INTRODUCTION TO CHIRAL EFFECTIVE FIELD THEORY

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Outline

- Effective Field Theories
- QCD at Low Energies
  - QCD and chiral symmetry
  - Chiral EFT
  - Nuclear bound states and reactions
  - Example: nuclear EDMs
  - Renormalization issues
  - Outlook & summary

Reference:

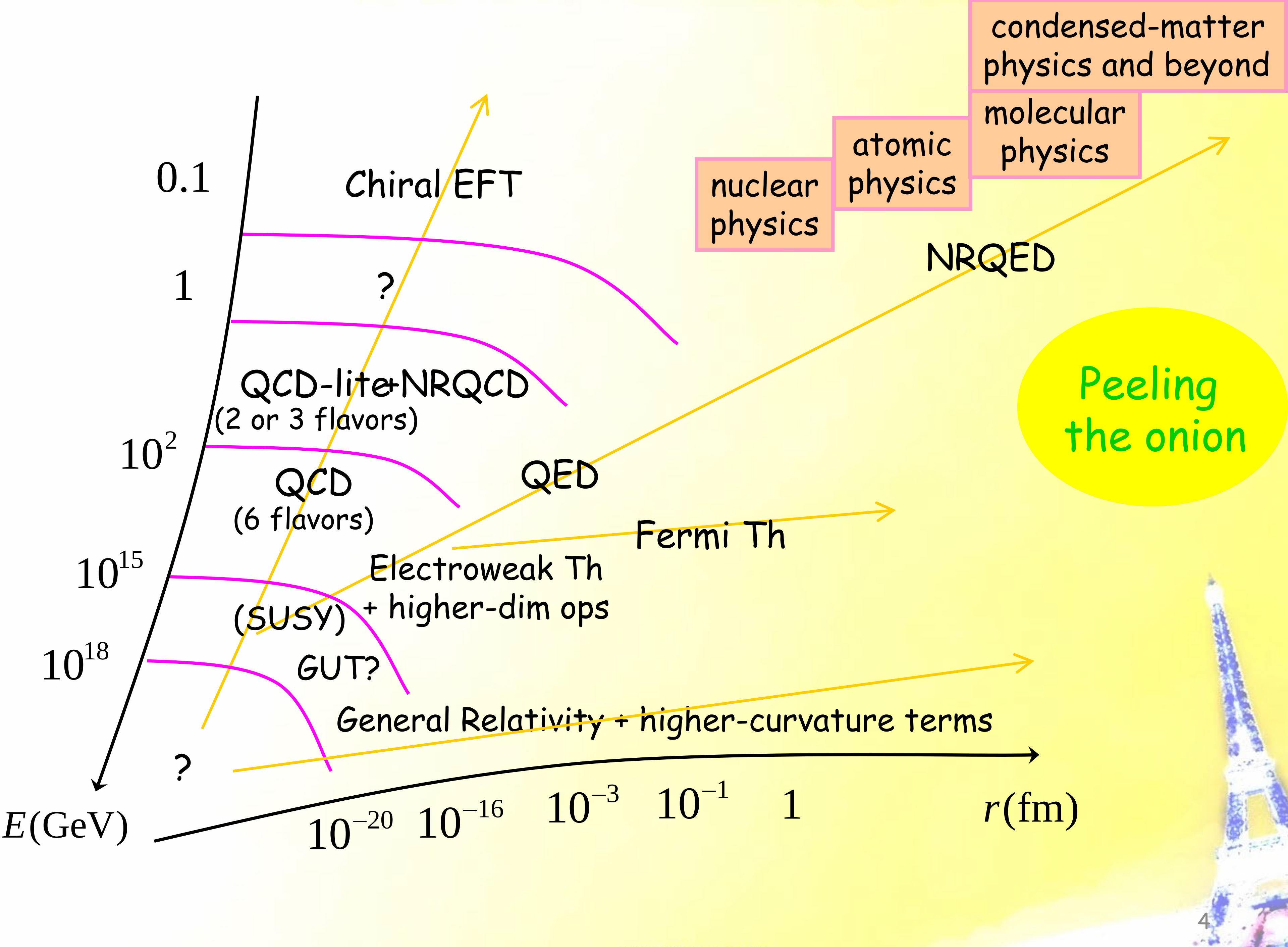
U. van Kolck,

Effective field theories of loosely bound nuclei,

in *The Euroschool on Exotic Beams, Vol. IV*

C. Scheidenberger and M. Pfützer (eds.), Springer, Berlin Heidelberg (2014)

Lect. Notes Phys. **879** (2014) 123



condensed-matter physics and beyond
molecular physics
atomic physics
nuclear physics
NRQED
Peeling the onion
0.1
Chiral EFT
1
?
QCD-lite+NRQCD
(2 or 3 flavors)
10^2
QCD
(6 flavors)
QED
Fermi Th
10^{15}
Electroweak Th
+ higher-dim ops
(SUSY)
10^{18}
GUT?
General Relativity + higher-curvature terms
?
E(GeV)
10^{-20}
10^{-16}
10^{-3}
10^{-1}
1
r(fm)

EFT at a few GeV= underlying theory for nuclear physics

d.o.f.s leptons: $l_f = \begin{pmatrix} l^+ \\ \nu \end{pmatrix}_f$ quarks: $q = \begin{pmatrix} u \\ d \end{pmatrix}$ photon: A_μ gluons: G_μ^a

symmetries: SO(3,1) global, $U_e(1)$ gauge, $SU_c(3)$ gauge

$$\mathcal{L}_{\text{und}} = \sum_{f=1}^{3} \bar{l}_f \left(i\not\partial + eQ_l \not A - m_f \right) l_f - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ \bar{q} \left(i\not\partial + eQ_q \not A + g_s \not G \right) q - \frac{1}{2} \mathrm{Tr}\left[G_{\mu\nu} G^{\mu\nu} \right]$$

$$- \frac{1}{2} (m_u + m_d) \bar{q}q - \frac{1}{2} (m_u - m_d) \bar{q}\tau_3 q$$

QED + QCD-lite

$$Q_l = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \qquad Q_q = \begin{pmatrix} 2/3 & 0 \\ 0 & -1/3 \end{pmatrix} = \frac{1+3\tau_3}{6}$$

$$+ \frac{m_u m_d}{m_u + m_d} \bar{\theta} \, \bar{q} i \gamma_5 q + \ldots$$

higher-dimension interactions: suppressed by larger masses

e.g. $G_F \propto 1/M_{W,Z}^2$

unnaturally small T violation (strong CP problem)

$\bar{\theta} \lesssim 10^{-9}$

Focus on strong-interacting sector: four parameters

1) $m_u = m_d = 0, \; e = 0, \; \bar{\theta} = 0$ "chiral limit"

single, *dimensionless* parameter

$$\int d^4x\, \mathcal{L}_{\text{QCD}} = \int d^4x \left\{ \bar{q}\left(i\partial\!\!\!/ + g_s G\!\!\!/\right) q - \frac{1}{2}\text{Tr}\, G^{\mu\nu} G_{\mu\nu} \right\}$$

invariant under scale transformations

$$\begin{cases} x \to \lambda^{-1} x \\ q \to \lambda^{3/2} q \\ G \to \lambda G \end{cases}$$

but in

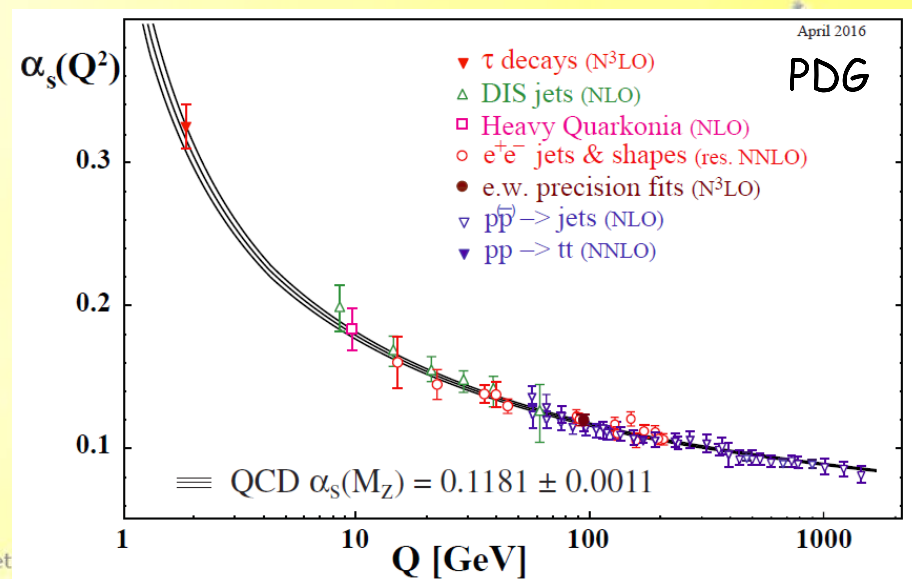
$$Z = \int DG \int D\bar{q} \int Dq\, \exp\left(i \int d^4x\, \mathcal{L}_{\text{QCD}}\right)$$

scale invariance
"anomalously broken"
by *dimensionful* regulator

⇨ coupling runs

$$\alpha_s\left(Q \sim 1\,\text{GeV}\right) \sim 1$$

("dimensional transmutation")



Non-perturbative physics at $Q \sim 1\ \mathrm{GeV}$

Assumption 1: <u>confinement</u>

only colorless states (“hadrons”) are asymptotic

Observation: (almost) all hadron masses $\gtrsim\ 1\ \mathrm{GeV}$

Assumption 2: <u>naturalness</u>

masses are determined by characteristic scale

⇨ $M_{\mathrm{QCD}} \sim 1\ \mathrm{GeV}$

Observation: pion mass $m_\pi \simeq 140\ \mathrm{MeV} \ll M_{\mathrm{QCD}}$

breakdown of naturalness? NO!

“spontaneous breaking” of chiral symmetry

Why is the pion special?

$$\mathcal{L}_{QCD} = \overline{q}_L \left(i\partial\!\!\!/ + g_s G\!\!\!/ \right) \underbrace{q_L}_{} + \overline{q}_R \left(i\partial\!\!\!/ + g_s G\!\!\!/ \right) \underbrace{q_R}_{} - \frac{1}{2} \mathrm{Tr}\, G^{\mu\nu} G_{\mu\nu}$$

$$q = \begin{pmatrix} u \\ d \end{pmatrix} \qquad \frac{1-\gamma_5}{2} q \qquad \frac{1+\gamma_5}{2} q$$

invariant under

$$q_{L(R)} \to \underbrace{\exp\left(i\boldsymbol{\alpha}_{L(R)} \cdot \boldsymbol{\tau} \right)}_{\equiv L(R)} q_{L(R)}$$

chiral symmetry

$$\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \sim \mathrm{SO}(4)$$

broken by vacuum down to

$$q \to \exp\left(i\boldsymbol{\alpha}_V \cdot \boldsymbol{\tau} \right) q$$

$$\boldsymbol{\alpha}_{R/L} = \boldsymbol{\alpha}_V \pm \boldsymbol{\alpha}_A$$

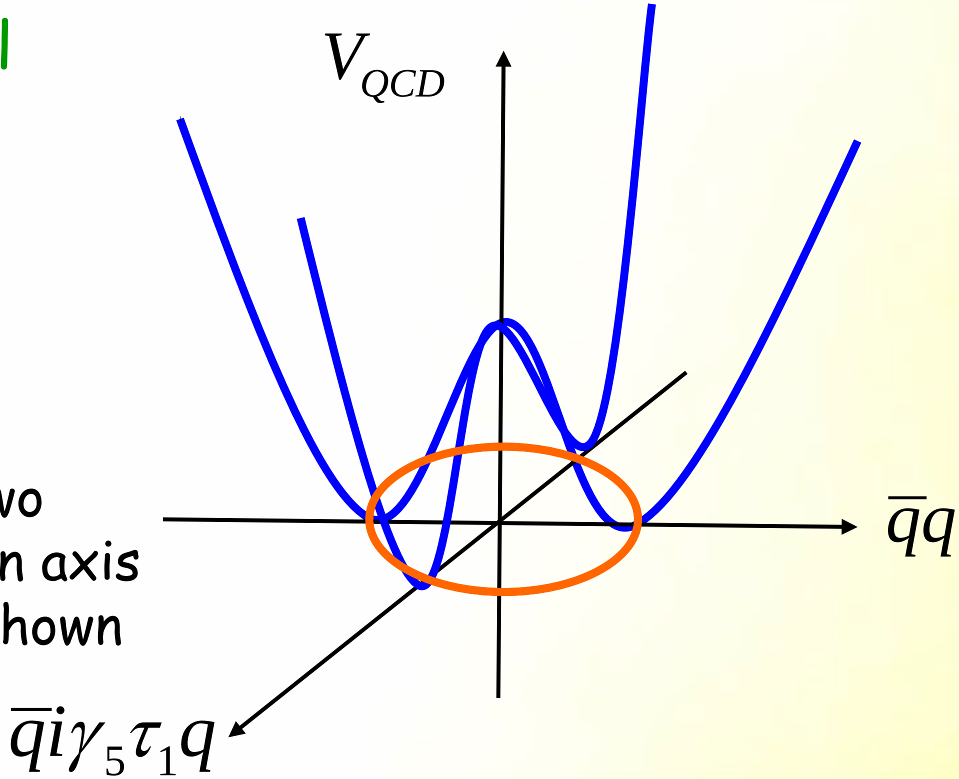
isospin

$$\mathrm{SU}(2)_V \sim \mathrm{SO}(3)$$

(axial transformations broken)

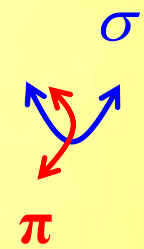
$$m_\sigma \gg m_\pi$$
$$m_{N_-} \gg m_{N_+}$$

Chiral Limit



two isospin axis not shown

chiral circle



f_π

pion decay constant (in chiral limit)

$\mathcal{L}_{\mathrm{EFT}} =$ piece invariant under $\boldsymbol{\pi} \to \boldsymbol{\pi} + \boldsymbol{\varepsilon}$ [function of $\partial_\mu \boldsymbol{\pi}$ on chiral circle]

$$\left(1 - \frac{\boldsymbol{\pi}^2}{4 f_\pi^2} + \ldots\right) \partial_\mu \boldsymbol{\pi}$$

2) $m_u \neq 0 \neq m_d, \;\; e = 0, \; \bar{\theta} = 0$

$$\mathcal{L}_{\mathrm{QCD}} = \bar{q}\left(i\partial\!\!\!/ + g_s G\!\!\!/\right)q - \frac{1}{2}\mathrm{Tr}\, G^{\mu\nu}G_{\mu\nu}$$

v.K. '93

$$+\frac{1}{2}(m_u + m_d)\underbrace{\bar{q}q} + \frac{1}{2}(m_u - m_d)\underbrace{\bar{q}\tau_3 q} + \ldots$$

4th component of $\mathrm{SO}(4)$ vector

$$S = \left(\bar{q}i\gamma_5\boldsymbol{\tau}q, \bar{q}q\right)$$

3rd component of $\mathrm{SO}(4)$ vector

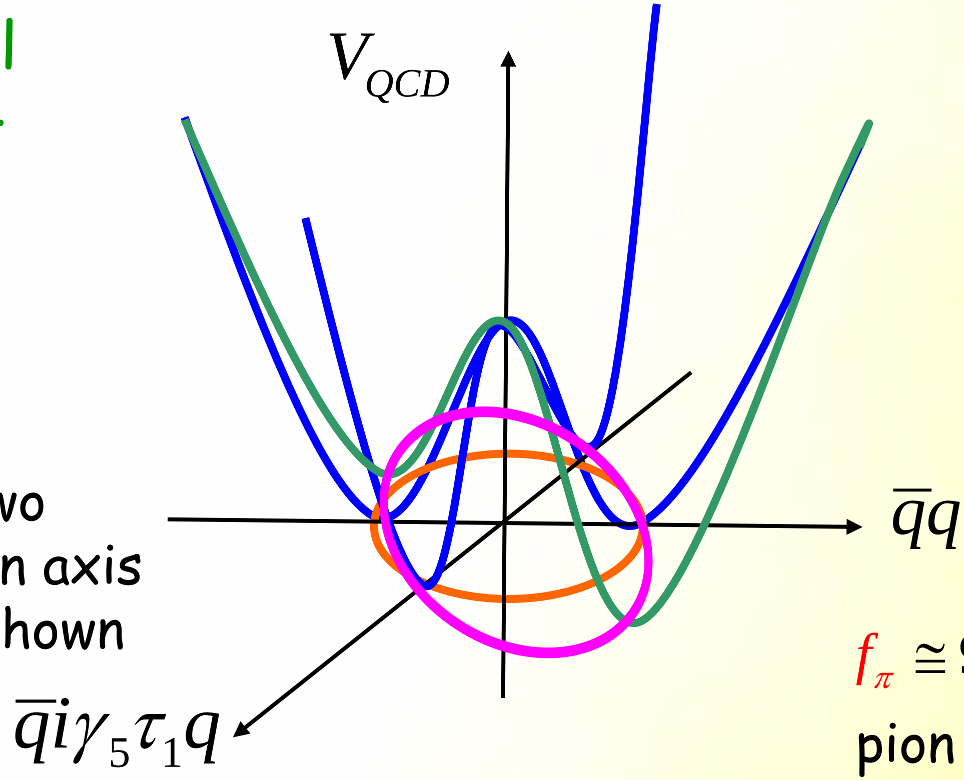
$$P = \left(\bar{q}\boldsymbol{\tau}q, \bar{q}i\gamma_5 q\right)$$

break

$\mathrm{SO}(4) \;\to \mathrm{SO}(3)$ $\quad\quad \to \mathrm{U}(1)$

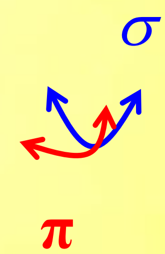
(explicit chiral-symmetry breaking) (isospin violation)

