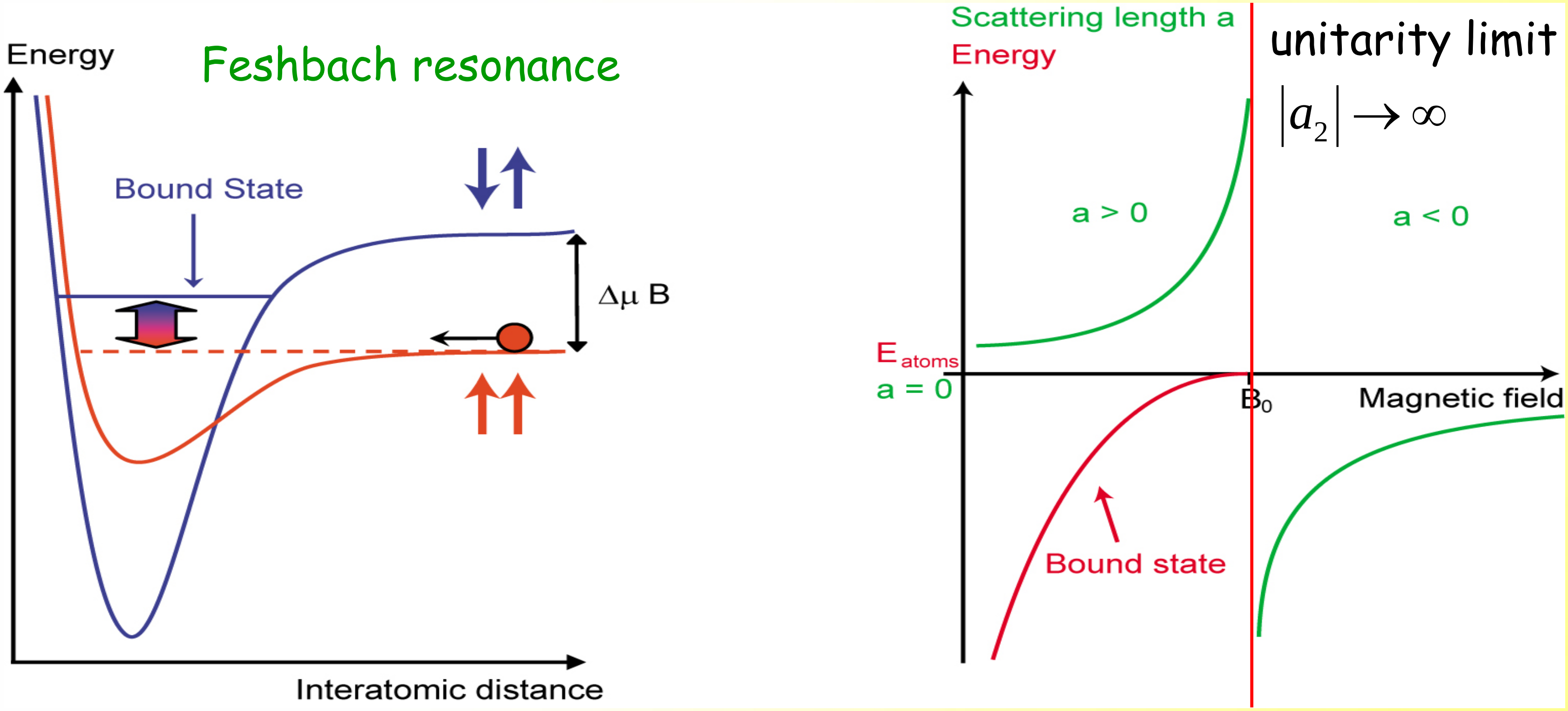


Large deuteron size because

$$m_\pi \sim m_\pi^*\left(M_{QCD}\right)$$

$$\aleph \sim \frac{m_\pi - m_\pi^*}{m_\pi^*} M_{nuc}$$

Cf. trapped fermions



Feshbach resonance

unitarity limit

$$|a_2| \to \infty$$

MIT group webpage

quark masses analog to magnetic field:
close to critical values

$$m_\pi^{*2} = \mathcal{O}\left(\left(m_u^* + m_d^*\right) M_{QCD}\right) \simeq \left(200\ \text{MeV}\right)^2$$

contact EFT can, and has been, used for atomic systems with large scatt lengths:

universality!

Example: square well $V(r) = -\frac{\alpha^2}{mR^2}\theta\left(1-\frac{r}{R}\right)$

$$\Rightarrow \quad T(k) = -i\left[e^{-2ikR}\frac{\sqrt{\alpha^2+(kR)^2}\cot\sqrt{\alpha^2+(kR)^2}+ikr}{\sqrt{\alpha^2+(kR)^2}\cot\sqrt{\alpha^2+(kR)^2}-ikr}-1\right]$$

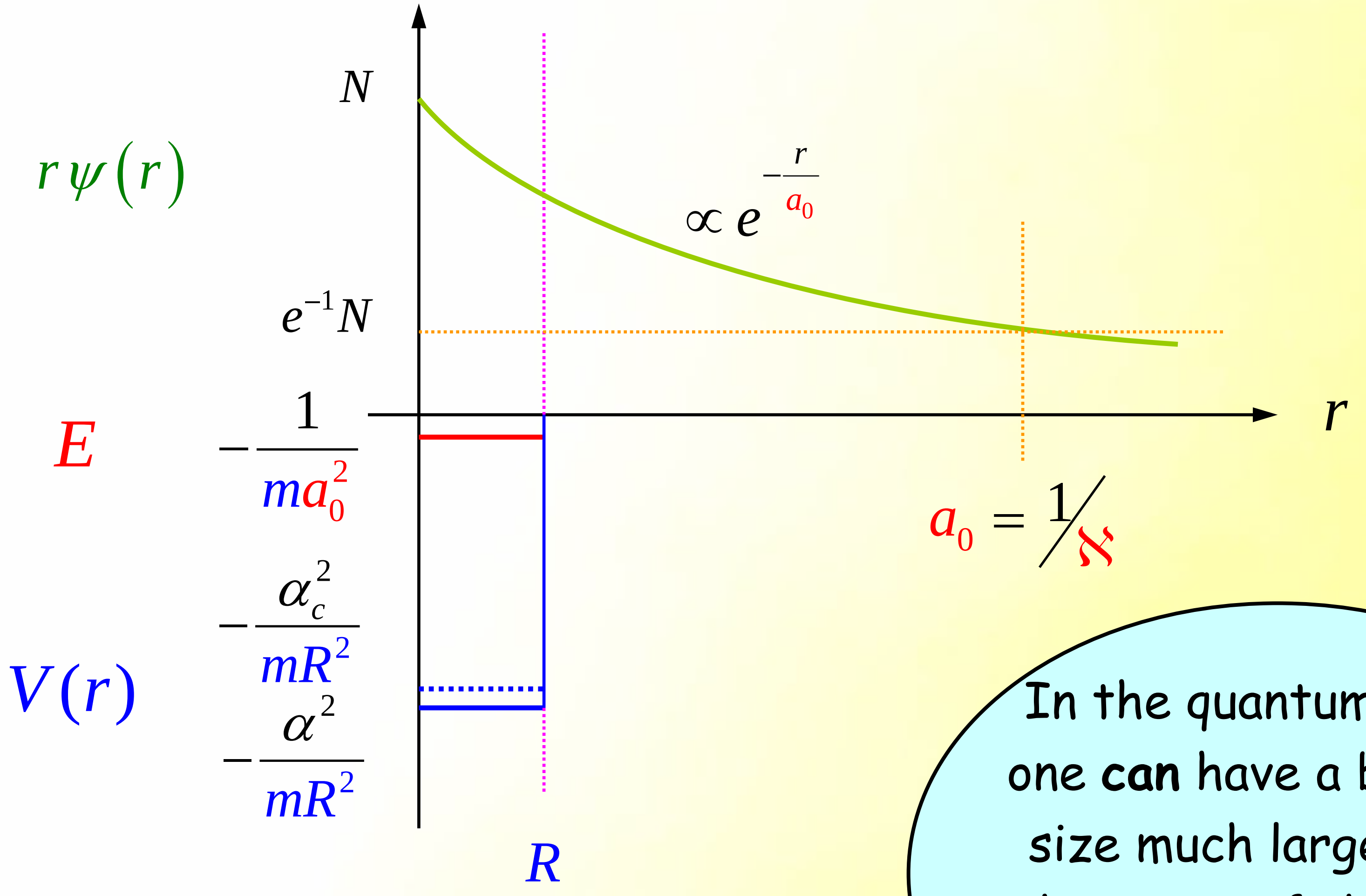
zero-energy poles when

$\alpha_c \equiv (2n+1)\pi/2$

	generic	fine-tuning
	$\alpha = \mathcal{O}(1)$	$\lvert 1-\alpha/\alpha_c\rvert \ll 1$
$a_0 = R\left(1-\frac{\tan\alpha}{\alpha}\right)$	$a_0 \sim R$	$a_0 = -\frac{R}{\alpha_c^2}\left(1-\frac{\alpha}{\alpha_c}\right)^{-1}\{1+\dots\} \sim \frac{1}{\aleph}$
$r_0 = R\left(1-\frac{R}{a_0\alpha^2}-\frac{R^2}{3a_0^2}\right)$	$r_0 \sim R$	$r_0 = R\{1+\dots\} \sim R$

etc.

$$\aleph \equiv \frac{\lvert 1-\alpha/\alpha_c\rvert}{R} \ll \frac{1}{R}$$



In the quantum world,
one **can** have a b.s. with
size much larger than
the range of the force
provided
there is fine-tuning

$Q \sim \aleph \ll M_{nuc}$

pionless EFT

- d.o.f.: nucleons
- symmetries: Lorentz, $\cancel{P}$, $\cancel{T}$

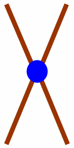
$$\mathcal{L}_{EFT} = N^{+}\left(i\partial_0 + \frac{\nabla^2}{2m_N}\right)N \; + C_0 \, N^{+}N \, N^{+}N$$

$$+ N^{+}\frac{\nabla^4}{8m_N^3}N + C_2 \, N^{+}N \, N^{+}\nabla^2 N$$

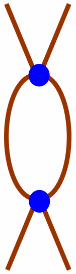
$$+ C_2' \, N^{+}\vec{\nabla}N \cdot N^{+}\vec{\nabla}N + \ldots$$

(omitting

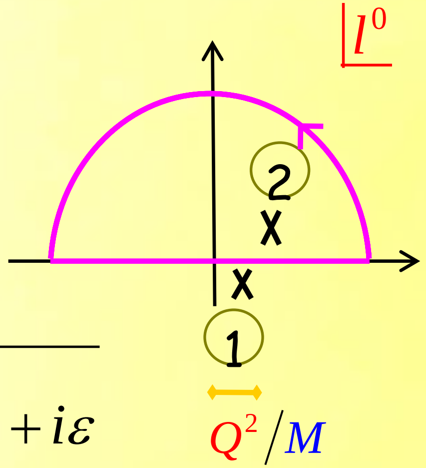
spin, isospin)



$\sim iC_0(\Lambda)$



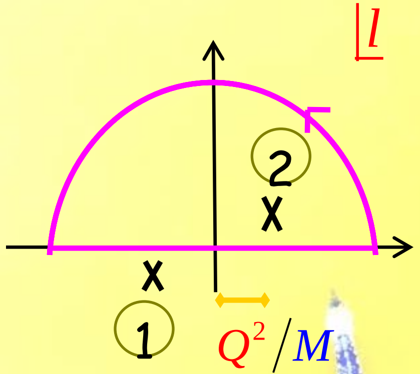
$$\sim C_0^2(\Lambda)\int\frac{d^4l}{(2\pi)^4}\frac{\overset{\textcircled{1}}{1}}{l^0+p^0-\frac{(\vec{l}+\vec{p})^2}{2m_N}+i\varepsilon}\;\frac{\overset{\textcircled{2}}{1}}{-l^0+p^0-\frac{(\vec{l}+\vec{p})^2}{2m_N}+i\varepsilon}$$



