Workshop on the sign problem in QCD and beyond

Monday 20 January 2025 - Friday 24 January 2025

University of Bern

Book of Abstracts

Book of abstracts

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Rotating gluodynamics and QCD: sign problem, mixed inhomogeneous phase and moment of inertia

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This report is devoted to the lattice study of rotating gluodynamics and QCD properties. The lattice simulation is conducted in a co-rotating reference frame, where the rotation is reduced to the effects of curved space-time. Unfortunately, a direct simulation of this system is hampered by the sign problem, which arises both in gluonic and fermionic sectors. To overcome the sign problem, we perform the simulation for imaginary angular velocities, and then analytically continue the results to the region of real rotation. We found a new spatially inhomogeneous phase in a rotating system. This mixed phase simultaneously possesses both confining and deconfining phases in thermal equilibrium. The position of the boundary between phases is determined by the local critical temperature, which increases with the radius for real angular velocity. In addition, the results for the equation of state of rotating (quark-)gluon plasma are presented. We found that the moment of inertia unexpectedly takes a negative value in the "supervortical"range of temperatures near the phase transition. We suppose that these results indicate the possible negative spin-vortical coupling for gluons resulting in a negative Barnett effect.
It is shown, that the peculiar properties of rotating QCD arise from quadratic in angular velocity terms of the action, i.e. from chromomagnetic components of the gluon fields. In contrast, the linear terms, which are responsible for the sign problem, play only a sub-leading role.

Thursday morning / 4

Kernels and integration cycles in complex Langevin simulations

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The complex Langevin method is an approach to solve the sign problem based on a stochastic evolution of the dynamical degrees of freedom. In principle, it solves the sign problem by trading the complex path integral weight for a real probability distribution in complexified field space. However, due to the complexification, the stochastic evolution sometimes converges to an equilibrium distribution that produces incorrect results for observables. This wrong convergence can be partially explained by the appearance of boundary terms, which spoil the formal proof of correctness of the method. The introduction of a kernel into the complex Langevin equation can prevent the emergence of boundary terms, but this on its own does not guarantee correct convergence. Indeed, the results may still be affected by unwanted so-called integration cycles, which are certain integration paths in complexified field space that might be sampled in a complex Langevin simulation. In this talk, we explore the relation between a kernel and the relevant integration cycles using simple toy models.

Wednesday afternoon (Uwe-Jens Wiese mini-symposium part 2) / 5

Following Uwe-Jens' Journey of Major Discoveries

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I first met Uwe-Jens in 1992 here at Bern University, where he introduced me to the lattice field theory. Ever since, he has given me opportunities to collaborate in a number of projects, all of which I thoroughly enjoyed. In particular, I was his postdoc from 1994 to 1996 at MIT, and later we crossed paths at numerous locations around the world.

It is my pleasure to revisit some of the highlights and anecdotes of this collaboration, which spans more than three decades. Our most significant endeavor is a textbook that we started working on about 20 years ago, with efforts finally intensifying during my recent sabbatical stays here in Bern. With a bit of luck, it will be published in time for the SIGN25 workshop.

Thursday afternoon / 6

Constant path integral contour shifts

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The Fermi-Hubbard model suffers from a severe sign problem, both for non-zero chemical potentials and on non-bipartite lattices. Over the years, considerable progress has been made in alleviating the sign problem by deforming the integration contour of the path integral into the complex plane. In this talk, I am going to present a surprisingly simple and yet powerful contour deformation by means of an optimised constant shift. First results for the molecule Perylene at finite doping are included. I will also discuss preliminary results using fermionic augmented tree tensor networks which are inherently sign problem free.

Monday afternoon / 7

Lattice QCD sign problem as an inverse problem

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Simulation of finite density lattice QCD at imaginary chemical potential is a popular workaround for the sign problem. One is then left with the problem of performing the analytic continuation of results to the real axis. We show how this continuation can be mapped to an inverse problem via the (integral) Cauchy formula.

Friday morning / 8

Diffusion models for complex Langevin dynamics

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The probability distribution effectively sampled by a complex Langevin process for theories with a sign problem is not known a priori and notoriously hard to understand. Diffusion models, a class of generative AI, can learn distributions from data. In this contribution, we explore the ability of diffusion models to learn the distributions created by a complex Langevin process.

