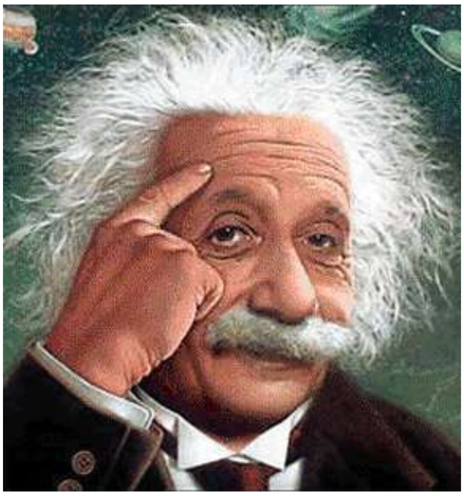

C1.2.4. Einstein

Once the main relativistic effects *-time dilation, length contraction*, *speed limit* and *equivalence of mass and energy-* have been established from the physical interpretation of the Lorentz transformation, we can switch to display some situations where the mentioned effects are checked or they have some practical application.

Although the form of the Lorentz transformation was established by the Dutch scientist of the same name, it was Albert Einstein who proposed to reconstruct all the science on these new principles, by the way unifying mechanics and electromagnetism and predicting the reality of these effects, giving rise to the possibility to test them. This possibility of verification or falsification trial was one of the facts that led to the success of this theory, which is now recognized as one of the strongest of Physics, whose predictions, however strange they may seem, have been confirmed.

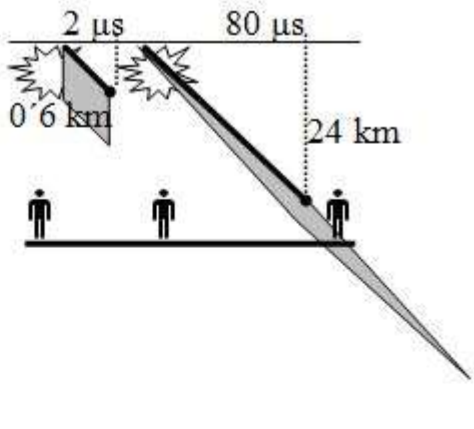

Figura 1.25

We will start with one of the first and more direct checks that are made from *time dilation:* the explanation of why muons from the upper atmosphere are able to arrive at the earth's surface.

The particles called muons can be produced in a laboratory, and it has been established that they have a lifetime of about a couple microseconds (2 μs).

Muons are also produced at about 20 km above the earth's surface as a result of collision of cosmic rays at very high energy with the atmosphere. These muons move at a speed which is very close to that of the light. Still, given that they only last two millionths of a second, they should not be able to advance more than 600 m in this time before disintegrating, so they would never come to the surface. However, at this very moment there are passing thousands of muons every second through our bodies (they hardly interact with matter, being this the reason of not producing appreciable effects in living organisms). This phenomenon can be explained if we consider the time dilation. Figure 1.25 shows the temporal scale vertically, and the spatial scale horizontally, to highlight the path followed by the muons from the top of the atmosphere (above) to the ground surface (below). We see at the left what would happen from the classical relativity (Galilean transformation): the muons, in their lifetime of 2 µs, would not reach the earth's surface. On the right you can see how the shape of the Lorentz transformation, by contrast, expands their lifetime time, reaching 80 µs (at the speed of these muons, time gets dilated by a factor of 40). At this time, muons produced in the upper atmosphere can travel up to 24 km, which is why they reach the Earth's surface. (In relation to the experience of the muons, see Annex 1: A1.5.1.2).

We can also use the effect of *time dilation* to explain the so-called "twin paradox". In a very brief statement, this paradox applies to two twin brothers, one of whom remains on Earth while the other goes to make a space travel back and forth at high speed. By the time dilation, the time of this twin traveler passes slower, so at his return he will be younger than his brother. The paradox appears if we consider that, from the point of view of the traveler, is his brother who is moving all the time, so at his return it would be his brother, who remained on Earth, who would be younger. And the question is: which of the two will be younger when they meet again? It is impossible that both of them are older than his brother. To understand this phenomenon, we can see in Figure 1.26 the viewpoint of the brother who stayed on Earth. We see that, for him, six years pass until his brother returns, while for the traveler only four years have, two for the trip away and two others to return.

