NUCLEAR PHYSICS: THE EFFECTIVE FIELD THEORY PERSPECTIVE

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Outline

- Effective Field Theories
- Nuclear EFTs
- Outlook
- Summary

Particle Physics

QCD at large distances
an unsolved part of the SM

nuclear matrix elements
for symmetry tests

Nuclear Physics

(here, =physics of strong interactions)

Nucleus as the simplest complex system:
quarks and gluons interacting strongly,
yet exhibiting many regularities

Atomic & Cond-Mat Physics

tools for non-perturbative
quantum (field) theories:
few- and many-bodies

Astrophysics & Cosmology

reaction rates for nucleosynthesis,
equation of state for stellar structure,
variation of parameters for cosmology

Nuclear Physics

PROPER SYMMETRIES
MODEL INDEPENDENCE

Nuclear Physics

PROPER SYMMETRIES
MODEL INDEPENDENCE
CONTROLLED UNCERTAINTY

Nuclear Physics

EFFECTIVE (FIELD) THEORIES ©

quantum mechanics
+
special relativity

$\hbar = 1, c = 1$

experiments probe only finite momenta Q
(or distances $r \gtrsim 1/Q$)

every virtual process allowed by symmetries happens

most general Hamiltonian with relevant degrees of freedom and SYMMETRIES

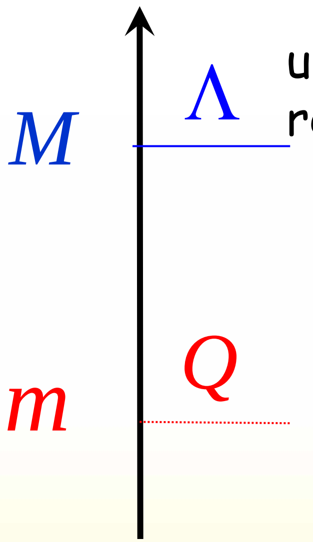
Weinberg '79

...

cf. Wilson '70s

Modern S-matrix theory

mass scales



order · normalization · expansion parameter · "low-energy constants"

$$S^{(\bar{\nu})}(Q\sim m\ll M)=\mathcal{N}(M)\sum_{\nu=\nu_{\min}}^{\bar{\nu}}\left[\frac{Q}{M}\right]^{\nu}F_{\nu}\left(\frac{Q}{m},\frac{Q}{\Lambda};c_i\left(\frac{m}{\Lambda}\right)\right)\times\left\{1+\mathcal{O}\left(\frac{Q}{M},\frac{Q}{\Lambda}\right)\right\}$$

non-analytic functions, from solution of dynamical equation (*e.g.* Schrödinger eq.)

CONTROLLED UNCERTAINTY

$$\frac{\Lambda}{S^{(\bar{\nu})}}\frac{\partial S^{(\bar{\nu})}}{\partial\Lambda}=\mathcal{O}\left(\frac{Q}{\Lambda}\right)$$

renormalization-group invariance

MODEL INDEPENDENCE

"power counting": connection between order and interactions in Hamiltonian

… avoids poorly defined questions such as

- do 3-body forces exist?
- are nucleons "modified by the medium"?

which are

- at one level, trivial:
  answer is yes, they are not forbidden by any symmetry;
  particle substructure in infinite number of interactions

- at another level, the real question is, are they *important*?
  answer depends on the resolution, *i.e.*, on the EFT
  --- but within an EFT, they do **not** depend on
  choice of fields, UV regulator, EFT speaker, *etc.*

Table 1. Seven Decades of Struggle: The Theory of Nuclear Forces

1935	**Yukawa: Meson Theory**
1950's	*The "Pion Theories"* One-Pion Exchange: o.k. Multi-Pion Exchange: disaster
1960's	Many pions ≡ multi-pion resonances: $\sigma, \rho, \omega, \ldots$ The One-Boson-Exchange Model
1970's	Refine meson theory: Sophisticated 2π exchange models (Stony Brook, Paris, Bonn)
1980's	Nuclear physicists discover **QCD** Quark Cluster Models
1990's and beyond	Nuclear physicists discover **EFT** Weinberg, van Kolck **Back to Meson Theory!** *But, with Chiral Symmetry*

The Nuclear Force Problem: Is the Never-Ending Story Coming to an End?

R. Machleidt

Department of Physics, University of Idaho, Moscow, Idaho, U.S.A.

