The 10th International Workshop on Chiral Dynamics

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Book of Abstracts

Contents

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ChPT and BSM dark mesons

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We plan to present the phenomenology and experimental searches of the dark pions, which are the lightest hadrons in a hidden sector confining gauge theory. Such a scenario arises in many extensions of the Standard Model (SM). We consider that the leading interactions between the light hidden sector quarks and the SM particles come from the mixing of the light hidden quarks with heavy electroweak doublet states through Higgs Yukawa couplings, so that the leading portals are the Z and Higgs bosons.

Summary:

Based on arXiv:1906.02198 and an upcoming project.

1

Fast & rigorous constraints on chiral three-nucleon forces from few-body observables

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We explore the constraints on the three-nucleon force (3NF) of chiral effective field theory (χEFT) that are provided by bound-state observables in the A = 3 and A = 4 sectors. Our statistically rigorous analysis incorporates experimental error, computational method uncertainty, and the un- certainty due to truncation of the χEFT expansion at next-to-next-to-leading order. A consistent solution for the 3H binding energy, the 4He binding energy and radius, and the 3H β-decay rate can only be obtained if χEFT truncation errors are included in the analysis. All of these except the β-decay rate give essentially degenerate constraints on the 3NF low-energy constants, so it is crucial for estimating these parameters. We use eigenvector continuation for fast and accurate emulation of No-Core Shell Model calculations of the considered few-nucleon observables. This facilitates sampling of the posterior probability distribution, allowing us to also determine the distributions of the hyperparameters that quantify the truncation error. We find a χEFT expansion parameter of Q = 0.33 ± 0.06 for these observables.

2

Theoretical aspects of virtual states, bound states, and resonances in Hadron physics from Friedrichs model

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Friedrichs model is a solvable model which is suitable to study the properties of the states that appear in scatterings. I will first review some theoretical aspects of the virtual state, bound state and resonances solutions for the Friedrichs model. Then some applications of this model to the hadron physics will be presented.

3

Theoretical analysis of the doubly radiative decays $\eta^{(\prime)} \to \pi^0\gamma\gamma$ and $\eta' \to \eta\gamma\gamma$

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The scalar and vector meson exchange contributions to the doubly radiative decays
$\eta^{(\prime)} \to \pi^0\gamma\gamma$ and $\eta' \to \eta\gamma\gamma$
are analysed within the Linear Sigma Model and Vector Meson Dominance frameworks, respectively.
Predictions for the diphoton invariant mass spectra and the associated integrated
branching ratios are given and compared with current available experimental data.
While a satisfactory description of the shape of the $\eta \to \pi^0\gamma\gamma$ and $\eta' \to \pi^0\gamma\gamma$ decay spectra is obtained, thus supporting the validity of the approach, the corresponding branching ratios cannot be reproduced simultaneously. A first theoretical prediction for the recently measured $\eta' \to \eta\gamma\gamma$ by the BESIII collaboration is also presented.

4

A theoretical analysis of the semileptonic decays $\eta^{(\prime)} \to \pi^0 l^+ l^-$ and $\eta' \to \eta l^+ l^-$

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Co-author: Pablo Sanchez-Puertas [3]

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A theoretical analysis of the C-conserving semileptonic decays $\eta^{(\prime)} \to \pi^0 l^+ l^-$ and $\eta' \to \eta l^+ l^-$ ($l = e$ or) is carried out within the framework of the Vector Meson Dominance model. A phenomenological model is then used to parametrise the VMD couplings and numerical values are obtained from an optimisation fit. The signature of CP-violating operators from the SMEFT on experimental observables is also investigated and quantified for the $l = \mu$ case.

5

Dilaton chiral perturbation theory and applications

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We review dilaton chiral perturbation theory (dChPT), the effective low-energy theory for the light sector of near-conformal, confining theories. dChPT provides a systematic expansion in both the fermion mass and the distance to the conformal window. It accounts for the pions and the light scalar, the approximate Nambu-Goldstone bosons for chiral and scale symmetry, respectively. A unique feature of dChPT is the existence of a large-mass regime in which the theory exhibits approximate hyperscaling, while the expansion nevertheless remains systematic.
We discuss applications to lattice data, presenting successes as well as directions for future work.

6

Chiral EFT of nucleons and pions in the presence of external gravitational field

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Effective chiral Lagrangian of nucleons and pions in external gravitational field and the corresponding energy-momentum tensor will be considered. Gravitational form factors of the nucleon and their relation to internal forces will be discussed.

7

Short-distance constraints in hadronic-light-by-light for the muon $g-2$

Authors: Antonio Rodríguez[1]; Johan Bijnens[2]; Nils Hermansson Truedsson[3]

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We have made recent progress in studying the short-distance properties of the hadronic light-by-light contribution to the muon $g-2$. The intermediate and short-distance part is a major contributor to the error of the hteoretical prediction, see the white paper [arxiv:2006.04822, Physics Reports 887 (2020) 1-166]. We have recently shown that the massless quark-loop is the first term in a systematic expansion at short-distance [arxiv:1908.03331, Phys.Lett. B798 (2019) 134994].This result already helped in the white paper in bringing down the error. Since then we have shown that both nonperturbative [arxiv:2008.13487, JHEP 10 (2020) 203] and the perturbative corrections [arxiv:2101.09169, JHEP 04 (2021) 240] are under control. The talk will describe these developments and how they fit in the total theopretical prediction for the muon $g-2$.

8

NNLO Positivity Bounds on Chiral Perturbation Theory for a General Number of Flavours

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We present positivity bounds, derived from the principles of analyticity, unitarity and crossing symmetry, that constrain the low-energy constants of chiral perturbation theory.
Bounds are produced for 2, 3 or more flavours with equal meson masses, up to and including next-to-next-to-leading order, using the second and higher derivatives of the amplitude. We enhance the bounds by using the most general isospin combinations posible (or higher-flavour counterparts thereof) and by analytically integrating the low-energy range of the amplitude. In addition, we present a powerful and general mathematical framework for efficiently managing large numbers of positivity bounds.

9

Three-pion scattering in the Chiral Perturbation Theory

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Within the framework of the massive O(N) nonlinear sigma model extended to the next-to-leading order in the chiral counting (for $N=3$ corresponding to the two(-quark)-flavor Chiral Perturbation Theory), we calculate the relativistic six-pion scattering amplitude at low energy up to and including terms $\mathcal{O}(p^4)$. Results for the pion mass, decay constant and the four-pion amplitude in the case of N (meson) flavors at $\mathcal{O}(p^4)$ are also presented.

10

On QCD contribution to vacuum energy

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In the framework of a two-loop order calculation for an effective field theory of scalar, vector and fermion fields interacting with the metric field we show that for the cosmological constant term which is fixed by the condition of vanishing vacuum energy, the graviton remains massless and there exists a self-consistent effective field theory of general relativity defined on a flat Minkowski background.
Next, using this result we address the issues of fine tuning of the strong interaction contribution to the vacuum energy and the compatibility of chiral symmetry in the light quark sector with the consistency of the effective field theory of general relativity in a flat Minkovski background.

11

Dispersive analysis of the Primakoff reaction $\gamma K \to K\pi$

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We provide a dispersion-theoretical representation of the reaction amplitudes $\gamma K \to K\pi$ in all charge channels, based on modern pion–kaon P-wave phase shift input. Crossed-channel singularities are fixed from phenomenology as far as possible.
We demonstrate how the subtraction constants can be matched to a low-energy theorem and radiative couplings of the $K^*(892)$ resonances, thereby providing a model-independent framework for future analyses of high-precision kaon Primakoff data.

12

Extracting few-body matrix elements from lattice QCD

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In this talk I will report on a recent lattice QCD determination of few-body matrix elements made by the NPLQCD Collaboration. One of them is the fraction of the longitudinal momentum of ^{3}He

that is carried by the isovector combination of u and d quarks. The ratio of this combination to that in the constituent nucleons is extracted in a calculation with quark masses corresponding to a pion mass of 800 MeV, and then extrapolated to the physical point, showing that it is consistent with, and significantly more precise than, determinations from global nuclear parton distribution function fits. The other quantity studied is the tritium axial charge, related to the Gamow-Teller matrix element, which is also computed with heavier-than-physical quark masses and then extrapolated and compared with the phenomenological value. The importance of this last study is that it demonstrates that QCD can explain the quenching of the triton axial charge.

13

Most charming dibaryon near unitarity from lattice QCD

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We present a first study on a pair of triply charmed baryons, $\Omega_{ccc}\Omega_{ccc}$ in the $^1S_0$ channel (the most charming dibaryon), on the basis of the HAL QCD method.
The calculations are perfomed on the $(2+1)$-flavor lattice QCD configurations with nearly physical light-quark masses and physical charm-quark mass.
We show that the system with the Coulomb repulsion taking into account the charge form factor of Ω_{ccc} leads to the sacttering length $a_0^{\mathrm{C}} \simeq -19$ fm and the effective range $r_{\mathrm{eff}}^{\mathrm{C}} \simeq 0.45$ fm, which indicates $\Omega_{ccc}\Omega_{ccc}$ is located in the unitary regime.

