HHIQCD2024

Monday, October 14, 2024 - Friday, November 15, 2024

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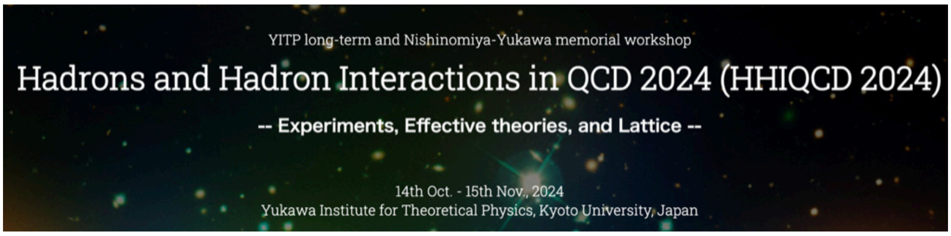

Book of Abstracts

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Seminar (1,2 week) / 4

QCD in the chiral SU(3) limit from baryon masses on Lattice QCD ensembles

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The baryon masses on CLS ensembles are used to determine the LEC that characterize QCD in the flavor-SU(3) limit with vanishing up, down, and strange quark masses.[1,2]
Here we reevaluate some of the baryon masses on flavor-symmetric ensembles with much-improved statistical precision, in particular for the decuplet states. These additional results then lead to a more significant chiral extrapolation of the Lattice data set to its chiral SU(3) limit. Our results are based on the chiral Lagrangian with baryon octet and decuplet fields considered at the one-loop level.[3,4]
Finite-box and discretization effects of the Lattice data are considered systematically. While in our global fit of the data we insist on large-Nc sum rules for the LEC that enter at N3LO, all other LEC are unconstrained. In particular, we obtain values for the chiral limit of the pion decay constant and the isospin-limit of the quark-mass ratio compatible with the FLAG report.[5]

[1] arXiv:1801.06417
[2] arXiv:2301.06837
[3] arXiv:2209.10601
[4] arXiv:2309.09695
[5] arXiv:2406.07442

Nishinomiya-Yukawa workshop / 5

The dispersive approach to nonperturbative QCD

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We propose a new analytical nonperturbative formalism, in whcih a dispersion relation obeyed by a correlation function is treated as an inverse problem. Given the operator product expansion of the correlation function in the deep Euclidean region as inputs, we solve for resonance properties at low energy directly from the dispersion relation. We demonstrate the power of this approach by presenting the analysis of nonperturbative QCD observables, including the rho meson mass, the glueball masses, the topological susceptability, and the leading-twist pion distribution amplitude.

1-day workshop (5th week) / 8

User driven quantum simulations with Rydberg atoms

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We review recent proposals to quantum simulate lattice gauge theories with configurable arrays of Rydberg atoms. We discuss possible implementations with remote access of facilities open to the general public. We discuss new methods to measure the entanglement entropy using a single copy of quantum systems.

Seminar (1,2 week) / 10

Where we are in understanding parton distributions from first principles

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Understanding how hadrons are made by quarks and gluons from Quantum Chromodynamics (QCD), the underlying theory of strong interaction, is a holy grail in theoretical physics. I will review where we are in this quest 10 years after the invention of the Large Momentum Effective Theory.

Seminar (1,2 week) / 11

Pions in nuclear and neutron star matter and the effective chiral Lagrangian.

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In most equations of state, the electron chemical potential in neutron star (NS) matter reaches the value of the free pion mass at rather moderate baryon densities. This would lead to pionization of NS matter when negative pions replace electrons. The repulsive s-wave pion-neutron interaction could prevent this.
We apply the effective chiral Lagrangian at the second chiral order to construct the s-and p-wave pion scattering amplitudes constrained by the on-threshold scattering data. The pion polarization operator including the nucleon short-range correlations is derived, and the pion spectrum is calculated. The importance of using the unitarized amplitudes is emphasized. The possibility of pionization of NS matter is analyzed for different forms of nuclear symmetry energy. Also, the possibility of the p-wave (pi+) and (p+-pi-) condensation is reexamined.
As has been known for decades, the p-wave piN scattering produces new branches in the pion spectrum at finite pion momenta in the NS matter. Taking into account the mean-field potentials acting on the nucleons we show that these new branches continue up to the vanishing pion momentum. The influence of these branches on the possibility of pion condensation is discussed.
strong text

Seminar (4th week) / 12

Generative modeling in neutron star physics

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Two recent applications of generative machine learning models to neutron star physics will be presented.

i) An anomaly detection framework based on normalizing flows (NF) models to detect the presence of a large (destabilizing) dense matter phase transition in neutron star (NS) observations of masses and radii, and relate the feasibility of detection with parameters of the underlying mass-radius sequence. The NF models allow to determine the likelihood of a first-order phase transition in a given set of M(R) observations featuring a discontinuity.

ii) An inference framework based on conditional variational autoencoders to reconstruct the neutron star equation of state from a given set of mass-radius observations will be presented.

Nishinomiya-Yukawa workshop / 13

Learning Hadron Interactions from Lattice QCD and Femtoscopy

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In this study, we delve into nuclear forces governed by Quantum Chromodynamics (QCD) utilizing the HAL QCD method alongside Femtoscopy. These methodologies offer valuable insights into hadron-hadron interactions derived from Lattice QCD simulations and empirical data from collision experiments. I will present our approach of using neural networks to model potential functions, which are learned unsupervisedly from NBS wave functions. This enables the neural networks to represent these potentials in a Schrödinger-like equation for detailed hadron interaction analysis. For Femtoscopy, we initially demonstrate the feasibility of extracting physical potentials from correlation data using a supervised learning approach. In the end, I will introduce the potential for joint learning from both Lattice QCD and Femtoscopy data to enhance our understanding of hadron interactions.

1-day Workshop (1st week) / 14

Examination of the $\phi - NN$ bound-state problem with HAL QCD $N - \phi$ potentials

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The lattice QCD analysis of the HAL QCD Collaboration has recently derived
spin $3/2$ $N-\phi$ potential based on the $(2+1)$-flavor lattice QCD simulations near the physical point $m_\pi \simeq 146.4$ MeV and $m_K \simeq 525$
MeV on a large lattice space- time volume $\simeq (8.1 \text{ fm})^4$.
We looked closely at phi-meson (ϕ) and two nucleons (NN) system making use of the HAL QCD Collaboration $N-\phi$ interactions and the realistic NN Malfliet-Tjon (MT) potential.
The developed Faddeev three-body calculations for $(I)J^\pi = (0)2^-$ $\phi{-}d$ system in maximum spin lead to ground state binding energy of about 7 MeV and a matter radius of about 8 fm. Our results indicate the possibility of the formation of new nuclear clusters.

Seminar (4th week) / 15

First principles calculations of atomic nuclei for constraining the nuclear equation of state and neutron star properties

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Breakthroughs in our treatment of nuclear forces constrained by QCD, the many-body problem, and AI/machine learning techniques are transforming modern nuclear theory into a true first-principles discipline. This allows us to now address some of the most exciting questions at the frontiers of nuclear structure, searches for physics beyond the standard model, and connections to nuclear astrophysics
In this talk I will briefly outline our many-body approach, the valence-space in-medium similarity renormalization group, and how recent advances have enabled breakthrough globally converged calculations of open-shell nuclei to the 208Pb region and beyond. In particular, I will discuss how the neutron skin and dipole polarizability in 208Pb correlate with and constrain the slope of the symmetry energy in the nuclear equation of state to pin down neutron star properties. In addition I will explore the possibility to further refine constraints from mirror charge radii differences as well as dipole quadrupole polarizabilities for constraining tidal deformabilities.

Seminar (1,2 week) / 16

Machine learning on exotic hadrons

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We study the nature of the hidden charm pentaquarks, i.e. the Pc(4312), Pc(4440) and Pc(4457), with a neural network approach in pionless effective field theory. In this framework, the normal fitting approach cannot distinguish the quantum numbers of the Pc(4440) and Pc(4457). In contrast to that, the neural network-based approach can discriminate them. In addition, we also illustrate the role of each experimental data bin of the invariant J/ψp mass distribution on the underlying physics in both neural network and fitting methods. Their similarities and differences demonstrate that neural network methods can use data information more effectively and directly. This study provides more insights about how the neural network-based approach predicts the nature of exotic states from the mass spectrum.

1-day workshop (5th week) / 17

Quantum computing of shear viscosity for 2+1D SU(2) gauge theory

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Relativistic hydrodynamics has been used to study collective behavior of light particles produced in heavy ion collisions. It has been shown that hydrodynamic calculations with a small shear viscosity give results that agree well with experimental data. Furthermore, a holographic calculation showed that the ratio of shear viscosity and entropy density is as small as 1/(4pi) for strongly coupled N=4 supersymmetric Yang-Mills theory, which is consistent with the value extracted from experimental data via hydrodynamic simulations. On the other hand, calculating shear viscosity in QCD is very challenging: Perturbative calculations are not applicable in the temperature range of interest and Euclidean lattice QCD calculations have uncontrolled systematic uncertainties caused by the ill-defined spectral reconstruction problem. In this talk, I will discuss the Hamiltonian lattice approach which enables real-time calculations. I will take the 2+1D SU(2) pure gauge theory as an example and show some results obtained on a small lattice. The calculations take into account the running coupling in the continuum limit and find the ratio of shear viscosity and entropy density is consistent with 1/(4pi). Finally I will discuss a quantum algorithm to calculate the shear viscosity, which may help us to perform calculations on bigger lattices.

Seminar (5th week) / 18

Z3 lattice gauge theory as a toy model of QCD

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The infinite-dimensional Hilbert space of SU(3) gauge field makes the quantum simulation of QCD difficult. In this talk, I would like to propose Z3 lattice gauge theory as a toy model with the finite-dimensional Hilbert space. I will discuss the similarity and difference compared with QCD and the application to quantum simulation.

Nishinomiya-Yukawa workshop / 19

Chiral EFT for nuclear interactions using gradient flow

Author: Evgeny Epelbaum[1]

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Low-energy nuclear structure and reactions can be described in a systematically improvable way using the framework of chiral EFT. This requires solving the quantum mechanical many-body problem with regularized nuclear interactions, derived from the most general effective chiral Lagrangian. To maintain the chiral and gauge symmetries, a symmetry preserving cutoff regularization has to be employed when deriving nuclear potentials. I will present our recent work along this line, which opens an avenue for high-accuracy studies of chiral dynamics beyond the two-nucleon sector.

Lecture / 20

Modern theory of nuclear forces

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The strong interaction between nucleons has been at the heart of nuclear physics since the very beginning of this field. Remarkable progress has been achieved in recent decades towards quantitative understanding of nuclear forces and the corresponding current operators in the framework of chiral effective field theory. Combined with modern ab-initio few-body methods and continuously increasing available computational resources, this approach opens the way for a systematically improvable and model independent description of light nuclei and low-energy dynamics in harmony with the symmetries of quantum chromodynamics. I will discuss different versions of effective field theory for nuclear systems focusing especially on the conceptual foundations, review various techniques to derive nuclear interactions and outline the state-of-the-art and remaining challenges in this field.

1-day Workshop (1st week) / 21

Utilizing Twisted Boundary Conditions to Determine DD* Scattering Phase Shifts

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In this presentation, we explore the low-energy behavior of DD^* scattering phase shifts using twisted boundary conditions. While Lüscher's method is typically employed to calculate scattering phase shifts between two hadrons from energy spectra, it becomes impractical to achieve high-resolution results using only periodic boundary conditions due to volume limitations. Conversely, twisted boundary conditions allow for a more detailed calculation of scattering phase shifts. Our research applies this technique to the DD^* system to gain a deeper understanding of its properties.

1-day workshop (4th week) / 22

Reconciling the HESS J1731-347 constraints with Parity doublet model

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The recent discovery of a central compact object (CCO) within the supernova remnant HESS J1731-347, characterized by a mass of approximately $0.77^{+0.20}_{-0.17} M_\odot$ and a radius of about $10.4^{+0.86}_{-0.78}$ km, has opened up a new window for the study of compact objects. This CCO is particularly intriguing because it is the lightest and smallest compact object ever observed, raising questions and challenging the existing theories.
To account for this light compact star, a mean-field model within the framework of parity doublet structure is applied to describe the hadron matter. Inside the model, part of the nucleon mass is associated with the chiral symmetry breaking while the other part is from the chiral invariant mass m_0 which is insensitive to the temperature/density. The value of m_0 affects the nuclear equation of state for uniform nuclear matter at low density and exhibits strong correlations with the radii of neutron stars. We point out that HESS J1731-347 can be explained as the lightest neutron star for $m_0 \simeq 850$\,MeV.