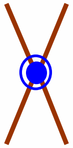
$p^0\equiv\frac{k^2}{2m_N}$

$$=-i\,m_NC_0^2(\Lambda)\int\frac{d^3l}{(2\pi)^3}\frac{1}{\vec{l}^{\,2}-k^2-i\varepsilon}$$

$$=-i\frac{m_N}{2\pi^2}C_0^2(\Lambda)\left\{\int_0^\Lambda dl+k^2\int_0^\Lambda dl\,\frac{\overset{\textcircled{1}}{1}}{l+k+i\varepsilon}\,\frac{\overset{\textcircled{2}}{1}}{l-k-i\varepsilon}\right\}$$



$$=-i\,m_NC_0^2(\Lambda)\left\{\underbrace{\frac{1}{2\pi^2}\Lambda}_{\text{absorbed in }C_0(\Lambda)}+i\underbrace{\boxed{\frac{k}{4\pi}}}_{\text{non-analytic in }E}+\mathcal{O}\underbrace{\left(\frac{k^2}{4\pi\Lambda}\right)}_{\text{absorbed in }C_2(\Lambda)}\right\}\equiv-i\,C_0^2(\Lambda)I_0(\Lambda)$$



$\sim i\,C_2(\Lambda)\,k^2$

etc.

$$\begin{cases} C_0(\Lambda) \to C_0^{(R)} \equiv C_0(\Lambda)\left\{1 - \dfrac{m_N\Lambda}{2\pi^2} C_0(\Lambda) + \ldots\right\} = \dfrac{C_0(\Lambda)}{1 + \dfrac{m_N\Lambda}{2\pi^2} C_0(\Lambda)} \\ C_2(\Lambda) \to C_2^{(R)} \equiv C_2(\Lambda) - \dfrac{m_N}{4\pi\Lambda} C_0^2(\Lambda) + \ldots \\ \ldots \end{cases}$$

Naïve dimensional analysis

$$C_0^{(R)} \equiv \frac{4\pi}{m_N M_0}$$

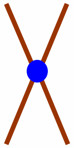
$$C_0^{(R)} \sim \frac{4\pi}{m_N M_{nuc}}$$ ➡ $M_0 \sim M_{nuc}$

$$C_2^{(R)} \equiv \frac{4\pi}{m_N M_{nuc} M_2^2}$$

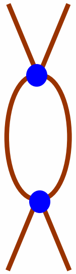
$$C_2^{(R)} \sim \frac{m_N}{4\pi M_{nuc}} C_0^{(R)2}$$ ➡ $M_2 \sim M_0$

etc.

But in this case:

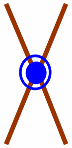


$$\rightarrow C_0^{(R)} \sim \frac{4\pi}{m_N M_0}$$



$$\rightarrow \frac{m_N Q}{4\pi} C_0^{(R)2} \sim \frac{4\pi}{m_N M_0}\frac{Q}{M_0}$$

$\ll 1$ for $M_0 \sim M_{nuc}$



$$\rightarrow C_2^{(R)} Q^2 \sim \frac{4\pi}{m_N M_0}\frac{Q^2}{M_{nuc} M_0}$$

$\ll 1$ if $M_0 \sim M_{nuc}$

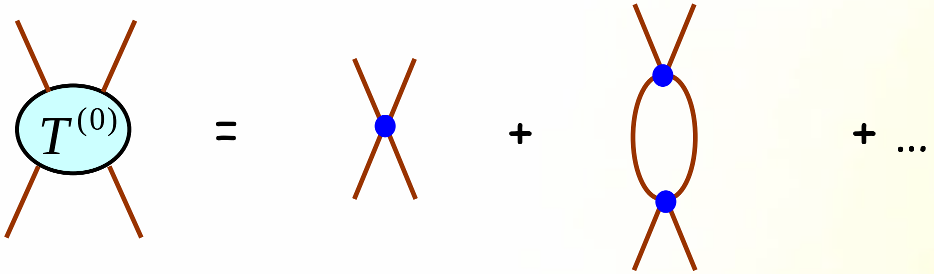
etc.

➡ no b.s. at $Q \lesssim M_{nuc}$, no good: just perturbation theory

need one fine-tuning: $M_0 \equiv \aleph \ll M_{nuc}$

assume no other, *e.g.* still $M_2 \sim M_0$, *etc.*

v.K. '97 '99
Kaplan, Savage + Wise '98
Gegelia '98



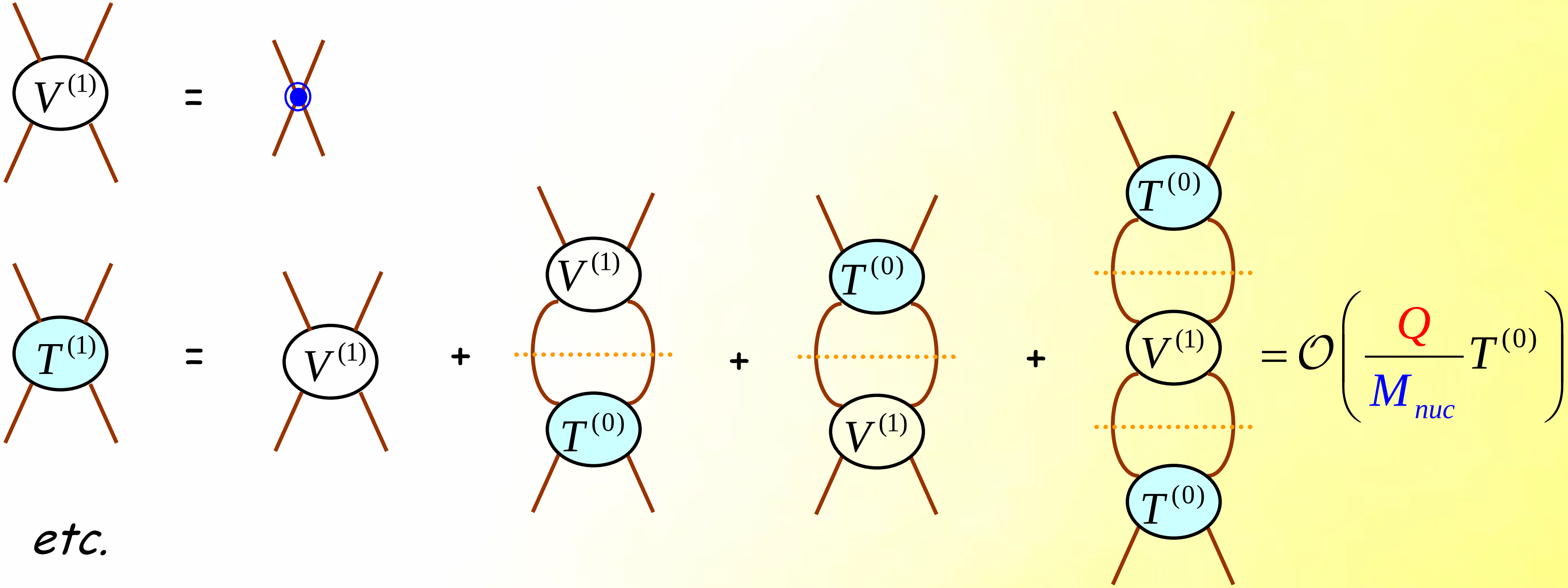
$$= iC_0\left\{1 - C_0 I_0 + \left(C_0 I_0\right)^2 + \ldots\right\} = \frac{i}{\frac{1}{C_0} + I_0} = \frac{4\pi}{m_N}\,\frac{i}{\underbrace{\frac{4\pi}{m_N C_0(\Lambda)} + \frac{2\Lambda}{\pi}}_{= \frac{4\pi}{m_N C_0^{(R)}} \equiv \aleph} + ik + \mathcal{O}\left(\frac{k^2}{\Lambda}\right)}$$

$k \sim \aleph$ ⇧

$$= \frac{4\pi}{m_N}\,\frac{i}{\aleph + ik}\left[1 + \mathcal{O}\left(\frac{k}{\Lambda}, \frac{k^2}{\aleph\Lambda}\right)\right]$$

cf. effective range expansion
s wave

- scattering length $a_0 = 1/\aleph$
- bound state $k = i\aleph$ $-E = \frac{\aleph^2}{2m_N}$



etc.

$$\Rightarrow \quad T_{NN} \sim \frac{4\pi}{m_N M_{nuc}} \left\{ \frac{M_{nuc}}{\aleph + iQ} + \left(\frac{Q}{\aleph + iQ} \right)^2 + \ldots \right\}$$

$\nu = -1$ $\nu = 0$

s wave

scattering length $a_0 \sim 1/\aleph$

effective range $r_0 \sim 1/M_{nuc}$

p, other waves

Kaplan '97
v.K. '99

Alternative: auxiliary field

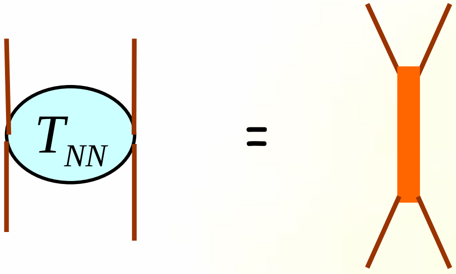
$$\mathcal{L}_{EFT} = N^+\left(i\partial_0 + \frac{\nabla^2}{2m_N}\right)N \;+ T^+\left(-\Delta\right)T + \frac{g}{\sqrt{2}}\left[T^+NN + N^+N^+T\right]$$