14

Structure-dependent electromagnetic finite-size effects

Author: Nils Hermansson-Truedsson[1]

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In this talk we present a relativistic and model-independent method to analytically derive electromagnetic finite-size effects beyond the point-like approximation. Structure-dependence appears in terms of physical form-factors and derivatives thereof. The values of these physical quantities can be taken either from experimental measurements or auxiliary lattice calculations. We first apply our method to the meson mass, and then to leptonic decays of pions and kaons. Knowledge of the latter allows for improved numerical control in extractions of the CKM-matrix element ratio $|V_{us}/V_{ud}|$ from lattice QCD+QED.

15

Nuclear structure corrections in muonic atoms from chiral effective field theory

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Precision spectroscopic measurement in muonic atoms require precision theoretical calculations. While quantum electrodynamics effects are very well known, nuclear structure corrections are presently the largest source of uncertainty and consequently the bottle-neck for fully exploiting the experimental precision in extracting nuclear radii.
Utilizing techniques and methods developed in few-body nuclear physics, we have been able to provide the so far most precise determination of nuclear structure corrections to the Lamb shift.

I will present our recent calculations for light muonic atoms, where we use chiral effective field theory potentials and perform a study
of the uncertainties coming from the order-by-order chiral expansion.

16

Strangeness S=-3 and -4 baryon-baryon interactions in chiral effective field theory

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The Jülich-Bonn-Munich Collaboration has applied chiral effective field theory
to investigate the baryon-baryon interaction involving hyperons.
These studies, performed so far up to next-to-leading order (NLO) in the chiral
expansion, have shown that for the strangeness $S = -1$ (ΛN, ΣN)
and $S = -2$ ($\Lambda\Lambda$, ΞN) sectors a consistent and satisfactory description
of the available scattering data and experimental constraints can be achieved within the
assumption of broken SU(3) flavor symmetry. In addition, applications of the resulting potentials
in bound-state calculations for light hypernuclei led to results close to the empirical values.

In the present contribution we discuss a possible extension of this approach to
strangeness $S = -3$ and $S = -4$ baryon-baryon systems where empirical information is
rather scarce. Specifically we address the question in how far measurements of two-body
correlation functions in heavy-ion collisions and/or in high energetic proton-proton
scattering can be used to pin down the interaction in channels like
$\Xi\Lambda$ or $\Xi\Xi$, at least on a semi-quantitative level.

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Precision calculations of charge radii of light nuclei

Authors: Andreas Nogga[1]; Arseniy Filin[2]; Christopher Körber[2]; Daniel Möller[2]; Evgeny Epelbaum[2]; Hermann Krebs[2]; Patrick Reinert[2]; Vadim Baru[2]

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We present a high-precision calculation of the deuteron, triton, ^{3}He and ^{4}He charge form factors based on the latest two- and three-nucleon forces, and charge density operators derived up through the fifth order in the chiral effective field theory.

We predict the values of the structure radius and the quadrupole moment of the deuteron, the ^{4}He charge radius, and the isoscalar combination of the 3N charge radii $(r^2(^3\text{H}) + 2r^2(^3\text{He}))/3$. A comprehensive and systematic analysis of various sources of uncertainty in all our predictions is performed.

Using the predicted value for the deuteron structure radius together with the very accurate atomic data for the difference of the deuteron and proton charge radii we extract the charge radius of the neutron.

Finally, using the predicted isoscalar combination of the 3N charge radii and preliminary experimental data on the ^{3}He charge radius we estimate the charge radius of the triton.

18

Explicit renormalization of the nucleon-nucleon interaction in chiral EFT and non-perturbative effects.

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Nucleon-nucleon interaction is studied within chiral effective field theory with a finite cutoff at next-to-leading order in the chiral expansion. The leading order interaction is resummed non-perturbatively, whereas the next-to-leading-order terms are taken into account in a perturbative manner. Explicit renormalizability of such a scheme is proven in certain important cases. In particular, it is verified whether the power-counting breaking terms originating from the integration regions with large momenta can be absorbed by the renormalization of the low energy constants. The importance of non-perturbative effects is analyzed in detail.

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Patterns of C- and CP-violation in hadronic η and η' three-body decays

Author: Hakan Akdag[1]

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We construct hadronic amplitudes for the three-body decays
$\eta^{(\prime)} \to \pi^+\pi^-\pi^0$ and $\eta' \to \eta\pi^+\pi^-$ in a non-perturbative fashion,
allowing for C- and CP-violating asymmetries in the $\pi^+\pi^-$ distributions.
These amplitudes are consistent with the constraints of analyticity and unitarity. We find that the currently most accurate Dalitz-plot distributions taken by the KLOE-2 and BESIII collaborations confine the patterns of these asymmetries to a relative per mille and per cent level, respectively.
Our dispersive representation allows us to extract the individual coupling strengths of the C- and CP-violating contributions arising from effective isoscalar and isotensor operators in $\eta^{(\prime)} \to \pi^+\pi^-\pi^0$ and an effective isovector operator in $\eta' \to \eta\pi^+\pi^-$, while the strongly different sensitivities to these operators can be understood from chiral power counting arguments.

20

Study of deuteron-dark matter scattering within the χEFT framework

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In this work we studied the deuteron-WIMP scattering, assuming the latter to be a Dirac particle. In order to describe the WIMP-nucleon interaction we used the χEFT framework, an EFT based on chiral symmetry which has pions and nucleons as effective degrees of
freedom.
The Lagrangian interaction terms have been obtained by placing the WIMP as an external source in the QCD Lagrangian. Therefore, considering only interactions invariant under parity, charge conjugation and time-reversal symmetries, we have examined five WIMP and
quarks interaction types (scalar, pseudoscalar, vector, axial and tensor).
We have applied this program to study the nuclear response to DM scattering up to second chiral order and finally to calculate the rate of WIMP scattering in a target of liquid deuterium. With respect to other calculations in the literature, we have included systematically the contributions of two-body currents and treated quark-WIMP vertex of tensor type. We plan to apply this formalism to study also helium-DM scattering since liquid helium has been proposed as a possible target for a new direct detection experiment.

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Two-particle scattering from finite-volume quantization conditions using the plane wave basis

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We propose an alternative approach to L\"uscher's formula for extracting two-body scattering phase shifts from finite volume spectra with no reliance on the partial wave expansion. We use an effective-field-theory-based Hamiltonian method in the plane wave basis and decompose the corresponding

matrix elements of operators into irreducible representations of the relevant point groups. The proposed approach allows one to benefit from the knowledge of the long-range interaction and avoids complications from partial wave mixing in a finite volume. We consider spin-singlet channels in the two-nucleon system and pion-pion scattering in the ρ-meson channel in the rest and moving frames to illustrate the method for non-relativistic and relativistic systems, respectively. For the two-nucleon system, the long-range interaction due to the one-pion exchange is found to make the single-channel L\"uscher formula unreliable at the physical pion mass. For S-wave dominated states, the single-channel L\"uscher method suffers from significant finite-volume artifacts for a $L=3$˜fm box, but it works well for boxes with $L>5$˜fm. However, for P-wave dominated states, significant partial wave mixing effects prevent the application of the single-channel L\"uscher formula regardless of the box size (except for the near-threshold region). Using a toy model to generate synthetic data for finite-volume energies, we show that our effective-field-theory-based approach in the plane wave basis is capable of a reliable extraction of the phase shifts. For pion-pion scattering, we employ a phenomenological model to fit lattice QCD results at the physical pion mass. The extracted P-wave phase shifts are found to be in a good agreement with the experimental results.

22

New insights into the nucleon form factor and proton radius from dispersive analysis

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We present a combined analysis of the electromagnetic form factors of the nucleon in the space- and timelike regions using dispersion theory.
Our framework provides a consistent description of the experimental data over the full range of momentum transfer, in line with the strictures from analyticity and unitarity. The statistical uncertainties of the extracted form factors are estimated using the bootstrap method, while systematic errors are determined from variations of the spectral functions.
We also perform a high-precision extraction of the nucleon radii and find good agreement with previous analyses of spacelike data alone. For the proton charge radius, we find

$r_E^p = 0.840^{+0.003+0.002}_{-0.002-0.002}$ fm,

where the first error is statistical and the second one is systematic.
The Zemach radius and third moment are in agreement with Lamb shift measurements and hyperfine splittings.
The combined data set of space- and timelike data disfavors a zero crossing of $\mu_p G_E^p/G_M^p$ in the spacelike region.
Finally, we discuss the status and perspectives of modulus and phase of the form factors in the timelike region in the context of future experiments as well as the onset of perturbative QCD.

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Neutron-antineutron oscillation and the deuteron lifetime

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A framework based on chiral effective filed theory to treat nuclear physics of baryon-number violation by two units is discussed. Neutron-antineutron oscillation and its relation to the deuteron lifetime is used as an application to illustrate this framework. The emphasis is given to how a consistent power counting is built and what statements can be drawn out of it.

