# TH Institute on Quantum Simulation & Computation in High-Energy Physics

# Report of Contributions

Contribution ID: **1** Type: **not specified**

# Obtaining truncated Hamiltonians for quantum simulations of QCD

*Monday, 8 September 2025 10:00 (1 hour)*

I will discuss some recent progress on obtaining truncated Hamiltonians for QCD. After a brief motivation, I will discuss how an expansion in 1/Nc yields a large reduction in the available Hilbert space as well as a much simpler Hamiltonian. This has allowed a simulation of 2+1D SU(3) YM theory on IBM quantum computers on an 8x8 lattice. Next, I will discuss how subleading orders in 1/Nc as well as higher order truncations can be included, and show that one reproduces the lowest lying glueball mass with surprisingly good accuracy. Motivated by the success at these low truncations, I will discuss in the final part of the talk a new method to bound uncertainties from the truncation of bosonic fields, yielding a dramatic improvement over prevoiusly existing bounds.

**Presenter:** BAUER, Christian Walter (Lawrence Berkeley National Lab. (US))

Contribution ID: **2** Type: **not specified**

# Observation of string breaking on a (2 + 1)D Rydberg quantum simulator

*Monday, 8 September 2025 14:00 (1 hour)*

Lattice gauge theories (LGTs) describe a broad range of phenomena in condensed matter and particle physics. A prominent example is confinement, responsible for bounding quarks inside hadrons such as protons or neutrons. When quark-antiquark pairs are separated, the energy stored in the string of gluon fields connecting them grows linearly with their distance, until there is enough energy to create new pairs from the vacuum and break the string. While such phenomena are ubiquitous in LGTs, simulating the resulting dynamics is a challenging task. In this talk, I will report the observation of string breaking in synthetic quantum matter using a programmable quantum simulator based on neutral atom arrays [Nature 642, 321–326 (2025)]. I will first show how a (2+1)D LGT with dynamical matter can be efficiently implemented when the atoms are placed on a Kagome geometry, with a local U(1) symmetry emerging from the Rydberg blockade, while long-range Rydberg interactions naturally give rise to a linear confining potential between pairs of charges. In the experiment, we probe string breaking in equilibrium by adiabatically preparing the ground state of the atom array in the presence of defects, distinguishing regions within the confined phase dominated by fluctuating strings or by broken string configurations. Finally, by harnessing local control over the atomic detuning, we quench string states and observe string breaking dynamics exhibiting a many-body resonance phenomenon. As an outlook, I will present a roadmap to further explore phenomena in high-energy physics using programmable quantum simulators.

**Presenter:** GONZÁLEZ CUADRA, Daniel

Contribution ID: **3** Type: **not specified**

# Leveraging Quantum Hardware for Fundamental Physics

*Tuesday, 9 September 2025 10:00 (1 hour)*

Recent advances in quantum hardware and quantum information science are opening new avenues for tackling longstanding challenges in fundamental physics. In this talk, I will discuss how emerging quantum platforms can be used to simulate aspects of QCD. A particular focus will be on trapped ion quantum computers, which offer a unique capability: they can naturally represent both fermionic and bosonic degrees of freedom within the same device, using ion spins as qubits and collective vibrational modes as continuous variables. This hybrid simulation approach can go beyond the reach of current superconducting quantum technologies. Furthermore, we will discuss how quantum optimal control and quantum hardware architecture design can be employed to improve our ability to simulate lattice gauge theories. Finally, I'll discuss how these techniques can be utilised in calculating time-dependent observables, such as Parton Distribution Functions.

**Presenter:** ARAZ, Jack Y. (City St George's, University of London)

Contribution ID: **4** Type: **not specified**

# Ultralight dark matter with and without self-interaction

*Tuesday, 9 September 2025 14:00 (1 hour)*

Ultralight scalar fields have emerged as a compelling alternative to the standard cold dark matter paradigm. Their wave-like nature, governed by the Schrödinger–Poisson system, leads to new predictions for structure formation, including the presence of solitonic cores with flat central density profiles in dark matter halos. In this talk, I present an overview of FDM models both with and without self-interactions, highlighting the modifications to soliton properties in different models. I will also present ideas on the application of quantum computing to the computation of solitons and their dynamics, which could achieve promising results.