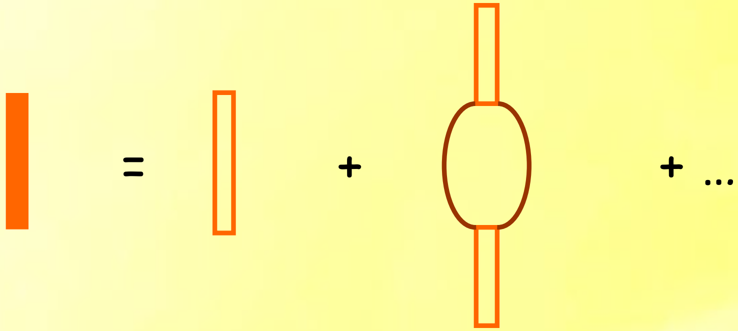
$$+ N^+\frac{\nabla^4}{8m_N^3}N + \sigma T^+\left(i\partial_0 + \frac{\nabla^2}{4m_N}\right)T + \dots$$

sig
n

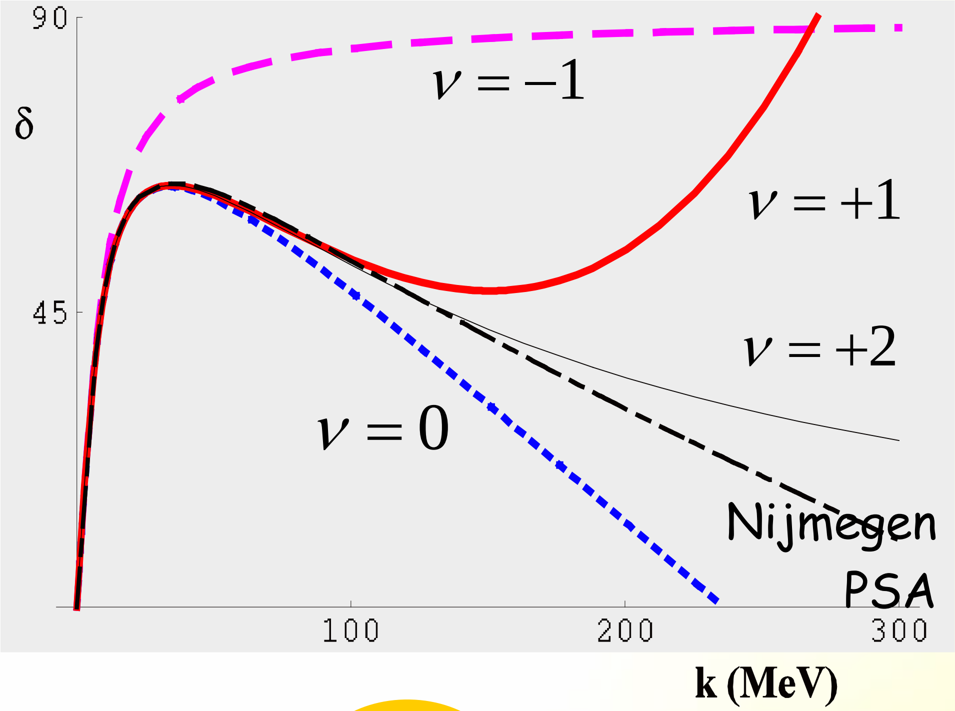
integrate out auxiliary field: same Lag as before with $C_0 = \frac{g^2}{\Delta}, \dots$

$$\Delta \sim \aleph, \quad \frac{g^2}{4\pi} \sim \frac{1}{m_N}, \quad \dots$$





Chen, Rupak + Savage '99



fitted $a_1 = 5.42\ \mathrm{fm}\ (\mathrm{exp})$

$r_1 = 1.75\ \mathrm{fm}\ (\mathrm{exp})$

predicted

$B_d\ =\ 1.91\ \mathrm{MeV}\ (\nu = 0)$

$B_d\ =\ 2.22\ \mathrm{MeV}\ (\mathrm{exp})$

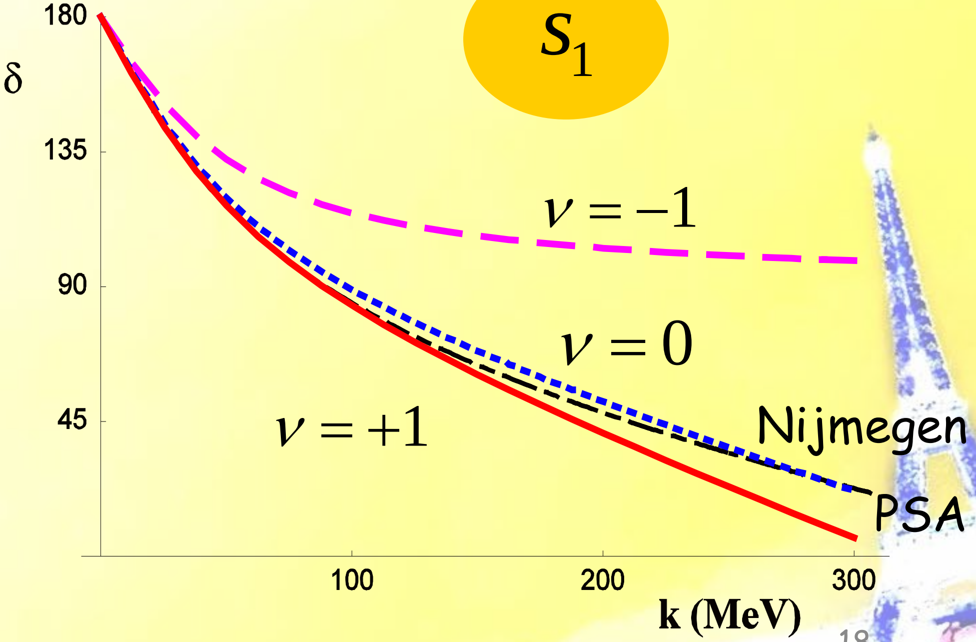
S_0

fitted $a_0 = -20.0\ \mathrm{fm}\ (\mathrm{exp})$

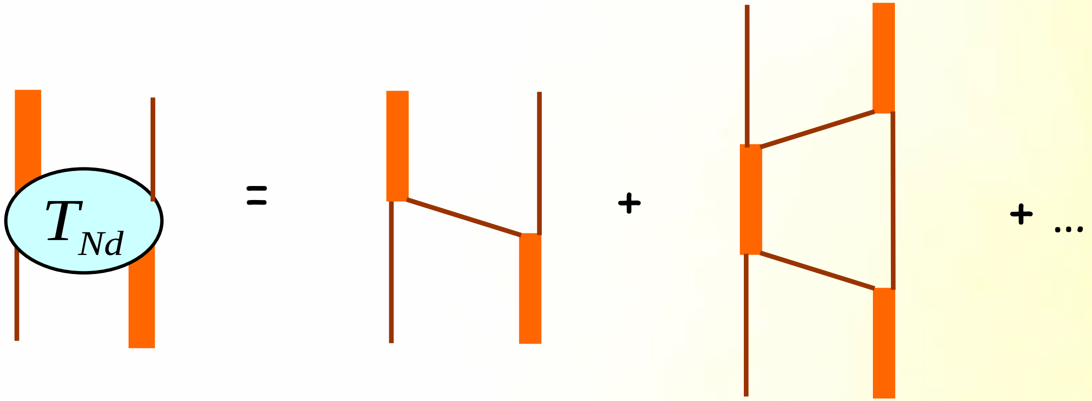
$r_0 =\ 2.78\ \mathrm{fm}\ (\mathrm{exp})$

predicted

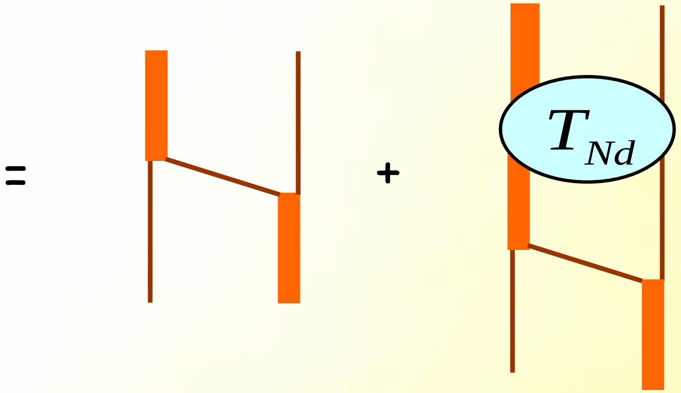
$B_{d^*}\ =\ 0.09\ \mathrm{MeV}\ (\nu = 0)$



S_1



$$\sim \frac{g^2}{Q^2/m_N} \qquad \sim \frac{Q^3}{4\pi}\left(\frac{g^2}{Q^2/m_N}\right)^2 \qquad \sim \frac{g^2}{Q^2/m_N}\,\frac{Q}{\aleph}$$



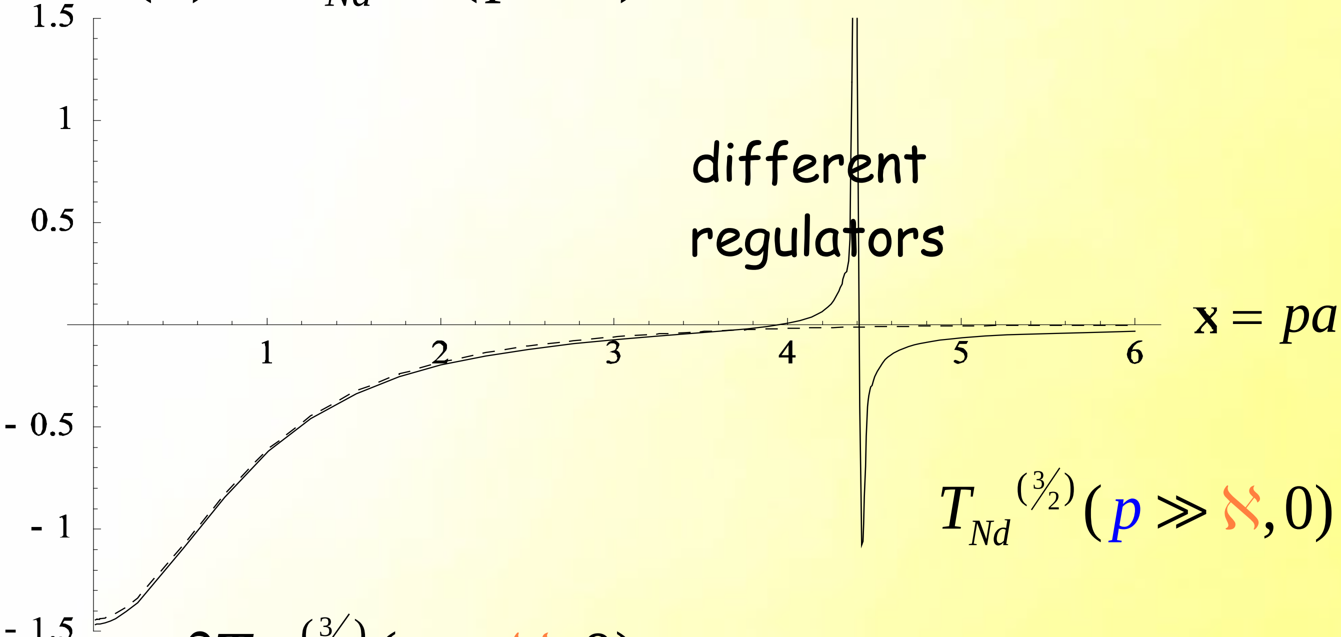
$$T_{Nd} = K_{ONE} + \lambda \int_0^{\Lambda} \frac{d^3 l}{(2\pi)^3}\,\frac{K_{ONE}\,T_{Nd}}{D}$$

renormalization: quartet s wave

$$\lambda \le \lambda_c \equiv \frac{3\sqrt{3}}{4\pi}$$

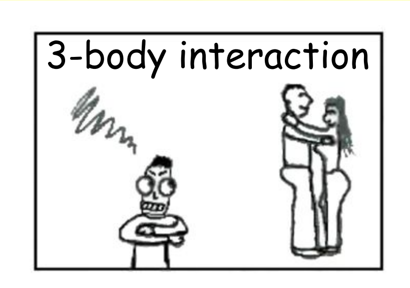
Skornyakov + Ter-Martirosian '60
Bedaque + v.K. '97
Bedaque, Hammer + v.K. '98

$$\mathbf{a}\,(x) \propto T_{Nd}^{(3/2)}(pa,0)$$



$$T_{Nd}^{(3/2)}(p \gg \aleph, 0) \propto \frac{1}{p^2}$$

$$\frac{\partial T_{Nd}^{(3/2)}(p \sim \aleph, 0)}{\partial \Lambda} \cong 0$$



$$\mathcal{L}_{EFT} = \ldots + D_0\, N^+N\, N^+N\, N^+N + \ldots$$

naïve
dimensional analysis

$$D_0 \sim \left(\frac{4\pi}{m_N}\right)^2 \frac{1}{M_{nuc}^3} \quad (\nu = +1)$$

$S_{3/2}$ no three-body force up to $\nu = +3$

Bedaque + v.K. '97
Bedaque, Hammer + v.K. '98
...