24

Dispersive approach to strong three-body decays of η and η' mesons

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I present a dispersion-theoretical analysis of the strong three-body decays in the η and η' sector. Based on analyticity and unitarity the dispersion relations resum the leading $\pi\pi$- and $\pi\eta$-rescattering effects to all orders, with the resulting amplitudes being solely dependent on the respective two-body scattering phase shifts. Due to the small available phase space only three decay channels are physically allowed: the two isospin breaking transitions $\eta/\eta' \to 3\pi$ and the isospin conserving transition $\eta' \to \pi\pi\eta$. Combining our dispersive representation of $\eta \to 3\pi$ with ChPT constraints, a fit to the high-statistics A2 and KLOE-2 Dalitz-plot distributions enables us to extract the light-quark mass double ratio Q. We update our previous analysis of $\eta' \to \pi\pi\eta$ by performing fits to new high-statistics measurements from A2 and BESIII. For the process $\eta' \to 3\pi$, we include both elastic two-pion rescattering corrections to the isospin-breaking decay amplitude as well as the inelastic effect due to an isospin-conserving decay $\eta' \to \pi\pi\eta$ and subsequent isospin-breaking $\pi\eta \to \pi\pi$ rescattering. In this way, the inelastic contribution to the unitarity relation connects all three decays. The resulting dispersive description of $\eta' \to 3\pi$ is fitted to the first available measurements of the Dalitz-plot distributions from BESIII.

25

A review on theoretical calculations of pi0 lifetime

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The neutral pi meson has a prominent role among all hadrons as being the lightest of them. The most important decay mode is the process into two photons, and it saturates the pi0 decay width by almost 99%. This is a fundamental process also from the theoretical point of view, connected with the famous chiral anomaly. The overview of the theoretical calculations will be presented

together with a comparison with experimental measurements. Impact on other processes will be briefly covered.

26

Review of light quark mass ratio determination via η→3π decay

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In this talk, we will show how $\eta \to 3\pi$ is the golden channel for determining the light quark mass ratio from experiment. We will review the different extractions and uncertainty assessment. The results will be compared with lattice QCD determinations and the opportunities for further improvement will be discussed.

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Two-loop calculation of the nucleon self-energy

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The nucleon-self energy
is calculated in SU(2) covariant chiral perturbation theory to study the pion mass dependence of the nucleon mass up to chiral order $O(q^6)$, i.e., including all two-loop diagrams.
Applying an algorithm from Tarasov (1997), the mathematical expressions of the diagrams were expressed by a small set of (scalar) master integrals.
These master integrals are solved as a chiral expansion in d dimensions, using the strategy of regions to differentiate the infrared singular and regular part.
Extended on-mass-shell renormalization is applied, making the renormalized expressions consistent with the power counting.

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Nuclear forces in a manifestly Lorentz-invariant formulation of chiral EFT

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We develop a systematic approach for chiral nuclear forces by applying time-ordered perturbation theory to manifestly Lorentz-ivariant formulation of chiral effective field theory. The effective potential and the scattering equation (Kadyshevsky equation) are obtained within the same framework.

Restricting the non-perturbative treatment to the (non-singular) leading order potential and assuming the validity of perturbation theory for higher-order interactions, one can systematically remove all divergences from the amplitude and, therefore, employ arbitrarily large values of the cutoff. Alternatively, the full effective potential can be treated non-perturbatively by taking the cutoff of the order of the hard scale. The milder UV behavior then offers a larger flexibility regarding admissible cutoff values.

Along this line, we have studied chiral two-body force up to next-to-next-to-leading order and achieved a rather good description of phase shifts and deuteron properties, although it is computationally more demanding as compared to its non-relativistic counterpart. We expect that our approach should lead to a better description of systems with larger numbers of nucleons.

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Analysis of Tcc including chiral dynamics and three-body cut

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A coupled-channel approach is applied to the charged tetraquark state T_{cc} recently discovered by the LHCb Collaboration with special attention paid to the three-body dynamics due to the finite life time of the D^*. The low-energy expansion of the D^*D scattering amplitude is performed and the low-energy parameters (the scattering length and the effective range) are extracted. The compositeness parameter of the T_{cc} is found to be close to unity, which implies that the T_{cc} is a hadronic molecule, generated by the interactions in the $D^{*+}D^0$ and $D^{*0}D^+$ channels. With help of heavy-quark spin symmetry, an isoscalar D^*D^* molecular partner of the T_{cc} with $J^P = 1^+$ is predicted under the assumption that the DD^*-D^*D^* coupled-channel effects can be neglected.

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Pion-mass dependence of $\gamma^{(*)}\pi \to \pi\pi$ and $\pi\pi \to \pi\pi$

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Recent years have witnessed drastic progress in the computation of hadronic
scattering via lattice QCD. Nevertheless, computations are often performed
at unphysically high pion masses. Here, we extrapolate lattice results of the

anomalous $\gamma^{(*)}\pi \to \pi\pi$ scattering to the physical pion mass via a dispersive framework, extract the associated chiral anomaly and the radiative coupling of the ρ-resonance to $\pi\gamma$. In addition, we confront unitarized 1- and 2-loop ChPT with $\pi\pi \to \pi\pi$ data, determine the characteristics of the ρ and assess the chiral convergence. The talk is based on arXiv:2110.11372 and arXiv:2009.04479.

31

Review of the experimental activity at RIKEN to explore the three-nucleon interactions

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Understanding the nuclear properties from bare nuclear forces is one of the main topics in nuclear physics. The importance of three-nucleon forces (3NFs), which appear when more than two nucleons interact, has been indicated in various nuclear phenomena, such as few-nucleon scattering, nuclei binding energies, and state equation of nuclear matter.

Nucleon-deuteron (Nd) scattering, where numerically exact solutions of the corresponding Faddeev equations for any 2N- and 3N-forces are feasible, offers a good opportunity to study dynamical aspects of 3NFs, that are momentum, spin, and isospin dependences. It provides not only cross sections but also a variety of spin observables at different incident nucleon energies.

Signatures of 3NF effects in the Nd elastic scattering was pointed out for the first time by Wita{\l}a et al., in 1998 [1]. Clear signals from 3NFs were found around the cross section minimum occurring at the center of mass angle around 120 degrees for incident energies above 70 MeV/nucleon. Since then, we have performed the measurements of elastic deuteron-proton scattering with a RIKEN polarized deuteron beam, providing precise data of the cross section (70 and 135 MeV/nucleon), all deuteron analyzing powers (70, 100, 135, 190, 250, 300 MeV/nucleon), and polarization transfer coefficients (135 MeV/nucleon).
In the workshop, I review the experimental activity at RIKEN to explore the three-nucleon interactions and touch upon our future plan.

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32

Renormalization of CP-violating nuclear forces

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Electric dipole moments of nuclei, diamagnetic atoms, and certain molecules are induced by CP-violating nuclear forces. Naive dimensional analysis predicts these forces to be dominated by long-range one-pionexchange processes with short-range forces entering only at next-to-next-to-leading order in the chiral expansion. Based on renormalization arguments we argue that a consistent picture of CP-violating nuclear forces requires a leading-order short-distance operator contributing to 1S0 - 3P0 transitions due to the attractive and singular nature of the strong tensor force in the 3P0 channel. The short-distance operator leads to O(1) corrections to static and oscillating, relevant for axion searches, electric dipole moments. We discuss strategies how the finite part of the associated low-energy constant can be determined in the case of CP violation from the QCD θ¯ term by the connection to charge-symmetry violation in nuclear systems.

33

Measurements of charged and neutral pion electromagnetic polarizabilities at GlueX

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Electromagnetic polarizabilities are fundamental properties of composite systems such as molecules, atoms, nuclei and hadrons. Measurements of hadron polarizabilities can test effective field theories, dispersion theories, and lattice calculations, with the charged pion polarizability providing a test of fundamental symmetries at leading order. Significant progress has been made in measurements of nucleon polarizabilities, with uncertainties at $\approx \pm 0.4 \times 10^{-4} e\ fm^3$ for the proton. However experimental constraints on the charged and neutral pion polarizabilities (CPP and NPP) are much weaker, $\approx \pm 2 \times 10^{-4} e\ fm^3$ for the π^+ and no measurement for the π^0. The CPP and NPP experiments at GlueX will utilize a new technique to measure pion polarizability, Primakoff photo-production of $\pi^+\pi^-$ and $\pi^0\pi^0$ pairs on a high Z target. Details of the experimental setup and technique will be presented in the talk, including the commissioning of a muon detection system constructed for the measurement. The CPP and NPP experiments are currently scheduled to run at JLab in mid-2022.

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OPE of Green functions and its phenomenological applications

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In this talk, we deliver an overview of our most recent results on the operator product expansion of the three-point correlators of chiral currents. Moreover, we present some phenomenological applications of these results within the context of the odd-intrinsic parity sector, such as the decays $\rho \to \gamma\pi$, $\omega \to \gamma\pi$ and the $g - 2$

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Preliminary results for elastic nucleon-pion scattering amplitudes from lattice QCD

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The prospects and difficulties of computing nucleon-pion scattering amplitudes from lattice QCD simulations are illustrated with high-statistics results on a single ensemble of gauge field configurations with dynamical up, down, and strange quarks and a pion mass $m_\pi = 200\mathrm{MeV}$. The stochastic-LapH approach to quark propagation enables an efficient computation of all required correlation functions, and a good statistical precision is achieved for the $I = 3/2$ amplitudes. The $I = 1/2$ channel is considerably more difficult, complicating direct lattice determination of both scattering lengths.

