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Lacanau, 28.09.2009

Modern Theory of Nuclear Forces

Lecture 1: Introduction & first look into ChPT

Lecture 2: EFTs for two nucleons

- Chiral Perturbation Theory (continued)
  - From effective Lagrangian to S-matrix
  - ChPT in the 1N sector
- EFT for two nucleons
  - Two nucleons at very low energies
  - EFT with perturbative pions
  - Nonperturbative pions a la Weinberg
  - How to renormalize LS equation: Toy model example

Lecture 3: Nuclear forces from chiral EFT

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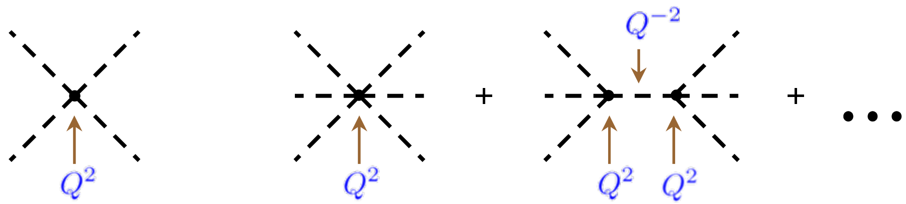
From effective Lagrangian to S-matrix

Lowest-order effective Lagrangian: $\mathcal{L}_\pi^{(2)} = \frac{F^2}{4}\left[\mathrm{Tr}(\partial_\mu U \partial^\mu U^\dagger) + \mathrm{Tr}(U\chi + U^\dagger \chi)\right]$

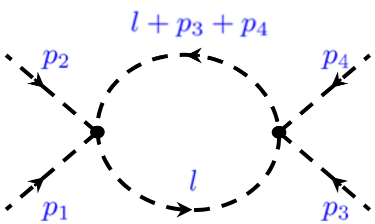
$$U = \frac{1}{F}[\sqrt{F^2 - \pi^2} + i\boldsymbol{\tau}\cdot\boldsymbol{\pi}] = 1 + \frac{i\boldsymbol{\tau}\cdot\boldsymbol{\pi}}{F} - \frac{\pi^2}{2F^2} + \ldots \Longrightarrow \mathcal{L}_\pi^{(2)} = \frac{\partial_\mu \boldsymbol{\pi}\cdot\partial^\mu\boldsymbol{\pi}}{2} - \frac{M^2\pi^2}{2} + \frac{(\partial_\mu\boldsymbol{\pi}\cdot\boldsymbol{\pi})^2}{2F^2} - \frac{M^2\pi^4}{8F^2} + \ldots$$

Tree-level multi-pion connected diagrams from $\mathcal{L}_\pi^{(2)}$ at low energy ($p_i \sim |\vec{p}_i| \sim M_\pi \sim Q$):



- *all diagrams scale as* Q^2
- *insertions from* $\mathcal{L}_\pi^{(4)}$, $\mathcal{L}_\pi^{(6)}$, … *suppressed by powers of* Q^2

What about quantum corrections (loop diagrams)?



$$\int \frac{d^4 l}{(2\pi)^4} \frac{p_1\cdot p_2\; p_3\cdot p_4}{[l^2 - M_\pi^2 + i\epsilon]\,[(l+p_3+p_4)^2 - M_\pi^2 + i\epsilon]} \sim \mathcal{O}(E^4) \Longrightarrow$$ suppressed…

UV divergences removed e.g. using DR, $\int d^4 l \to \mu^{d-4}\int d^d l$, and redefining LECs from $\mathcal{L}_\pi^{(4)}$

General observation: n-loop diagrams are suppressed by the factor Q^{2n} compared to the tree ones Q^2.

Power counting

Weinberg '79

amplitude *phase space factors*

Consider S-matrix element: $S = \delta^4(p_1 + p_2 + \ldots + p_N)\, M\, \Pi$

The amplitude can be rewritten as: $M \equiv M(E, \mu, g^r) = E^D f\left(\frac{E}{\mu}, g^r\right)$

combination of LECs

Dimensional analysis:

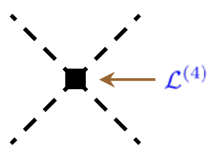
- pion propagators: $1/(p^2 - M_\pi^2) \sim 1/Q^2$
- momentum integrations: $d^4 l \sim Q^4$
- delta functions: $\delta^4(p - p') \sim 1/Q^4$
- derivatives: $\partial_\mu \sim Q$

# of loops *# of vertices with derivatives*

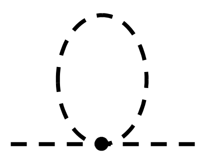
$\Longrightarrow$

$$D = 2 + 2L + \sum_d N_d (d - 2)$$

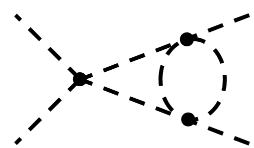
Examples:



$D = 2 + 0 + 2 = 4$



$D = 2 + 2 + 0 = 4$

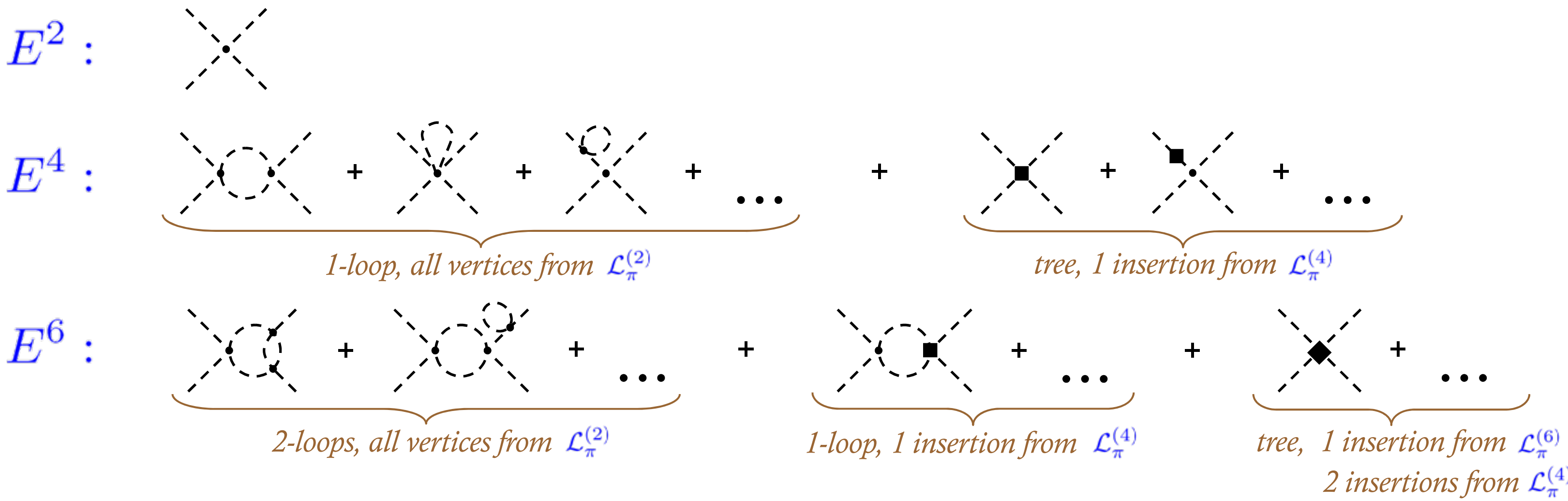


$D = 2 + 4 + 0 = 6$

Amplitude is obtained via expansion in E/Λ_χ. What is the value of Λ_χ?

- Chiral expansion breaks down for $E \sim M_\rho \quad \Longrightarrow \quad \Lambda_\chi \sim M_\rho = 770\ \text{MeV}$
- Consistency arguments yield: $\Lambda_\chi \leq 4\pi F_\pi = 1.2\ \text{GeV}$ *(Manohar & Georgi '84)*

Pion scattering lengths in ChPT



Predictive power?

$$\mathcal{L}_{\rm eff} = \mathcal{L}_\pi^{(2)} + \mathcal{L}_\pi^{(4)} + \mathcal{L}_\pi^{(6)} + \ldots$$

# of LECs increasing…

S-wave $\pi\pi$ scattering length

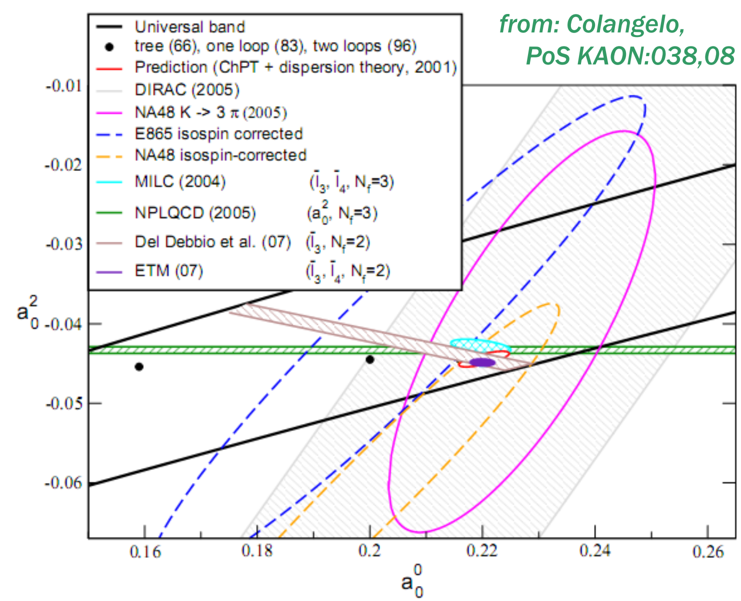
LO: $a_0^0 = 0.16$ *(Weinberg '66)*

NLO: $a_0^0 = 0.20$ *(GL '83)*

NNLO: $a_0^0 = 0.217$ *(Bijnens et al. '95)*

NNLO + dispersion relations:

$a_0^0 = 0.220 \pm 0.005$ *(Colangelo et al.'01)*



from: Colangelo, PoS KAON:038,08

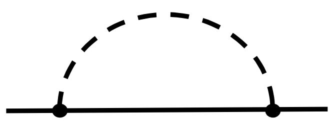
ChPT in the single-baryon sector

General formalim to construct the most general χ–invariant $\mathcal{L}_{\text{eff}}$ with matter fields (like e.g. nucleons) is given in *Coleman, Callan, Wess, Zumino, PR 177 (1969) 2239; 2247.*

Lowest-order: $\mathcal{L}_{\pi N}^{(1)} = \bar{N}\left(i\gamma^\mu D_\mu - m + \frac{g_A}{2}\gamma^\mu\gamma_5 u_\mu\right) N$

Problem: new hard mass scale $m \Longrightarrow$ power counting ??

For example: 1-loop correction to m *(Gasser, Sainio & Svarc '88)*



$\Longrightarrow$ $$\delta m \xrightarrow{M\to 0} -\frac{3g_A^2 m^3}{(4\pi F)^2}\left[\log\frac{m}{\mu} + \mu^{d-4}\left(\frac{1}{d-4} + const\right)\right]$$

Solution: heavy-baryon approach *(Jenkins & Manohar '91; Bernard et al. '92)*

$$\mathcal{L}_{\pi N}^{(1)} = N'^{\dagger}\left(iD_0 + \frac{g_A}{2}\vec{\sigma}\cdot\vec{u}\right) N' + \mathcal{O}(1/m)$$

m disappeared from $\mathcal{L}_{\pi N}^{(1)}$ $\Longrightarrow$ power counting manifest! For example: $(\delta m)^{\text{HB}} = -\frac{3g_A^2 M_\pi^3}{32\pi F^2}$

Notice: Lorentz invariant formulations preferable in certain cases!

