COSMIC RAYS & MUONS

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1. Preface

When we were still in the fifth year of Bilingual Education, we heard a lot about two panels being adjusted to the roof of the school to capture cosmic rays. Henk and Stefan already told us about it, but we never expected we would do the same in when we were in the sixth grade. By that time, we expected to build a huge “Strandbeest”, an idea of the Dutch man Theo Janssen. However, soon we found out that there was no mathematics involved, so we had to cancel our plans.

When we were asked to join the project HiSPARC, we were surprised and proud that they asked us. We did some research to learn more about HiSPARC and were enthusiastic immediately! Since that day we learned more and more about the particles surrounding us.

2. Introduction

Most people think that they know a lot, they know a lot about their job, they know a lot about the news, what is happening around us, and also at home, they know exactly how to function. However, in fact, most people don't even know what is surrounding them, literally. If you would ask a random person on the street, he or she would answer: air, wind, perhaps oxygen or carbon dioxide. But they don't know what other particles are surrounding them.

Science has shown us that there is so much more than we can visually see. We will try to explain what is surrounding us in such extent that you do get an image of it. We would like to tell you more about the cosmic rays, muons and show how they effect us.

We did our project in cooperation with the Leiden University of Science, where we investigated the mean lifetime and speed of muons.

Our research question concerning the experiments are:

- **What is the lifetime of a muon**
- **What is the speed of**
  - **-muons in the phototubes**
  - **-photones in the phototubes**
  - **-electrons in the wires**

For the theoretical part we will explain in full detail what cosmic rays and muons are.

We will discuss it fully in the following pages.

Enjoy!

3. Index

4. Cosmic Rays

4.1 What are cosmic rays?

Cosmic rays are not really "rays", but mostly pieces of atoms: protons (± 90%), helium nuclei (± 9%) and electrons (± 1%). These little bits of matter are highly accelerated; they travel with a speed, which is close to the speed of light. We can not determine where they come from precisely, as the magnetic fields of the Galaxy, out solar system and the Earth have changed their direction. Although they are much smaller than atoms, their energy is incredible.

Cosmic rays can be divided into two separate parts: the primary cosmic rays and the secondary cosmic rays. The primary cosmic rays are the particles which enter our atmosphere. When they collide with target nuclei, smaller particles are formed. These smaller particles are lighter and they can reach the Earths surface. They are the secondary particles.

Cosmic rays' energy is in electronvolt (eV). Most cosmic rays have energy between 100 MeV and 10 GeV.

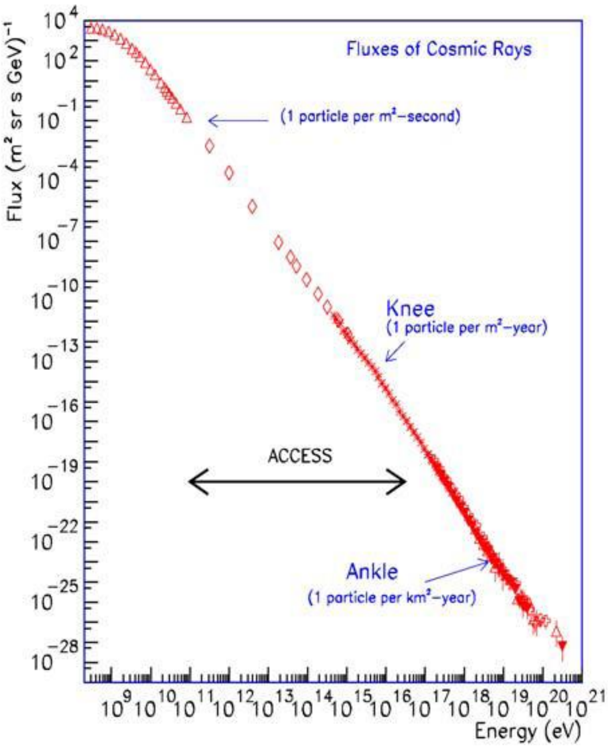


Figure 4.1.1
That particles with very high energy reach our earth is very rare as you can see in this figure.

4.2 The discovery

The history of cosmic ray research is a romantic story of scientific adventure. For three quarters of a century, cosmic ray researchers have climbed mountains, ridden hot-air ballons, and travelled to the far corners of the earth in the quest to understand these fast-moving particles from space. Their explorations have solved scientific mysteries—and revealed many more. The Pierre Auger Project continues the tradition as it begins the search for the unknown source of highest-energy cosmic rays ever observed.[1]

The first essential discovery was by Charles-Augustin de Coulomb before 1800. He found out that an electroscope discharged spontaneously. They concluded there was background radiation everywhere on earth. This radiation would come from the earths surface itself.
However, this hypothesis was proved wrong, when Theodore Wulf found out that on the Eiffel Tower the electroscope discharged quicker than on the ground. However, his discoveries were not widely accepted.

The next step was made by Victor Hess, who investigated the ionization rate on even higher levels. To do so, he had to create an electroscope, which could handle all types of weather and maintain well isolated. In 1912 he succeeded building this electroscope. He used a balloon, to get higher up in the air and found out that the speed of the discharging increased while getting higher.
He concluded that the radiation did not come from beneath us, but from above.
Because he also travelled during a near-total eclipse, he could also rule out that the sun is the main source of radiation.
In 1936 he received a Noble Prize for his discovery.

Figure 4.2.1.
Victor Hess in his balloon .

[1] http://www.ung.si/public/pao/history.php

4.3 The journey of cosmic rays

How does it all start?

The sun plays a very important role in the theory of muons. The radiation that is sent out by the sun is turned off towards the geomagnetic poles by the Earth's magnetic field. The amount of radiation that reaches the earth on a specific area depends on how close this area is located towards the geomagnetic poles. The equator, for example, receives a lower amount of radiation than when you go more to the south or to the north. The amount of energy that reaches the earth can be portrayed in a map, like figure 4.3.1.
When the particles contain a lot of energy, its velocity is big. These particles are not easily changed from direction and are the only ones that can reach the equator as the Earth's magnetic field can't change its direction.

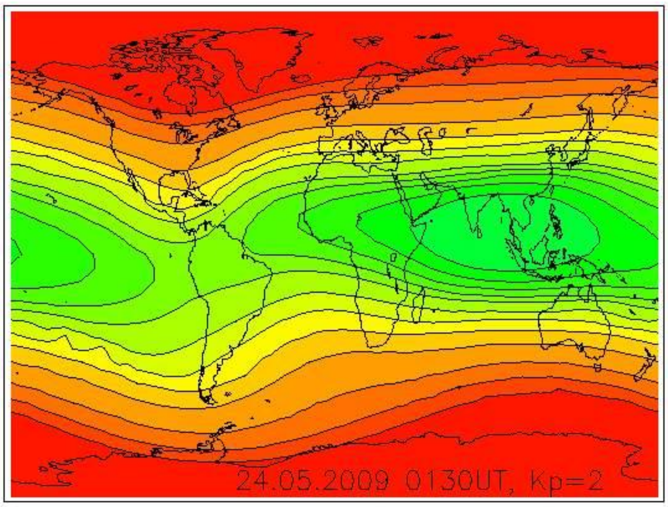


Figure 4.3.1.
A clear distinction of energy levels per altitude is shown in this map.

Physics explained
When a particle travels from the Sun to the Earth, it interferes with the Earths magnetic field. The force of the magnetic field is perpendicular to the magnetic field line and the velocity of the particle. This means that it is influenced by the Lorentz force. This means that the particles will be forced in a circular orbit, if it propagates in a perpendicular direction. The stronger the magnetic field (B) and the weaker the energy of the particle (the red +, with the arrow), the smaller the radius of its orbit.

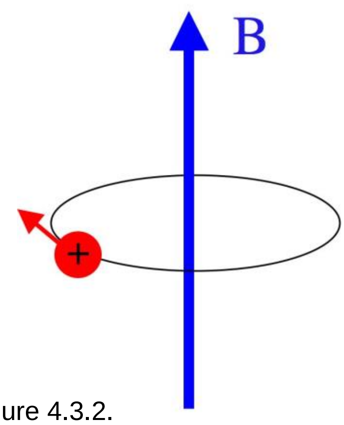


Figure 4.3.2.
A schematic drawing of how a proton travels around a magnetic field line.

How does the sun create cosmic rays?

The sun contains sunspots, these are areas where the temperature is 1000 degrees Celsius lower than the average temperature on the sun. This causes a decrease of light, making the areas look black. Yet, there is not a lot of information about sunspots, but scientists do know that there is a correlation to the strength of the magnetic field on the sun. When there is a maximum of sunspots, the magnetic field of the suns is highest. On the surface of the sun, solar flares eject particles like electrons, ions and atoms into space. These clouds of particles reach the Earth a day or two later.

Extra information
The heliosphere is a region of space around the sun. You could see it as a huge bubble, containing our solar system, solar wind and the solar magnetic field.

The solar wind derives from the sun and hit the interstellar space, which is the space that is not occupied by stars or planets. When the solar wind hits the interstellar medium, the bubble is formed. This bubble, the heliosphere, is the shield for our solar system from cosmic rays.

Other sources of cosmic rays

The sun is not the main source of cosmic rays. Most radiation comes from stars like nova's and supernova's. Their energy can be even over 1015 eV. These cosmic rays are hold back by the Milky Way of our Solar system, but also our sun protects us for all the radiation by using its heliosphere.
When a particles energy is more than 1018 eV, it is able to leave the Milky Way, because of their speed. However, this type of rays will not radiate towards to earth. Luckily, other rays of this type are pointed towards our earth. So we are able to capture an amount of rays. Thereby, is the speed so extremely high, that it does not change direction, so we can also measure where the rays come from.

What happens in interplanetary space?

The particles ejected by the sun, travel through space. Of course, there is a magnetic field in interplanetary space, but we assume that the particles travel through empty space until it encounters the magnetosphere as the magnetic field in interplanetary space is much weaker.
In figure 4.3.3 on the right is a simple image of the situation. The magnetosphere is represented as the blue circles around the earth.
The figure shows three types of orbits of cosmic ray.

