

TOWER OF NUCLEAR EFFECTIVE \leftarrow FIELD \rightarrow THEORIES: STATUS AND PERSPECTIVES

U. van Kolck

*Institut de Physique Nucléaire d'Orsay
and
University of Arizona*



Outline

- Effective Field Theories
- Nuclear EFTs
- Chiral EFT
- Pionless EFT
- Halo/Cluster EFT
- Summary



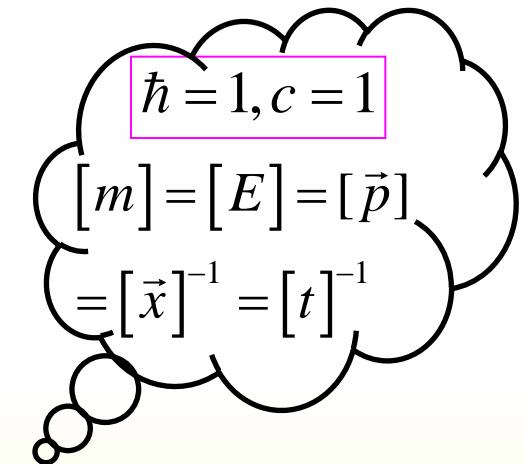
Modern S-Matrix Theory

-- S. Weinberg

Heisenberg's program:
only observable quantities
(S -matrix elements) matter

experiments only probe finite momenta $Q < M$

i.e. only distances $1/Q > 1/M$



EFFECTIVE FIELD THEORY

c

Weinberg '79

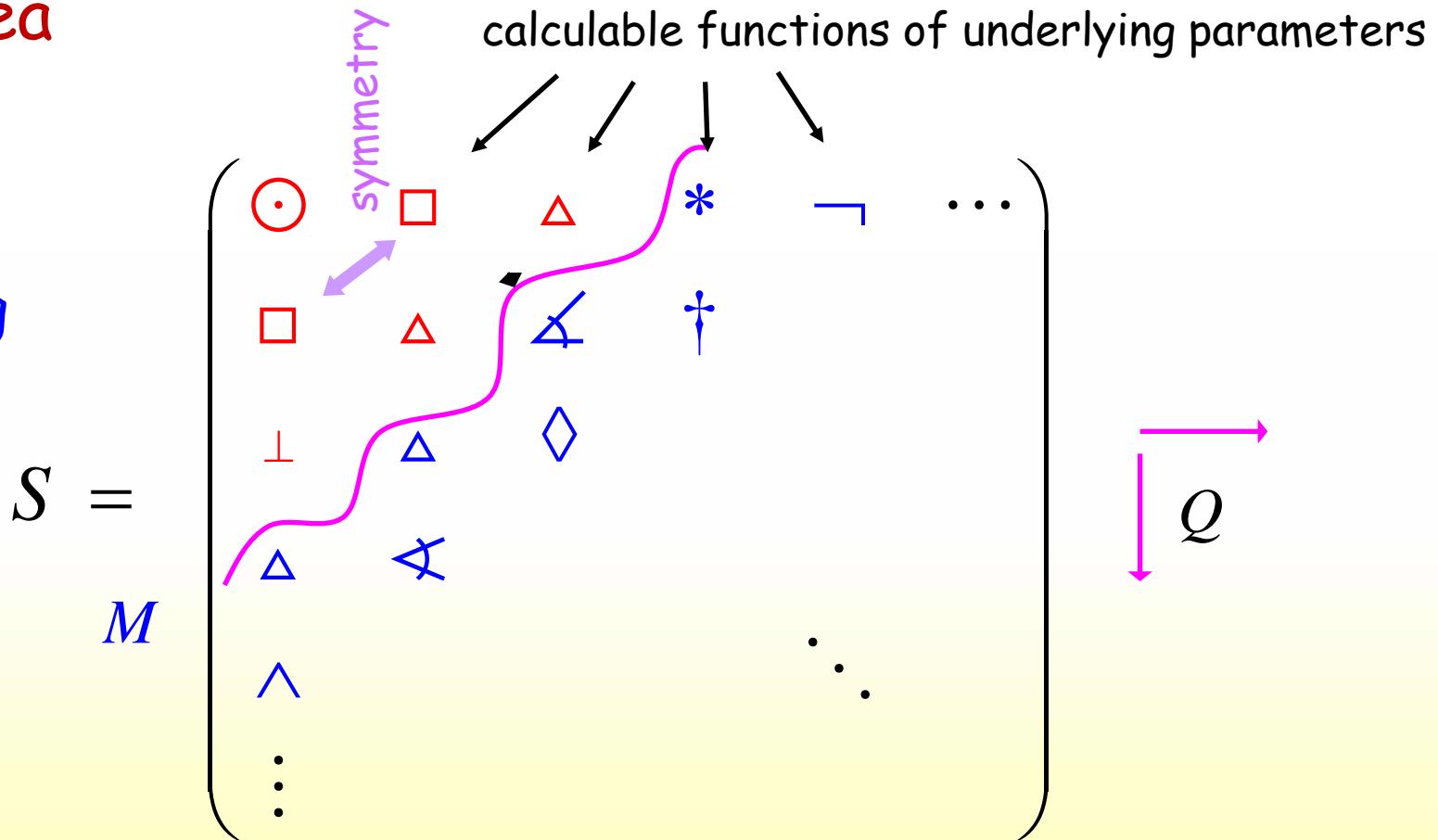
...