$$\lambda \le \lambda_c \equiv \frac{3\sqrt{3}}{4\pi}$$

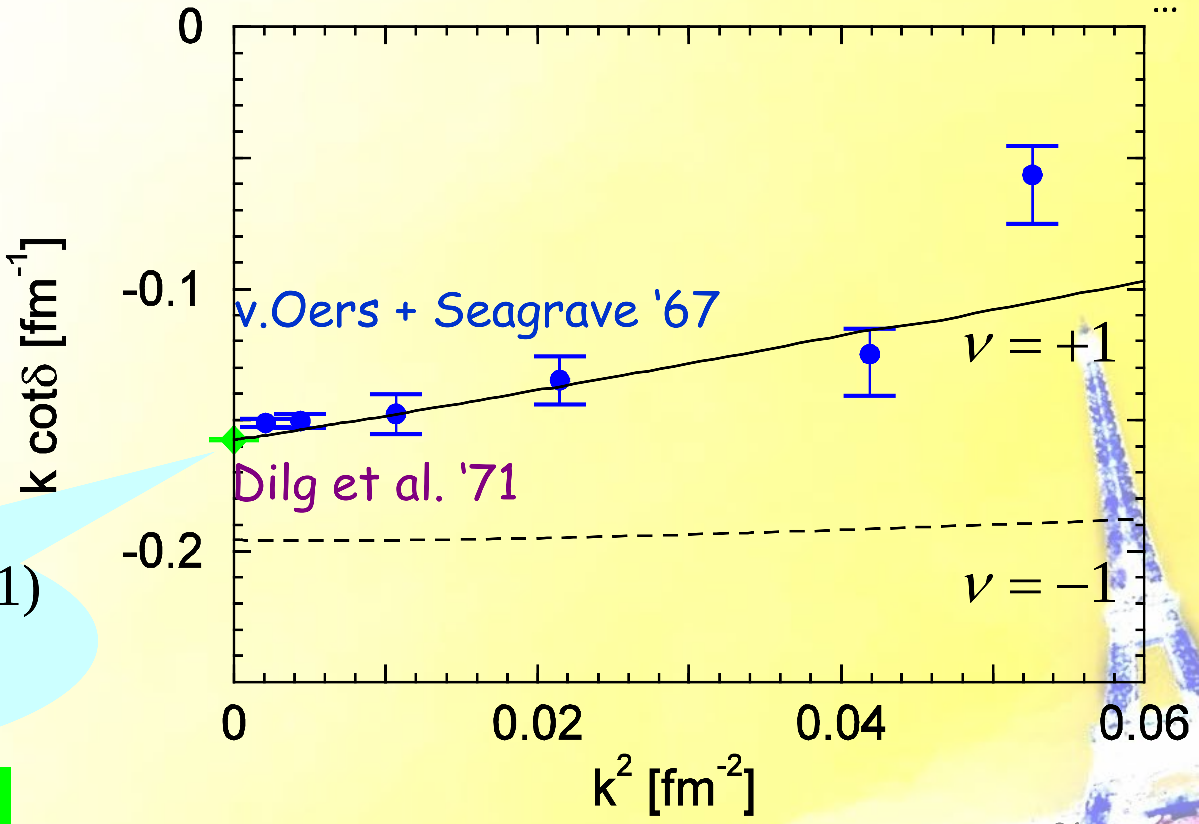
$$T_{Nd} \xrightarrow{p \gg \aleph} \frac{1}{p^2}$$

$$\Rightarrow \frac{\partial T_{Nd}}{\partial \Lambda} \xrightarrow{p \sim \aleph} 0$$

predicted

$$a_{3/2} = 6.33 \pm 0.10 \text{ fm } (\nu = +1)$$

$$a_{3/2} = 6.35 \pm 0.02 \text{ fm (exp)}$$



QED-like precision!

$S_{1/2}$

$$\lambda > \lambda_c \equiv \frac{3\sqrt{3}}{4\pi}$$

Bedaque, Hammer + v.K. '99 '00

Hammer + Mehen '01

Bedaque et al. '03

$$T_{Nd} \xrightarrow{p \gg \aleph} A \cos\left(s_0 \ln \frac{p}{\Lambda} + \delta \right) \Rightarrow \frac{\partial T_{Nd}}{\partial \Lambda} \xrightarrow{p \sim \aleph} \neq 0$$ unless

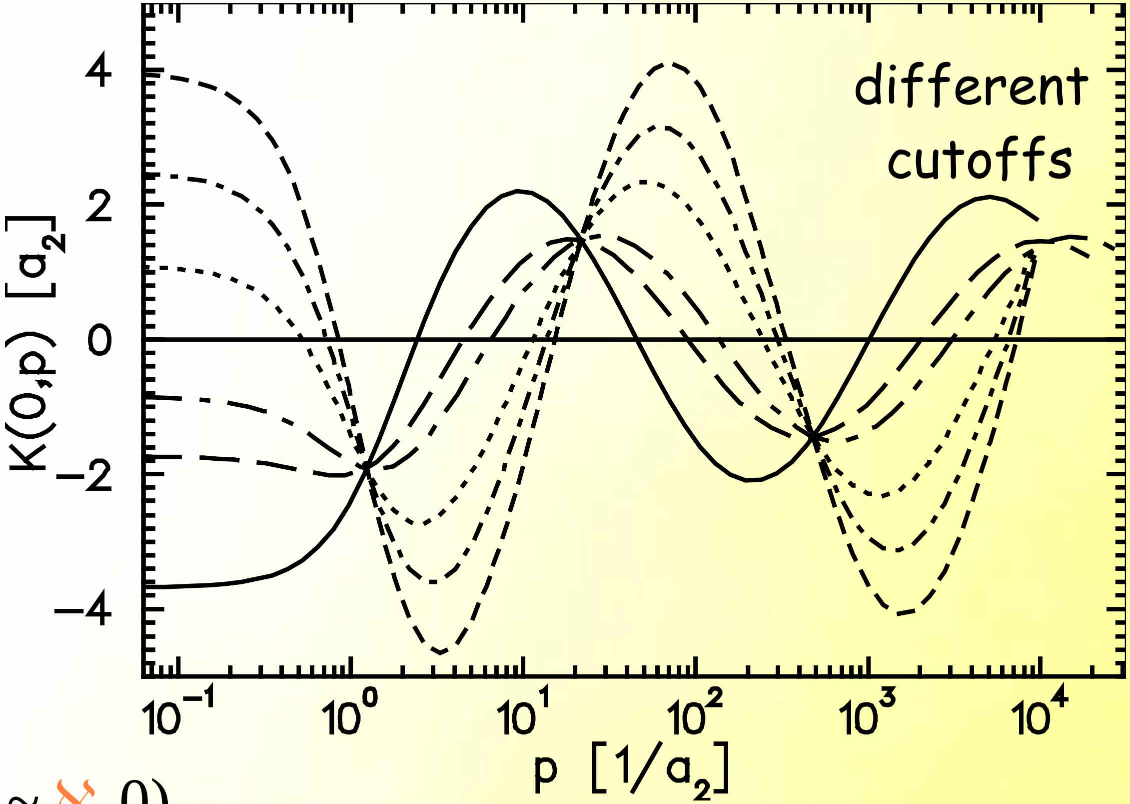
$$D_0 \sim \left(\frac{4\pi}{m_N} \right)^2 \frac{1}{\aleph^2 M_{nuc}} \quad (\nu = -1)$$

renormalization: doublet s wave -I

Danilov '63

Bedaque, Hammer + v.K. '99 '00

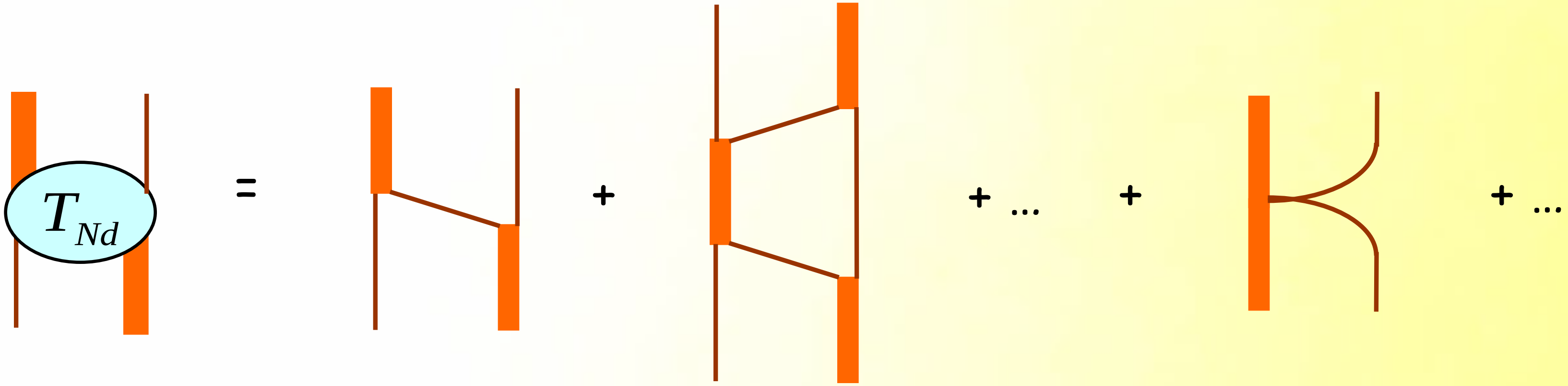
$$\lambda > \lambda_c \equiv \frac{3\sqrt{3}}{4\pi}$$



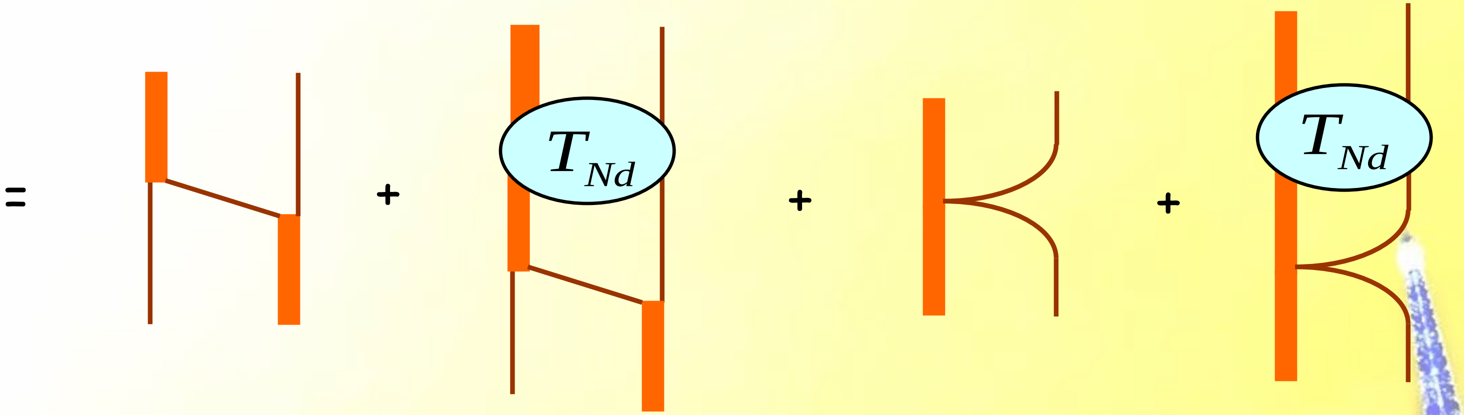
$$\frac{\partial T_{Nd}^{(1/2)}(p \sim \aleph, 0)}{\partial \Lambda} \neq 0$$