**Presenter:** GALAZO GARCÍA, Raquel (Laboratoire d'Astrophysique de Marseille)

Contribution ID: **5** Type: **not specified**

# Real-Time Dynamics in the (2+1)D Z2-Higgs model

*Wednesday, 10 September 2025 10:00 (1 hour)*

In this work, we probe string modes of motion with dynamical matter in a digital quantum simulation of a
(2+1) dimensional gauge theory using an IBM superconducting quantum processor with up to 144 qubits. The Z2-Higgs model is realized through a direct mapping of matter and gauge fields onto heavy-hex qubits, with circuit depths reaching nearly 200 entangling layers. By leveraging the structure of local gauge symmetries, we deploy a comprehensive set of error suppression, mitigation, and correction strategies to enable real-time observation and manipulation of electric strings connecting dynamical charges. This framework allows us to resolve a hierarchy of string excitations: longitudinal oscillations and transverse bending at string endpoints, precursors of hadronization and meson spectra. 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. Extensive tensor-network simulations provide large-scale predictions and validate our error-aware protocols. These results establish a milestone in the quantum simulation of non-perturbative gauge dynamics and advance our understanding of the real-time behavior of confining strings.
https://arxiv.org/pdf/2507.08088

**Presenter:** FRAXANET MORALES, Joana (IBM)

Contribution ID: **6** Type: **not specified**

# TH Colloquium - The end of measurement and the last lab

*Wednesday, 10 September 2025 14:00 (1 hour)*

Measurements in fundamental physics are becoming increasingly difficult. In particular, many high-precision measurements are now dealing with the intrinsic quantum mechanical noise of the detectors themselves. LIGO is an example: it is limited by Heisenberg uncertainty in the laser light. However, this quantum noise can in principle be engineered away by clever use of quantum resources. I will discuss these issues through some examples (cosmic neutrino detection, gravitational wave detection, and tests of quantum gravity), and offer some speculations on the practical and perhaps fundamental limitations on quantum engineering for measurements of this type.

**Presenter:** CARNEY, Daniel (Berkeley National Lab)

Contribution ID: **7** Type: **not specified**

# Quantum Computational Advantages of Fundamental Interactions

*Thursday, 11 September 2025 10:00 (1 hour)*

In quantum computing, non-stabilizerness – the magic – refers to the computational advantage of certain quantum states over classical computers and is an essential ingredient for universal quantum computation. We study the production of magic states in Quantum Electrodynamics (QED) via 2-to-2 scattering processes involving electrons and muons. Considering all 60 stabilizer initial states, which have zero magic, the angular dependence of magic produced in the final states is governed by only a few patterns. It turns out QED is not very efficient in generating non-stablizerness and, in most cases, the largest magic generated is significantly less than the maximal possible value for two-qubit systems. Our results raise the question of whether quantum advantage is a fundamental property of basic forces or an emergent phenomena of many-body systems. We will also discuss hints that the Standard Model of particle physics is quite special from the computational viewpoint.

**Presenter:** LOW, Ian

Contribution ID: **8** Type: **not specified**

# Quantum Metrology for High-energy Physics

*Friday, 12 September 2025 10:00 (1 hour)*

Quantum sensing offers significant advantages over classical techniques when detecting extremely weak signals, such as those from dark matter, by leveraging entanglement and superposition to achieve greater sensitivity and precision. There are two main approaches in quantum sensing: adapting classical signal processing methods to the quantum domain and developing novel quantum algorithms and protocols.
In the first approach, I will present my recent work on measuring dark matter properties and ongoing efforts to minimize measurement noise. In the second approach, I will explore how quantum entanglement can enhance measurement sensitivity beyond classical limits, as well as discuss additional applications, including quantum sensing with error correction and quantum data processing.

