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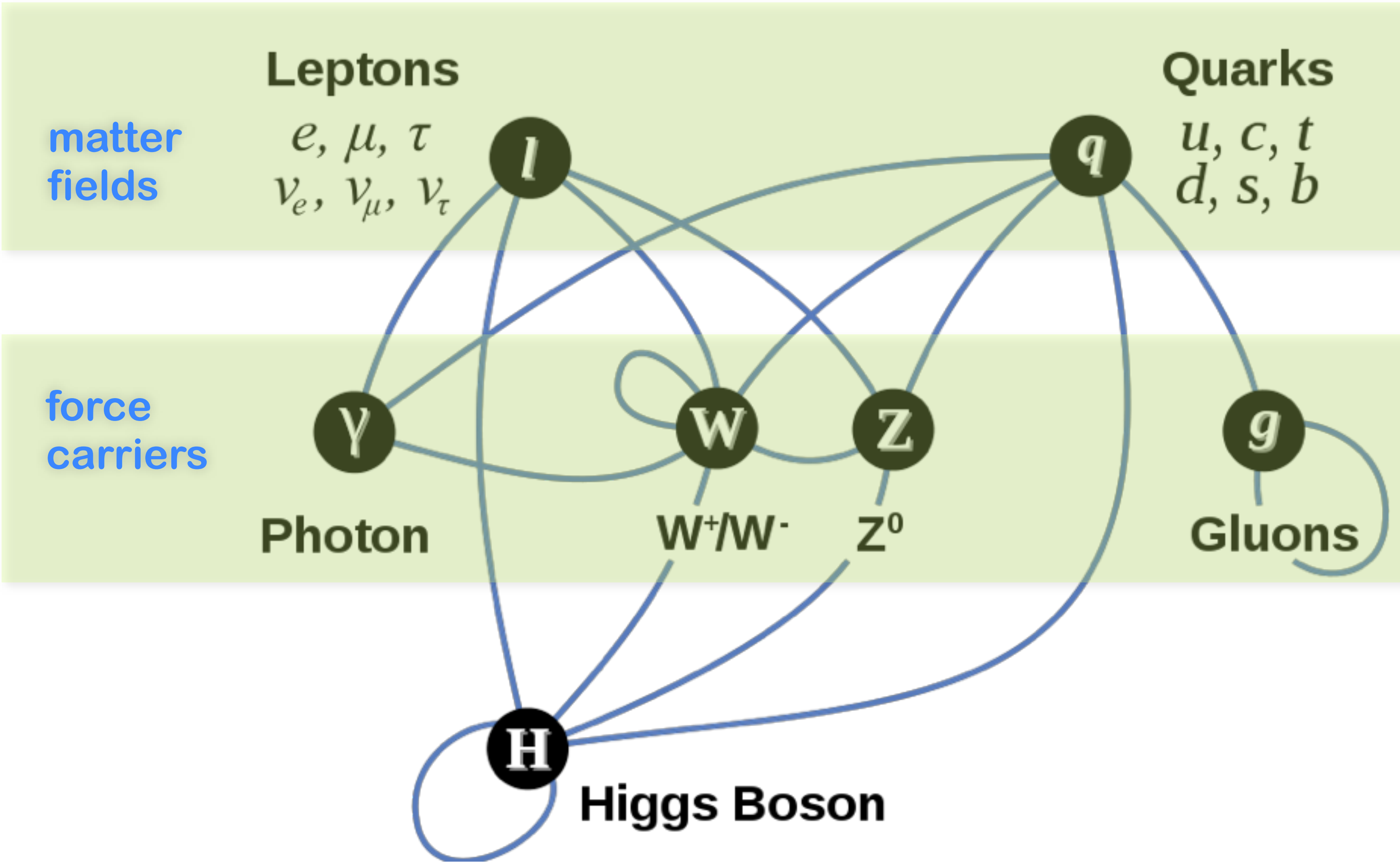
Universität Regensburg, 23.1.2012

Chiral dynamics: From hadrons to nuclei

Outline

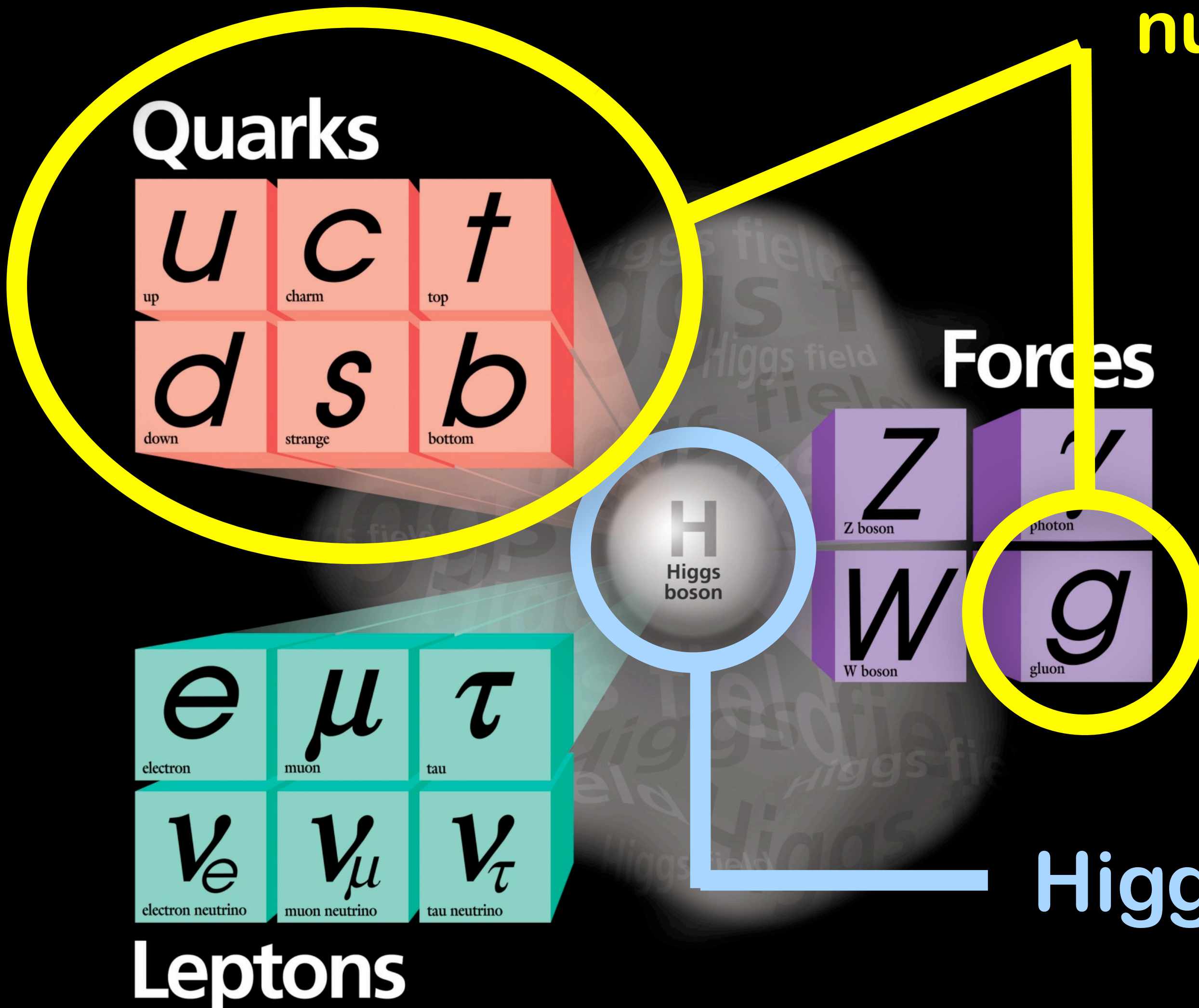
- Introduction
- Chiral perturbation theory
- Nuclear forces and light nuclei
- Few-N physics with external probes
- Nuclear dynamics on the lattice: the Hoyle state
- Summary & outlook

The Standard Model

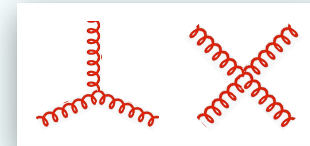
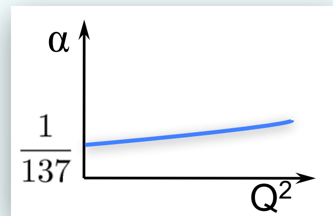
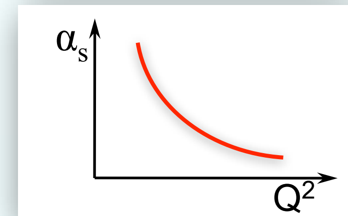
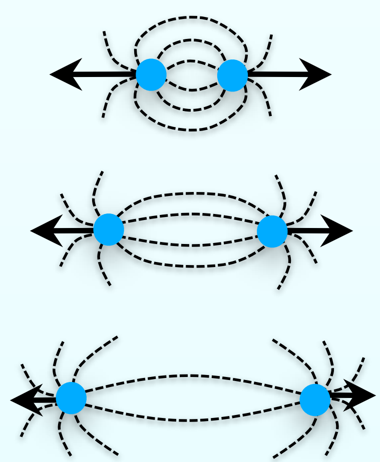
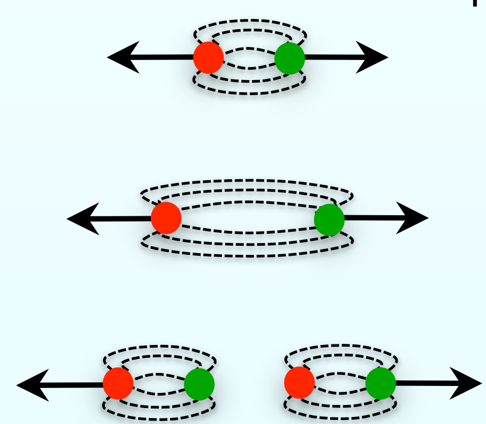


Open questions within the SM

QCD ⟷ hadron & nuclear physics

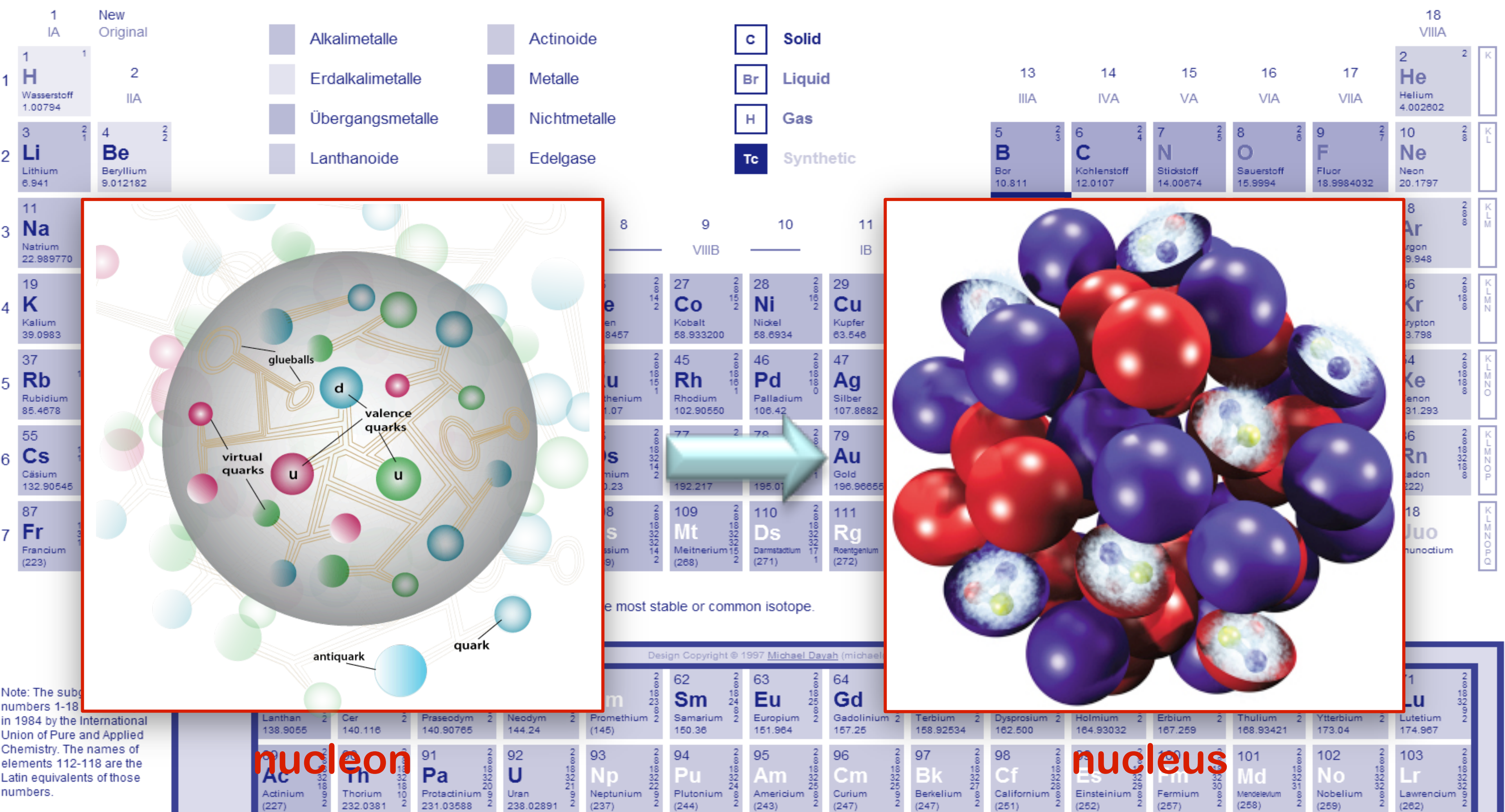


Higgs mechanism
(not yet verified)

