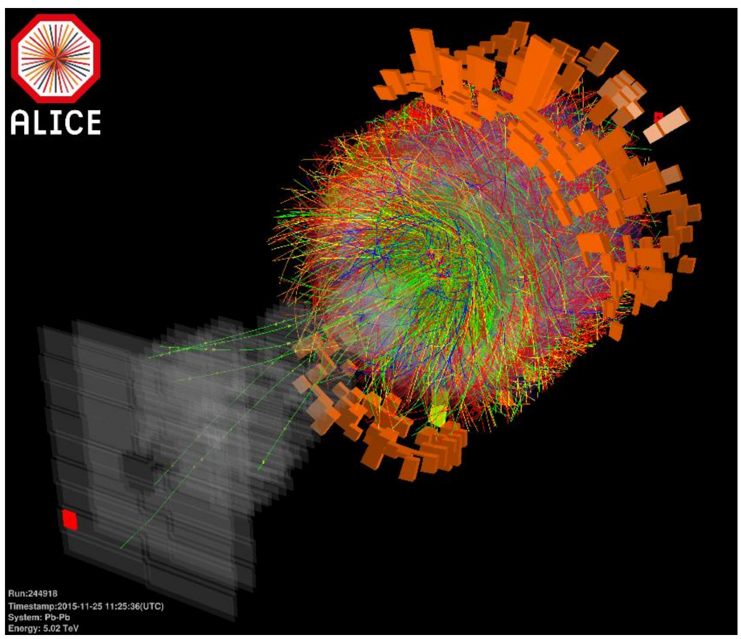
The Universe’s Primordial Soup

Experiments to prove a new state of matter, the quark-gluon plasma, which may have existed in the first microsecond after the Big Bang. Scientists try to recreate it in labs using high-energy collisions of heavy ions to reach the extreme conditions of temperature and density.

A Pb-Pb collision recorded by ALICE at the LHC

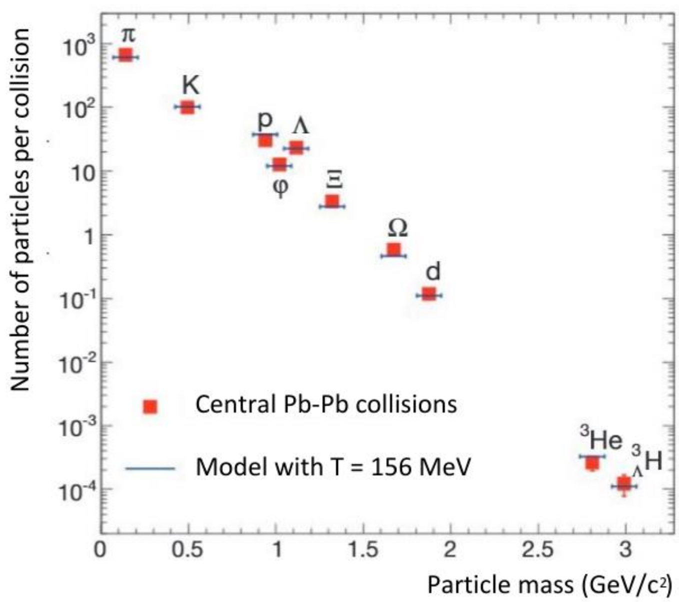
This collision, recorded in November 2015, gives an idea of the number of particles produced during these events: each coloured line represents the track left by a charged particle in the detector. The conversion of some of the collision’s (very high) energy into mass explains the profusion of the particles produced by lead ion collisions.



Credit: CERN

There are major questions surrounding the birth of the Universe. Ordinary matter is currently made up of atoms, which consist of a nucleus (of protons and neutrons) surrounded by an electron cloud. Protons and neutrons themselves are made up of quarks, the most elementary blocks of matter. Right after the Big Bang, quarks and gluons wandered freely and formed a plasma called the ‘quark-gluon plasma’ (QGP), in which they were not confined within nucleons, unlike ordinary matter. To recreate the extreme temperature and density conditions of nuclear matter, scientists use accelerators trigger head-on collisions between heavy ions, such as nuclei of lead (126 neutrons and 82 protons) or gold

(118 neutrons and 79 protons), using accelerators. At every event, thousand particles are produced and tracked by a detector that was specially designed for studying the properties of the matter created during the collision. The more violent the collision, the hotter the nuclear matter.



Such experiments are carried out at the Relativistic Heavy Ion Collider (RHIC) of Brookhaven National Laboratory (U.S.), using collisions involving various ions (copper, gold, uranium, etc.) and lighter nuclei (proton and deuterium). At CERN, LHC lead-lead (Pb-Pb) collisions occur one month a year, in addition to the proton-proton (p-p) collisions. The most head-on collisions concentrate up to 574 TeV of energy in a nucleus-like volume, i.e. a density 15 times higher than the one achieved at the RHIC. The matter thus generated is of very high temperature, conducive to the formation of a QGP. Once produced, the plasma cools down to the transition temperature at which quarks and gluons combine into hadrons under the effect of the strong interaction. Hadrons and the particles stemming from their decays are then detected. Three experiments analyse Pb-Pb collisions: ALICE, ATLAS and CMS.

Evaluating the formation temperature of hadron and nucleus in Pb-Pb collisions

The measured quantities of the various types of particles (hadrons and nuclei) produced in the head-on Pb-Pb collisions at the LHC are compared with the theoretical predictions. We can deduce temperature T at the time of the hadrons' formation: T = 1.8 trillion degrees Celsius (equivalent to an energy of 156 MeV). This temperature corresponds to the theoretical temperature predicted for the transition from a quark-gluon plasma to a hadron gas.

The ATLAS and CMS experiments were initially designed to analyse p-p collisions but are well suited for studying more violent phenomena between quarks and gluons, which occur in the first moments of the Pb-Pb collisions. By studying how quarks and gluons that were produced during the collision lose energy when they travel through the QGP, we can learn more about the composition of this plasma, its richness in gluons in particular.

The ALICE collaboration designed a detector capable of analysing in great detail the profusion of the particles produced – several thousand particles per collision, as illustrated below. From these data, we can deduce the temperature at the time the particles were produced. The results show that a QGP was formed for the most head-on collisions and that it behaves as a near-perfect fluid, whose viscosity is now being estimated.

Translated from 'La soupe primordiale de l'Univers', **Passeport pour les deux infinis,** ***IN2P3/Dunod, https://pass2i.ijclab.in2p3.fr/ (French); updated with ICHEP2024 conference (https://ichep2024.org) for IPPOG***