Technische Universität München
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Target of Opportunity program based on IceCube high energy neutrino on-line alerts

„Target of Opportunity“ Programm basierend auf von IceCube automatisch übermittelten Meldungen über hoch energetische Neutrinos

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Chapter 1

Neutrino Astronomy with IceCube

IceCube is a neutrino detector located in the glacial ice at the South Pole. One of the scientific goals of this telescope is to measure for the first time astrophysical neutrinos and to discover their origin [1]. After having recently observed a diffuse flux of astrophysical neutrinos with IceCube [2] the goal is now to identify the astrophysical origin of these neutrinos. A contribution to the identification of neutrino sources can be made by so called target of opportunity programs (compare 1.3) by combining the signal obtained by neutrinos with a different kind of observations like gamma-ray or optical astronomy. A target of opportunity program would be able to observe coincidences between neutrinos and other astrophysical messengers in space as well as in time leading to an increased significance and to the possibility of identifying the sources of astrophysical neutrinos.

1.1 The IceCube detector

IceCube has been build near the geographic South Pole at the Amundsen-Scott station and was completed in December 2010 (Figure. 1.1). One km^3 of very clear natural glacial ice in a depth between 1450 m and 2450 m is used as a particle detector. A total of 86 strings each carrying 60 Digital Optical Modules (DOMs) has been deployed in the glacial ice between 2005 and 2010. These DOMs measure the Cherenkov light emitted by particles moving faster than the speed of light in the ice like cosmic muons or secondary particles from neutrino interactions. Each DOM consists of a photomultiplier and electronics to digitize the collected signal, all contained in a pressure sphere [4]. After registering an event, each DOM sends the data through the string to the IceCube Lab at the surface where the signals are processed further and stored.

The detector consists mainly of three parts, the actual IceCube detector, DeepCore and IceTop. IceCube is an in ice array with 78 strings with a spacing of approximately 125 m between the strings and a spacing of 17 m between the DOMs on one string. It is the main instrument to detect high energetic astrophysical neutrinos in the TeV to PeV range by measuring the light produced in the ice by secondary particles from neutrino interactions [5].

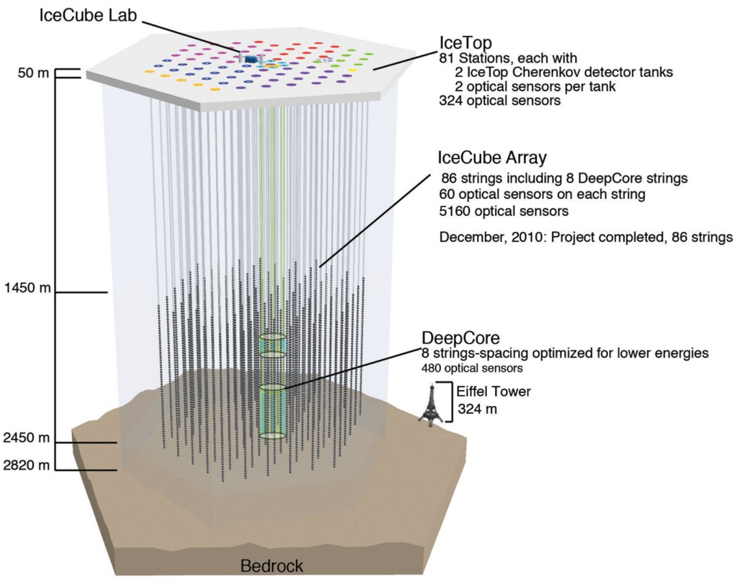


Figure 1.1: The IceCube detector in its final stage including the IceTop air shower detector and DeepCore an extension to lower energies (Ref:[3])

DeepCore is the low energy extension of IceCube, it consists of 8 strings in a denser geometry. The spacing between the strings is on average 72 m and the spacing between two DOMs on one string is 7 m. DeepCore is located at the bottom part of the array where the ice is extremely clear with a scattering length of the order of 40 m and a absorption length of the order of 200 m. The denser geometry and DOMs with a higher quantum efficiency allow DeepCore to lower the energy threshold to about 10 GeV and allow the study of atmospheric neutrino oscillation [6].

The last part is IceTop, an air shower detector that consists of 81 stations with each station consisting of two ice tanks. Two DOMs, similar to those in IceCube are deployed in each tank and measure the Cherenkov light produced by particles from cosmic air showers. IceTop is used to measure the cosmic ray spectrum up to EeV energies but is also used together with IceCube to veto muons from air showers [7].

1.2 Event Topology: Cascades and Tracks

In IceCube there are two event topologies, tracks and cascades. Tracks are the typical signature of a muon passing through the detector. The muon loses energy by several

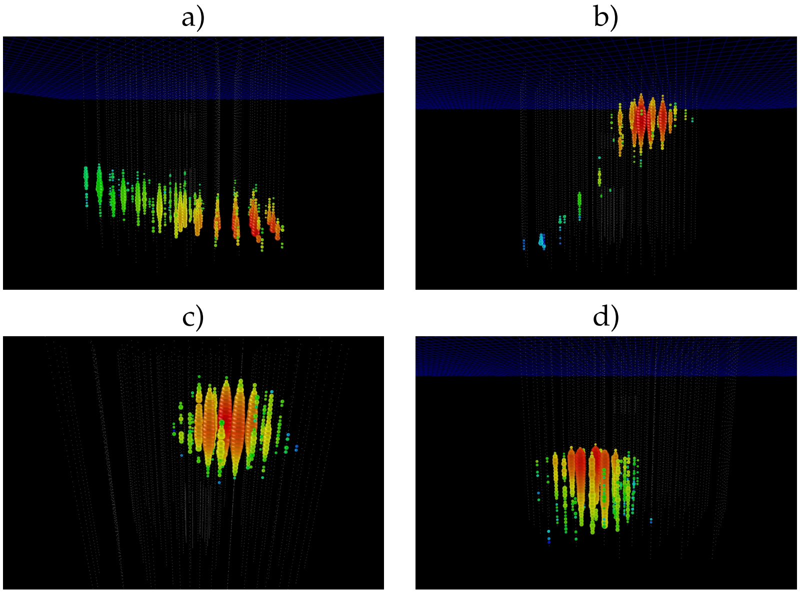


Figure 1.2: A view of some simulated neutrino events in IceCube. Each coloured bulb represents a DOM hit by one or more photons. The size of the bulb represents the total charge collected in the DOM which is a quantity to measure the number of photons detected. The color of the bulbs represents the time the DOM first detected a signal, the colour goes from red for early times to blue for late times. a) is the signature of a 600 TeV muon neutrino interacting below IceCube and producing a muon which is visible in the detector. b) shows a 150 TeV muon neutrino interacting in the detector. Both the hadronic cascade and the muon track are visible. c) is a cascade like event produced by a 1 PeV electron neutrino. The event in d) is produced by a 380 TeV muon neutrino, the secondary muon leaves the detector and the track can not be distinguished from the initial cascade.

effects like Cherenkov radiation or ionization all along its path. This energy is converted into light in the ice and the light is detected by the DOMs leaving a track of illuminated DOMs. From this track the direction of the muon can be deduced with a resolution of about one degree.

The detected muons are produced in cosmic air showers or in a charged current interaction between a muon neutrino and a nucleus or an electron[1]. The latter is the more relevant case for this work. In general the reaction products in a charged current interaction are a charged lepton, of the same flavour than the primary neutrino, and hadrons. In the case of a muon neutrino the produced muon can be, but not necessarily has to be, observed as a track. If the interaction happens outside IceCube but the neutrino comes from the northern hemisphere (Figure 1.2 a)) the track can be identified as neutrino induced because the earth filters out all muons. If the interaction happens inside the detector, additionally the hadronic products can be seen as a spherical cascade at the beginning of the muon track (Figure 1.2 b)). Depending on the energy and its distribution into the reaction products the hadronic cascade can be so bright that it outshines the muon track, which then leaves the detector unrecognised (Figure 1.2 d)).

Cascades are produced in all neutral current interactions and in charged current interactions of electron neutrinos and, depending on the energy and the type of decay of the secondary tau, of tau neutrinos.

Neutral current interactions are the same for all neutrino flavours, the neutrino scatters at a nucleus by the exchange of a neutral Z-Boson. The scattered neutrino leaves the detector and only the hadronic cascade is detected. In terms of IceCube the light emitted by the hadronic shower is point-like, which means the spacing between the DOMs is larger than the volume in which Cherenkov light is produced, and therefore the cascade event has a spherical geometry.

In case of an electron neutrino interaction, the topology is also a cascade (Figure 1.2 c)). The produced electron loses al its energy near the interaction vertex and the electromagnetic shower cannot be distinguished from the hadronic shower, so the emitted light appears to be from a point source, and the shape of the event is the same as for neutral current interactions.

In charged current interactions of a tau neutrino, it is predicted that if the energy of the neutrino is high enough, about a few PeV, the signature would be two nearby cascades. The first cascade is produced by the hadronic shower at the interaction point. The tau produced in the interaction is energetic enough to travel a few hundred meters and produces the second cascade when decaying into pions [1]. Such a "double bang" has not been observed jet.

At lower energies the tau does not travel far enough for the two cascades to be distinguished and the topology is the same as for electron neutrinos and neutral current interactions.

Based on the topology a simple flavour identification can be done by associating cascades with electron and tau neutrinos and tracks with muon neutrinos but one has to be careful since the neutral current interaction is the same for all flavours, a muon track may leave the detector unrecognised or even a tau may produce a muon track by decaying into a muon.

The most interesting topology to identify astrophysical point sources of neutrinos are tracks. At energies relevant for IceCube the direction of the muon track is nearly the same as the direction of the primary neutrino and due to the long lever arm the origin of the neutrino can be reconstructed very precisely, around a degree of resolution. It is also possible to reconstruct the direction of cascade-like events but by now the resolution cannot compete with tracks being in the range of 10 to 20 degrees.

1.3 Target of Opportunity Programs in IceCube

In terms of astronomy an object that was not planned to be observed, but is found to be worth observing is called a target of opportunity . This object is typically either unpredictable or predictable in a sense that it is predicted that these events happen but it is not known when or where they happen. Since it is not known when or where these events appear several telescopes offer the possibility to submit target of opportunity proposals for objects that are seen but need further investigations in coordination with other telescopes. This can be a follow-up observation or an observation using other methods or particles. An example for a target of opportunity would be an object like a gamma-ray burst or a supernova.

Currently there is an optical follow-up program using information from IceCube based on multiplets of muon neutrinos. It is looking for neutrinos from gamma-ray bursts and supernovae by sending alerts to the ROTSE (Robotic Optical Transient Search Experiment) telescopes [8].

Previously there has been a test run between AMANDA, IceCubes predecessor, and the gamma-ray telescope MAGIC where alerts were produced based on high energetic neutrino events. MAGIC then tried to observe the object in gamma-rays [9].

1.3.1 Neutrino Triggered Target of Opportunity test run with AMANDA-II and MAGIC

Between September and November 2006 a test run of a neutrino triggered target of opportunity program took place as a cooperation of the AMANDA and MAGIC collaborations. AMANDA (Antarctic Muon and Neutrino Detector Array) was the predecessor of IceCube installed at the same location and following the same approach by aiming at high-energy astrophysical neutrinos [9]. MAGIC (Major Atmospheric Gamma Imaging Cherenkov telescope) is a gamma-ray telescope located on La Palma.

