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Chiral dynamics: Quo vadis ?

Ulf-G. Meißner[a,b,c,*]

[a] *Helmholtz-Institut für Strahlen- und Kernphysik and Bethe Center for Theoretical Physics, Universität Bonn, D-53115 Bonn, Germany*

[b] *Institute for Advanced Simulation (IAS-4), Forschungszentrum Jülich, D-52425 Jülich, Germany*

[c] *Peng Huanwu Collaborative Center for Research and Education, Beihang University, Beijing 100191, China*

E-mail: meissner@hiskp.uni-bonn.de

I review the status of chiral dynamics. Topics include pion-pion scattering, dynamically generated states in the hadron spectrum and the emergence of two-pole structures, chiral symmetry in nuclear physics and chiral dynamics in the Big Bang.

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1. Introductory remarks

I start this talk with an anecdote. To my knowledge, one of the first papers that included "chiral perturbation theory" (in a slightly modified version) in the title was Ref. [1] from Bonn, which states in the first paragraph: "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, ...". This seems to make this talk obsolete. Of course, that paper was written before the emergence of effective field theories, which gave a very different meaning to the issue of renormalization, which was the main topic of Ref. [1]. In contrast to what was believed at that time, we know now that all fundamental quantum field theories are indeed effective field theories.

This brings me to the next basic issue, namely what precisely does chiral dynamics mean? This wording was first used by Julian Schwinger in Ref. [2], who replaced the cumbersome current algebra operator techniques by a numerical effective Lagrange function, which ultimately led to his source theory. I recommend the introduction of Weinberg's contribution to the symposium honoring Julian Schwinger on the occasion of his 60th birthday for a historical perspective of this work [3]. The terminology "chiral dynamics" is frequently used since then, but often with a different meaning. The wording "chiral perturbation theory" was used first in this strict form by Langacker and Pagels [4] but only became a household issue due to Gasser and Leutwyler [5, 6]. Thus, in what follows, I will use the following definitions:

- **Chiral perturbation theory (CHPT)** refers to a strict perturbative expansion in (a) small parameter(s), like the light quark masses and/or small momenta/energies.
- **Chiral dynamics (CD)** is used when some non-perturbative resummation is involved, say the kernel of a scattering process can be expanded using the CHPT counting rules but then the scattering matrix is solved non-perturbatively.

So in this talk, I will address issues in chiral dynamics. Of course, other persons use other definitions, thus it is important to clearly spell out what one is talking about. In any case, CHPT and CD explore the spontaneously and explicitly broken chiral symmetry of QCD and thus deepen our understanding of the Standard Model at low energies. In this talk, I review a number of recent developments. This is clearly based on a subjective choice, and other developments such as CHPT with axions, see the contribution by Feng-Kun Guo [7], are covered in many other interesting talks at this workshop.

2. Pion-pion scattering: The poster child and its offsprings

Pion-pion scattering (in the threshold region) is the purest process in two-flavor CHPT (and also chiral dynamics) because the up and down quarks are really light on the scale $\Lambda_{\rm QCD}$. I had talked about this fundamental reaction already at CD2012 [8] and at CD2018 [9], so I can be short on the basics and mostly (but not only) discuss progress in lattice QCD.

At threshold, the $\pi\pi$ scattering amplitude is given in terms of two numbers, the S-wave scattering lengths a_0 and a_2, corresponding to total isospin zero and two, respectively. The CHPT predictions are (I concentrate here on a_0): $a_0 = 0.16$ (LO) [10], $a_0 = 0.20 \pm 0.01$ (NLO) [5]

$a_0 = 0.217 \pm 0.009$ (NNLO) [11][1]. The fairly large corrections at NLO are understood from the strong pionic final-state interactions (FSI) in this channel and there are still sizeable corrections at NNLO despite the small expansion parameter $(M_\pi/\Lambda_\chi)^2 \simeq 0.02$ for $\Lambda_\chi = 1$ GeV.

The first offspring to improve on these works was the combination of CHPT with dispersion relations, which involved quite a number of people and works that I possibly can not discuss here. Matching the 2-loop CHPT representation of the $\pi\pi$ scattering amplitude to the Roy equation solution allows to make the prediction for a_0 much more precise, namely $a_0 = 0.220 \pm 0.005$ [12]. Even more, the dispersive analysis allowed also to precisely determine the mass and width of the lowest resonance in QCD, $M_\sigma = 441^{+16}_{-8}$ MeV and $\Gamma_\sigma/2 = 272^{+9}_{-13}$ MeV [13], nowadays called $f_0(500)$.