**Presenter:** FUKUDA, Hajime (The University of Tokyo)

Contribution ID: **9** Type: **not specified**

# Towards a quantum event generator in perturbative QFT

*Thursday, 11 September 2025 14:00 (1 hour)*

Theoretical predictions at high-energy colliders are based on encoding the quantum fluctuations that occur at very short distances in the collision by Feynman diagrams. These diagrams are made up of interaction vertices and propagators, which in fact represent a quantum superposition of propagation in the two directions between two interaction vertices. So, this allows us to map Feynman propagators to qubits and to analyse the causal properties of Feynman diagrams in a quantum computing approach, in particular in the Loop-Tree Duality (LTD) representation. The causal configurations of Feynman diagrams are equivalent to Directed Acyclic Graphs in graph theory, which allow us to leverage fundamental principles from graph theory to optimise the design of a quantum oracle. As a recent application of quantum algorithms in particle physics, we present the Quantum Adaptive Importance Sampling (QAIS) method for an efficient integration and sampling of multidimensional functions. The ultimate goal of QAIS is to build a quantum event generator with theoretical accuracy at the highest possible perturbative order to describe the hard scattering processes that occur at high-energy colliders.

**Presenter:** RODRIGO, German (IFIC UV-CSIC)

Contribution ID: **10** Type: **not specified**

# Simulating quantum field theories with continuous-variable quantum computers

*Friday, 12 September 2025 14:00 (1 hour)*

Non-perturbative processes such as scattering and false-vacuum decay in quantum field theory (QFT) play a central role in cosmology and particle physics, but remain intractable for classical simulation due to their highly entangled dynamics. We introduce a framework for simulating the real-time dynamics of interacting scalar QFTs in the continuous-variable quantum computing (CVQC) paradigm, mapping the theory to a spatially discretised lattice of qumodes, quantum oscillators with a continuous local Hilbert space. We demonstrate that the framework can be emulated using tensor networks, where the qumodes are represented by truncated bosonic modes with a corresponding Hilbert space large enough to capture the interactions in the Hamiltonian. Using time-evolving block decimation (TEBD) with Trotterised time evolution, we explore two use cases. First, we study real-time scattering processes in (1+1)-dimensional $\phi^4$ theory, outlining methods for preparing initial states with defined momentum. We validate the framework against analytical solutions via two-point correlation functions. Secondly, we capture the real-time dynamics of false-vacuum decay in a self-interacting scalar QFT. We initialise a metastable vacuum and observe the coherent entanglement growth that seeds true-vacuum bubble nucleation. Our approach establishes the qumode tensor-network as a scalable framework for non-equilibrium scalar QFT phenomena and paves the way for higher-dimensional studies and CVQC implementations.

**Presenter:** WILLIAMS, Simon Jonathan (Institute of Particle Physics Phenomenology, University of Durham)

Contribution ID: **11** Type: **not specified**

# Multiscale quantum simulations of QFTs

*Monday, 15 September 2025 10:00 (1 hour)*

I will describe how to use wavelets, a tool originally used for image compression, to simulate quantum field theory. I'll present a quantum algorithm for asymptotically optimal vacuum state preparation of scalar bosonic QFT. The wavelet encoding enables the direct simulation of particle scattering at multiple scales and facilitates efficient ground state preparation for theories with broken translational symmetry, e.g., mass defects. Next, I'll describe a new quantum algorithm for efficient block encoding of differential operators in the Shannon wavelet basis. These representations, also known as SLAC derivatives, are highly non-local but avoid the fermionic doubling problem and preserve chiral symmetry. The encoding can be used for real-time Hamiltonian evolution or for solving linear systems of differential equations.

**Presenter:** BRENNEN, Gavin

Contribution ID: **12** Type: **not specified**

# Quantum Machine Learning for Fundamental Physics

*Monday, 15 September 2025 14:00 (1 hour)*

The intersection of quantum computing and machine learning offers novel pathways to address long-standing challenges in fundamental physics. In this talk, I will present recent advances in applying quantum machine learning techniques to high-energy and many-body problems, highlighting how neural quantum states and variational quantum circuits can provide efficient representations of exponentially large Hilbert spaces. I will discuss the use of quantum annealers and continuous-variable devices as experimental platforms for studying field-theoretic dynamics, including tunnelling phenomena and non-perturbative processes. Beyond simulation, I will show how quantum-inspired methods can accelerate effective field theory parameter estimation and optimisation tasks that are computationally prohibitive for classical approaches. These developments point towards a quantum laboratory for fundamental physics, where machine learning and quantum hardware together open new avenues for exploration at the interface of theory, computation, and experiment.