- If the energy of the particle is too weak, so $E<E_0$, the particle will be send back to interplanetary space, bended by the magnetic field, without reaching the atmosphere.
- When the particle has just enough energy to reach the atmosphere, so $E>E_0$, it will show follow a curved path.
- The particle can also have a lot of energy, when this is the case, it will travel in a straight line down to the atmosphere. In this situation $E=\infty$

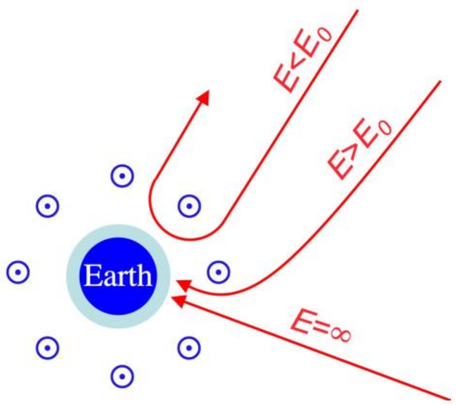


Figure 4.3.3.
The paths travelled by particles with different energies.

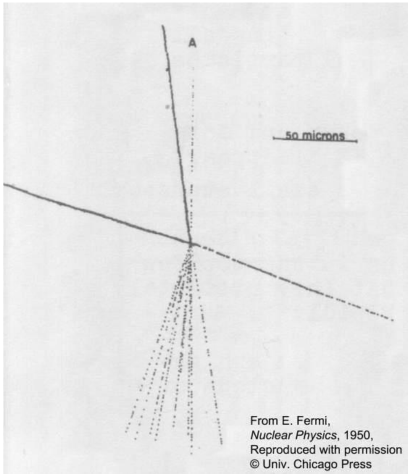


Figure 4.3.4.
Collision between a proton and the target nucleus.

Arrival in the atmosphere

When the high-energy particles, like protons or helium, passed the magnetosphere and arrive at Earth, they collide with the nuclei of atoms in the upper atmosphere. As you can see in figure 4.3.4, a particle (this can be a proton for example, travelling at 98% of the speed of light) collides with the target nucleus. If the energy is high enough, it will hit one or two individual nucleons in the target nucleus. Its result is an immediate kick out of hit nucleons, called knock-on nucleons, or a pion is formed. This is called the cascade phase of the interaction and it only takes 10^{-22} seconds. We will talk more about the particles that are formed later on.

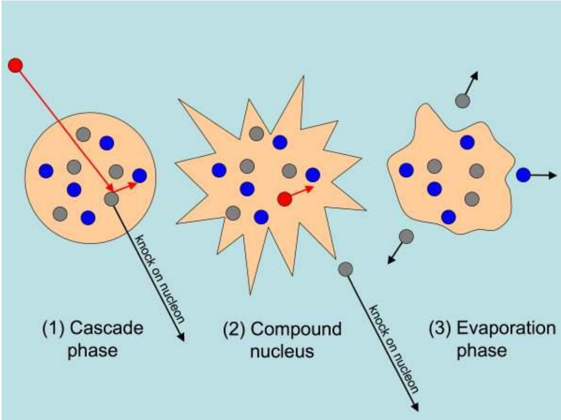
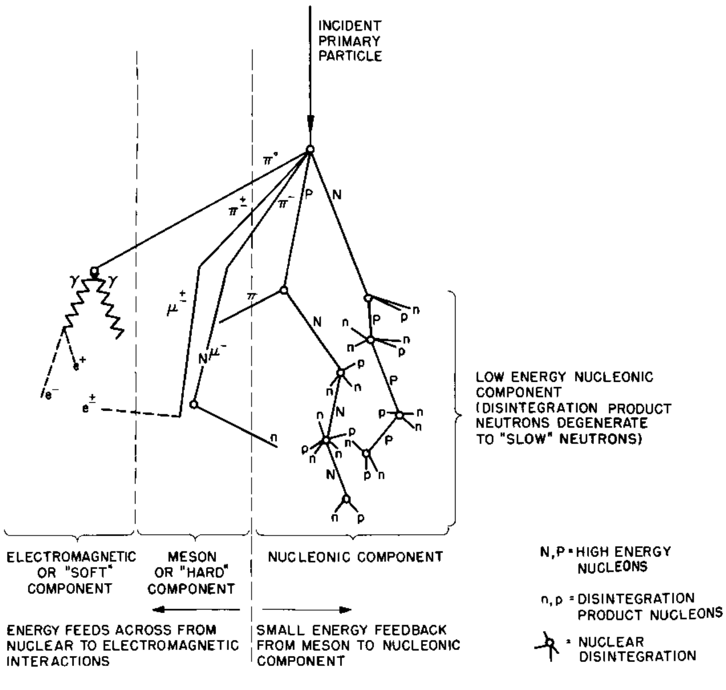


Figure 4.3.5.
A schematic image of the collision.

The cosmic ray particles that hit the target nucleus partly stay within the nucleus. These still have some energy left, which is shared with the components of the residual nucleus. The target nucleus is then called compound nucleus.
However, the residual nucleus do not have enough energy themselves to escape. By colliding with the cosmic ray nucleon fragments, it will acquire enough energy to be emitted. This takes 10^{-16} seconds, which is a million times longer than when the nucleus is kicked out immediately. They are called evaporation nucleons, as they boil off or evaporate eventually. In contrast of the cascade phase particles whom travel in the same direction as the original particle that hit the target nucleus, the evaporation nucleon leave the nucleus in any direction with an energy of some MeV.
This part of the interaction is called de-excitation phase or evaporation phase.
The particles lose a lot of energy the deeper they travel into the atmosphere. The primary cosmic rays should already have energy of 450 MeV or more to produce a significant number of secondary's that can reach sea level.

In figure 4.3.6 you see how a primary particle undergoes a cosmic ray cascade, forming a shower of particles. Most particles that are produced are pions. These pions are charged ($\pi^{\pm}$) or neutral (π^0).
The neutral pions decay into gamma-ray photons (γ). As a result of the gamma-ray photons, electron-poistron pairs are produced ($e^{\pm}$).
The charged pions decay into our well-known muons ($\mu^{\pm}$). The muons can also produce electrons and positrons, but also neutrons.
During the cosmic ray cascade fast nuleons, neutrons (N) and protons (P) are created as well. Only when they have enough energy, they can interact with other air nuclei. In this way, the evaporation nucleons and neutrons (n) and protons (p) with a lower energy are formed.
Because muons are least likely to interact with the atmosphere, most particles that reach sea level are muons



Schematic Diagram of Cosmic Ray Shower

Figure 4.3.6.
A cosmic ray cascade.

4.4 Observation

HiSPARC
HiSPARC makes use of cosmic ray detectors as well. The scintillators they use are very easy to make. A scintillator gives a lightpulse when a particle hits its surface. This lightpulse will be increase by a light amplifier. The bigger the pulse, the more energy the particle has.

Cosmic rays detectors

A nice way to visualize the interactions is to observe the tracks of charged particles in a special type of photographic emulsion. To do so, you must go to high mountains, use airplanes or balloons to detect the primary cosmic rays on different places. The energy of the particles and the direction can be determined with cosmic ray detectors. A network of detectors is needed to create a complete image. Such a network is called air shower array.
The biggest air shower array can be found in Japan, the Akeno Giant Air Shower Array (AGASA). It is build to study the origin of ultra-high-energy cosmic rays and to search for sources emitting cosmic rays at energies above 10^{17} MeV. Because of its 111 detectors and 27 muon detectors on only an area of 100 km^2 , very accurate readings can be measured. When a particle hits a scintillator a small computer will compare its energy with particles that hit other scintillators to decide whether it belongs to the same shower. If so, the data is sent to one computer, where all the data is combined. In this way, direction and energy of the original cosmic ray can be determined.
The AGASA makes use of four-layered scintillators, whom are very sensitive for pulses. Their biggest moment in history was on December the 3rd 1993, when a very large shower fell completely inside the detector area and in a nearly vertical direction.

High Resolution Fly's Eye

The "fly's eye" is a fluorescence detector developed at the University of Utah. They make use of the glow caused by the collisions of shower particles with air molecules in the atmosphere. The fluorescenes can only be measured on moonless nights with finely tuned light sensors. Several light sensors are pointed towards the sky in different directions. The shape and direction of the light helps to determine the the direction, energy and chemical composition of the incident particle.
The Pierre Auger Cosmic Ray Observatory in Pampa Amarilla, western Argentina, combines this method with the cosmic ray detectors. The scientists hope to get a better understanding of data from both detection methods and increase the accuracy of both techniques in this way.

Figure 4.4.1.
The High Resolution Fly's Eye

Particle accelerator

Another way to observe cosmic rays is to reconstruct the situation by using a particle accelerator. The largest one is the Large Hadron Collider (LHC) on CERN, near Genève, the most powerful accelerator in the world. The LHC lets protons collide with energy of 7 TeV. In this manner, people are able to produce particles with a mass of a few TeV, so even the most heavy particles of the Standard Model can be constructed like the top-quark of 0,175 TeV. Hence, more research can be done towards the existence of theoretical particles, which would complete the Standard Model like the Higgs particle.

The Standard Model

"The Standard Model explains how the basic building blocks of matter interact, governed by four fundamental forces."
More information on this subject will be given on page 15.

Higgs Boson

The Higgs particle is a still unknown mystery in science. Although research has shown its extinction, there is still a lot unknown. More information about the Higgs Boson can be found on page 15.

Cherenkov telescope

Cherenkov light is electromagnetic radiation, which is emitted when a charged particle, like an electron, passes through a medium at a speed greater than the velocity of light in that medium. This seems impossible but because light slows down when it enters a medium, it is possible. The Cherenkov telescope consist of large mirrors that focus the Cherenkov light onto photomultiplier tubes. The result is an image of the air shower. Unfortunately are they only able to operate on clear moonless nights, like the High Resolution Fly's Eye, as it are optical instruments. Thereby, are they only able to view a small piece of the sky at the time.

