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

Jesús Cobos[1], Joana Fraxanet[2], César Benito[3], Francesco di Marcantonio[1], Pedro Rivero[2] , Kornél Kapás[4], Miklós Antal Werner[4], Örs Legeza[4,5,6], Alejandro Bermudez[3], Enrique Rico[7,8,9]

[1] *EHU Quantum Center and Dept. of Phys. Chem., Univ. of the Basque Country, Bilbao*
[2] *IBM Quantum, IBM Thomas J Watson Research Center, Yorktown Heights, USA*
[3] *Instituto de Física Teórica, UAM-CSIC, Universidad Autónoma de Madrid, Spain*
[4] *Strongly Correlated Systems Lendület R.G., HUN-REN Wigner RCP, Budapest, Hungary*
[5] *Institute for Advanced Study, Technical University of Munich, Germany*
[6] *Parmenides Stiftung, Pöcking, Germany*
[7] *DIPC - Donostia International Physics Center, San Sebastián, Spain*
[8] *IKERBASQUE, Basque Foundation for Science, Bilbao, Spain*
[9] *CERN, Theoretical Physics Department, Geneva, Switzerland*

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 Z_2-Higgs model (Z_2HM) through an optimized embedding into a heavy-hex superconducting qubit architecture, directly mapping matter and gauge fields to vertex and link superconducting qubits, respectively [1]. 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 results are compared against extensive tensor network simulations. The ground state phase diagram of the Z_2 Higgs model has been analyzed by the density matrix renormalization group (DMRG), while the recently introduced "basis update and Galerkin" method has been used to predict large-scale real-time dynamics and validate our error-aware protocols [2]. This work establishes a milestone for probing non-perturbative gauge dynamics via superconducting quantum simulation and elucidates the real-time behavior of confining strings [1].

[1] J. Cobos, J. Fraxanet, C. Benito, F. di Marcantonio, P. Rivero, K. Kapás, M. A. Werner, Ö. Legeza, A. Bermudez, and E. Rico, arXiv:2507.08088 (2025).
[2] Gianluca Ceruti, Christian Lubich, and Dominik Sulz, SIAM Journal on Numerical Analysis 61, 194-222 (2023).