Chiral Limit



two isospin axis not shown

slightly-tilted chiral circle



$f_\pi \cong 92$ MeV

pion decay constant

$\mathcal{L}_{\rm EFT} =$ piece invariant under $\boldsymbol{\pi} \to \boldsymbol{\pi} + \boldsymbol{\varepsilon}$ [function of $\partial_\mu \boldsymbol{\pi}$] $\qquad \propto Q$

+ piece in $\bar{q}q$ direction [function of $\boldsymbol{\pi}$ explicitly] $\qquad \propto (m_u + m_d)$

+ isospin breaking $\qquad \propto (m_u - m_d)$

CHIRAL SYMMETRY ⇨ WEAK PION INTERACTIONS

3) $e \neq 0, \bar{\theta} = 0$

Two types of interactions:

- "soft" photons – explicit d.o.f. in the EFT

$$D_\mu = \partial_\mu - ieQ_q A_\mu$$
$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

- "hard" photons – "integrated out" of EFT

v.K. '93

$$\mathcal{L}_{\text{und}} = \ldots - e^2 \bar{q} Q_q \gamma_\mu q \, D^{\mu\nu}(\partial^2) \, \bar{q} Q_q \gamma_\nu q + \ldots$$

34 comp of antisymmetric tensor

$$F_\mu = \begin{pmatrix} \varepsilon_{ijk} \bar{q} i \gamma_\mu \gamma_5 \tau_k q & \bar{q} i \gamma_\mu \tau_j q \\ -\bar{q} i \gamma_\mu \tau_i q & 0 \end{pmatrix}$$

breaks $\mathrm{SO}(4)$ (and $\mathrm{SO}(3)$ in particular) $\to \mathrm{U}(1)$

⇨ $\mathcal{L}_{\text{EFT}} =$ soft photons $\propto e$

+ further isospin breaking $\propto \alpha / 4\pi$

4) $\bar{\theta} \neq 0$

$$\mathcal{L}_{\text{QCD}} = \ldots + \frac{m_u m_d}{m_u + m_d} \bar{\theta}\, \underbrace{\bar{q} i \gamma_5 q} + \ldots$$

4th component of $\mathrm{SO}(4)$ vector $P = \left(\bar{q}\boldsymbol{\tau}q, \bar{q}i\gamma_5 q\right)$

T violation linked to isospin violation: in EFT, combination is

$$-\frac{1}{2}\left(m_u - m_d\right) P_3 + \frac{m_u m_d}{m_u + m_d} \bar{\theta}\, P_4$$

Hockings,
Mereghetti + v.K., '10

5) continue with higher-order operators,

e.g. T-violating quark EDM and color-EDM

P-violating four-quark operators

De Vries, Mereghetti,
Timmermans + v.K., '12
...

...
Kaplan + Savage '96
Zhu, Maekawa, Holstein, Musolf + v.K. '02

Nuclear physics scales

"His scales are His pride", Book of Job

$\ln Q$

perturbative QCD

~1 GeV $M_{\rm QCD} \sim m_N, m_\rho, 4\pi f_\pi, \ldots$

brute force (lattice), …?

hadronic th with chiral sym

~100 MeV $M_{\rm nuc} \sim f_\pi, 1/r_{NN}, m_\pi, \ldots$

~30 MeV $\aleph \sim 1/a_{NN}$

this lecture: $Q/M_{\rm QCD}$

another time: $Q/M_{\rm nuc}$

no small coupling → expansion in ↑

Chiral EFT

$Q \sim m_\pi \ll M_{\rm QCD}$

- d.o.f.s: nucleons, pions, deltas, Roper? $(m_\Delta - m_N \sim 2m_\pi,\ m_{N'} - m_N \sim 3m_\pi)$

$$N = \begin{pmatrix} p \\ n \end{pmatrix} \qquad \boldsymbol{\pi} = \begin{pmatrix} \pi_1 \\ \pi_2 \\ \pi_3 \end{pmatrix} = \begin{pmatrix} (\pi^+ + \pi^-)/\sqrt{2} \\ -i(\pi^+ - \pi^-)/\sqrt{2} \\ \pi^0 \end{pmatrix} \qquad \Delta = \begin{pmatrix} \Delta^{++} \\ \Delta^+ \\ \Delta^0 \\ \Delta^- \end{pmatrix} \qquad N' = \begin{pmatrix} p' \\ n' \end{pmatrix}$$

- symmetries: Lorentz, ~~P~~, ~~T~~, ~~chiral~~

Non-linear realization of chiral symmetry

Weinberg '68
Callan, Coleman, Wess + Zumino '69

chiral invariants

+ S_4's, P_3's, F_{34}'s

(chiral) covariant derivatives

pion $\quad \boldsymbol{D}_\mu \equiv \left(\dfrac{\partial_\mu \boldsymbol{\pi}}{f_\pi}\right)\left(1 - \dfrac{\boldsymbol{\pi}^2}{4 f_\pi^2} + \ldots\right)$

fermions $\quad \mathcal{D}_\mu \equiv \left(\partial_\mu - \dfrac{i}{2}\boldsymbol{\tau}\cdot\boldsymbol{E}_\mu\right)$

$$\boldsymbol{E}_\mu \equiv \frac{\boldsymbol{\pi}}{f_\pi} \times \boldsymbol{D}_\mu$$

$$m_\pi^2 = \mathcal{O}\left((m_u + m_d) M_{\rm QCD}\right)$$

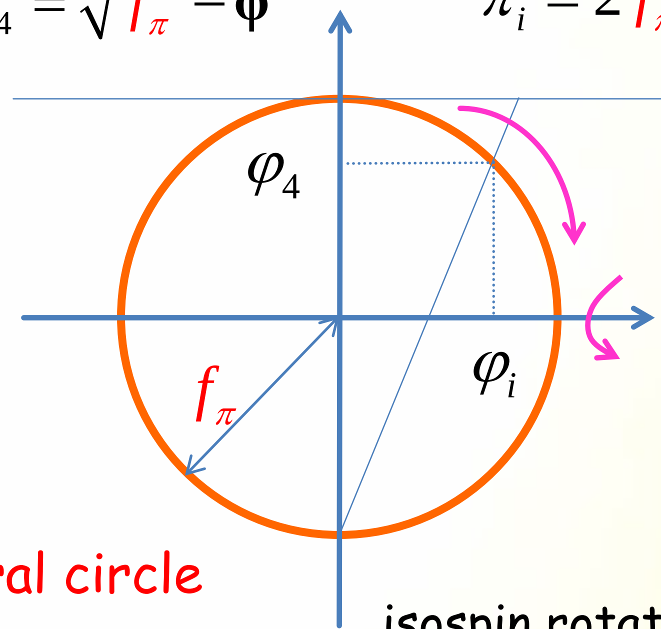
$$\Rightarrow m_u + m_d = \mathcal{O}\left(\frac{m_\pi^2}{M_{\rm QCD}}\right)$$

see for example Weinberg's Quantum Theory of Fields, vol 2

Open parentheses on parametrizations

$$\varphi_4 = \sqrt{f_\pi^2 - \boldsymbol{\varphi}^2} \qquad \pi_i = 2 f_\pi \frac{\varphi_i}{f_\pi + \varphi_4}$$

stereographic projection — Weinberg '68



chiral circle

axial rotation
$$\begin{cases} \boldsymbol{\varphi} \to \boldsymbol{\varphi} - \boldsymbol{\alpha}_A \varphi_4 \\ \varphi_4 \to \varphi_4 + \boldsymbol{\alpha}_A \cdot \boldsymbol{\varphi} \end{cases}$$

$$\Rightarrow \boldsymbol{\pi} \to \left(1 - \frac{\boldsymbol{\alpha}_A \cdot \boldsymbol{\pi}}{2 f_\pi}\right)\boldsymbol{\pi} - f_\pi \left(1 - \frac{\boldsymbol{\pi}^2}{4 f_\pi^2}\right)\boldsymbol{\alpha}_A$$

nonlinear!

$$\Rightarrow \mathbf{D}_\mu \to \mathbf{D}_\mu - \left(\boldsymbol{\alpha}_A \times \frac{\boldsymbol{\pi}}{2 f_\pi}\right) \times \mathbf{D}_\mu$$

rotates with $\boldsymbol{\alpha}_V \to i\left(\boldsymbol{\alpha}_A \times \frac{\boldsymbol{\pi}}{2 f_\pi}\right)$

analogous for $\mathcal{D}_\mu$

isospin rotation
$$\begin{cases} \boldsymbol{\varphi} \to \boldsymbol{\varphi} + i\boldsymbol{\alpha}_V \times \boldsymbol{\varphi} \\ \varphi_4 \to \varphi_4 \end{cases}$$

$$\Rightarrow \boldsymbol{\pi} \to \boldsymbol{\pi} + i\boldsymbol{\alpha}_V \times \boldsymbol{\pi}$$

$$\Rightarrow \mathbf{D}_\mu \to \mathbf{D}_\mu + i\boldsymbol{\alpha}_V \times \mathbf{D}_\mu$$

rotates

isospin symmetry of covariant objects ensures chiral invariance

Callan, Coleman, Wess
+ Zumino '69

$$\tilde{\Sigma} \equiv \varphi_4 + i\boldsymbol{\tau}\cdot\boldsymbol{\varphi} = f_\pi \exp\left(i\frac{\boldsymbol{\tau}\cdot\pi}{f_\pi}\right) \equiv f_\pi \Sigma$$

"sigma-model parametrization"

"exponential parametrization"

Choice of fields does <u>not</u> affect observables: all parametrizations are equivalent

$$\Sigma \to \exp\left(\frac{i}{2}\boldsymbol{\alpha}_L\cdot\boldsymbol{\tau}\right)\Sigma \exp\left(\frac{i}{2}\boldsymbol{\alpha}_R\cdot\boldsymbol{\tau}\right)$$

invariants constructed with Tr

e.g. $\Sigma^\dagger \partial_\mu \Sigma = 2i\boldsymbol{\tau}\cdot\boldsymbol{D}_\mu$

e.g. $\mathrm{Tr}\left[\left(\partial^\mu \Sigma^\dagger\right)\partial_\mu \Sigma\right] = 8\boldsymbol{D}^\mu\cdot\boldsymbol{D}_\mu$

less intuitive but easier to generalize to $\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$

chiral-breaking terms --- an example: common quark mass

- stereographic projection

4th component of $\mathrm{SO}(4)$ vector

$$S=\left(\bar{q}i\gamma_5\boldsymbol{\tau}q,\ \bar{q}q\right) \quad \Rightarrow \quad S=\left(\left(1+\frac{\boldsymbol{\pi}^2}{4f_\pi^2}\right)^{-1}\frac{\boldsymbol{\pi}}{f_\pi},\ \underbrace{1-\left(1+\frac{\boldsymbol{\pi}^2}{4f_\pi^2}\right)^{-1}\frac{\boldsymbol{\pi}^2}{2f_\pi^2}}\right)$$

$$=1-\frac{\boldsymbol{\pi}^2}{2f_\pi^2}+\frac{\boldsymbol{\pi}^4}{8f_\pi^4}+\ldots$$

pion mass term

- exponential parametrization

$$\frac{m_u+m_d}{2}\bar{q}q \rightarrow \frac{1}{2}\left[\bar{q}_L\bar{M}(x)q_R+\bar{q}_R\bar{M}^\dagger(x)q_L\right] \quad \Rightarrow \quad \underbrace{\frac{1}{2}\mathrm{Tr}\left[\Sigma^\dagger\bar{M}+\bar{M}^\dagger\Sigma\right]}$$

invariant if $\bar{M}(x)\rightarrow L\bar{M}(x)R^\dagger$

"spurion field"

$$=\frac{m_u+m_d}{2}\left(\frac{\boldsymbol{\pi}^2}{f_\pi^2}+\ldots\right)$$

pion mass term

chiral symmetry broken explicitly just as in QCD

Close parentheses

Schematically,

$$\mathcal{L}_{\rm EFT} = \sum_{\{n,p,f\}} c_{\{n,p,f\}} \left(\frac{\mathbf{D}, \mathcal{D}, m_R - m_N}{M_{\rm QCD}}\right)^n \left(\frac{m_\pi^2}{M_{\rm QCD}^2}\,\frac{\boldsymbol{\pi}^2}{f_\pi^2}\right)^{p/2} \left(\frac{\psi^+\psi}{f_\pi^2 M_{\rm QCD}}\right)^{f/2} f_\pi^2 M_{\rm QCD}^2$$

$= \mathcal{O}(1)$ isospin conserving

$= \mathcal{O}\left(\varepsilon, \frac{\alpha}{4\pi}\right)$ isospin breaking

NDA: naïve dimensional analysis

calculated from QCD: lattice, …
fitted to data

$$= \sum_{\Delta=0}^{\infty} \mathcal{L}^{(\Delta)} \qquad \Delta \equiv n + p + \frac{f}{2} - 2 \equiv d + \frac{f}{2} - 2 \geq 0$$

"chiral index"

chiral symmetry

$$\mathcal{L}^{(0)} = \frac{1}{2}(\partial_\mu \boldsymbol{\pi})^2\left(1-\frac{\boldsymbol{\pi}^2}{2f_\pi^2}+\ldots\right)-\frac{1}{2}m_\pi^2\boldsymbol{\pi}^2\left(1-\frac{\boldsymbol{\pi}^2}{4f_\pi^2}+\ldots\right)$$

$$+N^+\left[i\partial_0-\frac{1}{4f_\pi^2}\boldsymbol{\tau}\cdot(\boldsymbol{\pi}\times\partial_0\boldsymbol{\pi})+\ldots\right]N+\frac{g_A}{2f_\pi}N^+\boldsymbol{\tau}\vec{\sigma}N\cdot(\vec{\nabla}\boldsymbol{\pi})\left(1-\frac{\boldsymbol{\pi}^2}{4f_\pi^2}+\ldots\right)$$

$$+\Delta^+\left[i\partial_0-(m_\Delta-m_N)+\ldots\right]\Delta+\ldots+\frac{h_A}{2f_\pi}\left(N^+\mathbf{T}\vec{S}\Delta+\text{H.c.}\right)\cdot(\vec{\nabla}\boldsymbol{\pi})\,(1+\ldots)$$

$$-C_S\left(N^+N\right)^2-C_T\left(N^+\vec{\sigma}N\right)^2$$

$$\mathcal{L}^{(1)} = N^+\left[\frac{1}{2m_N}\left(\vec{\nabla}+\frac{1}{4f_\pi^2}\boldsymbol{\tau}\cdot(\boldsymbol{\pi}\times\vec{\nabla}\boldsymbol{\pi})+\ldots\right)^2+\frac{1}{2}(m_p-m_n)\left(\tau_3-\frac{1}{2f_\pi^2}\pi_3\boldsymbol{\pi}\cdot\boldsymbol{\tau}+\ldots\right)\right]N$$

$$+\frac{1}{f_\pi^2}N^+\left[b_2(\partial_0\boldsymbol{\pi})^2-b_3(\vec{\nabla}\boldsymbol{\pi})^2-2b_1m_\pi^2\boldsymbol{\pi}^2+ib_4\varepsilon_{ijk}\varepsilon_{abc}\sigma_k\tau_c(\partial_i\pi_b)(\partial_j\pi_c)\right]N+\ldots$$

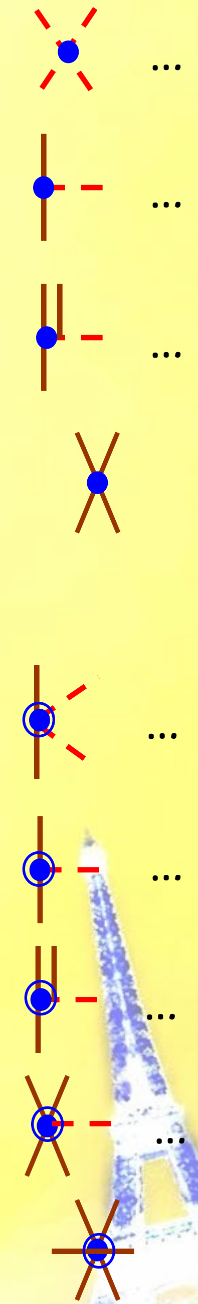
$$-\frac{g_A}{4m_Nf_\pi}\left[iN^+\boldsymbol{\tau}\vec{\sigma}\cdot\vec{\nabla}N+\text{H.c.}\right]\cdot(\partial_0\boldsymbol{\pi})\,(1+\ldots)$$

$$-\frac{h_A}{4m_Nf_\pi}\left[i\Delta^+\mathbf{T}\vec{S}\cdot\vec{\nabla}N+\text{H.c.}\right]\cdot(\partial_0\boldsymbol{\pi})\,(1+\ldots)$$

$$+\frac{d}{f_\pi}N^+N\;N^+\boldsymbol{\tau}\vec{\sigma}N\cdot(\vec{\nabla}\boldsymbol{\pi})\,(1+\ldots)$$

$$-E\left(N^+N\right)^3$$

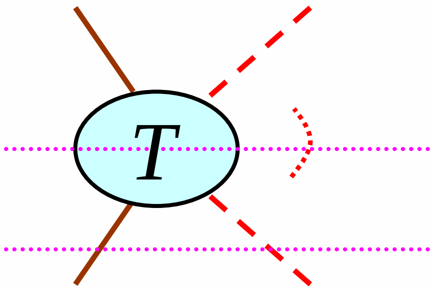
$$\mathcal{L}^{(2)} = \ldots$$



Form of pion interactions determined by chiral symmetry

A= 0, 1: chiral perturbation theory

Weinberg '79
Gasser + Leutwyler '84
...
Gasser, Sainio + Švarč '87
Bernard, Kaiser + Meißner '90
Jenkins + Manohar '91
...



