1 The strong interaction

The aim of physics is twofold : description and prediction. One would like to be able to describe all the phenomenons observed in nature, and given a certain context (launching a ball, looking at a nucleus...), being able to predict what will happen. To do so, physicists have been able to express all the interactions in nature in terms of forces. There are four forces in nature.

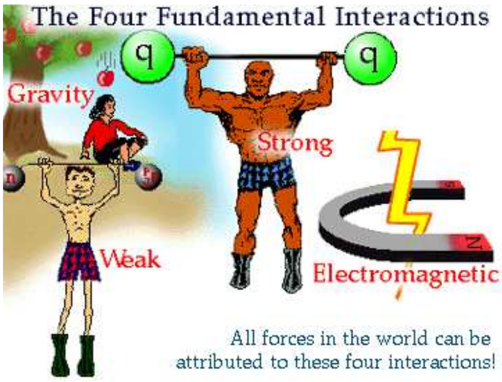

FIGURE 1 – The four forces in nature.

The ones that we daily experience are gravity and electromagnetism. The ones we do not necessarily know about are the weak and the strong forces (also called the weak and strong interactions). Among its actions, the weak force is responsible for the radioactive decays. The strong force is the one that bound the components of the nucleus of an atom together. Those components are the proton and the neutron, themselves formed by quarks, called valence quarks. There are six form of quarks in nature (sorted here from the lightest to the heaviest) : the up quark u, the down quark d, the strange quark s, the charmed quark c, the bottom quark b and the top quark [1] t. This force is a "strong" one in the sense that it is able to counterbalance the electromagnetic repulsive force that is exerced between the positive charges of the protons inside the nucleus.

2 Looking at a proton, first part

A proton at rest is formed by three quarks.

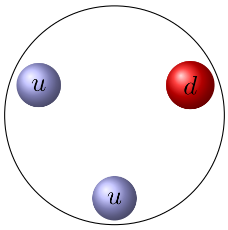

FIGURE 2 – A proton at rest. It is formed by two up quarks u and one down quark d

Those quarks are confined : they can't be observed travelling freely without their two fellows. This is a specificity of the strong interaction called the "quark confinement". This means that the force exerced between the quarks is indeed very strong at low energy. Physicists quantify this strength with a coupling constant - called α_S for the strong interaction, where the S stands for strong - which is an energy dependant quantity. Unfortunatelly, the theory that describes the strong force - called quantum chromodynamics, or QCD - is well understood only in its weak coupling sector, which means for α_S much smaller than 1. To compare theory with experiment, one therefore has to make experiments in the weak coupling sector. Surprinsingly, this sector is at

1. Predicted more thant 40 years ago and discoverd less than 15 years ago.

very high energy. This is counter intuitive : When one thinks about gravity, one expects that the further away two object are, the weaker the gravitational interaction is. The opposite happens for the strong force. A good analogy can be made with a string : when a string is tensed, it is subject to a restoring force that will tend to move closer the two edges of the string [2]. This property is called "asymptotic freedom" : at infinite energy, the confinement property does not hold anymore and the quarks can indeed move freely.

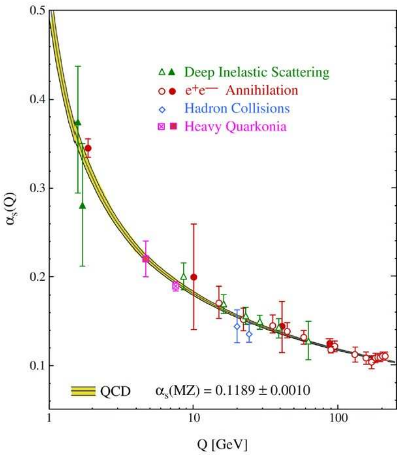

FIGURE 3 – The value of the coupling constant α_S as a function of energy, confirmed by several experiments. At low energies, $\alpha_S >> 1$, this is the confined regime of QCD. At high energies, $\alpha_S << 1$, this is the asymptotically free regime of QCD.

3 Heavy Ion collisions

Because theorists know well only the weak regime of the strong force, but still want to compare their predictions with experiments, people have built amazingly large colliders, to reach an energy scale sufficiently large to be in the weak coupling sector of the strong interaction.

FIGURE 4 – The Large Hadron Collider (LHC) built between France and Switzerland, that supplanted by more than one order of magnitude (in terms of energy) the relativistic heavy ion collider (RHIC), the biggest american collider.

2. It is interesting to know that "string theory", a very active field in theoretical physics which consider all objects to be formed by infinitesimal strings, was first developped in order to describe QCD and more precisely this striking feature of the intensity of the strong force.

