lab instructions for *"Eksperimentel Kerne- og Partikelfysik"*, 2011

Measuring Atmospheric Muons

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1. Introduction

1.1. Atmospheric Muons

On earth, nearly all naturally occurring muons are created by cosmic rays. The primary cosmic particles that enter the earth's atmosphere have their origin outside the solar system, and consist of 90% protons, 9% α-particles and 1% heavier nuclei. When such a primary cosmic ray particle collides with an atomic nucleus in the upper atmosphere, pions are created with high probability (as illustrated in Figure 1). These subsequently decay, mainly into muons and neutrinos by the decays:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$

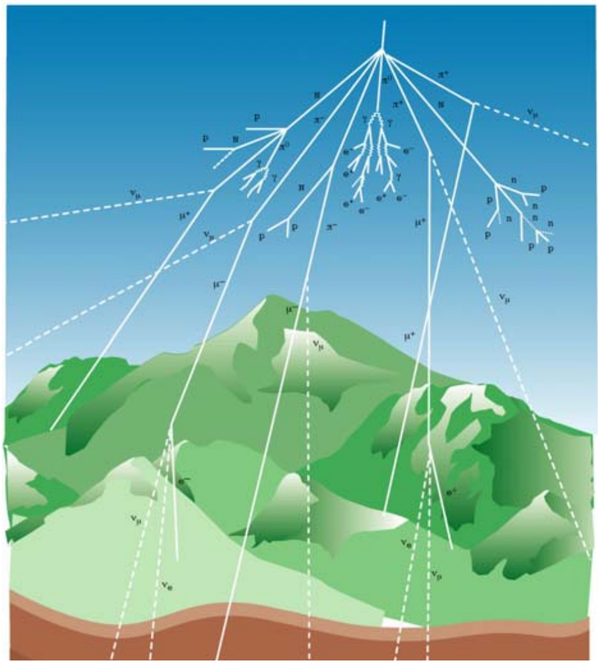


Figure 1 A cosmic ray particle interacts with an atomic nucleus at the top of the atmosphere.

The muons are often moving at very high velocities, thus despite their short lifetime (2.2μs), the time dilation effect of special relativity makes the most energetic ones survive the flight to the earth's surface where they form a major part of the natural ionizing background radiation. Due to their penetrating nature, they are also detectable deep underground and underwater. There are approximately an equal amount of μ^+ and μ^-, and at sea level the flux of muons is about 100 m^{-2}s^{-1}sr^{-1}. Figure 2 shows the muon flux measured at sea level as a function of their momentum.

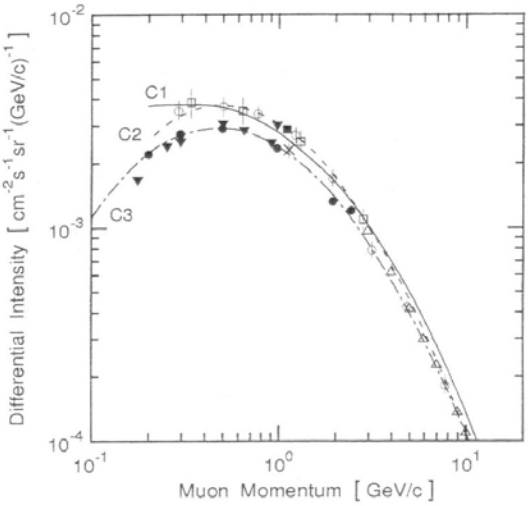


Figure 2 The measured flux of muons at sea level [1].

When a pion decays into a muon and a neutrino the muon will be polarized along its direction of motion. This must be the case in order to conserve angular momentum since the pion has zero spin and the neutrinos are either left or right handed.

Like all heavy charged particles that traverses a material, muons loses energy primarily by ionizing the atoms in the material (at higher energies charged particles also lose significant amounts of energy by emitting photons, so called "radiation losses". This contribution is however only relevant for electrons at energies below 100GeV due to their comparatively low mass). At energies typical for atmospheric muons the so called *stopping power* (*dE*/*dx*) lies between 1-2 MeV $g^{-1}cm^2$. This means that they, when traversing a material, lose 1-2 MeV of energy for every g/cm^3 of material density and for every cm it travels (see Figure 5).

When the muons finally decay it is mainly via the processes:

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

where the $e^\pm$ is emitted with an energy ranging from 0 to E_{max}=53MeV. The decay yields an asymmetric distribution of the $e^\pm$ momentum with respect to the muon spin according to:

$$dN = \rho(\varepsilon)d\varepsilon \frac{1 + a(\varepsilon)\cos\theta}{4\pi} d\Omega$$

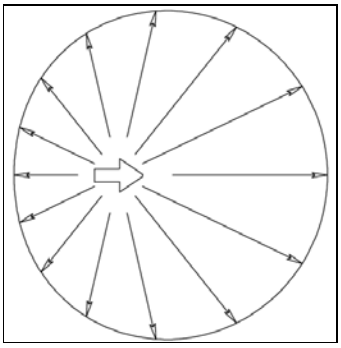


Figure 3 Asymmetry of the $e^\pm$ momentum in muon decay (integrated over energy)

where

$$a(\varepsilon) = (2\varepsilon - 1)/(3 - 2\varepsilon)$$
$$\rho(\varepsilon) = 2(3 - 2\varepsilon)\varepsilon^2$$

and $\varepsilon = E/E_{max}$, *E* being the $e^\pm$ energy. After integrating over all possible $e^\pm$ energies, the distribution looks like in Figure 3.

