Quantum Workshop Cyprus

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Book of Abstracts

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Exploring Phase structure of the Schwinger model on superconducting Quantum Computers

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We explore the phase structure of the lattice Schwinger model in the presence of a toplogical -term, a regime in which conventional Monte Carlo simulations suffer from the sign problem, using the variational quantum eigensolver (VQE). Constructing a suitable variational ansatz circuit for the lattice model using symmetry-preserving 2-qubit gates, we perform classical simulations showing that the ansatz is able to capture the relevant physics. In particular, we observe the remnants of the well known first-order phase transition at $\theta = \pi$ occurring in the continuum model for large enough fermion masses. Furthermore, we implement our ansatz on IBM's superconducting quantum hardware. Using state-of-the art noise suppression techniques, namely readout error mitigation, dynamical decoupling, Pauli twirling, and zero-noise extrapolation, we are able to explore the phase structure of the model directly on quantum hardware with up to 12 qubits. We study two regimes on the hardware device, a fermion mass well below the transition point and a fermion mass well above. In both cases, our ansatz performs well and we obtain data, which are in good agreement with exact diagonalization.

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Welcome

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Compute Excited States of the Schwinger Model with the Concurrent Variational Quantum Eigensolver

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The Schwinger model describes the QED in two-dimensional space-time. In this talk, I will present some results on the excited states of the lattice Schwinger model with the concurrent variational quantum eigensolver (cVQE). First, I will introduce elements of cVQE from the density matrix. Then, I will report results on the spectrum of the lattice Schwinger model, including nonvanishing background field, using a staggered Hamiltonian formulation. Finally, a novel method for extracting the additive mass renormalisation of the model from the energy gap will be discussed.

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Towards Exploring the Topological Vacuum Structure of the Schwinger

Model with digital Quantum Computers

This work investigates the capability of digital quantum computers to probe the phase diagram of the Schwinger model, which includes a single fermion flavor and a topological theta-term. The study aims to extend the analysis to higher dimensions where prevailing classical techniques exhibit inefficiency. Employing the variational quantum eigensolver (VQE), a range of ansatz architectures and gate types are evaluated to prepare quantum states. Through the application of error mitigation techniques, including zero noise extrapolation, ground states are successfully generated on digital quantum hardware. Various observables, such as electric field density and particle number, are measured to demonstrate the first-order phase transition of the model. Additionally, a continuum extrapolation at a constant volume for specific phase space parameters is presented, accomplished via matrix product states and density matrix renormalization group (DMRG). This extrapolation serves as a benchmark, providing insights into the quantum hardware requirements for executing such computations. The findings contribute to the ongoing advancement of quantum computing methodologies in studying complex quantum field theories and offer a stepping stone for future explorations into high-dimensional systems.

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Simulating fermion scattering using a quantum computing approach

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Collider experiments play a central role in understanding the subatomic structure of matter, as well as developing and verifying the fundamental theory of elementary particle interactions. However, comprehending scattering processes at a fundamental level in theory remains a significant challenge. The necessary involved time evolution and the with time rapidly increasing bond dimension in Tensor Networks make simulating the scattering process with this classical method challenging. On the other hand, quantum computers hold great promise to efficiently simulate real-time dynamics of lattice field theories. In this work, we take the first step in this direction toward simulating fermionic scattering using a digital-quantum computing approach. Specifically, we propose a method based on Givens rotation to prepare the initial state of the fermionic scattering process, which consists of two fermionic wave packets with opposite momenta. With a time evolution operator based on the underlying Hamiltonian acting on the initial state, the two fermionic wave packets propagate and interact with each other. Using the lattice Thirring model as the test bed and the Qiskit Statevector simulator, we observe an elastic scattering between fermions and anti-fermions in the strong interaction region. In addition, we clearly observe an entanglement production in the scattering process. We consider our work also as an indispensable step towards a quantum simulation of a scattering process on a real quantum device.