Seminar (4th week) / 23

Possibility of phase transition on superfluid vortex under Higgs-confinement crossover

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At finite densities of three-flavor QCD, a hadron (confinement) superfluid phase is expected to be realized at low densities, and a color superconducting (Higgs) phase at high densities. It is not well understood whether these two phases are connected with or without a phase transition. In this talk, we consider the Higgs-confinement transition with superfluidity in a $\mathrm{U}(1) \times \mathrm{U}(1)$ lattice model is a simple model. We found that a phase transition occurs on a superfluid vortex, although the bulk system does not exhibit a phase transition. We confirm this phase transition through analytical calculations using weak/strong coupling expansion and Monte Carlo simulations. We also discuss possible scenarios for QCD.

1-day Workshop (1st week) / 24

Characterizing the nuclear models informed by PREX and CREX: a view from Bayesian inference

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New measurements of the weak charge density distributions of ^{48}Ca and ^{208}Pb challenge existing nuclear models. In the post-PREX-CREX era, it is unclear if current models can simultaneously describe weak charge distributions along with accurate measurements of binding energy and charge radii. In this letter, we explore the parameter space of relativistic and non-relativistic models to study the differences between the form factors of the electric and weak charge distributions, $\Delta F = F_{ch} - F_W$, in ^{48}Ca and ^{208}Pb. We show, for the first time, which aspects of mean-field models are the most important in determining the relative magnitude of the neutron skin in lead and calcium nuclei. We carefully disentangle the tension between the PREX-2/CREX constraints and the ability of the RMF and Skyrme models to accurately describe binding energies and charge radii. We find that the nuclear symmetry energy coefficient $S_{\rm V}$ and the isovector spin-orbit coefficient b_4' play different roles in determining ΔF of ^{48}Ca and ^{208}Pb. Consequently, adjusting $S_{\rm V}$ or b_4' shifts predicted ΔF values toward or away from PREX-2/CREX measurements. Additionally, $S_{\rm V}$ and the slope L are marginally correlated given the prior constraints of our Bayesian inference, allowing us to infer them separately from PREX-2/CREX data.

Nishinomiya-Yukawa workshop / 25

Framework for phase transitions between the Maxwell and Gibbs constructions

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By taking the nucleon-to-quark phase transition within a neutron star as an example, we present a thermodynamically consistent method to calculate the equation of state of ambient matter so that transitions that are intermediate to those of the familiar Maxwell and Gibbs constructions can be described. This method does not address the poorly known surface tension between the two phases microscopically (as, for example, in the calculation of the core pasta phases via the Wigner-Seitz approximation) but instead combines the local and global charge neutrality conditions characteristic of the Maxwell and Gibbs constructions, respectively. Overall charge neutrality is achieved by dividing the leptons to those that obey local charge neutrality (Maxwell) and those that maintain global charge neutrality (Gibbs). The equation of state is obtained by using equilibrium constraints derived from minimizing the total energy density. The results of this minimization are then used to calculate neutron star mass-radius curves, tidal deformabilities, equilibrium and adiabatic sound speeds, and nonradial g-mode oscillation frequencies for several intermediate constructions. The equation of state at finite temperature and off-β-equilibrium, constructed from this framework, can be used to study the impact of first-order phase transitions in neutron star mergers and core-collapse supernovae.

Seminar (5th week) / 26

Quantum Simulations of the Schwinger Model: from vacuum to dense matter

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Quantum electrodynamics in 1+1 dimensions (the Schwinger model) exhibits a number of features similar to quantum chromodynamics in 3+1D, including confinement and a fermion condensate, making it the perfect sandbox during the NISQ era. In this talk, I will present new scalable algorithms that use the symmetries and hierarchy of length scales in the Schwinger model (and generally applicable to other confining theories) for simulating the real-time dynamics of hadrons on a quantum computer, and their realization on a 56-site lattice (112 qubits) using IBM's quantum computers. I will also comment on the discretization effects seen when studying heavy-hadrons propagating through a dense medium, such as energy loss and the destruction of entanglement.

1-day workshop (4th week) / 27

Reaching percolation and confromal limits in neutron stars

Author: Michał Marczenko[1]

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In this talk, I discuss the statistically determined equation of state of dense matter that fulfills the multimessenger constraints and determine the properties of dense matter found in neutron stars. I demonstrate that the speed of sound and trace anomaly are driven towards their conformal values at the center of maximally massive NSs. I argue that the local peak of the speed of sound is located at values of energy and particle densities consistent with deconfinement and percolation conditions in QCD matter. I also demonstrate that the curvature of the energy per particle may serve as an approximate order parameter that signifies the onset of strongly coupled conformal matter in the NS core.

talk based is on:
[1] M. Marczenko, L. McLerran, K. Redlich, C. Sasaki, Phys.Rev.C 107 (2023) 2, 025802
[2] M. Marczenko, K. Redlich, C. Sasaki, Phys.Rev.D 109 (2024) 4, L041302

Nishinomiya-Yukawa workshop / 28

Study of Chiral and Axial symmetry in $N_f = 2$ QCD using Mobius Domain Wall Fermions

Author: David Ward[1]

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We report on the ongoing study of symmetry of $N_f = 2$ QCD around the critical temperature. Our simulations of $N_f = 2$ QCD employ the Mobius domain-wall fermion action with residual mass $\sim$ 1MeV or less, maintaining a good chiral symmetry. Using the screening masses from the two point spatial correlators we compare the mass difference between channels connected through symmetry transformation. Our analysis focuses on restoration of the $SU(2)_L \times SU(2)_R$ as well as anomalously broken axial $U(1)_A$. We also present additional study of a potential $SU(2)_{CS}$ symmetry which may emerge at very high temperatures.

1-day workshop (4th week) / 29

The Effect of Isovector Scalar Meson on Neutron Star Matter Based on a Parity Doublet Model

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Co-authors: Masayasu Harada [1]; Takuya Minamikawa [1]

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We study the effect of the isovector-scalar meson a_0(980) on the properties of nuclear matter and the neutron star (NS) matter by constructing a parity doublet model with including the a_0 meson based on the chiral SU(2)$_L$×SU(2)$_R$ symmetry.
We also include the ω-ρ mixing contribution to adjust the slope parameter at the saturation.
We find that, when the chiral invariant mass of nucleon m_0 is smaller than about 800\,MeV, the existence of a_0(980) enlarges the symmetry energy by strengthening the repulsive ρ meson coupling.
On the other hand, for large m_0 where the Yukawa coupling of a_0(980) to nucleon is small, the symmetry energy is reduced by the effect of ω-ρ mixing.
We then construct the equation of state (EoS) of a neutron star matter to obtain the mass-radius relation of NS.
We find that, in most choices of m_0, the existence of a_0(980) stiffens the EoS and makes the radius of NS larger.
We then constrain the chiral invariant mass of nucleon from the observational data of NS, and find that 580 MeV
$lesssim m_0$
$lesssim 860$ MeV for $L_0 = 57.7$ MeV.

Nishinomiya-Yukawa workshop / 30

Grassmann bond-weighted tensor renormalization group approach to 1+1D two-color QCD with staggered fermions at finite density

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Tensor renormalization group is expected to be a promising method to simulate lattice field theories at finite density since it does not suffer from the sign problem. We construct a Grassmann tensor network representing the partition function of 1+1D SU(2) lattice gauge theory coupled with staggered fermions. At finite couplings, a random sampling is applied to discretize the group integration. The

initial bond dimension turns out to be $16K$ where K is the number of SU(2) matrices sampled for each link variable. We introduce an efficient initial tensor compression scheme to reduce the size of initial tensors. Then, Grassmann bond-weighted tensor renormalization group approach is adopted to investigate a phase diagram in the (m, μ) plane with the quark mass m and chemical potential μ. The free energy density, number density, and diquark condensate at different gauge couplings are computed as a function of the chemical potential. We discuss the efficiency of random sampling method, our initial tensor compression scheme, and the future application toward the corresponding higher-dimensional models.

Nishinomiya-Yukawa workshop / 31

Lambda(1405) in the flavor SU(3) limit from lattice QCD

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We perform a numerical study in lattice QCD on $\Lambda(1405)$ in the flavor SU(3) limit. One of the most promising interpretations of $\Lambda(1405)$ is the so-called two-pole structure: the spectrum corresponding to $\Lambda(1405)$ observed in experiments may be explained by two poles. In order to elucidate such property from lattice QCD, the HAL QCD method is employed, in which hadron interactions are extracted as potentials. Employing configurations in the flavor SU(3) limit, we calculate meson-baryon potentials in the octet and singlet channels, in which the poles corresponding to Lambda(1405) are expected to appear. We find that local potentials both in octet and singlet channels have singular behaviors at the vanishing point of NBS wave functions, which prevent us from reliably extracting binding energies. In this talk, I present two analyses that avoid such singular behaviors: one is the analysis by taking a linear combination of the NBS wave functions in the octet channel under certain assumptions, and the other is by introducing separable potentials in the HAL QCD method instead of the standard local approximation usually employed. I also discuss the physical interpretations of our results, including the singular behaviors of the local potentials.

Nishinomiya-Yukawa workshop / 32

Application of the Worldvolume HMC method to lattice field theories

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The Worldvolume Hybrid Monte Carlo (WV-HMC) method [arXiv:2012.08468] is a reliable and versatile algorithm for solving the sign problem. This method eliminates the ergodicity problem inherent in methods based on Lefschetz thimbles at low cost. In this talk, I will report recent results on the application of the WV-HMC method to lattice field theories. The discussion will focus on the Hubbard model, which is one of the simplest dynamical fermion systems that have the sign problem, and on pure Yang-Mills theories with topological terms.

Nishinomiya-Yukawa workshop / 33

Emergent Symmetries and Entanglement Suppression

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Symmetry is one of the most fundamental principles in nature, but where does it come from? I will discuss recent efforts to understand origin of symmetry from the perspective of quantum information and consider two very different physical systems with emergent symmetries. The first involves non-relativistic neutron-proton scattering in low-energy QCD, where the suppression of spin entanglement leads to Wigner's spin-flavor symmetry and Schrodinger's non-relativistic conformal invariance. The second system concerns two-Higgs-doublet models, the prototypical example for electroweak symmetry breaking and physics beyond the standard model, in which case the suppression of flavor entanglement leads to a maximal SO(8) symmetry and gives rise to a Standard-Model-like Higgs boson, as observed in nature.

Seminar (5th week) / 34

The theta angle dependence of the metastable vacuum energy in 2d $\mathbb{C}P^{N-1}$ model

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In this talk, I will discuss metastable vacua of 2d $\mathbb{C}P^{N-1}$ model in the large N limit.In particular we will focus on the theta angle dependence of the metastable vacuum energy.We will see the vacua become unstable at large theta angles due to high decay rates.This work is in collaboration with Tsubasa Sugeno and Kazuya Yonekura.

Seminar (1,2 week) / 35

Baryon-baryon scattering in SU(3)-flavour-symmetric QCD

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Understanding (hyper)nuclear physics from ab initio QCD has been a long-standing goal. By calculating finite-volume spectra on the lattice and using finite-volume quantization conditions, it is possible to determine baryon-baryon scattering phase shifts and bound states. I will discuss the challenges in these calculations, presenting results in the continuum limit at an SU(3) flavour-symmetric point, for the H dibaryon and the deuteron. As a spin-one state, the latter is complicated by the mixing of S and D waves, which we are able to resolve.

1-day Workshop (1st week) / 38

Analysis of bound and resonant states of doubly heavy tetraquaks as hadronic molecules

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Exotic hadrons are important subjects in the hadron physics. These states which lie slightly below the threshold have been expected to be hadronic molecules of two ordinary hadrons.

T_{cc} was reported by the LHCb experiment in 2022 and this state is consistent with an isoscalar state whose J-parity is 1^+. The Breit-Wigner mass relative to the $D^{*+}D^0$ threshold is $-0.273\,\mathrm{MeV}$. Therefore, we consider T_{cc} with $0(1^+)$ as $D^{(*)}D^{(*)}$ molecule where we employ the one boson exchange potential as the interaction. In this analysis, we solve the coupled channel Schrodinger equation due to the heavy quark spin symmetry (HQS). Here, we can explain T_{cc} with $0(1^+)$ as the hadronic molecule well. We also analysis the resonant state of T_{cc} with $0(1^+)$ and bound and resonant states of T_{cc} with other quantum number. However, these states are not obtained in our study. In addition, we investigate the bound and resonant states of T_{bb} as $B^{(*)}B^{(*)}$ molecules. There are many bound and resonant states of T_{bb}. Finally, we introduce the light cloud basis where we can decompose the spin wavefunction into the spins of heavy diquarks and light cloud. This basis classifies the bound and resonant states which are obtained by our analysis by their heavy quark spins and light cloud.