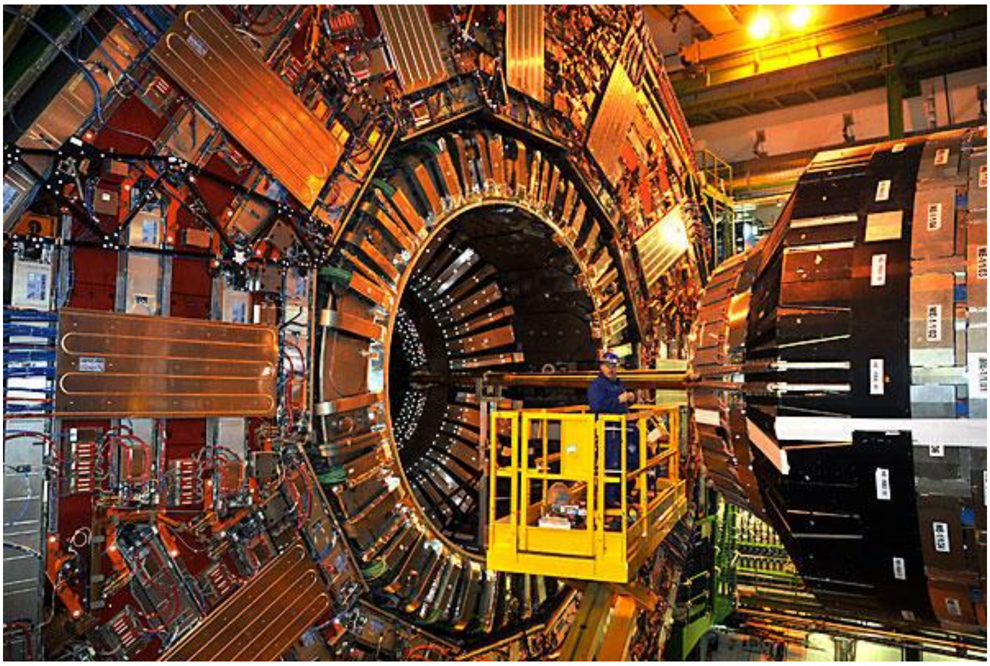


Figure 4.4.2.
The particle accelerator from CERN

4.5 Cosmic rays affecting us

In nature

After the discovery of cosmic rays, many people claimed that it had a negative effect on the Earth’s climate. It would increase cloud formation.
However, recent studies show otherwise. We found it worth mentioning as it does concern the development of our Earth.
A research team from the State University of New York-Albany and Pacific Northwest National Laboratory studied the concentration of ions in the atmosphere and how comic radiation influences these ions. If cosmic radiation would cause new particles, which would affect clouds, it would provoke new particles to form ions. These particles would collide forming smaller particles. The smaller particles will grow into cloud droplets and these would alter the energy balance of the planet. The scientist did admit, that it was plausible. Then, they tackled a key question: “are the variations during solar cycles large enough to produce a measurable influence on climate”. This is not the case, so the idea of negative influence of cosmic radiation was overruled.

Human health

Several dozen particles go through you body every second. Every year you receive 2.4 mSv of radiation. To get for example nausea, it takes 1 Sv of radiation in a short time and about 2-6 Sv to cause death. The extreme low amount of radiation caused by outer space is so small, that it won’t affect human health.

Even when you practice your job on a great height, where the cosmic ray flux increases exponentially, it will still be beneath the maximum amount of 1-4 Sv.

5. Muons

5.1 What are muons actually?

A muon can be characterized by its heavy mass, about 105,7 MeV/c^2. It's similar to the electron, but its mass is 207 times bigger. The muon is charged negatively, being symbolized as μ-. Anti-muons are symbolized as μ+ and have an equal mass and spin of ½. It is classified as a lepton, just like the electron, the tau and the elektronneutrino, muonneutrino and tauonneutrino, being part of the fermions. Muons are not just particles. They belong to the Standard Model, being of the second generation, behind the electron.

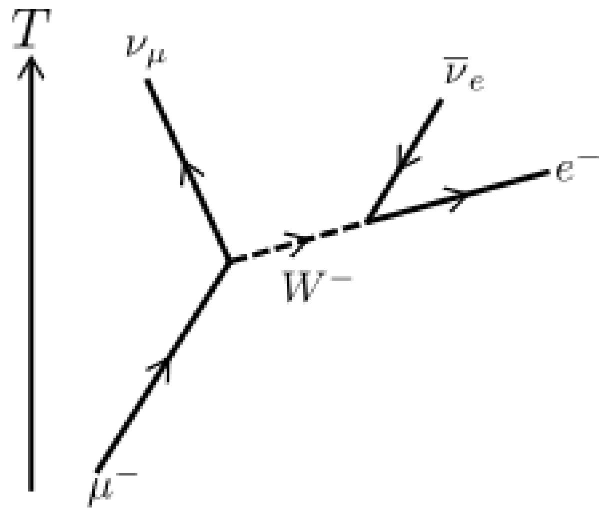


Figure 5.1.1.
The decay of a muon.

It's very unstable and only exists for about 2.1969811(22)×10^{-6} seconds. When a muon decays, it results into two neutrino's, namely the electron-neutrino (ν_e) and the muon-neutrino (ν_μ).

$$\mu^- \rightarrow e^- + \nu_e + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$$

Every minute, about 10,000 muons reach the earth's surface per square meter. They arrive as by-products of cosmic rays. Most of them do not reach the earth vertically, but under an angle of 12°.

5.2 How did they find out about muons?

Carl Anderson and Seth Neddermeyer discovered muons during their study of cosmic rays in 1936 in a cloud chamber. They were discovered while studying how the particles in a cosmic ray bent within an electromagnetic field. Anderson noticed that some particles bent less sharply than electrons did, but more sharply than protons did, for particles with the same velocity. This would mean that they must have been heavier particles than electrons, but smaller than protons. The published their findings in the "New Evidence for the Existence of a Particle Intermediate Between the Proton and Electron".

Figure 5.2.1.
Picrure of Carl Anderson

There was a theorist, who discovered the muon before Anderson and Neddermeyer, this was Hideki Yukawa. He predicted a mass of about 100 MeV/c^2, which is close to the actual muon. However, Yukawa had discovered another particle, with other properties, the pi meson. This was confirmed in 1947.

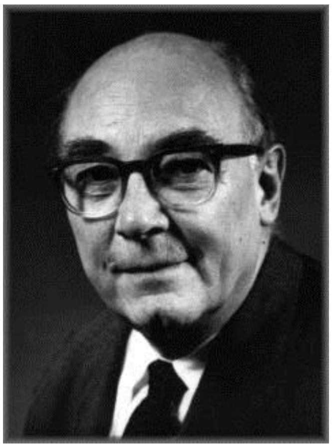


Figure 5.2.2.
Picture of Seth Neddermeyer

Hans Bethe and Robert Marshak suggested that the muon would be a decay product of Yukawa's particle, so they continued the search. This search resulted in the discovery of the pion.

The particle, we know nowadays as muon, was named "mu meson" in order to differentiate between the two different types of mesons.

5.3 Why are muons so important?

To study the weak interactions between particles, muons come in handy. As most particles that reach sea level are muons, the lifetime can be measured very accurately. In this way, we get to know more about the interactions of cosmic rays with the earth's atmosphere.
Thereby, the muon is an elementary particle, which means that it does not made of smaller particles, having a substructure. Being an elementary particle, it also belongs to the Standard Model. The Standard Model registers all the particles and their interactions. The muon is semi-stable, which means that it can travel for hundreds of meters before it decays and only loses a little amount of energy when it passes material. That is why it is easy to identify when it reaches the detector. This makes it a perfect particle for analysing new particles, to find more and new physics than the Standard Model.
One of those particles which are hard to find is what they call the 'Higgs Boson'. It was already mentioned in 1964 by Robert Brout and Francois Englert on 31st of August. However, they only mentioned the theory, not the particle itself. Later on, on the 15th of September Peter Higgs talked about the particle itself. But it were only predictions.
Around 2012, they used a Large Hadron Collider and found a particle which has the same mass as the predicted Higgs Boson.
At the moment, new findings show that the Higgs Boson really exists. Science in muons helps to build, for example, muon colliders. These machines use muon beams instead of electron beams to determine the properties of the Higgs sector.
The discovery of the Higgs Boson is of fundamental importance, as it will prove the Standard Model correctly, making it complete. In this way, all the other particles will get a fixed mass.

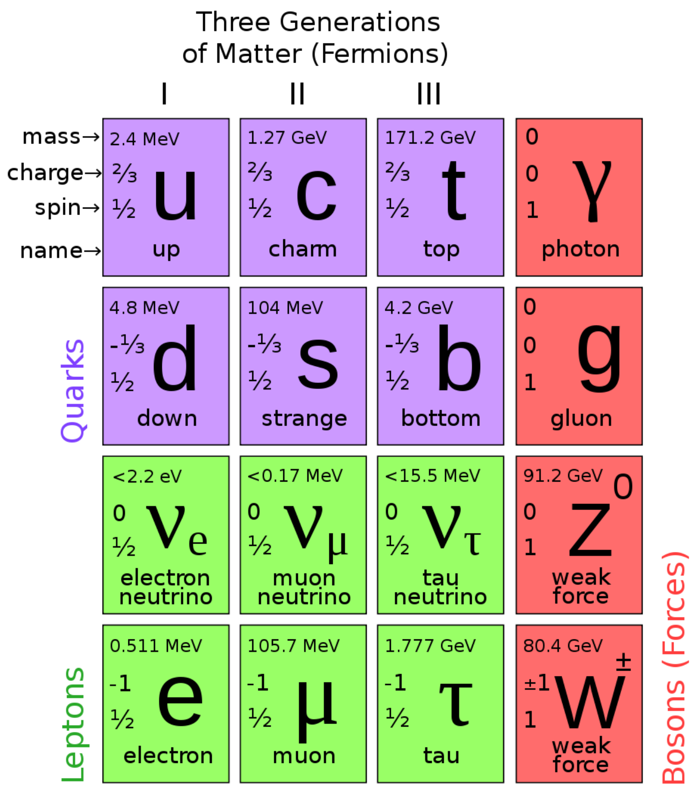


Figure 5.3.1 .
The Standard Model

On page 35 you will find a recent article about the Higgs Boson.

