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EFFECTIVE FIELD THEORIES IN NUCLEAR, PARTICLE AND ATOMIC PHYSICS*

337. WE-Heraeus-Seminar
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December 13 — 17, 2004

Johan Bijnens[1], **Ulf-G. Meißner**[2,3] and **Andreas Wirzba**[3]

[1]Department of Theoretical Physics, Lund University
Sölvegatan 14A, S22362 Lund, Sweden

[2]Universität Bonn , Helmholtz-Institut für Strahlen- und Kernphysik (Theorie)
D-53115 Bonn, Germany

[3]Forschungszentrum Jülich, Institut für Kernphysik (Theorie)
D-52425 Jülich, Germany

ABSTRACT

These are the proceedings of the workshop on "Effective Field Theories in Nuclear, Particle and Atomic Physics" held at the Physikzentrum Bad Honnef of the Deutsche Physikalische Gesellschaft, Bad Honnef, Germany from December 13 to 17, 2005. The workshop concentrated on Effective Field Theory in many contexts. A first part was concerned with Chiral Perturbation Theory in its various settings and explored strongly its use in relation with lattice QCD. The second part consisted of progress in effective field theories in systems with one, two or more nucleons as well as atomic physics. Included are a short contribution per talk.

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1 Introduction

The use of effective field theory techniques is an ever growing approach in various fields of theoretical physics. Along with the continuing application of Chiral Perturbation Theory and Nuclear Effective Field Theory, more recently, chiral symmetry in lattice QCD (chiral fermions, chiral extrapolations, finite volume effects) and atomic few-body systems have been the focus of many investigations. We therefore decided to organize the next topical workshop, with an emphasis of bringing together people from these various communities. This meeting followed the series of workshops in Ringberg (Germany), 1988, Dobogókö (Hungary), 1991, Karrebæksminde (Denmark), 1993, Trento (Italy), 1996 and Bad Honnef (Germany), 1998 and 2001. All these workshops shared the same features, about 50 participants, a fairly large amount of time devoted to discussions rather than presentations and an intimate environment with lots of discussion opportunities.

This meeting took place in late fall 2004 in the Physikzentrum Bad Honnef in Bad Honnef, Germany and the funding provided by the WE–Heraeus–Stiftung allowed us to provide for the local expenses for all participants and to support the travel of a fair amount of participants. The WE-Heraeus foundation also provided the administrative support for the workshop in the person of the able secretary Heike Uebel. We extend our sincere gratitude to the WE-Heraeus Stiftung for this support. We would also like to thank the staff of the Physikzentrum for the excellent service given to us during the workshop and last but not least the participants for making this an exciting and lively meeting.

The meeting had 58 participants whose names, institutes and email addresses are listed below. 48 of them presented results in presentations of various lengths. A short description of their contents and a list of the most relevant references can be found below. As in the previous three of these workshops we felt that this was more appropriate a framework than full-fledged proceedings. Most results are or will soon be published and available on the archives, so this way we can achieve speedy publication and avoid duplication of results in the archives.

Below follows first the program, then the list of participants followed by the abstracts of the talks. Most of them can also be obtained from the workshop website

`http://www.itkp.uni-bonn.de/∼eft04` .

Johan Bijnens, Ulf-G. Meißner and Andreas Wirzba

2 Program

Monday, December 13th 2004

Early Afternoon Session	
Chair: Johan Bijnens	**Chiral Perturbation Theory**
14:00 Ulf-G. Meißner / Ernst Dreisigacker	Introductory Remarks
14:20 Aneesh Manohar (La Jolla)	$1/N_c$ and pentaquarks
15:10 Heiri Leutwyler (Bern)	How well do we understand the interaction among the pions at low energies?
15:50	*Coffee*
Late Afternoon Session	
Chair: Andreas Wirzba	**Chiral Perturbation Theory**
16:20 Uwe-Jens Wiese (Bern)	Can one see the number of colors ?
17:00 Sébastien Descotes-Genon (Orsay)	Sea quark effects in three-flavour chiral perturbation theory
17:40 Barry Holstein (Massachusetts)	Linearized GDH sum rule
18:20	*End of Session*
18:30 *Dinner — Invitation by the*	*Wilhelm und Else Heraeus-Stiftung*

Tuesday, December 14th, 2004

Early Morning Session	
Chair: Ulf-G. Meißner	**Chiral Perturbation Theory**
09:00 Akaki Rusetsky (Bonn)	Determination of the πN scattering lengths from the experiments on pionic deuterium
09:40 Udit Raha (Bonn)	Spectrum and decay constants of kaonic hydrogen
10:00 Robin Nißler (Bonn)	Anomalous decays of η and η' with coupled channels
10:20	*Coffee*
Late Morning Session	
Chair: Ulf-G. Meißner	**Chiral Perturbation Theory**
10:50 Bastian Kubis (Bonn)	Radiative Ke3 decays revisited
11:15 Bashir Moussallam (Orsay)	Electromagnetic LEC's and QCD n-point functions resonance models
11:40 José A. Oller (Murcia)	Scalar mesons in D hadronic decays
12:15 Eulogio Oset (Valencia)	Chiral dynamics of baryon resonances
12:55	*End of Session*
13:00	*Lunch*
Early Afternoon Session	
Chair: Johan Bijnens	**Chiral Perturbation Theory**
14:20 Marc Knecht (Marseille)	The Dalitz decay $\pi^0 \to e^+e^-\gamma$
15:00 Gilberto Colangelo (Bern)	The pion vector form factor and the muon

	anomalous magnetic moment
15:40 Timo Lähde (Lund)	Partially quenched chiral perturbation theory at NNLO
16:05	*Coffee*
Late Afternoon Session	
Chair: Johan Bijnens	**Chiral Perturbation Theory**
16:35 Toni Pich (Valencia)	Effective lagrangians in the resonance region
17:15 Peter Bruns (Bonn)	Infrared regularization for spin-1 fields
17:40 Joaquim Prades (Granada)	A large Nc hadronic model
18:05 Matthias Frink (Bonn)	Baryon masses in cut-off regularized ChPT
18:25	*End of Session*
18:30	*Dinner*

Wednesday, December 15th, 2004

Early Morning Session	
Chair: Andreas Wirzba	**Nuclear Effective Theory**
09:00 Evgeny Epelbaum (Newport News)	Chiral dynamics in few-nucleon systems
09:40 Bira van Kolck (Tucson)	Charge-symmetry-breaking nuclear forces
10:15 Jambul Gegelia (Mainz)	Consistency of Weinberg's approach to the few-nucleon problem in EFT
10:35	*Coffee*
Late Morning Session	
Chair: Andreas Wirzba	**Nuclear Effective Theory**
11:05 Andreas Nogga (Jülich)	Renormalization of the 1pi exchange interaction in higher partial waves
11:30 Enrique Ruiz Arriola (Granada)	Renormalization group approach to NN-scattering with pion exchanges: removing the cut-offs
11:55 Luca Girlanda (Trento)	Chiral perturbation theory for heavy nuclei
12:20 Norbert Kaiser (Garching)	Chiral dynamics of nuclear matter: Role of two-pion exchange with virtual delta-isobar excitation
12:45	*End of Session*
13:00	*Lunch*
Early Afternoon Session	
Chair: Johan Bijnens	**EFT in Atomic and Nuclear Physics**
14:20 Hans-Werner Hammer (Seattle)	Limit cycle physics
15:00 Aurel Bulgac (Seattle)	What have we learned so far about dilute Fermi gases ?
15:40 Lucas Platter (Bonn)	An effective theory for the four-body system
16:05	*Coffee*

Late Afternoon Session	
Chair: Johan Bijnens	**EFT in Nuclear Physics**
16:40 Christoph Hanhart (Jülich)	Subtleties in pion production reactions on few nucleon systems
17:05 Hermann Krebs (Bonn)	Neutral pion electroproduction off the deuteron
17:30 Harald W. Grießhammer (Garching)	Nucleon polarisabilities from Compton scattering off the proton and deuteron
17:55	*End of Session*
18:30	*Dinner*

Thursday, December 16th, 2004

Early Morning Session	
Chair: Ulf-G. Meißner	**EFT in Particle Physics**
09:00 Jan Stern (Orsay)	Effective theory of Higgs-less electroweak symmetry breaking
09:40 Johannes Hirn (Valencia)	From mooses to 5D and back to large-Nc QCD ?
10:05 Felix Sassen (Jülich)	Charm-strange mesons
10:30	*Coffee*
Late Morning Session	
Chair: Ulf-G. Meißner	**Lattice QCD and ChPT**
11:00 Martin Savage (Seattle)	Lattice QCD and nuclear physics
11:40 Silas Beane (Durham)	Nucleons and nuclei from lattice QCD
12:20 Stephan Dürr (Bern)	Towards a lattice determinantion of NLO Gasser-Leutwyler coefficients
12:45	*End of Session*
13:00	*Lunch*
Early Afternoon Session	
Chair: Andreas Wirzba	**Lattice QCD and ChPT**
14:20 Karl Jansen (Zeuthen)	Going chiral: overlap and twisted mass fermions
15:00 Maarten Golterman (San Francisco)	Applications of ChPT to QCD with domain-wall fermions
15:40	*Coffee Late Afternoon Session*
Chair: Andreas Wirzba	**Lattice QCD and ChPT**
16:30 Christian B. Lang (Graz)	Excited hadrons states from lattice calculations: Approaching the chiral limit
17:10 Hartmut Wittig (Hamburg)	The epsilon-regime of QCD and its applications to non-leptonic Kaon decays
17:45 Thomas R. Hemmert (Garching)	Utilizing chiral effective field theory to understand lattice QCD simulations of baryon properties
18:20	*End of Session*
18:30	*Dinner*

Friday, December 17th, 2004

Early Morning Session	
Chair: Ulf-G. Meißner	Lattice QCD and ChPT
09:00 Elisabetta Pallante (Groningen)	Progress, challenges and strategies in lattice QCD
09:40 Jiunn-Wei Chen (Taipei)	Lattice theory for low energy fermions at finite chemical potential
10:20	*Coffee*
Late Morning Session	
Chair: Ulf-G. Meißner	**Lattice QCD and ChPT**
10:50 Bugra Borasoy (Bonn)	Finite volume effects using lattice chiral perturbation theory
11:15 Christoph Haefeli (Bern)	Finite volume effects for decay constants
11:35 Helmut Neufeld (Wien)	Isospin violation in semileptonic decays
12:00 Johan Bijnens (Lund)	Farewell
12:10	*Lunch and End of Workshop*

3 Participants and their email

S. R. Beane	Univ. of New Hampshire	silas@physics.unh.edu
V. Bernard	LPT Strasbourg	bernard@lpt6.u-strasbg.fr
J. Bijnens	Lund Univ.	bijnens@thep.lu.se
B. Borasoy	Univ. Bonn	borasoy@itkp.uni-bonn.de
P. C. Bruns	Univ. Bonn	bruns@itkp.uni-bonn.de
A. Bulgac	Univ. of Washington	bulgac@phys.washington.edu
P. Büttiker	Univ. Bonn	buettike@itkp.uni-bonn.de
J.-W. Chen	National Taiwan Univ.	jwc@phys.ntu.edu.tw
G. Colangelo	Univ. Bern	gilberto@itp.unibe.ch
S. Descotes-Genon	Univ. Paris-Sud	sebastian.descotes@th.u-psud.fr
E. Dreisigacker	WE-Heraeus-Stiftung	dreisigacker@we-heraeus-stiftung.de
S. Dürr	Univ. Bern	duerr@ifh.de
G. Ecker	Univ. Wien	gerhard.ecker@univie.ac.at
E. Epelbaum	Jefferson Lab	epelbaum@jlab.org
M. Frink	Univ. Bonn & FZ Jülich	mfrink@itkp.uni-bonn.de
J. Gegelia	Univ. Mainz	gegelia@kph.uni-mainz.de
L. Girlanda	ECT* Trento	girlanda@ect.it
M. Golterman	San Francisco State Univ.	maarten@stars.sfsu.edu
H.W. Grießhammer	TU München	hgrie@ph.tum.de
C. Haefeli	Univ. Bern	haefeli@itp.unibe.ch
H.-W. Hammer	Univ. of Washington	hammer@phys.washington.edu