Seminar (4th week) / 39

Surprises on the way to the QCD phase diagram

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Lattice constraints on the QCD phase diagram

A strong fermion sign problem prohibits direct lattice simulations of QCD at finite baryon density, so that knowledge of the phase diagram is limited to small chemical potentials. On the other hand, the phase diagram is severely constrained by information about the chiral limit.
I discuss recent lattice results at vanishing density, which show the chiral phase transition for theories with Nf=2-7 degenerate massless quarks to be of 2nd order, contrary to the predictions of the seminal 1984 paper by Pisarski and Wilczek. Current work in progress demonstrates that this 2nd order nature of the chiral transition does not change as a function of imaginary chemical potential, for which there is no sign problem.
On the other hand, at zero density an emergent chiral-spin symmetric temperature regime has been identified at the physical point, which must continue to finite density. Implications of both findings for the physical QCD phase diagram are discussed.

Nishinomiya-Yukawa workshop / 40

Index of lattice Dirac operators and K-theory

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We mathematically show an equality between the index of a Dirac operator on a flat continuum torus and the η invariant of the Wilson Dirac operator with a negative mass when the lattice spacing is sufficiently small. Unlike the standard approach, our formulation using the K-theory does not require the Ginsparg-Wilson relation or the modified chiral symmetry on the lattice. We prove that a one-parameter family of continuum massive Dirac operators and the corresponding Wilson Dirac operators belong to the same equivalence class of the K^1 group at a finite lattice spacing. Their indices, which are evaluated by the spectral flow or equivalently by the η invariant at finite masses, are proved to be equal.

Nishinomiya-Yukawa workshop / 41

Study of multiquark states based on effective models

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We propose a chiral quark model including the ω and ρ meson contributions in addition to the π and σ meson contributions. We show that the masses of the ground state baryons such as the nucleon, Λc and Λb are dramatically improved in the model with the vector mesons compared with the one without them. The study of the tetraquark Tcc is also performed in a coupled channel calculation and the resultant mass is much closer to the experiment than the result without vector meson contribution. This approach could be applied in future study of multi-quark systems.
[references: Phys. Rev. D 108, 054025 (2023) & Eur. Phys. J. C 83, 12 (2023)]

Seminar (5th week) / 42

Novel Lattice Formulation of 2D Chiral Gauge Theory via Bosonization

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Recently, lattice formulations of Abelian chiral gauge theory in two dimensions have been devised on the basis of the Abelian bosonization. A salient feature of these 2D lattice formulations is that the gauge invariance is exactly preserved for anomaly-free theories and thus is completely free from the question of the gauge mode decoupling. In the present paper, we propose a yet another lattice formulation sharing this desired property. A particularly unique point in our formulation is that the vertex operator of the dual scalar field, which carries the vector charge of the fermion and the "magnetic charge"in the bosonization, is represented by a "hole"excised from the lattice; this is the excision method formulated recently by Abe et al. in a somewhat different context.

1-day Workshop (1st week) / 43

$_{cJ}(2P)$ with hadronic molecules

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Some hadrons are hard to explain as normal hadrons made of quarks and antiquarks, or three quarks. These are called exotic hadrons. Since the Belle experiment reported $X(3872)$ in 2003, more exotic hadrons containing charm quarks have been found. Exotic hadrons are believed to have more complex structures than normal hadrons, but no conclusion has been reached yet.

The $X(3872)$ is one of the most famous exotic hadrons and has been seen in many experiments. It has the same quantum numbers as $_{c1}(2P)$, but its mass is different from what the quark model predicts. It is also very close in mass to the $D^0\bar{D}^{*0}$ threshold, with a difference of 0.04 MeV.

In this study, we analyze $_{cJ}(2P)$ as a mixture of a hadronic molecule state, like a deuteron, and a bare $_{cJ}(2P)$ core, comparing it to $X(3872)$ and others. We consider one-boson-exchange and core-molecule mixture potentials.

Seminar (1,2 week) / 44

Update on the strong coupling alpha_s

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The strong coupling alpha_s is a fundamental parameter of the Standard Model and high accuracy at the 0.5 percent level or better will be required to maximize the potential of the LHC and other experiments.
Lattice QCD is ideally placed to achieve this goal. As a member of the FLAG working group on alpha_s I present an update of the current situation and an outlook on future prospects.

1-day workshop (4th week) / 45

Nuclear matter and neutron stars in the Sakai-Sugimoto model

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In this talk, I will introduce dense baryonic matter in the Sakai-Sugimoto (SS) model, a popular variant of holographic QCD, using a homogeneous Ansatz for isospin symmetric matter and then for nonvanishing isospin chemical potential. I will also show that the isospin contribution to the energy, directly proportional to the symmetry energy, can be computed formally as a moment of inertia of the matter. Then I will show that it corresponds to the chemical potential via a gauge transformation. I will then discuss a technical subtlety of the Chern-Simons term in a model with discontinuous fields.

Finally, I will argue for a new fit of the SS model that leads to phenomenologically acceptable neutron stars.

1-day Workshop (1st week) / 46

Modified homotopy approach for diffractive production in the saturation region

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We present the results of using the homotopy method to solve the nonlinear evolution equation for diffractive production in deep inelastic scattering (DIS). Initially, we introduce part of the nonlinear corrections as the first step in this approach. This allows for an analytical solution to the simplified nonlinear evolution equation, taking into account the initial and boundary conditions. In the next step, we demonstrate that the perturbative procedure can be employed to address the remaining non-linear corrections. The results show that these corrections are small and can be effectively estimated using a regular iterative procedure.

Nishinomiya-Yukawa workshop / 47

Interplay between the weak-coupling results and the lattice data in dense QCD

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We discuss the interplay between two first-principles calculations of QCD at high density: perturbative results in the weak-coupling regime and the recent lattice-QCD result at finite isospin density. By comparing these two results, we verify empirically that the weak-coupling calculations of the bulk thermodynamics and the gap parameter for Cooper pairing between quarks can be applicable down to the quark chemical potential $\mu \sim 1$ GeV. Having verified the validity of the weak-coupling results in QCD at finite isospin density, we discuss possible effects on QCD at finite baryon density, which is relevant for the application to realistic environments such as neutron stars, by using the fact that QCD at finite baryon and isospin density have the common weak-coupling expansions. First, we show the size of the color-superconducting gap at finite baryon density is as small as a few MeV at $\mu = 1$ GeV, which implies that the color-flavor locked phase may be unstable against unpairing up to ~ 1.4 GeV even in the weak-coupling regime. We also introduce a prescription to reduce the ambiguity arising from the undetermined renormalization scale in the weak-coupling calculation by matching with the lattice-QCD data. We demonstrate the effect of such reduction on neutron-star phenomenology by performing the Bayesian analysis.

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[1] Y. Fujimoto, Phys. Rev. D 109, 054035 (2024)
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1-day workshop (4th week) / 48

Four-dimensional equation of state of QCD matter with multiple chemical potentials

Author: Akihiko Monnai[1]

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Elucidation of the QCD phase structure is an important topic in particle and nuclear physics. We construct a four-dimensional equation of state as a function of the temperature and the chemical potentials of net baryon (B), charge (Q), and strangeness (S) for the QCD matter created in nuclear collisions [1]. Lattice QCD simulations and a hadron resonance gas model are considered for the construction. We also develop an efficient numerical method for applying the equation of state to relativistic hydrodynamic models, which can be used for analyses of the nuclear collisions at beam energy scan energies and of different nuclear species at the BNL Relativistic Heavy Ion Collider.

[1] A. Monnai, G. Pihan, B. Schenke, and C. Shen, arXiv:2406.11610 [nucl-th]

1-day workshop (5th week) / 49

Dynamics of different field theory models and applications

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We demonstrate the steps to study the dynamics of a field theory model using a digital computer, with an example of the SYK model. We present calculations on IBM's superconducting quantum computer and state-of-the-art results using various error mitigation techniques. Specifically, we compute the vacuum return probability and out-of-time-order correlators (OTOC) at different times, standard observables for quantifying the chaotic nature of quantum systems.

Next, we consider the two-flavor Gross-Neveu model and compute the real-time evolution of probabilities relevant to the scattering phase shift calculation with a digital quantum computer. We outline the steps for preparing the ground state, generating a Gaussian wave packet, and performing a Quantum Fourier Transform on the quantum device. The phase shift is determined from the time delays measured from normalized probabilities with and without inter-flavor interaction.

Nishinomiya-Yukawa workshop / 50

Tensor Networks for Gauge Theories

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Gauge theories are fundamental to various areas of physics. In high-energy physics, the standard model, which is a gauge theory, explains three of the four fundamental forces of nature. While at high-energy scales quantum chromodynamics can be addressed perturbatively, this approach becomes ineffective at lower energies, necessitating nonperturbative techniques. This naturally leads to the development of lattice gauge theories, which provide a nonperturbative, gauge-invariant regularizations of quantum field theories. Significant progress has been made in studying these theories, particularly through Euclidean Monte Carlo simulations.

However, certain regimes remain challenging within this framework. Fermionic theories at finite density or with an odd number of fermion flavors can suffer from the sign problem, and computing real-time dynamics is difficult as Monte Carlo algorithms are typically formulated in Euclidean spacetime. Recently, several approaches have been explored to overcome these issues. One prominent example is quantum simulation, where lattice gauge theory Hamiltonians are realized on quantum devices.

While the formulation in terms of Hamiltonians is not new, it had a rennaissance in recent years. It is not only well-suited for quantum devices; it also allows for the variational treatment of lattice gauge theories using methods from condensed matter physics. A notable family of ansatz states utilized in this context is tensor networks.

In this talk, I will present an overview of the current advancements in tensor network simulations of lattice gauge theories. The first part will provide a broad overview of tensor networks and the architectures currently in use. In the second part, I will focus on a specific ansatz known as Gauged Gaussian Projected Entangled Pair States (GGPEPS). GGPEPS allows for the construction of tensor network states that describe fermionic matter coupled to dynamical gauge fields with full gauge invariance. These states enable efficient contractions and numerical computations in arbitrary space dimensions, especially when combined with Monte Carlo techniques, and are sign-problem free. I will introduce the GGPEPS states, detail their construction and analytical properties, and demonstrate their numerical capabilities.

Seminar (1,2 week) / 51

Pion and Kaon structure in light front dynamics

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Pion and kaon are one of the simplest meson structures to study the distribution function. In this work, we have calculated the time reversal quark transverse momentum-dependent parton distribution functions (TMDs) in the light-front based holographic model (LFHM) and quark model (LFQM) up to twist-4. We have presented the three dimensional structure of T-even TMDs for both the particles in both models. The transverse structure have been discussed with the help of two dimensional contour plot distribution in momentum space and average quark momenta in both the models. We have taken the overlap representation of LFHM wave function for orbital angular momentum $L_z = 0$ and $L_z = 1$, which makes the calculations more significant. The T-even TMDs have also been compared for both the models and evolved to higher Q^2 to compare with available TMDs extraction data for the case of pion. The collinear parton distribution functions (PDFs) have also been investigated in this work. The unpolarized $f_1(x)$ PDF have been evolved through DGLAP evolution from $Q^2 = 1$ GeV^2 to 16 GeV^2 and found significant behavior with experimental results. The inverse moments and Mellin moments have also been discussed in this work. The average longitudinal momentum fraction $< x >$ and transverse momenta $< \mathbf{k}_\perp^2 >$ of our calculation found to be consistent with other model result.
The spatial structure have also been studied through leading twist GPDs for both the particles in

LFQM and have been implicated to understand the form factors (FFs). The FFs found to be consistent with lattice result and experimental result. We have also tried to study the medium modification effect on PDFs in asymmetric matter.

Seminar (1,2 week) / **52**

Structures of exotic hadrons from heavy ion collisions

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Recently the productions of exotic hadrons are interested not only for pp and ee collisions, but also for relativistic heavy ion collisions. The latter can be regarded as the factory for producing exotic hadrons from light to heavy flavors. Especially, the inner structures of exotic hadrons can be sensitive to the production process, and more information may be obtained by researching exotic hadrons in heavy ion collisions. In this talk, I will survey the recent development and introduce our recent work on the light/heavy flavor exotic hadrons.