$$T_{Nd}^{(1/2)}(p \gg \aleph, 0) \propto \cos\left(s_0 \ln \frac{p}{\Lambda} + \delta\right)$$

$$s_0 \cong 1.0024$$



$$\sim \frac{g^2}{Q^2 / m_N} \qquad \sim \frac{4\pi}{\aleph^2}$$



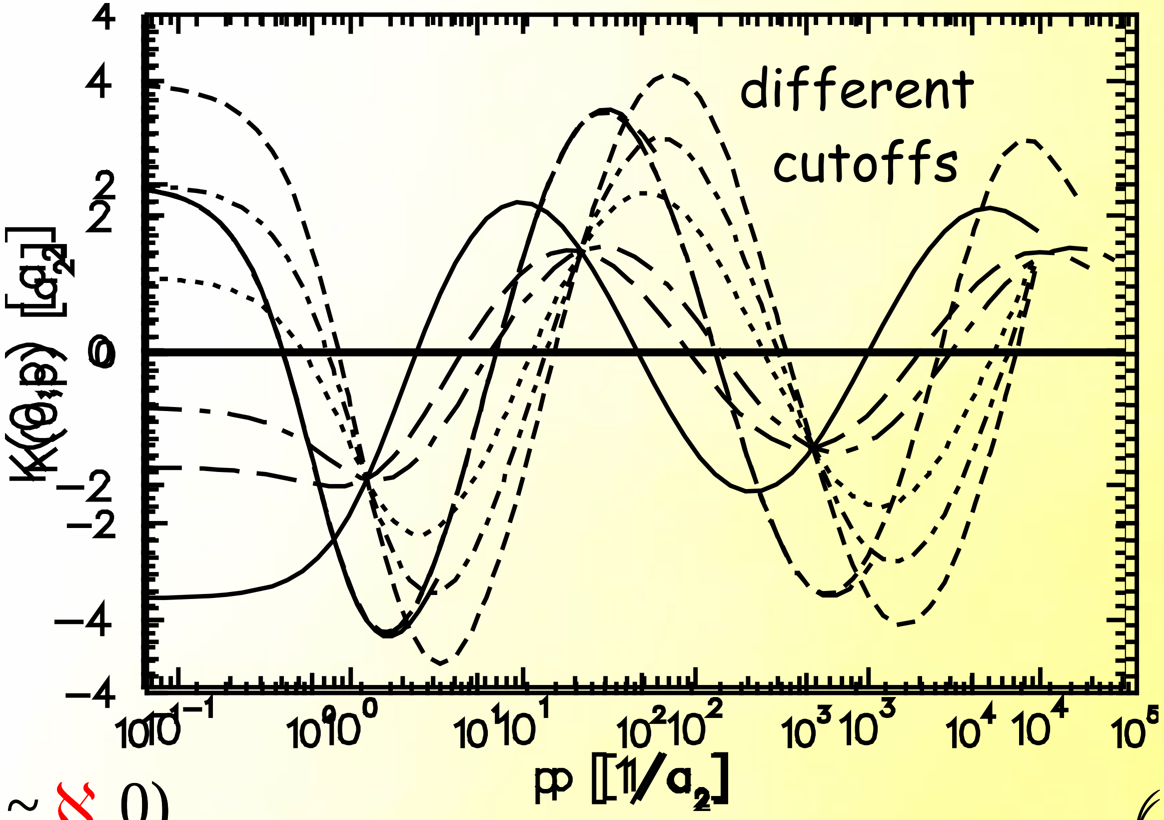
$$T_{Nd} = K_{ONE} + \lambda \int_0^{\Lambda} \frac{d^3 l}{(2\pi)^3} \frac{K_{ONE}\, T_{Nd}}{D} + K_{TBF} + \lambda \int_0^{\Lambda} \frac{d^3 l}{(2\pi)^3} \frac{K_{TBF}\, T_{Nd}}{D}$$

renormalization: doublet s wave -I

Danilov '63

Bedaque, Hammer + v.K. '99 '00

$$\lambda > \lambda_c \equiv \frac{3\sqrt{3}}{4\pi}$$



different cutoffs

$$\frac{\partial T_{Nd}^{(\frac{1}{2})}(p \sim \aleph, 0)}{\partial \Lambda} \ncong 0$$

$$T_{Nd}^{(\frac{1}{2})}(p \gg \aleph, 0) \propto \cos\left(s_0 \ln \frac{p}{\Lambda_*} + \delta \right)$$

$$s_0 \cong 1.0024$$

Bedaque, Hammer + v.K. ’99 ’00
Hammer + Mehen ’01
Bedaque et al. ’03
…

$S_{1/2}$

$$\lambda > \lambda_c \equiv \frac{3\sqrt{3}}{4\pi}$$

$$T_{Nd} \xrightarrow{p \gg \aleph} A \cos\left(s_0 \ln \frac{p}{\Lambda} + \delta \right) \Rightarrow \frac{\partial T_{Nd}}{\partial \Lambda} \xrightarrow{p \sim \aleph} \neq 0$$ unless

$$D_0 \sim \left(\frac{4\pi}{m_N} \right)^2 \frac{1}{\aleph^2 M_{nuc}} \quad (\nu = -1)$$

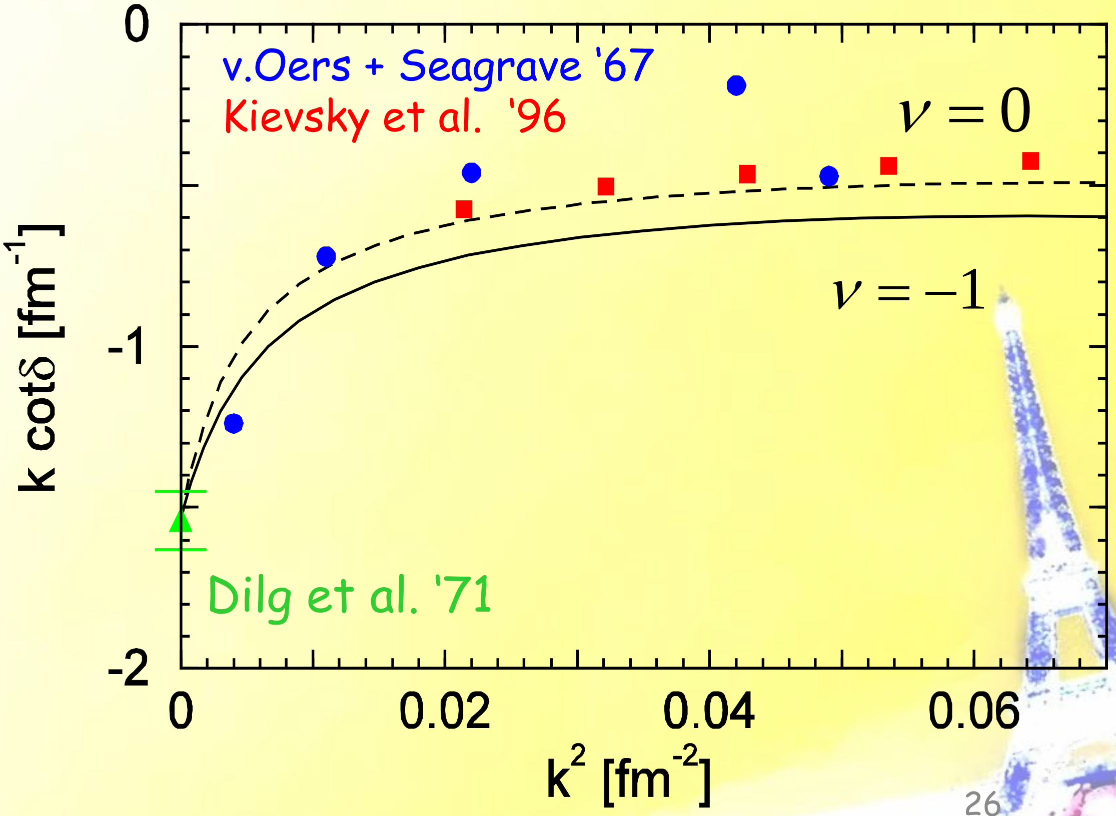
(limit cycle!)

fitted

$$a_{1/2} = 0.65\,\text{fm (exp)}$$

predicted

$$B_t = 8.3\,\text{MeV}\ (\nu = 0)$$
$$B_t = 8.48\,\text{MeV (expt)}$$

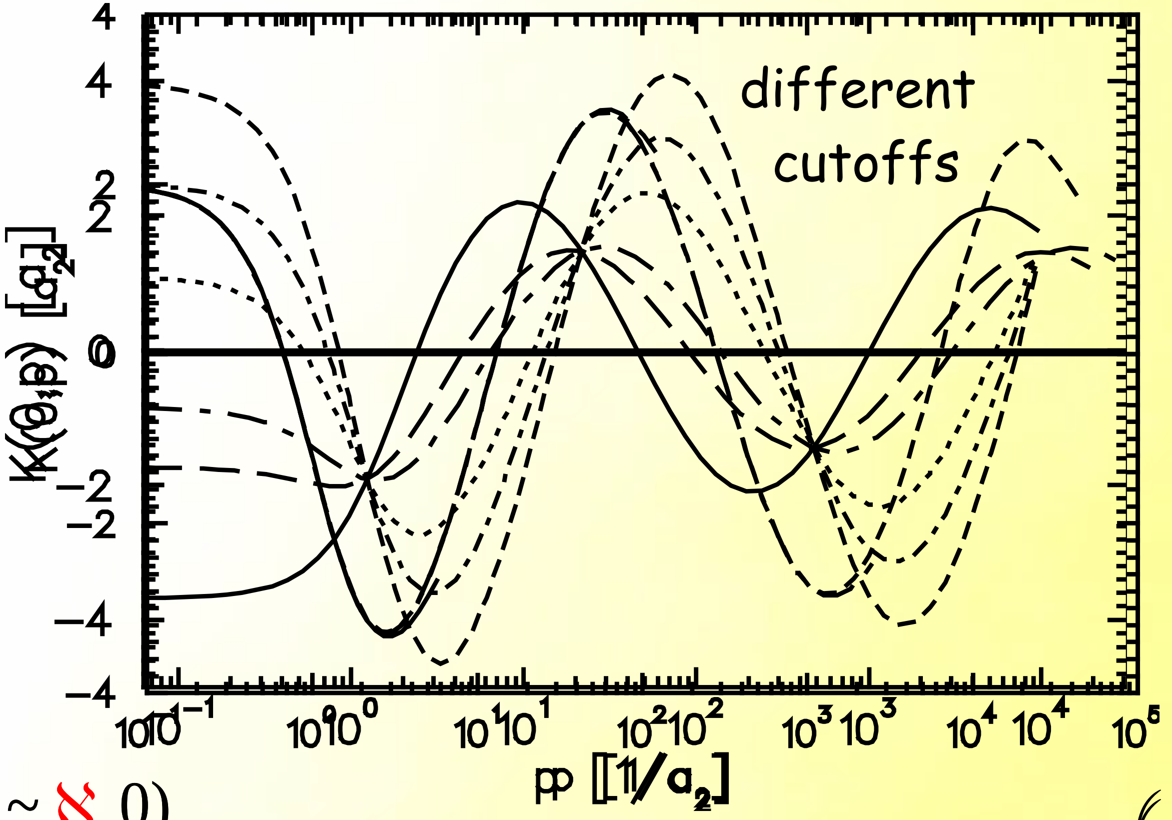


renormalization: doublet s wave -I

Danilov '63

Bedaque, Hammer + v.K. '99 '00

$$\lambda > \lambda_c \equiv \frac{3\sqrt{3}}{4\pi}$$



different cutoffs

$$\frac{\partial T_{Nd}^{(1/2)}(p \sim \aleph, 0)}{\partial \Lambda} \ncong 0$$

$$T_{Nd}^{(1/2)}(p \gg \aleph, 0) \propto \cos\left(s_0 \ln \frac{p}{\Lambda_*} + \delta\right)$$

