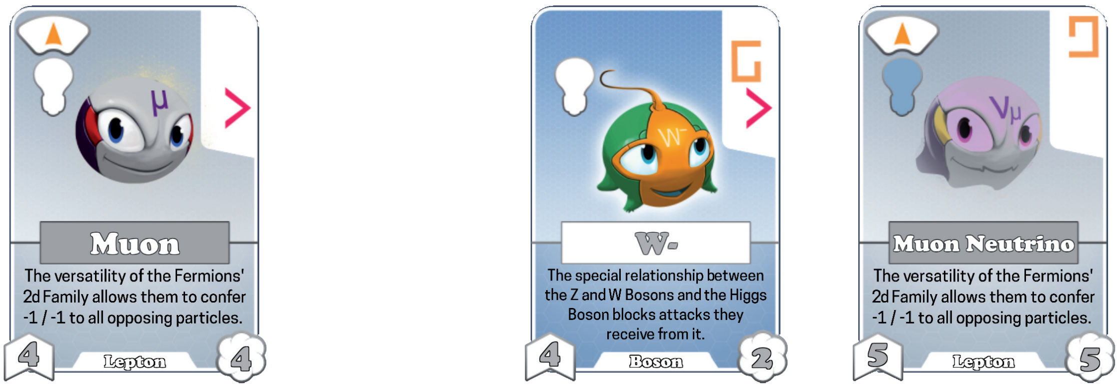
More about particle physics

Quark Clash involves cards representing the elementary particles that are the basic components of matter, and you must combine them in groups of three following specific rules. Actually, this is not just a game : these combinations of three elementary particles correspond to the way that an elementary particle can be affected by tne fundamental forces of Nature.

All the interactions between particles or their decays (for those which are not stable) can be viewed as the result of two such combinations. For example the muon has a lifetime of 2.2 microseconds. It decays into an electron, a muon-neutrino and an electron-antineutrino. This decay can be decomposed in two steps:

- First, the muon is transformed into a muon-neutrino under the action of a W- boson;



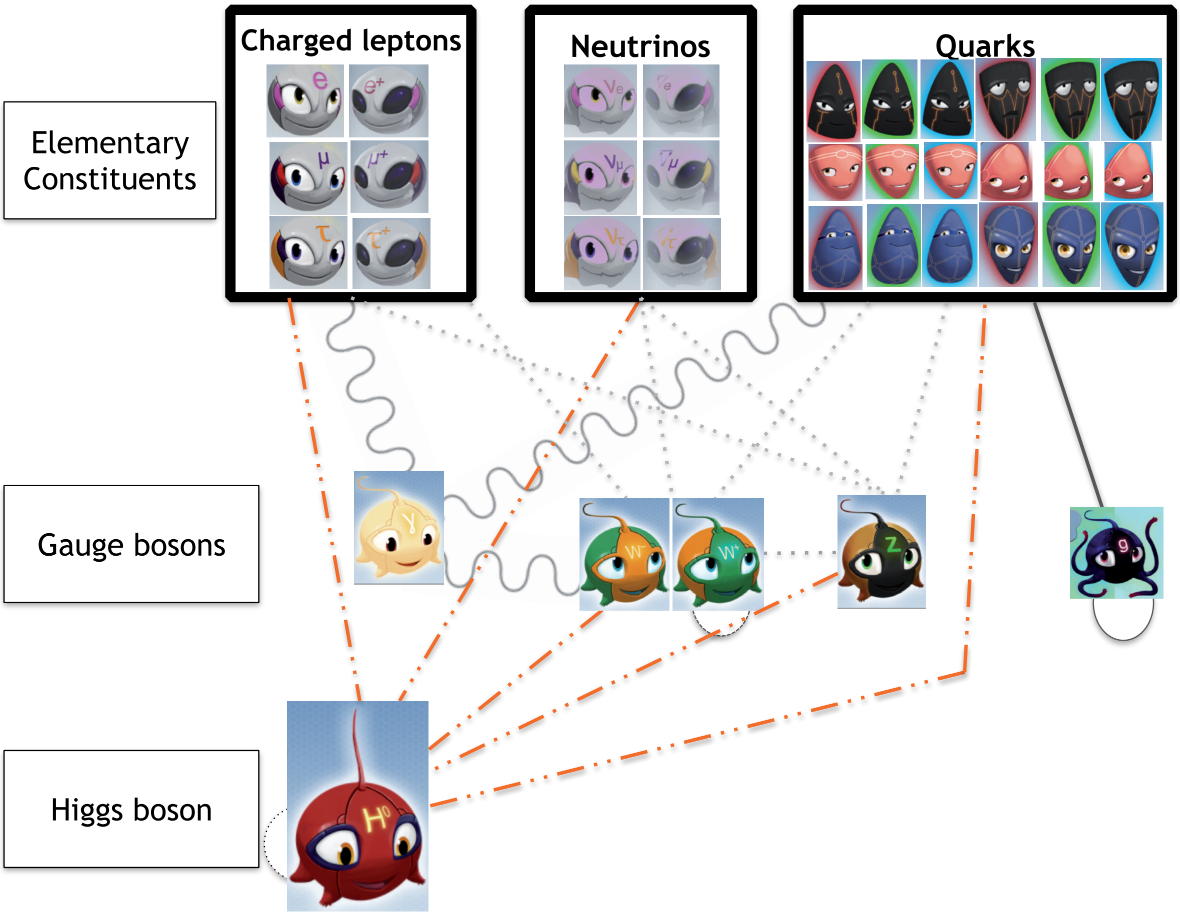
- Then, the W- boson decays into an electron and an electron-antineutrino.