Seminar (1,2 week) / **53**

Insights into molecular states and novel constraints for strange meson-baryon interactions with correlations at LHC

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In the last years the correlation measurements at LHC, particularly performed in small colliding systems such as proton-proton collisions, proved to be a powerful complementary experimental tool to access the strong interaction in hadronic systems with strange and charm content. The QCD dynamics driving the underlying interaction in these sectors is characterized by a rich presence of coupled-channels which, depending on the coupling strengths, can give rise to several dynamically generated states. The nature and inner composition of such states strongly depends on the interplay between the different coupled-channels and experimental constraints on their properties are typically obtained from dedicated mass invariant studies widely performed at LHC and as well at electron-positron colliders. In this talk we will discuss how femtoscopy can contribute to the search and understanding of these molecular states. We will present novel constraints on the $S = -1$ meson-baryon interaction with the first measurements of $\Xi^-\mathrm{K}^+$ correlations and we will conclude with new insights into the Ξ(1620) and Ξ(1690) states obtained from recently measured $\Lambda\mathrm{K}^-$ and $\Xi^-\pi^+$ correlations.

Lecture / **54**

Introduction to Lattice QCD

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Lattice QCD is the only known non-perturbative and gauge-invariant regularisation at present. The first-principles calculations of the lattice QCD based on the Monte Carlo methods have revealed various properties of QCD at low energies. In this lecture, the basics of Lattice QCD will be presented. As a final goal, I will discuss how hadron spectra are measured numerically.

Seminar (5th week) / 55

Instanton Density Operator in Lattice QCD from Higher Category Theory

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A long standing problem in lattice QCD is to naturally define the Yang-Mills instanton on the lattice. I will show how this problem is, and has to be, resolved by higher category theory.

To resolve the problem, the notion of lattice Yang-Mills must be refined at a conceptual level, in a way similar to how Villainization refines XY model and $U(1)$ lattice gauge theory. The remarkable point, however, is that it is mathematically impossible to achieve the needed refinement for lattice Yang-Mills using theoretical physicists' traditional toolbox of groups and fibre bundles, hence the more flexible language of categories becomes natural and necessary. While this might sound overly formal, the finally construction admits very intuitive physical interpretation. It allows us to naturally define 3d Chern-Simons term, 4d instanton and 5d Yang monopole in lattice $SU(N)$ Yang-Mills, as well as 2d Wess-Zumino-Witten term, 3d skrymion and 4d hedgehog in lattice S^3 (pion) non-linear sigma model.

In a larger scope, higher category theory enables us to rethink what a "lattice QFT" really is, as well as its relation to continuum QFT. I will sketch a systematic program to naturally construct generic topological operators that we expect from a continuum QFT onto the lattice.

Nishinomiya-Yukawa workshop / 57

Emergence of New Systematics for Open Charm Production in High Energy Collisions

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We show the production systematics of open charm hadron yields in high-energy collisions and their description based on the Statistical Hadronization Model. The rapidity density of D^0, D^+, D^{*+}, D_s^+ mesons and Λ_c^+ baryons in heavy ion and proton-proton collisions is analyzed for different collision energies and centralities.
The Statistical Hadronization Model is extended to open charm production in minimum-bias and

high-multiplicity pp collisions. In this context, we use the link between the rapidity density of open charm hadron yields, dN_i/dy, and the rapidity density of charm-anticharm quark pairs, $dN_{c\bar{c}}/d\eta$ to demonstrate that, in pp, pA and AA collisions, dN_i/dy scales in leading order with $dN_{c\bar{c}}/d\eta$ and the slope coefficient is quantified by the appropriate thermal density ratio calculated at the chiral crossover temperature, $T_c = 156.5$ MeV.

It is also shown that, in high energy collisions and within uncertainties, dN_i/dy exhibits a power law scaling with the charged-particle pseudo-rapidity density. Furthermore, presently available data on different ratios of open charm rapidity densities in high-energy collisions are independent of collision energy and system size, as expected in the Statistical Hadronization Model.

Nishinomiya-Yukawa workshop / 58

Internal structure of T_{cc} and $X(3872)$ by using compositeness

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In recent experiments in the heavy quark sector, various candidates of exotic hadrons have been observed. Most of exotic hadrons are discovered near the threshold of two-body scattering as represented by T_{cc} and $X(3872)$ [1,2]. Such near-threshold states are empirically considered as hadronic molecules [3]. To focus on the molecular structure, it is useful to calculate the compositeness, the fraction of the hadronic molecule component in the wavefunction [4]. By using the compositeness, we demonstrate that near-threshold bound states are usually molecular dominant [5] which is consistent with the consequence of the low-energy universality [6]. When we consider the decay and coupled-channels effects which are important for the exotic hadrons, the compositeness is found to be suppressed by these effects [5]. As an application, we discuss the internal structure of T_{cc} and $X(3872)$ by using a new interpretation of the complex compositeness [7].

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1-day workshop (5th week) / 59

Simulating Floquet scrambling circuits on trapped-ion quantum computers

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Complex quantum many-body dynamics spread initially localized quantum information across the entire system. Information scrambling refers to such a process, whose simulation is one of the promising applications of quantum computing. We demonstrate the Hayden-Preskill recovery protocol and the interferometric protocol for calculating out-of-time-ordered correlators to study the scrambling property of a one-dimensional kicked-Ising model on 20-qubit trapped-ion quantum processors. The simulated quantum circuits have a geometrically local structure that exhibits the ballistic growth of entanglement, resulting in the circuit depth being linear in the number of qubits for the entire state to be scrambled. We experimentally confirm the growth of signals in the Hayden-Preskill recovery protocol and the decay of out-of-time-ordered correlators at late times. As an application of the created scrambling circuits, we also experimentally demonstrate the calculation of the microcanonical expectation values of local operators adopting the idea of thermal pure quantum states.

1-day workshop (4th week) / 60

Superfluids of parity-doubled baryons in neutron stars

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Recent advances in multi-messenger astronomy have provided a key set of constraints on the equation of state (EoS) of QCD at high baryon density, via extraterrestrial observations of dense stellar objects such as neutron stars (NSs). It was suggested that the softening of the EoS at intermediate densities required to comply with the observed tidal deformability, together with the subsequent stiffening at high densities to protect the $2M_\odot$ NSs from their gravitational collapse, may indicate a phase transition at the core. This is often attributed to color deconfinement, although it is rather a heuristic guidance within simplistic approaches that do not account for the microscopic dynamics of underlying QCD.

Whereas the existence of quark matter is an intriguing option, a pure hadronic scenario has been shown to fully reconcile the modern constraints from observation, where the essential ingredients are the lowest nucleon $N(940)$ and its parity partner $N^*(1535)$ interacting with mesons in a chiral-invariant way. The properties of N and N^* can be well captured within the parity doublet model based on the mirror assignment of chirality: The mirror assignment is a more general representation for the nucleons with opposite parity, than the conventional one a la Gell-Mann and Levy, the naive assignment. It is a striking difference that the parity doublet model predicts the N and N^* being degenerate and massive when the chiral symmetry becomes restored, whereas the naive one inevitably leads to massless nucleons. The former, the mirror scenario, emerges in Nature, as confirmed by the recent lattice QCD simulations exhibiting a clear manifestation of parity doubling near the chiral crossover in the baryon spectra.

In this talk, we present novel superfluids of parity-doubled neutrons and discuss their properties in an effective Lagrangian approach. Our mean-field analyses reveal that (1) two vector-type condensates emerge, and (2) the dispersion relation of the gapped neutron leads to a strong spatial anisotropy. Some implications will be advocated.

Seminar (5th week) / 61

Phases of matter in systems with a discrete 1-form symmetry and the role of monopoles and center vortices

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I will discuss theories with the Z_N 1-form symmetry and argue that theories in 4d generically have three phases: the spontaneously broken phase, the restored (confined) phase and the coulomb phase. Natural string-like objects appear in this analysis, which we associate with the center vortices of the corresponding $SU(N)$ gauge theory. In addition the discussion also reveals particle-like objects which are naturally associated with monopoles. We will show that while the condensation of both of these is associated with the confined phase, the condensation of vortices alone causes a massless photon to appear. Since the massless photon phase should be there generically in any system with the same symmetry, I will show that it indeed appears in the Z_N lattice gauge theory.

Nishinomiya-Yukawa workshop / 63

Exploring the matter in the core of neutron stars

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Observations of the heaviest neutron stars, together with mass and radius measurements and gravitational wave signals from binary neutron star mergers, progressively tighten the constraints on the equation-of-state of dense baryonic matter. Using the presently available observational data base, results are presented of detailed Bayes inference analyses. A focus is on prerequisites and limitations for hypothetical phase transitions at the densities realised in neutron star cores. Consequences for the possible structure and composition of matter under such conditions are discussed.

Seminar (1,2 week) / 64

Nucleon polarizabilities, nucleon-pion scattering and pion electroweak production from lattice QCD

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I will discuss a lattice QCD calculation of the nucleon electric polarizabilities at the physical pion mass. Our findings reveal the substantial contributions of the Nπ states to these polarizabilities. Without considering these contributions, the lattice results fall significantly below the experimental values, consistent with previous lattice studies. This observation has motivated us to compute both the parity-negative Nπ scattering up to a nucleon momentum of ~ 0.5 GeV in the center-of-mass frame and corresponding $N\gamma^* \longrightarrow N\pi$ matrix elements using lattice QCD. Our results confirm that incorporating dynamic Nπ contributions is crucial for a reliable determination of the polarizabilities from lattice QCD. This methodology will also be beneficial for future lattice QCD studies of various lepton-nucleon inelastic scattering processes.

Nishinomiya-Yukawa workshop / 65

Veneziano's ghost and the chiral phase transition.

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An elementary argument suggests that for the chiral phase transition, if the interactions which violate the anomalous axial $U(1)_A$ symmetry are induced by instantons, then for three flavors, the chiral transition is inescapably of first order in the chiral limit. Numerical simulations on the lattice indicate that the first order region is much smaller than expected. I consider the effective Lagrangian for a large number of colors, which involves a ghost particle introduced by Veneziano. Generalizing this to a large number of flavors suggests the approximate restoration of the $U(1)_A$ symmetry near the chiral phase transition.

1-day Workshop (1st week) / 66

The three-body DD^*K system on the lattice

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We firstly employ the novel lattice EFT method to multi-hadron systems. The DD^*K three-body system is taken as an illustration to demonstrate the great power of lattice EFT to hadron physics, especially the potential application for many-body systems. The sub two-body interactions are fixed by the T_{cc}^+, $D_{s0}^*(2317)$ and $D_{s1}(2460)$ states.
When the three-body interaction is repulsive (even for the infinite repulsive interaction), the three-body energy is no larger than the $D_{s1}(2460)D$ threshold, making the three-body state existing unambiguously. To check the renormalization group invariance of our framework, we extract the first excited state. We find that when the ground state is fixed, the first excited states with various cutoffs coincide with each other when the cubic size goes larger. In addition, the standard angular momentum and parity projection technique is implemented for the quantum numbers of the ground and excited states. We find that both of them are S-wave state with quantum number $J^P = 1^-$. Because the three-body state contains two charm quarks, it is more easier to be detected in the Large Hadron Collider.

Nishinomiya-Yukawa workshop / 67

Femtoscopic study of the $\Omega\alpha$ interaction in heavy-ion collisions

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$\Omega -^4 He(\alpha)$ two-particle momentum correlation functions are studied.
Such correlations as an alternative source of information can help us further understand the interaction between Ω and nucleons (N).
$\Omega - \alpha$ potentials in the single-folding potential approach are constructed by employing two differents state-of-the-art $\Omega - N$ interactions in $^5S_2$ channel,i.e, one is based on the (2 + 1)-flavor lattice QCD simulations near the physical point by the HAL QCD collaboration, and another is based on the meson exchanges with effective Lagrangian.
By extracting the scattering length and the effective range from obtained $\Omega - \alpha$ potentials, the correlation functions are calculated within the Lednicky-Lyuboshits formalism.

Seminar (5th week) / 69

Fermion determinants on a quantum computer

Author: Judah Unmuth-Yockey[1]

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I discuss a quantum algorithm to compute the logarithm of the determinant of the staggered fermion matrix, assuming access to a classical lattice gauge field configuration. The algorithm uses the quantum eigenvalue transform, and quantum mean estimation, giving a query complexity that scales like O(V log(V)) in the matrix dimension V.

Seminar (1,2 week) / 70

Modelling QCD in Coulomb Gauge

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The Coulomb gauge description of QCD is reviewed. How models can be built in this approach is described and example applications to mesons, glueballs, hybrids, hybrid decays, and hybrid mixing are discussed.

Seminar (5th week) / 71

QED in two spatial dimensions: study confinement with quantum computing

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Current noisy quantum computers can be already used to investigate properties of quantum systems. Here we focus on lattice QED in (2+1)D including fermionic matter.
This complex quantum field theory with dynamical gauge and matter fields has similarities with QCD, in particular asymptotic freedom and confinement.
We define a suitable setup to measure the static potential between two static charges as a function of their distance and use a quantum computation to explore the Coulomb, the confinement and the string breaking regimes. A symmetry-preserving variational quantum circuit is employed for the creation of the ground state of the theory at various coupling constant values corresponding to different physical distances. We confirm that classical simulations for the static potential agree with quantum simulations of the system and also with results from quantum experiments on a trapped-ion device.
Moreover, we visualize the relevant flux configurations that contribute to the quantum ground state

in the different distance regimes of the potential giving thus insight into the mechanisms of confinement and string breaking.

