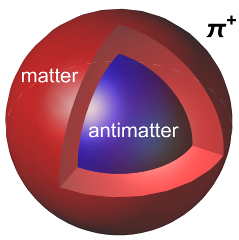
Nonperturbative structure of the pion

Meson π (the pion) is the lightest and also the most fundamental hadron, nevertheless, due to the non-perturbative nature of the strong interactions, its structure poses quite a challenge for both experimental and theoretical studies. On the experimental side, the difficulty in creating pion beams prevents direct scattering experiments, which are a fundamental tool for studying the structure of the microworld. This leaves more complicated processes, such as the so-called electroproduction of pions. On the theoretical side, a lot of pion data has been obtained in last years thanks to quantum chromodynamics (QCD) calculations on the lattice, where the method gives results that are conceptually accurate, but limited by the laatice resolution. A more phenomenological and intuitive theoretical approach is to create models based on the so-called chiral symmetry, which is one of the fundamental symmetries of QCD, which largely determines the nature of the pion as the so-called Goldsone pseudo-boson of spontaneously broken chiral symmetry. The project methodology uses such a model-based approach.

In the past, many properties of the pion have been calculated within the framework of so-called quark chiral models, such as the so-called form factors (spatial distribution) of the electric charge, mass distribution, the so-called structure functions, and the parton distributions. Within the framework of our project, a number of very interesting and completely novel results concerning the parton structure of the pion were obtained. One of the more spectacular and surprising results is the non-zero parton density distribution of the pion (appearing because u, the up quark, is slightly lighter than d, the down quark). This is illustrated in Fig. 1. A positively charged pion consists of a quark u carrying a positive baryon charge $frac13$ and an anti-quark $bard$ with a negative baryon charge $-frac13$. According to mechanistic intuition for a two-body system, the heavier $\bar{d}$ antiquark stays closer to the center of mass, hence a surplus of anti-baryon (anti-matter) charge is created at the center. On the other hand, the lighter u quark is pushed a bit more outward and brings a surplus of baryon charge (matter) there. Both surpluses add up to zero, since the pion as a meson carries no net baryon charge. We have shown that the effect of a non-zero baryon density of a charged pion can be determined from the analysis of experimental data for the process $e^+e^- \to \pi^+\pi^-$.

Other results of the project (correlations of vector and axial-vector currents, the Wigner and Husimi distributions, generalized quasiparton distributions, effects of the pion being outside of the mass shell, or parton-hadron duality in the structure functions) have been investigated for the first time and find reference to QCD simulations on the lattice and to planned future experiments, in particular on the Electron-Ion Coolider under construction. We trust that they will contribute to a better understanding of future results on parton pion structure.



Rysunek 1. An illustrative representation of the distribution of baryonic density (matter and antimatter) in a positively charged pion.