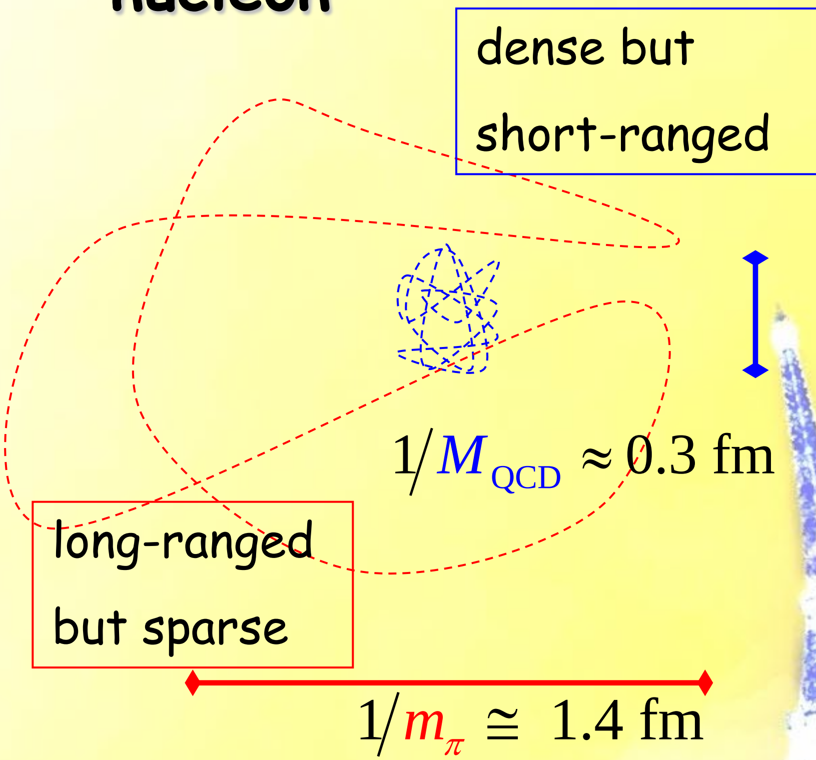
$$\frac{1}{\Delta E} \sim \frac{1}{Q}$$

$$\sim \sum_{\nu} c_{\nu} \left(\frac{Q}{M_{\rm QCD}} \right)^{\nu} F_{\nu}\left(\frac{Q}{m_{\pi}} \right)$$

$$\nu = 2 - A + 2L + \sum_i V_i \Delta_i \geq \nu_{\min} = 2 - A$$

L: # loops; V_i: # vertices of type i

nucleon

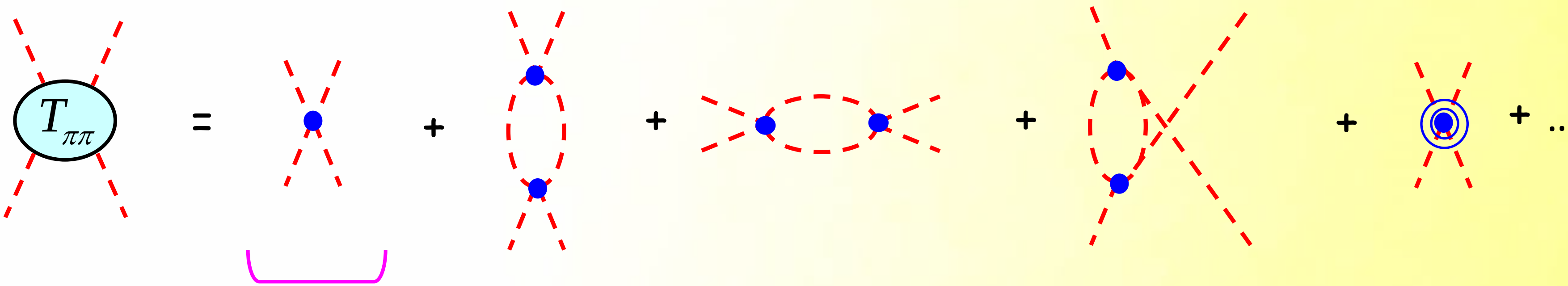


expansion in

$$\frac{Q}{M_{\rm QCD}} \sim \begin{cases} Q/m_N & \text{non-relativistic} \\ Q/m_{\rho}, \ldots & \text{multipole} \\ Q/4\pi f_{\pi} & \text{pion loop} \end{cases}$$

Analogous to NRQED…

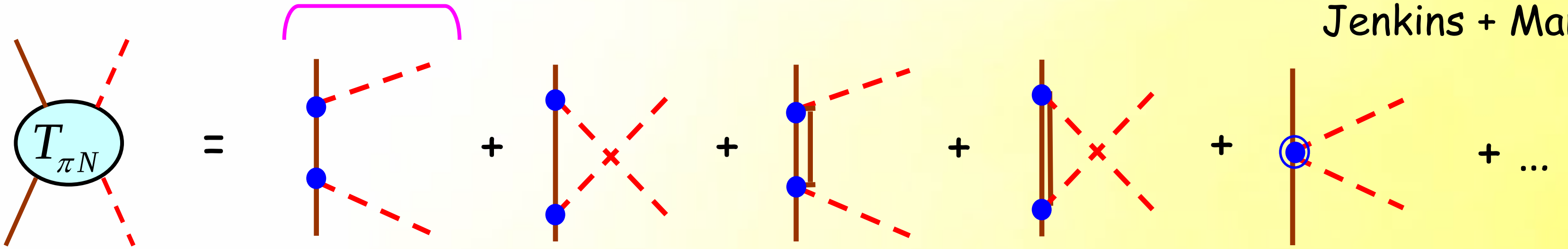
Weinberg '79
Gasser + Leutwyler '84
…



current algebra

Weinberg '66
…

Gasser, Sainio + Švarč '87
Bernard, Kaiser + Meißner '90
Jenkins + Manohar '91
…



etc.

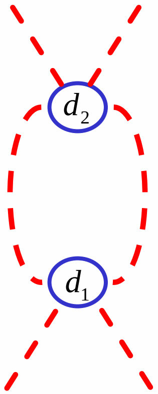
N.B. For $\left|E-(m_\Delta - m_N)\right| \lesssim \mathcal{O}\left(\frac{Q^3}{M_{QCD}^2}\right)$: resummation necessary

Phillips + Pascalutsa '02
Long + v.K. '08

⇒ $\left|E-(m_{N'} - m_N)\right| = \mathcal{O}(Q)$: Roper important

Long + v.K. '09

NDA



$$\sim \frac{Q^4}{(4\pi)^2}\frac{Q^{d_1+d_2}}{Q^4}c_{d_1}(\Lambda)\,c_{d_2}(\Lambda)$$

$$\sim \frac{\Lambda^{d_1+d_2-d}}{(4\pi)^2}c_{d_1}(\Lambda)\,c_{d_2}(\Lambda)\,Q^d+\ldots$$

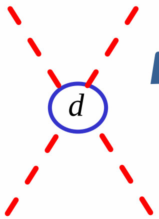
$$\sim c_d(\Lambda)$$

$d_1 = d_2 = d$

$$\Rightarrow\; c_d(\Lambda) \sim \frac{(4\pi)^2}{\Lambda^d}$$

naturalness

$$\Rightarrow\; c_d(M_{\rm QCD}) \sim \frac{(4\pi)^2}{M_{\rm QCD}^d}$$



momenta ~ cutoff
= short-range physics

Georgi + Manohar '86

arbitrary diagram
- fermions
- more loops, vertices
- other interactions

$$\Rightarrow\; c_i = \mathcal{O}\left(\frac{(4\pi)^{N-2}}{M_{\rm QCD}^{D-4}}\,c_i^{\rm red}\right)$$

number of fields in operator

dimension of operator

reduced coupling

$$c_i^{\rm red} = \mathcal{O}\left(\left(g^{\rm red}\right)^{\#}\right)$$

reduced underlying theory parameter

insertions

naïve dimensional analysis (NDA)

(perturbative renormalization)

Example

$$\mathcal{L}_{\text{QCD}} = \ldots + \frac{1}{2}(m_u + m_d)\,\bar{q}q + \ldots$$

$$(m_u + m_d)^{\text{red}} = \frac{M_{\text{QCD}}^{3-4}}{(4\pi)^{2-2}}(m_u + m_d) = \frac{m_u + m_d}{M_{\text{QCD}}}$$

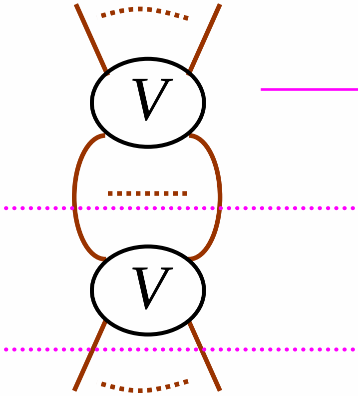
$$\mathcal{L}_{\text{EFT}} = \ldots - \frac{1}{2} m_\pi^2 \boldsymbol{\pi}^2 + \ldots$$

$$(m_\pi^2)^{\text{red}} = \frac{M_{\text{QCD}}^{2-4}}{(4\pi)^{2-2}} m_\pi^2 = \frac{m_\pi^2}{M_{\text{QCD}}^2}$$

$$(m_\pi^2)^{\text{red}} = \mathcal{O}\left((m_u + m_d)^{\text{red}}\right) \Rightarrow m_\pi^2 = \mathcal{O}\left((m_u + m_d)M_{\text{QCD}}\right)$$

A ≥ 2: resummed chiral perturbation theory

Weinberg '90, '91

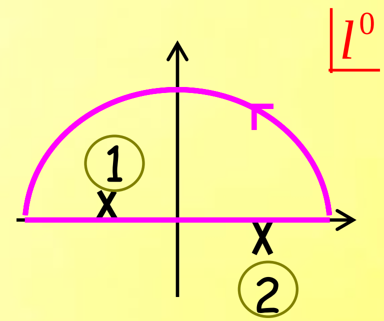


A-nucleon irreducible

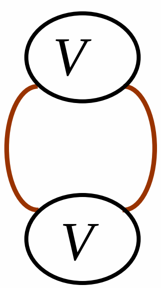
$$\frac{1}{\Delta E} \sim \frac{m_N}{Q^2}$$

infrared enhancement!

A-nucleon reducible



e.g.

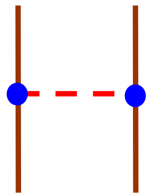


$$E = \frac{k^2}{m_N}$$

$$\simeq i\int \frac{d^4 l}{(2\pi)^4} V \underbrace{\frac{1}{l^0 + k^2/m_N - l^2/m_N - i\varepsilon}}_{①} \underbrace{\frac{1}{-l^0 + k^2/m_N - l^2/m_N - i\varepsilon}}_{②} V$$

$$= \int \frac{d^3 l}{(2\pi)^3} V \frac{m_N}{l^2 - k^2} V + \ldots \qquad \sim \mathcal{O}\left(\frac{m_N Q}{4\pi} V^2\right)$$

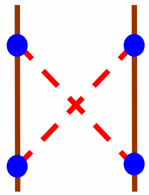
instead of $\frac{Q^2}{(4\pi)^2}$



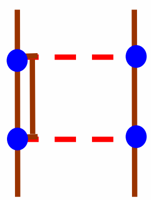
$$\sim i\left(\frac{g_A}{2f_\pi}\right)^2\left(\frac{\vec{q}^{\,2}}{\vec{q}^{\,2}+m_\pi^2}\right)\frac{\left(S_{12}(\hat{q})+\vec{\sigma}_1\cdot\vec{\sigma}_2\right)}{3}\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2\sim\frac{1}{f_\pi^2}$$

tensor force

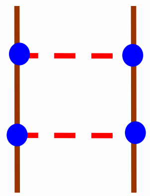
$$S_{12}(\hat{q})=3\vec{\sigma}_1\cdot\hat{q}\,\vec{\sigma}_2\cdot\hat{q}-\vec{\sigma}_1\cdot\vec{\sigma}_2$$



$$\sim\frac{1}{f_\pi^4}\frac{Q^3}{(4\pi)^2}\frac{1}{Q}\frac{1}{Q}\frac{Q^2}{Q^2}\frac{Q^2}{Q}\sim\frac{1}{f_\pi^2}\underbrace{\frac{Q^2}{\left(4\pi f_\pi\right)^2}}=\mathcal{O}\left(\frac{Q^2}{M_{QCD}^2}\right)$$



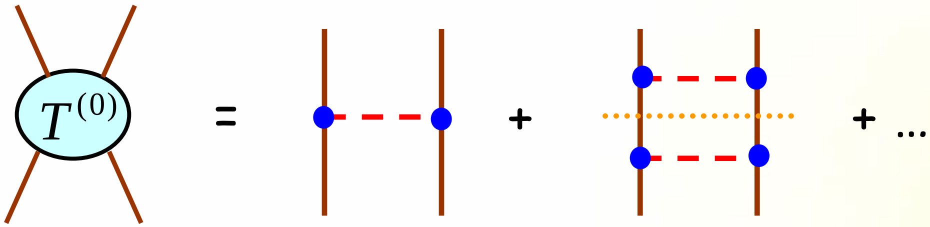
$$\sim\frac{1}{f_\pi^4}\frac{Q^3}{(4\pi)^2}\frac{1}{m_\Delta-m_N}\frac{1}{Q}\frac{Q^2}{Q^2}\frac{Q^2}{Q}\sim\frac{1}{f_\pi^2}\overbrace{\frac{Q^2}{\left(4\pi f_\pi\right)^2}}\underbrace{\frac{Q}{m_\Delta-m_N}}=\mathcal{O}(1)$$



$$\sim\frac{1}{f_\pi^4}\frac{Q^3}{4\pi}\frac{m_N}{Q^2}\frac{Q^2}{Q^2}\frac{Q^2}{Q^2}\sim\frac{1}{f_\pi^2}\frac{m_N}{4\pi f_\pi}\frac{Q}{f_\pi}\sim\frac{1}{f_\pi^2}\frac{Q}{M_{NN}}$$

$$\equiv 1/M_{NN}$$

$=\mathcal{O}(1)$ for $Q\sim M_{NN}$



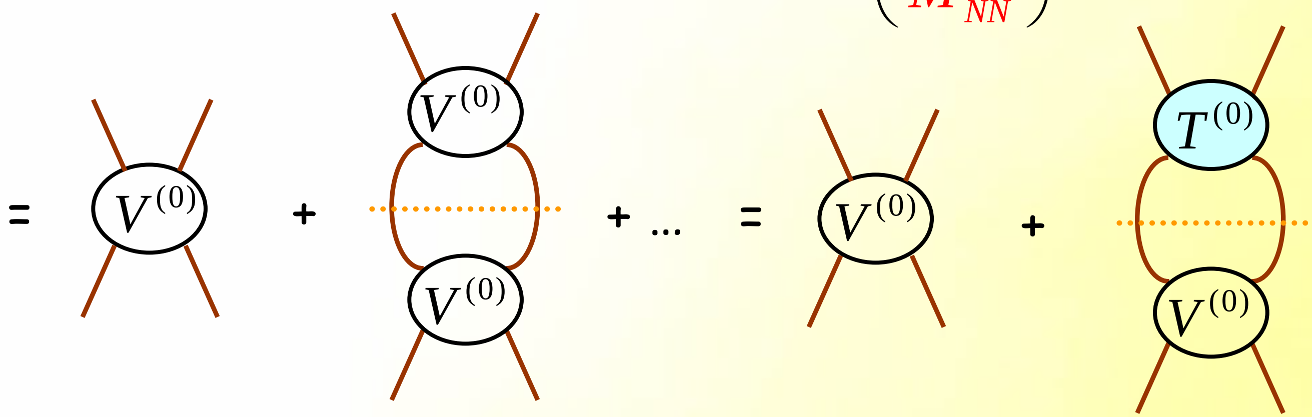
bound state at

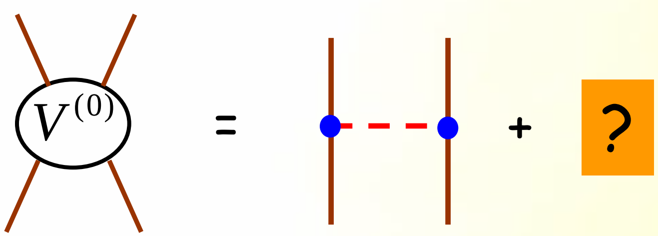
$$Q \sim M_{NN} \qquad -E \sim \frac{Q^2}{m_N} \sim \frac{M_{NN}^2}{M_{QCD}}$$

$$\sim \frac{1}{f_\pi^2}\left\{1+\mathcal{O}\left(\frac{Q}{M_{NN}}\right)+\ldots\right\} \sim \frac{1}{f_\pi^2}\frac{1}{1-\mathcal{O}\left(\frac{Q}{M_{NN}}\right)}$$

$$M_{\text{nuc}} = M_{NN} \sim \frac{4\pi f_\pi}{m_N} f_\pi \approx f_\pi$$

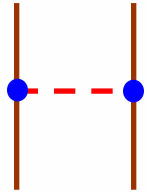
Nuclear scale arises naturally from chiral symmetry





Is 1PE all there is in leading order? That is, are observables cutoff independent with 1PE alone?