**Presenter:** SPANNOWSKY, Michael (IPPP Durham)

Contribution ID: **13** Type: **not specified**

# Thermalization in QFT via Quantum Computation

*Wednesday, 17 September 2025 10:00 (1 hour)*

Quantum computation offers a new avenue for studying thermalization in quantum field theory. In this talk, I present our work on $\phi^4$ theory in (0+1)D and (1+1)D using quantum computation. Specifically, we investigate particle production from an initial classical (coherent) field, analogous to classical problems such as reheating in the early universe and quark–gluon plasma formation in heavy-ion collisions. We observe qualitative differences between quantum and classical systems. Although we cannot draw firm conclusions about thermalization because of the limited number of qubits, our results raise intriguing questions about the meaning of thermalization in (effectively) few-body quantum systems.

**Presenter:** WU, Bin

Contribution ID: **14** Type: **not specified**

# Quantum-Enhanced Learning: From Information Theory to High-Energy Physics

*Wednesday, 17 September 2025 16:00 (1 hour)*

This talk will explore how tools from quantum information science can provide new paradigms for machine learning and data processing in high-energy physics. I will first discuss the theoretical relationship between learning and compression, a cornerstone of information theory which holds that effective learning models inherently extract and compress meaningful patterns from data. Then, I will show how quantum computers and quantum algorithms can process classical data, but also how quantum memories can allow the definition of new generative paradigms that require less data to make new predictions. Finally, I will show how other peculiar features of quantum mechanics, such as entanglement, can be used to learn hidden patterns and devise better detectors. These frameworks open two promising avenues for HEP applications: the development of quantum-enhanced detectors with superior sensing capabilities, and the efficient processing and storage of the immense datasets generated by modern colliders.

**Presenter:** BANCHI, Leonardo (UniFi / INFN-FI)

Contribution ID: **15** Type: **not specified**

# Tensor network algorithms for HEP quantum simulation

*Tuesday, 16 September 2025 10:00 (1 hour)*

We review some recent results on the development of efficient tensor network algorithms and their applications to quantum simulation for benchmarking and theoretical interpretation. In particular, we present results on lattice gauge theories in 2+1 and 3+1 dimensions at finite density, and out-of-equilibrium scattering dynamics in 1+1 dimensions In particular, scattering and induced false vacuum decay in the two-dimensional quantum Ising model. Moreover, we present a roadmap for future tensor network simulations of LGT of increasing complexity. Finally, we present the application of tensor network methods to the solution of hard classical combinatorial problems via mapping to many-body quantum hamiltonians, with applications in quantum compilation, factorization, and equational reasoning.

**Presenter:** MONTANGERO, Simone

Contribution ID: **16** Type: **not specified**

# Quantum simulation of lattice gauge theories with qudit systems

*Tuesday, 16 September 2025 14:00 (1 hour)*

Lattice gauge theories (LGTs) are fundamental in our understanding of high-energy and condensed matter systems, and have their relevance in topological quantum computation. Simulating LTGs on a classical computer is, however, challenging in many physically relevant regimes. Quantum simulation offers a promising path forward, but implementing LGTs on near-term quantum devices poses significant obstacles, including constrained physical Hilbert spaces, gauge invariance conditions, and complex many-body interactions. In this talk we will explore the use of qudit-based quantum systems for the simulation of Abelian and non-Abelian lattice gauge theories. Unlike conventional qubit platforms, qudits (quantum systems with d>2 levels) naturally accommodate the local degrees of freedom arising in gauge theories, enabling more efficient encodings. We utilize strategies for effective Hamiltonian formulations beyond (1+1)-dimensional settings, enabling local qudit encodings. Our approach towards quantum simulation of LGTs includes variational algorithms, implemented via hybrid quantum-classical feedback loops that can be realized on platforms such as trapped ions with native qudit gates. We demonstrate a path towards real-time dynamics and ground-state preparation for (2+1)-D Abelian U(1) models and ground-state preparation of non-Abelian $D_4$ lattice gauge theories. Furthermore, we investigate topological and fracton signatures in multi-flavour Schwinger models, showing how vacuum physics is affected by the presence of gauge fields with fractional topological charge. Notably, these effects are detectable even in highly truncated qudit systems, highlighting their relevance for near-term quantum simulation of gauge theories. Our results illustrate the power of qudit-based quantum architectures to access regimes beyond the reach of classical computation, offering a compelling direction for simulating gauge theories and probing topological phenomena in quantum field theory.