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Low-energy Kbar N interaction from high-energy nuclear collisions

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The two-particle momentum correlation function from high-energy nuclear collisions is beginning to be used to study hadron-hadron interaction. In this talk, the K^-p correlation function is discussed with employing the realistic KbarN-piSigma-piLambda coupled-channel potential based on the chiral SU(3) dynamics. With the reasonable source function parameters, the theoretical calculations well reproduce the recent ALICE data from various source sizes. The coupled-channel effect and source size dependence of the correlation function are investigated in detail. Finally, the application of femtoscopy to the other hadron systems are discussed.

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Determining the nucleon mass and sigma term from lattice QCD

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We report a preliminary, percent-level determination of the nucleon mass M_N and a roughly 5%-level determination of the sigma term $\sigma_{\pi N}$ from lattice QCD. We find that our M_N extrapolation to the physical point agrees with the PDG average. Next we review the significance of $\sigma_{\pi N}$ for direct dark matter searches, and we explore the sensitivity of this observable over choice of chiral models. For our lattice calculations, we employ Möbius domain wall fermions on $N_F = 2{+}1{+}1$ dynamically, highly-improved staggered quark fermions. We include five pion masses, ranging from 130 MeV to 350 MeV; four lattice spacings, ranging from 0.06 fm to 0.15 fm; and multiple lattice volumes.

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The radiative decay width measurement of the η-meson at GlueX.

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The PrimEx-eta experiment at Jefferson Lab is aiming to measure the radiative decay width of the η-meson with a 3.2$\%$ precision. This projected accuracy will ameliorate the calculation of all η-meson partial decay widths and in particular the hadronic contribution to the muon magnetic moment from lattice QCD. It will provide critical input to determine the η-η' mixing angle and the light quark mass ratio model independently. The first run was performed with the GlueX experimental setup in Hall D in 2019 and the second run in fall 2021. We will discuss the status of the experiment and how the radiative decay width is extracted via the Primakoff effect from the η-meson photoproduction off a helium nucleus. We will also discuss the measurement of Compton scattering off an atomic electron, which is used to control experimental systematics, including the detection efficiency, the luminosity, and the measurement stability over time.

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Fluctuations and phases in baryonic matter

Author: Len Brandes[1]

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The phase structure of baryonic matter is investigated with focus on the role of fluctuations beyond the mean-field approximation. The prototype test case studied is the chiral nucleon-meson model, with added comments on the chiral quark-meson model. Applications to nuclear matter include the liquid-gas phase transition. Extensions to high baryon densities are performed for both nuclear and neutron matter. The role of vacuum fluctuations is systematically explored. It is pointed out that such fluctuations tend to stabilize the hadronic phase characterized by spontaneously broken chiral symmetry, shifting the chiral restoration transition to very high densities. This stabilization effect is shown to be further enhanced by additional dynamical fluctuations treated with functional renormalisation group methods.

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Measurement of the neutral pion transition form factor at low Q2 at Jefferson Lab

Author: Ilya Larin[1]

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The neutral pion transition form factor (TFF) plays an important role in tests of low energy QCD, and in the determination of the hadronic-light-by-light (HLbL) scattering contribution to the muon anomalous magnetic moment, (g-2). Several measurements of this form factor exist in the large space-like Q2region, but the low Q2space-like region remains largely unexplored. This talk will present the details and impact of the proposed precision measurement of the TFF to be carried out in Hall B of Jefferson Lab. This experiment will use a 10.5 GeV electron beam, silicon target, and a low background beamline in Hall B to measure the Primakoff cross-section for neutral pion electro-production. These data will be used to extract the pion TFF in the Q2range of 0.001-0.1 GeV2, and constrain calculations for the HLbL contribution to a muon (g-2) at low Q2. The author acknowledges support from D.O.E. grant DE-FG02-88ER40415

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Deuteron VVCS and nuclear structure effects in muonic deuterium at N3LO in pionless EFT

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We calculate the forward unpolarised doubly-virtual Compton scattering (VVCS) off the deuteron in the framework of pionless effective field theory, up to next-to-next-to-next-to-leading order (N3LO) for the longitudinal and next-to-leading order (NLO) for the transverse amplitude. The charge elastic form factor of the deuteron, obtained from the residue of the longitudinal VVCS amplitude, is used to extract the value of the single unknown two-nucleon one-photon contact coupling that enters the longitudinal amplitude at N3LO.

Using the obtained deuteron VVCS amplitude as a high-precision model-independent input, we examine the two-photon-exchange (TPE) corrections to the Lamb shift of muonic deuterium, and find substantial differences with the recent dispersive evaluations. Namely, the elastic contribution appears to be larger by several standard deviations, thus ameliorating the current discrepancy between theory and experiment on the size of TPE effects. We investigate the correlation between the values of the deuteron charge and Friar radii and argue that it can be used to judge on the quality of a parametrisation of the deuteron charge elastic form factor. We also study other related effects, such as the TPE contribution to the proton-deuteron isotope shift and the spin-independent deuteron generalised polariabilities.

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A1(1260) from lattice QCD

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We report the first determination of universal parameters of the axial a1(1260) resonance from lattice QCD [arXiv:2107.03973 [hep-lat] in press at PRL]. Three-body quantization condition (FVU) is generalized and utilized to extract infinite-volume information from lattice eigenenergies. Subsequently, pole position and residua of the three-body resonance are extracted on the second Riemann sheet. Results are compared to the phenomenological ones.

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pi0-eta-eta' mixing from V->Pgamma and P->Vgamma decays

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An enhanced phenomenological model that includes isospin-symmetry breaking is presented in this letter.
The model is then used in a number of statistical fits to the most recent experimental data for the radiative transitions
$VP\gamma$ ($V = \rho, K^*, \omega, \phi$ and $P = \pi, K, \eta, \eta'$)
and estimations for the mixing angles amongst the three pseudoscalar states with vanishing third-component of isospin are obtained.
The quality of the performed fits is good, e.g.$\tilde{}\chi^2_{\rm min}/{\rm d.o.f} = 1.9$.
The current experimental uncertainties allow for isospin-symmetry violations with a confidence level of approximately 2.5σ.

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A dispersive analysis of low energy pion photo- and electroproduction

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A dispersive representation based on unitarity and analyticity is used to study the low energy $\gamma N \to \pi N$ and $\gamma^* N \to \pi N$ partial wave amplitudes.
Final state interactions of the πN system are critical to this analysis.
The left-hand cut contribution is estimated by invoking $\mathcal{O}(p^2)$ baryon chiral perturbation theory results,
while the right-hand cut contribution responsible for final state interaction effects is taken into account via an Omnes formalism with elastic phase shifts as input.

It is found that a good numerical fit can be achieved with only one subtraction parameter, and the experimental data of the multipole amplitudes E_0^+, S_0^+ in the energy region below the $\Delta(1232)$ are well described when the photon virtuality $Q^2 \leq 0.1\text{GeV}^2$.
Furthermore, we extend the partial wave amplitudes to the second Riemann sheet to extract the couplings of the subthreshold resonance $N^*(890)$.
The values of residue of the multipole amplitudes E_0^+, S_0^+ are almost the same as that of the $N^*(1535)$ resonance, indicating that $N^*(890)$ strongly couples to the πN system.

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The Pole Counting Rule and X, Y, Z States

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The pole counting rule, is a powerful and model-independent method to distinguish a confining state from a hadronic molecule. It has been applied to the explorations of $X(6900)$, $X_1(2900)$ as well as $Z_c(3900)$, $X(3872)$, $X(4660)$, etc. For $X(6900)$, both a confining state and a molecular state are possible, because lacking of enough data. For $X_1(2900)$, the analysis shows that it should be a $\bar{D}_1 K$ molecule, with $J^P = 1^-$ and an iso-singlet interpretation is much more favorable. Finally, it is noted that almost all X, Y, Z particles with exotic quantum numbers can be interpreted as hadronic molecules. The $X(3872)$ is, however, more like a charmonium, since it has a $\bar{c}c$ quantum number.

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The N/D study on the singularity structure of πN scattering amplitudes

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The N/D method is used to study the S_{11} channel low energy πN scattering amplitude. The inputs of left cuts are obtained from various phenomenological models at tree level. With the aid of the production representation, the total phase shifts can be decomposed into different contributions, and it further reveals that the existence of subthreshold resonance $N^*(890)$ doesn't depend on the details of the dynamical inputs. Additionally, it is found that there exist virtual states in partial waves, which are induced by the u channel nucleon exchanges. These virtual states accumulate at the end point of the u channel
segment cut. The end point is hence the essential singularity of the full amplitude on the second sheet of complex s plane.