1.2. Exponential lifetime

Elementary particles don't "age" like normal macroscopic objects such as biological cells, cars, humans and stars. The latter are all complicated composite objects, and the probability of them disintegrating typically gets higher the longer they have existed or the more they have been effected by their environment. One can in principle by observation tell if one car is closer to the end of its existence than another, also in the case when they appeared to be identical at the time of their production. This feature is closely connected to the fact that one can separate one object from another (even two brand new cars can be distinguished after close inspection).

Two elementary particles of the same type on the other hand, are identical and *non-separable* in a more fundamental sense. There is for instance no way one even in principle can tell if one particle is older than another. If one could, the particles would have to have some internal structure that kept track of its age (like the bumps on a car). One could of course argue that there might be such internal structure which we just haven't found yet.

However, a natural consequence of truly simple and non-separable particles is *exponential lifetime*. It can be explained as follows:

If there is no way to even in principle tell if a particle is older than an other, there can be no slow change or disintegration, and therefore a particle that was created one second ago will have exactly the same chance of decaying within the next second as a particle that was created one hour, one year or one nanosecond ago. Thus, the probability to decay within the next time interval *dt* is independent of when that time interval begins with respect to the time of creation of the particle.

Now, let the probability density distribution *dp*/*dt* signify the differential probability for a particle to decay after a time *t* when starting to observe it at *t*=0. If *dp*/*dt* for *t*=0 is equal to a value λ, it means that the probability for it to decay during a time interval *dt* (which is short enough for *dp*/*dt* to be constant over that interval) is given by λdt.

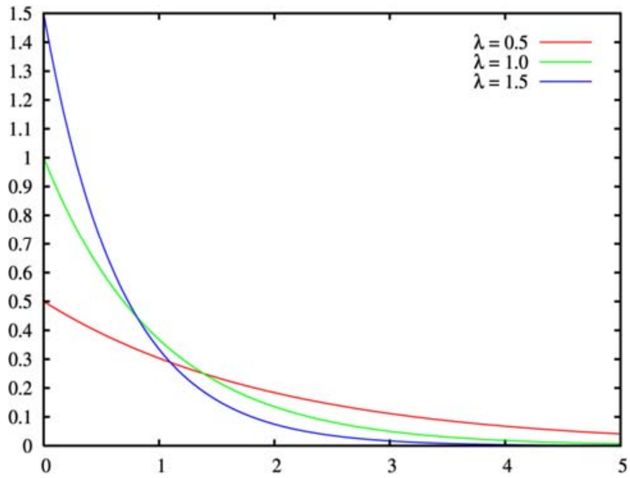


Figure 4 The exponential distribution

Let's now divide the time interval *t* into *N* equal parts: $t_0=0$, t_1, t_2, … $t_N=t$. Hence, *dt*=*t*/*N*. The probability that the particle will *survive* from *t*=0 and for a time interval *dt* until t_1 is then $1-\lambda dt = 1-\lambda t/N$ (the particle must either decay during the interval or survive until t_1). If we now make use of the fact that it doesn't matter when you start to observe the particle we conclude the probability that it will survive for two time intervals until $t_2=t_1+dt$ must be the product of the probability that it will survive the first interval and the probability that it will survive for the second one $(1-\lambda t/N)^2$. If we repeat the argument *N* times the probability for the particle to have survived until *t* (=t_N) is $(1-\lambda t/N)^N$. Letting *N* go towards infinity and *dt* towards 0, this expression approaches the value $e^{-\lambda t}$ (remember that this is the probability for the particle to *survive* until *t*).

So, if we start observing a particle at *t*=0 the probability that it will *decay* before a time *t* is $1-e^{-\lambda t}$. This must then be equal to the integrated differential probability $\int(dp/dt)dt$ where the integration goes from 0 to *t*. Thus, $dp/dt = \lambda e^{-\lambda t}$. The constant λ is usually written as $1/\tau$, where τ is the mean value of the continuous distribution $\boldsymbol{dp/dt=e^{-t/\tau}/\tau}$. One sees that *dp*/*dt* indeed is equal to λ at *t*=0. Check also that the integral of *dp*/*dt* over all *t* gives unit probability.

1.3. Detecting the Muons

MIPs and the Landau Distribution

In Figure 5a it can be seen that muons with a momentum compatible to that of the atmospheric lose a minimum amount of energy to ionization compared to those with lower and higher energies. In this energy range charged particles are referred to as Minimum Ionizing Particles (MIPs). The curve however only shows the energy loss when averaged over a large number of particles (a so called “truncated mean”). But because of the statistical nature of the energy loss, two muons with exactly the same energy traversing the same amount of material will have a significant probability of losing different amounts of energy. In the particular situation when the particle passes a reasonably thin layer of material, its energy loss is distributed according to the Landau-distribution shown in Figure 5b.

It is an asymmetric probability density function characterized by a narrow peak with a long tail on the high energy side. This tail is due to the small number of individual collisions, each with a small probability of transferring comparatively large amounts of energy. The mathematical definition of the Landau probability density function is:

$$p^{Land}(E:\bar{E},\xi)=\frac{1}{\pi}\int_0^{\infty} e^{-s\log(s)-\frac{E-\bar{E}}{\xi}s}\sin(\pi s)ds$$

(I use the notation $p(x{:}a,b)$ to indicate the x is the stochastic variable and a and b are parameters that decide the shape of the distribution.)

