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Researchers simulate important structural elements of the pion

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When it comes to describing the fundamental structure and composition of matter, the research field of quantum chromodynamics (QCD) comes into play. With the help of QCD, the strong interaction—one of the four fundamental forces of physics—between the elementary particles of quarks and gluons can be described in hadrons. Hadrons are subatomic particles held together by the strong interaction. The best-known examples are neutrons and protons (so-called baryons), and the lesser-known pion (a so-called meson) is also a hadron. "To a first approximation, the pions are the driving particles behind the strong interaction," says the physicist Urs Wenger, professor at the Institute for Theoretical Physics at the University of Bern.

The pion occurs only fleetingly in high-energy experiments, for example in the scattering of protons by heavy nuclei, or the collision of protons. Despite its important contribution in experiments, the structure of the pion has been difficult to study so far. New experiments are therefore planned, but understanding high-energy physics depends on theoretical descriptions. Due to the strong forces being studied, and the small masses of particles and complex algorithms, such theoretical descriptions can only be achieved with the help of computer simulations carried out on powerful supercomputers like Piz Daint.

Wenger together with other researchers from Switzerland, Germany and Cyprus did just that, and they have now succeeded in providing such a description for the momentum fractions of quarks and gluons in the pion. The study, which was recently published in *Physical Review Letters*, is the result of a long-term research collaboration.

A sea of particles

A quark with a certain momentum fraction in the pion can theoretically be determined via the so-called parton distribution function (PDF). "Using the PDF, however, I can only state that with a certain probability there is an up-quark with a certain momentum in the pion," says Karl Jansen from DESY-Zeuthen and co-author of the study.

Now, to be able to determine the real momentum fractions of the quarks and gluons in the pion, the researchers must calculate an entire "sea" of particles and how they interact with each other using the lattice theory of quantum chromodynamics (lattice QCD). This vast sea contains the quark building blocks of the pion, known as valence quarks; the virtual fractions of short-lived quarks (sea quarks) that are produced by the forces of the gluons acting in the quantum field; and the so-called unconnected contributions, in which the quarks interact exclusively via the gluons.

According to the complexity of the calculations of the "sea of particles," the path to the results, now available, was long and painstaking. During the past four years, the researchers developed ensembles of so-called gluon configurations within the framework of the Extended Twisted Mass Collaboration, in which they took into account the gluons and four types of quarks (flavors) that make up the pion and other hadrons. Pions consist of two quarks flavors—up- and a down-quarks—in different combinations. In total, there are six different quark flavors. In addition to the up- and down-quarks, the researchers also calculated the momentum fractions of the strange- and charm-quarks. "To complete the picture, we need to include all the contributions in the calculations and simulations, all the dynamics between all the particles including all the quantum fluctuations," Wenger says.

"Each particle has its own physics, and by including four quark flavors in the simulation, we have a great chance of being able to calculate the properties of other particles composed of these quarks from QCD and compare them with the experiment," adds Jansen. This not only allows us to understand the experiments, but also to learn something about the particles.

No hidden shares

The ensembles of configurations with their improved algorithms coupled with the high computer performance of "Piz Daint" made it possible to simulate the momentum fractions of the quarks and gluons in the pion. The fact that the determined momentum fractions of the four quarks and the gluon added up to a value of 1—i.e. 100 percent—within the statistical errors achieved showed that the results obtained were correct. "This shows us that we have captured all the important components, that the theory is correct and that there are no hidden components," says Wenger.

Crucial for the success of the calculations was that the researchers used the physical values of the quark masses. This has only been possible since a few years, though, as calculations with real masses are very complex and demanding. Another challenge for the researchers was to determine a statistically significant signal for the unconnected contributions of the sea quarks and gluons. This is because, according to Wenger, the quantum effects between the quarks and the gluons generate so much noise in the simulation that it would not have been possible to detect a clear signal. However, since the researchers benefited from better algorithms, strong computer performance, and carried out their calculations with real values of the quark masses, they were able to reduce both the statistical and systematic errors in the calculation and obtained the hoped-for signal.

For the present results, the researchers used a certain lattice spacing in lattice QCD. However, this automatically makes a mistake because we are on a discrete grid and not in the continuum in which we live, Jansen admits. To be able to extrapolate to the continuum, the grid spacing must approach zero. But the smaller the distance, the more complex the calculations become, creating a strain on capabilities. Nevertheless, the researchers have calculated even smaller grid spacings that will be evaluated. In the meantime, the researchers emphasize that the findings now available already help to better understand the results of new experiments as well as the particles involved in them.

More information: Constantia Alexandrou et al, Quark and Gluon Momentum Fractions in the Pion from Nf=2+1+1 Lattice QCD, *Physical Review Letters* (2021). DOI: 10.1103/PhysRevLett.127.252001

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