No renormalization-group invariance

split with particle physics

Life with models: refined description of two-body scattering; three-body forces?

connection with QCD

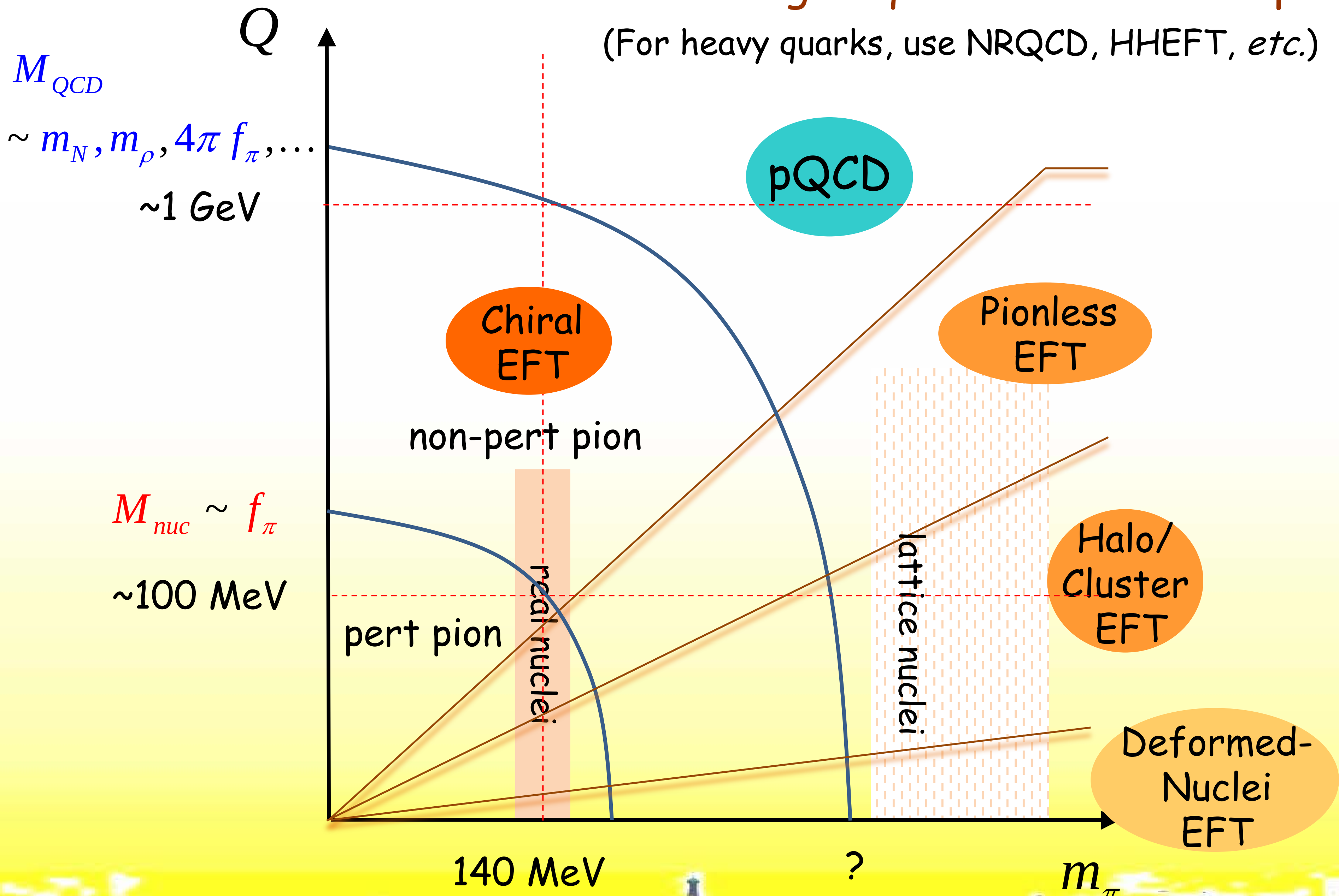
mass scales

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

$$m_\pi \sim \left(\frac{m_u + m_d}{2} M_{QCD} \right)^{1/2} \simeq 140\ \text{MeV}$$

The light-quark EFT Landscape

(For heavy quarks, use NRQCD, HHEFT, *etc.*)



