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Untersuchung der Langzeitstabilität des EDELWEISS Myon-Veto-Systems
(Investigation of the long term stability of the EDELWEISS muon veto system)

Bachelorarbeit
von

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Karlsruhe, den 30.10.2017, ____________________________

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Prof. Dr. Guido Drexlin

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1. Introduction

Astrophysical and cosmological observations over the last decades indicate the existence of some none-baryonic dark matter. By analyzing the anisotropy of cosmic microwave bacground, the dark matter energy contribution is estimated to be 27% of the universe. Yet no knowledge of the particle consitituent of the dark matter is obtained.

A generic class of hypothetical particles, the Weakly Interacting Massive Particle (WIMP), is a prominent candidate for the dark matter. WIMPs is often assumed to have mass of $\mathcal{O}(100\,\mathrm{GeV})$, with an interaction cross section with ordinary matter of the order of weak interaction scale.

The EDELWEISS experiment is aimed to search direct signal of elastic scattering of WIMP on germanium bolometers. Due to the expected low rate of WIMP-nucleus scattering, the main challenge of the experiment is to understand and exclude possibly all the background events.

The detectors are surrounded by multiple layers of external shielding, which absorb and reject bacground radioactivity. Further backgrounds from the radioactivity of the shieding materials can be discriminated by the simultaneous readout of heat and ionization measurements. ((cite)) The remaining neutron bacground causes a nuclear recoil in detectors, which cannot be distinguished from a WIMP-signal. The neutrons are produced respectively from the cosmic-ray muons. To protect the detectors from the cosmic muon bacgrounds, EDELWEISS is located in the underground laboratory in Modane (Laboratoire Souterrain de Modane,LSM), where the muon flux is reduced to $5\,\mu/\mathrm{m}^2/\mathrm{d}$,(!cite). The remaining muons are tagged by a muon-veto system of 46 plastic scintillator modules.

Since the start of EDELWEISS experiment, the modules as well as the electronics have decayed significantly. The goal of this presented work is to estimate the stability of the muon veto system over long term measurements. Four scintillator modules are equipped with LEDs to moniter the stability of the system. The LED induced events are first analysed to determine the stability of these modules. Muon events are selected and analysed for all 46 modules.

In chapter 2 the case of dark matter with focus on WIMPs is discussed.

2. Search of WIMPs with EDELWEISS experiment

Nowadays, the search for dark matter becomes one of the central topics in astroparticle physics. Numerous experiments aim to search for dark matter.

2.1. Evidences of dark matter

In 1933, while studying on the velocity dispersion of galaxies inside the Coma galaxy cluster, F.Zwicky inferred the existence of some kind of unseen mass, which he called *dunkle Materie* (dark matter). Since then, his idea was supported by numerous observations on different scales – e.g. CMB, the Bullet Cluster. The Bullet Cluster (1E 0657-56) consists of two clusters, which collided around 100 Myrs ago. Using gravitational lensing and X-Ray analysis, it is found that the two galaxy concentrations have moved ahead of their plasma clouds, which indicates the existence of weak-interacting dark matter. In the following a more detailed description of evidence of dark matter in galaxy is given.

Galaxy rotation curve

2.2. WIMP as dark matter candidate

2.3. EDELWEISS-III Experiment

The EDELWEISS experiment is dedicated to detect the scattering of WIMP on ordinary matter at kryogenic temperature. In order to achieve the expected sensitivity down to 10^{-9} pb, the main challenge is to exclude all the bacgrounds induced by radioactivity or cosmic rays. The general setup of the experiment and the possible backgrounds are summarized in section 2.3.1. The remaining backgrounds can be discriminated by measurements of two channels of the signal. This working principle of Germanium Bolometers is briefly described in section 2.3.2. The problematic muon-induced neutrons, which cannot be distinguished from the WIMP-signal, is described in detail in chapter 3.

2.3.1. Experimental setup and backgrounds at EDELWEISS

The EDELWEISS experiment is located in the underground laboratory of Mondane (*Laboratoire Souterrain de Modane*, LSM). Under 1780 meters of rock, the cosmic muon flux is reduced by more than a factor 10^6 to a reamaining rate of $5\,\mu/\mathrm{m}^2/\mathrm{d}$, The remaining throughgoing muons are tagged with an active muon-vetor system, which is the outermost layer of the setup. (see fig.2.1). A detailed description and working principle are given in chapter 3.