A second offspring was the development of NREFTs to give a different access to low-energy $\pi\pi$ scattering, more precisely, scattering at zero energy. This led to a precision theory for hadronic atoms, which is relevant for the $\pi\pi$, πK, πN, πd, Kp, Kd systems in the sector of the light quarks u, d, s. For a review, see Ref. [14]. For the case of pionium (the $\pi^+\pi^-$ bound state) experiment gives the scattering length combination $|a_0 - a_2| = 0.2533^{+0.0107}_{-0.0137}$ [15], which is consistent with the predictions [12]. I mention in passing that the experimental result of the the πK atom, $|a_0^{1/2} - a_0^{3/2}|/3 = 0.072^{+0.031}_{-0.020}$ [16] is incidentally consistent with the one-loop CHPT result 0.073(2) [17], but space does not allow for a more in-depth discussion on this fundamental reaction in three-flavor CHPT. For recent work on πK scattering with many references, see e.g. [18].

Another offspring is the analysis of the cusp that in $K \to 3\pi$ that can also be used to extract the pion-pion scattering lengths. Combining these with the FSI in K_{e4} decays leads to $a_0 = 0.2210 \pm 0.0047_{\rm stat} \pm 0.0040_{\rm sys}$ [19], again in nice agreement with theory.

Thus, experiment and chiral dynamics are well aligned, but what about lattice QCD (LQCD)? Recall that at the time of CD2012, no direct lattice a_0 determinations were available (due to the difficulty in taming the disconnected diagrams) and at the time of CD2018, two unquenched QCD simulations at unphysical pion masses were reported but the errors appeared too small. Now a number of better simulations are available, however, chiral extrapolation are still needed in most cases. The recent state of the art in the lattice determinations of the pion-pion S-wave scattering lengths with summary figures/tables can be found in Refs. [20, 21]. I focus here on the work of the GWU group [22] as their work concerns the S- and P-waves including the pertinent resonances (for a review on resonances from lattice QCD, see [23]). They find for the $I = 0$ S-wave $a_0 = 0.2132^{+0.008}_{-0.009}$ and a complex $f_0(500)$ mass of $M_\sigma = (443(3) - i\,221(6))$ MeV. While the central value of the mass is fine and in good agreement with the dispersive analysis whereas the width is somewhat small, I consider the errors underestimated. That can also be seen from the too small ρ mass, $M_\rho = (724^{+2}_{-4} - i\,67^{+1}_{-1})$ MeV, where the real part is many σ away from the empirical value ${\rm Re}\,M_\rho = 761 - 765$ MeV [24]. Note further that a recent calculation at the physical point gives $M_\rho = (796(5)(50) - i\,96(5)(16))$ MeV, which agrees with the PDG values within the sizeable errors [25], but has very different central values. So it is not yet time to declare victory, more LQCD work is certainly needed to precisely pin down even the lowest resonances in QCD.

[1]Note that in that paper, no error was given but two different solutions. I use here solution 1 as the central value and the difference to solution 2 as the uncertainty.

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3. Novel insights into the hadron spectrum from chiral dynamics

In CHPT, resonances are a limit, not active degrees of freedom. In very few cases, one can extend the chiral effective Lagrangian to include resonance fields explicitly (see below), whereas CD allows to investigate a larger number of unstable hadrons. In any case, one has to be aware of the decoupling theorem: The leading non-analytic terms in the S-matrix and transition currents stem from Goldstone boson one-loop graphs coupled to Goldstone bosons or ground state baryons [26]. This has a number of consequences. First, resonances must decouple, which is sometimes not accounted for. Second, the cuts and poles generated by the Goldstone bosons (GBs) are not affected by resonances. Still, the resonances leave their traces in saturating most of the low-energy constants (LECs) and further, the QCD chiral and large-N_C limits do not commute. Note that in the large-N_C limit, the nucleon and the $\Delta(1232)$ are degenerate in mass and thus the decoupling theorem is explicitly violated.