Tuesday morning / 9

BBGKY hierarchy for zero noise extrapolation in quantum error mitigation

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The phase diagram of QCD at finite densities remains numerically inaccessible by classical computations. Quantum computers, with their potential for exponential speedup, could overcome this challenge. However, their current physical implementations are affected by quantum noise. In this contribution, I will introduce a novel quantum error mitigation technique based on a BBGKY-like hierarchy, which is applicable to any arbitrary digital quantum simulation. The core idea is to improve zero-noise extrapolations by incorporating additional constraints from the hierarchy equations associated to the digital spin system. Our preliminary results indicate that the mitigation scheme systematically improves the quality of the (1+1)-Schwinger model measurements.

Wednesday morning (Uwe-Jens Wiese mini-symposium part 1) / 10

How many states are gauge invariant?

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Hamiltonian methods, such as quantum simulation, are often advocated as a long term solution to some sign problems. In this context, it is more natural to work with a finite-dimensional Hilbert space; as such, a truncation method must be employed. Moreover, for gauge theories, only a small subsets of states are gauge invariant and therefore physical. In this context, both for technical reasons and for resource estimation, it is sometimes useful to know the exact number of gauge invariant states. We show a full solution to this problem in the case where the Hilbert space truncation is achieved by replacing the gauge group with a finite subgroup, both for pure gauge theories and for gauge-scalar theories. We also discuss choices of bases for the gauge-invariant sector, with some applications. Finally, we also briefly consider other truncation methods, as well as ongoing work with gauge-fermion theories.

Wednesday morning (Uwe-Jens Wiese mini-symposium part 1) / 11

The Ising Model on a Curved Manifold – The Affine Conjecture

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A formulation of lattice field theory (LFT) for curved manifolds uses the Regge's triangulated (simplicial) manifold for the Einstein Hilbert action that solves the equation of motion (EOM) for classical GR in the continuum. For the metric field, $g_{\mu\nu}(x)$, this is piece-wise constant finite element method (FEM) which applies equally to the classical field PDEs. But quantizing lattice fields on even a fixed Regge manifold is more difficult.

The analytical solution for the 2d Ising model demonstrated that a precise map between the ***quantum field geometry*** and the ***Regge manifold geometry*** is required. By using this map locally on tangent planes, the Riemann sphere ($\mathbb{S}^2$) lattice Ising model converged to the exact CFT solution. We conjecture that a similar Affine map exists more generally. A sequence of theoretical investigations and numerical tests are underway for non-integrable examples of increasing complexity: e.g. ϕ^4 theory and QED3 on $\mathbb{R} \times \mathbb{S}^2$, with the goal to establish a new LFT framework for gauge theories, complementary to the bootstrap and the fuzzy sphere.

Tuesday morning / 12

Phase Diagram of the Schwinger Model by Adiabatic Preparation of States on a Quantum Simulator

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We demonstrate a method to study the phase diagram of a quantum system on quantum devices via adiabatic preparation of states. The method is a direct application of the adiabatic theorem due to M.

Born and V. Fock, Z. Phys. 51, 165 (1928). The key idea of the method is to individually evolve the ground state and the first-excited state using a Hamiltonian whose parameters are time-dependent. We successfully test the method in application to the Schwinger model with a topological θ-term. We recover the first-order-phase-transition and the transition-free regions of the corresponding phase diagram. We demonstrate the advantages of the method in some scenarios over another method from the literature that also uses adiabatic state preparation.

Thursday morning / 13

Machine learning kernels in complex Langevin for real time evolution

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Real time evolution in QFT poses a severe sign problem, which may be alleviated via a complex Langevin approach.
However, so far simulation results consistently fail to converge with a large real-time extent. A kernel in a complex Langevin equation is known to influence the appearance of the boundary terms, and thus kernel choice can improve the range of real-time extents with correct results. For multi-dimensional models the optimal kernel is searched for using machine learning methods. We test this approach by simulating the simplest possible case, a 0+1-dimensional scalar field theory, to which analytic solutions are known, and apply machine-learning approaches to different kernel ansatzes (constant, linear, polynomial). The ultimate goal of the project is to use a neural net as a kernel.

Thursday morning / 14

Enhancing Complex Langevin with Lefschetz Thimble-Based Regularizations

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The complex Langevin (CL) method is a promising tool for addressing the numerical sign problem.- Depending on the specific system, CL may produce unreliable results, which necessitates the use of ad-hoc stabilization methods. Building on the connection between CL and Lefschetz thimbles, we develop weight regularizations to enable correct convergence by deforming thimbles in systems with compact domains. This approach ensures success when a single compact thimble dominates the regularized system. Additionally, we introduce a bias correction procedure to recover results for the original theory where unregularized CL fails. We validate our method using several models, including the cosine model and the SU(2) and SU(3) Polyakov chains, for which CL previously was plagued by wrong convergence. Finally, we discuss the implications and potential applications of the insights gained by this technique to lattice field theories.

