Charge Ratio Determination of Cosmic Muons Using the Detector OPERA

Report for the DESY Summer Student Programme 2008

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Mit dir rede ich nicht; Du hast Probleme mit Cosmics!

A PhD-Student

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1 Introduction

The OPERA[1] (Oscillation Project with Emulsion-tRacking Apparatus) experiment is designed to detect tau-neutrinos in a nearly pure myon-neutrino beam coming from CERN. In this way OPERA is supposed to bring the first direct proof of $\nu_\mu \rightarrow \nu_\tau$ oscillations.

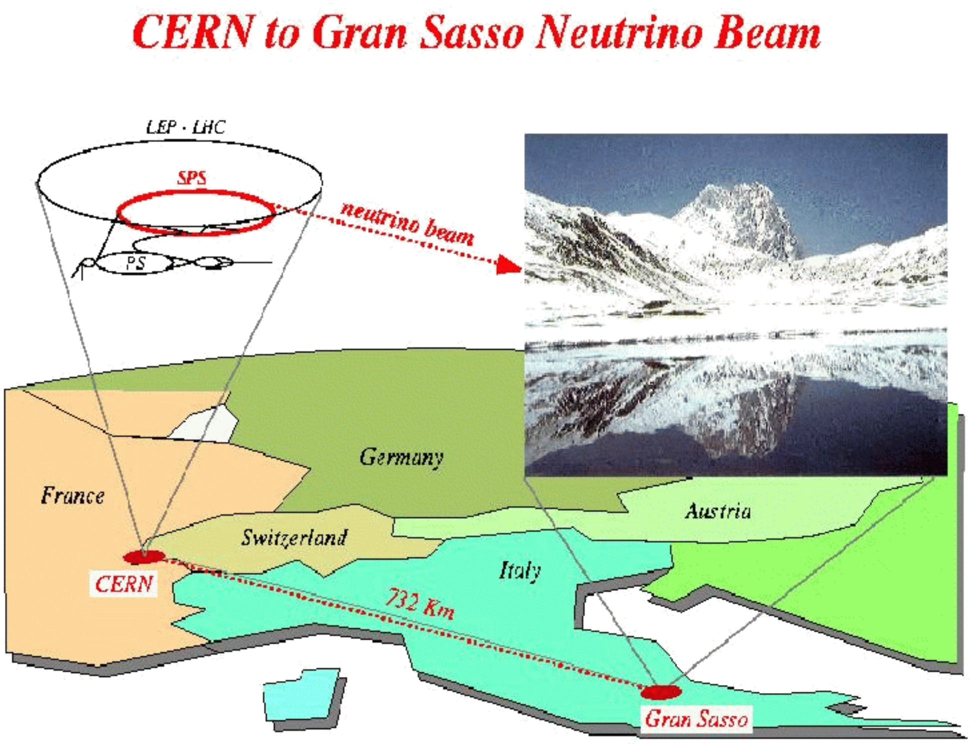


Figure 1: CERN neutrino beam to Gran Sasso

The detector is situated in the underground laboratory LNGS (Laboratori Nazionali del Gran Sasso) in the Gran Sasso massif (Italy). Indirect observations for neutrino oscillations have been well established by experiments like Kamiokande or SNO. Until today, there are several pieces of the neutrino puzzle, e.g. neutrino masses or the direct proof, missing. Neutrino oscillations, i.e. the change of lepton flavor of a neutrino, are of great importance for the Standard Model since they cannot happen with massless neutrinos. Also flavour-violation is well beyond the Standard Model and so the study of Neutrino oscillations is of great importance.

Apart from the neutrinos coming from CERN there are of course naturally occuring neutrinos, i.e. cosmic neutrinos. Also these neutrinos, or more precisely the muons that come from the interactions of these neutrinos, are measured with OPERA. Although Cosmic muons are measured with many experiments as a by-product, they

[1] www.cern.ch/opera

are in most cases not the object of specific studies and the situation becomes even worse if one wants to look at cosmic muons detected underground. Consequently the OPERA data gives a perfect oppurtunity to investigate on cosmic radiation. My task was to determine the charge ratio of these cosmic muons in the Gran Sasso massif using the data obtained up to now from the detector. Similar measurements available from the MINOS experiment, located partly in the Soudan Mine (USA), suggested a ratio of about $N(\mu_+)/N(\mu_-) \approx 1.37$ [1].

This report will cover the theory behind neutrino oscillations in the first chapter. It is based on [2, 3]. In the next chapter the experiment and its setup will be introduced, founded on [4, 5] and the forth chapter will present my work and results. Please note that throughout this report $c = 1$.

2 Neutrino Oscillations

2.1 A Bit of History...

In 1930 Wolfgang Pauli postulated a new particle to preserve conservation of energy, momentum and angular momentum in the β-decay [2]. Before, Hahn and Meissner had discoverd that the energy spectrum of this decay was continous although it was supposed to be sharp since the β-decay was assumed to be a two body decay:

$$B(A,Z) \rightarrow C(A,Z+1) + e^- \tag{2.1}$$

Thus the energy should have been

$$E_e = m_B - m_c$$

where m_B is the mass of the parental nucleus and m_C the mass of the daughter nucleus. Pauli modified (2.1) to describe the continous energy spectrum of the emitted electron and preserve the different conservation laws:

$$B(A,Z) \rightarrow C(A,Z+1) + e^- + \bar{\nu_e} \tag{2.2}$$

Fermi established the name neutrino for the new particle in 1931.

