Chiral dynamics: Quo vadis ?

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by CAS, PIFI

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by NRW-FAIR

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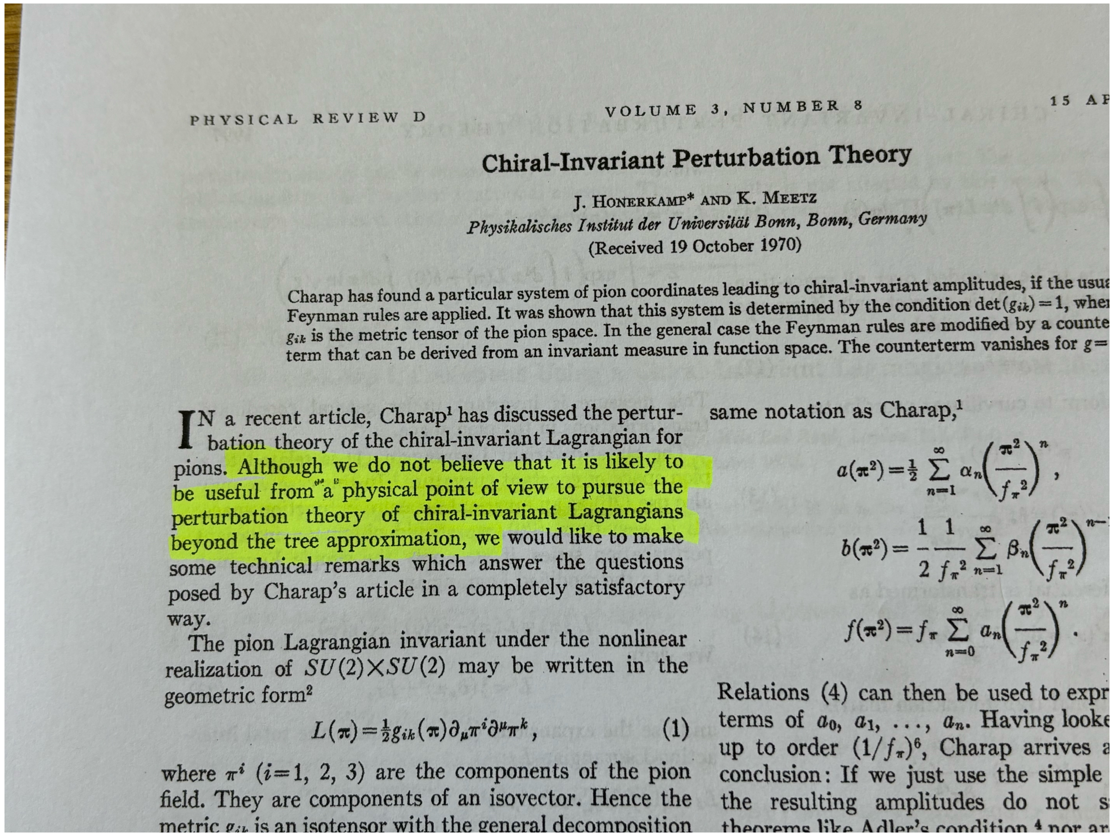
Introductory remarks

A small anecdote

- The first paper with “chiral perturbation theory” in the title

Phys. Rev. D **3** (1971) 1996


PHYSICAL REVIEW D VOLUME 3, NUMBER 8 15 AP

Chiral-Invariant Perturbation Theory

J. HONERKAMP* AND K. MEETZ
Physikalisches Institut der Universität Bonn, Bonn, Germany
(Received 19 October 1970)

Charap has found a particular system of pion coordinates leading to chiral-invariant amplitudes, if the usua Feynman rules are applied. It was shown that this system is determined by the condition $\det(g_{ik})=1$, whe g_{ik} is the metric tensor of the pion space. In the general case the Feynman rules are modified by a counte term that can be derived from an invariant measure in function space. The counterterm vanishes for $g=$

IN a recent article, Charap[1] has discussed the perturbation theory of the chiral-invariant Lagrangian for pions. Although we do not believe that it is likely to be useful from a physical point of view to pursue the perturbation theory of chiral-invariant Lagrangians beyond the tree approximation, we would like to make some technical remarks which answer the questions posed by Charap's article in a completely satisfactory way.

The pion Lagrangian invariant under the nonlinear realization of $SU(2)\times SU(2)$ may be written in the geometric form[2]

$$L(\pi)=\tfrac{1}{2}g_{ik}(\pi)\partial_\mu\pi^i\partial^\mu\pi^k\,, \qquad (1)$$

where π^i ($i=1, 2, 3$) are the components of the pion field. They are components of an isovector. Hence the metric g_{ik} is an isotensor with the general decomposition

same notation as Charap,[1]

$$a(\pi^2)=\tfrac{1}{2}\sum_{n=1}^{\infty}\alpha_n\left(\frac{\pi^2}{f_\pi^2}\right)^n,$$

$$b(\pi^2)=\frac{1}{2}\frac{1}{f_\pi^2}\sum_{n=1}^{\infty}\beta_n\left(\frac{\pi^2}{f_\pi^2}\right)^{n-}$$

$$f(\pi^2)=f_\pi\sum_{n=0}^{\infty}a_n\left(\frac{\pi^2}{f_\pi^2}\right)^n.$$

Relations (4) can then be used to expr terms of $a_0, a_1, \ldots, a_n$. Having looke up to order $(1/f_\pi)^6$, Charap arrives a conclusion: If we just use the simple the resulting amplitudes do not s theorems like Adler's condition,[4] nor ar

- Possible consequences:

  ↪ stop the talk here

  ↪ don’t always listen to Bonn people

What does “chiral dynamics” mean?

- First used in a paper by Julian Schwinger (1967)

Volume 24B, number 9 PHYSICS LETTERS 1 May 1967

CHIRAL DYNAMICS

J. SCHWINGER*
Harvard University, Cambridge, Massachusetts

Received 6 April 1967

The cumbersome operator techniques and weak interaction orientation of current algebra are replaced by a non-operator method based on strong interaction phenomenology. Some new results include alternative possibilities of $\pi\pi$ scattering lengths, and a treatment of ρ and A_1 decay widths that supports the interpretation of A_1 as the axial partner of ρ.

This note was stimulated by some recent work of Weinberg [1]. He has shown how the results of current-algebra can be easily reproduced by certain calculational rules used in conjunction with an appropriate Lagrange function. Current-algebra is still considered primary, however. I propose to further this simplification and clarification by eliminating all reference to current-algebra. The non-operator method that replaces it is the phenomenological source theory now under development [2]. For our present purposes, however, it suffices to think of a numerical effective Lagrange function, the coupling terms of which are directly applicable to the corresponding processes **.

- Historically, this was not the accepted terminology

- My view on this:

  Chiral perturbation theory (CHPT)

  $\longrightarrow$ strict perturbative expansion in
  (a) small parameter(s)

  Chiral dynamics

  $\longrightarrow$ involves some non-perturbative resummation

- Scan insirehep for “t chiral perturbation theory” or “t chiral dynamics”
  and look for the top entries
  [not to mention *chiral effective Lagrangians, chiral effective field theory,*...]

Some statistics

- Chiral perturbation theory

Baryon chiral perturbation theory in manifestly Lorentz invariant form #3
Thomas Becher (Bern U.), H. Leutwyler (Bern U.) (Jan, 1999)
Published in: *Eur.Phys.J.C* 9 (1999) 643-671 • e-Print: hep-ph/9901384 [hep-ph]
pdf DOI cite claim reference search 619 citations

Chiral perturbation theory #4
A. Pich (Valencia U.) (Feb, 1995)
Published in: *Rept.Prog.Phys.* 58 (1995) 563-610 • e-Print: hep-ph/9502366 [hep-ph]
pdf DOI cite claim reference search 578 citations

Chiral perturbation theory #5
G. Ecker (Vienna U.) (Dec, 1994)
Published in: *Prog.Part.Nucl.Phys.* 35 (1995) 1-80 • e-Print: hep-ph/9501357 [hep-ph]
pdf DOI cite claim reference search 640 citations

Chiral perturbation theory for hadrons containing a heavy quark #6
Mark B. Wise (Caltech) (Jan 31, 1992)
Published in: *Phys.Rev.D* 45 (1992) 7, R2188
pdf DOI cite claim reference search 889 citations

Baryon chiral perturbation theory using a heavy fermion Lagrangian #7
Elizabeth Ellen Jenkins (UC, San Diego), Aneesh V. Manohar (UC, San Diego) (Nov, 1990)
Published in: *Phys.Lett.B* 255 (1991) 558-562
DOI cite claim reference search 1,154 citations

The Role of Resonances in Chiral Perturbation Theory #8
G. Ecker (Vienna U.), J. Gasser (Bern U.), A. Pich (CERN), E. de Rafael (Marseille, CPT) (Sep, 1988)
Published in: *Nucl.Phys.B* 321 (1989) 311-342
DOI cite claim reference search 1,623 citations

Chiral Perturbation Theory: Expansions in the Mass of the Strange Quark #9
J. Gasser (Bern U.), H. Leutwyler (CERN) (Jan, 1984)
Published in: *Nucl.Phys.B* 250 (1985) 465-516
DOI cite claim reference search 4,354 citations

Chiral Perturbation Theory to One Loop #10
J. Gasser (Bern U.), H. Leutwyler (CERN) (Aug, 1983)
Published in: *Annals Phys.* 158 (1984) 142
pdf DOI cite claim reference search 4,757 citations

- Chiral dynamics

Chiral dynamics of the two Lambda(1405) states #1
D. Jido (Osaka U., Res. Ctr. Nucl. Phys. and Valencia U. and Valencia U., IFIC), J.A. Oller (Murcia U.), E. Oset (Valencia U. and Valencia U., IFIC), A. Ramos (Barcelona U., ECM), U.G. Meissner (Bonn U., HISKP) (Mar, 2003)
Published in: *Nucl.Phys.A* 725 (2003) 181-200 • e-Print: nucl-th/0303062 [nucl-th]
pdf DOI cite claim reference search 730 citations

Chiral dynamics in the presence of bound states: Kaon nucleon interactions revisited #2
J.A. Oller (Julich, Forschungszentrum), Ulf G. Meissner (Julich, Forschungszentrum) (Nov, 2000)
Published in: *Phys.Lett.B* 500 (2001) 263-272 • e-Print: hep-ph/0011146 [hep-ph]
pdf DOI cite claim reference search 929 citations