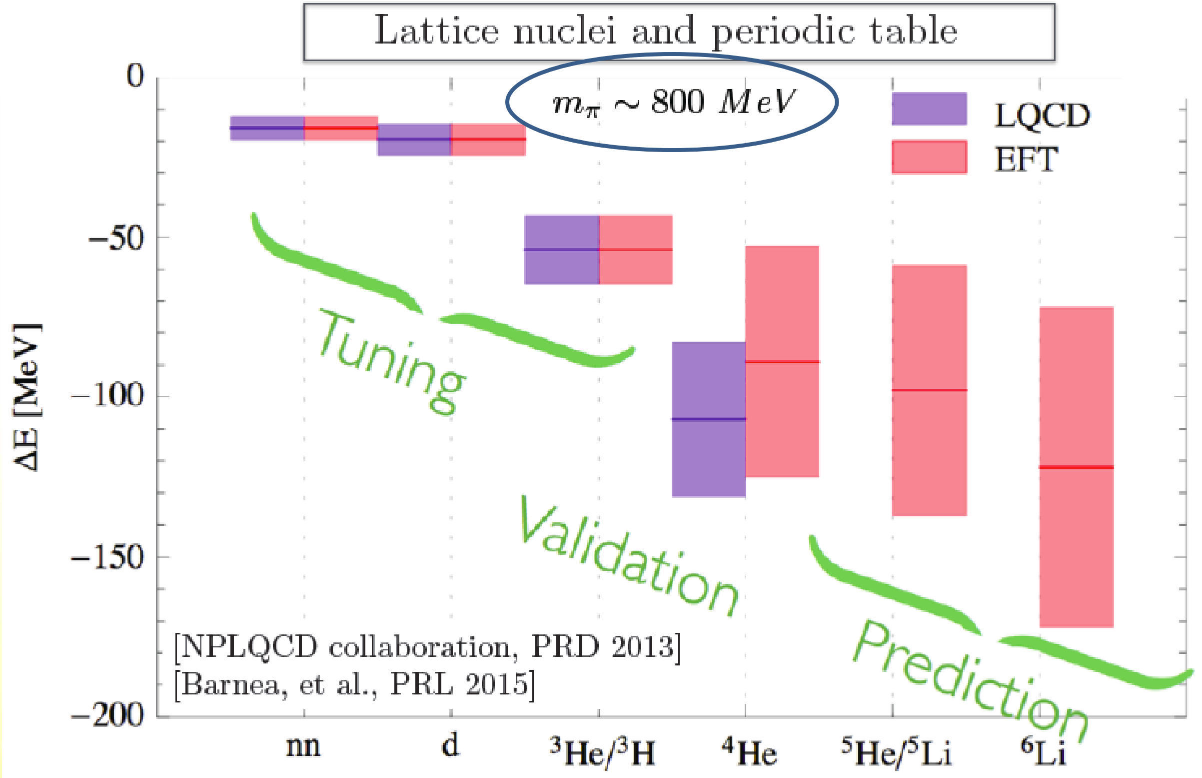
EFT	regime	d.o.f.s	symmetries
Perturbative QCD	$Q \gg M_{QCD}$	quarks, gluons, photon	$SU(3)_c, U(1)_{em}$ $SO(3,1), \not{B}, \not{T}, \not{P}$ $\cancel{SU(2)_L \times SU(2)_R}$
Chiral	$Q \sim m_\pi \ll M_{QCD}$	nucleons (+Delta, Roper), pions, photon	$SU(3)_c[\text{trivial}], U(1)_{em}$ $SO(3,1), \not{B}, \not{T}, \not{P}$ $\cancel{SU(2)_L \times SU(2)_R}$
Pionless	$Q \ll m_\pi \lesssim M_{QCD}$	nucleons, photon	$SU(3)_c[\text{trivial}], U(1)_{em}$ $SO(3,1), \not{B}, \not{T}, \not{P}$
Halo/ Cluster	$Q \ll \left(r_0 A^{1/3}\right)^{-1} \lesssim m_\pi$ $r_0 \approx 1.2 \text{ fm}$	nucleons, cores, photon	$SU(3)_c[\text{trivial}], U(1)_{em}$ $SO(3,1), \not{B}, \not{T}, \not{P}$
Deformed-Nuclei	$Q \ll \Omega_{\text{vib}} \ll m_\pi$ $\Omega_{\text{vib}} \approx 50 \text{ MeV}$	deformed nuclei, "spin waves", photon	$SU(3)_c[\text{trivial}], U(1)_{em}$ $SO(3,1), \not{B}, \not{T}, \not{P}$

Now highly personal choice of examples

(if I can't cover them all, thank Navin)

Nuclei from QCD

Barnea, Contessi, Gazit, Pederiva + v.K. '15
Beane *et al.* '15
Kirscher, Barnea, Gazit, Pederiva + v.K. '15



Pionless EFT at LO

Worlds at large quark masses just denser versions of ours?