The experimental discovery of the (electron-) neutrino was achieved by Reines and Cowan in 1956 using the inverse β-decay:

$$\bar{\nu_e} + p \rightarrow e^+ + n \tag{2.3}$$

Their neutrino source was a nuclear reactor and the neutrinos have been a side effect of the decay of neutrons in nuclear fission

$$n \rightarrow p + e^- + \bar{\nu_e} \tag{2.4}$$

Soon the question arose if the neutrinos that had been detected in muonic decays are the same kind of neutrinos. In 1962 physicists in Brookhaven found out that indeed the neutrinos of muonic decay are different particles. They are consequently called muon neutrinos. In 1975 a third kind of lepton, besides the electron and muon, was discovered at SLAC, the so-called tau lepton. The associated neutrino of the tau was discovered at Fermilab in 2000. Moreover experiments at CERN in 1989 at LEP showed that there exist only three generations of leptons. In the Standard Model (SM) of particle physics one orders the leptons in generations

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

according to growing masses of the charged leptons. Of course, there exists the same triplet for the antiparticles. All leptons are fermions, thus obey Fermi-Dirac statistics and Pauli's exclusion principle. The SM assumes neutrinos to have a rest mass of

zero but there is no invariance principle (as in the case of e.g. photons) that prohibits neutrinos to have a non-vanishing mass. Experiments indicate that neutrinos can "wander" between the different generation, i.e. their flavour oscillates. This would mean that neutrinos have a very small, non-zero mass. The theoretical discussion of neutrino oscillations started in 1957 and goes back to the Italian physicist Bruno Pontecorvo (*1913 - † 1993) and was further developed by Ziro Maki, Masami Nakagawa, and Shoichi Sakata.
On the experimental side there are important contributions from several experiments. One of the first experiment to ever examine neutrino oscillations was the Homestake experiment, residing in the abondoned Homestake gold mine in Lead, South Dakote, USA. It was a tank of 615 t of liquid perchloroethylene (C_2Cl_4) and was build to detect and count solar (electron) neutrinos via the reaction

$$\nu_e + {}^{37}C \rightarrow e^- + {}^{37}Ar \tag{2.5}$$

They observed only one-third of the expected solar neutrinos, giving rise to the "solar neutrino problem" that inspired neutrino physics much and that can be explained by neutrino oscillations. Of course, there are other experiments devoted to neutrino physics.
One of them is MINOS at Fermilab. This is a ν_μ-disappearance experiment, i.e. they look at a beam of ν_μ and measure how much of them have disappeared after certain distances (one detector at 1 km and one at 735 km).
Other important experiments are SNO, Kamiokande and Double Chooz.

2.2 The Physics of Neutrino Oscillations

As already mentionend, the existence of neutrino oscillations means that neutrinos have non-zero masses and that leptons mix [3].That neutrinos have mass can be understood as follows: if there exits a basis of mass eigentstates $|\nu_i\rangle$, with $i = 1, 2, ...$
Leptonic mixing can be understood by looking at the leptonic decay of the W-boson:

$$W^+ \rightarrow \nu_\alpha + l_\alpha^+ \tag{2.6}$$

$\alpha = e, \mu, \tau$ and l_e is the electron, l_μ the muon, and l_τ the tau. In general l_α is a charged lepton of flavour α. Thus mixing refers to the fact that W^+ decays to a charged lepton l_α but the mass eigenstate of the accompanying neutrino can be any of the different ν_i. $U_{\alpha i}^*$ denotes the probability amplitude for the production of a specific $\bar{l_\alpha} + \nu_i$ combination in the W^+ decay. The neutrino state of the neutrino emitted in the W^+ decay together with a specific lepton $\bar{l_\alpha}$ is

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle \tag{2.7}$$

In other words a neutrino of flavour α is a superposition of mass eigenstates.
$U_{\alpha i}$ is the (unitary) leptonic mixing matrix. It garantuees that from a neutrino ν_α a charged lepton l_α will emerge in an interaction, i.e. a charged lepton with the same

flavour as the neutrino's. Of course, (2.7) might be inverted such that each mass eigenstate can be described as a superposition of flavour eigenstates.

$$|\nu_i\rangle = \sum_\alpha U_{\alpha i}|\nu_\alpha\rangle \tag{2.8}$$

When a neutrino ν_i interacts with a detector, the probability that it produces a charged lepton of flavour β is given by $|U_{\beta i}|^2$. For brevity we will only deal with neutrino oscillations in vacuum in detail.

