Measurement of the mass of muon neutrino

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1 Background and theoretical considerations

Scientists have been highly interested in neutrinos in the last few years as neutrinos could be used for example to predict gravitational waves (in addition to gamma-ray bursts) or they could be the key to detect Dark Matter [1]. In our experiment we decided to focus on the muon-decay of the pion because there are many procedures to measure the properties of electron neutrinos in opposition to muon neutrinos and that is the challenge for us.

$$\pi^- \to \mu^- + \bar{\nu}_\mu$$

This is the reaction that we prefer to use during our experiment.The decay of pions is a two-body decay thus, due to the conservation of energy and momentum, in the restframe of pions the momentum taken by the muon (and by the neutrino) is going to be an exact, concrete value. The verification of this statement by measuring the momentum of pions and the produced muons can be the basis of our experiment. However the decay can produce electrons/positrons (depending on the charge of the pion) and the corresponding electron neutrinos, but fortunately the probability of this outcome is quite low, about 0.0123 percent. (By contract the probability of the decay what we would like to use is 99.9877 %).

2 Experimental setup

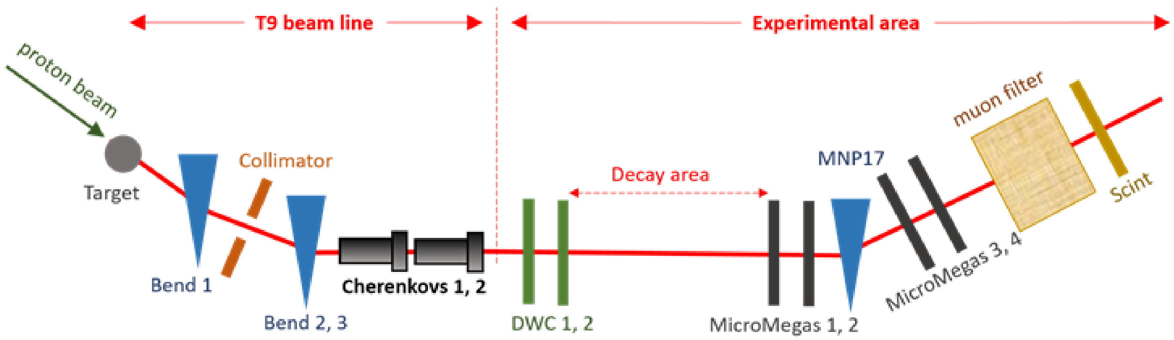


Figure 1: The fixed arrangement of the T9 beamline [2] (left to the red dashed line) and our setup for the experiment (right to the red dashed line).

Our experiment could be divided into five different phases in basis of what type of intervention do we perform on the beam, or what the particles in the beam do. The experimental setup can be seen in Figure 1.

2.1 Phase 1 - The beam

Phase 1 is the fixed arrangement of the T9 Beam line. A high-energy proton beam hits an aluminium or beryllium target, which generates particles including pions. By adjusting the energy and the polarity of the beam, we are able to change the composition of the leaving beam. The optimal energy of the beam for the proposed measurement is around 1 – 2 GeV, beacuse at this energy we get a great number of pions. With this energy the pions have got low beam velocity, too. This is also important, because more decays happen in the decay area (Phase 3) and in Phase 4 the MNP17 magnet bend the path of the muons with a greater angle due to the lower beam velocity. Then we can measure the momentum of the muons better. We think that the polarity of the beam must be negative, because there are more muons compared to the positive beam of the same energy in the T9 Beam line. The composition of the negative beam can be seen in Figure 2. However the measurement would be done with opposite polarity.

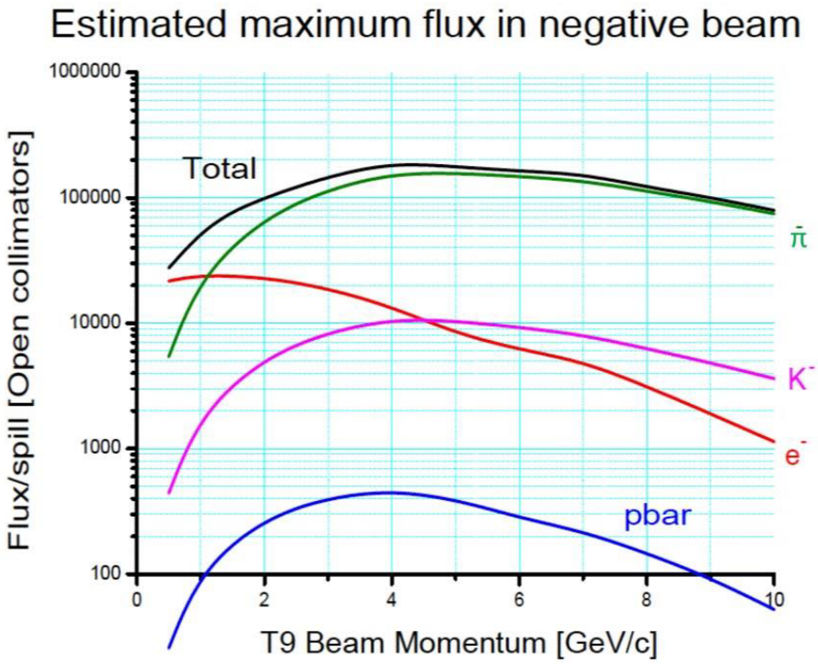


Figure 2: Composition of the T9 beamline [2].

