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Energy calibration of large underwater detectors using stopping muons

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Abstract

We propose to use stopping cosmic-ray muons in the energy calibration of planned and deployed large underwater detectors. The method is based on the proportionality between the incident muon energy and the length of the muon path before it stops. Simultaneous measurements of the muon path and the amplitude of the signal from the photomultiplier tubes allow a relation between the energy deposited in the sensitive volume of the detector and the observed signal to be derived, and also provide a test of detector simulations. We describe the proposed method and present the results of simulations.

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1. Introduction

Several large neutrino telescopes have been proposed and are being deployed deep under water or under ice [1, 2, 3, 4]. They are designed to measure the fluxes and spectra of high-energy astrophysical neutrinos by detecting muons produced via neutrino-nucleus interactions. While these telescopes are designed to detect up-going muons produced by neutrinos passing right through the Earth, they can also detect down-going atmospheric muons. For most applications, such muons are a background which can be suppressed by several orders of magnitude by the measurements of the arrival times of Cherenkov photons and proper reconstruction of the muon track. These muons, however, being of known origin with predictable flux and spectrum, can serve also to test detector Monte Carlo and calibration techniques. One possible application of atmospheric muons is the energy calibration of the detector.

The energy of a muon above 1 TeV can be derived from the number of collected Cherenkov photons (converted to the amplitude or ADC channel). Since for high-energy muons the mean energy loss is proportional to the muon path and energy (stochastic energy losses dominate over ionisation loss), the muon energy loss inside the detector volume (number of produced Cherenkov photons) can be a measure of muon energy if the muon path is reconstructed. This concept of muon energy measurement is proven by various simulations [3, 5, 6, 7]. The simulations are usually based on full three-dimensional Monte Carlo simulations of the detector including muon energy loss, production and propagation of Cherenkov photons, response of photomultiplier tubes and electronics. The question is: how well can all the characteristics of all the elements of the detector be known or how accurately can they be measured with test light sources such as LEDs and lasers? Is it possible to check the simulation based predictions independently? In other words: can we know the muon energy from some other independent source, which we can then compare with Monte Carlo predictions and the measurement of the signal amplitude?

In the physics of keV-MeV energies there is a simple answer to a similar question. There are specific radioactive sources with mono-energetic X-ray or gamma-ray lines which are routinely used for energy calibration of detectors. Only accelerators can provide a quasi-monoenergetic particle beam at GeV-TeV energies, but they are usually located far from large underwater or underground detectors. Underground neutrino telescopes and cosmic-ray muon detectors, being smaller in size (compared to underwater detectors) and segmented structure, cannot measure the energy of high-energy muons but can use their mean or peak energy losses together with their path to calibrate the detectors (see, for example, [8]). For the larger underwater detectors this method can hardly be applied because the peak in the muon energy loss distribution is smoothed by stochastic losses due to bremsstrahlung, pair production and inelastic scattering over the long muon path.

We propose to use stopping atmospheric muons for this task. They have the advantage that their incident energy can, in principle, be measured through their path in the sensitive volume of the detector and, hence, can be compared to the observed signal and predictions of simulations. In Section 2 the basic idea of calibration is described and in Section 3 main requirements for the detector hardware and software are given. Results of our simulations for a simplified detector are presented in Section 4 and the conclusions are given in Section 5.

2. Energy calibration of underwater detectors

Usually energy calibration means the relation between particle energy and the amplitude of the signal processed by DAQ. This definition is correct if the particle energy is totally absorbed in the detector. For underground detectors most muons are not absorbed in the detector and the relation can be derived only between the observed signal and the energy deposited in the detector. Usually it is assumed that this relation is linear.