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Fluctuations and phases in baryonic matter

Author: Len Brandes[1]

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The phase structure of baryonic matter is investigated with focus on the role of fluctuations beyond the mean-field approximation. The prototype test case studied is the chiral nucleon-meson model, with added comments on the chiral quark-meson model. Applications to nuclear matter include the liquid-gas phase transition. Extensions to high baryon densities are performed for both nuclear and neutron matter. The role of vacuum fluctuations is systematically explored. It is pointed out that such fluctuations tend to stabilize the hadronic phase characterized by spontaneously broken chiral symmetry, shifting the chiral restoration transition to very high densities. This stabilization effect is shown to be further enhanced by additional dynamical fluctuations treated with functional renormalisation group methods.

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The JLab Eta Factory (JEF) experiment

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The new experiment, JLab Eta Factory (JEF), in the experimental Hall D at Jefferson Lab will extend the physics potential of the GlueX detector beyond the main spectroscopy program and perform precision measurements of various $\eta^{(\prime)}$ decays with emphasis on rare neutral modes. The physics program of the experiment spans from precision tests of low-energy QCD to search of gauge bosons in the mass range below 1 GeV coupling the SM sector to the dark sector. Photoproduction of highly boosted $\eta^{(\prime)}$ mesons using a tagged photon beam, good detection of recoil proton and multi-photon final states will allow to suppress background and collect high-statistics data sample of η mesons. All these provide many advantages over other $\eta^{(\prime)}$ experiments. The JEF experiment requires to upgrade the inner part of the forward lead glass calorimeter of the GlueX detector with high-granularity, high-resolution lead tungstate PbWO4 scintillating crystals. The calorimeter insert is currently under construction at Jeffeson Lab. The detector will be ready to take data in 2024. An overview of the JEF project will be presented.

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Nucleon-level Effective Theory of μ → e Conversion

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The Mu2E and COMET μ→e collaborations plan to advance branching ratio sensitivities by four orders of magnitude, further constraining new sources of charged lepton flavor violation (CLFV). We formulate a non-relativistic nucleon-level effective theory for this process, in order to clarify what can and cannot be learned about CLFV operator coefficients from elastic μ→e conversion. Utilizing state-of-the-art shell model wave functions, we derive bounds on operator coefficients from existing μ→e conversion and μ→eγ results, and estimate the improvement in these bounds that will be possible if Mu2E, COMET, and MEG II reach their design goals. In the conversion process, we employ a treatment of the lepton Coulomb physics that is very accurate, yet yields transparent results and preserves connections to standard-model processes like β decay and μ capture. The formulation provides a bridge between the nuclear physics needed in form factor evaluations and the particle physics needed to relate low-energy constraints from μ→e conversion to UV sources of CLFV.

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Dispersive determination of low energy pi K interactions

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The determination of low energy πK scattering has been subject to debate during many years. The precise and robust extraction of these processes is relevant for both experimentalist and phenomenologists. In particular, the low energy expansion of the partial waves offers rich information for chiral perturbation theory practitioners and can be compared to modern lattice QCD calculations. Furthermore, the long debated $\kappa/K_0^*(700)$ resonance lives in the vecinity of the $I = 1/2\ \pi K$ scalar threshold. In this talk we present a dispersive, model-independent determination of these low energy interactions, including the low energy expansion parameters, and compare them to previous determinations. We first use a large set of dispersion relations as constrains on combined fits to $\pi K \to \pi K$ and $\pi\pi \to K\bar{K}$ data. Then we implement different sum rules to extract these low energy parameters, producing a final set of data driven dispersive results.

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Overview of TMD studies

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Transverse momentum dependent (TMD) parton distributions provide three-dimensional imaging of hadrons in the momentum space and the correlation with spins. The precise measurement of TMDs is one of the main goals of many JLab12 experiments and future EIC and EicC programs. It has become an important and very active area of hadron physics from both experimental and theoretical aspects. In this talk, I will give an overview of recent progress, present status and future outlook in TMD studies.

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Constraints on the Λ-neutron interaction from charge symmetry breaking of $A = 4$ hypernuclei

Author: Andreas Nogga[1]

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Charge symmetry breaking (CSB) of the Λ-nucleon interaction has been well established by the experimentally known difference of the Λ separation energies of the mirror hypernuclei ${}^4_\Lambda$He and ${}^4_\Lambda$H[1]. At the same time, accurate predictions for these quantities are possible based on solutions of Faddeev-Yakubovsky equations[2].

In this contribution, we employ chiral hyperon-nucleon interactions including the leading CSB contributions to constrain the Λ-neutron interaction. To this aim, we determine the strength of the two arising CSB contact terms by a fit to the differences of the separation energies of these hypernuclei in the 0^+ and 1^+ states, respectively, and then predict Λn scattering lengths[3]. Based on two version of the hyperon-nucleon interaction at next-to-leading order and using different momentum cutoffs, we also estimate uncertainties of these predictions. The impact of the possible changes of the experimental input is discussed in view of recently improved experimental results for the separation energies of ${}^4_\Lambda$He and ${}^4_\Lambda$H.

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Measurement of the neutral pion transition form factor at low Q2 at Jefferson Lab

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The neutral pion transition form factor (TFF) plays an important role in tests of low energy QCD, and in the determination of the hadronic-light-by-light (HLbL) scattering contribution to the muon anomalous magnetic moment, (g-2). Several measurements of this form factor exist in the large space-like Q2region, but the low Q2space-like region remains largely unexplored. This talk will present the details and impact of the proposed precision measurement of the TFF to be carried out in Hall B of Jefferson Lab. This experiment will use a 10.5 GeV electron beam, silicon target, and a low background beamline in Hall B to measure the Primakoff cross-section for neutral pion electroproduction. These data will be used to extract the pion TFF in the Q2range of 0.001-0.1 GeV2, and constrain calculations for the HLbL contribution to a muon (g-2) at low Q2. The author acknowledges support from D.O.E. grant DE-FG02-88ER40415

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Resonance dynamics in U(3) chiral theory and its relevance in the determination of light-quark mass

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I will first review our study of the resonance dynamics in the U(3) chiral theory. Then I will focus on the determination of the light-quark mass by taking the spectral functions from the U(3) chiral theory within the framework of QCD sum rule. It turns out that once the scalar dynamics in the spectral function is properly included, the resulting values of the light-quark mass in the isoscalar scalar QCD sum rules become compatible with those from other approaches.

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Hadron physics results at KLOE-2 experiment

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KLOE and KLOE-2 data (almost 8 fb^{-1}) constitute the largest sample ever collected at an electron-positron collider operating at the ϕ peak resonance.
In total it corresponds to the production of about 24 billion of ϕ mesons whose decays include about 8 billion pairs of neutral K mesons and about 300 million η mesons.
A wide hadron physics program, investigating rare meson decays, $\gamma-\gamma$ interaction, dark forces and hadronic cross section, is thus carried out by the KLOE-2 Collaboration.

The $\eta \rightarrow \pi^0\gamma\gamma$ decay is a test bench for various models and effective theories like VMD (Vector Meson Dominance) or ChPT (Chiral
Perturbation Theory) which predict BR far from experimental value. KLOE-2, with its highly pure η sample produced
in $\phi \rightarrow \eta\gamma$ process, has a new preliminary measurement of this branching ratio.
Following the many contributions KLOE and KLOE-2 has done to Dark Matter searches, an alternative model, where the Dark Force mediator is an hypothetical leptophobic B boson, is investigated in the $\phi \rightarrow \eta B \rightarrow \eta\pi^0\gamma\,, \eta \rightarrow \gamma\gamma$ channel.

A KLOE-2 distinctive feature is also the the possibility to investigate π^0 production from $\gamma\gamma$ scattering by
tagging final-state leptons from $e^+e^- \rightarrow \gamma^*\gamma^*e^+e^- \rightarrow \pi^0e^+e^-$ in coincidence with the π^0 in the barrel calorimeter. KLOE-2 aims to use this process to precisely measure the π^0 decay width into $\gamma\gamma$ to test low-energy QCD dynamics. Progresses made on the $\gamma^*\gamma^* \rightarrow \pi^0$ event counting will be reported.

A search for the P and CP violating decay $\eta \rightarrow \pi^+\pi^-$ has been recently published by KLOE-2 using 1.6˜fb^{-1} of KLOE data.
No signal is observed in the $\pi^+\pi^-$ invariant mass spectrum, and the
upper limit on the branching fraction at 90\% confidence level is B($\eta \rightarrow \pi^+\pi^-$)$< 4.9 \times 10^{-6}$, which is
three times lower than previous KLOE result. A combination of the two KLOE limits will be presented.

Moreover, the search for the double suppressed $\phi \rightarrow \eta\,\pi^+\pi^-$ and the conversion
$\phi \rightarrow \eta\,\mu^+\mu^-$ decays are performed at KLOE-2 with both $\eta \rightarrow \gamma\gamma$ and $\eta \rightarrow 3\pi^0$ final states. Clear signals are seen for the first time.

Finally, preliminary and promising results on the ω cross section measurement in the $e^+e^- \rightarrow \pi^+\pi^-\pi^0\gamma_{\text{ISR}}$ channel using the Initial State Radiation (ISR) method will be also presented.