	QED	QCD
matter particles	leptons (e, μ, τ)	quarks (u, d, s, c, b, t)
force couples to	electromagnetic charge	3 color charges (r,g,b)
exchange particles	photons (uncharged)	gluons (charged) 
coupling constant	increases as energy grows 	decreases as energy grows 
observed particles	leptons, photons	hadrons (bound states of quarks and gluons)
energy density	~ 1/r 	~ r 

Quantum Chromodynamics (QCD)

Periodensystem der Elemente



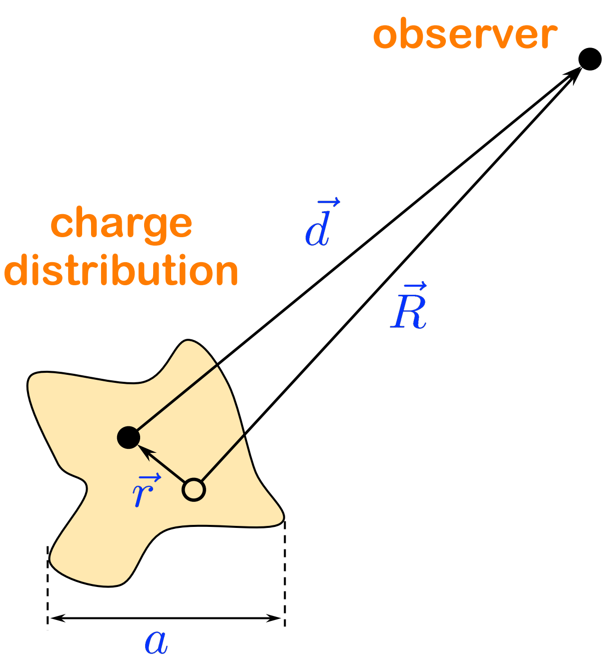
Effective Field Theories

What is effective?

Effective (field) theories = approximate theories to describe phenomena which occur at a chosen length/energy range.

Example: multipole expansion for electric potentials

Electric potential from a localized charge distribution: $V(\vec{R}) \propto \int d^3r \, \frac{\rho(\vec{r})}{|\vec{R}-\vec{r}|}$



Only moments of $\rho(\vec{r})$ are needed to determine $V(\vec{R})$ at large distances ($a \ll R$):

$$V(\vec{R}) = \frac{q}{R} + \frac{1}{R^3}\sum_i R_i P_i + \frac{1}{6R^5}\sum_{ij}(3R_iR_j - \delta_{ij}R^2)Q_{ij} + \ldots$$

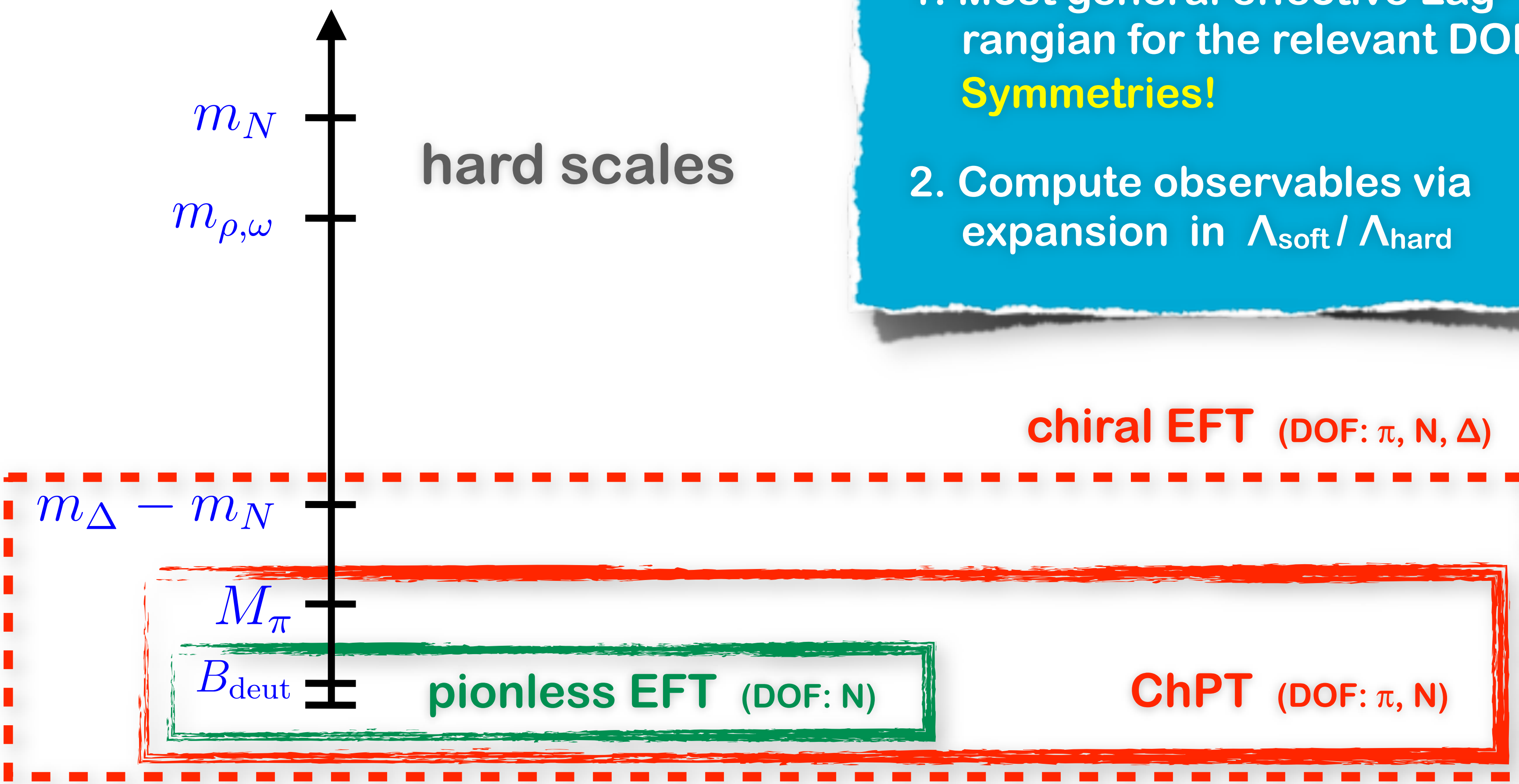
with the moments („low-energy constants"):

$$q = \int d^3r \, \rho(\vec{r}), \qquad P_i = \int d^3r \, \rho(\vec{r}) \, r_i, \qquad Q_{ij} = \int d^3r \, \rho(\vec{r})(3r_ir_j - \delta_{ij}r^2) \, .$$

Scales in nuclear physics

The EFT „recipe“

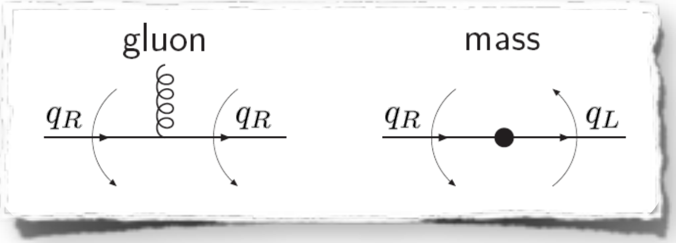
1. Most general effective Lagrangian for the relevant DOF
   Symmetries!
2. Compute observables via expansion in $\Lambda_{soft} / \Lambda_{hard}$



Chiral perturbation theory

QCD and chiral symmetry

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G_{\mu\nu}G^{\mu\nu} + \underbrace{\bar{q}_L i \not{D} q_L + \bar{q}_R i \not{D} q_R}_{\text{SU(2)}_L \text{ x SU(2)}_R \text{ invariant}} - \underbrace{\bar{q}_L \mathcal{M} q_R - \bar{q}_R \mathcal{M} q_L}_{\text{break chiral symmetry}}$$



Light quark masses ($\overline{\rm MS},\ \mu = 2$ GeV):

$$\begin{aligned} m_u &= 1.5 \ldots 3.3 \text{ MeV} \\ m_d &= 3.5 \ldots 6.0 \text{ MeV} \end{aligned} \ll \Lambda_{QCD} \sim 220 \text{ MeV}$$

→ $\mathcal{L}_{\rm QCD}$ is approx. $SU(2)_L$ x $SU(2)_R$ invariant

spontaneous breakdown to $SU(2)_V \subset SU(2)_L$ x $SU(2)_R$ → Goldston Bosons (pions)

Chiral perturbation theory

- Ideal world [$m_u = m_d = 0$], zero-energy limit: non-interacting massless GBs (+ strongly interacting massive hadrons)
- Real world [$m_u,\ m_d \ll \Lambda_{QCD}$], low energy: weakly interacting light GBs (+ strongly interacting massive hadrons)

→ expand about the ideal world (ChPT)

Chiral perturbation theory

Effective Lagrangian for hadronic DOF (π, N, ...) Chiral symmetry!

pion decay constant (in the chiral limit)

F_π ~ 94 MeV

pion fields

quark mass matrix

$$\mathcal{L}_\pi^{(2)} = \frac{F^2}{4}\left[\mathrm{Tr}(\partial_\mu U \partial^\mu U^\dagger) + \mathrm{Tr}(U\chi + U^\dagger\chi)\right], \quad \text{where } \chi = 2B\mathcal{M}.$$

$$\mathcal{L}_\pi^{(4)} = L_1[\mathrm{Tr}(\partial_\mu U^\dagger \partial^\mu U)]^2 + L_2 \mathrm{Tr}(\partial_\mu U^\dagger \partial_\nu U)\mathrm{Tr}(\partial^\mu U^\dagger \partial^\nu U) + \ldots + L_8 \mathrm{Tr}(\chi U \chi U + \chi U^\dagger \chi U^\dagger)$$

low-energy constants

Gasser, Leutwyler '84

- Low-energy observables computable via a perturbative expansion in $Q = \frac{p \sim M_\pi}{\Lambda_\chi}$

  Weinberg '79

  hard scale that enters L_i

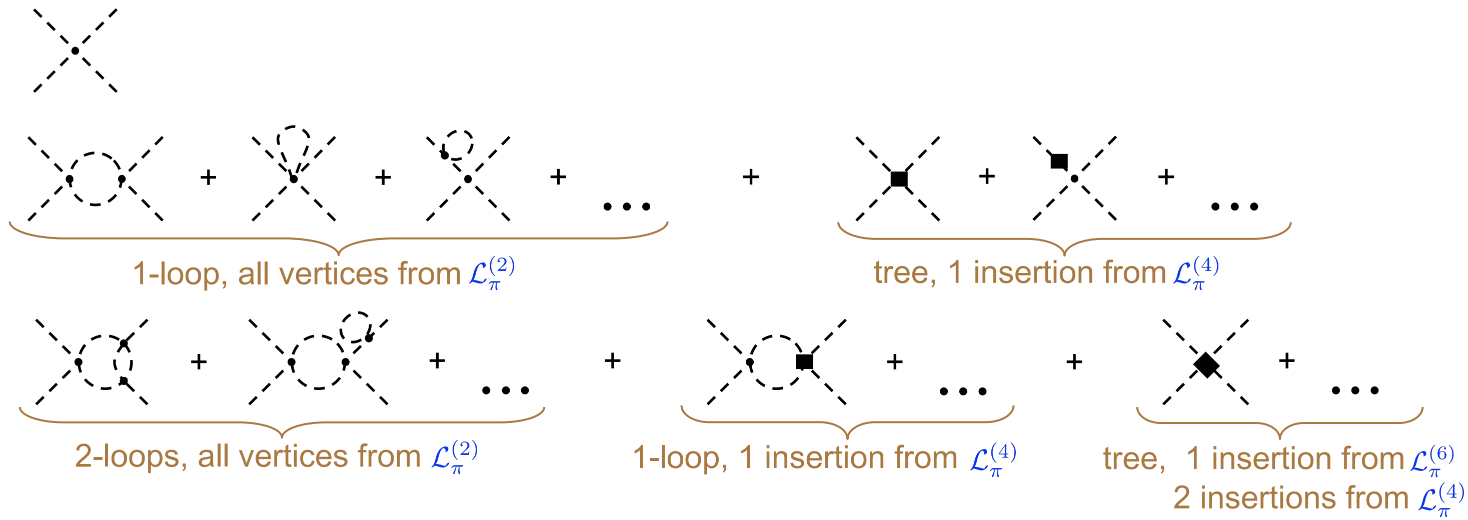
- At any order Q^n, a finite number of (unknown) LECs contribute

Pion scattering lengths in ChPT

Q^2 :

Q^4 :

Q^6 :



Predictive power?

