Role of the symmetries and anomalies of QCD on the phenomenology of mesons (OPUS 17, F. Giacosa)

In the realm of elementary particles, symmetries are very important, since they determine the properties of the theories that describe particles. In this project, we aim to exploit symmetries to understand quarks and the objects that contain them.
How do quarks interact with each other? They do so by exchanging particles called gluons. As the name (gluon – glue) tells us, the interaction is very strong, so strong that we cannot see an isolated quark (a property called confinement). A quark and an antiquark combine to form a bound state: many particles of this type, called mesons, have been found in experiments. Three quarks can also bind to form baryons, such as the protons and the neutrons that form the nuclei of atoms.

Each quark carries two intrinsic properties. The first is called color: a quark can be red, green, or blue. Of course, these are not real colors, yet they offer a useful mathematical analogy, which also gives the name to the theory describing quarks and gluons: Quantum Chromodynamics (QCD). However, mesons and baryons are 'white', i.e. the color charges of quarks inside them neutralize. The second property is called flavor: here we shall consider the three light flavors 'up', 'down', and 'strange'. Gluons are democratic: they interact with quarks 'up', 'down', and 'strange' with the same intensity. This is an important symmetry of QCD, known as *flavor symmetry*. As a consequence, there are nine possible combinations to put a quark and an antiquark together: up-antidown, up-antistrange, etc. Then, mesons appear in nonets (nonet – nine) with approximately the same mass.

But there is more: roughly speaking, a quark is like a small spinning ball and can be right-handed or left-handed, depending on the direction of the spinning. Gluons also interact with the same strength with right-handed and left-handed quarks. The consequences of this symmetry, named *chiral symmetry*, are important: for each nonet of mesons there is a second 'brother' nonet, which, naively, should have the same mass and similar properties. One speaks about 'chiral partners'. However, in experiments we do not find such nonets of chiral partners with the same mass. This is so because of an important phenomenon that occurs in many areas of physics: the underlying symmetry (here: chiral symmetry) is spontaneously broken. In order to understand what spontaneous symmetry breaking means in general, let us imagine a Mexican hat with a ball on the very top. The system is symmetric but also unstable: the ball will not stay there long, but it falls down in a certain (unpredictable) direction. One finds the ball somewhere along the circle: the original symmetry is not anymore visible. In QCD, such a spontaneous breaking causes a mass difference of the chiral partners. But, even if the chiral partners do not have the same mass, they are still related to each other: in some cases, we know which mesons are chiral partners, but in other cases we could not yet identify them. This is what we aim to improve.

Finally, there is still an important and very peculiar concept of QCD: the so-called 'anomalies', that occur when a symmetry of a theory is broken by quantum fluctuations (i.e., particles and antiparticles are created and destroyed continuously, even in the vacuum). The two anomalies, called scale and axial-anomaly, are a consequence of the fact that the QCD vacuum is a very complicated object.

In this project, we plan to study various mesons on the light of this (hidden) chiral symmetry as well as the anomalies. How to group mesons into chiral partners? Which are the consequences of the underlying symmetries and anomalies on the properties of mesons? In practice, we use the fundamental symmetries of QCD in order to build theoretical models that describe mesons: we then calculate their masses as well as how these mesons decay. There are many ongoing and planned experiments that deal with mesons made with light quark. Our aim is to link fundamental theoretical considerations based on symmetries to ongoing and future measurements of these short-living objects created in our laboratories.