2.2.1 Neutrino Oscillations in Vacuum

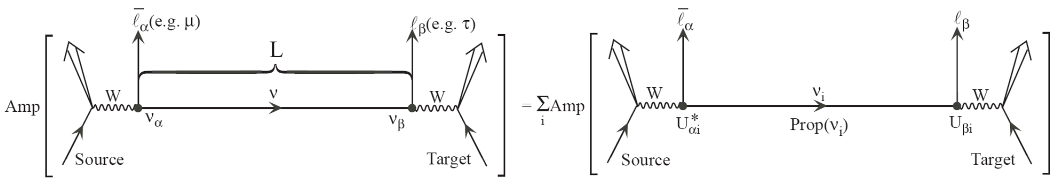


Figure 2: Neutrino oscillation in vcacuum. *Amp* is the abbreviation for amplitude

Neutrino oscillations can be thought of as follows: a neutrino source produces a neutrino together with a charged lepton $\bar{l_\alpha}$ of flavour α. At the beginning the neutrino is thus ν_α. Then it travels a distance L to a detector, interacts with some target and produces a second charged lepton l_β of flavour β. Consequently, the neutrino is at the time of its interaction in the detector a neutrino ν_β. If $\beta \neq \alpha$, e.g. l_α is a μ and l_β is a τ, the neutrino has changed from ν_α to ν_β during its travel. The probability for this transition is given by $P(\nu_\alpha \to \nu_\beta)$. Since ν_α is a superposition of mass states ν_i, the neutrino propagates from the source to the detector as one or another of the ν_i, s.t. one must add the contributions of the different ν_i (s. Fig. 2). The amplitude $Amp(\nu_\alpha \to \nu_\beta)$ is given by the right part of the figure. The contribution of each individual ν_i is a product of three factors:

1. The amplitude for the neutrino produced together with an $\bar{l_\alpha}$ at the source to be a ν_i: as said before, this amplitude is given by $U^*_{\alpha i}$.

2. The second factor is the amplitude of propagation from the source to the detector of the ν_i. It is denoted by $Prop(\nu_i)$.

3. The amplitude for the charged lepton created by the ν_i when it interacts in the detector, to be an l_β. This is given by $U_{\beta i}$ in (backwards) analogy to point 1.

Thus $Amp(\nu_\alpha \to \nu_\beta)$ is given by the expression:

$$Amp(\nu_\alpha \to \nu_\beta) = \sum_i U^*_{\alpha i} Prop(\nu_i) U_{\beta i} \tag{2.9}$$

Now one has to examine $Prop(\nu_i)$ closer. Therefore, one goes into the rest frame of ν_i having a time τ_i. ν_i obeys the Schrödinger equation if it has rest mass m_i

$$i\frac{\partial}{\partial\tau_i}|\nu_i(\tau_i)\rangle = m_i|\nu_i(\tau_i)\rangle \tag{2.10}$$

Since ν_i is an eigenstate of the Schrödinger equation, it follows for the time development

$$|\nu_i(\tau_i)\rangle = exp(-im_i\tau_i)|\nu_i(0)\rangle \tag{2.11}$$

Thus the amplitude for a neutrino to have changed its state from $|\nu_i(0)\rangle$ to $|\nu_i(\tau_i)\rangle$ in a time τ_i is given by $\langle\nu_i(0)|\nu_i(\tau_i)\rangle = exp(-im_i\tau_i)$. $Prop(\nu_i)$ is the probability amplitude of ν_i when travelling from the neutrino source to the detector in the time τ_i. This expression has to be re-expressed in the lab frame to be useful. In the lab frame one has the lab time t and the lab frame distance L. e.g. the neutrinos travel from the source to the detector (distance L) in the time t. By Lorentz invariance the phase $m_i\tau_i$ of the propagator $Prop(\nu_i)$ is given in terms of the lab-frame variables energy E_i and momentum p_i by

$$m_i\tau_i = E_it - p_iL \tag{2.12}$$

For an neutrino with the energy E, the mass eigenstate ν_i, having mass m_i, has a momentum p_i of

$$p_i = \sqrt{E^2 - m_i^2} \approx E - \frac{m_i^2}{2E}$$

in the limit $m_i^2 << E^2$. Thus the phase $m_i\tau_i$ can be approximated by

$$m_i\tau_i \cong E(t-L) + \frac{m_i^2}{2E}L \tag{2.13}$$

The term $E(t-L)$ can be neglected since it is the same for all interfering mass eigenstates und we obtain

$$Prop(\nu_i) = exp(-im_i^2\frac{L}{2E}) \tag{2.14}$$

With this (2.9), i.e. the amplitude for a neutrino to change from ν_α to ν_β traveling a distance L through vacuum with energy E, becomes

$$Amp(\nu_\alpha \to \nu_\beta) = \sum_i U_{\alpha i}^* e^{-im_i^2\frac{L}{2E}} U_{\beta i} \tag{2.15}$$

Thus the probability for the oscillation is given by

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta) &= |Amp(\nu_\alpha \to \nu_\beta)|^2 \\ &= \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2(\Delta m_{ij}^2 \frac{L}{4E}) \\ &+ 2\sum_{i>j} \Im(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin(\Delta m_{ij}^2 \frac{L}{2E}) \end{aligned} \tag{2.16}$$

with $\Delta m_{ij}^2 = m_i^2 - m_j^2$. This is the oscillation probability for an neutrino $\nu_\alpha \to \nu_\beta$. The oscillation probability for an antineutrino is given by $P(\bar{\nu_\alpha} \to \bar{\nu_\beta})$. But this might be found from (2.16) using CPT-invariance, i.e. the fact that the process $\bar{\nu_\alpha} \to \bar{\nu_\beta}$ is just the CPT-mirror of $\nu_\beta \to \nu_\alpha$. Thus

$$P(\bar{\nu_\alpha} \to \bar{\nu_\beta}) = P(\nu_\beta \to \nu_\alpha) \tag{2.17a}$$

$$P(\nu_\beta \to \nu_\alpha; U) = P(\nu_\alpha \to \nu_\beta; U^*) \tag{2.17b}$$

and we end up with

$$\begin{aligned} P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) &= |Amp(\nu_\alpha \to \nu_\beta)|^2 \\ &= \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2(\Delta m_{ij}^2 \frac{L}{4E}) \\ &\overset{+}{(-)}\, 2\sum_{i>j} \Im(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin(\Delta m_{ij}^2 \frac{L}{2E}) \end{aligned} \tag{2.18}$$

One immediately sees that the probabilities for neutrinos and anti-neutrinos to oscillate differs. The last formula has several interesting consequences:

1. If neutrinos were massless, i.e. $\Delta m_{ij}^2 = 0$, then $P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta}$. Thus oscillations only happen if neutrinos have a non-vanishing mass.