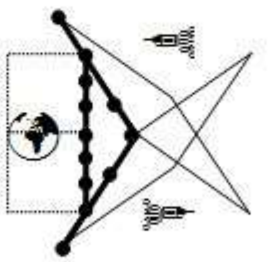

Figura 1.26

The paradox disappears if we observe that the situation is not symmetric: the brother who remains on Earth is at all times in an inertial reference system, while the traveler passes from one system to another that travels in the opposite direction, and in that change considerable acceleration appears, that only he feel, not his brother, so the the correct view is that of the twin which remains on earth: His brother will return younger than him after his trip through space (if he can survive these accelerations, of course!). The paradox of the twins is analyzed in more detail in Appendix 1: A1.5.1.1.

In 1971, it was made an experience with atomic clocks aboard aircraft who flew around the Earth in opposite directions on the same day, and the validity of the above considerations was checked (the experiment, carried out by Hafele and Keating, is described in Annex 1: A1.5.1.3).

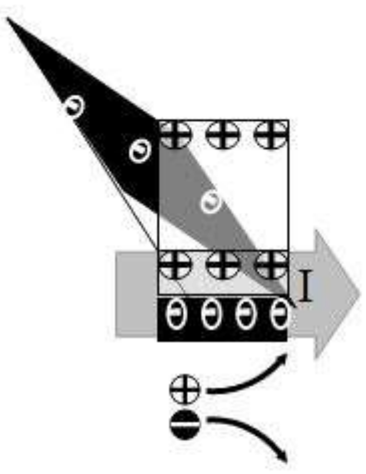

Figura 1.27

Lenght contraction helps to explain some of the most important phenomena of electromagnetism: the Lorentz force between charges and moving electrical currents, the attraction between parallel electric currents (Ampere's law), the behavior of magnets, coils and motors and particle accelerators.

We'll see just a figure that allows us to understand how these effects arise, which are explained classically by magnetic fields. Magnetic fields are mathematically complex elements, which makes the chapter of electromagnetism to be one of the most difficult of classical physics. The relativistic geometric explanation allows to achieve the same results without the need of such magnetic fields, a procedure which sometimes offers surprisingly simple solutions without any loss of accuracy.

We will discuss the event of one charged particle moving parallel to a linear conductor with an electric current of intensity I.

To model of this current is made in Figure 1.27 by two symmetrical flows of charges, the positive ones in the sense of the intensity, and the negative ones in the opposite direction. This is what happens, for example, in an electrolyte or in ion discharge tubes.

If the external charged particle is at rest (let's assume that it is positive), the symmetry of the figure would cause the attraction by negative charges on the driver to be exactly compensated by an equal repulsion of the positive charges.

But if the charge moves in the same direction as the flow of positive charges (in the figure to the right) and at their same speed, then we know that, for the external positive charge, the internal positive charges are at rest (white square) while the negative charges are moving with even greater speed in the opposite direction (to the left in the figure, black diamond). By the phenomenon of length contraction, the negative charges are more clustered than the positive ones (we see that in the same length occupied by three positive charges there are now four negative charges), and from the point of view of the external charge a net force of attraction appears , which causes it to bend toward the stream. If the charge is negative, it would bend in the opposite direction for the same reasons.

In section A1.5.2 of Annex 1 the various electromagnetic effects mentioned above are explained in more detail.

We will see how this phenomenon, called the Lorentz force, serves to explain in a very simple way the operation of a particle accelerator as complex as the existing premises at CERN in Geneva, called LHC (acronym for "Large Hadron Collider"), represented in an extremely schematic way in Figure 1.28.

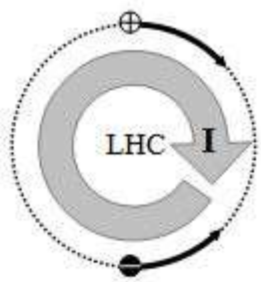

Figura 1.28

The LHC is housed in an underground tunnel 30 km in circumference inside which an electric circular current of great intensity is circulating (it is usually explained by large superconducting magnets, but their net effect is none other than the one described). In parallel with this very intense electric current, beams of positive particles are injected into the tunnel in the same direction of the intensity. By the effect of length contraction the reference system of the flow of negative charges of the electric current (the phenomenon seen above) creates a Lorentz force to the center of the circle, ie a centripetal force. Thus, the particles remain turning on the circumference of the tunnel, and in each turn an electric field is applied that accelerates them forward. In the same figure it is also represented a negative charge circulating in the opposite direction, which would feel also a centripetal force.