Finding how such combinations of three elements are realised in Nature provides a key to understand how particles collide now in modern particle accelerators like the LHC near Geneva, similarly to what happened during a very short period after the Big Bang. At that time where a lot of energy was available in the Universe, there were elementary particles which have disappeared since long from our present environment. Using particle colliders, it is possible to recreate such objects and study their properties.

The elementary constituents of matter

Since the discovery of the first elementary particle, the electron in 1897, to the detection of the Higgs boson in 2012, it took about one century for physicists to achieve a complete picture of all elementary objects at the heart of matter and their interactions.

All the elementary particles known up to now and presented in Quark Clash are gathered below, where the lines represent «who talks to whom».



We already know that this picture, which is called the Standard Model of particle physics, is incomplete in some aspects, as it describes the current experimental measurements well, but it does not answer many questions (for instance, why are we surrounded only by matter ? why are the particles structured in such a way ? why are there masses so different ?). Most probably, new elementary objects will be discovered to answer these questions, and they will have very different properties from those we have studied up to now.

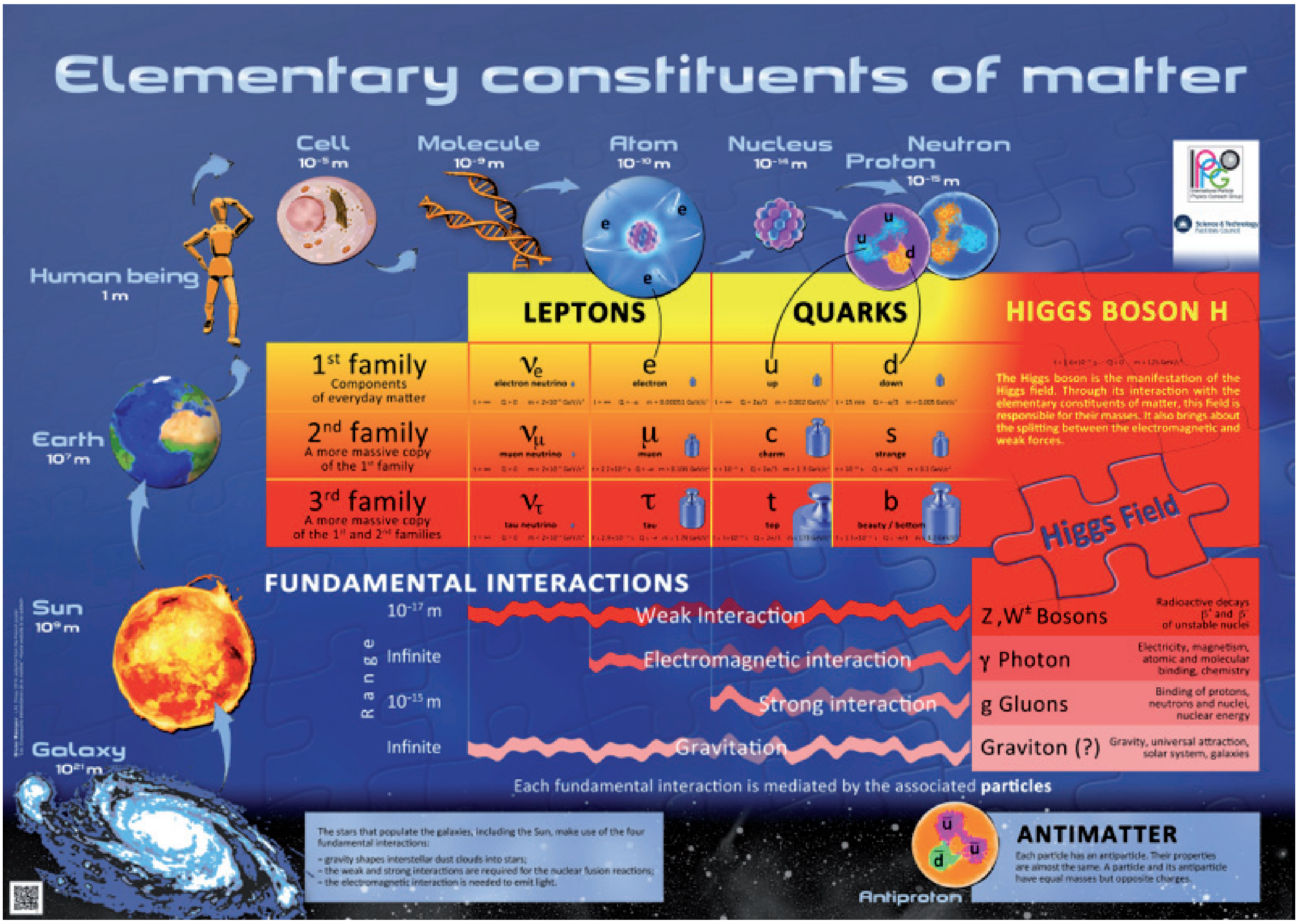
There are two different classes of elementary particles named fermions and bosons. These names correspond to quite different behaviours. Two identical fermions cannot stay at the same space location and at the same time, whereas several bosons can do so. Fermions correspond to matter constituents whereas bosons carry the fundamental interactions or forces.

The three families

Elementary constituents are distributed into three families. Each family contains two elements which are sensitive to the three interactions (the "quarks") and two elements which are sensitive only to two of the three interactions (the "leptons").

First family:	up down	neutrino-electron electron
Second family:	charm strange	neutrino-muon muon
Third family:	top beauty	neutrino-tau tau

A more complete picture of this organisation is provided in this poster of the elementary constituents of matter. Since 1989, we know that there is no other family of particles (at least none that would contain a light neutrino - the three known neutrinos have a very small mass, smaller than one millionth of the electron mass).



Particles which stand at the same position in two different families interact (almost) in the same way. The families essentially differ through the mass of their elements and they can be identified in Quark Clash through the dial in the top left corner of each card. Some explanations on the name, mass, lifetime and properties of each particle are given in Quark Clash, if you move the cursor over the corresponding card.