Ellis & Tang '98; Becher & Leutwyler '99; Gegelia et al. '03; ...

Further reading

Construction of the effective chiral Lagrangian

- *Weinberg, Phys. Rev. 166 (68) 1568*
- *Coleman, Wess, Zumino, Phys. Rev. 177 (69) 2239*
- *Callan, Coleman, Wess, Zumino, Phys. Rev. 177 (69) 2247*

Chiral perturbation theory: milestones

- *Weinberg, Physica A96 (79) 327*
- *Gasser, Leutwyler, Ann. Phys. 158 (84) 142; Nucl. Phys. B250 (85) 465*

Chiral perturbation theory: (some) review articles

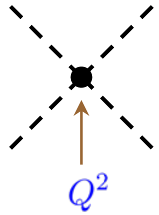
- *Bernard, Kaiser, Meißner, Int. J. Mod. Phys. E4 (95) 193*
- *Pich, Rep. Prog. Phys. 58 (1995) 563*
- *Bernard, Prog. Part. Nucl. Phys. 60 (07) 82*
- *Scherer, arXiv:0908.3425 [hep-ph], to appear in Prog. Part. Nucl. Phys.*

Chiral perturbation theory: (some) lecture notes

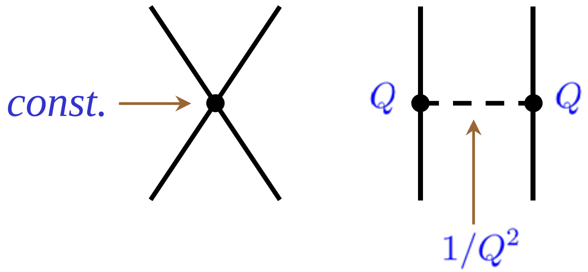
- *Scherer, Adv. Nucl. Phys. 27 (03) 277*
- *Gasser, Lect. Notes Phys. 629 (04) 1*

Two nucleons

In the $\pi\pi$, πN sectors, S-matrix can be evaluated in perturbation theory (Goldstone bosons do not interact at $E = 0,\ m_q = 0$)



But this is not the case for 2 and more nucleons:



do not vanish for $E = 0,\ m_q = 0$

The presence of shallow bound states (^{2}H, ^{3}H, ^{3}He, ^{4}He, …) indicates breakdown of perturbation theory even at very low energy!

Is EFT still useful for strongly interacting nucleons?

2N at very low Q: Effective Range Expansion

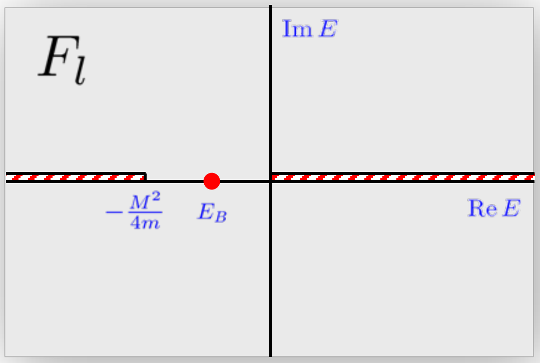
Blatt, Jackson '49; Bethe '49

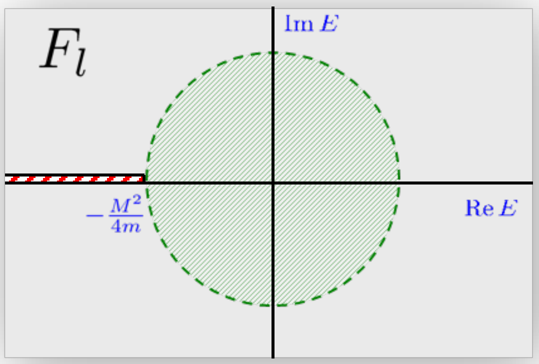
Nonrelativistic nucleon-nucleon scattering (uncoupled case):

effective-range function

$$S_l(k) = e^{2i\delta_l(k)} = 1 + i\frac{mk}{2\pi}T_l(k) \quad \text{where} \quad T_l(k) = \frac{4\pi}{m}\frac{k^{2l}}{F_l(k) - ik^{2l+1}} \quad \text{and} \quad F_l(k) \equiv k^{2l+1}\cot\delta_l(k)$$

If $V(r)$ satisfies certain conditions, F_l is a meromorphic function of k^2 near the origin





⇨ effective range expansion (ERE):

$$\boxed{F_l(k^2) = -\frac{1}{a} + \frac{1}{2}rk^2 + v_2k^4 + v_3k^6 + v_4k^8 + \ldots}$$

The range of convergence of the ERE depends on the range M^{-1} of $V(r)$ defined as

$$M = \min(\mu) \quad \text{such that} \quad \int_{R>0}^{\infty} |V(r)|\, e^{\mu r} dr = \infty$$