The next layer is a polyethylene (PE) shield of about 50 cm thickness to attenuate the neutron flux from the radioactivity of rock and experiment materials. The fast neutron flux with energy above 1 MeV, which produces similar recoils as from WIMPs, is reduced

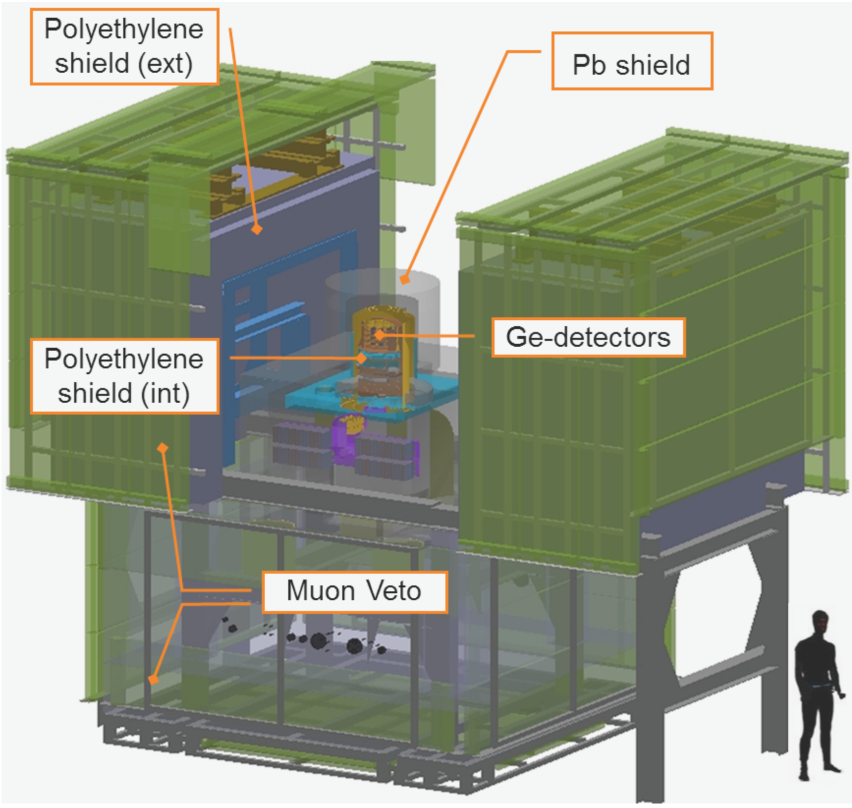

Figure 2.1.: Schematic view of EDELWEISS experimental setup. In the center are the Ge-bolometers hosted in a cryostat. The cryostat is surrounded by a lead shield, a PE shield and an active muon veto system to minimize the backgrounds.
Extracted from [Kéf16].

by 5 to 6 orders of magnitude. Next to the PE shield is a lead shield of 20 cm thickness to reduce the ambient γ background. The nature lead contains radioactive isotopes–e.g. ^{210}Pb, ^{238}U and ^{232}Th, which also contribute to the background. To reduce its natural raioactivity, the innermost 2 cm of the shield is made of Roman lead discovered in a sunken ship. The ^{210}Pb has a half-life of $T_{1/2} = 22$ years, so that it's abundance is decreased by two orders of magnitude. Another source of background is the ^{222}Rn as a decay product of ^{238}U. The upper part with the cryostat is installed in a clean room with renewing air to minimize the radon level. The space between the lead shield and the cryostat is flushed with filtered air. The upper part of the shieldings are mounted on rails and can be opened in halves to access the cryostat and electronics. Additional layers of PE and lead shields are installed inside the cryostat to reduce the background induced by electronics and cables.

The cryostat is a ^{3}He/^{4}He dilution refrigerator made of low-radioactivity materials. The detectors are enclosed in five thermal screens and the temperaturs decreases from room temperatur over 100 K, 40 K, 4 K, 1 k to 10 mK. In standard operations, the temperature of the detectors is tuned to $T = (18.000 \pm 0.002)$ mK.

2.3.2. Working principle of Ge Bolometer

The bolometers used in EDELWEISS experiment are made of high-purity monocrystalline germanium. They are equipped with aluminium ring electrodes and glued with 2 Neutron Transmutaion Doped (NTD) sensor.