In section A1.5.2.5 Annex 1 explains the operation of the circular accelerators.

The fact that, despite achieving fabulous energies the particles of LHC never reach the speed of light, is also a check of the phenomenon of the speed limit, and is explained in greater detail in Section A1.5.3 in Annex 1.

In these accelerators the *equivalence of mass and energy* is applied to make collide beams of particles that rotate in opposite directions. In these collisions the particles lose the huge amount of kinetic energy that they had stored and produce varied phenomena of creation of new particles. The kinetic energy, which can reach a value of about 2000 times the mass of the individual particles, can be converted into 2,000 new particles as they collide or even a new particle with a mass 2,000 times greater, and this type of events is the most interesting, in fact it is through this mechanism that the search for the "Higgs" particle has produced very interesting results that would complete the theoretical framework of the existing particles and confirm the process proposed by Higgs to explain the masses of the particles.

In Figure 1.29 we see a diagram of a collision between two particles (small white rhombuses) who travel with a speed such that its kinetic energy is equal to its mass.

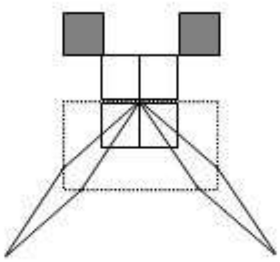

Figura 1.29

When they collide, this energy allows to produce two new particles (gray small squares) identical to the original (white small squares), appearing, therefore, four particles instead of two after the collision.

We can see in the figure that the extension of the sides of the rhombus in the Lorentz transformation is a direct measure of the kinetic energy in comparison with the mass of the particle. This is due to the fact that the same factor (called *gamma)* that measures the time dilation measures also the total energy (including mass) of the particle. After the collision, the particles lose their original kinetic energy (dotted line), remaining at rest (white small squares on the top). The excess energy, in this case, allows the production of two new particles (gray small squares).

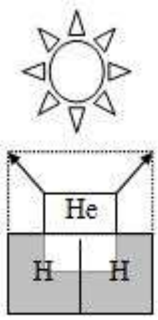

Figura 1.30

The creation of particles is also explained in Appendix 1: A1.5.4.5.

This same type of diagrams can explain the various manifestations of nuclear energy (see Annex 1: A1.5.4.4), as discussed in the case of nuclear fusion between two hydrogen nuclei to give a helium nucleus. The helium nucleus has a mass slightly less than the sum of the masses of two hydrogen nuclei (this is due to the fact that there is a binding energy of the nucleus of helium corresponding to an attractive potential and, therefore, negative). This energy loss of the set of nuclei is indicated in gray in Figure 1:30 (we can also understand it as a potential energy that had the positive nuclei if they were separated). This energy loss is compensated by the production of light particles (photons), indicated by pointed arrows in the figure.

This reaction is being constantly in stars like our Sun, and is therefore responsible for the solar energy we receive daily.

As a final example, we see that the Lorentz transformation is helpful to explain the origin, structure and evolution of the universe, according to the currently accepted cosmological theory, known as the *Big Bang*.

According to the Big Bang theory, the original Universe, about 15 billion years (15 Ga) ago, was a point at which spacetime began a uniform expansion that still continues today.

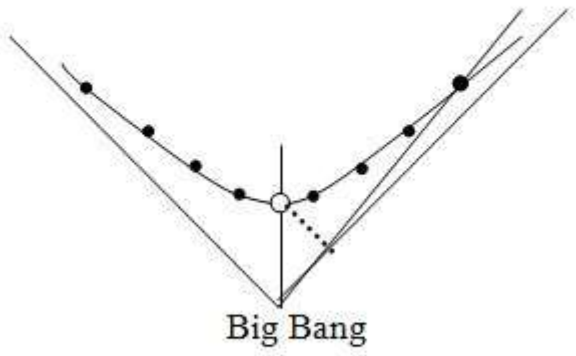

Figura 1.31

This process can be visualized by the spacetime diagram of Figure 1:31, in which the lower vertex is the Big Bang and the central small white circle represents our galaxy in this same moment.