Issue: relative importance of pion exchange and short-range interactions

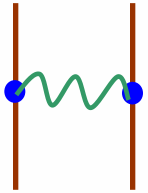


$$\sim i\left(\frac{g_A}{2f_\pi}\right)^2\left(\frac{\vec{q}^{\,2}}{\vec{q}^{\,2}+m_\pi^2}\right)\frac{\left(S_{12}(\hat{q})+\vec{\sigma}_1\cdot\vec{\sigma}_2\right)}{3}\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2\sim\frac{4\pi}{m_N M_{NN}}$$

$$\begin{cases} V(r)=\left(\dfrac{g_A}{2f_\pi}\right)^2\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2\left(-\delta^{(3)}(\vec{r})+\dfrac{m_\pi^2}{4\pi r}e^{-m_\pi r}\right) & S=0 \\ V(r)=\left(\dfrac{g_A}{2f_\pi}\right)^2\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2\left\{\dfrac{1}{3}\left(\delta^{(3)}(r)-\dfrac{m_\pi^2}{4\pi r}e^{-m_\pi r}\right)+\dfrac{m_\pi^2}{4\pi r}\left(\dfrac{1}{(m_\pi r)^2}+\dfrac{1}{m_\pi r}+\dfrac{1}{3}\right)e^{-m_\pi r}\left\langle S_{12}(\hat{r})\right\rangle\right\} & S=1 \end{cases}$$

$\langle S_{12}\rangle$	$j-1$	j	$j+1$
$j-1$	$-2\frac{j-1}{2j+1}$	0	$6\frac{\sqrt{j(j+1)}}{2j+1}$
j	0	2	0
$j+1$	$6\frac{\sqrt{j(j+1)}}{2j+1}$	0	$-2\frac{j+2}{2j+1}$

much more singular --and complicated!-- than

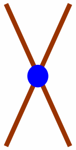


$$\sim\frac{i\,e^2}{\left(\vec{p}-\vec{p}\,'\right)^2-i\varepsilon}\sim\frac{4\pi\alpha}{Q^2}\quad\rightarrow V(r)=\frac{\alpha}{r}$$

Weinberg '90, '91
Ordóñez + v.K. '92
Ordóñez, Ray + v.K. '96
...
Entem + Machleidt '03
Epelbaum, Glöckle + Meißner '04
...

Assume contact interactions are driven by heavier dofs, and scale with $M_{\rm QCD}$ according to naïve dimensional analysis

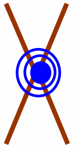
(W power counting)



$$\sim \underbrace{C_0^{(0)}}_{\equiv \frac{4\pi}{m_N M^{(0)}}} \frac{(\vec{\sigma}_1\cdot\vec{\sigma}_2+1)}{4} - \underbrace{C_0^{(1)}}_{\equiv \frac{4\pi}{m_N M^{(1)}}} \frac{(\vec{\sigma}_1\cdot\vec{\sigma}_2-3)}{4}$$

$$\begin{cases} V(r) = \dfrac{4\pi}{m_N M^{(0)}}\,\delta^{(3)}(\vec{r}) & S=0 \\ V(r) = \dfrac{4\pi}{m_N M^{(1)}}\,\delta^{(3)}(\vec{r}) & S=1 \end{cases}$$

$M^{(i)} \sim M_{NN}$ ⇨ $C_0^{(i)}$ in LO

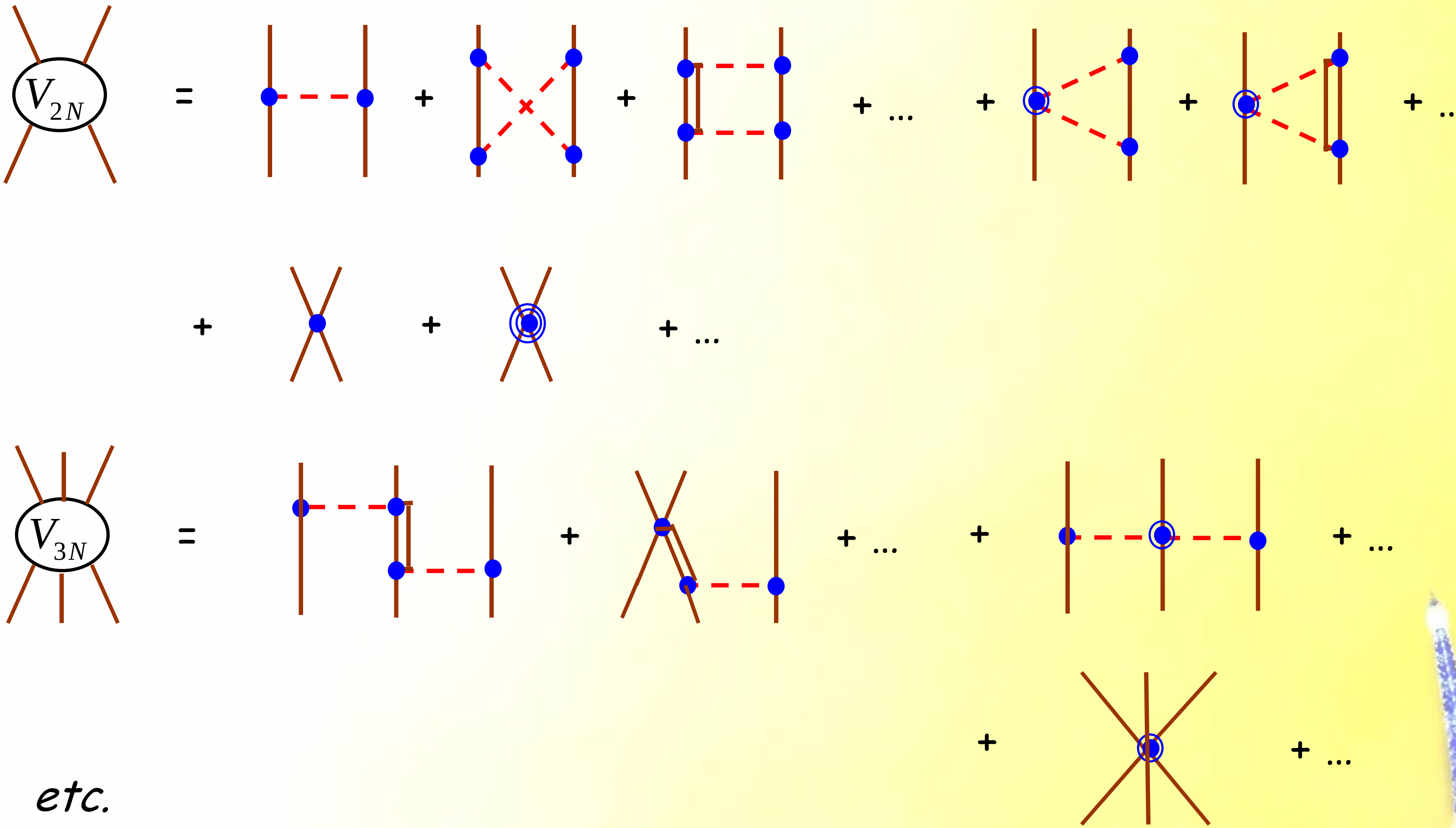


$$\sim \frac{4\pi}{m_N M_{NN}} \frac{Q^2}{M_{\rm QCD}^2}$$ ⇨ in NNLO

(NLO terms, linear in $Q/M_{\rm QCD}$, break *P*, *T*)

etc.

Ordóñez + v.K. '92
v.K. '94
...

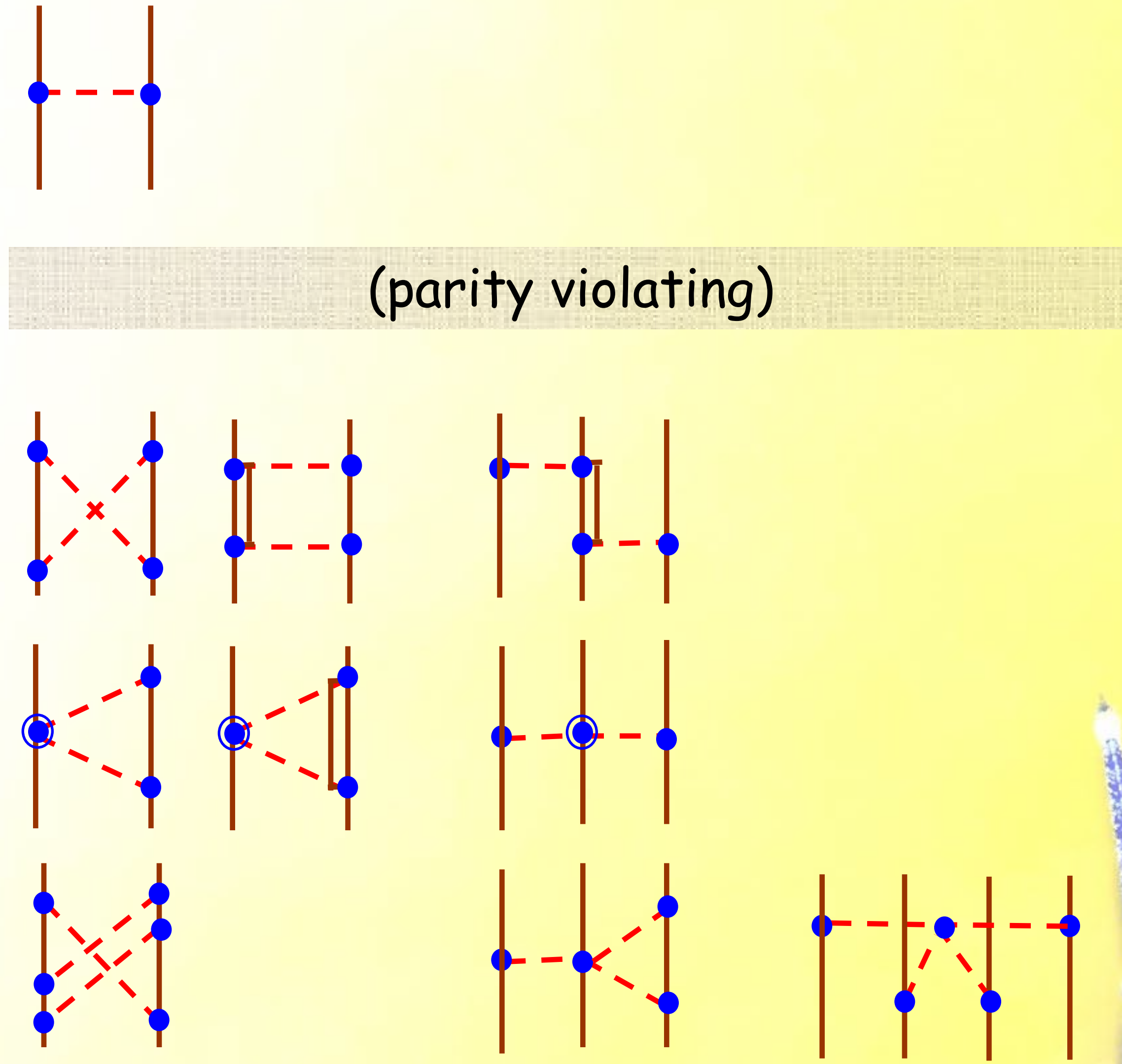


etc.

↓ more nucleons

→ higher powers of Q

		2-body	3-body	4-body	...
LO	$\mathcal{O}\left(\frac{1}{f_\pi^2}\right)$				
in German NLO	$\mathcal{O}\left(\frac{1}{f_\pi^2}\frac{Q}{M_{\mathrm{QCD}}}\right)$				
NNLO	$\mathcal{O}\left(\frac{1}{f_\pi^2}\frac{Q^2}{M_{\mathrm{QCD}}^2}\right)$				
NNNLO	$\mathcal{O}\left(\frac{1}{f_\pi^2}\frac{Q^3}{M_{\mathrm{QCD}}^3}\right)$				
NNNNLO	$\mathcal{O}\left(\frac{1}{f_\pi^2}\frac{Q^4}{M_{\mathrm{QCD}}^4}\right)$				
ETC.					



Hierarchies

many-body forces

$V_{2N} \gg V_{3N} \gg V_{4N} \gg \ldots$ A canon emerges! Weinberg '90, '91

isospin-breaking forces

Similar explanation for $\begin{cases} V_{\mathrm{IS}} \gg V_{\mathrm{IV}} \gg V_{\mathrm{CSB}} \\ J_{1N} \gg J_{2N} \gg J_{3N} \gg \ldots \end{cases}$