The fundamental forces

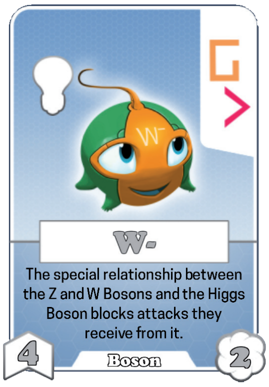
The elementary particles are sensitive to three fundamental forces or interactions: electromagnetic, weak and strong (gravitation can be neglected as the masses involved are very small). Each force is associated with one or more particles, called force carriers, and which are represented by additional cards in the game.

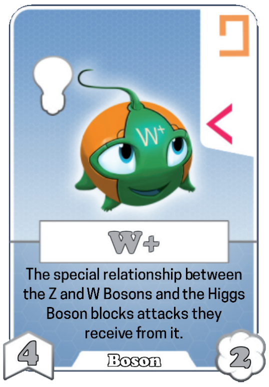
We are familiar with the electromagnetic interaction which governs essentially all phenomena in our environment: chemistry, biology, electronics, etc. The other two interactions manifest themselves at very short distances, inside the atom's nucleus. Though more discrete, they are also important for us. As an example, the weak interaction regulates the energy production by the Sun; without it, our star would have disappeared since long. Nuclear plants are using properties of the strong interaction to produce energy.

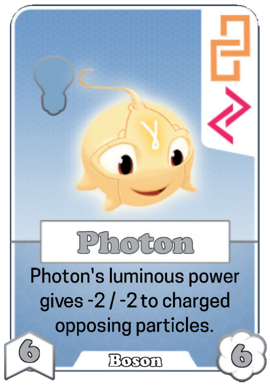
The electromagnetic interaction is transmitted by the photon. Z and $W^{\pm}$ bosons transmit the weak force whereas gluons generate the strong interaction.

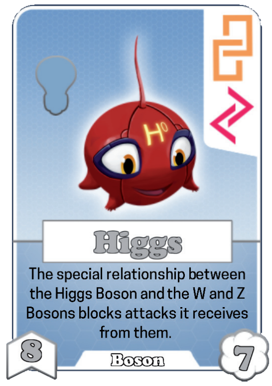
The action of electromagnetic and weak forces is coded in Quark Clash using two symbols (rectangles and triangles) and a light bulb (lit only for electrically charged particles) whereas colours (red, green blue) code the strong force. Both symbols and colours used are arbitrary: they have no literal physical meaning. Note that the forces that carry symbols (photon, Z, $W^{\pm}$ bosons) have no colour whereas those which have two colours (gluons) carry no symbol.

A given particle can be sensitive to all interactions (as quarks which are coloured and have a symbol) or only to some of these forces (for instance, neutrinos are only sensitive to the weak force: they are not coloured, are neutral but have a symbol).









The electromagnetic and weak forces

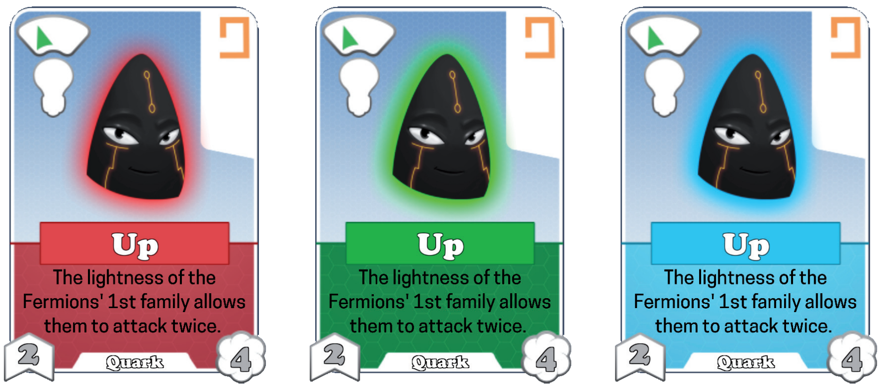
Since the mid of the seventies, electromagnetic and weak interactions have been unified into a single force. The "electroweak" interaction only appears at high energy, for instance when particles collide in an accelerator like the LHC. At lower energies, the electromagnetic and weak forces look really different. In this unified theory, the photon and the Z boson are combinations of two other neutral and massless fields.