We can see that the universe has a limited size, because the maximum speed of expansion may be the speed of light (sides of the "V"), which is a consequence of the relativistic phenomenon of the *speed limit.*The universe, according to the above, is a sphere of radius 15 gal (being 1 to the distance traveled by light in a year, or light-year), of which we see in the figure only a diameter (because from the beginning of these explanations we reduced the spatial dimensions from three to one.)

The funny thing is that each black dot represents a galaxy cluster with the same age as ours, which are separated from each other evenly throughout the Universe. There is, therefore, no limit to the number of galaxies containing the universe, which seems contradictory to the fact that it has a limited size. Observing the figure, we see that the galaxy clusters are arranged on the branches of a hyperbola, a figure we already anticipated when we explained the phenomenon of relativistic speed limit in Figure 1.22. The hyperbola is an ubiquitous figure in the relativistic diagrams, although it appears here for the first time, and its role in spacetime geometry is similar to the circumferences in the usual Euclidean geometry.

Because galaxy clusters are arranged regularly on the branches of the hyperbola, and these have no end, there will be an infinite number of galaxies in this limited universe. The limitation is given by the fact that the branches of the hyperbola are limited in their inclination by straight linews which are called asymptotes (in this case, they are the diagonal lines corresponding to the points that would expand with the speed of light).

If we make a horizontal cut in this figure, we can also explain the existence of infinite galaxies in a finite universe due to the phenomenon of spatial contraction, by which the galaxies from the *edge* would be moving away for us so quickly due to the length contraction that they would be as thin as smoking paper sheets or even further.

Observing the dotted line that goes from the right edge to the central white circle, we can see that it corresponds to a light signal that arrives at this very moment to one of our telescopes from the edge of the universe.

On first impression, it seems that age of the objects that emitted the light should be half the current age of the universe, ie, about 7.5 Ga (since it took that time to the object to get from the Big Bang to the place where it emitted the light, and this light took as much time in returning to where we are!)

We see, however, that when this light left the line corresponding to the last black point on the right (which could be one of the more distant quasars), the age of the quasar was almost a quarter of the age it has now, ie , about 4 Ga. Thus, as we see the light from the most distant objects of the Universe, we are receding into the past to reach practically the origins of the Big Bang. This is a consequence of the phenomenon of time dilation.

As a final point, we should not think that there is an edge in the universe, but if we could know the observations made from the objects that are close (for us) to that edge, as would be the case of the aforementioned quasar, we would see that, from its point of view, they would be in the center and it would be our galaxy which is located near the edge of the universe, in the opposite direction. This is a consequence of the principle of relativity, by which physical laws do not depend on the reference system in which they are located.

The final part of Annex 1 (Section A1.6) is devoted to give a detailed explanation of the Big Bang Cosmology, in which, as we have seen here very briefly, all relativistic are phenomena integrally collected, and where the geometry of spacetime is revealed in all its extension.

Then, in Table 1.4, we meet the figures seen so far, thus having a synthetic representation of the consequences and applications of the Theory of Special Relativity.