C. Hanhart	FZ Jülich	c.hanhart@fz-juelich.de
T. R. Hemmert	TU München	themmert@physik.tu-muenchen.de
R. P. Hildebrandt	TU München	rhildebr@ph.tum.de
J. Hirn	Univ. de Valencia	johannes.hirn@ific.uv.es
B. R. Holstein	Univ. of Massachusetts	holstein@physics.umass.edu
K. Jansen	DESY Zeuthen	karl.jansen@desy.de
N. Kaiser	TU München	nkaiser@ph.tum.de
M. Knecht	CNRS-Luminy Marseille	knecht@cpt.univ-mrs.fr
U. van Kolck	Univ. of Arizona	vankolck@physics.arizona.edu
H. Krebs	Univ. Bonn	hkrebs@itkp.uni-bonn.de
S. Krewald	FZ Jülich	s.krewald@fz-juelich.de
B. Kubis	Univ. Bonn	kubis@itkp.uni-bonn.de
T. Lähde	Lund Univ.	talahde@thep.lu.se
C. B. Lang	Univ. Graz	christian.lang@uni-graz.at
V. Lensky	FZ Jülich	v.lensky@fz-juelich.de
H. Leutwyler	Univ. Bern	leutwyler@itp.unibe.ch
A. V. Manohar	UC San Diego	manohar@ucsd.edu
U.-G. Meißner	Univ. Bonn & FZ Jülich	meissner@itkp.uni-bonn.de
B. Moussallam	Univ. Paris-Sud	moussall@ipno.in2p3.fr
H. Neufeld	Univ. Wien	neufeld@ap.univie.ac.at
R. Nißler	Univ. Bonn	rnissler@itkp.uni-bonn.de
A. Nogga	FZ Jülich	a.nogga@fz-juelich.de
J. A. Oller	Univ. de Murcia	oller@um.es
E. Oset	Univ. de Valencia	oset@ific.uv.es
E. Pallante	Univ. of Groningen	pallante@phys.rug.nl
H. R. Petry	Univ. Bonn	petry@itkp.uni-bonn.de
A. Pich	Univ. de Valencia	antonio.pich@ific.uv.es
L. Platter	Univ. Bonn & FZ Jülich	platter@itkp.uni-bonn.de
J. Prades	Univ. de Granada	prades@ugr.es
U. Raha	Univ. Bonn	udit@itkp.uni-bonn.de
E. Ruiz Arriola	Univ. de Granada	earriola@ugr.es
A. Rusetsky	Univ. Bonn	rusetsky@itkp.uni-bonn.de
M. J. Savage	Univ. of Washington	savage@phys.washington.edu
F. Sassen	FZ Jülich	f.sassen@fz-juelich.de
J. Stern	Univ. Paris-Sud	stern@ipno.in2p3.fr
U.-J. Wiese	Univ. Bern	wiese@itp.unibe.ch
A. Wirzba	FZ Jülich	a.wirzba@fz-juelich.de
H. Wittig	DESY Hamburg	hartmut.wittig@desy.de

1/N and Pentaquarks

Aneesh V. Manohar

Department of Physics, University of California at San Diego,
La Jolla, CA 92093-0319, USA.

The quantum numbers of exotic baryons states (those which are not qqq states) can be obtained in the quark model, the Skyrme model, and in QCD using the $1/N_c$ expansion [1,3]. The quantum numbers obtained using all three approaches agree. A quantum number, exoticness (E), is defined, and can be used to classify the states. The exotic baryons include the recently discovered $qqqq\bar{q}$ pentaquarks ($E = 1$), as well as exotic baryons with additional $q\bar{q}$ pairs ($E >= 1$). The mass formula for non-exotic and exotic baryons is given as an expansion in 1/N, and allows one to relate the moment of inertia of the Skyrme soliton to the mass of a constituent quark [1].

Masses and widths of the flavor **27** and **35** pentaquark states in the same tower as the Θ^+ are related by spin-flavor symmetry. The **27** and **35** states can decay within the pentaquark tower, as well as to normal baryons, and so have larger decay widths than the lightest pentaquark Θ^+. The widths and branching ratios of the excited pentaquarks can be computed using the $1/N$ expansion [2]. An efficient operator method was developed, that greatly simplifies the computation of quark model matrix elements [4], based on the coherent state picture for large N baryons [5].

The 1/N expansion also is applied to baryon exotics containing a single heavy antiquark. The decay widths of heavy pentaquarks via pion emission, and to normal baryons plus heavy $D^{(*)}$, $B^{(*)}$ mesons are studied, and relations following from large-N spin-flavor symmetry and from heavy quark symmetry are derived [2].

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How well do we understand the interaction among the pions at low energies ?

H. Leutwyler,
Institut für Theoretische Physik, Universität Bern, CH-3012 Bern, Switzerland

S. M. Roy has shown long ago that, at low energies, the $\pi\pi$ scattering amplitude can be expressed in terms of twice subtracted dispersion integrals over physical region imaginary parts. The crucial terms in his representation are the two subtraction constants: at energies below M_ρ, the poorly known contributions from the high energy part of the dispersion integrals are very small. The fact that χPT accurately predicts the values of the subtraction constants thus implies that, at low energies, the entire scattering amplitude can now be calculated to a remarkable degree of precision: as compared to the information gathered from phenomenology, the uncertainties of our results are typically smaller by an order of magnitude. For a more detailed review and references, see [1,2].

Then I discussed recent work [3] on the pion matrix elements of the scalar currents $\bar{u}u$, $\bar{d}d$, $\bar{s}s$ as well as the $K\pi$ transition matrix elements of $\bar{s}u$, $\bar{s}d$ and showed that the singularities occurring near the $K\bar{K}$ threshold generate striking features. Also, I reviewed the current state of knowledge of the scalar radii and compared the low energy theorems for these with recent experimental results. Lattice methods are now approaching the region of light quark masses, where it becomes meaningful to analyze the data in terms of the continuum effective theory. Although the available results must yet be taken with a substantial grain of salt, they do appear to confirm the simple picture that underlies our crude theoretical estimates of 20 years ago. We can look forward to reliable lattice measurements of several important effective couplings in the foreseeable future.

Ynduráin and Peláez have criticized our work on phenomenological grounds. I did not discuss that, for lack of time, but refer the interested reader to [2,3,4].

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Can one see the number of colors?

U.-J. Wiese

Institute for Theoretical Physics, Bern University, CH-3012 Bern

It is well known that we live in a world with three quark colors. However, in contrast to textbook knowledge, some standard pieces of "evidence" for $N_c = 3$ do not at all imply three colors. The most prominent example is the decay width $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ which is proportional to $[N_c(Q_u^2 - Q_d^2)]^2$. Standard textbooks assume the physical values of the quark charges $Q_u = \frac{2}{3}$ and $Q_d = -\frac{1}{3}$ and conclude that only $N_c = 3$ is consistent with the experimentally observed width. However, in a world with N_c colors, baryons consist of N_c quarks. For general odd N_c the baryons are fermions, and a proton consists of $\frac{1}{2}(N_c + 1)$ u-quarks and $\frac{1}{2}(N_c - 1)$ d-quarks, while a neutron contains $\frac{1}{2}(N_c - 1)$ u-quarks and $\frac{1}{2}(N_c + 1)$ d-quarks. In order to obtain the correct charges for proton and neutron, the quark charges must hence be adjusted to $Q_u = \frac{1}{2}(\frac{1}{N_c} + 1)$ and $Q_d = \frac{1}{2}(\frac{1}{N_c} - 1)$ which implies $N_c(Q_u^2 - Q_d^2) = 1$ and thus eliminates the explicit N_c-dependence of $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ [1]. Hence, the π^0 decay does not at all imply $N_c = 3$. Remarkably, the above values of the quark charges also result from the anomaly cancellation conditions in a generalized standard model with arbitrary N_c [1,2,3]. In particular, the cancellation of Witten's global anomaly implies that N_c must be odd.

At the level of chiral perturbation theory, for $N_f = 2$ flavors, the vertex for the $\pi^0 \rightarrow \gamma\gamma$ decay is contained in an N_c-independent Goldstone-Wilczek term. Indeed, for $N_f = 2$, it is impossible to infer the number of colors from low-energy experiments with pions and photons [1]. For $N_f = 3$, the $\pi^0 \rightarrow \gamma\gamma$ decay gets a contribution from the Wess-Zumino-Witten term which is proportional to N_c. However, this contribution is completely cancelled by the N_c-dependent contribution from a Goldstone-Wilczek term which, in this case, is proportional to $(1 - \frac{N_c}{3})$. Still, the N_c-dependence does not cancel in some other processes. For example, at tree level the width of the decay $\eta \rightarrow \pi^+\pi^-\gamma$ is proportional to N_c^2 [1]. However, loop corrections turn out to be large, and this process seems not to be well suited for determining N_c [4]. Due to mixing, the widths of the decays $\eta, \eta' \rightarrow \gamma\gamma$ have a complicated N_c-dependence [1]. Still, a loop calculation reveals that these processes indeed allow one to literally see the number of colors in low-energy experiments by detecting the photons emerging from the η and η' decays [5].

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Chiral extrapolations on the lattice with strange sea quarks

Sébastien Descotes-Genon

Laboratoire de Physique Théorique,
Bâtiment 210, Université Paris-Sud/CNRS,
91405 Orsay, France

The mass hierarchy among light quarks indicates that the (light but not-so-light) strange quark may play a special role in the low-energy dynamics of QCD. In particular, strange sea-quark pairs may induce significant differences between the patterns of chiral symmetry breaking in the chiral limits of $N_f = 2$ massless flavours ($m_u = m_d = 0$, m_s physical) and $N_f = 3$ ($m_u = m_d = m_s = 0$) [1]. Such a difference, related to a significant violation of the Zweig rule in the scalar sector, would lead to a value of the $N_f = 3$ quark condensate much smaller than its $N_f = 2$ counterpart, and thus to instabilities in three-flavour chiral series by suppressing leading-order terms and enhancing numerically next-to-leading-order terms [2]. Indirect dispersive estimates suggest that this damping effect could be significant [3].

I focus on how unquenched lattice simulations with three dynamical flavours could be sensitive to this suppression [4]. I explain how chiral extrapolations of masses and decay constants of the pion and kaon could be affected by the presence of massive $s\bar{s}$-pairs in the sea, and I estimate finite-size effects related to the periodic boundary conditions imposed in lattice simulations [5]. The impact of strange sea-quark pairs on three-flavour chiral symmetry breaking could be assessed through the quark-mass dependence of two ratios based on $F_\pi^2 M_\pi^2$ and $F_K^2 M_K^2$ and affected by only small finite-volume corrections for $L \sim 2.5$ fm.

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A Linearized GDH Sum Rule

Barry R. Holstein

Department of Physics-LGRT
University of Massachusetts
Amherst, MA 01003

The GDH sum rule relates a particle's anomalous magnetic moment κ to a weighted integral over polarized Compton scattering cross sections[1]—

$$\frac{2\pi\alpha}{M^2}\kappa^2 = \frac{1}{\pi}\int_0^\infty \frac{d\omega}{\omega}\Delta\sigma_s(\omega) \tag{1}$$

where

$$\Delta\sigma_s(\omega) = \sigma_{1+s}(\omega) - \sigma_{1-s}(\omega)$$

This has been well tested and seems to work at least in the case of the proton. In the case of QED, however, since κ itself is $\mathcal{O}(\alpha)$ one requires the cross sections at one loop level to get the well-known Schwinger result—$\kappa = \alpha/2\pi$. In addition, at $\mathcal{O}(\alpha)$ this leads to a consistency condition, as pointed out by Altarelli, Cabibbo, and Maiani[2].

Together with Vladimir Pascalutsa and Marc Vanderhaeghen we have developed a modified GDH sum rule that obviates this situation[3]. The idea is to add a Pauli moment κ_0 to the calculation and to calculate a derivative of the relevant cross sections with respect to this Pauli moment, which is then set to zero. The resulting sum rule reads (at lowest order)

$$\frac{4\pi\alpha}{M^2}\kappa = \frac{1}{\pi}\int_0^\infty \frac{d\omega}{\omega}\Delta\sigma_1(\omega) \tag{2}$$

and is now linear in κ, where $\Delta\sigma_1$ is the derivative of the cross section at zero Pauli moment. This allows, for example, the Schwinger moment to be found from tree level input. In the case of pion-nucleon scattering this allows a simple calculation of the one loop magnetic moment of the proton or neutron to all orders in m_π. Possible future applications could include a two loop calculation of the magnetic moment using one loop input.