**Presenter:** POPOV, Pavel (ICFO)

Contribution ID: **17** Type: **not specified**

# Simulations of real-time dynamics of QED systems

*Thursday, 18 September 2025 10:00 (1 hour)*

I will discuss recent progress in the study of real-time dynamics of quantum electrodynamics (QED) systems, ranging from one-dimensional lattice gauge models and string breaking to dynamical quantum phase transitions. The talk will cover numerical simulations and experimental realizations in digital quantum simulators and Rydberg atom platforms, strategies for error mitigation, and the emergence of non-Markovian effects in waveguide QED.

**Presenter:** FACCHI, Paolo

Contribution ID: **18** Type: **not specified**

# Mapping correlations in real-time simulations of (1+1)D LGT

*Thursday, 18 September 2025 14:00 (1 hour)*

We introduce local information flows as a diagnostic to characterize out-of-equilibrium quantum dynamics in lattice gauge theories. We employ the information lattice framework, a local decomposition of total information into spatial and scale-resolved contributions, to characterize the propagation and buildup of quantum correlations in real-time processes. Focusing on the Schwinger model — a canonical $(1+1)$-dimensional U(1) lattice gauge theory — we apply this framework to two scenarios. First, in the near-threshold scattering of two vector mesons, we demonstrate that the emergence of correlations at a longer length scale in the information lattice marks the production of a heavier scalar meson pair. Second, in the dynamics of electric field strings, we clearly distinguish between the confining regime, which evolves towards a steady state with a static correlation profile, and the string-breaking sector. The latter is characterized by a transition from static configurations to dynamic correlation patterns reflecting the sequential formation and annihilation of strings. This information-centric approach provides a direct, quantitative, and interpretable visualization of complex many-body phenomena, offering a promising tool for analyzing dynamics in higher-dimensional gauge theories and experiments on quantum hardware.

**Presenter:** LOURENCO HENRIQUES BARATA, Joao

Contribution ID: **19** Type: **not specified**

# Real-Time String Dynamics in a 2+1D Non-Abelian Lattice Gauge Theory: String Breaking, Glueball Formation, Baryon Blockade, and Tension Reduction

*Friday, 19 September 2025 10:00 (1 hour)*

Understanding flux string dynamics can provide insight into quark confinement and hadronization. First-principles quantum and numerical simulations have mostly focused on toy-model Abelian lattice gauge theories (LGTs). With the advent of state-of-the-art quantum simulation experiments, it is important to bridge this gap and study string dynamics in non-Abelian LGTs beyond one spatial dimension. Using tensor network methods, we simulate the real-time string dynamics of a 2+1D SU(2) Yang-Mills LGT with dynamical matter.
In the strong-coupling regime and at resonance, string breaking occurs through sharp Casimir reduction along with meson and baryon-antibaryon formation, a distinctively non-Abelian feature.
At finite baryon density, we discover a "baryon blockade" mechanism that delays string breaking.
Away from resonance, the magnetic term drives purely non-Abelian fluctuations: glueball loops and self-crossed strings that resolve two SU(2) intertwiners with distinct dynamics.
For higher-energy strings, we uncover representation-dependent tension-reduction resonances.
Our findings serve as a guide for upcoming quantum simulators of non-Abelian LGTs.