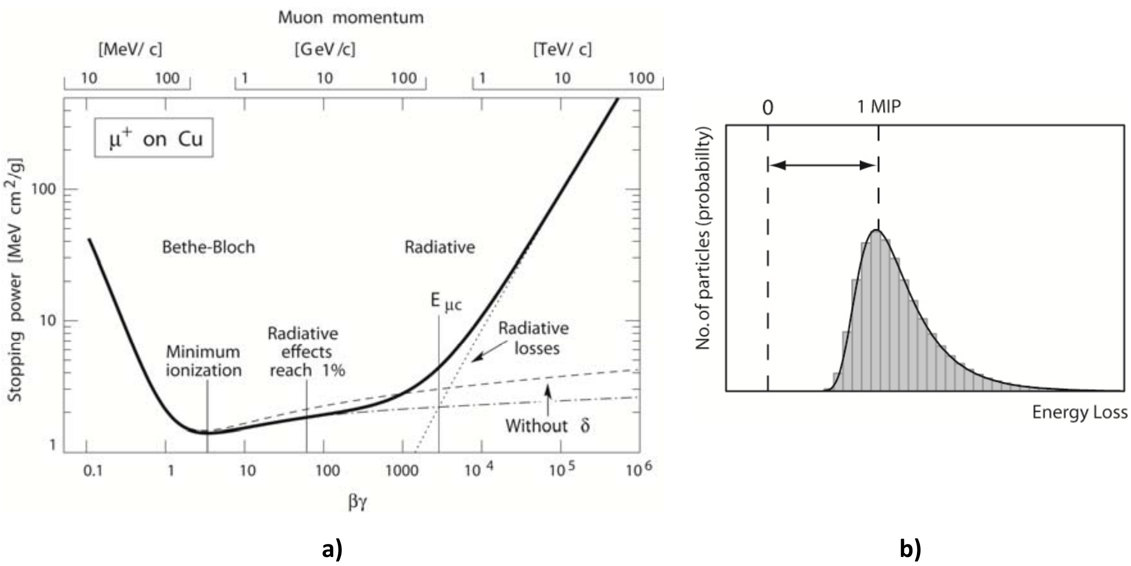


Figure 5 a) The muon “stopping power” (in copper) as a function of energy. b) The landau distribution.

The Landau distribution describes the differential probability for a particle to deposit the energy E, and it depends on two parameters: the most probable energy loss $\bar{E}$, and a material dependent constant ξ. The Landau distribution lacks a finite mean value, but one typically uses a method where the tail is cut off at some value, and the mean value of this truncated function is used. Doing this for a high number of samples and histogramming the mean values will yield a symmetric Gaussian distribution[1] of the mean energy loss dE/dx. This also means that the most probable 1 MIP value of the Landau distribution is lower than the mean value of the dE/dx.

[1] This is a result of the “central limit theorem” in statistic which states that if the sum (and therefore also the mean) of independent identically distributed random variables has a finite variance, then it will be approximately normally distributed.

Scintillators and PMTs

In these labs muons will be detected with plastic *scintillators*. The material in such devices has the property of emitting light by molecular excitations followed by de-excitations when traversed by ionizing particles. The number of photons emitted is proportional to the amount of energy lost to ionization by the traversing particle, and these photons will propagate through the transparent material and can subsequently be detected by some kind of light sensing device.

In our case some of the emitted photons are collected by a Photo Multiplier Tube (PMT), which is optically connected to the scintillator. In the PMT the photons will release photoelectrons that are multiplied by a number of high voltage gradient stages called *dynodes*. The highly multiplied (usually around a factor of 10000) number of electrons constitute a current pulse that can be fed to read-out electronic circuits.

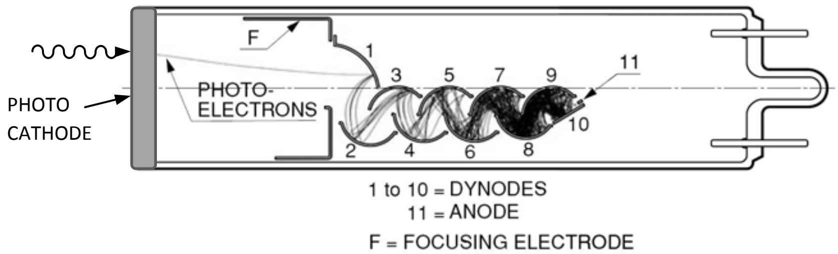


Figure 6 The working principle of a PMT.

Due to the fact that a discrete number of photons are emitted in the scintillator and that only a fraction of these will be detected by the PMT, statistical variation in addition to the Landau fluctuations in the ionization described above becomes significant. An example is [2]: A 0.32 cm thick scintillation emits about 50 photons within angle that will allow for them to be internally reflected in the scintillator towards the surface of the PMT. If the attenuation due to poor quality of the plastic reduces this number by a factor 2, there are about 25 photons arriving at the PMT's photocathode. In addition to this there is a probability less than 1 to convert the photon into a photoelectron. This *quantum efficiency*, at the wavelengths emitted by the scintillator may be of order 25%. There are now only 6 photoelectrons coming off the photocathode. This is a however a stochastic process where the number of emitted photoelectrons is Poisson distributed with a *mean-value* around 6. The Poisson distribution is a discrete probability distribution with a single parameter λ (both the mean value and the variance are given by λ):

$$P^{Pois}(n:\lambda) = \frac{\lambda^n e^{-\lambda}}{n!}$$

As λ grows the Poisson distribution approaches the normal distribution with mean and variance λ. Already at λ=6 the two distributions are rather similar as can be seen in Figure 7.

It can also be seen in the picture that there is a non negligible probability that no photoelectrons are generated at all. The system might therefore let particles pass undetected. One say that it is *inefficient*. The probability to produce zero photoelectrons (P^{Pois}(n=0: λ=6)) at a mean of 6 is 0.2% yielding a 99.8% efficiency in this example.

