QuantHEP 2025

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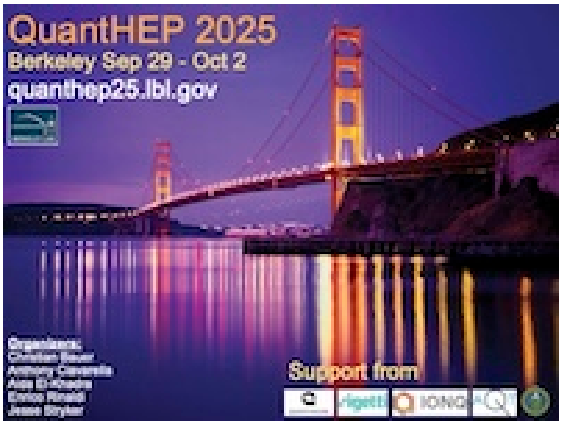
Lawrence Berkeley National Lab



Book of Abstracts

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Quantum simulation of Abelian models with Rydberg arrays

Author: Yannick Meurice[None]

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We motivate the use of rectangular arrays of Rydberg atoms as analog simulators for Abelian lattice gauge theories. We discuss the rich phase diagram of the simulators and the continuum limits that can be approached by varying the lattice spacing and the detuning. We compare the cost of estimating the entanglement entropy with twin copies and bitstring mutual information. We briefly introduce hybrid simulations that could be performed in this context.

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Euclidean-Monte-Carlo-informed ground-state preparation for quantum simulation of scalar field theory

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Quantum simulators offer great potential for investigating dynamical properties of quantum field theories. However, preparing accurate non-trivial initial states for these simulations is challenging. Classical Euclidean-time Monte-Carlo methods provide a wealth of information about states of interest to quantum simulations. Thus, it is desirable to facilitate state preparation on quantum simulators using this information. To this end, we present a fully classical pipeline for generating efficient quantum circuits for preparing the ground state of an interacting scalar field theory in 1+1 dimensions. The first element of this pipeline is a variational ansatz family based on the stellar hierarchy for bosonic quantum systems. The second element of this pipeline is the classical moment-optimization procedure that augments the standard variational energy minimization by penalizing deviations in selected sets of ground-state correlation functions (i.e., moments). The values of ground-state moments are sourced from classical Euclidean methods. The resulting states yield comparable ground-state energy estimates but exhibit distinct correlations and local non-Gaussianity. The third element of this pipeline is translating the moment-optimized ansatz into an efficient quantum circuit with an asymptotic cost that is polynomial in system size. This work opens the way to systematically applying classically obtained knowledge of states to prepare accurate initial states in quantum field theories of interest in nature.

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Thermalization from quantum entanglement: jet simulations in the massive Schwinger model

Author: Sebastian Grieninger[None]

Co-authors: Adrien Florio ; David Frenklakh ; Andrea Palermo ; Dmitri Kharzeev ; Shuzhe Shi

We investigate the emergence of thermalization in a quantum field-theoretic model mimicking the production of jets in QCD - the massive Schwinger model coupled to external sources. Specifically, we compute the expectation values of local operators as functions of time and compare them to their

thermal counterparts, quantify the overlap between the evolving density matrix and the thermal one, and compare the dynamics of the energy-momentum tensor to predictions from relativistic hydrodynamics. Through these studies, we find that the system approaches thermalization at late times and elucidate the mechanisms by which quantum entanglement drives thermalization in closed field-theoretic systems. Our results show how thermodynamic behavior emerges in real time from unitary quantum dynamics.

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Quantum simulation of QCD in the high-energy regime

Author: Herschel Chawdhry[1]

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A flagship application of quantum computing is the simulation of other quantum systems. In this talk, I will show how quantum computers can simulate scattering in the highest-energy regime of QCD probed by colliders like the LHC. In particular, I will present techniques to naturally calculate QCD Feynman diagrams and their interferences using a quantum computer. We simulate the colour parts of the interactions directly on the quantum computer, while the kinematic parts are for now pre-computed classically. For processes where some of the external particles are identical, we find the first hints of a potential quantum advantage. We validate our techniques using emulated quantum computers. Furthermore, for toy examples we also demonstrate our algorithms on a physical 56-qubit trapped-ion quantum computer. The work constitutes a further key step towards a full quantum simulation of generic high-energy QCD scattering processes at colliders like the LHC. [See arXiv:2507.07194 for further details.]