an algorithm to produce
the most general S -matrix consistent with symmetries

cf. Wilson '70s

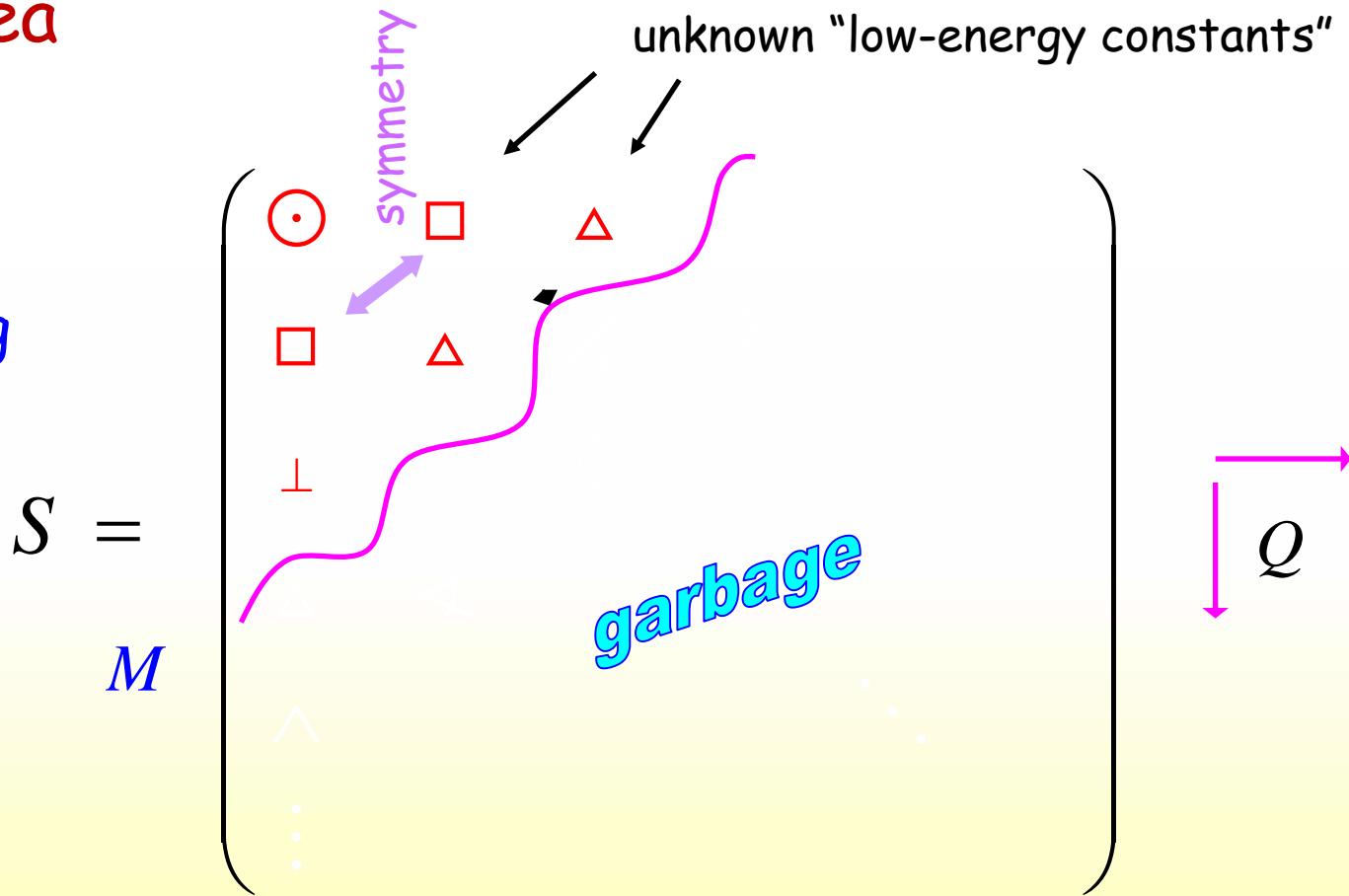
Basic idea

underlying
theory



Basic idea

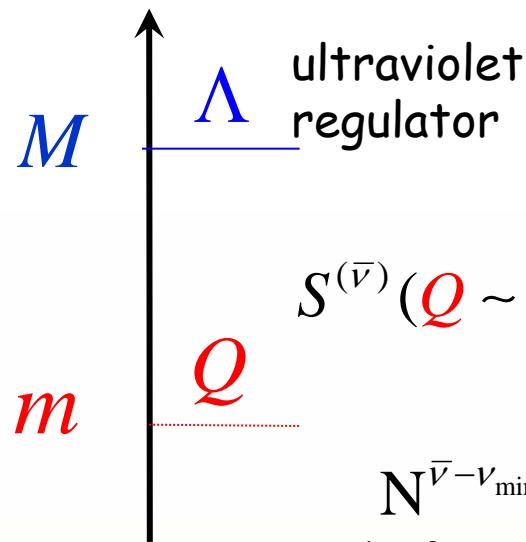
EFT
of
underlying
theory



from the most general Hamiltonian
with the same symmetries as underlying theory
using the rules of quantum field theory

non-analytic functions,
from solution of
dynamical equation
(e.g. Lippmann-
Schwinger)

mass scales



$N^{\bar{v}-\nu_{\min}}$ LO
(unfortunately
not the usage by
nuclear potential modelers)

order
expansion parameter

normalization

$$S^{(\bar{v})}(Q \sim m \ll M) = 1 + \overbrace{\mathcal{N}(M)}^{\text{normalization}} \sum_{v=v_{\min}}^{\bar{v}} \left[\frac{Q}{M} \right]^v F_v \left(\frac{Q}{m}, \frac{Q}{\Lambda}; \gamma_i \left(\frac{m}{\Lambda} \right) \right)$$

$\times \left\{ 1 + \mathcal{O} \left(\frac{Q^{\bar{v}+1}}{M^{\bar{v}+1}}, \frac{Q^{\bar{v}+1}}{M^{\bar{v}} \Lambda} \right) \right\}$

CONTROLLED UNCERTAINTY

"low-energy constants"

renormalization-group invariance

$$\frac{\Lambda}{S^{(\bar{v})}} \frac{\partial S^{(\bar{v})}}{\partial \Lambda} = \mathcal{O} \left(\frac{Q^{\bar{v}+1}}{M^{\bar{v}} \Lambda} \right)$$

MODEL INDEPENDENCE
(insensitivity to high-mom details)

For more, better,
see Grießhammer

N.B. Want large "model space" to reduce cutoff errors $\Lambda \gtrsim M$
but no need for (possibly ill-defined) $\Lambda \rightarrow \infty$

"Folk theorem"

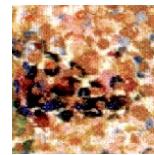
The quantum field theory generated by the most general Lagrangian with some assumed symmetries will produce the most general S matrix incorporating quantum mechanics, Lorentz invariance, unitarity, cluster decomposition and those symmetries, with no further physical content.

S. Weinberg '79

(could be disproven in the future ...
... but not yet)

The algorithm

1. identify degrees of freedom and symmetries



The algorithm

1. identify degrees of freedom and symmetries

$$\varphi: \Delta x \sim \frac{1}{Q} > \frac{1}{M}$$

2. construct most general Lagrangian

$$\mathcal{L}_{EFT} = \sum_{d,n=0}^{\infty} \sum_{i(d,n)} c_i(\mathbf{m}, \mathbf{M}, \Lambda) O_i(\partial^d \varphi^n)$$

bare LECs: local operators:
details of the underlying dynamics symmetries

3. make a guess for the sizes of the LECs and do power counting

"weak"
naturalness

After scales identified,
dimensionless parameters are $\mathcal{O}(1)$

't Hooft '79

Occam's razor

"strong"
naturalness

$$c_i(\mathbf{m}, \mathbf{M}, \Lambda) \sim c_i(\mathbf{m}, \mathbf{M}, \mathbf{M})$$

if, not "fine-tuning"

The algorithm

1. identify degrees of freedom and symmetries

$$\varphi: \Delta x \sim \frac{1}{Q} > \frac{1}{M}$$

2. construct most general Lagrangian

$$\mathcal{L}_{EFT} = \sum_{d,n=0}^{\infty} \sum_{i(d,n)} c_i(\mathbf{m}, \mathbf{M}, \Lambda) O_i(\partial^d \varphi^n)$$

bare LECs: local operators:
details of the underlying dynamics symmetries

3. make a guess for the sizes of the LECs and do power counting

$$v = v(d, n, \dots)$$

→ $c_i(\mathbf{m}, \mathbf{M}, \Lambda) = c_i\left(\gamma_i\left(\frac{\mathbf{m}}{\Lambda}\right), \mathbf{M}, \Lambda\right)$

e.g. # loops in a
Feynman diagram

4. calculate observables to $N^{\bar{\nu}-\nu_{\min}} \text{LO}$, $\bar{\nu} - \nu_{\min} = 0$

$$\sum_{\nu=\nu_{\min}}^{\bar{\nu}} \left[\frac{Q}{M} \right]^{\nu} F_{\nu} \left(\frac{Q}{m}, \frac{Q}{\Lambda}; \gamma_i \left(\frac{m}{\Lambda} \right) \right)$$

5. select a few observables to be reproduced at any Λ

see Franklin

from underlying theory
("matching") or experiment

$$\gamma_i \left(\frac{m}{\Lambda} \right) = \bar{\gamma}_i$$

6. check if other observables depend on negative powers of Λ
if no, go back to step 3 or, if that fails, 1 (you learned something)

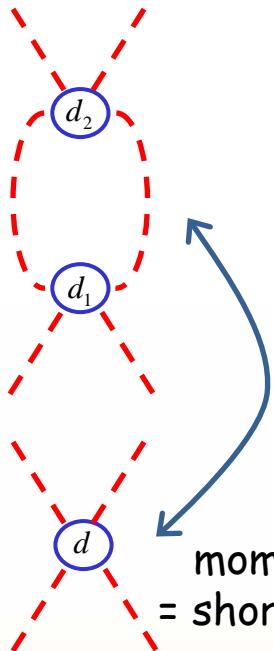
7. if yes, go back to step 4 at $N^{\bar{\nu}-\nu_{\min}+1} \text{LO}$ and repeat a few times

8. check if observables converge with increasing order
if no, go back to step 3 or, if that fails, 1 (you learned something)

9. if yes, check if observables converge to data
if no, go back to step 3 or, if that fails, 1 (you learned something)

10. if yes, move on to a different problem, you learned a lot

The guess



$$\begin{aligned} &\sim \frac{Q^4}{(4\pi)^2} \frac{Q^{d_1+d_2}}{Q^4} c_{d_1}(\Lambda) c_{d_2}(\Lambda) \\ &\sim \underbrace{\frac{\Lambda^{d_1+d_2-d}}{(4\pi)^2} c_{d_1}(\Lambda) c_{d_2}(\Lambda)}_{\sim c_d(\Lambda)} Q^d + \dots \end{aligned}$$

$$d_1 = d_2 = d \rightarrow c_d(\Lambda) \sim \frac{(4\pi)^2}{\Lambda^d}$$

"strong"
naturalness

$$\rightarrow c_d(M) \sim \frac{(4\pi)^2}{M^d}$$

arbitrary
diagram

fermions
more loops, vertices
other interactions

naïve dimensional analysis
(NDA)

(perturbative renormalization)

number of fields
in operator

$$c_i = \mathcal{O}\left(\frac{(4\pi)^{N-2}}{M^{D-4}} c_i^{\text{red}}\right)$$

dimension of
operator

Georgi + Manohar '86

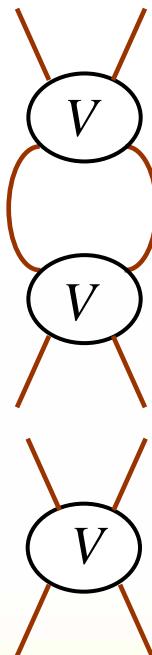
$$c_i^{\text{red}} = \mathcal{O}\left((g^{\text{red}})^\# \right)$$

reduced
underlying theory
parameter

reduced
coupling

insertions

different for heavy particles (as nucleons in nuclei!):

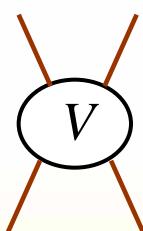


$$\sim \frac{Q^3}{4\pi} \frac{m}{Q^2} V^2$$

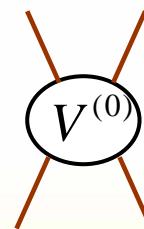
$$\frac{Q^2}{(4\pi)^2} \rightarrow \frac{mQ}{4\pi}$$

Weinberg '90

IR enhancement



= \sum irreducible diagrams



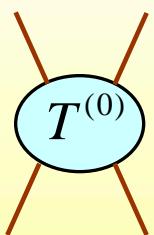
+



+ ...