2. Consider leptonic mixing and assume it was not there. Then the decay $W^+ \to l_\alpha^+ + \nu_\alpha$ would always involve the same neutrino mass eigenstate ν_i. Since neutrinos can change their flavour, it implies mixing.

3. Neutrino flavour change does not alter the total flux of a neutrino beam. It simply redistributes among the flavours, since $\sum_\beta P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = 1$

Consider now a special case of (2.18). Take only two different neutrino flavours. Further let us assume that there are only two mass eigenstates ν_1 and ν_2 and two flavour eigenstates ν_e and ν_μ. Then $\Delta m^2 = m_2^2 - m_1^2$. After moreover omitting phase factors (which have no effect on the oscillation), the mixing matrix takes the form

$$U = \begin{bmatrix} \cos\Theta & \sin\Theta \\ -\sin\Theta & \cos\Theta \end{bmatrix}$$

Θ is refered to as the mixing angle. Inserting this and the expression for Δm^2 into (2.18) gives:

$$P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = \sin^2 2\Theta \sin^2(\Delta m^2 \frac{L}{4E}) \tag{2.19}$$

2.2.2 Neutrino Oscillations in Matter

Neutrinos can interact with matter by weak interaction. The influence of matter on neutrinos is called MSW (Mikheyev, Smirnov and Wolfenstein) effect. While NC interactions are the same for all neutrinos, i.e. without overall effect, CC-interactions, mediated by $W^{\pm}$ bosons, are only possible for electron neutrinos. This leads to a modification of neutrinos oscillations in matter. But if one considers oscillations $\nu_\mu \rightarrow \nu_\tau$, as in OPERA, one gets after some algebraic gymnastics (for matter of constant density):

$$P_M(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\Theta_M \sin^2(\Delta m_M^2 \frac{L}{4E}) \tag{2.20}$$

which looks quite similar to the probability of oscillation in vacuum. Θ_M denotes the mixing angle in matter and Δm_M^2 the mass splitting in matter. The calculations in detail can be found in [3].

3 The OPERA Experiment

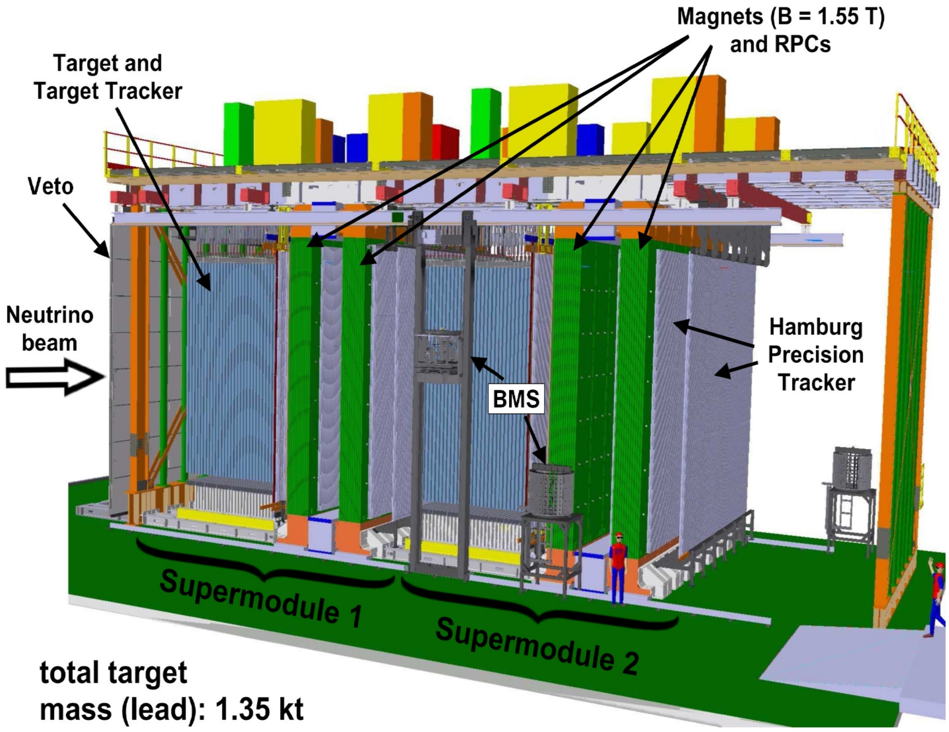


Figure 3: The OPERA Detector

Being the target of the CNGS-ν_μ-beam coming from CERN, the detector is located in hall C of the underground laboratory LNGS in the Gran Sasso massif, under 1400 m of rock. The cosmic radiation is thus reduced by a factor one million compared to cosmic radiation at surface level. This is necessary to reduce the influence of the cosmic neutrino background on the experiment. The detector consists of two (nearly) identical parts, the so-called "super-modules". Those modules consist of a target-area and a muon-spectrometer each [4, 5].