Coming up

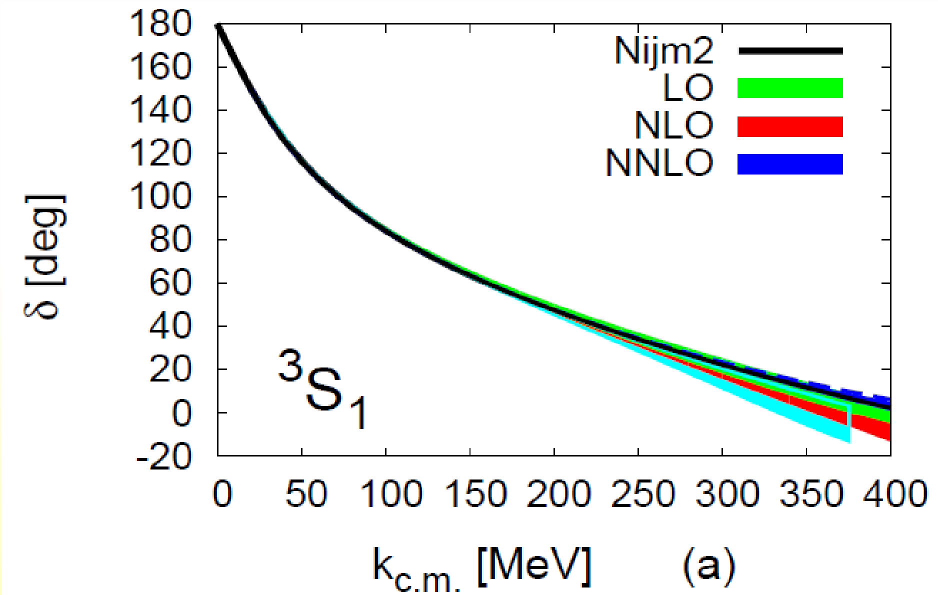
smaller quark masses in lattice QCD

- Pionless EFT at higher orders
- Chiral EFT

Nuclear Forces

Weinberg 90 '92
Ordóñez + v.K. '92
...
<u>Pavón Valderrama '10,'11</u>
Long + Yang '11, '12
...

