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Book of Abstract

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1 Plenary Sessions

1.1 An overview of recent nucleon spin structure measurements at Jefferson Lab

K. Allada
Thomas Jefferson National Accelerator Facility, Newport News, VA, USA

Our understanding of nucleon spin structure is still far from complete. Experiments conducted at Jefferson Lab have made significant contributions to improve our knowledge of the longitudinal spin structure by measuring polarized structure functions, g_1 and g_2, down to $Q^2 = 0.02$ GeV^2. The low Q^2 data is especially useful in testing the Chiral Perturbation theory (ChiPT) calculations. The spin-dependent sum rules and the spin polarizabilities, constructed from the moments of g_1 and g_2, provide an important tool to study the longitudinal spin structure. We will present an overview of the experimental program to measure these structure functions at Jefferson Lab, and present some recent results on the neutron polarizabilities, proton g_1 at low Q^2, and proton and neutron d_2 measurements. In addition to this, we will discuss the transverse spin structure of the nucleon which can be accessed using chiral-odd transversity distribution (h_1), and show our results from measurements done on polarized ^{3}He target in Hall A.

1.2 Hadronic weak interaction: The NPDGamma experiment

L. Barrón-Palos [for the NPDGamma Collaboration]
Universidad Nacional Autónoma de México, Ciudad de Mexico, Mexico

The measurement of very small parity-violating (PV) observables in few-nucleon systems, where nuclear wave functions are calculable, is a via for understanding the hadronic weak interaction (HWI), which remains enigmatic due to the dominance of the strong interaction in hadronic systems and the non-perturbative nature of Quantum Chromodynamics at low energies. Additionally, the study of the strangeness-conserving HWI could help to understand phenomena that have been observed in the strangeness-changing sector and that cannot be explained in the framework of existing theories, like the dominance of the $\Delta I = 1/2$ channel in the decay of kaons or the relative weak amplitudes in the non-leptonic decay of hyperons. The strangeness-conserving HWI also offers the possibility to study neutral currents at low energies, since charged currents are suppressed for the $\Delta I = 1$ nucleon-nucleon interactions. The $\Delta I = 1$ channel, accessible through the exchange of pions, dominates the strong interactions between nucleons at low energies. The availability of very intense neutron sources has allowed the development of experiments to measure PV effects in nuclear interactions between polarized slow neutrons and light nuclei with sensitivity in the 10^{-8} level. A pioneer among these is the NPDGamma experiment, which last year completed data acquisition at the Spallation Neutron Source at the Oak Ridge Natiobal Laboratory to determine the PV asymmetry in the spatial distribution of the gamma rays emitted in the capture of polarized cold neutrons by protons, A_γ. This asymmetry is dominated by the $\Delta I = 1$ $^3S_1 - {}^3P_1$ parity-odd transition in the $n-p$ system, therefore it is related to the weak coupling that characterizes the exchange of one pion in the HWI, h^1_π. A statistical uncertainty of $\sim 1.3 \times 10^{-8}$ was achieved in the determination of A_γ. I will describe the experiment and discuss preliminary results, as well as their comparison with theoretical calculations and previous experimental results.

1.3 Unexpected chiral dynamics from lattice QCD calculations of nuclear systems

S.R. Beane
Department of Physics, University of Washington, Seattle, WA, USA

I will review recent calculations of the properties and interactions of nuclei and hypernuclei from first principles using lattice QCD. Many interesting observables have now been computed at several (unphysical) values of the quark masses and the first rudimentary extrapolations to the physical point have been performed. The resulting picture of the quark mass dependence of nucleon and nuclear observables is somewhat surprising from the perspective of chiral dynamics.

1.4 Effective field theories and lattice QCD

C. Bernard
Washington University, Saint Louis, MO, USA

I describe some of the many connections between lattice QCD and effective field theories, focusing in particular on chiral effective theory, but also touching upon Symanzik effective theory and heavy quark effective theory. Ifirst discuss the ways in which effective theories have enabled and supported lattice QCD calculations. Particular attention is paid to the inclusion of discretization errors, for a variety of lattice QCD actions, into chiral effective theory. Several other examples of the usefulness of chiral perturbation theory, including the encoding of partial quenching and of twisted boundary conditions, are also described. In the second part of the talk, I turn to results from lattice QCD for the low energy constants of the two- and three-flavor chiral theories. I concentrate here on mesonic quantities, but a few results for nucleons are also mentioned. Finally I discuss some recent preliminary lattice QCD calculations by the MILC Collaboration relating to the three-flavor chiral limit.

1.5 Progress on the muon anomalous magnetic moment from lattice QCD

T. Blum
University of Connecticut, Storrs, CT, USA

Recent studies of the hadronic vacuum polarization and hadronic light-by-light scattering contributions to the muon anomalous magnetic moment (g-2) are reviewed. Attention is paid to systematic errors arising from finite volume and non-zero lattice spacing, among others. The problem of disconnected quark loop diagrams is also discussed.

1.6 Kaons at CERN: The NA62 experimental program

A. Ceccucci
CERN, Geneva, Switzerland

Kaons are a laboratory where a broad physics programme can be addressed. From the study of fundamental symmetries to the exploration of the hadron structure, from the search for phenomena beyond the Standard Model to the comprehension of the simplest hadronic states, many investigations profit from the remarkably clean theoretical and experimental environment provided by kaons. NA62 is a new experiment at CERN exploiting the high energy protons from the Super Proton Synchrotron. The main goal of NA62 is the study of very rare kaon decays and to this purpose the experiment incorporates state-of-the-art detectors including innovative trackers, high performance calorimetry and complete particle identification capability. The presentation will review the status of the experiment and its perspectives.

1.7 Electric dipole moments, new physics, and QCD

V. Cirigliano
Los Alamos National Laboratory, Los Alamos, NM, USA

Electric Dipole Moments (EDMs) of leptons, nucleons, atoms, and molecules are great probes of new sources of CP violation originating from physics beyond the Standard Model (BSM). In this talk I will discuss the central role that QCD and chiral dynamics play in the interpretation of current experimental searches. After an overview of the physics reach of various EDM searches, I will briefly review the chiral effective theory framework needed for the interpretation of hadronic and nuclear EDM searches. I will then present recent work towards the computation of the BSM-induced neutron and proton EDM using lattice QCD.

1.8 Dispersive treatment of the hadronic light-by-light contribution to $(g-2)_\mu$

G. Colangelo
University of Bern, Bern, Switzerland

I will describe recent progress in approaching the calculation of the hadronic light-by-light contribution to $(g-2)_\mu$ with dispersive methods. I will first discuss general properties of the four-point function of the electromagnetic current in QCD, its Lorentz decomposition and dispersive representation. For what concerns the pseudoscalar pole contributions, I will give an overview of the determination of the pseudoscalar transition form factors. I will then consider the pion-loop contribution and discuss the recently proposed Mandelstam representation thereof.

1.9 Recent progress in hadron structure from Lattice QCD

M. Constantinou
University of Cyprus, Nicosia, Cyprus

Understanding hadron structure from first principles is considered a milestone of hadronic physics and numerous experiments have been devoted to its study, starting with the measurements of the electromagnetic form factors more than 50 years ago. Lattice QCD (LQCD) is a powerful tool for the ab inition calculation of hadron observables that are either well determined experimentally, or not easily accessible in experiment. Thus, LQCD may provide input to phenomenology, as well as new input for beyond the Standard Model Physics.
Progress in the simulation of LQCD has been impressive, mainly due to improvements in the algorithms, development of new techniques and increase in computational power, that have enabled simulations to be carried out at parameters very close to their physical values. In this talk I will review developments in hadron structure with focus on recent achievements in the evaluation of nucleon quantities, such as the axial charge, electromagnetic form factors, the Dirac and Pauli radii, the quark momentum fraction and the spin content of the nucleon, in view of simulations close or at the physical value of the pion mass. I will also highlight selected results on hyperon and meson form factors.

1.10 Compton scattering and the nucleon polarizabilities

E.J. Downie[1]
The George Washington University, Washington DC, USA

Polarizabilities are fundamental properties of the nucleon which can be accessed by measuring the differential cross section, and singly and doubly polarized asymmetries in real Compton scattering (RCS). Their measurement gives rise to a better understanding of nucleon dynamics and structure. Polarizabilities play an important role in many areas of physics: from being the largest component of the theory error in the extraction of the radius of the proton from the Lamb shift, to influencing neutron star physics. Despite their all-pervading nature, and great theoretical interest, there is still a large uncertainty in the nucleon scalar polarizabilities, and the nucleon spin polarizabilities had, until recently, never been individually measured [1].
In a typical polarisability measurement such as that within the A2 experimental hall of the MAMI accelerator, in Mainz, Germany, one needs a high flux photon beam, here provided by tagged bremsstrahlung photon beam of the Glasgow Edinburgh Mainz Photon Tagger. This usually impinges on a liquid hydrogen or dynamically polarized frozen spin target. The scattered photons are detected in a large-solid-angle spectrometer, such as the NaI(Tl) Crystal Ball detector (when $20° < \theta < 160°$) and TAPS (when $\theta < 20°$) combination in A2, or, as at HIGS and Lund, in a set of large, high resolution NaI detectors. Above pion production threshold, a large acceptance detector system enables the suppression of many background processes, such as π^0 production.
The polarizabity measurement program relies on theory to extract the polarizabilities from the real Compton Scattering data. In order to minimize and control the model-dependence of the of the extraction, it is imperative to use a variety of different theory flavors and models. It is also important to measure over as broad an energy and angular range as possible in order to provide a strenuous test of the various theories. The small-cross-section RCS process can be difficult to cleanly extract from the data, it is therefore necessary to measure these RCS asymmetries at multiple laboratories with differing beam types and detector setups. To this end, there are active RCS programs at MAX-IV in Lund, and HIGS at TUNL in addition to MAMI.
The MAMI measurement program spans spin and scalar polarizabilities [2], with data taken on three different asymmetries (Σ_{2x}, Σ_{2z}, and Σ_3) in the region of the delta resonance in order to obtain the spin polarizabilities [3]. These are the first measurements of doubly polarized asymmetries in real Compton scattering. There has also been a measurement of Σ_3 below pion production threshold in order to extract the proton scalar electric and magnetic polarizabilities (α_{E1} and β_{M1}, respectively) independently from each other. At HIGS, there are planned Σ_{2x} and Σ_3 measurements and the neutron measurement program is also in progress. Al MAX-!V, the final nuclear physics measurement is planned to be RCS on the deuteron. MAMI too is moving towards neutron measurements with planned RCS cross section measurements on $^{3/4}$He. The theory development necessary for the interpretation of the data is also already well underway [4].
In these times of great change and new data, we will provide an overview of the current status of the experimental program across all three labs and the future outlook.

[1]This material is based upon work supported by the National Science Foundation under Grant Numbers PHY-1309130 & IIA-1358175.

References

1. H.W. Grießhammer, J.A. McGovern, D.R. Phillips, and G. Feldman, Prog. Part. Nucl. Phys. **67**, 841 (2012).
2. E.J. Downie and H. Fonvieille, Eur. Phys. J. ST **198**, 287 (2011).
3. P.P. Martel *et al.*, Phys. Rev. Lett. **114**, 112501 (2015).
4. H.W. Grießhammer, D.R. Phillips, and B. Strandberg, in preparation.

1.11 Status of chiral perturbation theory for light mesons

G. Ecker
University of Vienna, Vienna, Austria

I will review some recent activities in mesonic chiral perturbation theory. Our present knowledge of low-energy constants in the strong sector up to and including next-to-next-to-leading order will be discussed. I will also assess the present status of CKM unitarity. Further topics are pion polarizabilities, kaon and η decays.

1.12 Meson resonances on the lattice

R.G. Edwards
Thomas Jefferson National Accelerator Facility, Newport News, Virginia, USA

There has been recent, significant, advances in the determination of the meson spectrum of QCD. Current efforts have focused on the development and application of finite-volume formalisms that allow for the determination of scattering amplitudes as well as resonance behavior in coupled channel systems. I will review some of these recent developments, and demonstrate the viability of the method in meson systems.

1.13 Muon anomalous magnetic moment and hadronic vacuum polarization: Recent developments

S. Eidelman[a,b]

[a] *Budker Institute of Nuclear Physics, Novosibirsk, Russia*

[b] *Novosibirsk State University, Novosibirsk, Russia*

We discuss the current status of the theoretical prediction for the muon anomalous magnetic moment in Standard Model. Recent developments in estimation of hadronic vacuum polarization are described based on measurements of $e^+e^- \to$ hadrons cross section in Novosibirsk and Beijing as well as those with ISR at KLOE, BaBar and Belle. We also briefly review expectations for experiment and theory in close future.

1.14 Nuclear chiral EFT in the precision era

E. Epelbaum
Ruhr University of Bochum, Bochum, Germany

Chiral effective field theory provides a systematically improvable perturbative approach to deriving nuclear forces in harmony with the symmetries of QCD. Combined with modern few- and many-body methods, this framework represents a commonly accepted procedure for *ab initio* studies of nuclear structure and reactions.
Recently, a new generation of nucleon-nucleon (NN) forces up to fifth order in the chiral expansion has been developed [1, 2]. By employing an appropriate regularization in coordinate space, which maintains the analytic structure of the amplitude, it was possible to significantly reduce the amount of finite-cutoff artefacts. In addition, a simple approach to estimating the theoretical uncertainty in few- and many-nucleon calculations from the truncation of the chiral expansion was proposed [1].
I will present the applications of the novel NN chiral potentials, along with the new analysis of the theoretical truncation errors, to NN and nucleon-deuteron scattering and to the properties of ^{2}H, ^{3}H, ^{4}He and ^{6}Li [1, 2, 3].

References

1. E. Epelbaum, H. Krebs, and Ulf-G. Meissner, Eur. Phys. J. A **51**, 53 (2015).
2. E. Epelbaum, H. Krebs, and Ulf-G. Meissner, arXiv:1412.4623 [nucl-th].
3. LENPIC Collaboration, arXiv:1505.07218 [nucl-th].

1.15 Extracting (pion) form factors from finite volume lattices

H. Fukaya and T. Suzuki [for JLQCD collaboration]
Osaka University, Toyonaka, Osaka, Japan

In lattice QCD simulations, there is a strong tendency to over-estimate the form factors (and therefore, under-estimate the related charge radii) of pions and other hadrons. In fact, the three major systematic in lattice QCD: finite lattice spacing a, lack of chiral symmetry, and finite volume all could contribute to the over-estimation of the form factors. This can be easily understood within the chiral effective theory, as a distortion of the chiral logarithm :

$$\ln M_\pi^2 \to \ln(M_\pi^2 + \delta m^2), \tag{1}$$

where M_π denotes the pion mass, and δm is the unphysical mass scale induced by finite a, and/or explicit chiral symmetry breaking, and/or finite lattice size.

In this talk, we would like to focus on the finite volume effects using chiral perturbation theory [1] and discuss how to avoid such an over-estimation of the (pion) form factors. We also present our recent lattice results with dynamical overlap (Ref. [2] and Fig. 1) and Möbius domain-wall fermions [3].

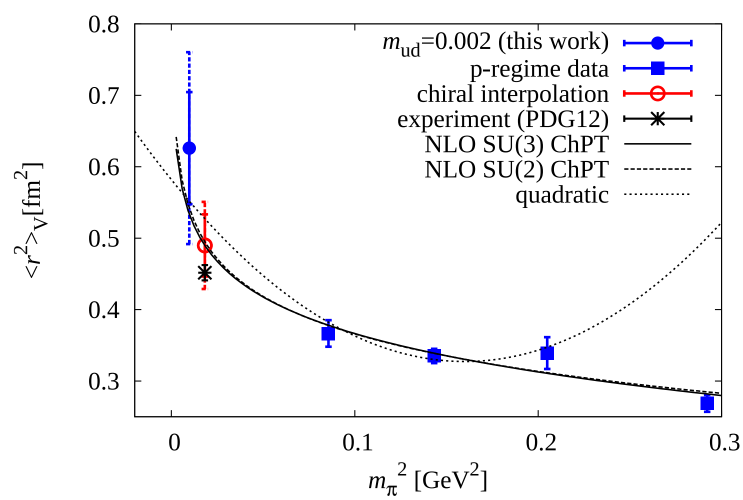

Figure 1: Result for pion charge radius [2].

References

1. H. Fukaya and T. Suzuki, Phys. Rev. D **90**, 114508 (2014)[arXiv:1409.0327].
2. JLQCD collaboration, Phys. Rev. D **90**, 034506 (2014) [arXiv:1405.4077].
3. JLQCD collaboration, work in progress.

1.16 Probes for fundamental QCD symmetries and a dark gauge boson via light meson decays

L. Gan
University of North Carolina at Wilmington, Wilmington, NC, USA

Light Meson decays provide a unique laboratory to probe fundamental QCD symmetries and to search for new physics beyond the Standard Model. A comprehensive Primakoff experimental program at Jefferson Laboratory (Jlab) is aimed at gathering high precision measurements on the two-photon decay widths and transition form factors at low Q^2 of π^0, η and η' via the Primakoff effect. Completed experiments on the π^0 radiative decay width at Jlab 6 GeV, and planned measurements of η and η' at Jlab 12 GeV will provide sensitive probes to test the chiral anomaly and to study the origin and dynamics of chiral symmetry breaking in QCD confinement. On the other hand, a recently developed Jlab Eta Factory (JEF) experiment will measure various η decays. The experimental approach, which combines a state of the art $PbWO_4$ crystal calorimeter, a 12 GeV tagged photon beam, and recoil particle measurement, will reduce the background by almost two orders of magnitude in the rare neutral modes compared to other competitors in the world. Reduction of the uncertainty on the light quark mass ratio will be achieved by increasing the world datasets for both the charged and neutral $\eta \to 3\pi$ Dalitz distributions by a factor of ~ 3 while controlling systematic uncertainties with relatively flat detection efficiencies over the phase space due to significantly boosted η's. A low-background measurement of the rare decay $\eta \to \pi^0\gamma\gamma$ will provide a clean, rare window into $\mathcal{O}(p^6)$ in chiral perturbation theory, while offering a unique opportunity to search for a dark leptophobic gauge boson (B) in the 140-550 MeV mass range, with sensitivity to the baryonic fine structure constant α_B as low as 10^{-7}. The SM forbidden decays, such as $\eta \to 3\gamma$ and $\eta \to 2\pi^0\gamma$, will allow the best direct constraints on new C violating, P conserving reactions. A overview of these experimental activities and their physics impacts will be presented.

Acknowledgments
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1.17 Latest results on few-body physics from HIγS

H. Gao[a,b,c]

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An important goal in modern nuclear physics is to understand how one can describe the structure of nuclei and nuclear forces from first principles of quantum chromodynamics (QCD), the fundamental theory describing the strong interaction. Few-nucleon systems provide important testing grounds for state-of-the-art few-body calculations, calculations based on effective field theories, and more recently predictions from lattice QCD. As such they are important laboratories to investigate nucleon-nucleon interaction and nuclear forces, and connect them to QCD. With the availability of high-intensity, near monochromatic, highly (linearly or circularly) polarized gamma rays from The High Intensity Gamma ray Source (HIγS) facility at the Duke University Free Electron Laser Laboratory, new few-body experiments utilizing these unique features of the beam and polarized targets have been carried out or are underway. In this talk, I will discuss these experiments and present latest results on few-body physics from HIγS. This work is supported in part by the U.S. Department of Energy under Contact No. DE-FG02-03ER41231.