3.1 The Target-Area

Since the neutrino crosssection is small, one needs a high detector mass to directly measure a τ-neutrino interaction of the form

$$\nu_\tau + n \rightarrow \tau^- + X \tag{3.1}$$

Moreover due to the short τ-livetime, i.e. short decay path, one needs a good spatial resolution. This is achieved by using more than 100'000 bricks, i.e cuboids of 8.3 kg mass and dimensions $12.8 \times 10.2 \times 7.5\ cm^3$. In each supermodule they are arranged in

31 walls orthogonal to the CNGS-beam direction with 64 rows per wall and 52 bricks in per row. Each of this bricks consists of an alternating arrangement of 56 lead slices and 57 photo emulsion plates. To protect the bricks from light they are encapsulated in alumimium foil and were moreover produced in vacuum to exclude other disturbing effects like chemical reactions. During the run of the experiment, bricks are taken out for analysis via an automated robotor system, called BMS (Brick Manipulator System). This happens if the electronic equipment, e.g. the Target Tracker - that will be explained below -, identifies a brick in which might have happened a neutrino interaction.
Each brick-wall is accompanied by a Target Tracker wall, consisting of plastic scintilator-strips covering the whole target-area. The Target Tracker's main task is to determine roughly in which target one can find the vertex of the neutrino reaction, s.t. the brick can be extracted. As a secondary task, they work as calorimeters for hadronic showers.

3.2 The Muon-Spectrometer

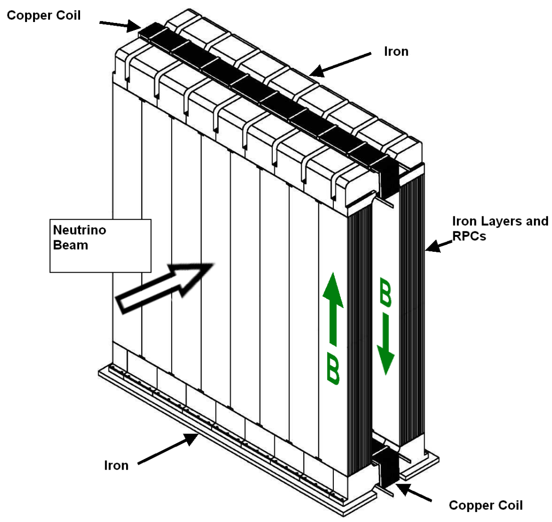


Figure 4: Magnet of a Muon-Spectrometer (also visible RPCs)

The muon-spectrometers are situated behind the target-area of a super-module. It has a mass of 990 t. Every spectrometer consists of a dipole-magnet, RPCs (Resistive Plate Chambers), XPCs, i.e. crossed RPCs, and the Precision Tracker. The spectrometer consists of two iron walls perpenpicular to the beam direction, each divided into 12 iron layers of 5 cm thickness and a seperation of 2 cm. The intervening space accommodates the RPCs. In an area of $8.75 \times 8.00\ m^2$ the magnet creates a homogenic magnetic field, having a flux density of 1.55 T. The field lines are vertical and opposite to each other in the two iron walls.
The RPCs (21 in total per iron layer) cover the whole magnet area. In principle, the

RPC is built from two bakelit-electrodes seperated by 2 mm and works like a Geiger-counter. The exterior side of the electrodes is coated with graphite to which a voltage of 5.8kV is applied. The gap is filled with a gas mixture of Ar, $C_2H_2F_4$, iso-C_4H_{10}, and SF_6. When a charged particle passes through the RPC, it might ionize atoms and molecules of the gas mixture. The electrons (and ions) get accelerated in the external field and one can measure a current in the RPC. As usual, the dead-time poses a problem, since for the time when there are ions within the gas volume, the RPC is unsensitive to other incoming charged particles. The RPCs can be used to reconstruct the tracks of charged particles within the magnet and moreover work as calorimeters and can help in determining the range of muons that are stopped within the magnet. Behind the Target and directly in front of the magnet, there are the XPCs. Their main difference to the RPCs is that they are made from glass and that their electrodes are inclined with respect to the horizontal plane. They are used to reduce the error in the reconstruction of a particle track with respect to the other detector components.
The RPCs also play an important role in deciding which events one can dismiss: in front of the detector, there is the so-called Veto. This is a construction of two glass-RPCs that cover more than the whole detector area. If a charged particle is detected in the Veto, is comes form a reaction outside the detector, such that it is of no importance for the experiment and the event can be neglected. This procedure is very important to avoid unnecessary extractions of lead/emulsion-bricks form the target.

