The intricate structure of the simplest hadron

The π meson (pion) is the lightest particle formed by strong interactions (hadron), and its role is special: as proposed by Yukawa already in 1935, it is the main mediator of strong nuclear forces, whose attractive nature binds the atomic nuclei together. Although we know today that the pion itself is a composite particle formed by a quark and antiquark pair, its structure and behavior is far more intricate than Yukawa could have ever anticipated. It has a size and it possesses a distribution of electric charge or mass, which determine the "shape" in its widest sense. The pion reacts to external provocations; it may absorb light (or other probes) and then re-emit it, and the way it does so reflects its varied anatomy. At very high collision energies, this response tells us not only how the momentum of the constituents of the pion is distributed, but also how the quark and antiquark inside are entangled and correlated.

As the strong interactions binding the hadrons are indeed strong, the above features of the pion structure are "non-perturbative", that is to say, not possible to treat with "easy" simple approaches to the dynamics as a good starting approximation to be improved with more elaborated calculations. The problem is very fundamental and at the same time, very difficult; the starting point is still a matter of debate and in many respects an open field for imaginative proposals building on solid principles. One way to tackle it is to perform numerical simulations of strong interactions on the so-called lattice – discretized space-time placed in the computer. These are probably the largest computations that mankind has ever carried out, with millions of processor hours of number cranking! The answers coming out from these lattice calculations are more and more accurate and reliable, playing the role of "experimental" measurements, but they are, as mere numerical answers, difficult to comprehend in simple terms and do not provide a pictorial image, which in physics is undeniably associated with the process of understanding. This is where our proposal comes. We wish to analyze the non-perturbative structure of the pion in simple cleverly focused models which are approximate, but do grasp the essential features of the strong binding mechanism. That way we will be able to understand the lattice results, and more generally the structure of the pion, and to assess which features of the dynamics are essential.

One type of models that we will use, already very successful in other related studies, relies on the fact that the pion is a quark-antiquark state, but the quarks themselves are "dressed" massive objects, different from the quarks seen in perturbative experiments. This dressing feature follows from a very basic property of strong interactions, related to a mechanism similar to the famous generation of mass by the Higgs boson – "the God's particle". A complementary approach that we will use represents the external probes hitting the pion as quark-antiquarks (meson) fields themselves, which upon being absorbed by the pion excite it to become another meson. This approach realizes the so-called quark-hadron duality, which is a very interesting principle holding in strong interactions. Our novel results will be compared one-to-one to the very recent state-of-the-art lattice data, hopefully explaining these numerical "experiments" and contributing in simple terms to our understanding of relevant aspects of strong interactions. Our study will also provide a future outreach for the lattice simulations, as we can predict new, yet not studied, properties of the pion.