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

# of LECs increasing…

S-wave $\pi\pi$ scattering length

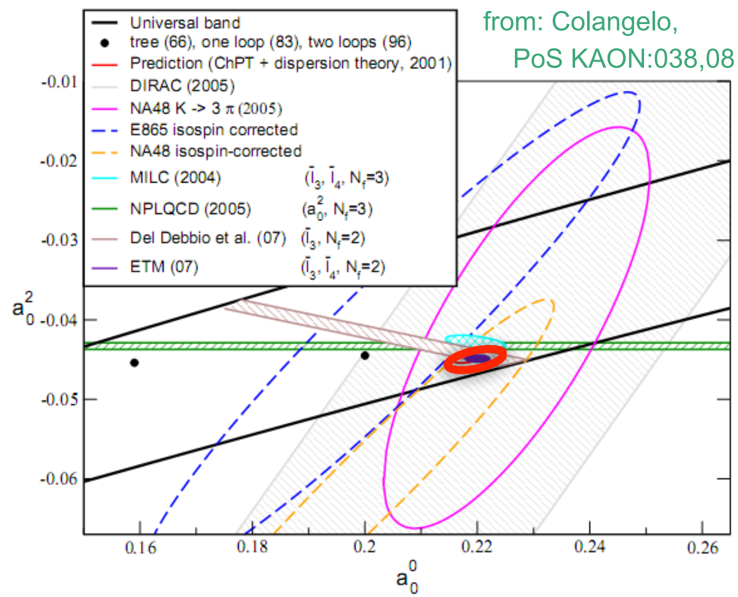
LO: $a_0^0 = 0.16$ (Weinberg '66)

NLO: $a_0^0 = 0.20$ (Gasser, Leutwyler '83)

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

NNLO + disp. relations: (Colangelo et al.)

$$a_0^0 = 0.217 \pm 0.008\,(\rm exp) \pm 0.006\,(\rm th)$$

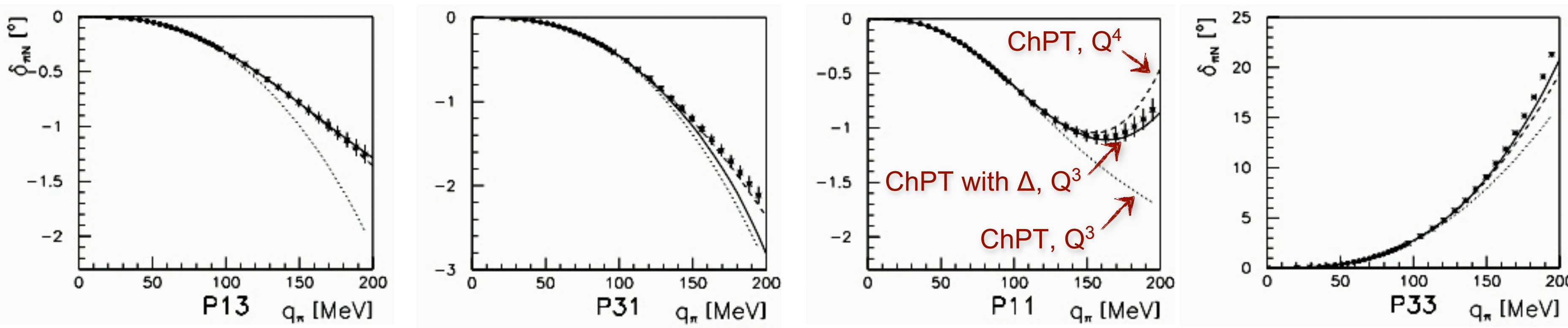


from: Colangelo, PoS KAON:038,08

Pion-nucleon scattering

Pion-nucleon scattering in heavy-baryon ChPT

Fettes, Meißner ’01

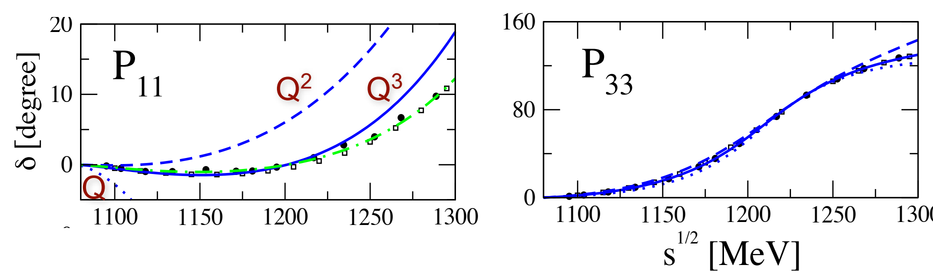


Some recent developments

- ChEFT with explicit Δ(1232) DOF
  Hemmert, Meißner, Pascalutsa, EE, Krebs, ...
- covariant formulations
  Alarcon, Camalich, Oller, ...
- unitarized ChPT
  Gasparyan, Lutz

πN scattering in Unitarized ChPT

Gasparyan, Lutz ’11



Few nucleons

Low-energy NN interaction is strong (shallow bound states) → need nonperturbative methods

Simplification: nonrelativistic problem ($|\vec{p}_i| \sim M_\pi \ll m_N$) → the QM A-body problem...

Weinberg '91,'92

$$\left[\left(\sum_{i=1}^{A} \frac{\vec{\nabla}_i^2}{2m_N} + \mathcal{O}(m_N^{-3})\right) + \underbrace{V_{2N} + V_{3N} + V_{4N} + \ldots}_{\text{derived within in ChPT}}\right]|\Psi\rangle = E|\Psi\rangle$$

Derivation methods:

- matching to the amplitude Kaiser, van Kolck, Friar, Higa, Robilotta, ...
- decoupling of pions & nucleons via a UT EE, Glöckle, Meissner, Krebs, Bernard

Chiral expansion of the nuclear Hamiltonian:

$$V_{2\mathrm{N}} = V_{2\mathrm{N}}^{(0)} + V_{2\mathrm{N}}^{(2)} + V_{2\mathrm{N}}^{(3)} + V_{2\mathrm{N}}^{(4)} + \ldots \quad \longleftarrow \quad \langle V_{2\mathrm{N}}\rangle \sim 20\ \mathrm{MeV/pair}$$

$$V_{3\mathrm{N}} = V_{3\mathrm{N}}^{(3)} + V_{3\mathrm{N}}^{(4)} + \ldots \quad \longleftarrow \quad \langle V_{3\mathrm{N}}\rangle \sim 1\ \mathrm{MeV/triplet}$$

$$V_{4\mathrm{N}} = V_{4\mathrm{N}}^{(4)} + \ldots \quad \longleftarrow \quad \langle V_{4\mathrm{N}}\rangle \sim 0.1\ \mathrm{MeV/quartet}$$

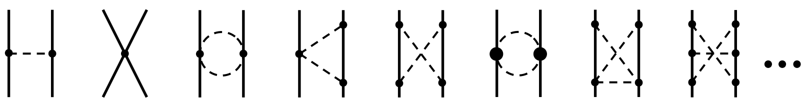
(from Pudliner et al., PRL 74 (95) 4396)

Nucleon-nucleon potential

Ordonez et al. ’94; Friar & Coon ’94; Kaiser et al. ’97; E.E. et al. ’98,‘03; Kaiser ’99-’01; Higa, Robilotta ’03; …

State of the art: N³LO (Q^4) in the χ expansion

Entem-Machleidt, EE-Glöckle-Meissner

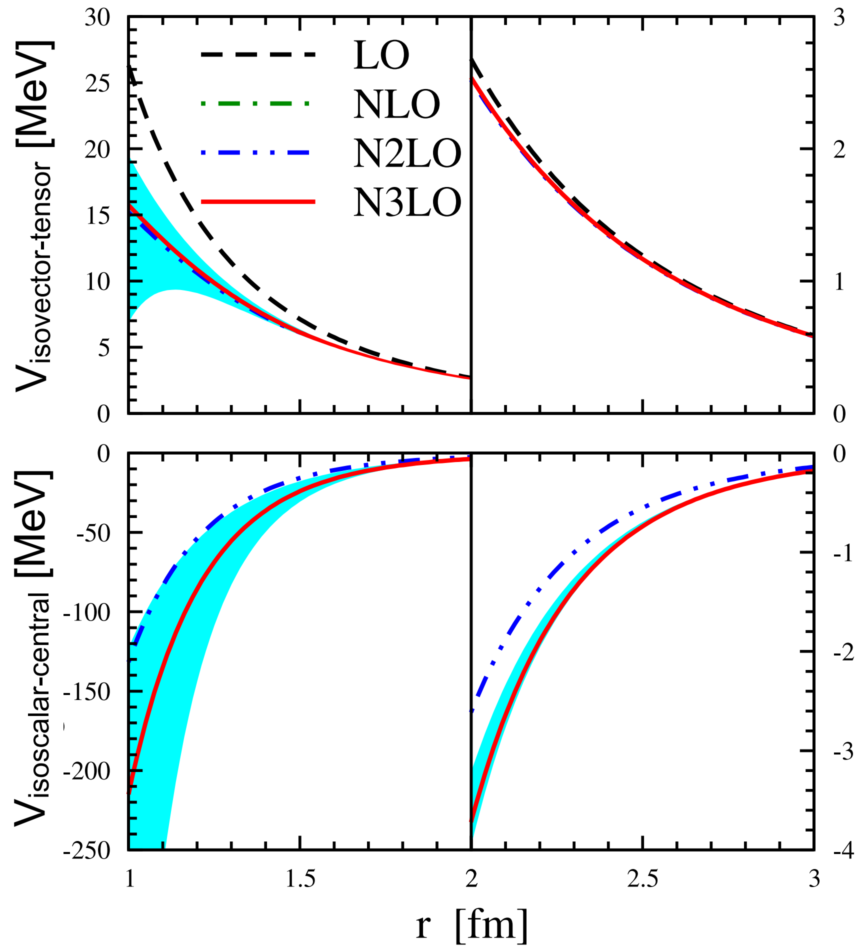


- Long-range part: 1π, 2π and 3π exchange (parameter-free: all LECs from πN scattering)
- Short-range part: 24 short-range operators, LECs fixed from NN data
- Isospin-breaking corrections

Further details in recent review articles:

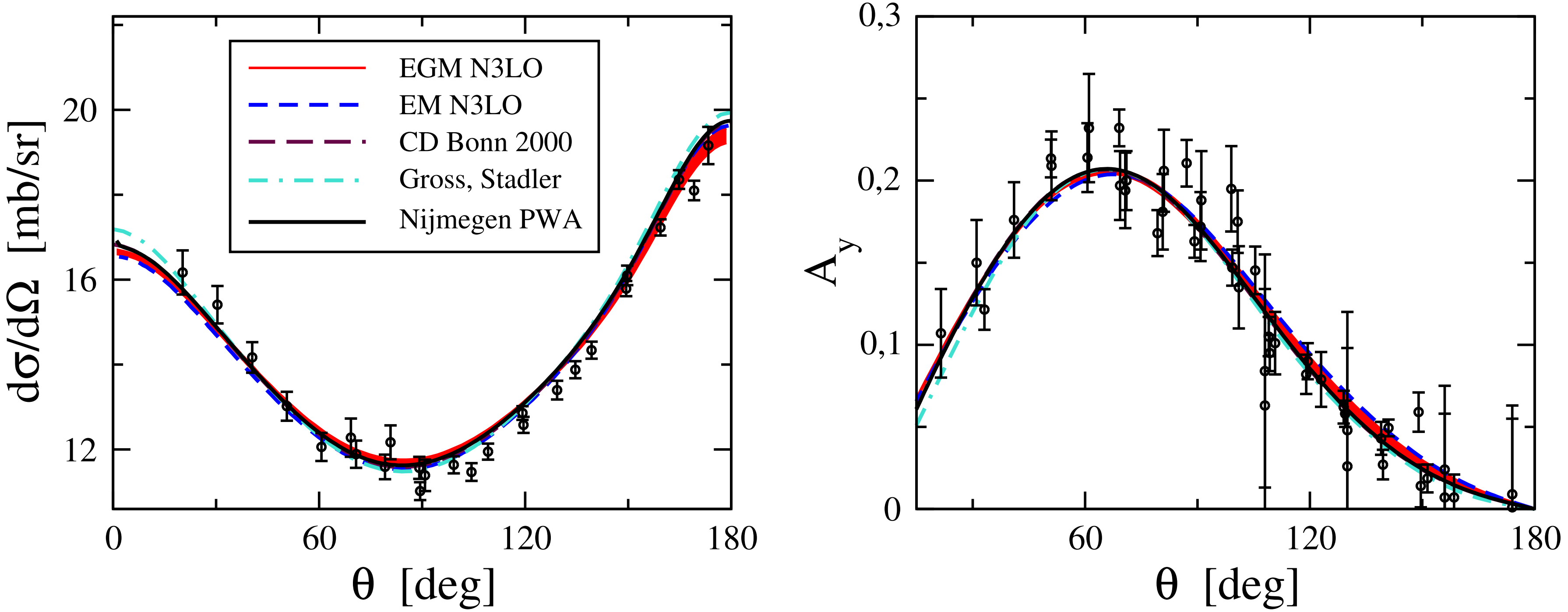
EE, Prog. Part Nucl. Phys. 57 (06) 654
EE, Hammer, Meißner, Rev. Mod. Phys. 81 (09) 1773
Entem, Machleidt, Phys. Rept. 503 (11) 1
EE, Meißner, arXiv:1201.2136,
submitted to Ann. Rev. Nucl. Part. Sci.

