

# ALICE: Extraordinary nuclear adventures underground

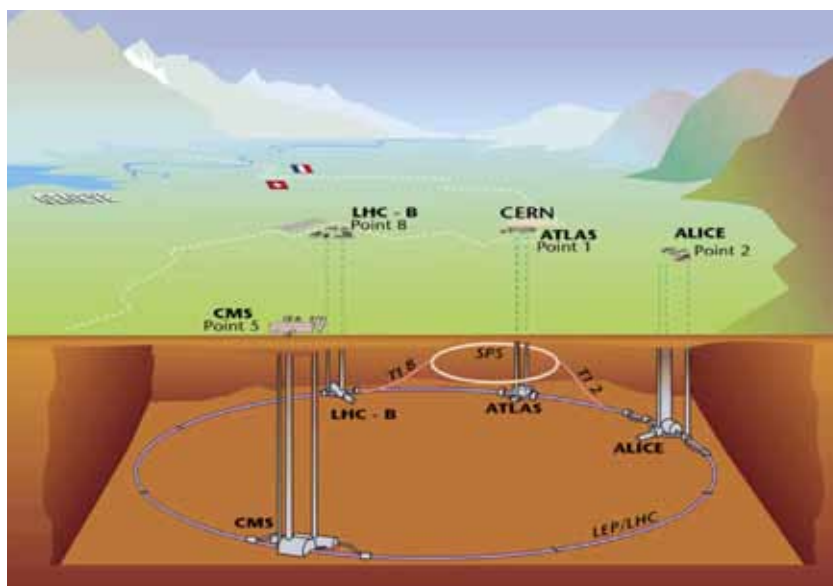
The Large Hadron Collider at the CERN laboratory, Geneva, is now famous for the discovery of the Higgs boson. However, as, **Zoe Matthews** of Liverpool University explains, scientists hope to learn much more from this hot-spot of physics research.

**A**LICE, short for A Large Ion Collider Experiment, is an experiment at the Large Hadron Collider (LHC). It breaks down nuclear matter into its smallest components, melting it into a state that it hasn't been in since the dawn of time. The experiment measures collisions of lead nuclei at close to the speed of light. Why? So that a collaboration of over a thousand scientists can study the peculiar soup that the universe existed in just fractions of a second after the Big Bang.

## LHC: Super Collider

The LHC is a 27 km circumference particle accelerator crossing the border of France and Switzerland. It is the most powerful accelerator in the world to date. Since 2010, protons have been travelling in its tunnels at 99.999 996% of the speed of light before being smashed together. It also accelerates lead nuclei to close to this speed.

The LHC is a synchrotron; it uses electric fields to accelerate charged particles as they travel round its ring, and the fields are synchronised to the increasing speeds of the particles. It uses strong magnetic fields to deflect the particles sideways so that they follow a circular path. The ring is an evacuated tube – any molecules of air remaining in the tube would collide with the fast-moving particles, reducing their energy.



The LHC ring sits 50-100 m below the Franco-Swiss border, and four major experiments (ATLAS, CMS, LHC-B and ALICE) observe its particle collisions.

## Mass and energy

When a particle is made to accelerate, its speed and hence its energy increases. Einstein's equation  $E = mc^2$  tells us that energy  $E$  and mass  $m$  are equivalent so that, as the particle goes faster, its kinetic energy increases and so its mass also increases. This makes it harder to accelerate – that's why we can never make a particle travel at the speed of light – its mass would become infinite.

When high-speed particles collide, they generally lose energy. The energy they lose appears as new particles whose mass has come from the lost energy.

## Key words

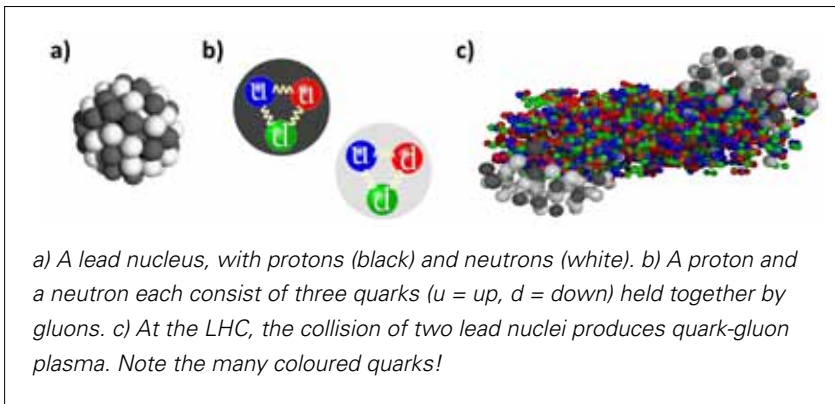
particles  
fundamental forces  
collisions  
momentum

Protons in the LHC travel at just 12 m/s below the speed of light. Lead nuclei have more mass so they don't travel quite as fast.