In those colliders, proton beams are accelerated to reach almost the speed of light, and are then collided.

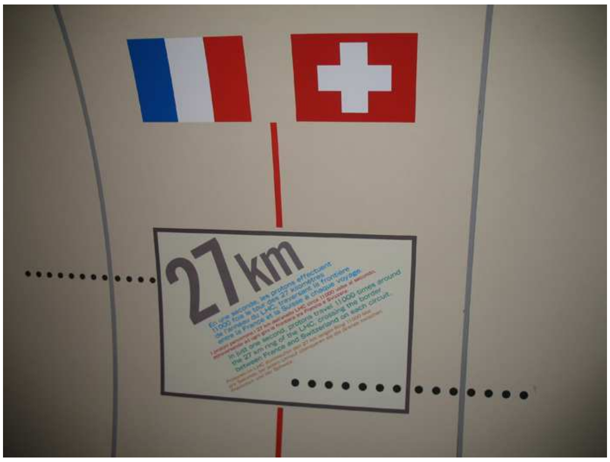

FIGURE 5 – The protons inside the LHC are travelling at more than 99% of the speed of light, which means that they travel 11.000 times in one second the LHC ring of diameter $27km$.

The products of these collisions and more precisely what immediatly happens after the collision is what interests us.

4 Looking at a proton, second part

The picture given before for a proton is only valid when it is at rest. When the proton is moving at the speed of light, the picture is drastically changed. There are millions of other constituents that appear inside it. They are called partons, a generic term that qualify the sea quarks (in opposition to the valence quarks, the sea quarks are quarks that are not the fundamental constituent of the proton and only appear at high energy) and the gluons, which are the mediators of the strong interaction, as the photons are the mediators of the electromagnetic force. Why is it so ? This is related to one of the most important principle of quantum theory called the Heisenberg uncertainty principle. What this principle essentially says is that it is not possible to know exactly at the same time the position and the speed of a particle, nor is it possible to know exactly the energy at a given time. This last uncertainty implies that on sufficiently small time scales - and in a heavy ion collision, we are speaking about a few times 10^{-24} seconds - there are incredibly high vacuum energy fluctuations at any point of space, and sometime some of these points can acquire sufficiently high energy that a pair of particles is created. This is called vacuum fluctuations, and is one of the explanation for such a rich population of a proton at high energy. The other is that the valence quarks themselves become very energetic, and in order to "get rid" of this energy they emit gluons.

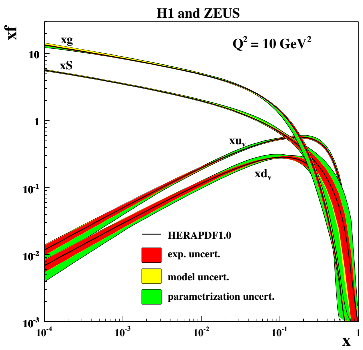

FIGURE 6 – Fraction of the total energy of the proton carried by the gluons xg, the sea quarks xS, the valence quarks xu_v and xd_v.

Physicists quantify the energy E scale of a collision with a quantity called x and which is inversely proportional to E. At very high energy, we therefore speak about small x physics. At low energy (large x), one expects that only the valence quarks carry energy, and that is what is indeed observed (2/3 for the u because they are 2 out of the 3 quarks in the proton, and 1/3 for the d). At very high energy, most of the energy is carried by the gluons and gluonic physics is therefore (mostly) the one of interest at very small x. This is the physics that we want to describe.

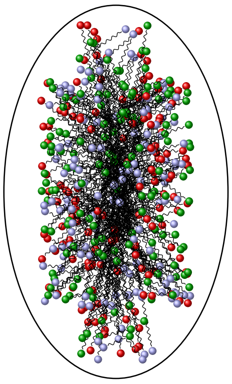

FIGURE 7 – A proton at high energy. The balls are representing quarks and the lines gluons.

5 The quark-gluon-plasma : experimental evidences

When two heavy ion collide at very high energy, the product of their collision is extremely complicated, since millions of gluons from one nucleus can interact with millions from the other. The matter formed by this collision is called the quark-gluon-plasma.