Monday afternoon / 15

QCD deconfinement transition line up to $\mu_B = 400$˜MeV from finite volume lattice simulations

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The QCD cross-over line in the temperature (T) – baryo-chemical potential (μ_B) plane has been computed by several lattice groups by calculating the chiral order parameter and its susceptibility at finite values of μ_B. In this work we focus on the deconfinement aspect of the transition between hadronic and Quark Gluon Plasma (QGP) phases. We define the deconfinement temperature as the peak position of the static quark entropy ($S_Q(T, \mu_B)$) in T, which is based on the renormalized Polyakov loop. We extrapolate $S_Q(T, \mu_B)$ based on high statistics finite temperature ensembles on a $16^3 \times 8$ lattice to finite density by means of a Taylor expansion to eighth order in μ_B (NNNLO) along the strangeness neutral line. For the simulations the 4HEX staggered action was used with 2+1 flavors at physical quark masses. In this setup the phase diagram can be drawn up to unprecedentedly high chemical potentials. Our results for the deconfinement temperature are in rough agreement with phenomenological estimates of the freeze-out curve in relativistic heavy ion collisions. In addition, we study the width of the deconfinement crossover. We show that up to $\mu_B \approx 400$˜MeV, the deconfinement transition gets broader at higher densities, disfavoring the existence of a deconfinement critical endpoint in this range. Finally, we examine the transition line without the strangeness neutrality condition and observe a hint for the narrowing of the crossover towards large μ_B.

Friday morning / 16

Towards Real-Time Observables from First Principles: Correlators in 3+1D Yang-Mills Theory

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Real-time quantum field theories remain challenging due to the severity of the numerical sign problem. In this work, we successfully apply the complex Langevin (CL) method to SU(2) Yang-Mills theory in 3+1 dimensions. By introducing an anisotropic kernel, we stabilize simulations for real-time evolutions beyond the inverse temperature, enabling the first ab initio computations of unequal-time correlation functions in this setting. We verify consistency relations among propagators, observe time-translation invariance, and achieve agreement with Monte Carlo results in thermal equilibrium. Strikingly, our approach allows an independent verification of the fluctuation-dissipation relation for the integrated magnetic energy correlator. These results represent significant progress toward extracting real-time observables, such as transport coefficients, from non-Abelian gauge theories within a first-principles framework.

Tuesday afternoon / 17

Abelian Gauge Theories in 1+1D with Correlated Cluster Algorithms

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The Hamiltonian formulation of lattice gauge theories offers a pathway to new quantum and classical simulation techniques, providing new ways to circumvent different sign problems.In this work, we address different formulations of various Abelian gauge theories within the Hamiltonian framework in 1+1 dimensions. Using Correlated Cluster Algorithms, we exactly solve Gauss's law for $\mathbb{Z}_n$, truncated link, and quantum link models. This approach enables the efficient exploration of systems at finite θ-angle and with multiple flavors, avoiding the sign problem.
We leverage these algorithms to analyze different formulations of the theory, investigate their behavior at finite θ-angle, and examine their approach to the continuum limit. Our numerical results demonstrate that $\mathbb{Z}_n$ and truncated link models serve as more effective truncation schemes, offering improved convergence towards the infinite Hilbert space limit at each gauge link.

Tuesday afternoon / 18

Correlated Cluster Algorithms

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Cluster algorithms are Monte Carlo algorithms that provide efficient non-local updates of the configurations. They can avoid critical slowing down when approaching a second-order phase transition and solve severe sign problems in well-tailored cases. The clusters group degrees of freedom that can be updated independently of one another. While highly efficient, the range of models that can be simulated this way is limited. In this talk, I will introduce an extension of the cluster algorithm approach referred to as Correlated Cluster Algorithms. This new method allows for simulation of models where clusters cannot be updated independently of one another. If the interdependence of the clusters can be encoded in a tree structure, configuration updates can be chosen using a dynamic programming approach. Models that can be simulated with the new approach include interacting particles in the canonical ensemble and 1+1D gauge theories in the Hamiltonian formulation, which are subjected to Gauss's law. Additionally, the inclusion of topological θ-terms does not offer any challenge to this approach.