The thermalized phonon signals are measured via the change of resistence of the NTD Ge sensors. The small temperature rise resulted by a energy deposit E_{rec} is

$$\Delta T = \frac{E_{\mathrm{rec}}}{CT} \tag{2.1}$$

by which $C(T)$ is the total heat capacity of the germanium crystal and two NTD sensors. The temperature dependency of resistence is given by

$$RT = R_0 exp\sqrt{\frac{T}{T_0}} \tag{2.2}$$

with charakteristic constants $R_0 = \mathcal{O}(0.1\,\Omega)$ and $T_0 = \mathcal{O}(1\,\mathrm{K})$. At the operating temerature of 18 mK, the resistence becomes a few MΩ. The NTD sensors are biased with a square modulated current and the resistence change is obtained by change of the voltage.

For each event, the ionization energy E_{ion} is simultaneously measured. Electron-hole pairs are produced in the germanium crystal for a energy deposit over 2.96 eV.The created charged carriers are drifted to the biased electodes and collected.

The discrimination between electron recoils and nuclear recoils is based on the the ionization yield Q, defined as the fraction of ionization energy and recoil energy:

$$Q = \frac{E_{\mathrm{ion}}}{E_{\mathrm{rec}}} \tag{2.3}$$

Since the WIMPs and neutrons scatter off nuclei, the required energy to produce a pair of charge carriers is higher than which of electron recoil. The most energy deposited by nuclear recoils are directly trainsmitted to phonons, which leads to a generally smaller ionization yield than electron reocoils.

The heat and ionization channels are calibrated with the 356 keV line of ^{133}Ba, which induces electron recoils.With the ionization yield of electron recoils set to 1, the neutron ionization yield is determined with a neutron calibration:

$$Q_{\mathrm{n}} = 0.16 \cdot (E_{\mathrm{rec}}[\mathrm{keV}])^{0.18} \tag{2.4}$$

With combination of the heat and ionization measurements, the electron recoils can be distinguished from the neutron recoils. Therefore, the remaining problematic background is neutrons, respectively produced in muon-induced showers or muon-nuclear interactions.

3. Muon detection in EDELWEISS experiment

Despite the rock overburden of LSM reduces the cosmic muon flux by 6 orders of magnitude, the remaining muons can produce neutrons and mimick WIMP signals WIMPs. These muons are tagged by an active veto system. The general setup and the working principle of the system is described in this chapter. The description is mainly based on the doctoral thesis of Kéfélian. [Kéf16]

3.1. Setup of the Muon veto system

- General Setup
- Scintillation Module

The muon-veto system is the outermost layer of shieldings and covers a surface of $100\,\mathrm{m}^2$. As shown in the fig. 3.1, it is made of 46 plastic scintillator modules. The modules are labelled from 1 to 48. Each wall is labelled according to the orientation. The western wall is named "Nemo", which is the name of the neighbour experiment in LSM. The muon-veto is divided in two levels, the upper level made of 30 modules locates in a clean room and host the cryostat and the detectors. The lower level has 16 modules. As described in section 2.3.1, the upper level is mounted on rails and can be opened in two parts to grant access to electronics.

To cover the gap resulted from the opening of the upper parts, M7, M8, M15 and M16 are installed in 2010. The four extra modules are equipped with LEDs to moniter the stability of the system. M7 and M8 have 3 LEDs along their axis, each of M15 and M16 has one LED installed in the middle. M7 and M8 are 2.1 m long. M15 and M16 are around 1 m long and cover only partly the opening of upper part.

The other modules have a width of 65 cm and a thickness of 5 cm. Their lengths varies from 2 m to 4 m. Due to the opening for electronics and the shorter length of some modules, the overall geometric efficiency is 98%. However, the muon going through the gap can partly be detected via the particle showers induced by them.

A group of four Photomultiplier Tubes (PMT) are installed at each module end. Each PMT group is individually biased with a high voltage (HV). The HV values are set around $-1500\,\mathrm{V}$ and seldom changed over years to compensate the aging effect of the modules. To ensure the system is fully closed while operating, two lasers measure the position of two halves of the upper part every 15 minutes. One measures the distance from the western wall to M6, the other from the eastern wall to M8. The gap width is calculated by substracting the two distances.