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$A = 4 - 7$ Ξ hypernuclei based on interactions from chiral effective field theory

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Experimental information on hypernuclei with double strangeness, in particular Ξ systems, is very limited because of low intensity of kaon beams and the extremely short life times of hyperons. In this contribution, I report on an investigation of the possible existence of bound Ξ states in systems with $A = 4 - 7$ baryons using the Jacobi NCSM [1] approach in combination with chiral NN [2] and ΞN [3] interactions. Three shallow bound states for the NNNΞ system (with $(J^\pi, T) = (1^+, 0)$, $(0^+, 1)$ and $(1^+, 1)$) with quite similar binding energies are found. The ${}^{5}_{\Xi}\mathrm{H}(\frac{1}{2}^+, \frac{1}{2})$ and ${}^{7}_{\Xi}\mathrm{H}(\frac{1}{2}^+, \frac{3}{2})$ hypernuclei are also clearly bound with respect to the thresholds ${}^4\mathrm{He} + \Xi$ and ${}^6\mathrm{He} + \Xi$, respectively. A perturbative estimate suggests that the decay widths of these states could be sufficiently small enough for them to be observed in experiment. Such an observation would provide important experimental constraints on ΞN interactions.

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Results on spin sum rules and polarizabilities at low Q^2.

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We will report on recently published experimental results on spin sum rules, and particularly on the generalized spin polarizabilities $\gamma_0(Q^2)$ (for both the proton and neutron) and $\delta_{LT}(Q^2)$ (for the neutron).
The data were taken at Jefferson Lab in Hall A (neutron) and B (proton and deuteron) by experiments E97-110 and EG4, respectively. They covered the very low Q^2 domain, down to $Q^2 \sim 0.02$ GeV^2, where Chiral Effective Field Theory (χEFT) predictions should be valid. While some obervables agree with the state-of-the-art χEFT theoretical predictions, others are in tensions, including $\delta^n_{LT}(Q^2)$ for which χEFT prediction was expected to be robust. This suggests that χEFT does not yet consistently describe nucleon spin observables, even in the very low Q^2 domain covered by the experiments.

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The REDTOP experiment: a low energy meson factory to explore dark matter and physics beyond the Standard model

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The η and η' mesons are almost unique in the particle universe since they are Goldstone boson and the dynamics of their decay are strongly constrained. The integrated eta meson samples collected in earlier experiments have been about ~10^9 events, dominated by the WASA at Cosy experiment, limiting considerably the search for such rare decays. A new experiment, REDTOP, is being proposed, with the intent
of collecting more than 10^{13} eta/yr (10^{11} eta'/yr) for studying of rare η decays.
Such statistics are sufficient for investigating several symmetry violations, and for searches of new particles beyond the Standard Model.
With tagged-eta experiment the fully constrained kinematic of the process allows for searches of light dark matter with a "Missing 4-momentum technique" which, at present, cannot be exploited by any other existing or proposed experiment.
The physics program and the detector for REDTOP will be discussed during the presentation.

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The Muon Proton Scattering Experiment (MUSE) at PSI

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In 2010, high-precision studies of muonic hydrogen found notably smaller values for the charge radius than earlier results that have been extracted from elastic electron-scattering data and through the spectroscopy of atomic hydrogen. The MUon Scattering Experiment (MUSE) at the Paul Scherrer Institute (PSI) has been developed to address this so-called proton-radius puzzle. The experiment will measure elastic electron-proton and muon-proton scattering data with positively and negatively charged beams in a four-momentum-transfer range from 0.002 to 0.08 GeV2. Each of the four sets of data will allow the extraction of the proton charge radius. In combination, the data test possible differences between the electron and muon interactions and two-photon exchange effects. The status of the experiment will be discussed.

- This material is based upon work supported by the National Science Foundation under NSF grant PHY-1913653. The MUSE experiment is supported by the Department of Energy, NSF, PSI, and the US-Israel Binational Science Foundation.

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Overview of GPD Studies

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Generalized Parton distributions (GPDs) are a new theoretical tool that was developed in the late 90s. GPDs not only link the well-known form factors and parton distribution functions but also provide much richer correlation information between the transverse location and the longitudinal momentum of partons. More importantly, they can access the contribution of the orbital angular momentum of quarks (and gluons) to the nucleon spin via Ji's spin sum-rule. Several exclusive physics processes can probe GPDs, including Deeply Virtual Compton Scattering (DVCS), Deep Virtual Meson Production (DVMP), Time-Like Compton Scattering (TCS), as well as the Double DVCS. A brief introduction of the GPDs will be given followed by a review of past, ongoing and future experimental programs at Jefferson Lab (SoLID, CLAS12, etc), Electron-Ion Collider in China and the U.S., and other places.

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HVP contribution to g-2

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Hadronic vacuum polarization currently yields the dominant uncertainty in the Standard-Model prediction for the anomalous magnetic moment of the muon. While the phenomenological approach is only as accurate as the hadronic cross sections used as input, there are several aspects related to chiral dynamics that can be used as cross checks, including pi pi dynamics and the chiral anomaly. In the talk I will give an overview over such aspects, including recent work to extrapolate the isovector HVP contribution to unphysical quark masses.

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VCS and generalized polarizabilities from Mainz and JLab: Overview and new results

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The Generalized Polarizabilities (GPs) are fundamental properties of the nucleon. They characterize the nucleon's response to an applied electromagnetic field, giving access to the polarization densities inside the nucleon. As such the GPs represent a central path towards a complete understanding of the nucleon dynamics. Previous measurements of the proton electric GP at intermediate four-momentum transfer squared have challenged the predictions of theoretical calculations, raising questions in regard to the underlying reasons responsible for a local enhancement of the electric GP. The measurement of the magnetic GP on the other hand promises to quantify the interplay of the paramagnetism and diamagnetism contributions inside the proton. An overview on this topic, new results from JLab and future prospects will be discussed in this talk.

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A theory of dark pions

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We present a complete model of a dark QCD sector with light dark pions, broadly motivated by hidden naturalness arguments. The dark quarks couple to the Standard Model via irrelevant Z-and Higgs-portal operators, which encode the low-energy effects of TeV-scale fermions interacting through Yukawa couplings with the Higgs field. The dark pions, depending on their CP properties, behave as either composite axion-like particles (ALPs) mixing with the Z or scalars mixing with the Higgs. The dark pion lifetimes fall naturally in the most interesting region for present and proposed searches for long-lived particles, at the LHC and beyond. This is demonstrated by studying in detail three benchmark scenarios for the symmetries and structure of the theory. Within a coherent framework, we analyze and compare the GeV-scale signatures of flavor-changing meson decays to dark pions, the weak-scale decays of Z and Higgs bosons to hidden hadrons, and the TeV-scale signals of the ultraviolet theory. New constraints are derived from B decays at CMS and from Z-initiated dark showers at LHCb, focusing on the displaced dimuon signature. We also emphasize the strong potential sensitivity of ATLAS and CMS to dark shower signals with large multiplicities and long lifetimes of the dark pions. As a key part of our phenomenological study, we perform a new data-driven calculation of the decays of a light ALP to exclusive hadronic Standard Model final states. The results are provided in a general form, applicable to any model with arbitrary flavor-diagonal couplings of the ALP to fermions.

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A Low Qˆ2 Measurement of the Proton Spin Structure Function g2p

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We have extracted the spin structure functions g_1 and g_2 of the proton and their moments at Q^2 < 0.13 GeV^2. This data was obtained with the Jefferson Lab polarized electron beam, a polarized solid NH3 target, and the Jefferson Lab Hall A High Resolution Spectrometers. The structure functions were measured by calculating the asymmetry for both transverse and longitudinal kinematics and using it to form polarized cross section differences $\Delta\sigma_{\parallel}(\nu, Q^2)$ and $\Delta\sigma_{\perp}(\nu, Q^2)$. These structure functions were used to form several moments, many of which can be directly compared to predictions of Chiral Perturbation Theory (χPT): $\overline{\Gamma_2}$, δ_{LT}, $\overline{d_2}$, γ_0, and I_{LT}. These results represent the first experimental determination of δ_{LT} for the proton at low Q^2. Current χPT calculations differ in the measured region, and our data shows a strong preference for one of these calculations. Data published in 2004 showed a strong disagreement between neutron δ_{LT} data and chiral theory at low Q^2, this "δ_{LT} Puzzle" has since been well studied, but recently published neutron data shows a new discrepancy, making it very important to study the behavior of this moment for the proton. The proton results shown in this talk agree well with the χPT calculation using a delta power counting scheme and less well with the calculation which uses an epsilon power counting scheme, with the difference in power counting being one known difference between the two.

Summary:

We present proton spin structure function results g_1^p and g_2^p as well as their moments, comparing to leading calculations of chiral perturbation theory. These results show good agreement with one of these calculations for several 0th and 2nd order SSF moments.