5.4 Einsteins theory

Muons are formed about 6000 meters above sea level. Their lifetime is 2,2 microseconds. At the speed of light its range would be:
299,792,458 x 2,2 x 10^{-6} = 659,54 meters

So how can the muon ever reach our Earth?
To answer this question we should look at the Special Theory of Relativity by Einstein.
Einstein already predicted with his formula that time and distance were relative. Time goes slower for particles that travel with the speed of light. The distance they have to cover will also be shorter.
How we measure time, depends on in what situation we are in: how we move forward and whether the space constricts or stretches out as we accelerate or decelerate.

An example:
A moving walkway at the airport moves with a speed of 4,5 km/h, so if you are standing on the walkway you move with 4,5 km/h. if you start to walk with 3,0 km/h, you yourself could say that you are walking with 3,0 km/h. However, someone standing still next to walkway, sees you move with 7,5 km/h.

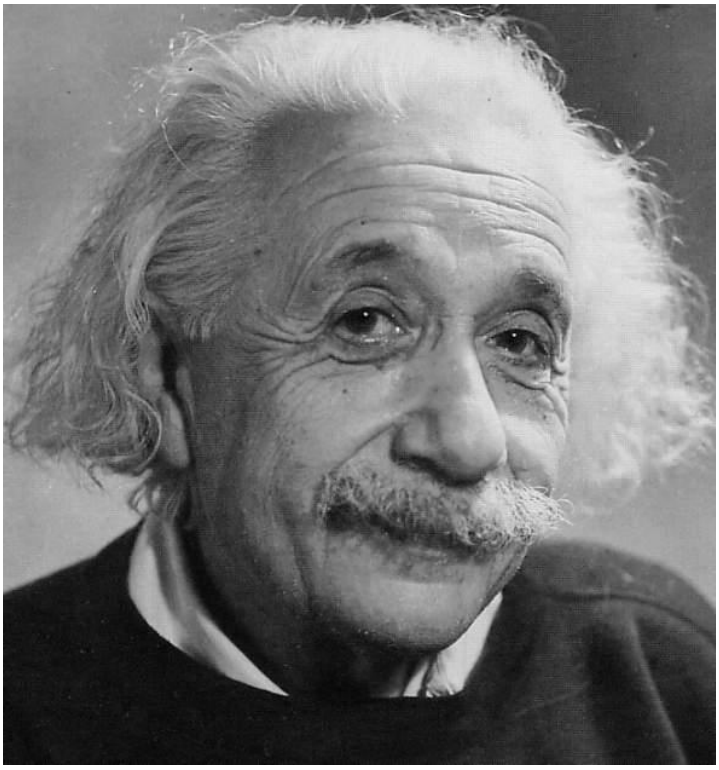


Figure 5.4.1.
Picture of the famous Albert Einstein.

If the person on the walkway walks from the opposite direction with a speed of 4,5 km/h. He or she could say that their speed is 4,5 km/h, but for someone next to the walkway it would seem as the stood still. So someone can increase their velocity, but the distance they travel decreases.

The same happens with muons. The particles travel with a speed that is close to the speed of light(0,97·c), which causes the time to pass slower. A second, as we know on Earth is for a muon much longer. Its lifetime is increased immensely. That is why the muon can reach our sea level.

6 The experiments

6.1 Our experiences

17-11-12

Leiden experiment.
Day 1 out of 4.

On Friday the 16th of November, we went to Leiden for the first time. After having found the building, finally, we found ourselves in the physics department where you could feel the intelligence around you. We met the student who would help and advise us for the coming few weeks. His name is Leandros and he is studying physics.

He showed us around the lab quickly and then started up the equipment, which would gather the readings for our experiment. The equipment used is described fully in chapter 6.1, day 2 out of 4. This was all we could do that day, concerning the experiments. What was left was the theoretical part.

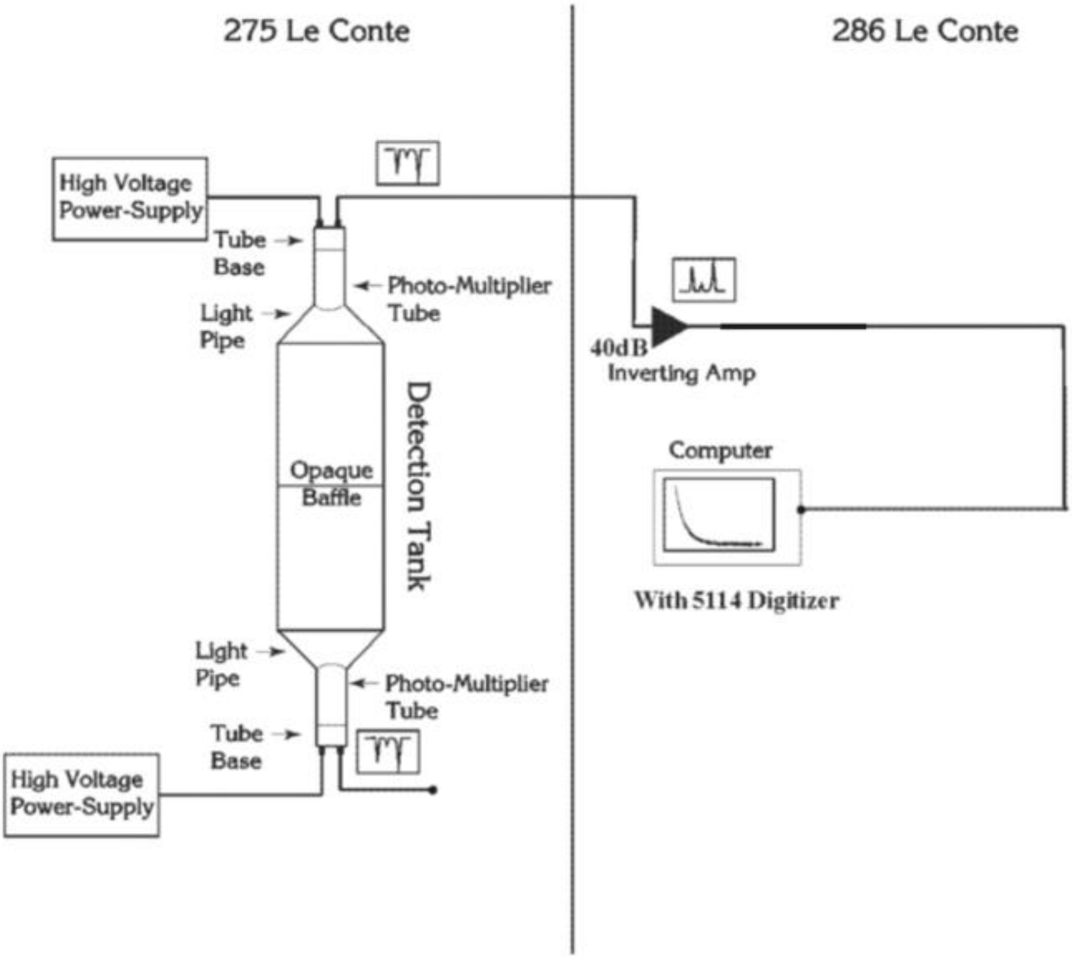
To understand more about the exponential distribution of the mean life of muons we had to finish a stencil containing mathematical questions concerning probabilities, limits and functions. You will find this stencil in the back, with all the other attachments. This will help us later on, when we have to calculate the speed of mesons.

In two weeks time we will have to come back. The scintillator will have gathered enough data by then, to get a proper result.

Leiden, day 2 out of 4

Now all the data is received so we can start working with that. There was a guiding stencil that helped us convert the data into the actual mean life.

Firstly, I will discuss the equipment used in order to do this experiment.
This is what the experiment looked like:



There are two phototubes detect photons when they hit the equipment. These photons emerge when muons hit the phototubes. If a muon decays while in the phototube, another light pulse will be detected. The time in between these two pulses is the mean lifetime.

Our prediction is that we will have a result just above the 2.2 micro seconds that it should be. This is because it is an experiment so you will never have the exact right lifetime and there will be a slight delay since the pulses have to travel through the wires as well. The detector of the pulse will also give the data a slight delay so therefor we expected this.

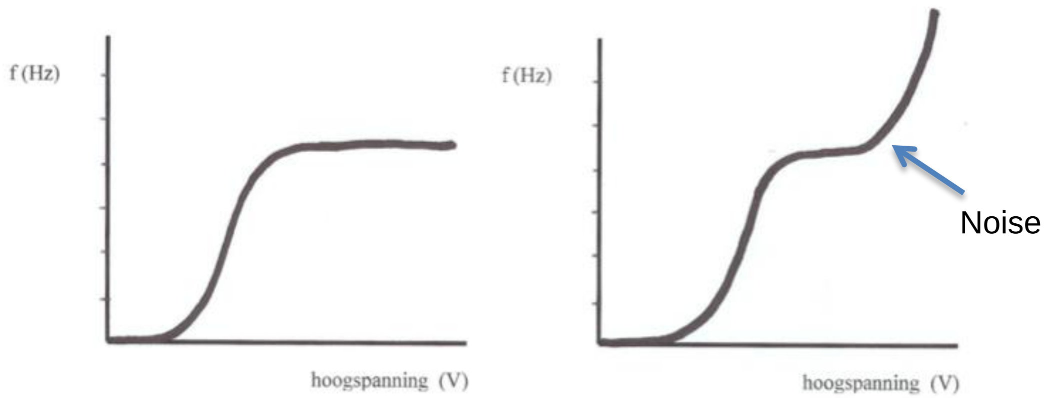
Brief summary of our experiences in Leiden 04-01-13
Day 3 out of 4

During the Christmas holiday, we went to Leiden for our second experiment. The day didn’t start well. We were advised to take the bus to the university, but they had pointed out the wrong bus, so ended up in the middle of nowhere. Luckily, we did arrive on time eventually. Leandros was already waiting for us.
We went to the chemistry lab, where two scintillators were already waiting for us. We started immediately. The second experiment would consist of three parts. We would calculate the speed of the mesons within the scintillators, the speed of the mesons within the wires and the speed of the photons within the scintillators.
Unfortunately, after having done a few measurements, we had to conclude that the scintillators were not properly adjusted.
However, this also gave us the opportunity to learn how to calibrate the scintillators. This is has to be done to avoid noise, which could influence our readings.