High-energy neutrino events registered in AMANDA where used as a trigger if they came from predefined directions. Due to low statistics no multiplets but only single events where used that are very likely to be of atmospheric origin. [9]. The reconstruction of the neutrino events was done on-line and if an event was reconstructed within a range of a few degrees to one of the predefined sources an alert was sent to the MAGIC telescope. MAGIC then performed a follow-up observation looking for flares in gamma-rays [9].

Although no coincidences could be found the test run was successful in triggering alerts and showed for the first time that a target of opportunity program is possible with AMANDA and IceCube.

1.3.2 Optical follow-up program in cooperation with ROTSE

Gamma-ray bursts (GRBs) are among the candidates to produce the highest energetic cosmic rays as well as high-energetic neutrinos in ultra-relativistic jets [10]. Unfortunately the rate of GRBs with ultra-relativistic jets is small, but it is also possible that supernovae could produce mildly relativistic jets more frequently [11]. These mildly relativistic jets would be stalled in the outer layers of the collapsing star which leads to the absorption of the electromagnetic radiation but also to an efficient production of high-energetic neutrinos [10]. Therefore the hypothesis of such jets is difficult to test by observing electromagnetic radiation but is accessible for IceCube through neutrinos.

To connect possible neutrino events to this kind of supernovae an optical follow-up program in cooperation with the ROTSE (Robotic Optical Transient Search Experiment) telescopes has been operating since fall of 2008 [11]. IceCube is looking for neutrino burst, which are at least two events in a time window of 100 s with an angular difference between the reconstructed directions of less than 4°, and then sends out the direction information to the ROTSE telescopes which perform an optical follow-up observation [10].

In order to alert the optical telescopes in a reasonable time the reconstruction is running on-line directly at the South Pole. The search for neutrino events is limited to the Northern Hemisphere to get rid of muons from air showers that get absorbed by the Earth. The selection consist of different steps to remove the misreconstructed muon events from the South and is optimized to obtain about 25 background multilplets, which is the maximum number of alerts accepted by ROTSE. The background consists of muons from the south that are still misreconstructed and neutrinos produced in the atmosphere in air showers [10].

A multiplet is defined as two or more events in a time window of less than 100 s and an angular difference in the reconstructed direction of less than 4°. The size of the time window is motivated by the typical length of gamma-ray emission from GRBs of 40 s and the angular difference corresponds to the angular resolution of IceCube.

Multiplets are used instead of single neutrinos because it is most likely that a single neutrino is produced in the atmosphere and is no astrophysical neutrino. Additionally the rate of single neutrinos is far too high to alert on. If a multiplet is registered the direction information of the two events is combined and then sent out to the ROTSE telescopes.

Once the alert reaches the four ROTSE telescopes, installed in Australia, Namibia, the USA and Turkey, they start observing the corresponding region within a few seconds, adjusting their view automatically. This prompt observation is performed to detect the afterglow of a GRB with a fast decaying light-curve. Additionally a follow-up observation is conducted to register the rising light-curve of a possible supernova. [11].

After taking the images they are checked for an optical counterpart for the neutrino events, like the rising of a light-curve of a supernova. As of today no optical counterpart has been found which allows to set limits for the presence and properties of mildly relativistic jets in supernovae [10].

1.3.3 Alerts on High Energy Starting Events

The target of opportunity programs described above are using events that are most likely to be atmospheric neutrinos and then perform follow-up observations to check if the neutrino events were of astrophysical origin. By following this approach the majority of alerts produced are from background events and signal events only show up in an exceeding number of produced alerts or if coincidences are found in the follow-up observations. A problem is that in order to avoid accidental coincidences one has to limit the number of alerts produced, e.g. by looking for multiplets of events only, which reduces the sensitivity to signal events.

Since an event selection, described in section 1.4, has been developed by the IceCube Collaboration, which only selects events that have a high probability to be of astrophysical origin [12], it is now mandatory to think about a target of opportunity program based on these signal events. A diffuse flux of astrophysical neutrinos has already been discovered [2] and a target of opportunity program could help to identify the sources of these neutrinos, especially if they are emitted by transient sources.

1.4 High energy starting events

The High Energy Starting Event event selection, in the following called HESE, is an event selection used to detect a flux of high-energetic astrophysical neutrinos [2]. It is optimized to obtain only neutrino events from astrophysical origin and to remove background from muons and atmospheric neutrinos.

To remove the background from muons produced in air showers, the HESE selection aims for events that start in the detector. Only neutrinos can induce a signal where an interaction happens in the detector but nothing is seen entering the detector. To select these events, a veto region is used as shown in Figure 1.3.

If the first light detected from the event is somewhere in the veto layer the event is rejected. This should remove through-going muons from the atmosphere, nevertheless some muons may not deposit enough energy to produce light in the veto layer. To make sure that this is not the case, it is required that the total amount of light produced by the event is high enough that finding none of it in the veto layer

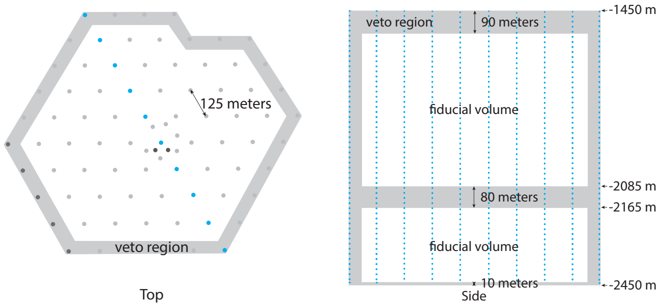


Figure 1.3: Graphic showing the IceCube array from above (left) and from the side (right). The gray shaded area is the veto layer used for the HESE selection. The veto is thicker at the top because most muon background comes directly from above. The veto region in the middle of the detector is used because there is a dust layer where the absorption of light is high and therefore muons could enter without triggering the veto. (Ref:[12])

is very unlikely [12]. The amount of light produced by the event is approximated with the total charge collected by the DOMs, in this case it is required that the total charge exceeds the equivalent of the charge produced by 6000 photo electrons (p.e.).

This selection also removes some of the atmospheric neutrino background. Coming from the Southern Hemisphere atmospheric neutrinos are usually accompanied by muons produced in the same air shower that deposit charge in the veto region, and therefore trigger the veto in 70% of cases[12], [14].

Also the spectrum of the atmospheric muons falls rapidly with increasing energy and thus for high energies the expected rate is small [1] and opens a window for the observation of astrophysical neutrinos which are predicted to have a harder spectrum (Figure 1.4). Figure 1.5 gives a summary of the expected backgrounds and the observed flux dependent on the deposited charge.

1.5 Limitations of the High Energy Starting Events selection

An event selection used for a target of opportunity program needs to focus on well reconstructed events to be able to alert other telescopes precisely. The requirements may differ, but so far the reconstruction of cascade-like events in IceCube cannot compete with the reconstruction of track-like events which sets the focus on tracks to be used for target of opportunity programs.

In Figure 1.6 the so-called Effective Area dependency on the energy for the HESE event selection is shown. The Effective Area is a quantity which measures the

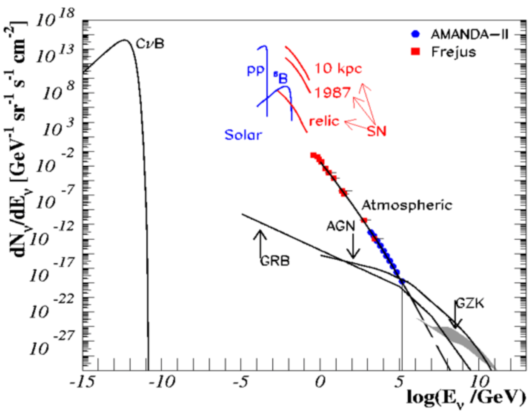


Figure 1.4: Neutrino spectrum of some cosmic sources. The displayed sources are the Big Bang (CνB), the Sun, supernovae (SN), gamma-ray bursts (GRB), active galactic nuclei (AGN), atmospheric neutrinos and cosmogenic (GZK) neutrinos. Above about 100 TeV the spectrum is dominated by astrophysical sources like gamma-ray bursts or active galactic nuclei. (Ref: [13])

sensitivity to a certain neutrino flux. The event rate can be obtained by multiplying the Effective Area with the solid angle and the neutrino flux. The Effective Area depends on the neutrino flavour and is the lowest for muon neutrinos. By aiming for events with good angular resolution, this is problematic because track like events are usually produced by muon neutrinos.

The reason for the lower sensitivity for muon neutrinos compared to other flavours is the charge cut applied in the HESE selection. The track produced by a muon neutrino in a charged current interaction is typically larger than the detector, meaning that the muon leaves the detector depositing a part of its energy outside the detector. Cascades are small enough to be mainly contained in the detector and deposit their energy inside the detector. The total charge collected in the DOMs increases with a higher energy deposition and so a muon neutrino with the same energy as for example a electron neutrino is less likely to pass the charge cut because a part of the energy is deposited outside the detector by the track of the leaving muon.

Another issue is the bottom layer veto. It prevents the HESE selection from containing upward tracks which are produced by neutrinos. These tracks may also be interesting because they are known to be neutrino induced and if they are high-

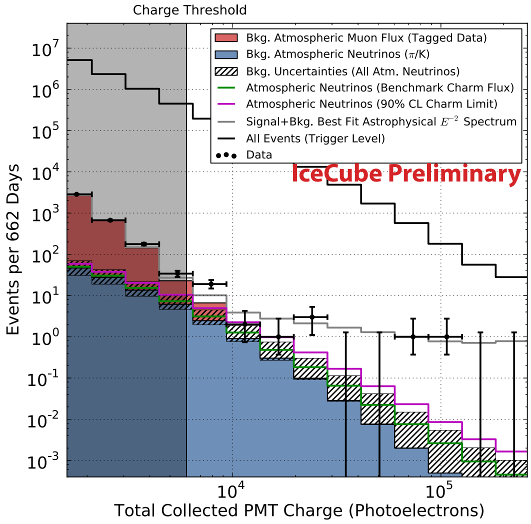


Figure 1.5: Summary of the expected background in the HESE selection dependent on the deposited charge. The black dots show the data collected in 662 days. The gray line gives the best fit, a E^{-2} astrophysical spectrum. The shaded region is the part excluded by the charge cut of at least 6000 p.e. (Ref:[12])

energetic enough to pass the charge cut they are also likely to be of astrophysical origin.

Concerning these limitations of the HESE selection we focus here in adjusting the selection for a target of opportunity program for a better acceptance of muon neutrinos. A way to do this would be to lower the charge cut in order to raise the sensitivity for muon neutrinos, open the bottom layer to include upward tracks and search for variables that are suitable to select only track-like events.

What also has to be considered is that by now the HESE analysis is done off-line. The obtained data from typically one year is first collected and then processed altogether. To use the HESE events in a target of opportunity program, the selection must run on-line at the South Pole which excludes methods that are slow like the reconstruction currently used in off-line processing.

In the following chapter it is examined how to improve the HESE selection for a target of opportunity program.