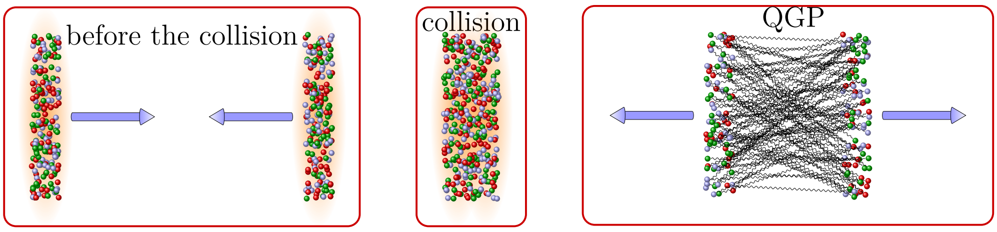

FIGURE 8 – The formation of a quark-gluon-plasma (or QGP) out of a heavy ion collision.

What are the evidence for this new form of matter, never observed in nature before ? The best one is the observation of the flux of very energetic, very located in space particles called "jets". Let's assume for the time being that the QGP exists. In a heavy ion collision, as already mentionned, milllions of product are observed in the detectors of the RHIC and the LHC. But out of these products, some of them are way more energetic than others. Those are the result of collision of the most energetic objects in the nuclei. When this collision happens in the center of the QGP created by the nuclei, one will usually observe two "back-to-back" jets, which means two very energetic beams of produced particles that hit the detector in opposite directions. But if this very energetic collision happens in the edge of the QGP, then one of the jet will only have to cross a tiny region of the QGP, while the other has to cross most of the QGP. During this crossing, the jet will interact with the QGP and looses most of its energy. So if the QGP exists, one should sometime observe in a heavy ion collision two "back-to-back" jets, one being much more energetic than the other.

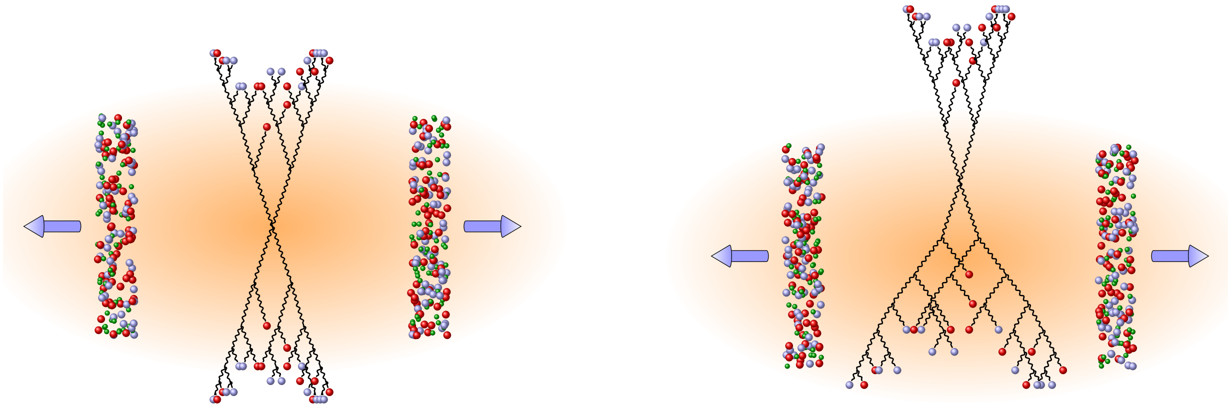

FIGURE 9 – Evidence for the existence of the QGP. On the left, a central energetic collision that produces two back-to-back jets that will hit the detector with almost the same energy. On the right, a peripheric collision that will produce two back-to-back jets, one (on top) being much more energetic than the other(on bottom).

Those tests have of course being performed and here is what have been obtained by the CMS group, one of the experimental team working at the LHC.