Tuesday afternoon / 19

Prospects for Quantum Simulations of the Strong Coupling Expansion

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We present Monte Carlo simulations for the phase diagram based on the strong coupling expansion including $\mathcal{O}(\beta^2)$ and discuss the severity of the sign problem as a function of the inverse gauge coupling β, which limits the range of validity of the strong coupling expansion. We also present the formulation of the strong coupling expansion that is suitable for quantum simulations, where the sign does not pose a problem, and explain the quantum computational requirements for such simulations.

Tuesday morning / **20**

Convex methods for sign problems

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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.

Thursday afternoon / **21**

Variational Quantum Eigensolver for (2+1)-Dimensional QED at Finite Density

Authors: Emil Otis Rosanowski[None]; Arianna Crippa[1]; Karl Jansen[1]; Lena Funcke[2]; Paulo Itaborai[3]; Stefan Kühn[4]

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In this talk, we present an implementation of multiple fermion flavors in both the Kogut-Susskind and Wilson formulations for quantum simulations of (2+1)-dimensional Quantum Electrodynamics (QED). Our first results show a particular type of level crossing with one flavor of fermions at zero density, as expected from analytical Chern number calculations. Moving forward, we explore the multi-flavor system at finite density by including a chemical potential. Finally, we present results from inference runs executed on real quantum hardware.

Tuesday morning / **22**

Complex instanton gas approximation for the Hubbard model away of half-filling

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We present recent advancements towards the alleviation of the sign problem for the Hubbard model away of half filling. We couple the thimble decomposition approach with certain approximations, which allow us to predict the structure of the thimble decomposition in advance, before actual Quantum Monte Carlo simulations.

First, we show that the saddle points for the Hubbard model with charge-coupled auxiliary field have simple and regular structure both at half filling and away of it. They are collections of instantons: objects, localized both in space and Euclidean time. Auxiliary fields inside instantons are real at half filling, but acquire non zero imaginary part at finite chemical potential thus leading to complex saddle points.

Instanton gas approximation, initially developed for the Hubbard model at half filing [Phys. Rev. B 107, 045143], is able to predict the share of particular thimble in the full partition function. We expand this approximation to (now complex) instantons away of half filling, showing that we can still predict both weights and phases of corresponding thimbles using relatively simple analytical expressions.

Using the results of this study, we can compute analytically the residual sign problem from the phases of various thimbles participating in the partition function. Formally, this phase shows rapid exponential decay with inverse temperature and system size, thus we can essentially prove a no-go theorem that straightforward thimble decomposition approach can not work for the Hubbard model away of half-filling for the auxiliary field coupled with charge density.

However, since the phases and the weights of the thimbles are known with high precision, we can perform resummation still allowing us to extract meaningful results for observables at least in Gaussian approximation to the thimble integrals around exact complex saddle points. We study charge density and superconducting order parameters depending on the chemical potential.

We also discuss possible further developments, in particular the connections between thimble decomposition and Constrained Path Quantum Monte Carlo.

Tuesday afternoon / 23

Wormhole quantum Monte Carlo for quantum dissipative spin systems

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The phases and phase transitions of low-dimensional quantum magnets are often described using simple quantum spin models. It is an open question how the properties of these systems are affected by a coupling to the environment, which is always present in any experimental realization. One of the simplest setups for such an open quantum system is the spin-boson model where a single spin is coupled to a bosonic bath with a continuous spectrum. In this talk, I will show how spin-bath interactions can be simulated efficiently within the directed-loop and worm algorithms using retarded interactions. To this end, I will introduce the novel wormhole updates which allow for nonlocal moves through a world-line configuration. The novel wormhole updates give access to

a new class of retarded spin-flip interactions relevant for the description of quantum dissipative systems and light-matter coupling. I will demonstrate this algorithm using two examples: First, I will discuss an SU(2)-symmetric spin-boson model which exhibits a fixed-point annihilation that can be tracked numerically and gives rise to a plethora of critical and pseudocritical phenomena. Moreover, I will present work on the quantum Heisenberg chain where the local coupling to an ohmic bath stabilizes long-range antiferromagnetic order beyond the Mermin-Wagner theorem.