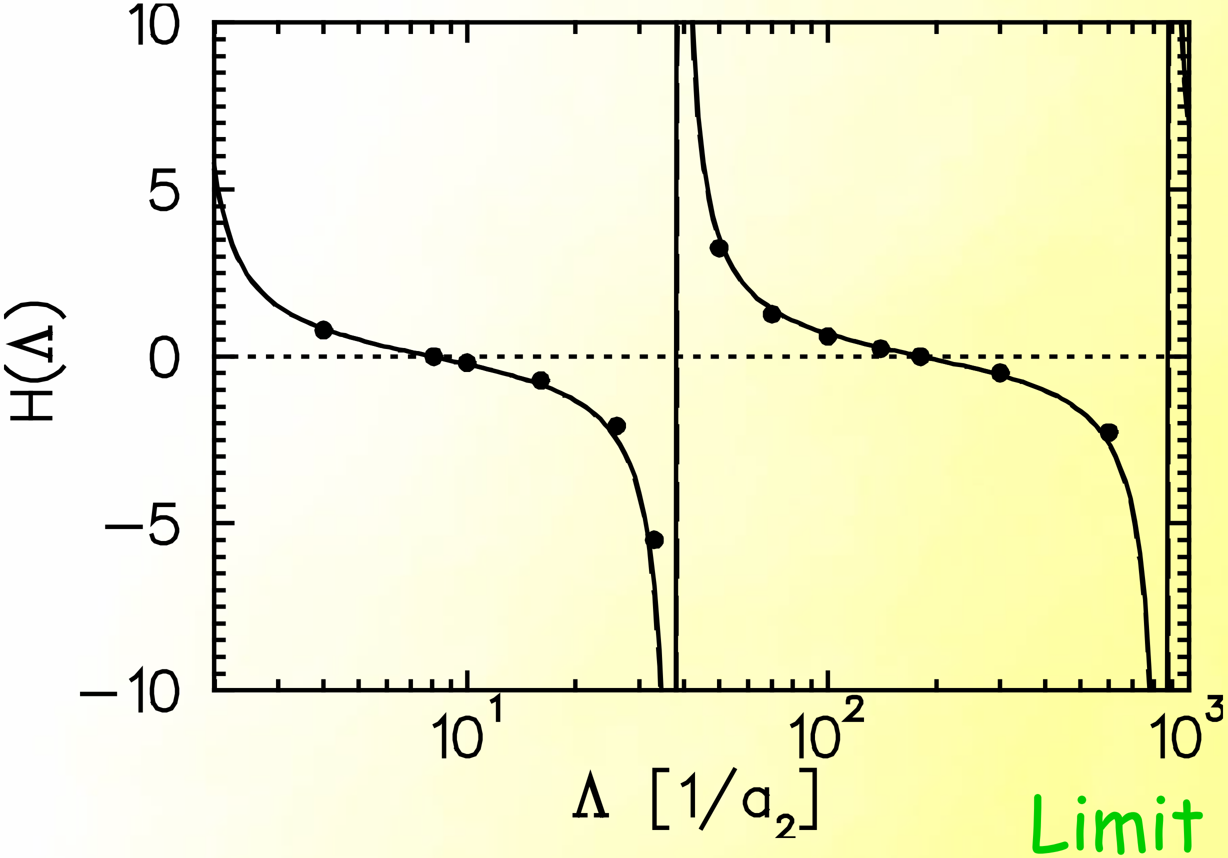
$$s_0 \cong 1.0024$$

renormalization: doublet s wave -II

Bedaque, Hammer + v.K. ’99 ’00

$$D_0 \sim \left(\frac{4\pi}{m_N}\right)^2 \frac{1}{\aleph^2 M_{nuc}} H(\Lambda)$$

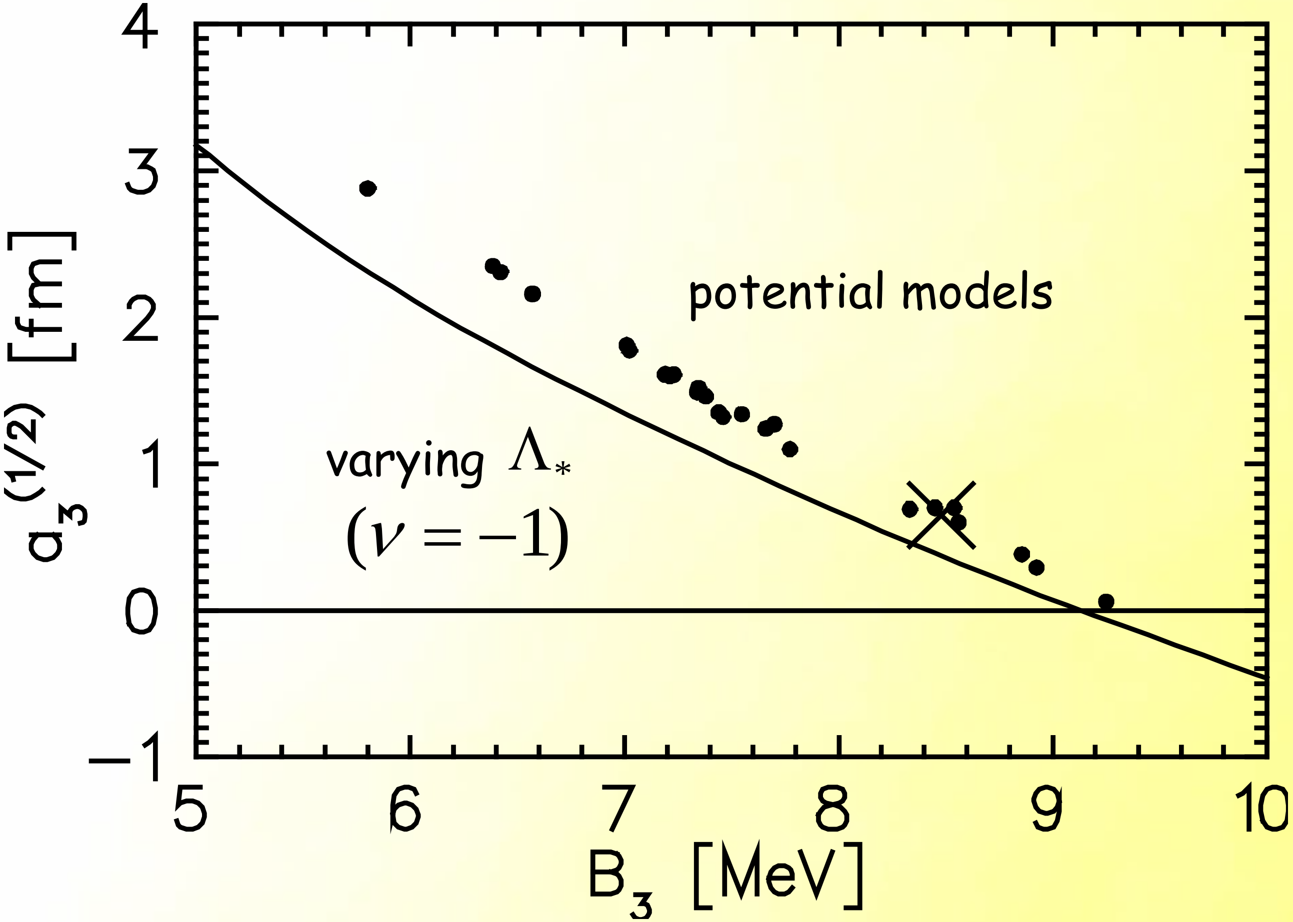
$$H(\Lambda) = \frac{\sin\left(\ln(\Lambda/\Lambda_*) + \arctan(1/s_0)\right)}{\sin\left(\ln(\Lambda/\Lambda_*) - \arctan(1/s_0)\right)}$$



Limit cycle !

Phillips line

Bedaque, Hammer + v.K. '99 '00



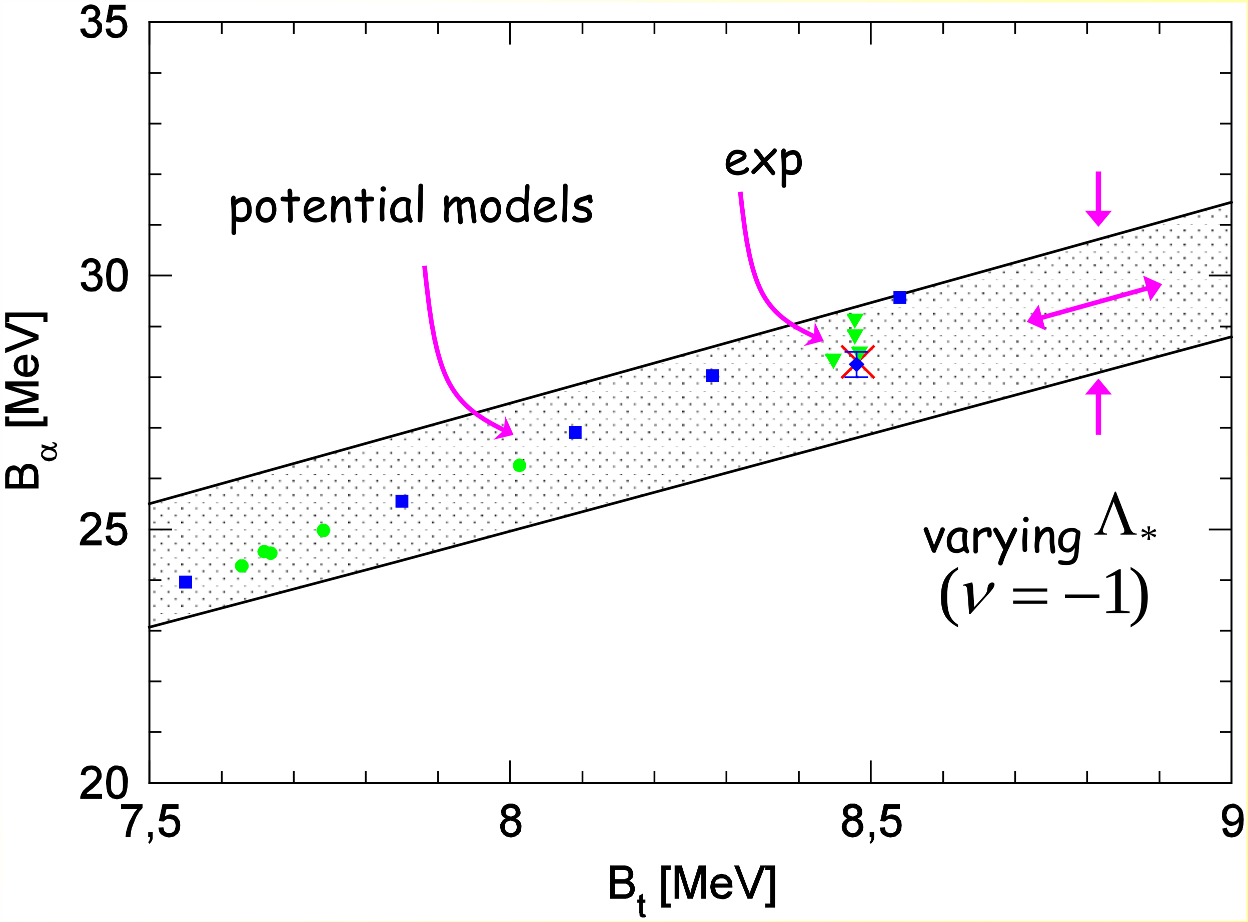
www.getcliparts.com

- four-body bound state can be addressed similarly

⇨ no four-body force at $\nu = -1$

Hammer, Meissner + Platter '04

Tjon line



Summary:

Expansion parameter $\frac{Q}{M_{nuc}} \sim \frac{\aleph}{M_{nuc}} \sim \frac{r_0}{a_0}$

- LO: two two-nucleon + one three-nucleon interactions

$$C_0^{(0)},\ C_0^{(1)},\ D_0$$

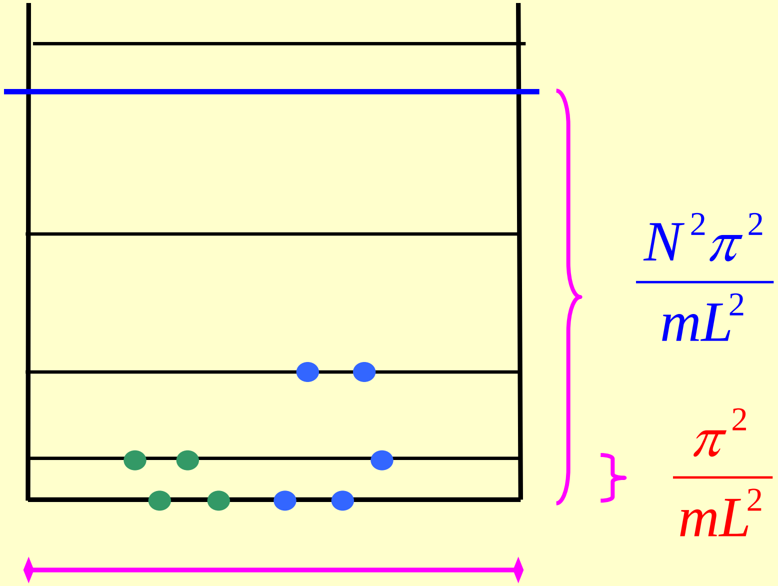
- NLO: two more two-nucleon interactions
- *etc.*

~ larger nuclei?

As A grows,
given computational power limits
number of accessible one-nucleon states ➡ IR cutoff $\lambda \ll Q$
in addition to
UV cutoff $\Lambda \gg Q$

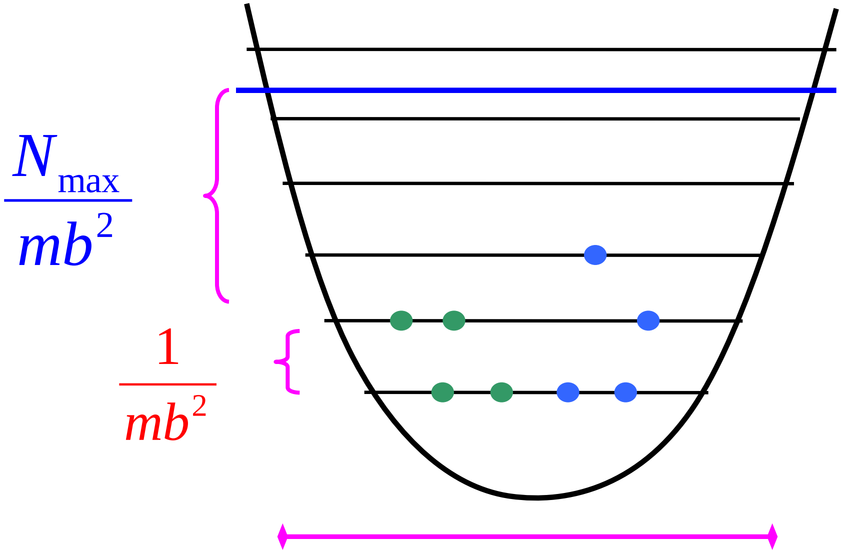
Finite Volume

Lattice Box



$$L = Na$$

Harmonic Oscillator



$$b = \frac{1}{\sqrt{m\omega}}$$

nuclear matter

Mueller, Seki, Koonin + v.K. '99

few nucleons

Lee *et al* '05

...

finite nuclei

Stetcu, Barrett + v.K. '07

Rotureau, Stetcu, Barrett + v.K. '12

few atoms

Stetcu, Barrett + v.K. '09

Rotureau, Stetcu, Barrett + v.K. '10

Rotureau et al. '11

Two possible approaches

Lattice EFT

Harmonic EFT

- Use input EFT infinite-volume potential $\left(0, \Lambda_0\right)$;
  minimize regulator mismatch with $\Lambda \ll \Lambda_0$

Lee *et al* '05

…

Barrett, Vary + Zhang '93

…

"No-Core Shell Model"

- Define EFT directly within finite volume $\left(\lambda, \Lambda\right)$;
  fit parameters to binding energies or to *E* given by

$$\sqrt{mE}\cot\delta\left(E\right) = \frac{1}{\pi L}\left[\sum_{\mathbf{n}}^{|\mathbf{n}|<N} \frac{1}{\mathbf{n}^2 - \frac{mEL^2}{4\pi^2}} - 4\pi N\right]$$

$$\sqrt{mE}\cot\delta\left(E\right) = -\frac{2}{b}\frac{\Gamma\left(\frac{3}{4} - \frac{Emb^2}{2}\right)}{\Gamma\left(\frac{1}{4} - \frac{Emb^2}{2}\right)}$$

cf. Fukuda + Newton '54

Luescher '91

Busch *et al.* '98

Both being actively pursued

- many-body systems get complicated rapidly

\+ (continuing) focus on simpler ***halo/cluster nuclei***

one or more loosely-bound nucleons around one or more cores

$$\aleph \equiv \sqrt{m_N E_p} \ll \sqrt{m_N E_c} \equiv M_c$$

(esp. near driplines)

particle separation energy

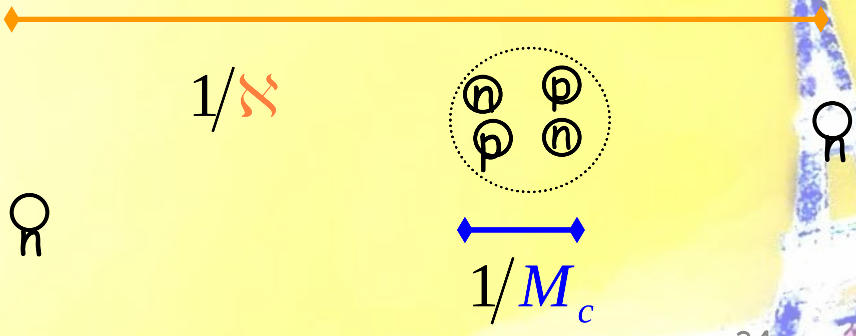
core excitation energy

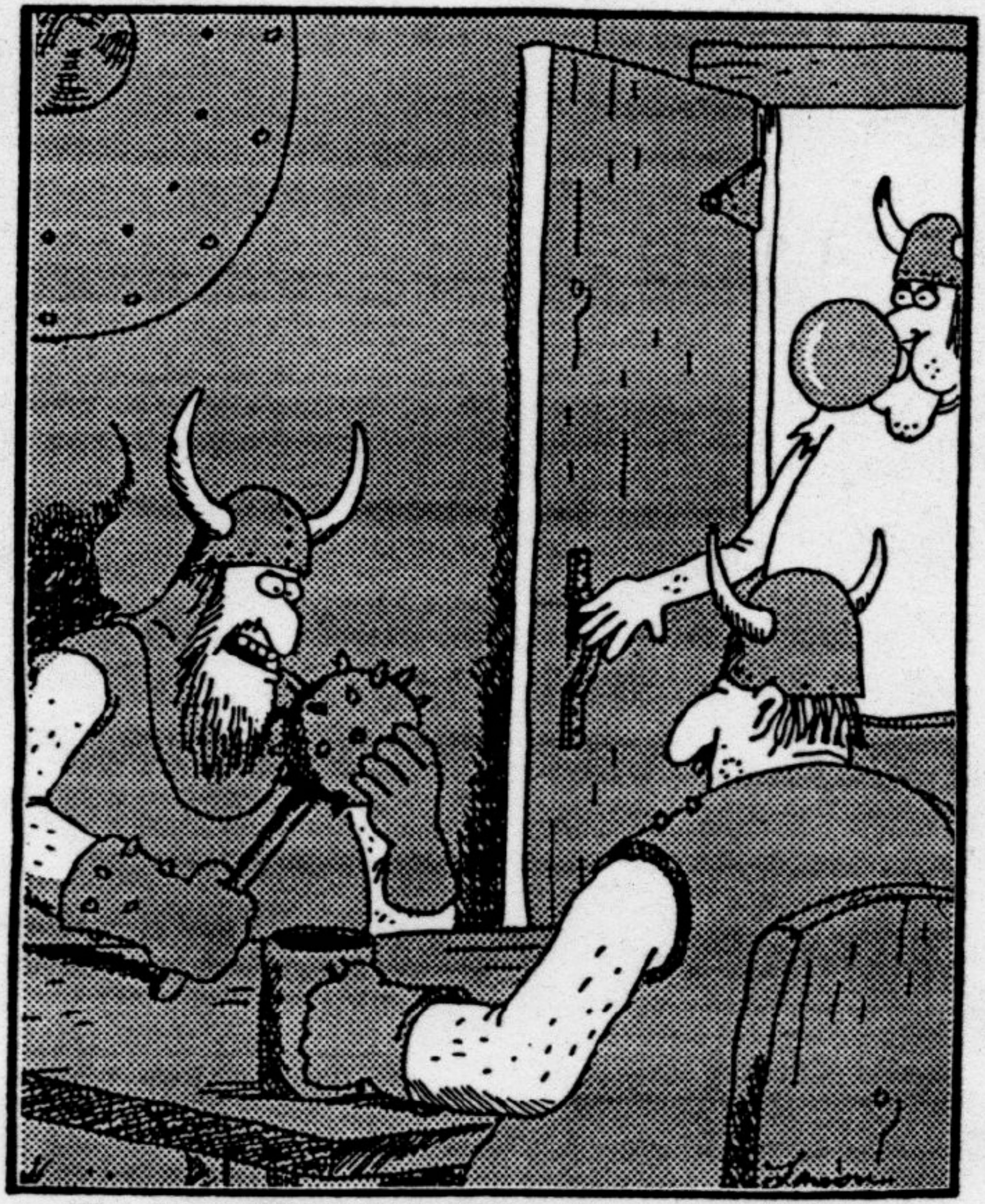
e.g.

$^4\mathrm{He}$ $$\left.\begin{aligned} B_{\alpha^*} &\cong \ 8 \ \mathrm{MeV} \\ B_\alpha &\cong \ 28 \ \mathrm{MeV} \end{aligned}\right\} E_\alpha = B_\alpha - B_{\alpha^*} \cong \ 20 \ \mathrm{MeV}$$

"$^5\mathrm{He}$" $p_{3/2}$ resonance at $E_n \sim 1 \ \mathrm{MeV}$

$^6\mathrm{He}$ s_0 bound state at $E_{2n} \sim 1 \ \mathrm{MeV}$





"You know, Bjorg, there's something about holding a good, solid mace in your hand—you just look for an excuse to smash something."