Since there is no mono-energetic source of muons underwater, normal methods of calibration cannot be applied. A mono-energetic source is not necessary, however, if we can determine the muon energy from another measurement. There is no way to measure the energy of individual muons from the whole muon population, but there exists a sub-sample consisting of stopping muons for which the incident energy can be known from the measurement of the muon path length between the point where the muon enters the sensitive volume of the detector and the point where it stops. The idea of the method is to measure the muon path if it stops within the sensitive volume of the detector, to calculate its initial energy using the energy-range relation and to compare it to the measured signal amplitude, thus deriving the relation between the amplitude and the deposited energy and checking Monte Carlo predictions. Subsequently, the relation between the measured amplitude and the energy deposition can be used to estimate the energy of through-going TeV muons.

One of the crucial points of the method is an estimation of incident muon energy from the muon path length. Simple considerations show that, since low energy muons (only such muons stop in the detector) mainly lose energy via ionisation and atomic excitation without undergoing stochastic energy loss, for most muons a simple linear relation will work without large fluctuations. The results of the simulations will be shown in Section 4.

Another important question is: can large underwater detectors measure path length of a stopping muon with sufficient accuracy? This is discussed in the following section.

3. Detector performance

What are the performance requirements of an underwater detector for it to be able to use stopping muons for energy calibration?

1. Such a detector should be sensitive to down-going atmospheric muons. This is not necessarily true since neutrino telescopes have most (and possibly all) optical modules looking downwards. Measurements of the depth-intensity relation for down-going muons by the AMANDA and Baikal Collaborations [2, 9] prove that down-going muons can be reconstructed and their fluxes can be measured.

2. Separation between optical modules should not be large to allow i) the detection of weak signals from low-energy muons and ii) the determination of the stopping point of the muon with sufficient accuracy. Requirement i) may reduce the sensitive volume of the detector for this task but is unlikely to make the energy calibration impossible. (Note, that the Baikal energy threshold has been estimated as 10 GeV [1] which is well matched to our requirements). The requirement ii) is the most important. The distance between optical modules on one string varies from 6 to 20 metres, while the distance between strings is 20-80 metres for different arrays. Simulations performed by the ANTARES Collaboration [3, 7] for neutrino oscillation studies show, however, that contained and semi-contained neutrino-induced events can be successfully discriminated from through-

going muons and, hence, both the points of muon production and absorption can be determined. Full reconstruction of muon events is more difficult, of course, in the case of down-going muons because of their large number. But even a fraction of stopping muon events (well-reconstructed) may be enough for energy calibration. (Note, however, that there is a danger of selecting a sub-sample of reconstructed stopping muons with characteristics different from those of the whole population of stopping muons).

3. The rate of stopping muon events should be large enough to perform calibration in a feasible period of time. This requirement may be more difficult to satisfy at deep sites. We will present our estimates in Section 4.

4. Even if all requirements are satisfied, the proposed method cannot avoid the use of detector simulation. This is due to the dependence of the observed amplitude on the distance to the muon track. Imagine two vertical muon tracks, one close to the string of optical modules and another far away from the string. Even if the lengths of the tracks are equal and the incident muon energies are equal too, the observed signals will be different due to different distances from the tracks to the phototubes. Such simulations have already been performed by the collaborations [2, 3, 6]. The results depend strongly on the properties of water/ice. The propagation of Cherenkov photons is not included in our simulations, the assumption being that appropriate corrections for the distance between optical modules and muon track can be made for a particular detector if the track coordinates are fully reconstructed.

5. Finally, multiple muon events can present a source of background for stopping muons. Again, measured depth-intensity curves [2, 9] prove that at least some of the muon tracks can be reconstructed properly.

As previously mentioned, there is a problem of possible bias in the calibration if the sample of stopping muons that can be reconstructed has particular characteristics different from those of the whole population (for example, energy loss higher than the mean value). However, the probability of enhanced energy loss along the whole muon track is extremely low. High amplitude photomultiplier hits due to occasional muon-induced local cascades can be excluded from the analysis. The presence of bias can be detected by comparing the shape of the measured distribution of specific energy loss with the simulated distribution.