NN scattering



Chiral EFT at NNLO

bands:
coordinate-space cutoff variation 0.6 – 0.9 fm

cyan:
NNLO in Weinberg's scheme

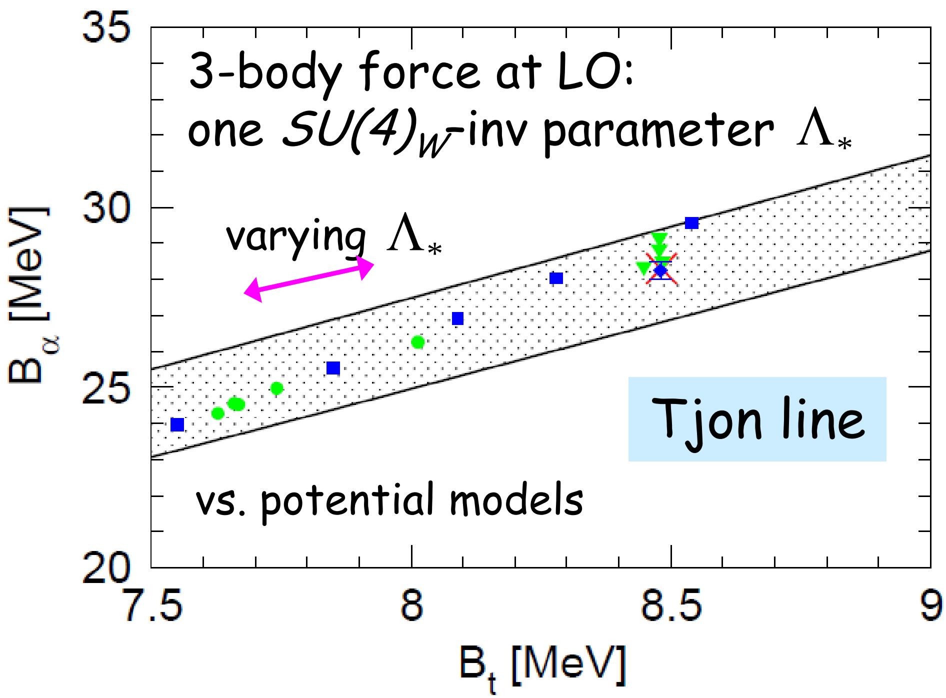
Coming up

better understanding of renormalization of nuclear forces

Few-Body Systems

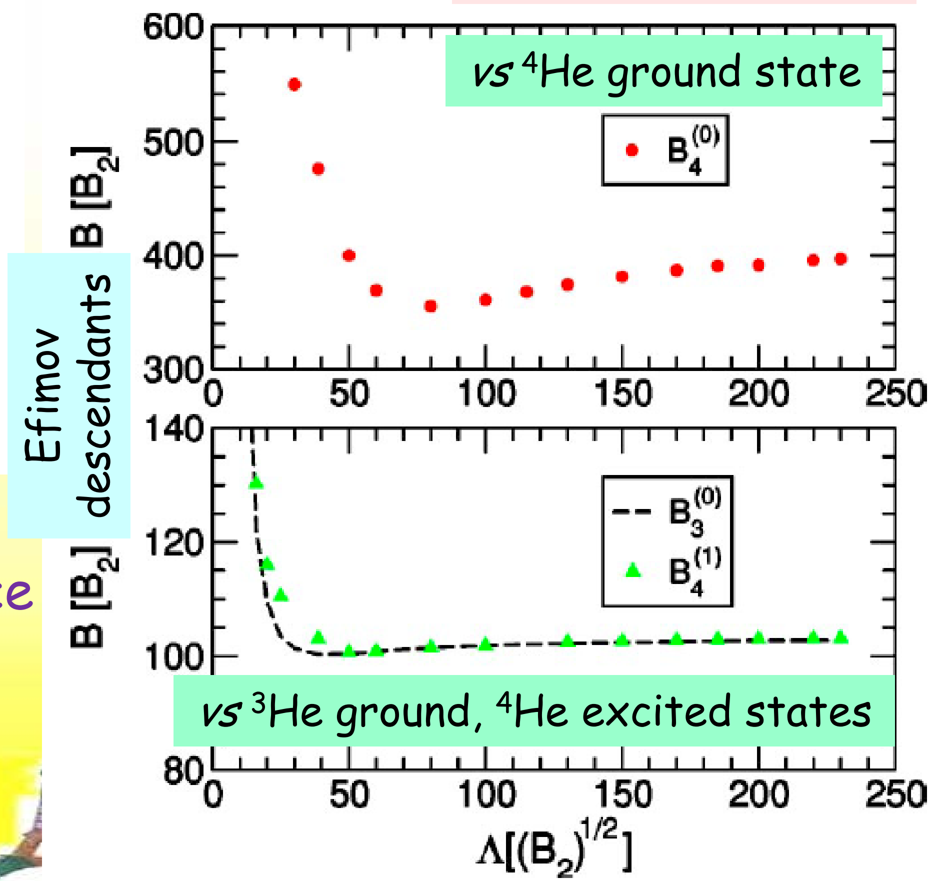
Bedaque + v.K. '97
Bedaque, Hammer + v.K. '98, '99
...
Hammer, Meißner + Platter '04, '05
Hammer + Platter '07
...