Chiral dynamics and the low-energy kaon - nucleon interaction #3
Norbert Kaiser (Munich, Tech. U.), P.B. Siegel (Munich, Tech. U.), W. Weise (Munich, Tech. U.) (May, 1995)
Published in: *Nucl.Phys.A* 594 (1995) 325-345 • e-Print: nucl-th/9505043 [nucl-th]
pdf DOI cite claim reference search 748 citations

The Spectrum of the nucleons and the strange hyperons and chiral dynamics #4
L.Ya. Glozman (Graz U. and Inst. Power Eng. Almaty), D.O. Riska (Washington U., Seattle and Helsinki U.) (May, 1995)
Published in: *Phys.Rept.* 268 (1996) 263-303 • e-Print: hep-ph/9505422 [hep-ph]
pdf DOI cite claim reference search 718 citations

Chiral dynamics in nucleons and nuclei #5
V. Bernard (Strasbourg, CRN), Norbert Kaiser (Munich, Tech. U.), Ulf-G. Meissner (Bonn U.) (Jan, 1995)
Published in: *Int.J.Mod.Phys.E* 4 (1995) 193-346 • e-Print: hep-ph/9501384 [hep-ph]
pdf DOI cite claim reference search 1,263 citations

Heavy quark symmetry and chiral dynamics #6
Tung-Mow Yan (Taiwan, Inst. Phys. and Cornell U., LNS), Hai-Yang Cheng (Taiwan, Inst. Phys.), Chi-Yee Cheung (Taiwan, Inst. Phys.), Guey-Lin Lin (Taiwan, Inst. Phys.), Y.C. Lin (Taiwan, Natl. Central U.) et al. (Mar 10, 1992)
Published in: *Phys.Rev.D* 46 (1992) 1148-1164, *Phys.Rev.D* 55 (1997) 5851 (erratum)
pdf DOI cite claim reference search 786 citations

Chiral Dynamics in the Large n Limit #7
P. Di Vecchia (Freie U., Berlin), G. Veneziano (CERN) (Feb, 1980)
Published in: *Nucl.Phys.B* 171 (1980) 253-272
DOI cite claim reference search 798 citations

Large N Chiral Dynamics #8
Edward Witten (Harvard U.) (Jan, 1980)
Published in: *Annals Phys.* 128 (1980) 363
pdf DOI cite claim reference search 713 citations

$\hookrightarrow$ will talk here about **chiral dynamics** in the broader sense

Pion-pion scattering: The posterchild and its offsprings

Elastic pion-pion scattering @ threshold

- Purest process in two-flavor chiral dynamics (really light quarks)

  [CD2012, CD2018]

- Scattering amplitude at threshold: two numbers (a_0, a_2)

- History of the prediction for a_0 based on CHPT:

LO (tree):	$a_0 = 0.16$	Weinberg 1966
NLO (1-loop):	$a_0 = 0.20 \pm 0.01$	Gasser, Leutwyler 1983
NNLO (2-loop):	$a_0 = 0.217 \pm 0.009$	Bijnens et al. 1996

$\hookrightarrow$ In CA, pion-pion scattering the most complicated case for pion-hadron scattering

$\hookrightarrow$ fairly large corrections from LO to NLO $\rightarrow$ strong final-state interactions

$\hookrightarrow$ still sizeable corrections at NNLO despite $(M_\pi/\Lambda_\chi)^2 \simeq 0.14^2 \simeq 0.02$

- a_2 is small and exhibits very small corrections (will not be considered further)

Elastic pion-pion scattering: the first offspring

Donoghue, Gasser, Leutwyler, UGM, Truong, Pelaez, Büttiker, Ananthanarayan...

- Combine CHPT with dispersion relations to
  - extend the range of applicability
  - increase the precision

- For $\pi\pi \to \pi\pi$: match 2-loop representation to the Roy equation solution

$$a_0 = 0.220 \pm 0.005$$

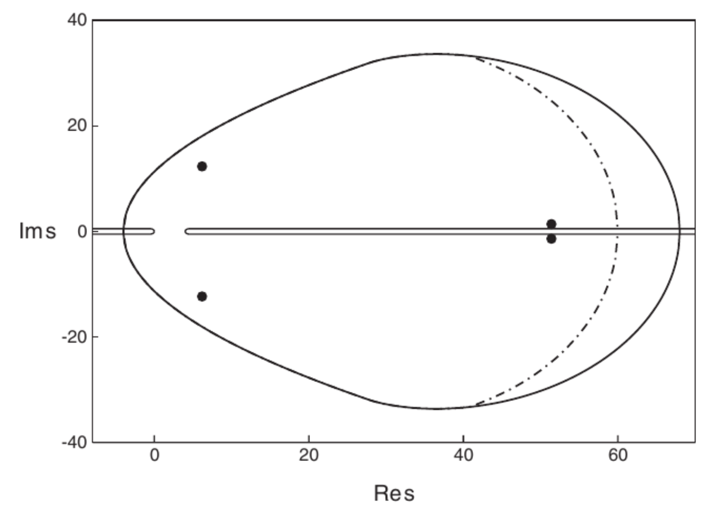
Colangelo, Gasser, Leutwyler (2000)

- And more: pin down the the lowest resonance in QCD [nowadays called $f_0(500)$]

$$M_\sigma = 441^{+16}_{-8}\ \text{MeV}$$

$$\Gamma_\sigma = 272^{+9}_{-13}\ \text{MeV}$$

Caprini, Colangelo, Leutwyler (2006)

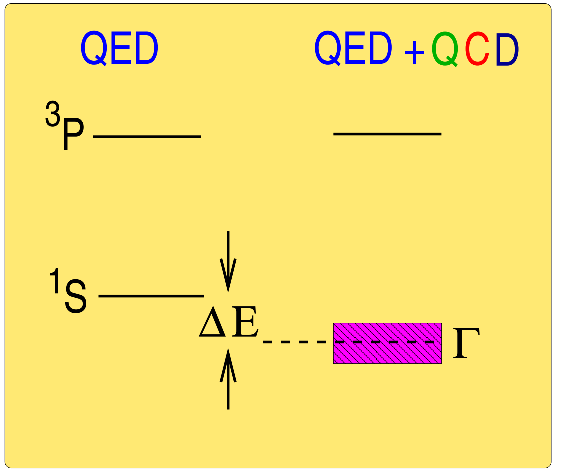


Elastic pion-pion scattering: further offsprings I

Colangelo, Gasser, Ivanov, Kubis, UGM, Raha, Rusetsky, Schweitzer, ...

- Develop NREFTs to better access low-energy $\pi\pi$ scattering

- Theory of hadronic atoms (scattering at zero energy)



$\hookrightarrow$ Bound state properties with complex LECs

$\hookrightarrow$ Beyond the Deser formula: high-precision achieved

$\hookrightarrow$ Relevant for $\pi\pi$, πK, πN, πd, Kp, Kd

- Experiment for pionium:

$$|a_0 - a_2| = 0.2533^{+0.0107}_{-0.0137}$$

Adeva et al. [DIRAC Coll.] Phys. Lett. B704 (2011) 24

Schweizer, Phys. Lett. B **587** (2004) 33

- Same for πK (a separate talk):

$$\frac{1}{3}|a_0^{1/2} - a_0^{3/2}| = 0.072^{+0.031}_{-0.020} \qquad \text{[CHPT: } 0.073(2)\text{]}$$

Yazkov [DIRAC Coll.] EPJ Web of Conferences **181** (2018)

Bernard, Kaiser, UGM, Nucl. Phys. B **357** (1991) 129

Elastic pion-pion scattering: further offsprings II

Budini, Fonda, Cabbibo, Colangelo, Gasser, Kubis, UGM, Rusetsky, Steininger, ...

- Cusps in kaon decays using NREFT ($K \to 3\pi$)

$\hookrightarrow$ Quickly converging approach

$\hookrightarrow$ Used to analyze large data set from NA48 at CERN

- Combine with FSI in K_{e4} decays:

$$a_0 = 0.2210 \pm 0.0047_{\rm stat} \pm 0.0040_{\rm sys}$$

Batley et al. [NA48/2 Coll.] Eur. Phys. J. C **70** (2010) 635

- Experiment and chiral dynamics well aligned,

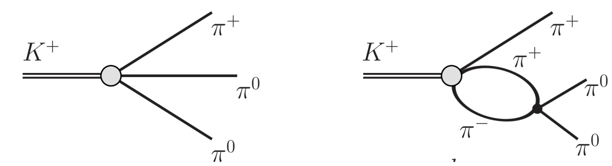
how about the lattice? $\longrightarrow$ next slide

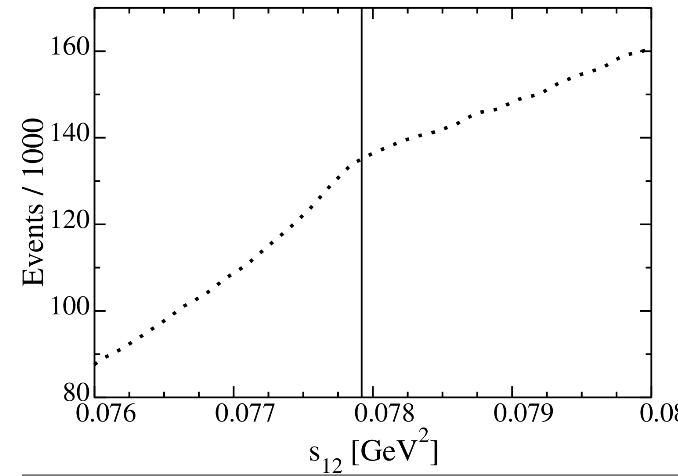
- Cusp also prominent in CHPT analysis of $\gamma p \to \pi^0 p$

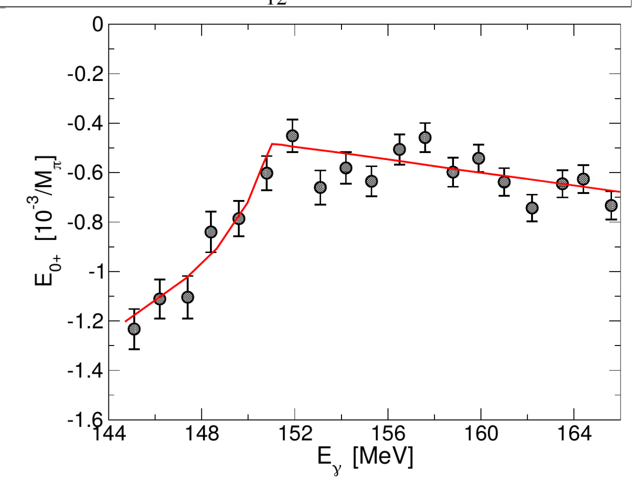
Bernard, Kubis, UGM, Eur. Phys. J. A **25** (2005) 419