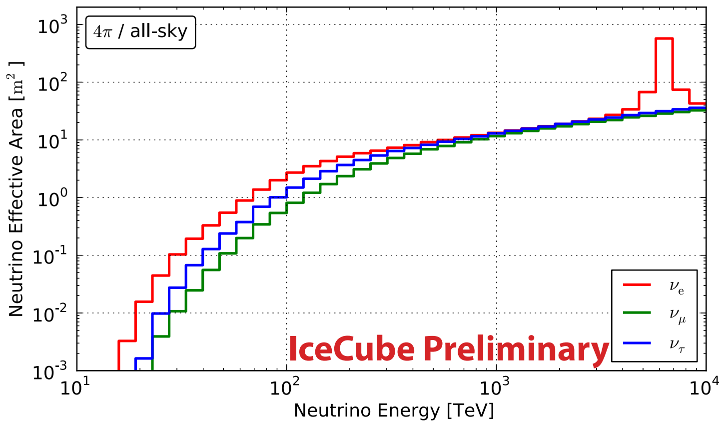


Figure 1.6: Effective Areas for all three neutrino flavours averaged over all arrival angles and assuming an equal flux of neutrinos and anti neutrinos. An event rate can be obtained by multiplying the Effective Area by the neutrino flux and 4π. The excess of the Effective Area in electron neutrinos at about 6 PeV is due to the resonant production of a real W-Boson by the reaction of an electron antineutrino with an electron from the ice. (Ref:[12])

Chapter 2

Optimization of the High Energy Starting Events selection for the usage in a target of opportunity program

To examine the consequences of the changes in the HESE event selection, Monte-Carlo simulations of neutrinos interacting in IceCube were used. The true and the reconstructed directions of the single events are compared in order to determine the quality of tracks selected. Additionally parameters like the neutrino energies are calculated in order to compute the Effective Area, similar to the one in Figure 1.6, for the improved selection.

To obtain enough high-energetic events, simulation data sets with a neutrino energy spectrum proportional to E^{-1} or E^{-2} were used. A more natural neutrino spectrum, like a pure E^{-2} spectrum, can be obtained via a re-weighting of the simulated spectrum. In the following the weighting was done according to a neutrino flux $\phi(E)$ for a single flavour of

$$\frac{\mathrm{d}\phi(E)}{\mathrm{d}E} \cdot E^2 = 1 \times 10^{-8} \, \frac{\mathrm{GeV}}{\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr}} \tag{2.1}$$

This is approximately the same as the best fit of the astrophysical HESE flux of $\frac{\mathrm{d}\phi(E)}{\mathrm{d}E} \cdot E^2 = 0.95(30) \times 10^{-8} \, \frac{\mathrm{GeV}}{\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr}}$ [2].

The way considered in this study to lower the threshold of the HESE selection for muon neutrinos and thus for track-like events is to lower the charge cut, to remove the bottom layer veto and to select only the good reconstructed events (compare section 1.5). In a first step the effects of the changes in the charge cut and the veto layer are discussed in section 2.1. In a second step a possible selection for well reconstructed muon neutrino events only is developed in section 2.2.

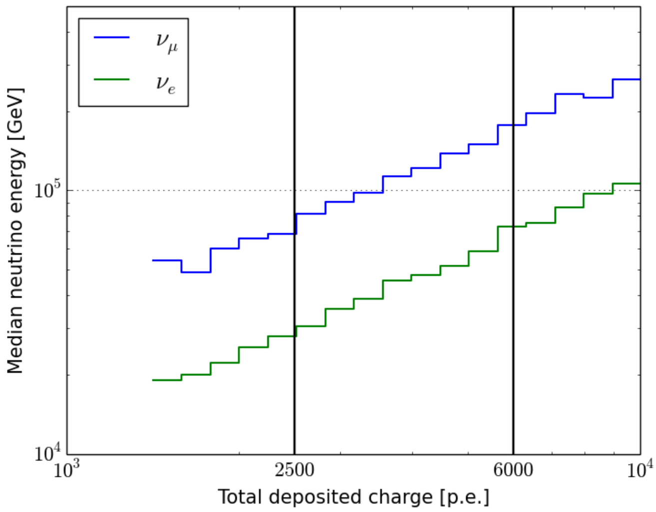


Figure 2.1: Median of the true neutrino energy dependent on the total deposited charge. The vertical black lines show the charge cut for the HESE selection at 6000 p.e. and the charge cut of 2500 p.e. used in this work.

2.1 Step 1: Relaxing the charge cut and removing the bottom layer veto

In Figure 2.1 the median of the neutrino energy depending on the total deposited charge is shown. The energy needed to deposit a certain amount of charge is higher for muon neutrinos than for electron neutrinos. This is because of the muon track that usually leaves the detector depositing energy outside the detector even if the event is a starting event. At a deposited charge of 2500 p.e. the median of the neutrino energy for muon neutrinos is roughly the same as for electron neutrinos depositing 6000 p.e. Therefore the charge cut was lowered to 2500 p.e., which should lead to muon neutrino energies similar to the energies of electron neutrinos accepted by the HESE selection.

The starting point for the following studies were data sets of simulated muon and electron neutrinos. The simulated events were selected according to a modified HESE selection where the charge cut was lowered to 2500 p.e. and the veto region at the bottom part of the detector was removed[1].

Figure 2.2 shows the Effective Area of the optimized selection compared to the HESE Effective Area, averaged over all incoming directions. At low energies the

[1]The data sets with events that passed the modified HESE selection were provided by Stefan Coenders

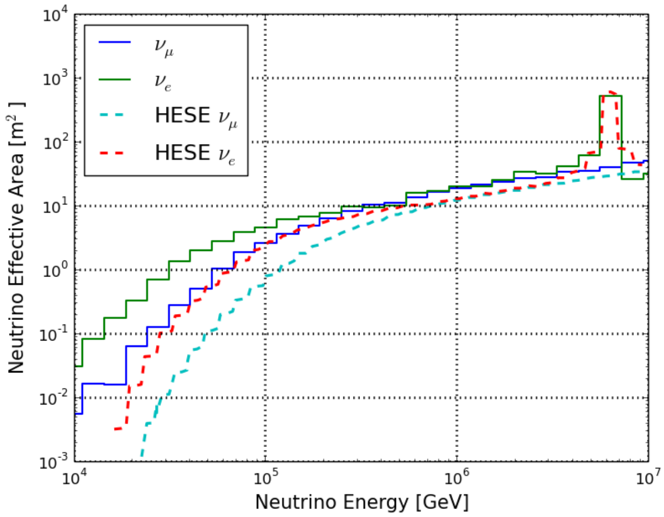


Figure 2.2: Effective Area of the modified HESE selection with a charge cut lowered to 2500 p.e. and a removed bottom layer compared to the original HESE selection. All areas are averaged over all space angles

change in the charge cut leads to a significant higher Effective Area for both muon and electron neutrinos. The lowered charge cut increases the sensitivity for neutrinos with energies up to several hundred TeV by requiring less energy deposition. At higher energies – above about 300 TeV for the modified selection and above 700 TeV for the HESE selection – the Effective Area is the same for muon and electron neutrinos because at these energies every starting event is depositing enough energy to pass the charge cut. It is also to be observed a small increase in the Effective Area for the modified selection compared to the HESE selection at high energies, which is most likely an effect of the removal of the bottom layer veto since at high energies the level of the charge cut should not be relevant any more. This small increase is the same for electron and muon neutrinos, this implies that the increase at high energies is not caused by up-going tracks but probably by events enlightening the detector from below leaving the signature of a partial contained cascade.

This effect was investigated by looking into new events that passed the optimized cuts and in Figure 2.3 such an event is reported. A 3.4 PeV muon neutrino is coming from above, interacting below the detector at the big white bulb. A part of the hadronic cascade is detected, enlightening the detector from below. If such events are always neutrino induced or if muon background can also cause them is not investigated here. But if only track-like events are selected they should be removed anyway, while keeping up-going tracks entering through the bottom layer.

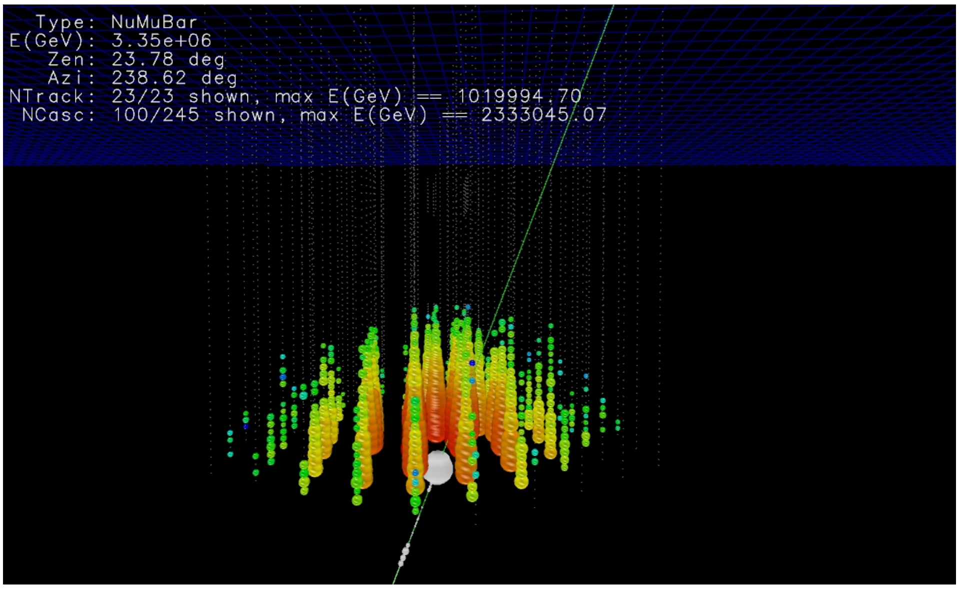


Figure 2.3: High energy event obtained by removing the bottom layer veto. The green track is the direction of the incoming 3.4 PeV muon neutrino. The neutrino comes from above and interacts below the detector at the big white bulb, producing a cascade partially visible in the detector.

The Effective Area for muon neutrinos obtained with the modified selection is very similar to the Effective Area of the HESE selection for electron neutrinos, but it has to be considered that not all detected muon neutrinos produce a clear track. This leads to muon neutrino events classified as cascades without a good directional resolution. In section 2.2 the development of the cuts for the selection of well reconstructed tracks, the events needed for a target of opportunity, is summarized.

2.2 Step 2: The selection of well reconstructed tracks

In this section the development of the selection to extract the well reconstructed tracks, the signals we aim to be sent as a target of opportunity, is described. Hereafter, well reconstructed tracks are defined as events with the reconstructed direction using the MPEFit differing less than 4° from the true direction. The MPEFit (Multi-Photo-Electron-Fit) is a reconstruction which uses the information from all photons detected in the DOMs [15]. It tries to fit a track to the detected signals and is therefore optimized for track-like events. The MPEFit is not the best reconstruction available, but it was chosen because it is fast enough to run it on-line and is quite accurate for track-like events (Figure 2.10).