## A journey to the heart of matter

Back in 1910, Rutherford's gold foil experiment shone a light on the heart of the atom itself – a tiny positively charged nucleus. We now know that the nucleus is made up of protons and neutrons. Let us consider the lead (Pb) nucleus, which contains 82 protons, and around 126 neutrons (depending on the isotope). As an atom, the lead nucleus is surrounded by 82 electrons.

However, protons and neutrons (collectively known as nucleons) are not fundamental like electrons – they have structure. Scientists have found that protons and neutrons are made of smaller particles called quarks, bound together by the strongest force in the universe – the nuclear strong force. Massless particles called gluons are responsible for the force. They travel between quarks, gluing them together.



As well as having an electric charge, quarks have another kind of charge that scientists call colour, and the strong force is felt between them in the same way that electric force is felt between electric charges (or magnetic force between magnetic poles). The colour charges prefer to be neutral, in the same way that positive and negative electric charges attract each other and cancel each other out in a neutral atom.

You might expect all of the protons in a nucleus to repel each other because of their positive charges, so that the nucleus would fly apart. However, the strong force is 100 times stronger than the electric force, and this is why the nucleons are bound so tightly at the centre of the atom, and why we never see isolated quarks in nature. In fact, if you try to pull a proton apart with lots of energy, the energy is used to make new particles and keep colour conserved. Remember, Einstein's equation  $E = mc^2$  tells us that energy can be used to make matter (and vice versa).

	electromagnetic force	strong nuclear force	gravity
strength (relative to gravity)	$10^{36}$	$10^{38}$	1
carrier	photon	gluon	'graviton' – not yet found
charge	electric (positive, negative)	colour (red, green, blue)	0?

Comparing three of the fundamental forces of nature

The table compares three of the four fundamental forces of nature. Each force is carried between particles by a different carrier particle. (The fourth force is the weak nuclear force.)

However, there is a way to free quarks from the clutches of the strong force. By colliding lead nuclei at high speeds, a blob of extremely hot, dense nuclear matter can undergo a phase transition (it 'melts'), so that the strong force is effectively weakened and quarks are no longer bound together to form colourless particles such as protons.

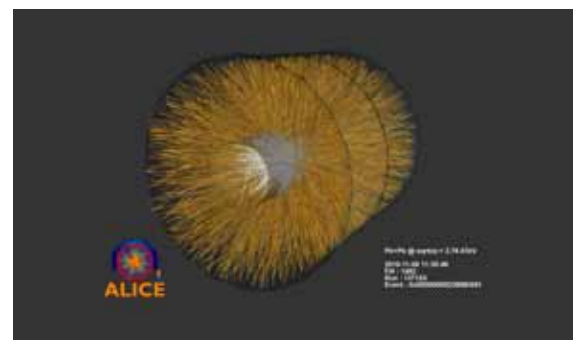
At the ALICE Experiment, temperatures exceed one million million million degrees (100 000 times hotter than the heart of the Sun). This molten nuclear matter is known as quark-gluon plasma, and is thought to have existed for the first few millionths of a second after the Big Bang. At ALICE it will last for less than  $10^{-30}$  seconds before expanding and cooling into many particles.

## How to spot quark-gluon plasma

When lead ions collide with high energy in the detector, up to six thousand particles are produced. The detector needs to measure and identify these particles to understand what is happening in the initial collision, a little like piecing together the debris of an explosion to understand what caused it.