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Determination of the πN scattering lengths from the experiments on pionic deuterium

Ulf-G. Meißner[1,2], Udit Raha[1] and **Akaki Rusetsky**[1,3]

[1]Universität Bonn, Helmholtz-Institut für Strahlen- und Kernphysik (Theorie),
Nußallee 14-16, D-53115 Bonn, Germany

[2]Forschungszentrum Jülich, Institut für Kenphysik (Theorie),
D-52425 Jülich, Germany

[3]On leave of absence from: High Energy Physics Institute,
Tbilisi State University, University St. 9, 380086 Tbilisi, Georgia

We use the framework of effective field theories to discuss the determination of the S-wave πN scattering lengths a_+ and a_- from the recent high-precision measurements of pionic deuterium observables [1]. Initially, the precise value of the pion-deuteron scattering length $a_{\pi d}$ is extracted from the experimental data. Next, $a_{\pi d}$ is related to the S-wave πN scattering lengths in the multiple-scattering series, which are derived in the so-called Heavy Pion effective field theory. We discuss the use of the information, coming from pionic deuterium, for constraining the values of the πN scattering lengths in the full analysis, which also includes the input from the pionic hydrogen energy shift and width measurements. In particular, we throughly investigate the accuracy limits for this procedure and give a detailed comparison to other effective field theory approaches [2,3,4], as well as with the earlier work on the subject, carried out within the potential framework. The present results will be published elsewhere [5].

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Spectrum and decays of the Kaonic Hydrogen

U.-G. Meißner, **U. Raha**, and A. Rusetsky

Helmholtz-Institut für Strahlen- und Kernphysik, Universität Bonn
Nußallee 14-16, 53115 Bonn, Germany

Recent accurate measurements [1,2] of the strong energy shift and the lifetime of the ground state of kaonic hydrogen by DEAR collaboration at LNF-INFN allow one to extract the precise values of the KN scattering lengths from the data. To this end, one needs to relate the latter quantities to the observables of the kaonic hydrogen at the accuracy that matches the experimental precision. In our recent investigations, the problem is considered within the non-relativistic effective Lagrangian approach, which has been previously used to describe the bound $\pi^+\pi^-$, π^-p and πK systems (see, e.g. [3,4,5,6]). We obtain [7] a general expression of the strong shift of the level energy and the decay width in terms of the KN scattering lengths, at $\mathcal{O}(\alpha, m_d - m_u)$ as compared to the leading-order result. It is shown that, due to the presence of the unitarity cusp in the K^-p elastic scattering amplitude above threshold, the isospin-breaking corrections turn out to be very large. This, however, does not affect the accuracy of the extraction of the scattering lengths from the experiment.

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Anomalous decays of η and η' with coupled channels

B. Borasoy and **R. Nißler**

Helmholtz-Institut für Strahlen- und Kernphysik,
Universität Bonn, 53115 Bonn, Germany.

The axial anomaly of QCD dominates various low-energy processes involving light mesons. Interesting examples for such anomalous processes are the decays of π^0, η and η' into two photons and the decays $\eta, \eta' \to \pi^+\pi^-\gamma$, since they reveal information on both the chiral and—involving the η'—the axial $U(1)$ anomaly.

An analysis of the experimental data of the anomalous η and η' decays demands for the inclusion of resonances in the theoretical framework. To this end we combine the effective $U(3)$ chiral Lagrangian with a coupled channel Bethe-Salpeter equation which satisfies unitarity constraints and generates vector-mesons from composite states of two pseudoscalar mesons. The phase shifts of meson-meson scattering, particularly in the important ρ-resonance channel, are precisely reproduced.

The resulting T matrix for meson-meson rescattering is then used as an effective vertex which is included in the loop calculation of the decay amplitudes. This procedure manifestly preserves electromagnetic gauge invariance and exactly matches to the amplitudes obtained in one-loop Chiral Perturbation Theory. Furthermore, in the chiral limit our approach naturally reproduces the results dictated by the chiral anomaly of QCD. Overall good agreement with the available experimental spectra and decay parameters is obtained [1,2].

Contrary to the common picture of Vector Meson Dominance, where the simultaneous exchange of two vector mesons is the only contribution to the two-photon decays with both photons being off-shell, the corresponding diagram in our approach is highly suppressed with respect to the excitation of only one p-wave resonance. Therefore, the resulting transition form factor in the process $\eta' \to \gamma^*\gamma^*$ is significantly smaller. This prediction may be verified at the planned WASA@COSY facility and is also of interest for the determination of the hadronic contribution to the anomalous magnetic moment of the muon.

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Radiative K_{e3} decays revisited

Jürg Gasser[1], **Bastian Kubis**[1,2], Nello Paver[3] and Michela Verbeni[4]

[1]Institut für theoret. Physik, Universität Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland

[2]HISKP (Abt. Theorie), Universität Bonn, Nussallee 14-16, D-53115 Bonn, Germany

[3]Dip. di Fis. Teor., Univ. di Trieste, and INFN-Trieste, Str. Costiera 11, I-34100 Trieste, Italy

[4]Depto. Física Teórica y del Cosmos, Univ. de Granada, E-18002 Granada, Spain

We have studied [1] the process $K_L \to \pi^\mp e^\pm \nu_e \gamma$ $[K_{e3\gamma}]$ by combining two theoretical concepts: Low's theorem yields the bremsstrahlung amplitude in terms of the K_{e3} form factors f_+ and f_2 [2], while Chiral Perturbation Theory (ChPT) at one loop [3] and beyond [1] provides an assessment of the structure dependent contributions.

For the ratio of radiative decay rate (with cuts on photon energy, $E_\gamma^* > 30\,\text{MeV}$, and photon-electron angle, $\theta_{e\gamma}^* > 20°$) to the non-radiative rate, we find

$$R = \Gamma(K_{e3\gamma})/\Gamma(K_{e3}) = (0.96 \pm 0.01) \times 10^{-2} \quad .$$

This value is very insensitive to the precise shape of f_+, while the effect of f_2 is suppressed by powers of m_e and can be neglected. Structure dependent terms contribute less than 1% to R. Logarithmically enhanced effects from radiative corrections have been included, the remaining electromagnetic corrections dominate the uncertainty quoted. This prediction agrees very well with a recent measurement by NA48 [4], but is at variance with results from KTeV [5,6].

Structure dependent terms can be accessed experimentally via differential distributions. We have demonstrated that $d\Gamma/dE_\gamma^*$ is sensitive to essentially only one linear combination of structure functions. In ChPT, these are real and constant to a reasonable approximation, and we find, for the relevant combination,

$$C' = -1.6 \pm 0.4 \quad ,$$

to be compared with the experimental result $C' = -2.5^{+1.5}_{-1.0} \pm 1.5$ [5].

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Electromagnetic LEC's and QCD n-point functions resonance models

B. Ananthanarayan[1], **B. Moussallam**[2]

[1] Centre for High Energy Physics, IISc, Bangalore, 560012,India

[2]IPN, Université Paris-Sud, 91406 Orsay Cédex, France

The search for approximate estimates of the chiral couplings (LEC's) is important for improving the predictivity and for a better understanding of the workings of the chiral expansion. The strategy is to establish relations with QCD Green's functions for which approximations may be built based on the large N_c expansion and constraints from low as well as large energies[1]. The chiral-electromagnetic LEC's are linked to QCD correlators via convolution integrals[2]. Convergence is controlled by the QED counterterms, implying that some electromagnetic LEC's depend on the short distance renormalization scale μ_0. As an application, an answer to the question raised in ref.[3] of defining a "pure QCD" quark mass $\overline{m}_f(\mu, \mu_0)$ in terms of the physical quark mass $m_f(\mu_0)$ is provided by

$$\overline{m}_f(\mu, \mu_0) = m_f(\mu_0)(1 + 4e^2 Q_f^2 (K_9^r(\mu, \mu_0) + K_{10}^r(\mu, \mu_0))) \ , \tag{1}$$

and $K_9 + K_{10}$ could be determined model independently using input from τ decays. A number of LEC's are related to QCD 4-point functions which we have recently investigated[4]. We consider a large N_c modeling starting from the resonance Lagrangian of ref.[1] in which resonances maybe ascribed a chiral order and which contains all terms of order p^4. At this level a number of asymptotic constraints fail to get fulfilled, the resonance Lagrangian is then extended to include a set of terms of order p^6, restricting ourselves to terms of the form $RR'\pi$. The asymptotic constraints can then be obeyed and this gives rise to a set of Weinberg-type equations. It turns out that all the needed resonance coupling constants get determined in this way.

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Final State Interactions in Hadronic D Decays

José A. Oller

Departamento de Fsica, Universidad de Murcia,
E-30071 Murcia, Spain

We study the final state interactions of the three light pseudoscalars produced in the D decays, $D_s^+ \to \pi^-\pi^+\pi^+$ [1], $D^+ \to \pi^-\pi^+\pi^+$ [2] and $D^+ \to K^-\pi^+\pi^+$ [3], where high statistically significant evidences for the light scalar resonances κ or $K^*0(800)$ and σ or $f_0(600)$ are obtained from high statistics data [1,2,3] with dominating S-wave dynamics. We discuss why in these reactions the κ and σ poles are clearly visible as broad bumps in contrast with the scattering amplitudes, where one can only see slowly increasing amplitudes as shoulders. Regarding the final state interactions of the producing pseudoscalars, we assume as in the experimental analyses refs.[1,2,3] the spectator approach in terms of Bose-symmetrized amplitudes. However, we are able to show that the large final state interactions corrections present in the data are compatible with the pseudoscalar-pseudoscalar two body scattering amplitudes. This aspect was an unsolved issue by the experimental analyses that used a coherent sum of Breit-Wigner's, following the isobar model, which did not give rise to the same phases as those measured in scattering experiments. Similar problems also appear in B decays, see refs.[4] for earlier and related partial discussions. Our agreement with the rather precise data on D to 3π and $K2\pi$, where S-wave dynamics dominate, also implies an interesting experimental confirmation of the S-wave T-matrices obtained from unitary CHPT [5,6].

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Chiral dynamics of baryon resonances

E. Oset
Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC,
Institutos de Investigación de Paterna, Aptd. 22085, 46071 Valencia, Spain

One of the interesting topics in Hadron Physics is the dynamical generation of baryon resonances using tools of unitary chiral perturbation theory. Admitting that most of the resonances can approximately qualify as made of three constituent quark states, some of them are better represented as kind of molecular states of a meson and a baryon, and using unitarized versions of chiral perturbation theory one can make a systematic study of these states.A study of poles of the scattering matrix of coupled channels in the interaction of the octet of baryons of $1/2^+$ with the octet of mesons of 0^- was shown in [1] to lead to two octets and one singlet of dynamically generated resonances, most of which correspond to well known resonances of $1/2^-$, while there is a prediction for new resonances. Particularly it was found that there are two states close to the nominal $\Lambda(1405)$. Some reactions where these two states could be disentangled are the $K^- p \to \gamma\Lambda(1405)$ [2] and $\gamma p \to K^*\Lambda(1405)$ [3].

On the other hand the interaction of the decuplet of baryons of the Δ with the octet of pseudoscalar mesons also leads to a group of well known resonances, while there are predictions for new ones [4]. One of the striking examples of this latter case is a resonance formed with the interaction of ΔK in isospin I=1 [5]. This resonance leads to large cross sections for ΔK in I=1, compared to the case with I=2, which are amenable of experimental search in some pp collisions leading to ΔK in the final state.

