# Reconstruction of coincident events in the KM3NeT-detector

Peter Steiglechner

BACHELORTHESIS

course

Physics B.Sc.

in Erlangen

Date: 12.5.2016

# Declaration

I hereby declare and confirm that this thesis is entirely the result of my own original work. Where other sources of information have been used, they have been indicated as such and properly acknowledged. I further declare that this or similar work has not been submitted for credit elsewhere.

Erlangen, May 12, 2016

Peter Steiglechner

# Contents

# Chapter 1

# Introduction

Neutrino physics has become one of the leading fields of research in physics over the last decades. Since the first cosmic neutrinos have been detected by IceCube in 2012 [**Aartsen et al. 2013**], research in this field holds great potential for finding evidence for astrophysical theories concerning e.g. dark matter.

The purpose of this thesis is to enhance investigations on features of the neutrino reconstruction for KM3NeT, a large Cherenkov light detector, which is currently built in the Mediterranean Sea.

In particular, this work focuses on the response of the detector for coincident events.
For example atmospheric muon bundles with $E > 10\,\mathrm{TeV}$ appear with a rate of 3.3 Hz at the detector. Therefore, coincidences of neutrinos with the bundles, as well as, atmospheric muon bundles with themselves are likely scenarios.

This aspect has not been fully investigated, yet. However, [**Adrian-Martinez et al. 2016**] states it is "anticipated that resolving multiple components will prove feasible" for the detector.
Indeed, the calculation of a quality evaluation parameter, $\Lambda$, for the reconstruction as well as the reconstruction algorithms themselves, such as the hit selection filter, are especially designed for single events. Naturally, these are also by far the more frequent events compared to coincidences.
It is, however possible that the performance of the reconstruction is disturbed by coincident events, in which case the quality parameter or the angular resolution of the track direction might contain misleading information. For example, two down going atmospheric muon bundles might be reconstructed as an up going track with a good quality parameter. This would strongly falsify the interpretation of the reconstructed event.

Therefore, I present my work on a detailed analysis of specific coincident events, such as a twofold atmospheric muon bundles and a cosmic neutrino event coinciding with an atmospheric muon bundle. Also, I describe the production of new Monte Carlo sets of these coincident events and present a first analysis. These productions are subject to further investigation and are stored on the internal storage for further usage (for the Folder structure see Section 5).

The thesis includes a short introduction to the KM3NeT detector, neutrino interactions and the methods used by KM3NeT to detect neutrinos. Furthermore, the process of simulating the output of the detector via Monte Carlo productions is explained. In the analysis, I investigate the behaviour of the quality parameter $\Lambda$ and the angular resolution of the reconstruction $\alpha$ of two coincident events with different relative time offsets. This section also aims to find a maximum time offset between two coincident events, for which the events interfere significantly.

Using the results from this preliminary investigation, I describe the production of Monte Carlo sets including coincident events. In order to get statistically relevant results, I analyse the livetime and rates of the productions and look at statistical fractions and features of misreconstructed events due to the coincidences. Also the overall performance of $\Lambda$ is evaluated for the coincident productions.

For the thesis only the reconstruction algorithm reco-LNS is used due to problems concerning JGandalf, which are described in Section 3.

# Chapter 2

# KM3NeT and theoretical background for the detection of neutrinos

## 2.1 What is KM3NeT?

KM3NeT, a cubic kilometer neutrino telescope, is the infrastructure of a huge photon detector in the Mediterranean sea. KM3NeT is built to serve two main purposes:

- The Astroparticle detector (ARCA) aims to observe high-energetic cosmic neutrinos. From this information, researchers want to learn about possible point sources for neutrinos in the universe and, consequently, find information about, for example, dark matter or supernovae.
- Furthermore, the Oscillation detector (ORCA) uses mostly the same detector, in order to find the mass hierarchy of the different flavoured neutrinos.

An earlier research collaboration, IceCube, has discovered high-energy neutrinos from cosmic sources by measuring Cherenkov light in ice in the Antarctica. The evidence is presented in [**Aartsen et al.** 2013]. Due to lower scattering of the Cherenkov light in the sea water an increase in the reconstruction resolution is expected to be achieved for KM3NeT compared to IceCube (for example [**Katz** 2003]). Furthermore, IceCube is much more sensitive to neutrinos coming from the Northern hemisphere. KM3NeT can, therefore, complete the cosmic neutrino map of the sky from IceCube, by looking at the southern hemisphere with increased sensitivity. As the galactic center is in the southern hemisphere, the flux of neutrinos traversing the earth is assumed to be higher for KM3NeT.

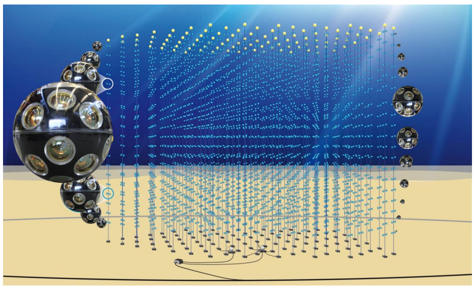


**Figure 2.1:** KM3NeT

KM3NeT itself consists of 3 independent infrastructures (2 for ARCA, 1 for ORCA), which are currently under construction. Each detector contains 115 vertical strings with several digital optical modules attached at different heights. By lowering the strings to the bottom of the sea this grid of optical modules is able to observe a large volume in the water. The horizontal spacing between the modules is 20m and 95m in the ORCA- and ARCA-detector, respectively. The total height of the detector amounts to roughly 200m and 700m for ORCA and ARCA, respectively. One digital optical module (DOM) observes the surrounding nearly isotropically for a large range of angles as 31 photomultipliers (pmt) are aligned in a sphere, in order to detect photons coming from all different directions.

By filtering this data from the pmts, which is described in Section 2.2, single cosmic neutrino events can be reconstructed. The purpose is to find distributions of direction and energy of these neutrinos.

## 2.2 Interactions of neutrinos, Cherenkov light and particle detection

### Neutrino interactions – shower vs. track

As extra-galactic neutrinos appear in the atmosphere, they interact via the weak force with atmospheric particles to a lepton, which is called charged current interaction, or to a neutrino with lower energy, which is called neutral current interaction. In both cases energy is transferred to the reaction particle, thus, resulting in electromagnetic or hadronic showers. The former consists of several electrons and photons created in the relaxation of the particle, the latter mainly of pions and sometimes other mesons. While the neutrino with less energy but unchanged flavour remains in a neutral current (NC) interaction, it is transformed to a lepton of the according neutrino flavour in the charged current (CC) interaction. These leptons carry vast fractions of the energy of the neutrino and can be detected when they travel through the detector. Their direction corresponds to the initial neutrino direction. The flux of the neutrinos from cosmic sources is, roughly, proportional to $E^{-2.5}$ in a energy range from 25 TeV to a few PeV [**Aartsen et al. 2015**].

In this thesis only muon neutrinos will be analysed as their corresponding lepton, the muon, can travel long distances and pass the detector. Electrons and taus have a much smaller range than the muon, even at very high energies. A muon with $E = 1\,\mathrm{TeV}$ has a typical range of $1\,\mathrm{km}$.

When charged particles pass through a dielectric medium with a velocity higher than the local speed of light $c_{\mathrm{m}} = \frac{c_0}{n_{\mathrm{refr}}}$ they emit Cherenkov light. The charged particles, travelling through the medium, microscopically polarise the surrounding atoms. While, usually, the electromagnetic waves interfere destructively for slow charged particles, this is not possible when the particles travel faster than the wave's velocity. A Cherenkov-light cone is built following the particles trajectory with a specific velocity depending Cherenkov angle.

The resulting muon from a charged current (CC) interaction creates a track-like signature of Cherenkov light in the detector. It is straight forward to reconstruct the particles' direction from the information of this light cone. The energy loss due to Cherenkov light emission and, hence, the number of emitted photons of the muon is correlated to the energy of the initial particle. From this information the neutrino energy can be estimated.

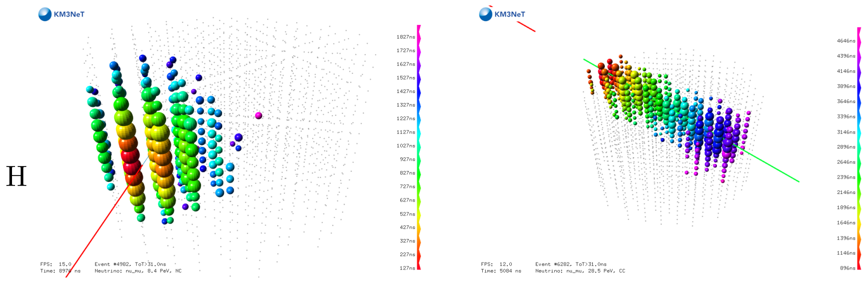
However, for a neutral current (NC) interaction that takes place close to or even in the detector both Cherenkov light from the hadronic cascade particles as well as photons from the electromagnetic cascade create a spherical shower-like signature in the detector.

The reason for this is that the cascade develops an excess of electrons when energies are low enough for photons to Compton scatter and for positrons to be sucked up. This non-zero net-charge of the cascade creates a roughly isotropic Cherenkov emission. Further details on the loss of energy of the particles can be found in [**Olive et al. 2014**].

Figure 2.2 shows typical examples of Cherenkov light detected by the pmts of KM3NeT of the two different interaction types.

The Cherenkov light emission of the muon is not an important energy loss, though. For highly relativistic muons at energies $E > 100\,\mathrm{GeV}$ radiative effects, such as bremsstrahlung, pair production or nuclear interactions, start to dominate the energy loss over the ionization. The cross-section for these processes decreases rapidly for a larger fractional energy loss. Thus, the muon roughly keeps its energy for large distances making a hard energy loss the most probable loss [**Olive et al. 2014**]. This is another reason, why muons are used for the detection of neutrinos at KM3NeT.

The muon, which comes from a charged current interaction of the neutrino and passes the detector, is simply called a '(cosmic) neutrino event', a 'single high-energetic muon' or 'numuCC - event' in Figures in this thesis.



**(a)** NC **(b)** CC

**Figure 2.2:** Examples of Cherenkov light of shower events from NC interactions (left) and track-like events from CC interactions (right) in the KM3NeT detector visualised with RainbowAlga. The circles represent the hits at pmts for a specific DOM. The colour corresponds to the time scale.

### Particle detection at KM3NeT and hit selection

The Cherenkov light is measured with photomultipliers (pmts), which trigger if a certain voltage threshold is deceeded. The more photons arrive at a pmt, the longer it will stay under this threshold. Therefore the ToT, the time over threshold, corresponds to the illumination at the position of the pmt.
The signal transferred from the DOM under water to the Computing Centre on-shore includes the start time and ToT of each so-called 'hit'.
In order to save resources each DOM only triggers, if more pmts of that DOM have received photons in a causally related timeslot (typically 10 ns). All events that do not pass this filter, so-called L1-filter, can be neglected. Still background light, which is mostly due to $K^{40}$ radioactive decay or bioluminescence, makes up for more than half of the L1-hits.

Therefore, there is a further cut process off-shore, called the 'hit-selection' (see in more detail in [**Adrian-Martinez et al. 2016**]), in order to increase the resolution of the reconstruction at a computationally feasible effort.
The hit selection tends to focus on the first DOM that sends a signal. Then, basically, only such DOMs, whose signal can be causally related in terms of distance in time and space of the hits at nearby DOMs, pass the hit selection.