There are essentially three ways of including resonances: First, the inclusion as *matter fields* is possible in a few cases, here one mostly deals with the $\Delta(1232)$, see my talk at CD2018. This clearly requires an extended power counting and/or the complex-mass scheme. Second, in some cases, *CHPT combined with dispersion relations* (DRs) allows to study resonances, such as the already mentioned $f_0(500)$ as well as the $f_0(980)$, $\rho(770)$, $K_0^*(700)$, $K^*(890)$ in the meson sector and the $\Delta(1232)$ and the Roper $N^*(1440)$ in the baryon sector. Of course, DRs are a fine tool to study resonances in general, but this is mostly limited by the available data on the pertinent scattering processes, as witnessed by the renowned work of the Karlsruhe-Helsinki group many decades ago [27]. That work set a standard on the extraction of resonance properties which is unfortunately not always achieved in present day analyses. Here, I will give one example of recent work in this field and refer for more details to the talk by Jacobo Ruiz de Elvira in these proceedings [28]. Third, single channel unitarization or the more general *coupled-channel chiral dynamics* (non-perturbative unitarity) allows to study certain resonances (ρ, σ,..) and, in particular, to deal with the strange baryons [29]. For a nice review with a historical perspective, see [30].

The Roy equation program for $\pi\pi$ scattering can also be performed in the pion-nucleon system, where the basic equations are the so-called Roy-Steiner equations, see Ref. [31] and references therein. First, this allows for a high-precision determination of the πN σ-term including isospin-breaking corrections, $\sigma_{\pi N} = 59.0(3.5)\,\text{MeV}$ [32]. Second, the dimension-two πN LECs $c_{1,2,3,4}$ can be determined precisely, namely $c_1 = 1.10(3)$, $c_2 = 3.57(4)$, $c_3 = -5.54(6)$ and $c_4 = 4.17(4)$, all in GeV^{-1}, and similarly for some of the dimension-three LECs $\bar{d}_i$, namely $\bar{d}_1 + \bar{d}_2$, $\bar{d}_3$, $\bar{d}_5$ and $\bar{d}_{14} - \bar{d}_{15}$. These will be needed in the discussion of chiral symmetry in nuclei, see below. Third, the lowest nucleon resonances and their couplings to various mesons ($f_0(500)$, $f_0(980)$, and $\rho(770)$) can be extracted from the Roy-Steiner analysis, such as $M_\Delta = (1209.5(1.1) + i\,98.5(1.2))\,\text{MeV}$ and $M_R = (1374(3)(4) + i\,215(18)(8))\,\text{MeV}$. It is important to stress that the couplings of the various mesons to these baryons are complex-valued, as is the case for any unstable state. For more details see Ref. [33].

The basic idea of coupled-channel chiral dynamics can be spelled out easily. Consider a given $2 \to 2$ scattering process that involves a number of coupled channels. In the first step, one uses CHPT[2] to construct the potential $V = V_{\rm LO} + V_{\rm NLO} + \ldots$, which is then resummed, often in the

[2]Or some combination of CHPT and heavy quark symmetries, e.g. for Goldstone bosons scattering off the D-meson

on-shell approximation, $T = V/[1 + GV]$, where T is the scattering matrix and G the pertinent two-hadron loop function, see Fig. 1. Note that T, V and G are matrices in channel space and any

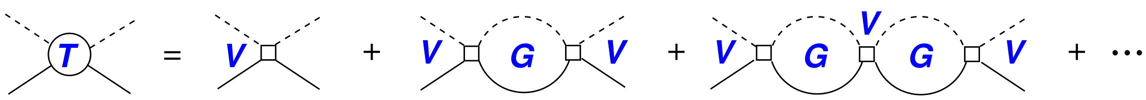

Figure 1: Unitarization of GB scattering (dashed lines) off baryons (solid lines) .