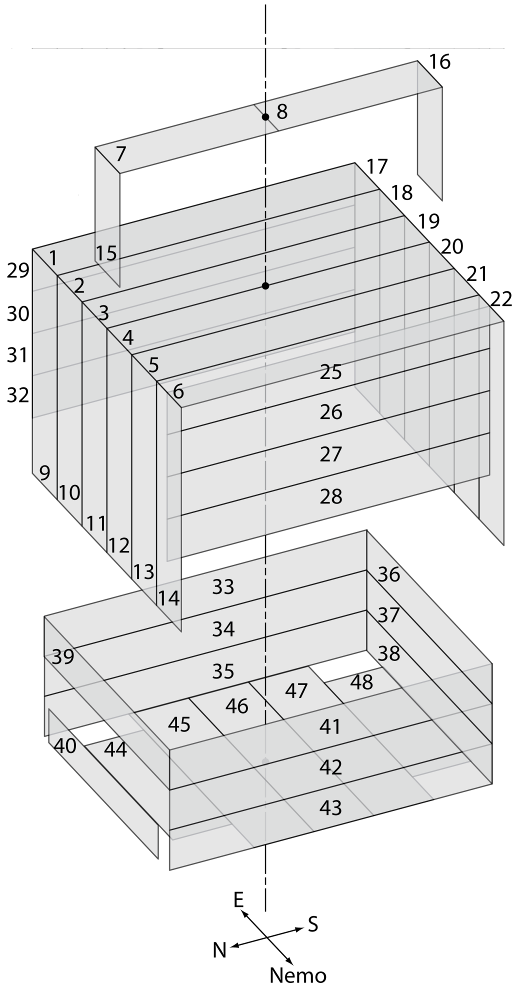

Figure 3.1.: Schematic view of Muon-Veto System. Each wall of the system is labelled according to its geometric orientation in the laboratory.

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3.2. Working Principle of Muon veto system

- Muon Energy deposit / scintillation light
- (Electronic,data aquisation)
- available values of the ROOT data (ADC,TDC...)

3.2.1. Muon Energy deposit in the scintillator modules

The average muon energy at LSM is $< E_{\mu} >_{\mathrm{LSM}} \approx 260\,\mathrm{GeV}$. The high energy muons deposit 2 MeV/cm in the muon-veto modules according to the Bethe formula. Since the scintillator modules have thickness of 5cm, the muon energy deposit in a module is typically above 10 MeV. Therefore, the muon events can be separated from the background events with energy deposit normally lower than 4 MeV, which reduces the deadtime of the experiment. The stochastic process of muon energy deposit can be described by a Landau distribution.[Lan44] Such distribution is asymmetric and has a long tail towards high energy region. To avoid the contribution of large energy deposit from the long tail, the most probable value (MPV) is usually taken to characterize the distribution. The total energy deposit of muon is also dependent on its path length in a module. The spectrum is thus smeared due to the different orientation of modules and the angular distribution of muon flux. Most muons at LSM have small zenith angle, therefore the muons deposit minimal energy in top and bottom modules and the track length is of the order of the module thickness. It is also possible that a muon goes through the edge of a module, which is called a *grazing muon*. In such case, the muon traverses only partly the module thickness and deposits lower energy.

Position-dependent light output

3.2.2. Readout electronic chain

The scintillation photons reflect in the module and are guided to the PMT groups. In a PMT group, the photons are then converted to electrons and amplified to a measurable electric signal. Once the signal amplitude is over the trigger threshold, the signal is integrated in the Analog-to-Digital-Converter (ADC) card to obtain the total energy deposit of muon in a module. At the mean time, the Time-to-Digital Converter (TDC) card stores the time of the signal. If there is a coincidence of 2 PMT groups within 100 ns time window, all non-zero signals of the muon-veto system are stored as one event. After the triggering, there is dead-time of $\tau = 0.16\,\mathrm{ms}$ when no events can be detected. The trigger threshold is set to 150 mV to ensure the detection efficiency of low energy events without introducing to much dead-time.

3.2.3. Available Data of the Muon-Veto Run

4. Analysis of the LED data

As described in Chapter 3, the four extra modules added in 2010 covering the gap of veto system are equipped with LEDs. M7 and M8 have three LEDs: one at the center and the other two at two ends. M15 and M16 both have one LED installed at the center. The LEDs send out pulses every eight hours. The LED data are used to perform a stability controll of the μ-veto system. They are clearly defined comparing to muon induced events, therefore the LED events are good probe to estimate the long term stability of these four modules.