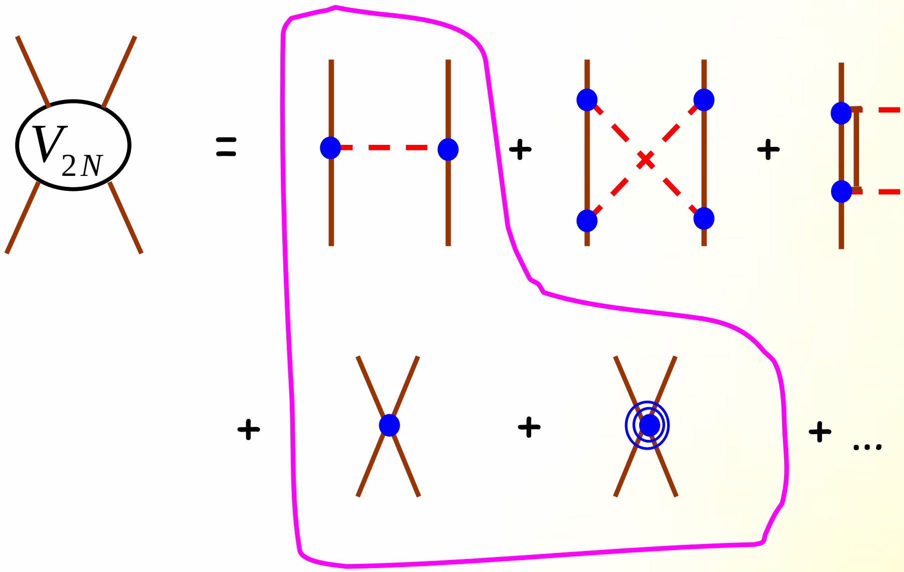
v.K. '93

Rho '92

external currents

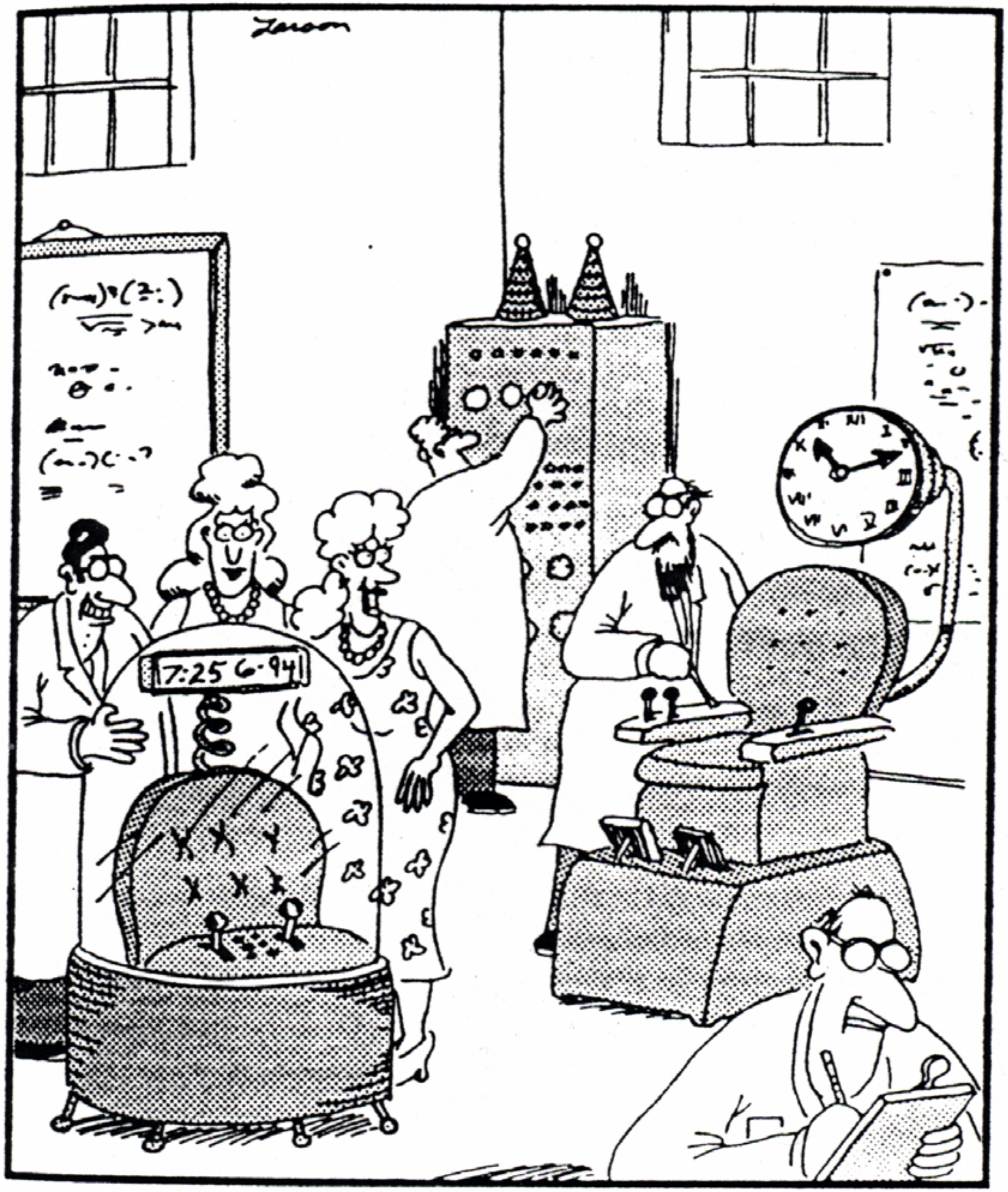
other canons emerge!

Ordóñez + v.K. '92
v.K. '94
...



similar to phenomenological
potential models,
e.g. AV18 – (OPE)^2 + non-local terms

Stoks, Wiringa + Pieper '94

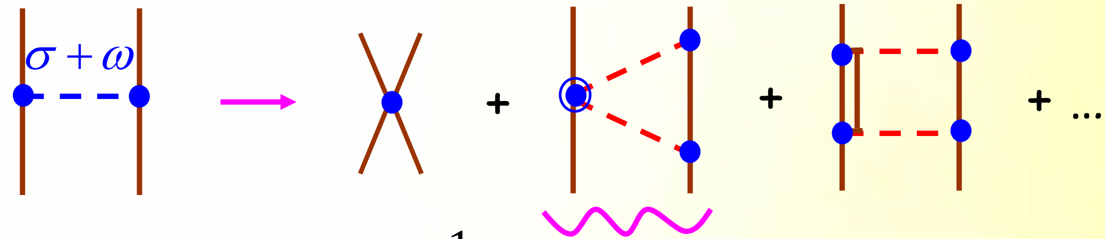


"Oh, Professor DeWitt! Have you seen Professor *Weinberg's* time machine? ... It's digital!"

But: NOT your usual potential!

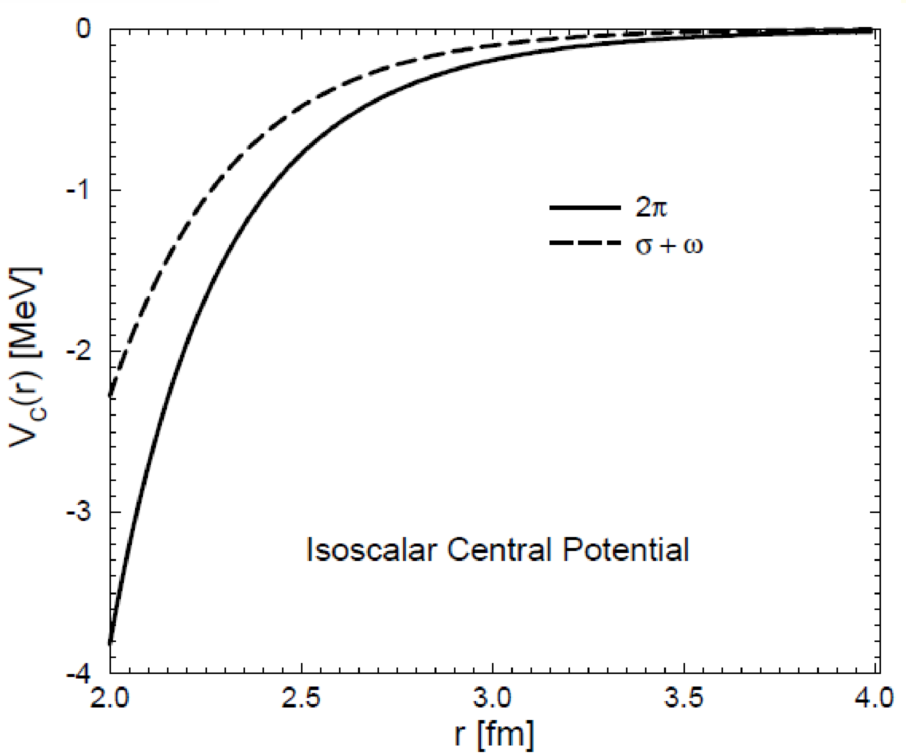
Ordóñez + v.K. '92
(*cf.* Stony Brook TPE)

e.g.,



chiral v.d. Waals force $\sim \frac{1}{r^6}$ for $m_\pi^2 \to 0$

Kaiser, Brockmann + Weise '97



Similar results in other channels, *e.g.* spin-orbit force!

Rentmeester et al. '01, '03

Nijmegen PSA of 1,951 *pp* data

long-range pot	# bc	χ^2_{min}
OPE	31	2026.2
OPE + TPE (*lo*)	28	1984.7
OPE + TPE (*nlo*)	23	1934.5
Nijm78	19	1968.7

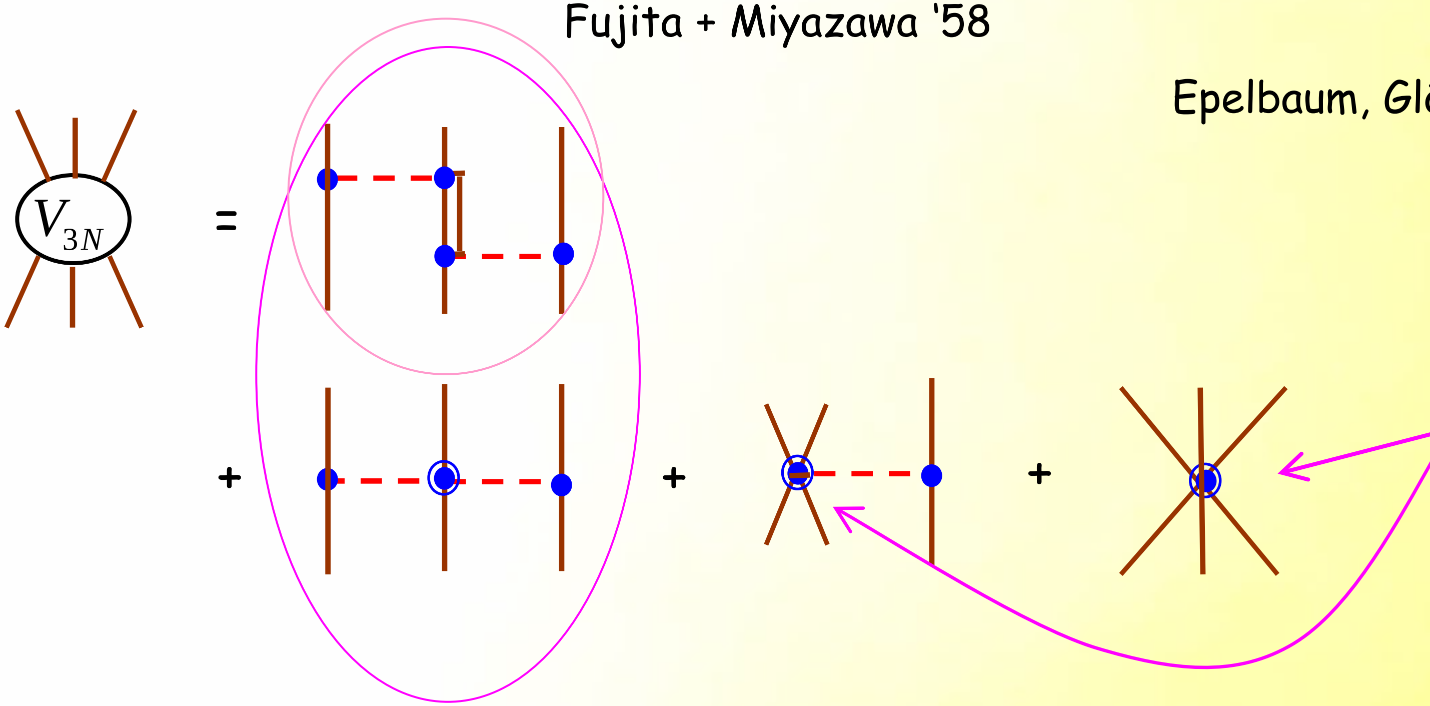
parameters found consistent with πN data!

at least as good!

models with σ, ω, ... might be misleading...

v.K. '94
Friar, Hüber + v.K. '99
Coon + Han '99
Epelbaum, Glöckle + Meißner '02
...

Fujita + Miyazawa '58



two unknown parameters

+ ...

Tucson-Melbourne pot with

Coon *et al.* '78

$$\begin{cases} a \to a - 2m_\pi^2 c \\ c \to 0 \end{cases}$$

TM' potential

$$\left(t_{\pi N}\left(\vec{q},\vec{q}\,'\right)\right)_{\alpha\beta} = \delta_{\alpha\beta}\left[a + b\vec{q}\cdot\vec{q}\,' + c\left(\vec{q}^{\,2} + \vec{q}\,'^{2}\right)\right] - d\varepsilon_{\alpha\beta\gamma}\tau_{3\gamma}\vec{\sigma}\cdot\vec{q}\times\vec{q}\,' + \ldots$$

Ordóñez, Ray + v.K. '96
…
Epelbaum, Glöckle + Meißner '02
Entem + Machleidt '03
…

Many successes of Weinberg's counting, *e.g.*,

- ✓ To NNNNLO (w/o deltas), fit to NN phase shifts comparable to those of "realistic" phenomenological potentials

Entem + Machleidt '03

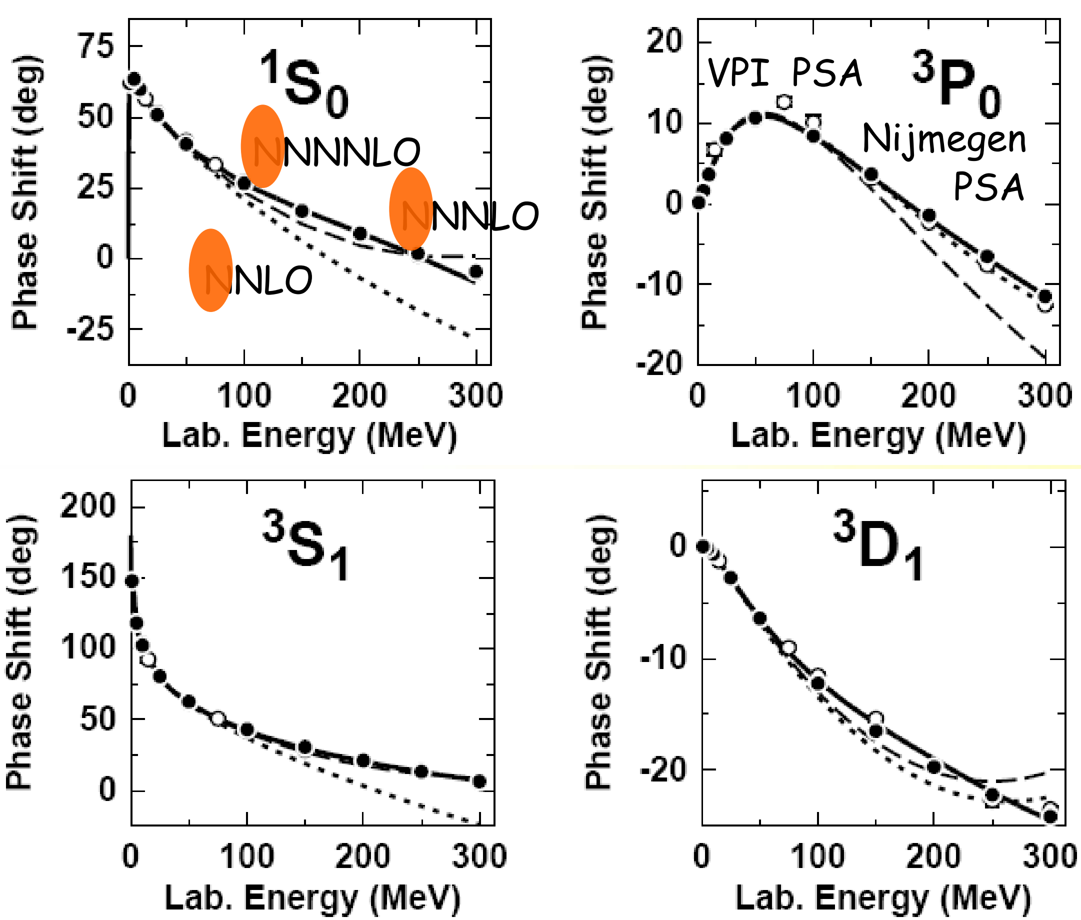


TABLE II. χ^2/datum for the reproduction of the 1999 *np* database [40] below 290 MeV by various *np* potentials.

Bin (MeV)	No. of data	N^3LO[a]	NNLO[b]	NLO[b]	AV18[c]
0–100	1058	1.06	1.71	5.20	0.95
100–190	501	1.08	12.9	49.3	1.10
190–290	843	1.15	19.2	68.3	1.11
0–290	2402	1.10	10.1	36.2	1.04

TABLE V. Two- and three-nucleon bound-state properties. (Deuteron binding energy B_d; asymptotic *S* state A_S; asymptotic *D*/*S* state η; deuteron radius r_d; quadrupole moment *Q*; *D*-state probability P_D; triton binding energy B_t.)

	N^3LO[a]	CD-Bonn [10]	AV18 [22]	Empirical[b]
Deuteron				
B_d(MeV)	2.224575	2.224575	2.224575	2.224575(9)
A_S($fm^{-1/2}$)	0.8843	0.8846	0.8850	0.8846(9)
η	0.0256	0.0256	0.0250	0.0256(4)
r_d(fm)	1.978[c]	1.970[c]	1.971[c]	1.97535(85)
Q(fm^2)	0.285[d]	0.280[d]	0.280[d]	0.2859(3)
P_D(%)	4.51	4.85	5.76	
Triton				
B_t(MeV)[e]	7.855	8.00	7.62	8.48

- ✓ With NNNNLO 2N and NNNLO 3N potentials (w/o deltas), good description of
- 3N observables and 4N binding energy
- levels of p-shell nuclei

Epelbaum *et al.* '02

Gueorguiev *et al.* '07

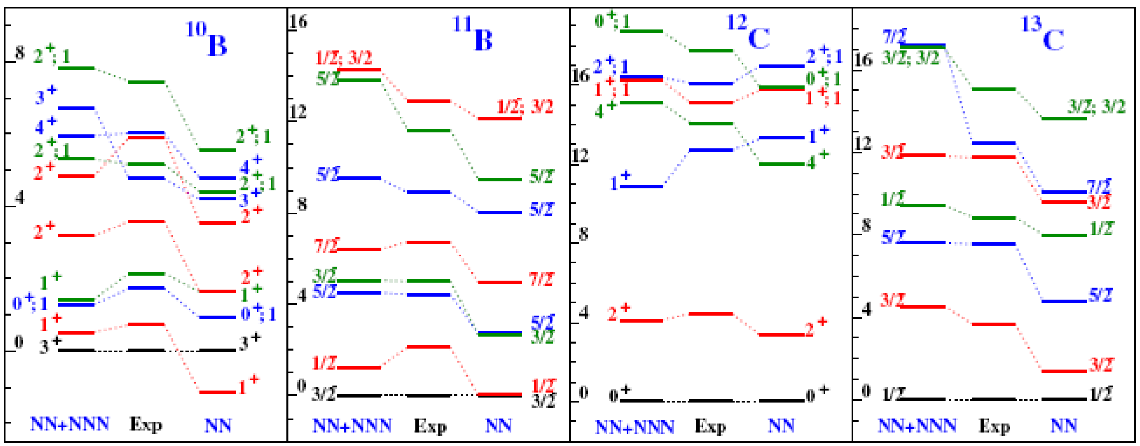


FIG. 4 (color online). States dominated by p-shell configurations for ^{10}B, ^{11}B, ^{12}C, and ^{13}C calculated at $N_{max} = 6$ using $\hbar\Omega = 15$ MeV (14 MeV for ^{10}B). Most of the eigenstates are isospin $T = 0$ or $1/2$, the isospin label is explicitly shown only for states with $T = 1$ or $3/2$. The excitation energy scales are in MeV.

