Quantum Simulation of Lattice Gauge Theories with Ultracold Atoms in Optical Lattices

Erez Zohar[1,*]

[1]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany.*

Gauge theories are in the core of the standard model of high energy physics (HEP): they describe the gauge bosons, which mediate interactions between matter particles. However, they still involve yet unexplored nonperturbative phenomena, which could not be resolved using the standard techniques of quantum field theory (QFT).

One successful avenue for the investigation of gauge theories is lattice gauge theory (LGT) [1, 2], in which space, or spacetime, is discretized, and many physical quantities may be computed thus, using classical Monte-Carlo methods. These methods, on the other hand, suffer from the computationally hard sign-problem [3], which arises for fermions with a finite chemical potential, hence preventing the access to some interesting phases of quantum chromodynamics, for example, or to the study of confinement of *dynamic* quarks. Another problem is that due to the Euclidean spacetime used in these calculations, real time dynamics could not be observed.

In the last years, the quantum physics community has shown a growing interest in LGTs , as they suggest a clear path for the application of current quantum [4–18] and classical [16, 19–26] simulation methods to QFTs and HEP.

A quantum simulator of a gauge theory must meet some requirements whose fulfillment in quantum simulating systems is nontrivial [11, 18]: They must (a) involve both bosons (gauge particles) and fermions (matter); (b) have a relativistic causal structure; and (c) have a *local* gauge symmetry. (a) can be met with ultracold atoms in optical lattices; (b) is fulfilled using LGT, which has a relativistic continuum limit; (c) is the most challenging one, as local gauge invariance does not seem "natural" in the context of ultracold atoms. However, it can be met as well, either by imposing gauge invariance as a constraint, hence resulting in an emerging, low-energy symmetry, or by mapping intrinsic symmetries of the simulating system (such as conservation of hyperfine angular momentum in atomic collisions [11]) into gauge symmetry. Such quantum simulators should allow the observation of nonperturbative phenomena such as quark confinement, and, unlike Monte-Carlo calculations, they do not encounter the fermionic sign problem and allow for real time dynamics.

I will give an overview of our proposals for quantum simulation of LGTs [4, 5, 8, 9, 11], as summarized in the recent review paper [18] (*collaboration with J.I. Cirac and B. Reznik*), and also present a new description of LGTs in terms of "atomic" ingredients [16], which allows for the quantum simulation of gauge invariant models with local finite Hilbert spaces, as required for physical implementation in current simulators, and provides a connection between LGTs, as they arise in the context of HEP, and topological models with discrete gauge groups, such as quantum double models and string nets, known in condensed matter physics (*collaboration with M. Burrello*).

---

* erez.zohar@mpq.mpg.de

[1] K. G. Wilson, Phys. Rev. D **10**, 2445 (1974).
[2] J. Kogut and L. Susskind, Phys. Rev. D **11**, 395 (1975).
[3] M. Troyer and U.-J. Wiese, Phys. Rev. Lett. **94**, 170201 (2005).
[4] E. Zohar and B. Reznik, Phys. Rev. Lett. **107**, 275301 (2011).
[5] E. Zohar, J. I. Cirac, and B. Reznik, Phys. Rev. Lett. **109**, 125302 (2012).
[6] D. Banerjee, M. Dalmonte, M. Müller, E. Rico, P. Stebler, U.-J. Wiese, and P. Zoller, Phys. Rev. Lett. **109**, 175302 (2012).
[7] L. Tagliacozzo, A. Celi, A. Zamora, and M. Lewenstein, Annals of Physics **330**, 160 (2013).
[8] E. Zohar, J. I. Cirac, and B. Reznik, Phys. Rev. Lett. **110**, 055302 (2013).
[9] E. Zohar, J. I. Cirac, and B. Reznik, Phys. Rev. Lett. **110**, 125304 (2013).
[10] D. Banerjee, M. Bögli, M. Dalmonte, E. Rico, P. Stebler, U.-J. Wiese, and P. Zoller, Phys. Rev. Lett. **110**, 125303 (2013).
[11] E. Zohar, J. I. Cirac, and B. Reznik, Phys. Rev. A **88**, 023617 (2013).
[12] L. Tagliacozzo, A. Celi, P. Orland, and M. Lewenstein, Nat. Commun. **4** (2013).
[13] D. Marcos, P. Rabl, E. Rico, and P. Zoller, Phys. Rev. Lett. **111**, 110504 (2013).
[14] K. Stannigel, P. Hauke, D. Marcos, M. Hafezi, S. Diehl, M. Dalmonte, and P. Zoller, Phys. Rev. Lett. **112**, 120406 (2014).
[15] P. Hauke, D. Marcos, M. Dalmonte, and P. Zoller, Phys. Rev. X **3**, 041018 (2013).
[16] E. Zohar and M. Burrello, Phys. Rev. D **91**, 054506 (2015).
[17] U.-J. Wiese, Annalen der Physik **525**, 777 (2013).
[18] E. Zohar, J. I. Cirac, and B. Reznik, arXiv:1503.02312 [quant-ph] (2015).
[19] M. Bañuls, K. Cichy, J. Cirac, and K. Jansen, Journal of High Energy Physics **2013**, 158 (2013).
[20] M. Bañuls, K. Cichy, J. Cirac, K. Jansen, and H. Saito, Proc. Sci. LATTICE 2013 **332** (2013).
[21] B. Buyens, J. Haegeman, K. Van Acoleyen, H. Verschelde, and F. Verstraete, Phys. Rev. Lett. **113**, 091601 (2014).
[22] E. Rico, T. Pichler, M. Dalmonte, P. Zoller, and S. Montangero, Phys. Rev. Lett. **112**, 201601 (2014).
[23] S. Kühn, J. I. Cirac, and M.-C. Bañuls, Phys. Rev. A **90**, 042305 (2014).
[24] P. Silvi, E. Rico, T. Calarco, and S. Montangero, New Journal of Physics **16**, 103015 (2014).
[25] L. Tagliacozzo, A. Celi, and M. Lewenstein, Phys. Rev. X **4**, 041024 (2014).
[26] J. Haegeman, K. Van Acoleyen, N. Schuch, J. I. Cirac, and F. Verstraete, Phys. Rev. X **5**, 011024 (2015).