channel index is suppressed for simplicity. The two-hadron loop function and the resummation procedure require regularization, and this seems to introduce some model-dependence. It can, however, be overcome by going to sufficiently high orders. More importantly, the resummation allows for the generation of resonances, in particular the elusive $\Lambda(1405)$, see Refs. [34, 35] for reviews. Before discussing this particular state, let me point out that such dynamically generated resonances are an integer part of the hadron spectrum, thus any model, that does not allow for the inclusion of such states, is not a faithful representation of QCD and thus should be abandoned. In particular, the analysis of $\bar{K}N$ scattering in unitarized CHPT has revealed a new class of players in the hadron spectrum, the so-called two-pole structures. See the talk by Lisheng Geng in these proceedings [36]. The terminus "two-pole structure" refers to the fact that particular single states in the hadron spectrum as listed in the PDG tables are indeed two states. In terms of unitarized CHPT, this was first observed in Ref. [37] in a re-analysis of coupled-channel K^-p scattering. In that work, a number of technical improvements were introduced, such as the subtracted meson-baryon loop function with dimensional regularization, which has become a standard methodology by now, the coupled-channel approach to the $\pi\Sigma$ mass distribution and matching formulas to any order in chiral perturbation theory were established. Most importantly, it was found that the $\Lambda(1405)$ is indeed described by two poles with rather different imaginary parts, that exhibit a clear departure from the Breit-Wigner (BW) situation (the latter issue is of particular importance for experimental collaborations that often misuse the BW parameterization). The emergence of these two poles starting from the SU(3) limit of three-flavor QCD was worked out in [38]. When all quark masses are equal, $m_u = m_d = m_s$, the masses of the mesons in the GB octet are all the same and all baryon masses in the ground state octet are equal, thus all the baryons are stable and reside on the real axis. Consider the scattering of the GBs off the octet baryons. Simple group theory gives $8 \otimes 8 = 1 \oplus 8_s \oplus 8_a \oplus 10 \oplus \overline{10} \oplus 27$, where one has binding at LO in the singlet and the two octets. This generates 17 mostly degenerate bound states (the two octets are accidentally degenerate and the singlet is somewhat lighter). From these 17 bound states, only a few survive when one switches on the SU(3) symmetry breaking, in particular two states with $I = 0$ in the vicinity of the $\Lambda(1405)$, one close to the $\bar{K}N$ and the other close to the $\pi\Sigma$ threshold, respectively. This is how CD generates these two poles (and a few others). The two-pole structure of the $\Lambda(1405)$ has been verified by many groups world-wide. However, the lower pole is not yet precisely determined. In the PDG tables, now two poles appear, the two-star resonance $\Lambda(1380)$ (the low-mass pole) and the four-star resonance $\Lambda(1405)$ (the high-mass pole). Even more interesting, more of such two-pole structures have been found, as reviewed in Ref. [39] and discussed here by Geng [36]. So the chiral dynamics

triplet, or other types of extensions.

leaves clear imprints in the hadron spectrum, which is certainly a very unexpected development and it is an open question how many of these two-pole structures will indeed be found.

4. Chiral symmetry in nuclear interactions and in nuclei

As it is well-known, the pion was introduced by Yukawa in 1935 as the carrier of the strong force [40], and was found in emulsion experiments about a decade later [41]. Only in the early 1970ties, the pion was firmly established in nuclei by resolving the long-standing discrepancy between the theoretical predictions for the threshold neutron capture reaction, $n + p \to d + \gamma$, in the impulse approximation, $\sigma_{\rm IA} = 302.5(4.0)$ mb, and the measured value $\sigma_{\rm exp} = 334.2(5)$ mb, as meson-exchange currents (MECs) just provide the missing 10% [42]. Such pionic MECs now appear naturally in the chiral EFT of nuclear forces and currents, see e.g. the early work in [43]. Then came the 1993 shock, when Bertsch, Frankfurt and Strikman questioned the role of nuclear pions by analyzing a number of medium- and high-energy experiments [44]. Quickly, a number of (questionable?) solutions to recover the pions was published, but let me return back to chiral symmetry. As pointed out so clearly by Weinberg (and others), chiral symmetry breaking in QCD relates *many* processes. One of the best examples are the dimension-two (three) vertices from the effective πN Lagrangian $\sim c_i$ ($\bar{d}_i$) already mentioned above. The corresponding LECs can be precisely determined in pion-nucleon scattering and leave their traces in the two- as well as the three-nucleon interactions, see Fig. 2. Here, I concentrate on the NN interaction. The two-pion