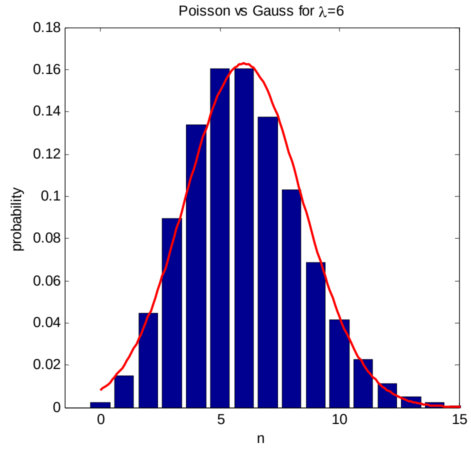


Figure 7 The Poisson distribution with l=5 and the normal distribution with mean=5 and variance=5.

The process of converting the energy lost by the muon in the scintillator to an electrical pulse apparently involves a number of stages where various physical processes take part. However, what is important is that a particle which loses much energy in the scintillator will create more photons, and thus release more electrons in the PMT, resulting in a stronger electrical pulse. It turns out that the total process is reasonably linear which means that a pulse with twice as much charge will on average be generated when a muon loses twice as much energy in the scintillator.

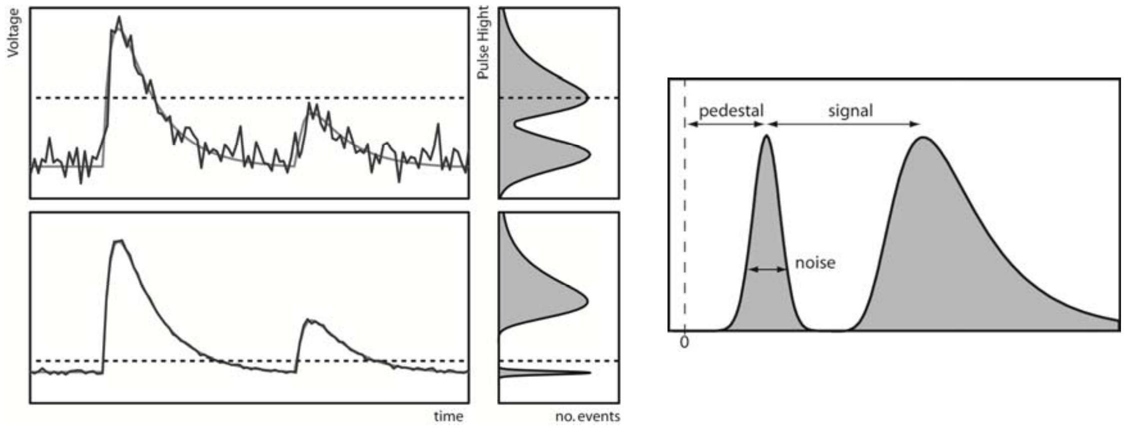
The shape of the signal distribution is influenced by both random processes described above; the Landau distributed energy loss and the Poisson distributed number of generated photoelectrons.

Discriminator, Noise and Efficiency

The simplest electronic circuit used to detect single PMT pulses is called a *discriminator*. This device uses a *threshold* level to generate a binary output. The output will be logically “high” when the voltage on the analog input is above the threshold and “low” when it is below. Pulses of various strengths arriving on the discriminator’s input can thus be detected by selecting a sufficiently low threshold level. A complicating factor is however electronic noise.

Noise normally consists of randomly changing voltage levels that permanently is generated in a powered electronic device. It is most often normal-distributed around a base-line level (pedestal) and is characterized by its rms-amplitude which represents the width of the distribution. Due to noise, there is a limit to how low the threshold level can be set in order for the discriminator not to generate “false” detections.

An important factor for a detector-electronics system is the Signal to Noise Ratio (SNR). In our case the SNR is the ratio between the width of the noise distribution and the location of the peak of the Landau distribution (with respect to the pedestal). Figure 8 illustrates how a big SNR will force the use of a to high threshold value which will result in an inefficient detection of the relevant pulses.



a) **b)**

Figure 8 a) The significance of SNR. The line indicates a discriminator threshold. It can be seen that the threshold in the top figure has to be high in order to avoid the noise, which results in an efficiency loss. b) Illustration of the pedestal, noise and signal.

2. Lab Descriptions

There are several different muon experiments, and since they will be performed with tutor assistance and carefully explained during the lab occasion, they will here only be briefly described.

Lab 1: Detector Efficiency and Flux Measurement

The *efficiency* of a particle detector normally represents the ratio between the number of particles that has been detected and the number of particles that has passed the detector and ideally should have been detected. In this lab we will estimate the efficiency of two scintillator detectors by counting pulses.

In the lab you will create logic to count the number of muons that i) has passed a scintillator and ii) the number of particles that has been registered by a scintillator as a function of discriminator threshold. The hardware and the way to use it will be demonstrated at the lab.

In Figure 2 you see a plot of the flux of atmospheric muons in units of $cm^{-2}s^{-1}sr^{-1}$. Integrate this flux over all momenta and check if the value is in accordance with what you measure. How to calculate the geometrical factor G ($cm^2 sr$) you can read about in [3]. Download it from http://www.nbi.dk/~lundq/Sullivan.pdf.

Preparations:

- Think about the relation between noise, discriminator threshold and efficiency illustrated in Figure 8.
- Two identical detectors (A and B) are placed on top of each other and muons that are known to have passed through both detectors are counted by electronics connected to the detectors. There are 3 counters: Two of them count the pulses on each detector (C_A and C_B), and one counts the pulses that occurs simultaneous on both detectors ($C_{A\&B}$). Estimate the efficiency of the two detectors if the values when you stop the counters are 9998, 10000 and 9995 on C_A,C_B and $C_{A\&B}$ respectively.