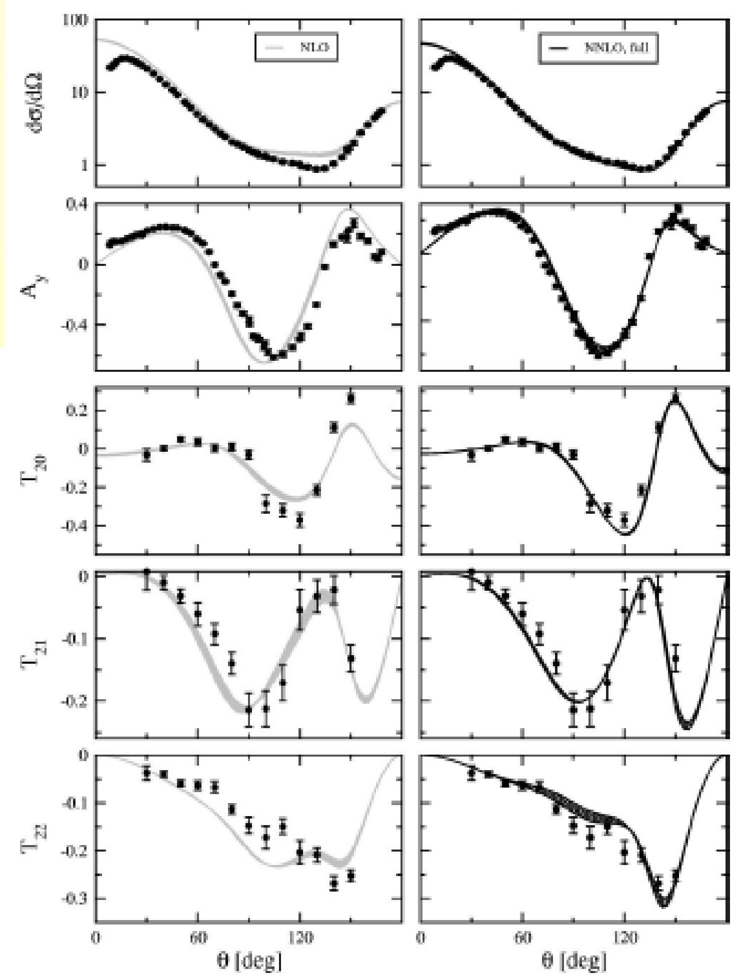


FIG. 6. *nd* elastic scattering observables at 65 MeV at NLO (left column) and NNLO (right column). The filled circles are *pd* data [63,69]. The bands correspond to the cutoff variation between 500 and 600 MeV. The unit of the cross section is mb/sr.

Many reactions

$\gamma d \to d\gamma$

measured: Illinois '94, SAL '00, Lund '03

extracted nucleon polarizabilities: Beane, Malheiro, McGovern, Phillips + v.K. '04

$\gamma d \to d\pi^0$

threshold amplitude <u>predicted</u>: Beane, Bernard, Lee, Meißner + v.K. '97

<u>confirmed</u>: SAL '98, Mainz '01

$pn \to d\pi^0$

CSB asymmetry sign <u>predicted</u>: Miller, Niskanen + v.K. '00

<u>confirmed</u>: TRIUMF '03

$dd \to \alpha\pi^0$

estimated: Gårdestig, Miller + v.K.

<u>discovered</u>: IUCF '03

+ many more, including **PARITY, TIME-REVERSAL VIOLATION**, *etc.*

Example: T violation

Q ↑

$M_{\not{T}} \sim ?$

unknown physics

single Higgs: $\varphi_u^i = \varepsilon^{ij}\varphi_{dj}^*$

$M_{\mathrm{SM}} \sim \langle\varphi\rangle, M_{Z,W}$
$\sim 100\ \mathrm{GeV}$

$$\mathcal{L}_{\mathrm{SM}} = \ldots - \frac{1}{M_{\not{T}}^2}\bar{q}_L\sigma^{\mu\nu}\tilde{G}_{\mu\nu}\left(\hat{g}_u\varphi_u u_R + \hat{g}_d\varphi_d d_R\right) + \ldots$$

$\hat{g}_{u,d} = \mathcal{O}(1)$

$M_{\mathrm{QCD}} \sim m_N, m_\rho, 4\pi f_\pi, \ldots$
$\sim 1\ \mathrm{GeV}$

$$\mathcal{L}_{\mathrm{QCD}} = \ldots - \frac{1}{2}\bar{q}\left(c_q^{(0)} + c_q^{(1)}\tau_3\right)\sigma_{\mu\nu}\tilde{G}^{\mu\nu}q + \ldots$$

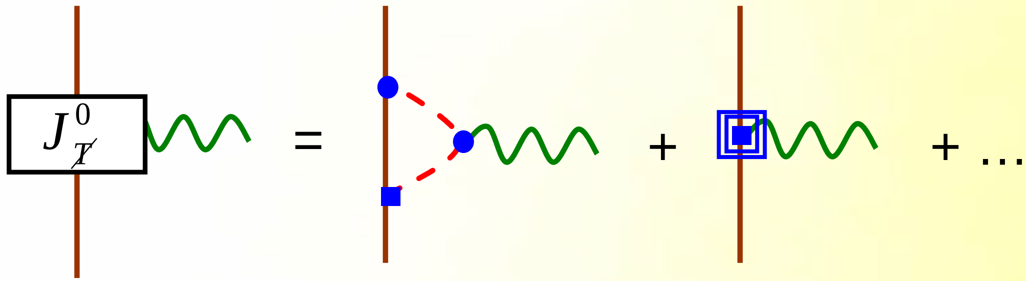
quark color-EDM $\quad c_q^{(i)} = \mathcal{O}\left(\frac{\hat{g}}{f}\frac{\bar{m}}{M_{\not{T}}^2}\right)$

$M_{\mathrm{nuc}} \sim f_\pi, 1/r_{NN}, m_\pi, \ldots$
$\sim 100\ \mathrm{MeV}$

$$\mathcal{L}_{\chi\mathrm{EFT}} = -\frac{1}{2f_\pi}\bar{N}\left[\bar{g}_0\boldsymbol{\tau}\cdot\boldsymbol{\pi} + \bar{g}_1\pi_3\right]N + \ldots$$

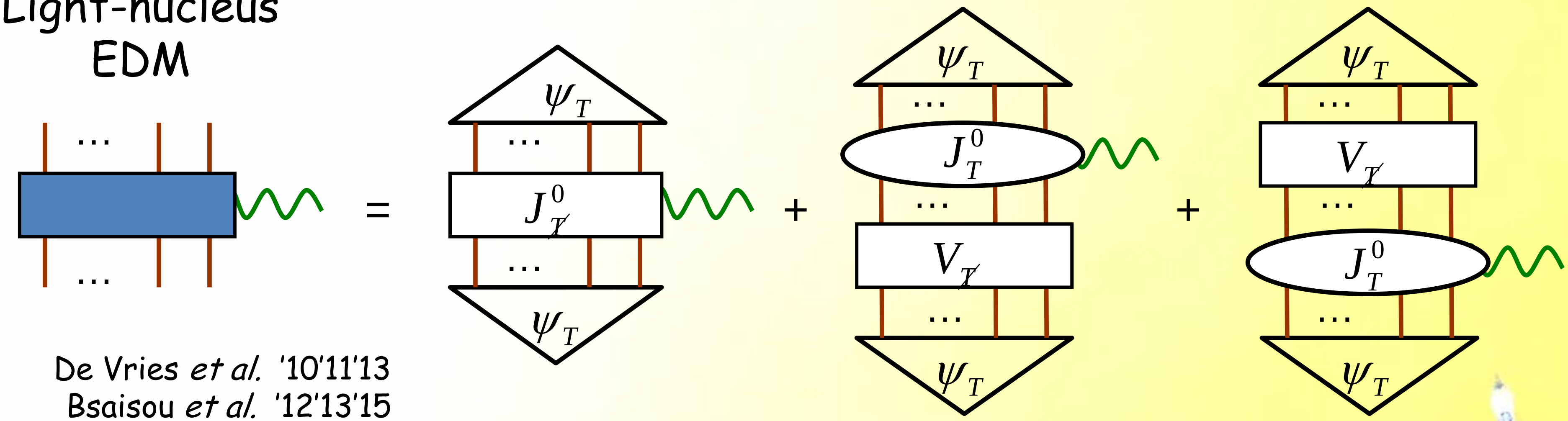
$$\bar{g}_{0,1} = \mathcal{O}\left(\frac{\hat{g}}{f}\frac{m_\pi^2 M_{QCD}}{M_{\not{T}}^2}\right)$$

Nucleon EDM



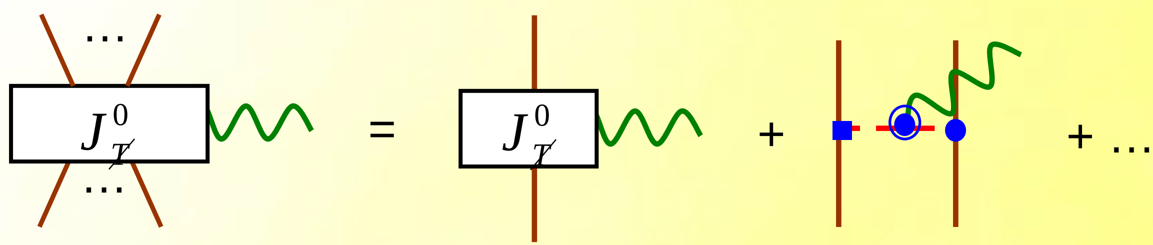
Crewther *et al.* '79
...
Hockings + v.K. 05
Narison '08
Ottnad *et al.* '10
De Vries *et al.* '11

Light-nucleus EDM

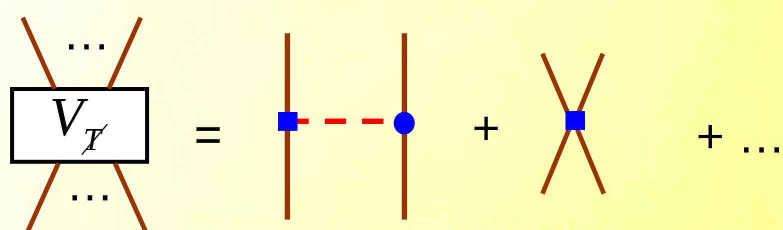


De Vries *et al.* '10'11'13
Bsaisou *et al.* '12'13'15
Dekens *et al.* '14

De Vries *et al.* '11



Maekawa *et al.* '11



$$\mathcal{L}_{\rm QCD} = \ldots + \frac{\bar{m}}{2}\left(1-\varepsilon^2\right)\bar{\theta}\ \bar{q}i\gamma_5 q - \frac{1}{2}\bar{q}\left(c_q^{(0)}+c_q^{(1)}\tau_3\right)\sigma_{\mu\nu}\tilde{G}^{\mu\nu}q - \frac{1}{2}\bar{q}\left(d_q^{(0)}+d_q^{(1)}\tau_3\right)\sigma_{\mu\nu}q\ \tilde{F}^{\mu\nu}$$

$$+\frac{c_G}{6} f^{abc} G^a_{\mu\nu}\tilde{G}^{b\nu\rho}G^{c\mu}_{\rho} + \frac{C_1}{4}\left(\bar{q}q\ \bar{q}i\gamma_5 q - \bar{q}\boldsymbol{\tau}q\cdot\bar{q}i\gamma_5\boldsymbol{\tau}q\right) + \frac{C_8}{4}\left(\bar{q}\lambda^a q\ \bar{q}i\gamma_5\lambda^a q - \bar{q}\boldsymbol{\tau}\lambda^a q\cdot\bar{q}i\gamma_5\boldsymbol{\tau}\lambda^a q\right)$$

$$+\frac{D_1}{4}\varepsilon_{3ij}\ \bar{q}\tau_i\gamma^\mu q\ \bar{q}\tau_j\gamma_\mu\gamma_5 q + \frac{D_8}{4}\varepsilon_{3ij}\ \bar{q}\tau_i\gamma^\mu\lambda^a q\ \bar{q}\tau_j\gamma_\mu\gamma_5\lambda^a q + \ldots$$

De Vries *et al.* '10'11'13
Bsaisou *et al.* '12'13'15
Dekens *et al.* '14

Neutron EDM d_n can be produced by any source, but
different chiral properties of sources → different magnitudes for nuclear EDMs

		θ term	qCEDM	qEDM	gCEDM, PS4QO	LR4QO
^{1}H	d_p/d_n	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
^{2}H	d_d/d_n	$\mathcal{O}(1)$	$\mathcal{O}\left(M^2_{\rm QCD}/m^2_\pi\right)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}\left(M^2_{\rm QCD}/m^2_\pi\right)$
^{3}He	d_h/d_n	$\mathcal{O}\left(M^2_{\rm QCD}/m^2_\pi\right)$	$\mathcal{O}\left(M^2_{\rm QCD}/m^2_\pi\right)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}\left(M^2_{\rm QCD}/m^2_\pi\right)$
^{3}H	d_t/d_h	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$

+ specific relations

Farley *et al.* '04
…

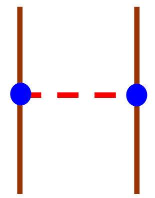
storage-ring measurements (CERN?) could teach us about sources!

Chiral EFT has been recognized as
the basis for nuclear physics.
Now it is the favorite input for
the blossoming "*ab initio*" methods
that are revolutionizing
nuclear structure/reaction physics.

BUT

Is Weinberg's power counting consistent?

No!



$$\sim \left(\frac{g_A}{2 f_\pi}\right)^2 \frac{m_\pi^3}{4\pi} \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \left\{ \frac{S_{12}(\hat{r})}{(m_\pi r)^3} + \ldots \right\} e^{-m_\pi r}$$

attractive in some channels

singular potential

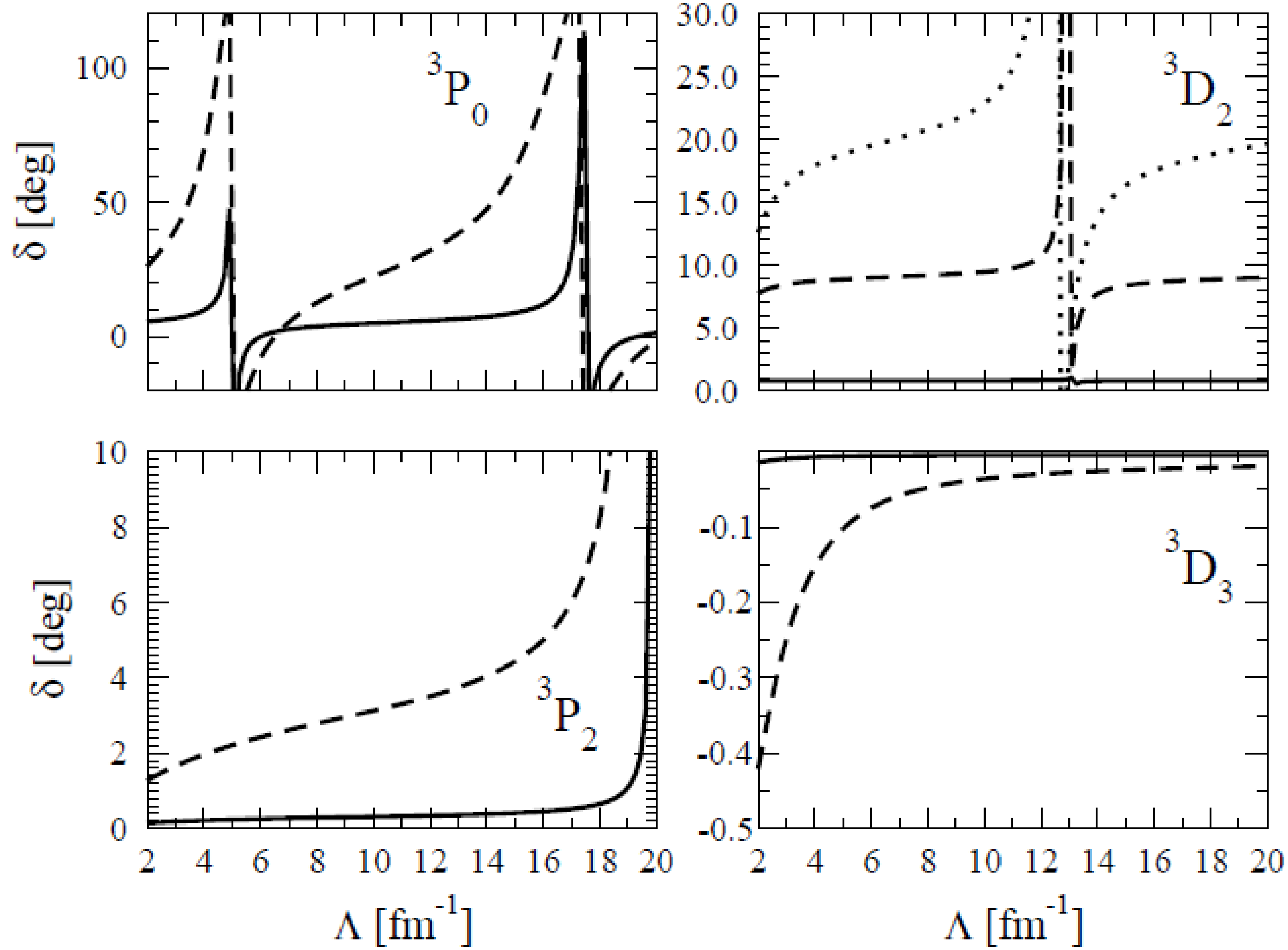
not enough contact interactions

for renormalization-group invariance even at LO

Nogga, Timmermans + v.K. '05
Pavón Valderrama + Ruiz-Arriola '06

Problems!