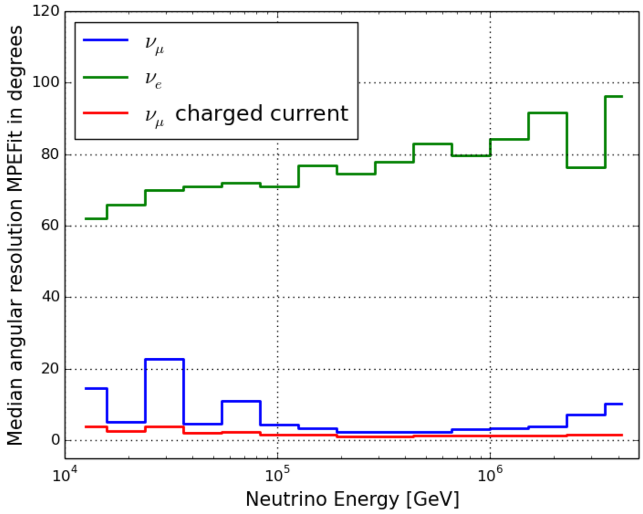


Figure 2.4: Median of the resolution of the MPEFit dependent on the neutrino energy for electron neutrinos, all muon neutrinos and muon neutrinos interacting through a charged current interaction.

Figure 2.4 shows the median of the angular resolution of the MPEFit depending on the energy for all muon neutrinos, all electron neutrinos and muon neutrinos interacting through a charged current interaction. The resolution for electron neutrinos and therefore cascades is worse than 60° over all energies which makes the approach to focus on selecting only well reconstructed muon neutrino events plausible. There are other specific reconstructions in IceCube that can reconstruct cascades better.

The median resolution for charged current muon neutrino interactions is smaller than 5° independent on the energy. This shows that there are some well reconstructed events. The fraction of well reconstructed events with a resolution better than 4° is shown in Figure 2.5 for all muon neutrinos and for neutrino interactions through a charged current.

The fraction of well reconstructed events in charged current interactions is about 15 % higher than in all muon neutrino events independent of the energy. This is the effect of the neutral current interactions which produce cascades which are characterized by a much poorer angular resolution. The probability of a muon neutrino event to be well reconstructed depends on the neutrino energy: It is lower for low energies, rises with the energy to a maximum at about 200 TeV and then decreases for higher energy. At lower energies the secondary muon is probably not energetic enough to produce a clearly visible track so that the reconstruction is difficult. At high energies the hadronic cascade may outshine the muon track

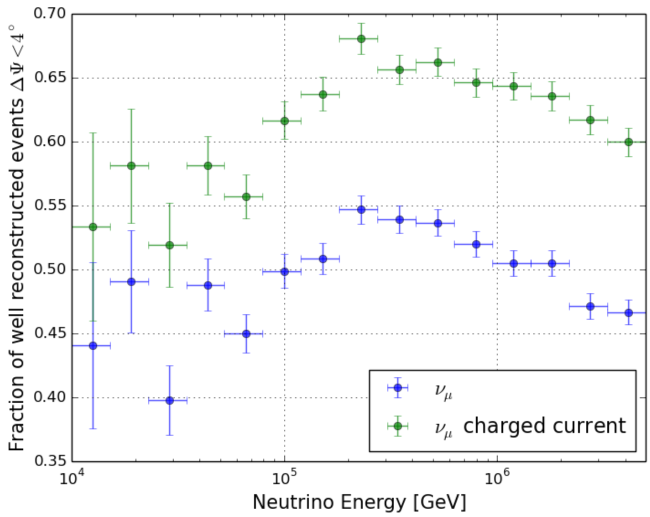


Figure 2.5: Fraction of well reconstructed events dependent on the neutrino energy. A well reconstructed event requires that the difference between the true direction and the direction of the MPEFit is smaller than 4°.

eliminating the directional information. Events with an interaction vertex below the detector, like the one shown in Figure 2.3, also contribute to the number of bad reconstructed events but it was not investigated how big this effect is. Averaged over all simulated energies from 10 GeV to 1×10^9 GeV about 50 % of all muon neutrinos and 62 % of charged current muon neutrino events are well reconstructed. Improved algorithms for the reconstruction of high-energy tracks, including the effect of large stochastic energy losses, is under go, but not considered in this work.

The energy dependence on the fraction of well reconstructed events has to be considered in selecting only track like events. Even if the sensitivity to well reconstructed events is independent of the energy, the selection might get energy dependent just from the fact that the fraction of well reconstructed events is dependent on energy.

2.2.1 Identification of variables useful to select well reconstructed events

To select the well reconstructed events, variables are needed for deciding if the event is well or badly reconstructed. If such variables can be identified, cuts can be applied on the variables, which select only events that are likely to be well reconstructed.

For example a variable that describes the geometry of the event can be useful to exclude spherical cascades. Since the MPEFit is optimized for tracks, variables that describe the quality of the fit are also candidates to select well reconstructed events. A few such variables were computed for the simulated events.

The distributions of the computed variables for electron neutrino events and well reconstructed muon neutrino events were compared and some variables were found to be useful to select only well reconstructed tracks. Finally five variables were chosen to use them in the final selection. It was ensured that the variables do not have a strong dependence on the neutrino energy or on the zenith angle, so that no energy range or zenith angle is removed cutting on the variable.

In the appendix A the histograms for the distributions of the variables are plotted for electron neutrinos, all muon neutrinos and well reconstructed muon neutrinos. Also included is some experimental data, 10% of the collected data from 2011 and 10% from 2012, which was also selected with the modified HESE selection.

The five variables used in the final cuts are described below:

Length of FiniteRecoFit The FiniteRecoFit uses the direction of a reconstruction and tries to fit an interaction vertex and a length to the event. In the case of a track the event is elongated in one direction and the length should be long compared to the extension of cascades.

Angle between LineFit and MPEFit The LineFit [15] is another simple reconstruction for track-like events. Comparing the reconstructed directions of two independent fits should lead to a small angle if the reconstruction is good and to a bigger angle if one fit or both fits fail to reconstruct the event properly.

Tensor of Inertia Evalratio The Tensor of Inertia is computed similar to the tensor of inertia of a rigid body. The mass is replaced with the deposited charge in the DOMs. The tensor is diagonalized which gives the three moments of inertia I_{min}, I_2 and I_3 for the three main axes. I_{min} is the smallest value. The Evalratio is computed as $\frac{I_{\mathrm{min}}}{I_{\mathrm{min}}+I_2+I_3}$. For cascades this ratio should be near 1/3 due to their spherical geometry which leads to similar values for all three moments of inertia. For elongated tracks I_{min} is significantly smaller than I_2 and I_3 which gives a smaller value for the Evalratio.

MPEFit logarithm of the reduced likelihood A measurement for the quality of the MPEFit. It can be used to cut away obviously misreconstructed events.

MPEFit Direct Hits track length The maximal distance along the track of the MPEFit between two DOMs directly hit. A DOM is hit directly if a photon is detected in a time window around the time an unscattered photon coming from the track is expected. Here the definition for the time window was between −15 ns and 125 ns from the unscattered photon.

In addition to the five variables used in the final cuts, there were other quantities that were also considered for use in the selection. It was found that cutting on additional variables does not add more power to the selection, because the cascades are already removed by the cuts on the other variables.

2.2.2 Determination of the cuts

In order to select only well reconstructed muon neutrino events some straight cuts on the five variables mentioned before were developed.

The determination where to place the cuts was done on the cumulated distributions of the variables. The focus was to cut away as much electron neutrino events as possible and to keep most of the well reconstructed muon neutrinos. The procedure is described exemplary for the angle between the directions of the LineFit and the MPEFit.

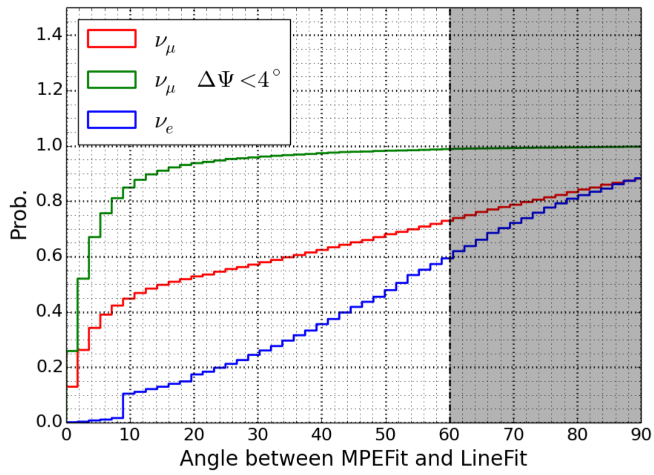


Figure 2.6: Cumulative distribution for the angular difference in the reconstructed directions of the MPEFit and the LineFit. The shaded area represents the regions that are removed by the cut. The interception of the distributions and the vertical line at the position of the cut gives the fraction of remaining events after the cut.

Figure 2.6 shows the cumulative distribution of the angle between the directions of the LineFit and the MPEFit for well reconstructed muon neutrinos (green), all muon neutrinos (red) and electron neutrinos (blue). The dashed black line gives the position where the cut was placed. Here the cut was placed in such a way that the event is required to have an angular difference of less than 60° in order to pass the selection. So all events with a value of more than 60° for the difference – the gray shaded area in the plot – get removed. The fraction of events remaining after the cut is given by the intersection of the cumulated distribution and the vertical line at the position of the cut. By selecting only events with less than 60° angular difference, almost all well reconstructed muon neutrinos but only 60% of the electron neutrinos pass the selection.

A cut at 60° may seem very lax since cutting at 30° would remove 75% of the electron neutrinos while keeping 90% of the well reconstructed muon neutrinos but since five variables are used for cutting, the cuts do not have to be placed harsh. Most of the cascades not removed by one cut will be removed by one of the other cuts.

The plots similar to the one in Figure 2.6 for the other variables are appended in B. The final cuts used to select only the well reconstructed events are listed in Table 2.1. To be selected an event has to fulfil all conditions at the same time.

Variable	Condition
Angle between LineFit and MPEFit	$< 60^\circ$
MPEFit logarithm of the reduced likelihood	< 9.25
MPEFit Direct Hits track length	$> 250\,\mathrm{m}$
Length of FiniteRecoFit	$> 450\,\mathrm{m}$
Tensor of Inertia Evalratio	< 0.295

Table 2.1: Cuts used for the selection of well reconstructed track-like moun neutrino events. An event passes the selection if all five conditions are fulfilled.

2.3 Results of the applied cuts

2.3.1 Effective Area

Although the cuts developed in section 2.2.2 are optimized to select muon neutrinos, the Effective Area from Figure 2.2 may change since there are also neutral current interactions and badly reconstructed muon neutrino events (Figure 2.5) that should be removed.