3.3 The Precision Tracker

3.3.1 Setup and Working Principle

The task of the Precision Tracker is to measure the coordinate of muon tracks in the horizontal plane in front of, inside, and behind the magnets and to determine the sign of the muon charge. The Precision Tracker consists of 9504 drifttubes, each having a length of 7.9 m. As in the case of the RPC, drifttubes make use of the ionisations that occur when charged particles traverse matter. Drifttubes are build from an conducting tube having a wire exactly in its middle. One applies a high voltage between the tube and the wire. In this way the wire acts as an anode and the tube as the cathode. The tube is filled, like the RPC, with a gas mixture but a different one. A charged particle that crosses the drift tube ionizes gas molecules on its path (primary ionization). Depending on its energy, the particle might cause further ionizations (secondary ionization) and so groups of electrons, ions respectively, so-called cluster, drift along the electric field lines of the

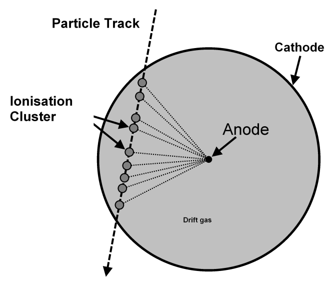


Figure 5: The profile of a drifttube

applied electric field. The electrons gain high energies in the vicinity of the anode and ionize further molecules due to the high field strength at the wire. This process is called gas-amplification and makes it possible to measure an electric signal. One can determine the position where the charged particle crossed the drift tube as follows:

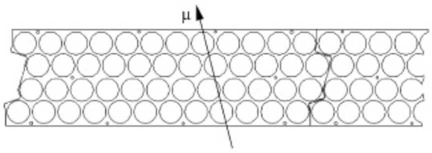


Figure 6: Scheme of a module

At first one detemines the time when an ionized particle is measured. Since one can assume a particle velocity of the speed of light, this time is assumed to be identical to the beginning of the formation of the cluster. Then one measures the time when the electrons arrive at the anode (up to 1.6 μs). In this way one can calculate the circle around the anode wire to which the incoming charged particle was tangent. Using several drift-tubes one can thus reconstruct the particle track. The Precision Tracker is build from 198 modules, having 48 drift tubes each. The modules are 50cm wide and are installed in 12 planes (three with 15 modules, the other ones with 17). Each module is divided into four layers of drift tubes arranged in hexagonal closest packing. With this arrangement the number of hit tubes per track is maximized.

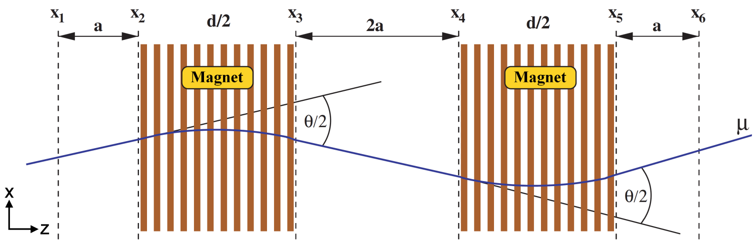
3.3.2 Charge Determination

To determine the momenta of the particles, i.e. the sign of the particle charge, one uses the fact that moving charges are subject to the Lorentz force in a magnetic field and deflected with respect to their path about the angle

$$\theta \approx \frac{qBd}{p} \tag{3.2}$$

with q being the particle charge, d the path of flight in the magnetic field, B the magnetic flux density and p the momentum. When travelling through the spectrometer the particles get deflected twice about the same angle horizontally[2] but in opposite directions due to the arrangement of the magnets. The angle can then be determined

Figure 7: Horizontal view of the muon spectrometer. Schematic view of the path of a muon. The dotted lines indicate the position of the Precision Tracker planes.



[2]In fact due to energy loss it is not precisely the same angular deflection

as follows:

$$\begin{aligned}\theta &= \frac{x_2 - x_1}{a} - \frac{x_4 - x_3}{2a} + \frac{x_6 - x_5}{a} - \frac{x_4 - x_3}{2a} \\ &= \frac{1}{a}(x_2 - x_1 + x_6 - x_5 - x_4 + x_3)\end{aligned} \tag{3.3}$$

Thus one can determine from the deflection angle and the direction of the B-field, the sign of the passing particle.

3.4 The CNGS-Neutrino-Beam

As already mentioned in the introduction, OPERA uses a beam of muon neutrinos from CERN to search for neutrino oscillations. To get a very pure muon beam, CERN shoots protons at 400 GeV from the SPS accelerator onto the CNGS (CERN neutrinos to Gran Sasso) target. The CNGS-target is cooled by helium and is made