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2+1-dimensional QED with Quantum Computing

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We extend the analysis of the study of 2+1D Quantum Electrodynamics with an approach suitable for quantum computers by developing an algorithm that computes the Hamiltonian in both electric and magnetic basis for a lattice with generic size.
The system that we are considering for a matching with MCMC (Markov Chain Monte Carlo) data is 3x3 pure gauge lattice with periodic boundary conditions. The idea is to match quantities like the energy gap or the expectation value of the plaquette operator, in a regime that is suitable for a classical analysis with Monte Carlo. With the latter technique, one can then go to larger volume and find the lattice spacing, while with quantum computing one should be able to reach regimes when the coupling constant is low and impracticable for MC.
We also started to look into how to implement the Gray encoding on a quantum Ansatz for a generic value in the truncation applied to gauge fields, for simulations on real quantum devices.

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(2+1)d QED at vanishing temporal lattice spacing

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The rapid development of quantum technologies gives hope for unprecedented physical simulations in the upcoming years. One of them is lattice QCD, which however is computationally too expensive at the moment. This motivates the study of simpler theories resembling its features. One is QED in 2+1 dimensions, showing a confining phase and dynamical mass generation. In this work we present a study of the Hamiltonian limit of this theory, computed in the Lagrangian formalism. As Hamiltonian simulations are presently limited to very small volumes, this is an important step to match the two formalisms. In fact, having a connection point opens the window for the removal of finite volume effects, while exploiting the full potential of Hamiltonian simulations.

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QCNN for Jet Image Classification

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In recent years, machine learning has emerged as a prominent subfield of artificial intelligence, finding widespread applications in various scientific domains. Concurrently, the promising potential of quantum computing has inspired the exploration of leveraging its computational advantages to construct quantum machine learning models. Building upon the remarkable success of classical Convolutional Neural Networks (CNNs) in image classification tasks, Quantum Convolutional Neural Networks (QCNNs) were introduced with the aim of surpassing their classical counterparts. In this study, we employ a QCNN model for the task of classifying jet images and rigorously assess its

performance in comparison to a corresponding classical CNN model.

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Combining QUBO with classical approach to particle tracking

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The use of quadratic unconstrained binary optimisation (QUBO) for charged particle track reconstruction has been studied alongside a classical tracking algorithm using combinatorial Kalman Filter (CKF). QUBO can be efficiently solved on quantum computers through methods like quantum annealing or variational quantum eigensolver. The QUBO and CKF tracking methods not only differ in terms of the type of computers they can run on but also in their fundamental approaches to solving tracking problems. Consequently, there is potential for leveraging the advantages of both techniques. In this presentation, I will delve into the complementarity of these two approaches and explore various strategies to integrate the two.

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Exploring a 4D quantum algorithm for pattern recognition of charged particle tracks

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Particle track reconstruction plays a crucial role in the exploration of new physical phenomena, particularly when rare signal tracks are obscured by a significant background. The formulation of the reconstruction task as Quadratic Unconstrained Binary Optimisation (QUBO) enables the use of quantum computers, which are believed to offer an advantage over classical computers in such optimisation scenarios. Adding temporal information to the previously only spatially based parameters elevates the algorithm to a 4D quantum algorithm. This study is conducted in the context of a muon collider, which is a future collider facility that utilizes temporal information in the tracking detector to suppress overwhelmingly large beam-induced background. To demonstrate the effectiveness of the 4D QUBO approach, the quantum algorithm is used to reconstruct signal tracks from samples consisting of Monte Carlo simulated charged particles overlaid with background hits. I will present the obtained reconstruction performance and discuss possible paths for further improvements.

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Precise Quantum Angle Generator Designed for Noisy Quantum Devices

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Our way towards quantum generative models for experimental calorimeter shower generation and lessons learned are described.