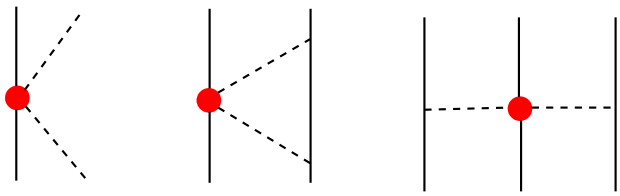

Figure 2: The LECs c_i (red circles) in pion-nucleon scattering (left), the two-pion exchange potential in the NN (middle) and the 3N (right) forces, respectively. Solid (dashed) lines denote nucleons (pions).

exchange (TPE) was already studied in the framework of the chiral NN forces in [45, 46], but a truely quantitative description was only achieved later with the N4LO [47] and N4LO$^+$ potentials [48]. The leading two-pion exchanges $\sim c_i$ and $\sim d_i$ appear at N2LO and N4LO, leading to parameter-free contributions at N2LO and N4LO from TPE. In both cases, there is a clear improvement in the description of the *np* and *pp* scattering data when going from NLO to N2LO and from N3LO to N4LO, respectively, due to this parameter-free TPE, see e.g. Table III in Ref. [48]. Clearly, this is not an absolute measure as the potential is not an observable.

Still, one might ask the question whether pions are really required in nuclear structure? First, many relativistic mean-field models based mostly on σ, ω, ρ exchanges work rather well, but they are not consistent with chiral symmetry and thus have no foundation in QCD. Furthermore, one can formulate nuclear physics based on EFTs just employing contact interactions without any pions. Such pionless EFT approaches are also not constrained by chiral symmetry. I mention here the EFT build around the so-called unitary limit [49] or the so-called minimal nuclear action of NLEFT [50] based on Wigner's SU(4) symmetry [51], that allows one to describe neutron matter up to saturation

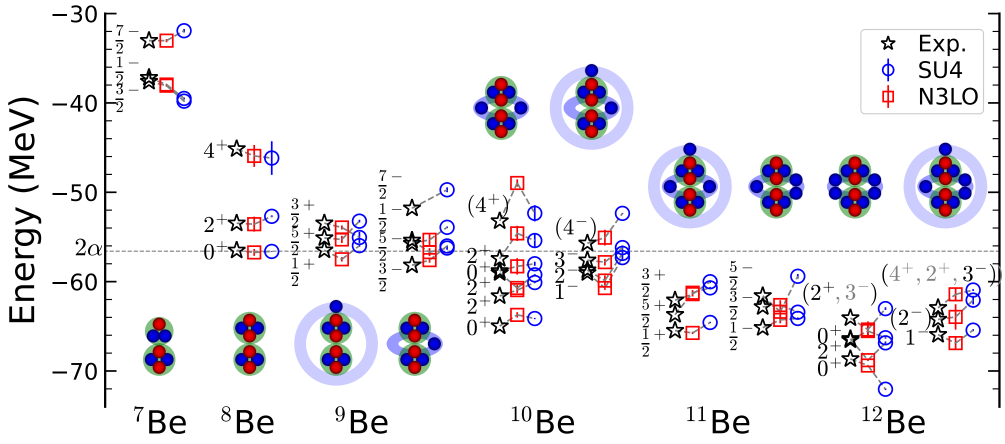

Figure 3: Low-lying spectrum from ^{7}Be to ^{12}Be calculated by NLEFT using the N3LO interaction [55] and the SU(4) interaction [52], compared to the data. The error bars correspond to one standard deviation errors include stochastic errors and uncertainties in the Euclidean time extrapolation. The two α threshold is denoted by horizontal dashed line. The cartoons display the dominant structure of each isotope. Figure courtesy of Shihang Shen.