4. Simulation of stopping muons

In this section the results of simulations are presented which demonstrate that energy calibration, in principle, can be performed using stopping muons. Further investigation of this question can be made for each individual detector using appropriate software packages including the detector design and characteristics.

The simulation was done in the following way: muons were sampled according to their energy spectrum and angular distribution at a particular depth underwater, propagated through the detector volume and their initial and final characteristics were stored on disk. Energy spectra and angular distribution of muons under water were obtained by propagating muons with various initial energies from sea level down to various depths in water using the muon transport package MUSIC [10]. Then, muon energy distributions underwater were convolved with muon spectra at sea level using the relevant parameterisation from [11].

To check the correctness of the procedure we calculated the muon “depth – vertical intensity” relation and compared it with those measured by the Baikal [9] and AMANDA [2] experiments. The results are shown in Figure 1. Measured relations are well fitted

to the calculated relation assuming the power index of the primary spectrum is equal to 2.78 – in good agreement with underground experiments [12, 13].

A special package was developed to sample single muons according to their spectra and angular distribution underwater: MUSUN (MUon Simulation UNderwater/UNderground) [14]. As an example, we present here the results for the depth of 2 km under water. This corresponds approximately to the depth at which ANTARES will be deployed [15] and is 0.5 km deeper than the AMANDA site. A simple detector in the form of cylinder with a radius of 100 metres and a height of 500 metres was used. This cylinder represented the sensitive volume of the detector. Muons were sampled uniformly on the upper surface of the cylinder. We required also that the muon track (real or extended if the muon stopped) crossed the lower flat surface of the cylinder. It was assumed that the muon track and stopping point can be accurately reconstructed if the muon traversed between 100 metres and 400 metres of water inside the cylinder.

Figure 2 shows a scatter plot of initial energy versus track length for stopping muons with track lengths between 100 and 400 metres. No systematic uncertainty in track reconstruction was included. There is a clear proportionality between track length and initial energy with small fluctuations for most muons. Some of them, however, undergo, a large stochastic energy loss. Figure 2 can be converted into the distribution of specific energy losses (per unit track length). This is shown by a dash-dotted line in Figure 3 for the same stopping muon sample. The distribution is characterised by a narrow prominent peak which corresponds to the most probable specific energy loss. In practice, the track length can be reconstructed with some finite accuracy. If we assume that the reconstructed track length distribution follows a Gaussian distribution with mean value equal to the true value of the track length and standard deviation equal to 40 metres (at least twice the vertical distance between the modules on the string) the peak becomes smoother but is still present (dashed line in Figure 3). (Note, that the simulations of the ANTARES performance for neutrino oscillation study [3] show that the starting and stopping points of more than half up-going muons can be reconstructed with an accuracy of better than 30 m).

All previous results have been obtained assuming no fluctuations in the number of detected photons due to various distances between the optical modules and muon track. Such assumption is equivalent to the precise reconstruction of the position of the muon track with respect to the optical modules and correction for such fluctuations. It is unlikely, however, that this scenario is realised in practice. To account for the fluctuations in the number of collected photons in our simulations we sampled the reconstructed energy deposition according to a Gaussian distribution on the $\log(E)$ scale with mean value equal to the true energy deposition (which came as an output from the muon propagation code) and standard deviation equal to 0.176 on the $\log(E)$ scale (factor 1.5). The choice of the standard deviation for simulations was based on the known fact that the energy of multi-TeV through-going muons can be reconstructed with an accuracy of 0.4-0.5 on the $\log(E)$ scale [3, 6]. For high-energy through-going muons, however, the energy resolution is determined mainly by the energy loss fluctuations, while this effect (being much smaller for low-energy stopping muons) is included separately in our simulations. We included also the statistical fluctuations in the number of detected photoelectrons assuming that on average an atmospheric muon produces about 1 photoelectron per 1 GeV of energy deposition. To derive this number we used the mean number of photoelectrons produced by an atmospheric muon in the Baikal detector, quoted in [1] (23 photoelectrons), the