2N at very low Q: pionless EFT

Effective Lagrangian: for $Q \ll M_\pi$ only point-like interactions

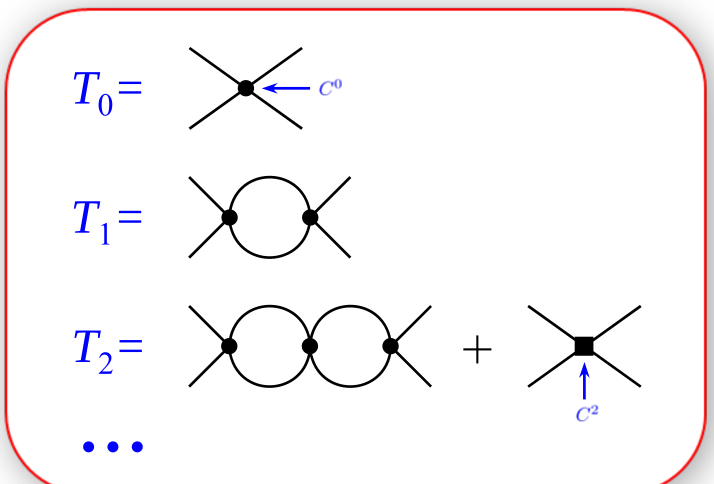
$$\mathcal{L}_{\rm eff} = N^\dagger \left(i\partial_0 + \frac{\vec{\nabla}^2}{2m} \right) N - \frac{1}{2} C_1^0 (N^\dagger N)^2 - \frac{1}{2} C_2^0 (N^\dagger \vec{\sigma} N)^2 - \frac{1}{4} C_1^2 (N^\dagger \vec{\nabla}^2 N)(N^\dagger N) + \text{h.c.} + \ldots$$

Scattering amplitude (S-waves):

$$S = e^{2i\delta} = 1 - i \left(\frac{km}{2\pi} \right) T\,, \qquad T = -\frac{4\pi}{m} \frac{1}{k \cot\delta - ik} = -\frac{4\pi}{m} \frac{1}{(-\frac{1}{a} + \frac{1}{2} r_0 k^2 + v_2 k^4 + v_3 k^6 + \ldots) - ik}$$

- **Natural case**

$$|a| \sim M_\pi^{-1}\,,\ |r| \sim M_\pi^{-1}\,,\ \ldots \quad \Longrightarrow \quad T = T_0 + T_1 + T_2 + \ldots = \frac{4\pi a}{m} \Big[\underset{\substack{\uparrow \\ \sim Q^0}}{1} - \underset{\substack{\uparrow \\ \sim Q^1}}{iak} + \underbrace{\left(\frac{a r_0}{2} - a^2 \right) k^2}_{\sim Q^2} + \ldots \Big]$$



The EFT expansion can be arranged to match the above expansion for T.

Using e.g. dimensional or subtractive ragularization yields:

- perturbative expansion for T;
- scaling of the LECs: $C^i \sim Q^0$

In reality: $a_{^1S_0} = -23.741 \text{ fm} = -16.6\, M_\pi^{-1} \qquad a_{^3S_1} = -5.42 \text{ fm} = 3.8\, M_\pi^{-1}$

2N at very low Q: pionless EFT

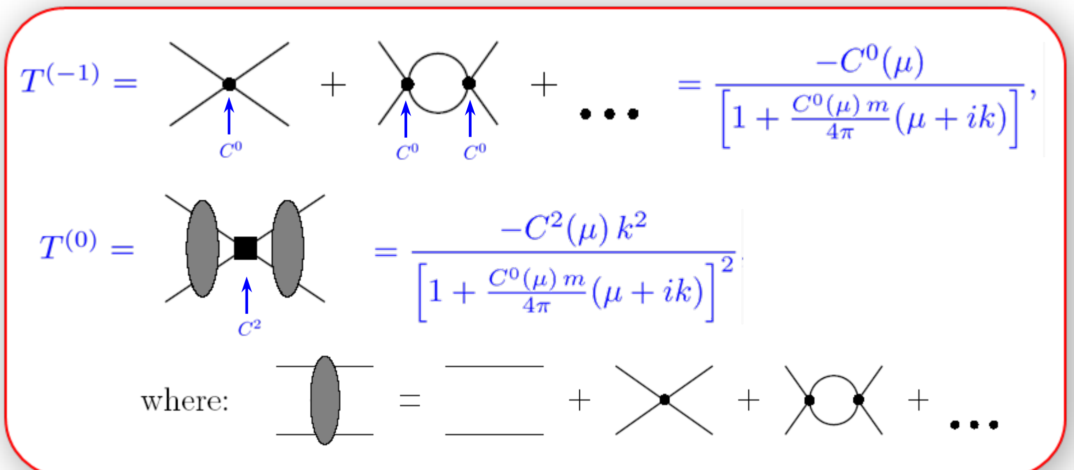
- **Unnatural case:** $|a| \gg M_\pi^{-1}$ *(Kaplan, Savage & Wise '97)*

  Keep ak fixed, i.e. count $a \sim Q^{-1}$:

$$T = -\frac{4\pi}{m}\frac{1}{\left(-\frac{1}{a}+\frac{1}{2}r_0k^2+v_2k^4+v_3k^6+\ldots\right)-ik} = \frac{4\pi}{m}\frac{1}{(1+iak)}\Bigg[\underbrace{a}_{\sim Q^{-1}}+\underbrace{\frac{ar_0}{2(a^{-1}+ik)}k^2}_{\sim Q^{0}}+\underbrace{\ldots}_{\sim Q^{1}}\Bigg].$$

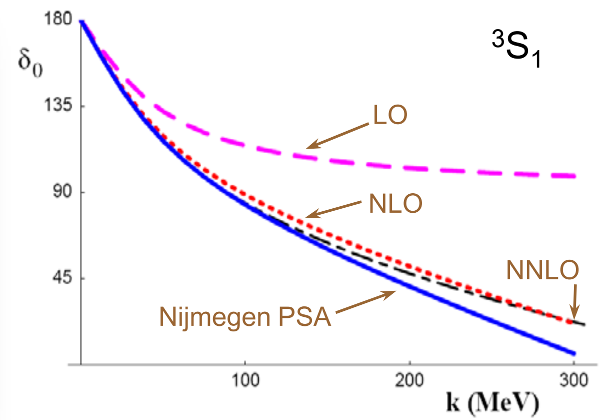
  Notice: perturbation theory breaks down
  (T has a pole at $|k| \sim |a|^{-1} \ll M_\pi$)