Chiral expansion of the long-range two-nucleon potential



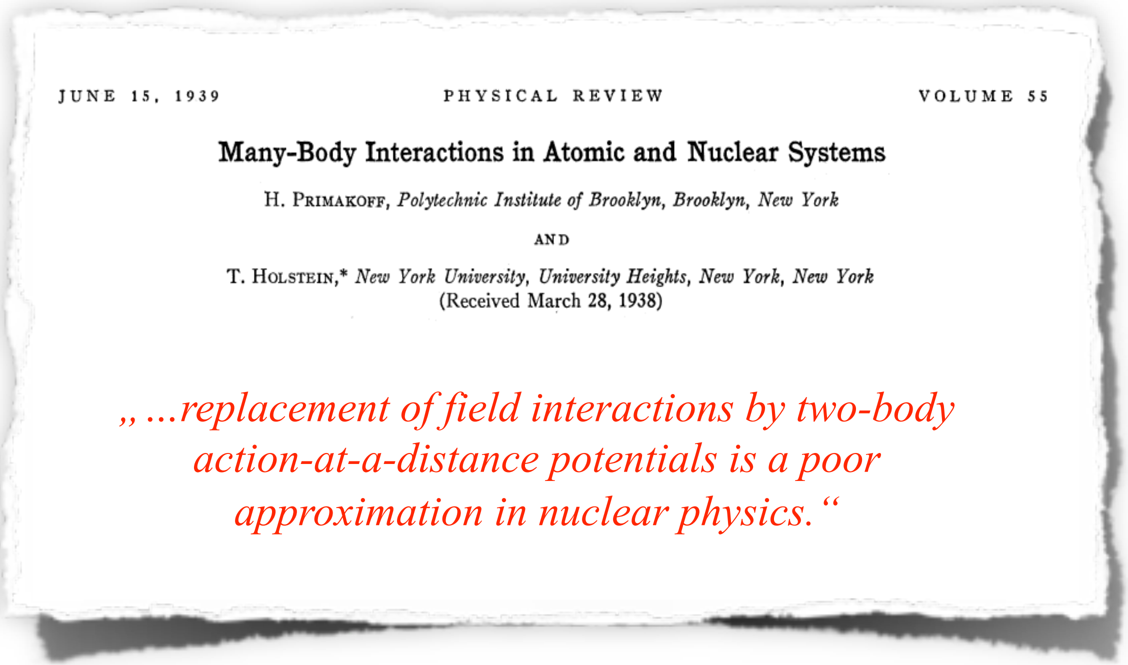
Nucleon-nucleon scattering

Neutron-proton differential cross section and analyzing power at $E_{lab} = 50$ MeV



accurate description of data up to $E_{lab} \sim 200$ MeV at N^{3}LO is comparable to modern phenomenological potentials

Three-nucleon force



JUNE 15, 1939 PHYSICAL REVIEW VOLUME 55

Many-Body Interactions in Atomic and Nuclear Systems

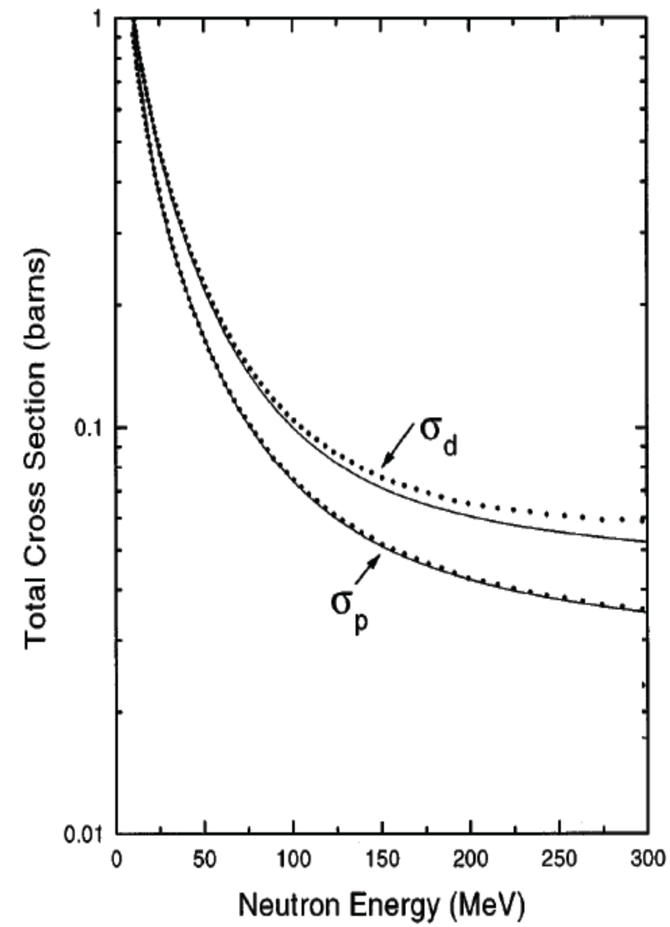
H. PRIMAKOFF, *Polytechnic Institute of Brooklyn, Brooklyn, New York*

AND

T. HOLSTEIN,* *New York University, University Heights, New York, New York*

(Received March 28, 1938)

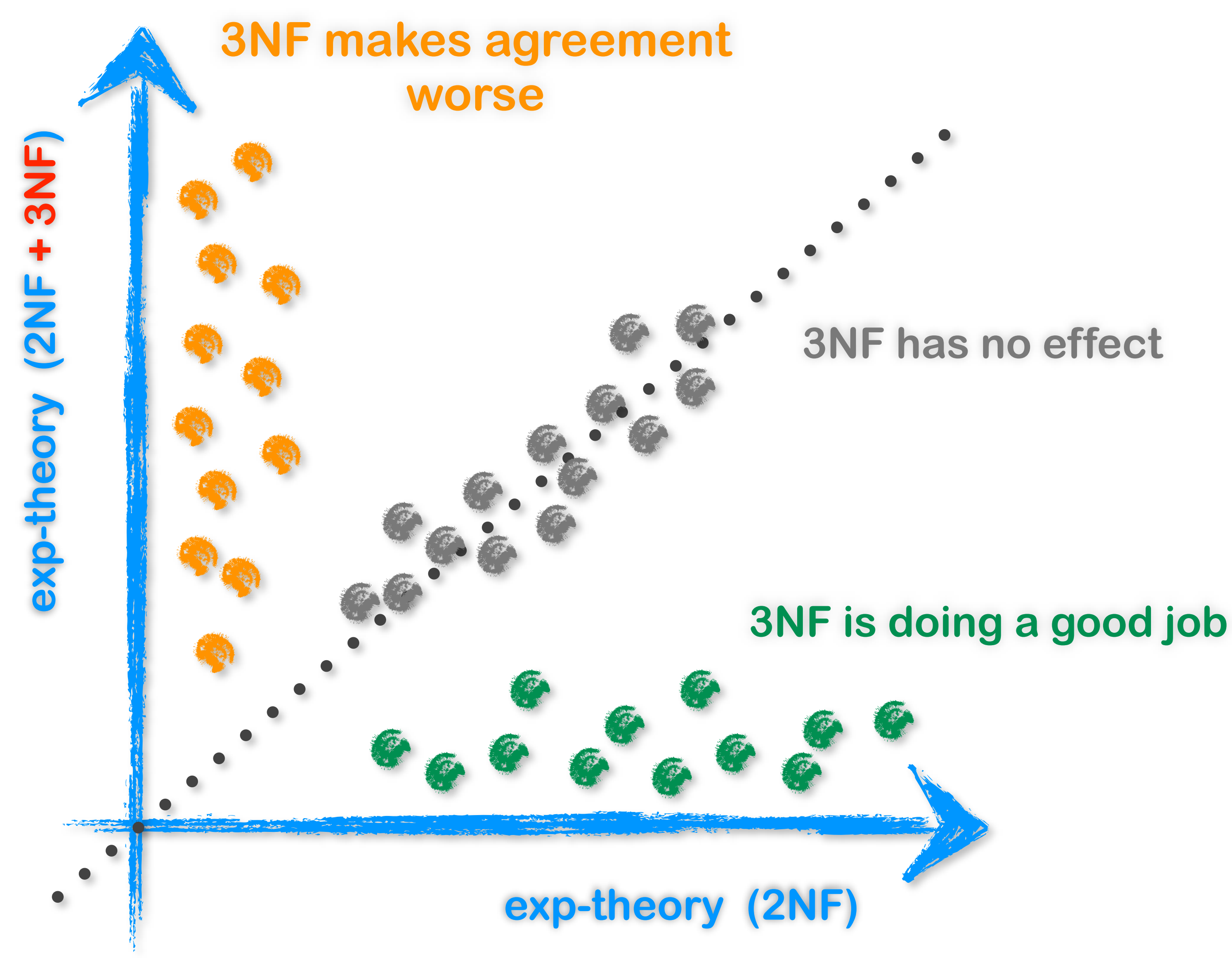
„ ...replacement of field interactions by two-body action-at-a-distance potentials is a poor approximation in nuclear physics.“



Some indications of the 3NF

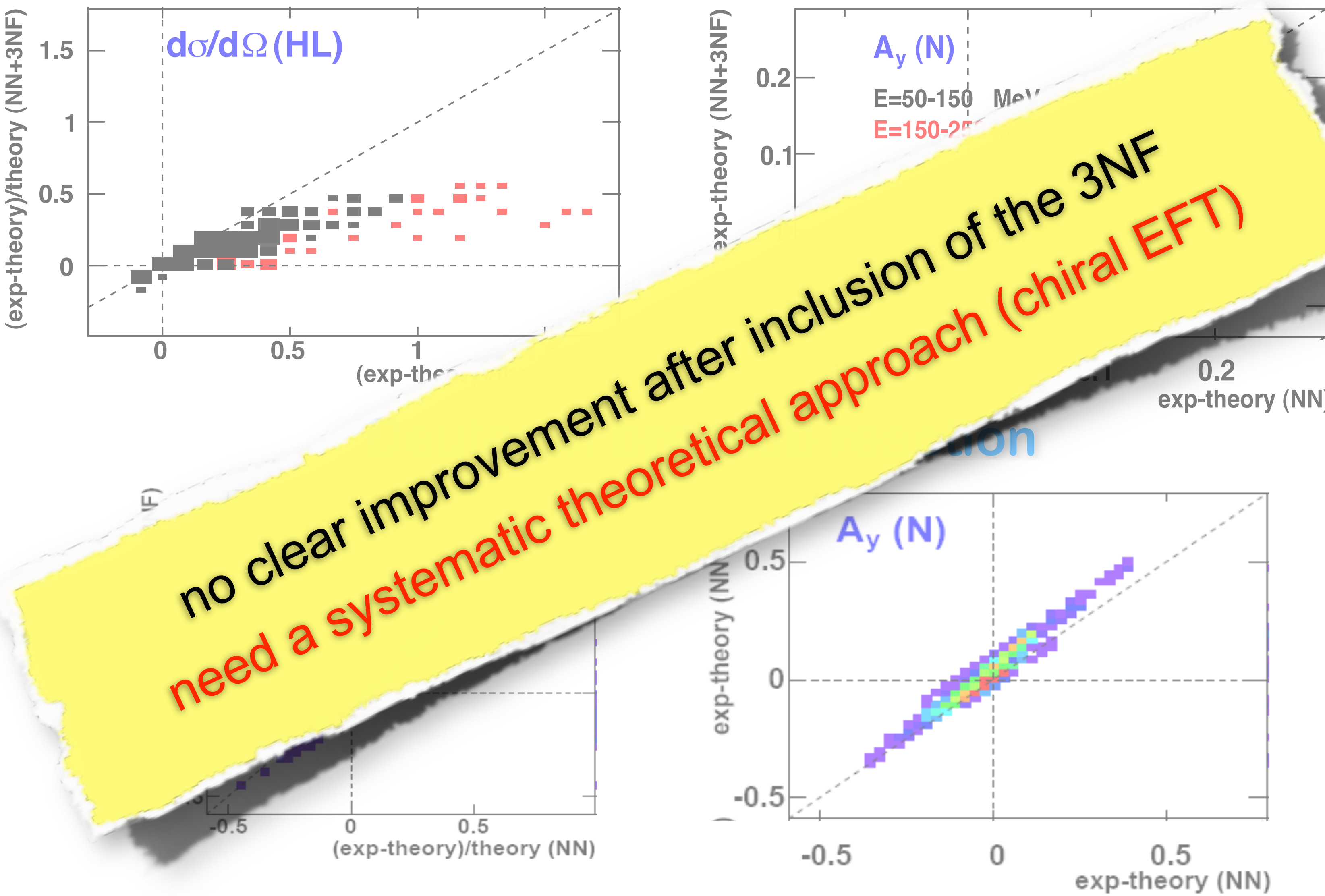
- ^{3}H binding energy calculated based on V_{NN} is typically underbound by ~ 1 MeV
- Three-nucleon continuum...