- Cusps play a much bigger role now $\hookrightarrow$ exotic hadrons

Guo, Liu, Sakai, Prog. Part. Nucl. Phys. **112** (2020) 103757

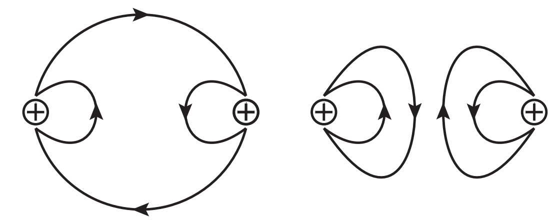






Elastic pion-pion scattering on the lattice - history

- The interesting observable a_0 took a **long** time (disconnected diagrams)



- My talk at CD2012@JLab: no direct a_0 determinations

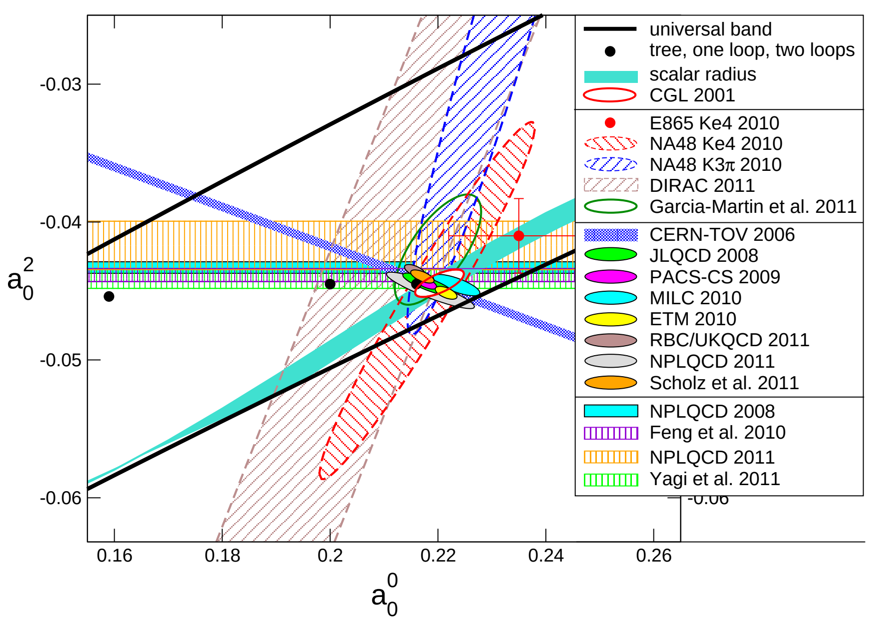


Fig. courtesy H. Leutwyler

- My talk at CD2018@Duke Univ.: 2 unquenched QCD simulations, but errors doubtful

Author(s)	a_0	Pion mass range
Fu	0.214(4)(7)	240 - 430 MeV
Liu et al.	0.198(9)(6)	250 - 320 MeV

Fu, Phys. Rev. D **87** (2013) 074501
Liu et al., Phys. Rev. D **96** (2017) 054516

Elastic pion-pion scattering on the lattice - now

- Now a number of better simulations available, still chiral extrapolation needed

- Focus here on the work of the GW group (S- and P-waves, incl. resonances)

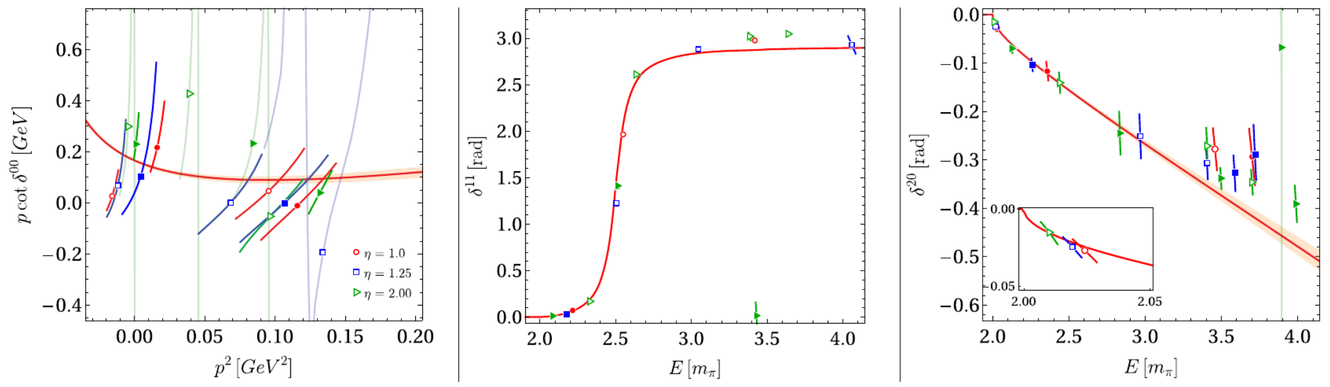
- $\boldsymbol{I = 0}$ S-wave:

$$\boldsymbol{a_0 = 0.2132^{+0.0008}_{-0.0009}}$$

$$\boldsymbol{M_\sigma = 443(3) - i\,221(6)}\text{ MeV}$$

$\hookrightarrow$ central values fine

$\hookrightarrow$ errors too small



Mai, Culver, Alexandru, Döring, Lee, Phys. Rev. D **100** (2019) 114514

- A real problem: $\boldsymbol{\rho}$ mass too small $\quad \boldsymbol{M_\rho = (724^{+2}_{-4} - i\,67^{+1}_{-1})}$ MeV

- A recent calc. at the physical point: $\quad \boldsymbol{M_\rho = 796(5)(50) - i\,96(5)(16)}$ MeV
  Boyle et al., arXiv:2406.19194

$\hookrightarrow$ we are still not done, LQCD people need to work harder!

Novel insights into the hadron spectrum from chiral dynamics

Hadron resonances in chiral dynamics - basics

- In CHPT, resonances are a limit, not active dofs!
- Be aware of the decoupling theorem: Gasser, Zepeda (1980)

> The leading non-analytic terms stem from Goldstone boson one-loop graphs coupled to Goldstone bosons or ground state baryons

$\hookrightarrow$ Resonances must decouple (sometimes overlooked)

$\hookrightarrow$ Cuts and poles generated by GBs are not affected by resonances

$\hookrightarrow$ Resonances saturate most of the LECs Donoghue, Holstein, Gasser, Leutwyler, Ecker, Pich,...

$\hookrightarrow$ QCD chiral and large-N_C limits do not commute

- Still, we want to go beyond the GB (+ ground state baryon octet) theory

Including hadron resonances into chiral dynamics

- There are essentially 3 ways of including resonances:

  – Inclusion as **matter fields**, mostly $\Delta(1232)$, see my talk at CD2018

  $\hookrightarrow$ requires an extended power counting and/or complex-mass scheme

  Jenkins, Manohar, Bernard, Kaiser, UGM, Hemmert, Holstein, Kambor, Gegelia, Phillips, Pascalutsa,...

  – In a **few** cases, CHPT combined w/ dispersion relations allows to study resonances

  $f_o(500)$, $f_0(980)$, $\rho(770)$, $K_0^*(700)$, $K^*(890)$, $\boxed{\Delta, N^*(1440)}$ $\rightarrow$ next slide

  Caprini, Colangelo, Leutwyler, Pelaez, Rodas, Hoferichter, Ruiz de Elvira, Kubis, UGM,...

  $\hookrightarrow$ of course, DRs are a fine tool to study resonances in general (but limited)

  – Single channel unitarization and **coupled-channel chiral dynamics** (non-pert. unitarity)

  $\hookrightarrow$ allows to study certain resonances (ρ, σ,..)

  $\hookrightarrow$ allows to deal with strange baryons

  Truong, Dobado, Herrera, Oset, Oller, Pelaez, Gasser, UGM, ...
  Kaiser, Siegel, Weise, Ramos, Oset, Oller, UGM, Lutz, Kolomeitsev, Hosaka, Jido, Hyodo,...

$\pi N \to \pi N$: Dispersion relations matched to CHPT

Hoferichter, Ruiz de Elvira, Kubis, UGM; Büttiker

- The Roy equation program can also be performed in the pion-nucleon system

  $\hookrightarrow$ Roy-Steiner equations for $\pi N \to \pi N$ $\quad\to$ talk by J. Ruiz de Elvira

- Many results, I just list three of relevance for this talk:

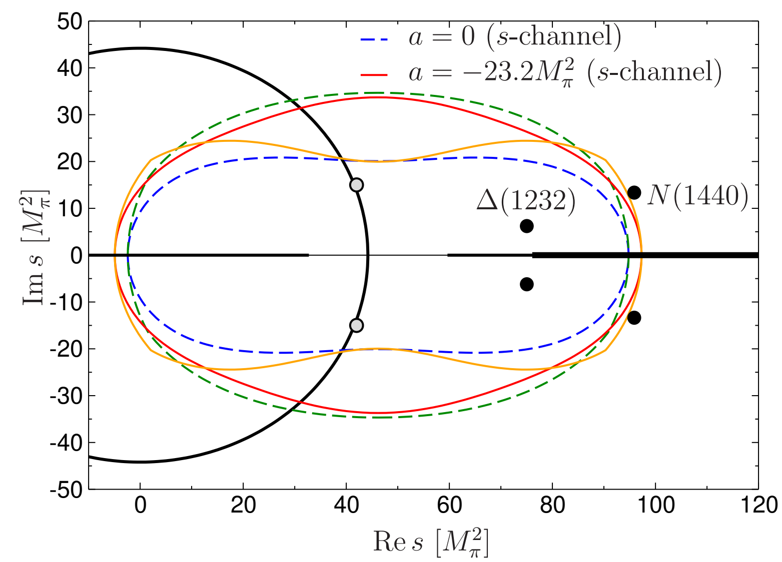
  – High-precision determination of the σ term: $\sigma_{\pi N} = 59.0(3.5)$ MeV

  – High-precision determination of the LECs c_i [in GeV^{-1}] from $\mathcal{L}^{(2)}_{\pi N}$

  $$c_1 = 1.10(3)\,, \quad c_2 = 3.57(4)$$
  $$c_3 = -5.54(6)\,, \quad c_4 = 4.17(4)$$

  – the lowest nucleon resonances & couplings

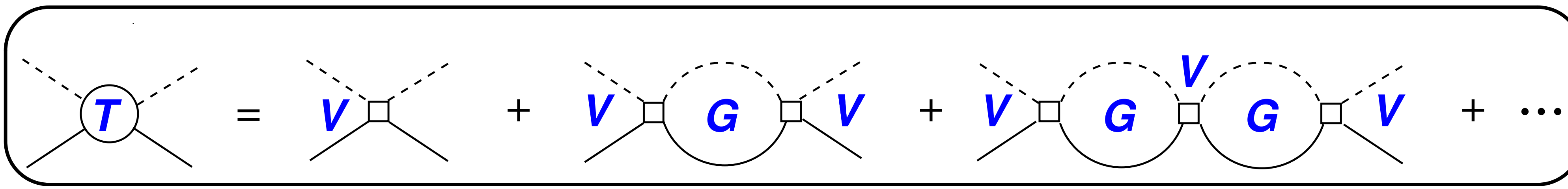
  $$M_\Delta = (1209.5(1.1) + i\,98.5(1.2))\ \text{MeV}$$
  $$M_R = (1374(3)(4) + i\,215(18)(8))\ \text{MeV}$$



Hadron resonances in chiral dynamics - coupled channels

Kaiser, Siegel, Weise, Ramos, Oset, Oller, UGM, Lutz, Kolomeitsev, Hosaka, Jido, Hyodo,...