Figure 2.7 shows the Effective Area for muon neutrinos after the final cuts compared to the Effective Area before the cuts and to the HESE Effective Areas. Selecting only well reconstructed tracks reduces the Effective Area. This cannot be avoided because, as seen before, not all muon neutrino events are well reconstructed. Nevertheless the Effective Area is still larger than the HESE Effective Area for energies up to about 200 TeV. Here the effect of the change in the charge cut is bigger than

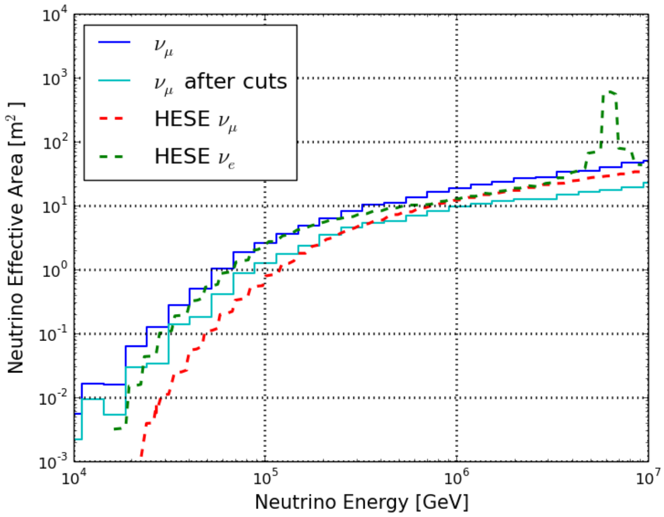


Figure 2.7: Effective Area for muon neutrinos of the modified HESE selection after selecting only well reconstructed events compared to the initial selection which includes all events, and to the HESE Effective Areas. All Effective Areas are averaged over all zenith angles.

the effect of the restriction to only well reconstructed events. At higher energies removing the badly reconstructed events causes the Effective Area to be smaller than the Effective Area for muon neutrinos in the HESE selection. But it has to be considered that the HESE Effective Area still includes the events that do not have a nice track to ensure a good reconstruction.

At about 800 TeV the Effective Area in the HESE selection is the same for muon and electron neutrinos. This illustrates that at this energy nearly all events starting in the detector deposit enough energy to pass the charge cut. At this point it is not possible any more to improve the sensitivity for muon neutrinos by relaxing the charge cut. Additionally the earth gets opaque for neutrinos at these energies and the removal of the bottom layer veto is not expected to lead to additional up-going tracks.

2.3.2 Performance of the cuts in selecting well reconstructed events and rejecting cascades

The performance of the cuts from Table 2.1 in selecting well reconstructed events and rejecting cascades is examined on the basis of the fraction of events passing the cuts. The fraction should be as large as possible for well reconstructed events and small

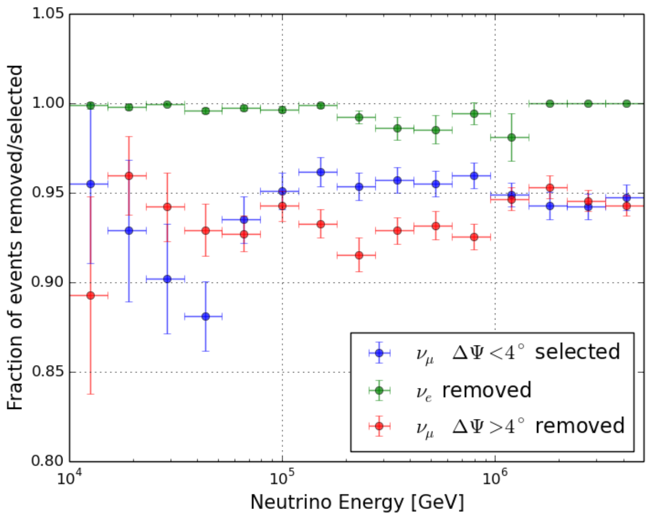


Figure 2.8: Fraction of well reconstructed muon neutrinos passing the cuts and fraction of badly reconstructed muon neutrinos and electron neutrinos that get removed by the cuts. The errors where estimated using (2.2).

for cascades and for badly reconstructed muon neutrino events. These fractions can be computed by using the weights given to the events by the simulation. Dividing the sum of weights after the cuts by the sum of weights before the cuts gives a probability for the events to pass the selection.

The error σ for this probability was estimated by:

$$\sigma = \frac{\sqrt{\epsilon(1-\epsilon)}}{\sqrt{N}} \tag{2.2}$$

where ϵ is the number of simulated events remaining after the selection divided by the number of events before the selection. N is the number of simulated events before the selection.

The probability, dependent on the energy, for a well reconstructed muon neutrino event to pass the cuts is shown in Figure 2.8. Also included is the probability for a badly reconstructed muon neutrino and an electron neutrino to be rejected by the selection.

The selection is slightly dependent on the energy: It seems that at energies around several hundred TeV the selection is laxer filtering out less electron neutrinos and badly reconstructed muon neutrinos and letting more well reconstructed muon neutrinos pass. The small energy dependence shows that the variables used for

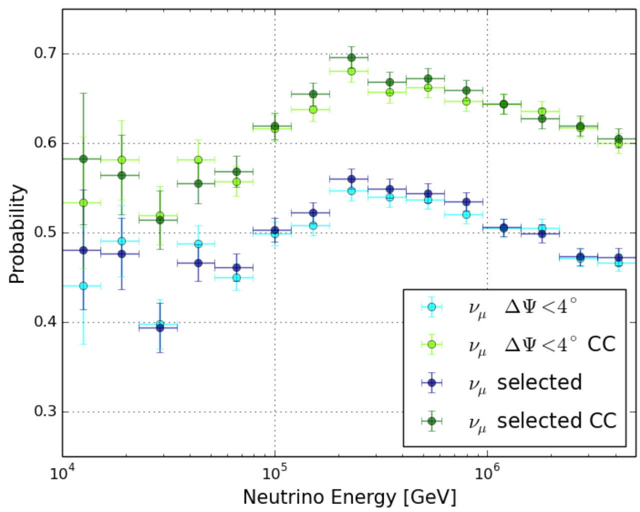


Figure 2.9: Probabilities for muon neutrino events to pass the selection depending on the energy, compared to the probability for a muon neutrino event to be well reconstructed. Shown are the probabilities for all muon neutrino events and for only charged current (CC) events. Since the numbers for all muon neutrinos also include the neutral current events which are producing cascades, the fraction of well reconstructed and selected events is moved down compared to the charged current events.

cutting are not completely energy independent but the effect is small compared to the dependence in energy on the fraction of well reconstructed events (Figure 2.5).

Figure 2.9 shows the fraction of the muon neutrinos that are classified as tracks after passing the cuts compared to the fraction of well reconstructed muon neutrino events, respectively for all muon neutrino events and for only charged current events.

The fraction of events seen as tracks is nearly the same as the fraction of events that are well reconstructed. The approximately 5% of well reconstructed events that do not pass the selection are compensated by the badly reconstructed events that survive the cuts.

The probabilities from Figure 2.8 can be condensed into one number by taking the average over all energies. By doing so the weighting becomes important and the result depends on the assumed flux. It was assumed that the dependence of the neutrino flux on energy follows equation (2.1). In Table 2.2 the fractions for some different types of events passing the applied cuts are listed. Also included are the expected numbers of events in one year of experimental data for the different types of events.

	Expected number of events per year before cuts	Expected number of events per year after cuts	Fraction of events passing the cuts
ν_μ	$4.45(4)$	$2.23(3)$	50.1 %
ν_μ CC	$3.54(4)$	$2.22(3)$	62.7 %
ν_μ $\Delta\Psi < 4^\circ$	$2.21(3)$	$2.09(3)$	94.5 %
ν_μ $\Delta\Psi > 4^\circ$	$2.24(3)$	$0.14(1)$	6.5 %
ν_e	$7.42(61)$	$0.63(59)$	8.5 %

Table 2.2: Expected numbers of events in one year of data for different types of events before and after the cuts. The neutrino flux was assumed to follow (2.1), the best fit for the astrophysical neutrino flux obtained by the HESE events. Considered were all neutrino energies in the energy range of the simulations from 10 GeV to 1×10^9 GeV. Here $\Delta\Psi$ is the angle between the MPEFit and the true direction therefore the events with $\Delta\Psi < 4^\circ$ are the well reconstructed events and the events with $\Delta\Psi > 4^\circ$ are the badly reconstructed events. The charged current events are marked as CC.

Overall the cuts are removing most of the cascades from electron neutrinos and are keeping most of the well reconstructed muon neutrinos. But since only about half of the muon neutrinos are producing a track, meaning that the reconstruction is accurate, the selection is removing about 50 % of the muon neutrinos and about 40 % of the muon neutrino events from charged current interactions.

2.3.3 Angular resolution of the selected muon neutrino events

An important quality feature of the selected events is the angular resolution. If a neutrino event gets forwarded as an alert in a target of opportunity program, a good resolution avoids random coincidences and increases the significance if a possible counterpart for the neutrino event is observed. Figure 2.10 shows the median of the angular resolution of the MPEFit for the muon neutrino events that pass the cuts.

The median of the resolution is energy dependent, getting better with increasing energy up to about 200 TeV and being approximately constant for higher energies at about 0.6°. Since the selection is optimized for a good resolution of the MPEFit the resolution might be different if other reconstructions are used.

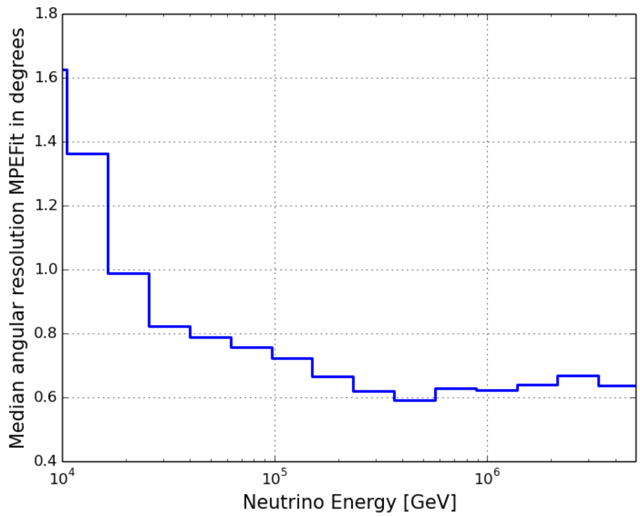


Figure 2.10: Median of the angular resolution of the MPEFit for the muon neutrino events that pass the selection. The resolution is given in degrees.

2.4 Possible improvements of the selection

To find possible ways to improve the selection some simulated events that get classified falsely were examined. The events were studied directly on the basis of the event views (Figures 2.11 to 2.16) . In these event views each coloured bulb represents a DOM that was hit by a photon and the size of the bulbs is proportional to the collected charge. The colour represents the time the DOM was first hit – the colour goes from red for early times to blue for late times. In each picture the green line is the track of the incoming neutrino and after the interaction the secondary muon travels along the same track. The red line shows the direction of the MPEFit. In the upper left corner the properties of the events are listed. Displayed are the neutrino flavour and its energy as well as the direction of the neutrino and the distribution of the energy in the secondary muon and the cascade. A table shows the quantities of the variables used to cut on, the neutrino energy and the difference between the true and the MPEFit direction. Since almost all of the electron neutrino events with an energy lower than 5 PeV are already removed by the developed selection, the focus is to improve the acceptance for well reconstructed tracks and to decrease the number of badly reconstructed events that pass the selection.

2.4.1 Badly reconstructed events that pass the selection

In Figures 2.11, 2.12 and 2.13 some events are shown that passed the selection but are badly reconstructed by the MPEFit. The events in figures 2.11 and 2.12 do not contain visible tracks which makes the reconstruction difficult. Since the interactions happen at the edge or bottom of the detector the events are only partially contained which makes the geometry look more elongated than it actually is. The selection therefore classifies the visible part of the hadronic cascade as a track and the event passes the selection.