KSW expansion (DR + Power Divergence Subtraction $\Rightarrow$ $C^0 \sim 1/Q, \quad C^2 \sim 1/Q^2, \quad \ldots$)



$$T^{(-1)} = \ldots = \frac{-C^0(\mu)}{\left[1+\frac{C^0(\mu)\,m}{4\pi}(\mu+ik)\right]},$$

$$T^{(0)} = \ldots = \frac{-C^2(\mu)\,k^2}{\left[1+\frac{C^0(\mu)\,m}{4\pi}(\mu+ik)\right]^2}$$



from: *Chen, Rupak & Savage NPA653 (1999)*

- Astrophysical applications *(Butler, Chen, Kong, Ravndal, Rupak, Savage, ...)*
- Universal properties of few-body systems for $a \to \infty$, *(Braaten & Hammer, Phys. Rept. 428 (06) 259)*
- Halo-nuclei *(Bedaque, Bertulani, Hammer, Higa, van Kolck, ...)* & many other topics…

Further reading

Pionless effective field theory: milestones

- *Kaplan, Savage, Wise, Phys. Lett. B424 (98) 390; Nucl. Phys. B534 (98) 329*
- *Bedaque, Hammer, van Kolck, Phys. Rev. Lett. 92 (99) 463; Nucl. Phys. A646 (99) 444*

Pionless effective field theory: (some) review articles

- *Beane et al., arXiv:nucl-th/0008064, in Boris Ioffe Festschrift, ed. By M. Shifman, World Scientific*
- *Bedaque, van Kolck, Ann. Rev. Nucl. Part. Sci. 52 (02) 339*
- *Braaten, Hammer, Phys. Rept. 428 (06) 259*

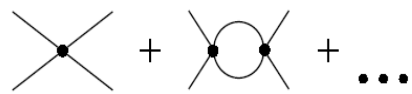
Two nucleons: EFT with pions

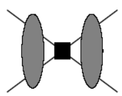
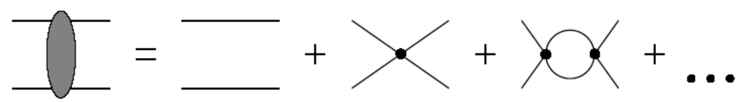
Chiral EFT for few nucleons: are pions perturbative?

It is straightforward to generalize the *KSW* power counting assuming that π-exchanges can be treated in perturbation theory, i.e.:

$$T(k) = T^{(-1)}(k) + T^{(0)}(k) + T^{(1)}(k) + \ldots$$

- **EFT without pions**

$T^{(-1)} =$ 

$T^{(0)} =$  where: 

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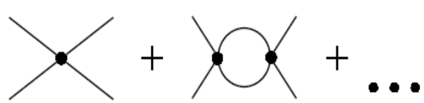
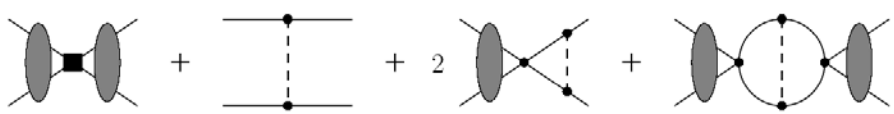
- **EFT with perturbative pions**

$T^{(-1)} =$ 

$T^{(0)} =$ 

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Two nucleons: EFT with pions

Does KSW expansion based on perturbative pions converge?

- **"Low-energy theorems"** *(Cohen & Hansen '99,'00; E.E. & Gegelia '09)*

  If pions are properly incorporated, one should be able to go beyond the effective range expansion, i.e. to predict the shape parameters.

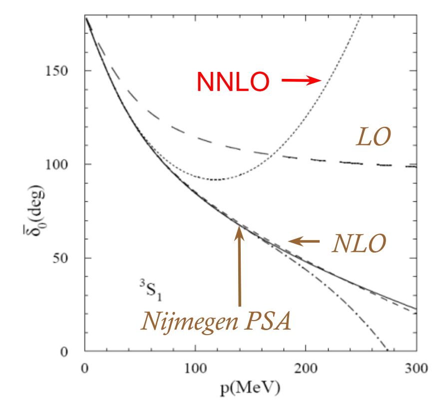
$^1S_0$ at NLO: $k \cot\delta = -a^{-1} + \frac{1}{2} r k^2 + v_2 k^4 + v_3 k^6 + v_4 k^8 + \ldots$

$$v_2 = \frac{g_A^2 m}{16\pi F_\pi^2}\left(-\frac{16}{3a^2 M_\pi^4} + \frac{32}{5a M_\pi^3} - \frac{2}{M_\pi^2}\right) \qquad v_3 = \frac{g_A^2 m}{16\pi F_\pi^2}\left(\frac{16}{a^2 M_\pi^6} - \frac{128}{7a M_\pi^5} + \frac{16}{3M_\pi^4}\right)$$

	v_2 (fm^3)	v_3 (fm^5)	v_4 (fm^7)	v_2 (fm^3)	v_3 (fm^5)	v_4 (fm^7)
theory	-3.3	17.8	-108.	-0.95	4.6	-25.
data	-0.5	3.8	-17.	0.04	0.7	-4.0
	spin-singlet			*spin-triplet*		