Resum when

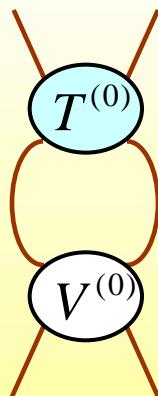
$$\frac{mQ}{4\pi} V^{(0)} \gtrsim 1$$



=



+



non-perturbative
renormalization:
a totally different beast,
*NDA usually not right
for contact interactions*

Beane et al. '01

Pavón Valderrama +
Ruiz Arriola '03

Rest: distorted-wave Born perturbation

Moral: in EFT potential **NOT A BLACK BOX**

...

"Modern S-matrix theory"

- ✓ No dependence on specific fields
- ✓ Quantum field theory a tool to generate most general S matrix

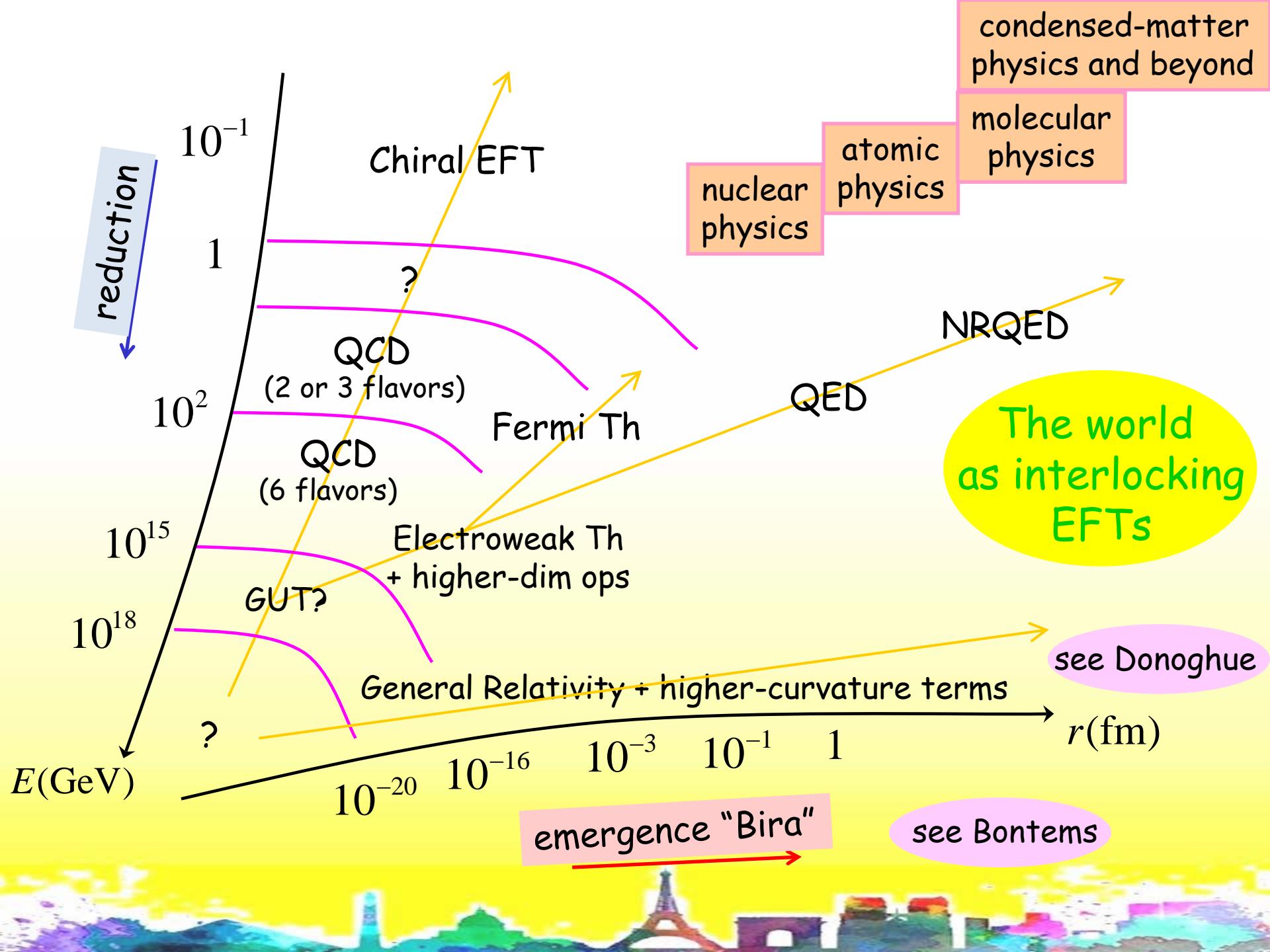
"New conceptualization" of renormalization

see Grinbaum

- ✓ Reg + renorm is the process of connecting Lag to observables
- ✓ No infinities, nothing under the rug
- ✓ Choice of reg is psychology, RG invariance is physics
- ✓ Importance of lowest-dimension operators explained

The mother of all models

- models have fewer, but *ad hoc*, interactions and do not necessarily match the underlying theory
- models useful in the identification of relevant degrees of freedom and symmetries, but plagued with uncontrolled errors
- models with the correct symmetry pattern can be reproduced by EFT with an infinite number of constraints in the LECs



Bira's equation

(fundamental – effective) theory \approx theology



QCD

d.o.f.s

quarks: $q = \begin{pmatrix} u \\ d \end{pmatrix}$ gluons: G_μ^a (photon: A_μ)

$Q \lesssim M_{EW}$

symmetries

$SO(3,1)$ global, $SU_c(3)$ gauge ($+U_{em}(1)$ gauge)

$$\mathcal{L}_{QCD} = \underbrace{\bar{q}(i\partial + g_s G)q - \frac{1}{2}\text{Tr } G^{\mu\nu}G_{\mu\nu}}_{\text{Basic}} + \underbrace{\bar{m}\bar{q}(1 - \varepsilon\tau_3)q}_{\text{mass scales}} + \dots$$

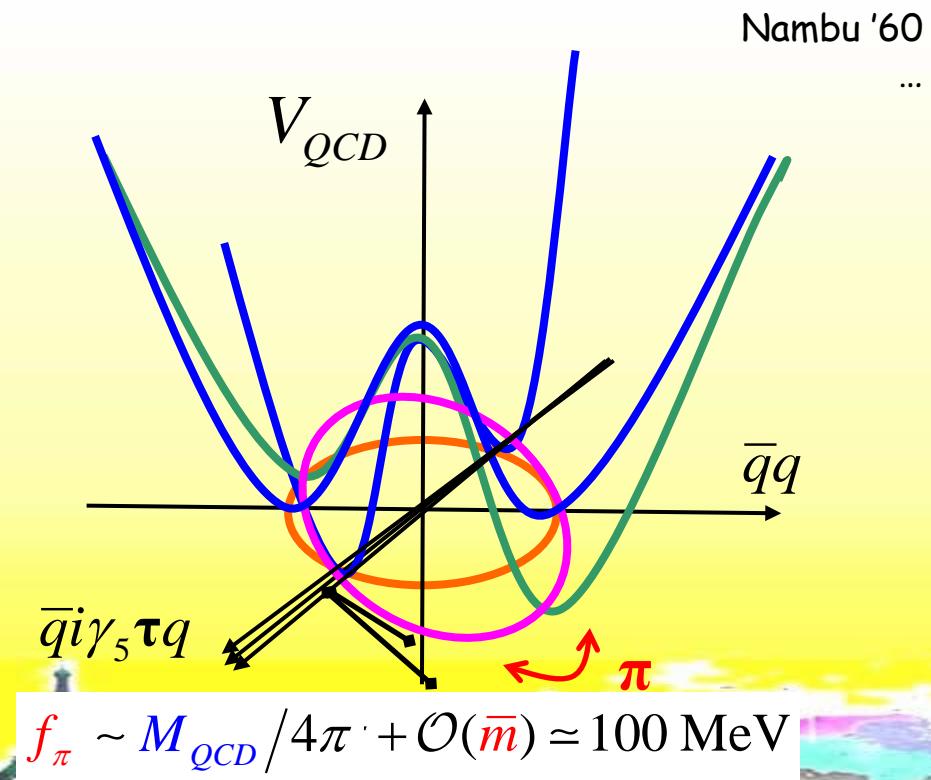
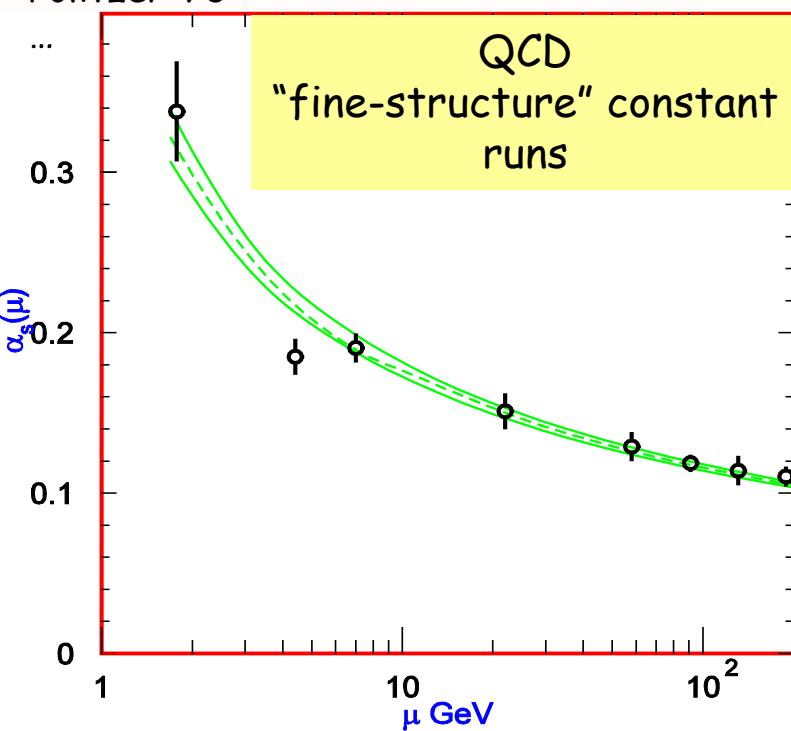
mass scales