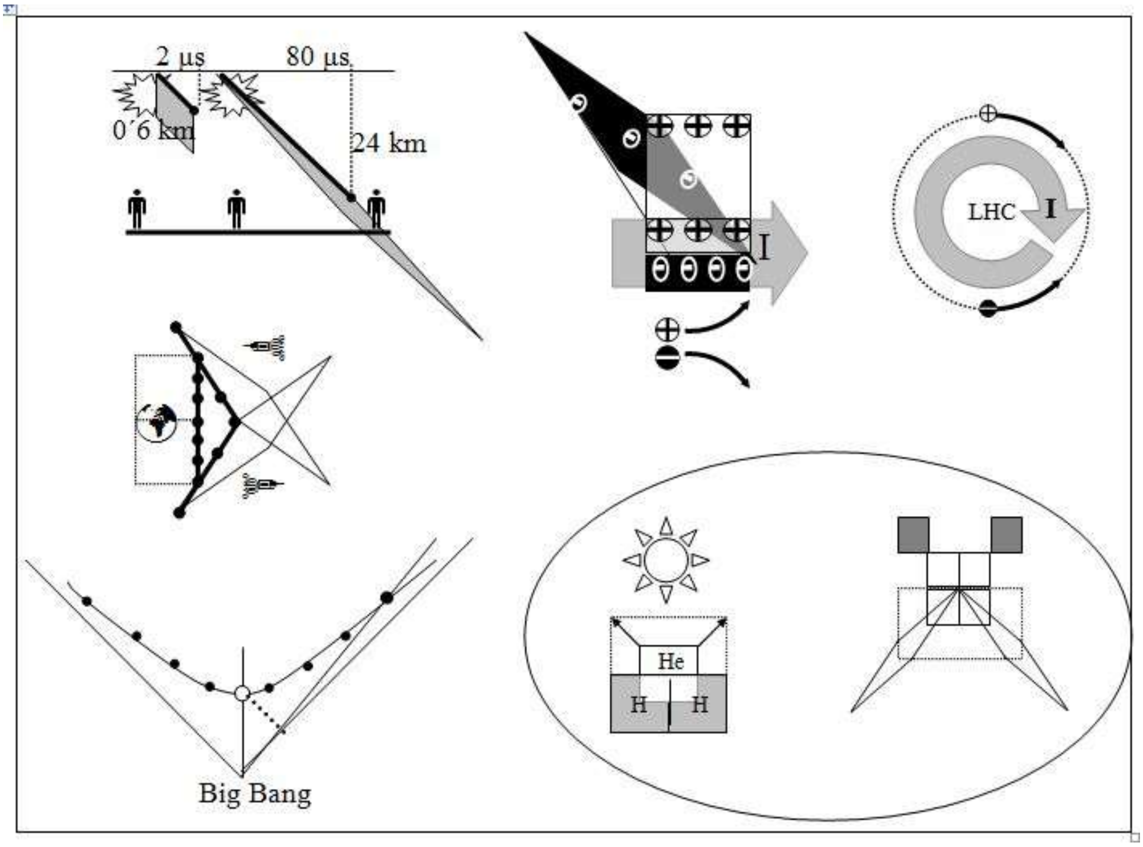

Table 1.4: visualization of the consequences and applications of the theory of relativity

In the top left of the picture we observe a justification of the observations with atmospheric muons at high speed, being time dilation which allows them to reach the earth's surface. The same phenomenon of time dilation is applied to the central figure to the left to explain the effect known as the twin paradox: by the time dilation, the twin traveler returns younger than his brother who remained at home.

Top right are two figures corresponding to the applications of length contraction: electromagnetic phenomena as the Lorentz force (which is the basis of the magnetism) are explained by the length contraction of moving charges, causing an increase in their density in such a way as to produce an effect which is greater than those at rest. Also explained by this same phenomenon is the operation of a circular accelerator (upper right corner).

We also note in the lower right a couple of figures relating to the consequences of the equivalence of mass and energy: nuclear energy and the creation of new particles from inelastic energy of a collision at high speed.

Finally, the figure at the bottom left of the chart illustrates how for the cosmology of the expanding universe or Big Bang are put into play in a combined way different relativistic phenomena described so far separately. It thus appears highlighted another of the great potential of the Minkowski geometric method for SR: the ability of geometry to produce figures which can explained in an elegantly simple way phenomena that would otherwise be very difficult to analyze (in this case, the explanation that there may exist a multitude of galaxies in a limited universe, as well as the fact that can see the initial moment of the Big Bang).

This set of figures is titled with the name *Einstein* because it was the intuition and genius of this German physicist which made it possible to understand a wide variety of phenomena that classical physics had no way to justify, and to make a lot of predictions which have been proven over time. Similarly, virtually all technological developments of recent decades are based in one way or another in Einstein´s SR .

The particularity, shown for the first time by Minkowski, that all SR has a matching geometry, constitutes one of the most important features of this theory, which has been applied consistently by Einstein for the subsequent development of the General Theory of Relativity.

In the teaching proposal which is justified, presented and discussed in these pages, this trait is used to facilitate the approach of the students to the qualitative and visual aspects of the theory, not to mention that the same geometric representation contains all the quantitative potential of the usual mathematical treatments for SR.