Attractive-tensor channels:



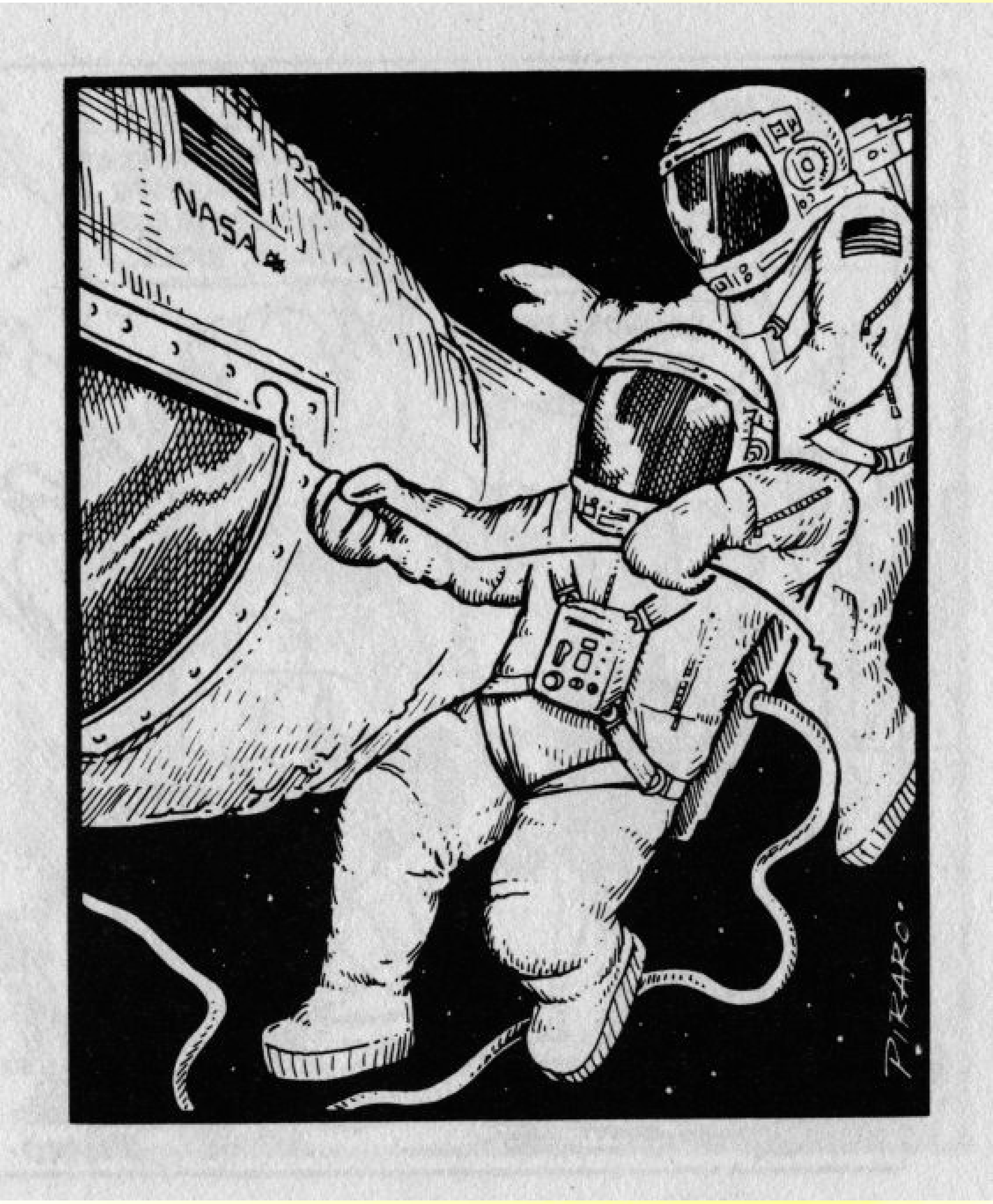
E (MeV)

10 ——

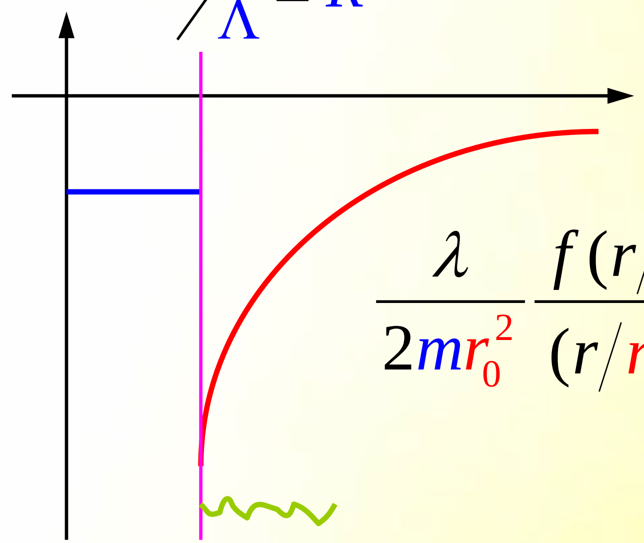
50 - - -

100 ....

incorrect renormalization...


NASA

Renormalization of the $-1/r^n$ potential



$$C_0(\Lambda)\,\delta^{(3)}_{\Lambda}(\vec{r})$$

$$\rightarrow V_0(R)\,\theta\left(1-\frac{r}{R}\right)$$

$$\frac{\lambda}{2mr_0^2}\,\frac{f(r/r_0)}{(r/r_0)^n}$$

OPE:

$$\begin{cases} m = m_N/2 \\ r_0 = 1/m_\pi \\ \lambda = m_\pi/M_{NN} \\ f(r/r_0) = \exp(-r/r_0) \end{cases}$$

s wave

$$\psi_n\left(r \sim R \ll r_0\right) \equiv \frac{u_n(r)}{r}$$

matching

$$\sqrt{-2mR^2V_0}\,\cot\sqrt{-2mR^2V_0} = F_n\left(\lambda, r_0, R\right)$$

so that

$$\frac{R}{T_s}\frac{\partial T_s}{\partial R}\left(k \sim 1/r_0\right) = \mathcal{O}\left(\frac{R}{r_0}\right)$$

$n \geq 2$

Beane, Bedaque, Childress, Kryjevski, McGuire + v.K. '02

Two **regular** solutions that oscillate!

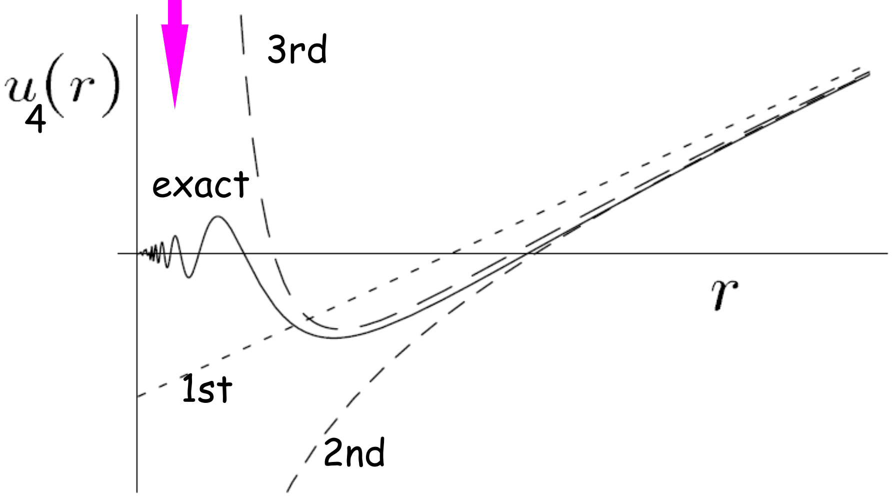
if no counterterm, will depend on cutoff R

➡ model dependence

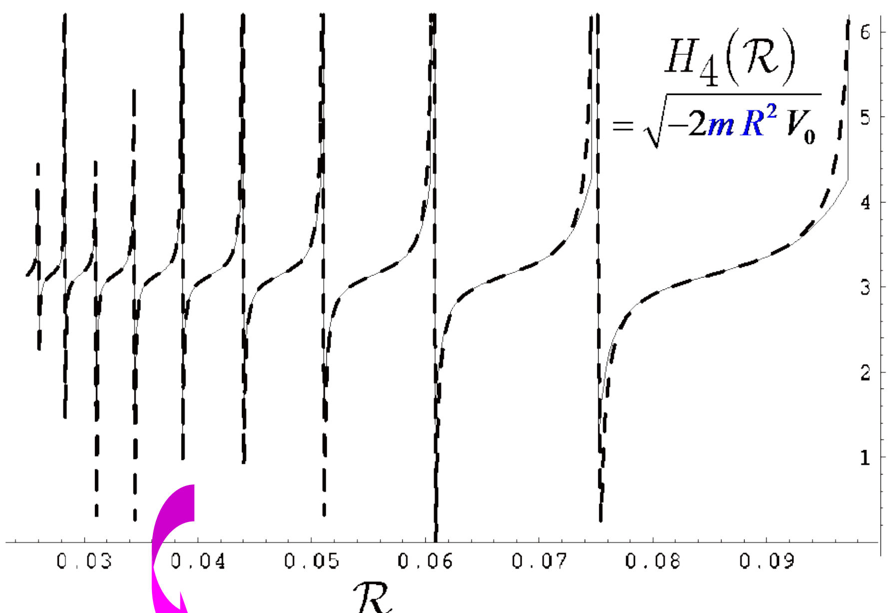
$$u_n(r \ll r_0) = \left(\frac{\lambda}{(r/r_0)^n}\right)^{-\frac{1}{4}} \cos\left(\frac{\sqrt{\lambda}}{(n/2-1)(r/r_0)^{n/2-1}} + \delta_n\right) + \ldots$$

determined by low-energy data

$$F_n(\lambda, r_0, R) = \frac{n}{4} - \sqrt{\lambda}\left(\frac{R}{r_0}\right)^{1-n/2} \tan\left(\frac{\sqrt{\lambda}}{(n/2-1)(R/r_0)^{n/2-1}} + \delta_n\right) + \ldots$$

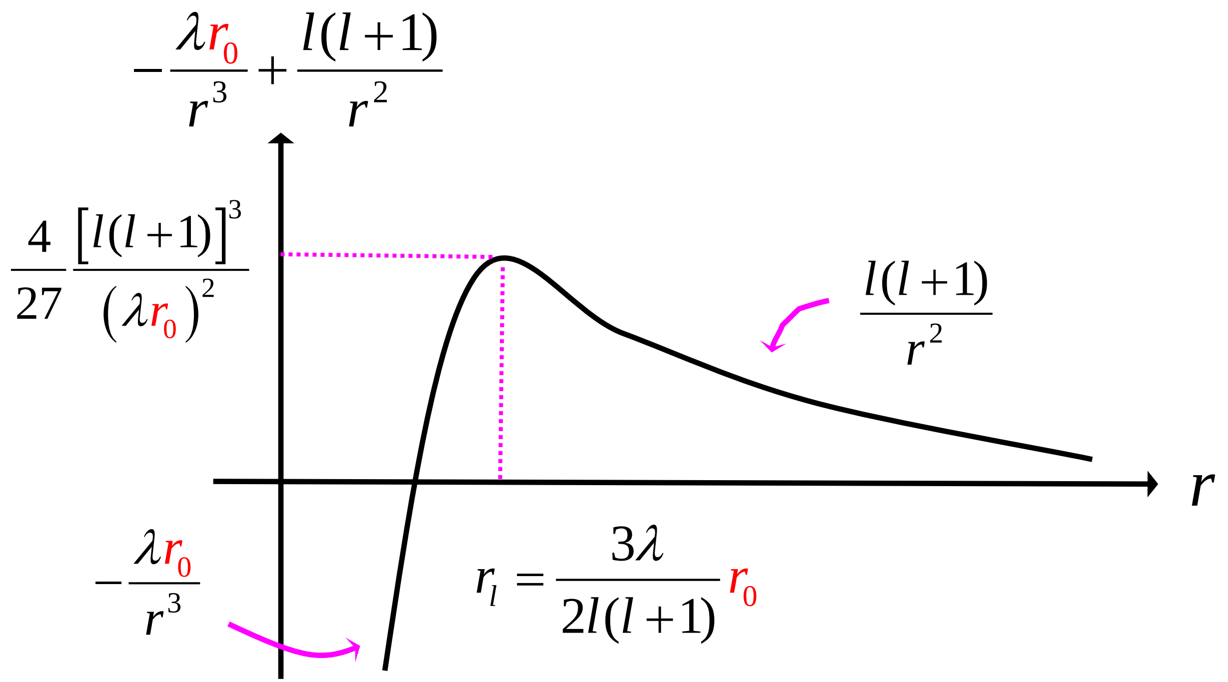


exact vs perturbation th



limit-cycle-like behavior

Same is true in all channels where attractive singular potential is iterated

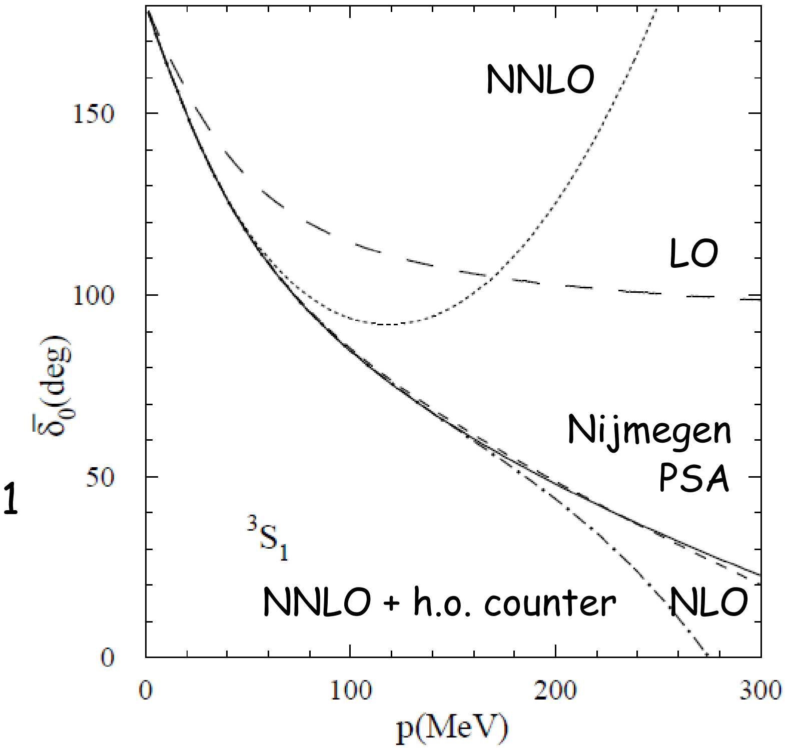


but $r_l \sim \frac{1}{M} \ll r_0$ for $l(l+1) \gg \lambda$

⇒ singular potential only needs to be iterated in a few waves, where counterterms are needed

"Perturbative pions" $\lambda = \frac{m_\pi}{M_{NN}} \ll 1$

Kaplan, Savage + Wise '98



Fleming, Mehen + Stewart '01

➡ $M_{NN} \sim f_\pi$ indeed

Partly perturbative pions

$$l(l+1) \gtrsim \frac{3M_{\mathrm{QCD}}}{2M_{NN}} \sim 5 \quad ➡ \quad l \gtrsim 2$$

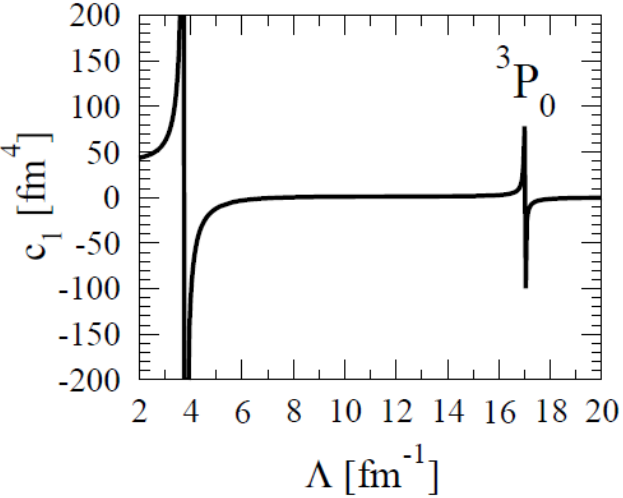
Beane, Bedaque, Savage + v.K. '02
Nogga, Timmermans + v.K. '05
Pavón Valderrama + Ruiz-Arriola '06
Birse, '06'07
Long + v.K. '07
Pavón Valderrama '10'11
Long + Yang '11'12
...