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The Dalitz Decay $\pi^0 \to e^+e^-\gamma$

Karol Kampf[1], **Marc Knecht**[2] and Jiří Novotný[1]

[1]Institute of Particle and Nuclear Physics, Charles University,
V Holesovickach 2, 180 00 Prague 8, Czech Republic

[2]Centre de Physique Théorique[1], CNRS-Luminy, Case 907,
F-13288 Marseille Cedex 9, France

The $\mathcal{O}(\alpha)$ corrections to the Dalitz decay $\pi^0 \to e^+e^-\gamma$ have been studied [1] in the framework of two-flavour chiral perturbation theory with virtual photons and leptons [2]. Besides the fact that it constitutes the second most important decay channel of the pion, the Dalitz decay gives access to the off-shell $\pi^0 - \gamma^* - \gamma^*$ transition form factor $\mathcal{A}_{\pi^0\gamma^*\gamma^*}(q_1^2, q_2^2)$ at low energies, and in particular to its slope parameter a_π, defined as $\mathcal{A}_{\pi^0\gamma^*\gamma^*}(q^2, 0) = 1 + a_\pi(q^2/M_{\pi^0}^2 + \cdots$. We have not only considered the $\mathcal{O}(e^5)$ one photon reducible corrections to the leading, $\mathcal{O}(e^3)$, amplitude, but also the NLO corrections generated by the one fermion reducible and the one particle irreducible contributions to the Dalitz plot distribution, $\frac{d\Gamma}{dxdy} = [1 + \delta(x,y)]\,\frac{d\Gamma^{LO}}{dxdy}$. We have used a large-$N_C$ inspired representation [3] of the form factor $\mathcal{A}_{\pi^0\gamma^*\gamma^*}(q_1^2, q_2^2)$, based on its known chiral and QCD short distances properties.

Although their contribution to the total decay rate is very mall, we have found that the one particle irreducible $\mathcal{O}(e^5)$ corrections are sizeable in some region of the Dalitz plot. Within this framework, we obtain the following prediction for the slope parameter: $a_\pi = 0.034 \pm 0.005$, which agrees well with the value obtained from (model dependent) extrapolations of the form factor $\mathcal{A}_{\pi^0\gamma^*\gamma^*}(q^2, 0)$ measured at higher energies. Omission of the $\mathcal{O}(e^5)$ one photon irreducible radiative corrections in the extraction of a_π from the experimental Dalitz plot distribution, $d\Gamma^{exp}/dx - \delta_{QED}(x)\,(d\Gamma^{LO}/dx) = (d\Gamma^{LO}/dx)[1 + a_\pi x]$, would decrease this experimental determination of a_π by 0.005.

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[1] Unité mixte de recherhce (UMR 6207) du CNRS et des universités Aix-Marseille I, Aix-Marseille II, et du Sud Toulon Var; laboratoire affilié à la FRUMAM (FR 2291).

The pion vector form factor and the muon anomalous magnetic moment

Gilberto Colangelo

Institut für Theoretische Physik der Universität Bern
Sidlerstr. 5, 3012 Bern, Switzerland

The hadronic vacuum polarization contribution to a_μ is dominated by the $\pi\pi$ contribution (see, e.g. [1]), which is given by the pion vector form factor. The Omnés representation expresses the latter in terms of its phase which, below 16 M_π^2 exactly, and up to 4 M_K^2 to a good approximation, is equal to the $\pi\pi$ P-wave phase shift. The latter is strongly constrained by analyticity, unitarity and chiral symmetry [2]. We call the Omnés function constructed with the $\pi\pi$ P-wave phase shift $G_1(s)$, and represent the physical vector pion form factor as a product of three terms:

$$F_\pi(s) = G_1(s)G_2(s)G_\omega(s) \tag{1}$$

where $G_2(s)$ accounts for inelastic effects, and $G_\omega(s)$ takes into account the contribution of the ω through its interference with the ρ. Both functions G_2 and G_ω can be described in terms of a small number of parameters which are fixed by fitting the data. Moreover, the phase of the inelastic contribution is constrained by an inequality due to Lukaszuk [3].

I have presented preliminary results (see also [4]) for a calculation of the hadronic vacuum polarization contribution to a_μ below 1 GeV obtained on the basis of Eq. (1) and on the analysis of e^+e^- data [5,6].

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Partially Quenched Chiral Perturbation Theory at NNLO

Johan Bijnens[1] and **Timo Lähde**[1]

[1]Department of Theoretical Physics, Lund University,
Sölvegatan 14A, SE - 22362 Lund, Sweden

For computational reasons, the inclusion of the fermionic determinant, or the sea quark effects, into Lattice QCD simulations is still impractical for sea quark masses that are close to the physical u, d quark masses. However, recent progress has made Lattice QCD simulations with sea quark masses of a few tens of MeV available, a situation which is referred to as partially quenched (PQ) QCD. The simulation results then have to be extrapolated to the physical quark masses using Chiral Perturbation Theory (χPT). The generalization of χPT to the quenched case (without sea quarks) or to the partially quenched case (sea quark masses different from the valence ones) has been carried out by Bernard and Golterman in Refs. [1]. The quark mass dependence of partially quenched chiral perturbation theory (PQχPT) is explicit, and thus the limit where the sea quark masses become equal to the valence quark masses can be taken. As a consequence, χPT is included in PQχPT and the free parameters, or low-energy constants (LEC:s), of χPT can be directly obtained from those of PQχPT [1,2].

The calculation of charged pseudoscalar meson masses and decay constants to one loop (NLO) in PQχPT has been carried out in Refs. [1,2], and first results for the mass of a charged pseudoscalar meson at two loops, or next-to-next-to-leading order (NNLO) in PQχPT, may be found for degenerate sea quark masses in Ref. [3]. The NNLO result for the decay constants of the charged pseudoscalar mesons in three-flavor PQχPT has recently appeared in Ref. [4]. The need for such calculations is clear as NNLO effects have already been detected in Lattice QCD simulations [5]. A calculation of the pseudoscalar meson masses for nondegenerate sea quarks is in progress.

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Effective Lagrangians in the Resonance Region

Antonio Pich

Departament de Física Teòrica, IFIC, Universitat de València – CSIC,
Apt. Correus 22085, E-46071 València, Spain

In the resonance region chiral perturbation theory is no longer valid and one must introduce a different effective field theory with explicit massive fields. Chiral symmetry still provides stringent dynamical constraints, but the usual chiral power counting breaks down in the presence of higher energy scales. The limit of an infinite number of quark colours provides an alternative power counting to describe the meson interactions [1]. Assuming confinement, the strong dynamics at large N_C is given by tree diagrams with infinite sums of hadron exchanges, which correspond to the tree approximation to some local effective lagrangian [2,3]. Hadron loops generate corrections suppressed by factors of $1/N_C$.

The large N_C limit of the "Resonance Chiral Theory" [4] has been investigated in many works and a very successful leading order phenomenology already exists [5,6,7,8,9,10]. More recently, the problems associated with quantum corrections involving heavy resonance propagators have been investigated [11]. This constitutes a first step towards a systematic procedure to evaluate next-to-leading order contributions in the $1/N_C$ counting.

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Infrared regularization for spin-1 fields

Peter C. Bruns[1] and Ulf-G. Meißner[1,2]

[1]Univ. Bonn, HISKP (Th), D-53115 Bonn, Germany

[2]FZ Jülich, IKP (Th), D-52425 Jülich, Germany

We consider chiral perturbation theory with explicit spin-1 degrees of freedom (vector and axial-vector mesons), utilizing the antisymmetric tensor field formulation. When vector mesons appear in loops, the appearance of the large mass scale (the vector/axial-vector meson mass in the chiral limit) complicates the power counting. In essence, loop diagrams pick up large contributions when the loop momentum is close to the vector meson mass. To the contrary, the contribution from the soft poles (momenta of the order of the pion mass) that leads to the interesting chiral terms of the low-energy EFT (chiral logs and alike) obeys power counting. The standard case of infrared regularization [1], where the heavy particle line is conserved in the (one-loop) graphs, can only be applied to a subset of interesting loop graphs with vector mesons. In the case of spin-1 fields, new classes of self-energy graphs appear. The case for lines with small external momenta but a vector meson line appearing inside the diagram was analyzed in [2] and the infrared singular part for such types of integrals was explicitly constructed. As explicit examples, the Goldstone boson self-energy and the triangle diagram are worked out. As an application, we consider the pion mass dependence of the ρ-meson mass M_ρ. We show that although there are many contributions with unknown low-energy constants, still one is able to derive a compact formula for the pion (quark) mass dependence of M_ρ. We analyze existing lattice data [3] and conclude that the ρ-meson mass in the chiral limit is bounded between 650 and 800 MeV. We have also discussed the $\pi\rho$ sigma term.

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A Large N$_c$ Hadronic Model

Johan Bijnens[1], Elvira Gámiz[2], and **Joaquim Prades**[3]

[1] Department of Theoretical Physics 2, Lund University
Sölvegatan 14A, S 22362 Lund, Sweden.

[2] Department of Physics & Astronomy, University of Glasgow
Glasgow G12 8QQ, United Kingdom.

[3] Departamento de Física Teórica y del Cosmos, Universidad de Granada
Campus de Fuente Nueva, E-18002 Granada, Spain.

We present a large N_c hadronic model with a single hadronic state per channel and construct all two, three-point and some four-point Green's functions in the chiral limit. These Green's functions contain all the constraints from CHPT at NLO, the large N_c structure, and the maximum of the short-distance constraints, namely, OPE and Brodsky-Lepage-like (or quark-counting-rule) ones. We point out a general problem for large N_c hadronic models that prevents from imposing all those short-distance constraints on three-point and higher Green's functions with a finite number of resonances. This problem also exists for Green's functions that vanish to all orders in massless perturbative QCD. We also give the complete result outside the chiral limit for two-point functions, and some three-point ones in the chiral limit. Three-point functions outside the chiral limit are under way [2]. We also comment on the application to calculate the $\hat{B}_K$ parameter in the chiral limit for which we present preliminary results and outside the chiral limit [3]

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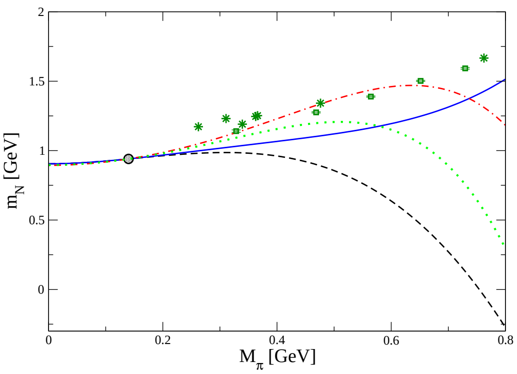
Baryon masses in CHPT and from the lattice

Matthias Frink[1,2], Ulf-G. Meißner[1,2] and Ilka Scheller[1]

[1]Univ. Bonn, HISKP (Th), D-53115 Bonn, Germany
[2]FZ Jülich, IKP (Th), D-52425 Jülich, Germany

We analyze the masses of the ground state octet baryons in a version of cut-off regularized and in dimensionally regularized baryon CHPT at third, improved third and fourth order in the chiral expansion [1], based on Ref.[2] (and using earlier calculations of baryon masses [3,4]). The corresponding LECs are determined by the conditions that the nucleon mass m_N takes its physical value for the physical values of M_π and M_K and that one obtains a fair description of the MILC data [5] already at third order including the improvement term.

Shown is the pion mass dependence of the nucleon mass in dimensional regularization at third (dashed), improved third (solid) and fourth (dot-dashed) order, respectively. The dotted line represents the fourth order calculation from [3]. The three flavor data (staggered fermions) are from the MILC collaboration [5]. The filled circle gives $m_N = 940\,\text{MeV}$ at $M_\pi = 140\,\text{MeV}$.



From the kaon mass dependence of m_N, we deduce that the octet mass in the chiral limit lies in the range from 770 MeV to 1070 MeV. We have also given extrapolation functions for the Λ, the Σ and the Ξ and compared to the MILC data. We find that the chiral extrapolation functions (with all parameters fixed from the nucleon mass) are flatter than what is indicated by these data.

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Chiral dynamics in few–nucleon systems

Evgeny Epelbaum[1]

[1]Jefferson Laboratory, Theory Division, Newport News, VA 23606, USA.

Chiral Effective Field Theory (EFT) has become a standard tool for analyzing the properties of hadronic systems at low energy in a systematic and controlled way based upon the approximate and spontaneously broken chiral symmetry of Quantum Chromodynamics (QCD). Based on Weinberg's idea to use chiral EFT to derive nuclear forces, this method has also been successfully applied to few–nucleon problems [1,2]. Energy–independent and hermitian nuclear potentials can be derived from the chiral Lagrangian e.g. using the method of unitary transformation [3]. This scheme can also be applied to derive the corresponding nuclear current operator. We have used this framework to study the 2N system at next–to–next–to–next–to–leading order (N^3LO) in the chiral expansion [4], see also [5]. The theoretical uncertainty for scattering observables at N^3LO is expected to be of the order $\sim 0.5\%$, 7% and 25% at laboratory energy ~ 50, 150 and 250 MeV. Our findings agree well with these estimations.