For this events the variables on which the cuts were placed have values quite near to the cuts. It could be possible to combine the variables and to reject such events that passed all cuts hardly and do not show a clear evidence of a track in any variable.

Figure 2.13 shows an event that contains a track visible by eye, but the reconstruction of the MPEFit is bad. In this special case it might be because of the dust layer that somehow cuts away a part of the initial cascade. An event like this still contains the directional information and may be better reconstructed using a different type of reconstruction and therefore it is not crucial that such an event passes the selection.

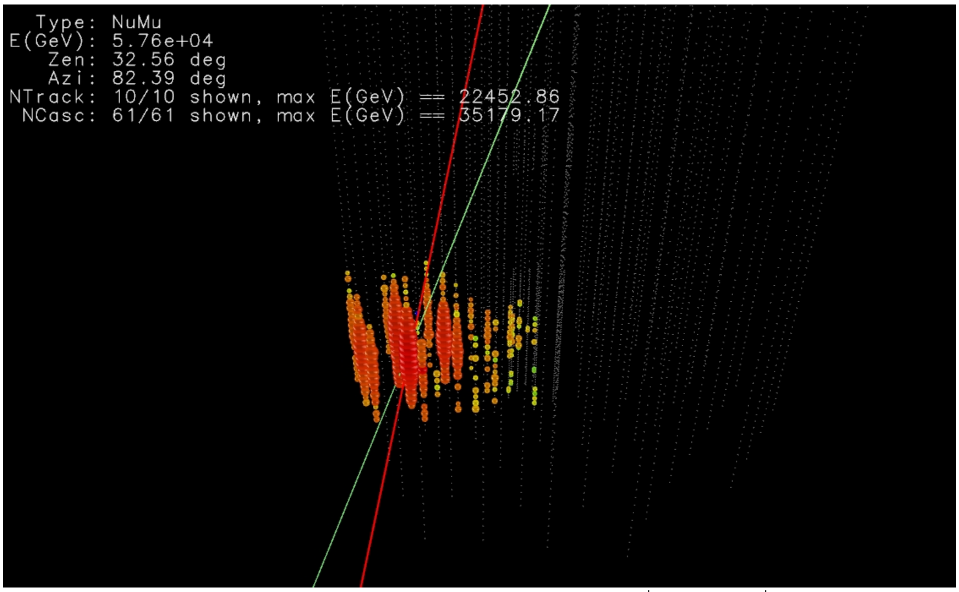
2.4.2 Well reconstructed events that are rejected

Figures 2.15, 2.16 and 2.14 show three events that are well reconstructed but rejected by the selection.

The event in Figure 2.14 looks more like a cascade without any track while the reconstruction is still good. The reconstruction may be good by pure coincidence or the MPEFit is somehow able to see a track hidden under the cascade. However such an event would very likely be classified as a cascade and therefore it is not intended to select such events.

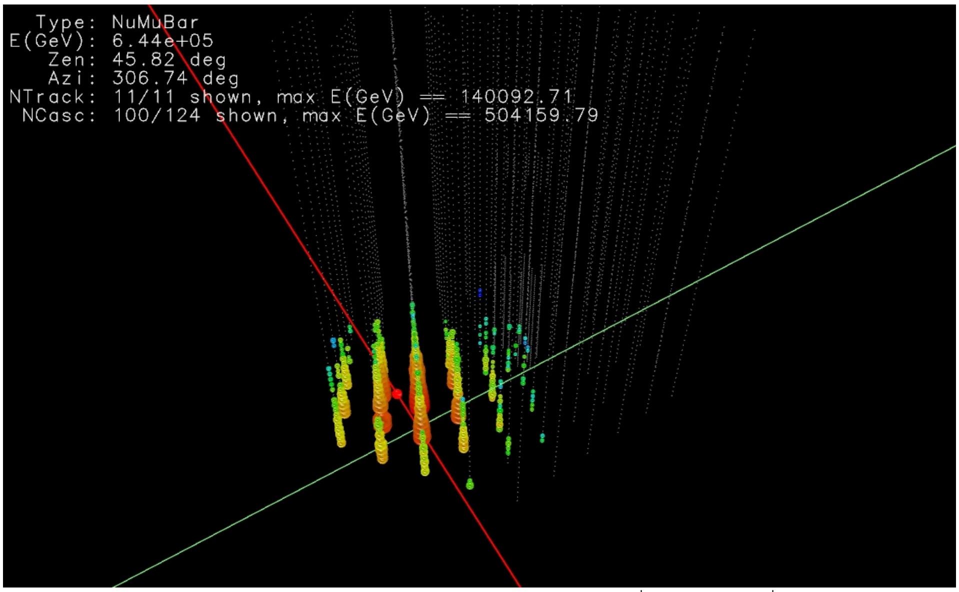
In two cases (Figures 2.15 and 2.16) a track is visible but each event does not fulfil one condition to pass the cuts. The event in Figure 2.15 has a very faint track compared to the bright cascade. The cuts are not passed because the Tensor of Inertia Evalratio indicates a spherical symmetry. The event in Figure 2.16 is a clear track only separated by the dust-layer, but the LineFit fails to reconstruct the event properly which leads to an angular difference to the MPEFit to big to pass the cuts.

To obtain such events with the selection as well, it can be tried to additionally select events that show a clear hint that they are tracks on one or more variables. For example for the event in Figure 2.16 the Tensor of Inertia Evalratio has a value that almost excludes an electron neutrino induced cascade (Figure B.5).



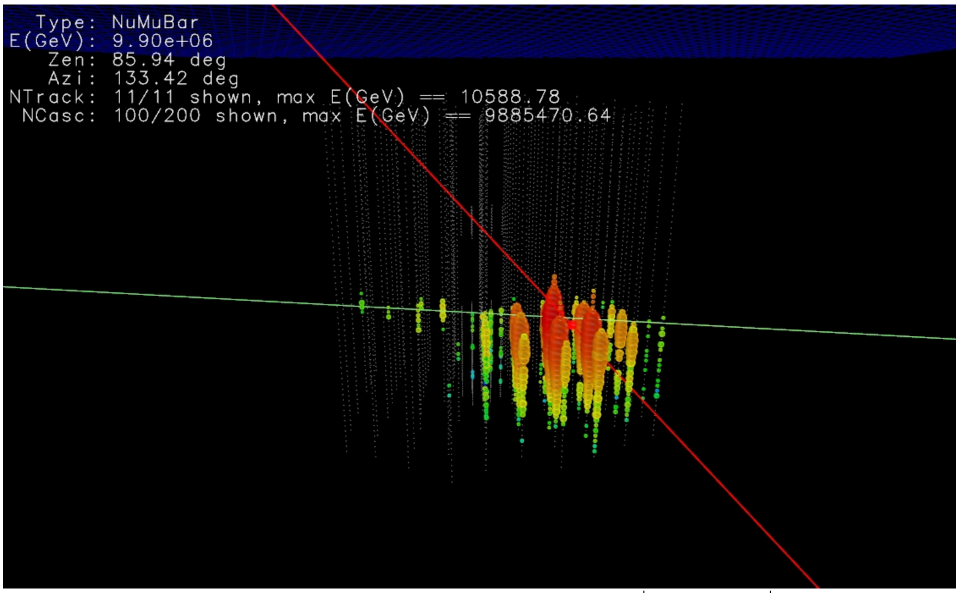
Variable	Value	Cut
Angle between LineFit and MPEFit	55°	$< 60°$
MPEFit logarithm of the reduced likelihood	8.81	< 9.25
MPEFit Direct Hits track length	276 m	> 250 m
Length of FiniteRecoFit	580 m	> 450 m
Tensor of Inertia Evalratio	0.285	< 0.295
Neutrino Energy	58 TeV	
Angular deviation MPEFit	115°	

Figure 2.11: Badly reconstructed event that passed the selection. There is no visible track which makes the reconstruction difficult but since the event starts at the edge of the detector the shape of the event is not spherical and is classified as a track by the selection.



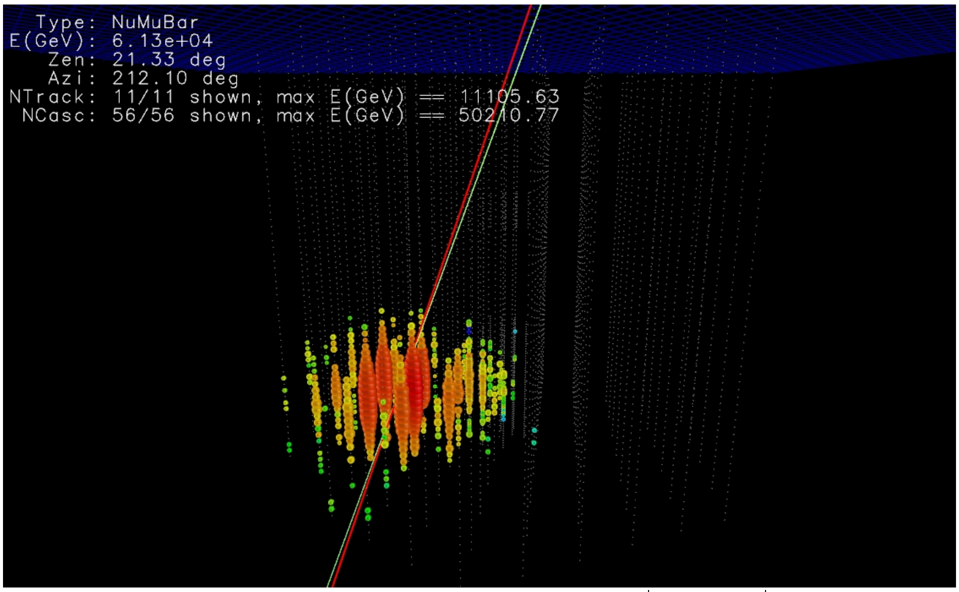
Variable	Value	Cut
Angle between LineFit and MPEFit	36°	$< 60°$
MPEFit logarithm of the reduced likelihood	7.94	< 9.25
MPEFit Direct Hits track length	309 m	> 250 m
Length of FiniteRecoFit	511 m	> 450 m
Tensor of Inertia Evalratio	0.261	< 0.295
Neutrino Energy	644 TeV	
Angular deviation MPEFit	98°	

Figure 2.12: Badly reconstructed event that passed the selection. The interaction at the bottom part of the detector causes the muon track to be outside the detector. Since the event is only partially contained, the geometry looks more elongated than it actually is, which causes the selection to classify the event as a track.