Three-nucleon force



Three-nucleon force

Elastic nucleon-deuteron scattering



no clear improvement after inclusion of the 3NF

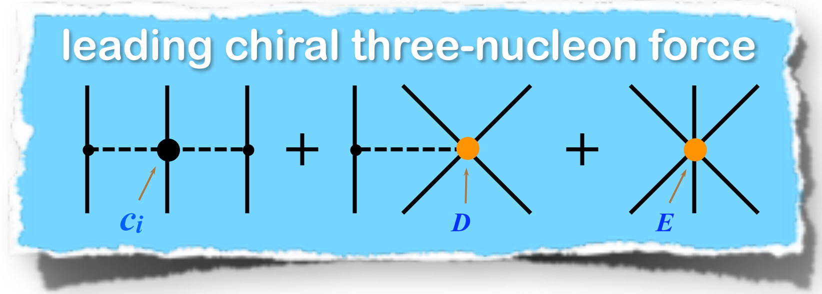
need a systematic theoretical approach (chiral EFT)

from: Kalantar-Nayestanaki, EE, Messchendorp, Nogga, Rev. Mod. Phys. 75 (2012) 016301

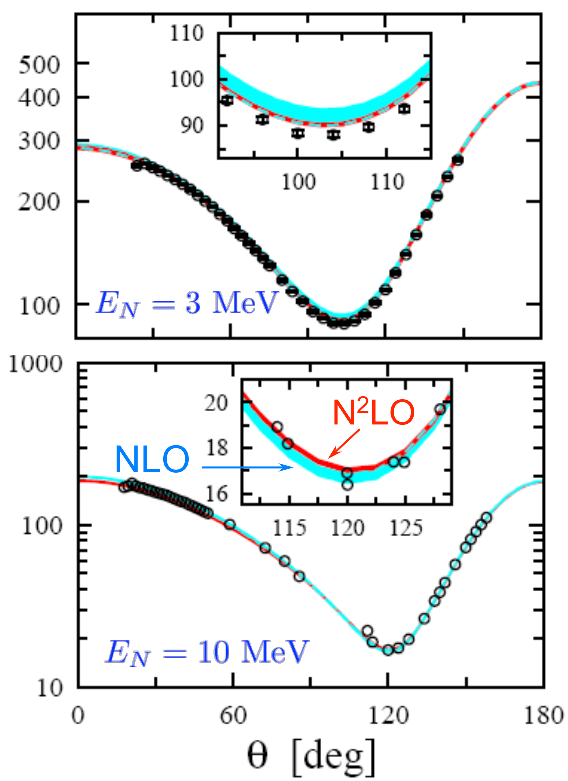
Chiral three-nucleon force

3NF first appears ar N^2LO

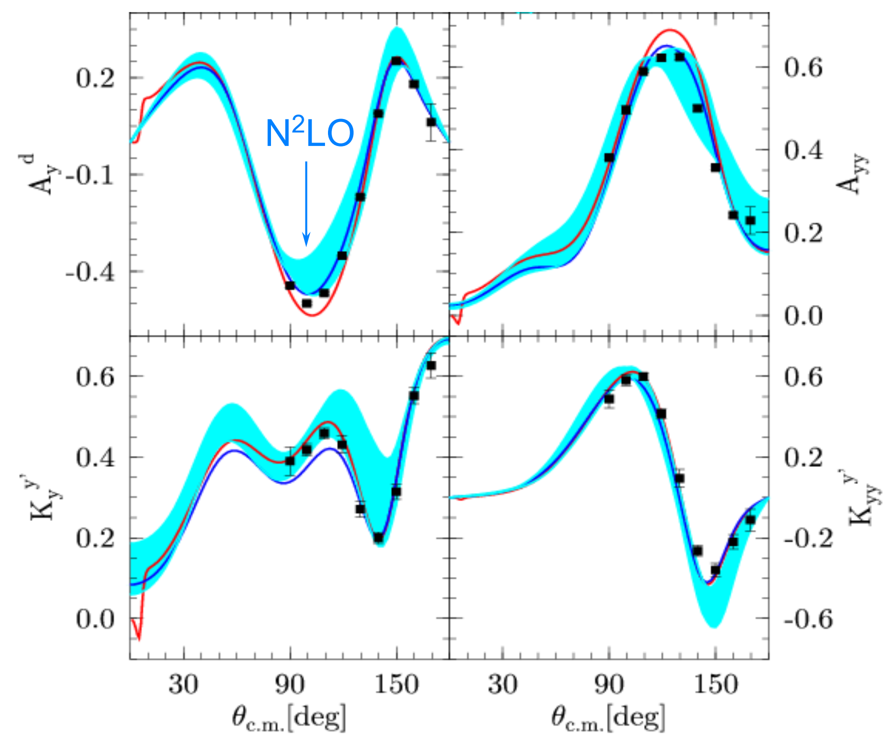
The LECs D,E can be fixed e.g. from ^3H BE and nd doublet scattering length EE, Nogga et al.



Nd elastic cross sections at low energies



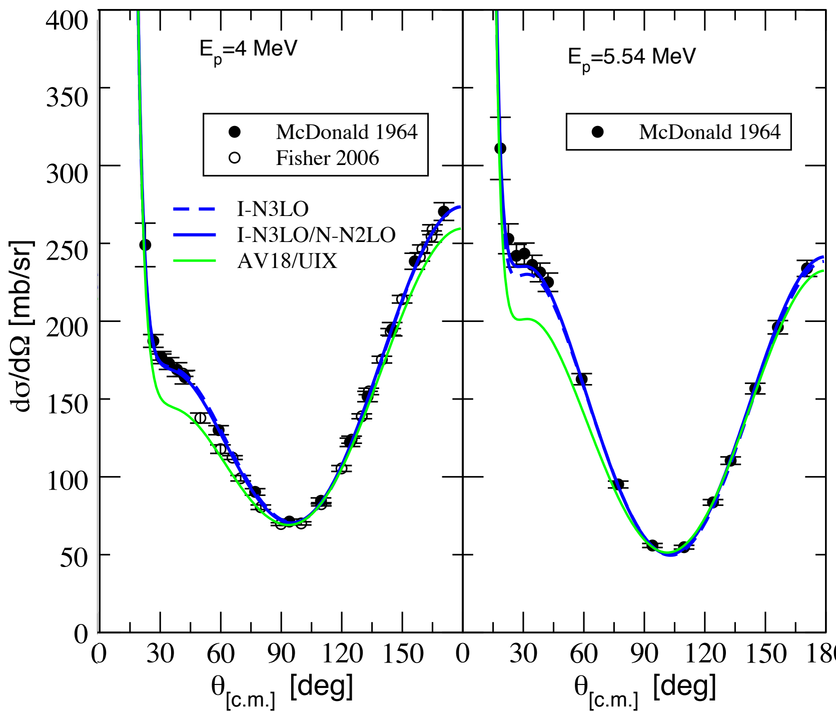
Nd elastic scattering at E_N=90 MeV



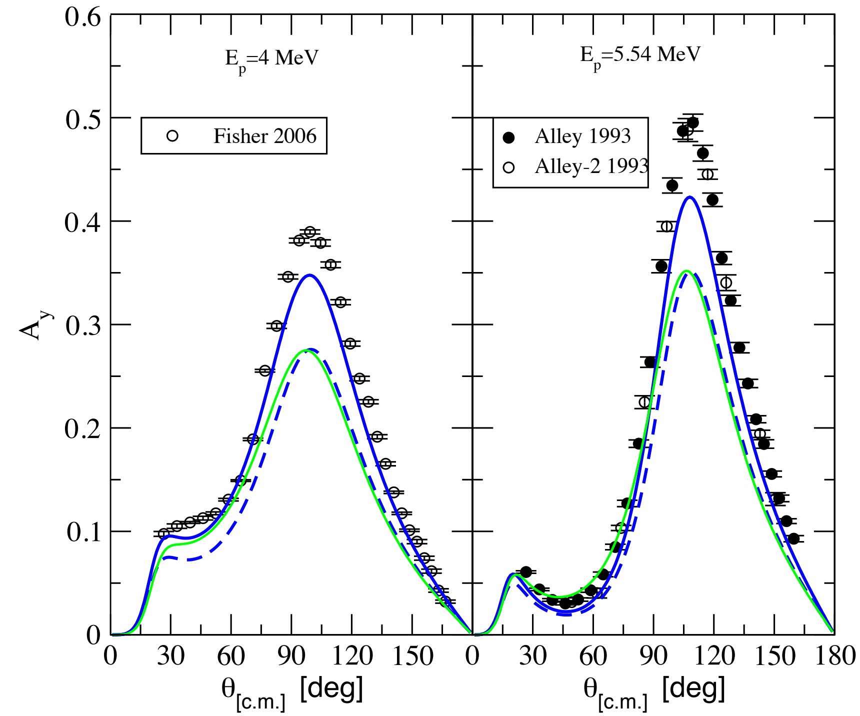
Chiral 3NF effects in 4N scattering

Viviani, Girlanda, Kievsky, Marcucci, Rosatti arXiv:1004.1306

p-^{3}He differential cross section



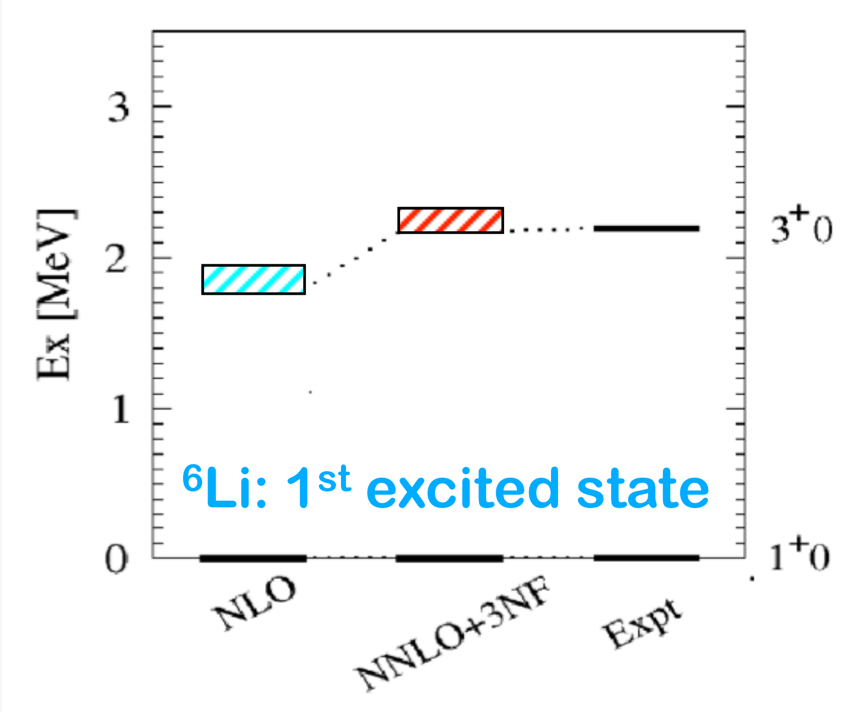
A_y-puzzle in p-^{3}He elastic scattering

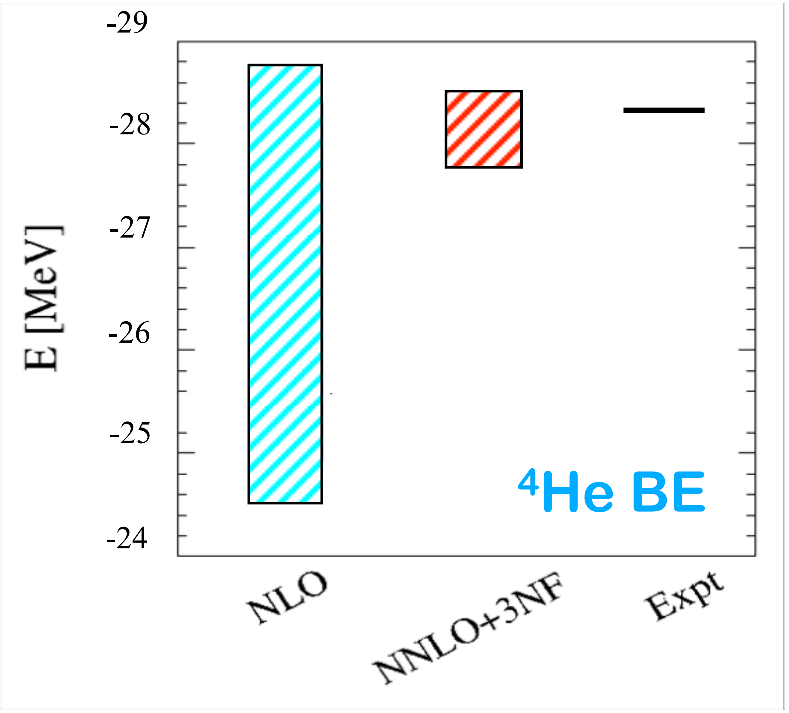


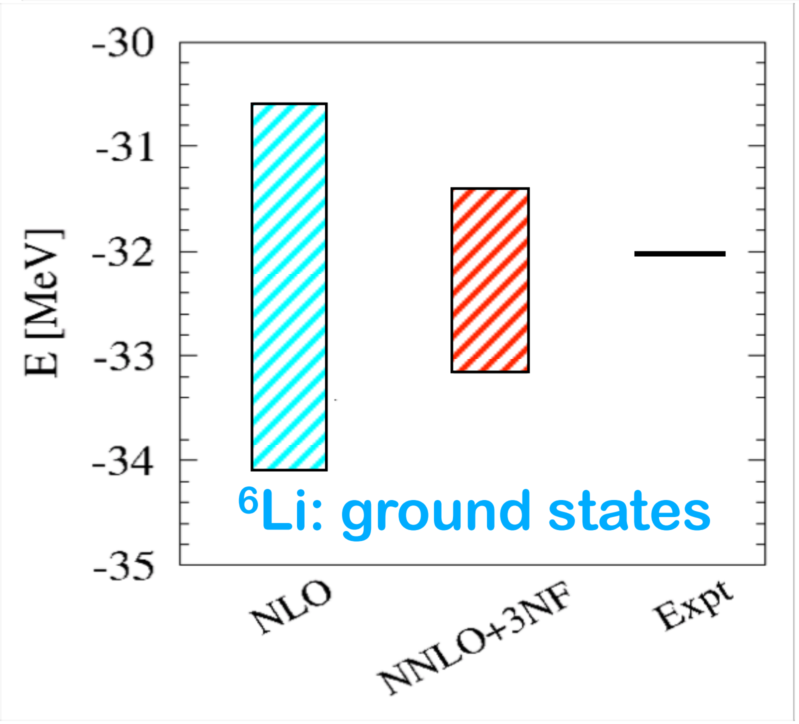
(the LECs D,E are tuned to the ^{3}H and ^{4}He binding energies)

Light nuclei from chiral forces

Nogga et al.