To calibrate the scintillators, a low voltage was applied first. In the mean time we measured the amount of hits per second.
To avoid noise, the voltage of the PMT (photomultiplier) and the threshold voltage for the height of the pulses must be adjusted properly.
When a meson hits the scintillator, a signal is sent to the comparator. The comparator compares this signal to the threshold voltage. When the signal is higher than the threshold voltage, the comparator will sent a signal of 5 Volt. When the comparator changes from 0 V to 5 V, a signal is counted as a pulse.

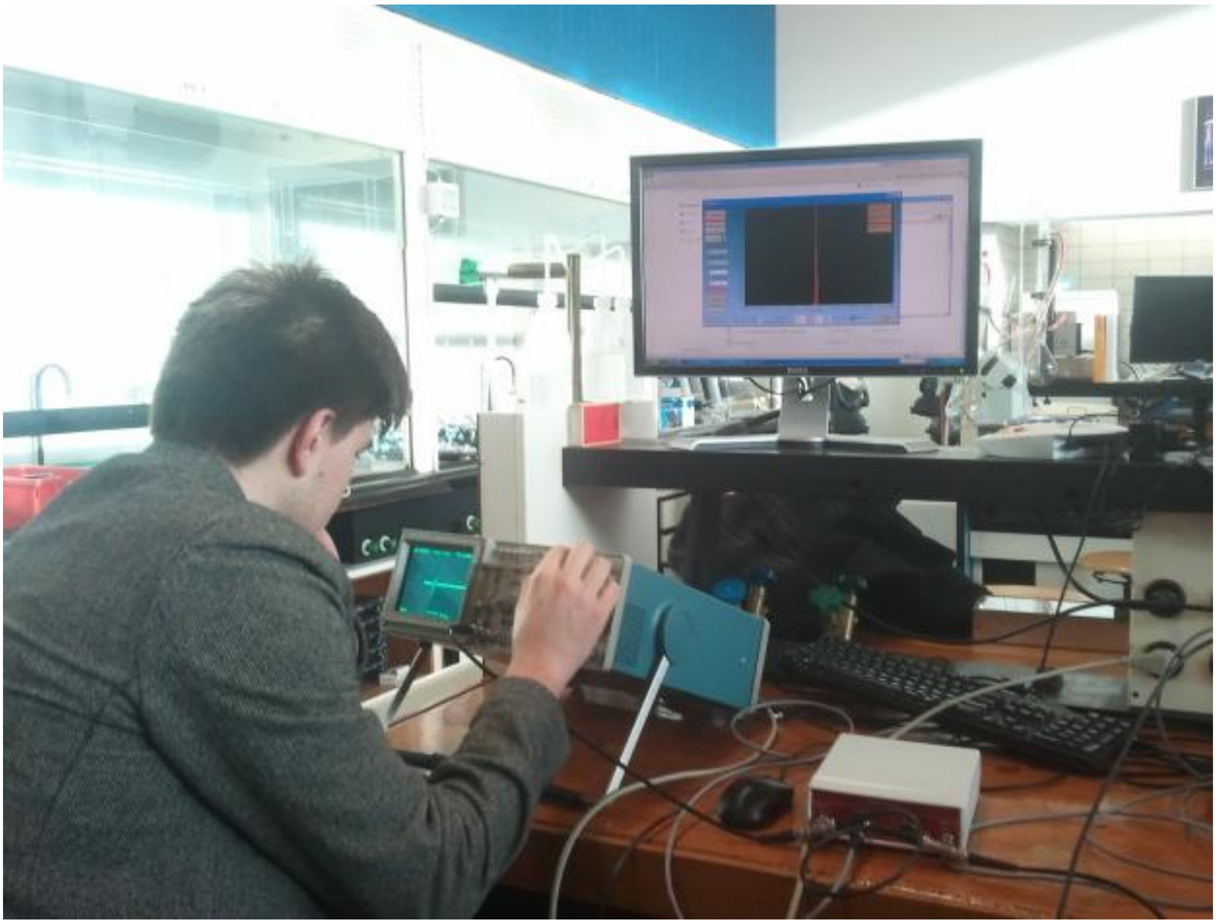
If the threshold voltage is not adjusted properly, more pulses will be counted, than there should be.

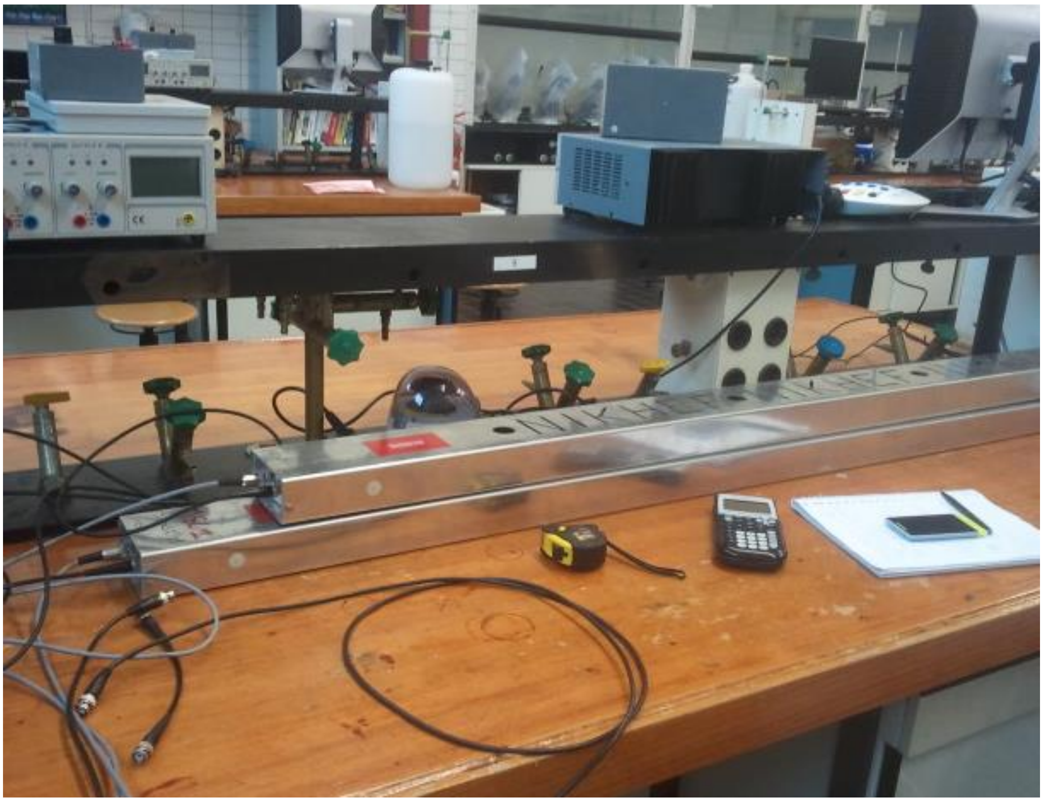
In the figures underneath, you see the difference. The first figure shows a perfect threshold voltage. When the voltage increases, the amount of hits per second is steady. When there is a noise, more hits per second are counted, when the voltage is increased.



Having finished the calibrating the scintillators, we were finished for the day and could go home.

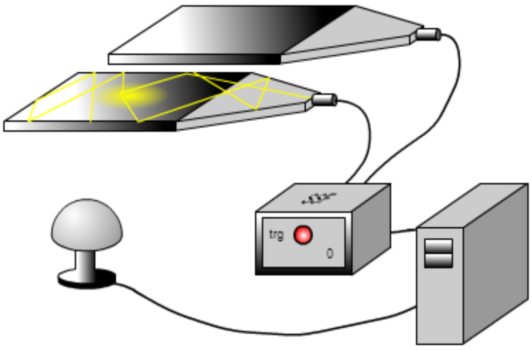

PANNEH



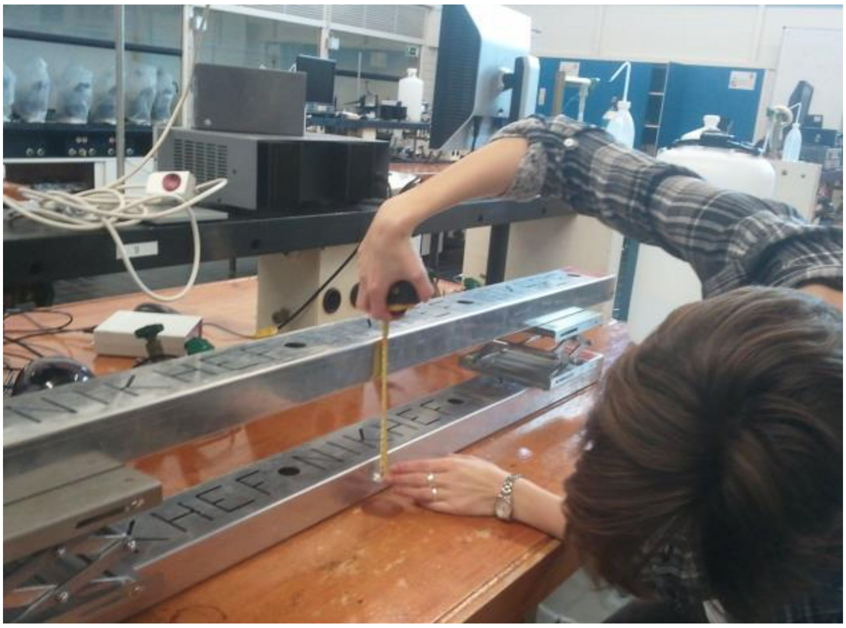


Leiden, day 4 out of 4

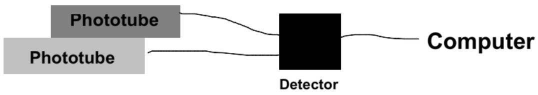
The very last day! We were really exited to go because we knew what was expected from us.
This time, the scintillators were properly calibrated which made it possible to do the three experiments.
We were going to determine the speed of the muons in the tubes, the speed of the electrons in the wires and the speed of the protons in tubes.
Before we started we discussed what the arrangements would be for the different experiments.