Seminar (1,2 week) / 72

Doubly charmed tetraquark T_{cc}^{+} and left-hand cut

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In this talk, I will first present the D^*D scattering results obtained using $(2+1)$-flavor lattice QCD simulations with a nearly physical pion mass of $m_\pi = 146$ MeV, which is crucial for understanding the first doubly charmed tetraquark T_{cc}^{+}. Next, I will discuss the left-hand cut singularity, which has been recently pointed out to be relevant for analyzing T_{cc}^{+}. Special focus will be given on its origin in both non-relativistic and relativistic scatterings, how this singularity appears/disappears in the infinite/finite volume scattering, as well as its implications.

Seminar (1,2 week) / 73

Gravitational form factors and Mechanical properties of nucleon

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The gravitational form factors of the proton provide essential information on its mechanical structure such as its mass, spin, mechanical pressure, and shear force. In the current talk, we present a series of recent results for the flavor decomposition of the gravitational form factors~(GFFs) of the proton in a pion mean-field approach or the chiral quark-soliton model. We analyze problems arising from the flavor decomposition of the mass distribution, as evidenced through the non-conserved $\bar{c}(q^2)$ form factor of the nucleon. We discuss subtle points related to the twist-2 and twist-4 contributions to the flavor-decomposed masses and $\bar{c}$ form factors. We study not only the decomposition of the total angular momentum into the orbital angular momentum and intrinsic spin, but also its flavor decomposition. We then examine the intricate interplay between the D-term and $\bar{c}$ form factors and their collaborative impact on the stabilization of the nucleon system. Questioning the assumption of'large N_c blindness" concerning $D^{u-d} \sim 0$ in a recent experimental analysis, we compute it within both the flavor SU(2) and SU(3) framework. We conclude that such an assumption finds justification predominantly within the framework of flavor SU(3) symmetry.

Seminar (5th week) / 74

Non Abelian Lattice Gauge Theories: From Quantum Simulation to Ergodicity

Authors: Claire Edmunds[1]; Darvin Wanisch[2]; Giovanni Cataldi[2]; Giuseppe Calajo'[3]; Jad Halimeh[4]; Martin Ringbauer[1]; Pietro Silvi[5]; Simone Montangero[2]

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Non-abelian gauge theories play a pivotal role in our description of the universe, from low to high-energies, but their complexity hinders our understanding of their emergent phenomena. In this talk, we will consider a one-dimensional SU(2) lattice gauge theory with dynamical matter, the simplest theory supporting the existence of baryons and mesons. We will show how to build a quantum simulator based on trapped ions of this theory and which phenomena can be explored with this experimental toolbox. Moreover, we will analyse real-time dynamics phenomena related to ergodicity, first of all the emergence of quantum scars, in various dynamical regimes.

Nishinomiya-Yukawa workshop / 75

Lattice QCD applications of optimised meson operators in the distillation framework

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It has been demonstrated that distillation profiles can be employed to build optimised quarkonium interpolators for spectroscopy calculations in lattice QCD. The use of optimal profiles increases the overlap with the ground state significantly and grants access to excited states, for multiple quantum numbers. After reviewing the method, we report exemplary results on the low-lying charmonium spectrum from lattice QCD simulations with dynamical quarks, test the usefulness of profiles in distillation space for heavy-light systems and sketch the handling of momenta in this framework. As further applications, recent and ongoing studies of static-light meson spectroscopy as well as the system of light mesons, charmonium and glueballs in the flavour singlet channels, where they can mix, are also discussed.

Seminar (5th week) / 77

Computing mass spectra of gauge theories in the Hamiltonian formalism

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We present a couple of methods to compute the mass spectra of composite particles (hadrons) in gauge theories,

which can be implemented in quantum computing or tensor networks in the Hamiltonian formalism.
The hadron mass can be efficiently computed from the one-point function, combining the correlation function to deal with the operator mixing.
Alternatively, we can obtain the dispersion relation directly by measuring the energy and momentum of the excited states,
where the isospin quantum numbers are used to distinguish the type of hadrons.
We demonstrated these methods in the 2-flavor Schwingr model using the density-matrix renormalization group
and obtained precise results even in the large θ region where the Monte Carlo simulation fails due to the sign problem.
Then the pion and the sigma meson are identified as stable particles of the model, whereas the eta meson becomes unstable at nonzero θ.
The meson masses computed by the distinct methods agree with each other and are also consistent with the calculation by the bosonized model.

Seminar (1,2 week) / 78

Effective range expansion with the left-hand cut

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The validity range of the time-honored effective range expansion can be very limited due to the presence of a left-hand cut close to the two-particle threshold. Such a left-hand cut arises in the two-particle interaction involving a light particle exchange with a mass small or slightly heavier than the mass difference of the two particles, a scenario encountered in a wide range of systems. This can hinder a precise extraction of low-energy scattering observables and resonance poles. To address this issue, we propose a new parameterization for the low-energy scattering amplitude that accounts for the left-hand cut. The parameterization is like a Pad\'e approximation but with nonanalytic terms from the left-hand cut and can be regarded as an extension of the effective range expansion. It is ready to be applied to a broad class of scatterings and, in particular, should be invaluable in understanding various near-threshold hadron resonances. As byproducts, we also show that the parameterization can be used to extract the couplings of the exchanged particle to the scattering particles, and derive expressions for amplitude zeros caused by the interplay between the short- and long-range interactions.

Nishinomiya-Yukawa workshop / 79

Parton Distributions from Lattice and Impacts on Global QCD analysis

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There have been rapid developments in the direct calculation in lattice QCD (LQCD) of the Bjorken-x dependence of hadron structure through large-momentum effective theory (LaMET) and other similar effective approaches. These methods overcome the previous limitation of LQCD to moments (that is, integrals over Bjorken-x) of hadron structure, allowing LQCD to directly provide the kinematic Bjorken-x regions where the experimental values are least known. In this talk, I will show

some selected recent progress along these directions and examples of how including lattice-QCD calculations in the global QCD analysis can play a significant role in improving our understanding of parton distributions in the future.

1-day workshop (5th week) / 80

Convex methods in quantum field theory

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Quantum mechanical theories have an underlying convex geometry defined by the fact that the Hilbert-space norm is positive definite. Positivity is a surprisingly strong constraint, which when combined with other information (such as lattice data, Schwinger-Dyson relations, or equations of motion), allows one to establish qualitatively tight bounds on the behavior of many quantum systems, including lattice quantum field theories. In this talk I show how these observations in combination with standard methods from convex optimization, allow us to perform simulations of regimes forbidden to quantum Monte Carlo methods, including finite density fermions and real-time dynamics.

1-day workshop (5th week) / 81

Simulating Floquet prethermalization of lattice gauge theory using superconducting qubits

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Motivated by recent developments in quantum computing, many efforts have been devoted to exploring their potential applications in high-energy physics, particularly in simulation of lattice gauge theories. However, the capability of present quantum computers is very limited due to noise, and simulating the physics problems is still challenging. In this presentation, we talk about a digital quantum simulation of a physics motivated problem feasible to quantum computers i.e., thermalization in Floquet circuit made of lattice gauge theories. We show experimental results computed using IBM's quantum processor named ibm_fez that consists of 156 superconducting qubits. We demonstrate that even present noisy quantum computers can simulate short time physics such as the emergence of Floquet prethermal plateau by implementing error mitigation.

Nishinomiya-Yukawa workshop / 82

Threshold cusp structures in multi-channel scattering

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Near-threshold exotic hadrons are studied actively. In order to understand the nature of them, it is necessary to determine the scattering length from experimental data, because the scattering length governs the near-threshold scatterings. The cusp structure of cross sections reflects the value of the scattering length. In this work, we study the behavior of threshold cusp in multi-channel scattering using the general scattering amplitude near the threshold[1].

[1] K. Sone and T. Hyodo, arXiv:2405.08436 [hep-ph].

Seminar (4th week) / 83

Quark number susceptibility and conserved charge fluctuation for (2+1)-flavor QCD with Möbius domain wall fermions

Author: Jishnu Goswami[1]

Co-authors: Hidenori Fukaya [2]; Issaku Kanamori [3]; Shoji Hashimoto [4]; Takashi Kaneko [5]; Yasumichi Aoki [3]; Yoshifumi Nakamura [3]; Yu Zhang

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We explore the phase diagram of (2+1)-flavour QCD through the fluctuations of conserved charges calculated with Möbius domain-wall Fermions (MDWF). We present quark number susceptibilities and conserved charge fluctuations at pion masses around 220 MeV and 135 MeV for aspect ratios of lattices LT=2 and LT=3, respectively. Results are compared with the previous works by HotQCD and Wuppertal-Budapest collaborations obtained with the staggered quarks.

Nishinomiya-Yukawa workshop / 84

$\pi\pi$ scattering on the lattice and its application

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We discuss the RBC/UKQCD calculation of two-pion scattering at physical pion and kaon masses. Recent RBC/UKQCD results for related topics such as $K \to \pi\pi$ decay and long-distance HVP contribution to muon $g-2$ will also be presented.

Seminar (5th week) / 85

Persistent order and beyond-BKT phase transitions

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I'll discuss a Monte Carlo and analytic exploration of some simple lattice models that feature persistent order, namely that they are in an ordered phase at all temperatures. These models have BKT-like phase transitions that separate regions with spontaneous symmetry breaking and CFT phases. Understanding how to study such systems using Monte Carlo methods is a first step toward the study of certain chiral gauge theories on the lattice.

Seminar (5th week) / 86

Formulation of SU(N) Lattice Gauge Theories with Schwinger Fermions

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The recent advancements towards scalable fault-tolerant quantum computing have brought excitement about simulating lattice gauge theories on quantum computers. However, digital quantum computers require truncating the infinite-dimensional link Hilbert space to finite dimensions. In this talk, we focus on the $\mathrm{SU}(N)$ gauge theory coupled to N_f flavor of quarks and propose a formulation of the gauge field using Schwinger fermions. Remarkably, the resulting theory can be expressed purely in terms of gauge-invariant operators. This formulation applies to any $\mathrm{SU}(N)$ gauge group in any spacetime dimension. To explore the potential for reproducing the continuum physics, we study this model at $N = 2$ in two spacetime dimensions, where the low-energy continuum physics is expected to be described by a coset Wess-Zumino-Witten (WZW) model. Using tensor network methods, we find that the critical theory can indeed be understood as an $\mathrm{SU}(2)_1$ WZW model.

Nishinomiya-Yukawa workshop / 87

Born-Oppenehimer EFT (BOEFT) for quarkonium, tetraquark, hybrids, pentaquarks and doubly heavy baryons

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In this talk I will show how the BOEFT, derived from Quantum Chromodynamics on the basis of scale separation and symmetries, can address XYZ exotics of any composition. We derive the Schr ̈odinger coupled equations that describe hybrids,tetraquarks, pentaquarks, doubly heavy baryons, and quarkonia at leading order, incorporating nonadiabatic terms, and present the predicted multiplets. We define the static potentials in terms of the QCD static energies for all relevant cases. We provide the precise form of the nonperturbative low-energy gauge-invariant correlators required for the BOEFT: static energies, generalized Wilson loops, gluelumps, and adjoint mesons. These are to

be calculated on the lattice and we calculate here their short-distance behavior. Furthermore, we outline how spin-dependent corrections and mixing terms can be incorporated using matching computations. Lastly, we discuss how static energies with the same BO quantum numbers mix at large distances leading to the phenomenon of avoided level crossing. This effect is crucial to understand the emergence of exotics with molecular characteristics, such as the χc1(3872). With BOEFT both the tetraquark and the molecular picture appear as part of the same description. We discuss also some applications to the χc1(3872).

Seminar (4th week) / 88

The Inevitable Quark Three-Body Force and its Implications for Exotic States

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Three-body nuclear forces are essential for explaining the properties of light nuclei with a nucleon number greater than three. Building on insights from nuclear physics, we extract the form of quark three-body interactions and demonstrate that these terms are crucial for extending the quark model fit of the meson spectrum to include baryons using the same parameter set. We then discuss the implications of our findings for exotic configurations involving more than three quarks, such as the T_{cc} and $\chi_{c1}(3872)$. We find that the quark three-body interactions provide additional repulsion on the order of 10 MeV for the compact configurations of both the T_{cc} and $\chi_{c1}(3872)$. This result, combined with previous calculations, strongly suggests that these tetraquark states are molecular rather than compact states.