length of Baikal string which is equal to 72 metres, and the mean energy deposition in water which is about 300 MeV/m. We assumed also that the energy threshold of the detector is equal to 20 GeV. The results of the simulations are shown in Figure 3 by solid curve. The distribution of specific energy losses is broader than in the simpler case when we did not account for the fluctuations in the number of detected photons. For comparison, we present also a similar distribution for through-going muons which pass more than 400 metres of water in the sensitive volume of the detector. It is obvious, that the distribution of specific energy losses for stopping muons is more favourable for the use in the energy calibration procedure. This does not exclude, however, the possibility to use such a distribution for the through-going muon sample either as an additional test or in the case that our assumptions about possible fluctuations were too optimistic.

The position of the peak calculated for each individual detector can be used to convert the measured track length of a stopping muon to its initial energy which can then be compared to the measured signal. For our simple detector at 2 km depth the rate of stopping muons which can be reconstructed is about 0.3 s^{-1} .

Another important issue which we want to address in the discussion, is the contamination from multiple muons. Multiple muons contribute from a few percent to a few ten percent of the total muon flux even for very large detectors. Their contribution decreases with depth. Such events produce more light and hence, may be detected with higher probability than single muons. If so, they can smooth the observed distribution of specific energy losses.

To estimate the effect from multiple muons we simulated the development of vertical Extensive Air Showers initiated by primary protons using the code CORSIKA [16]. Then, we propagated all muons down to 2 km of water with MUSIC and repeated simulations of muons (both single and multiple) in the detector. The results are presented in Figure 4. Solid curve shows the distribution of specific energy losses for single muons. Note that the distributions shown by solid curves in Figures 3 and 4 are very similar, though only vertical muons have been simulated with CORSIKA. Then, we assumed that only events with total observed energy more than 20 GeV, regardless of the muon multiplicity, can be detected. We assumed also that multiple muon events could be reconstructed as stopping single muons only if all muons stopped inside the detector. In this case the reconstructed track length corresponded to the muon with the longest range. The results are shown in Figure 4 by dashed curve. From Figure 4 we conclude that multiple muons do not change significantly the distribution of specific energy losses for stopping muons. The contribution of multiple muons from heavy primaries and from inclined directions can modify slightly calculated distribution of specific energy losses but is unlikely to change this conclusion.

It is possible that the number of Cherenkov photons emitted by a low-energy muon is not enough to hit a phototube if the muon does not pass very close to it. In this case, only muons passing very close to the strings can be used for calibration and a single string analysis technique can be used (each string represents a separate detector). The basic features of the method remain the same, however, due to the reduced acceptance, the rate of reconstructed stopping muons will be approximately 2 orders of magnitude less (if a 10 m radius single string detector is used).

5. Conclusions

A method of energy calibration of large underwater detectors using stopping muons

has been described. The method is proven to work by Monte Carlo simulations for a simple (“ideal”) detector. Further investigations involving structure and characteristics of specific neutrino telescopes are needed.