For a track-like reconstruction the hit selection searches, after receiving the first signal, for further triggered DOMs in a cylindrical volume around the DOM of the first signal. For the shower reconstruction the hit-selection accepts triggered DOMs in a spherical volume around the first triggered DOM. Only, if more than 5 of these DOM's have also triggered coincidentally, the event reconstruction sets in.

Naturally, though, the selection process is not straight forward anymore as soon as two events appear coincidentally in the detector. This selection process has big influence on the quality of the reconstruction, which is analysed in the thesis later.

**Atmospheric muon bundles**

A huge obstacle of KM3NeT is to distinguish neutrino events from the background radiation.

Next to the background radiation from radioactive decay from $K^{40}$ or bioluminescence in the water, which can rather easily be filtered by the hit selection, many atmospheric muon bundles reach the detector. The Cherenkov light of these can create a signature that is very similar to track-like cosmic neutrino events.

Atmospheric muon bundles are created when cosmic particles interact with atmospheric nuclei to charged mesons, which will most likely be high-energetic pions. Their decay leads to the excess of multiple or single muons – so called extensive air showers (EAS) – which propagate to the detector [**Carminati, Margiotta, and Spurio 2008**]. The rate of the cosmic rays is proportional to $E^{-2.7}$. With another factor of $E^{-1}$ – accounting for the decay probability of the pions, which were created in the interaction of the cosmic particles with atmospheric nuclei – the flux of these atmospheric muon bundles goes like $E^{-3.7}$.

The rate of the atmospheric muon bundles $R_\mu$ arriving at the KM3NeT detector can be retained from the tags 'livetime' $\tau_\mu$ of the underlying Monte Carlo productions ('MUPAGE' productions of atmospheric muon bundles described in [**Carminati, Margiotta, and Spurio 2008**]) and the number of events per file in tag 'norma':

$$\begin{aligned} R_\mu &= \frac{\text{norma}}{\tau_\mu} = \frac{25000\,(\text{evts})}{7540\,\text{s}} \\ &= 3.3\frac{1}{\text{s}}\,, \end{aligned} \tag{2.1}$$

for muon bundles with energy $E > 10\,\text{TeV}$. [**Carminati, Margiotta, and Spurio 2008**] reports a rate of $R_\mu = 27\frac{1}{\text{s}}$ for $E > 3\,\text{TeV}$ atmospheric muon bundles. Bundles including muons with $E > 100\,\text{GeV}$ appear with a rate of $R_\mu \approx 917\,\text{Hz}$ at the detector according to the Monte Carlo files.

An easy approach to distinguish cosmic neutrino events from atmospheric muon bundles is to just accept up going neutrinos. Only the cross section of neutrinos is small enough to have a chance to traverse the earth

and interact on the other side. Hence, neutrinos from the southern sky are detected in KM3NeT. With this approach all atmospheric muon bundles and down going cosmic neutrino events would be discarded. This technique is used for the point-source search for cosmic neutrinos of KM3NeT.
In the analysis section I calculate the chance for two coincident down going atmospheric muon bundles to be reconstructed upwards and, therefore, misreconstructed due to the interference of the Cherenkov light.

However, the cross section of neutrinos increases with their energy. Typically, all neutrinos with $E > 10\,\mathrm{TeV}$ get absorbed when passing through the core of the earth. For a diffuse search of high-energetic neutrinos (with energies in PeV-range), also down going cosmic neutrinos have to be considered.

For the reconstruction of the muon bundle only the muon with the highest energy is important. All Cherenkov photons from other muons in the bundle are not causally related and, therefore discarded by the hit selection, which initially tends to focus on the muon with the highest energy (i.e. most emitted Cherenkov photons) [**T. Heid, private communication, May 2016**].

Because of the high rates, coincidences of atmospheric muon bundles with other bundles or with cosmic neutrino events are likely and the response of the detector should be evaluated. A more detailed rate calculation is presented in Section 5.

The atmospheric muon bundles are sometimes also called ‘MUPAGE events’, ‘atmospheric muon background’, ‘atmmu-events’ or similar expressions in this thesis.

# Chapter 3

# Simulation

### Monte Carlo productions

The algorithms to interpret the data collected from the photomultipliers are tested on simulated data until the full completion of the detector.

However, it is impossible to calculate the real physical output of the detector from the neutrino fluxes. One would have to integrate over all interactions of the incoming particles in the atmosphere. These are too many degrees of freedom and the integration is not computable.

Instead, Monte Carlo (MC) productions are used for KM3NeT. In the Monte Carlo process a large number of events with initial start parameters are generated. These parameters are chosen either randomly, like position or time, or according to their reported physical distribution, like the energy of the neutrinos. Due to the large number of generated events in a Monte Carlo simulation a statistically relevant output of the detector can be extracted.

For the purposes of the detector, the high-energetic events are the most interesting to simulate and reconstruct. However, in order to obtain reliable statistics for these events, a long livetime containing many less useful low-energetic events would have to be simulated alongside.

Fortunately, the Monte Carlo simulation can be forced, though, to contain more high-energetic events. The events are then assigned with a weighting factor, that accounts for the low rate of the high-energetic events. This is described and investigated further in Section 5.

In Figure 3.1 the initial energies of all events are shown for a MC production of neutrino events. For $E > 10\,\mathrm{TeV}$ the distribution resembles more a flux of $E^{-0.25}$ rather than the reported $E^{-2.5}$ flux from the high-energy astrophysical neutrino flux in IceCube for $E \in [10\,\mathrm{TeV},\ 1\,\mathrm{PeV}]$.

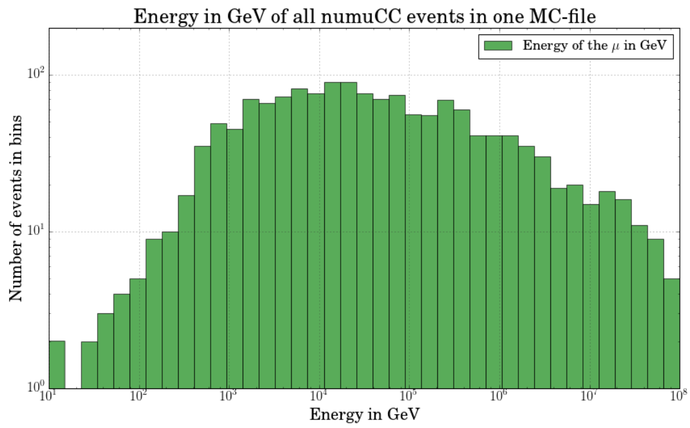



**Figure 3.1:** Histogram of energies of all events in one Monte Carlo set of neutrino events. The high energetic events are clearly over-represented for the assumed $E^{-2.5}$ astrophysical neutrino flux observed in IceCube for $E \in [10\,\text{TeV}, 1\,\text{PeV}]$.

### Stages of the Monte Carlo simulation

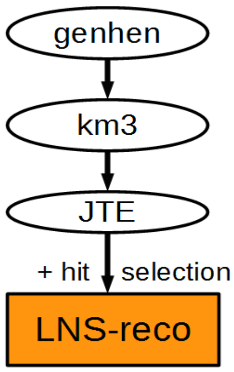



**Figure 3.2:** Procedure of the simulation and reconstruction of events.

The simulation of the output of the photomultipliers for a Monte Carlo event happens at different stages. After having chosen values for the degrees of freedom via the Monte Carlo run, the initial and secondary particles that occur in the interaction type with each particle's specific properties like position at time $t = 0$, energy, or travelling direction are generated. These features are stored in the tag 'track_in:'.

Secondly, at the km3 stage the resulting photons from the reaction and the Cherenkov light from each charged particles arriving at the pmts of the detector are calculated and written in the tags 'hit:'.

In a third stage, a program – the JTrigger Efficiency (JTE) – simulates a random background noise, for example from light of radioactive decay, and further calculates the digital output of the pmt, i.e. whether the pmt's threshold is exceeded and how long the time over threshold is.

The background in all my simulations has the previously used rate specifications, for example, in [**Adrian-Martinez et al. 2016**]. This stage represents the actual output signal, which is sent to the shore, assuming that this specific event of the Monte Carlo set has happened. Figure 3.2 visualises the whole simulation process.

If the signal passes the hit selection on-shore, described earlier, a reconstruction algorithm searches for the direction and energy of the event from fits to the data of the Cherenkov light.

At the time of this thesis two algorithms have been used and investigated on the simulated data by the collaboration: First, LNS-reco and, second, the unreleased algorithm JGandalf.

Both work via a maximum-likelihood approach and try to find the best fit to the Cherenkov light data by comparing simulated output with the acquired data.
Obviously, the algorithms act differently for a shower reconstruction and a track-like reconstruction. This thesis only focusses on the track reconstruction.

In order to evaluate the reconstruction a quality parameter is calculated. For LNS-reco this is $\Lambda$:

$$\Lambda = -\frac{\log L}{N_{\text{fit}-\text{points}} - 5}\,, \tag{3.1}$$

with the likelihood $L$ and the number of fit points in the last fitting process $N_{\text{fit}-\text{points}}$, i.e. after all cuts and pre-selections have taken place. These parameters are written as ‘speed:’ and ‘ts:’ tag in the output file of the reconstruction algorithm. In the next sections part of the analysis is to check whether this goodness parameter $\Lambda$ is still reliable for coincident events or has to be further investigated.

The resolution for the angular deviation from the initial neutrino has been improved to up to $0.2°$ with reco-LNS [**Adrian-Martinez et al. 2016**]. A well reconstructed event is, depending on the purpose of the study, defined for a $\Lambda$ of roughly $\Lambda > -6$, $\Lambda > -5.6$ or even $\Lambda > -5$.

#### Reconstruction algorithm: JGandalf

All results in this thesis are based on the reconstruction algorithm reco-LNS. However, as pointed out in [**Adrian-Martinez et al. 2016**], there have been improvements in the resolution with a different, new reconstruction algorithm called JGandalf. As this is not an officially released algorithm the performance of the algorithm is not yet fully analysed. The reconstruction of one of the produced MC files with roughly 4000 coincidences of a neutrino event and a MUPAGE event would have taken up to several hundred hours of computational time. Due to time constraints of this project this inability of JGandalf could not be further analysed, but has been reported. A first check implies that the number of hits is simply too large for JGandalf to process. As soon as this issue is solved, one can simply run the produced '.root' MC files at the JTE stage with JGandalf. A plot evaluating the quality of the reconstruction, which is for example the parameter $\chi^2$, over the reconstruction angle or the zenith angle should yield similar results as the ones shown in Section 5.

# Chapter 4

# Preliminary Investigation

## 4.1 Method

This chapter shows how I have investigated coincident events by merging two events.

In general, three sorts of coincidences are possible – first, neutrino muon events with atmospheric muon background and, second, atmospheric muon bundles with themselves. The third possibility – neutrino events coinciding with other neutrinos – is so unlikely that it is statistically not relevant. The rate of these $\nu_\mu - \nu_\mu$-coincidences is less than 1 per year. The calculation is shown in Section 5. Therefore, I have only looked at the features of coincidences of a neutrino with atmospheric muons in the first part of this preliminary investigation and coincident MUPAGE events in the second part. A particular goal of this investigation is to see what time offsets between two events are relevant for the production of coincidence events.

Finally, I describe how these results are used to create MC production for coincidences and show a first analysis of the productions in chapter 5.

To simulate the coincidences, I merge two different events from existing MC files containing single events at km3 stage. The two events at km3 stage are simply merged by writing all 'hit:' – tags of the '.evt' files from both events into one event. Furthermore, for an easier analysis also the 'track_in:' tags, i.e. the particles' information, are copied in one event. It is not necessary to add all particles on the 'gen' stage first, and run the km3 software afterwards as this software calculates the emitted light from each particle listed in the files individually anyway.