- How would you make sure a muon actually has passed both detectors and not only one of them?

Lab 2: Pulse Spectrum

As mentioned earlier, the strength of the signal coming from a PMT is proportional to the Landau distributed energy deposited by the particle when passing the detector. But on top of this there are a number of additional random effects that will influence the signal strength. One is the number of photons arriving at the PMT surface. Another is the number of electrons created via the photo-electric effect in dynode stages inside the PMT. All additional effects can be modeled by adding a “smearing” of the signal with the shape of a Gaussian distribution with mean value 0 and some variance σ^2.

The probability density function (pdf) of a random variable that is the sum of two other random variables is given by something called the *convolution* of the pdfs of those two variables. It is defined by:

$$P^{1+2} = (P^1 * P^2) \equiv \int_{-\infty}^{\infty} P^1(x-t : a_1, b_1, \ldots) \cdot P^2(t : a_2, b_2, \ldots) dt$$

In this definition the resulting pdf will depend on all the parameters a_1, b_1, …, a_2, b_2, …. In our case the convolution is then given by:

$$P^{Land+Gauss}(x : mpv, \sigma_l, \sigma_g) = \int_{-\infty}^{\infty} P^{Land}(x-t : mpv, \sigma_l) \cdot P^{Gauss}(t : 0, \sigma_g) dt$$

Where *mpv* is the most probable value of the measured signal and σ_l and σ_g are the width of the Landau distribution and the Gaussian smearing.

In this lab you will measure a spectrum of a scintillator + PMT and fit the result with the function above. The data you collect will be written to a text file you can use for analysis.

To do this you will use an ADC (Analog to Digital Converter). There are many types of such devices, but the one used in this will just integrate the charge it receives on one of the 12 channels during a time defined by a *gate* signal. Hence when the gate is logically high, charge will be collected, and when the gate goes low again the ADC value can be read by a computer.

- Form a trigger signal from the two smaller scintillators, using the NIM discriminator unit and the coincidence unit.

- Compare the coincidence signal on the oscilloscope to the pulse from one of the big scintillators. Use the delay unit and the width adjustment on the coincidence signal so it can be used as a gate signal.

- Connect the PMT pulse and the gate signal to the ADC and start the DAQ (data acquisition) program on the computer.

- Note the Landau distributed spectrum and the pedestal, and use the real time fitting function in the DAQ software to fit the data.

- When you have recorded enough data you will get an ascii-file containing the values of the ADC counts for all triggers. Also measure the trigger rate in order to make an estimate of the muon flux.

Fitting the ADC spectrum

If you are analyzing the data with Root you can follow the steps below.

1. Do step 1 and 2 and 3 described in Lab 4 (page 10).

2. Add data to the histograms with `ML.AddAdcData(`***`Filename,offset`***`)` where *Filename* is the name of the data file (including relative path). *Offset* is the pedestal shift.

3. Look at the histogram with `ML.GetAdc().Draw()`

4. Declare the function for fitting the data. Do it with:
   `TF1 *glan = new TF1("gauslan",LanGauss,0,500,4)`

5. For the fit converge you should set the initial parameter values with
   `glan->SetParameters(`***`par1,par2,par3,par4`***`)`.
   The parameters are the values of *mpv* (par1), σ_l (par2), σ_g (par3) and an overall normalization factor (par4). Make a guess of the parameters (for the value of *par4* you can use the total number of triggers) .

6. Make the fit with `ML.GetAdc()->Fit(glan,"","",`***`Low,High`***`)` where *Low* and *High* are the limits between which you want to fit the function.

Estimate Efficiency

Set a software threshold at a certain ADC value to simulate a true discriminator threshold which only accepts triggers where energy above this level has been deposited. Use an analysis program of your choice to calculate and plot the efficiency as a function of this threshold value. Compare the result to what you measured in Lab3.

Lab 3: Time of Flight Measurement

In this lab you will measure the velocity of the atmospheric muons with a ToF (Time of Flight) measurement setup.

Preparation:

- Use the data in Figure 2 to calculate the velocity of atmospheric muons.

- Use the assumption that that the muons are created at the top of the atmosphere and estimate how much energy they lose when passing through the atmosphere and the 4 level NBI building.

- Show that the momentum resolution $\Delta p/p$ that can be achieved in a ToF measurement depends on the accuracy Δt and p/m_0 in the timing measurement according to (m_0 is rest mass of the particle):

$$\frac{\Delta p}{p} = \frac{\Delta t}{t_c^{pass}} \frac{p}{m_0} \sqrt{1 + \frac{p^2}{m_0^2}}$$

Where t_c^{pass} is the time it takes for light to pass the ToF apparatus. Is it feasible to measure a muon spectrum with the ToF setup used in this lab?