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High-energy plasma dynamics and memory effects in a 60-atom lattice gauge quantum simulator

Author: Daniel Mark[1]

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We use a 60-atom Rydberg quantum simulator to experimentally investigate a lattice gauge theory of quantum electrodynamics in one spatial dimension. We report several experimental surprises in its dynamics: despite the quench being at infinite temperature, correlations propagate ballistically to long distances, and there are short-range correlations that do not reach thermal equilibrium within experimental timescales. Our observations are simply explained in terms of plasma oscillations arising from pair production in response to electric fields. This description yields a number of physical insights, including new families of many-body scars and a method to visualize the many-body dynamics with Wigner distributions. We also identify an interference mechanism which results in a long memory of clustering of charged particles, an effect which is not present in the continuum field theory. Our work discovers a common, gauge-theoretic origin to many dynamical phenomena in Rydberg blockaded systems, resolving existing questions and expanding the phenomenology,

and hint at the possibilities for discoveries from detailed quantum simulations of lattice gauge theories.

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Real-Time Dynamics in a (2+1)-D Gauge Theory: The Stringy Nature on a Superconducting Quantum Simulator

Author: Enrique Rico Ortega[None]

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Understanding the confinement mechanism in gauge theories and the universality of effective string-like descriptions of gauge flux tubes remains a fundamental challenge in modern physics. We probe string modes of motion with dynamical matter in a digital quantum simulation of a (2+1) dimensional gauge theory using a superconducting quantum processor with up to 144 qubits, stretching the hardware capabilities with quantum-circuit depths comprising up to 192 two-qubit layers. We realize the Z2-Higgs model through an optimized embedding into a heavy-hex superconducting qubit architecture, directly mapping matter and gauge fields to vertex and link superconducting qubits, respectively. Using the structure of local gauge symmetries, we implement a comprehensive suite of error suppression, mitigation, and correction strategies to enable real-time observation and manipulation of electric strings connecting dynamical charges. Our results resolve a dynamical hierarchy of longitudinal oscillations and transverse bending at the end points of the string, which are precursors to hadronization and rotational spectra of mesons. We further explore multi-string processes, observing the fragmentation and recombination of strings. The experimental design supports 300,000 measurement shots per circuit, totaling 600,000 shots per time step, enabling high-fidelity statistics. We employ extensive tensor network simulations using the basis update and Galerkin method to predict large-scale real-time dynamics and validate our error-aware protocols. This work establishes a milestone for probing non-perturbative gauge dynamics via superconducting quantum simulation and elucidates the real-time behavior of confining strings.
https://arxiv.org/abs/2507.08088
Jesús Cobos, Joana Fraxanet, César Benito, Francesco di Marcantonio, Pedro Rivero, Kornél Kapás, Miklós Antal Werner, Örs Legeza, Alejandro Bermudez, Enrique Rico

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Quantum Computing for Transport and Energy Correlators

Author: Xiaojun Yao[1]

Co-authors: Anthony Ciavarella [2]; Francesco Turro ; Kyle Lee [3]

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In this talk, I will discuss some quantum algorithms for computing real-time correlation functions. These correlators are not time-ordered but contain interesting physical information. For example, retarded two-point correlators of stress-energy tensors can be used to extract transport coefficients such as the shear viscosity, which are physical quantities of great interest in heavy ion collisions and neutron star merging. Furthermore, a generic four-point correlator also appears in the definition of energy-energy correlators, which are collider observables that have attracted a lot of interest recently. I will show some interesting classical results that are obtained from exact diagonalization, as well as some benchmark results obtained from quantum simulators, for SU(2) pure gauge theory on small honeycomb lattices with significant truncation.

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Quantum simulations with non-compact variables

Author: Masanori Hanada[None]

We point out that theories using non-compact variables for bosons – such as scalar QFT, matrix models, and orbifold lattices – enjoy a universal and efficient quantum simulation protocol. This demonstrates that the technical challenges in the traditional Kogut-Susskind approach arise from its use of compact variables. We show that the Kogut-Susskind Hamiltonian can be realized as a special limit of the orbifold lattice, and therefore, it can also be simulated efficiently using the universal protocol developed for non-compact variables.