To simulate this coinciding event, one of the single events is assigned with a small time offset of order of a few $\mu$s relative to the other event. I have implemented a program called 'shift-time.cpp', which adds this time offset to all 'track'- and 'hit'-tags of one of the events before the events get merged via a separate program 'merge.cpp'. All other parameters, obviously, have to stay the same during the time shift and the merging. The index of a 'hit' or 'track_id' does not influence the calculation and can be neglected.

The number of hits of both events are summed up in the 'total_hits:' tag, which correlates with the energy of the measured particle [**Adrian-Martinez et al. 2016**]. Tags like the 'weights' etc. are not important for this preliminary analysis as they only contain relevant information for the statistics of the files, which is described further in Section 5.

However, it is necessary to merge the events before running the JTriggerEfficiency. This ensures that the background is calculated only once and does not add up from both events. Also, the actual behaviour of the pmts and DOMs might change, for example, due to coincidences at DOMs that appear only when both events are present in the detector or due to multiple photons hitting the pmt and increasing the ToT consequently. After running the JTriggerEfficieny program, the merged events can be reconstructed by the LNS-reconstruction algorithm like any other event.

The following section shows the typical behaviour and impact of coincident events in terms of the reconstruction performance.

## 4.2 Coincidence of a $\nu_\mu$-event with an atmospheric muon bundle

The first results are shown for high-energetic muons from cosmic neutrinos, which coincide with atmospheric muon bundles with a lower energy barrier of $E > 10\,\text{TeV}$. The events are taken from a existing neutrino Monte Carlo productions, i.e. here from the file 'km3_v4_numuCC9.km3_v5r1.evt' in the folder 'in2p3/km3net/mc/prod/v4/'; the atmospheric muon bundles with energy cut $E > 10\,\text{TeV}$ are from the MUPAGE production 'km3net_jul13_90m_atmmu10T990.km3_v5r1.evt' in 'in2p3/km3net/mc/prod/mu_july14/'.

The purpose of ARCA and ORCA is to reconstruct the single high-energetic muon's energy and direction in order to find information about the $\nu_\mu$ neutrino from which the muon origins.

Hereby, the reconstruction is evaluated with $\Lambda$ – the quality parameter of the reconstruction – but also the angle between the initial muon and the reconstructed track.

To measure the impact that the coincident atmospheric muon event has on the reconstruction, this scenario is repeated for different time shifts of the neutrino event relative to the MUPAGE event, which will be simply referred to as the time shift $\Delta t$ from now on. For each step the reconstruction values are retained from the output of the LNS Reconstruction.

I have started with the $\nu_\mu$-event clearly before the time when the atmospheric muons reach the detector. This corresponds to a negative time shift relative to the arrival time of the atmospheric muon bundle. Then, in steps of $10^3$ ns or smaller I have shifted the arrival of the high-energy muon later.

My expectation of this is that the hit selection already focuses on one of the events, excluding all hits that are not in the causally related cylindrical volume around one selected DOM. Obviously, the reconstruction is supposed to reconstruct the $\nu_\mu$ event very well for large negative time shifts $\Delta t$ and, accordingly, reconstruct the muon bundle well for large positive time shifts while ignoring the much later incoming neutrino event. The time in between is considered the critical time window W when the Cherenkov light of the two coincident events disturb each other so much that none of the events gets reconstructed well.

In order to get clear results of this behaviour, the following examples include well reconstructible $\nu_\mu$ events, i.e. a $\Lambda$-cut at $\Lambda < -5.2$ pre-selects all $\nu_\mu$-events. Naturally, it is hard to define a time range, in which the muon bundle severely disturbs the reconstruction for events that are already barely reconstructible by themselves. Also the muon bundle has been chosen (by eye) so that it creates a clear track-like signature in the detector in order to match the neutrino event. That means, for example events that do not pass the detector fully are discarded.

Figure 4.1 shows the illustration of a typical example of two coincident events arriving at KM3NeT, which produce two clearly distinguishable track signatures. For some time offset the Cherenkov light of the two events interferes at the bottom of the detector.

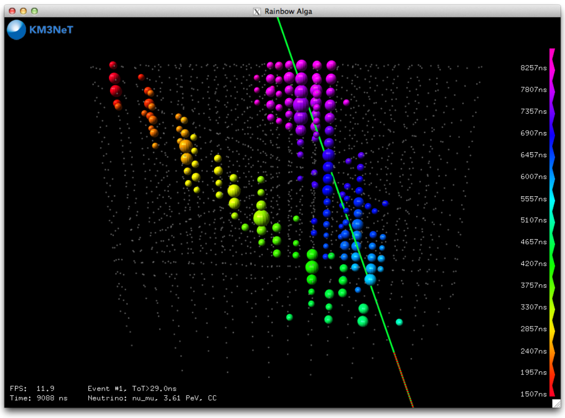



**Figure 4.1:** The visualization with RainbowAlga of a single-muon event (green line) with a neutrino with the energy $E = 3.6\,\text{PeV}$ and an atmospheric muon bundle (max. energy of one muon from the bundle is 28.1 TeV), which appear with a relative time shift of 5400 ns at the detector. The blobs correspond to the triggered DOM's in the detector and their colour to the time of the hits at the pmts. The size of the DOM's is proportional to the ToT. Background hits have been filtered out by applying a ToT-cut at $ToT > 29\,\text{ns}$.

### Typical behaviour of Λ for coincident neutrino and atmospheric muon events

An example of the analysis of a single-muon event with an initial muon energy of $E = 2.7\,\text{PeV}$ passing through the detector and a simultaneous atmospheric muon bundle (max. energy of muons from the bundle is 28.1 TeV) is shown in the Figures 4.2 to 4.5.

Figure 4.2 shows the quality of the reconstruction, $\Lambda$, for different time shifts $\Delta t$ of the neutrino event. The, mostly, constant behaviour (blue line) belongs to the single neutrino event, the green plot corresponds to the coincident event. A second run with more time shifts in the critical transition region around $\Delta t \approx 1000\,\text{ns}$ is also shown in Figure 4.2 and a close-up of this data is presented in Figure 4.3.

Like expected from the way the hit selection tends to select the first hits (Section 2.2), $\Lambda$ is at roughly $\Lambda \approx -5.2$ for negative time shifts for the coincident event (see Figure 4.4a), which represents a good reconstruction of the neutrino event. The reconstruction for these events is almost as good as for just the single neutrino event.

In the area of time shifts from 0 ns to 2000 ns the hit selection or the fit algorithms can not focus on one of the events. Figure 4.4b shows that those hits, which occur spatially close to each other in the detector, do also happen at similar times (represented by the colour).

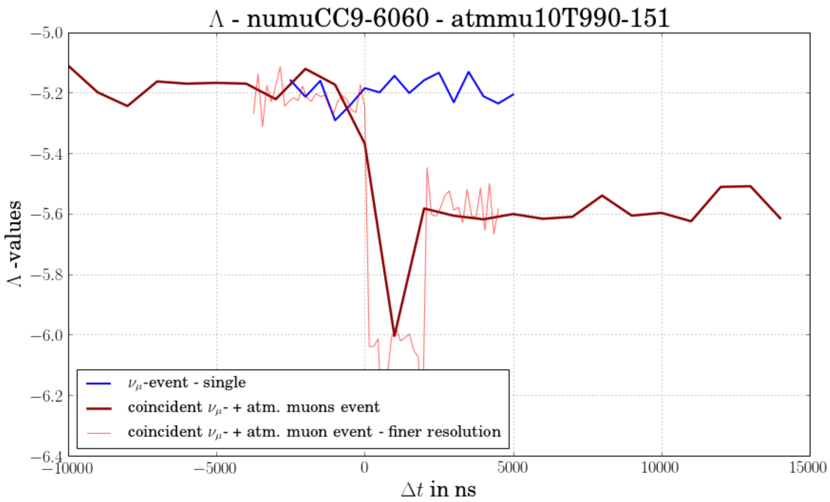



**Figure 4.2:** Rough Λ-behaviour for large time shifts of a neutrino event ($E = 2.7\,\mathrm{PeV}$) and an atmospheric muon bundle. For reference the blue line shows the reconstruction of just the single muon event, which has only little fluctuations. Furthermore, the red line shows a second run with smaller steps of the time shift and increased resolution of the critical transition region, which is also shown in the next Figure 4.3.

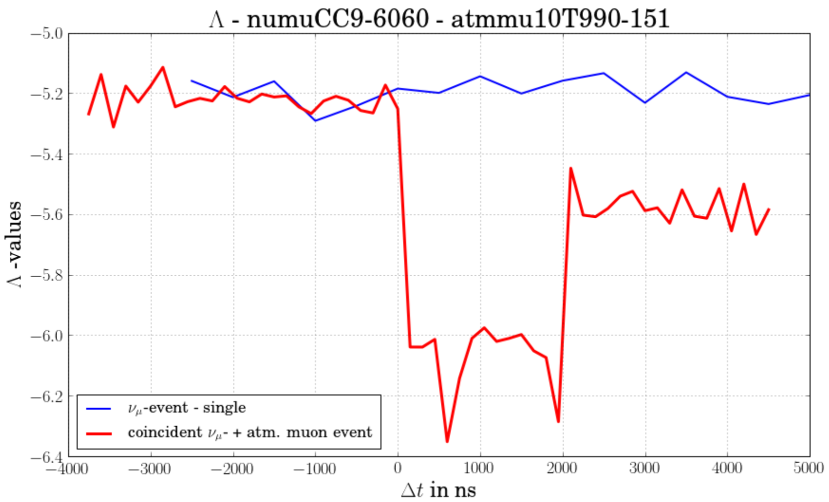
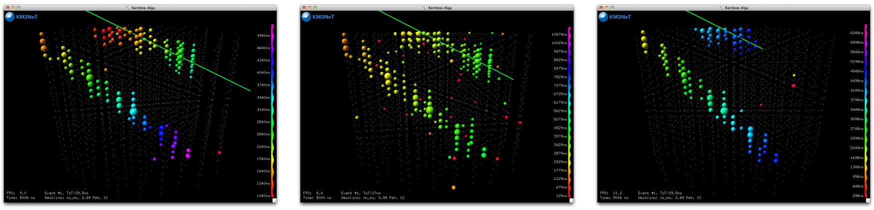



**Figure 4.3:** Zoomed in plot of Λ of the reconstruction for different time shifts of a single-muon event ($E = 2.7\,\mathrm{PeV}$) and an atmospheric muon bundle. For reference the blue line shows the reconstruction of just the single muon event, which has only little fluctuations.



(a) $\Delta t = -300\,\mathrm{ns}$ (b) $\Delta t = 1000\,\mathrm{ns}$ (c) $\Delta t = 2600\,\mathrm{ns}$

**Figure 4.4:** Visualisation of the merged events with different time shifts of the neutrino event (green line represents the muon from the charged current interaction). The left event in each picture is the atmospheric muon bundle, which stays constant in time. All pictures are taken at the same absolute time in regard to the atmospheric bundle.

If the neutrino event is shifted further ahead in time the hit selection seems to focus completely on the atmospheric muon bundle (see Figure 4.4c) and cut away all hits from the neutrino event. This happens regardless of the much lower energy and, therefore, also lower number of hits of the atmospheric muon bundle.

### Typical behaviour of angle $\alpha$ for coincident neutrino and atmospheric muon events

This change in the hit selection is even more obvious looking at the reconstructed direction, in particular, the deviation of the reconstructed track from the initial neutrino direction.