- **Higher-order KSW calculation** *(Mehen & Stewart '00)*

  NNLO results obtained by Mehen & Stewart show no signs of convergence in spin-triplet channels



it seems necessary to treat pions non-perturbatively at momenta $p \sim M_\pi$

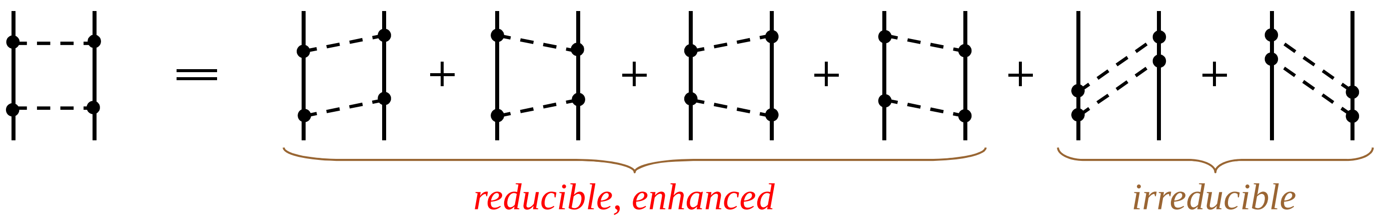
see, however, Beane, Kaplan, Vuorinen, arXiv:0812.3938 for an alternative scenario

Two nucleons: chiral EFT à la Weinberg

Weinberg '90, '91

Perturbation theory fails due to enhancement caused by reducible (i.e. infrared divergent in the limit $m_N \to \infty$) diagrams.

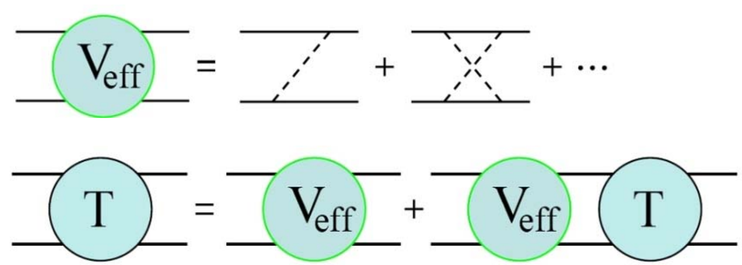
Switch to time-ordered theory: $\mathrm{Amp} = \langle NN|H^I|NN\rangle + \sum_\Psi \frac{\langle NN|H^I|\Psi\rangle\langle\Psi|H^I|NN\rangle}{E_{NN} - E_\Psi + i\epsilon} + \ldots$



$$\frac{1}{E_{NN} - E_\Psi} = \frac{m_N}{\vec{p}^{\,2} - \vec{q}^{\,2}} \sim \frac{m_N}{Q^2} \gg \frac{1}{Q} \qquad \frac{1}{E_{NN} - E_\Psi} \sim \frac{1}{M_\pi} \sim \frac{1}{Q}$$

Weinberg's approach

- Irreducible contributions can be calcu-lated using ChPT
- Reducible contributions enhanced and should be summed up to infinite order



Two nucleons: chiral EFT à la Weinberg

$V_{\rm cont}$, V_π grow with increasing momenta ⟹ LS equation must be regularized & renormalized

$$T(\vec p,\vec k\,) = \left[V_{\rm cont}(\vec p,\vec k\,) + V_\pi(\vec p,\vec k\,)\right] + \int \frac{d^3q}{(2\pi)^3}\left[V_{\rm cont}(\vec p,\vec q\,) + V_\pi(\vec p,\vec q\,)\right]\frac{m}{k^2-q^2+i\epsilon}T(\vec q,\vec k\,)$$

Regularization of the LS equation

- DR difficult to implement numerically due to appearance of power-law divergences
  Phillips et al.'00
- Cutoff (employed in most applications)
  — needs to be chosen $\Lambda \gg M_\pi$ to avoid large artifacts (i.e. large $1/\Lambda^n$-terms)
  — Λ can be employed at the level of $\mathcal{L}_{\rm eff}$ in order to preserve all relevant symmetries
  Slavnov '71; Djukanovic et al. '05,'07; also Donoghue, Holstein, Borasoy '98,'99

Renormalization à la Lepage

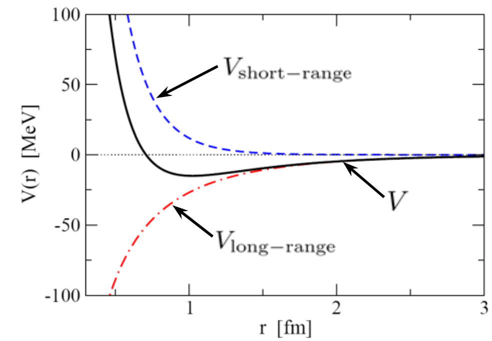
Ordonez et al.'96; Park et al.'99; E.E. et al.'00,'04,'05; Entem, Machleidt '02,'03

Choose $\Lambda \sim M_{\rm hard}$ & tune the strengths of $C_i(\Lambda)$ to fit low-energy observables.

- generally, can only be done numerically; requires solving nonlinear equations for $C_i(\Lambda)$,
- self-consistency checks via „Lepage plots“,
- residual Λ dependence in observables survives

Toy model example

$$V(\vec{q}) = \underbrace{\frac{\alpha_l}{\vec{q}^2 + M_l^2}}_{M_l = 200 \text{ MeV}} + \underbrace{\frac{\alpha_h}{\vec{q}^2 + M_h^2}}_{M_h = 750 \text{ MeV}} \quad \rightarrow \quad V(\vec{r}) = \underbrace{\frac{\alpha_l}{4\pi r} e^{-M_l r}}_{\textit{long-range}} + \underbrace{\frac{\alpha_h}{4\pi r} e^{-M_h r}}_{\textit{short-range}}$$