Three– and more–nucleon systems have been considered so far up to next–to–next–to–leading order [6]. For the first time, the complete chiral three–nucleon force has been included in few–body calculations, which starts to contribute at this order. N^3LO analysis of $> 2N$ systems is in progress.

Recently we have worked out the leading and subleading isospin–violating 3N forces using the method of unitary transformation [7], which are largely driven by nucleon and pion mass differences. The work on isospin–breaking 2N forces is underway.

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Charge-Symmetry-Breaking Nuclear Forces

U. van Kolck

Department of Physics, University of Arizona,
Tucson, AZ 85750, USA

Charge symmetry is a particular isospin transformation. While electromagnetic interactions break isospin in general, the quark-mass difference breaks charge symmetry in particular. Charge-symmetry-breaking (CSB) quantities can thus be linear in the quark-mass difference. An example is the nucleon mass difference, whose two main components are linear in the quark masses and in the fine-structure constant, respectively. These components can be separated by the pion interactions they generate [1], which are different because of the different ways quark masses and electromagnetism break chiral symmetry explicitly.

An important source of CSB is the nuclear potential, whose derivation is facilitated by a field redefinition that eliminates the nucleon mass difference from asymptotic states [2]. Isospin-violating effects can be organized according to the expansion parameters associated with the quark mass difference, $\epsilon(m_\pi/m_\rho)^2$ (with $\epsilon = (m_u - m_d)/(m_u + m_d)$), and electromagnetism, $\alpha \sim \epsilon(m_\pi/m_\rho)^3$ (numerically) [1]. The leading CSB components of the two- and three-nucleon potentials have been obtained in Refs. [3,4,2] and in Refs. [5,6], respectively.

Estimates [4,6] show that the *pp*-*nn* scattering-length and ^{3}He-^{3}H binding-energy differences can be explained with natural parameters. The best hope for a separation of nucleon-mass components probably rests on pion production [7].

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Consistency of Weinberg's approach to the few-nucleon problem in EFT

D. Djukanovic[1], M. R. Schindler[1], **J. Gegelia**[1,2] and S. Scherer[1]

[1]Institut für Kernphysik, Johannes Gutenberg-Universität,
D-55099 Mainz, Germany.

[2]High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia.

Weinberg's approach to the few-nucleon sector of EFT [1] has encountered various problems. They originate from the renormalization of the LS equation with non-renormalizable potentials. A consistent subtractive renormalization requires the inclusion of an infinite number of counterterm contributions and it has been argued that due to this problem Weinberg's approach is inconsistent. To address the issue of consistency and make some of the "abstract arguments" of Ref. [2] more explicit we have introduced a new formulation of baryon chiral perturbation theory [3]. While preserving all symmetries of the effective theory, it leads to equations in the few nucleon (NN, NNN, etc.) sector which are free of divergences and therefore one does not need to include the contributions of an infinite number of counterterms. The new formulation improves the ultraviolet behavior of propagators and can be interpreted as a smooth cutoff regularization scheme. Unlike the usual cutoff regularization, our 'cutoffs' are parameters of the Lagrangian and do not have to be removed. Our new formulation is equivalent to the standard approach and is equally well defined in the vacuum, one- and few-nucleon sectors of the theory. It preserves all symmetries and therefore satisfies the Ward identities.

To improve the ultraviolet behavior of the propagators we introduce additional *symmetry-preserving* terms into the Lagrangian. These additional terms do not render all loop diagrams finite. However, the remaining divergent diagrams contribute either in physical quantities of the vacuum and the one-nucleon sectors, or they appear as sub-diagrams in the potentials of the few-nucleon sector. Therefore these diagrams can be regularized using standard dimensional regularization and the iterations of the LS equation do not generate any additional divergences.

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Renormalization of the 1π exchange interaction in higher partial waves

Andreas Nogga[1]

[1]Forschungszentrum Jülich, D-52425 Jülich, Germany.

Chiral perturbation theory was successfully applied to the nucleon-nucleon system in the past [1,2,3]. The approach is based on the resummation of reducible diagrams using a Lippmann-Schwinger (LS) equation, which needs to be regularized using a cutoff Λ. But the singularity of the potentials entering the LS equation necessarily generates a strong Λ dependence in some partial waves. In practice, this restricts Λ to values well below the typical $\Lambda_{QCD} \approx 1$ GeV.

This has been studied for the S-waves before [4,5]. Here, we study the cutoff dependence for the leading 1π exchange quantitatively also for the higher partial waves [6]. We confirm a strong, periodic dependence on Λ in some partial waves [7] for the leading order 1π exchange and show that this dependence can be absorbed into one counter term for each of these partial waves. The energy dependence of the resulting phase shifts is in good agreement with the data.

Alternatively, we find that, for low energies, ranges of cutoffs exist for which the phase shifts only mildly depend on Λ. The predictions for those cutoffs do also agree with the data. Therefore, we propose two strategies. For most higher partial waves, the ranges with mild cutoff dependence are large. For the leading 1π exchange interaction, $\Lambda \approx 8$ fm^{-1} is a sensible choice and we find good agreement with the data in most cases. For some lower partial waves, most prominently the $^3P_0$, the regions of mild Λ dependence are not large. Here, it seems advisable to promote counter terms, which can then absorb the Λ dependence completely. In this case also the 3N binding energy is Λ independent.

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Renormalization Group Approach to NN-Scattering with Pion Exchanges: Removing the Cut-Offs [1]

M. Pavón Valderrama and **E. Ruiz Arriola**

Departamento de Física Moderna,
Universidad de Granada, E-18071 Granada, Spain.

A non perturbative renormalization scheme for Nucleon-Nucleon interaction based on boundary conditions at short distances is presented and applied to the One and Two Pion Exchange Potential. It is free of off-shell ambiguities and ultraviolet divergences, provides finite results at any step of the calculation and allows to remove the short distance cut-off in a suitable way. Actually we see that our approach is equivalent to the Variable S-matrix approach and offers a unique way to extract low energy threshold parameters for a given NN potential. We extract those parameters for the np system from the NijmII and Reid93 potentials, to all partial waves with total angular momentum $j \leq 5$. After having done that, low energy constants and their non-perturbative evolution can directly be obtained from experimental threshold parameters in a completely unique and model independent way when the long range explicit pion effects are eliminated. This allows to compute scattering phase shifts which are, by construction consistent with the effective range expansion to a given order in the C.M. momentum p. In the singlet $^1S_0$ and triplet $^3S_1 -^3 D_1$ channels ultraviolet fixed points and cycles are obtained respectively for the threshold parameters, and consequently for the low energy constants. This explains why it has been difficult to remove the cut-offs by performing large scale fits to the data. We find that, after properly removing the cut-off, scattering data are described satisfactorily up to CM momenta of about $p \sim m_\pi$.

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Chiral Perturbation Theory for Heavy Nuclei

Luca Girlanda[1], Akaki Rusetsky[2,3] and Wolfram Weise[4]

[1]ECT*, Strada delle Tabarelle 286,
I-38050 Villazzano, Trento, Italy

[2]HISKP (Theorie), University of Bonn,
Nußallee 14-16, 53115 Bonn, Germany

[3]HEPI, Tbilisi State University,
University St. 9, 380086 Tbilisi, Georgia

[4]Physik-Department, TU München,
D-85747 Garching, Germany

We present an extension of the In-Medium Chiral Perturbation Theory [1], in which the nuclear background is characterized by a static, non-uniform distribution of the baryon number describing the finite nucleus [2]. The nuclear structure information is encoded in a set of nuclear matrix elements of free-nucleon field operators. The chiral counting applied to such matrix elements allows to reduce considerably the nuclear input needed. As an illustration the charged pion self-energy in the background of a heavy nucleus is calculated at $O(p^5)$ of the chiral expansion and the complete set of terms in the pion-nucleus optical potential arising at this order is generated. We are able to identify unambiguously the nuclear finite size effects and disentangle the $S-$, $P-$ and $D-$wave contributions to the optical potential without invoking the local density approximation. We include consistently the complete isospin violating effects arising at order $O(p^5)$, including electromagnetic effects, which were not taken into account in the literature. Our analysis only concerns the leading (linear) terms in density, because these are the only ones showing up at this order. However it is well known that non-linear terms, coming from double scattering diagrams or pion absorption, give important contributions to the binding energies and widths of pionic atoms. For these reasons, in order for our analysis to be relevant phenomenologically, it should be extended to chiral order $O(p^6)$. Whether our framework can ben straightforwardly extended to this order, however, remains to be seen.

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Chiral Dynamics of Nuclear Matter: Role of Two-Pion Exchange with Virtual Delta-Isobar Excitation

Stefan Fritsch, **Norbert Kaiser** and Wolfram Weise

Physik Dept. T39, TU München, D-85747 Garching, Germany.

We extend a recent three-loop calculation of nuclear matter [1] in chiral perturbation theory by including the effects from two-pion exchange with single and double virtual $\Delta(1232)$-isobar excitation [2]. Regularization dependent short-range contributions from pion-loops etc. are encoded in a few NN-contact coupling constants. The empirical saturation point of nuclear matter, $\bar{E}_0 = -16\,\text{MeV}$, $\rho_0 = 0.16\,\text{fm}^{-3}$, can be well reproduced by adjusting the strength of a two-body term linear in density (and tuning an emerging three-body term quadratic in density). The nuclear matter compressibility comes out as $K = 304\,\text{MeV}$. The real single-particle potential $U(p, k_{f0})$ [3] is substantially improved by the inclusion of the chiral $\pi N\Delta$-dynamics: it grows now monotonically with the nucleon momentum p. The effective nucleon mass at the Fermi surface takes on a realistic value of $M^*(k_{f0}) = 0.88M$. As a consequence, the critical temperature of the liquid-gas phase transition [4] gets lowered to the value $T_c \simeq 15\,\text{MeV}$. We continue the complex single-particle potential $U(p, k_f) + i\,W(p, k_f)$ also into the region above the Fermi surface $p > k_f$. Furthermore, we find that the isospin properties of nuclear matter get significantly improved by including the chiral $\pi N\Delta$-dynamics. Instead of bending downward above ρ_0 as in previous chiral calculations [1], the energy per particle of pure neutron matter $\bar{E}_n(k_n)$ and the asymmetry energy $A(k_f)$ now grow monotonically with density [2]. In the density regime $\rho = 2\rho_n < 0.2\,\text{fm}^{-3}$ relevant for conventional nuclear physics our results agree well with sophisticated many-body calculations and (semi)-empirical values. Furthermore, we calculate the spin-asymmetry energy $S(k_f)$ [5] and find that the inclusion of the chiral $\pi N\Delta$-dynamics is crucial in order to guarantee the spin-stability of nuclear matter: $S(k_f) > 0$. Finally, the density dependent Landau parameters $f_0(k_f)$, $f_1(k_f)$, $f_0'(k_f)$, $g_0(k_f)$, $g_0'(k_f)$, $h_0(k_f)$, $h_0'(k_f)$ are calculated in the same framework. These quantities reveal the spin- and isospin dependent interaction (including tensor components) of quasi-nucleons at the Fermi surface.

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Limit Cycle Physics

H.-W. Hammer

Institute for Nuclear Theory, University of Washington
Seattle, WA 98195-1550, USA

The renormalization group (RG) is an important tool in many branches of physics. Its applications range from critical phenomena in condensed matter physics to the nonperturbative formulation of quantum field theories in particle physics. While most RG flows show a simple fixed point behavior, more complex solutions are possible as well. Wilson suggested already in 1971 that RG solutions could display a limit cycle behavior [1].

One important example of a theory with a limit cycle is the effective field theory (EFT) for non-relativistic three-body systems with large scattering length [2]. Its applications range from cold atoms to light nuclei. The large scattering length a leads to universal properties independent of the short-distance dynamics. In particular, one can derive universal expressions for three-body observables with log-periodic dependence on a and the three-body parameter Λ_*. Furthermore, there are universal scaling functions relating different few-body observables. For a detailed review of these properties, see Ref. [3].