4.1. Data selection

The data of muon-veto Run70 to Run138 are used to analyze the aging effect of the veto system. This corresponds to a date from 24.08.2010 to 28.03.2017. When converting the raw data to ROOT-format, the events induced by LED firing are flagged. Therefore, they are easily separated from other events. The LEDs fire three times every day. Each LED fires 60 pulses in one minute and they fire one after another, which also allows a separation of signals from different LEDs in M7 and M8.

4.2. Long term stability

The LEDs are fixed on the modules, so the energy spectrum is not smeared by the position dependent light readout. Also, the LEDs are supposed to have constant light output over short time. Thus the spectrum can be fitted with a gaussian function to get the average ADC values of several series. To increase the statistical power of a single point, events of nine shot series (three days) are combined to perfom a gaussian fit. An example of such fit is illustrated in fig.4.1.

The mean ADC values obtained from each gaussian fit are plotted over time. A change of these values over time could be due to various effects, e.g. decrease of the LED light output, aging of scintillator modules, problem of the PMTs or readout elctronics. To identify the contribution of different factors, the values are plotted separately for two PMT groups and three LEDs (for M7 and M8). Linear regressions are made for each data set, see fig.4.2. The lines with different color represent the data from different LEDs.

As can be seen in the figure, the mean ADC values of two off-center LEDs differ about 1000 canals from the far end to the near end.

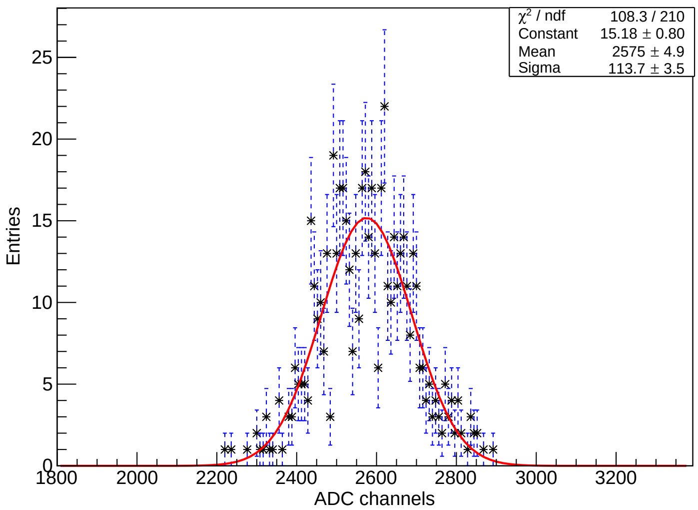


Figure 4.1.: Example of an gaussian fit to nine LED fire series in Module 8, north PMT group. The spectrum is fitted with log likelihood method in ROOT.