- Basic idea of coupled-channel chiral dynamics:



$\hookrightarrow$ use CHPT to construct the potential $V = V_{\rm LO} + V_{\rm NLO} + \ldots$, then resum

$\hookrightarrow$ often on-shell approximation: $T = V/[1 + GV]$ [all matrices]

$\hookrightarrow$ resummation requires regularization $\to$ different approaches of different quality used

$\hookrightarrow$ generation of resonances, in particular the elusive $\boxed{\Lambda(1405)}$

$\hookrightarrow$ extension to heavy-light mesons   Burdman, Cheng, Donoghue, Du, Guo, Hanhart, Lutz, Nieves, Wise, Yan,Yao, Zou, ...

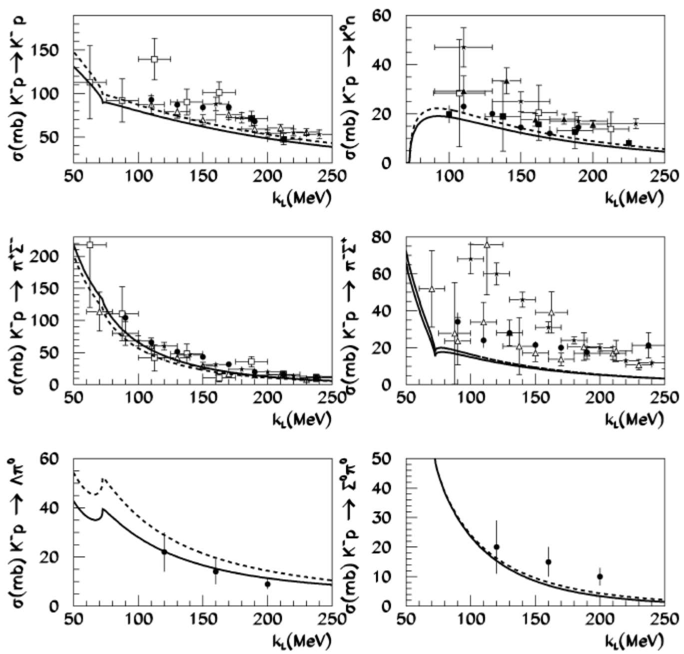
$\hookrightarrow$ a new player in hadron spectroscopy: **two-pole structures** $\longrightarrow$ talk by Lisheng Geng

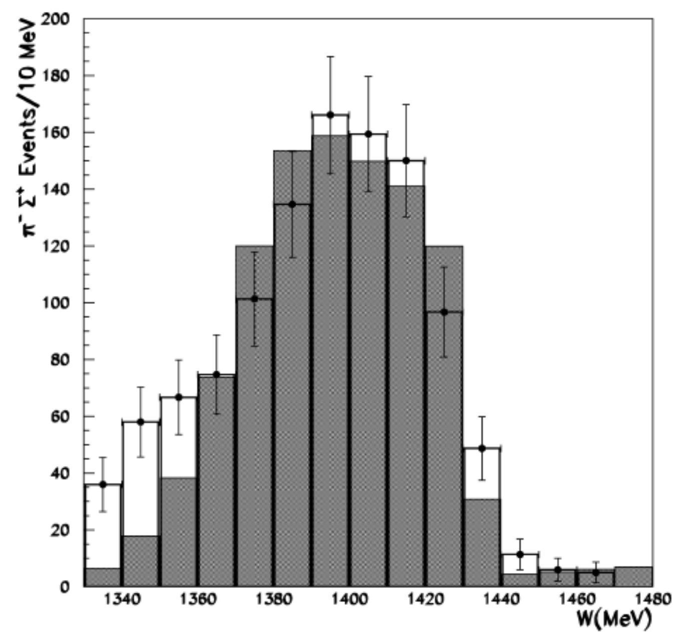
The first two-pole structure from chiral dynamics I

- Re-analysis of coupled-channel $K^- p$ scattering and the $\Lambda(1405)$

  Oller, UGM Phys. Lett. B **500** (2001) 263

- A number of technical improvements:
  - Subtracted meson-baryon loop with dim reg $\hookrightarrow$ standard method
  - Coupled-channel approach to the $\pi\Sigma$ mass distribution
  - Matching formulas to any order in chiral perturbation theory established





A few new data since then

The first two-pole structure from chiral dynamics II

- Re-analysis of coupled-channel K^-p scattering and the $\Lambda(1405)$

Oller, UGM Phys. Lett. B **500** (2001) 263

- Most **significant finding**:

> "Note that the $\Lambda(1405)$ resonance is described by **two poles** on sheets II and III with rather different imaginary parts indicating a clear departure from the Breit-Wigner situation..."

$\hookrightarrow$ Pole locations:

Pole 1: $(1379.2 - i27.6)$ MeV on RS II

Pole 2: $(1433.7 - i11.0)$ MeV on RS II

$\hookrightarrow$ **Chiral dynamics generates two poles**, but: how?

Jido, Oller, Oset, Ramos, UGM, Nucl. Phys. A **725** (2003) 181

SU(3) symmetry considerations - details

Jido, Oller, Oset, Ramos, UGM, Nucl. Phys. A **725** (2003) 181

- SU(3) limit: $m_u = m_d = m_s \neq 0$

$\hookrightarrow$ all GB mesons have equal mass M_0 , all octet baryons have equal mass m_0

$\Rightarrow$ from the SU(3) limit at $x = 0$
to the physical world w/ $x = 1$

$$m_i(x) = m_0 + x(m_i - m_0)$$

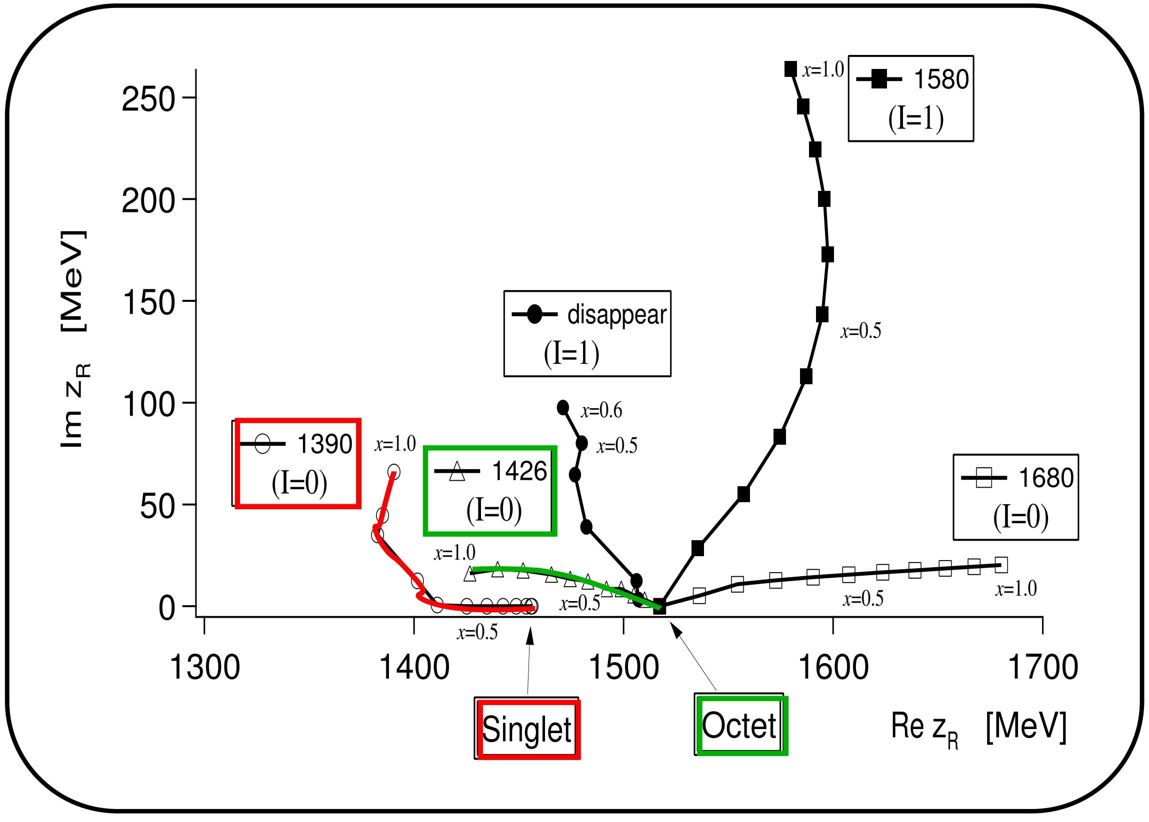
$$M_i^2(x) = M_0^2 + x(M_i^2 - M_0^2)$$

$$a_i(x) = a_0 + x(a_i - a_0)$$

$m_0 = 1151$ MeV

$M_0 = 368$ MeV

$a_0 = -2.148$



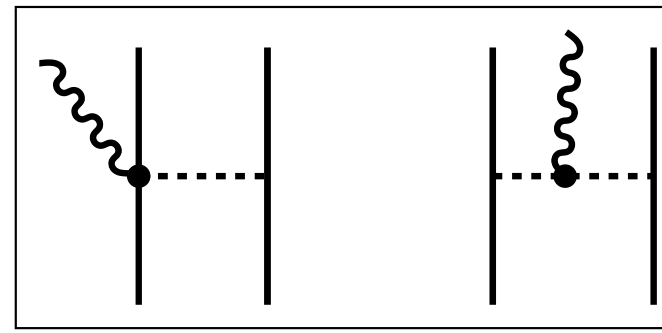
$\hookrightarrow$ more details and recent developments, see UGM, Symmetry **12** (2020) 981, and talk by Geng

Chiral symmetry in nuclear interactions and nuclei

The pion in nuclei: some history

- The pion was predicted as the strong force carrier by Yukawa in 1935  1949
- Found in emulsion experiments in 1947 Lattes et al. (1947)  1950
- Established in nuclei in resolving the $np \to d\gamma$ XS discrepancy

$$\sigma_{\rm exp} = 334.2(5)\ \text{mb}$$
$$\sigma_{\rm IA} = 302.5(4.0)\ \text{mb}$$



$\hookrightarrow$ MECs are just provide the missing 10%

Riska, Brown (1972), Gari, Hyuga (1973)

$\hookrightarrow$ Pions in nuclei firmly established

- Then came the 1993 shock:

PERSPECTIVES

Where Are the Nuclear Pions?