6. Acknowledgements

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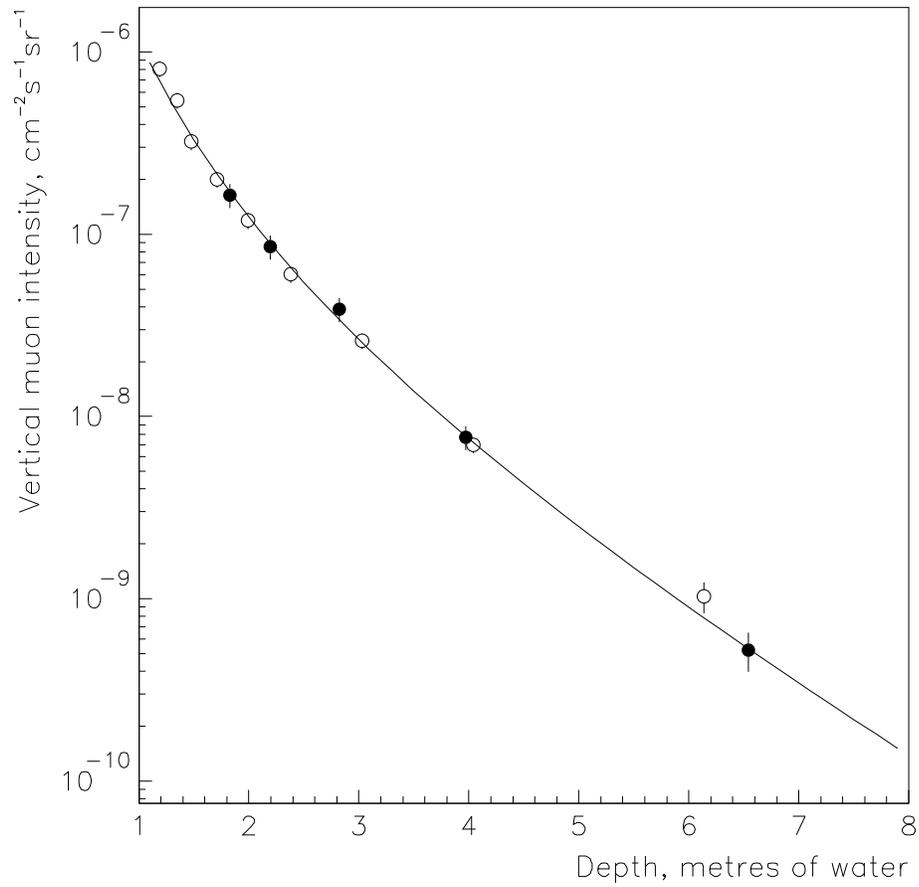


Figure 1: Measured depth – vertical muon intensity relation under water fitted to the model described in the text. Data are from [2] (filled circles) and [9] (open circles).