The success of this EFT for nuclear few-body systems demonstrates that QCD is close to an infrared limit cycle. We have conjectured, that QCD could be tuned to the critical trajectory for the limit cycle by adjusting the up and down quark masses. The limit cycle would then be manifest in the Efimov effect for the triton [4]. It may be possible to demonstrate the existence of this infrared RG limit cycle in QCD using Lattice QCD and EFT.

In two spatial dimensions, there is no limit cycle and no three-body parameter Λ_* because of the c-theorem. However, for bosons with a weakly bound dimer, asymptotic freedom leads to remarkable universal properties of N-boson droplets, such as an exponential behavior of binding energies and droplet sizes [5].

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What have we learned so far about dilute fermions in the unitary limit?

Aurel Bulgac

Department of Physics, University of Washington
P.O. Box 351560, Seattle, WA 98195-1560, USA

In the last couple of years we have witnessed a tremendous progress in the field of cold fermionic atoms, both experimentally and theoretically. After the first successful trapping of a fermionic atomic cloud [1] a real breakthrough was the creation and the subsequent study of the expansion of a strongly interacting degenerate Fermi gas[2]. After that experimentalists have been able to study the formation of extremely weakly bound molecules [3], the decay properties of ensembles of such dimers[4], the BEC of dimers[5], a number of features of the BCS to BEC crossover[6], the collective oscillations[7], the formation of some kind of condensate, with some still unclear properties[8] and finally the appearance of a gap in the excitation spectrum[9].

Eagles, Leggett and others have envisioned theoretically such a BCS to BEC crossover[10] and were able to describe qualitatively its main features. Qualitative features of the BCS dilute atomic Fermi superfluid have been discussed by a number of authors in recent years[11]. The theoretical description was based essentially on the weak coupling BCS formalism, which is known to over predict the value of the gap by a significant factor[12]. The crossover theory of Leggett and its followers was based on a more or less straightforward extension of the weak coupling BCS formalism to the strong coupling regime. In the BEC limit there is an equally significant correction of this results[13]. As it was noted by Bertsch[14], a dilute Fermi system acquires universal properties at, what nowadays we call, the Feshbach resonance. The initial studies of the Bertsch MBX challenge showed that such a system is stable[15,16]. Only relatively recently that was confirmed both theoretically[17,18,19] and experimentally[2].

While the race is still on for providing the compelling evidence for superfluidity of such systems, many experimental results are in clear agreement with its existence [20]. On the theoretical side our overall understanding of these remarkable many body systems has improved tremendously, even though many questions remain yet unanswered. I shall present a review of the major experimental results and of their present theoretical interpretation, along with a shopping list of issues awaiting their resolution either in experiments and/or in theory.

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An Effective Theory for the Four-Body System

Lucas Platter

HISKP (Abt. Theorie), Universität Bonn,
Nussallee 14-16, 53115 Bonn, Germany

Forschungszentrum Jülich, IKP(Th)
52425 Jülich, Germany.

We use an effective theory with contact interactions to compute universal properties of four-body systems with a large two-body scattering length a. Along with the corresponding power counting this effective theory is a systematic expansion in ℓ/a, where ℓ denotes the typical low-energy scale of the underlying interaction. By generating the leading order effective potential and employing the Yakubovsky equations we are able to compute binding energies of four-body systems. This approach has been applied to bosons [1] (the ^{4}He tetramer) and to fermions (the α-particle) [2].

A particular characteristic of this approach is, that in the three-body system a three-body force at leading order is needed to renormalize observables [3]. It is not a priori clear whether a four-body force is needed in the four-body system at leading order. However, an analysis of the renormalization properties of the four-body system shows that this is not the case. Further, it turns out that a well-known linear correlation between the three-body binding energies and the four-body binding energies shows up naturally within this approach and can be considered as a consequence of the large scattering length in the two-body subsystem.

In the future other observables like scattering amplitudes or electromagnetic properties in the four-body sector will be computed.

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Subtleties in pion production reactions on few nucleon systems

Christoph Hanhart

Institut für Kernphysik,
Forschungszentrum Jülich,
52428 Jülich,
Germany

Meson reactions on light nuclei were discussed. The focus was on the role of the nucleon recoil corrections in low energy meson–nucleus interactions. We demonstrated explicitly when calculations within the static approximation are justified and when the recoils need to be kept explictly in the propagators, depending on whether the intermediate two nucleon state is Pauli blocked or not, while the meson is in flight.

In reactions where a two nucleon intermediate state, that occurs while the pion is in flight, is allowed the two nucleons may interact. We demonstrated that—as a consequence of the large NN scattering lengths—these contributions are numerically significant and argue that this observation is in line with the ideas of Weingbergs power counting.

As examples the reactions $\pi d \to \pi d$ and $\gamma d \to \pi^+ nn$ are presented [2]. Consequences for the chiral counting for reactions on nuclei were discussed.

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Neutral pion electroproduction off the deuteron

V. Bernard[1], **H. Krebs**[2], Ulf-G. Meißner[2,3]

[1]Laboratoire de Physique Théorique, Université Louis Pasteur,
F-67037 Strasbourg Cedex 2, France,

[2]Helmholtz Institut für Strahlen- und Kernphysik (Theorie), Universität Bonn,
Nußallee 14-16, D-53115 Bonn, Germany

[3]Institut für Kernphysik (Theorie), Forschungszentrum Jülich,
D-52425 Jülich, Germany

I present our latest calculations on neutral pion electroproduction off deuterium in chiral perturbation theory. The interaction kernel and the deuteron wave functions are described consistently with each other in a novel formalism of chiral nuclear EFT [1] based on the $\hat{Q}$-box approach of Kuo and collaborators [2]. The interaction kernel decomposes into single nucleon (impulse approximation) and three-body (meson exchange) pieces. Calculating the latter to third order in the chiral expansion [3] leads to a satisfactory description of the data at photon virtuality $Q^2 = 0.1\,\mathrm{GeV}^2$ from MAMI-B [4]. The theoretical uncertainties at this chiral order given by the two different fit procedures we are using to fix the two low–energy constants related to the elementary pion electroproduction on a neutron amplitude are of the same size as the error bars of the MAMI data.

The complete fourth order calculation of the three–body contribution [5], with all new parameters fixed from the earlier studies of πN and NN phase shifts [6], leads to a decrease of the theoretical uncertainties and to a further improvement in the description of the data.

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Nucleon Polarisabilities from Elastic Compton Scattering

Harald W. Grießhammer[1]

[1]Institut für Theoretische Physik (T39), TU München, Germany

Chiral EFT is the tool to accurately determine the proton and neutron spin-independent and spin-dependent dipole polarisabilities. Dynamical polarisabilities, defined by a multipole-analysis at fixed photon energy [1,2], allow one to quantitatively understand the dispersive effects from the nucleon's internal degrees of freedom: Whereas pions suffice to describe data at less than 70 MeV [3], the energy- and angular dependence of the polarisabilities induced by the explicit $\Delta(1232)$-degree of freedom is mandatory at higher energies, in particular to understand deuteron Compton scattering data at 95 MeV [4].

Predicting this energy-dependence at LO by Chiral Perturbation Theory with explicit Δ, one finds from all proton Compton data below 180 MeV the static values $\bar{\alpha}^p = 11.0 \pm 1.4_{\mathrm{stat}} \pm 0.4_{\mathrm{Baldin}}$, $\bar{\beta}^p = 2.8 \mp 1.4_{\mathrm{stat}} \pm 0.4_{\mathrm{Baldin}}$ (in 10^{-4} fm^3), which compares favourably both in magnitude and error with alternative extractions [2]. For the static iso-scalar dipole polarisabilities, deuteron Compton data at 69 and 94 MeV gives $\bar{\alpha}^s = 12.6 \pm 0.8_{\mathrm{stat}} \pm 0.7_{\mathrm{wavefu}} \pm 0.6_{\mathrm{Baldin}}$, $\bar{\beta}^s = 1.9 \mp 0.8_{\mathrm{stat}} \mp 0.7_{\mathrm{wavefu}} \pm 0.6_{\mathrm{Baldin}}$ [4]. Thus, proton and neutron polarisabilities are identical within the accuracy of available data. Both times, the Baldin sum rule is well-matched in a free fit. We propose also to dis-entangle the thus far ill-determined spin-dependent polarisabilities from asymmetries in experiments with polarised beams and targets around the pion production threshold both on the proton and neutron, and present predictions [5]. Future precision experiments will allow for a multipole-analysis, in which the energy-dependence of the dipole polarisabilities can be probed directly even in the resonance region.

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Effective Theory of Higgs-less Electroweak Symmetry Breaking

Jan Stern

Groupe de Physique Theorique, IPN,
Universite de Paris-Sud, 91405 Orsay, France

The generic low-energy effective theory (LEET) of Higgs-less electroweak symmetry breaking is considered operating with naturally light gauge bosons and chiral fermions in addition to three Goldstone bosons arising from a symmetry breaking of $SU(2)_L \times SU(2)_R$. In such a theory, low-energy and loop expansions are related by the same Weinberg power counting formula as in the $ChPT$. Our goal is a systematic LEET ($p \ll 4\pi v \sim 3TeV$), in which symmetries and chiral power counting guarantee that at leading order the theory coincides with the Standard Model without a Higgs particle Previous attempts failed to satisfy the latter requirement. In order to suppress the $0(p^2)$ non-standard couplings, the LEET has to be based on a symmetry S_{nat} that is larger than $SU(2)_L \times U(1)_Y$, including, in particular, the custodial symmetry. Exact S_{nat} forbids couplings of the three Goldstone bosons to elementary massless $SU(2) \times SU(2) \times U(1)_{B-L}$ gauge fields and to fermions. The coupling is introduced and the symmetry is reduced to the electroweak $SU(2) \times U(1)_Y$ via constraints which eliminate the redundant fields keeping track of the whole local symmetry S_{nat}. This procedure is **equivalent** to introducing non propagating scalar 'spurion fields" with definite transformation properties under S_{nat} and with vanishing covariant derivatives [1]. Spurions play a similar role as quark masses in $ChPT$ describing a hierarchy of symmetry breaking effects. The whole LEET is defined as a double expansion in powers of momenta and spurions. At the leading order ($0(p^2)$, no spurion insertion) one recovers the SM couplings of massive W and Z to massless fermion doublets with no scalar particle left in the spectrum [2]. The fermion masses are the first manifestation of spurions. Further necessary consequence is a tiny lepton number violation and Majorana neutrino masses. The NLO ($0(p^2)$, two spurion insertions) consists of specific universal corrections to the vector boson - fermion vertices. Power counting predicts the latter to contribute before loops and to be potentially more important than the oblique corrections which first appear at the NNLO.

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From mooses to 5D and back to large-N_c QCD ?

Johannes Hirn

IFIC, Universitat de València, València, Spain

Consider $K+1$ Goldstone boson (GB) multiplets, each describing the spontaneous breaking $\mathrm{SU}(N_f)_{L_k} \times \mathrm{SU}(N_f)_{R_k} \rightarrow \mathrm{SU}(N_f)_{L_k+R_k}$, $(k=0,\cdots,K)$. Introduce K $\mathrm{SU}(N_f)_{G_k}$ Yang-Mills theories. To obtain the open linear moose, identify each gauge group $\mathrm{SU}(N_f)_{G_k}$ $(k=1,\cdots,K)$, with $\mathrm{SU}(N_f)_{R_{k-1}+L_k}$. All vectors get masses via K Higgs mechanisms, leaving one GB multiplet in the spectrum.

Sticking to tree level [1], one can impose an *approximate locality* on the moose interpreted as a deconstructed fifth dimension. For $N_f=2$, the model reproduces some interesting results involving pions and vector resonances [2]. However, the approximately local moose yields (at tree-level) K generalized Weinberg sum rules (GWSRs) [3], as opposed to two in QCD. Note tat the GWSRs are not related to a symmetry of the moose lagrangian, but reflect the approximate locality.

Nevertheless, the GWSRs can be interpreted as a consequence of a larger symmetry reduced by spurions [3]. In this way, one gains a perturbative control of the fifth dimension locality and corrections to the GWSRs in a systematic low-energy expansion. Still, in this expansion, the masses of the resonances are expansion parameters $m \ll 4\pi f_\pi$, which is unrealistic for QCD, except for large N_c [4]: the moose provides a general framework for the introduction of *light* massive vector fields into a low-energy effective theory of Goldstone bosons.