Friday morning / 24

Testing dynamical stabilization of Complex Langevin simulations of QCD

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We study complex Langevin simulations of a toy model as well as QCD, supplemented with a dynamical stabilization (DS) term, which was proposed to regularize the complexified process at lower temperatures. We compare the results to reweghting from zero chemical potential to measure the bias that the inclusion of the stabilization term causes, depending on its strength. At high temperatures the stabilization term is not needed. At low temperatures (below deconfinement transition) the DS term has a beneficial stabilizing effect, but too strong DS term causes phase quenching on the system. We observed that the bias of the dynamical stabilization can be to a good accuracy removed by extrapolating to zero dynamical stabilization force using a sigmoid fit.

Thursday morning / 25

System specific prior knowledge - a key tool to tackle the sign problem

Author: Alexander Rothkopf[1]

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Here I present our recently developed strategy to exploit system specific prior knowledge [1], such as space-time symmetries, as a loophole to the computational challenge posed by NP-hard sign problems. As explicit example, I will showcase how complex Langevin simulations of strongly coupled scalar fields [2] can be amended with relevant prior information using learned kernels. Developments towards preservation of space-time symmetries in numerical simulations [3] will be discussed.

[1] D. Alvestad, R. Larsen, A.R. JHEP 04 (2023) 057 [arXiv:2211.15625]
[2] D. Alvestad, A.R., D. Sexty PRD Letter 109 (2024) 3, L031502 [arXiv:2310.08053]
[3] A.R., W.A. Horowitz, J. Nordström [arXiv: 2404.18676]

Monday afternoon / 29

Easing the sign problem in many-body physics

Author: Jens Eisert[None]

The sign problem is a well-known challenge in quantum many-body physics. It presents significant obstacles for Monte Carlo sampling methods, which are otherwise powerful tools in the field. Specifically, when a system exhibits a sign problem, these methods struggle to perform efficiently. However, it is important to note that the sign problem is basis-dependent. In this talk, we will explore the computational complexity of easing the sign problem [1]. Along the way, we will examine key insights, introduce a figure of merit, and provide a rigorous proof regarding the computational complexity. Looking ahead, we will discuss how tensor network methods might help alleviate the burden of the sign problem [2], investigate lower bounds for ground state energies [3], and explore the connection between the phenomenon of pseudo-quantum chaos and the sign problem [4].

[1] Science Advances 6, eabb8341 (2020).
[2] Phys. Rev. B 104, 075137 (2021).
[3] Phys. Rev. A, in press (2025).
[4] arXiv:2410.18196 (2024).

Wednesday morning (Uwe-Jens Wiese mini-symposium part 1) / 30

Homotopic Action: A Pathway to Convergent Diagrammatic Theories

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The major obstacle preventing Feynman diagrammatic expansions from accurately solving many-fermion systems in strongly correlated regimes is the series slow convergence or divergence problem. Several techniques have been proposed to address this issue: series resummation by conformal mapping, changing the nature of the starting point of the expansion by shifted action tools, and applying the homotopy analysis method to the Dyson-Schwinger equation. They emerge as dissimilar mathematical procedures aimed at different aspects of the problem. The proposed homotopic action offers a universal and systematic framework for unifying the existing—and generating new—methods and ideas to formulate a physical system in terms of a convergent diagrammatic series. It eliminates the need for resummation, allows one to introduce effective interactions, enables a controlled ultraviolet regularization of continuous-space theories, and reduces the intrinsic polynomial complexity of the diagrammatic Monte Carlo method. We illustrate this approach by an application to the Hubbard model.

Friday morning / 31

External and Dynamic Gauge Fields in Strong-Field QED

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Understanding nonperturbative regimes in Strong-Field Quantum Electrodynamics (SFQED) is essential for exploring fundamental processes in high-intensity laser-matter interactions. Despite significant progress in analyzing the Schwinger model, a systematic comparison of the underlying

frameworks remains incomplete. In particular, direct contrasts between U(1) and Z_n models within standard lattice gauge QED, as well as bridging the gap to the semi-classical kinetic approach to Schwinger pair production, remain largely underexplored.
Here, we present a parametric exploration of the validity regimes of various SFQED approaches focusing on Schwinger pair-production rate and its connections to related processes. This poster highlights preliminary results from these studies, advancing our understanding of SFQED and informing future theoretical and computational strategies.

Monday afternoon / 32

Minimal pole representation and controlled analytic continuation of Matsubara response functions

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Analytic continuation is a central step in the simulation of finite-temperature field theories in which numerically obtained Matsubara data are continued to the real frequency axis for a physical interpretation. Numerical analytic continuation is considered to be an ill-posed problem where uncertainties on the Matsubara axis are amplified exponentially. Here, we present a systematic and controlled procedure that approximates any Matsubara function by a minimal pole representation to within a predefined precision. We then show a systematic convergence to the exact spectral function on the real axis as a function of our control parameter for a range of physically relevant setups. Our methodology is robust to noise and paves the way towards reliable analytic continuation in many-body theory and, by providing access to the analytic structure of the functions, a direct theoretical interpretation of physical properties.