3, 4-body energies



Pionless EFT at LO

bosons at unitarity



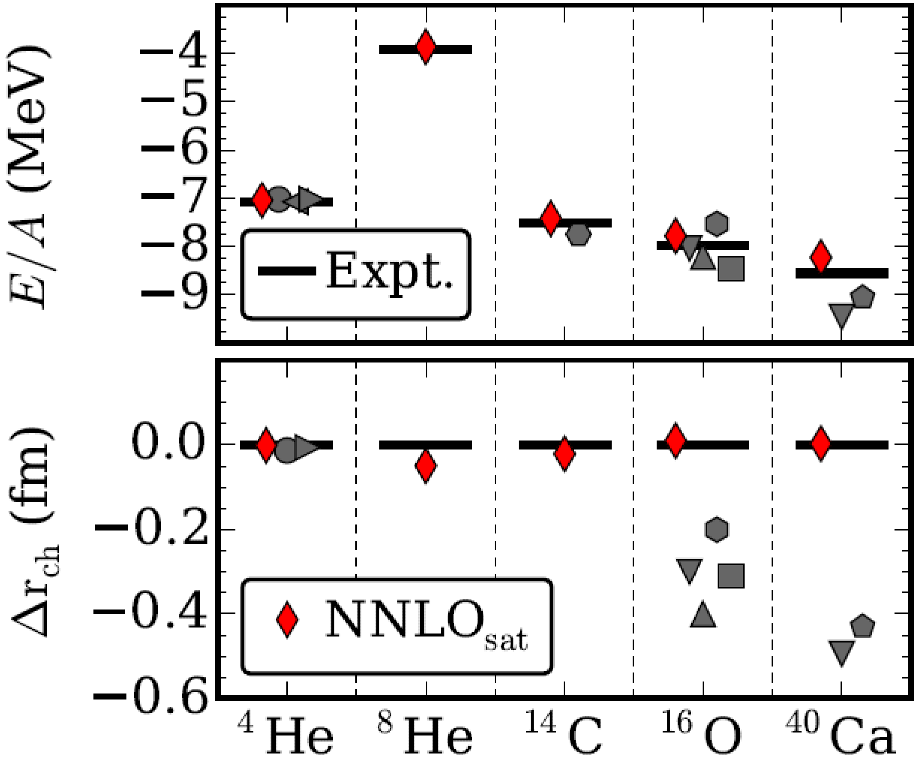
Coming up

Role of discrete scale invariance and $SU(4)_W$?
Limit of Pionless EFT as *A* increases?

Nuclear Structure

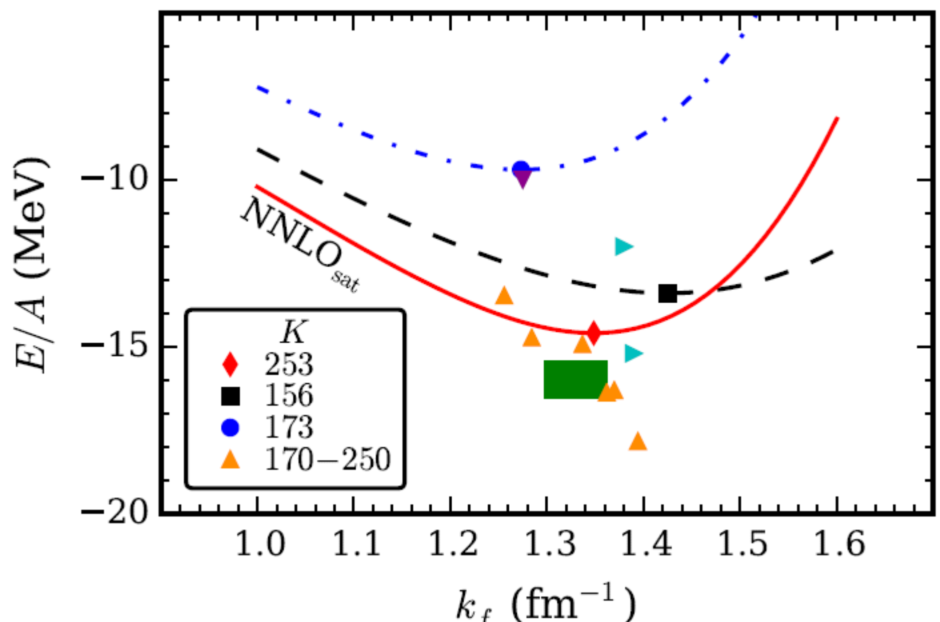
...
Ekström *et al.* '15
...