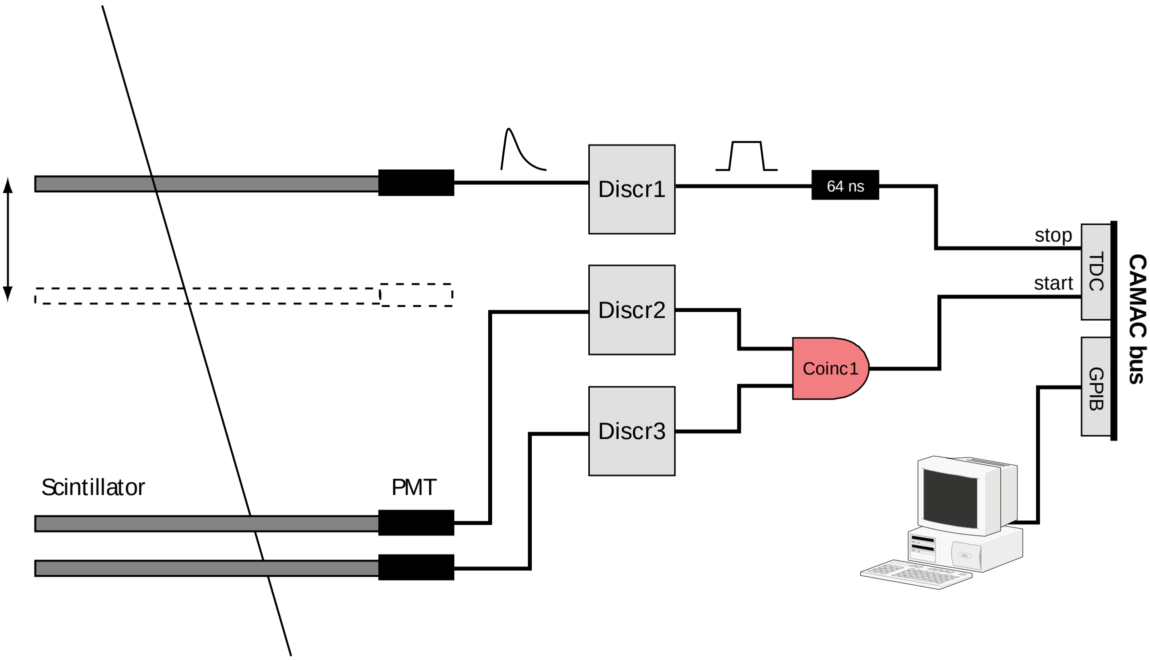


Figure 9 Test setup for the velocity measurement. The upper scintillator can be moved to different positions. and by measuring the difference between two locations one eliminates systematic errors.

Lab 4: Muon Lifetime

In this lab you will measure the lifetime of the atmospheric muons. Some of the incoming muons are stopped in a block of aluminium where they subsequently decay. The lifetime is measured by means of a scaler (counter) which is started when there is a signal in the detectors above the aluminium block but no signal (a so called *veto*) in the detectors below. The counter is stopped when the decay product (the electron or positron) traverses the planes either above or below. Depending on if it exits above or below it will be defined as an up- or down-event.

There is also an option to generate a magnetic field in the aluminium. This means that the muon, due to its magnetic moment, will undergo precessions while waiting to decay. As the electron has a higher probability be emitted along the polarization direction of the muon, a periodic variation in the number of up- and down-events as a function of lifetime will be present. The period of this variation depends on the magnetic field strength and the muon's magnetic moment, which then can be inferred. Figure 10 illustrates this principle. In Figure 11 the schematic used in the lab is shown. Look at it and Follow the steps below when connecting the circuit:

- Look at the raw and the discriminated PMT pulses from all channels with the oscilloscope to make sure there is a signal.

- Make the coincidence 1.AND.2 and 3.AND.4 (with the 64 ns delays) and tune the width of the output pulse to about 50ns.

- Make the veto signals with Gate1 and Gate2. Make sure they cover the coincident pulses (the veto pulse from 1.OR.2 should cover the coincidence 3.AND.4 and vice versa, think about what does these veto signals do!), then connect the veto signals to the coincidence.

- Connect the output of Coinc1 to Gate3 with a 128ns delay. Look at the outputs from Coinc1 and Gate3 to make sure they don't overlap (what is the purpose of Gate3?).

- Connect the logic units and Gate4. Look at the output from Log3 to make sure the pulser is generating a signal for the counter.

- Connect the rest of the circuit and start the DAQ.

When analyzing the data you can choose any program of your choice. If you however chose to your Root you can use software written for the purpose of analyzing this particular data. You can get the file from:

http://svn.nbi.ku.dk/viewvc/HEP_studentlabs/trunk/code/MuLab.cpp?view=co.

This is how you use it:

1. Start Root from the directory where you put the MuLab.cpp file.

2. Load the file with the command **`.L MuLab.cpp`** and create a MuLab object with **`MuLab ML`**.

3. Create empty histograms with **`ML.CreateHistograms(`*`Low,High,Nbins`*`)`** where *Low* and *High* are the upper and lower limits of your histogram, and *Nbins* is the number of bins. These numbers you have to figure out, but the first time you run the program you can just create histograms with 100 bins between 0 and 2000 and use it to take a first look at the data.

   Attention! If you are not certain that a number represents an integer use the decimal format like: 400.0 etc.

4. Add data to the histograms with **`ML.AddLifeTimeData(`*`"Filename",k,m`*`)`** where *Filename* is the name of the data file (including the relative path). *k* and *m* are two numbers you can use to adjust your data (remember that the data in the file represents the number of clock counts and not time values, and that the start and stop conditions are reversed which means that a long lived particle will give a small low count and vice versa). The value that will be added to a histogram is *k**(data in file)+*m*. When looking at the data for the first time you can just set *k*=1 and *m*=0.

5. Look at the histograms for the two type of events with **`ML.GetT1().Draw()`** and **`ML.GetT2().Draw()`**.

6. You can repeat step 3 and 4 and adjust *k* and *m* until you have a histogram you want to fit with an exponential function.

7. Now you can create a function for fitting the data. Do it with:
   `TF1 *fa = new TF1("exponential","[0]+[1]*exp(-[2]*x)",0,25)`

8. Make the fit with `ML.GetT1()->Fit(fa,"","",`***`Low`***`,`***`High`***`)` where *Low* and *High* are the limits between which you want to fit the function. If the fit doesn't converge you can try to set the initial parameter values with `fa->SetParameters(`***`par1`***`,`***`par2`***`,`***`par3`***`)`.