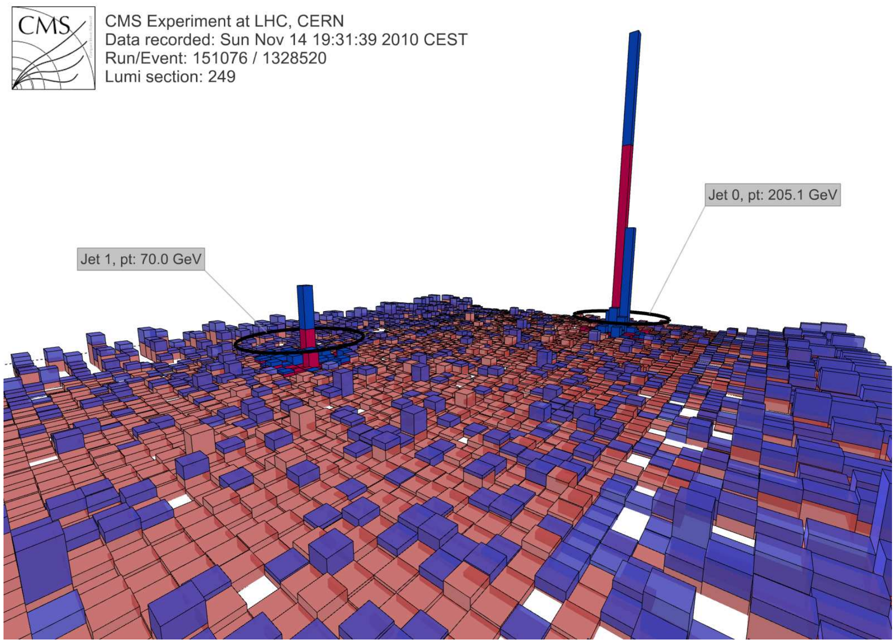

FIGURE 10 – Evidence for the existence of the QGP : two back-to-back jets with very asymmetric energies hit the CMS detector (the two peaks).

6 quark-gluon-plasma : the puzzle

Theoretical model trying to describe this quark-gluon-plasm have been intensively developped in the past twenty years. The conclusion of all this models is that the QGP should experience an inital phase where it is very far from being at thermal equilibrium. This equilibrium implies some constraints on the QGP at both the macroscopic and microscopic level. At the further, there should be a one to one relation between the energy and the pressure of the system : an equation called equation of state. At the latter, the agencement of the particle in function of their energy shoud be dictated by a function. This function, called the occupation number (or distribution function) should follow a Bose-Einstein statistics for gluons.

Meanwhile, many experiments being performed at the RHIC and the LHC, other less fundamental models try to reproduce the output of the collision. One of the best one to do so is called relativistic hydrodynamics. This theory relies on the Navier-Stokes equations, that describe the properties and behaviour of a relativistic fluid. It can either being ideal or viscous, as the fluid being itself the further or the latter. It is a macroscopic theory : it describes the system with a very limited amount of macroscopic parameters - the energy of the fluid, its pressure and velocity. It turns out that relativistic hydrodynamics has been so succesfull in describing the outcome of the experiments that a puzzle currently plagues the field since more than ten years.

The issue is the following : in order for relativistic hydrodynamics to work, it requires some postulates, one of the most important being the very short thermal equilibration of the QGP. But as already mentionned, more fundamental theoretical models that adopt a microscopic description of the QGP fail to predict such a short thermalization time.

People have therefore been working hard on the theoretical side in order to be able to predict a short transition from an out of thermal equilibrium QGP (also called Glasma) to a thermalized QGP.

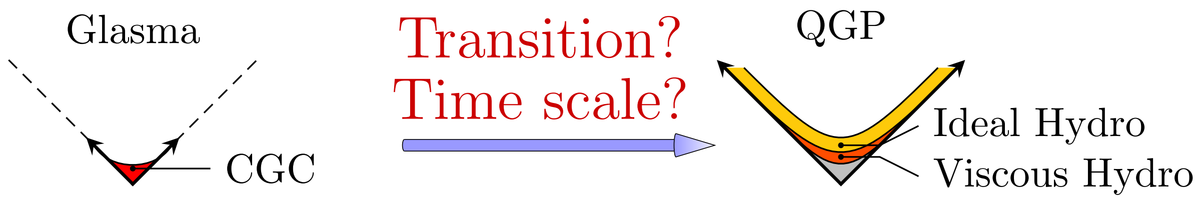

FIGURE 11 – The current puzzle on the theoretical side of heavy ion collisions. The sigle CGC, standing for "color glass condensate" indicates one of the most promising theoretical model that could describe the transition.

One of the best model to study the microscopic properties of the QGP is called the color glass condensate.

7 Other applications

Since the heavy ion collisions are so energetic, there are sometimes called the "little-bangs".