To determine the speed of the muons we decided to place the tubes on top of each other and use this as the first data. Then comparing this with the data collected when placing the tubes on top of each other with some distance between them.



For the speed of the protons in the tubes we would use the same first data, tubes exactly on top of each other. Then we would follow to measure with the tubes placed like this:



Last, to determine the speed of the electrons we used two different sets of data. One with the two wires going from the phototubes to the detector, when the wires have the same length. And one with one very short and one very long wire.

6.2 The experiments

<u>'DE MUONPARADOX' by Marcel Vreeswijk</u>

The Muonparadox is the first document we studied. It is an introduction on our experiments. It explains why and how we should perform the experiments.
Our first experiment was to determine the lifetime of a muon particle. To do so we needed to use the special theory of relativity. Furthermore this document introduces us to how we could measure the speed of the muon.
Since this part of physics is new to us, we prepared for this experiment by reading 'de Muonparadox' and making the assignments in it.

Just like every other particle, the muon particle decays. The average lifetime of a muon is $2x10^{-6}$ s. Muons do reach earth within this short amount of time. What speed would you expect, according to Newton?
s/t = v   10000 / $2x10^{-6 =}$
(we assume that muons are being produced at 10 km high.)

How could you measure the lifetime of muons? What formula could you use?
$T = (1xt')/((1\text{-}v/c^2)^{1/2})$

Why doesn't the time the light takes to go through the scintillator material play a part in measuring the lifetime?
This amount of time is so little that it can be neglected.

Make a schematic drawing for the set up of the speed measurements, for which you use scintillation material and one or more phototubes.
'DE MUONPARADOX' by Marcel Vreeswijk

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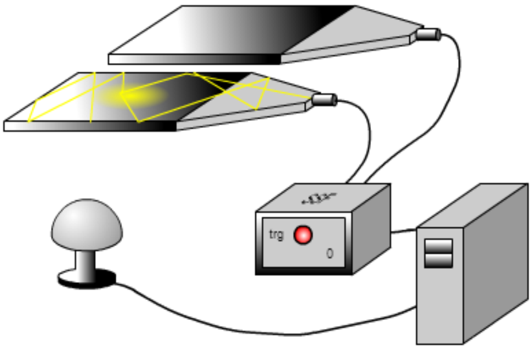
This amount of time is so little that it can be neglected.

Make a schematic drawing for the set up of the speed measurements, for which you use scintillation material and one or more phototubes.



What information do you need to determine the speed. And how accurate should your observation be in order to measure the speed of the muons.
We need to know the different times at which the muons hit the phototubes in order to determine their speed. The accuracy would be 2 decimal.

The muons that hit the detector can come from any direction. Explain that you can't directly measure the speed but only a distribution.
The measurements will be collected and put into a histogram, with the speed intervals on the horizontal axis and the vertical axis shows how many hits there are within that interval. This means we have a distribution of measurements, and not directly the speed. Later, when we work out the experiment that determines the speed, we will show you how to calculate the speed.

What do you expect for the angular distribution?
We don't expect a lot of vertical muons since they clash with all kinds of material on their journey towards us. Also, they deflect because of the magnetic fields. All of this causes them to hit the phototubes with a certain angle.

If a pulse reaches the end of the phototube, it has to reach the readout electronics through cables. How fast do you this a pulse will travel though these cables.
In 'de Muonparadox' we found that there are 10 measurements in 5 minutes, therefore it travels 30 s per measurement.
*Experiment nr 3 is to determine the speed of the electrons in the cables.
What effects could influence the measurements of the time at which the muon passes the detector?
It takes time for the pulse to transfer from the cathode to the anode.

The amount of radiation measured increases when you go higher in the atmosphere but it decreases at greater heights, what could be the explanation for this?
In the atmosphere, particles crash into other particles, causing them to loose energy, so the amount of radiation measured decreases when the particles have lost more energy, are closer to earth. Then again, at great heights you could be past the source of radiation.

How fast should muons be in order to travel 10 km in about 2 microseconds? How is this a problem?
Muons should be as fast as 3 times the speed of light. This is a problem since it is impossible.
In the coming experiments we are going to try to figure out how muons get to our surface with such a short lifetime.

HISPARC exponential distribution

The First time we went to Leiden, we set up the experiment to determine the lifetime of a muon. After arranging the experiment, we filled in the worksheet ‘exponentiële verdeling’ as preparation for the next steps. You can find the worksheet attached at the end of the paper.

Worksheet:
Rule 1: Composed change: if two events exclude each other, for example throwing a 1 or 2 with a dice, the change on the sum of the two events is the sum of the two separate changes.
Rule 2: Independent change: if two events are independent, for example throwing 6 with a dice twice, de change on that event is the product of the two separate changes.
Basic assumption: in every time interval dt, an event has the same changes to happen. This change is rdt.

1.What is the unit of r?
Dt is in s and a change has no unit, therefore r is in 1/s

We split up T in N pieces Δt. So:
T=N Δt

2. Apply rule 1 to find the change on no event.
$P(0) = 1 - r\,\Delta t$

3. What is the change that in N intervals, nothing happens. Use rule 2.
$P(\Delta t) = (1 - r\Delta t)^N$

We belittle the intervals by enlarging N:
Δt= T/N
We use the mathematical verity:
$Lim\ (1 + a/x)^{x} = e^{a}$

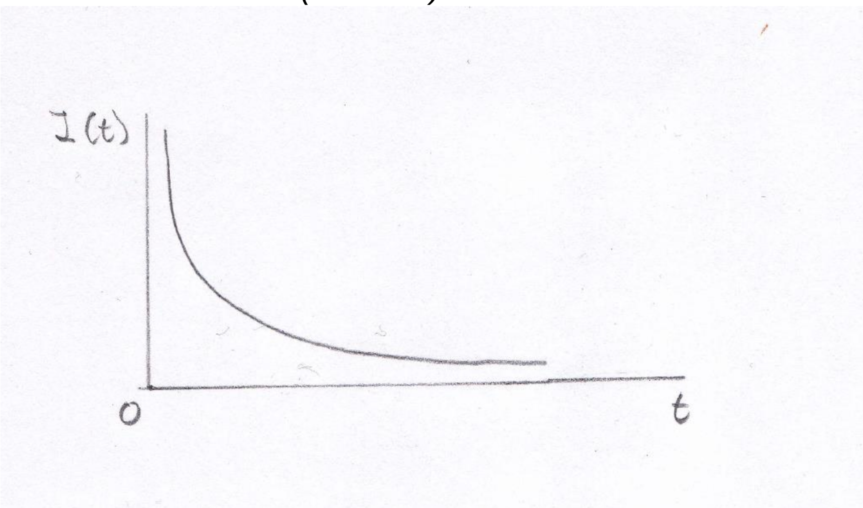
4. Apply this to $lim(1 - rT/N)^N$
$Lim\ (1 - rT/N)^N = e^{-rT}$

5. Give the change that in the next interval Δt there is an event
$P(\Delta t) = r\,\Delta t$

6. Give the change that we observe a pulse after T
$P(\Delta t) = P_0(t) \times r\,\Delta t$

If $I_1(t)\,\Delta t$ *is the differential change for a pulse interval of length t, according to rule 2:*
$I_1(t)\,\Delta t = P_0(t)\,r\,\Delta t = e^{-n} r\,\Delta t$ *applies.*
So $I_1(t)\,\Delta t = re^{-n}$ *is the interval distribution funciton.*

7. Draw this function (a sketch)

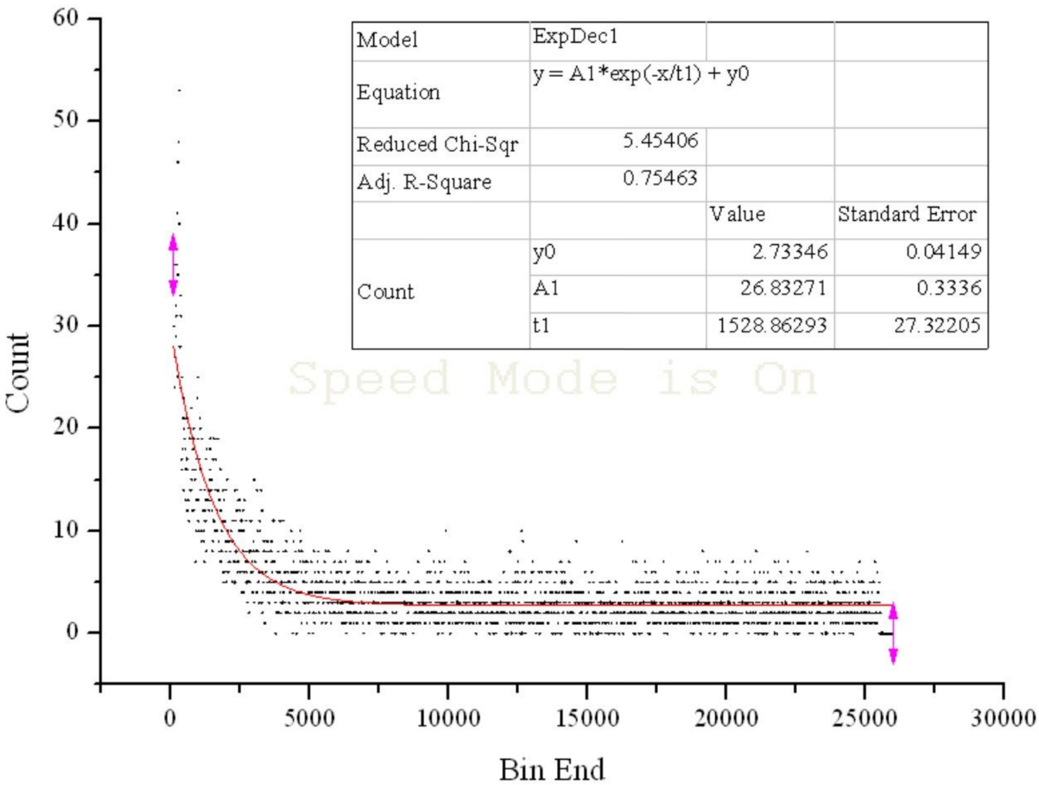


HISPARC lifetime data

The second time to Leiden, ready to process the collected data! We processed it by following the worksheet 'lifetime data' and using excel. The worksheet 'lifetime data' and the data are included as attachments.