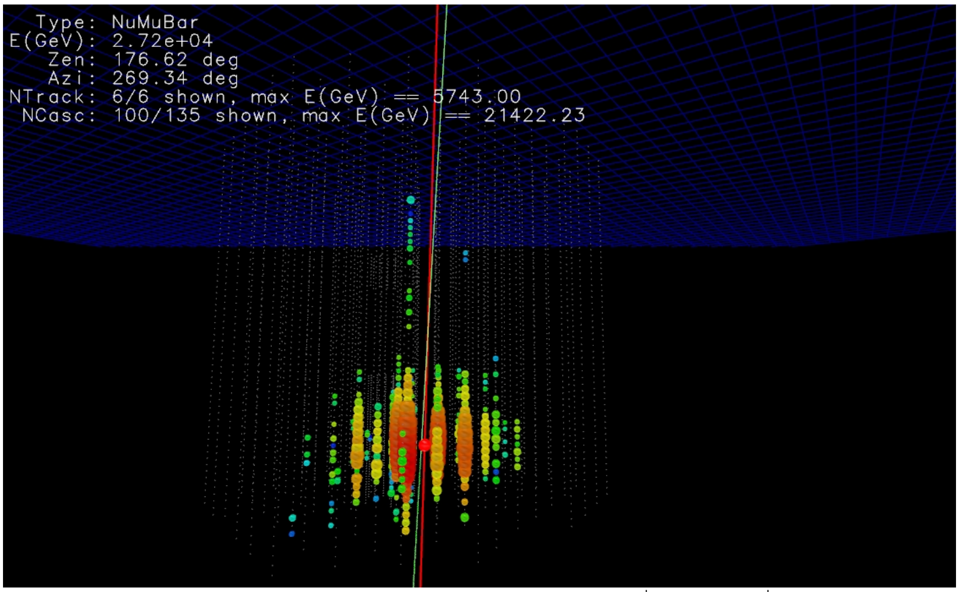
Variable	Value	Cut
Angle between LineFit and MPEFit	48°	$< 60°$
MPEFit logarithm of the reduced likelihood	8.44	< 9.25
MPEFit Direct Hits track length	267 m	> 250 m
Length of FiniteRecoFit	643 m	> 450 m
Tensor of Inertia Evalratio	0.274	< 0.295
Neutrino Energy	9.9 PeV	
Angular deviation MPEFit	122°	

Figure 2.13: Badly reconstructed event that passed the selection. There is a visible track but the MPEFit fails in reconstructing the direction properly.



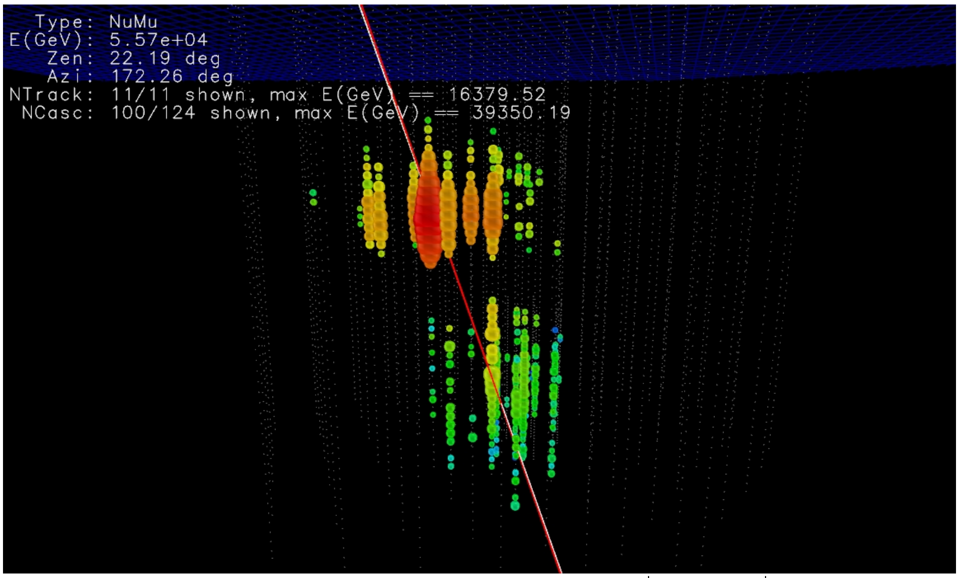
Variable	Value	Cut
Angle between LineFit and MPEFit	$48°$	$< 60°$
MPEFit logarithm of the reduced likelihood	8.41	< 9.25
MPEFit Direct Hits track length	210 m	> 250 m
Length of FiniteRecoFit	400 m	> 450 m
Tensor of Inertia Evalratio	0.292	< 0.295
Neutrino Energy	61 TeV	
Angular deviation MPEFit	$2.5°$	

Figure 2.14: Well reconstructed event that did not pass the selection. The geometry seems to be that of a cascade but the reconstruction is better than expected.



Variable	Value	Cut
Angle between LineFit and MPEFit	22°	< 60°
MPEFit logarithm of the reduced likelihood	7.99	< 9.25
MPEFit Direct Hits track length	578 m	> 250 m
Length of FiniteRecoFit	1003 m	> 450 m
Tensor of Inertia Evalratio	0.304	< 0.295
Neutrino Energy	27 TeV	
Angular deviation MPEFit	2.5°	

Figure 2.15: Well reconstructed event that did not pass the selection. The geometry is quite spherical and the event does not survive the cut on the Tensor of Inertia Evalratio



Variable	Value	Cut
Angle between LineFit and MPEFit	64°	$< 60°$
MPEFit logarithm of the reduced likelihood	7.98	< 9.25
MPEFit Direct Hits track length	474 m	> 250 m
Length of FiniteRecoFit	760 m	> 450 m
Tensor of Inertia Evalratio	0.133	< 0.295
Neutrino Energy	56 TeV	
Angular deviation MPEFit	1.8°	

Figure 2.16: Well reconstructed event that did not pass the selection. The event passes all cuts but one: The direction of the LineFit deviates to much from the direction of the MPEFit. The event seems separated because of the dust layer where the produced light is absorbed.

Chapter 3

Conclusions

The selection developed in this work focused on the distinction of well reconstructed track-like events from cascades. Some cuts were developed that are useful to remove the cascades from astrophysical neutrinos and to keep the well reconstructed astrophysical muon neutrino events. The developed selection is, averaged over all energies, removing 91 % of electron neutrino events and 93 % of the badly reconstructed muon neutrino events while keeping 94 % of the well reconstructed muon neutrino events. How this numbers can be possibly improved was considered in section 2.4.

What still has to be considered is the background stemming from atmospheric muons and atmospheric neutrinos. An estimation of the background can be done on the basis of events from experimental data that pass the selection. The histograms in section A include the distributions for some experimental data that passed the modified HESE selection before the selection for well reconstructed tracks. The distributions of the experimental data are more similar to the distributions for well reconstructed tracks than to the distributions for electron neutrinos. This is a hint that the experimental data is still dominated by background.

Assuming only astrophysical neutrinos with a flavour ratio of 1:1:1, it is expected that most of the events have a cascade-like geometry. Taking into account that the majority of tracks is produced by muon neutrinos, rarely tracks are produced in a decay of a secondary tau into a muon or from a muon produced in a hadronic shower, this leads to an expected track-to-cascade ratio of $1/6$ for high-energy astrophysical neutrinos. The additional factor $1/2$ results in the fact that only half of the muon neutrinos produce a track-like event (Section 2.2). Therefore the experimental data contains some additional tracks most likely from muons sneaking through the veto layer or atmospheric muon neutrinos (the flavour ratio for atmospheric neutrinos is shifted to muon neutrinos).

On the basis of the experimental data it was estimated that the final selection will lead to about 400 events per year. This is much more than the expected signal events (Table 2.2). Depending on the intended purity of the final sample it may be necessary to develop additional ways to reject the muon background besides the veto layer.

After implementing some improvements the next steps would be to collaborate with people interested in the targets of opportunity and to run the selection on-line to be able to send alerts.

Appendix A

Histograms of variables used for the selection of well reconstructed tracks

The distributions of the variables used for the cuts in the selection of well reconstructed tracks. All histograms are normed due to a better visibility. In the middle the histogram of the variable is shown. On the left the negative cumulated distribution is indicated, starting from one and subtracting the area under the bins recursively. On this graph the percentage of events remaining if selecting only events with larger values can be read off. On the right the cumulated distribution is shown which gives the percentage of remaining events selecting only smaller values. In each histogram the blue line gives the distribution of electron neutrinos, the green line the distribution for all muon neutrinos and the dashed red line the distribution for the well reconstructed muon neutrino events. The black dots show the distribution of some experimental data, 10% of the data collected in 2011 and 10% of the data collected in 2012. These 10% of the experimental data is called the Burnsample which is used for testing an analysis to avoid bias.

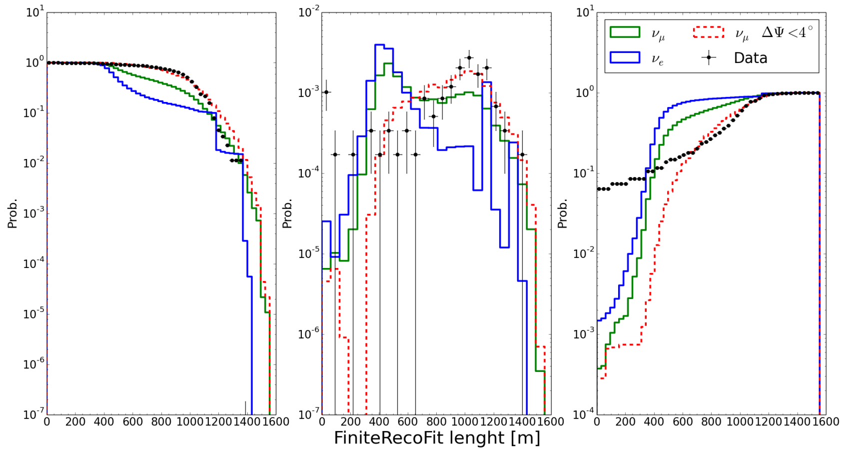


Figure A.1: Length of FiniteRecoFit

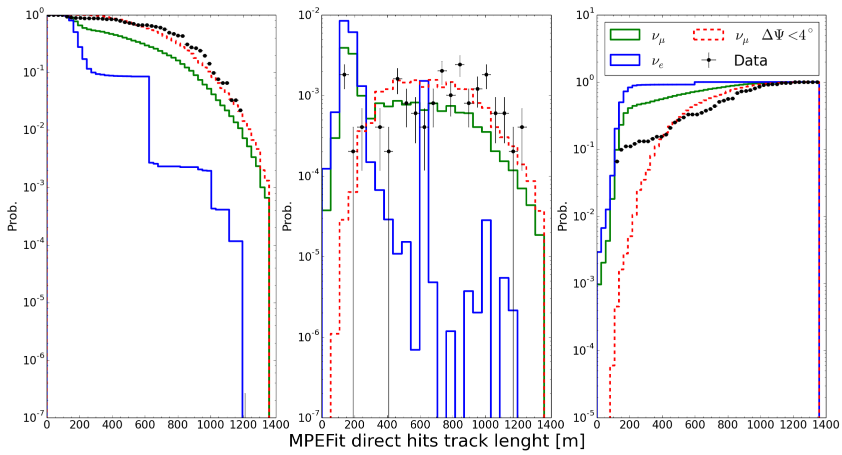


Figure A.2: Direct hits track length using the MPEFit reconstruction and a definition for the time window from -15 ns to 125 ns from the arrival time of an unscattered photon