1.18 Photopion physics at MAMI

D. Hornidge [for the A2 Collaboration at MAMI]
Mount Allison University, Sackville, NB, Canada

Recent measurements and future plans for photopion experiments with the CB-TAPS detector system in the A2 hall at the Mainzer Microtron will be presented. First, a measurement with linearly polarized photons and an unpolarized liquid-hydrogen target will be discussed. The beam asymmetry along with differential cross sections provide the most stringent test to date of the predictions of Chiral Perturbation Theory and its energy region of convergence [1]. Second, a more recent measurement was performed using both circularly polarized photons and a transversely polarized butanol frozen-spin target to extract the polarization-dependent differential cross section associated with the target asymmetry [2]. Results from both measurements have been used for a model independent determination of S- and P-wave multipoles in the π^0 threshold region, which includes for the first time a direct determination of the imaginary part of the E_{0+} multipole. Finally, plans for a novel π^0 photoproduction measurement on ^{3}He to obtain the elusive E_{0+} multipole for the neutron channel will be introduced.

References

1. D. Hornidge *et al.*, Phys. Rev. Lett. **111**, 062004 (2013).
2. S. Schumann *et al.*, in preparation.

1.19 Nuclear physics from QCD on lattice

T. Inoue [for HAL QCD Collaboration]
Nihon University, College of Bioresource Sciences, Kanagawa, Japan

Explaining and predicting properties of nuclei starting from QCD is one of the most challenging problems in physics. There are several attempts to extract mass of nuclei in lattice QCD simulations, but direct extractions are limited only to very light nuclei, *i.e.* mass number $A \leq 4$, due to computation costs and, more severely, due to several fundamental difficulties. We propose an alternative approach to study nuclei starting from QCD. We deduce mass and structure of ^{4}He, ^{16}O, and ^{40}Ca nuclei from QCD.
First, we extract two-nucleon potentials in lattice QCD numerical simulations with the recently developed HAL QCD method, at large quark masses for the moment. Obtained QCD induced NN potentials posses common features of phenomenological ones, namely, strong repulsion at short distance, attraction at medium and long distance, and strong tensor force, although their strength are weaker due to the large quark masses. Accordingly, the potentials reproduce experimental two-nucleon scattering data qualitatively.
Then, we apply the potentials to few-body technique or many-body theory to study the nuclei: a variational method for ^{4}He and the Brückner-Hartree-Fock (BHF) theory for ^{16}O and ^{40}Ca. We find that these nuclei are bound for a large quark mass corresponding to a pseudo-scalar meson mass of 469 MeV and a nucleon mass of 1161 MeV.

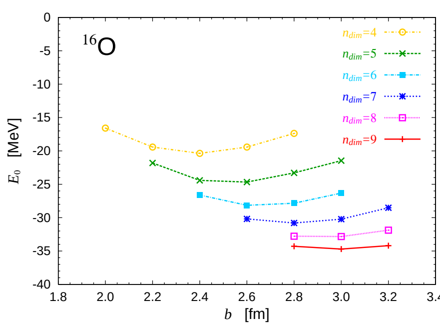

Figure 1: Ground state energy of ^{16}O.

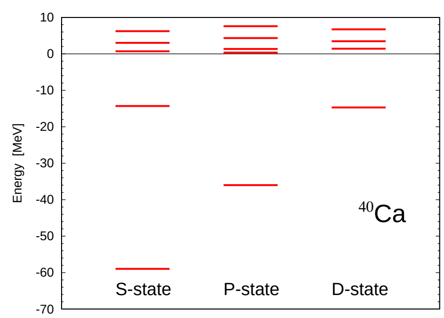

Figure 2: Single particle levels of ^{40}Ca.

Fig. 1 shows obtained ground state energy of ^{16}O as a function of parameters used in our BHF calculation. Fig. 2 shows obtained single particle levels of ^{40}Ca. Total binding energies, 5 MeV for ^{4}He, 35 MeV for ^{16}O, and 113 MeV for ^{40}Ca, are rather smaller than the experimental data, but this is primarily because of the unrealistic quark mass in our lattice QCD simulation. This result shows that one can deduce properties of medium-heavy nuclei from QCD as well as light ones in the HAL QCD approach. This must be significant progress in nuclear physics.

References

1. T. Inoue *et al.* [HAL QCD Collaboration], Nucl. Phys. A **881**, 28 (2012).
2. T. Inoue *et al.* [HAL QCD Collaboration], Phys. Rev. Lett. **111**, 112503 (2013).
3. T. Inoue *et al.* [HAL QCD Collaboration], Phys. Rev. C **91**, 011001 (2015).

1.20 Pion–nucleon scattering at low energies

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Ever since Weinberg's seminal predictions of the pion–nucleon scattering amplitudes at threshold, this process has been of central interest for the study of chiral dynamics involving nucleons. Quantities like the scattering lengths or the pion–nucleon σ-term are fundamental quantities characterizing the explicit breaking of chiral symmetry by means of the light quark masses. On the other hand, pion–nucleon dynamics also strongly affects the long-range part of nucleon–nucleon potentials, and hence has a far-reaching impact on nuclear physics. I will review various approaches to analyze pion–nucleon scattering in the framework of baryon chiral perturbation theory—in the heavy-baryon formalism, or using different manifestly covariant formulations. Finally, I will discuss the fruitful combination of dispersion-theoretical methods, in particular in the form of Roy–Steiner equations, with chiral dynamics to determine pion–nucleon scattering amplitudes at low energies with high precision.

1.21 Theoretical aspects of chiral dynamics

L. Leutwyler
University of Bern, Bremgarten, Switzerland

Many of the quantities of interest at the precision frontier in particle physics require a good understanding of the low energy properties of the strong interaction. I intend to focus on the fact that applications of effective field theory methods usually involve two aspects: dependence on the quark masses and dependence on the momenta. On the one hand, I will review some of the work done in dispersion theory, which led to an improved understanding of the momentum dependence. On the other hand, some of the results gained by means of lattice methods concerning the quark mass dependence will be discussed. As an illustrative example, I plan to critically examine recent work on the mass difference between proton and neutron.

1.22 QED corrections to hadronic processes in lattice QCD

V. Lubicz
Università Roma Tre, Roma, Italy

Recently, a method has been proposed for the first time to compute electromagnetic effects in hadronic processes using lattice simulations. The method can be applied, for example, to the leptonic and semileptonic decays of light or heavy pseudoscalar mesons. For these quantities the presence of infrared divergences in intermediate stages of the calculation makes the procedure more complicated than is the case for the hadronic spectrum, for which lattice calculations already exist. In this talk, I illustrate the method for the leptonic decays of a pseudoscalar meson. Its practical implementation, although challenging, is within reach of the present lattice technology. Electromagnetic and isospin breaking corrections to quark and hadron masses will be also briefly reviewed, mainly relying on the analysis performed by the FLAG working group.

References

1. N. Carrasco, V. Lubicz, G. Martinelli, C. T. Sachrajda, N. Tantalo, C. Tarantino, and M. Testa, arXiv:1502.00257 [hep-lat].
2. FLAG Working Group, S. Aoki *et al.*, Eur. Phys. J. C **74**, 2890 (2014).

1.23 Polarisabilities of the proton and neutron from Compton scattering

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We have recently completed a high-precision extraction of the proton spin-independent polarisabilities from the world database of low-energy Compton scattering experiments, within the framework of chiral effective field theory (χEFT) with pions, nucleons, and the Delta(1232) as explicit degrees of freedom [1]. Our Baldin-sum-rule-constrained results are [2]

$$\begin{aligned}\alpha_p &= 10.65 \pm 0.35(\text{stat}) \pm 0.2(\text{Baldin}) \pm 0.3(\text{theory}),\\ \beta_p &= 3.15 \mp 0.35(\text{stat}) \pm 0.2(\text{Baldin}) \mp 0.3(\text{theory}).\end{aligned}$$

These were obtained in the heavy-baryon formulation, but almost identical results have been obtained in a covariant calculation [3].
With the publication this year by Myers *et al.* of the results of the deuteron Compton scattering experiment using the Tagged-Photon Facility at the MAX IV Laboratory in Lund, Sweden, the world γ-d database has doubled in size, allowing the extraction of the isoscalar polarisabilities with unprecedented accuracy, and combined with the proton results we obtain [4]

$$\begin{aligned}\alpha_n &= 11.65 \pm 1.25(\text{stat}) \pm 0.2(\text{Baldin}) \pm 0.8(\text{theory}),\\ \beta_n &= 3.55 \mp 1.25(\text{stat}) \pm 0.2(\text{Baldin}) \mp 0.8(\text{theory}).\end{aligned}$$

A new generation of experiments with polarised beams have been performed at the Mainz Microtron, with the first results published this year by Martel *et al.* [5]. These experiments are sensitive to the spin polarisabilities, and we will discuss the predictions of χEFT for the relevant cross sections cross sections and asymmetries.

References

1. H. W. Grießhammer, J. A. McGovern, D. R. Phillips and G. Feldman, Prog. Part. Nucl. Phys. **67**, 841 (2012) [arXiv:1203.6834 [nucl-th]].
2. J. A. McGovern, D. R. Phillips and H. W. Grießhammer, Eur. Phys. J. A **49**, 12 (2013) [arXiv:1210.4104 [nucl-th]].
3. V. Lensky and J. A. McGovern, Phys. Rev. C **89**, 032202 (2014) [arXiv:1401.3320 [nucl-th]].
4. L. S. Myers *et al.* [COMPTON@MAX-lab Collaboration], Phys. Rev. Lett. **113**, 262506 (2014) [arXiv:1409.3705 [nucl-ex]].
5. P. P. Martel *et al.* [A2 Collaboration], Phys. Rev. Lett. **114**, 112501 (2015) [arXiv:1408.1576 [nucl-ex]].

1.24 Inclusion of isospin breaking effects in lattice simulations

A. Portelli
University of Southampton, Southampton, UK

Isospin symmetry is explicitly broken in the Standard Model by the mass and electric charge of the up and down quarks. These effects represent a perturbation of hadronic amplitudes at the percent level. Although these contributions are small, they play a crucial role in hadronic and nuclear physics. Moreover, as lattice computations are becoming increasingly precise, it is becoming more and more important to include these effects in numerical simulations. We summarize here how to properly define QCD and QED on a finite and discrete space-time so that isospin corrections to hadronic observables can be computed ab-initio and we review the main results on the isospin corrections to the hadron spectrum. We mainly focus on the recent work going beyond the electro-quenched approximation.

1.25 How well does the chiral expansion converge in nuclear and neutron matter?

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The equations of state of nuclear and neutron matter (and, more generally, neutron-rich matter) play a fundamental role towards the understanding of a broad spectrum of systems, ranging from the skins of neutron-rich nuclei to the structure of compact stars.
After a brief introduction on different approaches to the properties of nuclear/neutron matter, we will focus on error quantification in effective field theory. The various sources of uncertainty and their impact in infinite matter will be explored.
We will report on recent calculations of the nuclear and neutron matter equations of state [1] at different orders of the chiral expansion as well as changing resolution scale. We will discuss the significance of such predictions as a foundation for future studies of convergence of the chiral perturbation series.

References

1. F. Sammarruca, L. Coraggio, J.W. Holt, N. Itaco, R. Machleidt, and L.E. Marcucci, Phys. Rev. C **91**, 054311 (2015).

1.26 Pion photo- and electroproduction and the chiral MAID interface

M. Hilt, S. Scherer, and L. Tiator
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We discuss the extended on-mass-shell scheme for manifestly Lorentz-invariant baryon chiral perturbation theory. We present a calculation of pion photo- and electroproduction up to and including order q^4 . The low-energy constants have been fixed by fitting experimental data in all available reaction channels. Our results can be accessed via a web interface, the so-called chiral MAID (http://www.kph.uni-mainz.de/MAID/chiralmaid, see Fig. 1. We explain how our program works and how it can be used for further analysis.

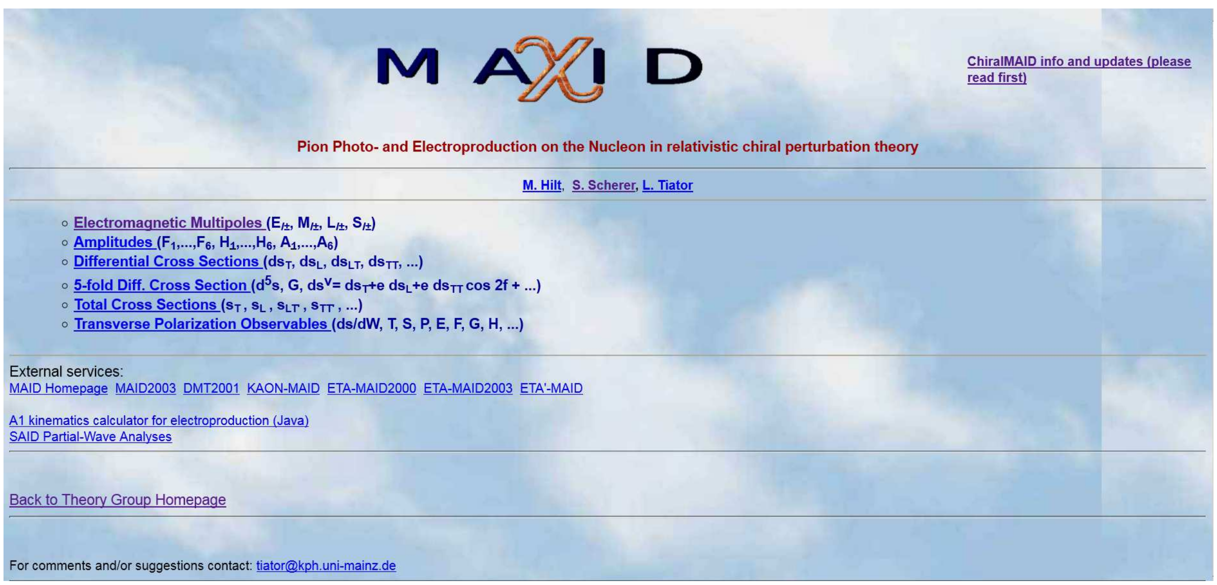

Figure 1: Chiral MAID interface

References

1. M. Hilt, B.C. Lehnhart, S. Scherer, and L. Tiator, Phys. Rev. C **88**, 055207 (2013).

1.27 Studies of light nuclei in χEFT: A status report

R. Schiavilla
Thomas Jefferson National Accelerator Facility, Newport News, VA, USA

A status report on χEFT studies of light-nuclei electro-weak structure and dynamics is provided, including electromagnetic elastic form factors of few-nucleon systems, magnetic moments and M1 radiative widths in $A = 6$–10 nuclei, the *pp* weak fusion and muon weak captures on deuteron and ^{3}He, and a number of parity-violating processes induced by hadronic weak interactions.

2 Goldstone boson working group

2.1 *Leading Talk* Chiral methods at the electroweak scale

O. Cata
Ludwig Maximilian University, Munich, Germany

After the discovery of the Higgs particle at the LHC in its first run, one of the priorities of the second run will be to ascertain its nature and understand the dynamics that trigger the breaking of electroweak symmetry. However, in order to search for deviations from a standard Higgs one needs a framework that goes beyond the Standard Model. In this talk I will discuss in which way techniques borrowed from chiral dynamics can be used to provide such a general framework and will point out which processes are most sensitive to nonstandard Higgs signatures.

2.2 *Leading Talk* η and η' physics at BESIII

S. Fang
Institute of High Energy Physics, Beijing, China

The BESIII Experiment at the Beijing Electron Positron Collider (BEPCII) has accumulated the world's largest samples of e^+e^- collisions in the tau-charm region. From a sample of 1.3 billions J/ψ decays, BESIII has produced many new results in the decays of η and η'. This talk will review the current status of these analyses, especially on the Dalitz plot of η/η', observations of $\eta' \to 4\pi$, $\gamma\gamma\pi^0$ and γe^+e^-.

2.3 *Leading Talk* Exploratory lattice QCD study of the rare kaon decay $K^+ \to \pi^+\nu\bar{\nu}$

N.H. Christ[a], X. Feng[a], A. Jüttner[b], A. Lawson[b], A. Portelli[b], and C.T. Sachrajda[b]

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[b] *School of Physics and Astronomy, University of Southampton, Southampton, UK*

The rare kaon decays, $K \to \pi\nu\bar{\nu}$, have attracted increasing interest during the past few decades. As flavor changing neutral current processes, these decays are highly suppressed in the standard model and thus provide ideal probes for the observation of new physics effects.

As second-order weak interactions, the ultra-rare decays $K \to \pi\nu\bar{\nu}$ represent a significant challenge in experiments. After 40 years search, only 7 $K^+ \to \pi^+\nu\bar{\nu}$ events have been collected in BNL E787 and E949 by 2008 [1]. A new generation of experiment, NA62 in CERN [2], aims at an observation of $O(100)$ events and a 10%-precision measurement of the branching ratio in two years.

The standard model predictions of $K \to \pi\nu\bar{\nu}$ branching ratios are dominated by short-distance contributions. The long-distance contributions below the energy scale of the charm quark mass are safely neglected in $K_L \to \pi^0\nu\bar{\nu}$ and are expected to be small in $K^+ \to \pi^+\nu\bar{\nu}$. Although small, the long-distance contributions estimated from a phenomenological ansatz involving both chiral perturbation theory and operator production expansion enhance the branching ratio by 6%[3]. Recognizing that the standard model predictions will soon be confronted with new experimental results, a lattice QCD calculation of the long-distance contribution to $K^+ \to \pi^+\nu\bar{\nu}$ is important.

In this talk I will present an exploratory calculation of the long-distance contributions to the $K^+ \to \pi^+\nu\bar{\nu}$ decay amplitude from first principles using lattice QCD.

References

1. A. Artamonov*et al.* (E949 Collaboration), Phys. Rev. Lett. **79**, 2204 (1997).
2. M. Moulson (NA62 Collaboration), arXiv:1310.7816 (2013).
3. G. Isidori, F. Mescia, and C. Smith, Nucl. Phys. B **718**, 319 (2005).

2.4 *Leading Talk* $K \to \pi\pi$ decays and the $\Delta I = 1/2$ rule

N. Garron
Plymouth University, Plymouth, UK

CP violation was discovered in Kaon decays 50 years ago but still remains a challenge for theorists. A complete theoretical description will be a crucial test for the Standard Model and will provide us with a rich source of information on new physics theories. In the past recent years, realistic computations of A2, the amplitude of $K \to (\pi\pi)_{(I=2)}$, have become possible and reached a level of 10% accuracy. I will explain how this computation has become possible and will report on the other channel, much more challenging, in which the two-pion state has isospin $I = 0$. I will also report on a possible explanation for the Delta $I = 1/2$ rule, the fact the magnitude of the amplitude A0 is around 20 times larger than the one of A2, although a naive computation only gives a factor of 2.

2.5 *Leading Talk* Form factor in $VP\gamma^*$ transitions and study of the $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot at KLOE

S. Giovannella
INFN–Laboratorio Nazionale di Frascati, Frascati, Italy

The KLOE experiment has collected 2.5 fb^-1 at the peak of the ϕ resonance at the e^+e^- collider DAPHNE in Frascati.
The $V \to P\gamma$ Dalitz decays, associated to internal conversion of the photon into a lepton pair, are not well described by the Vector Meson Dominance (VMD) models, as in the case of the process $\omega \to \pi^0\mu^+\mu^-$, measured by the NA60 collaboration. The only existing data on $\phi \to \eta e^+e^-$ come from the SND experiment, which has measured the Mee invariant mass distribution on the basis of 213 events. At KLOE, a detailed study of this decay has been performed using $\eta \to \pi^0\pi^0\pi^0$ final state. We obtain the measurement of the branching fraction for the process $\phi \to \eta e^+e^-$, with an accuracy improved by a factor of five with respect to the previous most precise measurement, and the transition form factor, which is in agreement with VMD expectations. We have also studied the decay $\phi \to \pi^0e^+e^-$, where no data are available on transition form factor. Dedicated analysis cuts strongly reduce the main background component of Bhabha events to ∼20%, leading to ∼4000 signal events in the whole KLOE data set.
We have also obtained a new, precise results on the isospin-violating decay $\eta \to \pi^+\pi^-\pi^0$, sensitive to the light-quark mass ratio. This study, overcoming in precision previous results published by KLOE in 2008, was suggested by the theoretical work: Leutwyler, Mod. Phys. Lett. A **28** 1360014 (2013), aiming to a better determination of the light-quark mass ratio through the dispersive analysis of the $\eta \to 3\pi$ decay. The new analysis, performed with an independent and larger data set (1.7 fb^-1) and a new analysis scheme and improved Monte Carlo simulation, determines with very good accuracy the parameters of the decay matrix element.