What is the shortest time registered?
81.25 ns
What is the next time?
87.5 ns
What is the longest time registered?
25531.25 ns
What is the size of the time steps?
6.25 ns

We made a histogram of our data.
The general formula is:
$Y = Ae^{-t/B}+C$
You can find the parameters A, B and C here:



A= 40
t=B → $e^{-t/t} = e^{-1}$
C = 6
$Y= 40 * e^{-1} +6 = 20.7$

t=B=543

so: $y= 40*e^{-t/543}+6$

This formula is just a guess, since we do not know this for sure, we read the parameters A, B and C from the graph.

To improve the formula we used RMS, root means square to optimize the parameters.
(see attachments, excel file: Muonfit Ellemieke Esmeé)

After improving this fit we found the decay using these formulas:

$N(t) = N_0 * e^{-t/T}$

$N(t) = N_0 * e^{-\lambda t}$

$N(t) = N_0 * (1/2)^{t/t}$

$-t/T = - \lambda t$

$T = 1/\lambda$

$N(t) = N_0 * (1/2)^{t/t}$

$N(t) = N_0 * 2^{-t/t}$

$2^{-t/t} = e^{-t/T}$

$Ln (2^{-t/t}) = -t/T$

$Ln(2)/ t_{1/2} = T$

$T = Ln(2)/ t_{1/2}$

T=1528.86 micro seconds

This is way too high compared to what the lifetime of a muon should be. The reasons for this difference is that at the time of this experiment, the scintillators were not correctly calibrated.

Sometimes muons are not correctly registered, which causes odd data. Often, the first 100 data are not very reliable.

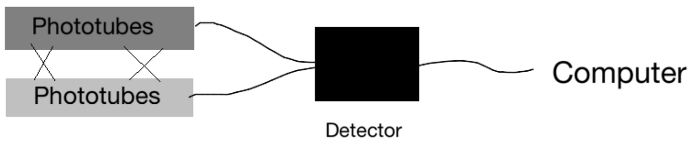
Though, if you take into consideration the delay caused by the speed of the electrons and photons, the incorrectly calibrated tubes and the fact that some muons are simply not counted, this lifetime is still way too high.

So we decided to eliminate the first 100 data, after which we processed the data in the same way.
This turned out to do a lot of good.
The new lifetime we found was not included in the data we received from Leandros.

The reason for this is that the voltage, thresholds and delays were not at the right values at the beginning of the experiment. The voltage has a warm up time, which is very likely to cause the first 100 data to not be true.

Hisparc, speed of the muon, electron, proton

The last time we went to Leiden, we did three experiments to determine the speed of the muons in the tubes, the speed of the electrons in the wires and to determine the speed of the protons in the tubes.

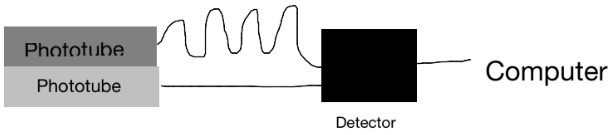


To determine the speed in the tubes we did two measurements. One with the phototubes on top of each other, on with a distance between them.

1) d = 11.5 cm
   t = 2.33 ns
2) d = 5.9 cm
   t = 2.62 ns

a* x + b = t
a= 1/v
x=d=distance between the tubes
t result of the experiment

11.5 a + b = 2.33
5.9 a + b = 2.62
A= 0.0518 (absoluut → tubes measured in the reversed way)
V = 19.3 cm/ns
The speed of the muons in the tubes is 1.93×10^{8} m/s

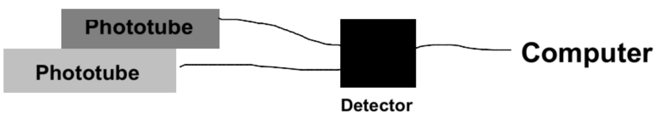


To determine the speed of the electrons we used the same method, now using the different wires. The first time we used two wires with the same length, second time one very long and one very short one.

1) d = 0 (difference in length of the wires)
   t = 2.62 ns
   2) d = 279.2 cm
      t = 16.15

t = -0,0518 x + 2,95 + d* C
x= 5,9 cm
a, b known from the last experiment
d = 297.2 cm
C = 1/v (v= speed of the electrons in the wire)

C = 0.048
V= 20.64 cm/ ns
So the speed of the electrons in the wires is 2.064 x 10^8 m/s



Last but not least we determined the speed of the photons in the tubes.
T = -0,0518 x + 2,93 + d * D
X = 5,9 cm
d = the distance between the different tubes
D = 1/v (v= the speed of the photons in the tubes)
T = known from the experiment

D= -0,0904
V = 11.1 cm/ns
So the speed of the photons in the tubes is 1.11×10^8 m/s

So:

The muons in the tubes:	1.93×10^{8} m/s
The photons in the tubes:	1.11×10^8 m/s
The electrons in the wires:	2.064×10^8 m/s

As you can see, the speed of the different particles are very close to each other. Also, they are not too far away from the $2{,}99 \times 10^8$ m/s that is the speed of light.

The speed compared to the lifetime we measured is evidence to support the theory of special relativity.
If we use our 'way to high' lifetime:
$T = 1.52886 \times 10^{-9}$ s
$V = 1.93 \times 10^8$ m/s

$S = (1.93 \times 10^8) \times (1.52886 \times 10^{-9})$
$S = 0.29506998$ m

If the lifetime would be the correct 2.2×10^{-6} s:
$T = 2.2 \times 10^{-6}$
$V = 1.93 \times 10^8$ m/s

$S = (1.93 \times 10^8) \times (2.2 \times 10^{-6})$
$S = 424.6$ m

Either way, with this speed, the muon would normally never reach the earth. But when using the theory of special relativity it will.

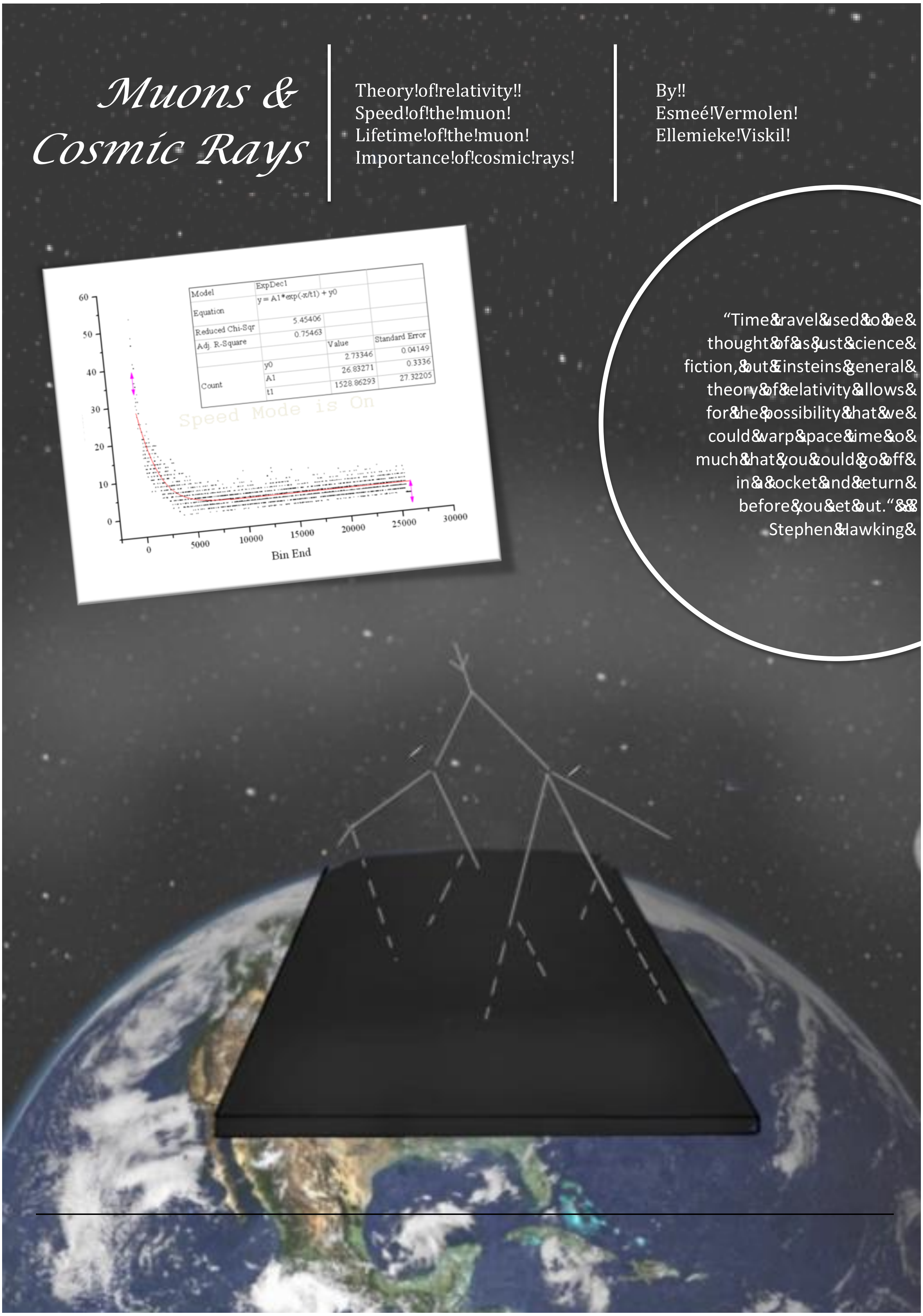
Conclusion

As the experiments have its own conclusions, we decided to fill the conclusion with our own experiences.