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

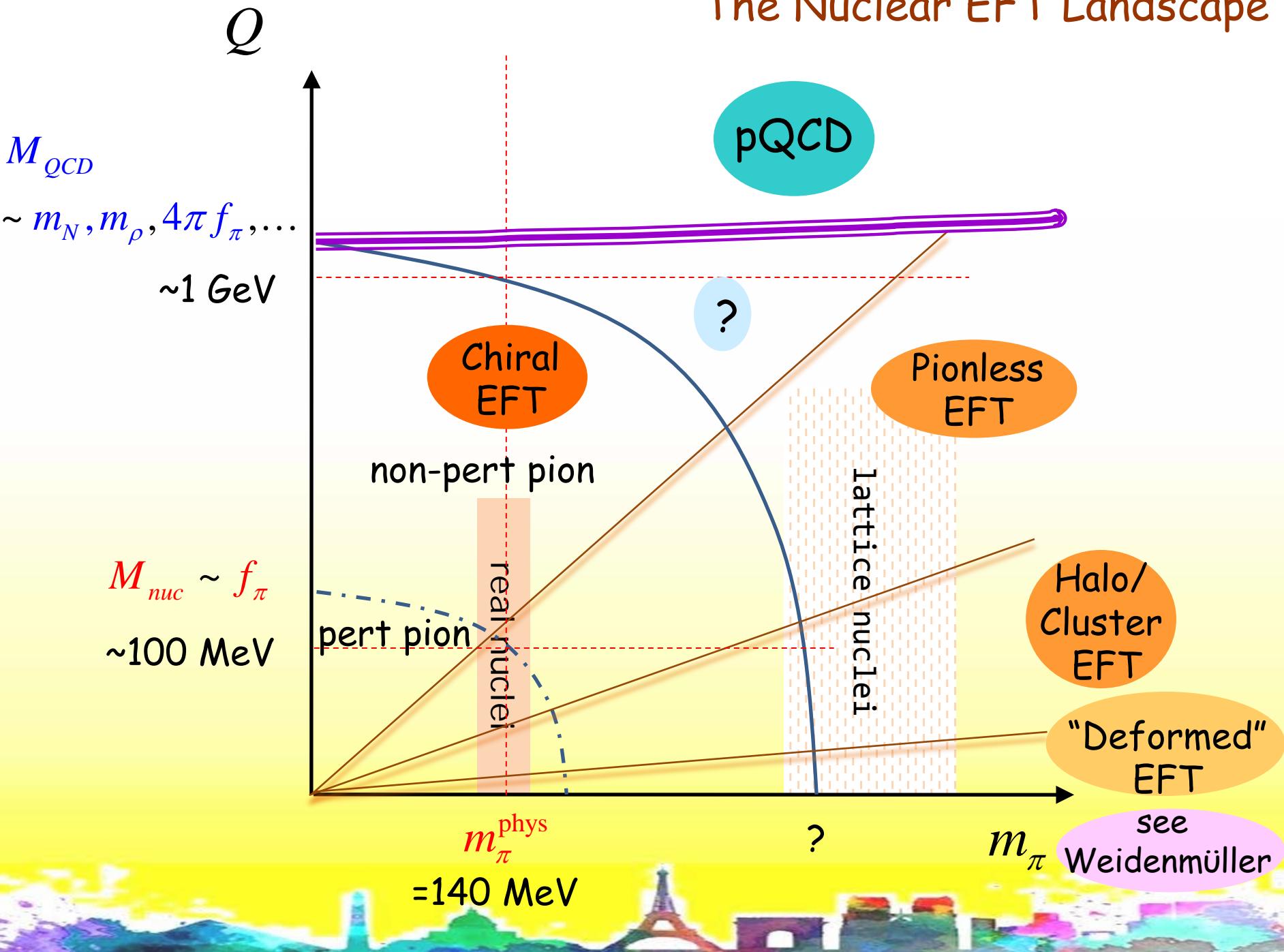
$$m_\pi \sim \sqrt{\bar{m}M_{QCD}} \simeq 140 \text{ MeV}$$

Gross + Wilczek '73

Politzer '73



The Nuclear EFT Landscape



EFTs

regime

d.o.f.s

symmetries

Chiral

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

nucleons
(+Delta, Roper),
pions, photon

$SU(3)_c$ [trivial], $U(1)_{em}$
 $SO(3,1)$, $\cancel{B}, \cancel{T}, \cancel{P}$
 $\cancel{SU(2)_L} \times \cancel{SU(2)_R}$

XEFT

light baryons \rightarrow heavy hadrons

Pionless

$$Q \ll m_\pi \lesssim M_{QCD}$$

nucleons,
photon

$SU(3)_c$ [trivial], $U(1)_{em}$
 $SO(3,1)$, $\cancel{B}, \cancel{T}, \cancel{P}$

vd Waals-less

$$Q \ll 1/l_{vdW} \ll 1/R_{atom}$$

nucleons \rightarrow neutral atoms

Halo/
Cluster

$$Q \ll (r_0 A^{1/3})^{-1} \lesssim m_\pi$$

$r_0 \approx 1.2 \text{ fm}$

nucleons,
clusters,
photon

$SU(3)_c$ [trivial], $U(1)_{em}$
 $SO(3,1)$, $\cancel{B}, \cancel{T}, \cancel{P}$

History Digest

- ❖ before late 1940s: the early model era
- ❖ late 40s-50s: the era of pion theories
 - "too many divergences" → fairwell field theory;
 - "too many interactions" → nuclear and particle physics part ways
- ❖ 60s-90s: the late model era
 - pions and form factors
 - "too many forces" → data fitting trumps consistency
- ❖ 90s-today: the era of EFT
 - ✓ renormalization
 - ✓ power counting → nuclear and particle physics re-united
consistency before fitting

❖ early 90s:

guess based on naïve dimensional analysis (NDA)

not much cutoff dependence

not such a bad fit to data

$N^3\text{LO}$

$\Lambda = 0.5, 0.8, 1 \text{ GeV}$

Weinberg '90'91'92

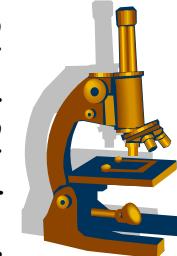
Rho '91

Ordóñez + v.K. '92

v.K. '94

Ordóñez, Ray + v.K.

'94'96



❖ mid 90s-mid 00s: there is cutoff dependence already at LO

short-range
two-nucleon
interactions

chiral-breaking 1S_0

chiral-symmetric $^3P_0, ^3P_0 - ^3F_2,$
 $^3D_0 - ^3G_2, ^3D_3$

Kaplan, Savage + Wise '96

Nogga, Timmermans+ v.K. '05

Pavón Valderrama

+ Ruiz Arriola '05

Birse 05

❖ late 90s: split between EFT and EFT-inspired potentials

cutoff independence of amplitudes not needed and/or not desirable ...

live with physical form factors and NDA
excellent fits to data

see

lots of other talks

Entem + Machleidt '03

Epelbaum, Glöckle + Meiñner '05

...