2.6 Constraints on the $\omega\pi$ form factor from analyticity and unitarity

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[b] *Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
[c] *University of Bonn, Bonn, Germany*

Motivated by the discrepancies noted recently between the theoretical calculations of the electromagnetic $\omega\pi$ form factor and certain experimental data, we investigate this form factor using analyticity and unitarity in a framework known as the method of unitarity bounds. We use a QCD correlator computed on the spacelike axis by operator product expansion and perturbative QCD as input, and exploit unitarity and the positivity of its spectral function, including the two-pion contribution that can be reliably calculated using high-precision data on the pion form factor. From this information, we derive upper and lower bounds on the modulus of the $\omega\pi$ form factor in the elastic region. The results provide a significant check on those obtained with standard dispersion relations, confirming the existence of a disagreement with experimental data in the region around 0.6 GeV.

2.7 Axial $U(1)$ symmetry in the chiral symmetric phase of 2-flavor QCD at finite temperature

S. Aoki
Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto, Japan

We discuss the fate of the axial $U(1)$ symmetry in 2-flavor QCD, when the non-singlet chiral symmetries are recovered at finite temperature. We theoretically investigate the constraints on the eigenvalue density of the Dirac operator, derived from the non-singlet chiral symmetries among various multi-point correlation functions in the chiral limit. We show that the axial $U(1)$ symmetry, broken by the anomaly at low temperature, is "effectively" recovered in the chiral symmetric phases of 2-flavor QCD above the critical temperature. Here the effective recovery of the axial $U(1)$ symmetry means, for example, that the susceptibility of non-singlet (π) and singlet (η) pseudo-scalar mesons become identical in the symmetric phase, which implies that the axial $U(1)$ anomaly is invisible in these channels. We next consider recent numerical investigations on the axial $U(1)$ symmetry in 2-flavor lattice QCD with exact lattice chiral symmetry, which is shown to be crucial for this problem. Numerical results in these study confirm our theoretical expectation mentioned above. We finally discuss an implication of our results to the phase structure of lattice QCD at finite temperature.

2.8 The $\pi^0 \to \gamma\gamma^*$ decay rate and form factor

A. Bernstein
Massachusetts Institute of Technology, Cambridge, MA, USA

The $\pi^0 \to \gamma\gamma$ decay rate is dominated by the QCD axial anomaly that is increased by $\simeq 4.5\% \pm 1.0\%$ by the mixing of the π^0 wave function with the $\eta, \eta^{'}$ mesons. This relatively large isospin breaking effect is proportional to the mass difference of the up and down quarks. It has been calculated in Chiral Perturbation Theory (ChPT) by three slightly different methods with good agreement between them. This is a solid QCD prediction; the error is due to the uncertainty due to our knowledge of the low energy constants of ChPT and not by higher order terms.The accuracy of the present experiments are significantly less than the theoretical prediction and represents a significant experimental challenge. A summary of the three three experimental methods to perform this measurement and current efforts to improve them will be briefly reviewed with emphasis on one by the COMPASS collaboration at CERN.
For the $\pi^0 \to \gamma\gamma^*$ decay the form factor can be written as $F(Q^2) = F(0)(1- < r^2 >_{\pi^0} Q^2/6 + ...)$ at low Q^2. This suggests a possible way to measure the size("anomaly radius") of the π^0 meson which does not have a charge or magnetic radius. Using the latest, most accurate, calculated value of the slope parameter obtained from a dispersive analysis of the pion transition form factor, this RMS radius is 5% smaller than the $\pi^{\pm}$ electric radius. Using vector dominance these radii are expected to be equal. However this similarity, and the difference between these values, calls for a careful theoretical and experimental examination of this fundamental quantity. Clearly the charge and "anomaly" radii correspond to the expectation values of different operations. A comparison of the scalar and electromagnetic radii of the pion and proton with some interesting (puzzling?) differences will be presented.

2.9 Combined analysis of the decays $\tau^- \to K_S \pi^- \nu_\tau$ and $\tau^- \to K^- \eta \nu_\tau$

R. Escribano
Autonomous University of Barcelona, Barcelona, Spain

In a combined study of the decay spectra of $\tau^- \to K_S \pi^- \nu_\tau$ and $\tau^- \to K^- \eta \nu_\tau$ decays within a dispersive representation of the required form factors, we illustrate how the $K^*(1410)$ resonance parameters, defined through the pole position in the complex plane, can be extracted with improved precision as compared to previous studies. While we obtain a substantial improvement in the mass, the uncertainty in the width is only slightly reduced, with the findings $M(K^{*\prime}) = 1304 \pm 17$ MeV and $\Gamma(K^{*\prime}) = 171 \pm 62$ MeV. Further constraints on the width could result from updated analyses of the $K\pi$ and/or $K\eta$ spectra using the full Belle-I data sample. Prospects for Belle-II are also discussed. As the $K - \pi^0$ vector form factor enters the description of the decay $\tau^- \to K^- \eta \nu_\tau$, we are in a position to investigate isospin violations in its parameters like the form factor slopes. In this respect also making available the spectrum of the transition $\tau^- \to K^- \pi^0 \nu_\tau$ would be extremely useful, as it would allow to study those isospin violations with much higher precision.

2.10 Precision measurement of the neutral pion radiative decay width at Jefferson Lab

A. Gasparian
North Carolina A&T State University, Greensboro, NC, USA

The neutral pion is the lightest strongly interacting particle in Nature. Therefore, the properties of π^0 decay are especially sensitive to the underlying fundamental symmetries of quantum chromodynamics (QCD). In particular, the $\pi^0 \to \gamma\gamma$ decay width is primarily defined by the spontaneous chiral symmetry breaking effect (chiral anomaly) in QCD. Theoretical activities in this domain over the past several years have resulted in a high precision (1% level) prediction for the $\pi^0 \to \gamma\gamma$ decay width. The PrimEx collaboration at Jefferson Lab has developed and performed two new experiments to measure the $\pi^0 \to \gamma\gamma$ decay width with high precision using the Primakoff effect. The published result from the first experiment (PrimEx-I), $\Gamma(\pi^0 \to \gamma\gamma) = 7.82 \pm 0.14$ (stat.) $\pm\, 0.17$ (syst.) eV, is a factor of 2.1 more precise than the currently accepted value, and it is in agreement with the chiral anomaly prediction. The second experiment (PrimEx-II) was performed in 2010 with a goal of 1.4% total uncertainty to address the next-to-leading-order chiral perturbation theory calculations. The preliminary results from the PrimEx-II experiment will be presented in this talk.

2.11 Low-energy constants from ALEPH hadronic tau decay data

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[b] *Autonomous University of Barcelona, Barcelona, Spain*
[c] *York University, Toronto, Canada*
[d] *University of Sao Paulo, Sao Paolo, SP, Brazil*

We determined the NLO chiral low-energy constant $L_1 0$, and various combinations of NNLO chiral low-energy constants employing recently revised ALEPH results for the non-strange vector (V) and axial-vector (A) hadronic tau decay distributions and recently updated RBC/UKQCD lattice data for the non-strange V-A two-point function. In this talk, we explain the ingredients of this determination. Our errors are at or below the level expected for contributions of yet higher order in the chiral expansion, and we therefore believe that our analysis exhausts the possibilities of what can be meaningfully achieved in an NNLO analysis.

2.12 From OPE to chiral perturbation theory in holographic QCD

D. Greynat, G. D'Ambrosio, and L. Cappiello
INFN–Napoli, Napoli, Italy

We will show how it is possible to implement a chiral symmetry breaking mechanism in soft-wall model of holographic QCD. We show also that it is possible to reproduce the exact Operator Product Expansion and the Regge spectra of the vector-vector and axial-axial correlators in the Large Nc limit. This method provides a nice way to perform the analytic continuation of the OPE and to predict the chiral constants: F_π and L_{10}.

2.13 K-π scattering lengths from lattice QCD

P. Boyle[a], T. Janowski[b], A. Jüttner[b], and C. T. Sachrajda[b]
[a] *University of Edinburgh, Edinburgh, UK*
[b] *University of Southampton, Southampton, UK*

We present the recent lattice QCD calculation of K-π I=3/2 and I=1/2 scattering lengths by the RBC-UKQCD collaboration. Our calculation is the first lattice calculation of these quantities performed using physical point ensembles [1]. This allows us to bypass the error due to chiral extraploation, which in current calculations is the dominant source of systematic errors [2, 3, 4, 5]. Preliminary results are presented and compared to those from earlier studies which were obtained at heavier pion masses and extrapolated to the physical point.

References

1. T. Blum *et al.* [RBC and UKQCD Collaborations], arXiv:1411.7017 [hep-lat].
2. S.R. Beane, P.F. Bedaque, T.C. Luu, K. Orginos, E. Pallante, A. Parreno, and M.J. Savage, Phys. Rev. D **74**, 114503 (2006) [hep-lat/0607036].
3. Z. Fu, JHEP **1201**, 017 (2012) [arXiv:1110.5975 [hep-lat]].
4. Z. Fu, Phys. Rev. D **85**, 074501 (2012) [arXiv:1110.1422 [hep-lat]].
5. K. Sasaki *et al.* [PACS-CS Collaboration], Phys. Rev. D **89**, 054502 (2014) [arXiv:1311.7226[hep-lat]].

2.14 π^0: The lightest hadron

K. Kampf
Charles University, Prague, Czech Republic

In this talk I will present basic properties of the lightest meson, π^0. I will discuss its decay modes, mainly two photon decay, Dalitz decay and e^+e^- production and focus on its recent theoretical and experimental studies. Connection with the theoretical calculation of the hadronic light-by-light scattering contribution in the $g-2$ type experiment will be outlined.

2.15 B_{l4} decays and the extraction of $|V_{ub}|$

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The Cabibbo-Kobayashi-Maskawa matrix element $|V_{ub}|$ is not well determined yet. It can be extracted from both inclusive or exclusive decays, like $B \to \rho(\pi)l\bar{\nu}_l$. However, the exclusive determination from $B \to \rho l\bar{\nu}_l$, in particular, suffers from a large model dependence. In this talk, I will elaborate our proposal [1]: extracting $|V_{ub}|$ from the four-body semileptonic decay $B \to \pi\pi l\bar{\nu}_l$, where the form factors for the pion-pion system are treated in dispersion theory. This is a model-independent approach that takes into account the $\pi\pi$ rescattering effects, as well as the effect of the ρ meson. We demonstrate that both finite-width effects of the ρ meson as well as scalar $\pi\pi$ contributions can be considered completely in this way.

References

1. X.-W. Kang, B. Kubis, C. Hanhart, and Ulf-G. Meissner, Phys. Rev. D **89**, 053015 (2014).

2.16 Isospin breaking effects in the K_{e4}^{+} decays

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The very precise data obtained by the NA48/2 collaboration at the CERN SPS on the decay channels $K^{\pm} \to \pi^{+}\pi^{-}e^{\pm} \overset{(-)}{\nu_e}$ and $K^{\pm} \to \pi^{0}\pi^{0}e^{\pm} \overset{(-)}{\nu_e}$ have made it necessary to address issues related to isospin breaking. Three aspects related to this issue will be considered: isospin breaking due to the pion mass difference in the phases of the form factors for the $K^{\pm} \to \pi^{+}\pi^{-}e^{\pm} \overset{(-)}{\nu_e}$ decay amplitude, the cusp in the decay distribution of the $K^{\pm} \to \pi^{0}\pi^{0}e^{\pm} \overset{(-)}{\nu_e}$ mode, and radiative corrections.

2.17 Extraction of low energy QCD parameters from η to 3π and beyond

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The η to 3π decays are a valuable source of information on low energy QCD. Yet they were not used for an extraction of the three flavor chiral symmetry breaking order parameters until now. We use a bayesian approach in the framework of resummed chiral perturbation theory to extract information on the quark condensate and pseudoscalar decay constant in the chiral limit, as well as the mass difference of the light quarks. We compare our results with recent CHPT and lattice QCD fits and find some tension, as the η to 3π data seem to prefer a larger ratio of the chiral order parameters. The results also seem to exclude a large value of the chiral decay constant, which was found by some recent works. In addition, we present preliminary results of a combined analysis including η to 3π decays and $\pi - \pi$ scattering.

2.18 $\eta - \eta'$ mixing in Large-N_c ChPT: Discussion, phenomenology, and prospects

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A detailed and systematic study of the $\eta - \eta'$ mixing in Large-N_c ChPT will be presented [1], with special emphasis on the role of the next-to-next-to-leading order contributions in the combined p^2 and N_c expansion. At such order, loop corrections as well as OZI-violating pieces are relevant for an appropriate and stable numerical result for the mixing angle. Pseudoscalar masses as well as pseudoscalar decay constants within this framework will be also presented. Comparison with recent phenomenological approaches [2] together with the impact of the mixing in $\eta^{(\prime)} \to \gamma\gamma$ and $\eta^{(\prime)} \to \pi\pi\gamma$ decays will also be discussed.

References

1. P. Bickert, P. Masjuan, and S. Scherer, in preparation.
2. R. Escribano, P. Masjuan, and P. Sanchez-Puertas, Phys. Rev. D **89**, 034014 (2014) [arXiv:1307:2061 [hep-[h]].

2.19 a_0–f_0 mixing in the Khuri-Treiman equations for $\eta \to 3\pi$

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The isospin violating $\eta \to 3\pi$ decays are expected to provide the best observables for the determination of the $u - d$ quark mass difference. However, using the chiral expansion of the $\eta \to 3\pi$ amplitude in the physical region has proved problematic, as it fails to reproduce the recent precise measurements of the Dalitz plot parameters. In order to circumvent this problem, it was proposed to combine the chiral expansion, used in an unphysical region, together with the dispersive formalism of Khuri and Treiman. We discuss here the possibility of extending this formalism, which so far accounts for only elastic $\pi - \pi$ rescattering, in order to further account for the effects of both inelastic $\pi - \pi$ rescattering and $\eta - \pi$ rescattering. In the 1 GeV region of the dispersive integrands, in particular, these effects are enhanced by the f_0 as well as the a_0 resonances. The effect of the isospin violating $K^+ - K^0$ mass difference, influenced by these resonances, is then also accounted for in the dispersive integrals.

2.20 Studies of the decay $K^+ \to \pi^+\pi^0 e^+ e^-$ at NA48

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We report the first observation of the very rare decay $K^\pm \to \pi^\pm\pi^0 e^+ e^-$ by the NA48/2 experiment. From a clean sample of almost 2000 reconstructed signal events, we have determined the branching fraction with high precision and measured the e^+e^- invariant mass distribution, which allows to differentiate between different decay models.

2.21 Masses, decay constants and electromagnetic form-factors with twisted boundary conditions

J. Relefors and J. Bijnens
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The talk will describe the recent work at one-loop Chiral perturbation Theory with twisted boundary conditions [1]. We point out that due to the broken Lorentz and reflection symmetry a number of new terms show up in the expressions. The pseudo-scalar octet masses, axial-vector and pseudo-scalar decay constants and electromagnetic form-factors will be discussed explicitly. We show how the Ward identities are satisfied using the momentum dependent masses and the non-zero vacuum-expectation-values values for the electromagnetic (vector) currents. A short discussion of the needed one-loop twisted finite volume integrals as well as the the ongoing work for the $K_{\ell 3}$ form factors will be included [2].

References

1. J. Bijnens and J. Relefors, JHEP **1405**, 015 (2014).
2. C. Bernard, J. Bijnens, E. Gamiz, and J. Relefors, work in progress.

2.22 The meson spectroscopy program with CLAS12 at Jefferson Laboratory

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The study of the hadronic spectrum is one of the most powerful tools to investigate the mechanism at the basis of quark confinement within hadrons. A precise determination of the spectrum allows not only to asses the properties of the hadrons in their fundamental and excited states, but also to investigate the existence of states resulting from alternative configurations of quarks and gluons, such as the glue-balls, hybrid mesons and many-quarks models.
The mesonic part of the spectrum can play a central role in this investigation because several of the hybrid mesons are supposed to have different quantum numbers with respect to standard $q\bar{q}$ states, due to the presence of explicit gluonic degrees of freedom.
The hybrid mesons are expected to decay into multi-particles final states [1], requiring high performances in terms of rate capability, resolution and acceptance for their detection. New-generation experiments are planned at Jefferson Laboratory (JLAB) for which an unprecedented statistics of events with fully reconstructed kinematics for large multiplicity decays will be available.
A wide scientific program that will start in 2016 has been deployed for meson spectrum investigation with the CLAS12 apparatus in Hall B at energies up to 11 GeV.
A key role in such program is played by the Forward Tagger [2], which will allow to extend the study of meson electro-production to very low Q^2, in a quasi-real photo production kinematical region, where the production of hybrid mesons is expected to be favorite.
The analysis required to extract the signal from hybrid states should go beyond the standard Partial Wave analysis techniques and a new analysis framework is being set up through the Haspect Network. The Haspect Network gather people involved into theoretical and experimental hadronic physics all over the world, to investigate and propose new analysis models (such as the Szczepaniak-Pennington model [3]) and new statistical techniques to unfold signal and background. The new analysis framework is being tested using the existing CLAS data and results are projected to the CLAS12 performances, showing that the quest for hybrid exotic mesons is at reach.

References

1. A. Szczepaniak, Phys.Rev. D **59**, 034016 (1999).
2. The CLAS collaboration, https://www.jlab.org/Hall-B/clas12-web/docs/ft-tdr.2.0.pdf
3 A. Szczepaniak and M.R. Pennington, arXiv:1403.5782v1 [hep-ph].

2.23 Chiral dynamics in the low-temperature phase of QCD

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We investigate the low-temperature phase of strongly interacting matter and the crossover region with two light flavors of quarks in Lattice QCD. Based on Chiral Ward Identities we test the applicability of a fixed-temperature chiral expansion given that chiral symmetry is spontaneously broken. It indicates that a sharp real-time excitation persists with the quantum numbers of the pion consistently with Goldstone's theorem even at $T = 150$ MeV. We determine the real part of the pole and its residue in the axial-charge density correlator at zero and finite momentum. The time-dependent correlators are also analyzed using the Maximum Entropy method and the Backus-Gilbert method yielding consistent results. In addition, we also test the predictions of ordinary chiral perturbation theory around the point $(T = 0, m = 0)$ for the temperature dependence of static observables. Around the crossover region, we find that all quantities considered depend only mildly on the quark mass in the range $8\text{MeV} \leq \overline{m}^{\overline{\text{MS}}} \leq 15\text{MeV}$.

2.24 Resonances in the electroweak chiral Lagrangian

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We study strongly coupled models of electroweak symmetry breaking with a light Higgs boson. We use a resonance effective Lagrangian with bosonic massive resonances together with the Standard Model degrees of freedom, including a light Higgs. We consider constraints from the phenomenology and from the assumed high-energy behavior of the underlying theory. This resonance effective theory can be used to estimate the low-energy constants (LECs) of the Electroweak Effective Theory (Electroweak Chiral Lagrangian) in terms of resonance parameters and to make predictions of low-energy observables like, for instance, the oblique parameters. Note that the theoretical framework is completely analogous to the Resonance Chiral Theory description of QCD at GeV energies.

2.25 Finite volume for masses and decay constants

T. Rössler and J. Bijnens
Lund University, Lund, Sweden

The talk will cover the recent progress in Chiral Perturbation Theory at two-loop order in finite volume. The techniques used in the two-loop finite volume integrals [1] will be described shortly and afterwards applications to masses and decay constants both for the standard case in two and three flavours [2] and partially quenched for three sea quark flavours [3] will be discussed.

