Quantum Information in Quantum Field Theories and Holography: Dynamics and Complexity

Abstract for the general public

Unifying quantum mechanics and general relativity, the two experimentally confirmed building blocks of theoretical physics, remains the main open challenge of fundamental science. Recently, however, we realized that some strongly-interacting particles secretly know about solutions of Einstein's gravity in one extra dimension. This phenomenon is generically referred to as the AdS/CFT correspondence or "holography". Even though AdS/CFT is known to hold in several examples, we are still missing the basic mechanism behind it and the answer to the key question: "How quantum particles encode information about Einstein's geometry?".

Surprisingly, we noticed that quantum information may be the key to this puzzle. Namely, we discovered a deep relation between the laws of quantum entanglement and Einstein's equations. These developments lead to a hypothesis that holographic geometry may be encoded in the way that particles are entangled with each other. The aim of my project is to advance this program and develop necessary tools for understanding quantum information properties of strongly-interacting particles.

My group at Warsaw University will be the first in Poland and one of the first in Europe focused on this fundamental challenge. In the project, we will explore Feynman's Path Integrals (that describes quantum configurations of particles) from the perspective of quantum information and quantum computation. More precisely, we will use Path Integrals to extract geometric patterns of quantum entanglement from dynamical particles and to quantify how complex a given configuration is (i.e. complexity of a given configuration of particles). Our new approach will allow us to better distinguish and compare dynamical "entanglement geometries" with full-fledged solutions of Einstein's gravity.

This interdisciplinary project will not only bring important insights to quantum gravity, but also to quantum information and computation. Indeed, discovering new features on how information is encoded in spacetime geometry can help unravel patterns that are hard to see in the conventional formulations. Finally, understanding holography may teach us that gravity emerges from entanglement in quantum mechanics and my goal is to check this exciting hypothesis.