1-day Workshop (1st week) / 89

Mass and Interaction of 1^+ Diquark and Charm Quark in Σ_c

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In this study, we present a lattice QCD analysis of the $J^P = 1^+$
diquark within the charmed baryon $_c^{++}(uuc)$.

Treating $_c$ as a bound state of a charm quark and a uu 1^+ diquark,
we utilize an extended HAL QCD potential method to determine both the
mass of the 1^+ diquark and the potential between the charm quark and
the 1^+ diquark.

Unlike the standard HAL QCD approach, the mass of the 1^+ diquark is a
non-trivial quantity that cannot be straightforwardly obtained from
the two-point correlator due to the color confinement.

To address this, we employ the Kawanai-Sasaki extension of the HAL QCD
method, originally developed to self-consistently determine the charm
quark mass alongside the ccbar potential within the HAL QCD framework.

Our lattice QCD Monte Carlo calculations are performed using 2+1 flavor QCD gauge configurations on a $L^3 \times T = 32^3 \times 64$ lattice, generated by the PACS-CS collaboration, corresponding to a pion mass of approximately 700 MeV.

We find a spin-independent central potential of Cornell-type along with a short-ranged, spin-dependent central potential, which takes the form of a smeared delta-function.

The resulting mass of the 1^+ diquark is about 867 MeV, slightly lower than anticipated. This discrepancy is likely due to statistical noise in the Nambu-Bethe-Salpeter wave functions at long distances.

Seminar (1,2 week) / 90

Diquark Mass and Quark-Diquark Potential from Lattice QCD

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In this work, to calculate the diquark mass together with the quark-diquark potential, we apply an extended HAL QCD potential method to a baryonic system made up from a static quark and a diquark where we consider various types of diquarks (eg: scalar 0^+ diquark, axial-vector 1^+ diquark etc). Numerical calculations are performed employing 2+1 flavor QCD gauge configurations generated by CP-PACS and JLQCD Collaborations on a $L^3 \times T = 16^3 \times 32$ lattice with $m_\pi \sim 1$ GeV. We consider several combinations of source and sink operator for the quark propagators, for example, wall-source with point sink and Gaussian smeared source with Gaussian smeared sink etc. To improve the statistical noise in the propagators of the static quark, we also employ the HYP smearing on the gauge links. Two-point correlators of quark-diquark baryonic system are then computed to obtain their ground-state energies. For the baryonic system made up from a scalar diquark and a static quark, we apply an extended HAL QCD method to study the scalar diquark mass and the quark-diquark potential where, in order to determine the diquark mass self-consistently in the HAL QCD method, we demand that the baryonic spectrum in the p-wave sector should be reproduced by the potential obtained from the baryonic system in the s-wave sector. We obtain the scalar diquark mass of roughly $(2/3)m_N$, i.e., twice the naïve estimates of a constituent quark mass together with the quark-diquark potential of Cornell type (Coulomb + linear).

1-day workshop (4th week) / 91

Equation of state in neutron stars from a bottom-up holographic QCD model

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We derived equations of state for neutron stars using a bottom-up holographic QCD model. Our calculations include mass-radius relationships of neutron stars and the sound velocity in high-density QCD matter. We also obtained partial restoration of chiral symmetry in finite baryon density.

Nishinomiya-Yukawa workshop / 92

Investigating the Σ potential in nuclear matter toward solving the hyperon puzzle of neutron stars

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The hyperon puzzle of neutron stars refers to the problem that most of the equations of state with hyperons are not sufficiently stiff to support the observed massive neutron stars. One promising solution to the puzzle is that the three-body forces between a hyperon and medium nucleons produces such strong repulsion that Λ's do not appear in neutron stars. The Λ single-particle potential [1] (Λ potential) in nuclear matter that fulfills the solution is calculated from chiral effective field theory with the three-body forces estimated via the decuplet saturation. To test the feasibility of the solution, the repulsive Λ potential at high densities should be verified by using experimental data. The consistency with the heavy-ion collision [2] and hypernuclear [3] data has been verified by one of the authors.

In this talk, we will discuss the Σ potential, which can be calculated based on the same interactions as the Λ potential. By using the low-energy constants that reproduce the empirical value of the Λ potential, the Σ potential at the saturation density is found to vary by several tens of MeV, ranging from repulsion to attraction. Interestingly, it turns out that the low-energy constants can be chosen in such a way that Λ's do not appear in neutron stars, and the empirical value of the Σ potential at the saturation density, 30 ± 20 MeV [4], is reproduced.

[1] D. Gerstung, N. Kaiser, and W. Weise, Eur. Phys. J. A **56** (2020) 175.
[2] Y. Nara, A. Jinno, K. Murase, and A. Ohnishi, Phys. Rev. C **106** (2022) 044902.
[3] A. Jinno, Y. Nara, K. Murase, and A. Ohnishi, Phys. Rev. C **108** (2023) 065803.
[4] A. Gal, E.V. Hungerford, and D.J. Millener, Rev. Mod. Phys. **88** (2016) 035004.

Nishinomiya-Yukawa workshop / 93

Lee-Yang zeros for locating a critical point

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We propose a new method to use Lee-Yang zeros to search for a critical point in numerical analyses. We show that the ratios of the Lee-Yang zeros calculated on various spatial volumes have a crossing at the critical parameter. We find that this property allows us to determine the location of a critical point that appears in a model in a straightforward manner. The method is adopted to locate the critical point in the 3-dimensional 3-state Potts model at nonzero external field.

Seminar (4th week) / 94

The QCD phase diagram at finite temperature and baryochemical potential from the lattice

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I will shortly review recent lattice QCD results on the bulk thermodynamics of QCD at finite temperature and baryochemical potential. I will discuss calculations of the equation of state and fluctuations of conserved charges. I will also comment on the search for the coveted critical endpoint of QCD.

Seminar (5th week) / 95

Quantum Many-Body Scars in 2+1D Gauge Theories

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Real-time dynamics of Quantum Chromodynamics and other strongly coupled gauge theories present significant challenges for standard Monte Carlo methods due to severe sign problems. This limitation makes these problems ideal candidates for quantum simulation techniques. Identifying phenomena that can be tackled using near-term quantum simulators is crucial for understanding real-time dynamics in strongly coupled gauge theories.

Systems exhibiting quantum many-body scars challenge established notions of thermalization. They fail to thermalize after a long time when starting from a small subset of initial states. I will discuss the emergence of quantum many-body scarring in U(1) gauge theories in (2+1)-d and arbitrary dimension of the gauge links. We uncover an analytical structure that allows for the construction of scar states. These results shed light on how many-body systems may fail to thermalize and can guide near-term experimental characterization of novel phenomena in gauge theories.

1-day workshop (5th week) / 96

Quantum Simulation of Real-Time Dynamics in Particle Physics

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Quantum computers offer a promising new approach to studying real-time dynamics, which remains challenging for traditional methods like Monte Carlo simulations and tensor networks. In this talk, I will present progress on two key areas: simulating particle scattering and calculating parton distribution functions (PDFs) in 1+1 dimensions using digital quantum computing.

We propose a setup to simulate particle scattering by preparing two wave packets with opposite momenta. By applying a time evolution operator, we simulate their collision, capturing snapshots at each step to gain deeper insights into the process. Additionally, we explore the calculation of PDFs, which describe hadronic structures in high-energy collisions, demonstrating how quantum computing can advance our understanding of particle physics.

Seminar (5th week) / 97

Lattice Weyl Fermion on a single spherical domain-wall 2

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We discuss a single domain-wall system with a nontrivial curved background by considering a massive fermion on a 3D square lattice, where the domain-wall is a 2D sphere. In the presence of a topologically nontrivial U(1) link gauge field, we observe the emergence of a zero mode with opposite chirality localized at the center where the gauge field is singular. This results in the low-energy effective theory becoming vectorlike rather than chiral. We also discuss how to circumvent this obstacle in formulating lattice chiral gauge theory in the single domain-wall fermion system.

Seminar (1,2 week) / 98

From Lattice QCD to experimental data with the chiral Lagrangian

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The application of the chiral Lagrangian to results from Lattice QCD simulations played an important role in the early days of the field when it was impossible to generate ensembles at the physical pion mass. With the tremendous improvement of hardware and simulation technologies it is now possible and rather wide spread to do simulations for selected physical quantities at sufficiently small quark masses. Nevertheless, it is still very much desirable to gain a better understanding in how to use the chiral Lagrangian from small quark masses, for which Lattice simulations are still rather expensive, to larger quark masses, for which Lattice simulations are much more economical in energy consumption and budgets. While the chiral Lagrangian with three light flavors was almost declared useless by the community, the two-flavor version with light up and down quark masses is still frequently been used, however mostly for ensembles with rather small quark masses. This reflects an unfortunate and possibly questionable assumption on the applicability domain of the chiral Lagrangian.

In this talk I will discuss a novel development which suggests a much more favorite applicability domain of the chiral Lagrangian with not only two but also three light flavors [1,2]. This would open a new path towards more sustainable approaches to QCD, which is based on Lattice QCD simulation at quark masses significantly larger than the values required to reproduce the physical pion mass and properly combined with a chiral effective field theory. The key observation which may lead to such an avenue is that the use of on-shell hadron masses inside the loop correction terms as implied by chiral Lagrangian does affect its truncation properties. We illustrate our claim at the hand of the chiral Lagrangian as applied to baryon masses and the axial vector form factors [3,4].

There are various technical challenges to be overcome. Firstly, how to organize such a summed chiral perturbation theory without jeopardizing the chiral Ward identities of QCD. This is particularly cumbersome in the presence of a heavy field, which is known to cause power-counting violating terms. They have to be renormalized away in a systematic manner [3]. Secondly, how can we incorporate the effects of isobar fields, which are expected to limit the convergence domain to pion masses smaller than $m_\pi < M_\Delta - M_N \simeq$ 300 MeV [2,4]? Here the available Lattice QCD data on flavor SU(2) ensembles are particularly useful. Conclusions on the convergence properties cannot be blurred here by the role of strange quarks.

[1] arXiv:1801.06417
[2] arXiv:2003.10158
[3] arXiv:2309.09695
[4] arXiv:2402.04905

Nishinomiya-Yukawa workshop / 99

Exploring Exotic Hadrons: A Machine Learning Approach to Amplitude Analysis

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Understanding the non-perturbative confinement regime of quantum chromodynamics (QCD) necessitates identifying states within the hadronic spectrum. Recently, numerous new states have been discovered by various experimental collaborations. However, not all observed signals correspond to excitations of low-lying hadrons. Rigorous amplitude analysis techniques are essential to determine which observed signals are genuinely part of the hadronic spectrum.

In this talk, I will discuss how machine learning can be utilized in amplitude analysis to classify observed signals. Specifically, a deep neural network (DNN) can be trained to map input line shape space to output interpretation space. To ensure the DNN functions as a universal approximator, the training dataset must consist of input line shapes generated from a model-independent general amplitude parametrization. I will demonstrate that a trained DNN can distinguish the nature of poles using only the line shape above the threshold of a single-channel two-hadron scattering system. Additionally, I will show that kinematical enhancements, such as the triangle singularity, can be differentiated from pole-based enhancements using the same DNN principles.

Seminar (1,2 week) / 100

Lattice QCD studies of Hadron interactions from the HAL QCD method

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The determination of hadron interactions is one of the most important subjects in nuclear physics, and the obtained interactions serve as the key quantities which bridge different hierarchies of physics, particle physics, nuclear physics and astrophysics.
Recently, a novel theoretical method (HAL QCD method) was proposed to calculate hadron interactions from first-principles calculations by lattice QCD, and various interactions have been successfully determined.
In this talk, I will present selected topics for lattice QCD studies of hadron interactions using the HAL QCD method. The results include the latest calculations performed on the physical point using the state-of-the-art supercomputer, "Fugaku".

Seminar (5th week) / 101

Bridging two semiclassical confinement mechanisms: monopole and center vortex

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The two promising scenarios for quark confinement are monopole and center-vortex mechanisms. These mechanisms are realized in the weakly coupled semiclassical frameworks: monopole semiclassics on $\mathbb{R}^3 \times S^1$ and center-vortex semiclassics on $\mathbb{R}^2 \times T^2$. In this presentation, we will bridge two semiclassical descriptions, illustrating how the BPS and KK monopoles evolve into center vortices.

Lecture / 102

Nonrelativistic Effective field theories of QCD with application to the study of XYZ exotics states

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Nonrelativistic bound states lie at the core of quantum physics, permeating the fabric of nature across diverse realms, spanning particle to nuclear physics, and from condensed matter to astrophysics. These systems are pivotal in addressing contemporary challenges at the forefront of particle physics. Characterized by distinct energy scales, they serve as unique probes of complex environments. Historically, their incorporation into quantum field theory was fraught with difficulty until the emergence of nonrelativistic effective field theories (NREFTs).