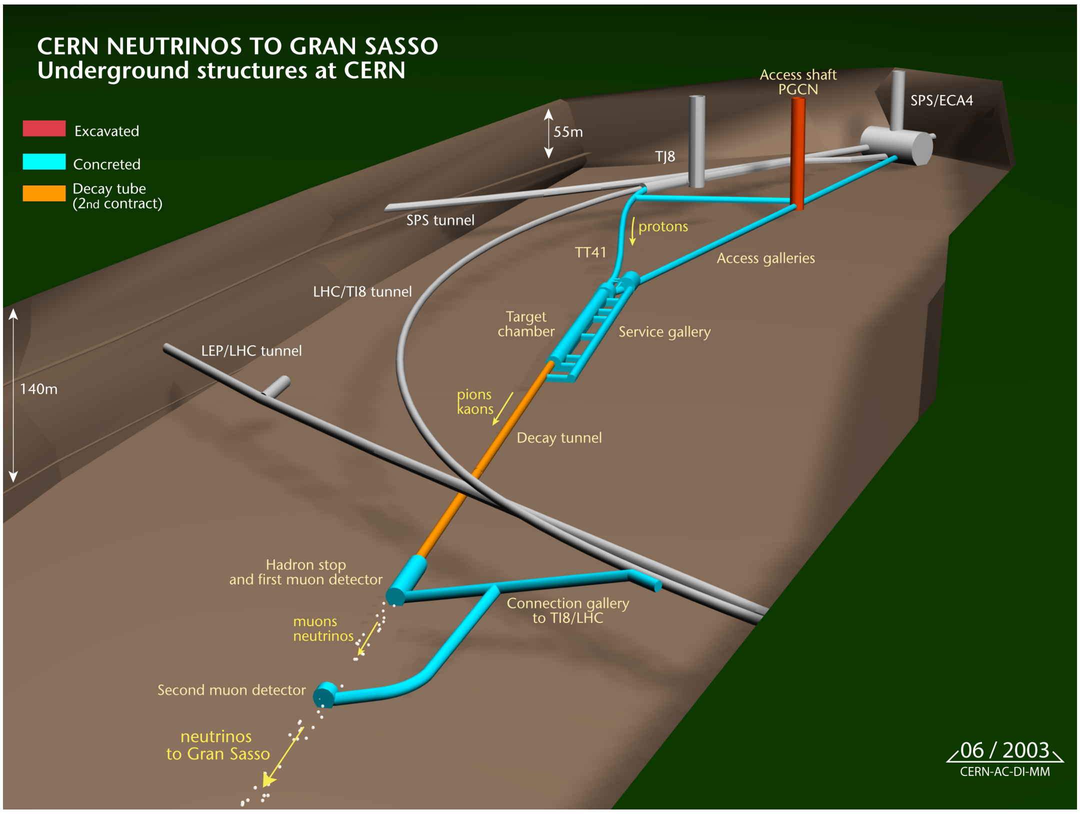


Figure 8: CNGS faciltity for the production of the muonic neutrino beam at CERN

from several thin graphite sticks. The protons interact with the carbon atoms and a secondary beam of Π^+ and K^+ is created. Via magnetic lenses, called horn and reflector, the secondary beam gets focused for its voyage to Gran Sasso. Negatively charged particles are filtered out by the magetic lenses. Behind the reflector, there is a tunnel of one kilometer length in which a part of the pions and kaons decay. The decay channels are given in the following table.

Decay Channel	Probability [%]
$\pi^+ \rightarrow \mu^+ + \nu_\mu$	99.998
$K^+ \rightarrow \pi^+ + \pi^0$	21.03
$K^+ \rightarrow \pi^+ + \pi^0 + \pi^0$	1.76
$K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$	5.59
$K^+ \rightarrow \pi^0 + e^+ + \nu_e$	4.39
$K^+ \rightarrow \pi^0 + \mu^+ + \nu_\mu$	63.39

Table 1: Decay channels [6]

The tunnel is evacuated since interactions of the secondary beam with air molecules would mean a loss of intensity of about 30%. At the end of the tunnel is the so-called "Hadron Stop", a 2 kt and 18 m long block of iron and graphite build to stop all protons, pions and kaons still present in the beam. Muons can pass the stop, however, and can be detected in two muon spectrometers behind the Hadron Stop. Since these muons arise from the same decays as the neutrinos, their presence can give hints on intensity and shape of the neutrino beam. The muons still present are absorbed in rock about 100 m behind the second spectrometer. The neutrinos that go from CERN to Gran Sasso need about 2.5 ms to travel that distance. They have a mean energy of 18 GeV which is far more than enough to produce tau leptons (3.5 GeV production threshold). The beam consists of more than 97% muon neutrinos. It is contaminated by anti-neutrinos and neutrinos of other flavours, unfortunately also a fraction of ν_τ.

4 Determination of the Cosmic Muon Charge Ratio

My task was to determine the charge ratio of muons originating from cosmic radiation measured with the OPERA detector located underground at Gran Sasso. This ratio is defined as:

$$R = \frac{N(\mu^+)}{N(\mu^-)} \tag{4.1}$$

where $N(\mu)$ is the number of positive or negative muons.
The similar experiment MINOS suggested a ratio of about $R \approx 1.37$ and MACRO, the experiment that was before OPERA in Hall C of LNGS, obtained an result of $R \approx 1.35$ for Gran Sasso[1, 7].

4.1 The Algorithms

4.1.1 aPar

The first algorithm I used is based on an parameter called aPar. It is a vector having five parameters. It contains dynamical information of the detected muons, like the inverse of the momentum (aPar(4)) or its polar angle (aPar(3)), and gets them not only from the drifttubes but also from the RPCs, Target Tracker, etc. To determine which charge the detected muon has, one gets from aPar the sign of the momentum and has immediatly the charge of the passing particle. The programme code to get this information looks like the following:

```
if(evtHeader->OnTimeWithCNGS() == 0){  // use only cosmics events

if(aPar(4)>0){ muplus++;
cout << "Particle is a Mu+" << endl;}

else if(aPar(4)<0){muminus++;
cout << "Particle is a Mu-" << endl;}

   else{cout << "Particle is not identified" << endl;}
}
```

By default, aPar sets the charge to -1 if it cannot determine the particle charge. This is reasonable for events that are due to beam neutrinos since the beam consists to more than 98% of ν_μ that interact to give μ^- in case of CC-events but is not applicable for cosmic events. aPar was initially designed to give the momentum (energy) of the detected particles, but the Kalman-filter it uses is in an early stage and needs improvement [7].

