Quarks

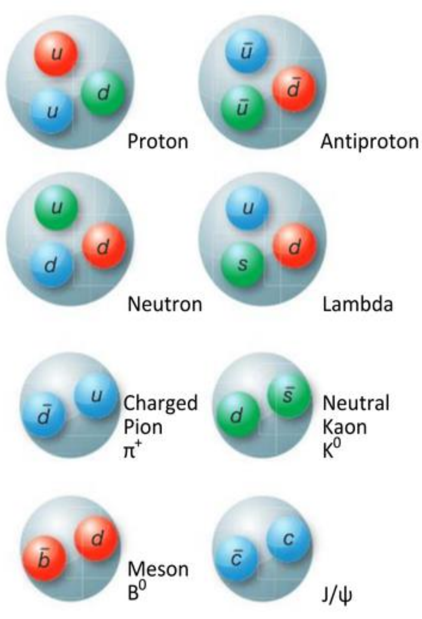
Thanks to collisions recorded in accelerators, scientists have discovered hundreds of particles sensitive to the strong interaction. This apparent variety can be explained by the fact that they are all composed of even more fundamental particles, known as quarks.

Quark content of some hadrons

There are two types of hadrons: baryons are composed of three quarks, each of a different colour (blue, red and green), while mesons consist of a quark-antiquark pair of corresponding colour and anticolour (e.g. blue and antiblue).

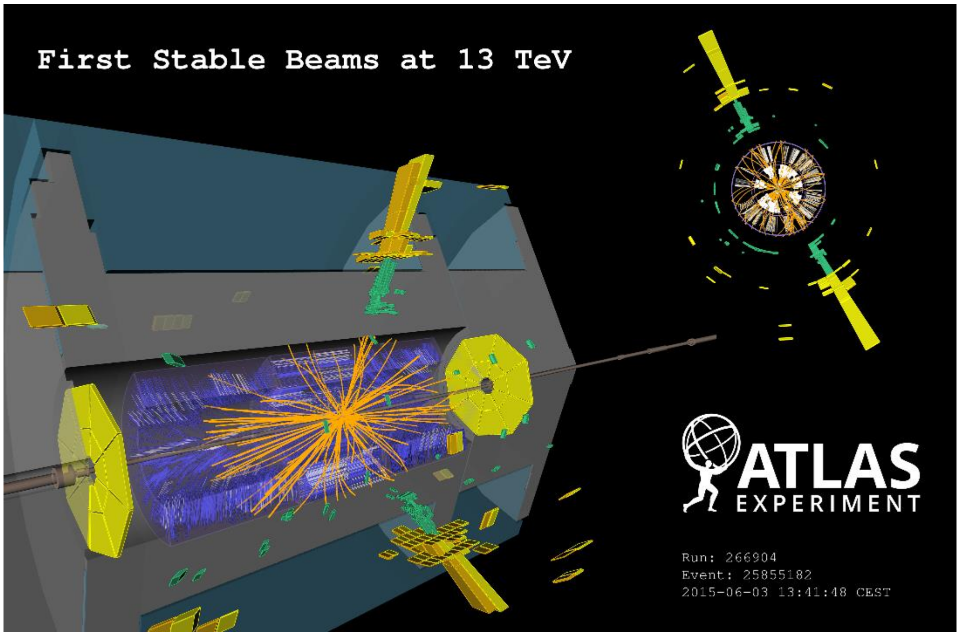
Until the mid-20th century, protons and neutrons were believed to be elementary. To explain the multitude of particles observed in cosmic rays or produced in accelerators, physicists Murray Gell-Mann and George Zweig suggested the existence of quarks in 1964 as constituents of protons, neutrons, and other observed particles.

We now know that there are six types of quarks, more poetically called flavours: up and down quarks make up protons and neutrons; the strange quark has been observed in cosmic rays; and the other three quarks, charm, bottom and top quarks, were discovered in accelerators. Each quark has a corresponding antiparticle, called an antiquark.



Credit: B. Mazoyer

Quarks have electric charges of –1/3 or +2/3, in units where the proton's charge is +1. The proton is made up of two up quarks (+2/3 charge) and one down quark (–1/3 charge), while the neutrons (zero electric charge) is made up of two down quarks and one up quark. Thus, quarks combine to form the 'elementary' particles detected in experiments, called hadrons. Assemblies of three quarks are called baryons, while quark-antiquark pairs are called mesons. Like zoologists, particle physicists have named the mesons and baryons encountered in their experiments over the years: their properties are listed in a particle directory called the Particle Data Book. In recent years, researchers have identified exotic hadrons, such as tetraquarks (consisting of two quarks and two antiquarks) and pentaquarks (consisting of four quarks and one antiquark), whose properties remain to be explored.



Credit: CERN

In hadrons, quarks are held together by the very specific nuclear force, or strong interaction, which is mediated by the exchange of gluons. This force increases with the distance between quarks, preventing them from existing in isolation; therefore, quarks can only be observed in groups within hadrons. Another intriguing aspect is that most of a hadron's mass (1 GeV/c^2 for a proton) does not come from the mass of the quarks composing it (around a dozen MeV/c^2 for the proton) but from the energy of the gluons binding the quarks together.

Physicists classify quarks into pairs within identical families that differ only in their masses. The mass difference between the lightest quark, the up quark, and the heaviest, the top quark, is a factor of 60,000. What is the origin of such a wide range of masses? Why are there only six quarks? And what accounts for their charges? To date, no satisfactory answers have been found to these questions.

Proton-proton collisions in ATLAS

Some events observed in accelerators correspond to the creation of a quark-antiquark pair. Once separated, the two particles cannot remain isolated; they generate two jets composed of numerous hadrons. This distinctive structure is illustrated above in the 3D view of the products of a high-energy collision in the ATLAS detector. Each coloured track represents a particle produced by the collision, while the green and yellow outer blocks indicate the amount of energy deposited in various parts of the detector. The two jets consolidate a large number of tracks and energy deposits. Their directions correspond to those of quarks, antiquarks, or gluons produced immediately after the collision.

Translated from 'Les quarks', Passeport pour les deux infinis, IN2P3/Dunod, https://pass2i.ijclab.in2p3.fr/ (French); updated with ICHEP2024 conference (https://ichep2024.org) for IPPOG