References

1. J. Bijnens, E. Boström, and T.A. Lähde, JHEP **1401**, 019 (2014).
2. J. Bijnens and T. Rössler, JHEP **1501**, 034 (2015).
3. J. Bijnens and T. Rössler, work in progress.

2.26 Pseudoscalar decays into lepton pairs from rational approximants

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Pseudoscalar-meson decays (π^0, η, η') into lepton pairs ($e^+e^-, \mu^+\mu^-$) are unique in its kind as they probe the neutral pseudoscalar meson structure in the whole energy-range. This structure, which is encoded in the doubly virtual transition form factor (TFF) governing their interactions with two photons, needs a complete energy description.

In this work, we identify the relevant energy regimes related to this processes and propose the use of rational approximants for describing the TFF, emphasizing the correct low-energy description and high-energy implementation. Motivated by the range spanned by the pseudoscalar masses, we will discuss the use of different rational approximants: Padé approximants, which have been successfully used in the past [1, 2], its necessary extension to their bivariate version (Canterbury approximants) [3], and, as a novel approach, Quadratic approximants [4], which are very interesting, specially, for the η' case. Finally, we calculate the branching ratios for the different processes and estimate the different uncertainties, highlighting possible future experiments that may improve our description.

References

1. P. Masjuan, Phys. Rev. D **86**, 094021 (2012).
2. R. Escribano, P. Masjuan, and P. Sanchez-Puertas, Phys. Rev. D **89**, 034014 (2014).
3. P. Masjuan and P. Sanchez-Puertas, in preparation.
4. S. González-Solís, P. Masjuan, and P. Sanchez-Puertas, in preparation.

2.27 Study of two and three meson tau lepton decay modes with Monte Carlo generator TAUOLA

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TAUOLA is a Monte Carlo generator dedicated to generating tau-lepton decays and it is used in the analysis of experimental data both at B-factories and LHC. TAUOLA is a long term project that started in the 90's and has been under development up to now. In the last years substantial progress for the simulation of the process: $\tau \to 3\pi\nu_\tau$ was achieved. It is related with a new parametrization of the corresponding hadronic current based on the Resonance Chiral Lagrangian (RChL) and with the recent availability of the unfolded distributions from BaBar analysis for all invariant hadronic masses. The choice of this channel was motivated by its relatively large branching ratio and the already non-trivial dynamics of three-pion final state. A set of the hadronic currents within RChL for other final states with two and three pseudoscalars is also installed in TAUOLA.
In this talk we review our results on the three-pion decay mode as well present a new fitting framework. It allows to perform fits for an arbitrary tau decay mode, using either Fortran or C++ code. Using the new framework the theoretical model parameters are fitted to the one-dimensional distributions provided by the BaBar Collaboration, in the case of the three meson decay modes, and to the Belle data, for the two pion form factor. The results of the fit are discussed. Based on the obtained results the pole mass of the involved resonances are estimated.

2.28 A dispersive treatment of $K_{\ell 4}$ decays

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$K_{\ell 4}$ decays have several features of interest: they allow an accurate measurement of $\pi\pi$-scattering lengths; the decay is the best source for the determination of some low-energy constants of chiral perturbation theory (χPT); one form factor of the decay is connected to the chiral anomaly.
We present the final results of our dispersive analysis of $K_{\ell 4}$ decays, which provides a resummation of $\pi\pi$- and $K\pi$-rescattering effects [1, 2]. The free parameters of the dispersion relation are fitted to the data of the high-statistics experiments E865 [3, 4] and NA48/2 [5, 6]. The data input is corrected for additional isospin-breaking effects, which were not taken into account in the experimental analyses [7]. By matching to χPT at NLO and NNLO, we determine the low-energy constants L_1^r, L_2^r and L_3^r. Recently published data [6] from NA48/2 allow even a determination of L_9^r.
In contrast to a pure chiral treatment, the dispersion relation describes the observed curvature of one of the $K_{\ell 4}$ form factors, which we understand as an effect of rescattering beyond NNLO.

References

1. G. Colangelo, E. Passemar, and P. Stoffer, arXiv:1501.05627 [hep-ph].
2. P. Stoffer, PhD thesis, University of Bern, 2014, arXiv:1412.5171 [hep-ph].
3. S. Pislak *et al.* (BNL-E865 Collaboration), Phys. Rev. Lett. **87**, 221801 (2001), [Erratum-ibid. **105**, 019901 (2010)], arXiv:hep-ex/0106071].
4. S. Pislak *et al.* (BNL-E865 Collaboration), Phys. Rev. D **67**, 072004 (2003), [Erratum-ibid. **81**, 119903 (2010)], [arXiv:hep-ex/0301040].
5. J. Batley *et al.* (NA48-2 Collaboration), Eur. Phys. J. C **70**, 635 (2010).
6. J. Batley *et al.* (NA48/2 Collaboration), Phys. Lett. B **715**, 105 (2012), [arXiv:1206.7065 [hep-ex]], [Addendum-ibid. **740**, 364 (2015)].
7. P. Stoffer, Eur. Phys. J. C **74**, 2749 (2014), [arXiv:1312.2066 [hep-ph]].

2.29 Dispersion relation for hadronic light-by-light scattering and the muon $g-2$

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The anomalous magnetic moment of the muon $(g-2)_\mu$ has been measured and computed to very high precision of about 0.5 ppm. For more than a decade, a discrepancy has persisted between experiment and Standard Model prediction, now of about 3σ. The main uncertainty of the theory prediction is due to strong interaction effects. With the expected improvement of the input for hadronic vacuum polarisation, in a few years the subleading hadronic light-by-light (HLbL) contribution will dominate the theory error.
While some constraints from QCD exist, the calculation of the HLbL contribution to the $(g-2)_\mu$ is plagued by a substantial model dependence. In this talk, I will present a dispersive approach to HLbL scattering, based on the fundamental principles of unitarity and analyticity [1]. We have derived a Lorentz decomposition of the HLbL tensor that is fully gauge-invariant and crossing symmetric [2, 3]. The scalar coefficient functions of this tensor decomposition are free of kinematic singularities and zeros and fulfil Mandelstam's double-dispersive representation. The dispersive formalism defines unambiguously and in a model-independent way both the pion-pole and the pion-loop contribution. Two-pion rescattering effects are included in a partial-wave picture. Our dispersive formalism shows a path towards a data-driven determination of the HLbL contribution to the $(g-2)_\mu$ [4].

References

1. G. Colangelo, M. Hoferichter, M. Procura, and P. Stoffer, JHEP **1409**, 091 (2014), [arXiv:1402.7081 [hep-ph]].
2. G. Colangelo, M. Hoferichter, M. Procura, and P. Stoffer, arXiv:1506.01386 [hep-ph], submitted to JHEP.
3. P. Stoffer, PhD thesis, University of Bern, 2014, arXiv:1412.5171 [hep-ph].
4. G. Colangelo, M. Hoferichter, B. Kubis, M. Procura, and P. Stoffer, Phys. Lett. B **738**, 6 (2014), [arXiv:1408.2517 [hep-ph]].

2.30 Studies of the $Ke4$ decay at NA48

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The NA48/2 experiment has recently published a detailed study of the Ke4 decay mode $K \to \pi^0\pi^0 e\nu$ based on 65000 candidates with a low 1% background contamination. The achieved experimental precision brings evidence for isospin breaking mass effects and final state $\pi\pi$ scattering. Theoretical calculations will have to face a new precision challenge when using such improved inputs to extract for example low energy constants of Chiral Perturbation Theory.

3 Hadron structure and meson-baryon interaction working group

3.1 *Leading Talk* Leading logarithms for mesons and nucleons

J. Bijnens and A. A. Vladimirov
Lund University, Lund, Sweden

The talk will give an overview of the work done recently in calculating leading logarithms to high order and the underlying methods used. The method used [1, 2] will be done and an over view of applications which have been done to very high order in the massless case and up to seven loops in the massive case [3, 4, 5]. The talk will concentrate mainly on the new aspects needed for the nucleon sector where we can also obtain subleading logarithms in some cases. We also present some numerical results [5].

References

1. J. Bijnens and L. Carloni, Nucl.Phys. B **827**, 237 (2010).
2. N. Kivel, M.V. Polyakov, and A. Vladimirov, Phys. Rev. Lett. **101**, 262001 (2008).
3. J. Bijnens, K. Kampf, and S. Lanz, Nucl. Phys. B **860**, 245 (2012).
4. J. Bijnens, K. Kampf, and S. Lanz, Nucl. Phys. B **873**, 137 (2013).
5. J. Bijnens, A.A. Vladimirov, Nucl. Phys. B **891**, 700 (2015).

3.2 *Leading Talk* Review of the proton size puzzle

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The proton charge radius puzzle exists because the proton charge radius appears different when measured with electrons than when measured with muons. “Ordinary” explanations include problems with the extrapolations or theoretical corrections involved in the measurements, and “exotic” explanations include such beyond the standard model ideas as a breakdown of electron-muon universality. We will discuss possibilities in both categories.

3.3 *Leading Talk* Compton scattering and nucleon polarisabilities in Chiral EFT: The next steps

H. W. Grießhammer
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Compton scattering from protons and neutrons probes the two-photon response of the nucleon in electric and magnetic fields at fixed photon frequency and multipolarity [1]. It provides detailed tests of the symmetries and strengths of the interactions of the nucleonic constituents with each other and with photons. Proton-neutron differences explore the interplay between chiral symmetry breaking and short-distance Physics. At low energies, the process is parametrised by six energy-dependent dipole polarisabilities. For convenience, the information is however often compressed into the two scalar dipole polarisabilities α_{E1} and β_{M1} at the static point. In combination with emerging lattice QCD determinations, they provide stringent tests for our theoretical description of hadron structure. A plenary talk by J. A. McGovern discusses new high-accuracy extractions of the proton and neutron static electric and magnetic scalar dipole polarisabilities from all published elastic data below 300 MeV in Chiral EFT with explicit $\Delta(1232)$ degrees of freedom and model-independent estimates of higher-order corrections [2, 3].

This contribution addresses opportunities for χEFT to serve as intermediary between first-principle calculations in lattice QCD and efforts which are ongoing or approved at MAX-lab, HIγS and MAMI (cf. E. Downie's plenary talk). Such high-intensity experiments with polarised targets and polarised beams allow the extraction not only of scalar polarisabilities, but in particular of the so-far poorly explored spin-polarisabilities which parametrise the stiffness of the nucleon spin in external electro-magnetic fields (nucleonic bi-refringence/Faraday effect).

New chiral predictions for a comprehensive study of proton, deuteron and ^{3}He observables extend the analysis to higher energies and higher orders and help to better determine spin and neutron polarisabilities [4, 5]. They also serve to relate emerging lattice QCD simulations at $m_\pi > 200$ MeV to data at the physical point. In chiral lattice extrapolations, the relative theoretical uncertainties increase with m_π: the magnitudes of the polarisabilities decrease; the χEFT expansion parameter itself increases; and the $\Delta(1232)$ becomes more important, leading to a re-ordering of contributions. We quantify such uncertainties using a widely applicable method and compare to existing simulations [6].

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References

1. H.W. Grießhammer, J.A. McGovern, D.R. Phillips, and G. Feldman, Prog. Part. Nucl. Phys. **67**, 841 (2012).
2. J.A. McGovern, D.R. Phillips, and H.W. Grießhammer, Eur. Phys. J. A **49**, 12 (2013).
3. L.S. Myers *et al.*, Phys. Rev. Lett. **113**, 262506 (2014).
4. H.W. Grießhammer, Eur. Phys. J. A **49** (2013) 100.
5. B. Sandberg, H.W. Grießhammer, J.A. McGovern, and D.R. Phillips, forthcoming
6. H.W. Grießhammer, J.A. McGovern, and D.R. Phillips, forthcoming

3.4 *Leading Talk* Evidence that the $\Lambda(1405)$ is a molecular antikaon-nucleon bound state

W. Kamleh
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We present lattice QCD results showing that the strange magnetic form factor of the $\Lambda(1405)$ vanishes, signaling the formation of an antikaon-nucleon. Together with a Hamiltonian effective-field-theory model analysis of the lattice QCD energy levels, this strongly suggests that the structure is dominated by a bound antikaon-nucleon component. This result clarifies that not all states occurring in nature can be described within a simple quark model framework and points to the existence of exotic molecular meson-nucleon bound states.

3.5 *Leading Talk* Hermes results on 3D imaging of the nucleon

L.L. Pappalardo [on behalf of the Hermes Collaboration]
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In the context of rapid theoretical developments in non-perturbative QCD, a formalism of Transverse Momentum Dependent parton distribution functions (TMDs) and of Generalized Parton Distributions (GPDs) was introduced in the last two decades, providing a more comprehensive multi-dimensional description of the nucleon. TMDs and GPDs allow in fact for complementary descriptions of the nucleon in three dimensions (nucleon tomography), spanned by the quarks longitudinal momenta and, respectively, by the their transverse momenta components and transverse spatial coordinates. They thus contribute, with different approaches, to the full phase-space description of the nucleon structure. Furthermore, they provide complementary insights into the yet unmeasured quark orbital angular momentum. Experimentally, TMDs and GPDs can be accessed through the analysis of specific azimuthal asymmetries measured, respectively, in semi-inclusive deep-inelastic scattering and hard exclusive processes, such as hard leptoproduction of real photons or mesons. The HERMES experiment has collected wealth of data on scattering of a longitudinally polarized lepton (electron or positron) beam from HERA off unpolarized, longitudinally and transversely polarized internal gas targets. Collected data allowed to measure a variety of asymmetries with respect to beam charge, beam helicity and target polarization. A selection of HERMES results on observables sensitive to TMDs and GPDs will be presented.

3.6 *Leading Talk* Precise dispersive determination of πN scattering and the $\sigma_{\pi N}$

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Starting from hyperbolic dispersion relations for the invariant amplitudes of πN scattering together with crossing symmetry and unitarity, we derive and solve a closed system of integral equations for the partial waves of both s-channel ($\pi N \to \pi N$) and t-channel ($\pi\pi \to \bar{N}N$) reactions, called Roy-Steiner equations. Special attention is given to the possible sources of uncertainties and to the obtained $\sigma_{\pi N}$ term value.

3.7 Improved description of the nucleon polarizabilities with relativistic chiral effective field theory

J.M. Alarcon
University of Bonn, Bonn, Germany

The electromagnetic structure of the nucleon has an increasing interest for experimental searches of physics beyond the standard model in the precision frontier. The reason is that, due to the remarkable accuracy of the experimental measurements, it is crucial to have a good understanding over all possible contributions. The polarizabilities give the information about the two photon exchange contributions stemming from the internal electromagnetic structure of the nucleon. This is specially important for the so-called "Proton Radius Puzzle". In this talk I will show how in a recent calculation in the relativistic formulation of chiral effective field theory with the Delta degrees of freedom, we could achieve a prediction of the low Q^2 behaviour of the scalar and spin polarizabilities that is in good agreement with the MAID model and experimental data. Finally I will show the impact of this improved theoretical approach to the estimation of the order α_{em}^5 polarizability correction to the Lamb shift.

3.8 Status of the OLYMPUS experiment

R. Alarcon
Arizona State University, Tempe, AR, USA

The OLYMPUS experiment will determine the multiple-photon exchange contribution to elastic lepton-proton scattering, the most likely candidate to resolve the discrepancy between measurements of the proton electric to magnetic form factor ratio, determined using the Rosenbluth separation technique and polarization transfer methods. To this end, the experiment measured the cross section ratio of positron-proton to electron-proton elastic scattering. Data taking took place during 2012 on the DORIS storage ring at the DESY Laboratory in Hamburg, Germany. Electron and positron beams of 2.01 GeV energy were incident on an unpolarized hydrogen target and the elastic scattering cross sections were measured for both beams using a large acceptance spectrometer. This talk will cover the motivation, experiment, and current status of the analysis.

3.9 Impact of the Δ (1232) resonance in neutral pion photoproduction in chiral perturbation theory

L. W. Cawthorne and J. A. McGovern
The University of Manchester, Manchester, UK

In this talk we will discuss the reaction $p + \gamma \rightarrow p + \pi^0$ and how it has been described using Chiral Perturbation Theory (χPT).
Since the early 1990s χPT has been applied to pion photoproduction. The first study was that of Bernard *et al.* [2, 3], detailing a $\mathcal{O}(p^3)$ relativistic approach to describe the data from Mainz [3] and Saclay [4] from threshold, $E_\gamma \approx 145$ MeV, to $E_\gamma \approx 160$ MeV. In 1996 and 2001 the same authors revisited this phenomenon in $\mathcal{O}(p^4)$ heavy baryon χPT [5, 6]. They improved on previous results by fitting to data from threshold to $E_\gamma \approx 165$ MeV.
There has been a resurgence of interest in this topic following the publication of the results from the A2 and CB-TAPS collaborations at the Mainz Microtron (MAMI)[7]. This data has reached unprecedented levels of accuracy from the threshold region through to the first excited hadronic state, the $\Delta(1232)$. This data was analyzed by Fernández-Ramírez *et al.* [8] using rel. χPT and HBχPT. They concluded that for energies above $E_\gamma \approx 170$ MeV both the theories fail.
All of the above studies acknowledge that the $\Delta(1232)$ is important but do not include it in their work. It was incorporated into a $\mathcal{O}(p^3)$ EOMS covariant theory late last year by Blin *et al.* [9]. Their analysis showed how including the resonance improves the fit.
Another aspect highlighted by Fernández-Ramírez *et al.* [10] is that calculations often limit the angular momentum to P-waves, when it is not fully understood if the interference produced from D-wave states (or higher) are negligible.
In our discussion, we will detail both the relativistic and the heavy baryon approach. Furthermore, we will show the effects of including the $\Delta(1232)$, and how this improves theoretical descriptions of this phenomenon. Finally, we will discuss the consequences of truncating the angular-momentum to P-waves, compared to including D-waves and higher.

References

1. V. Bernard *et al.*, Nucl. Phys. B **383**, 442 (1992).
2. V. Bernard *et al.*, Phys. Reps. **246**, 315 (1994).
3. E. Mazzucato *et al.*, Phys. Rev. Lett. **57**, 3144 (1986).
4. R. Beck *et al.*, Phys. Rev. Lett. **65**, 1841 (1990).
5. V. Bernard *et al.*, Z. Phys. C **70**, 483 (1996).
6. V. Bernard *et al.*, Eur. Phys. J. A **11**, 209 (2001).
7. D. Hornidge *et al.*, Phys. Rev. Lett. **111**, 062004 (2013).
8. C. Fernández-Ramírez *et al.*, EPJ Web Conf. **73**, 04007 (2014).
9. A. Blin *et al.*, arXiv:1412.4083.
10. C. Fernández-Ramírez *et al.*, Phys. Rev. C **80**, 065201 (2009).

3.10 The K cascade production in coupled channel chiral models up to next-to-leading order

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The meson-baryon interaction in the S=-1 sector is studied by means of a chiral $SU(3)$ Lagrangian up to next-to-leading order, implementing unitarization in coupled channels. The parameters of the Lagrangian have been fitted to a large set of experimental data in two-body channels. We focused on $K - p \to K$ Cascade reactions because they show the strongest sensitivity to the next-to-leading order (NLO) coefficients, due to the zero tree level contribution of the leading-order terms. As we will see, the leading order Lagrangian, even taking into account the contributions via unitaritzation, can not build enough strength to reproduce the experimental data. Thus, NLO corrections are absolutely mandatory in the K Cascade production channels. In order to improve the the description of the total and differential $K - p \to K$ Cascade cross sections, and to analyse the accuracy and stability of the obtained NLO parameters, phenomenological contributions of massive high spin resonances in K Cascade channels have been introduced and studied. The resulting K Cascade interaction has been also applied to study of the decay process $Lambda_b \to J/\Psi K \Xi$, which can be studied by the LHCb Collaboration.