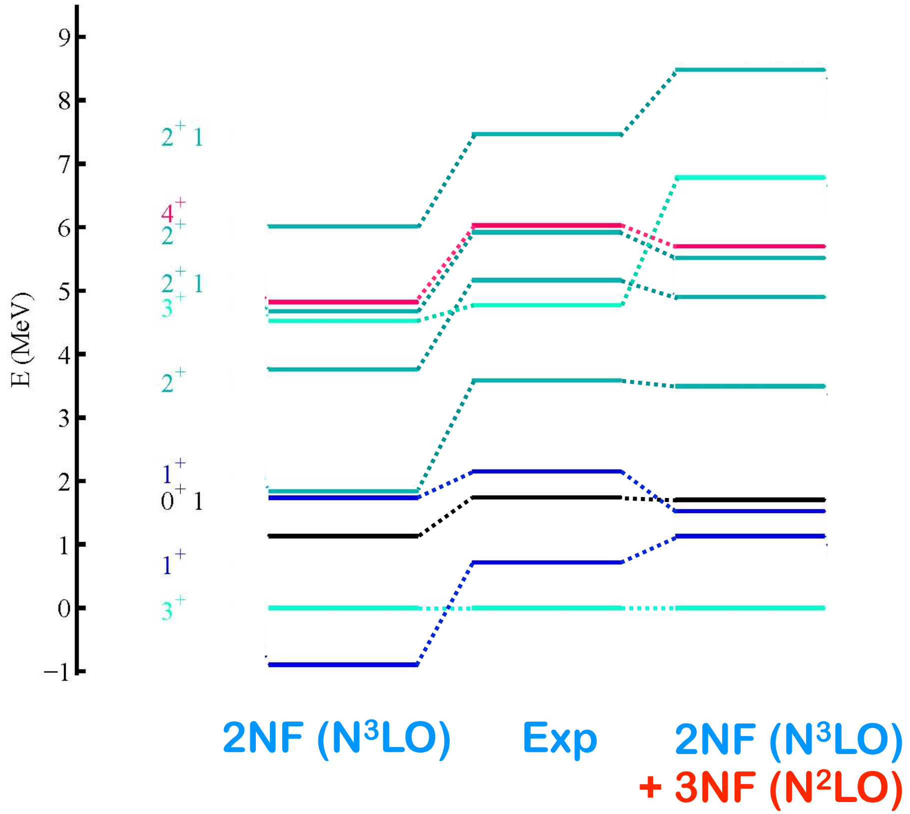






Nuclear structure with chiral forces

^{10}B



Navratil et al., PRL 99 (2007) 042501

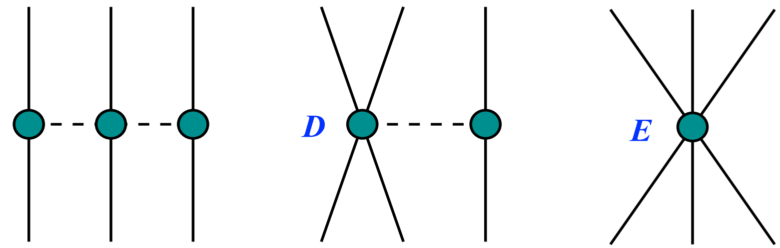
Chiral 3NF at N^2LO are also found to play important role in

- explaining the long lifetime of ^{14}C Holt, Kaiser, Weise '10
- constraining the properties of neutron-rich matter & neutron star radii Hebeler et al.'10
- explaining the structure of Ca isotopes Holt, Otsuka, Schwenk, Suzuki '10

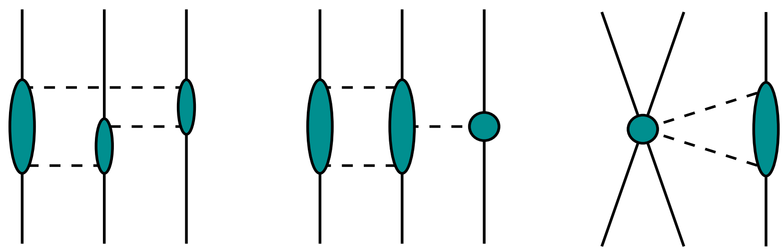
Chiral 3NF beyond N^{2}LO

The first corrections to the leading 3NF are available!

Ishikawa, Robilotta, PRC76 (07); Bernard, EE, Krebs, Meißner, PRC77 (08); PRC84 (11)



- start contributing at N^{2}LO
- fairly restricted operator structure
- also included in various models



- first appear at N^{3}LO
- very rich operator structure
- parameter-free
- effects in Nd scatt., nuclear structure ?

$$V = \frac{2}{3}\boldsymbol{\tau}_2\cdot\boldsymbol{\tau}_3\,\vec{\sigma}_2\cdot\hat{r}_{12}\,\vec{\sigma}_3\cdot\hat{r}_{13}\;f_1(r_{12}, r_{13}, r_{23}) + \left[2+\frac{2}{3}(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2+\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_3+\boldsymbol{\tau}_2\cdot\boldsymbol{\tau}_3)\right]\;f_2(r_{12}, r_{13}, r_{23}) + \ldots$$

at large distances completely determined by chiral symmetry & experimental πN data,

highly nontrivial benchmarks with lattice QCD...

Few-nucleon physics with external probes

Pion-deuteron scattering

Pion-nucleon amplitude at threshold (in the isospin limit): $T^{ba}_{\pi N} \propto \left[\delta^{ab} \boldsymbol{a}^+ + i\epsilon^{bac}\tau^c \boldsymbol{a}^-\right]$

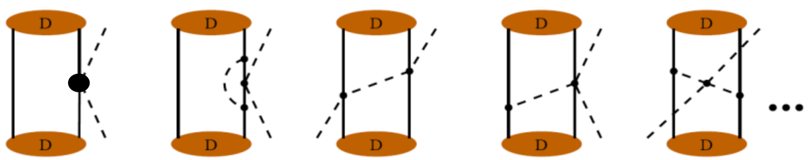
Recent data on hadronic atoms:

πH: $\epsilon_{1s} = (-7.120 \pm 0.012)\,\mathrm{eV}, \quad \Gamma_{1s} = (0.823 \pm 0.019)\,\mathrm{eV}$ Gotta et al., Lect. Notes. Phys. 745 (08) 165

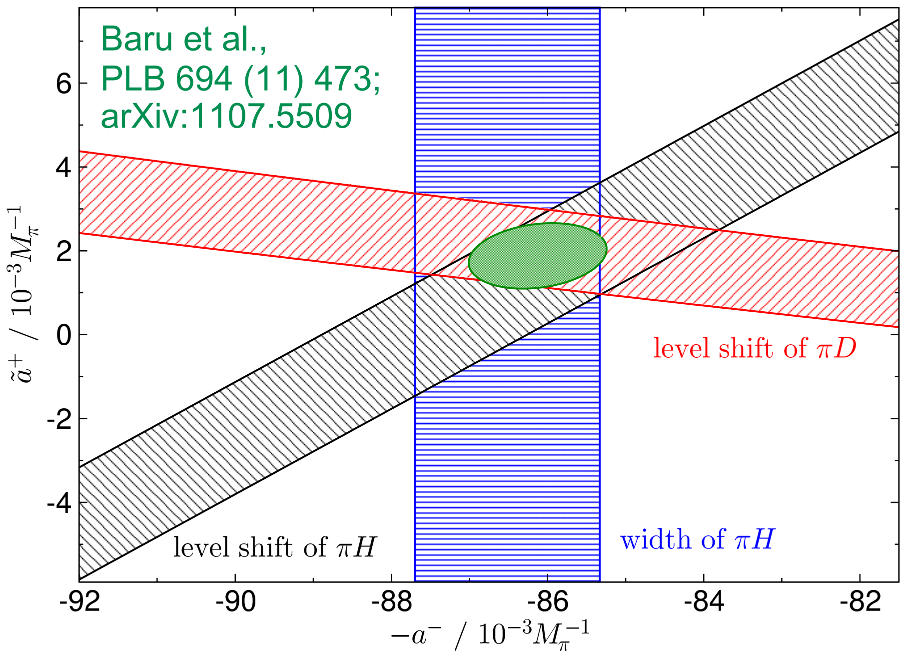
πD: $\epsilon^D_{1s} = (2.356 \pm 0.031)\,\mathrm{eV}$ Strauch et al., Eur. Phys. J A47 (11) 88

Use chiral EFT to extract information on a^+ and a^- from $a_{\pi d}$

Weinberg; Beane, Bernard, Lee, Meißner, EE, Phillips;
Baru, Liebig, Hoferichter, Hanhart, Nogga, ...



- careful analysis of IB effects
- radiative corrections included



Isospin breaking & few-N systems

Origin of isospin breaking in the Standard Model: $m_u \neq m_d$, photons

- Manifestation in the hadron spectrum: mass splittings

$$M_{\pi^\pm} = 139.57 \text{ MeV}, \quad M_{\pi^0} = 134.98 \text{ MeV} \quad \leftarrow \text{ mainly of electromagnetic origin}$$

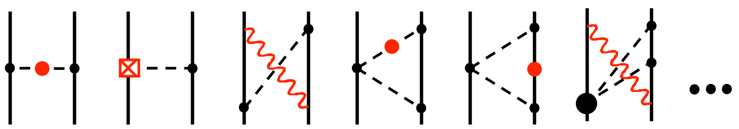
$$m_p = 938.27 \text{ MeV}, \quad m_n = 939.57 \text{ MeV} \quad \leftarrow \text{ both strong and electromagnetic}$$

$$\delta m_N^{\rm str} \equiv (m_n - m_p)^{\rm str} = 2.05 \pm 0.3 \text{ MeV}$$ Gasser, Leutwyler '82 (Cottingham sum rule)

$$\delta m_N^{\rm em} \equiv (m_n - m_p)^{\rm em} = -0.76 \pm 0.3 \text{ MeV}$$

- Different (strong) forces between nn, np and pp

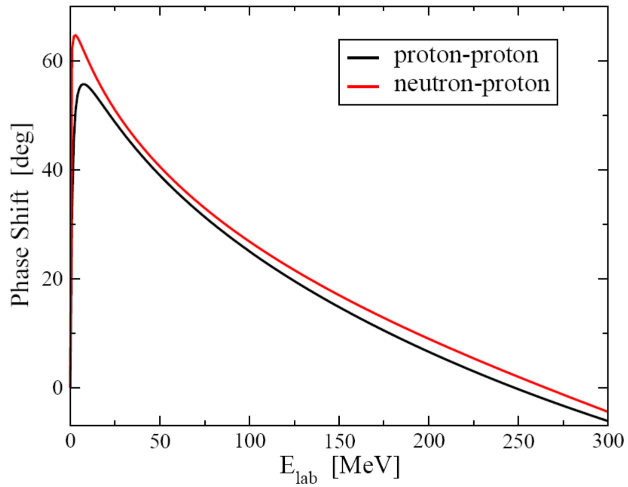
  van Kolck, Friar, Niskanen, Kaiser, EE, Meißner, …



Some manifestations

– differences in NN phase shifts,

– BE differences in mirror nuclei (CSB)



Isospin breaking & few-N systems

The challenge: can we extract the strong nucleon mass shift from hadronic reactions?

- $dd \rightarrow \alpha\pi^0$ cross section measurement at IUCF @ 228.5 / 231.8 MeV

  Stephenson et al. ’03

$$\sigma = 12.7 \pm 2.2 \,/\, 15.1 \pm 3.1 \text{ pb}$$

Theoretical analysis challenging; first estimations yield the right order of magnitude.