density and the ground state properties of nuclei up to calcium with only four parameters. In this approach, the spectrum of carbon can also be well described [52] and the data on the ^{4}He transition form factor are reproduced precisely [53], see also the talk by Dean Lee [54] in these proceedings. So pions don't seem to be needed? They are, because there are much different nuclear systems that can not be described by these methods and also, the precision is limited. To overcome the sign oscillations that prevented NLEFT calculations beyond N2LO, which limits the precision of the calculations, the new quantum many-body method of *wavefunction matching* was introduced in Ref. [55], see also [54]. In a nutshell, wavefunction matching (WFM) transforms the high-fidelity interaction (in our case the N3LO chiral nuclear Hamiltonian) between particles (in our case nucleons) so that the wave functions of the high-fidelity Hamiltonian up to some finite range matches that of an easily computable Hamiltonian, where the latter gives an approximate solution of the many-body problem and is largely free of the disturbing sign oscillations. More precisely, wavefunction matching operates entirely in the two-nucleon sector. For the nuclear case, this simplified Hamiltonian consists of Wigner SU(4) symmetric two-nucleon forces and properly regularized one-pion exchange, and it is treated fully non-pertubatively. To bring the chiral Hamiltonian H_χ close to the simplified Hamiltonian H_S, a unitary transformation is performed leading to $H'_\chi = U^\dagger H_\chi U$, and the differences to the full chiral Hamiltonian, $H'_\chi - H_S$, are then calculated in first order perturbation theory. Finally, fitting the various locally and non-locally smeared 3NF operators to the nuclear binding energies with $3 \leq A \leq 58$, one can predict the corresponding nuclear charge radii as well as the equation of state of pure neutron as well as nuclear matter. All of these quantities agree with the data. This would not be possible without the OPE in the simple Hamiltonian, so **pions are indeed needed in nuclear structure**. The form of the simple Hamiltonian also gives further credit to Weinberg's power counting in chiral nuclear EFT.

As an application of the power of WFM, in Fig. 3 I display the low-lying states of the p-shell beryllium isotopes from ^{7}Be to ^{12}Be using the state-of-the-art full N3LO interaction and also the SU(4) interaction [56]. One finds good agreement of the energies, radii, and electromagnetic properties with the data. Clearly, the SU(4) approach does not precisely give these energies (as mentioned above), but still works astonishingly well. More interestingly, the different geometrical properties of these isotopes come out consistent with what is known, namely two-center cluster structures as well as one- and two-neutron halos (as shown by the cartoons in Fig. 3, but worked out in more detail using tomographic methods in [56]). These results are quite intriguing because generally, different approaches are used for these different structures, like cluster models or halo-EFT.

5. Chiral dynamics in the Big Bang

The light elements are generated in the Big Bang during the first 15 minutes of the Universe, which is called Big Bang Nucleosynthesis (BBN). This reaction network is characterized by a number of fine-tunings, in particular let me mention the so-called deuterium bottleneck, where the produced deuterium is disintegrated by the abundant photons until the Universe has cooled down sufficiently. This is by the way very different to high-energy heavy ion collisions, which are often described as the Big Bang in the laboratory. But let me come back to the primordial nucleosynthesis. These can indeed be used to set limits on the possible variations of the fundamental constants of the Standard Model, in particular the light quark masses and the electromagnetic fine-structure constant α, an idea first entertained by Dirac [57]. For recent reviews on these and related issues, see Refs. [58, 59].

Here, I report on some recent results obtained in collaboration with Bernard Metsch and Helen Meyer, see also Helen Meyer's talk at this workshop [60]. First, we obtained new results for the dependence of the primordial nuclear abundances as a function of α, keeping all other fundamental constants fixed [61]. This included updates on the leading nuclear reaction rates, and the inclusion of the temperature-dependence of the leading nuclear reactions rates. Furthermore, the systematic uncertainties were assessed by using five different publicly available codes for BBN. The current values for the observationally based ^{2}H and ^{4}He abundances restrict the fractional change in α to less than 2%, which is a tighter bound than found in earlier works on the subject.

More interesting from the view of chiral dynamics are the bounds on the quark mass variations, which has been a topic of many papers, see e.g. Appendix B in Ref. [62]. In general, the pion mass dependence in nuclear systems can be most easily understood by looking at the LO nucleon-nucleon (NN) interaction in the Weinberg scheme, see Fig. 4. Due to the Gell-Mann–Oakes–Renner relation, $M_\pi^2 = B_0(m_u+m_d)$, the light quark mass dependence can be mapped onto the pion mass dependence, which is either explicit (pion propagator) or implicit (nucleon mass, pion-nucleon coupling, 4N LECs). In the most recent work [62], we considered the possible variations of the Higgs VEV v. Keeping, as mostly done, the Yukawa couplings fixed, the variation of the light quark masses is proportional to the variation of v. In this work, we included in particular the new value of the strong neutron-proton mass splitting from Ref. [63], $(m_n - m_p)_{\rm QCD} = (1.87 \pm 0.16)$ MeV, and for the NN contact terms and deuteron binding energy we combined LQCD data with the low-energy theorems from Refs. [64, 65]. Here, the detailed balance between the capture $n + p \to d + \gamma$ and dissociation $\gamma + d \to n + p$ reactions is very sensitive to the change in the deuteron binding energy, leading to