Wednesday afternoon (Uwe-Jens Wiese mini-symposium part 2) / 33

Confronting the sign problem for frustrated magnets

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Kitaev materials are a class of crystals that are believed to show fractionalization in terms of Majorana fermions. These models do not allow for negative sign free formulations. Here we show that by optimizing the path integral formulation, we can reach temperature scales down to 40K, a scale relevant to experiments. In fact we will show that we can reproduce experimental results for a specific Kitaev material RuCl3. If time allows I will also touch on Kondo lattice physics, and its relation to U(1) gauge theories.

Thursday afternoon / 34

Quantum Computing for Lattice Field Theory

Author: Lena Funcke[1]

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In this talk, we review recent advances in applying quantum computing to lattice field theory. Quantum technology offers the prospect to efficiently simulate sign-problem afflicted regimes in lattice field theory, such as the presence of topological terms, chemical potentials, and out-of-equilibrium dynamics. First proof-of-concept simulations of Abelian and non-Abelian gauge theories in (1+1)D and (2+1)D have been accomplished, and resource efficient formulations of gauge theories for quantum computations have been developed. The path towards quantum simulations of (3+1)-dimensional lattice gauge theories requires many incremental steps of improving both quantum hardware and quantum algorithms. After reviewing these requirements and recent advances, we discuss the main challenges and future directions.

Wednesday morning (Uwe-Jens Wiese mini-symposium part 1) / 35

Sign-blessed thermodynamics of interacting fermions

Author: Nikolay Prokofiev[1]

[1] *University of Massachusetts Amherst*

I will review several key features associated with the conventional sign problem and argue that for regular interacting fermionic systems none of them applies if the calculation is done with the help of Feynman diagrams. The diagrammatic approach generically solves the computational complexity problem and can be used for obtaining numerical solutions for interacting fermions. I will illustrate the concept with results for the Fermi-Hubbard and Coulomb gas models and explain why this method is not the "death of theoretical physics".

Wednesday afternoon (Uwe-Jens Wiese mini-symposium part 2) / 36

Sign Problem Free Qubit Regularized Hamiltonian Lattice Gauge Theories

Author: Shailesh Chandrasekharan[1]

[1] *Duke University*

Qubit regularization may offer a new approach to Hamiltonian lattice gauge theories. If we insist on working with the Kogut Susskind Hamiltonian, one often encounters sign problems even in the pure gauge theory sector. However, since we are ultimately interested in quantum critical points where the form of the Hamiltonian should not play an important role, we can explore if alternate sign problem free Hamiltonians can be constructed that reproduce the desired critical points. Here we show we can construct simple sign problem free Hamiltonians and provide envidence that they contain some of the expected finite temperature confinement-deconfinement transitions in pure gauge theory in two and three spatial dimensions. We also show the existence of zero temperature transitions using an example of a Monte Carlo calculation in continuous Euclidean time in one spatial dimension.

Thursday afternoon / 37

Contour optimisation for the sign problem with an efficient evaluation of the Jacobian

Author: Michael Kroyter[1]

[1] *Holon Institute of Technology*

In previous work, with Francis Bursa, we considered the approach of addressing the sign problem using simple contour deformations. As a toy model for examining the approach we used the one-dimensional Bose gas with chemical potential. The contour deformations that were considered are local and they lead to simple forms of the Jacobian that can be simulated fast.

However, the periodic boundary conditions complicated the form of the Jacobian and lead either to an increase of the complexity of the simulation time or to a reduction of the effectiveness of the approach. Naturally, this problem is especially significant for $d > 1$, in which case it was effectively impossible to go beyond some given value of the chemical potential using a fast algorithm.

Now, a modification of the previous approach is presented that does not suffer from this problem, while retaining efficient complexity of the algorithm. While for small values of the chemical potential the new approach can be somewhat less effective than the previous ones, it remains effective in reducing the sign problem also for larger values of the chemical potential. We consider ansätze within the new approach and examine its effectiveness in reducing the sign problem.

Wednesday afternoon (Uwe-Jens Wiese mini-symposium part 2) / 39

Personal reflections

Opening / 40

Welcoming notes

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End