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Computing composite-particle mass spectra in the Hamiltonian formalism

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We study the massive 2-flavor Schwinger model with a theta term in the Hamiltonian formalism using the density-matrix renormalization group (DMRG).
We propose a new method for computing mass spectra by directly analyzing the energy and momentum of the excited states, where the dispersion relations for hadronic excitations are observed by identifying their quantum numbers.
We obtained reliable results even for large θ, where the naive Monte Carlo simulation fails due to the notorious sign problem.
The resulting mass spectra agree with those by existing methods and are consistent with the analytic prediction by the bosonized model.
We also discuss the potential application of this Hamiltonian-based method to a quantum computer with at least 40 logical qubits.
References:

[1] E. Itou, A. Matsumoto, and Y. Tanizaki, JHEP11 (2023) 231.
[2] E. Itou, A. Matsumoto, and Y. Tanizaki, JHEP09 (2024) 155.

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Towards a Quantum Information Theory of Hadronization

Author: Zhiquan Sun[None]

Co-authors: Johannes Michel ; Kyle Lee ; Rebecca von Kuk

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We pioneer the application of quantum information theory to experimentally distinguish between classes of hadronization models.
We adapt the CHSH inequality to the fragmentation of a single parton to hadron pairs, a violation of which would rule out classical dynamics of hadronization altogether. Furthermore, we apply and extend the theory of quantum contextuality and local quantum systems to the neutral polarization of

a single spin-1 hadronic system, namely the light constituents of excited Sigma baryons $\Sigma^*_{c,b}$ formed in the fragmentation of heavy quarks.

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Obtaining continuum physics from dynamical simulations of Hamiltonian lattice gauge theories

Author: Christopher Kane[1]

Co-authors: Christian Bauer [2]; Siddharth Hariprakash [3]

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Taking the continuum limit is essential for extracting physical observables from quantum simulations of lattice gauge theories. Achieving the correct continuum limit requires careful control of all systematic uncertainties, including those arising from approximate implementations of the time evolution operator. In this work, we review existing approaches based on renormalization techniques, and point out their limitations. To overcome these limitations, we introduce a new general framework —the Statistically-Bounded Time Evolution (SBTE) protocol —for rigorously controlling the impact of approximate time evolution on the continuum limit. The central insight is that, since exact time evolution introduces no UV divergences, errors from approximate evolution can be treated as a source of systematic uncertainty that can be neglected if reduced below the working statistical uncertainty. We show that, using the SBTE protocol, which prescribes driving the approximate time evolution error below the working statistical uncertainty, leads to a simplified renormalization procedure. Furthermore, we show that, due to the existence of rigorous error bounds, one can guarantee a priori that such errors are negligible and do not affect the continuum limit. Ultimately, our protocol lays the foundation for performing systematic and fair comparisons between different simulation algorithms for lattice gauge theory simulations.

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Entanglement and thermalization in jet production in massive Schwinger model

Authors: Adrien Florio[None]; Andrea Palermo[None]; David Frenklakh[None]; Dmitri Kharzeev[None]; Sebastian Grieninger[None]; Shuzhe Shi[None]

We study thermalization in an isolated quantum gauge theory using real-time simulations of the lattice Schwinger model (1+1D QED) subject to a quench simulating high-energy jet injection that drives the system far from equilibrium. We observe that local observables and entanglement entropy all relax to values consistent with a single, universal temperature indicating emergent thermal behavior. Computing the fidelity between the full quantum state and thermal density matrices we confirm that the system evolves toward the thermal state with the highest overlap at that universal temperature. Our results highlight the role of entanglement in driving thermalization and demonstrate the power of real-time quantum simulation methods in addressing nonequilibrium dynamics in strongly interacting systems.

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Quantum thermodynamics of nonequilibrium processes in lattice gauge theories

Authors: Christopher Jarzynski[1]; Connor Powers[1]; Greeshma Oruganti[1]; Nicole Yunger Halpern[1]; Niklas Mueller[2]; Zohreh Davoudi[1]