Extrapolating to a five-dimensional *model*, one expects an infinite set of GWSRs [5]. In a Randall-Sundrum set-up, we propose a model with two $\mathrm{U}(N_f)$ bulk gauge fields (identified on the IR brane) and bulk scalars (to account for a non-zero quark condensate by providing a shortcut between the left and right chiral sources, as well as to introduce (pseudo)-scalar resonances) [6]. We *ask* whether this hadronic model can reproduce high-energy perturbative QCD results (two Weinberg sum rules, $\Pi_{VV}(Q^2) \sim \ln Q^2$ [2], Brodsky-Lepage behavior).

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Charm-strange mesons

Felix Sassen[1], S. Krewald[1], U.-G. Meißner[1,2] and C. Hanhart[1]
[1]FZ Jülich, IKP(Th), D-52425 Jülich, Germany.
[2]Univ. Bonn, HISKP(Th), D-53115 Bonn, Germany.

The charm-strange resonances $D^*_{sJ}(2317)$, $D_{sJ}(2460)$ and $D_{sJ}(2632)$ discovered by the BaBar, CLEO and Selex collaborations may be accommodated in the spectrum expected for a heavy-light system by the chiral doubler scenario[1]. Meson-meson-dynamics is considered as a possible mechanism to generate the $D^*_{sJ}(2317)$ [2]. We present an analysis of the interaction in the KD-channel to check this proposition. As one would have expected from the quark structure, which is very similar to the $K\bar{K}$ channel, an isoscalar molecule is formed in the KD channel. Therefore the question arises how to discriminate a chiral doubler from a molecule. One way to distinguish a molecular state from a genuine state was suggested long ago by Weinberg with respect to the structure of the deuteron[3]. He introduced the normalization factor $Z = \sum_i |\langle D^{*i}_{s0}|D^*_{sJ}(2317)\rangle|$ to define the elementary content ($\sum_i D^{*i}_{s0}$) of an observed state ($D^*_{sJ}(2317)$) and related it to the effective range parameters a and r via

$$a = -\frac{2(1-Z)}{2-Z}R + \mathcal{O}\left(\frac{1}{\beta}\right) \qquad \text{and} \qquad r = -\frac{Z}{1-Z}R + \mathcal{O}\left(\frac{1}{\beta}\right).$$

Here $1/\beta$ denotes the range of the binding force and $R = 1/\sqrt{2\mu\epsilon}$ depends on the binding energy ϵ and the reduced mass μ. We find this approach to work even in the inelastic case, as indicated in ref.[4]. However it may break down if two poles are close to the threshold. The molecular picture predicts a larger width for the $D^*_{sJ}(2317)$ than the chiral doubler scenario does, if isospin violations via $\pi\eta$-mixing and via mass differences of charged and neutral mesons are considered. We checked our $SU(4)$ estimates for the coupling constants by calculating the decay widths of the D^{*+} and comparing the results to experimental data. The agreement was rather good and changing the couplings within reasonable bounds does not alter our results.

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Nuclear Physics from Lattice QCD

Martin J. Savage

Department of Physics, University of Washington
Seattle, Washington, USA

Determination of the properties and interactions of the deuteron directly from QCD will establish a milestone in theoretical physics. As lattice QCD is the only known method for rigorous QCD calculations, it will be a coherent effort in lattice QCD and other areas of theoretical nuclear physics that first achieves this goal. As the deuteron is the simplest nucleus, such computations will usher in a new era of nuclear physics, an era in which model-independent calculations of nuclei and their interactions will, for the first-time, become possible. A significant effort is already underway toward this goal. In addition to LHPC [1], one lattice collaboration, NPLQCD [2], has been formed within the last year whose main objective is to perform such calculations which are only now becoming feasible due to advances in technology and in theoretical nuclear physics.

Within the last couple of years, a number of papers have explored the requirements for and constraints on rigorously extracting the properties of the two-nucleon sector, the NN phases-shifts, electroweak matrix elements and static properties of the deuteron [1,2]. While it will be comforting to recover these well-known quantities, it is just a first step to computing interactions in regions that are not accessible to experiment. This analysis has been extended to systems containing strange quarks, where the theoretical framework for extracting hyperon-nucleon interactions from lattice QCD has been put in place [3]. As of January 2005, the NPLQCD collaboration was awarded 7×10^5 processor-hours on the JLab cluster by SciDAC, for studies that include the NN, the ΛN and $\Lambda\Lambda$ interactions on the publicly available dynamical, staggered MILC lattices.

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Nucleons and nuclei from lattice QCD

Silas R. Beane[1,2]

[1]Dept. of Physics, University of New Hampshire, Durham, NH 03824-3568.
[2]Jefferson Laboratory, 12000 Jefferson Avenue, Newport News, VA 23606.

Despite remarkable technical advances, lattice QCD simulations necessitate the use of quark masses, m_q, that are significantly larger than the physical values, lattice spacings, a, that are not significantly smaller than the physical scales of interest, and lattice sizes, L, that are not significantly larger than the pion Compton wavelength. Fortunately, in many cases, the dependence of hadronic physics on these parameters can be calculated analytically in the low-energy effective field theory, thus allowing rigorous extrapolations to remove lattice artifacts. Sometimes lattice artifacts are critical to the extraction of physics from the simulation. The Maiani-Testa theorem [1] precludes determination of scattering amplitudes away from kinematic thresholds from Euclidean-space Green functions at infinite volume. By generalizing a result from non-relativistic quantum mechanics to quantum field theory, Lüscher [2] realized that one can access $2 \to 2$ scattering amplitudes from lattice simulations performed at *finite* volume. This method opens up the study of nuclear physics to lattice QCD simulations. (Only one lattice QCD calculation of the nucleon-nucleon scattering lengths [3] has been attempted.) There is a sizable separation of length scales in nuclear physics, and as a result, the scattering lengths in both $S-$wave channels are unnaturally-large compared to all typical strong-interaction length scales, including the range of the nuclear potential, which is determined by the pion Compton wavelength. Perhaps counter-intuitively, in simulating two-nucleon processes, the relevant lengths scales are those of the nuclear potential and *not* the scattering lengths, and thus as long as the lattice is large compared to the inverse of the pion mass one can in principle “simply ” determine matrix elements and scattering parameters [4]. Recently a new lattice QCD collaboration, NPLQCD [5], has formed to begin lattice QCD simulations of simple nuclear systems.

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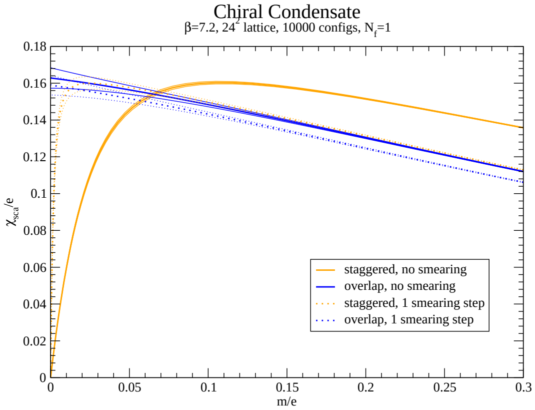
Towards a lattice determination of chiral NLO coefficients

Stephan Dürr[1]

[1]Universität Bern, ITP, Sidlerstr. 5, 3012 Bern, Switzerland

For those QCD low-energy constants that describe the quark mass dependence of Green's functions, e.g. l_3, l_4, l_7 in the $SU(2)$ framework of XPT [1], a lattice determination seems promising, since there m is a parameter which can, in principle, take arbitrary values. In practice three (major) complications arise. First, it gets expensive to take m light, both in the quark propagators and in the functional determinant. Second, the continuum limit must be taken, since cut-off effects may be particularly large close to the chiral limit. That $ma \ll 1$ (and $Ma \ll 1$) is not sufficient to have small discretization errors is borne out in the figure to the left, see [2]. Here the scalar condensate in the Schwinger model is plotted versus the quark mass, and only one of the two formulations reproduces the analytic result $\lim_{m=0} \langle\bar{\psi}\psi\rangle/e = 0.1599...$ within errors. Thus, cut-off effects can completely mask the underlying continuum physics. The third complication is that even in todays dynamical ($N_f = 2$) simulations the way the scale is set still matters. I have compared the NLO chiral prediction for the degenerate ($m = m_u = m_d$) quark mass dependence of the pseudo-Goldstone boson mass to the perturbatively renormalized data (at 1-loop) [3,4]. Setting the scale through r_0 the data are consistent with the chiral prediction, even if one fixes the parameter F_π to its physical value. Notably, there is no indication that l_3 could be different from the original GL estimate [1], but it is hard to turn this into a positive statement, since only some of the data are likely in a regime where XPT applies [4]. Furthermore, regarding the consistency with XPT Aoki reaches an adverse conclusion, based on the same data, after setting the scale through M_ρ [5]. Thus, the only safe prediction is that the issue will be with us for some time.



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Going chiral: overlap and twisted mass fermions

Karl Jansen[1]

[1]John von Neumann-Institute for Computing,
Platanenallee 6, 15738 Zeuthen, Germany

We present lattice simulations that aim at reaching small values of the pion mass such that contact to chiral perturbation theory can safely be made. To this end we compare Wilson twisted mass and chirally invariant overlap fermions and found that both formulations of lattice QCD can reach this goal [1] since with them quenched simulations at $m_\pi \approx 230\text{MeV}$ become possible. However, Wilson twisted mass fermions cost a factor 10-40 less computertime than overlap fermions [2]. In refs. [3,4] we used twisted mass fermions for studying the phase diagram of lattice QCD and found a surprising phase structure with pronounced signals of first order phase transitions. We demonstrated in refs. [5,6] that finite size effects may be the largest systematic error in the computation of moments of parton distribution functions on the lattice. Here it would be very helpful to have analytical calculations, as e.g. from chiral perturbation theory, to describe these finite size effects.

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Applications of ChPT to QCD with domain-wall fermions

Maarten Golterman[1] and Yigal Shamir[2]

[1]Department of Physics and Astronomy, San Francisco State University
San Francisco, CA 94132, USA

[2]School of Physics and Astronomy,
Tel-Aviv University, Ramat Aviv, 69978 ISRAEL.

Reporting on recent work [1], we discuss the very different roles of the valence-quark and the sea-quark residual masses ($m^v_{\rm res}$ and $m^s_{\rm res}$) in dynamical domain-wall fermions simulations [2]. Focusing on matrix elements of the effective weak hamiltonian containing a power divergence [3], we find that $m^v_{\rm res}$ can be a source of a much bigger systematic error. To keep all systematic errors due to residual masses at the 1% level, we estimate that one needs $am^s_{\rm res} \lesssim 10^{-3}$ and $am^v_{\rm res} \lesssim 10^{-5}$, at a lattice spacing $a \sim 0.1$ fm, if only the single power-divergent subtraction already present in the continuum theory is performed.

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Excited Hadrons from Lattice Calculations: Approaching the Chiral Limit

Dirk Brömmel[1], Tommy Burch[1], Christof Gattringer[1], Leonid Ya. Glozman[2],
Christian Hagen[1], Dieter Hierl[1], Reinhard Kleindl[2],
C. B. Lang[2], and Andreas Schäfer[1]
(BGR [Bern-Graz-Regensburg] Collaboration)

[1]Institut für Theoretische Physik, Universität Regensburg,
D-93040 Regensburg, Germany

Institut für Physik, FB Theoretische Physik, Universität Graz,
A-8010 Graz, Austria

Ground state spectroscopy for quenched lattice QCD is well understood. However, it is still a challenge to obtain results for excited hadron states [2]. In our study we present results from a new approach for determining spatially optimized operators for lattice spectroscopy of excited hadrons.

In order to be able to approach physical quark masses we work with the chirally improved Dirac operator [1], i.e., approximate Ginsparg-Wilson fermions. Since these are computationally expensive we restrict ourselves to a few quark sources. We use Jacobi smeared quark sources with different widths and combine them to construct hadron operators with different spatial wave functions [3]. The cross-correlation matrix is then analyzed with the variational method. This leads to optimized combinations of hadron operators that provide us with better signals for the excited states.