George F. Bertsch, Leonid Frankfurt, Mark Strikman

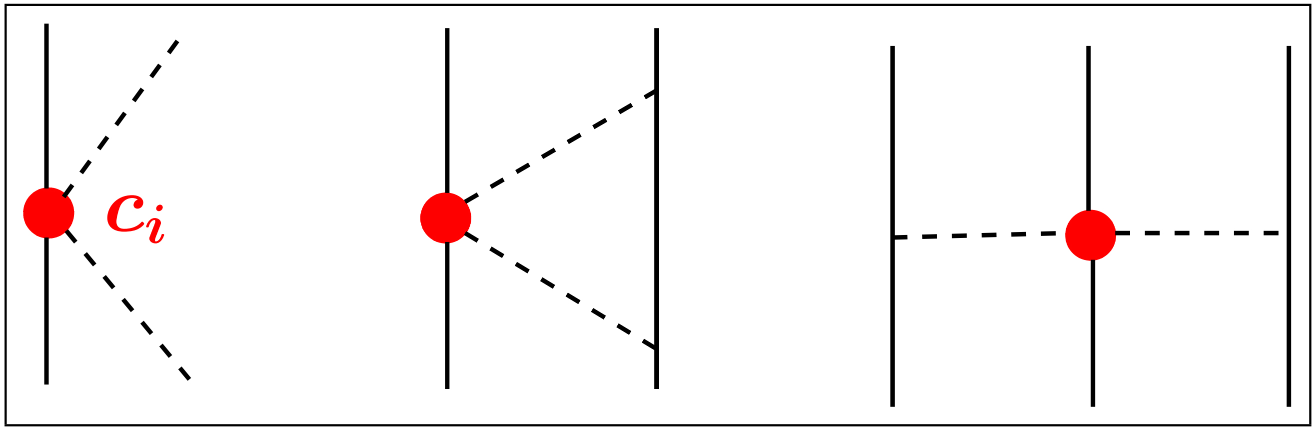
Science **259** (1993) 773

$\hookrightarrow$ a number of (questionable?) solutions,

but let us return back to chiral symmetry!

Chiral symmetry in nuclear interactions

- Chiral symmetry breaking in QCD relates *many* processes — Weinberg
- One of the best examples: dimension-two vertices from the effective πN Lagrangian ($\sim c_i$)



$\pi N \to \pi N$ $NN \to NN$ $3N$-force

- Strategy: Fix in $\pi N \to \pi N$ and the explore in few-nucleon interactions

$\hookrightarrow$ the first step has been done most precisely using Roy-Steiner equations

Hoferichter, Ruiz de Elvira, Kubis, UGM, Phys. Rev. Lett. **115** (2015) 192301; Phys. Rept. **625** (2016) 1

$\hookrightarrow$ now let us see how this is reflected in the NN interaction

$\hookrightarrow$ no time for the 3NFs, ask the locals: Hermann Krebs, Evgeny Epelbaum,...

Two-pion exchanges in the nuclear interactions

- Has already been studied earlier, not at high orders/precision

Kaiser, Gerstendorfer, Weise, Nucl. Phys. A **637** (1998) 395, ...

- Now let us look at N4LO and N4LO+ potentials:

Epelbaum, Krebs, UGM, Phys. Rev. Lett. **115** (2015) 122301; Reinert, Krebs, Epelbaum, Eur. Phys. J. A **54** (2018) 86

$\hookrightarrow$ leading two-pion exchanges $\sim c_i$ and $\sim d_i$ appear at N2LO and N4LO

$\hookrightarrow$ parameter-free contributions at N2LO and N4LO from TPE

$E_{\rm lab}$ bin	LO	NLO	N^{2}LO	N^{3}LO	N^{4}LO	N^{4}LO+
neutron-proton phase shifts						
0–100	73	2.2	1.2	1.08	1.07	1.08
0–200	62	5.4	1.7	1.10	1.08	1.07
0–300	75	**14** $\rightarrow$	**4.1**	**2.01** $\rightarrow$	**1.16**	1.06
proton-proton phase shifts						
0–100	2290	10	2.2	0.90	0.88	0.86
0–200	1770	90	37	1.99	1.42	0.95
0–300	1380	**91** $\rightarrow$	**41**	**3.43** $\rightarrow$	**1.67**	1.00

$\hookrightarrow$ clear sign of TPE (not an absolute measure!)

Pions in nuclear structure

- Are pions really required?

$\hookrightarrow$ many relativistic mean-field models (σ, ω, ρ) work quite well

Walecka, Serot, Ring, Schuck, Meng, Geng, Zhao, ...

$\hookrightarrow$ nuclear physics is close to the unitary limit $\rightarrow$ contact interactions

Bedaque, Hammer, van Kolck, Grießhammer, König, ...

$\hookrightarrow$ the minimal nuclear interaction of NLEFT $\rightarrow$ see Dean Lee's talk for intro and more

- Highly SU(4) symmetric LO action without pions, only **four** parameters

$$H_{\rm SU(4)} = H_{\rm free} + \frac{1}{2!} C_2 \sum_n \tilde{\rho}(n)^2 + \frac{1}{3!} C_3 \sum_n \tilde{\rho}(n)^3$$

$$\tilde{\rho}(n) = \sum_i \tilde{a}_i^\dagger(n)\tilde{a}_i(n) + s_L \sum_{|n'-n|=1} \sum_i \tilde{a}_i^\dagger(n')\tilde{a}_i(n')$$

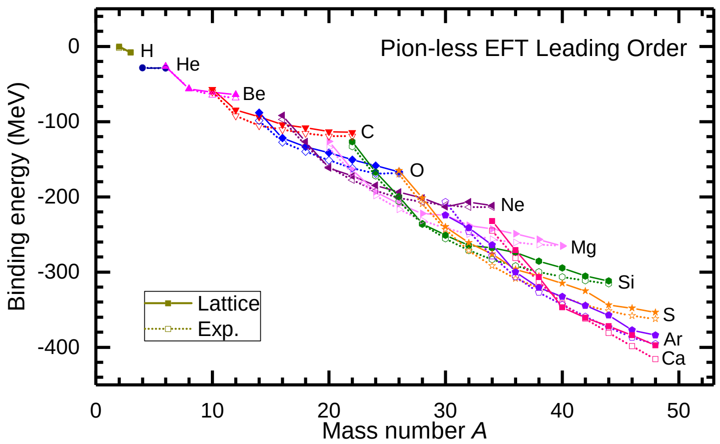
$$\tilde{a}_i(n) = a_i(n) + s_{NL} \sum_{|n'-n|=1} a_i(n')$$

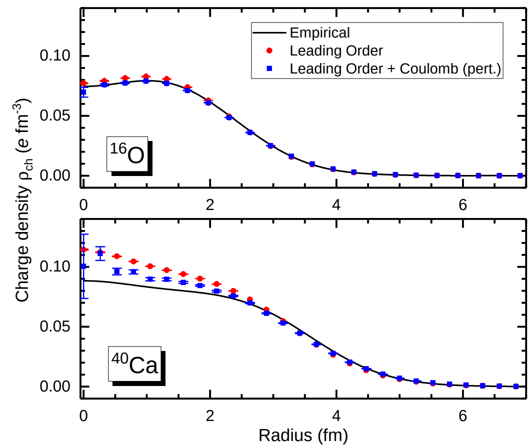
$\rightarrow$ describes binding energies, radii, charge densities and the EoS of neutron matter

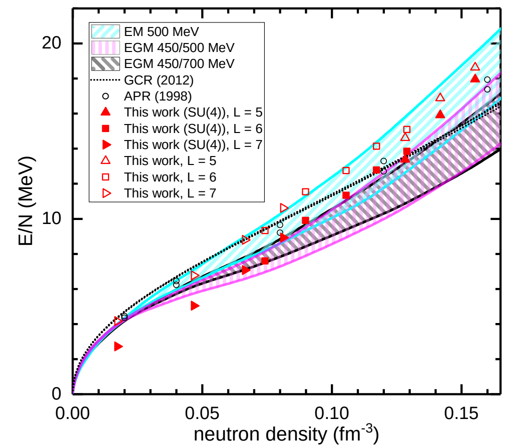
The minimal nuclear interaction

- Works astonishingly well

Lu, Li, Elhatisari, Epelbaum, Lee, UGM, Phys. Lett. B **797** (2019) 134863

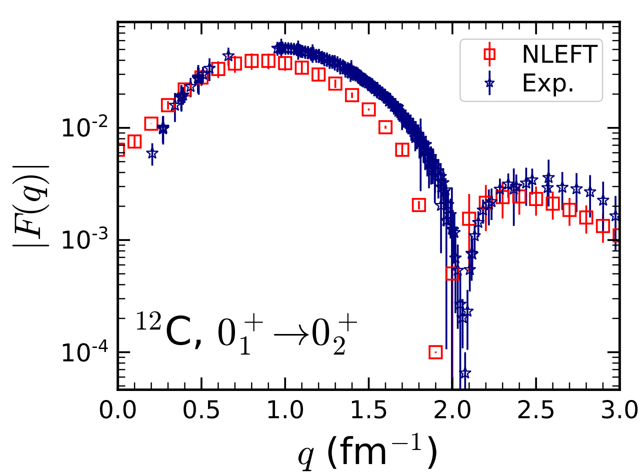




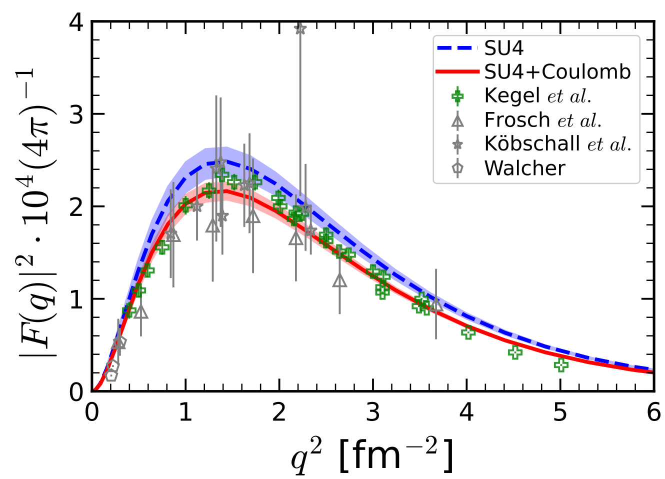


- Even works for em transitions/ solves a puzzle

Shen, Elhatisari, Lähde, Lee, Lu, UGM, Nature Commun. **14** (2023) 2777 UGM, Shen, Elhatisari, Lee, Phys. Rev. Lett. **132** (2024) 062501



Chernykh et al., Phys. Rev. Lett. **105** (2010) 022501



Kegel et al., Phys. Rev. Lett. **130** (2023) 152502

Pions strike back – wavefunction matching

- So pions don't seem to be needed?