Pionless EFT to understand renormalization and power counting

Halo/Cluster EFT for cluster states

new power counting for Chiral EFT

rest of this talk

d.o.f.s nucleons: $N = \begin{pmatrix} p \\ n \end{pmatrix}$ (+ Delta isobar, Roper)

Chiral EFT

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

pions: $\boldsymbol{\pi} = \begin{pmatrix} (\pi^+ + \pi^-)/\sqrt{2} \\ -i(\pi^+ - \pi^-)/\sqrt{2} \\ \pi^0 \end{pmatrix}$ (photon: A_μ)

symmetries

$SO(3,1)$ global, $SU(2)_L \times SU(2)_R$ global (+ $U_{em}(1)$ gauge)

$$\mathcal{L}_{\chi EFT} = \frac{1}{2} \mathbf{D}_\mu \boldsymbol{\pi} \cdot \mathbf{D}^\mu \boldsymbol{\pi} - \frac{m_\pi^2}{2} \frac{\boldsymbol{\pi}^2}{1 + \boldsymbol{\pi}^2/4f_\pi^2} + N^+ \left(i\mathcal{D}_0 + \frac{\vec{\mathcal{D}}^2}{2m_N} \right) N + \frac{g_A}{2f_\pi} N^+ \vec{S} \boldsymbol{\tau} N \cdot \vec{\mathcal{D}} \boldsymbol{\pi}$$

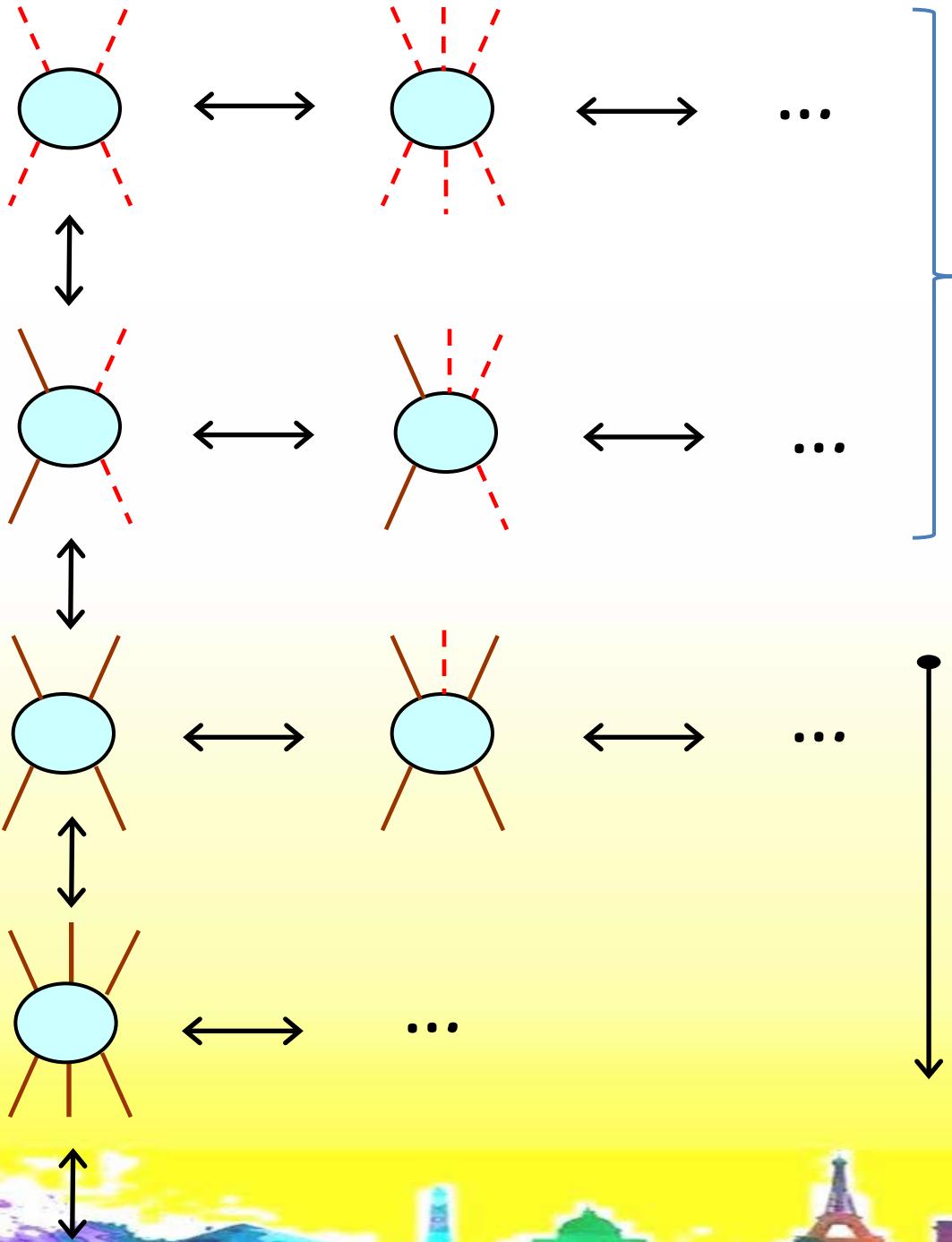
$$+ C_0 N^+ N N^+ N + C'_2 N^+ N \left(\vec{\mathcal{D}} N^+ \right) \cdot \vec{\mathcal{D}} N + \dots$$

$$D_\mu = \left(1 + \boldsymbol{\pi}^2 / 4f_\pi^2 \right)^{-1} \partial_\mu$$

$$\mathcal{D}_\mu = \partial_\mu + \frac{i}{2f_\pi^2} \left(\boldsymbol{\pi} \times D_\mu \boldsymbol{\pi} \right) \cdot \mathbf{t}^{(I)}$$

chiral covariant derivatives

other spin/isospin ,
more derivatives,
powers of pion mass,
Deltas and Ropers,
few-body forces,
etc.



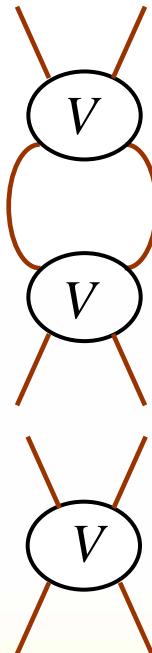
Chiral Perturbation Theory

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

Non-perturbative!

Weinberg '90
 Rho '91
 Weinberg '91
 Ordóñez + v.K. '92
 Weinberg '92
 v.K. '94
 ...

different for heavy particles (as nucleons in nuclei!):

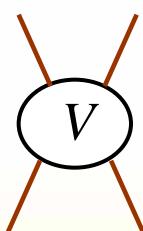


$$\sim \frac{Q^3}{4\pi} \frac{m}{Q^2} V^2$$

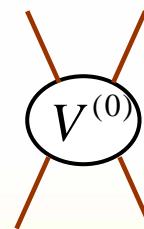
$$\frac{Q^2}{(4\pi)^2} \rightarrow \frac{mQ}{4\pi}$$

Weinberg '90

IR enhancement



= \sum irreducible diagrams



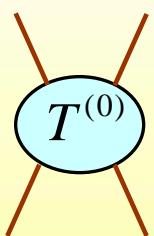
+



+ ...

Resum when

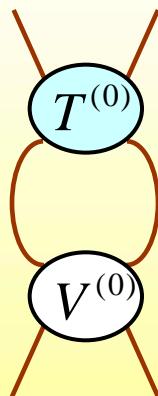
$$\frac{mQ}{4\pi} V^{(0)} \gtrsim 1$$



=



+



non-perturbative
renormalization:
a totally different beast,
*NDA usually not right
for contact interactions*

Beane et al. '01

Pavón Valderrama +
Ruiz Arriola '03

Rest: distorted-wave Born perturbation

Moral: in EFT potential **NOT A BLACK BOX**

...

2-nucleon

3-nucleon

4-nucleon

...

LO

in German

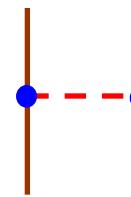
NLO

NNLO

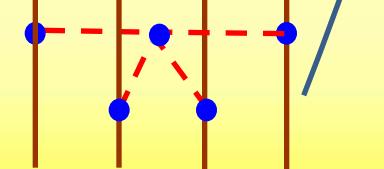
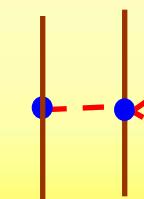
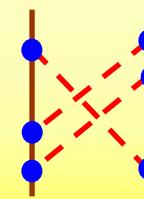
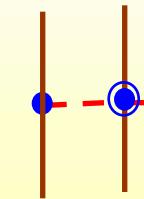
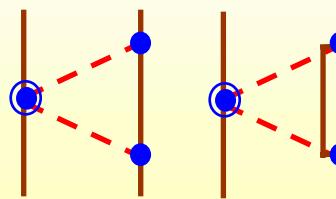
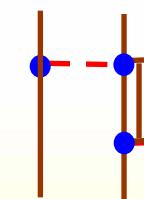
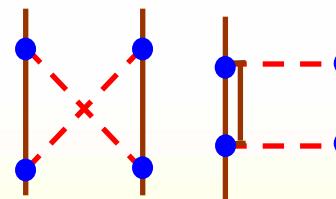
NNNLO

NNNNLO

etc.