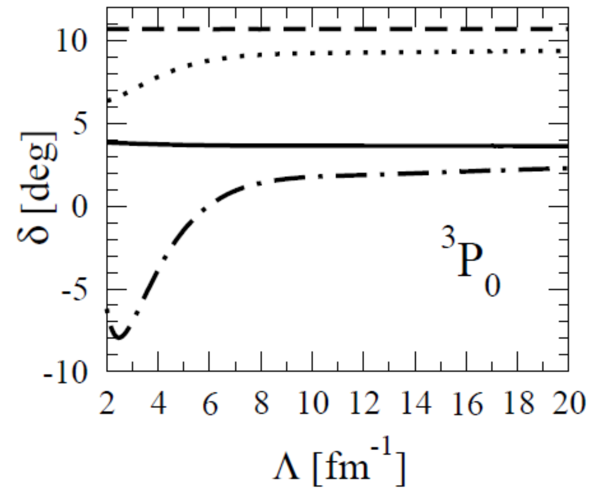
+ subleading orders: in perturbation theory, as in NRQED

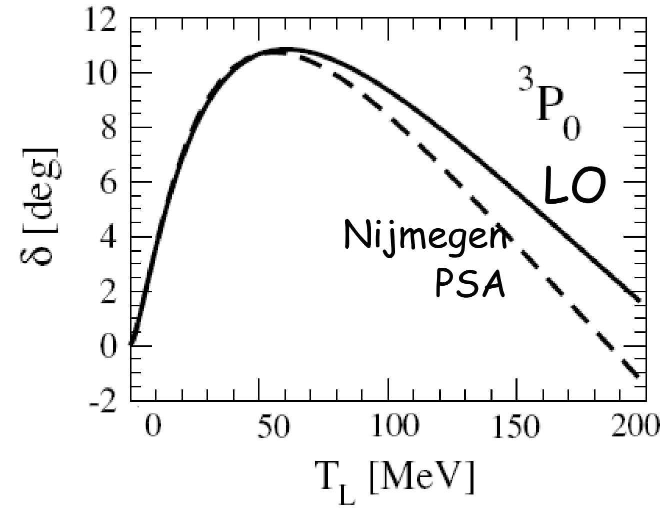
Nogga, Timmermans + v.K. '05
(cf. Pavón Valderrama + Ruiz-Arriola, '06)

Add counterterms

$$V_{l=1,j=0} = \frac{c_1}{(2\pi)^3}\, pp'$$



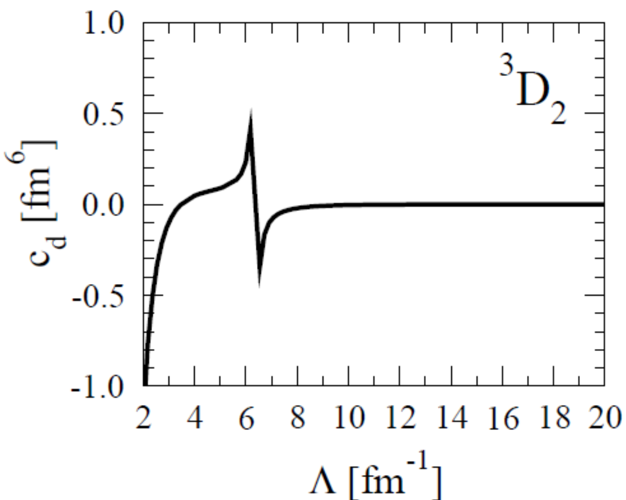


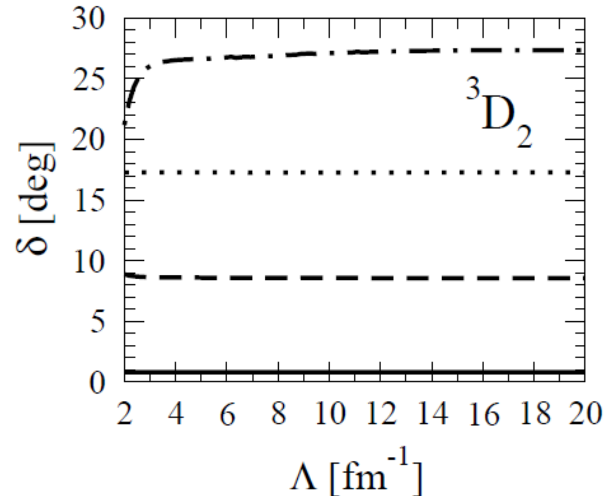


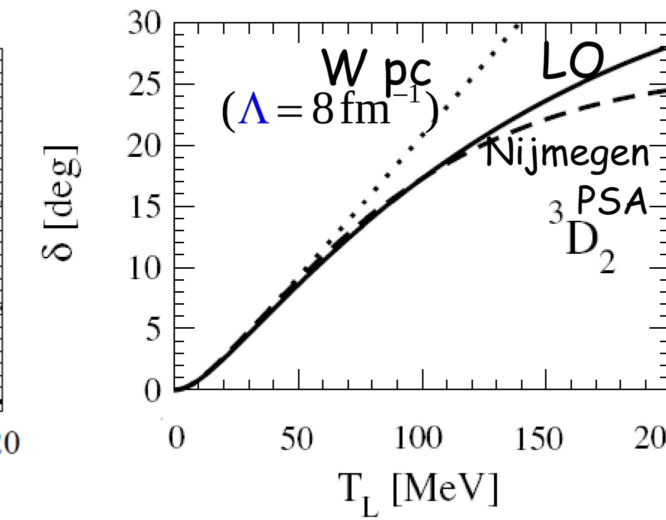
E (MeV)

10	solid
50	dashed
100	dotted
190	dash-dot

$$V_{l=2,j=2} = \frac{c_d}{(2\pi)^3}\, p^2 p'^2$$







certain counterterms that in Weinberg's counting

were assumed suppressed by powers of $\frac{Q}{M_{\rm QCD}}$

are in fact suppressed by powers of $\frac{Q}{l f_{\pi}}$

$\Downarrow$

short-range physics more important than assumed by Weinberg's;

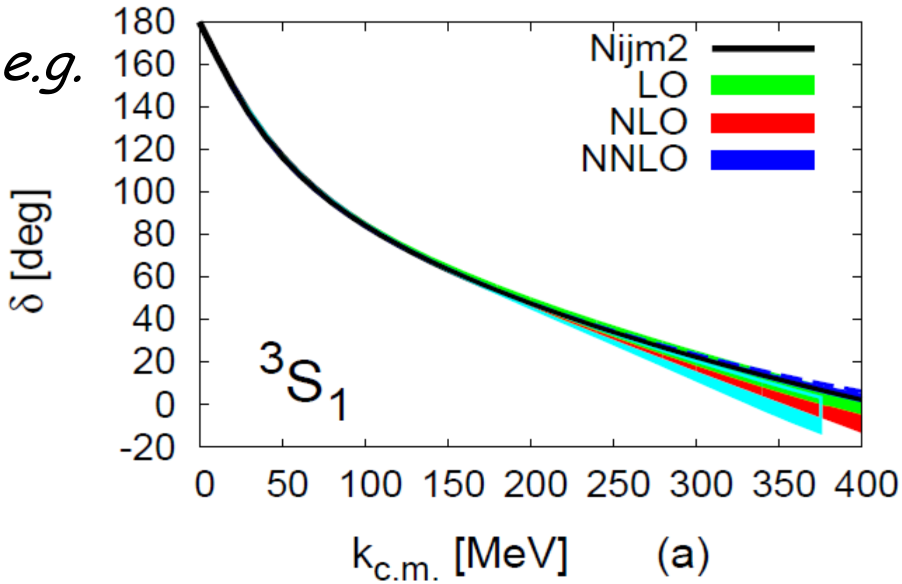
most qualitative conclusions unchanged,

but quantitative results need improvement

ACTIVE RESEARCH AREA

new PC

e.g.

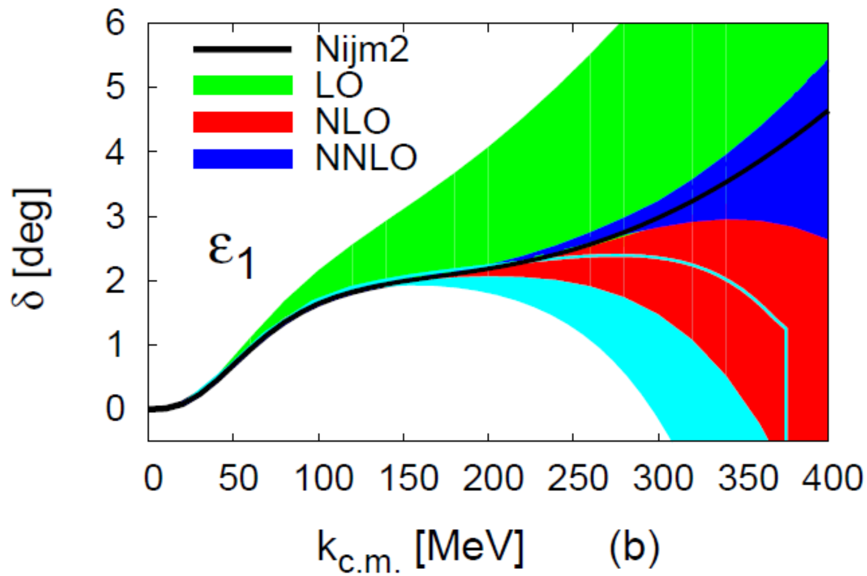


Fits to data

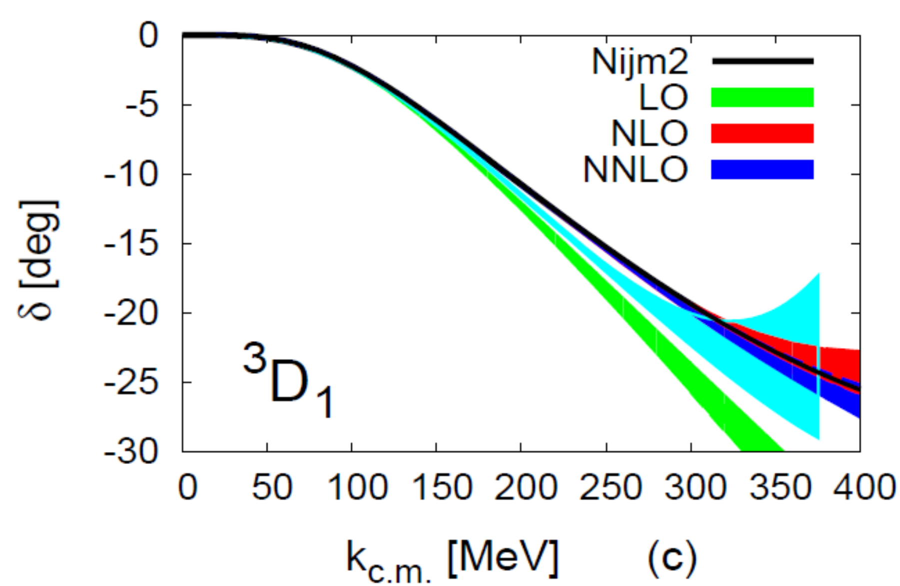
Pavón Valderrama '10'11
Long + Yang '11'12

bands (not error estimates):
coordinate-space cutoff variation
0.6 – 0.9 fm

cyan:
NNLO in Weinberg's scheme



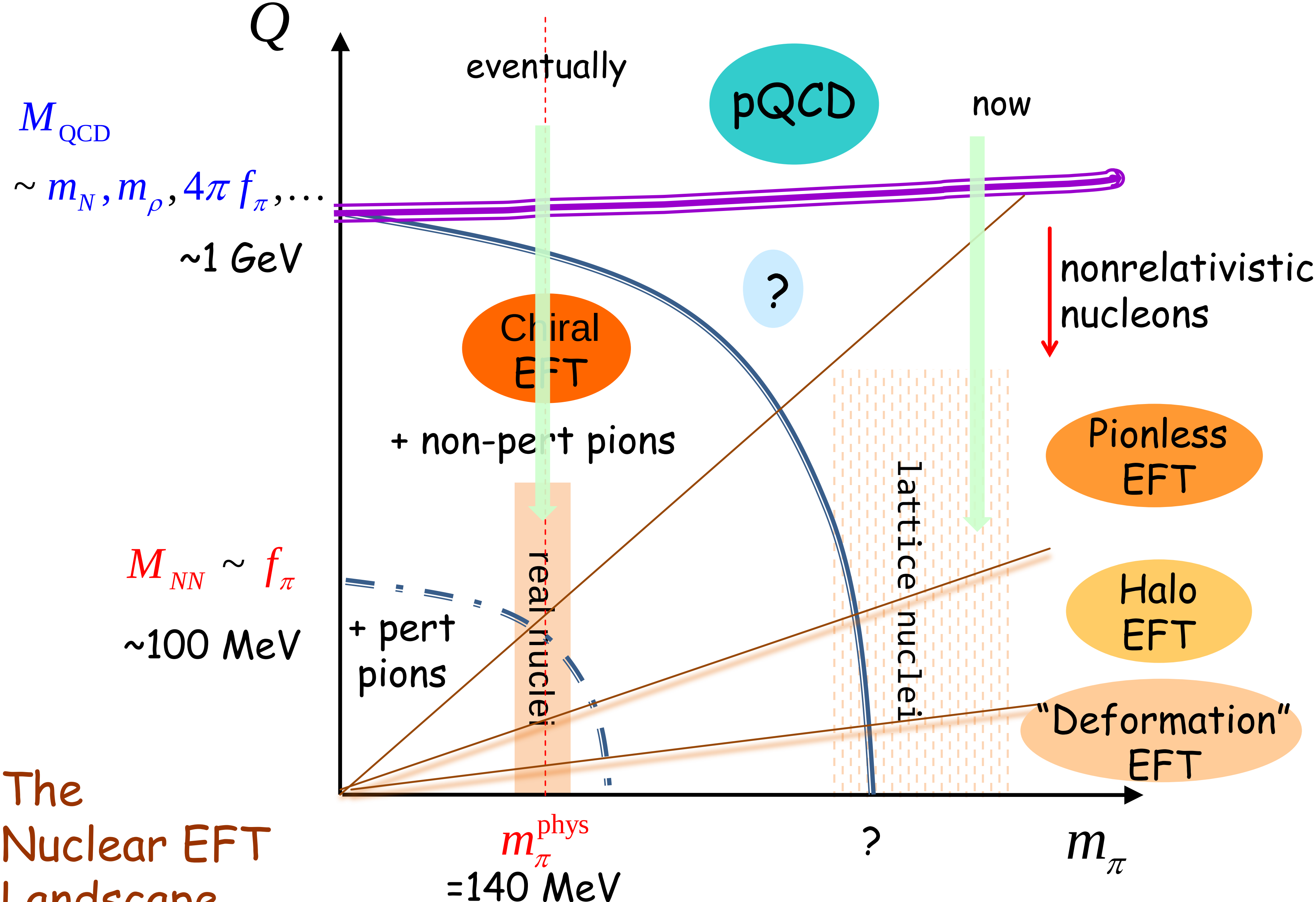
Pavon Valderrama '10



Summary

- A low-energy EFT of QCD has been constructed and used to describe nuclear systems
- Chiral symmetry plays an important role, in particular setting the scale for nuclear bound states
- Nuclear physics canons emerge from chiral potential
- A new power counting has been formulated: more counterterms at each order relative to Weinberg's; expect even better description of observables

Outlook



The Nuclear EFT Landscape

Conclusion

EFT is a general framework for theory construction

- ✓ same method across scales
- ✓ model independent
- ✓ controlled expansion

EFT is (very slowly) becoming the paradigm in nuclear physics

- ✓ encodes QCD (and, more generally, B/SM)
- ✓ incorporates hadronic physics
- ✓ generates nuclear structure

The nuclear EFT frontier: many bodies & lattice QCD

- ❑ interplay with *ab initio* methods
- ❑ new EFTs