Gardestig et al. ’04; Nogga et al.’06

- forward-backward asymetry in $np \rightarrow d\pi^0$ @ 279.5 MeV (TRIUMF)

  Opper et al. ’03

$$A_{\rm fb} = \frac{\int [d\sigma/d\Omega(\theta) - d\sigma/d\Omega(\pi-\theta)]\, d[cos\theta]}{\int [d\sigma/d\Omega(\theta) + d\sigma/d\Omega(\pi-\theta)]\, d[cos\theta]} = \left[17.2 \pm 8(\text{stat}) \pm 5.5(\text{sys})\right] \times 10^{-4}$$

$np \to d\pi^0$ & the np mass difference

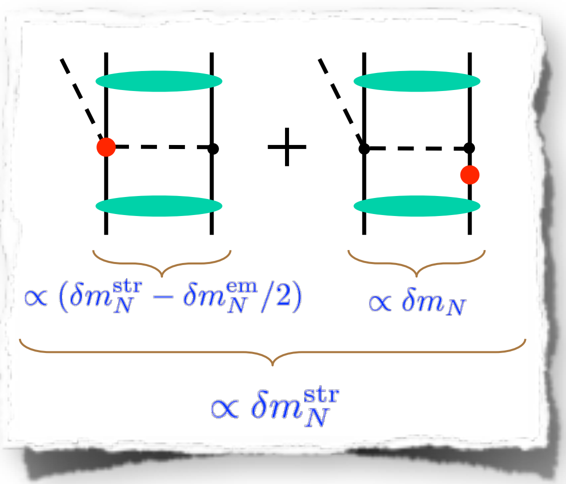
Bolton, Miller '09; Filin, Baru, E.E., Haidenbauer, Hanhart, Kudryavtsev, Meißner '09

$$\frac{d\sigma}{d\Omega} = A_0 + \underbrace{A_1 P_1(\cos\theta_\pi)}_{\text{gives rise to } A_{fb}} + A_2 P_2(\cos\theta_\pi) + \ldots \longrightarrow A_{fb} \simeq \frac{A_1}{2A_0}$$

- A_0 can be determined from the pionic deuterium lifetime measurement @ PSI:

$$\sigma(np \to d\pi^0) = \frac{1}{2}\sigma(nn \to d\pi^-) = \frac{1}{2} \times 252^{+5}_{-11}\,\eta\ [\mu\text{b}] \longrightarrow A_0 = 10.0^{+0.2}_{-0.4}\,\eta\ [\mu\text{b}]$$

- A_1 at LO in chiral EFT $\longrightarrow$ $A_{\rm fb}^{\rm LO} = (11.5 \pm 3.5) \times 10^{-4}\ \delta m_N^{\rm str}/\text{MeV}$ Baru et al.'09



Experiment: $A_{\rm fb} = \left[17.2 \pm 8(\text{stat}) \pm 5.5(\text{sys})\right] \times 10^{-4}$

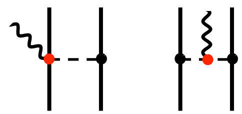
$\longrightarrow$ $\delta m_N^{\rm str} = 1.5 \pm 0.8\,(\text{exp.}) \pm 0.5\,(\text{th.})\ \text{MeV}$

Lattice: $\delta m_N^{\rm str} = 2.26 \pm 0.57 \pm 0.42 \pm 0.10\ \text{MeV}$ Beane et al.'07

Cottingham SR: $\delta m_N^{\rm str} = 2.05 \pm 0.3\ \text{MeV}$ Gasser, Leutwyler '82

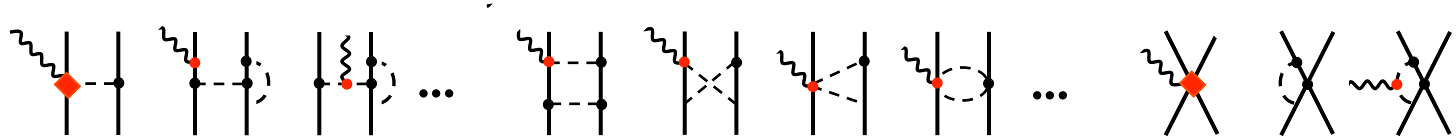
Photon-induced reactions

Order eQ^{-1} :



well known since decades   Chemtob, Rho, Friar, Riska, Adam, …

Order eQ :



- **Threshold kinematics**   Park, Min, Rho '95; Park, Kubodera, Min, Rho;   Song, Lazauskas, Park, Min, ...

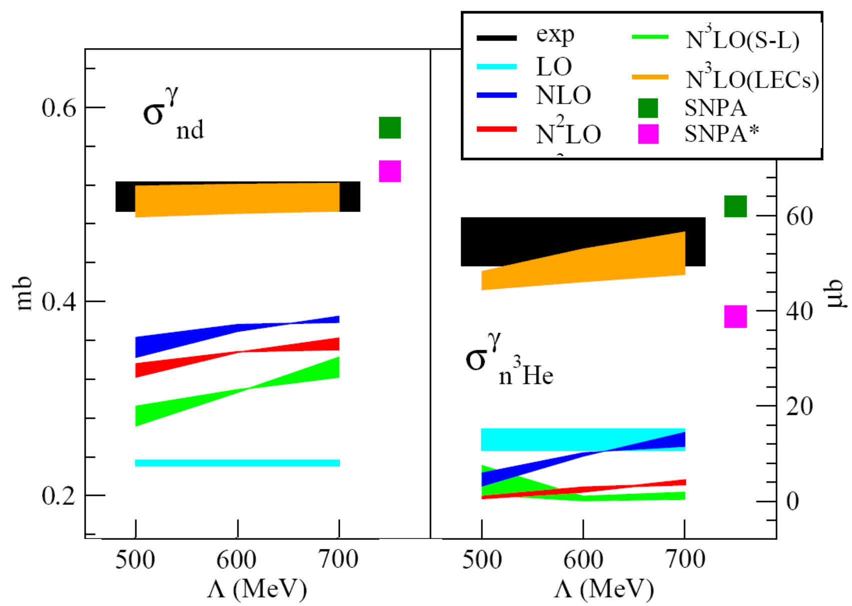
  Application to $np \to d\gamma$ at threshold: $\sigma_{1N} = 306.6 \text{ mb} \quad \longrightarrow \quad \sigma_{1N+2N} = 334 \pm 3 \text{ mb}$

  to be compared with $\sigma_{\rm exp} = 334.2 \pm 0.5 \text{ mb}$

- **General kinematics**   Pastore, Schiavilla, Girlanda, Viviani, '08-'11; Kölling, Krebs, EE, Meißner, '09-'11

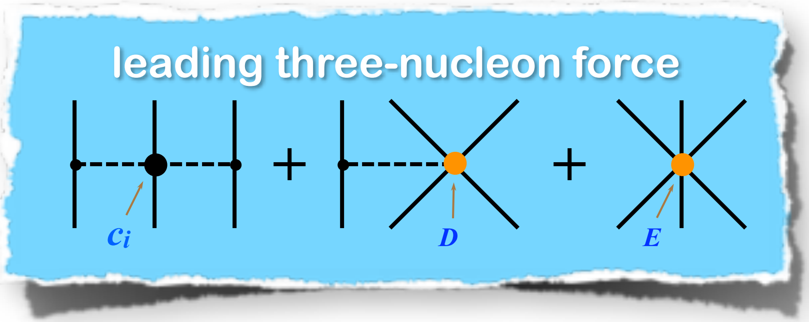
  Application: Radiative capture of light nuclei

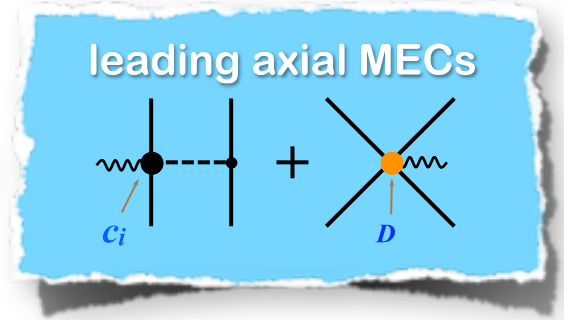
  - LECs fixed assuming Δ-dominance and magnetic moments of ^{2}H, ^{3}H, ^{3}He + σ^γ_{np}
  - predictions for nd, n^{3}He radiative capture reactions for thermal neutrons (MEC dominated)

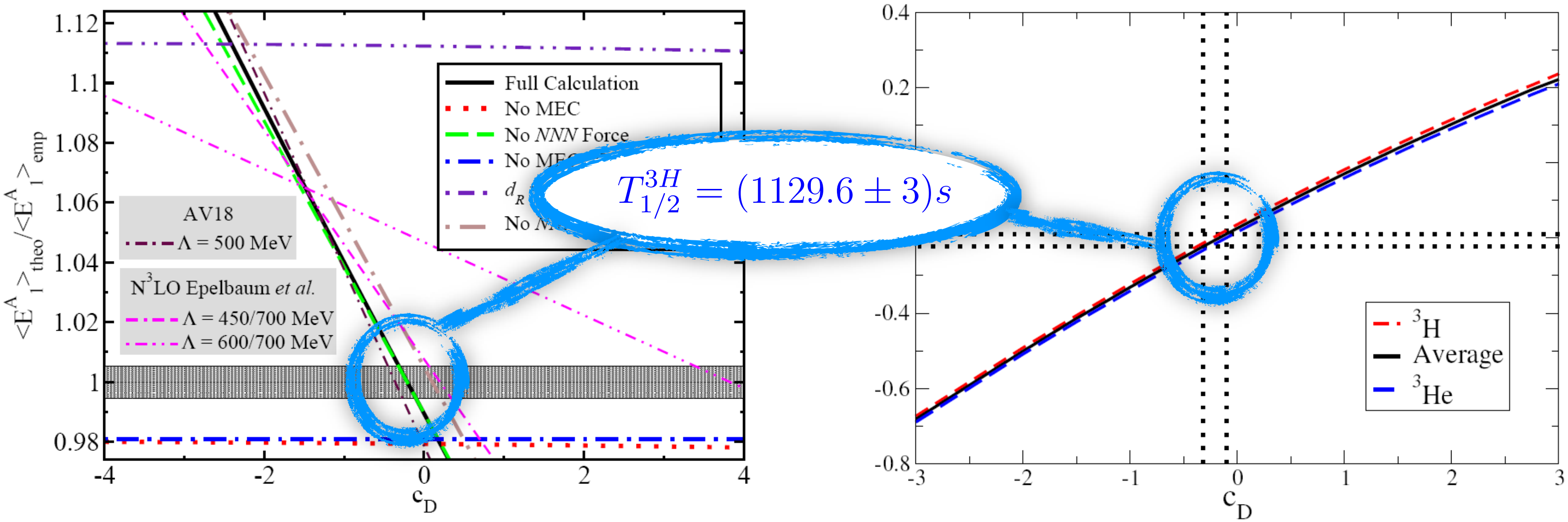


3N force & axial currents

Gazit, Quaglioni, Navratil, PRL 103 (2009) 102502







	^{3}H		^{3}He		^{4}He	
	$E_{g.s.}$	$\langle r_p^2 \rangle^{1/2}$	$E_{g.s.}$	$\langle r_p^2 \rangle^{1/2}$	$E_{g.s.}$	$\langle r_p^2 \rangle^{1/2}$
NN	−7.852(4)	1.651(5)	−7.124(4)	1.847(5)	−25.39(1)	1.515(2)
$NN+NNN$	−8.473(4)	1.605(5)	−7.727(4)	1.786(5)	−28.50(2)	1.461(2)
Expt.	−8.482	1.60	−7.718	1.77	−28.296	1.467(13)

3N force & axial currents

The determined value of D can be used to compute the muon doublet capture rate in

$$\mu^- + d \rightarrow n + n + \nu_\mu$$

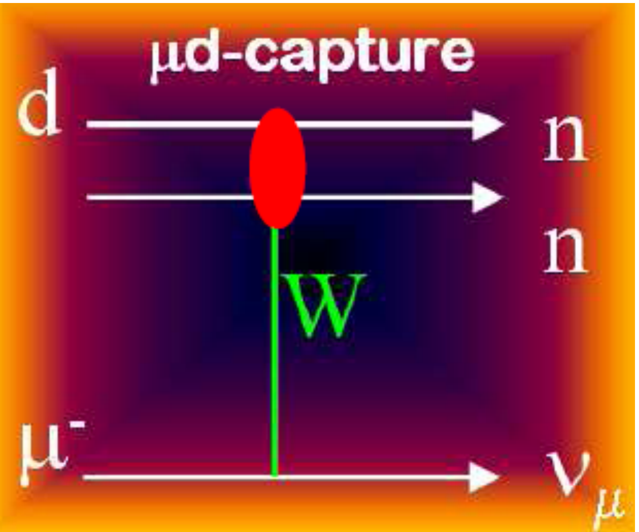
→ $\Lambda_{1/2} = (405.5 \pm 4.3)\ s^{-1}$ Adam, Tater, Truhlik, EE, Machleidt, Ricci '11

(a somewhat different value reported by Marcucci et al.'11)

Exp: $\Lambda_{1/2} = (470.0 \pm 29) s^{-1}$ Martino '86

$\Lambda_{1/2} = (409.0 \pm 40) s^{-1}$ Cargnelli et al., '86, '87

Ongoing measurement by the MuSun Collaboration @ PSI: 1.5% accuracy for $\Lambda_{1/2}$



→

- Test chiral EFT
- Precision calculation of weak nuclear reactions

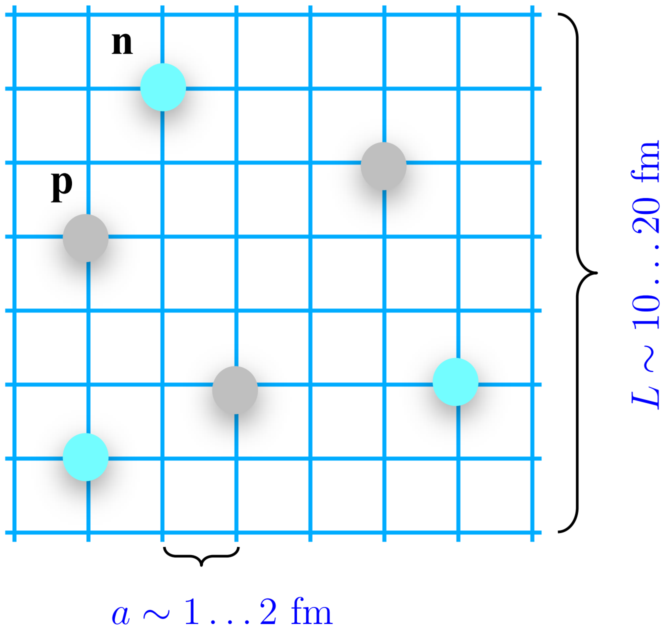
$$\begin{aligned} p + p &\rightarrow d + e^+ + \nu_e\,, \\ p + p + e^- &\rightarrow d + \nu_e\,, \\ p + {}^3He &\rightarrow {}^4He + e^+ + \nu_e\,, \\ {}^7Be + e^- &\rightarrow {}^7Li + \nu_e\,, \\ {}^8B &\rightarrow {}^8Be^* + e^+ + \nu_e \end{aligned}$$