(parity violating)



...



$$V^{(0)} = \text{contact} + \text{crossed loop} \sim \frac{1}{f_\pi^2} \equiv \frac{4\pi}{m_N M_{NN}}$$

$$M_{NN} \equiv \frac{4\pi f_\pi}{m_N} f_\pi \sim f_\pi$$

Resum when
 $Q \gtrsim M_{NN}$

$$T^{(0)} = \text{contact} + \text{crossed loop with } T^{(0)}$$

b.s. at

$$B \sim \frac{M_{NN}^2}{m_N} \sim \frac{f_\pi}{4\pi} \simeq 10 \text{ MeV}$$

Renormalization:

$$\text{crossed loop} = C_0(^3S_1) + C_0(^1S_0) + m_\pi^2 D_2(^1S_0) + C_2(^3P_0) p' p + C_2(^3P_2) p' p + C_4(^3D_2) p'^2 p^2 + C_4(^3D_3) p'^2 p^2$$

larger than NDA, e.g., $C_2(^3P_0) \rightarrow \frac{4\pi}{m_N M_{NN}^3} \gg \frac{4\pi}{m_N M_{NN} M_{QCD}^2}$

Rest: NDA relative to LO (except spin-singlet S wave)

Some current issues

➤ Waves, order for perturbative pion exchange

...

Pavón Valderrama *et al.* '16

➤ Role of fine tuning in spin-singlet S wave

...

Sánchez Sánchez *et al.*, in preparation

➤ Fit to data

Someone should work on this...

➤ Size of few-body forces

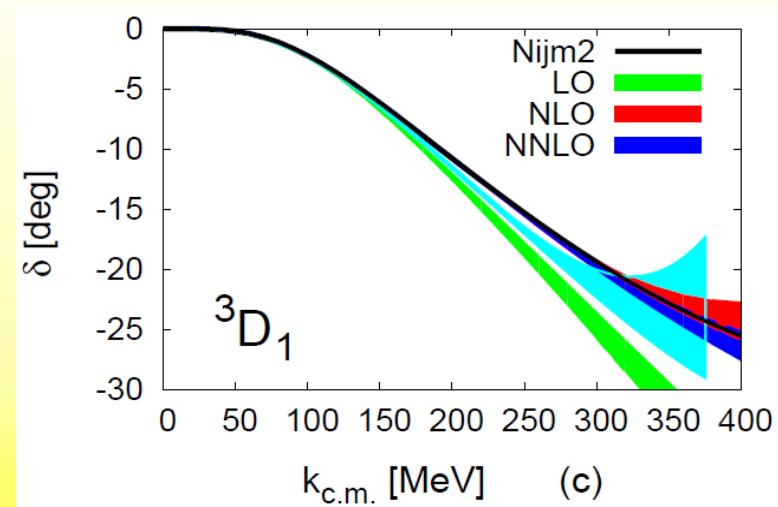
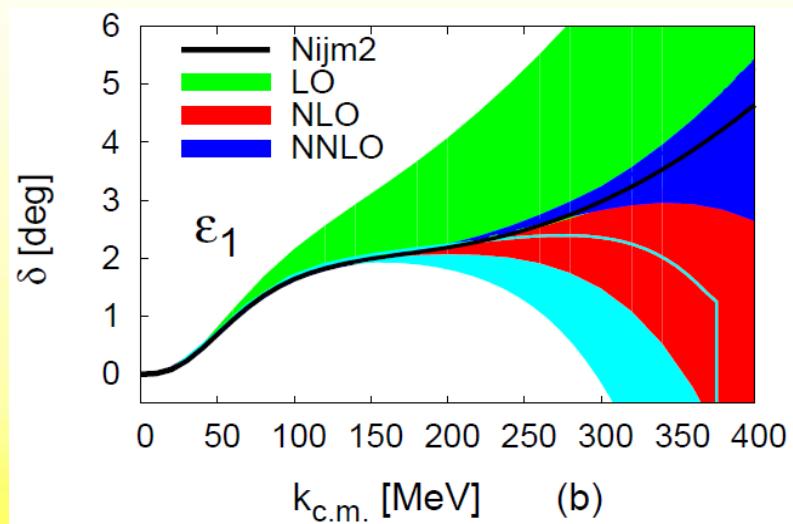
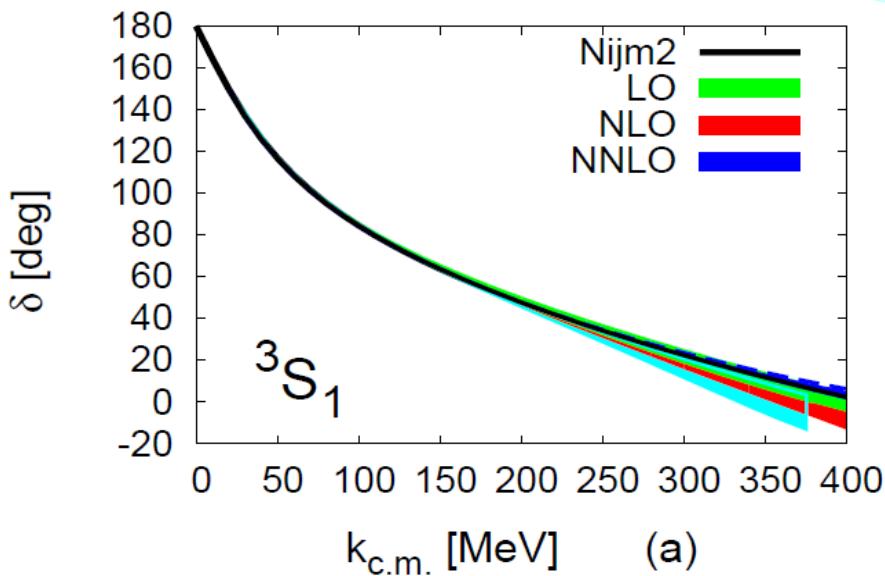
...

Gattobigio, Girlanda, Kievsky + Viviani '16

Song, Lazauskas + v.K. '16

NN system

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

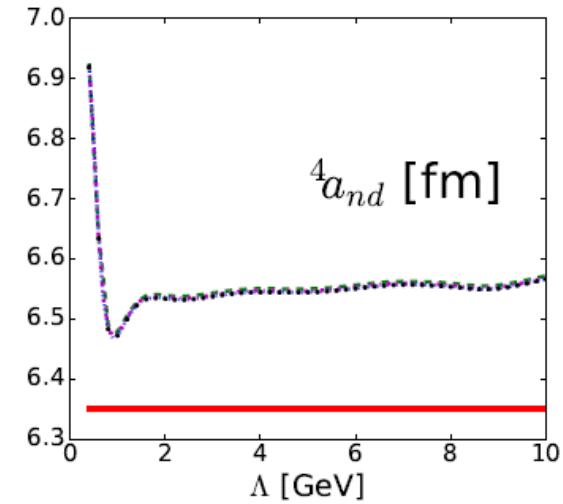
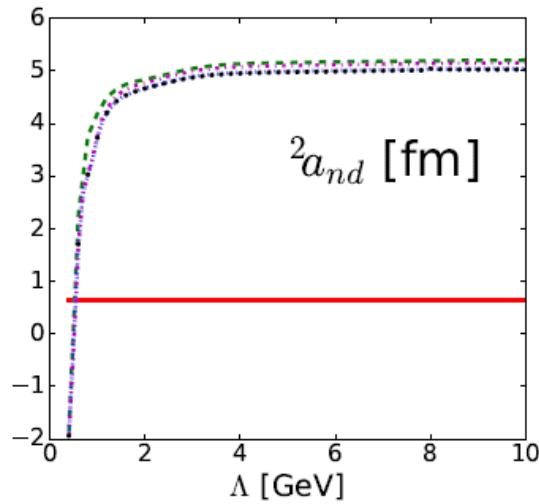
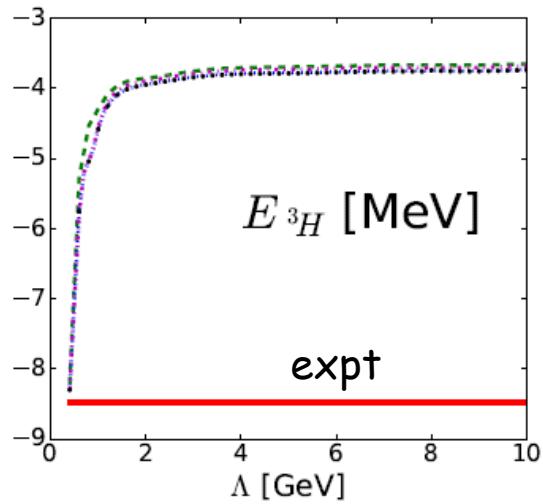


bands:
coordinate-space cutoff
variation 0.6 - 0.9 fm
cyan:
NNLO in Weinberg's scheme