9. From the fit parameters, calculate the muon lifetime τ described earlier.

Preparation:

- We don't measure the time between the creation of the muons high up in the atmosphere and the time they decay in the aluminium. How come we still claim to measure their lifetime?

- Why are some muons stopped in the Aluminium?

- Make sure you understand the principle of the circuit in Figure 11 What is the purpose of the 20 us gate signal generated by Gate3?

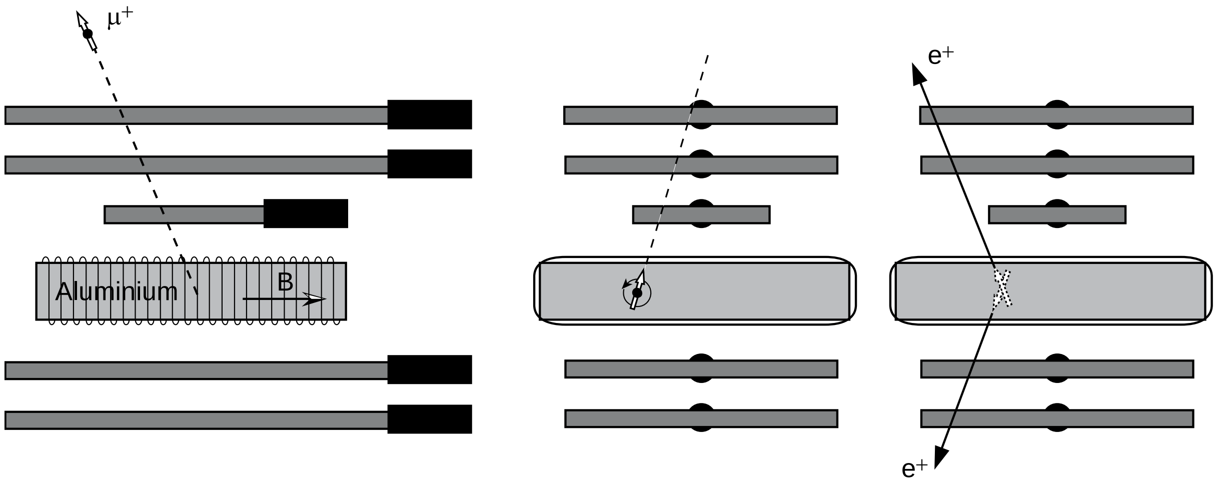


Figure 10 (Left) The muon enters the aluminium block. (Middle) While waiting to decay it precesses in the magnetic field. (Right) The decay product is detected either above or below the aluminium block.

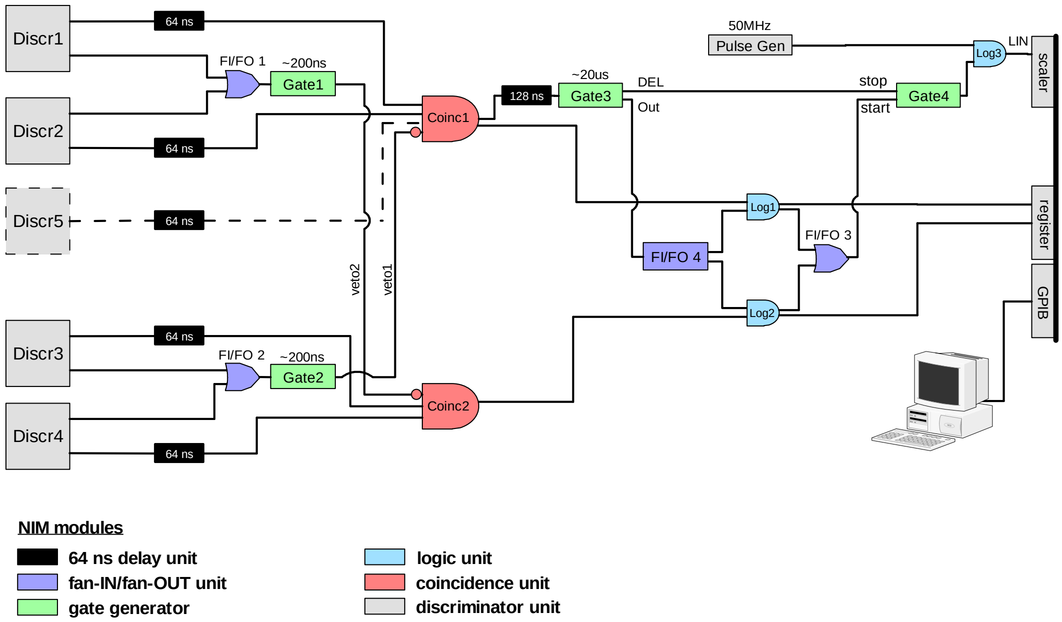


Figure 11 Schematic for the lifetime measurement.