3.11 New results for Compton scattering on deuterium: A better determination of the neutron electromagnetic polarizabilities

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The electric and magnetic polarizabilities of the proton are now relatively well known, owing to Compton scattering measurements on hydrogen targets over the past 20 years [1]. However, in the case of the neutron, these structure constants are still quite uncertain, due to the fact that there are no free neutron targets and that quasi-free Compton scattering on a neutron in a nucleus has a significantly reduced cross section compared to that of a proton because the neutron is uncharged. These issues can be addressed by performing elastic Compton scattering on deuterium – in this case, the scattering cross section is higher, but the contributions from the proton and meson-exchange effects need to be taken into account in order to extract meaningful information about the neutron. To investigate this question, a multi-institutional collaboration has been conducting a program of elastic Compton scattering experiments on deuterium at the MAX IV Laboratory in Lund, Sweden using tagged photons in the energy range $E_\gamma = 65 - 115$ MeV. We have assembled at one laboratory, for the first time, three of the world's largest NaI detectors– CATS (from Mainz), BUNI (from Boston University), and DIANA (from the University of Kentucky) – each having better than $\Delta E/E \sim 2\%$ photon energy resolution. We have measured elastic Compton scattering cross sections at laboratory angles of $\theta_\gamma = 60^o, 90^o, 120^o$ and 150^o over this energy range in 8 MeV steps. This effectively doubles the world's set of elastic Compton scattering data from deuterium and provides valuable input for chiral effective field theory (χEFT) calculations [2]. The absolute normalization of the current data was rigorously checked via separate measurements of elastic Compton scattering on carbon [3], which can be compared with precise values in the literature. These new deuterium data overlap previous measurements and extend them by 20 MeV to higher energies where the sensitivity of the cross section to the polarizabilities is enhanced. Based on χEFT fits to the expanded world data set, new values for the neutron electric and magnetic polarizabilities have been obtained with greater accuracy than previously achieved, decreasing the statistical error by more than 30 % [4].

References

1. J.A. McGovern, D.R. Phillips, and H.W. Grießhammer, Eur. Phys. J. A **49**, 12 (2013).
2. H.W. Grießhammer, J.A. McGovern, D.R. Phillips, and G. Feldman, Prog. Part. Nucl.

Phys. **67**, 841 (2012).
3. L.S. Myers *et al.*, Phys. Rev. C **89**, 035202 (2014).
4. L.S. Myers *et al.*, Phys. Rev. Lett. **113**, 262506 (2014).

3.12 Extending the baryon ChPT beyond the low-energy region

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We suggest an extension of the one-nucleon sector of baryon chiral perturbation theory beyond the low-energy region. Applicability of the proposed approach for higher energies is restricted to small scattering angles, i.e. the kinematical region where the quark structure of hadrons cannot be resolved. The main idea is to re-arrange the low-energy effective Lagrangian according to a new power counting and for loop diagrams exploit the freedom of the choice of the renormalization condition. We generalize the extended on-mass-shell scheme for the one-nucleon sector of the baryon chiral perturbation theory by choosing a sliding scale, i.e. expand the physical amplitudes around kinematical points far beyond the threshold. This requires an introduction of complex-valued renormalized coupling constants which can be either extracted from experimental data, or calculated using the renormalization group evolution of coupling constants fixed in threshold region.

3.13 Peripheral transverse densities in the light-front formulation of chiral dynamics

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[b] *Thomas Jefferson National Accelerator Facility, Newport News, VA, USA*

The transverse densities of charge and magnetization in the nucleon are studied at peripheral transverse distances ($\sim O(M_\pi^{-1})$), where they are dominated by chiral dynamics and can be calculated model-independently using ChEFT. The densities are represented as overlap integrals of chiral light-front wave functions, describing the transition of the initial nucleon to soft pion-nucleon (and Delta) intermediate states and back [1]. This first-quantized representation of chiral dynamics permits a simple quantum-mechanical interpretation and reveals new features of the transverse densities. The orbital motion of the peripheral pion causes a large left-right asymmetry of the current in a transversely polarized nucleon, which results in the approximate equality of the peripheral charge and magnetization densities. The striking effect testifies to the essentially relativistic nature of chiral dynamics and could be observed in nucleon electromagnetic form factor measurements at low momentum transfer. The methodology developed here can be applied to nucleon form factors of other operators, such as the energy-momentum tensor.

References

1. C. Granados and C. Weiss, arXiv:1503.02055, arXiv:1503.04839

3.14 Chiral perturbation theory of hyperfine splitting in muonic hydrogen

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We present the predictions of baryon chiral perturbation theory (BChPT) for the proton polarizability contribution to the $2P-2S$ Lamb shift and the $2S$ hyperfine splitting (HFS) in muonic hydrogen, and compare them to the results of dispersive calculations.
The spin-dependent part of the forward doubly-virtual Compton scattering amplitude ($S_{1,2}$) contributes to the $2S$ HFS, whereas the spin-independent part of the amplitude ($T_{1,2}$) to the $2P-2S$ Lamb shift. All invariant amplitudes are related to photoabsorption cross sections by dispersion sum rules, however the amplitude T_1 requires a subtracted dispersion relation. Therefore, in contrast to the HFS, the polarizability contribution to the Lamb shift is not determined by the empirical information (on structure functions) alone and requires a rigorous theoretical input. Such an input has been provided by recent ChPT calculations, cf. [1] and references therein. We extend the calculation of Ref. [1] to the HFS, where the reliability of both ChPT and dispersive calculations is put to the test.

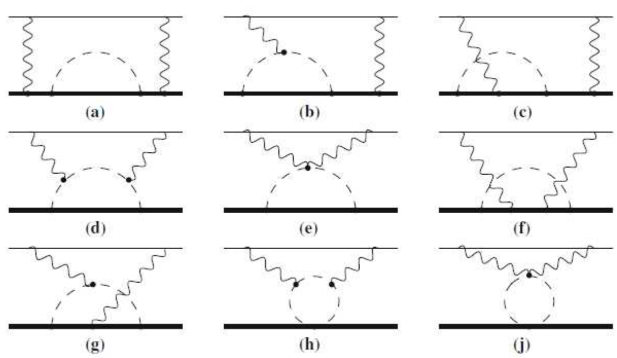

Figure 1: The two-photon exchange diagrams of elastic lepton-nucleon scattering to $O(p^3)$ in ChPT. Diagrams obtained from these by crossing and time-reversal symmetry are not drawn.

References

1. J.M. Alarcon, V. Lensky, and V. Pascalutsa, Eur. Phys. J. C **74**, 2852 (2014).

3.15 Chiral dynamics in the $\gamma p \to p\pi^0$ reaction

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We investigate the neutral pion photoproduction on the proton near threshold in covariant chiral perturbation theory with the explicit inclusion of Δ degrees of freedom. This channel is specially sensitive to chiral dynamics and the advent of very precise data from the Mainz microtron has shown the limits of the convergence of the chiral series for both the heavy baryon and the covariant approaches. We show that the inclusion of the Delta resonance substantially improves the convergence leading to a good agreement with data for a wider range of energies.

3.16 The H–dibaryon in two flavor lattice QCD

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We present preliminary results from a lattice QCD calculation of the H-dibaryon using two flavors of $\mathcal{O}$(a) improved Wilson fermions. We employ six quark interpolating operators with the appropriate quantum numbers of the H-dibaryon and also explore its couplings to two-baryon channels. We apply two smearings to improve the overlap to the ground state, which is obtained by solving a generalised eigenvalue problem. The inclusion of multi-particle operators enables the application of Lüscher's finite volume formalism to obtain information on the nature of the infinite volume interaction of two particles. Further, the correlators are projected to three moving frames enabling the isolation of the infinite volume bound/scattering state. Preliminary results on pion mass of 1 GeV indicate the H-dibaryon is bound in the infinite volume. Results at a lower pion mass of 451 MeV will also be presented.

3.17 Odd moments of nucleon charge and magnetization distribution in ChPT

N. Krupina and V. Pascalutsa
Johannes Gutenberg-University of Mainz, Mainz, Germany

We consider the predictions of Chiral Perturbation Theory (ChPT) for the third Zemach moment and Zemach radius and confront them with empirical values. We look at implications of these results for the Lamb shift and hyperfine structure of (muonic) hydrogen.

3.18 Narrow S–wave resonance in pion-baryon system

B. Long
University of Sichuan, Chengdu, China

As the pion mass approaches a critical value $m_\pi^\star$, an S-wave baryon resonance can cross pion-baryon threshold, thus driving the scattering length to diverge. Charmed baryon resonance $\Lambda_c^+(2595)$ appears to be a realization of such a system. I explore the consequences of chiral symmetry for m_π near $m_\pi^\star$, which are all centered around the finding that if $m_\pi^\star$ is not too large, the effective range of such a system is unexpectedly large, proportional to $4\pi f_\pi^2/m_\pi^3$.

3.19 Recoil corrections in antikaon-deuteron scattering

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The recoil retardation effect in the $K^- d$ scattering length is studied. Using the nonrelativistic effective field theory approach, it is demonstrated that a systematic perturbative expansion of the recoil corrections in the parameter $\xi = M_K/m_N$ is possible in spite of the fact that $K - d$ scattering at low energies is inherently nonperturbative due to the large values of the $K^- N$ scattering lengths.
The first-order correction to the $K^- d$ scattering length due to single insertion of the retardation term in the multiple-scattering series is calculated. The recoil effect turns out to be reasonably small even at the physical value of $M_K/m_N \sim 0.5$. In the talk I will present these results as well as our more recent estimation of higher order corrections and the possibility to resum the recoil corrections to all orders.

3.20 Joint Physics Analysis Center activities

V. Mathieu
Indiana University, Bloomington, IN, USA

The Joint Physics Analysis Center gathers theorists working on tools development for the analysis of hadon spectroscopy experiments. Our aim is to provide to experimentalists flexible amplitudes to fit data and easily extract the physics of a specific reaction. I will report on the latest results including pion-nucleon and kaon-nucleon elastic scattering, eta/omega/phi mesons decays in three pions and photoproduction on strange mesons.

3.21 Evolution of the $\bar{K}N - \pi\Sigma$ system with M_π^2 in a box from UχPT

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The George Washington University, Washington, DC, USA

The $\Lambda(1405)$ baryon is of continued interest in hadronic physics, being absent in many quark model calculations and supposedly manifesting itself in a two-pole structure. Finite-volume Lattice-QCD eigenvalues for different quark masses were recently reported by the Adelaide group [1]. We compare these eigenvalues to those of a unitary Chiral Perturbation Theory (UχPT) model [2], evaluated in the finite volume [3]. The UχPT calculation predicts the quark mass dependence remarkably well. It also explains the overlap pattern with different meson-baryon components, mainly $\pi\Sigma$ and $\bar{K}N$, at different quark masses. Some of the results of our calculation are shown in Fig. 1. We will study the properties of the two lower states in the box as predicted by UχPT and compare to those of the two poles of the $\Lambda(1405)$ in the infinite limit. More accurate Lattice QCD are required to draw definite conclusions on the nature of the $\Lambda(1405)$.

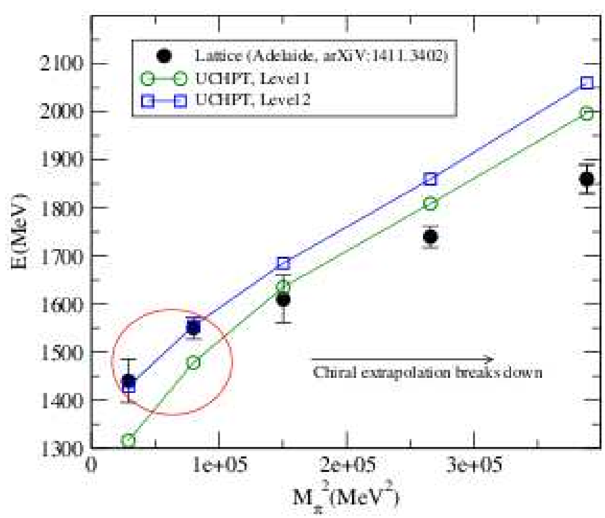

Figure 1: Comparison between the Lattice data from the Adelaide group and the predictions from UχPT.

References

1. J.M.M. Hall, W. Kamleh, D.B. Leinweber, B.J. Menadue, B.J. Owen, A W. Thomas, and R.D. Young, Phys. Rev. Lett. **114**, 132002 (2015).
2. E. Oset, A. Ramos, and C. Bennhold, Phys. Lett. B **527**, 99 (2002). [Phys. Lett. B **530**, 260 (2002)].
3. M. Doring, J. Haidenbauer, Ulf-G. Meissner, and A. Rusetsky, Eur. Phys. J. A **47**, 163 (2011).

3.22 Octet baryon masses in covariant baryon chiral perturbation theory up to $\mathcal{O}(p^4)$

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We report on a recent study of the ground-state octet baryon masses and sigma terms in the covariant baryon chiral perturbation theory (ChPT) with the extended-on-mass-shell (EOMS) renormalization scheme up to next-to-next-to-next-to-leading order (N^3LO). To take into account lattice QCD artifacts, the finite-volume corrections (FVCs) and finite lattice spacing discretization effects are carefully examined.
We performed a simultaneous fit of all the publicly available $n_f = 2 + 1$ lattice QCD data from the PACS-CS, LHPC, HSC, QCDSF-UKQCD and NPLQCD collaborations and found that the N^3LO EOMS BChPT can describe the data reasonably well with $\chi^2/\text{d.o.f.} = 1.0$. Our study showed that the various lattice simulations are consistent with each other. Although the finite lattice spacing discretization effects up to $\mathcal{O}(\dashv^\in)$ can be safely ignored, but the finite volume corrections cannot even for configurations with $M_\phi L > 4$. As an application, we predicted the octet baryon sigma terms using the Feynman-Hellmann theorem. In particular, the pion- and strangeness-nucleon sigma terms are found to be $\sigma_{\pi N} = 55(1)(4)$ MeV and $\sigma_{sN} = 27(27)(4)$ MeV, respectively.

3.23 Combined analysis of $\pi N \to \pi N$ and $\pi N \to \pi\pi N$ in ChPT

D. Siemens
Ruhr University of Bochum, Bochum, Germany

In my talk, I will focus on the reactions $\pi N \to \pi N$ and $\pi N \to \pi\pi N$ which are studied at one-loop level in the frameworks of covariant and heavy baryon chiral perturbation theory. Performing combined fits to determine the relevant low-energy constants, predictions are made for various observables. In addition, first attempts to include $\Delta(1232)$ and $R(1440)$ as explicit degrees of freedom will be discussed [1].

References

1. D. Siemens *et al.*, Phys. Rev. C. **89**, 065211 (2014).

3.24 Excited-state contamination in nucleon correlators from chiral perturbation theory

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Techniques to compute hadron properties from lattice QCD rely upon the limit of long time separation. For baryons, the signal-to-noise problem often restricts one to time separations that are not ideally long, and for which couplings to excited states can obstruct the isolation of ground-state baryon properties. We consider excited-state contamination in nucleon two- and three-point functions. Using chiral perturbation theory, we determine couplings to pion-nucleon and pion-delta excited states. In two-point functions, these contributions are small, in accordance with general properties of the spectral density on a torus. For the axial-current correlation function in the nucleon, the sign of excited-state contributions suggests overestimation of the nucleon axial charge. Thus contamination from pion-nucleon excited states will not likely explain the trend in lattice QCD data.

3.25 Hadronic uncertainties and isospin violation in supersymmetric dark matter models

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Current limits from dark matter direct-detection experiments place a powerful constraint on the parameter space of the Minimal Supersymmetric Standard Model (MSSM). The interpretation of these limits, however, depends sensitively on the hadronic uncertainties associated with the scattering of supersymmetric dark matter particles off nucleons. For spin-independent scattering, we review the role of chiral perturbation theory in the determination of these hadronic uncertainties, and quantify the amount of isospin violation within several simplified versions of the MSSM. In each case, we identify parameter-space configurations that produce (almost) vanishing cross sections and examine the complementarity of constraints due to direct-detection, flavour, and collider experiments. In the vicinity of these so-called blind spots, we find that isospin violation is much larger than typically expected in the MSSM.

3.26 $SU(3)$ flavor breaking in baryon octet light-cone distribution amplitudes

P. Wein
University of Regensburg, Regensburg, Germany

We present a leading one-loop calculation in the framework of three-flavor baryon chiral perturbation theory (BChPT) for three-quark light-cone distribution amplitudes, which parametrize the momentum distribution in the leading Fock state and are relevant for the description of hard exclusive processes. Such a calculation automatically yields model-independent results for the leading SU(3) flavor breaking effects. It is possible to find a minimal set of distribution amplitudes (DAs) that do not mix under chiral extrapolation towards the physical point and naturally embed the Λ baryon. For the wave function normalization constants and for the first moments of the leading twist DA we will provide first results obtained from fits to preliminary lattice QCD data.

3.27 The proton spin-dependent structure function g_2 at low Q^2

R. Zielinski
University of New Hampshire, Dover, NH, USA

The Jefferson Laboratory accelerator has been used to great effect in the study of the polarized structure of nucleons. Measurements of the spin-dependent structure functions have been proven to be powerful tools in testing the validity of effective theories of Quantum Chromodynamics. While the neutron spin structure functions, g_1^n and g_2^n , and the longitudinal proton spin structure function, g_1^p, have been measured over a wide kinematic range, the second proton spin structure function, g_2^p, has not. This talk will present the E08-027 (g_2^p) experiment, which was an inclusive measurement of g_2^p in the resonance region at Jefferson Lab's Hall A. This is the first measurement of g_2^p covering 0.02 $\text{GeV}^2 < Q^2 < 0.2\ \text{GeV}^2$. The experiment will allow us to test the Burkhardt-Cottingham Sum Rule at low Q^2 as well as extract the longitudinal-transverse generalized spin polarizability and compare it to predictions made by Chiral Perturbation Theory. In addition, the data will reduce the systematic uncertainty of calculations of the hyperfine splitting of hydrogen. An update on the status of the analysis, along with preliminary results, will be presented.

4 Few-body physics working group

4.1 *Leading Talk* Clustering in nuclei from ab initio nuclear lattice simulations

Ulf-G. Meissner
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In this talk, I discuss the emergence of clustering in ab initio nuclear lattice simulations. The spectrum and the structure of the ^{12}C and ^{16}O nuclei are displayed. I also consider some issues related to the breaking of rotational symmetry in alpha cluster-models and show how these lattice artifacts can be tamed.

4.2 *Leading Talk* Uncertainty quantification and chiral dynamics

D.R. Phillips
Ohio University, Athens, OH, USA

I will show that combining effective field theories (EFTs) with Bayesian data analysis facilitates the rigorous quantification of theoretical uncertainties [1]. Bayesian methods are sometimes attacked on the grounds that the use of priors produces a subjective result. I will argue that, in fact, incorporating priors in the analysis permits the consistent application of analysis assumptions that are otherwise only implicit or imposed in an ad hoc way. In a Bayesian framework such assumptions can then be tested, and, if necessary, modified in light of new information.
In this talk the general framework for incorporating Bayesian priors that encode the expectation that low-energy coefficients (LECs) in the EFT are natural will first be presented. Applications such as:

- computation of higher-order uncertainties in chiral EFT calculations of NN scattering [2];
- the extraction of low-energy constants in toy models designed to mimic EFTs with both natural and unnatural coefficients [3];
- the extrapolation of lattice data on the nucleon mass to the physical pion mass,

will be discussed.
This work was performed by the BUQEYE collaboration and is supported by the National Science Foundation and the US Department of Energy.