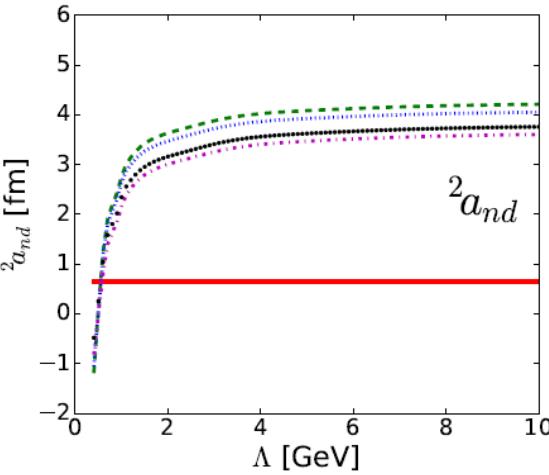
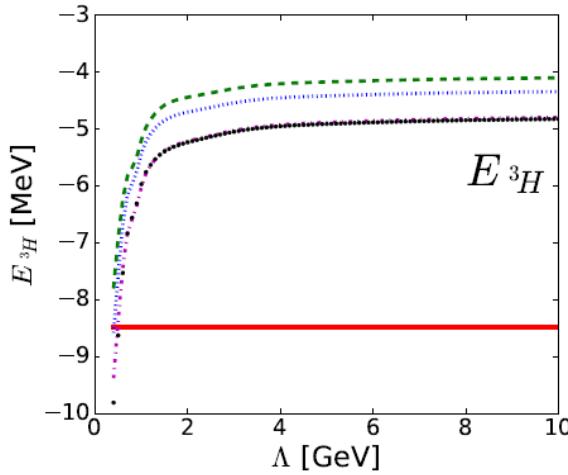
No obstacle to pursue a consistent description of data

3N system

LO



NLO



different
regulator
functions

No renormalization argument for a three-nucleon force up to NLO. But...

d.o.f.s nucleons: $N = \begin{pmatrix} p \\ n \end{pmatrix}$ (+ Delta isobar, Roper)

Pionless EFT

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

symmetries

pions: $\pi = \begin{pmatrix} (\pi^+ + \pi^-)/\sqrt{2} \\ -i(\pi^+ - \pi^-)/\sqrt{2} \\ \pi^0 \end{pmatrix}$ (photon: A_μ)

$SO(3,1)$ global (+ $U_{em}(1)$ gauge)

$$\mathcal{L}_{\chi EFT} = \frac{1}{2} D_\mu \pi \cdot D^\mu \pi - \frac{m_\pi^2}{2} N^+ \left(\frac{\pi^2}{1 + \frac{\pi^2}{4f_\pi^2} m_N^2} + \frac{\nabla^2}{4f_\pi^2 m_N^2} + N \right) N \left(i \not{D}_0 + \frac{\vec{D}^2}{2m_N} \right) N + \frac{g_A}{2f_\pi} N^+ \vec{S} \tau N \cdot \vec{D} \pi$$

$$+ C_0 N^+ N N^+ N + C'_0 \not{D}_0^+ N \left(\vec{D} N^+ N \right) \cdot \vec{D} N + \dots$$

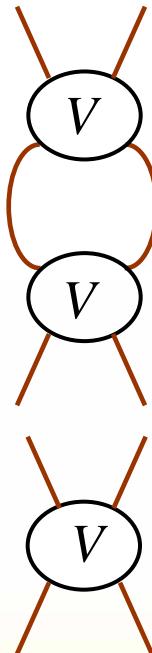
$$D_\mu = \left(1 + \frac{\pi^2}{4f_\pi^2} \right)^{-1} \partial_\mu$$

$$\mathcal{D}_\mu \text{ (but different legs)}$$

chiral covariant derivatives

other spin/isospin,
other spin/isospin,
more derivatives,
more derivatives,
powers of pion mass,
more-body forces,
etc.
etc.

different for heavy particles (as nucleons in nuclei!):

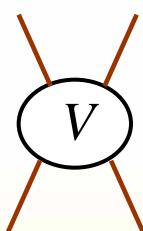


$$\sim \frac{Q^3}{4\pi} \frac{m}{Q^2} V^2$$

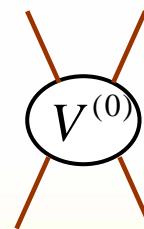
$$\frac{Q^2}{(4\pi)^2} \rightarrow \frac{mQ}{4\pi}$$

Weinberg '90

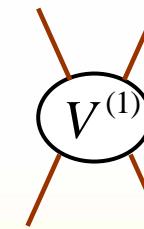
IR enhancement



= \sum irreducible diagrams



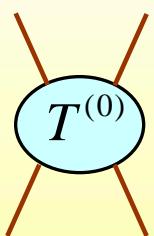
+



+ ...

Resum when

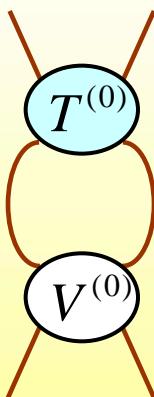
$$\frac{mQ}{4\pi} V^{(0)} \gtrsim 1$$



=



+



non-perturbative
renormalization:
a totally different beast,
*NDA usually not right
for contact interactions*

Beane et al. '01

Pavón Valderrama +
Ruiz Arriola '03

Rest: distorted-wave Born perturbation

Moral: in EFT potential **NOT A BLACK BOX**

...

Fine tuning

Renormalization:



$$C_0(\Lambda) = \frac{4\pi}{m_N \Lambda} \left(1 + \frac{1}{a_0 \Lambda} + \dots \right)$$

v.K. '97

cancels

cutoff dependence

scattering length

$1/a_0 \ll m_\pi$ when b.s. close
to threshold

In amplitude:

$$C_0^{(R)} = \frac{4\pi a_0}{m_N} \ll \frac{4\pi}{m_N M} \sim C_0(M)$$

No show-stopper: incorporate new scale in power counting

$$\aleph \sim 1/a_0 \ll m_\pi$$

Example, from renormalization of 3N system:



$$D_0^{(R)} \sim \frac{(4\pi)^2}{m_N \aleph^4}$$

Bedaque, Hammer + v.K. '98 '99

v.K. '97

Kaplan, Savage + Wise '98

Bedaque, Hammer + v.K. '98 '99

...

2-nucleon

3-nucleon

4-nucleon

...

LO



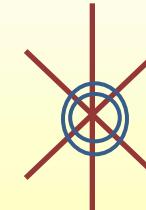
NLO



NNLO



etc.



?

?



Some current issues

➤ NLO for $A > 3$

Bazak *et al.* in preparation

➤ Convergence as A increases

...

Contessi *et al.* in preparation

➤ Role of unitarity

König, Grießhammer, Hammer + v.K. '16

➤ Matching to lattice QCD

Barnea *et al.* '14

Beane *et al.* '15

Kirscher *et al.* 15

Contessi *et al.* in preparation

For more, better,
see Barnea

^4He and ^{16}O ^4He

Λ	$m_\pi = 140 \text{ MeV}$	$m_\pi = 510 \text{ MeV}$	$m_\pi = 805 \text{ MeV}$
2 fm^{-1}	-23.17 ± 0.02	-31.15 ± 0.02	-88.09 ± 0.01
4 fm^{-1}	-23.63 ± 0.03	-34.88 ± 0.03	-91.40 ± 0.03
6 fm^{-1}	-25.06 ± 0.02	-36.89 ± 0.02	-96.97 ± 0.01
8 fm^{-1}	-26.04 ± 0.05	-37.65 ± 0.03	-101.72 ± 0.03
$\rightarrow \infty$	$-30_{\pm 2}^{\pm 0.3} (\text{sys})$	$-39_{\pm 2}^{\pm 1} (\text{sys})$	$-124_{\pm 1}^{\pm 3} (\text{sys})$
Exp.	-28.30	—	—
LQCD	—	-43.0 ± 14.4	-107.0 ± 24.2