In this lecture we will introduce the QCD nonrelativistic effective field theories called nonrelativistic QCD and potential NRQCD and show how they are the most appropriate tool to treat heavy quark bound states. pNRQCD in particular allows to obtain the Schroedinger equation as zero order problem from QCD. We will show that a generalization of pNRQCD, called Born-Oppenheimer EFT, allows us to address the newly discovered XYZ exotics state in the same, QCD derived, framework.

Nishinomiya-Yukawa workshop / 103

Exploring the hadronic interactions in three-body systems at the LHC

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The femtoscopy technique has been recently used at the Large Hadron Collider to perform new studies on hadronic interactions in few-body systems. The method exploits high-energy collisions as sources of hadrons and analyse the momentum correlation among the emitted particles to pin down the effects induced by their final state interaction. The interpretation of three-particle correlation measurements for p–p–p, p–p–Λ and p–d required sophisticated full-fledged calculations to account for the complex few-body dynamics among the particles in the systems. Those measurements evidenced the presence of significant genuine three-body effects. In this contribution I will provide an overview on the results obtained by ALICE in pp collisions at the LHC during the Run 2 data taking and I will present the preliminary Run 3 measurements. The correlation measurements will provide important information on the few-body interaction of hadrons with impact on the equation of state of dense nuclear matter.

1-day Workshop (1st week) / 104

One-pion exchange potential in a strong magnetic field

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The properties of QCD matter in a strong magnetic field have attracted much attention because of their relevance to the physics of relativistic heavy-ion collisions and magnetars. For example, the effects of magnetic fields are intensely studied in both single-body and many-body problems, such as modifications of the hadron mass spectrum and the QCD phase diagram. On the other hand, recent progress in lattice QCD and femtoscopy has enabled more direct investigations of hadron-hadron interactions. Given these developments, it is now timely to investigate the hadron-hadron interaction in the presence of strong magnetic fields.
In this study, we analyze how a strong magnetic field affects the long-range behavior of the nuclear force, specifically the one-pion exchange potential. Based on chiral perturbation theory in magnetic fields, we demonstrate that the potential between the proton and neutron is strongly modified, acquiring anisotropy due to charged pion exchange.

Nishinomiya-Yukawa workshop / 105

DbarN interaction from the HALQCD method (and scattering theory in the near-threshold region based on analyticity of the S-matrix)

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Many candidates of exotic hadrons have recently been found near the two-body threshold of hadronic channels. As an example, there have been studies predicting a near-threshold bound state or virtual state in the DbarN system. In this talk I will show the latest results of the DbarN interaction simulated by the HALQCD method near the physical point and discuss its consequences.

I also plan to briefly discuss the general analytical properties of the S-matrix and introduce a pole expansion that describes the near-threshold hadronic spectra by combining the notion of uniformization with the Mittag-Leffler Expansion.

Nishinomiya-Yukawa workshop / 106

Hydrodynamics of superfluid phases in neutron star inner crusts

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In many-body systems where continuous symmetry is spontaneously broken, gapless Nambu-Goldstone modes emerge, significantly influencing low-energy real-time dynamics. These dynamics are best described by hydrodynamic equations that incorporate the effects of these Nambu-Goldstone modes. In this talk, I will present a thermodynamic framework for deriving such hydrodynamic equations in symmetry-broken phases, with a focus on their application to the superfluid phase of dense nuclear matter in the inner crust of neutron stars.

Nishinomiya-Yukawa workshop / 107

Stabilised Wilson fermions – from large-scale to master-field simulations

Author: Patrick Fritzsch[1]

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Simulating QCD in the traditional way on very large lattices leads to conceptual and technical issues with impact on performance and reliability. In view of the new master-field framework, simulations with dynamical fermions are particularly challenging. The proposed stabilising measures comprise algorithmic changes as well as a new O(a)-improved Wilson action with exponential clover term.
In this talk, the motivation for stabilising measures and its effects are reviewed as both, standard-sized and master-field simulations, profit from its implementation. Furthermore, the current status and prospects of such simulations are presented.

Seminar (5th week) / 108

D-Theory: Asymptotically Free Quantum Fields from the Dimensional Reduction of Discrete Variables

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CP(N-1) models in (1+1)-d have a global SU(N) symmetry and share many features with QCD. They are asyptotically free, have a non-perturbatively generated mass gap, and non-trivial theta-vacuum states. CP(N-1) models can be regularized unconventionally by using discrete SU(N) quantum spins forming a (2+1)-d spin ladder that consists of n transversely coupled quantum spin chains. The (1+1)-d asymptotically free CP(N-1) fields then emerge from dimensional reduction when n is increased. Even n leads to the vacuum angle theta = 0, while odd n leads to theta = pi. In a similar way, gluon fields emerge naturally from the dimensional reduction of (4+1)-d quantum links, which are discrete gauge variables that generalize quantum spins. In this formulation, quarks arise as domain wall fermions. In contrast to the usual quantum fields, quantum spins and quantum links realize asymptotically free field theories with finite-dimensional local Hilbert spaces, directly representable by qubits. This is advantageous in the context of quantum simulation and quantum computation.

Seminar (5th week) / 109

Gauging C on the Lattice

Author: Theo Jacobson[1]

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We will discuss general aspects of charge conjugation symmetry in Euclidean lattice field theories including its dynamical gauging. As an application, we construct O(2) gauge theory on the lattice using a non-abelian generalization of the Villain formulation. This lattice discretization preserves a myriad of generalized global symmetries of the continuum theory, and we describe how to construct the associated symmetry operators and discuss their implications and associated selection rules.

1-day Workshop (1st week) / 110

Applications of femtoscopy in studies of exotic hadrons

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Since 2003, many hadrons that do not fit into the conventional quark model of qqbar mesons and qqq baryons have been discovered experimentally. Because most (if not all) of these states are located at the thresholds of a pair of conventional hadrons, they have been conjectured to be hadronic molecules. There have been extensive theoretical and experimental studies to verify or refute the molecular picture from different perspectives. In the past few years, we have proposed using femtoscopy to directly extract the underlying hadron-hadron interactions, which are key for forming hadronic molecules. In this talk, I will provide a pedagogic introduction to femtoscopy and its recent applications in understanding the nature of a few key candidates of hadronic molecules, such as Ds0*(2317), Pc(4457/4440), and Zc(3900)/Zcs(3985)

Nishinomiya-Yukawa workshop / 111

The phi-N and phi-nucleus interaction from theory and experiment

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While the phi meson vacuum properties, such as mass and width, are well known, it is not clear how these properties will change once it is put in a dense environment such as nuclear matter. To study how the phi meson behaves at finite density has been the goal of several past and near future experiments at KEK, COSY-ANKE and J-PARC. Recently, ALICE has also obtained novel experimental data constraining the phi-N interaction.
In this talk, I will discuss how these new data can be interpreted from a theoretical point of view, and how they possibly can be used to constrain the nuclear matter properties of the phi meson, including its longitudinal and transverse polarization modes, which due to the breaking of Lorentz symmetry in nuclear matter, can be modified differently. I will review theoretical predictions for the in-medium modifications of these quantities and discuss how they could be measured at the future J-PARC E16 and E88 experiments.

Seminar (5th week) / 112

Lattice Weyl Fermion on a single spherical domain-wall 1

Author: Shoto Aoki[1]

Co-authors: Hidenori Fukaya [2]; Naoto Kan [3]

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In the standard lattice domain-wall fermion formulation, two flat domain-walls are put where both of the left- and right-handed massless modes appear on the walls. In this work we investigate a single spherical domain-wall fermion mass term embedded into a flat square three-dimensional lattice. In the free fermion case, we find that a single Weyl fermion appears at the wall and it feels gravity through the induced spin connection. With nontrivial link variables we discuss the perturbative anomaly inflow between the bulk and edge fermions.

1-day workshop (4th week) / 113

Two-color QCD as a laboratory of cold and dense matter

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Two-color ($N_c = 2$) QCD world is one of the useful testing grounds to delineate cold and dense QCD matter, since the lattice QCD simulation is straightforwardly applicable thanks to the disappearance

of the sign problem. Motivated by recent numerical results from the lattice QCD activities, I am being investigating properties of dense two-color QCD by constructing the linear sigma model (LSM). In this talk, I summarize my recent works based on my LSM, such as the modifications of hadron mass spectrum, topological susceptibility, and the sound-velocity peak in cold and dense two-color QCD.

References:
[1] D. Suenaga, K Murakami, E. Itou and K. Iida, Phys.Rev.D 107 (2023) 5, 054001,
[2] M. Kawaguchi and D. Suenaga, JHEP 08 (2023) 189,
[3] D. Suenaga, K. Murakami, E. Itou, K. Iida, Phys.Rev.D 109 (2024) 7, 074031,
[4] M. Kawaguchi and D. Suenaga, Phys.Rev.D 109 (2024) 9, 9.

Seminar (5th week) / 114

Quantum simulation of string-breaking in SU(2)k lattice gauge theory

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Simulating dynamical properties of non-abelian gauge theories is considered to be an ideal target for quantum computers.
In this talk, I will present recent progress toward simulating a confining flux string and its breaking due to creation of dynamical charges in a minimal setup. Our proposal is based on a q-deformed formulation of SU(2) lattice gauge theory, truncating the gauge group to SU(2)k. Focusing on small k and a ladder geometry, I will show how this enables an efficient implementation on qudit architectures. Together with explicit gate decompositions tailored to existing trapped-ion hardware, our work paves the way for digital simulations of string-breaking in a non-abelian gauge theory.

Seminar (1,2 week) / 115

Recent highlights and future prospects of hypernuclear physics at J-PARC

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Research on hypernuclei plays an essential role in answering how the hierarchy of nuclei is constructed from quarks. We are going to review the recent achievements in hypernuclear programs in J-PARC. One of the recent achievements is the realization of an accurate hyperon-nucleon scattering experiment. The differential cross sections of the Σ+p, Σ−p elastic scatterings and Σ−p $\longrightarrow$ Λn inelastic scattering have been measured with drastically improved accuracy. These new data will become essential inputs to improve the theories of the two-body baryon-baryon interaction. Another achievement is the big progress of research on the double hypernuclei. A lot of information on double Λ hypernuclei and Ξ hypernuclei has been accumulated through the observation of the double hypernuclear events in the nuclear emulsion in the series of experiments at KEK and J-PARC. Other experiments to study S=-2 system were also carried out and the analysis is ongoing. In presentation, the progress of the hypernuclear program in J-PARC is presented with a focus on these experimental results. Future prospects are also discussed briefly.

Seminar (5th week) / 116

Chiral gauge theory on the lattice

Author: David Kaplan[1]

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A fermion representation with exact chiral symmetry can be obtained on a 5-dimensional lattice with a single boundary, circumventing the Nielsen-Ninomiya theorem. I discuss this as well as a proposal for gauging the theory, and objections that have been raised.

1-day workshop (4th week) / 117

Gravitational waves from binary-neutron-star mergers and the equation of state

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Gravitational waves from binary-neutron-star mergers enable us to observe accurately the orbital evolution and postmerger dynamics. On the one hand, the orbital evolution tells us about intermediate-density matter characterizing premerger neutron stars. On the other hand, postmerger dynamics may reflect how hadrons transition to quarks at high density. In this talk, I will discuss the current status and future prospects of binary-neutron-star mergers, focusing primarily on our recent investigations on hadron-quark crossover.

Nishinomiya-Yukawa workshop / 118

Connecting quarks to the cosmos: The role of quark masses.

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I will discuss quark mass-dependent operators in the Chiral Perturbation Theory, their effects on the equation of state of dense matter, and their implications for astrophysics. I highlight how these operators influence three-body forces and the possibility of pion and axion condensation in neutron stars.

Lecture / 119

Lectures on dense baryonic matter: from quarks to nuclei and neutron stars

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An introductory overview will be given summarizing various aspects of the QCD phase diagram, with special emphasis on cold dense matter as it is realised in neutron star centers. This includes state-of-the-art results from Bayes inference of observational data. Also included are theoretical considerations at the scales relevant to neutron star physics: spontaneously broken chiral symmetry of QCD, the structure of the nucleon, nuclear effective field theory methods and functional renormalization group approaches, the neutron star cores as relativistic Fermi liquids, and the quest for a hadrons-to-quarks continuous crossover at high densities.