ground-state energies and charge-radius residuals



EFT-inspired potential

equation of state, symmetric matter



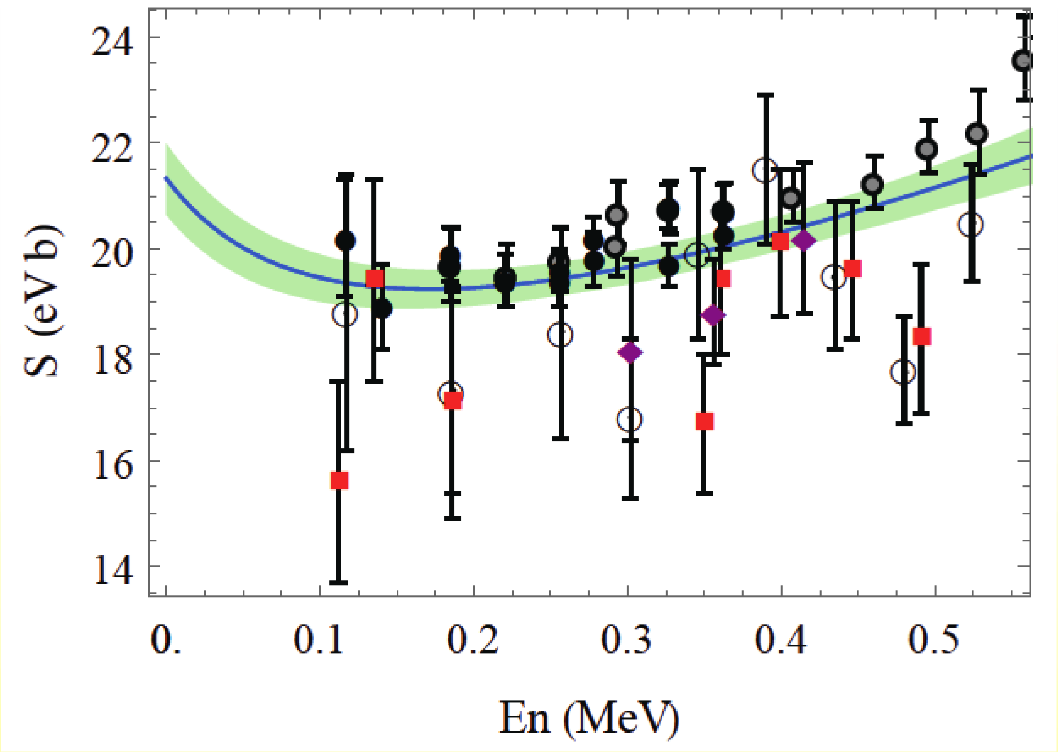
Coming up

reduction of cutoff dependence; role of *3N* forces?

Bertulani, Hammer + v.K. '02
Bedaque, Hammer + v.K. '03
...
Zhang, Nollet, Phillips '14, '15
...

Halo Nuclei

$p + {}^7\mathrm{Be} \rightarrow {}^8\mathrm{B} + \gamma$



Halo/Cluster EFT at NLO

with Bayesian analysis

$$S\,(E = 0\,\mathrm{MeV}) = 21.3 \pm 0.7\ \mathrm{eV\ b.}$$

half of previous error

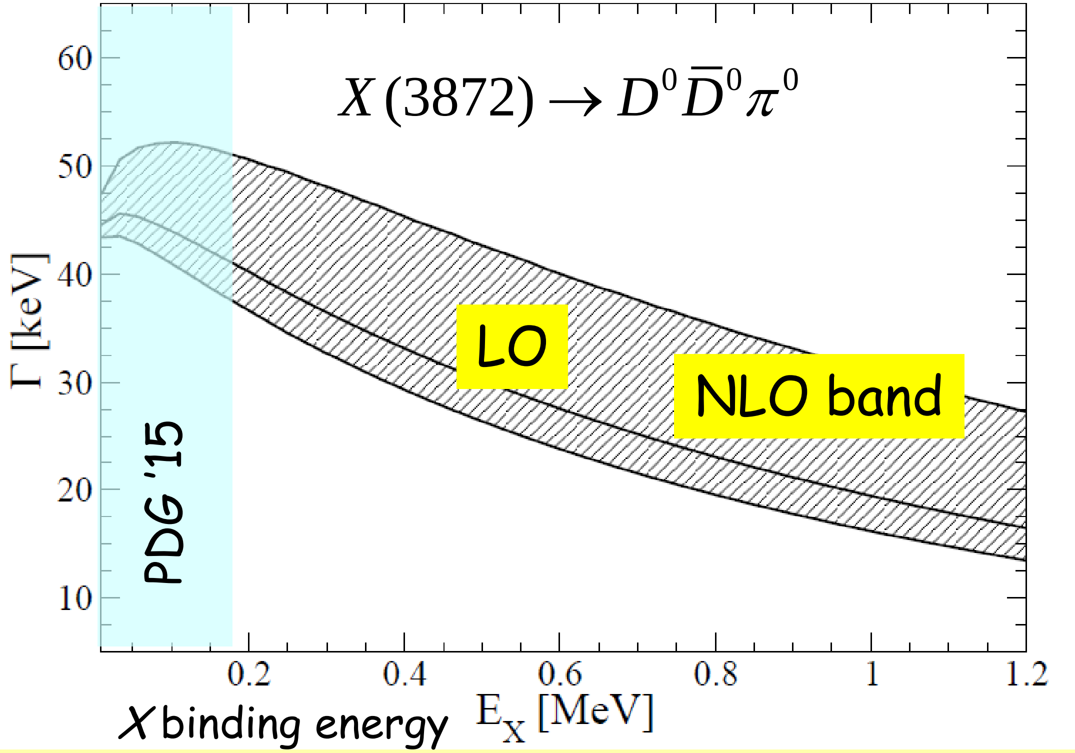
Coming up

study of a variety of other systems
of experimental & astrophysical interest;
extent of clusterization in nuclei?