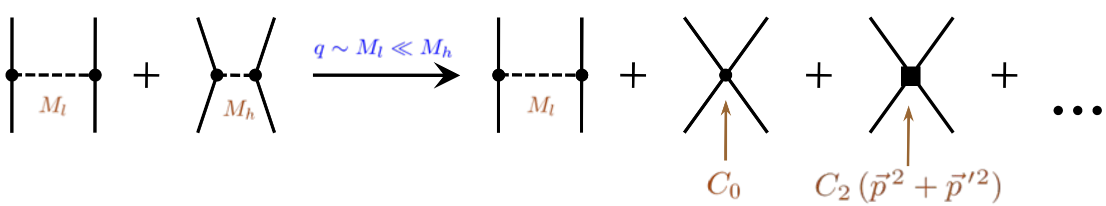
$$\left.\begin{array}{l} \alpha_l = -1.50 \\ \alpha_h = 10.81 \end{array}\right\} \Longrightarrow$$ S-wave bound state with: $E_B = 2.2229$ MeV

Effective theory

At low energy, $q \sim M_l \ll M_h$, the precise structure of $V_{\text{short-range}}$ is irrelevant

$\Longrightarrow$ mimic $V_{\text{short-range}}$ by a generic set of point-like interactions

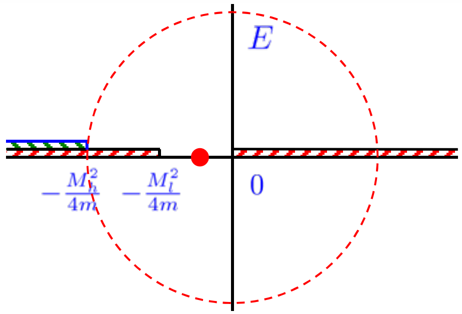
$$\boxed{V \rightarrow V_{\text{eff}} = V_{\text{long-range}} + C_0 + C_2 \left(\vec{p}^{\,2} + \vec{p}^{\,\prime 2} \right) + C_4 \, \vec{p}^{\,2} \vec{p}^{\,\prime 2} + \ldots}$$



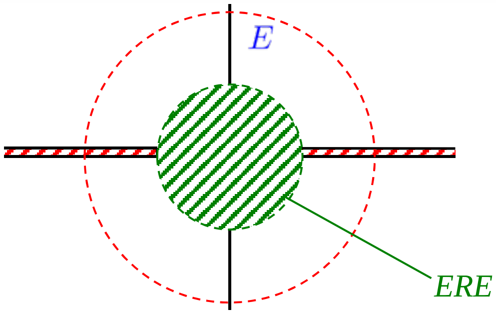
Toy model example

What to expect?

S-matrix, underlying theory



S-matrix, effective theory



- should work for momenta up to $|k| \leq \frac{M_h}{2} = 375\ \mathrm{MeV}$ or, equivalently, up to energy $E_{\mathrm{lab}} \leq \frac{M_h^2}{2m} \sim 300\ \mathrm{MeV}$
- should be able to go beyond the effective range expansion which converges for $|k| \leq \frac{M_l}{2} = 100\ \mathrm{MeV}$ or $E_{\mathrm{lab}} \leq \frac{M_l^2}{2m} \sim 20\ \mathrm{MeV}$

Toy model example

Effective theory: $V \to V_{\rm eff} = V_{\rm long-range} + C_0 + C_2\,(\vec{p}^{\,2} + \vec{p}^{\,\prime 2}) + C_4\,\vec{p}^{\,2}\vec{p}^{\,\prime 2} + \ldots$

T-matrix:

probe high-momentum physics, integral diverges…

- weak interaction, $|\alpha_{l,h}| \ll 1$: $\langle f|T|i\rangle \simeq \langle f|V_{\rm eff}|i\rangle$
- strong interaction, $|\alpha_{l,h}| \geq 1$: $\langle f|T|i\rangle = \langle f|V_{\rm eff}|i\rangle + \sum_n \frac{\langle f|V_{\rm eff}|n\rangle\langle n|V_{\rm eff}|i\rangle}{E_i - E_n + i\epsilon} + \ldots$

Solution: introduce ultraviolet cutoff Λ: $M_l \ll \Lambda \sim M_h$

Fix $C_{2i}(\Lambda)$ from some low-energy data and make predictions!

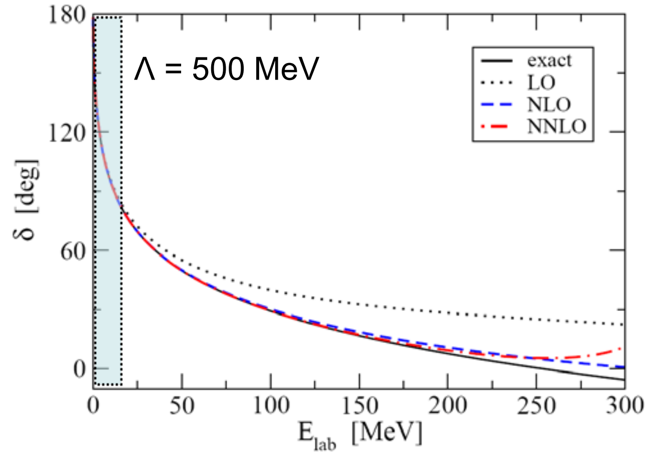
For example, the coefficients in the ERE: $k \cot\delta = -\frac{1}{a} + \frac{1}{2} r k^2 + v_2 k^4 + v_3 k^6 + \ldots$