References
1. R.J. Furnstahl, D.R. Phillips, and S. Wesolowski, J. Phys. G **42**, 034028 (2015).
2. R.J. Furnstahl, N. Klco, D.R. Phillips, and S. Wesolowski, in preparation.
3. S. Wesolowski, N. Klco, A. Thapaliya, R.J. Furnstahl, and D.R. Phillips, in preparation.

4.3 *Leading Talk* Magnetic properties of light nuclei from Lattice QCD

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I will present the recent results of lattice QCD calculations of the interactions of nucleons and light nuclei with magnetic fields. Their magnetic moments and polarizabilities have been calculated at pion masses of 805 MeV and 450 MeV. Interestingly, the magnetic moments, when given in terms of natural nuclear magnetons, are found to be consistent with the experimental values. I also present first results for the cross section for $n + p \to d + \gamma$.

4.4 *Leading Talk* Hadronic parity violation in effective field theory

M. Schindler
University of South Carolina, Columbia, SC, USA

Parity-violating interactions between nucleons are the manifestation of an interplay of strong and weak interactions between quarks in the nucleons. Because of the short range of the weak interactions, these parity-violating forces provide a unique probe of low-energy strong interactions. An ongoing experimental program is mapping out this weak component of the nuclear force in few-nucleon systems. Recent theoretical progress in analyzing and interpreting hadronic parity violation in such systems, based on effective field theory methods, will be described. In particular, important information on parity-violating nucleon-nucleon interactions can be gained from an asymmetry in deuteron photodisintegration, which might be measurable at a future high-intensity photon source such as the proposed upgraded HIGS facility. Recent theoretical calculations of this parity-violating asymmetry and the impact of such a measurement on our understanding of hadronic parity violation will be discussed.

4.5 Recent developments in neutron-proton scattering with lattice effective field theory

J.M. Alarcon
University of Bonn, Bonn, Germany

In this talk I want to present the recent progresses in neutron-proton scattering on the lattice with lattice EFT. Among them, the study of the different lattice actions in describing the scattering observables and binding energy of the deuteron. The convergence of the chiral series for these observables will be analyzed as well, and will be shown to be in good agreement with the expected behaviour of a perturbative approach. Finally, I will comment on the problem regarding the description of the mixing angle on the lattice, which is one of the remaining problems since the beginning of the lattice EFT calculations.

4.6 Compton Scattering from ^{3}He and ^{4}He using an active target

J. Annand
University of Glasgow, Glasgow, UK

An experiment to measure the differential cross section for Compton scattering from ^{3}He and ^{4}He at the MAMI tagged photon facility in Mainz is described. The objective is to measure the isoscalar nucleon electromagnetic polarisabilities and thus access the neutron polarisabilities. The experiment will use a high-pressure gas-scintillator active target to measure recoiling He ions in coincidence with the scattered photon, detected in the Crystal Ball and TAPS 4π electromagnetic calorimeter. Recent work to develop a chiral effective field theory treatment of Compton scattering on ^{3}He is also described, and the relative merits of using ^{2}H, ^{3}He or ^{4}He as "neutron targets" discussed in the light of recent experiments on ^{2}H.

4.7 Nuclear axial current in chiral effective field theory

A. Baroni
Department of Physics, Old Dominion University, Norfolk, VA, USA

We present the derivation of two-nucleon axial charge and current operators in chiral effective field theory up to order Q in the power counting, where Q denotes generically the low momentum scale. The derivation is based on time-ordered perturbation theory, and accounts for cancellations between the contributions of irreducible diagrams and those due to non-static corrections from energy denominators of reducible diagrams. Renormalized terms in the axial charge are obtained by isolating divergencies in loop corrections via dimensional regularization, and reabsorbing them in a subset of the low-energy constants of contact operators entering the theory at order Q. The axial current contains no divergencies at order Q and also no contact terms at this order.

4.8 Application of low-energy theorems to NN scattering at unphysical pion masses

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The low-energy theorems (LET) for NN scattering are known to provide important relations between the coefficients in the effective-range expansion (ERE) of the amplitude, which are governed by the long-range part of the potential, see, e.g., Refs. [1, 2]. Therefore, as long as the long-range physics is appropriately included in the calculation, these relations should yield model independent predictions for the coefficients in the ERE, provided some of these coefficients are known. In particular, using the NN scattering length in the $^3S_1$ channel as input, the effective range and the shape parameters predicted in Ref. [3] appear to be in a good agreement with those extracted from Nijmegen PWA [4]. In this work we extend the LET to the case of unphysical pion masses. It is emphasized that correlations provided by LET can be used as nontrivial consistency checks for the lattice calculations. As an example, we use the m_π dependence of the effective range suggested in the recent lattice study [5] as input to predict the m_π dependence of the binding energy and the shape parameters.
Further, we discuss the results of chiral extrapolations calculated to NLO using the modified Weinberg formulation of chiral effective field theory.

References

1. T.D. Cohen and J.M. Hansen, Phys. Rev. C **59**, 13 (1999); Phys. Rev. C **59**, 3049 (1999).
2. E. Epelbaum and J. Gegelia, Eur. Phys. J. A **41**, 341 (2009).
3. E. Epelbaum and J. Gegelia, Phys. Lett. B **716**, 338 (2012).
4. J.J. de Swart, C.P.F. Terheggen, and V.G.J. Stoks, `nucl-th/9509032`.
5. S.R. Beane *et al.* [NPLQCD Collaboration], Phys. Rev. C **88**, 024003 (2013).

4.9 The nuclear contact: From nucleus photodisintegration to nucleons momentum distributions

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Recently, Tan suggested that the properties of universal quantum gases depend on a new characteristic quantity, called the contact. The contact describes the probability of two particles coming close to each other, i.e. it is a measure of the number of close particle pairs in the system. Utilizing the contact, this theory predicts the energy, pressure and other properties of the system. It was proven right in a series of ultracold atomic experiments. We generalize Tan's contact to nuclear systems, introducing the various nuclear contacts, taking into account all possible pair configurations. The leading neutron-proton contact is then evaluated from medium energy photodisintegration experiments. To this end, the Levinger quasi-deuteron model of nuclear photodisintegration is reformulated, and the bridge between the Levinger constant and the contact is established. Using experimental evaluations of Levinger's constant the value of the neutron-proton contact in finite nuclei and in symmetric nuclear matter is extracted, and compared to the universal theory. Utilizing the contact, a new asymptotic connection between the one-nucleon and two-nucleon momentum distributions, describing the two-body short-range correlations in nuclei, is obtained. Using available numerical data, we extract few connections between the different contacts and verify their relations to the momentum distributions.

4.10 Effective theory for Lattice nuclei

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The development of a many-body theory having a clear interpretation in the framework of QCD and, at the same time, capable to reach a very high precision in calculating observables is a longstanding quest.
In the last years Lattice QCD has substantially improved its predictive power for light nuclei [1, 2, 3]. Now we have access to data for light nuclei in systems with high pionic mass. We argue that the proper low-energy theory is a contact (or pionless) approach, since for these systems pion effects are of short-range. By means of this effective theory it is possible to extend LQCD predictions to heavier nuclei.
The low energy constants of the theory at leading order can be determined using LQCD data of binding energy of deuteron, triton and helion. I will present predictions [4] for binding energy of ^{4}He, ^{5}He, ^{5}Li and ^{6}Li calculated with effective-interaction hyperspherical harmonics (EIHH) and auxiliary field diffusion montecarlo (AFDMC), then discuss the extension of the method, done with AFDMC, for much heavier nuclei.

In this way we illustrate for the first time how to make predictions on nuclei starting from LQCD results, anticipating the procedure that should be adopted with chiral dynamics, once LQCD will be able to give results with smaller pion mass.

References

1. T. Yamazaki, K. Ishikawa, Y. Kuramashi, and A. Ukawa, Phys. Rev. D **86**, 074514 (2012).
2. S.R. Beane *et al.* (NPLQCD Collaboration), Phys. Rev. D **87**, 034506 (2013).
3. S.R. Beane *et al.* (NPLQCD Collaboration), Phys. Rev. C **88**, 024003 (2013).
4. N. Barnea, L. Contessi, D. Gazit, F. Pederiva, and U. van Kolck, Phys. Rev. Lett. **114**, 052501 (2015).

4.11 Extracting neutron polarizabilities from compton scattering on quasi-free neutrons in $\gamma d \to \gamma np$

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Compton scattering processes are ideal to study electric and magnetic dipole polarizability coefficients of nucleons [1]. These fundamental quantities parametrize the response to a monochromatic photon probe. In this work, the inelastic channel $\gamma d \to \gamma np$ is treated in χEFT, with a focus on the NQFP - neutron quasi-free peak - kinematic region. In this region, the momentum of the outgoing proton is small enough that it is considered to remain at rest. This provides access to the Compton scattering process $\gamma n \to \gamma n$ from which the neutron scalar polarizabilites α and β are extracted. Using χEFT, differential cross-sections, $d^3\sigma/dE_n d\Omega_{\gamma'}\Omega_n$, in the photon energy range of 200-400 MeV are computed. The biggest contribution comes from the impulse approximation, with small corrections stemming from final state interaction, meson exchange currents and rescattering. A new extraction of neutron polarizabilities from a two-parameter fit to the Kossert *et al.* [2] data taken at MAMI in 2002 is presented. Previously, the experiment was designed and the data analysed based on a theoretical model [3] that computed the NQFP differential cross-sections. The re-analysis of this data in a consistent, model independent framework - χEFT - provides reliable extraction of polarizabilies with controlled uncertainties.

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References

1. H.W. Grießhammer, J.A. McGovern, D.R. Phillips, and G. Feldman, Prog. Part. Nucl. Phys. **67**, 841 (2012).
2. K. Kossert *et al.*, Phys. Rev. Lett. **88**, 162301 (2002).
3. M.I. Levchuk, A.I. L'vov, and V.A. Petrun'kin, Few-Body Syst. **16**, 101 (1994).

4.12 *Ab initio* alpha-alpha scattering

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We present *ab initio* lattice calculations of α–α clusters scattering at next-to-next-to-leading order in chiral effective field theory using the adiabatic projection method. The adiabatic projection method is a general framework for scattering and reactions on the lattice which uses a set of initial cluster states and Euclidean time projection to give a systematically improvable description of the low-lying scattering cluster states. By imposing spherical wall boundary condition, we extract scattering phase shifts directly from asymptotic cluster wave functions with less sensitivity to small stochastic and systematic errors than using finite-volume energy methods. We present lattice results for the α–α S-wave and D-wave scattering phase shifts at next-to-next-to-leading order in chiral effective field theory and compare with experimental data.

4.13 Pion production in nucleon-nucleon collisions near threshold: Complete NNLO calculation in chiral EFT

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Study of pion production near threshold is interesting for several reasons: it tests applicability of chiral EFT at intermediate energies, probes nucleon-nucleon dynamics at relatively large transferred momenta, and gives possibility to study isospin violation in few-body processes.
The neutral pion production in $pp \to pp\pi^0$ channel has been known to be the most puzzling process for a long time. The data for near-threshold cross section in this channel is suppressed by more than an order of magnitude compared to charged pion-production channels. This suppression agrees with conclusions made using chiral EFT, namely that there is almost no leading order contribution to $pp \to pp\pi^0$ and the higher order effects are expected to be important for quantitative understanding of neutral pion production. We present the results for the full pion production operator near threshold calculated up-to-and-including next-to-next-to-leading order (NNLO) in chiral effective field theory [2, 3], which includes pions, nucleons and delta degrees of freedom. Our analysis of chiral loops at NNLO reveals new mechanisms which are important, but haven't been considered in phenomenological studies so far. The obtained production operator, being convolved with nucleon-nucleon wave functions derived recently based on chiral EFT [4] is used to compute the pion production amplitudes. First results for the observables in $NN \to NN\pi$ are going to be presented.

References

1. V. Baru, C. Hanhart, and F. Myhrer, Int. J. Mod. Phys. E **23**, 1430004 (2014).
2. A.A. Filin, V. Baru, E. Epelbaum, H. Krebs, C. Hanhart, A.E. Kudryavtsev, and F. Myhrer, Phys. Rev. C **85**, 054001 (2012).
3. A.A. Filin, V. Baru, E. Epelbaum, C. Hanhart, H. Krebs, and F. Myhrer, Phys. Rev. C **88**, 064003 (2013).
4. E. Epelbaum, H. Krebs, and Ulf-G. Meissner, arXiv:1412.0142 [nucl-th] (2014).

4.14 Scaling of tetramer properties close to the unitary limit

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The universal properties of weakly bound tetramers close to the unitary limit are obtained by solving Faddeev-Yakubovsky (FY) equations for identical bosons with a zero-range interaction. The solution of these equations demand beside a short-range three-body scale another one for the four-boson system. We explore the correlation between trimer and tetramer energies are shown to be universal, and exhibits the effect of the new scale, which is conveniently represented by a scaling function depending only on dimensionless quantities. Furthermore, the effective range changes the scaling functions in a way distinct from variations of the three- and four-body short range scales. The universal scaling functions for trimer and tetramers are sensitive to the effective range, and in particular, the correlation between the positions of the four-atom recombination peaks. We show that the shift in the position of the tetramer resonance peaks for cesium atoms, coming from the finite effective range, are consistent with the existing experimental data for these broad Feshbach resonances.

4.15 Chiral two-nucleon dynamics, analyticity and dispersion relations

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Nucleon-nucleon interaction is studied using relativistic form of the chiral Lagrangian. Partial-wave amplitudes are computed in chiral perturbation theory at next-to-next-to-leading order in the subthreshold region. The most general constraints set by analyticity and unitarity are implemented to extrapolate the amplitudes into the physical region using the method developed in Refs. [1, 2]. Empirical phase shifts are described up to laboratory energies $T_{\mathrm{lab}} \simeq 250$ MeV. The issues related with renormalization and convergence of perturbation theory are investigated.

References

1. A. Gasparyan and M.F.M. Lutz, Nucl. Phys. A **848**, 126 (2010).
2. A.M. Gasparyan, M.F.M. Lutz, and E. Epelbaum, Eur. Phys. J. A **49**, 115 (2013).

4.16 The n3He experiment: Hadronic parity violation in cold neutron capture on ^{3}He

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The n3He experiment aims to measure the parity violating asymmetry in the direction of proton emission in the reaction $\vec{n} +^3 He \to T + p$, using the capture of polarized cold neutrons in an unpolarized gaseous ^{3}He target. Using effective field theory based calculations, the size of the asymmetry is estimated to be in the range of $(-9.5 \to 2.5) \times 10^{-8}$, and our goal measurement accuracy is 2×10^{-8}. The asymmetry is a result of the low energy weak interaction between nucleons and its measurement will provide a benchmark for modern effective field theory calculations. The asymmetry isolates the I = 0 components of the hadronic weak interaction. The experiment uses a ^{3}He multiwire ionization chamber as the combined target and detector operated in current mode. The n3He experiment was installed and commissioned in December 2014 on the Fundamental Neutron Physics Beamline at the Spallation Neutron Source at Oak Ridge National Laboratory. The experiment is currently taking production data. I will provide an overview of the experiment and the physics and will discuss some of the data collected to date.

4.17 Progress in the quest for a realistic three-nucleon force

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Despite long-lasting efforts in the determination of a realistic three-nucleon force (TNF), none of the presently available models leads to a satisfactory description of bound and scattering states of the $A = 3$ system. It seems natural to ascribe the above situation to the fact that these models include a very small number of adjustable parameters, compared to the two-nucleon interaction case. For example, in the framework of the chiral expansion, only 2 low-energy constants (LECs) enter up to and including N3LO. At the following order (N4LO) one encounters 10 additional LECs, which parametrize the short-range component of the TNF, and are unconstrained by chiral symmetry. As such, they could provide the necessary flexibility to arrive at a truly realistic model for the TNF. In this contribution we will report about our progress along these lines. In particular we examine to which extent the AV18 NN interaction, supplemented by the leading and subleading contact-range TNF, provides a satisfactory fit to $N - d$ scattering data.

4.18 Assessing theory errors using residual cutoff dependence

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The past few years have witnessed a renewed emphasis of the need to quantify residual theoretical uncertainties [1, 2]. Ideally, "double-blind" calculations would assess them based on input and method, and not by comparison to data. This is particularly important if data is absent or its consistency needs to be checked. Effective Field Theories promise a well-defined scheme to provide such reproducible, objective, quantitative error estimates. While straightforward in a perturbative EFT like the purely mesonic or one-baryon sector of χEFT, how can one validate the expansion in a non-perturbative EFT? This is a particularly nagging question for few-nucleon systems, where a fully consistent chiral EFT is still under development since the NN interaction is non-perturbative, leading to heated discussions which of the proposed power countings is consistent. A reliable uncertainty estimate is not just a cornerstone of the Effective Field Theory methodology. To be able to falsify predictions of a theory is central to the Scientific Method. This talk proposes a means to check the internal consistency of a non-perturbative expansion on a semi-quantitative level.
One can indeed quantify the consistency of an EFT from the dependence of observables $\mathcal{O}(k;\Lambda)$ at low momentum k on the cutoff Λ employed in numerical calculations [2]. This way, one actually turns into an advantage the annoying fact that most nonperturbative systems do not allow for closed-form calculations. The power-counting in the small, dimension-less quantity $Q \propto k$ of an EFT predicts (up to logarithmic corrections)

$$1 - \frac{\mathcal{O}(k;\Lambda_1)}{\mathcal{O}(k;\Lambda_2)} \propto \left(\frac{k}{\bar{\Lambda}_{\mathrm{EFT}}}\right)^{n+1} \qquad (2)$$

for a calculation at order Q^n, where $\bar{\Lambda}_{\mathrm{EFT}}$ is the typical high-energy scale at which the EFT description breaks down [3]. The slope of a double-logarithmic plot of a suitable quantity against k reveals thus the order of accuracy n and an estimate of $\bar{\Lambda}_{\mathrm{EFT}}$. In contradistinction to a method proposed by Lepage [4], this approach does not compare to data to assess uncertainties. The method is not the solution to all problems but another arrow in the quiver. Its advantages and shortcomings are discussed with various examples, including some from recent literature.

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References

1. Editorial, Phys. Rev. A **83**, 040001 (2011).
2. J. Phys. G **42** (issue 3, Feb 2015): Special Focus Issue "Enhancing the Interaction between Nuclear Experiment and Theory through Information and Statistics".
3. H. W. Grießhammer, Nucl. Phys. A **744**, 192 (2004), and forthcoming.
4. G. P. Lepage, nucl-th/9706029.

4.19 Precise calculations of the deuteron quadrupole moment

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Until recently, precision calculations of the deuteron quadrupole moment, Q_d, have consistently under-predicted its value by several percent, leaving the calculation of this quantity an "unresolved problem" in few body physics. I will report on two recent calculations that predict Q_d to better than 1%. One of these uses chiral effective field theory and the other uses the covariant spectator theory, and comparing these very different approaches gives interesting insights into both of them.

4.20 Hyperons in nuclear matter studied in chiral EFT

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We present results for the in-medium properties of a hyperon-nucleon (YN) interaction derived within chiral effective field theory (EFT) and fitted to ΛN and ΣN scattering data. The single-particle potentials for the Λ and Σ hyperons in nuclear matter are evaluated in a conventional G-matrix calculation, and the Scheerbaum factor associated with the hyperon-nucleus spin-orbit interaction is computed [1]. We consider a leading-order (LO) YN interaction published in 2006 which accounts well for the bulk properties of the ΛN and ΣN system [2], and our recent YN potential derived up to next-to-leading order (NLO) in chiral EFT which provides an excellent description of the available low-energy ΛN and ΣN cross sections and the inelastic capture ratio at rest [3].
The predictions for the Λ single-particle potential are found to be in good qualitative agreement with the empirical values inferred from hypernuclear data. A depth of about -25 MeV is predicted by the NLO interaction and of about -36 MeV by the LO potential. The Σ-nuclear potential turns out to be repulsive, in agreement with phenomenological information, with values around 15–20 MeV.
Empirical information suggests that the Λ-nucleus spin-orbit interaction should be rather weak. Therefore, we investigate also the spin-orbit interaction and, in particular, the role of the antisymmetric spin-orbit force in the YN system. The chiral EFT approach yields a potential that contains, besides pseudoscalar meson exchanges (π, K, η), a series of contact interactions with an increasing number of derivatives. In this approach a contact term representing an antisymmetric spin-orbit force arises already at NLO. It induces ${}^1P_1$–${}^3P_1$ transitions in the coupled ($I = 1/2$) ΛN–ΣN system. The low-energy constant associated with the contact term could not be pinned down by a fit to the existing ΛN and ΣN scattering data as found in Ref. [3] and, thus, it was simply put to zero in that work. However, it turns out that its value can be fixed from investigating the properties of the Λ hyperon in nuclear matter and, specifically, it can be utilized to achieve a weak Λ-nuclear spin-orbit potential [1].