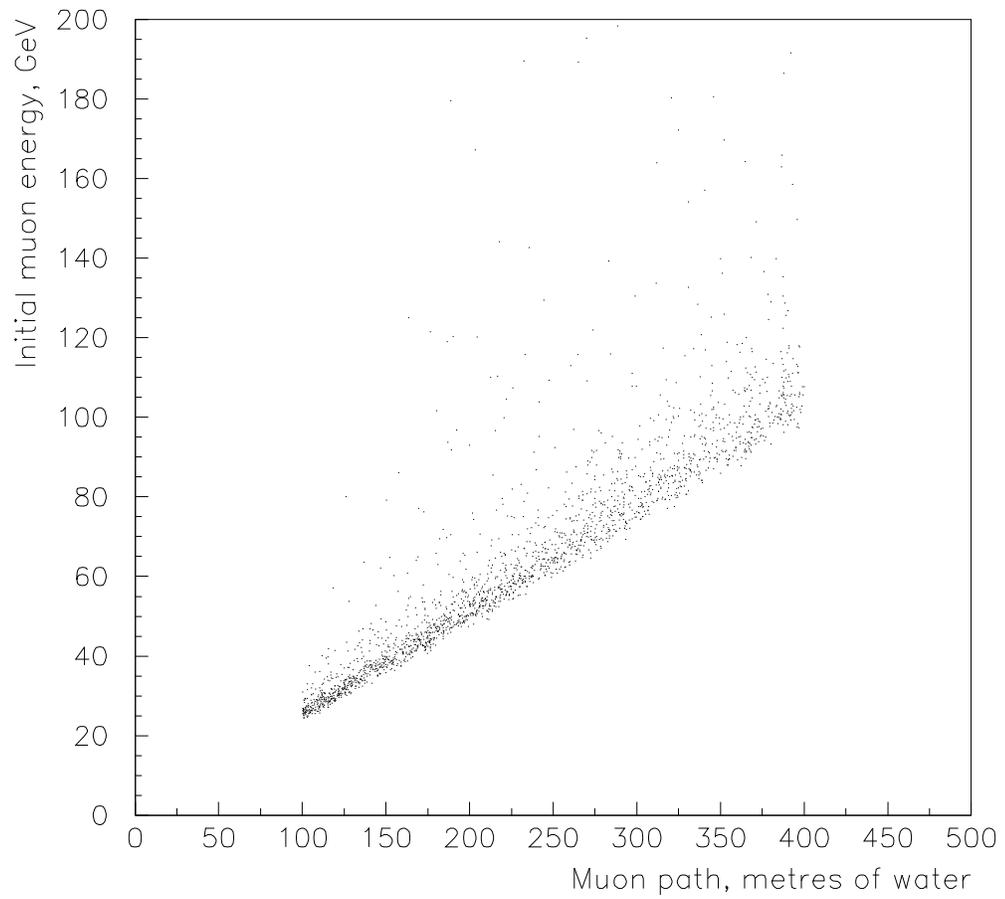


Figure 2: Scatter plot of initial muon energy versus muon path for muons stopping in the underwater detector (see text for details).