Braaten + Kusunoki '04, '05
...
Fleming, Kusunoki, Mehen + v.K. '07
...

Hidden-Flavor "Nuclei"

X(3872) as a $D^0\bar{D}^{0*} + D^{0*}\bar{D}^0$ bound state



Chiral EFT at NLO

A new realm of nuclear physics with nucleons replaced by heavy hadrons!

Coming up

rich interplay between theory and experiment to test "molecular" nature of new states

Park, Min + Rho '95
...
De Vries, Mereghetti, Timmermans + v.K. '11
De Vries, Higa, Liu, Mereghetti, Timmermans + v.K.'11
...

"Fundamental" Symmetries

Nuclear electric dipole moments

Chiral EFT at LO

light nuclear EDMs can differentiate among the six dimension-6 sources of T violation!

proposed storage-ring measurements (KAIST, COSY) promising!

e.g.	$m_n d_n / e$	$d_{^2\mathrm{H}} / d_n$	$d_{^3\mathrm{He}} / d_n$
θ term	$\mathcal{O}\left(\bar{\theta}\,\frac{M_{nuc}^2}{M_{QCD}^2}\right)$	$\mathcal{O}(1)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{M_{nuc}^2}\right)$
quark color-EDM	$\mathcal{O}\left(\tilde{\delta}_{u,d}\,\frac{M_{nuc}^2}{M_{\not T}^2}\right)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{M_{nuc}^2}\right)$	$\mathcal{O}\left(\frac{M_{QCD}^2}{M_{nuc}^2}\right)$
quark EDM	$\mathcal{O}\left(\delta_{u,d}\,\frac{M_{nuc}^2}{M_{\not T}^2}\right)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
...			

Coming up

T in larger systems;
other symmetries: B, L, Lorentz

OUTLOOK

LATTICE QCD

↓

EFFECTIVE (FIELD) THEORIES

+

"EXACT" *"AB INITIO"* METHODS

↓

LIGHT, MEDIUM-MASS NUCLEI

↓

+ ?

HEAVY NUCLEI, NUCLEAR MATTER

LATTICE QCD

↓

EFFECTIVE (FIELD) THEORIES

- ✓ Emerging
- ✓ Will receive increased attention for years to come

  - Could shed light on nuclear fine-tuning
  - Holds promise to complement experiment, *eg.* hypernuclear interactions

opportunity

In France: IPNO

- ✓ Astonishing development over last decade
- ✓ Increasing ability to use nuclear properties to constrain interactions
- ✓ Starting to expose renormalization issues of chiral potentials

EFFECTIVE (FIELD) THEORIES

+

"EXACT" *"AB INITIO"* METHODS

↓

LIGHT, MEDIUM-MASS NUCLEI

- Should assess role of few-body forces
- Can explore emergence of weak binding: unitarity (discrete scale inv, $SU(4)_W$), halos, clusters
- Can extend work on symmetries: T, B, L, ...?

opportunity

In France: CEA-Saclay, IPNO, Strasbourg (+CEA-Bruyère)

EFFECTIVE (FIELD) THEORIES

- ✓ Exploratory studies, beset by power counting issues, except in special cases, eg. heavy deformed nuclei
  - o Open field: no known power counting
  - o What new EFT(s) apply?

In France: lots of expertise on mean-field models, shell model; can bridge to EFT?

cf. Grasso, Lacroix + Yang

↓

+ ?

opportunity

HEAVY NUCLEI, NUCLEAR MATTER

Summary

EFT is a general framework for *theory* construction

- ✓ proper symmetries
- ✓ model independent
- ✓ controlled expansion

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

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

Opportunities exist that connect with other efforts

- o hypernuclear EFT for lattice QCD
- o role of unitarity and clusterization
- o EFT for nuclear matter and heavy nuclei
- o …