2.2 Phase 2 - Measure the pions

In phase 2 there are two Delay Wire Chamber (DWC) detectors to be found. Both of these detectors are going to give us the current (x, y) coordinates of the particles: they can give us a plane section of the beam. We would like to use at least two of them to get data about the path/trajectory of the particles – these particles technically will just be pions. The method to measure the momentum of pions is written in the Momentum of pions subsection in details.

2.3 Phase 3 - Pion decay

Phase 3 is a dedicated decay area, when pions are allowed to decay freely. According to our estimations a vacuum tube is not needed for this. The number of decays is calculated in Number of muons section.

2.4 Phase 4 - Muon spectrometer

Phase 4 is a spectrometer. It includes 2 tracking (optimally the MicroMegas) detectors, the MNP17 magnet and another 2 tracking detectors. The MNP17 magnet is a polarity changeable, horizontal dipole magnet[hivatkozás]. It will deflect the muons, and from the muon trajectory, its momentum and direction is measurable. From the measurement, it should be possible to extrapolate the trajectory back to the decay area, to be sure that the decay took place there. From the momentum of pions and muons, we can calculate the mass of the neutrinos. These calculations are mentioned in section Momentum of muons. If we have the momentum of pions and muons, we can calculate the mass of the neutrinos. To see the theoretical summary, look at section Decay of pions.

2.5 Phase 5 - Reduce the background

In phase 5 a muon filter and a scintillator can be found. Its function is to be a muon trigger. This should reduce the fraction of non-decayed events drastically, to increase the useful data rate. Can accept 'background' of late decays (e.g. inside or behind spectrometer) or interactions, the aim is to reject most of the direct beam.

3 Mathematical consideration and calculations

3.1 Momentum of pions

With the two DWCs, we can measure the path, thus the direction of the momentum of the pions. From the energy of the beam and the data measured by the DWCs, we can calculate the three-momentum $\vec{P}_\pi$ of a pion.

3.2 Number of muons

We are going to use a negative beam with an energy about $K = 2$ GeV. This means that the number of particles in a spill is going to be $N(0) \approx 10^5$ and the number of pions in a spill is going to be $N_\pi(0) \approx 3.6\times10^4$ (Figure 2). We got the information $m_\pi \approx$ 139,57 MeV/c^2 and $(c\tau_\pi) \approx 7.8045$ m for pions[2]. The number of muons will be produced through the decay area with a length $l \approx 4$ m is going to be:

$$N_\mu = \Delta N_\pi = N(0)_\pi \Big(1 - e^{\frac{-ct}{(c\tau_\pi)\gamma}}\Big)$$

where $t \approx \frac{1}{c}0.26$ m is the time to get the pion through the decay area calculated from the given data. This means that we will get $N_\mu \approx 80$ number of muons to measure in every spill.

3.3 Momentum of muons

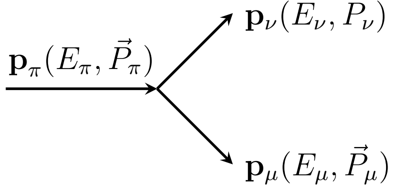
We can measure the three-momentum of muon with the spectrometer mentioned above, by using the MNP17 magnet and the 4 tracking (MicroMegas) detectors. If a particle goes through a homogeneous, vertical magnetic field B in a length of l, due to the relativistic effects its path (as its momentum) will bend with a horizontal angle θ, where:

$$\theta = \frac{Bql}{P_{\mu z}}$$

By measuring θ, we can get $P_{\mu z}$. Over a length of 2 m, the muon will be bent approximately by 20 cm, which is well measurable.

3.4 Decay of pions

The four-momentum is conserved in the pion decay:



$$\mathbf{p}_\pi = \mathbf{p}_\mu + \mathbf{p}_\nu \qquad \rightarrow \qquad \mathbf{p}_\nu = \mathbf{p}_\pi - \mathbf{p}_\mu$$

$$\mathbf{p}_\nu^2 = (\mathbf{p}_\pi - \mathbf{p}_\mu)^2$$

$$m_0^2 = \mathbf{p}^2 \qquad \text{(relativistic square)}$$

$$m_\nu^2 = \mathbf{p}_\pi^2 + \mathbf{p}_\mu^2 - 2\mathbf{p}_\pi\mathbf{p}_\mu$$

$$m_\nu^2 = m_\pi^2 + m_\mu^2 - 2(E_\pi E_\mu - \vec{P}_\pi\vec{P}_\mu)$$

It is known that $E = \sqrt{m^2 + \vec{P}^2}$, then:

$$m_\nu^2 = m_\pi^2 + m_\mu^2 - 2\sqrt{(m_\pi^2 + \vec{P}_\pi^2)(m_\mu^2 + \vec{P}_\mu^2)} + 2\vec{P}_\pi\vec{P}_\mu$$

So if we measure $\vec{P}_\pi$ and $\vec{P}_\mu$ we can calculate m_ν^2. By measurement error, m_ν^2 will fluctuate, and may even be negative.

4 Predictions

As the mass of a neutrino is extremely small, we can only hope to give an upper limit, probably the measured value (of the mass square) will be a peak around zero.

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References

[1] https://www.ligo.org/science/Publication-S5LV_ANTARES/index.php

[2] https://beamline-for-schools.web.cern.ch/sites/beamline-for-schools.web.cern.ch/files/BL4S-Beam-and-detectors_2018_1.pdf

[3] http://pdg.lbl.gov/