This approach allows us to identify the Roper state and other excited baryons and mesons, also in the strange sector. We find that excited states may be more affected by finite volume effects, but also be more sensitive to the quenched approximation. Finite volume studies, including also scaling properties, are under way.

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The ϵ-regime of QCD and its applications to non-leptonic Kaon decays

Hartmut Wittig
DESY, Notkestr. 85, 22603 Hamburg, Germany

A quantitative understanding of $K \to \pi\pi$ decays and the associated $\Delta I = 1/2$ rule has been elusive for many years. A successful treatment in the context of QCD should reproduce the large ratio of decay amplitudes, $A_0/A_2 \approx 22$, where the subscript labels the isospin of the pion pair in the final state. In ref. [1] we proposed a strategy which seeks to disentangle various possible origins of the $\Delta I = 1/2$ rule and clarifies the specific rôle of the charm quark. The goal is a precise determination of the LECs $g_1^{\pm}$, which appear in the effective low-energy description of $\Delta S = 1$ transitions, using lattice simulations. These LECs are linked to the ratio A_0/A_2. The rôle of charm can be studied by comparing the values of $g_1^{\pm}$ obtained for an unphysically light charm quark $m_u = m_c$ to those computed for $m_c \gg m_u$. Thus, in contrast to other lattice studies, we keep the charm quark active. The other key ingredients of our strategy are the use of overlap fermions, which preserve chiral symmetry at non-zero lattice spacing, and a matching of QCD to ChPT via the so-called ϵ-regime. Chiral symmetry ensures that the matching of lattice data to ChPT is on a solid footing. Furthermore, it is guaranteed that the subtraction of power divergences can be avoided at all stages of the calculation, provided that the charm quark is active. The chiral counting rules of the ϵ-regime imply that no additional coupling terms with unknown coefficients are generated at NLO in the treatment of $\Delta S = 1$ transitions. Thus, the matching of correlation functions of four-quark operators to the expressions of ChPT can be easily performed at NLO. The use of overlap fermions requires efficient numerical techniques [2,3]. In the ϵ-regime the intrinsic statistical fluctuations of correlation functions turn out to be particularly large. The signal can be greatly improved by making specific use of the low modes of the Dirac operator [3,4]. Results for the case $m_c = m_u$ will be published shortly.

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Chiral Extrapolation of Baryon Properties—Recent Progress

Thomas R. Hemmert

Physik Department T39, TU München, Germany

The methods of chiral effective field theory (ChEFT) can be used to study the quark-mass dependence of baryon properties. In this talk I have given an update regarding recent developments in this field. I have discussed predictions for the quark-mass dependence of the nucleon mass and the nucleon sigma term in relativistic/covariant Baryon Chiral Perturbation Theory (BChPT) to next-to-leading one-loop order (NLO) [1]. Furthermore, I have presented evidence that such a calculation is in accordance with the principles of ChEFT out to relatively large pion masses around 500 MeV [2]. An analysis of the uncertainty-/error-bands of this NLO calculation was presented [3]. As a second topic I discussed the chiral extrapolation of the magnetic moments of the nucleon utilizing the methods of covariant/relativistic BChPT. It was argued that the previously observed breakdown of NLO calculations for pion-masses around 300 MeV is connected with an insufficient treatment of the quark-mass dependence of the analytic structures. A method of self-consistent propagators was presented to overcome this problem [4]. First results for the quark-mass dependence of the mass of Delta(1232) were also shown [5]. Finally, new predictions illuminating the role of explicit Delta(1232) degrees of freedom in the volume dependence of the mass of the nucleon [6] and of the axial coupling of the nucleon [7] were presented.

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Progress, Challenges and Strategies in Lattice QCD**

Elisabetta Pallante

Centre for Theoretical Physics, Physics Dept., Groningen University,
Nijenborgh 4, 9747AG Groningen, The Netherlands.

** *This talk can be found at http://www.itkp.uni-bonn.de/∼eft04/talks/pallante.pdf*

Recent years have seen a substantial progress in Lattice QCD. After reaching a better comprehension of quenched diseases and related systematic uncertainties, we finally entered the *dynamical era*. A promising result is the determination of *real world* light and strange quark masses, $f_\pi, f_K, |V_{us}|$ by the MILC collaboration [1]. Progress continues with the optimization of four alternative formulations of lattice fermion actions: staggered, domain wall, overlap and twisted mass Wilson fermions [2]. Recently, staggered χPT and twisted mass χPT have been added to the list of frameworks to guide lattice extrapolations to the chiral and continuum limit [3].

The challenge remains the determination of non-leptonic two-body weak decays, in particular $K \to \pi\pi$, where the essential role of final state interactions (FSI) and their proper treatment in the computation of ϵ'/ϵ was addressed in [4]. Hence, the necessity of incorporating FSI into the lattice determination of $K \to \pi\pi$ led to lattice strategies at *finite volume* [5], which overcome the Maiani-Testa theorem, and for different regimes of quark masses and volumes: the p-regime, the ϵ'- and ϵ-regime when approaching the chiral limit.

The charm quark and GIM mechanism are expected to play a central role in the $\Delta I = 1/2$ rule. The enhancement should come from the *eye-like* Wick contraction, which is zero at $m_u = m_c$. Since Nature provided us with $m_c > \Lambda_\chi$, we expect the bulk of the effect coming from that region. That is why the study of an active charm with mass $m_c < \Lambda_\chi$ (i.e. SU(4) χPT) [6], while being an instructive exercise, will not explain the bulk of the physical effect, and as expected, will originate a numerically suppressed octet enhancement due to threshold effects $m_c \log m_c/\Lambda_\chi$. The new generation of Teraflop computers might finally be enough to attack the $\Delta I = 1/2$ problem from first principles.

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Topics in Effective Field Theory

Jiunn-Wei Chen

Department of Physics and National Center for Theoretical Sciences at Taipei,
National Taiwan University, Taipei, Taiwan

Several recently effective field theory applications are discussed:

1) **Lattice theory for cold atom systems:** We construct a lattice theory describing a system of interacting nonrelativistic spin s=1/2 fermions at nonzero chemical potential [1]. The theory is applicable whenever the interparticle separation is large compared to the range of the two-body potential, and does not suffer from a sign problem. In particular, the theory could be useful in studying the thermodynamic limit of fermion systems for which the scattering length is much larger than the interparticle spacing, with applications to realistic atomic systems such as the BEC to BCS transitions and dilute neutron gases.

2) **Inequalities for light nuclei in the Wigner symmetry limit:** Using effective field theory we derive inequalities for light nuclei in the Wigner (isospin and spin) symmetry limit [2]. We prove that the energy of any three-nucleon state is bounded below by the average energy of the lowest two-nucleon and four-nucleon states. We show how this is modified by lowest-order terms breaking Wigner symmetry and prove general energy convexity results for SU(N). We also discuss the inclusion of Wigner-symmetric three and four-nucleon force terms.

3) **Universality of the EMC effect:** Using effective field theory, we investigate nuclear modification of nucleon parton distributions (for example, the EMC effect) [3]. We show that the universality of the shape distortion in nuclear parton distributions (the factorization of the Bjorken x and atomic number (A) dependence) is model independent and emerges naturally in effective field theory. We then extend our analysis to study the analogous nuclear modifications in isospin and spin dependent parton distributions and generalized parton distributions.

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Finite volume effects using lattice chiral perturbation theory

B. Borasoy[1] and R. Lewis[2]

[1]Helmholtz-Institut für Strahlen und Kernphysik,
Universität Bonn, Nußallee 14-16, D-53115 Bonn, Germany

[2]Department of Physics,
University of Regina, Regina, SK, S4S 0A2,Canada

The physics of pions within a finite volume is explored using lattice regularized chiral perturbation theory. This regularization scheme permits a straightforward computational approach to be used in place of analytical continuum techniques.

The continuum limit must be identical to any viable continuum regulator, but lattice regularization has the feature of being easy to manage numerically. A suggested advantage of this regularization scheme is that the renormalization can be carried out numerically, leaving fewer analytical steps to be performed. Beginning from a Lagrangian that displays the lattice spacing explicitly and also maintains exact chiral symmetry [1,2] one can simply derive the Feynman propagators and vertices then type those directly into a computer program. Loop diagrams are just summations of a finite number of momentum values and the numerics are finite at every step. For a sufficiently small lattice spacing, observables must be independent of the lattice spacing.

Using the pion mass, decay constant, form factor and charge radius as examples, it is shown how numerical results for volume dependences are obtained at the one-loop level [3,4]. The expressions for the pion mass and decay constant are known in dimensional regularization [5], and results from the two regularization schemes agree numerically.

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Finite Volume effects for Decay Constants

Christoph Haefeli[1]

[1]Institut für Theoretische Physik, Universität Bern

This talk is based on joint work with G. Colangelo and S. Dürr [1].

Lattice calculations are performed in a finite volume and since the extrapolation to the infinite volume is numerically quite expensive, it is deserving that one may rely on analytical methods. In the p-regime, i.e. $M_\pi L \gg 1$, the asymptotic formula of Lüscher [2] offers an efficient way to investigate these effects. It has been applied within the framework of CHPT to the pion mass [3] and has been extended also to decay constants [1]. For the pion decay constant, it reads

$$F_\pi(L) - F_\pi = \frac{3}{8\pi^2 M_\pi L} \int_{-\infty}^{\infty} dy \; e^{-\sqrt{M_\pi^2+y^2}L} N_F(iy) + O(e^{-\bar{M}L}) \,, \tag{1}$$

where $F_\pi(L)$ is the pion decay constant in finite volume, $\bar{M} \geq \sqrt{3/2}M_\pi$ and $N_F(\nu)$ denotes the subtracted infinite volume forward scattering amplitude of the matrix element with three pions created out of the vacuum with an axial current. By employing the chiral expansion of $N_F(\nu)$ up to NLO, we were able to investigate Eq.(1) numerically. The main results are:

- the finite volume corrections are exponentially suppressed for large values of $M_\pi L$ and become negligible rather quickly;
- the leading term in the chiral expansion of the asymptotic formula receives large corrections even for the physical values of the quark masses;
- the contributions from the cut terms in N_F turn out to be very small, such that even a second order polynomial for the amplitude N_F is already a good approximation. The finite volume shift can then be written in a very compact manner, in terms of two modified Bessel functions.

I have also discussed an extension of Eq.(1), which allows to estimate sub leading contributions.

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Isospin violation in semileptonic decays

Helmut Neufeld

Institut für Theoretische Physik der Universität Wien,
Boltzmanngasse 5, A-1090 Wien, Austria.

The appropriate theoretical framework for the treatment of isospin-violating effects in semileptonic decays is provided by chiral perturbation theory with virtual photons and leptons [1]. This effective quantum field theory describes the interactions of the pseudoscalar octet, the photon and the light leptons at low energies and allows a comparison of experimental data with the predictions of the standard model. It has been applied for the analysis of semileptonic kaon [2] and pion [3] decays.

The combined analysis of K^0_{e3} and K^+_{e3} data may serve as an illustration. The standard model allows for a remarkably precise prediction of the quantity $r_{+0} := f_+^{K^+\pi^0}(0)/f_+^{K^0\pi^-}(0)$. This quantity is largely insensitive to the dominating theoretical uncertainties, in particular the contributions of order p^6. The theoretical prediction [4], $r_{+0}^{\rm th} = 1.022 \pm 0.003 - 16\pi\alpha X_1$, depends only on the (unknown) electromagnetic low-energy coupling X_1 [1]. Already simple dimensional analysis ($|X_1| \leq 1/(4\pi)^2$) confines r_{+0} to the rather narrow band $1.017 \leq r_{+0}^{\rm th} \leq 1.027$, leading to a stringent test for the corresponding observable quantity $r_{+0}^{\rm exp}$ [4]. Using the most recent K^+ and K_L data [5], one finds $r_{+0}^{\rm exp} = 1.038 \pm 0.007\,(1.036 \pm 0.008)$ where linear (quadratic) form factor fits have been used. The corresponding numbers using K_S data read $r_{+0}^{\rm exp} = 1.036 \pm 0.010\,(1.035 \pm 0.011)$.

The (small) discrepancy between present data and the standard model prediction should encourage further experimental and theoretical efforts on this issue.

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