Neutral bosons interact only with matter constituents which belong to the same family, the same anti-family or a family and its corresponding antifamily. The $W^{\pm}$ bosons are the only force carriers which can interact with quarks (only, not with leptons) belonging to different families. This different behaviour of the $W^{\pm}$ bosons relative to quarks and leptons originates from the extremely low mass of neutrinos. Interactions with the $W^{\pm}$ bosons have different strengths depending on whether the quarks involved belong to the same family or to different families. Heavy quarks and leptons can decay into lighter ones through this interaction: this explains why most of elementary particles are unstable and they are not observed in our present environment.

The interaction with the Higgs boson (H) can explain how the Z boson gets a large mass (about one hundred times the proton mass) whereas the photon is strictly massless. In the game, this unification is illustrated by the fact that the same symbols are used for electromagnetic and weak interactions. The Higgs boson is also responsible for a mechanism which explains how elementary constituents of matter can have masses.

The strong force

The quarks have been discovered by colliding high energy electrons on protons and analyzing the characteristics of the emitted particles. However, no single free quark has ever been observed in Nature. During a collision, quarks can be produced or ejected from a proton or a neutron, but they always remain bound to an antiquark or to two other quarks in this process. Indeed only configurations involving a quark-antiquark pair or three quarks configurations are allowed by the strong interaction, in tiny volumes having a characteristic size of 10^{-15} m. Even though the theory of strong interactions has been known for forty years and extensively verified by experiments, it remains very difficult to handle theoretically. One often relies to solving the quations numerically, requiring very powerful computers even to study rather simple phenomena.



The strong interaction is described introducing an index to quarks whose values are 1, 2 or 3, or more conventionally, red, green and blue. This index is named colour for quarks and anticolour for antiquarks. Gluons, which transmit the strong interaction, act on these indices: they correspond to 3x3 complex matrices obeying some specific constraints (there are eight such matrices, each associated with one of the eight gluons). Each gluon can thus be viewed as having a colour and an anti-colour, but the intensity of the strong interaction does not depend on the value of these indices. It can be noted that strong interactions have no connection with electroweak interactions. This is illustrated by the absence of symbols on the gluon cards, and by the fact that the photon and Z and W bosons carry no colour.

The quark index is named colour in relation with the combinations of quarks and antiquarks that are observed in Nature. If we view stable combinationsof quarks as uncoloured or « white », such combinations can be obtained using fundamental colours (red, green and blue). Combining a red quark, a blue one and a green one gives a white combination (for instance to get a proton uud or a neutron udd). Similarly, if we assign anticolours to antiquarks, combining a red quark with an anti-red antiquark yields white again. Such white combinations have no strong interaction unless another particle enters the tiny volume corresponding to this bound state and it is able to distinguish the colours of the quarks inside. It is said that the strong force is confined, as it occurs only in limited volumes and keeps coloured quarks and antiquarks « hidden » in white objects.

In Quark Clash, colour and anticolour are not distinguished for gluons. For this reason there are only four different types of cards for gluons. There are also point-like interactions involving four gluons, which are not included in Quark Clash.

The interactions

In Quark Clash, an initial particle is transformed into two other particles. At least one of the three particles must be a force to induce the transformation. Valid combinations are obtained by checking that:

- the symbol(s) on the initial card are retrieved on the two other cards (this is essentially a generalization of the well-known electric charge conservation in chemical reactions involving ions);