$Q \sim \aleph \ll M_c$

halo EFT

- degrees of freedom: nucleons, cores
- symmetries: Lorentz, $\cancel{P}$, $\cancel{T}$
- expansion in:

$$\frac{Q}{M_c} = \begin{cases} Q/m_N\,,\; Q/m_c & \text{non-relativistic} \\ Q/m_\pi\,, \cdots & \text{multipole} \end{cases}$$

simplest formulation: auxiliary fields for core + nucleon states

e.g.

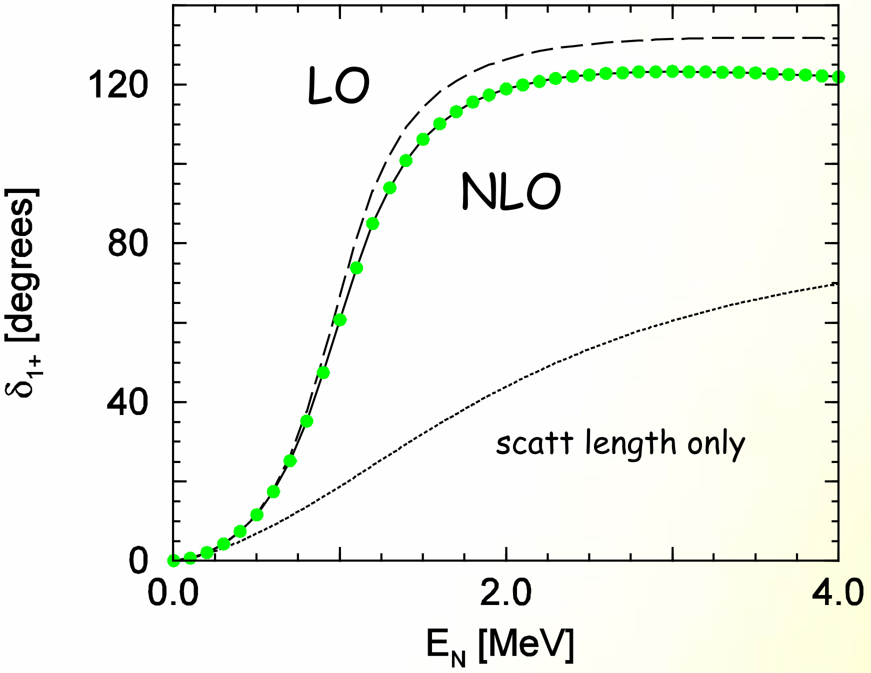
$${}^4\text{He} \;\mapsto\; \text{scalar field } \varphi$$

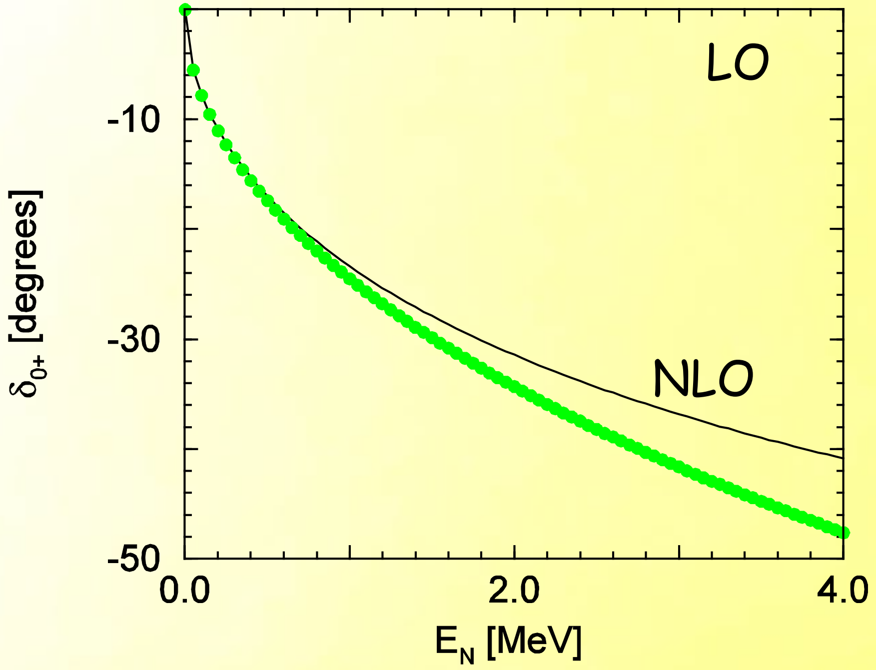
$${}^4\text{He} + \text{N} \;\begin{cases} s_{1/2} \equiv 0+ \;\mapsto \text{spin - 0 field } s \\ p_{1/2} \equiv 1- \;\mapsto \text{spin -1/2 field } T_1 \\ p_{3/2} \equiv 1+ \;\mapsto \text{spin - 3/2 field } T_3 \\ \vdots \end{cases}$$

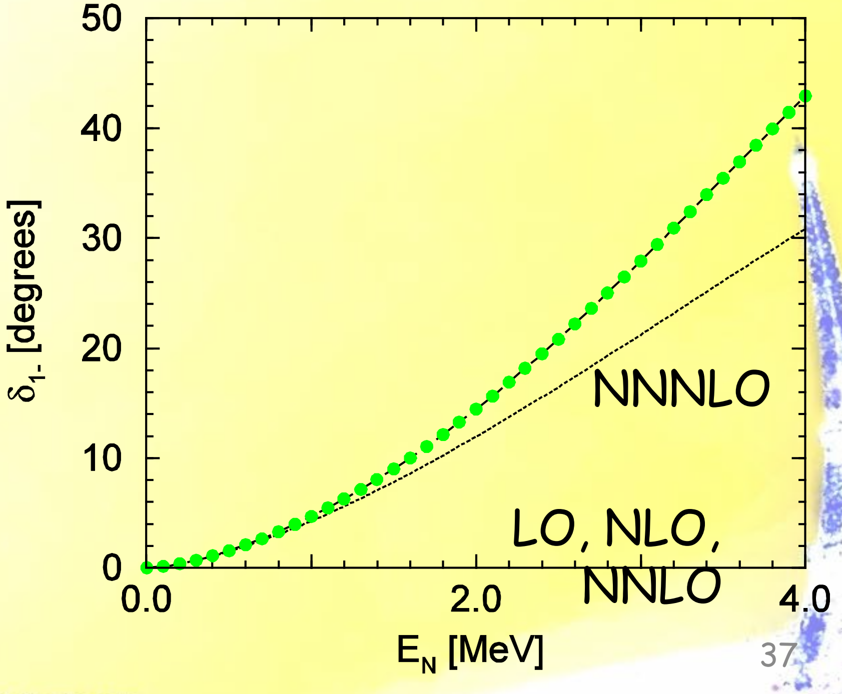
$N\alpha$

Bertulani, Hammer + v.K. '02

● PSA, Arndt et al. '73





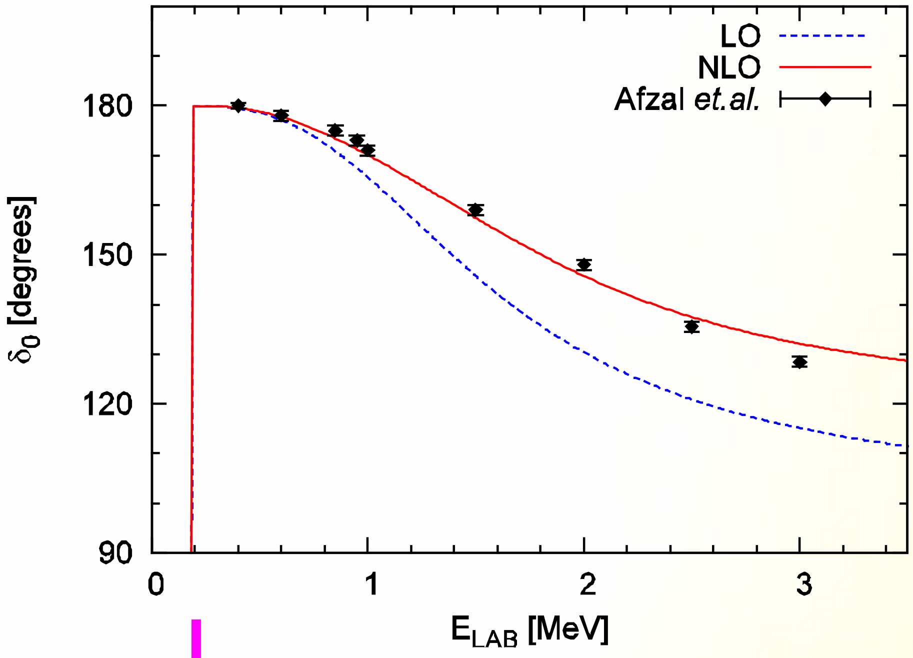


$$E_R \cong 0.80 \text{ MeV}$$

$$\Gamma(E_R) \cong 0.55 \text{ MeV}$$

Higa, Hammer + v.K. '08

$\alpha\alpha$



Extra
fitting parameters

→ $\tilde{P}_0 = P_0 + \frac{1}{15k_C^3}$

→ none

Bohr radius

$$\frac{1}{k_C} \equiv \frac{1}{Z_\alpha^2 \alpha_{em} \mu}$$

$$\simeq 3.6 \text{ fm}$$

$$\left.\begin{aligned} E_R &= 92.07 \pm 0.03 \text{ keV} \\ \Gamma(E_R) &= 5.57 \pm 0.25 \text{ eV} \end{aligned}\right\}$$

fitted with a_0 and $\tilde{r}_0 = r_0 - \frac{1}{3k_C}$

More fine-tuning!!!

	a_0 (10^3 fm)	r_0 (fm)	$\mathcal{P}_0$ (fm^3)
LO	-1.80	1.083	—
NLO	-1.92 ± 0.09	1.098 ± 0.005	-1.46 ± 0.08

fine-tuning of 1 in 1000!

$$\left\{\begin{aligned} &|a_0| \sim M_c^2/\aleph^3 && r_0 \sim 1/M_c \\ &\left|a_0^{E\&M}\right| = \mathcal{O}(1/2k_C) \simeq 1.8 \text{ fm} && \tilde{r}_0 = -0.13 \text{ fm} \end{aligned}\right\}$$

fine-tuning of 1 in 10

What next

- Coulomb interaction in higher waves:

  e.g. $p + {}^4\mathrm{He} \rightarrow {}^4\mathrm{He} + p$ Bertulani, Higa + v.K., in progress

  [cf. $p + p \rightarrow p + p$ Kong + Ravndal '99]

- three-body bound states:

  e.g. 1) ${}^6\mathrm{He} = \mathrm{b.s.}\left({}^4\mathrm{He} + n + n\right)$ Rotureau + v.K., '12 + in progress

  2) ${}^{12}\mathrm{C} = \mathrm{b.s.}\left({}^4\mathrm{He} + {}^4\mathrm{He} + {}^4\mathrm{He}\right)$

  [cf. ${}^3\mathrm{H} = \mathrm{b.s.}\left(p + n + n\right)$ Bedaque, Hammer + v.K. '99]

- reactions:

  e.g. $p + {}^7\mathrm{Be} \rightarrow {}^8\mathrm{B} + \gamma$ Higa + Rupak, in progress

  [cf. $p + n \rightarrow d + \gamma$ Chen et al. '00]

Conclusion

EFT the framework to describe nuclei within the SM

- ✓ is consistent with symmetries
- ✓ incorporates hadronic physics
- ✓ has controlled expansion

many successes so far, but still much to do

grow to larger nuclei!

➤ new, systematic approach to physics near drip lines?