  $\hookrightarrow$ no, because there are much different nuclear systems

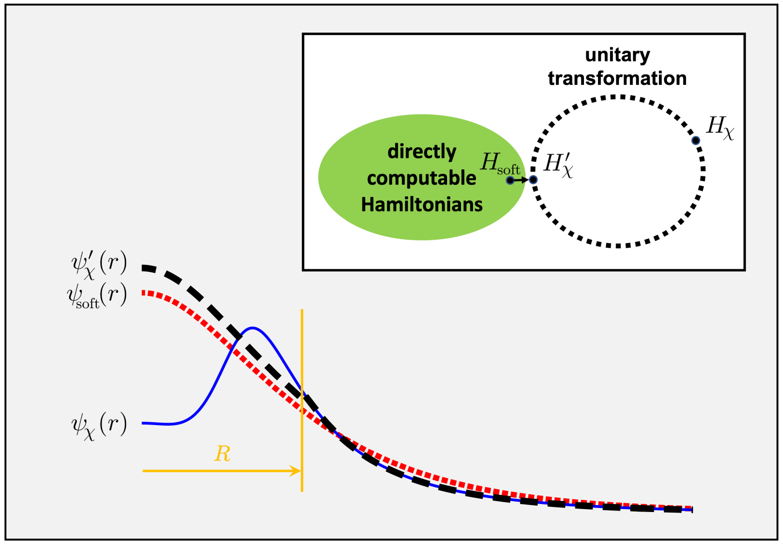
  $\hookrightarrow$ no, the precision is limited

- Wavefunction matching at N3LO

Elhatisari et al., Nature **630** (2024) 59

$\hookrightarrow$ the soft Hamiltonian requires pions!

$$H_{\rm soft} = K + V_{\rm OPE} + V_{\rm Coulomb} + \underbrace{V_{\rm 3N}^{Q^3} + V_{\rm 2N}^{Q^4} + W_{\rm 2N}^{Q^4}}_{\rm SU(4)-symmetric}$$



$$V_{\rm OPE} = \frac{g_A^2}{8f_\pi^2} \sum_{{\bf n}',{\bf n},S',S,I} : \rho^{(0)}_{S',I}(\vec{n}') f_{S',S}(\vec{n}'-\vec{n}) \rho^{(0)}_{S,I}(\vec{n}) :$$

$$-C_\pi \frac{g_A^2}{8f_\pi^2} \sum_{{\bf n}',{\bf n},S,I} : \rho^{(0)}_{S,I}(\vec{n}') f^\pi(\vec{n}'-\vec{n}) \rho^{(0)}_{S,I}(\vec{n}) :$$

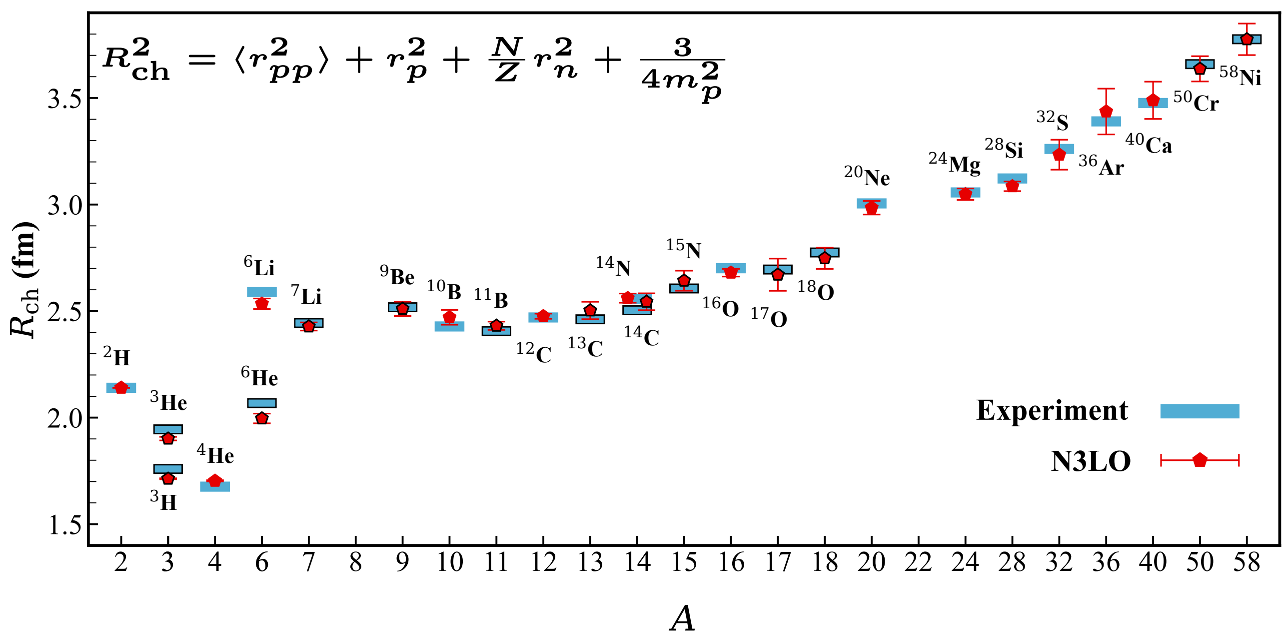
$\longrightarrow$ see also Dean Lee's talk!

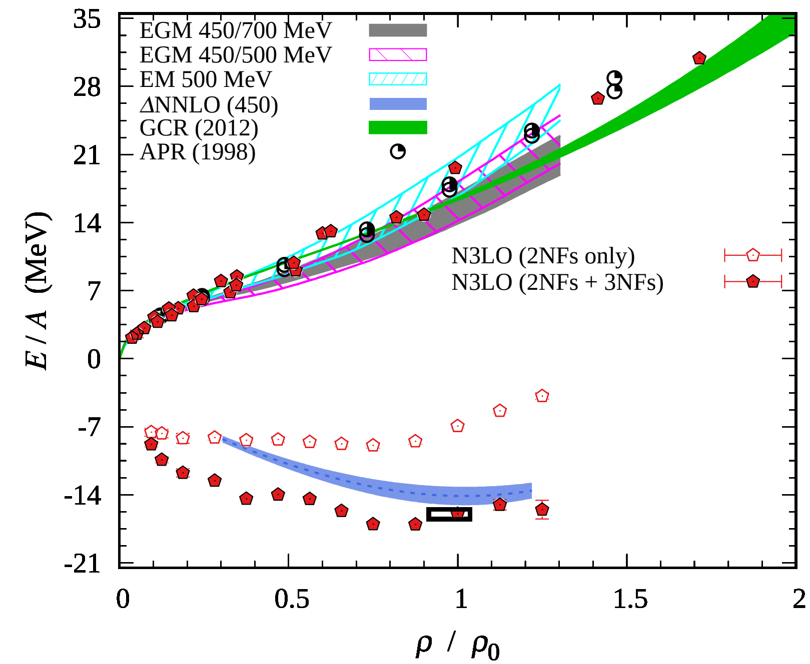
$\hookrightarrow$ properly regulated!

$\hookrightarrow$ fit smeared 3NFs to g.s. energies $A = 3 - 58$ $\to$ make predictions

Predictions from wavefunction matching

- Nuclear charge radii and the EoSs of nuclear and neutron matter





$\hookrightarrow$ Pions to the rescue - they are there!

$\hookrightarrow$ Much more results available $\rightarrow$ Dean Lee's talk

$\hookrightarrow$ To do list (work in progress):

— full chiral NN force and currents

— 3NFs can still be improved

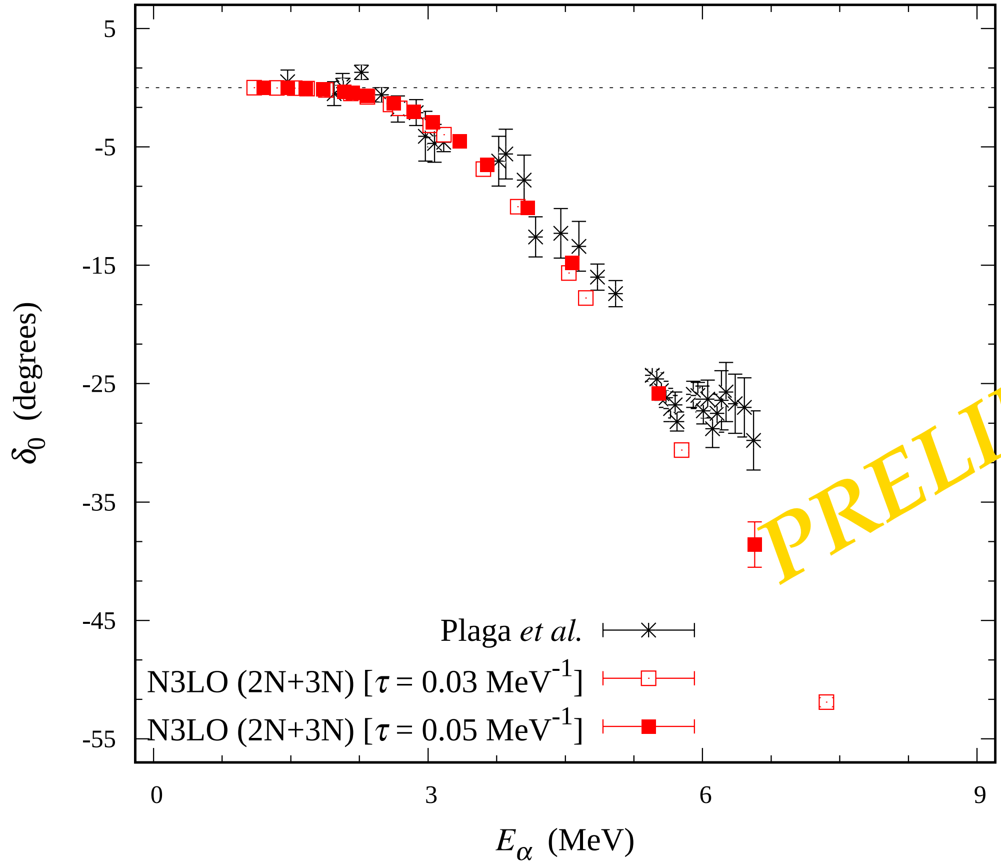
— Nuclear reactions with N3LO forces, show one appetizer