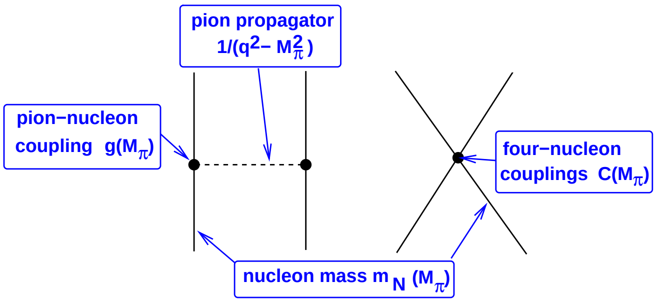

Figure 4: Pion mass dependence of the NN interaction through the OPE and the LO contact interactions. Solid (dashed) lines denote nucleons (pions).

very stringent bounds on possible variations of the Higgs VEV, namely $\delta v/v \in [-0.0069, 0.0039]$ from the ^{4}He abundance and $\delta v/v \in [-0.0007, -0.0002]$ from the ^{2}H abundance (by comparing to the PDG values). Two points are in particular noticeable: In contrast to most earlier investigations, the deuterium abundance sets a stronger bound than the one from ^{4}He, and second, these bounds are much tighter than earlier ones, see e.g. the recent work [66].

6. Summary & outlook

Although CD is a mature field, still some basic predictions are just getting precisely tested now like the chiral anomaly in the process $\gamma \to 3\pi$, see the talk by Maltsev for the COMPASS collaboration [67]. As it is usually the case in this field, there is a strong interplay between theory and experiment, see the talk by Bai-Long Hoid [68]. There is also an on-going tension between the pion-nucleon σ-term from the RS equations and lattice QCD determinations, see the talk by Jacobo Ruiz de Elvira [28], which adds to the tensions discussed in the context of pion-pion scattering. To my opinion, these can only be resolved by more lattice work, accounting for all possible systematic effects such as excited state contaminations, see e.g. [69].

In the hadron spectrum, the emergence of two-pole structures is tightly connected to the remaining ground state SU(3)$_V$ symmetry of QCD and its explicit symmetry breaking, which is an integer part of chiral dynamics. This is a new and fairly unexpected manifestation of chiral dynamics, which is based on a fruitful interplay of experiment, theory and LQCD. The coupled-channel methods developed in this context can also serve to better analyze experimental as well as lattice data, see e.g. Ref. [70]. Experimenters often use Breit-Wigner parameterizations in situations were they are not applicable. In fact, many resonance properties in the PDG tables are obtained in that way, which requires modifications.

That pions play an important role in nuclei is known since long [71], in particular through the excitation of the $\Delta(1232)$ resonance. There have been recent attempts to include the $\Delta(1232)$ in the nuclear interactions, which not always fulfill the decoupling theorem. It is undoutable that for a QCD-based precision nuclear physics approach, pions are an indispensable ingredient, although in certain cases (few-nucleon reactions) they can be integrated out and one still can make precise calculations based on pionless EFT, see e.g. Refs. [72–74], but this is more the exception than the rule.

Another playground of chiral dynamics is the investigation of fine-tunings in certain nuclear reactions, as the pion mass dependence can be used to set bounds on possible variations of the quark masses or the Higgs VEV. Here, input from lattice QCD at unphysical quark masses is very much needed, as Nature provides us only with one set of quark masses (and other fundamental constants).

So can I answer the question posed in the title of this talk? The answer is yes and no. There are still a number of open ends, some of which I mentioned. Here, especially the lattice community can contribute significantly, however, the errors quoted often appear too small in my view, which generates some (unnecessary) tensions. In particular, I would like to see more few-nucleon results at lower quark masses, which e.g. would serve to tighten the constraints on the variations of the fundamental parameters in nuclear reactions, besides from being interesting by themselves. One could argue that chiral dynamics might become obsolete if lattice QCD operates at physical quark masses and has all the systematics under control. Looking at the topics discussed, I do not think that this will happen but rather one should continue combining the various theoretical tools to make the most precise predictions to be confronted by precision experiments.

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