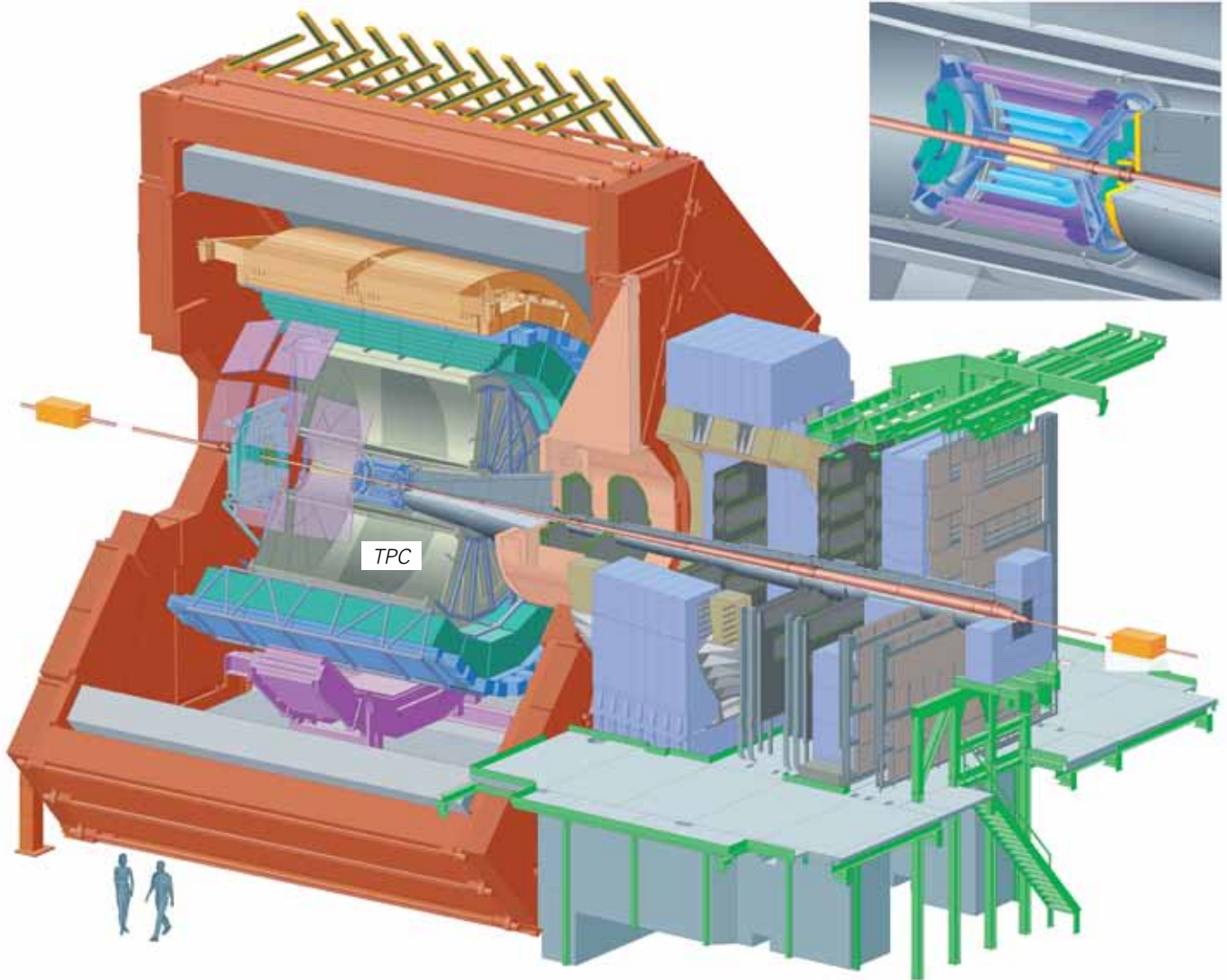
The image showing a spray of yellow particle tracks is a simulation of what we see when two lead ions collide. Each track represents the path of a single newly-created particle. By measuring the tracks, we can determine what each particle is.

Here is how the detector works. The time projection chamber (TPC) is a large cylinder filled with a gas mixture (90% neon, 10% carbon dioxide). It is positioned inside a large solenoid magnet which creates a magnetic field to bend the trajectory of charged particles. A high voltage (potential difference) is put across the gas (1000 kV) and, as charged particles travel through it, they ionise the gas. This means that they knock electrons out of the atoms in the gas. These electrons drift in the electric field to the end plates of the TPC. The position of its impact gives a 2-dimensional map of a particle's path (X and Y co-ordinates), and the time the electrons take to reach the end gives the third dimension (Z co-ordinate) of the track. The momentum of the particles can be determined from the curvature of their paths and they can then be identified.



A simulation of what is observed when two lead ions collide





The ALICE detector; the Time Projection Chamber (TPC) surrounds the point where ions collide as they travel along the central beam line.

## Jet quenching: the mark of quark-gluon plasma

Jet quenching is one way scientists can spot the formation of quark-gluon plasma. When two protons collide at high energy, it is really the quarks and gluons inside that are colliding. When two quarks hit each other head on, their momentum changes. Imagine two sumo wrestlers crashing into each other – they start out with a large momentum in opposite directions and when they collide they share that momentum and rebound from each other. Similarly, when two quarks collide, they bounce off each other in opposite directions, forming two distinct showers of particles called ‘jets’ that can be spotted in the detector.

Most of the lead ion collisions at ALICE happen quite differently. Once the quarks have collided with high momentum, they rebound away but find themselves within the dense soup of the quark-gluon plasma. Imagine now the sumo wrestlers falling back into a pool of treacle. A wrestler close to the edge of the pool may escape, but the other

one will have too much treacle to travel through, all the while losing momentum, so that he eventually stops, having given his kinetic energy to the treacle. This is what happens to the quarks in quark-gluon plasma; we see one high-momentum particle jet but the other one is missing, having lost energy in the plasma.

ALICE scientists made an interesting discovery recently – they found that if the quarks collide with extremely high momentum, both of them are able to escape the plasma to form jets.

*After completing a PhD at the University of Birmingham, Zoe Matthews worked at the University of Liverpool as a research scientist in Nuclear Physics.*

### Look here!

More about UK scientists and the LHC:  
<http://www.lhc.ac.uk/>

Panoramic images of ALICE and the LHC by Peter McCready:  
<http://petermccready.com/>