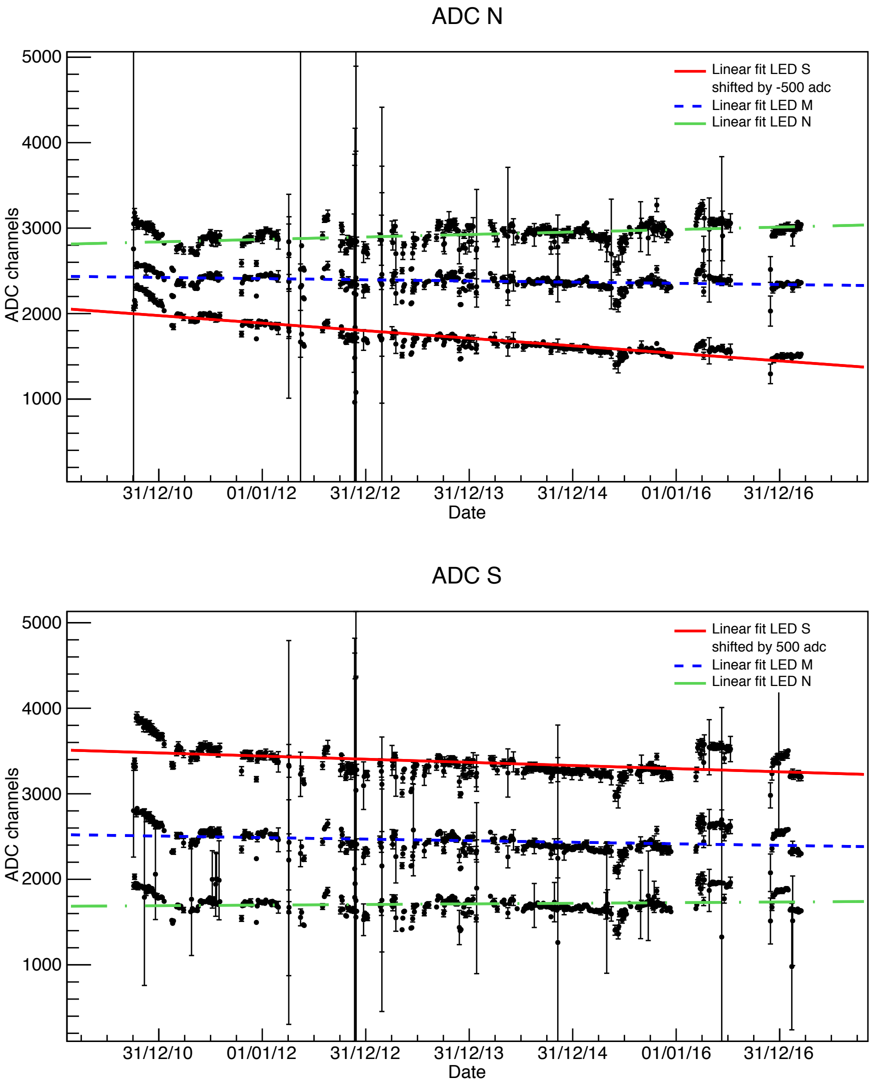
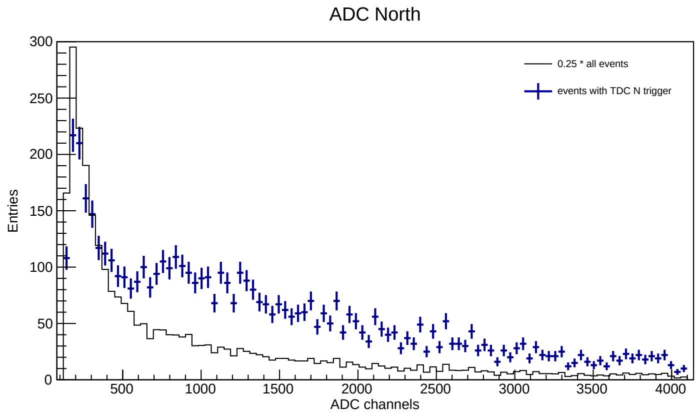


Figure 4.2.: The ADC values of LED signals over time in Module 8.
The energy deposit of LED signals in ADC channels from Run70 to Run138 are plotted separately for 2 PMT groups (north in upper chart, south in lower chart). The trend of ADC values of different LEDs over time are approximated by linear fits: the green line (LED north), the blue line (LED middle), and the red line (LED south). For clarity reasons, the signals of the south LED are decreased by 500 channels in upper chart and increased by 500 in lower chart.

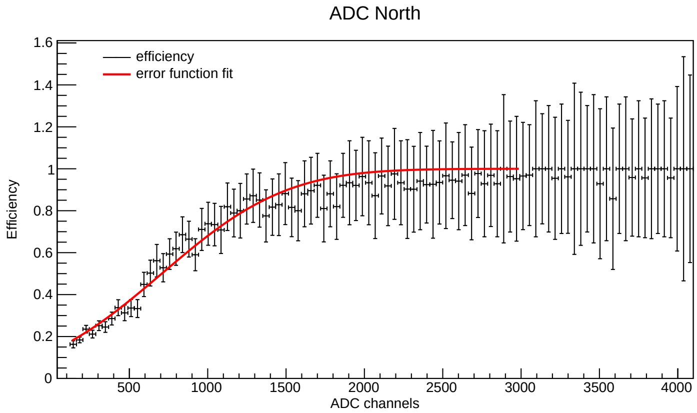
5. Determination of the long term stability using muon events

5.1. Determination of the effective threshold

- conversion threshold,effective threshold
- method to determine threshold
- result, change of efficiency



(a)



(b)

6. Conclusions

Appendix

A. First Appendix Section

Wonderful Appendix!

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