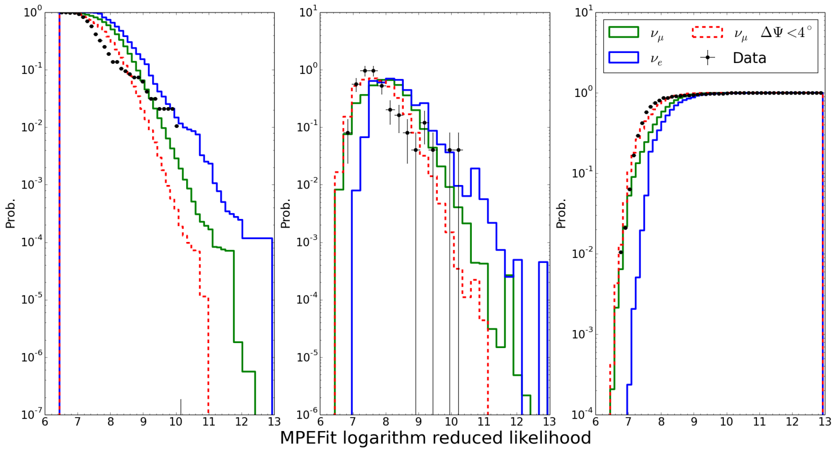


Figure A.3: Logarithm of the reduced likelihood of the MPEFit

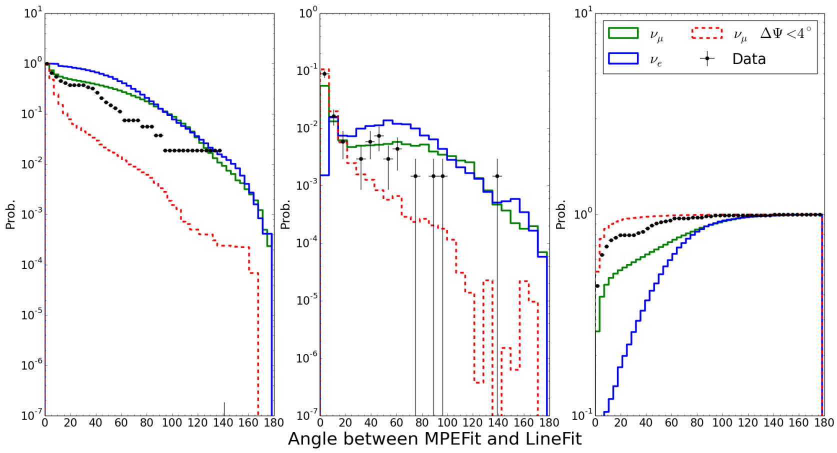


Figure A.4: Angle between the reconstructed directions of the MPEFit and the LineFit

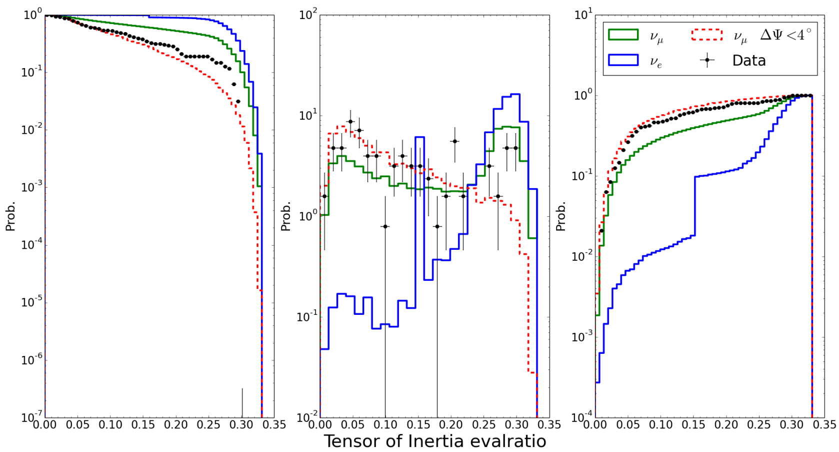


Figure A.5: Tensor of Inertia Evalratio

Appendix B

Cumulated distributions of variables used for the selection of well reconstructed tracks

The cumulated distributions for well reconstructed muon neutrinos, all muon neutrinos and electron neutrinos used to place the cuts. Events in the shaded region get cut away, the interception of the cut with the cumulated distribution gives the fraction of remaining events after the cut. The cuts are placed in a way that most of the well reconstructed events are kept while as many electron neutrino events – and thus cascades – as possible are removed.

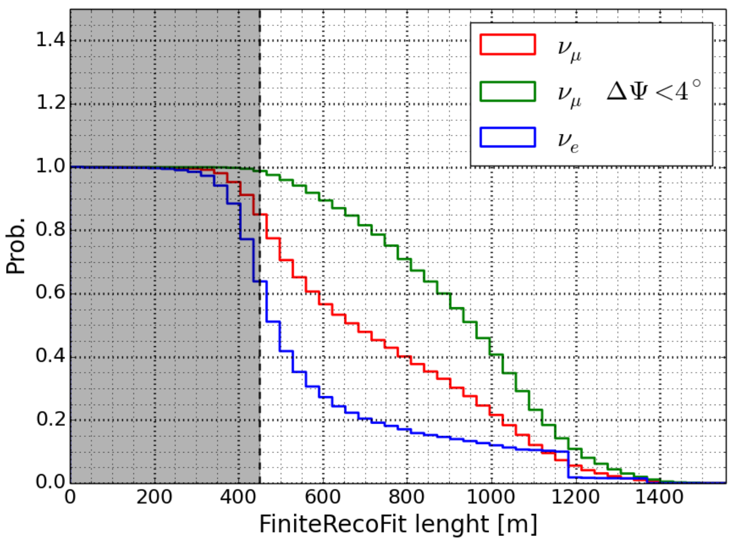


Figure B.1: Length of FiniteRecoFit

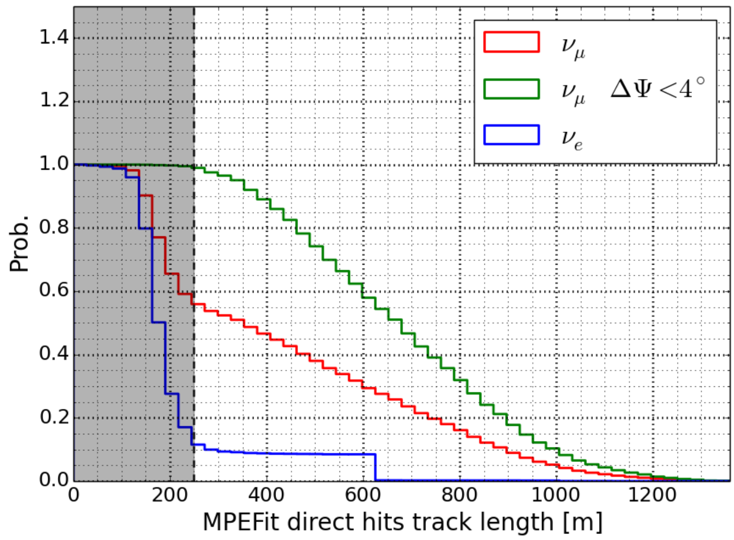


Figure B.2: Direct hits track length using the MPEFit reconstruction and a definition for the time window from -15 ns to 125 ns from the arrival time of an unscattered photon

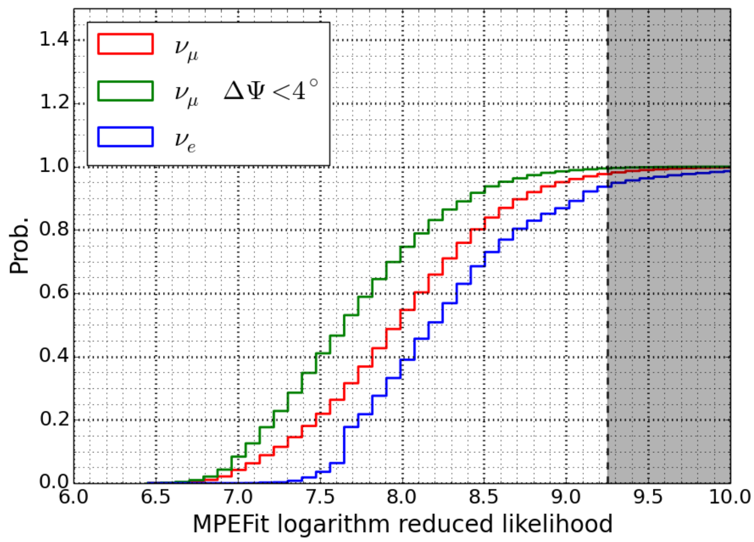


Figure B.3: Logarithm of the reduced likelihood of the MPEFit

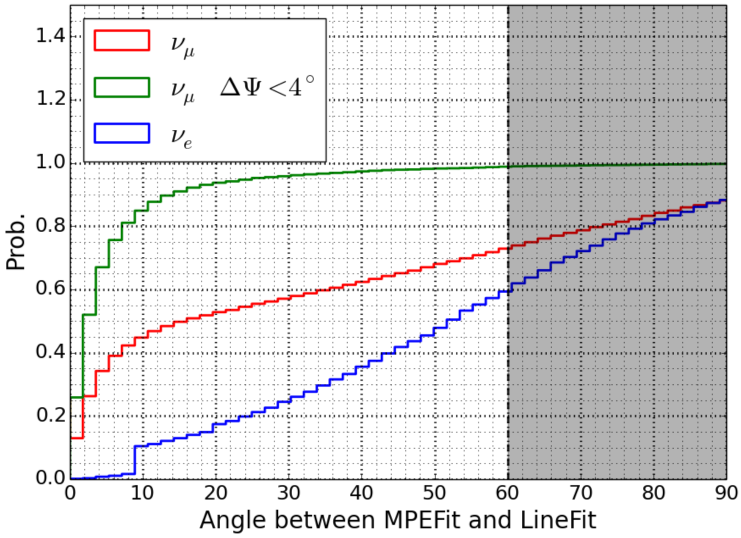


Figure B.4: Angle between the reconstructed directions of the MPEFit and the LineFit

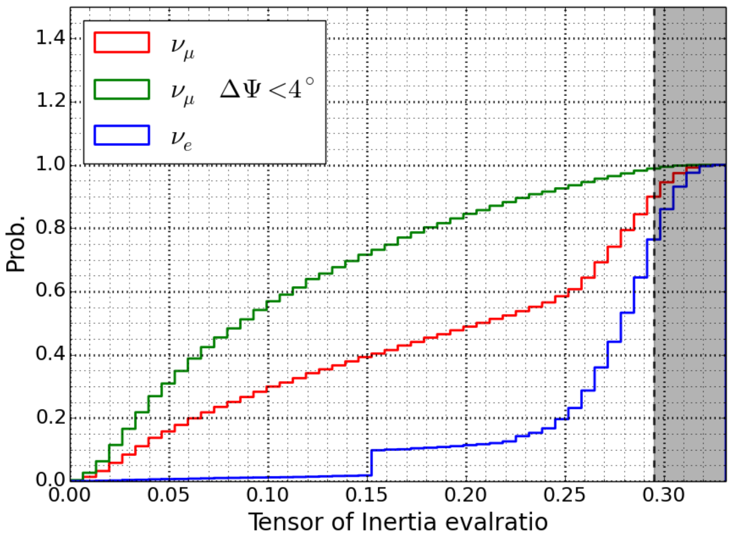


Figure B.5: Tensor of Inertia Evalratio

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