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A key objective in nuclear and high-energy physics is to describe nonequilibrium dynamics of matter, e.g., in the early universe and in particle colliders, starting from the Standard Model. Classical-computing methods, via the framework of lattice gauge theory (LGT), have experienced limited success in this mission. Quantum simulation of lattice gauge theories holds promise for overcoming computational limitations. Hamiltonian formulations of LGTs are most naturally suited for quantum simulation, but these formulations have an intricate Hilbert-space structure due to local constraints, Gauss's laws. This structure complicates the separation of the two constituents—a system and a reservoir—of a bipartite system. Such a situation mimics those encountered in strong-coupling quantum thermodynamics, a framework that has recently burgeoned within the field of quantum thermodynamics. Within this framework, we demonstrate how to define thermodynamic quantities such as work and heat during instantaneous quench processes—simple non-equilibrium processes created in quantum simulation. To illustrate our framework, we compute the work and heat exchanged during a chemical potential quench in a $\mathbb{Z}2$ lattice gauge theory coupled to matter in 1+1 dimensions. The thermodynamic quantities, as functions of the quench parameter, evidence a phase transition. For general thermal states, we derive a simple relation between a quantum many-body system's entanglement Hamiltonian, measurable with quantum-information-processing tools, and the Hamiltonian of mean force, used to define strong-coupling thermodynamic quantities. This relation potentially allows for experimental verification of the quantum-thermodynamic framework for LGTs.

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Thermalization in SU(2) LGT: ETH and Entanglement

Author: Clemens Seidl[1]

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We report progress toward a full quantum understanding of thermalization in non-Abelian gauge theories.
We present numerical evidence supporting the hypothesis that the Hamiltonian SU(2) gauge theory, discretized on a lattice, obeys the eigenstate thermalization hypothesis.
We study entanglement entropy, highlighting the emergence of Page curves, the transition from area-law to volume-law scaling, and the absence of quantum many-body scars when higher representations of the gauge field are included.
Furthermore, we investigate the dynamics of entanglement and non-stabilizerness, observing that the latter reaches its peak during the thermalization process.

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Digital quantum simulations of scattering in quantum field theories using W states

Authors: John Preskill[None]; Marc Illa[None]; Nikita Zemlevskiy[None]; Roland Farrell[None]

High-energy particle collisions can convert energy into matter through the inelastic production of new particles. Quantum computers are well suited for simulating the out-of-equilibrium dynamics of the collision and the formation of the subsequent many-particle state. In this talk, I will present results from quantum simulations of inelastic scattering in 1D Ising field theory. These scattering experiments were performed on 100 qubits of IBM's quantum computers and used up to 6,412 two-qubit gates to access the post-collision dynamics. Integral to these simulations is a new quantum algorithm for preparing wavepackets that builds off recent advances in efficient W state preparation using mid-circuit measurement and feedforward. The required circuit depth is independent of wavepacket size and spatial dimension, representing a superexponential improvement over previous methods. The wavepacket preparation algorithm can be applied to a wide range of lattice models and I will presemt results from classical simulations of 1D scalar field theory, the Schwinger model, and 2D Ising field theory.

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Real-time Estimators for Scattering Observables

Authors: Ivan Mauricio Burbano Aldana[1]; Marco Carrillo[2]; Rana Urek[3]; Anthony Ciavarella[4]; Raul Briceno[3]

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The real-time correlators of quantum field theories can be directly probed through new approaches to simulation, such as quantum computing and tensor networks. This provides a new framework for computing scattering observables in lattice formulations of strongly interacting theories, such as lattice quantum chromodynamics. In this talk, we will go over the proof given in arXiv: 2506.06511, showing that the proposal of real-time estimators of scattering observables is universally applicable to all scattering observables of gapped quantum field theories. All finite-volume errors are exponentially suppressed, and the rate of this suppression is controlled by the regulator considered, namely, a displacement of the spectrum of the theory into the complex plane. A partial restoration of Lorentz symmetry by averaging over different boosts gives an additional suppression of finite volume errors. Our results also apply to the simulation of wavepacket scattering, where a similar averaging is performed to construct the wavepackets that regulate the finite volume effects. We also comment on potential applications of our results to traditional computational schemes.

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Explorations of Full Gauge-Fixed SU(2)

Author: Dorota Grabowska[None]

In order to carry out quantum simulations of lattice gauge theories, it is necessary to use the Hamiltonian formulation. This can lead to complications during simulations due to incomplete gauge fixing. In recent years, much effort has been focused on figuring out various formulations, using myriad bases, truncation schemes and degrees of gauge fixing. Ideally, a formulation would be efficient for fine lattices, systematically improvable and gauge invariant. No such formulation has yet been developed and so usually one of these desired properties is sacrificed. In this talk, I focus on a formulation that has been developed in the last several years: a fully gauge-fixed formulations utilizing the axis-angle representation of SU(2). I discuss the advantages and disadvantages of this formulation and present recent work on implementing this formulation on real-world quantum devices.