References

1. J. Haidenbauer and Ulf-G. Meissner, Nucl. Phys. A **936**, 29 (2015).
2. H. Polinder, J. Haidenbauer, and Ulf-G. Meissner, Nucl. Phys. A **779**, 244 (2006).
3. J. Haidenbauer, S. Petschauer, N. Kaiser, Ulf-G. Meissner, A. Nogga, and W. Weise, Nucl. Phys. A **915**, 24 (2013).

4.21 Studies of Λ-neutron interaction through polarization observables for final-state interactions in exclusive Λ photoproduction off the deuteron

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Theoretical studies suggest that experimental observables for hyperon production reactions can place stringent constraints on the free parameters of hyperon-nucleon potentials, which are critical for the understanding of hypernuclear matter and neutron stars. We will present preliminary experimental results for the polarization observables σ, P_y, O_x, O_z, C_x, and C_z for final-state interactions (FSI) in exclusive Lambda photoproduction off the deuteron. The observables were obtained from data collected during the E06-103 (g13) experiment with the CEBAF Large Acceptance Spectrometer in Hall B at Jefferson Lab. The g13 experiment ran with unpolarized deuteron target and circularly- and linearly-polarized photon beams with energies between 0.5 GeV and 2.5 GeV and collected about $5\times$??10^{10} events with multiple charged particles in the final state. To select the reaction of interest, the kaon and Lambda decay products, a proton and a negative pion, were detected in CLAS. Missing-mass technique was used to further reduce the event sample. Final-state interaction events were selected by requesting that the reconstructed neutron has a momentum larger than 200 MeV/c. The large statistics of E06-103 provided statistically meaningful FSI event samples, which allow for the extraction of one- and two-fold differential single- and double-polarization observables. In this talk we will show preliminary results for a set of six observables for photon energies between 0.9 GeV and 2.3 GeV and for several kinematic variables in the Lambda-neutron center-of-mass frame. Comparison with theoretical calculations will also be discussed. Our results are the very first measurements of polarization observables for FSI in hyperon photoproduction and will be used to constrain the free parameters of hyperon-nucleon potentials.

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4.22 Antinucleon-nucleon interaction and the related hadron physics

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The recent development of the antinucleon-nucleon ($\bar{N}N$) interaction in chiral effective field theory [1] will be reported and the phenomenological meson-exchange models (taking Jülich model as an example) will be mentioned as well. With such potentials and the distorted-wave Born approximation, we examine the influence of the antiproton-proton ($\bar{p}p$) interaction on the mass spectrum in various reactions containing the $\bar{p}p$ pair, e.g., $J/\psi \to \gamma\bar{p}p, \omega\bar{p}p, \pi^0\bar{p}p$ and $e^+e^- \leftrightarrow \bar{p}p$. It turns out that the low-energy mass spectra up to excess energy of 100 MeV for all the mentioned processes can be described by our treatment of the final or initial state ($\bar{p}p$) interactions. In $J/\psi \to \gamma\bar{p}p$ the quite prominent peak near $\bar{p}p$ threshold is observed in BES experiment, and to describe it, a bound state in isospin-1 $^1S_0$ is needed in our calculation [2]. The electromagnetic form factors of the proton in the time-like region are also predicted [3]. The role of $\bar{N}N$ intermediate states played in the ractions $e^+e^- \to$ multi-pions will be also discussed, which concerns for the dip structure observed around $\bar{N}N$ threshold in the experiments.

References

1. X.-W. Kang, J. Haidenbauer, and Ulf-G. Meissner, JHEP **1402**, 113 (2014).
2. X.-W. Kang, J. Haidenbauer, and Ulf-G. Meissner, arXiv:1502.00880 [nucl-th].
3. J. Haidenbauer, X.-W. Kang, and Ulf-G. Meissner, Nucl. Phys. A **929**, 102 (2014).

4.23 Applying Efimov physics to few nucleon systems

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Efimov physics has been intensively studied in the $L = 0$, spatially symmetric state of the three-boson system. In the case of three nucleons, the three and four-body systems have a large symmetric component allowing the study of Efimov physics. To be recalled in this context the large values of the singlet and triplet two-nucleon scattering lengths. In this presentation we will show results for low energy observables using simple potential models with variable strength. In this way the dependence with the triplet and singlet scattering length values can be analyzed, in particular at the unitary limit, $1/a = 0$. On the other hand, at the physical values of the scattering length and using a three-body force different observables can be quantitatively reproduced as the doublet and quartet $n - d$ scattering lengths, the low energy s-wave $n - d$ phases and the binding energies of the ground and excited states of the α particle. The impact in the six nucleon system will be analyzed.

4.24 Chiral three-nucleon forces up to N^4LO

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Three-nucleon forces play very important role in few and many-body simulations of nuclei/nuclear reactions at low energy. Knowledge of their precise form might lead to resolution of long standing puzzles in few-nucleon physics (e.g. A_y-puzzle in elastic nucleon-deuteron scattering). Chiral effective field theory provides a systematically improvable tool for their calculation. By now three-nucleon forces have been calculated up to N^3LO (partly up to N^4LO) in chiral expansion. In my talk I will discuss the current status of their construction and their ongoing implementation in few-body calculations.

4.25 Nuclear matter calculations with chiral interactions

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We calculate the energy per particle of symmetric nuclear matter and pure neutron matter using the many-body Brückner-Hartree-Fock (BHF) approach and employing the Chiral Next-to-next-to-next-to leading order (N3LO) nucleon-nucleon (NN) potential supplemented with various parametrizations of the Chiral Next-to-next-to leading order (N2LO) three-nucleon force. Such combination is able to reproduce several observables of the physics of light nuclei for suitable choices of the three-nucleon force parameters. We find that some of these parametrizations, provide also resonable values for the observables of nuclear matter at the saturation point.

4.26 The nucleon-nucleon interaction up to sixth order in the chiral expansion

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We have calculated the nucleon-nucleon (NN) interaction up to sixth order (N5LO) of chiral perturbation theory [1, 2]. Previous calculations [3] extended only up to N3LO (fourth order) and typically showed a surplus of attraction, particularly, when the πN LECs from πN analysis were applied consistently. Furthermore, the contributions at N2LO and N3LO are both fairly sizeable, thus, raising concerns about the convergence of the chiral expansion. We show that the N4LO contribution is repulsive and, essentially, cancels the excessive attraction of N3LO. The N5LO contribution turns out to be considerably smaller than the N4LO one, hence establishing the desired trend of convergence. The predictions at N5LO are in excellent agreement with the empirical phase shifts of peripheral partial waves (cf. Fig. 1).

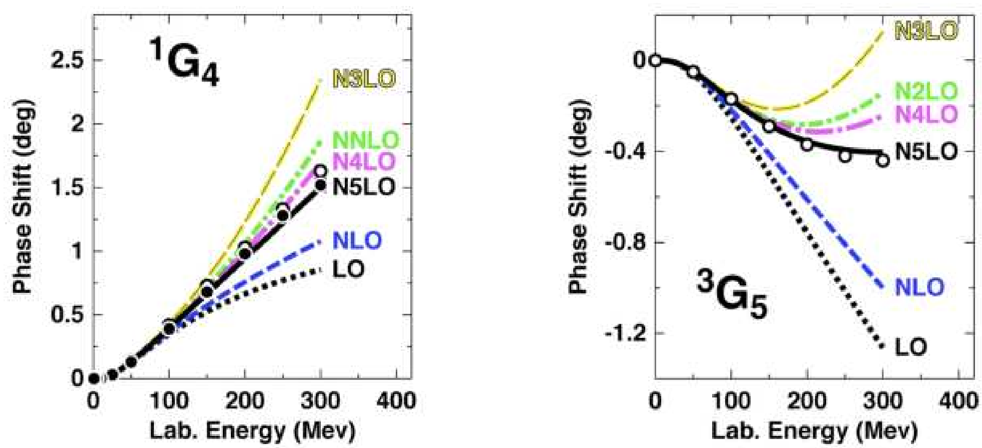

Figure 1: Order-by-order evolution of the np phase shifts in the $^1G_4$ and $^3G_5$ partial waves. Predictions from LO to N5LO are shown as denoted. The filled and open circles represent results from NN phase shift analysis.

References

1. D. R. Entem, N. Kaiser, R. Machleidt, and Y. Nosyk, Phys. Rev. C **91**, 014002 (2015).
2. D. R. Entem, N. Kaiser, R. Machleidt, and Y. Nosyk, arXiv:1505.03562 [nucl-th].
3. R. Machleidt and D. R. Entem, Phys. Rep. **503**, 1 (2011).

4.27 Constraints on the chiral unitary KN amplitude from $\pi\Sigma K$ photoproduction data

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A chiral unitary approach for antikaon-nucleon scattering in on-shell factorization is studied. We find multiple sets of parameters for which the model describes all existing hadronic data similarly well. We confirm the two-pole structure of the $\Lambda(1405)$. The narrow $\Lambda(1405)$ pole appears at comparable positions in the complex energy plane, whereas the location of the broad pole suffers from a large uncertainty. In the second step, we use a simple model for photoproduction of $K^+\pi\Sigma$ off the proton and confront it with the experimental data from the CLAS Collaboration. It is found that only a few of the hadronic solutions allow for a consistent description of the CLAS data within the assumed reaction mechanism.

4.28 Causality constraint on bound states and scattering with zero- range force, or do perturbative pions deserve another chance?

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The present treatment of the nucleon-nucleon and few-nucleon forces in chiral effective theory is semi-relativistic. One of the immediate diffculties of this description is that, in accordance with Wigner's causality bound, the leading-order (zero-range) interaction yields zero effective range. This leads to the necessity of "promoting" the subleading three-body force to leading order, in the pionless theory. It eventually becomes the major reason for "non-perturbative pions"" I argue that these diffculties are absent in relativistically causal theory. On a simple field-theoretic example [1, 2], I demostrate relativistic zero-range potential scattering surpasses Wigner's causality bound without violating causality [3]. The relativistic theory exhibits a K-matrix pole necessarily accompanying the bound-state solution. Possible implications of these results for the effective-
eld theory of nuclear forces will be discussed, time permitting.

References

1. V. Pascalutsa and M. Vanderhaeghen, Phys. Rev. Lett. **105**, 201603 (2010) [arXiv:1008.1088 [hep-ph]].
2. V. Pauk, V. Pascalutsa, and M. Vanderhaeghen, Phys. Lett. B **725**, 504 (2013).
3. V. Pascalutsa, arXiv:1402.4973 [nucl-th].

4.29 Quantum Monte Carlo calculations of electromagnetic moments and transitions in $A \leq 10$ nuclei with two-body χEFT currents

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In this talk, I will present a number of Quantum Monte Carlo calculations of electromagnetic observables in light nuclei ($A \leq 10$) including electromagnetic moments, M1 and E2 transitions. These calculations use wave functions generated from nuclear Hamiltonians with two- and three-nucleon realistic potentials. In addition to impulse approximation terms, nuclear electromagnetic currents account for two-body operators derived from chiral effective field theory. These studies show that many-body contributions in both nuclear Hamiltonians and transition currents are crucial to reach agreement with the experimental data.

4.30 Power counting of currents in effective field theory

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Effective field theories are generic descriptions of low-energy phenomena for which a fundamental theory is unknown or impractical to solve. The formulation of EFTs is grounded on symmetries and power counting. While symmetries provide the connection with the underlying theory, power counting — how to order the effective interactions from more to less relevant — makes EFTs predictive and systematic. However power counting is in general not trivial. For systems that are perturbative at low energies one can establish the counting using naive dimensional analysis (NDA), which states that the dimensionful couplings of EFT scale as powers of M. But when low energy physics is non-perturbative, the choice of a counting that is theoretically consistent and phenomenologically acceptable is a much more involved task. For nuclear physics, which is non-perturbative (e.g. the deuteron), NDA fails. Yet we know now how to organize the counting, though until recently only in the two-body sector.
In this contribution we explain how to extend power counting to reactions involving an external probe – such as a photon, electron or neutrino – and two nucleons. We use renormalization group analysis (RGA) as the tool to determine the size of nuclear two-body currents. The findings we made are compatible with well-known observations in the previous literature, for instance, the necessity of a two-body current in radiative neutron capture or that deuteron form factors can be explained to good accuracy without contact two-body currents. In the pionless case we find that there are important departures from NDA in a few reactions, particularly those involving the $^1S_0$ singlet channel, indicating that many previous EFT calculations could be improved by taking these changes in consideration.

4.31 Scattering cluster wave functions on the lattice using the adiabatic projection method.

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The adiabatic projection method is a general framework for obtaining low-energy effective Hamiltonian for clusters. Previous studies [1, 2] have used the adiabatic projection method in combination with the finite-volume energy Lüscher method to extract scattering phase shifts. We discuss several methods to calculate elastic phase shifts directly from asymptotic cluster wave functions obtained from the effective cluster Hamiltonian for examples in one and three dimensions. This approach is less sensitive than the finite-volume energy Lüscher method to stochastic and systematic errors which appear in the application of the adiabatic projection method.

References

1. M. Pine *et al.*, Eur. Phys. J. A **49**, 151 (2013).
2. S. Elhatisari *et al.*, Phys. Rev. C **90**, 064001 (2014).

4.32 Study of the electroweak processes in the two and three-nucleon systems with local chiral forces

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In the recent decade the chiral Effective Field Theory (χEFT) has proven its predictive power in low energy nuclear physics. Within this approach the two- and three-nucleon (3N) forces have been derived perturbatively in a consistent manner [1, 2]. The three-nucleon force (3NF) occurs for the first time at the next-to-next-to leading order (N^2LO) of chiral expansion. Inclusion of N^2LO 3NF to study three-nucleon processes has revealed an overall good agreement between theoretical predictions and data [3]. The quality of data description is similar to those obtained with semi-phenomenological potentials. The remaining discrepancies are partially related to poor spin structure of these chiral forces. The further improvement in data description is expected when higher order chiral forces will be taken into account. Unfortunately, the 3NF at the next order (N^3LO) has much more complex structure [4, 5] and its inclusion in theoretical studies is much more challenging. In recent papers [6, 7] we have studied the role of full chiral N^3LO 3NF in a description of the nucleon-deuteron elastic scattering and the deuteron breakup and found no improvement in data description. Moreover unnaturally large values of the two free parameters (low energy constants) of this 3NF have to be used to describe ^{3}H binding energy and the neutron-deuteron doublet scattering length.
The studies [6, 7] already accelerated work on the new generation of chiral NN and 3N forces. Recently, the improved chiral NN potentials up to N^3LO [8] and N^4LO [9] have been derived by E.Epelbaum and collaborators. The most interesting feature of theses forces is a substantial reduction of the cut-off artifacts in comparison with the older models used in Refs. [6, 7].
In this contribution the first results obtained with these very new forces up to N^4LO for the deuteron photodisintegration process, the nucleon-deuteron radiative capture and the muon capture on the ^{3}He will be reported. Since the consistent chiral nuclear electromagnetic and weak currents are not available yet, we have included the electromagnetic meson exchange currents via the Siegert theorem.
In all cases the convergence of the theoretical predictions in respect to chiral expansion as well as the dependence of predictions on cut-off parameters of the used forces will be discussed.

References

1. E. Epelbaum, H.-W. Hammer, and Ulf-G. Meissner, Rev. Mod. Phys. **81**, 1773 (2009).
2. R. Machleidt and D.R. Entem, Phys. Rep. **503**, 1 (2011).
3. E. Epelbaum *et al.*, Phys. Rev. C **66**, 064001 (2002).
4. V. Bernard *et al.*, Phys. Rev. C **77**, 064004 (2008).
5. V. Bernard *et al.*, Phys. Rev. C **84**, 054001 (2011).
6. H. Witała *et al.*, J. Phys. G: Nucl. Part. Phys. **41**, 094011 (2014).
7. J. Golak *et al.*, Eur. Phys. J. A **50**, 177 (2014).
8. E. Epelbaum *et al.*, arXiv:1412.0142 [nucl-th].
9. E. Epelbaum *et al.*, arXiv:1412.4623 [nucl-th].

4.33 Experimental tests of nuclear interaction models in few-nucleon systems

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Systems of three nucleons can serve as a validation tool for the modern approaches to describe nuclear interaction. At the first stage the investigations were mainly focused on elastic nucleon-deuteron scattering, slowly extending to systematic measurements of the deuteron breakup reaction [1, 2, 3]. Intermediate energies, below the threshold for pion production, deserve special attention: it is the region where comparison with exact theoretical calculations is possible, while the sensitivity to various aspects of interaction, like subtle effects of the dynamics beyond the pairwise nucleon-nucleon force, Coulomb interaction between protons, or relativistic effects, is significant. In addition to differential cross section, the observables related to nuclear polarization are studied, like vector and tensor analyzing powers, spin-correlation coefficients or polarization transfer coefficients. All these effects vary with energy and appear with different strength in certain observables and phase space regions, what calls for systematic investigations of a possibly rich set of observables determined in a wide range of energies.
Recently, the data base for the reaction of deuteron breakup in collision with proton has been significantly enriched in the domain of medium energies. High precision experimental data for cross section, vector (proton) analyzing power and vector and tensor (deuteron) analyzing powers were collected with detection systems covering large part of the phase space of the ^{1}H($\vec{\mathrm{d}}$,pp)n and ^{2}H($\vec{\mathrm{p}}$,pp)n reactions. Usage of the multidetector systems with significant solid angle coverage provides not only very rich data sets but also good opportunities for controlling consistency of the results.
The experimental results are compared with the theoretical predictions, in which the full dynamics of the three-nucleon ($3N$) system is obtained in different ways: Realistic nucleon-nucleon (NN) potentials are combined with model $3N$ forces or with an effective $3N$ interaction resulting from the explicit treatment of the Δ-isobar excitation. Alternatively, the chiral perturbation theory approach is used: At the next-to-next-to-leading order with all relevant NN and $3N$ contributions taken into account, while at the next order (N3LO) without taking into account the corresponding 3NF contributions.
The next step in complication of the system are studies of reactions involving 4 nucleons - more sensitive, as expected, to subtle dynamics beyond the pairwise interaction. A survey of recent and planned experiments in the 3- and 4-nucleon systems will be given.

References

1. K. Sagara, Few-Body Syst. **48**, 59 (2010).
2. N. Kalantar-Nayestanaki, E. Epelbaum, J.G. Meschendorp, and A. Nogga, Rep. Prog. Phys. **75**, 016301 (2012).
3. St. Kistryn and E. Stephan, J. Phys. G: Nucl. Part. Phys. **40**, 063101 (2013).