4.1.2 GetCharge

The algorithm I mainly used is called "GetCharge" and was written by Raoul Zimmermann. It uses reconstructed data from the drifttubes, i.e. the angular deflection of the charged particles in the magnetic field, to determine the sign of the charge.

For this to be possible, at least four successive of the twelve planes (s. section (3.3)) have to be hit, since two planes give one angle and thus four planes give one angular deflection and consequently the charge. In the following two consecutive planes will be called station. This procedure can be refined by looking at the deflection angles in all the hit stations and then adding the outcome to get a kind of "netto" charge. Moreover one has to demand that the angular deflection is bigger than the error of the angle measurements (in this case 3σ).

4.2 Comparison: Monte Carlo Data and OPERA Data

4.2.1 Monte Carlo Data - Simulated Cosmic Events

The algorithms were applied to 100000 Monte Carlo Events.

μ-charge ratio from aPar (in detector)	$1.25 \pm 0.04_{stat}$
μ-charge ratio from GetCharge (in detector)	$1.11 \pm 0.03_{stat}$
Efficiency for $\mu^{\pm}$(aPar)	0.4
Efficiency for $\mu^{\pm}$(GetCharge)	0.7

Table 2: The algorithms applied to Cosmic MC-files (magnets on)

μ-charge ratio from aPar (in detector)	$1.42 \pm 0.09_{stat}$
μ-charge ratio from GetCharge (in detector)	$1.01 \pm 0.06_{stat}$
Efficiency for $\mu^{\pm}$ (aPar)	0.5
Efficiency for $\mu^{\pm}$ (GetCharge)	0.3

Table 3: The algorithms applied to Cosmic MC-files (magnets off)

One obtains for GetCharge:
Magnet-on-events: GetCharge yields an efficiency, i.e. correct determination of the sign of the charge, of about 70%. Given that one has a prescribed muon charge ratio of 1.35 in the MC-files, this means that one should detected, e.g. 1350 μ^+ and 1000 μ^-. But since 30% of the muons are detected with the wrong sign, one detects 1245 μ^+ and 1105 μ^-, i.e. a muon charge ratio of about 1.13 for magnet-on events. This is fulfilled.
Magnet-off-events: Since one cannot distinguish between μ^+ and μ^- anymore, one expects as ratio of 1. Obviously, the efficiency for magnet-off events is decreased drastically since without magnet the distinction between μ^+ and μ^- is more or less guessing. Thus GetCharge works perfectly fine for Monte-Carlo generated events.

What about sign determination via aPar?
Magnet-on-events: For aPar one obtains an efficiency of about 40%, i.e. one should expect an charge ratio of 0.94. As seen from the table this is not met. Since one should achieve an efficiency of 50% by pure guessing this means that aPar performs very bad in this case.
Magnet-off-events: The same should hold as before for GetCharge. Again, aPar does

not meet the expectations.

4.2.2 OPERA Data

The algorithms were applied to the extractions 790 - 840. This corresponds to about 25 days of data. Since aPar has much more data available, not only the drifttube data, it detects much more muons in total.

Detected μ^+ (aPar)	31916 $\pm$ 179
Detected μ^- (aPar)	24213 $\pm$ 156
Detected μ^+ (GetCharge)	636 $\pm$ 25
Detected μ^- (GetCharge)	473 $\pm$ 22
Detected $\mu^\pm$ (aPar)	56129 $\pm$ 237
Detected $\mu^\pm$ (GetCharge)	1109 $\pm$ 33

Table 4: Detected muons in OPERA extractions 790 - 840

This gives a muon charge ratio for cosmic muons of

$$\begin{aligned} R_{aPar} &= 1.32 \pm 0.01_{stat} \\ R_{GetCharge} &= 1.34 \pm 0.02_{stat} \end{aligned} \tag{4.2}$$

Still, one has to mention several things when comparing Monte Carlo data with real OPERA data. Although Monte Carlo data is supposed to be used to "simulate" real data, in this case it is only partially applicable. Firstly, the reconstruction of MC-data is in some aspects different to those of real data, e.g. in real data the reconstruction software only uses the best tracks. In other words one uses different cuts. Secondly, in the Monte Carlo data the detector is assumed to be perfectly aligned, whereas in reality it is not. This alignment problems affect geometrical alignment as well as time alignment. In the course of this Summer Student Programme there was unfortunately not enough time to investigate on these problems further to optimize the algortihms more.

5 Results and Outlook

As obtained in the previous section, the algorithm GetCharge nicely reproduces the MACRO measurements and obtains

$$R_{GetCharge} = 1.34 \pm 0.02_{stat}$$

aPar is close to the expected result but fails to obtain it (even within its error)

$$R_{aPar} = 1.32 \pm 0.01_{stat}$$

Nevertheless, the Monte Carlo data revealed that aPar does not work too well and this could reflect in the actual data. The reasons for this remain unclear due to lack of time. Additionally there are still the unsolved issues regarding momentum determination for aPar. Nonetheless, there are several interesting topics to investigate further in the future:

- Is the ratio dependend on the energy/momentum of the detected muons?
- Is the ratio dependend on the zenith angle?
- How is the ratio dependence on the rock depth?
- Why does aPar not work properly?
- Can one use GetCharge to determine a particle's momentum?

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