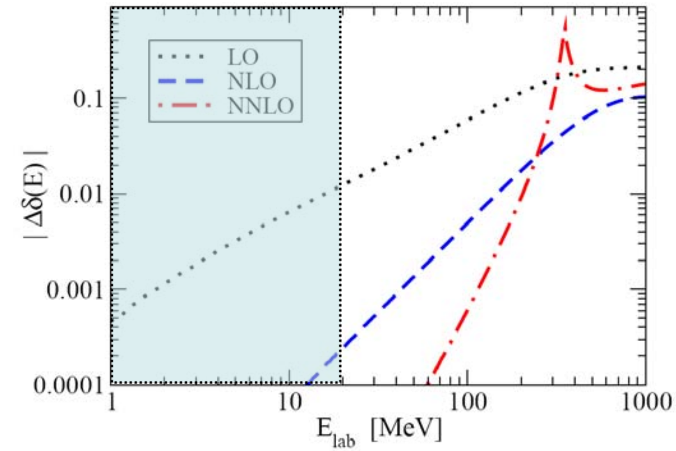
LO: $V_{\rm eff} = V_{\rm long-range} + C_0\, f_\Lambda(p, p')$, *where:* $\underbrace{f_\Lambda(p,\, p')}_{\text{cutoff function}} = e^{-\frac{\vec{p}^{\,2} + \vec{p}^{\,\prime 2}}{\Lambda^2}}$ $\longleftarrow$ C_0 *from* a

NLO: $V_{\rm eff} = V_{\rm long-range} + \left[C_0 + C_2(\vec{p}^{\,2} + \vec{p}^{\,\prime 2})\right] f_\Lambda(p, p')$ $\longleftarrow$ $C_{0,2}$ *from* $a,\ r$

NNLO: $V_{\rm eff} = V_{\rm long-range} + \left[C_0 + C_2(\vec{p}^{\,2} + \vec{p}^{\,\prime 2}) + C_4\,\vec{p}^{\,2}\vec{p}^{\,\prime 2}\right] f_\Lambda(p, p')$ $\longleftarrow$ $C_{0,2,4}$ *from* $a,\ r,\ v_2$

Toy model example





Error at order ν : $\Delta\delta(k) \sim (k/\bar{\Lambda})^{2\nu}$, $\bar{\Lambda} \sim 400$ MeV ⟸ agrees with $\bar{\Lambda} \sim M_h/2$

Results for the bound state: $E_B = \underbrace{2.1594}_{LO} + \underbrace{0.0638}_{NLO} - \underbrace{0.0003}_{NNLO} = 2.2229$ MeV

Lesson learned:

- Incorporate the correct long-range force.
- Add local correction terms to $V_{\rm eff}$. Respect symmetries.
- Introduce an ultraviolet cutoff Λ (large enough but not necessarily ∞).
- Fix unknown constants from some date and make predictions.

⟹ At low energy model independent and systematically improvable approach!

For more details see: *G.P.Lepage, "How to renormalize the Schrödinger equation", nucl-th/9706029*

Further reading

Breakdown of NN EFT with perturbative pions

- *Cohen, Hansen, Phys. Rev. C59 (99) 13; Phys. Rev. C59 (99) 3047; arXiv:nucl-th/9908049*
- *Fleming, Mehen, Stewart, Nucl. Phys. A677 (00) 313*

How to renormalize the Schrödinger equation

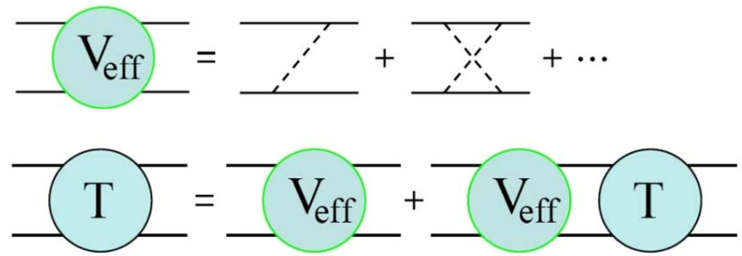
- *Lepage, "How to renormalize the Schrödinger equation", arXiv:nucl-th/9706029*
- *Lepage, "Tutorial: renormalizing the Schrödinger equation", talk at the INT Program 00-2 "Effective Field Theories and Effective Interactions", see:*
  http://www.int.washington.edu/talks/WorkShops/int_00_2/People/Lepage_TUT/ht/01.html
- *E.E., Gegelia, Eur. Phys. J. A41 (09) 341*

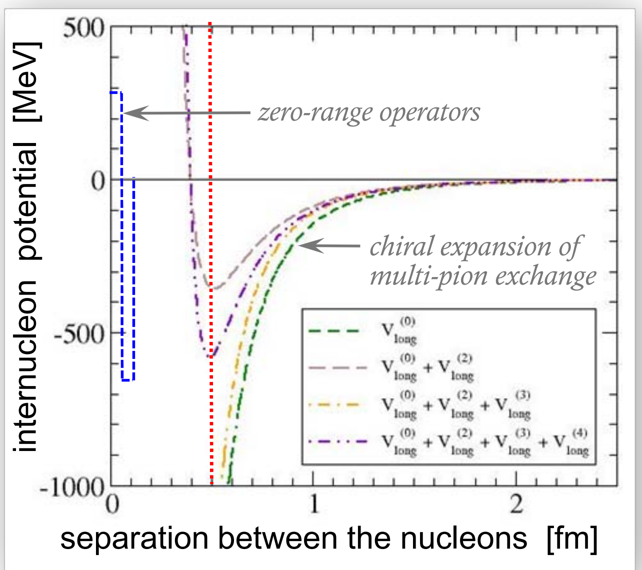
Nuclear chiral EFT à la Weinberg

Weinberg '90,'91

Weinberg's approach

- Irreducible contributions can be calcu-lated using ChPT
- Reducible contributions enhanced and should be summed up to infinite order





Structure of chiral nuclear forces

$$V_{\rm eff} = \sum_{\nu} \Big[\underbrace{V^{(\nu)}_{\rm short-range}}_{\text{parametrized}} + \underbrace{V^{(\nu)}_{\rm long-range}}_{\chi\text{-symm. constrained}} \Big]$$

— how to derive nuclear forces from $\mathcal{L}_{\rm eff}$?

— results for few-nucleon systems ?

→ see next lecture…