I, Esmeé, have really enjoyed this project. It has been very interesting to learn about this subject. Both cosmic rays and muons are not part of our normal physics program, which didn't make this very easy. Both of us had to read a lot before we could really start this paper. Luckily, I really liked to learn about the mysteries of the cosmic rays. Also, being able to do all the experiments in Leiden and to attend the Hisparc Symposium were great opportunities. It showed us a little bit of what it will be like to be at the university next year. Al together this project has been a great learning opportunity and I would like to thank everyone helping us to create this paper.

Ellemieke:
With physics we learned a lot about particles and how they interact. However, I would never have known how they establish and develop, if we hadn't done this project. Although it is a fascinating and interesting process. So I would recommend our physics department to include this subject in the school program.
That we were allowed to do our experiments in Leiden was amazing. In this way, we could experience how real scientists work, but also get a closer look at the whole process of examining.
I have really enjoyed doing this project! And I hope that we have been able to create a paper, which is understandable for anyone whom would like to know more about muons and cosmic rays and make them as enthusiastic as we are about this subject!

Poster symposium

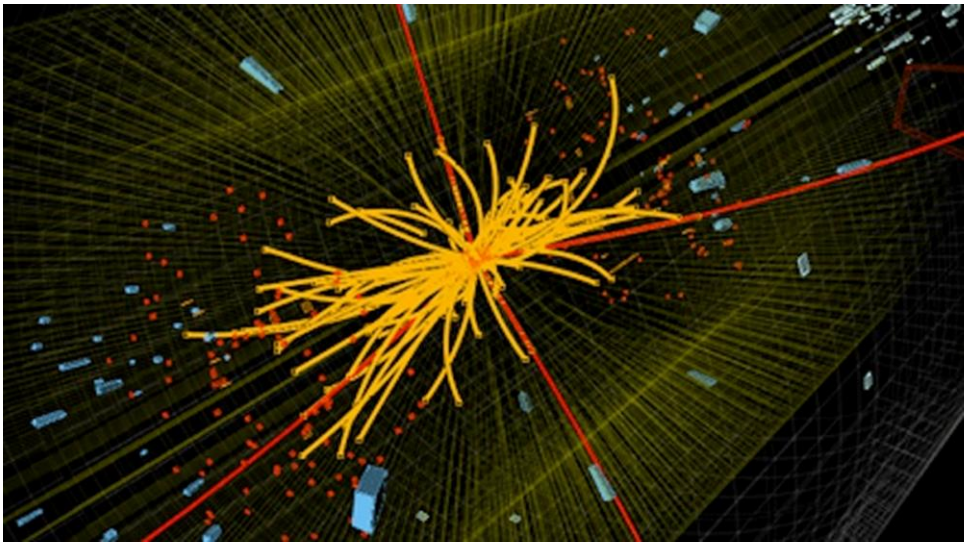


What is new in Science?

SCIENCE & NATURE

Particle looking 'more and more' like Higgs - scientists

BY **AGENCE FRANCE-PRESSE**
POSTED ON 03/07/2013 7:03 AM | UPDATED 03/07/2013 8:33 AM



Proton-proton collision in the Compact Muon Solenoid (CMS) experiment producing four high-energy muons (red lines). The event shows characteristics expected from the decay of a Higgs boson but it is also consistent with background Standard Model physics processes. Photo courtesy of CERN/CMS

PARIS, France - The subatomic particle whose discovery was announced amid much fanfare last year, is looking "more and more" like it could indeed be the elusive Higgs boson believed to explain why matter has mass, scientists said Wednesday, March 6.

But in the latest update, physicists told a conference in La Thuile, Italy, that more analysis is needed before a definitive statement can be made.

Key to a positive identification of the particle is a detailed analysis of its properties and how it interacts with other particles, the European Organisation for Nuclear Research (CERN) explained in a statement.

Since scientists' announcement last July that they had found a particle likely to be the Higgs, much data has been analyzed, and its properties are becoming clearer.

One property that will allow several teams researching the particle to declare whether or not it is a Higgs, is called spin.

Atmospheric Sciences & Global Change Division   Research Highlights

February 2013

Extraterrestrial Effects on Climate? Not So Much.

The influence of cosmic rays on cloud droplet formation explored in a global climate model

The physical mechanisms by which cosmic rays could influence the climate remain elusive. Enlarge Image

Results: A research team from the State University of New York-Albany and Pacific Northwest National Laboratory used a global atmospheric model to estimate that charged ions produced by cosmic rays in the atmosphere increase new atmospheric particles formed by a factor of ten when compared with particles formed by a corresponding neutral, non-charged, mechanism. Though cosmic rays ionization is important in forming aerosol particles and altering the make-up of clouds, the team determined that the changes during the solar cycle are insufficient to produce a measurable change in the Earth's energy balance.

Why It Matters: It's not the stuff of Buck Rogers. Scientists want to know: do cosmic rays alter clouds and climate? Some studies show a connection between measured variations in cosmic radiation, such as solar flares coming from the sun's surface, and climate, but establishing a physical mechanism remains elusive. One proposed mechanism is a chain of events that form new particles which affect clouds. In this scenario, cosmic radiation influences the concentration of ions in the atmosphere, which provokes new particles forming from the ions. Then, as the particles collide and condense on other gasses in the atmosphere, the new particles grow until they are large enough to form cloud droplets. Finally, the cloud droplets' surface area is thus altered affecting the energy balance of the planet. Although all of these mechanisms are plausible, the scientists in this study tackled a key question: whether the variations during solar cycles are large enough to produce a measurable influence on climate. Their verdict: not so much.

Methods: For this study, researchers from SUNY-Albany and PNNL added an ion-mediated nucleation mechanism to a global climate model that already represented other mechanisms for new particle formation. In the model, they first compared the total nucleation rates, cloud droplet numbers and the Earth's energy balance calculated with and without the presence of ionization. Then, they simulated variations in those quantities using measured changes in cosmic rays during different phases of the eleven-year solar cycle. The average change in the global energy balance between the solar minimum

10. Sources

Information about cosmic rays:

What are cosmic rays?

http://home.web.cern.ch/about/physics/cosmic-rays-particles-outer-space
http://imagine.gsfc.nasa.gov/docs/science/know_l1/cosmic_rays.html

The discovery

http://home.web.cern.ch/about/physics/cosmic-rays-particles-outer-space
http://www2.fisica.unlp.edu.ar/~veiga/experiments.html

The journey of cosmic rays

Kosmische straling NLT
http://www.nmdb.eu/?q=node/172#Sec1.3
http://helios.gsfc.nasa.gov/heliosph.html

Observation

http://dare.uva.nl/document/443627
http://www.auger.org/cosmic_rays/big_events.html
http://adsabs.harvard.edu/full/1991ICRC....2..700C
http://www.lanl.gov/milagro/detecting.shtml

Cosmic rays affecting us

http://www.pnnl.gov/science/highlights/highlight.asp?id=1292
http://www.wisegeek.com/what-are-the-health-effects-of-cosmic-rays-on-the-human-body.htm

Information about muons:

What are muons actually?

www.wikipedia.com

What did they find out about muons?

http://hyperphysics.phy-astr.gsu.edu/hbase/particles/muonhist.html
www.wikipedia.com

Why are they so important?

http://home.web.cern.ch/about/physics/standard-model
http://home.web.cern.ch/about/physics/search-higgs-boson
www.wikipedia.com

Einsteins theory

www.wikipedia.com
www.youtube.com
http://www.space.com/17661-theory-general-relativity.html

Articles

http://www.pnnl.gov/science/highlights/highlight.asp?id=1292
http://www.rappler.com/science-nature/23235-particle-looking-more-and-more-like-higgs-scientists

Experiments

http://www.hisparc.nl/docent-student/hisparc-detector/
http://www.advancedlab.org/mediawiki/index.php/File:Muon_Equip_New_fig1.png

11. Logbook

Ellemieke Viskil

Activity	Date	Time taken
Research for information about muons and do activities of “Muon Paradox”	14-11-12	3 hours
First day to university Leiden	16-11-12	8 hours
Processing information of the first day to Leiden and write journal	17-11-12	1 hour
Working on PWS	19-11-12	3 hours
Working on PWS	20-11-12	3 hours
Second day to university Leiden	05-12-12	8 hours
Working on PWS	09-12-12	3 hours
Third day to university Leiden	03-01-13	8 hours
Processing information of the first day to Leiden and write journal	04-01-13	3 hours
Fourth day to university Leiden	29-01-13	8 hours
Working on PWS	02-02-13	4 hours
Working on PWS	14-02-13	4 hours
Working on PWS	15-02-13	2 hours
Working on PWS	16-02-13	2 hours
Creating poster Symposium	03-03-13	5 hours
Working on PWS	08-03-13	3 hours
Symposium	13-03-13	5 hours
Working on PWS	20-03-13	3 hours
Finishing touch PWS	23-03-13	1 hour
		------------------
		77 hours

Esmeé Vermolen

Activity	Date	Time taken
Research for information about muons and do activities of “Muon Paradox”	14-11-12	3 hours
First day to university Leiden	16-11-12	8 hours
Looking into some background information	17-11-12	1 hour
Working on PWS	21-11-12	2 hours
Second day to university Leiden	20-11-12	3 hours
Processing second day in Leiden.	05-12-12	8 hours
Working on PWS	02-01-13	3 hours
Third day to university Leiden	03-01-13	8 hours
Processing information of the second day in leiden	12-01-13	2 hours
Fourth day to university Leiden	29-01-13	8 hours
Working on PWS	01-02-13	4 hours
Working on PWS	02-02-13	4 hours
Working on PWS	18-02-13	2 hours
Working on PWS	23-02-13	2 hours
Creating poster Symposium	02-03-13	3 hours
Working on PWS	12-03-13	3 hours
Symposium	13-03-13	5 hours
Working on PWS	15-03-13	3 hours
Working on PWS	16-03-13	1 hour
Working on PWS	22-03-13	2 hours
Finishing touch PWS	25-03-13	4 hours

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76 hours