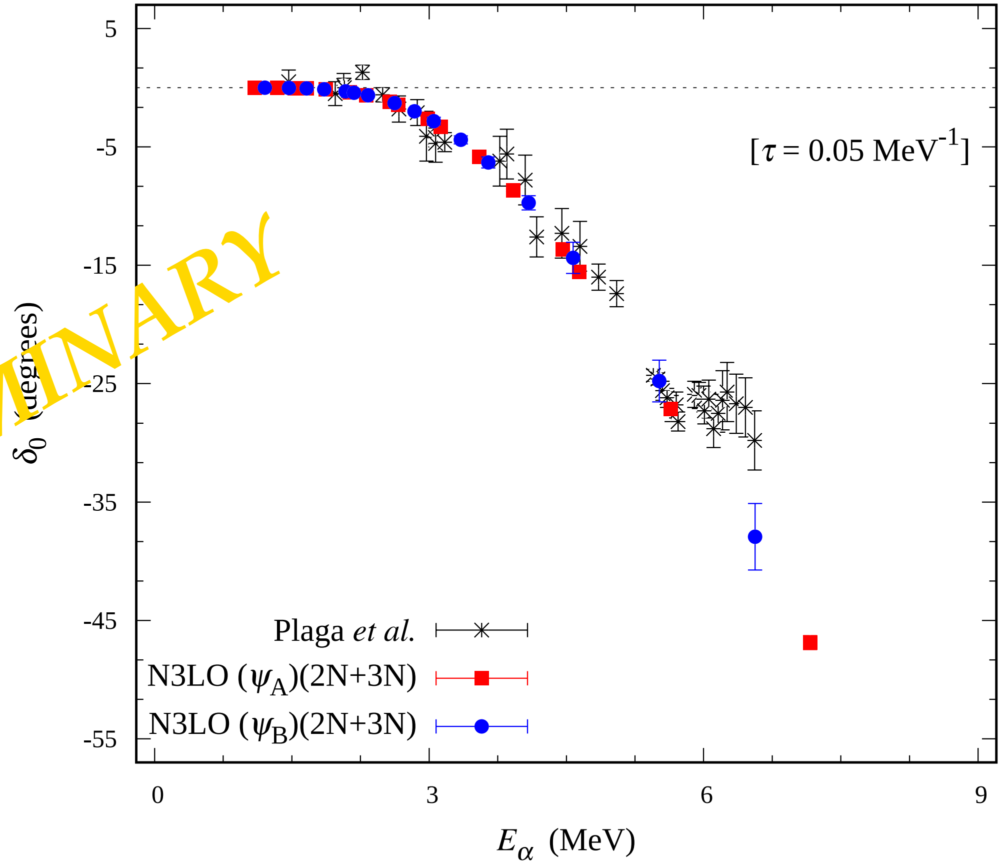
Alpha-carbon scattering at N3LO

Elhatisari, Hildenbrand, UGM, ... NLEFT, in progress

- Use the Adiabatic Projection Method, first step for the holy grail of nuclear astrophysics

  ↪ different Euclidean times & different initial states





Plaga et al., Nucl. Phys. A **465** (1987) 291

$\psi_A \sim {}^{16}$O , $\psi_B \sim {}^{12}$C+^{4}He

Chiral dynamics in the Big Bang

Element generation

- Elements are generated in the Big Bang & in stars through the **fusion** of protons & nuclei [pp chain or CNO-cycle]

- All is simple until ^{4}He

- Only elements up to Be are produced in the Big Bang [BBNucleosynthesis]

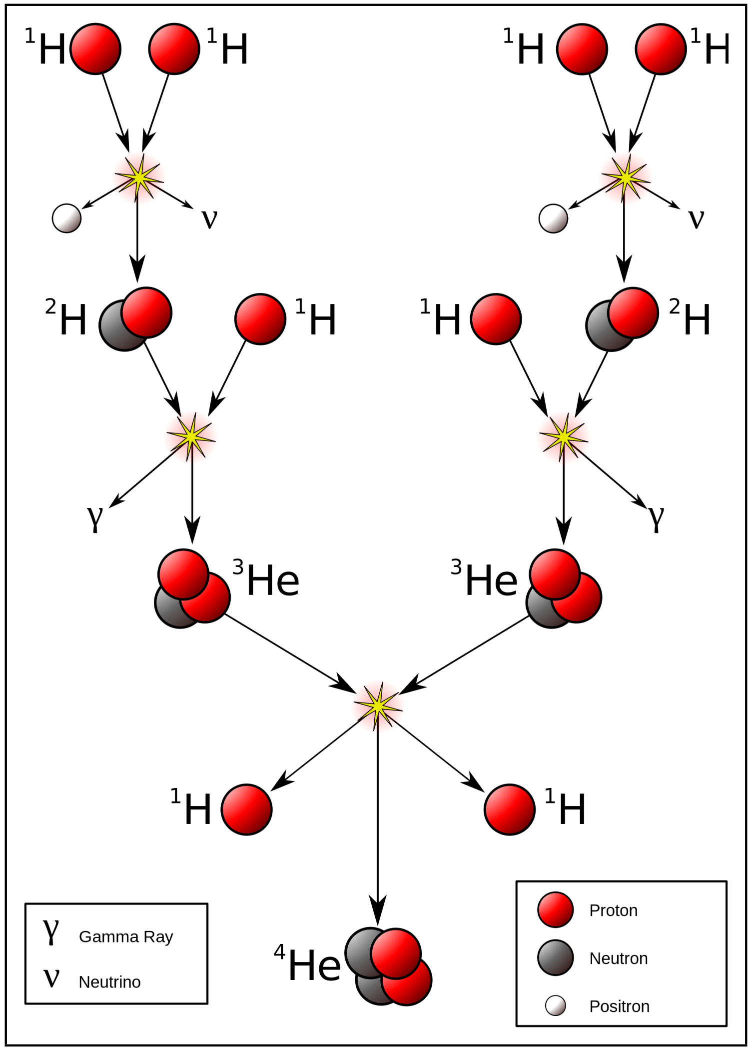
- How fine-tuned is the BBNucleosythesis?

- Depends on

  $\hookrightarrow$ the Higgs VEV v (light quark mass)

  $$\boxed{m_f = g_f\, v}$$

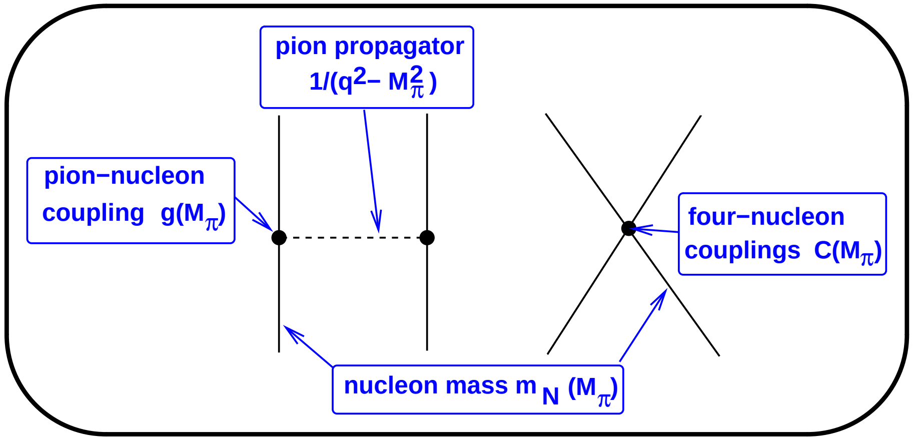
  $\hookrightarrow$ the em fine-structure constant $\alpha_{\rm EM}$



[from Wikipedia]

Pion mass dependence in nuclear systems I

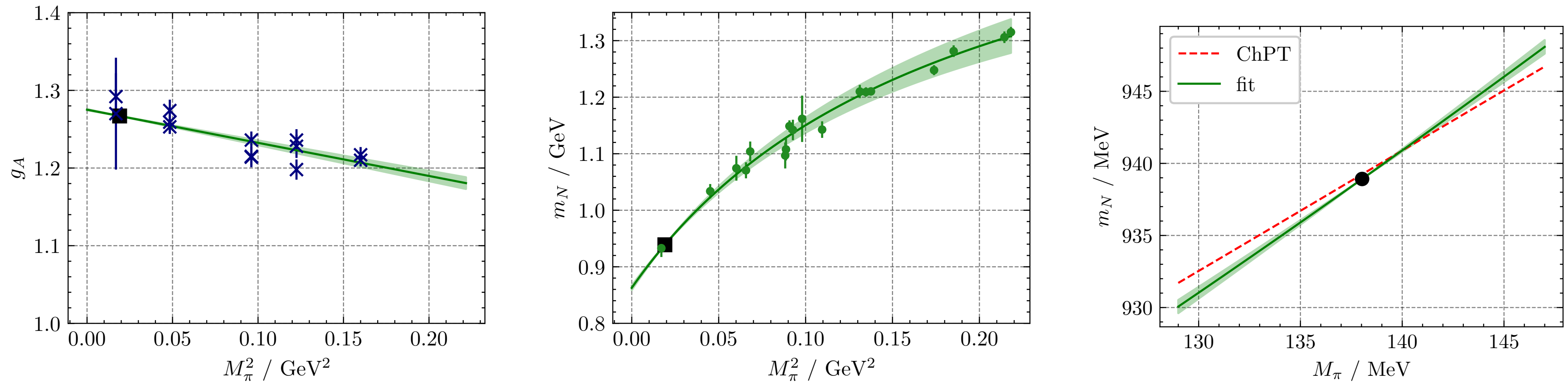
- Consider M_π changes as *small perturbations*
- Pion mass from CHPT + LQCD
- Nucleon mass from LQCD (guided by CHPT)
- Axial-vector coupling from LQCD (or two-loop CHPT)
- Neutron-proton mass splitting from Cottingham SR