4.34 Subtractive renormalization and scaling in low-energy few-body physics

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Renormalized fixed-point Hamiltonians are formulated for systems described by interactions that originally contain point-like singularities (as the Dirac-delta and/or its derivatives). They express the renormalization group invariance of quantum mechanics. The approach has been applied in the study low-energy scattering observables, such as the nucleon-nucleon interaction with one pion exchange potentials, as well as bound-state systems. In case of low-energy bound-state systems, this subtractive procedure was found convenient to introduce the scales in formalisms with zero-range interactions, when renormalizing the theory. Of particular interest in recent years has been the studies of neutron-rich light nuclei, with two-neutron halos and a core, dominated by s-wave short-range two-body interactions. In this case, the observables are expressed by universal scaling laws obtained in the limit of a renormalized zero-range force, expected to be model independent for large halos. The corresponding scaling functions are determined by the neutron-neutron and neutron-core low-energy information, such as scattering lengths and short-range parameters. By using recent experimental data, which constrain the two-neutron separation energy, we study the core momentum distribution for large halo nuclei, like Lithium-11, Carbon-20 and Carbon-22.

4.35 Resonances in coupled-channel scattering from lattice QCD

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Recently it has become possible to obtain coupled-channel scattering amplitudes using lattice QCD. Using a large basis of operators we are able to obtain a reliable finite volume spectrum describing the coupled $\pi - K$, $\eta - K$ system. Utilising the finite volume formalism proposed by Luescher and extended by several others, we are able to describe the spectra from each lattice symmetry group and this enables constraints to be derived for S, P and D–wave scattering. We find resonant scattering amplitudes and investigate their structure in the complex plane, finding poles that display a pattern similar to the physical $K^\star(892)$, $K_0^\star(1430)$ and $K_2^\star(1435)$ resonances.

4.36 Elastic nucleon-deuteron scattering and breakup with chiral forces

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Comparison of theoretical predictions based on a nucleon-nucleon potential with data for elastic nucleon-deuteron (Nd) scattering and nucleon induced deuteron breakup reveals the importance of the three-nucleon force (3NF). Inclusion of semi-phenomenological 3NF models into calculations in many cases improves the data description. However, some serious discrepancies remain even when 3NF is included.
At low energies the prominent examples were found for the vector analyzing power in elastic Nd scattering and for the neutron-deuteron (nd) breakup cross sections in neutron-neutron (nn) quasi-free-scattering (QFS) and symmetric-space-star (SST) geometries [1]. Since both these configurations depend predominantly on the S-wave nucleon-nucleon (NN) force components, these cross section discrepancies have serious consequences for the nn $^1S_0$ force component.
At energies above ≈ 100 MeV current 3NF's only partially improve the description of data for cross section and spin observables in elastic Nd scattering and breakup. The complex angular and energy behavior of analyzing powers, spin correlation and spin transfer coefficients fails to be explained by standard nucleon-nucleon interactions alone or combined with current models of 3NF's [2, 3].
One of the reasons for the above disagreements could be a lack of consistency between 2N and 3N phenomenological potentials used or/and omission of important terms in the applied 3NF. The Chiral Effective Field Theory approach provides consistent two- and three-nucleon forces. The 3NF occurs for the first time at next-to-next-to leading order (N^2LO) of chiral expansion. The chiral NN potentials have been constructed up to N^4LO order of chiral expansion [4]. The N^3LO and N^4LO NN forces when used in 3N calculations provide description of NN data of the same quality as standard, realistic NN potentials.
The chiral 3NF at N^3LO, derived recently, consists of long range parts with the 2π-exchange, 1π-2π and ring terms [5] and a short-range contributions 2π-contact and relativistic corrections of order 1/m [6]. This is supplemented by 1π- and 3N- contact terms. Preliminary results obtained with chiral forces for elastic Nd scattering and breakup will be presented.

References

1. H. Witała *et al.*, Phys. Rev. C **83**, 034004 (2011).
2. Y. Maeda *et al.*, Phys. Rev. C **76**, 014004 (2007).
3. K. Sekiguchi *et al.*, Phys. Rev. C **79**, 054008 (2009).
4. E. Epelbaum *et al.*, arXiv:1412.4623.
5. V. Bernard *et al.*, Phys. Rev. C **77**, 064004 (2008).
6. V. Bernard *et al.*, Phys. Rev. C **84**, 054001 (2011).

4.37 Nuclear electric dipole moment of light nuclei in the Gaussian expansion method

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The nuclear electric dipole moment is a very sensitive probe of CP violation beyond the standard model, and for light nuclei, it can be evaluated accurately using the few-body calculational methods. In this work, we evaluate the electric dipole moment of the deuteron, ^{3}He, ^{3}H, ^{6}Li, and ^{9}Be in the Gaussian expansion method with realistic nuclear force, and assuming the one-meson exchange model for the P, CP-odd nuclear force. We then give the future prospects for BSM models such as the supersymmetry within the prospective experimental sensitivity.

5 Poster Session

5.1 Glueball Decay in the Witten-Sakai-Sugimoto model

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I present new results on glueball decay rates in the Sakai-Sugimoto model, a holographic top-down approach for QCD with chiral quarks based on a probe-brane construction within Witten's holographic model of nonsupersymmetric Yang-Mills theory. We calculated [1] rates for decays into two pions, two vector mesons and four pions, using a range of the 't Hooft coupling which closely reproduces the decay rate of ρ and ω mesons and leads to a value for the gluon condensate consistent with QCD sum rules. We concluded that the holographic mode corresponding to the lowest excitation of a dilatonic scalar provides a narrow glueball state in the right mass range for an identifiation with f_0 (1500) or f_0 (1710), while the results actually favour the latter as a glueball candidate. This conclusion receives further support from our latest work [2] on implementing finite masses for pseudoscalar mesons by extrapolating from the calculable vertex of glueball fields and the η' meson, which is a consequence of the Witten-Veneziano mechanism. In line with the mechanism of chiral suppression [3], we found a considerable enhancement of the decay of scalar glueballs into kaons and the η meson, in close agreement with experimental data on f_0 (1710).

References

1. F. Brünner, D. Parganlija, and A. Rebhan, arXiv:1501.07906.
2. F. Brünner and A. Rebhan, arXiv:1504.05815.
3. M. Chanowitz, Phys. Rev. Lett. **95**, 172001 (2005).

5.2 Status of chiral-scale perturbation theory

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We observe that flavor current conservation constrains the structure of chiral-scale perturbation theory ChPT_σ. This theory addresses the disagreement between experiment and lowest order chiral $SU(3) \times SU(3)$ perturbation theory (ChPT_3) for amplitudes involving the $f_0(500)$ resonance and $O(m_K)$ extrapolations in momenta. In ChPT_σ, it is assumed that 3-flavor QCD has an infrared fixed point where the chiral condensate induces nine Nambu-Goldstone bosons: π, K, η and a QCD dilaton σ which we identify with $f_0(500)$. In the leading order of ChPT_σ, dilaton-pole dominance explains the $\Delta I = 1/2$ rule in nonleptonic K-decays. The effect of the simplification noted above is that the theory becomes more predictive for the decays $\sigma \to \pi\pi$ and $\sigma \to \gamma\gamma$ and hence for the σNN coupling.

5.3 Muon capture on the deuteron

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The study of few-nucleon system is interesting and important. It gives a microscopic description of complex systems within the framework of modern concepts of nucleon-nucleon and many-body interactions. Using the muon capture process is an ideal tool to study few-nucleon systems. In this work we plan to investigate the $\mu^- + d \to \nu_\mu + n + n$ capture reaction. This reaction is interesting for several reasons. First of all, it offers a testing ground for the nuclear wave functions, which for any nucleon-nucleon (NN) forces can be constructed for such light systems with great accuracy. This reaction, is treated as the decay of the corresponding muonic atom, with the muon initially on the lowest K shell. The muon binding energy in this atom can be safely neglected and in the initial state we deal essentially with the deuteron and muon at rest. The general formalism for dealing with electroweak reactions on the deuteron will be presented. We will concentrate on the nuclear matrix elements of the corresponding weak current operator calculated in the momentum space within partial wave decomposition scheme. In the current operator apart from the relatively well known single nucleon contributions, the two-nucleon parts (generated by various meson exchange) play an important role. Their details are not well known and several models should be considered [1]. We will employ various models of NN and 3N forces, such as the Bonn B [2] or chiral NNLO potentials [3]. Additionally, we will be able to use for the first time the so-called "improved" chiral nucleon-nucleon potentials from the Bochum-Bonn group [4] for the $\mu^- + d \to \nu_\mu + n + n$ capture reaction, we will show our predictions for all the available five orders of the chiral expansion and for all the five regulators at each order. The estimate of the total decay rates and differential capture rates as a function of the neutron momentum will be presented in a comparison with the experimental data. The decay rates will be investigated in the energy spectrum of the omitted neutrinos. Our results with the single nucleon currents look already very promising and we hope for the improvement in the description of the experimental data, when dominant two-nucleon current operators are included in our framework.

References

1. L.E. Marcucci *et al.*, Phys. Rev. C **83**, 014002 (2011).
2. R. Machleidt, Adv. Nucl. Phys. **19**, 189 (1989).
3. E. Epelbaum, Prog. Part. Nucl. Phys. **57**, 654 (2006).
4. E. Epelbaum, H. Krebs, Ulf-G. Meissner, arXiv:1412.0142 [nucl-th] (2014).

5.4 Single and double Dalitz decays of η and η' through rational approximants

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I will analyze the anomalous single and double Dalitz decays of the neutral pseudoscalar mesons, $\mathcal{P} \to \ell^+\ell^-\gamma$ and $\mathcal{P} \to \ell^+\ell^-\ell^+\ell^-$ ($\mathcal{P} = \pi', \eta, \eta'$; $\ell = e$ or μ), employing a model-independent transition form factor (TFF) of the $\mathcal{P}\gamma^*\gamma^{(*)}$ vertices built up, through the use of rational approximants, from the current experimental data of the space-like TFF $\gamma^*\gamma \to \mathcal{P}$. Predictions for the branching ratios and the spectra will be given and compared with present experimental status.

References

1. R. Escribano and S. Gonzàlez-Solìs, in preparation.
2. S. Gonzàlez-Solìs, P. Masjuan, and P. Sanchez-Puerts in preparation.

5.5 Chiral symmetry breaking and monopoles

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In previous works we have shown the relation between chiral symmetry breaking, instantons, and monopoles by adding the monopoles to quenched SU(3) configurations [1, 2]. We found that (i) one pair of monopoles makes one instanton. (ii) the monopole pair induces chiral symmetry breaking. This was done by measuring the chiral condensate computed from the eigenvalues and eigenvectors of the Overlap Dirac operator.
In this study, we compare the low-lying (improved) eigenvalues λ_i of the Overlap operator with the prediction of the random matrix theory [3, 4]. First, we perform a scale-independent test using the low-lying eigenvalues as in Ref. [5]. Our results are consistent with their results and the prediction of the random matrix theory (RMT).
Next, we add one pair of monopoles with charges m_c varying from zero to four, to the SU(3) quenched configurations, and compare the low-lying eigenvalues with the prediction of the random matrix theory. We find that the results of the scale-independent tests are consistent with the prediction of the random matrix theory as shown in Fig. 1 ($\lambda_j < \lambda_k$, $1 \leq j, k \leq 4$, $j \neq k$). Therefore, the added pair of monopoles does not affect the spectra of the Overlap Dirac operator. Moreover, we show that the spectral density $\rho(\lambda)$ increases with the monopole charges m_c as shown in Fig. 2. These results indicate that the monopoles are related to the chiral symmetry breaking.
We are presently calculating the chiral condensate, and the Banks-Casher relation. In this talk, we would like to present preliminary results showing the relation between the chiral symmetry breaking and monopoles.

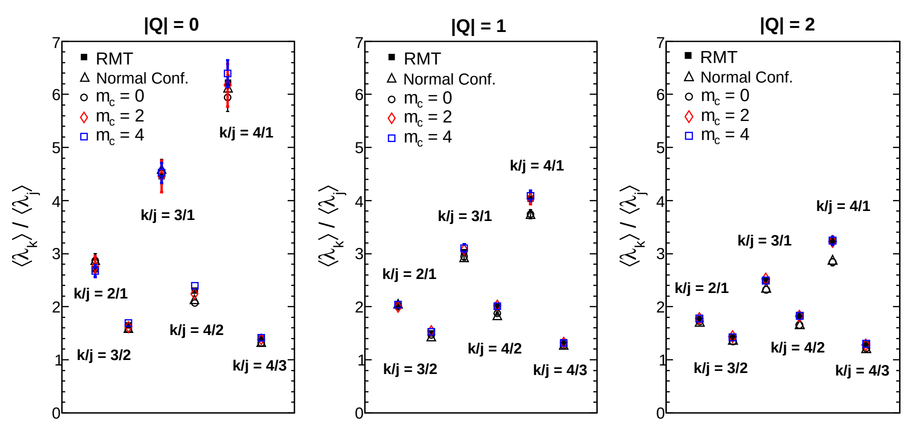

Figure 1: These figures are the same as Figure 2 in Ref. [5], and show the conformity with the random matrix theory. The lattice is $V = 14^4, \beta = 6.00$. RMT is indicated the results computed from the random matrix theory.

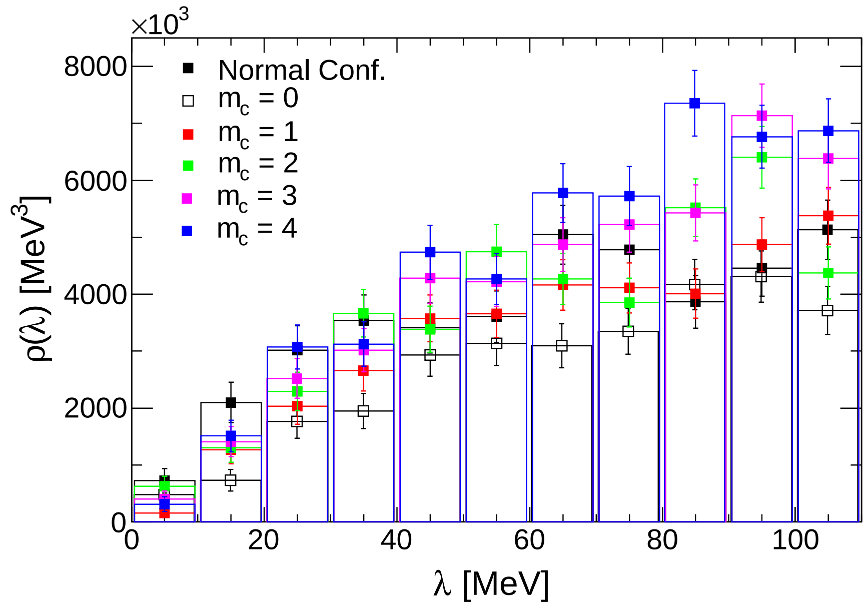

Figure 2: The spectral density $\rho(\lambda)$ except the zero eigenvalues. The lattice is $V = 14^4, \beta = 6.00$.

References

1. A. Di Giacomo and M. Hasegawa, arXiv:1412.2704.
2. A. Di Giacomo and M. Hasegawa, Phys. Rev. D **91**, 054512 (2015).
3. S.M. Nishigaki, P.H. Damgaard, and T. Wettig, Phys. Rev. D **58**, 087704 (1998).
4. P.H. Damgaard and S.M. Nishigaki, Phys. Rev. D **63**, 045012 (2001) [hep-th/0006111].
5. L. Giusti, M. Lüscher, P. Weisz, and H. Wittig, J. High Energy Phys. **11**, 023 (2003).

5.6 Hyperon forward spin polarizability γ_0 in baryon chiral perturbation theory

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We present the calculation of the hyperon forward spin polarizability γ_0 using manifestly Lorentz covariant baryon chiral perturbation theory including the intermediate contribution of the isospin-3/2 states. As at the considered order the extraction of γ_0 is a pure prediction of chiral perturbation theory and does not depend on renormalization schemes, the obtained values are a good test for this theory. Our results have a very good agreement with the experimental data for nucleons. Therefore we extend our frame to hyperons to give predictions to their γ_0 values.

5.7 Hypernuclear decay of strangeness −2 hypernuclei

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Since the discovery in 1952 of the first strange fragment in emulsion chamber experiments, many efforts have been put in extending our knowledge of the nuclear chart, including the $SU(3)$ sector. Worldwide, the study of the interactions among nucleons and hyperons has been a priority in the research plan of many experimental facilities. After more than sixty years of Λ-hypernuclear studies, some attention has moved to more strange systems, with the production of $\Lambda\Lambda$-hypernuclei and more recently, with proposals to study Ξ-hypernuclear spectroscopy.

Our main objective is to calculate the decay rate for the weak decay of $\Lambda\Lambda$-hypernuclei, including all the intermediate baryonic channels allowed by the strong interaction. I will focus on the analysis of the decay induced by the Λ hyperon, i.e., starting with a $\Lambda\Lambda$ pair. The weak decay mechanism describing the two-body weak interaction is modelled by the exchange of mesons belonging to the ground state of pseudoscalar and vector octets. The tree-level values for the baryon-baryon-meson coupling constants are derived using $SU(3)$ symmetry for pseudoscalar mesons and the Hidden Local Symmetry for vector mesons. In the computation of the decay rate, the effects of the strong interaction on the initial state are introduced through the solution of a G-matrix equation, with the input of realistic baryon-baryon potentials, while the final hyperon-nucleon wavefunctions are obtained in an analogous way, by solving the corresponding T-matrix equation.

5.8 Understanding pion through QCD

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We present recent advances in the study of the Pion structure through Dyson–Schwinger Equations, the equations of motion of QCD. In particular, we discuss the neutral pion to two photons transition form factor, a problem which involves careful parametrizations of the quark propagator and Bethe–Salpeter Amplitudes. This calculation is relevant for future experiments to be conducted at Belle II.

5.9 Roper mass in chiral perturbation theory

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Understanding the nature of the Roper resonance is of particular interest. Its mass, for example, shows a very unusual pattern: it is lower than the negative parity state $N(1535)$. Also, the Roper is expected to play a role in low energy observables due to its closeness to the nucleon and $\Delta(1232)$.
We report on a systematic study of the nucleon, $\Delta(1232)$, and Roper masses in heavy baryon chiral perturbation theory up to next-to-next-to-leading order. For the first time, the contributions due to the mixing between the nucleon and the Roper allowed by chiral symmetry are taken into account. Recently, several lattice QCD collaborations have reported some results on the Roper mass, assuming this particle is always stable. A chiral extrapolation of these data will also be shown as an application of our results.
This work is done in collaboration with V. Bernard, U. van Kolck, L.S. Geng, and J. Meng.

5.10 The $a_0(980)$ revisited

T. Wolkanowski[a], F. Giacosa[a,b] and Dirk H. Rischke[a]
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A way to understand the light scalar sector of hadron physics is by applying a type of dynamical generation in which additional resonances arise as companion poles from quark-antiquark seed states by incorporating mesonic loops at the level of S-wave propagators [1, 2, 3]. Along this line, we first repeat and complete the calculations of previous works of Törnqvist and Roos (TR) and Boglione and Pennington (BP), where the resonance $a_0(980)$ appears as an additional pole of the propagator of the predominately quark-antiquark state $a_0(1450)$. Both works were important as they demonstrated the feasibility of the idea of companion poles – however, we show that in TR, the same as in BP, the pole width of both states is too large by a factor of 2 when compared to data, and that in BP the pole mass of $a_0(1450)$ is too large of about 400 MeV.
We then construct an effective model Lagrangian for $a_0(1450)$ coupling to pseudoscalar mesons with both non-derivative and derivative interactions, and calculate its propagator. We demonstrate that it is indeed possible to obtain two poles, one for $a_0(980)$ and one for $a_0(1450)$, in good agreement with data, thus showing that the mechanism of companion poles can deliver not only qualitative but also quantitative correct results.

References

1. N. A. Törnqvist, Z. Phys. C **68**, 647 (1995).
2. N. A. Törnqvist and M. Roos, Phys. Rev. Lett. **76**, 1575 (1996).
3. M. Boglione and M. R. Pennington, Phys. Rev. D **65**, 114010 (2002).