Nuclear Lattice Simulations

In collaboration with:

Dean Lee (North Carolina), Hermann Krebs (Bochum), Ulf-G. Meißner (Bonn/Jülich)

Borasoy, E.E., Krebs, Lee, Meißner, Eur. Phys. J. A31 (07) 105,
Eur. Phys. J. A34 (07) 185,
Eur. Phys. J. A35 (08) 343,
Eur. Phys. J. A35 (08) 357,
E.E., Krebs, Lee, Meißner, Eur. Phys. J A40 (09) 199,
Eur. Phys. J A41 (09) 125,
Phys. Rev. Lett 104 (10) 142501,
Eur. Phys. J. 45 (10) 335,
Phys. Rev. Lett. 106 (11) 192501

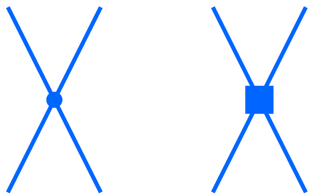


Calculation strategy

Lattice action (improved to minimize discr. errors, accurate to Q^3)

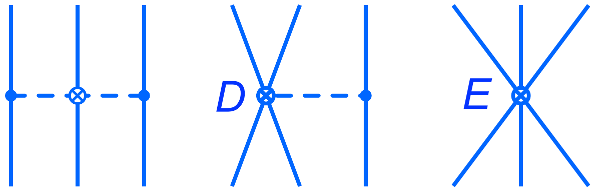
Lanczos method

Solve 2N Schröd. Eq. with the spherical wall boundary cond. ⟹ phase shifts ⟹ fix the LO and NLO (perturbatively) contact terms



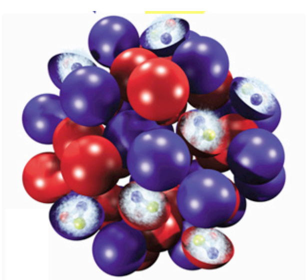
projection Monte Carlo (with auxiliary fields)

Determine the LECs D, E from ^3H and ^4He BEs ⟹ the nuclear Hamiltonian completely fixed up to NNLO (Q^3)



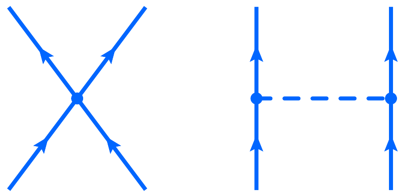
(Multi-channel) projection Monte Carlo with auxiliary fields

Simulate the ground (and excited) states of light nuclei



Lattice actions

Q^0

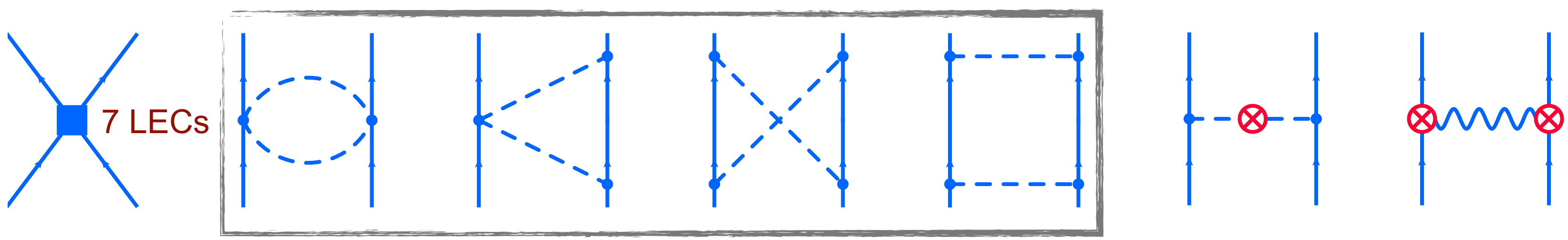


Different actions employed
- LO1: no smearing,
- LO2: smearing in all waves,
- LO3: smearing in even-l waves

used in the simulation

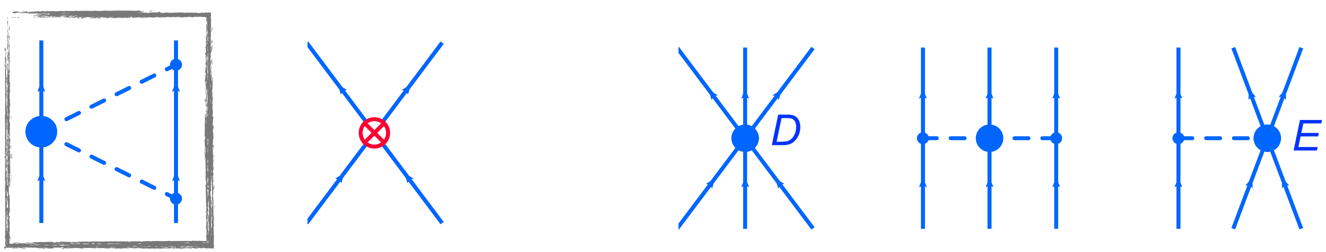
inserted perturbatively

Q^2



for a ~ 2 fm (Λ ~ 314 MeV) can well be represented by contact terms

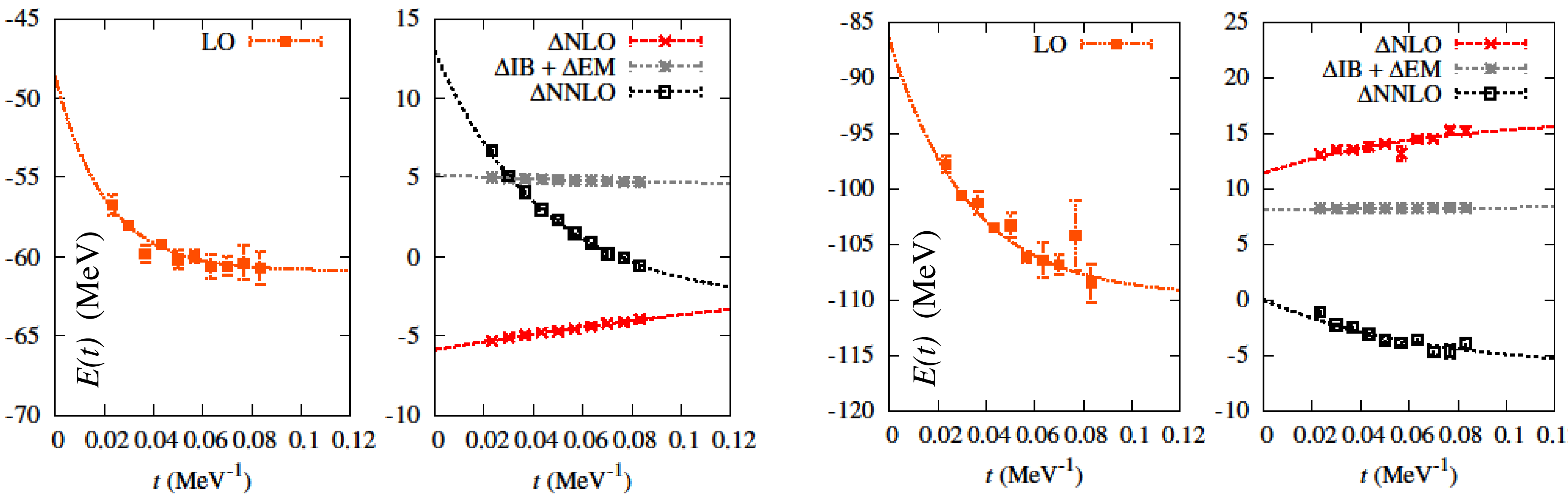
Q^3



Ground states of ^{8}Be and ^{12}C

E.E., Krebs, Lee, Meißner, PRL 106 (11) 192501

Simulations for ^{8}Be and ^{12}C, L=11.8 fm

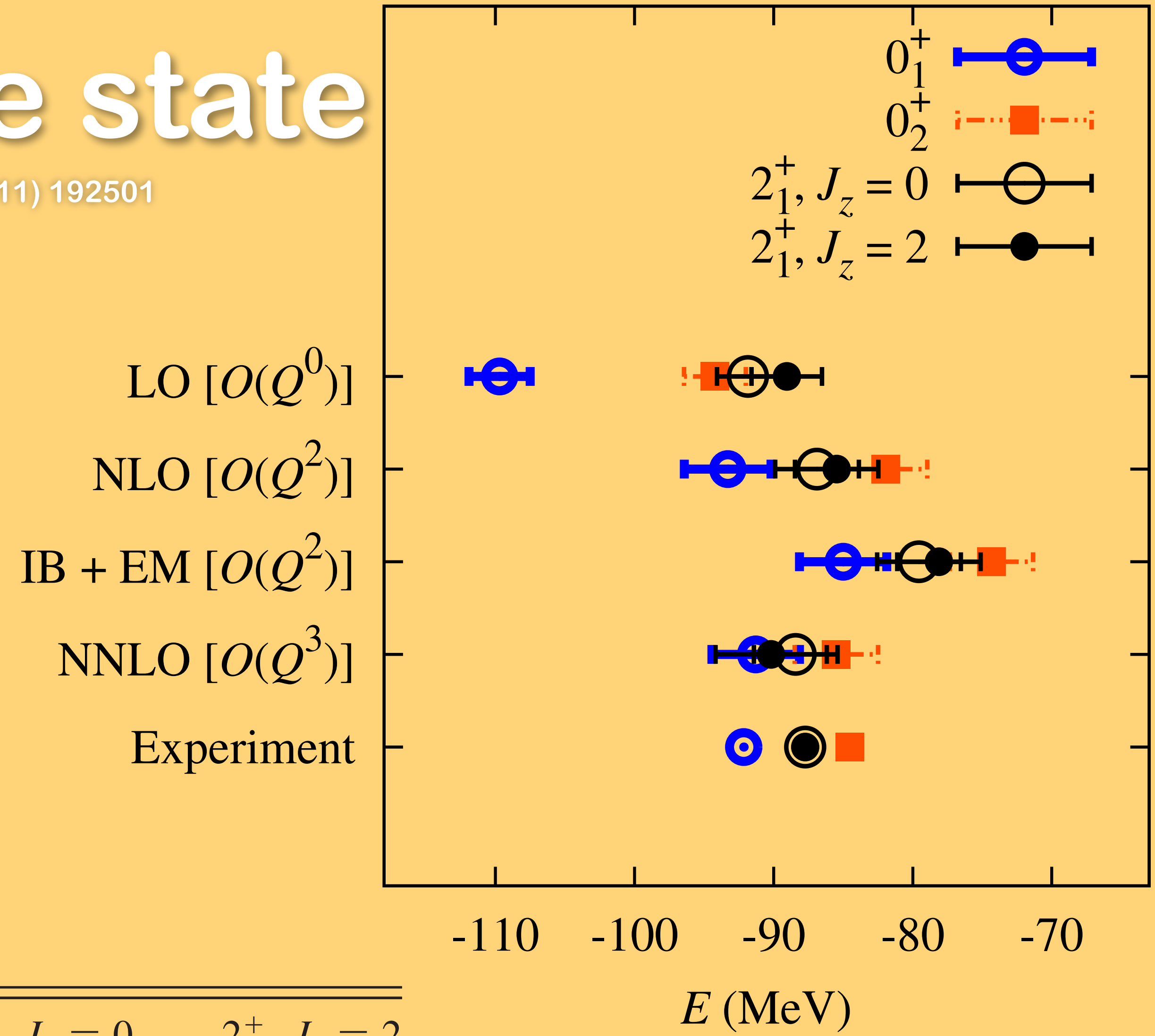


Various contributions to ^{4}He, ^{8}Be and ^{12}C

	^{4}He	^{8}Be	^{12}C
LO $[O(Q^0)]$	−24.8(2)	−60.9(7)	−110(2)
NLO $[O(Q^2)]$	−24.7(2)	−60(2)	−93(3)
IB + EM $[O(Q^2)]$	−23.8(2)	−55(2)	−85(3)
NNLO $[O(Q^3)]$	−28.4(3)	−58(2)	−91(3)
Experiment	−28.30	−56.50	−92.16

The Hoyle state

E.E., Krebs, Lee, Meißner, PRL 106 (11) 192501



	0_2^+	$2_1^+, J_z = 0$	$2_1^+, J_z = 2$
LO [$O(Q^0)$]	−94(2)	−92(2)	−89(2)
NLO [$O(Q^2)$]	−82(3)	−87(3)	−85(3)
IB + EM [$O(Q^2)$]	−74(3)	−80(3)	−78(3)
NNLO [$O(Q^3)$]	−85(3)	−88(3)	−90(4)
Experiment	−84.51	−87.72	

Summary & outlook

Nuclear chiral EFT enters precision era:

accurate nuclear potentials at N^3LO
detailed analyses of electroweak currents
high-precision determination of πN scatt. lengths
precision calculations of the radiative/muon capture reactions, ...

Time to address unsolved problems:

e.g. the structure of the 3NF (work in progress...)

New trends/directions:

combining EFT with ab-initio many-body methods → access to light nuclei
bridging strong, weak and e.m. few-N reactions, ...

Further topics (not covered in the talk):

nuclear parity violation
hypernuclear physics
few-N systems and physics beyond the Standard Models (e.g. neutron EDM), ...