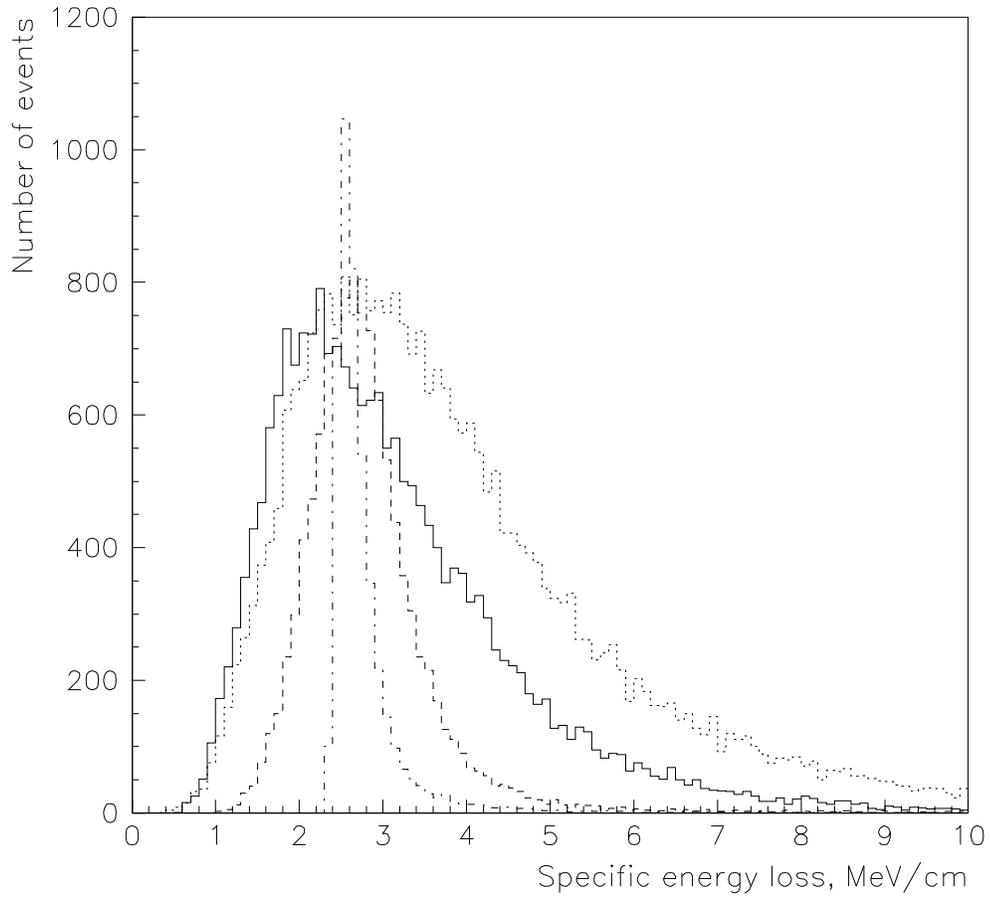


Figure 3: Distribution of specific muon energy losses (energy losses per unit track length). Dash-dotted curve – stopping muons without uncertainty in the track reconstruction and measured energy deposition (scaled down by a factor of 5); dashed curve – stopping muons with 40 m uncertainty in the track length reconstruction (scaled down by a factor of 2); solid curve – stopping muons with the uncertainties in the measured energy deposition and track length; dotted curve – through-going muons with the uncertainties in the measured energy deposition and track length (see text).

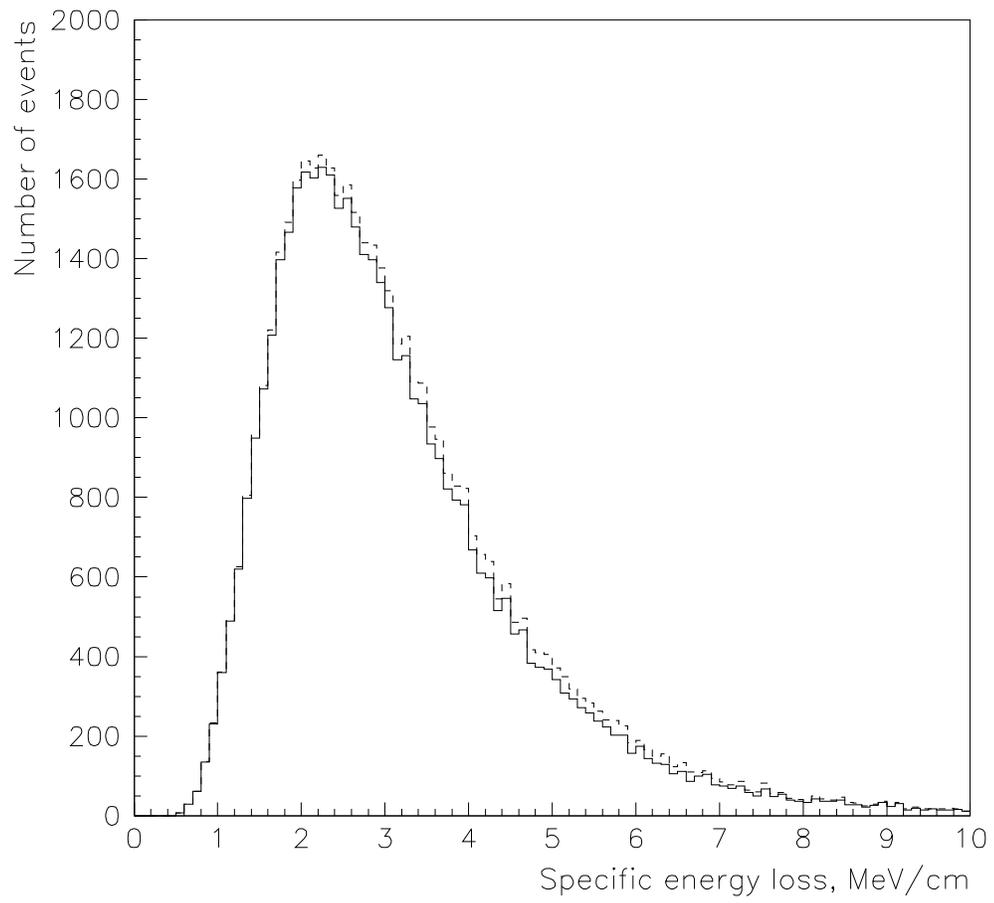


Figure 4: Distribution of specific muon energy losses for single muons (solid curve) and single+multiple muons (dashed curve).