For this, the angle between the initial track from the chosen event in the Monte Carlo-Set and the reconstructed track

$$\alpha = \cos^{-1}(\vec{v}_\nu \cdot \vec{v}_{\mathrm{reco}})\,, \tag{4.1}$$

with the normalised direction vectors $\vec{v}_\nu$ of the neutrino (and subsequently the high-energetic muon) and $\vec{v}_{\mathrm{reco}}$ – the reconstructed direction – is considered and calculated for each time shift again.

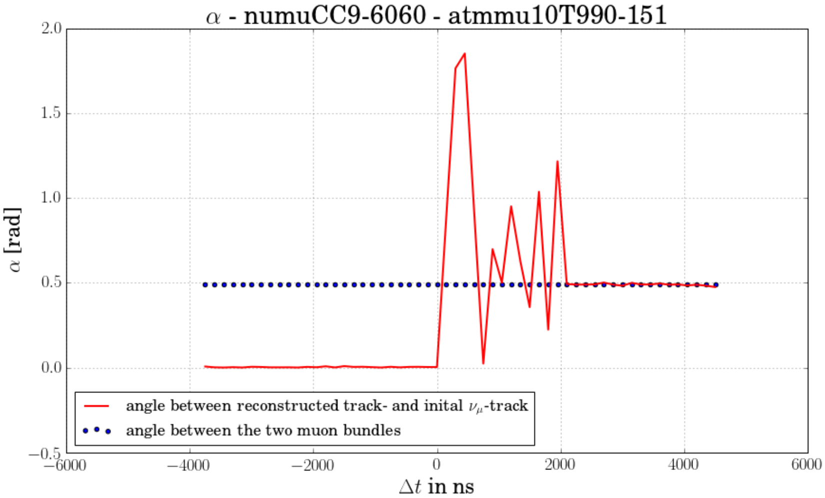



**Figure 4.5:** Angle $\alpha$ [rad] between the initial track of the single-muon event and the reconstructed track (red). Also the angle between the initial tracks of the single muon and atmospheric muon bundle is shown (blue).

It can clearly be observed how the reconstruction algorithm is fixed on the atmospheric muon bundle for large time shifts and, therefore, reconstructs the bundle with both good $\Lambda$ and good angular resolution.

From this information I have created a plot showing the correlation between angular resolution of the initial track of the single muon $\alpha$ and $\Lambda$ in Figure 4.6.

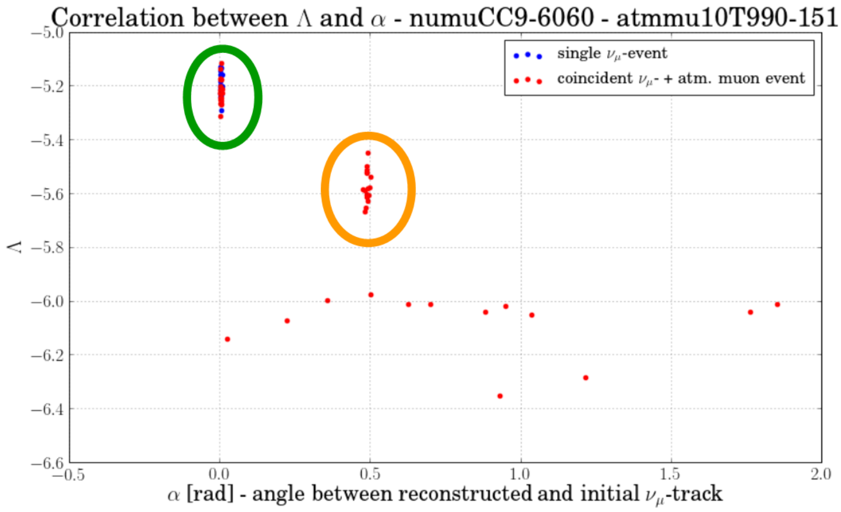



**Figure 4.6:** Correlation between Λ and $\alpha$ for the single and coincident event. The points in the orange circle correspond to the well reconstructed ($\Lambda \approx -5.5$) atmospheric muon bundle for large time shifts. The green circle shows the desired output of the reconstruction algorithm, which includes all the reconstructed single events (blue).

Figure 4.6 shows that one, obviously, has to be careful to only apply Λ-cuts without further investigation of the event in order to find muons from cosmic neutrinos. All events in the green circle, such as the single events, clearly reconstruct the neutrino event, which is the desired result. However, for the events in the orange circle the muon bundle is reconstructed but still similar Λ-values are obtained. All other events have no causal relation to the neutrino event or the muon bundle and have, consequently, a very low reconstruction quality Λ.

### Time window W for coincidences

For this coincident event a time window W can be defined for which the light from the two events disturbs each other so much that good reconstruction is impossible. In terms of both evaluation values – Λ in Figure 4.3 and $\alpha$ in Figure 4.5 – the reconstruction is poor for time shifts 0 ns to 2000 ns, i.e. the time window W is roughly 2000 ns. This time window obviously varies due to positions, directions and energies of the events. The time window will be used to calculate a probability of coincidence and, therefore, the rate of coincidences that could possibly influence the reconstruction performance.

The results from above can be reproduced with different (but still track-like) atmospheric muon bundles and $\nu_\mu$-event, e.g. in Figure 4.7.

The bottom left plot in Figure 4.8 (with atmospheric muon bundle Nr.

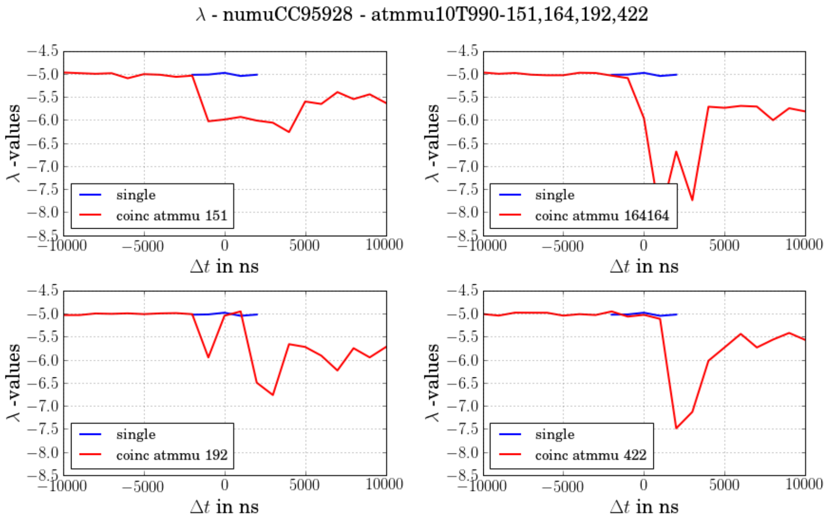



**Figure 4.7:** The Λ-behaviour of a $\nu_\mu$-event with different coincident atmospheric muon bundles with energies $E > 10\,\mathrm{TeV}$

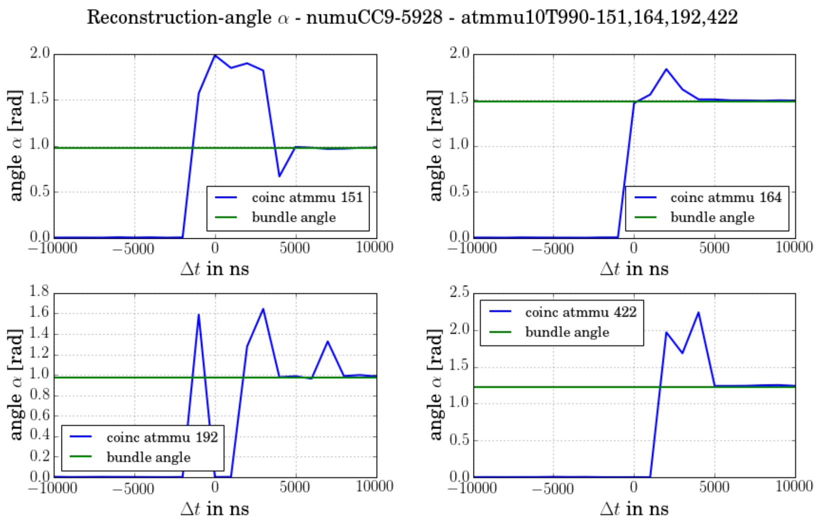



**Figure 4.8:** Behaviour of $\alpha$ of a $\nu_\mu$-event with different atmospheric muon bundles with a energy cut at $E > 10\,\mathrm{TeV}$.

192) shows one difficulty at the determination of the time window. At time shift $\Delta t = 7000\,\mathrm{ns}$ the reconstructed direction is off the atmospheric muon bundle by more than 20 degrees, even though it was reconstructed well for smaller time offsets. A possible explanation for this might be the background

hits, but could also be the additional hits from the neutrino event.

Indeed, the typical behaviour of $\Lambda$ or $\alpha$ has only been observed so clearly for the case when both events – the neutrino and the atmospheric muon bundle – could be reconstructed well. I have looked at many other events and only present the plots showing characteristic features, here.
For other events, e.g. for events whose Cherenkov cone just slightly overlaps with the detector, I was unable to detect any systematic change in the behaviour of the reconstruction. The determination of the time window is arbitrarily difficult with low reconstructibility of both single events.

## 4.3 Coincidence of two atmospheric muon bundles

So far, I have looked at a muon from a charged current interaction of a cosmic neutrino coinciding with an atmospheric muon bundle event. Considering the small flux of neutrino events, atmospheric bundles are much more likely to coincide with each other than with a cosmic neutrino event. The rate calculation is shown for Monte Carlo productions in Section 5. For this analysis I have chosen random atmospheric muon bundles from one Monte Carlo set with lower energy barrier of $E > 10\,\mathrm{TeV}$. The file used is 'km3net_jul13_atmmu10T990.evt' from the MUPAGE productions in 'in2p3/km3net/mc/prod/mu_july14/'. The original, single MUPAGE events are merged in the same way as the coincidences of neutrino event and atmospheric muon event before.

#### Typical behaviour of $\Lambda$ and $\alpha$ for twofold MUPAGE events

After recognizing that, again, interesting results can only be obtained for well reconstructible events, I have cut away all single events, which were badly reconstructed, i.e. here $\Lambda < -5.6$. Thus, I have obtained the mean $\overline{\Lambda}$ of the reconstruction of the single MUPAGE events for a few (3 to 5) different time shifts and discarded the event, if $\Lambda$ was not good enough. The averaging over a few time shifts is necessary even for a single event, as often due to background or choices of initial parameters the reconstruction algorithm can vary a lot in the quality of the reconstructed track. This applies also for the coincident neutrino events before where I have simulated $\Lambda$ for different time shifts of the single $\nu_\mu$-event for comparison.

In Figure 4.9 the same behaviour of $\Lambda$, which was seen with coincident neutrino events before, is obtained now for well-reconstructible twofold MUPAGE events with $E > 10\,\mathrm{TeV}$. In nearly all cases the first muon bundle is reconstructed well for large negative time shifts. Then for $\Delta t$ in a time window W the Cherenkov light interferes severely, so that the quality of the reconstruction $\Lambda$ drops significantly, before the second muon bundle is reconstructed well. The behaviour of $\alpha$ again emphasises this behaviour. In the time window from $\Delta t = -2000\,\mathrm{ns}$

to $\Delta t = 3000\,\text{ns}$ the direction of the reconstructed track neither fits to the first muon bundle (corresponds to $\alpha = 0$) nor to the second muon bundle (corresponds to $\alpha \approx$ constant angle between the two bundles (blue)).