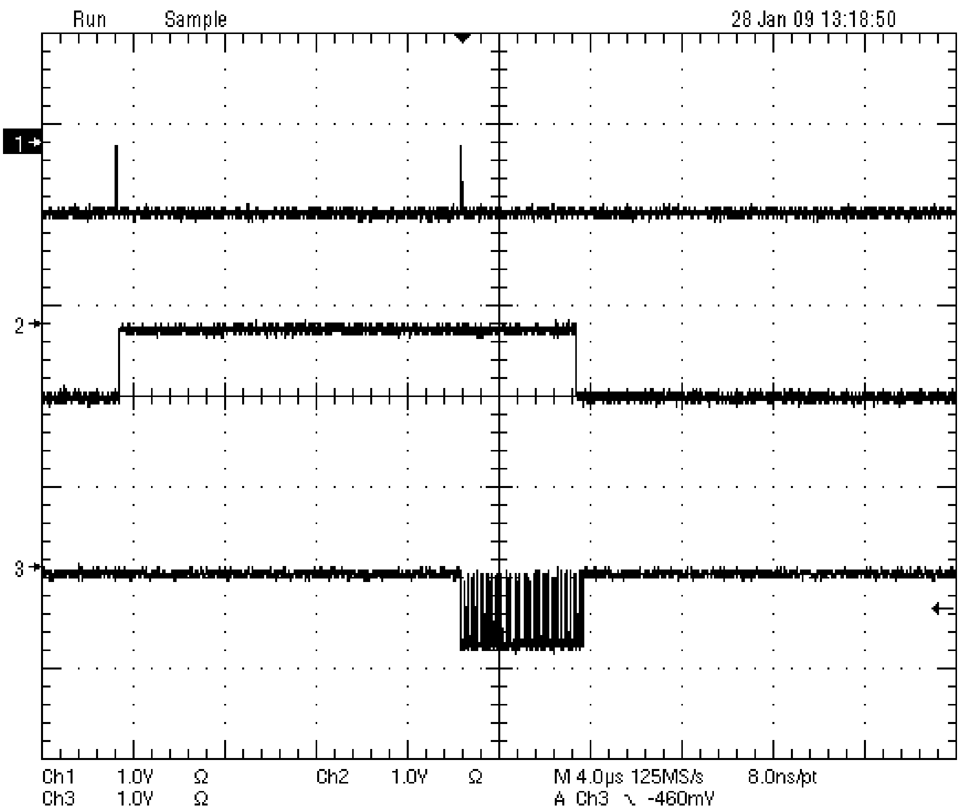


Figure 12 An oscilloscope screen dump showing the timing of the output of Coinc1 (channel 1), the “Out”-output of Gate3 (channel 2) and the output of Gate4 (channel 3). As can be seen the time between the muon enters the two top scintillators and the decay product leaves through the same pair of scintillators is ~38us (an unusually long lived muon unless it is a background event). One can also see that the lifetime is given by the length of the fixed gate interval (channel 2) *minus* the measured interval (channel 3)

Lab 5: Coincident rate as a function of distance

The use of additional muon detectors placed horizontally as the main detector, and separated by some distance, makes it possible to carry out significant new experiments. No coincidences due to a single muon are possible in such condition, and the detected coincidences originate from different, related, particles. Such coincidences were first investigated in the second half of 1930's and it was found that coincident events could be observed even when the detectors were hundreds of meters apart, although with a very low rate.

When two detectors are operated in coincidence, the coincidence rate between the two detectors is a rapid decreasing function of the detector separation. Such dependence of the counter coincidence rate upon the detector separation is called the decoherence curve. The measurement of the decoherence curve may be done within a few meters distance between the detectors, and may be found that the coincidence rate decreases dramatically as the separation of the detectors increases, for instance by a factor 5 when going from 0.5 to 2 m. The result is much steeper than the characteristic shower width expected on the basis of the Moliere radius, which amounts to about 80 m at sea level. This sharp decrease is due to the central shower core which has a lateral spread of only a few meters. For larger separations between the two detectors, in the order of 10-50 m, the observed decrease is not so steep, and a relatively constant coincidence rate may be observed in this range. However the absolute counting rates are much lower than those observed in the range 0.5-2 m, by a factor which exceeds two orders of magnitudes.

In order to carry out such experiments, at least two detectors are needed, which can be moved in the same horizontal plane. For distances up to a few meters, the experiments are easier, since the two detectors may be placed inside the same lab, and the counting rates are relatively manageable. However, for larger separations, a better organization of the detector set-up is needed, in order to have two detectors working at tens of meters distance (power supplies, attenuation of the signal in the cables, timing between the two detectors etc). Moreover, the counting rates will be very low, requiring running times in the order of a few days to get adequate statistics.

This lab examins the relationship between the flux of muons from extended air showers and the distance between the detectors that detect them, for a range of 0-10 m meters maximum in distance. The measurements can be compared with data from a simulation program (an example can be provided or you can try to simulate yourself). Try to interpret the data observed.

Set-up

The experiment uses two scintillator plates. The two plates are located at the attic of the A-building at Niels Bohr Institute. Each of the plates is via coaxial cables connected to an electronics board with discriminators that sends a standard pulse on to an FPGA (programmable logic) if it receives a signal stronger than a certain threshold that can be programmed. The coincidence is registered and counted if it receives two overlapping signals within a time window of abt. 100ns from each plate. Arrangements have been made that use the same length of cable from each of the plates to the coincidence logic, so a signal coming from both plates left from the same shower will arrive consistently to the electronics. With this setup, count how many times a particle is detected in both plates simultaneously, i.e. within an interval of 100ns. When two particles hit simultaneously in each plate, it is assumed that they have come from the same shower. The time interval is sufficiently small that it is unlikely that two particles from different showers hit the plates within this time interval.

Plates are spaced at a specific distance from each other, and you should observe how many coincidences are measured during a period of 1000 sec. The distance between the plates can be varied from about 3m to around 14m.

Measure the flux dependence by the distance between the plates, and explain what you see. Compare it to what you would expect.

3. References

[1] Greider, P.K.F., Cosmic Rays at Earth, (2001, Elsevier, Amsterdam)

[2] Example from"The Physics of Particle Detectors", Dan Green, Cambridge, ISBN-10:0521675685

[3] J.D. Sullivan, Nuclear Instruments And Methods 95 (1971) 5-11.