Gasser, Leutwyler, Rusetsky, Phys. Lett. B **814** (2021) 136087

$$Q_N = m_n - m_p = (1.87 \mp 0.16)\left(1 + \frac{\delta v}{v}\right)$$ [as usual: keep Yukawas fixed]

$$\hookrightarrow m_p(\delta v) = m_N(\delta v) - Q_N(\delta v)/2\ , \ \ m_n(\delta v) = m_p(\delta v) + Q_N(\delta v)$$

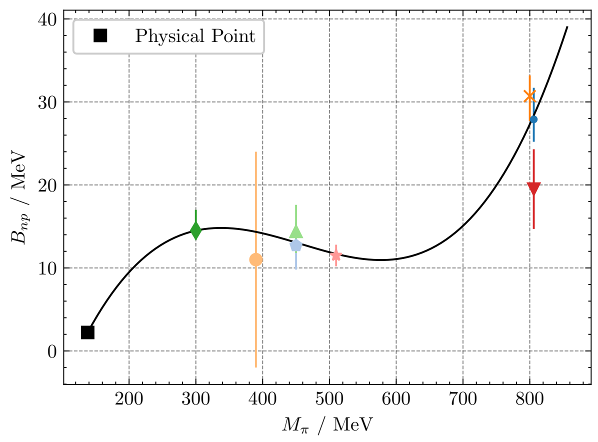


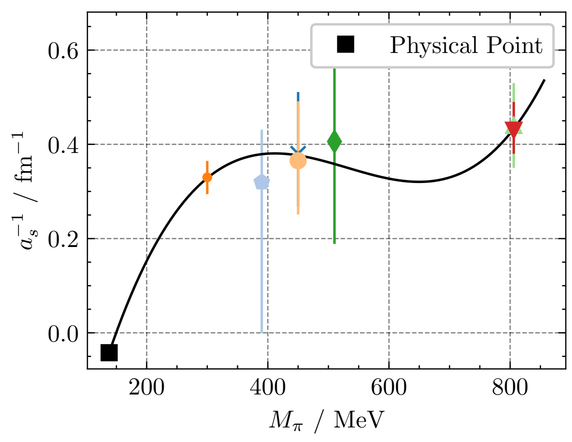
Meyer, UGM, JHEP **06** (2024) 074 $\longrightarrow$ more details in Helen Meyer's talk!

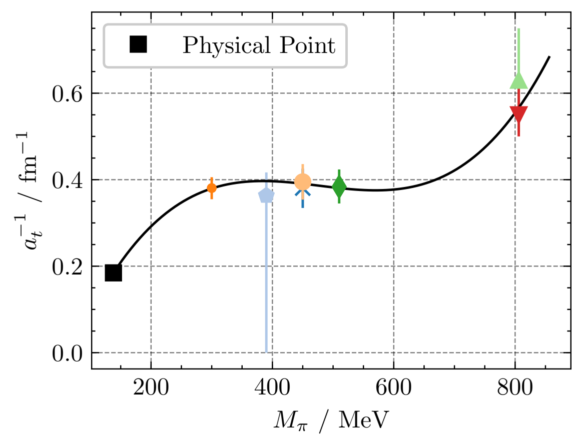
Pion mass dependence in nuclear systems II

- More tricky: NN contact terms and deuteron BE $\longrightarrow$ resort to LQCD + LETs

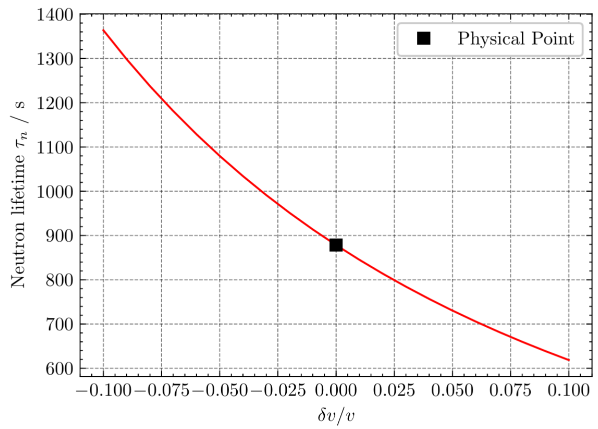
Baru, Epelbaum, Filin, Gegelia (2015,2016)

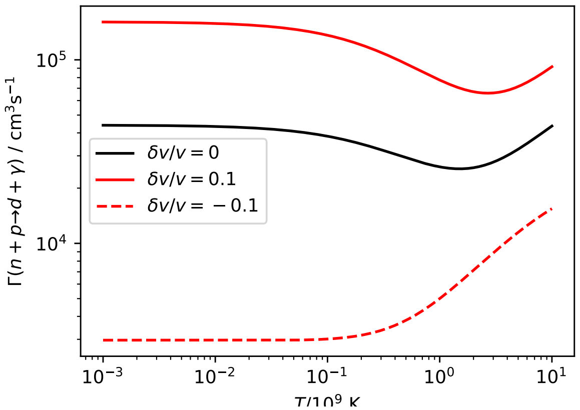






- Also important: Neutron lifetime and $np \to d\gamma$ (deuterium bottleneck)





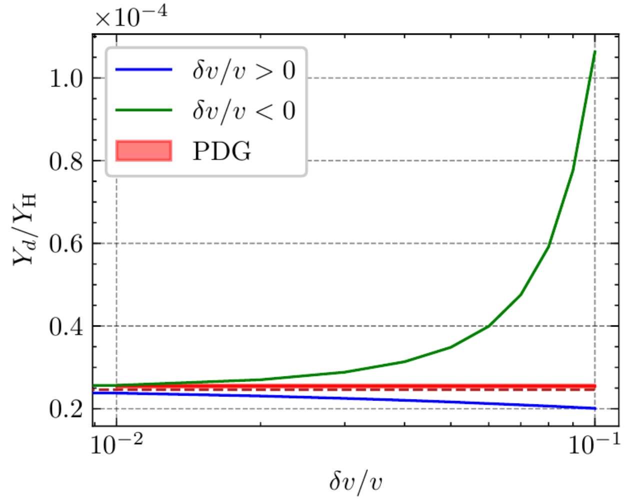
$\hookrightarrow$ insert into the BBN network and see how abundances vary

Higgs VEV variations

- Study the Higgs VEV limits on $\delta v/v$ from the deuterium & ^{4}He abundances

	^{4}He	d
PDG	$-0.014, 0.026$	$-0.005, -0.001$
EMPRESS	$0.011, 0.055$	

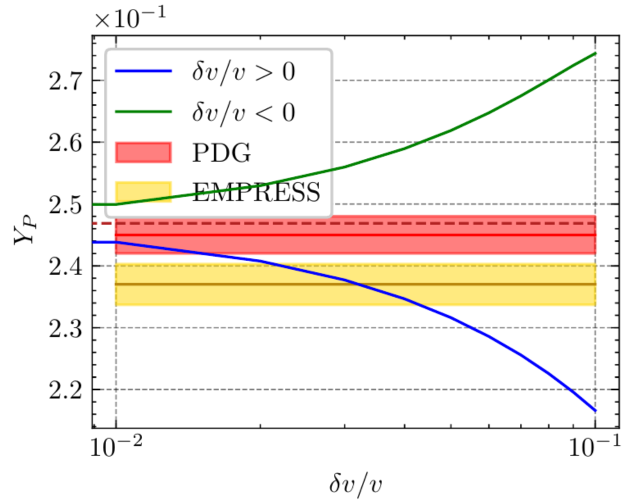
PDG: Workman et al., Review of Particle Physics, PTEP **2022** (2022) 083C01
EMPRESS: Matsumoto et al., Astrophys. J. **941** (2022) 167



- Deuterium more stringent that ^{4}He
  $\hookrightarrow$ different from all earlier investigations
  $\hookrightarrow$ also very asymmetric w.r.t. sign of the vev

- Quite a fine-tuning: $\delta v/v$ less than 0.5%

- Can be improved by better NN LQCD calculations closer to (or at) the physical point



- For variations on $\alpha_{\rm EM}$, see

UGM, Metsch, Meyer, Eur. Phys. J. A **59** (2023) 223 $\longrightarrow$ more details in Helen Meyer's talk!

Summary & outlook

- Hadron-hadron interactions continue to be an important playground of Chiral Dynamics
  - $\hookrightarrow$ strong focus on 3-pion/3-particle interactions — Bijnens, Briceno, Döring, Hansen, Mai, Romero-Lopez, Rusetsky, Sharpe, ...
  - $\hookrightarrow$ first LQCD calculation of the $\omega(782)$ [stressed in CD 2018] — Yan, Garafolo, Mai, UGM, C. Liu, L. Liu, Urbach
  - $\hookrightarrow$ still lots to be done, e.g. $R \to N\pi\pi$, also BSM searches in B-decays etc
  - $\hookrightarrow$ $\pi N \to \pi N$ from LQCD made progress since CD2018, but still ... — Bulava, Hanlon, Morningstar, Feng, Liu, Alexandrou, Petschlies, ...
- Ever increasing role in the hadron spectrum
  - $\hookrightarrow$ two-pole structures (nice interplay of CD + LQCD + Exp.)
  - $\hookrightarrow$ standard tool to approach the physical point, but problems remain, ...
  - $\hookrightarrow$ OPE contribution to exotic states gains relevance (pentaquarks,...)
- Pions in nuclei: they are there, but hard to quantify [indirect measures]
- New avenues of chiral dynamics:
  - $\hookrightarrow$ axion physics — Spalinski, di Luzio, Martinelli, Cortona, Hardy, Villadoro, Vega, Guo, UGM , Vonk,...
  - $\hookrightarrow$ ....

Final slide

Finally, can I answer the question:

"Chiral dynamics: Quo vadis?"

$\rightarrow$ **Well, let us see at CD 2027 @ ... !**