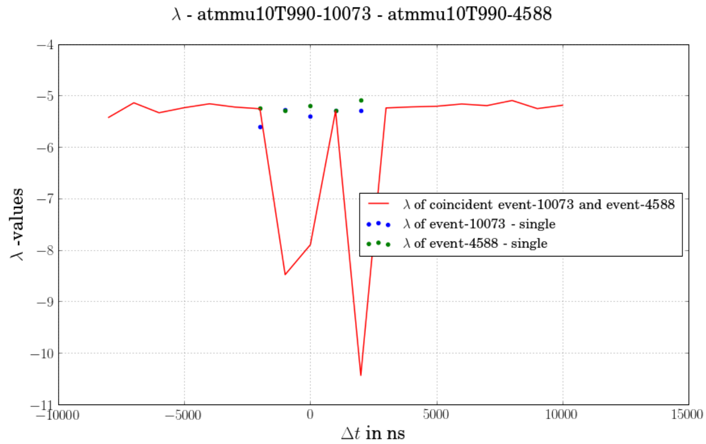



**Figure 4.9:** Λ-behaviour for different time shifts $\Delta t$ for two coincident MUPAGE-events

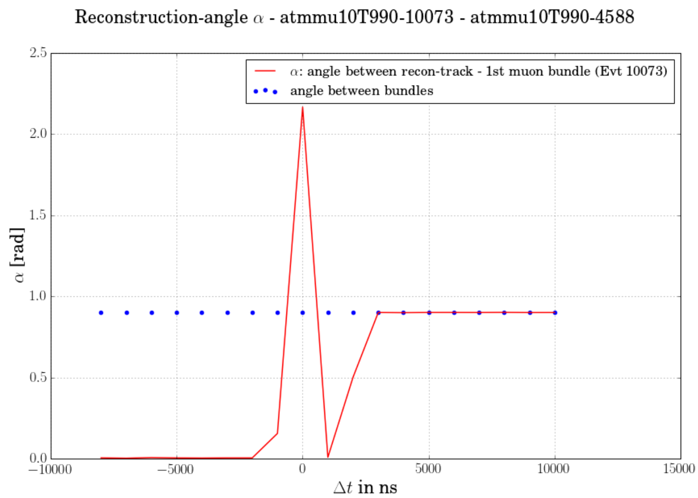
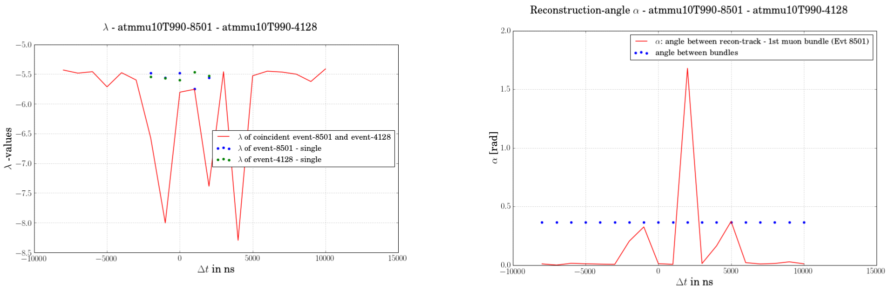



**Figure 4.10:** Behaviour of $\alpha$ for two coincident MUPAGE events. The angle $\alpha$ represents the angle between the reconstructed track and the track of the first muon bundle. Therefore, for large time shifts $\alpha$ converges to the constant angle between the two single muon bundles.




**(a)** $\Lambda$ over $\Delta t$

**(b)** $\alpha$ over $\Delta t$

**Figure 4.11:** Twofold MUPAGE events which deviate from the typical behaviour of the reconstruction of coincident muon bundles as described above.

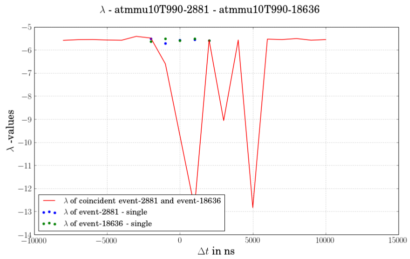
### Exceptions to typical behaviour

However, a few coincident events deviate from this behaviour such as the reconstruction of the two muon bundles in Figure 4.11.
The reconstruction seems to be able to focus on one of the muon bundles in irregular intervals but results in a bad reconstruction in between. I suppose this effect is due to random choices for the initial settings of the reconstruction algorithm, which seem to make a huge difference for the reconstruction output in this case.

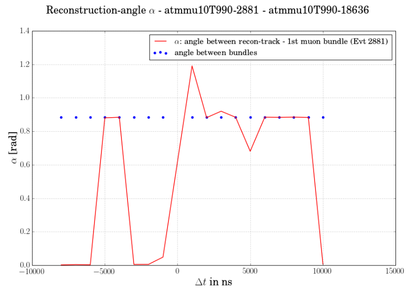
Furthermore, in some cases it is unclear whether the reconstruction is reconstructing the events well or whether background or the random selection of initial values of the algorithm play a dominant role. In Figure 4.12 at a time shift of $\Delta t = -3000\,\text{ns}$ the reconstructed track switches from the second muon bundle, which was reconstructed well for $\Delta t = -5000\,\text{ns}$ and $\Delta t = -4000\,\text{ns}$, back to the first muon bundle. The quality $\Lambda$ does not seem to drop, compared to the time shifts, in which no good reconstruction is obtained. I have not been able to further investigate or verify the ideas from above to explain this behaviour.
However, in most cases the reconstruction of the twofold MUPAGE events (with $\Lambda > -5.6$ for the single MUPAGE events) behaved just as expected and described in the beginning of this section.

In general, the worse $\Lambda$ is for the single events, the more do these contributions dominate the reconstruction output. Hence, this makes it quite hard to extract valid information.

Note, though, that with worse $\Lambda$, still in many cases the same drop in $\Lambda$ is observed and the features (e.g. time window W) do not differ much from

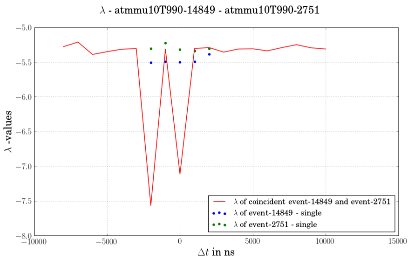



**(a)** $\Lambda$ over $\Delta t$

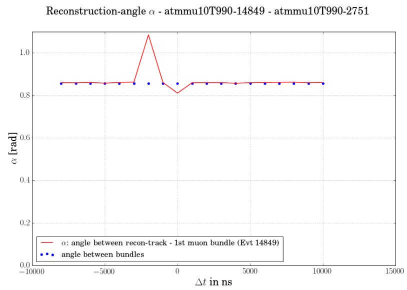



**(b)** $\alpha$ over $\Delta t$

**Figure 4.12:** Twofold MUPAGE events with unclear behaviour at time shift $\Delta t = -50000$ ns, when the reconstructed track equals the second muon bundle's direction.




**(a)** $\Lambda$ over $\Delta t$




**(b)** $\alpha$ over $\Delta t$

**Figure 4.13:** Twofold MUPAGE events with unusual behaviour.

the coincidence of well reconstructible MUPAGE events .

In some rare cases the usual change of the hit-selection's focus is not obtained at all, for example in Figure 4.13. The algorithm reconstructs the track of the second event even for large negative time shifts. From $\Delta t = -3000$ ns to $\Delta t = 1000$ ns the quality $\Lambda$ still drops just as usual.

### Time Window W of coincidence

From many typical coincident events a statistical distribution of the time windows $W$ can be obtained, for which the two events truly coincide.

I have experienced a lot of difficulty in distinguishing whether the poorly reconstructed events are due to influence of random background or due to the coincident second muon bundle (as seen for example in Figure 4.12 and also for coincident neutrino events in Figure 4.7 ). This analysis has been done purely by eye. One idea, to analyse the coincidences in a more rigorous way, would be to implement a tool that calculates this time window via the standard deviation of $\Lambda$, for example. For this, one could trigger a time window variable as soon as $\Lambda$ falls below values that exceed the normal standard deviation. In order to exclude bad reconstructions that are purely due to background, one would have to analyse this several times consecutively.

Anyway, as described above in Figure 4.11 for example, sometimes the time window observed for $\Lambda$ differs from the one in $\alpha$. In these cases I have chosen the larger time window for the statistics.

Figure 4.14 shows a rough distribution, including some runs without any $\Lambda$-cut, of the time-windows W for 140 events with two coincident MUPAGE events.

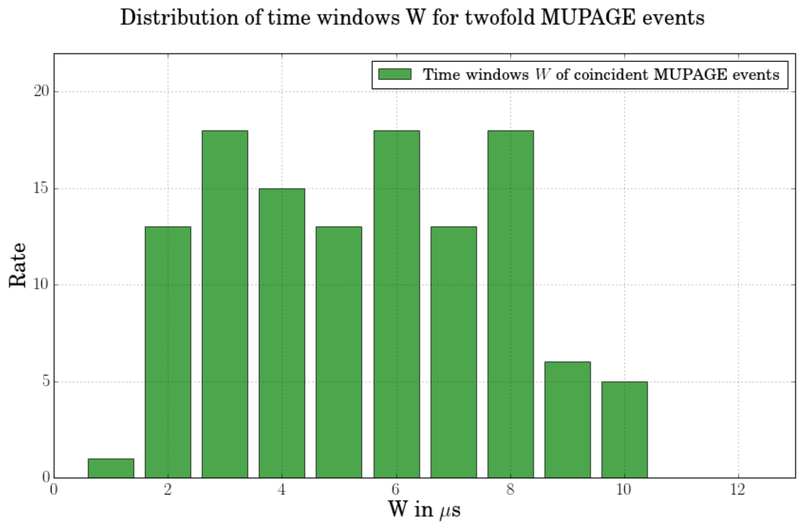



**Figure 4.14:** Distribution of the time windows W, in which the two events interfere resulting in a bad reconstruction. This analysis is for twofold MUPAGE events with no particular $\Lambda$-cut. The maximum $W$ (with a resolution of integer $\mu$s values) found in this statistics is $W = 10\,\mu$s.

Assuming a maximum time slot between the two events, for which they can coincide, of roughly about $W = 10\,\mu$s all possible coincidences should be included.

In order to check the feasibility of these numbers, I have calculated how far the muons usually travel through the detector. With radius 500 m and height 700 m a typical passage is about 1 km:

$$\begin{aligned}\Delta t &= \frac{\text{distance}}{|v_\mu|} \\ &\approx \frac{1\,\text{km}}{3\cdot 10^{8}\,\frac{\text{m}}{\text{s}}} \\ &= 3.33\cdot 10^{-6}\,\text{s} = 3.33\,\mu\text{s}\,. \end{aligned} \tag{4.2}$$

This is of the same order as the time window, in which the Cherenkov light of the two events interfere. Also, the light propagates in a different direction than the particle, which means it can stay longer in the detector and disturb the reconstruction of other particles.

With this time window the rate of coincident atmospheric muon bundles can be calculated as presented in Section 5.

**Zenith angle of reconstructed tracks**

For ORCA (and, partly, also ARCA) the goal is to find up going muon tracks. These muons can only originate from a charged current interaction of a neutrino, which has passed the earth and decayed near the detector. All atmospheric muon bundles have down going tracks, though. Therefore, a possible issue is to have coincident down going muon bundles from the atmosphere, which, for some odd reason, get reconstructed upwards and, consequently, mistaken as a cosmic neutrino event.