Seminar (4th week) / 120

What we learned about heavy-quark hadronization in small and large collision systems

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The LHC experiment has provided valuable insights into how charm and beauty quarks hadronize into various mesons and baryons under different collision systems. Contrary to our initial assumption that charm quarks hadronize independently of the collision system, with a universal fragmentation function that can be empirically parameterized, the LHC measurements suggest that additional hadronization mechanisms may need to be considered. In this talk, we will present measurements of heavy-quark hadronization across a range of collision systems, from small to large. We will also discuss various hadronization mechanisms, such as recombination, and their impact on baryon-to-meson ratios. Additionally, we will compare these findings with results from the light hadrons and production inside jets. This results show the critical importance of understanding the hadronization process, which is essential for interpreting results from heavy-ion collision experiments and refining theoretical models that describe these phenomena.

Seminar (1,2 week) / 121

Higher partial waves in femtoscopy

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Recently, femtoscopy in high-energy heavy-ion collisions has been gathering attention as a new approach to hadron-hadron interaction, and two-particle momentum correlation is widely measured in experiments [1]. Existing studies have mainly assumed the s-wave interaction, where the contributions from p-wave and d-wave have been neglected for simplicity. However, the correlation function gets contributions from all higher partial waves in general. The effect becomes particularly significant in the presence of resonances of higher partial waves. For example, a peak observed in the K-p correlation [2] is attributed to the d-wave resonance $\Lambda(1520)$.

In this talk, we discuss the effect of higher partial waves on the correlation function based on the Koonin-Pratt formula, which gives the correlation function as an integral of the two-particle source $S(\mathbf{r})$ and the relative wave function $\phi_{\mathbf{q}}^{(-)}(\mathbf{r})$. We first consider the partial-wave expansion of the correlation function under the spherical source, where the correlation is shown to be the sum of the contributions from each wave. We also attempt an extension of the Lednicky–Lyuboshits (LL) formula [3] for the s-wave interaction. Assuming a short interaction range, a Gaussian source, and the effective range expansion of the s-wave scattering amplitude f_0, the LL formula gives a parametrized form of the correlation function in terms of the scattering length a_0 and the effective range r_0. Using similar assumptions, we obtain a generalized LL formula for the higher partial waves. In this procedure, we give an insight into the structure of the LL formula and discuss a relation to the optical theorem. We also check the applicability of the generalized LL formula using typical potentials such as the potential well.

[1] S. Cho et al. [ExHIC], Prog. Part. Nucl. Phys. 95, 279-322 (2017).
[2] S. Acharya et al. [ALICE], Phys. Rev. Lett. 124, no.9, 092301 (2020).
[3] R. Lednicky and V. L. Lyuboshits, Yad. Fiz. 35, 1316-1330 (1981).

Seminar (5th week) / 122

Towards quantum simulating QCD: loop string hadron approach

Author: Indrakshi Raychowdhury[1]

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Full-fledged Quantum computation/simulation of lattice QCD is a long-term goal and requires developing a set of strategies starting from foundational level. This includes a convenient Hamiltonian framework for the theory along with the Hilbert space construction compatible with the principle of gauge invariance. The recently developed Loop-string-hadron approach is a promising framework for this goal. In this talk, I'll briefly introduce the framework and discuss its applications in the context of quantum computation and benchmarking the same using classical computers.

Nishinomiya-Yukawa workshop / 123

Studies of Heavy dibaryons and QCD topology from Lattice QCD

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In this talk, I will present recent developments in heavy quark dibaryons and QCD matter under extreme conditions. There has been significant interest recently in studying heavy quark exotic states, particularly with numerous lattice QCD calculations focusing on tetraquarks. Additionally, there have been multiple studies on dibaryons containing heavy quarks.

I will focus on two recent calculations. The first involves two-flavor deuteron-like dibaryons with heavy quarks in the spin triplet channel, where ground state results for different combinations of heavy flavors will be discussed. The second calculation examines the ground states of two-flavor heavy dibaryons in the spin singlet channel. I will also present evidence suggesting the emergence of heavy quark spin symmetry in these systems.

QCD topological susceptibility at high temperatures (~1 GeV) is of great interest for axion studies. Such calculations can only be reliably performed using lattice QCD. I will introduce a novel Hybrid Monte Carlo (HMC) algorithm that computes the temperature dependence of susceptibility in pure glue within a single lattice calculation. To extend such calculations to include fermions, high-precision scale setting methods are required. I will present a method that achieves percent-level accuracy in scale setting directly at finite temperature.

Seminar (1,2 week) / 124

Correlations and the Analytic Inversion of the TOV Equation

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There are many examples of correlations among neutron star properties and parameters of the dense matter equation of state near the saturation density. Motivated by the discovery of correlations among the neutron star maximum mass, its radius, central density and pressure, and perturbative expansions in radius of the mass, energy density and pressure near the centers of neutron stars, a nearly universal analytic inversion of the TOV structure equations is developed. It's accuracy in determining the underlying equation of state (i.e., the energy density - pressure relation), as well as the corresponding number density and chemical potential, is of order 0.5%. This treatment is extended to the general estimation of the central density and pressure of an arbitrary mass neutron star in terms of its radius and the inverse slope dR/dM of the M-R curve. The technique is applied to the determination of the equation of state from observations of masses and radii including their uncertainties.

Nishinomiya-Yukawa workshop / 125

Strongly coupled dynamics of quantum field theory and topologies

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TBA

Nishinomiya-Yukawa workshop / 126

Chiral symmetry in nuclear medium observed in spectroscopy of pionic atoms

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We discuss quantitative evaluation of chiral condensate in nuclear medium based on high-precision experimental information of pionic atoms. We made spectroscopy of deeply bound pionic Sn 121 atoms and determined the binding energies and the widths of the pionic orbitals. We deduced pion-nucleus interaction to evaluate the chiral condensate at nuclear saturation density, which was found to be reduced by a factor of 60+-3% (T. Nishi, K. Itahashi et al., Nature Phys. (2023) doi:10.1038/s41567-023-02001-x) compared with that in the vacuum. We also briefly discuss our activities of the spectroscopy of eta'-mesic nuclei to study axial U(1) anomaly.

Seminar (4th week) / 127

2+1+1 flavor QCD equation of state with Highly Improved Staggered Quarks

Author: Alexei Bazavov[1]

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Recent results on the QCD equation of state (EoS) with 2+1+1 flavors of highly improved staggered quarks (HISQ) are presented. The trace anomaly is computed on ensembles with temporal extent 6, 8, 10 and 12. The pressure is reconstructed from the trace anomaly with the integral method. The available temperature range extends up to about 960 MeV on the coarser ensembles. Along the line of constant physics, the strange and charm quark masses are tuned to the physical values while the light quark mass corresponds to the pion mass of about 300 MeV in the continuum limit.

Lecture / 128

Lectures on Lattice QCD study of Hadron interactions

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QCD governs the dynamics of quarks and gluons, and ultimately properties of hadrons and nuclei as well as nuclear astrophysical phenomena such as binary neutron star merges. Lattice QCD is the unique method which can solve QCD in a first-principle manner, and it can make predictions (or postdictions) for basic hadronic quantities.
The calculation of hadron interactions, however, is non-trivial, since lattice QCD is formulated on a finite volume with Euclidean time. There is also a challenge for reliable calculations due to the infamous (bad) signal/noise ratio problem in simulations. In this lecture, we review the two major methods currently available in lattice QCD, Luscher's finite volume method and the HAL QCD method. The importance of controlling systematic errors is emphasized and critical review for the past calculations as well as recent progresses are presented.

Seminar (1,2 week) / 129

Study on hadron-hadron interaction with femtoscopic technique

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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. Because this observable is sensitive to the low-energy interaction, it is useful to study the nature of the near-threshold resonances and the underlying mechanism of the interaction. The meson-baryon and baryon-baryon interaction in strangeness sector is the good target of this approach.

In the first part of this talk, I discuss the current the theoretical and experimental situation of the femtoscopic study. We see that the coupled-channel source effect gives the important enhancement and the source size dependence of the correlation function is key to investigate the interaction detail from the correlation data.
Next, we discuss the correlation function using the 4He (alpha) particle. Because alpha is the composite particle whose central nuclear density reaches 2 normal nuclear density, it is expected that the correlation function. I show the results with the Lambda-alpha correlation [2] and Xi alpha correlation [3] using the effective models and discuss how the detailed N-Lambda and N-Xi interaction can be determined from the measurement.

[1] Published in: Y. Kamiya, et al, Phys. Rev. Lett. 124 (2020) 13, 132501
[2] A. Jinno, Y. Kamiya, T. Hyodo, and A. Ohnishi, Phys. Rev. C 110 (2024) 1, 014001
[3] Y. Kamiya, A. Jinno, T. Hyodo, and A. Ohnishi, in preparation

Lecture / **130**

Introduction to Lattice QCD

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Lattice QCD is the only known non-perturbative and gauge-invariant regularisation at present. The first-principles calculations of the lattice QCD based on the Monte Carlo methods have revealed various properties of QCD at low energies. In this lecture, the basics of Lattice QCD will be presented. As a final goal, I will discuss how hadron spectra are measured numerically.

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Toward Quantum Simulating the Strong Force

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What does the phase diagram of matter, such as matter in the interior of neutron stars, look like? How does matter evolve and thermalize after energetic processes such as after the Big Bang or in particle colliders? How do quarks and gluons and their interactions give rise to the complex structure of a proton or a nucleus, and their response to various probes? A successful lattice chromodynamics (QCD) program has enabled a first-principles look into some properties of matter with the aid of classical computing. At the same time, we have yet to come up with a more powerful computational tool to predict the complex dynamics of matter from the underlying interactions. Can a large reliable (digital or analog) quantum simulator eventually enable studies of the strong force? What does a quantum simulator have to offer to simulate QCD, and how far away are we from such a dream? In this talk, I will describe a vision for how we may go on a journey toward quantum simulating QCD, by taking insights from early developments of lattice QCD and its achievements, by motivating the need for novel theoretical, algorithmic, and hardware approaches to quantum-simulating this unique problem, and by providing examples of the early steps taken to date in establishing a quantum-computational lattice-QCD program.

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Lectures on Lattice QCD study of Hadron interactions

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QCD governs the dynamics of quarks and gluons, and ultimately properties of hadrons and nuclei as well as nuclear astrophysical phenomena such as binary neutron star merges. Lattice QCD is the unique method which can solve QCD in a first-principle manner, and it can make predictions (or postdictions) for basic hadronic quantities.
The calculation of hadron interactions, however, is non-trivial, since
lattice QCD is formulated on a finite volume with Euclidean time. There is also a challenge for reliable calculations due to the infamous (bad) signal/noise ratio problem in simulations. In this lecture, we review the two major methods currently available in lattice QCD, Luscher's finite volume method and the HAL QCD method. The importance of controlling systematic errors is emphasized and critical review for the past calculations as well as recent progresses are presented.

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Modern theory of nuclear forces

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The strong interaction between nucleons has been at the heart of nuclear physics since the very beginning of this field. Remarkable progress has been achieved in recent decades towards quantitative understanding of nuclear forces and the corresponding current operators in the framework of chiral effective field theory. Combined with modern ab-initio few-body methods and continuously increasing available computational resources, this approach opens the way for a systematically improvable and model independent description of light nuclei and low-energy dynamics in harmony with the symmetries of quantum chromodynamics. I will discuss different versions of effective field theory for nuclear systems focusing especially on the conceptual foundations, review various techniques to derive nuclear interactions and outline the state-of-the-art and remaining challenges in this field.

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Lectures on dense baryonic matter: from quarks to nuclei and neutron stars

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An introductory overview will be given summarizing various aspects of the QCD phase diagram, with special emphasis on cold dense matter as it is realised in neutron star centers. This includes state-of-the-art results from Bayes inference of observational data. Also included are theoretical considerations at the scales relevant to neutron star physics: spontaneously broken chiral symmetry of QCD, the structure of the nucleon, nuclear effective field theory methods and functional renormalization group approaches, the neutron star cores as relativistic Fermi liquids, and the quest for a hadrons-to-quarks continuous crossover at high densities.

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Nonrelativistic Effective field theories of QCD with application to the study of XYZ exotics states

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Nonrelativistic bound states lie at the core of quantum physics, permeating the fabric of nature across diverse realms, spanning particle to nuclear physics, and from condensed matter to astrophysics. These systems are pivotal in addressing contemporary challenges at the forefront of particle physics. Characterized by distinct energy scales, they serve as unique probes of complex environments. Historically, their incorporation into quantum field theory was fraught with difficulty until the emergence of nonrelativistic effective field theories (NREFTs).

In this lecture we will introduce the QCD nonrelativistic effective field theories called nonrelativistic QCD and potential NRQCD and show how they are the most appropriate tool to treat heavy quark bound states. pNRQCD in particular allows to obtain the Schroedinger equation as zero order problem from QCD. We will show that a generalization of pNRQCD, called Born-Oppenheimer EFT, allows us to address the newly discovered XYZ exotics state in the same, QCD derived, framework.