**Presenter:** CATALDI, Giovanni (Max Planck Institute of Quantum Optics)

Contribution ID: **20** Type: **not specified**

# Properties of Fundamental Particles from Quantum Information?

*Friday, 19 September 2025 14:00 (1 hour)*

Scattering processes provide a natural arena to explore how quantum information concepts manifest in particle physics. Beginning with low-energy nucleon–nucleon scattering, I show how characteristic entanglement patterns are tied to emergent symmetries such as the Wigner SU(4) symmetry. Turning to gauge and gravitational interactions, gluon and graviton scattering (and their supersymmetric counterparts) exhibit maximal entanglement at perpendicular kinematics, while magic remains below its maximal theoretical value. However, it is noteworthy that there exist an anticorrelation between magic production and the spin of the participating particles. Finally, a surprising link emerges when studying entanglement in electroweak $2 \longrightarrow 2$ processes at $\pi/2$ scattering angles: the amount of entanglement is minimized when the Cabibbo–Kobayashi–Maskawa (CKM) matrix is nearly (but not exactly) diagonal, in qualitative agreement with observation. Extending this reasoning to the lepton sector, the same principle favors a Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix with two large angles and a smaller one, again consistent with data, together with a possible indication of suppressed CP violation. These recurring patterns suggest that information-theoretic measures may provide a new perspective on the structure of fundamental interactions.

**Presenter:** TRIFINOPOULOS, Sokratis

Contribution ID: **21** Type: **not specified**

# Introduction

*Monday, 8 September 2025 09:45 (15 minutes)*

Contribution ID: **22** Type: **not specified**

# Topological Charge Estimation in Quantum Rotor Model Using Quantum Encoding

*Wednesday, 10 September 2025 16:00 (1 hour)*

The quantum rotor provides a simplified yet nontrivial framework for investigating topological charge in one spatial dimension. In classical lattice field theory, accessing fixed topological sectors typically requires reweighting techniques or constrained sampling. Quantum simulation, by contrast, offers a natural alternative: projective measurements collapse the system into sectors with well-defined topological charge Q, enabling the direct evaluation of sector-resolved observables ⟨O⟩Q. In this work, we present an implementation of the 1D rotor model. We compute the topological correlator for small system sizes, analyze its behavior against theoretical expectations, and include exponential corrections arising from finite-volume effects.

**Presenter:** BAUTISTA GUZMAN, Irais (Autonomous University of Puebla (MX))

Contribution ID: **24** Type: **not specified**

# Quantum computation of Feynman diagrams for high-energy QCD simulations

*Thursday, 11 September 2025 16:00 (1 hour)*

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 high-energy regime of QCD probed by colliders like the LHC. In particular, I will present techniques to calculate QCD Feynman diagrams and their interferences using a quantum computer. The colour parts of the interactions are simulated 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, the first hints of a potential quantum advantage are found. The techniques were validated using emulated quantum computers. Furthermore, for toy examples, we also demonstrate our algorithms on a state-of-the-art 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.

**Presenter:** CHAWDHRY, Herschel (Florida State University)

Contribution ID: **25** Type: **not specified**

# Quantum Spectral Sampling for the SO(3) Quantum Link Model

*Tuesday, 16 September 2025 16:00 (1 hour)*

Quantum link models (QLMs) have gained attention in recent years, as a framework for discretising gauge theories which is especially suited to quantum computation approaches, and which often exhibit exotic phases of matter, allowing one to address dynamical properties related to quantum many-body scarring and Hilbert-space fragmentation which are otherwise difficult to study. We choose to focus on the SO(3) QLM because of qualitative properties it is known to share with QCD, including fermionic baryon bound states, and spontaneous chiral symmetry breaking (in (1+1)d). More recently, a subset of us have studied the matter-free SO(3) QLM in (2+1)d using quantum algorithms to demonstrate spontaneous symmetry breaking.

In recent work to be reviewed in this talk, we have constructed the gauge-invariant state space for the SO(3) QLM in (2+1)d with dynamical fermions, and obtained ED results which demonstrate spontaneous symmetry breaking and a non-trivial phase space for a single plaquette. In this talk, we demonstrate how a recently proposed quantum algorithm for whole-spectrum sampling, which takes advantage of maximally-mixed states, can be applied to QLMs to great effect.

Such methods have general applicability across the domain of quantum simulation for physical systems, and in presenting an algorithm which may be unfamiliar to many practitioners, we will emphasize several distinct types of physical data which can be efficiently extracted by such a technique. We will also tentatively explore how the spectral sampling algorithm may be modified to examine nonzero baryon-densities, and the practicalities of performing efficient hardware experiments.

**Presenter:** VAN GOFFRIER, Graham (CERN)