To strengthen or rule out this argumentation, I have looked at the zenith angle of initial and reconstructed events. The coordinate system used in the geometry of the detector has its origin on the sea bottom in the center of the circle and its z-direction is pointing upwards. The zenith angle $\theta = 0$ corresponds to upwards direction, $\theta = \pi$ equals downwards. This is of course equivalent to considering $v_z$ the direction of the track, with $\cos(\theta) = \frac{v_z}{|v|}$, where the direction is normalised $|v| = 1$.

Figure 4.15 shows the zenith angle of the reconstructed tracks for different time shifts for the same coincident atmospheric muon events (blue) from the example above in Figure 4.9 and 4.10. For comparison the zenith angle of the single atmospheric muon events are also shown (green and red). The behaviour of the $\theta$ reproduces the statements from the analysis before. While the track of the first muon bundle is reconstructed well for time shifts $\Delta t < -1000$ ns, the zenith angle equals the direction of the second muon bundle for $\Delta t > 3000$ ns. In between (time window $W$) the reconstruction is unable to find any correlated track.

Indeed, I find that in certain cases the reconstructed zenith angle exceeds 90 degrees ($\cos(\theta) > 0$), i.e. an upwards pointing track, for time

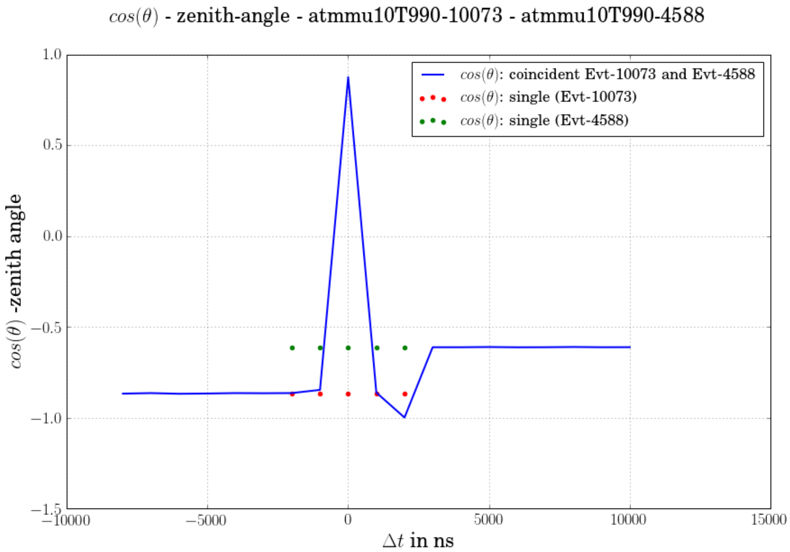



**Figure 4.15:** Typical behaviour of the zenith angle $\cos(\theta)$ of the reconstructed track for two coincident MUPAGE events. At time shift $\Delta t = 0\,\mathrm{ns}$ the reconstructed track of the donwgoing muon bundles points upwards. In red and green are the zenith angle of the initial muon bundles for comparison.

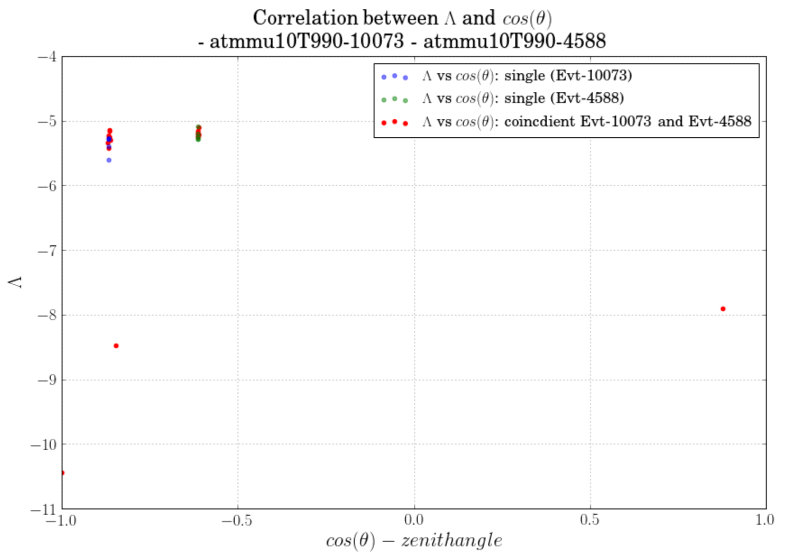



**Figure 4.16:** Correlation between reconstructed zenith angle and the quality of the reconstruction $\Lambda$. $\cos(\theta) > 0$ corresponds to upward-pointing, reconstructed tracks. A $\Lambda$-cut of $\Lambda > -7.5$ would here already be sufficient to exclude the reconstructed up-going track (the single red dot one the right side here).

shifts in the time window W. In Figure 4.15 the reconstructed track of two down going coincident muon bundles at time shift $\Delta t = 0\,\mathrm{ns}$ is pointing upwards.
However, looking at the correlation between $\Lambda$ and $\cos(\theta)$ in Figure 4.16, a simple $\Lambda$-cut is sufficient to select these cases. All well reconstructed tracks are in the region of $\Lambda \in [-5.6, -5.0]$ including the single events, of course. Thus, a cut accepting only coincident events with $\Lambda > -7.5$ would already exclude the upwards pointing track.

A statistically relevant value for this $\Lambda$-cut in order, to rule out the possibility of accepting up going tracks, is shown in the section covering the statistical analysis with Monte Carlo productions (Section 5). Also the frequency of these cases is obtained from the Monte Carlo sets in that section.

# Chapter 5

# Monte Carlo productions of coincident events

## 5.1 Method for producing Monte Carlo sets

In order to perform a statistical analysis of coincident events, I have produced Monte Carlo (MC) sets. These can be accessed in the folder 'in2p3.fr/km3net/mc/test/muon_twofold/' in KM3NeT's internal storage for further investigation on this topic.
The Monte Carlo productions have been created by merging two events at km3 stage with a random relative time shift $\Delta t \in [0, W]$, which is described in the previous Section 4, and simply writing multiple of those events of the merged files in one bigger file. Furthermore, the livetime has been calculated for all MC productions and the information from the header changed.

In order to reproduce the results in the future, a C++ program reads in the information from the MUPAGE productions or the neutrino files like the rate, weights, livetime and number of events in the file and calculates the livetime and rates of the new MC set of coincident events automatically. These calculations are presented below.
In order to be able to study the source of the coincident MC productions, a tag 'original_evt_file' is written in the header and a tag 'original_numu_eventnumber' (or 'original_atmmu_eventnumber') for each event in the '.evt' file.

All these files can be used for further research on coincident twofold atmospheric muon events or coincident $\nu_\mu$ -atmospheric muon events.

**Rate of coincidence**

The rate of any coincidence in the detector concerning the $\mu$-neutrino events is:

$$\begin{aligned} R_{\text{all}-\text{coin}} &= R_{\mu\mu-\text{coin}} + R_{\nu\nu-\text{coin}} + R_{\nu\mu-\text{coin}} + R_{\mu\nu-\text{coin}} \\ &= R_\mu \cdot W \cdot R_\mu + R_\nu \cdot W \cdot R_\nu + 2 \cdot R_\nu \cdot W \cdot R_\mu \,, \end{aligned} \tag{5.1}$$

with the rate of MUPAGE events $R_\mu$ and the rate for a muon from a neutrino event $R_\nu$.
Hence, the rate for coincident MUPAGE events is

$$R_{\mu\mu-\text{coin}} = W \cdot R_\mu^2 \tag{5.2}$$

and the rate for neutrino events coinciding with a MUPAGE event is

$$R_{\mu\nu-\text{coin}} = 2W \cdot R_\mu \cdot R_\nu \,. \tag{5.3}$$

Then, an easy way to calculate the livetime $\tau_{\text{i, coin}}$ for each MC file of coincidence type i is

$$\tau_{\text{i, coin}} = \frac{N_{\text{coin}}}{R_{\text{i, coin}}} \,, \tag{5.4}$$

with $N_{\text{coin}}$ being the number of events in the new MC file.
The rates $R_\mu$ and (slightly more complicated) $R_\nu$ can be extracted from each of the original MC files, separately. However, there is a more accurate calculation for the livetime calculation for the neutrino events. This is described for both types in the next subsections.

The rate for two neutrino events coinciding is negligibly small and this case is not discussed further in this thesis:

$$\begin{aligned} R_{\nu-\nu-\text{coin}} &= R_\nu \cdot R_\nu \cdot W \\ &\approx \frac{1}{1.5\text{yrs}} \,. \end{aligned} \tag{5.5}$$

### 5.1.1 Livetime and rate calculation for twofold atmospheric muon bundle Monte Carlo productions

For the first type of coincidences – a double MUPAGE event – I have chosen two events from the same MC set of the MUPAGE productions randomly. The atmospheric muon bundles used have cuts to the muon energy at $E >$ 10 TeV. There are no further restrictions or any order of the events in the original MUPAGE productions. Hence, each of the two coincident events can really be chosen completely randomly from this file. The created MC sets are stored separately in subfolders in terms of the energy cut of the original MUPAGE-file, $E >$ 10 TeV and $E >$ 100 GeV, respectively. Furthermore, the files are provided at km3-stage, at JTE-stage (in .root format and .evt

| subfolder | file name | file size |
|---|---|---|
| 10T/km3 | km3net_apr16_coincident_muatm10T99**i**.km3_v5r1.evt | 150 MB |
| 10T/JTE | km3net_apr16_coincident_muatm10T99**i**.km3_v5r1.evt.JTE.evt/.root | 820 MB/800 MB |
| 10T/LNS | km3net_apr16_coincident_muatm10T99**i**.km3_v5r1.evt.JTE.evt.LNS.evt | 800 MB |
| 100G/km3 | km3net_apr16_coincident_muatm100G**i**.km3_v5r1.evt | 3.8 MB |
| 100G/JTE | km3net_apr16_coincident_muatm100G**i**.km3_v5r1.evt.JTE.evt/.root | 45 MB/40 MB |
| 100G/LNS | km3net_apr16_coincident_muatm100G**i**.km3_v5r1.evt.JTE.evt.LNS.evt | 38 MB |

**Table 5.1:** Subfolder of 'in2p3/km3net/test/muon_twofold/double_mupage', file name convention and size for coincident MUPAGE MC productions with 10000 events. The index **i** is to be replaced by a number $i \in 0..9$.

format) and after the LNS-reconstruction in each folder separately (see table 5.1).

The production of one chain of Monte Carlo files, including the reconstruction, of 10000 coincident double MUPAGE events takes about 17 hours for the MUAPGE events with $E > 10\,\mathrm{TeV}$, and 2 hours for the events with energy cut at $E > 100\,\mathrm{GeV}$.

The following analysis and calculation is performed only for twofold MUPAGE events with $E > 10\,\mathrm{TeV}$.