LQCD input error

Beane *et al.* '12 $\sim 30\%$ Yamazaki *et al.* '12For different,
see BarbieriAuxiliary Field Diffusion
Monte Carlostatistical +
extrapolation errors

truncation error

LO $\sim 30\%$ ^{16}O

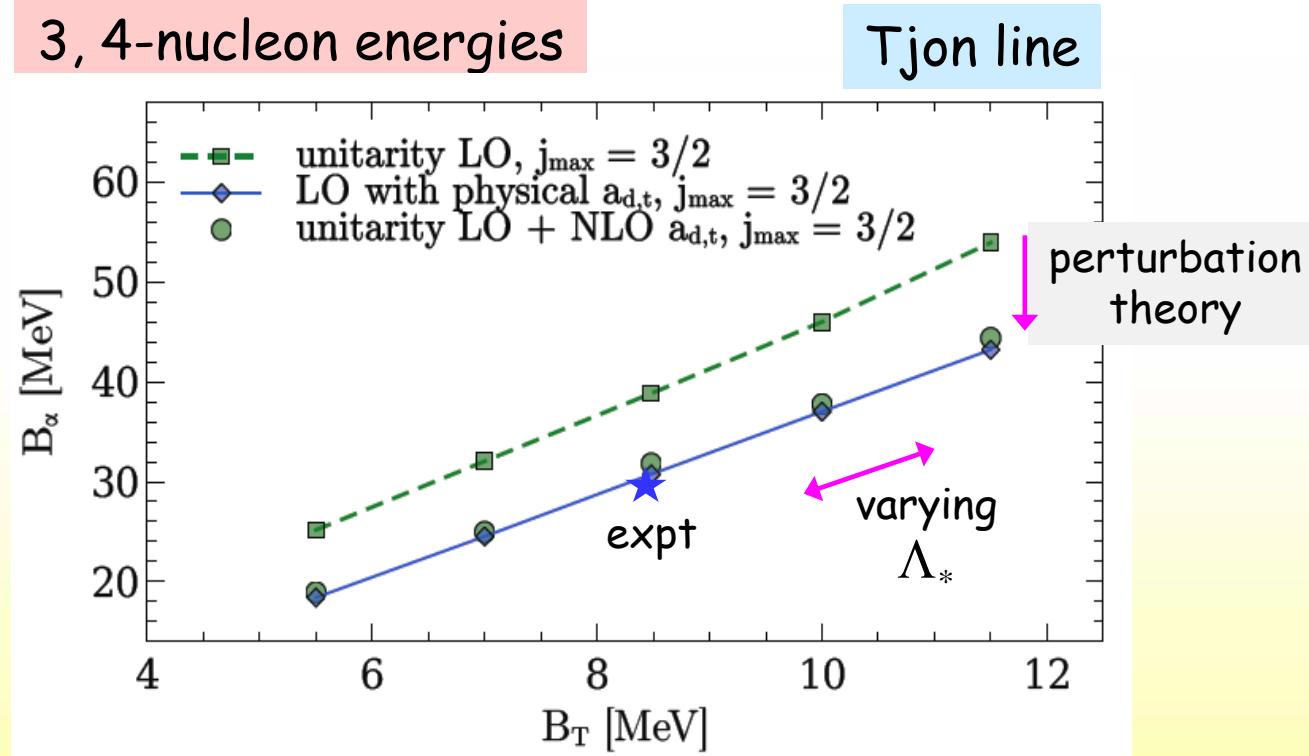
Λ	$m_\pi = 140 \text{ MeV}$	$m_\pi = 510 \text{ MeV}$	$m_\pi = 805 \text{ MeV}$
2 fm^{-1}	-97.19 ± 0.06	-116.59 ± 0.08	-350.69 ± 0.05
4 fm^{-1}	-92.23 ± 0.14	-137.15 ± 0.15	-362.92 ± 0.07
6 fm^{-1}	-97.51 ± 0.14	-143.84 ± 0.17	-382.17 ± 0.25
8 fm^{-1}	-100.97 ± 0.20	-146.37 ± 0.27	-402.24 ± 0.39
$\rightarrow \infty$	$-115_{\pm 8}^{\pm 1} (\text{sys})$	$-151_{\pm 10}^{\pm 2} (\text{sys})$	$-504_{\pm 12}^{\pm 20} (\text{sys})$
Exp.	-127.62	—	—

Pionless EFT might work for medium-mass nuclei

Unitarity

3-body force at LO:
single parameter Λ_*
and
discrete scale invariance
at two-body unitarity

↔
similar to
atomic
boson fluids



Nuclear physics with a single essential parameter?

d.o.f.s nucleons: $N = \binom{p}{n}$

Pionless EFT EFT

clusters: e.g. α for alpha particles

$$Q \ll (m_\alpha A_{\sim}^{1/3} M_{QCD})^{-1} \quad m_\pi \ll M_{QCD} \quad (\text{photon: } A_\mu)$$

$$r_0 \approx 1.2 \text{ fm}$$

symmetries

$SO(3,1)$ global

($+U_{em}(1)$ gauge)

$$\begin{aligned} \mathcal{L}_{H/\text{CEFT}} = & N^+ N \left[i \partial_0 \left(\frac{\nabla^2 \nabla^2}{2m_N^2} \right) N \right] N \alpha^+ \left[i \partial_0 \left(\frac{\nabla^2 \nabla^2}{2m_\alpha^2} \right) \alpha \right] + \\ & + C_0^\alpha \alpha^+ \alpha \left(\nabla^2 N^+ N^+ \cdot \nabla^2 N^+ N^+ D_0^\alpha \alpha^+ \cdot \alpha \right) N^+ N N^+ N + \dots \end{aligned}$$

(but different LECs)

other spin/isospin,
more derivatives,
more-body forces,
etc.

Bertulani, Hammer + v.K. '04

Bedaque, Hammer + v.K. '05

Higa, Hammer + v.K. '08

...

Rotureau + v.K. '12

Ji + Phillips '14

...

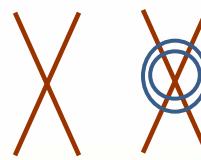
2-body

3-body

4-body

...

LO



?

NLO



?

?

etc.



Some current issues

➤ Different clusters, reactions

Forssén, Ji, Hammer, Higa, Phillips, Platter, Rupak, Ryberg, Vaghani, ...

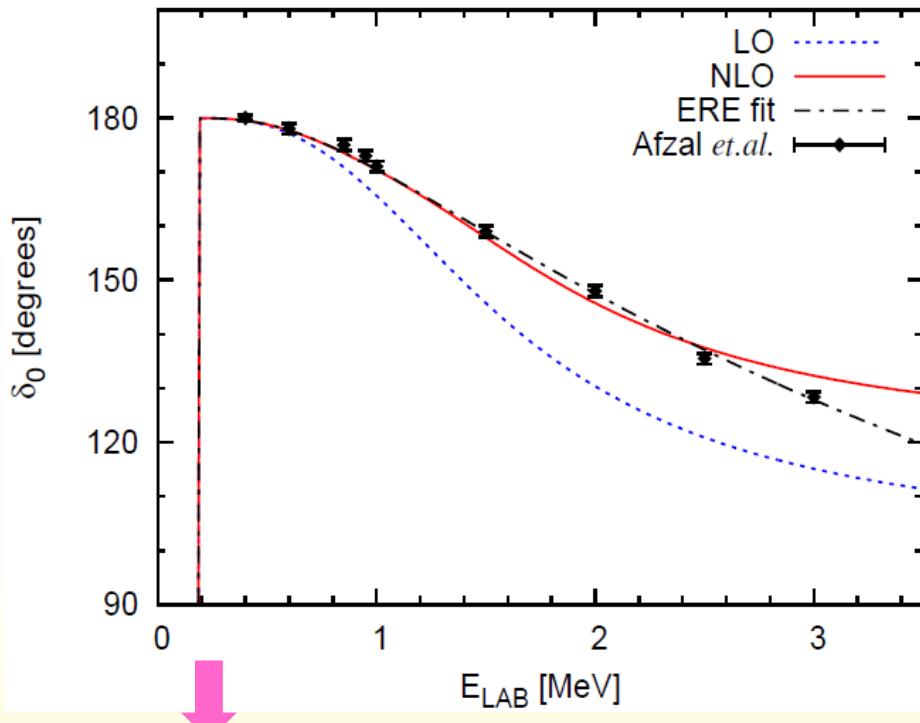
➤ Power counting for heavy clusters

Ryberg, Forssén + v.K. in preparation

➤ Fine tuning in alpha systems

v.K. in wish list

For more, better,
see Ji



aa scattering

Fitting parameters

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

$$\left\{ \begin{array}{l} a_0 \\ \tilde{r}_0 = r_0 - \frac{1}{3k_C} \end{array} \right.$$

Bohr radius

$$\frac{1}{3k_C} \equiv \frac{1}{3Z_\alpha^2 \alpha_{em} \mu} \simeq 1.2 \text{ fm}$$

$$E_R = 92.07 \pm 0.03 \text{ keV}$$

$$\Gamma(E_R) = 5.57 \pm 0.25 \text{ eV}$$

fine-tuning of
1 in 1000!

	a ₀ (10 ³ fm)	r ₀ (fm)	P ₀ (fm ³)
LO	-1.80	1.083	—
NLO	-1.92 ± 0.09	1.098 ± 0.005	-1.46 ± 0.08
ERE [13]	-1.65 ± 0.17	1.084 ± 0.011	-1.76 ± 0.22

Extent of fine-tuning and clusterization in nuclei?

For more, different,
see Meißner

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

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