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State Preparation in SU(3) Lattice Gauge Theory

Author: Drishti Gupta[1]

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In this talk, I will present our recent work toward preparing the ground state of SU(3) lattice gauge theory on quantum computers. We explore two methods: (1) a variational approach, and (2) a time-dependent adiabatic evolution from the perturbative strong-coupling regime to moderately weak couplings. We also introduce a new truncation method based on the energy density associated with site-singlets. Performance of both state preparation methods is benchmarked against strong coupling perturbation theory and exact diagonalization of the Kogut–Susskind Hamiltonian, in d=2 and d=3 spatial dimensions, for a range of couplings and truncations.

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Genuine 2+1D string breaking dynamics and glueball formation in 2+1D lattice gauge theories

Author: Jad Halimeh[1]

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With the advent of advanced quantum processors capable of probing lattice gauge theories (LGTs) in higher spatial dimensions, it is crucial to understand string dynamics in such models to guide upcoming experiments and to make connections to high-energy physics (HEP). In the first part of the talk, we show tensor network results on the far-from-equilibrium quench dynamics of electric flux strings between two static charges in $2+1$D LGTs with dynamical matter. We calculate the probabilities of finding the time-evolved wave function in string configurations of the same length as the initial string. At resonances determined by the the electric field strength and the mass, we identify various string breaking processes accompanied with matter creation. Away from resonance, strings exhibit intriguing confined dynamics which, for strong electric fields, we fully characterize through effective perturbative models. Starting in maximal-length strings, we find that the wave function enters a dynamical regime where it splits into shorter strings and disconnected loops, with the latter bearing qualitative resemblance to glueballs in quantum chromodynamics (QCD). In the second part of the talk, we show that the plaquette term plays a crucial role in *genuine* $2+1$D string dynamics deep in the confined regime. In its absence and for minimal-length (Manhattan-distance) strings, we demonstrate how string breaking, although on a lattice in $d=2$ spatial dimensions, can be effectively mapped to a $1+1$D dynamical process independently of lattice geometry. Our findings not only answer the question of what qualifies as genuine $2+1$D string dynamics, but also serve as a clear guide for future quantum simulation experiments of $2+1$D LGTs.

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Simulating Real-Time Dynamics of Lattice Gauge Theories with Fermions at Large Nc

Author: Neel Modi[1]

Co-authors: Anthony Ciavarella [2]; Christian Bauer [3]; Jad Halimeh [4]

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The most direct method to observe real-time dynamics of Lattice Gauge Theories (LGTs) is by exact time evolution. Simulating time evolution on classical or quantum hardware requires truncating the infinitely-many degrees of freedom represented by the gauge group down to finitely-many relevant degrees of freedom that can capture the low-energy physics. Truncation strategies have previously been developed for pure gauge theories by using techniques such as large-N counting. We present a new truncation strategy developed for LGTs with fermions, and discuss the phenomenology of string-breaking and glueball formation in the resulting real-time dynamics.

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Scalable Quantum Simulations of Scattering in Quantum Field Theories

Author: Nikita Zemlevskiy[1]

Co-authors: John Preskill [2]; Marc Illa [1]; Roland Farrell [2]

[1] *University of Washington*

[2] *Caltech*

Quantum simulations exceeding the capabilities of brute-force classical computations are becoming possible. Simulations of high-energy inelastic scattering events are expected to have an exponential advantage over classical methods. In this talk I will describe how new scalable state preparation methods, together with new error mitigation techniques and careful tuning of simulation parameters, enabled the study of inelastic collisions of fundamental particles on quantum computers available today. I will conclude with an outlook for simulations of scattering in higher dimensions, where a near-term quantum advantage may be possible.

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The success and limitation of Euclidean lattice calculations

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Quantum information science and formal theory

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

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Quantum Simulations of Energy-Loss and Hadronization

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High Energy Physics and possibilies for quantum simulation

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Overview of quantum hardware technologies

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Tensor networks for Hamiltonian lattice gauge theories

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Quantum Computing for HEP: View from the DOE

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Pathfinding Quantum Simulations of Neutrinoless Double-β Decay

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Towards a Loop-String-Hadron Formulation for SU(3) Yang-Mills Theory

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A lattice gauge theory ground state calculation through subspace diagonalization

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Welcome