The Monte Carlo productions contain $N_{\mathrm{coin}} = 10000$ events. With an average rate of $R_\mu = 3.3\,\mathrm{Hz}$ (Equation (2.1)) for atmospheric muon bundles with an energy $E > 10\,\mathrm{TeV}$ and a time window of coincidence $W = 10\,\mu\mathrm{s}$ this MC production corresponds to a livetime of

$$\tau_{\mathrm{coin}} = \frac{N_{\mathrm{coin}}}{R_\mu \cdot W \cdot R_\mu} \approx 9.1 \cdot 10^7\,\mathrm{s} \approx 2.9\,\mathrm{yrs} \quad (5.6)$$

and a rate $R_{\mathrm{coin}}$ of

$$R_{\mathrm{coin}} = \frac{1}{9.1 \cdot 10^3\,s}\,. \quad (5.7)$$

For productions of coincident MUPAGE events with lower energy cut ($E > 3\,\mathrm{TeV}$) this rate would increase to

$$R_{\mathrm{coin,\,3\,TeV}} = (27\,\mathrm{Hz})^2 \cdot 10^{-5}\,\mu\mathrm{s} = \frac{1}{137\,\mathrm{s}} \quad (5.8)$$

The analysis of these produced MC sets of coincident atmospheric muon bundles is presented in Section 5.2.1.

### 5.1.2 Weight and livetime calculation of $\nu_\mu$-events coinciding with atmospheric muon bundles

In the following I present the work on producing Monte Carlo simulations for the case of an atmospheric muon coinciding with a $\nu_\mu$ event. The coincident

events have been chosen from MC productions of single neutrino events and MUPAGE productions with different lower energy limit. The productions are stored in the subfolder 'numu_atmmu10T'.
Again, each production consists of files at km3-stage, JTE-stage and after the reconstruction with the LNS algorithm (see Table 5.2). One chain of MC files for the roughly 4000 coincident events takes about 7.5 hours to run.

| subfolder | file name | file size |
|---|---|---|
| km3 | km3net_apr16_coincident_numu_atmmu10T_**i**.evt | 380 MB |
| JTE | km3net_apr16_coincident_numu_atmmu10T_**i**.evt.JTE.evt /.root | 650MB / 460MB |
| LNS | km3net_apr16_coincident_numu_atmmu10T_**i**.evt.JTE.evt.LNS.evt | 630 MB |

**Table 5.2:** Subfolder of 'in2p3/km3net/test/muon_twofold/numu_atmmu10T/', file name convention, size and duration of computation for coincident MUPAGE MC productions with 10.000 events. **i** is replaced by a number $i \in 0..9$.

For this type of coincidences I have additionally adjusted the weights that contain information about the rates of the MC events, accordingly. This and the calculation of the livetime using the weight factors is shown in this section.

The events in the Monte Carlo production over-represent the higher energy range in order to get a better statistics for these events without having to simulate several years of data. Thus, the calculation of the rate and livetime of the MC set is not trivial. Each event has additional tags – the weight factors – that account for the over-representation.

A weight factor w1 includes the volume of the detector and is therefore not changed for coincident events. More interestingly, the $w2$ – weight represents the fundamental rate of the events generated, which is implemented in the first step of the MC simulation. Multiplying this number by the Bartol flux of atmospheric neutrinos $\Phi$ (with $[\Phi] = \text{m}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}\ \text{GeV}^{-1}]$) gives the 'global' rate of the specific cosmic neutrino event $w3$ with $[w3] = \frac{1}{\text{yr}}$:

$$w3 = w2 \cdot \Phi \,. \tag{5.9}$$

In order to have a set of $\nu_\mu$-events coinciding with an atmospheric muon bundle, the weight factors have to be adjusted appropriately. The rate $w3_{\text{coin}}$ is proportional to the probability $P_{\text{mupage}}$ of the MUPAGE event arriving in a certain time window $W$ after or before the $\nu_\mu$-event. In the production I have chosen either the $\nu_\mu$-event or the atmospheric muon bundle randomly to be the first event. The other event is then shifted for a positive time shift $\Delta t \in [0, W]$ relative to the first event. Thus, the new rate for each coincident event is the product of the rates from both events and the time window:

$$w3_{\text{coin}} = w3 \cdot P_{\text{mupage}} = w3 \cdot R_{\text{mupage}} \cdot (2 \cdot W) \,, \tag{5.10}$$

with $[w3_{\text{coin}}] = \frac{1}{\text{year}}$ in the output file. The probability $P_{\text{mupage}}$ represents the probability obtained for the rate calculation above in Equation (5.1). I use the same time window as in the calculation for the twofold MUPAGE events $W = 10\,\mu$s.

Obviously, the new generation weight is then $w2_{\text{coin}} = w3_{\text{coin}} \cdot \Phi$.

The output in the produced MC files is then for every event:

$$\text{weights}: \quad \text{w1} \quad \text{w2}_{\text{coin}} \quad \text{w3}_{\text{coin}}$$

The tags ‘w2-list’ and ‘w3-list’ are unchanged.

### $\tau_{\text{coin}}$ - calculation for coincident $\nu_\mu$-events

The rate $R_\nu$ for a Monte Carlo production of $\nu_\mu$-events is

$$R_\nu = \frac{1}{N_{\text{gen}}} \cdot \sum_{\text{i}=1}^{N_{\text{passed}}} w3_{\text{i}}\,. \tag{5.11}$$

Here, $N_{\text{gen}}$ is the number of the total generated events. Many of these do not reach the detector, though, and therefore do not get triggered and written into the MC files, i.e. cut away, but they are included in the calculation of the w3 rates.
One could include further cuts, like energetic or $\Lambda$-cuts later as well. The number that passed the initial cuts is $N_{\text{passed}}$.
The livetime for this production can be approximated by

$$\tau_\nu = \frac{N_{\text{passed}}}{R_\nu}\,. \tag{5.12}$$

I use this first rough approximation of the livetime and calculated $\tau_{\text{coin}}$ of the coincident Monte Carlo files for neutrino events and MUPAGE events via

$$\tau_{\text{coin}} = \frac{N_{\text{coin}}}{\left(\frac{1}{N_{\text{gen}}} \cdot \sum_{\text{i}=1}^{N_{\text{gen}}} w3_i\right) \cdot P_{\text{coin}}}\,. \tag{5.13}$$

Typically, $N_{\text{gen}} = 1 \cdot 10^8$ particles are generated per Monte Carlo file for $\nu_\mu$-events. For the coincident production I take all the events triggering in the detector and assign/merge them with randomly chosen atmospheric muon events. One of the neutrino productions, for example, gives $N_\nu = 3963 = N_{\text{coin}}$ events in the coincident MC set. With the previously calculated atmospheric muon rate, the time window $W = 10\,\mu$s and the sum of all w3-rates of the generated particles in the detector (here $4.6 \cdot 10^6 \frac{1}{\text{s}}$), summed up by a separate C++ program, the livetime of this example coincident Monte Carlo file is of order of

$$\tau_{\text{coin}} \approx 41,4\,\text{yrs}\,. \tag{5.14}$$

This is just a rough approximation of the livetime, though. Obviously, the rates w3 of events differ a lot. High-energetic events can have weights $w3 \approx 0$ as they rarely appear. Adding many of these to the Monte Carlo production will therefore not increase the sum of the rates w3. However, it does increase the number of events $N_{\text{passed}}$ in the file and therefore the livetime, which is obviously not correct as for a larger livetime the number of low-energetic events would increase much faster.

A better approach for calculating the livetime is taken from [**C. James, private communication, March 2016**] and presented in the following. A so-called effective number of particles in the file is introduced as

$$N_{\text{eff}} = \frac{N_{\text{passed}}}{\frac{1}{N_{\text{passed}}} \cdot \sum_{\text{i}=1}^{N_{\text{passed}}} \left(\frac{w3_{\text{i}}}{\overline{w3}}\right)^2}\,, \tag{5.15}$$

with the average rate $\overline{w3} = \frac{\sum_{\text{i}=1}^{N_{\text{passed}}} w3_{\text{i}}}{N_{\text{passed}}}$. Simplifying this expression yields

$$N_{\text{eff}} = \frac{\left(\sum_{\text{i}=1}^{N_{\text{passed}}} w3_{\text{i}}\right)^2}{\sum_{\text{i}=1}^{N_{\text{passed}}} (w3_{\text{i}})^2}\,. \tag{5.16}$$

The livetime for a MC file containing $N_{\text{passed}}$ neutrino events is then

$$\begin{aligned} \tau_\nu &= \frac{N_{\text{eff}}}{R_\nu} \\ &= \frac{\left(\sum_{\text{i}=1}^{N_{\text{passed}}} w3_{\text{i}}\right)^2}{\left(\sum_{\text{i}=1}^{N_{\text{passed}}} (w3_{\text{i}})^2\right) \cdot \frac{1}{N_{\text{gen}}} \cdot \sum_{\text{i}=1}^{N_{\text{gen}}} w3_{\text{i}}}\,. \end{aligned} \tag{5.17}$$

In the coincident MC production the livetime for $N_{\text{coin}} = N_{\text{passed}}$ events is consequently calculated via

$$\begin{aligned} \tau_{\text{coin}} &= \frac{N_{\text{coin,eff}}}{R_{\text{coin}}} \\ &= \frac{N_{\text{passed,eff}}}{P_{\text{mupage}} \cdot R_\mu \cdot R_\nu} \\ &= \frac{\left(\sum_{\text{i}=1}^{N_{\text{passed}}} w3_{\text{i}}\right)^2}{\sum_{\text{i}=1}^{N_{\text{passed}}} (w3_{\text{i}})^2} \cdot \frac{1}{P_{\text{mupage}} \cdot \frac{1}{N_{\text{gen}}} \sum_{\text{i}=1}^{N_{\text{passed}}} w3_{\text{i}}} \\ &= \frac{N_{\text{gen}} \cdot \sum_{\text{i}=1}^{N_{\text{passed}}} w3_{\text{i}}}{2W \cdot R_\mu \cdot \sum_{\text{i}=1}^{N_{\text{passed}}} (w3_{\text{i}})^2}\,. \end{aligned} \tag{5.18}$$

For the example above, this approach yields a livetime of

$$\tau_{\text{coin, accurateMethod}} = 5.8 \cdot 10^8\,\text{s} \approx 18.5\,\text{yrs}\,. \tag{5.19}$$

Hence, the simple approach for the livetime before differs by roughly less than one order of magnitude from this accurate approach. For the production of the coincident Monte Carlo sets I use the accurate method.

For a probability of a MUPAGE event $P_\mu > 1$, i.e. including triple, ... coincidences, that method is not really accurate either. One can imagine an infinite rate of atmospheric muons, so that the detector receives atmospheric muon bundles all the time. For every neutrino event there would be many coincident atmospheric muons present in the detector. The livetime of the coincident MC set is then simply the livetime of the neutrino events used. However, with the calculation in Equation (5.18) this would not be the case as $P_\mu \to \infty$ and the livetime converges to zero. As the rate and time window are very small for the MUPAGE events with Energy $E > 10\,\mathrm{TeV}$ these double coincidences do not matter. Even for the atmospheric muon bundles with $E > 100\,\mathrm{GeV}$ ($P_\mu \approx \frac{1}{100}$) this effect would be rather small.

The livetime of the single neutrino MC production can simply be calculated via the accurate method from before using the the weights $w3$ from the original $\nu_\mu$-MC production

$$\tau_\nu = 3.87 \cdot 10^4\,\mathrm{s}\,. \tag{5.20}$$

This is a lower barrier for the livetime of the coincidences. When many of the cosmic neutrino events do not have atmospheric muon bundles present, which is the case here, the livetime is a lot larger.

My assumption is, that the calculated livetime in Equation (5.18) is more accurate – even for the coincident MC set with MUPAGE events with $E > 100\,\mathrm{GeV}$.

Usually, $\tau$ is presented as a function of the energy bins $\tau(E)$, but for this thesis I use the total $\tau$ of the complete Monte Carlo-file.