Our best model: the Quantum Angle Generator (QAG) is a new quantum machine learning model designed to produce precise images on current Noise Intermediate Scale (NISQ) Quantum devices. The QAG model uses variational quantum circuits as its core, and multiple circuit architectures are evaluated. With the addition of the MERA-up sampling architecture, the QAG model achieves exceptional results that are analyzed and evaluated in detail. To the best of our knowledge, this is the first quantum model to achieve such accurate outcomes. This study explores the QAG model's noise robustness through an extensive quantum noise study. The results indicate that the model when trained on a quantum device, can learn the hardware noise behavior and produce excellent outcomes. When simulated quantum hardware noise is included, the model's results remain stable until approximately 1.5% of noise during inference and almost 3% in training. However, running the noise-less trained model on real quantum hardware leads to a decrease in accuracy. If the model is trained on hardware, it can learn the underlying noise behavior, where the same precision is achieved by the noisy simulator. Additionally, the training showed that the model can recover even with significant hardware calibration changes during training with up to 8% of noise. This work demonstrates the QAG model's ability to learn hardware noise behavior and deliver accurate results in the presence of realistic noise levels expected in real-world quantum hardware. The QAG model is utilized on simulated calorimeter shower images, which are significant in high-energy physics simulations used to determine particle energies and identify unknown particles at CERN's Large Hadron Collider.
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Assessing the potential of quantum annealers for track reconstruction at LUXE

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LUXE (Laser Und XFEL Experiment) is a proposed experiment at DESY using the electron beam of the European XFEL and a high-
intensity laser. The experiment's primary aim is to investigate the transition from the well-probed perturbative to the non-perturbative Quantum Electrodynamics regime.
In LUXE, positrons are generated and directed towards a four-layered silicon pixel detector, with occupancies of up to 100 hits/mm2 for the initial phase. Reconstructing tracks from a substantial set of hits poses a significant challenge for classical computers.
To address this challenge, we adopt a novel approach based on formulating the track pattern recognition task as a quadratic unconstrained binary optimisation (QUBO) problem. This formulation allows the problem to be solved with a quantum annealer. Classically, the expected performance of a quantum annealer for QUBO problems can be studied using Simulated Annealing. In this talk, a comprehensive study of various aspects of the problem, including QUBO encoding, algorithm scalability and tracking performance, will be given using DWAVE's annealing simulator. The results will be compared to classical track reconstruction using the Combinatorial Kalmann Filter and to results using Qiskits gate-based quantum computing simulator.

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Equivariant Quantum Neural Networks in the NISQ era

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Recent researches suggest Geometric Quantum Machine Learning (GQML) using Equivariant Quantum Neural Networks (EQNN) as a potential solution to overcome the main challenges encountered in QML, such as trainability and generalization. EQNN injects inductive bias based on the prior knowledge of the underlying geometry in the dataset to build a more robust model against changes in the input data and increase generalization power. Despite the promising progress, the studies are still limited to theoretical tests, and the role of realistic hardware noise in EQNN training has never been explored in depth. This work studies the impact of hardware noise on EQNN and compares it with non-equivariant models. We train a simple EQNN on two toy datasets in the presence of different types of noises and analyse the relation between the final training performance and the action of noises on the quantum state.

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Quantum Boltzmann Machines for classification tasks

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In this work we propose an algorithm for a QBM using DualQITE for the Gibbs state preparation. The choice of the Hamiltonian, which defines model connectivity, and the ansatz, used for preparation of the Gibbs state, plays a crucial role in performance of QBMs. With an application to classification tasks, we conduct a study on semi-restricted and fully-connected QBMs to explore the influence of the Hamiltonian choice. We consider synthetic datasets which are hard to tackle with classical machine learning techniques. As the first step, we implemented a 3- and 4-qubit QBMs to validate the proposed algorithm. We use different data-encodings, including symmetry-inspired ones, to use the efficient number of tunable parameters depending on the properties of the dataset. For the considered small benchmark models the performance of QBM reaches more than 95\% accuracy with our approach. As the next step, we are working on scaling up the system size and application to the realistic datasets.