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Data-driven dispersive analysis of the $\pi\pi$ and πK scattering

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We present a data-driven analysis of the resonant S-wave $\pi\pi \to \pi\pi$ and $\pi K \to \pi K$ reactions using the partial-wave dispersion relation. The contributions from the left-hand cuts are accounted for using the Taylor expansion in a suitably constructed conformal variable. The fits are performed to experimental and lattice data as well as Roy analyses. For the $\pi\pi$ scattering we present both a single- and coupled-channel analysis by including additionally the $K\bar{K}$ channel. For the latter the central result is the Omn\'es matrix, which is consistent with the most recent Roy and Roy-Steiner results on $\pi\pi \to \pi\pi$ and $\pi\pi \to K\bar{K}$, respectively. By the analytic continuation to the complex plane, we found poles associated with the lightest scalar resonances $\sigma/f_0(500)$, $f_0(980)$, and $\kappa/K_0^*(700)$ for the physical pion mass value and in the case of $\sigma/f_0(500)$, $\kappa/K_0^*(700)$ also for unphysical pion mass values.

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Probing few-body nuclear dynamics via 3H and 3He (e,e' p) cross-section measurements at Jefferson Lab

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While great progress has been made toward understanding the strong nucleon-nucleon (NN) interaction, there is still substantial uncertainty about the short-distance behavior of the nuclear force. Specifically, Quantum Monte Carlo (QMC) calculations using different state-of-the-art NN potential models can still make vastly different predictions at distance scales below 1 fm (small-r). Nucleon pairs at this separation distance are called Short-Range Correlations (SRCs). As a result of their repulsive small-r interaction, nucleons in an SRC pair fly apart from one another with high momenta (high-k). The study of SRCs is a powerful tool to constrain the NN interaction at small-r and high-k, and has significant implications not only nuclear structure, but to other fields as well, such as the astrophysics of neutron stars and the behavior of cold atomic gasses. In this talk, I will present results from the first measurement of the 3He and 3H(e,e'p) reactions in Hall A of the Thomas Jefferson National Accelerator Facility in kinematics in which the measured cross sections are expected to be sensitive to the underlying nucleon momentum distributions in the range 40 to 500 MeV/c. The resulting absolute cross sections were compared to precise cross-section calculations. These results defy the expectation of a 3He/3H ratio approaching unity for protons at high-k. This forces us to re-evaluate our understanding the reaction mechanism, of the A=3 wave function, and even of the NN interaction. The extracted absolute cross sections can be used to understand the shortcomings of current 3He and 3H cross section calculations and as a benchmark for future ones. Including the effects of outgoing nucleon rescattering improves agreement with the data at high missing momentum and suggests contributions from charge-exchange (SCX) rescattering. The isoscalar sum of 3He plus 3H is described by calculations to within the accuracy of the data over the entire pmiss range. This
validates current models of the ground state of the three-nucleon system up to very high initial nucleon momenta.

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First covariant high-precision chiral nucleon-nucleon interaction up to next-to-next-to-leading order

Author: Lisheng Geng[1]

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We construct the next-to-leading and next-to-next-to-leading chiral nucleon-nucleon interaction in covariant baryon chiral perturbation theory. We show that a rather good description of the np phase shifts up to $E_{\rm lab} = 200$ MeV can be achieved with a $\chi^2/\mathrm{d.o.f.}$ less than 1. The resulting potential can be employed in ab initio studies of nuclear structure and reactions in a covariant framework.

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Recent global fits of the polarized and » unpolarized PDFs from JAM collaboration

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The JAM collaboration has carried out several recent works in global QCD analysis, and I will summarize some of them in this talk.
The JAM-20-SIDIS, which was published in 2020, features simultaneous fit of the PDFs and FFs including unidentified charged hadrons and confirms the suppression of the strange quark PDF observed in JAM19.
More recently in October 2021, an analysis using the latest DIS data on helium and tritium from the MARATHON collaboration was published, which reveals an isovector component to the EMC effect at high x using a simultaneous study of nucleon PDFs and nuclear effects.
Later in this year, a simultaneous extraction of both helicity basis PDFs will be available on arXiv, in which we also critically studies the impact of theory assumptions on the spin-dependent PDFs.
Lastly, I will talk about the sea asymmetries ($\overline{u} - \overline{d}$ or $\Delta\overline{u} - \Delta\overline{d}$) extracted with the latest data from the SeaQuest and STAR collaborations.

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Three pion and kaon scattering from lattice QCD

Author: Christopher Culver[1]

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Hadron scattering information can be indirectly accessed through lattice QCD calculations of the finite-volume spectrum of multi-hadron states. The quantization condition connects the finite-volume energies to a description of scattering in the infinite-volume and has been very successful in the two-hadron sector. We will present an extension of the quantization condition to three-particle systems(FVU) and discuss its application to lattice results for three pion and kaon systems.

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Possible bound states of J/ψJ/ψ

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In a recent measurement LHCb reported pronounced structures in the $J/\psi J/\psi$ spectrum. One of the various possible explanations of those is that they emerge from non-perturbative interactions of vector charmonia. It is thus important to understand whether it is possible to form a bound state of two charmonia interacting through the exchange of gluons, which hadronise into two pions at the longest distance. In this paper, we demonstrate that, given our current understanding of hadron-hadron interactions, the exchange of correlated light mesons (pions and kaons) is able to provide sizeable attraction to the di-J/ψ system, and it is possible for two J/ψ mesons to form a bound state.

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Detecting the pure triangle singularity effect through the ψ（2S） decay

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In this talk, the triangle singularity mechanism is investigated in the two reactions of ψ decay, ψ(2S) → $p\bar{p}\eta$ and ψ(2S) →π +π−K+K−. They would generate a very narrow peak in the invariant mass spectrum of final states. In these processes, all the involved vertices are constrained by the experimental data. Thus, we can make a precise prediction here. We expect these effects can be observed by the Beijing Spectrometer and Super Tau-Charm Facility in the future.

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Baryon masses and currents in SU(3) BChPT x 1/Nc

Authors: Ishara Fernando[1]; Jose Goity[2]

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Baryon Chiral Perturbation Theory (BChPT) and the 1/Nc expansion provide systematic frameworks for the strong interactions at low energy. A combined framework of both expansions has been developed and applied for baryons with three light-quark-flavors. The small scale expansion of the combined approach is identified as the ξ-expansion, in which the power counting of the expansions is linked according to O(p) = O(1/Nc) = O(ξ). Results obtained from applying the combined framework to baryon masses, sigma terms and vector & axial-vector currents in SU(3) will be discussed in this talk.

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Towards the Study of Short Range Correlations in Radioactive Nuclei: The transparent nucleus in inverse kinematics

Author: Julian Kahlbow[1]

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Understanding the structure of a strongly-interacting quantum mechanical system such as atomic nuclei is a formidable challenge in physics. Nucleon knockout reactions with high energy probes are widely used to reveal the inner structure of nuclei, however they cannot be applied to study unstable nuclei. We recently demonstrated the feasibility to access Short-Range Correlation (SRC) properties in nuclei with hadronic probes in inverse kinematics, opening the pathway for such studies in short-lived nuclei at upcoming accelerator facilities. The experiment was carried out at the JINR (Russia), a 12C beam at 48 GeV/c impinged on a liquid hydrogen target and the reaction products were measured kinematically complete with the BM@N detector setup. We show that by selecting the fragment in the 12C(p,2p)11B reaction limitations posed by final-state interactions are overcome and single nucleon properties are probed in a single-step knockout reaction. The extracted ground-state distributions are in agreement with theoretical calculations. We probe SRCs in the same way by the break up of SRC pairs in 12C(p,2pN)10B/10Be reactions. We not only identify SRCs in such kinematical conditions for the first time but also deduce factorization and other pair properties from direct measurements. I will discuss the recent results and the future experimental program towards the study of SRCs in radioactive nuclei.

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opening speech

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Chiral Dynamics: Theory and Experiment - A Tribute to Aron Bernstein

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Highlights of BESIII Physics

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Plenary session (Chair: Xiaoyan Shen) / 77

Chiral effective theory in the Higgs sector

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Theoretical aspects of virtual states, bound states, and resonances in hadron physics from Friedrichs model

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Experimental Status on the Proton Charge Radius

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Statistically rigorous analyses of light nuclei with chiral interactions

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Goldstone Boson Dynamics (Chair: Bastian Kubis) / 81

Review of theoretical calculations on pi0 radiative decay width

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Status of pi0, eta and eta’ experimental program in KLOE-II

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Light Meson decays at BESIII

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Dispersive approach to strong three-body decays of eta and eta’ mesons

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Goldstone Boson Dynamics (Chair: Liping Gan) / 85

pi0-eta-eta' mixing from V->Pgamma and P->Vgamma decays

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Goldstone Boson Dynamics (Chair: Bastian Kubis) / 86

A theoretical analysis of the semileptonic decays eta/etaprime–>pi0 l+l- and etaprime–>eta l+l-

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Goldstone Boson Dynamics (Chair: Bastian Kubis) / 87

Patterns of C- and CP-violation in hadronic eta and eta' three-body decays

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Review of light quark mass ratio determination via eta–>3pi

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Theoretical analysis of the doubly radiative decays eta/etaprime–>pi0 gamma gamma and etaprime–>eta gamma gamma

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The JLab Eta Factory (JEF) experiment

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The radiative decay width measurement of the η-meson at GlueX

