T2b: 1 V_{NN}: chiral EFT vs. pionless

2 available chiral NN potentials

3 3N forces at N^2LO and N^3LO

4 impact of 3N forces on few-nucleon systems

Nuclear forces: chiral EFT vs. pionless

explicit pions → systematic expansion of long-range part
→ expand $V_{N...N}$ and solve Schrödinger eqn. (no perturbative scheme beyond LO)
→ highly singular potentials complicate renormalization.
large cutoffs require inclusion of higher-order contact interactions already at LO

→ Q^ν with $\nu = 0, 2, 3, 4, \ldots$
odd powers in NN due to pion exchange predicted! no LECs to be adjusted in N...N
even powers in 3N

→ 3N forces enter at N^2LO (weaker than NN)

→ spin-orbit forces enter in NLO vs. high order in pionless.

→ available NN potentials from M26

→ slides → emphasize where contacts enter
→ NLO + N^2LO bands similar Why?

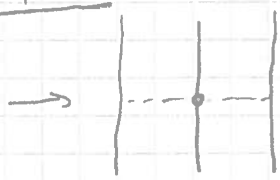
3N forces 1

need for 3N forces → cutoff variation / different V_{NN} lead to different $B(^3H)$, a_{n-d} and 3-body scattering observables
→ Phillips and Tjon line

dominant 3N mechanism

Fujita-Miyazawa 3N force (1957)
+ earlier works

in chiral EFT without explicit Δ



+ shorter-range topologies
with no loops L=0

$$\nu = -4 + \underset{\underset{3}{\|}}{2 \cdot N} + \underset{\underset{0}{\|}}{2 \cdot L} + \sum_i \underset{\underset{0}{\|}}{\Delta_i} \rightarrow \nu = 2$$

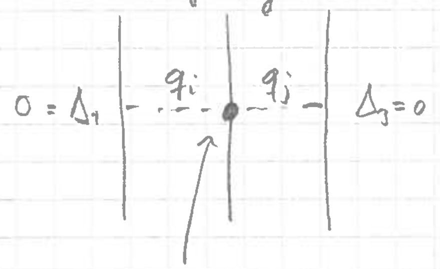
6-body 3N forces

$\Delta_i = 0$ from $\mathcal{L}^{(0)}$

evaluating the $\nu=2$ 3N forces shows that they cancel against iterated energy-dep. NN pot.
van Kolck (1994)

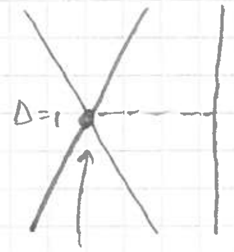
$\nu = 3$ 3N forces

long-range



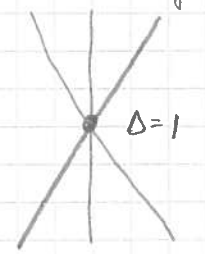
c_i from $\mathcal{L}^{(1)}$

mid-range



D from $\mathcal{L}^{(1)}$

short-range



E from $\mathcal{L}^{(1)}$

↳ only one coupling between antisym 3N states

$$V^{(3)}_{3N,2\pi} = \frac{1}{2} \sum_{i \neq j \neq k = 1}^{3} \left(\frac{g_A}{2 f_\pi}\right)^2 \frac{\vec{\sigma}_i \cdot \vec{q}_i \; \vec{\sigma}_j \cdot \vec{q}_j}{(q_i^2 + m_\pi^2)(q_j^2 + m_\pi^2)} \tau_i^\alpha \tau_j^\beta F_{ijk}^{\alpha\beta}$$

$$F_{ijk}^{\alpha\beta} = \delta_{\alpha\beta} \left(- \frac{4 c_1 m_\pi^2}{f_\pi^2} + \frac{2 c_3}{f_\pi^2} \vec{q}_i \cdot \vec{q}_j \right) + \varepsilon_{\alpha\beta\gamma} \frac{c_4}{f_\pi^2} \tau_k^\gamma \; \vec{\sigma}_k \cdot (\vec{q}_i \times \vec{q}_j)$$

↳ contributes to spin-orbit force

S-wave P-wave

πN scattering

$l = 0$ $\Rightarrow N(\frac{1}{2}^-)$ 1535 MeV

$l = 0 \rightarrow \frac{3}{2}^+$ Δ resonance! 1232 MeV and $\frac{1}{2}^+$ $N(1440)$

$\pi(0^-)$ $N(\frac{1}{2})^+$

$\Rightarrow$ expect $c_3 > c_1$, single Δ Fujita Miyazawa 3N force $c_1 = 0$

$c_3 \sim -3\,\mathrm{GeV}^{-1}$

$c_3 = -c_4/2$

c_3, c_4 large due to  $\sim \frac{1}{m_\Delta - m_N}$ enhancement

$\sim \frac{1}{0.3}\,\mathrm{GeV}^{-1}$

chiral EFT is general basis, so expect $c_1 \neq 0$, c_3, c_4 large but $c_3 \neq -\frac{c_4}{2}$

fit c_i in πN or NN   and predict long-range N^2LO 3N!

Consistency important!

Sources of difference in the c_i extractions

- finite-order extraction $\rightarrow$ truncation error $\frac{Q}{\Lambda_b}$ $\longrightarrow$ for 3N see N^3LO 3N forces
- πN vs. NN: different kinematics

shorter-range N^2LO 3N forces

$$V^{(3)}_{3N,\pi} = \sum_{i\neq j\neq k} \left(-D\,\frac{g_A}{8f_\pi^2}\right) \frac{\vec{\sigma}_j\cdot\vec{q}_j\;\vec{\sigma}_i\cdot\vec{q}_j}{q_j^2+m_\pi^2}\;\vec{\tau}_i\cdot\vec{\tau}_j$$

$$V^{(3)}_{3N,\text{contact}} = \sum_{i\neq j\neq k} \frac{E}{2}\,\vec{\tau}_j\cdot\vec{\tau}_k$$

convention: dimensionless coupling $c_D = D\,f_\pi^2\Lambda_\chi$ with $\Lambda_\chi = 700\,\text{MeV}$ (choice)

$c_E = E\,f_\pi^4\Lambda_\chi$

N^2LO 3N forces only have 2 LECs: c_D, c_E $\rightarrow$ fit to $A=3,4$ Q: Why light nuclei?

usually fit to $B(^3H)$ + a_{n-d}

or " + $r(^4He)$

or " + ^3H β-decay half-life $\longrightarrow$ see Thursday

$\longrightarrow$ predict structure + scattering/reactions to N^2LO (NN+3N)

majority of calculations with N^3LO NN + N^2LO 3N because full N^3LO 3N forces only derived recently

$\underline{N^3LO \text{ 3N forces}}$: Q^4, no new contact interactions! $\longrightarrow$ parameter free

$\underline{N^3LO \text{ 4N forces}}$: Q^4, all vertices $\Delta_i = 0$ (no cancellation like for NLO 3N)

also parameter-free

4N contact only at N^5LO

Q^6

$\nu = -4 + 2\cdot 4 + 0 + \Delta_i = 6$

$\Delta_i = 0 + \frac{8}{2} - 2$