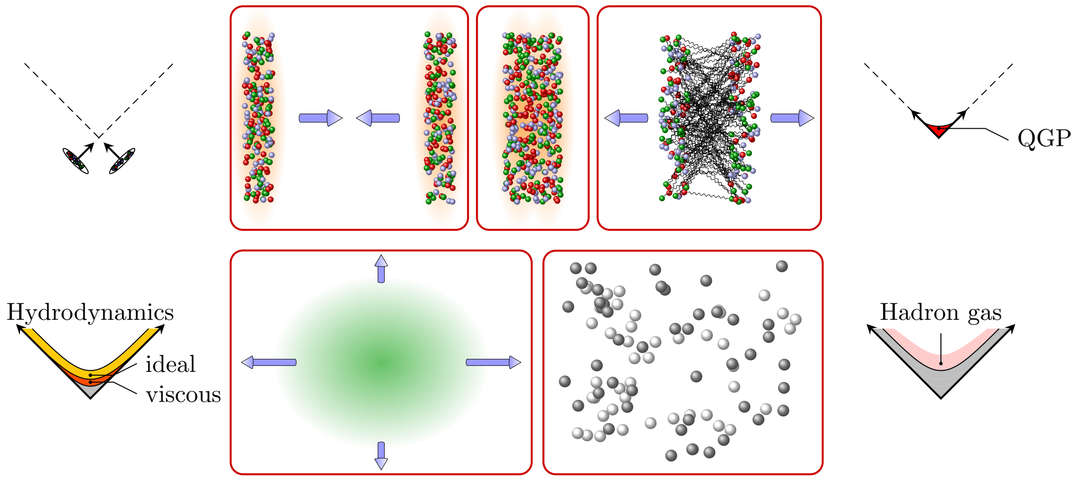

FIGURE 12 – The little bang. phase 1 to 5 (from left to right, top to bottom) : two very energetic heavy ion approch each other at almost the speed of light. They collide and form a new state of matter called the out of equilibrium QGP (or glasma). This glasma is assumed to thermalize very fast, and therefore the products of the collision can be described as an ideal or viscous fluid. This fluid then form particles (a process named "hadronization") that go hit the detector.

This analogy is due to the fact that the little-bang has many similarities with the big-bang, with the upside of being easily reproducible. This is why some theoretical physicists study the little-bangs in order to learn more about the big-bang. In particular, an hypothetic phase during the creation of the universe called the inflation could be understood better. This inflation is an expansion of the structure of the universe itself at a speed way faster than the speed of light during an infinitesimal time. It has been introduced in the 70's, when people discovered a relic of the formation of the universe called the Cosmic Microwave Background (or CMB). This radiation has the specificity to have a black body temperature of 2.8 Kelvin everywhere in the universe, even in region that are not causaly related. The inflation could be able to explain this paradox. But at the present time, no one understand how thermalization in every region of the universe occurs at the end of the inflation. This thing that can be better understood with the study of the QGP.

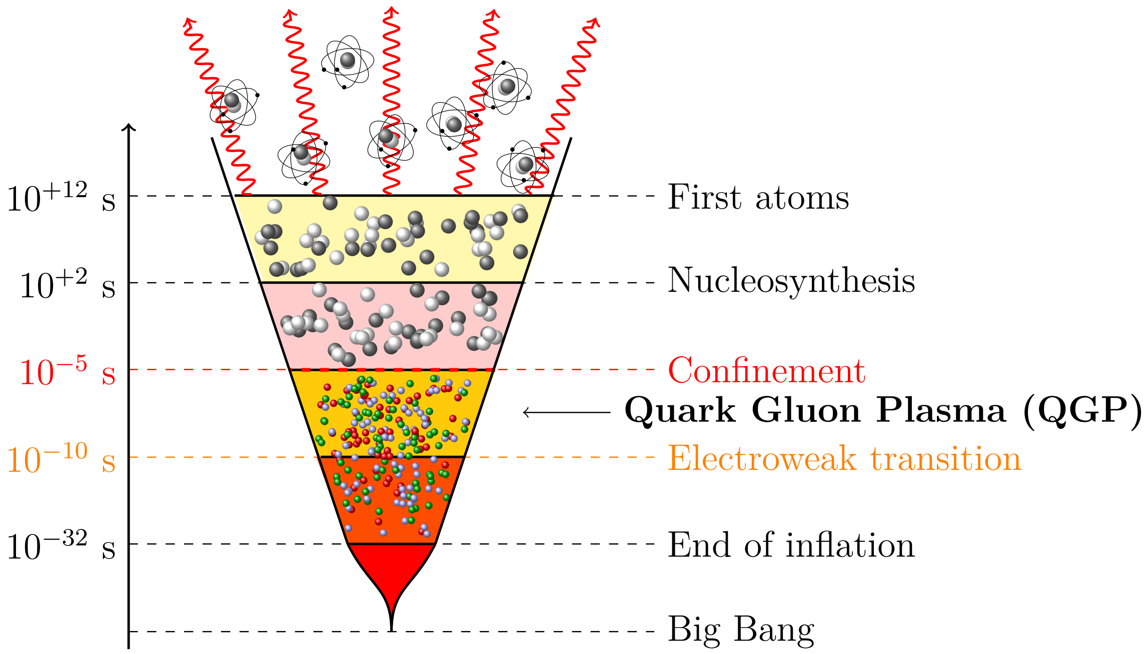

FIGURE 13 – The schematic view of the big-bang.