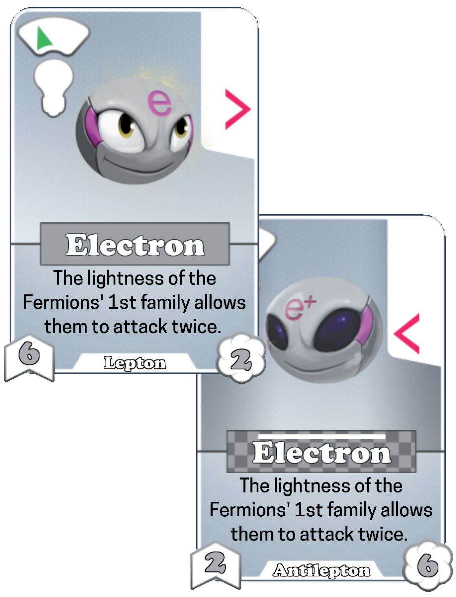
- the colour(s) of the initial card are retrieved on the two final cards (this is a simplification of the way that the strong interaction operates:it corresponds to the limit where the number of colours would be very large rather than three)

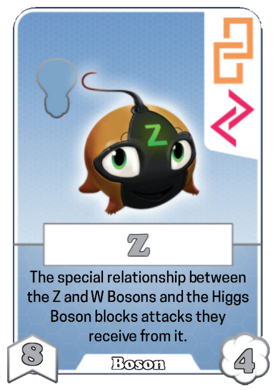
In Quark Clash, we do not require that the energy is conserved in these transformations, even though the mass of the initial particle is smaller than the sum of the masses of the resulting cards for many combinations. Indeed, one should also take into account the kinetic energy of the incoming particles, which may be large enough to allow for these interactions while satisfying the conservation of total energy. On the other hand, it is essential to obey the rules concerning symbols and colours at each point-like interaction of three objects (these are conservation laws which are essential in particle physics).

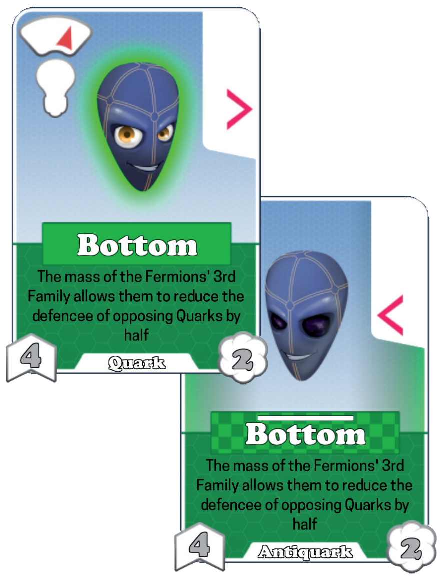
For example collisions between electrons and positrons were studied at the LEP collider at CERN between 1989 and 2000 (before the LHC collider was installed to search for the Higgs boson). Some of these reactions correspond to the creation of a quark-antiquark pair from the collision of an electron and a positron. It can be decomposed in two steps:

e+ e- -> Z followed by Z -> quark antiquark

corresponding again to two point-like interactions of three particles.







At LEP, the electron and positron had a collision energy of 90 GeV in total and all types of quarks can be produced, apart the top quark which has a mass of 173 GeV. We have represented here a case where a quark bottom and the corresponding antiquark were produced.

More generally, particle physics exploits Einstein's relation between mass and energy $E=mc^2$ to create heavy (and unstable) particles by performing very energetic collisions between light particles (such as electrons or light quarks and gluons inside protons). The double difficutly consists in building accelerators able to make these light particles reach very high energies and in designing detectors able to measure precisely the heavy particles before their decay. This led in particular to the discovery of the Higgs boson in 2012 at the Large Hadron Collider (or LHC), confirming the Standard Model of particle physics after a hunt for several decades.

More links

More detail (in French) on particles, starting with atoms and ending with the new physics that could be discovered at LHC (CERN, Geneva) can be found on

http://elementaire.lal.in2p3.fr/

The poster of the elementary constituents of matter can be downloaded at

http://tinyurl.com/posterElementaryConstituents

More explanations and ressources around this poster are available at

http://www.particuleselementaires.fr

Another important source of information is available on the CERN web site

http://home.web.cern.ch