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Measurement of the pi0 Transition Form Factor via the Primakoff effect

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Pion electronic decay and lepton universality

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Measurements of charged and neutral pion electromagnetic polarizabilities at GlueX

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Short-distance constraints in hadronic-light-by-light for the muon g-2

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HVP contribution to g-2

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OPE of Green functions and its phenomenological applications

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Dilaton chiral perturbation theory and applications

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NNLO Positivity Bounds on Chiral Perturbation Theory for a General Number of Flavours

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Three-pion scattering in the Chiral Perturbation Theory

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The REDTOP experiment: a low energy meson factory to explore dark matter and physics beyond the Standard model

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ChPT and BSM dark mesons

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A dispersive analysis of low energy pion photo- and electroproduction

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The dispersive analysis of pip and piK scattering

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Dispersive determination of low energy pi K interactions

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Dispersive analysis of the Primakoff reaction γK→Kπ

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Spin sum rules and polarizabiities at long distance

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Weak transitions in light nuclei using chiEFT interactions and currents

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An overview on muonic spectroscopy with light nuclei at CREMA

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Precision calculations of charge radii of light nuclei

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Nuclear Equation of State with EFT uncertainties rigorously quantified

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The PrimEx result on the pi0 lifetime

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Hadronic Light-by-light contribution to muon (g-2)

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Corresponding Author: dr_guozhihui@163.com

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Chiral EFT of nucleon polarizabilities and two-photon-exchange corrections in muonic hydrogen

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A high-precision covariant chiral nucleon-nucleon interaction

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Corresponding Author: bingwei@scu.edu.cn

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Constraints on the Lambda-neutron interaction from charge symmetry breaking of A=4 hypernuclei

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Fast & rigorous constraints on chiral three-nucleon forces from few-body observables

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The Generalized GDH Sum Rule: Measuring the 3He Spin Structure at Low Q2

Author: Chao Peng[1]

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The Gerasimov-Drell-Hearn (GDH) sum rule, as a fundamental relation between real photon absorption and the anomalous magnetic moment to the spin structure of the target. The generalized form of GDH sum rule extends this relation to finite four-momentum transfer squared (Q2). Jefferson Lab experiment E97-110 was carried out with longitudinally polarized electron beam scattering off the polarized 3He target in Hall A. The experiment measured the spin dependent structure functions g1 and g2 for 3He at small scattering angles of 6◦ and 9◦ with a beam energy from 1.1 GeV to 4.4 GeV. The genearlized GDH sum and moments of the spin dependent structure functions were extracted by integrating the measured g1 and g2 over the quasi-elastic and resonance region, and beyond at low Q2
from 0.02 to 0.3 GeV2. The data in this low Q2 region benchmarks predictions regarding
the neutron spin structure by Chiral Perturbation Effective Field Theories.Recovery of the real-photon point (Q2 → 0) for the generalized GDH sum rule is also tested with the low Q2 results. In this talk, we will present the experimental results of various moments for 3He.

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Nucleon Polarizabilities from Few-Nucleon Systems

Author: Harald W. Griesshammer[1]

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An Update Low-energy Compton scattering probes the nucleon's two-photon response to electric and magnetic fields. It tests the symmetries and strengths of the interactions between constituents, and with photons. For convenience, this energy-dependent information is often compressed into the two scalar dipole polarizabilities α_{E1} and β_{M1} at zero photon energy. In addition, spin polarizabilities are particularly interesting since they parametrize the stiffness of the spin in external electro-magnetic fields (nucleonic Faraday effect) and probe the spin-dependent pion-nucleon interaction. Combined with emerging lattice QCD computations, polarizabilities provide stringent tests of chiral symmetry and hadron structure. Compton scattering in light nuclei also tests the chiral symmetry of the charged pion-exchange contribution to nuclear binding. %This talk focuses on the first-ever description of 4He. It uses the transition-density formalism, an efficient and general method for calculating interactions of external probes with light nuclei. One- and two-body transition densities that encode the nuclear structure of the target are evaluated once and stored. They are then convoluted with an interaction kernel to produce observables. The same densities can be used with different kernels for any reaction in which a probe interacts perturbatively with the target. The method exploits factorization between nuclear structure and interaction kernel in Chiral EFT at energies $\sim m_\pi$. It takes full advantage of the numerical power of modern few-nucleon methods, is markedly more computationally efficient and applicable to a wide array of nuclei and reactions. %The 4He Compton results converge well order-by-order and are in good agreement with the data between 50 and $90\ \mathrm{MeV}$, with the expected residual dependence on the NN and 3N potential. However, data appear noisier than the reported experimental uncertainties allow for, so an extraction of the polarizabilities is not attempted.

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Pion electronic decay and lepton universality

Author: Dinko Počanić[1]

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Involving only light elementary particles, charged pion decays are characterized by simple dynamics, few available decay channels, and extremely well controlled radiative and loop cor rections. The comparative simplicity of pion (and muon) decays allows them to be described with unprecedented precision within the Standard Model, (SM), typically with relative un certainties of ~ 10−4 or lower, reflecting the strong influence of the applicable SM symmetries. Given the highly precise SM theoretical description, pion decays are used as selective and sensitive probes of SM parameters, and of possible SM extensions. In particular, V −A helic ity suppression of the π + ⟶ e +νe(γ), or πe2(γ) decay amplifies the sensitivity to pseudoscalar terms by a factor of ~ 8000, enabling indirect searches for non-SM pseudoscalar terms, as well as scalar and tensor terms, through loop effects, with good sensitivity to interesting regions of the beyond-SM parameter space, such as supersymmetric extensions.

Experimental data on the allowed rare electronic decay of charged pions: πe2(γ) , the muon radiative decay, μ + ⟶ e +νeν¯μγ as well as the semileptonic, π + ⟶ π 0 e +ν(γ), or πe3(γ) decay, present an internally consistent picture, so far in excellent agreement with SM predictions. However, experimental accuracy is lagging behind that of the theoretical description for all above processes. The PEN experiment at PSI is studying the πe2(γ) decay with the primary goal to reach a relative precision of 5 × 10−4 in Rπ e/μ, its branching ratio. We review the current status of the field, the PEN research program, the present status of the PEN data analysis, and the expected uncertainty limits.

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Two-nucleons with various methods

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Lattice QCD calculations of two-nucleon systems have suffered from a significant systematic uncertainty for more than a decade. Two different methods of computing the interaction energy have yielded qualitatively different solutions: the use of local creation operators yields deeply bound di-nucleon systems, while calculations that use momentum space creation operators or the HAL QCD potential observe both di-nucleon systems to be unbound. These observations have been made with heavy pions masses where the stochastic signal-to-noise is exponentially larger than at light pion masses. This is not an academic exercise, but a challenge that must be overcome in order for the lattice QCD and broader physics communities to have confidence in lattice QCD calculations of two-nucleon (two-baryon) interactions and two-nucleon electroweak matrix elements. I will present progress that is being made in computing the two-nucleon system with all methods in use, the local creation operators, momentum space creation operators and the HAL QCD potential, for the first time on the same set of gauge configurations. This will enable us to isolate the discrepancy in the spectrum to the method used, and hopefully, resolve this long-standing discrepancy.

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Improved Standard-Model prediction for the dilepton decay of the neutral pion （20’）

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Hadron physics results at KLOE-2 experiment

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Large-N_c constraints for Beyond the Standard Model few-nucleon currents in effective field theory

Author: Thomas R. Richardson[1]

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Low energy experiments that search for Beyond the Standard Model (BSM) physics often rely on nuclear targets.
Therefore, it is imperative that we obtain a clear theoretical picture of the nuclear physics involved.
Effective field theory (EFT) provides a model-independent framework to capture the nuclear physics in terms of few-nucleon currents.
However, every operator in an EFT is accompanied by an undetermined low energy coefficient that must be determined from data or a nonperturbative quantum chromodynamics (QCD) calculation such as a lattice calculation.
For many processes, these determinations are not yet possible; thus, other theoretical constraints are necessary in order to guide the interpretation of experimental bounds.
Here, we review recent constraints obtained from the large-N_c limit of QCD, where N_c is the number of colors, for BSM few-nucleon currents relevant for neutrinoless double beta decay and dark matter direct detection.

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Status of pi0, eta and eta' experimental program in KLOE-II

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Isospin breaking effects in radiative corrections to the axial charge in neutron beta decay

Author: Leendert Hayen[1]

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Precision searches in neutron beta decay have been at the inception and continued testing of the Standard Model, fueled in part by progress in electroweak radiative corrections. Recently, a substantial shift in the evaluation of the so-called γW box have caused a significant shift in V_{ud}, the up-down CKM matrix element, inspiring substantial additional research including radiative corrections to the weak axial charge. The latter is additionally a clean channel when looking for exotic right-handed currents by comparing to precision lattice QCD results. As additional electroweak radiative corrections can mimic New Physics, we have performed heavy-baryon effective field theory calculations and quantify the effects of explicit isospin symmetry breaking. We will present the current state of the art and report on progress and future paths.

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Dispersive analysis of the Primakoff reaction γK→Kπ

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Recent results from NA62 (20')

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