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Stochastic Noise as a Tool for VQE's Escape from Local Minima and saddle points

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In the application of the Variational Quantum Eigensolver (VQE) for determining ground state energies of hamiltonian, getting trapped in local minima or saddle points is a recurrent challenge. This talk explores the unconventional idea of utilizing stochastic noise as an ally, rather than an adversary. Drawing parallels with classical optimization, we'll discuss how noise can aid VQE in navigating complex energy landscapes, enhancing its convergence to the true global minimum. This perspective opens up innovative strategies for optimization in the noisy intermediate-scale quantum (NISQ) era.

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Influence of expressibility and entanglement capability of parameterized quantum circuits on the performance of VQE for combinatorial optimization

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Combinatorial optimization (CO) has many important applications in business and science. Many CO problems are NP-hard and are routinely solved by classical heuristics. It is widely believed that quantum computers cannot solve such problems efficiently, but significant effort is put into designing quantum algorithms that provide fast and reliable approximate solutions. In the era of noisy intermediate-state quantum (NISQ) computers, two candidates are the variational quantum eigensolver (VQE) and the quantum approximate optimization algorithm (QAOA). Both algorithms use a parameterized quantum circuit $|\psi(\vartheta)\rangle$ to minimize the expectation value $\langle H(\vartheta)\rangle = \langle\psi(\vartheta)|H|\psi(\vartheta)\rangle$ of a given Hamiltonian H by solving $\min_{\vartheta}\langle H(\vartheta)\rangle$.
While QAOA utilizes a quantum circuit that implements problem structure to apply trotterized time evolution, VQE circuits typically use problem agnostic designs that are tuned to run efficiently on NISQ hardware. In this empirical study, we test a variety of ansatz structures to address the weighted Max-Cut problem on 3-regular graphs for small instances and typical VQE settings. We do not observe a strong dependence of the algorithm's performance in terms of approximation ratio and probability of measuring the ground state on circuit design. Since solutions to CO problems are classical, the role of circuit expressibility and entanglement capabilitites are not clear. There are no correlations between expressibility and entanglement capabilities of the circuits and the algorithm's performance visible in our experiments. This suggests that these common circuit properties are not useful for designing circuits for CO and problem inspired designs, such as QAOA, are to be preferred.

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Ideas to bring Matrix Models on a quantum computer

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The aim of this talk is to introduce matrix models and discuss how and why to compute them on the quantum computer.

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Lattice Chern-Simons term for (2+1)-dimensional QED

Chern-Simons gauge theories have a deep and broad impact on a wide range of physics research, ranging from parity anomalies in quantum field theory to the theory of the integer and fractional quantum Hall effects, and the effective field theory description of chiral spin liquids in condensed matter physics. Despite the fact that Chern-Simons theories are well understood as a continuum field theory, there is still limited knowledge on how to find a compact Hamiltonian lattice formulation in 2+1 dimensions. This task turns out to be highly nontrivial, and we take a first step towards a lattice formulation by considering quantum electrodynamics on the lattice in the presence of a Chern-Simons term. We propose a compact lattice formulation for the Chern-Simons term in terms of the usual operators acting on the links, which we benchmark numerically against theoretical predictions. Our formulation is completely general and also suited for other Hamiltonian approaches such as quantum computing.

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Variational Time Evolution for the study of Meson Melting in the 1d Ising Model

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This project focuses on the development of methods for computing real-time dynamics of thermal states for quantum field theories on quantum devices using the 1D Ising model as a testbed. This research is motivated by the challenges faced by conventional classical methods for such systems.

We propose to prepare the thermal state on a quantum state via variational imaginary time evolution starting from a Thermofield Double state using the DualQITE approach. Subsequently, the thermal state can be evolved using standard methods and the thermal correlators can be measured over time. In the final stage, we conduct signal analysis of this data. This analysis allows us to observe the dynamics of the system and accurately measure the masses of the bound states that emerge during the evolution process.

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Constructing and Benchmarking Noise Models for Quantum Computing

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