## 5.2 Analysis of coincident Monte Carlo productions

The following section contains my analysis of the statistical coincident events from the produced Monte Carlo-sets described above.

### 5.2.1 Analysis of MC files containing twofold atmospheric muon bundles

For two muon bundles reaching the detector coincidentally the zenith angle in relation to the quality parameter $\Lambda$ is analysed, in particular, whether the quality or rate of reconstructed up going tracks changes due to the coincidences.

| | $N_{\text{single}}$ | $N_{\text{double}}$ | $F_{\text{single}}$ | $F_{\text{double}}$ |
|---|---|---|---|---|
| km3 | 25000 | 10000 | 1 | 1 |
| JTE | 6928 | 4756 | 0.28 | 0.47 |
| LNS | 6602 | 4553 | 0.26 | 0.45 |

**Table 5.3:** Raw numbers and fraction of events that are written in each file for single and twofold atmospheric muon bundles

This analysis is based on the twofold MUPAGE productions for a energy cut on $E > 10\,\text{TeV}$ in the original MC sets, which are stored in folder 'in2p3/km3net/test/muon_twofold/double_mupage/10T' (see table 5.1). A further production of coincident events with atmospheric muon bundles with $E > 100\,\text{GeV}$ can be accessed in folder 'in2p3/km3net/test/muon_twofold/double_mupage/100G/' but has not been investigated in this thesis.

### Fraction of triggered and reconstructed events in single and coincident MC prodcutions

Each of the original, single MUPAGE files contains $N_{\text{km3}} = 25000$ events. However, due to the long livetime of the coincident events I have decided that it is sufficient to include only 10000 events per coincident MC production. A lot of these 25000 or 10000 events are not triggered at running the JTriggerEfficiency or not sufficient to be reconstructed by the LNS reconstruction algorithm, though. A table showing the numbers that survive the filters at each stage is shown in 5.3.

As the coincident events include two instead of one MUPAGE events, the fraction of triggered events should be higher for the twofold muon bundles. Indeed, this yields for the produced MC files. As an representative example, one of the coincident MC files shows that the fraction of triggered events in this file can be analytically obtained from the observed fraction for triggered single MUPAGE events

$$\begin{aligned} F_{\text{triggered, single}} &= \frac{N_{\text{LNS, single}}}{N_{\text{km3, single}}} \\ &\approx 0.26 \end{aligned} \tag{5.21}$$

by adding the fractions of triggered events of the first or the second event:

$$\begin{aligned} F_{\text{trigger,double}} &= F_{1^{\text{st}}\text{ triggers}} + F_{2^{\text{nd}}\text{ triggers}} + F_{\text{both trigger}} \\ &= 1 - F_{\text{none triggers}}\,. \end{aligned} \tag{5.22}$$

Hence, the fraction of triggered events is

$$\begin{aligned} F_{\text{trigger,double}} &= 1 - F_{\text{none triggers, double}} \\ &= 1 - (1 - F_{\text{triggered, single}})^2 \\ &= 0.45\,, \end{aligned} \tag{5.23}$$

which corresponds to the observed fraction in the MC file:

$$\begin{aligned} F_{\text{triggered, double}} &= \frac{N_{\text{LNS, double}}}{N_{\text{km3, double}}} \\ &= \frac{4553}{100000} \\ &\approx 0.45\,. \end{aligned} \tag{5.24}$$

That is why one has to be careful comparing absolute numbers here. I have normalised numbers, where necessary, with the number of events in the LNS-files. However, this does also strongly indicate that the coincident muon bundles are mostly independently. If the muon bundles had a strong influence on the reconstruction, the number of triggered and reconstructed events could as well increase when two events, which are not sufficient enough to be reconstructed as single events, have enough hits to be reconstructed when they appear coincidentally.
This result of the low interaction between the coincident events is backed up by the analysis of the reconstruction quality in Section 5.2.1.

### Impact on the quality of the reconstruction

As all atmospheric muon bundles are down going tracks, none of the reconstructed tracks is supposed to point upwards. I have observed, as shown in the preliminary investigation, though, that this indeed does happen. In order to find the statistical relevance of this effect for coincident MUPAGE events, I have evaluated the MC sets in terms of the quality of the reconstruction $\Lambda$ and the zenith angle $\theta$.

Figure 5.1 shows $\Lambda$ over the zenith angle $\cos(\theta)$ of the reconstructed events for productions of single (25k red dots) and twofold (10k blue dots) MUPAGE events. By comparing these, the statistical impact of the coincident second MUPAGE on the performance of the reconstruction is investigated.

In both cases I find badly reconstructed events ($\lambda < -6$) for which the reconstructed track goes upwards, i.e. $\cos(\theta) > 0$. By eye, there seem to be no statistically significant differences between the reconstruction of single events and coincident events in terms of quality or zenith angle.

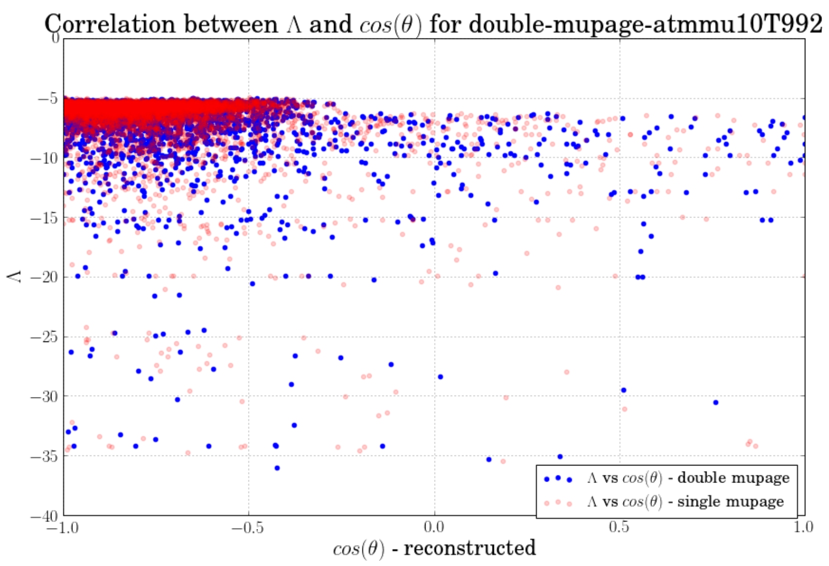



**Figure 5.1:** $\Lambda$ over the zenith angle of the reconstructed tracks of a single (red) or two coinciding(blue) MUPAGE events. The Figure shows the reconstructed events of 25000 single and 100000 coincident events at km3 stage.

The average $\Lambda$ is slightly decreasing when a coincident event is apparent as Figure 5.2 shows for different MC productions. However, this is only a very small decrease:

$$\bar{\Lambda}_{\text{double}} = -6.81 \pm 0.02 \tag{5.25}$$

$$\bar{\Lambda}_{\text{single}} = -6.70 \pm 0.01 \tag{5.26}$$

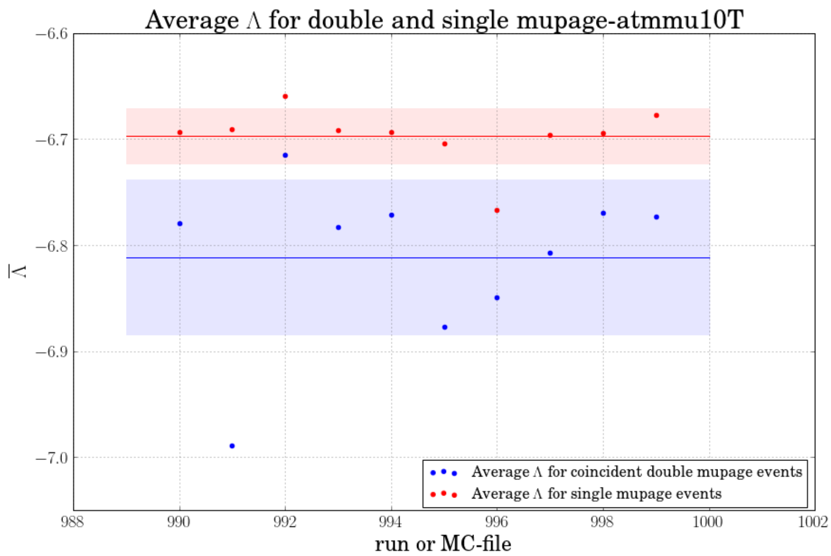



**Figure 5.2:** Average $\Lambda$ for single events (red) and coincident double MUPAGE events (blue) for 10 coincident MC files. The standard deviation $s$ is shown for both averages. The statistical error is then $\Delta\bar{\Lambda} = \frac{s}{\sqrt{10}}$.

With a standard t-test the significance of this decrease in $\Lambda$ is:

$$\begin{aligned} t &= \frac{\bar{\Lambda}_{\text{single}} - \bar{\Lambda}_{\text{double}}}{\sqrt{\Delta\bar{\Lambda}^2_{\text{single}} + \Delta\bar{\Lambda}^2_{\text{double}}}} \\ &= \frac{6.81 - 6.70}{\sqrt{0.01^2 + 0.02^2}} \\ &\approx 4.91\,. \end{aligned} \tag{5.27}$$

Hence, the small decrease of $\Lambda$ for coincident MUPAGE events is observed with a high significance of $t = 4.91$.

The statistical similarity becomes even more obvious by looking closer at the same plot with a cut at $\Lambda > -8$ in Figure 5.3.

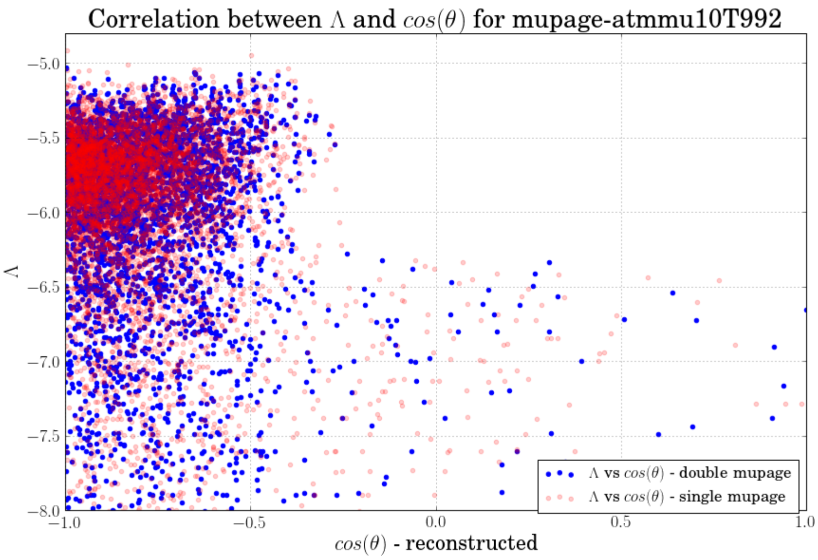



**Figure 5.3:** Closer look on the $\Lambda$-$cos(\theta)$-plot for single (red) and twofold (blue) MUPAGE events

A significant fraction of the events is reconstructed upwards for both, the single and double MUPAGE events. None of the 10 produced twofold MUPAGE sets with $E > 10\,\text{TeV}$ showed any upwards reconstructed track with $\Lambda > -6$, though. Also the majority of the events is reconstructed downwards and has $\Lambda \in [-6 : -5.4]$.

The distribution of $\Lambda$ is shown in Figure 5.4. This again emphasises the similarities between the single and double MUPAGE events. In other words, the second muon bundle has statistically almost no influence on the quality $\Lambda$ of the reconstruction.

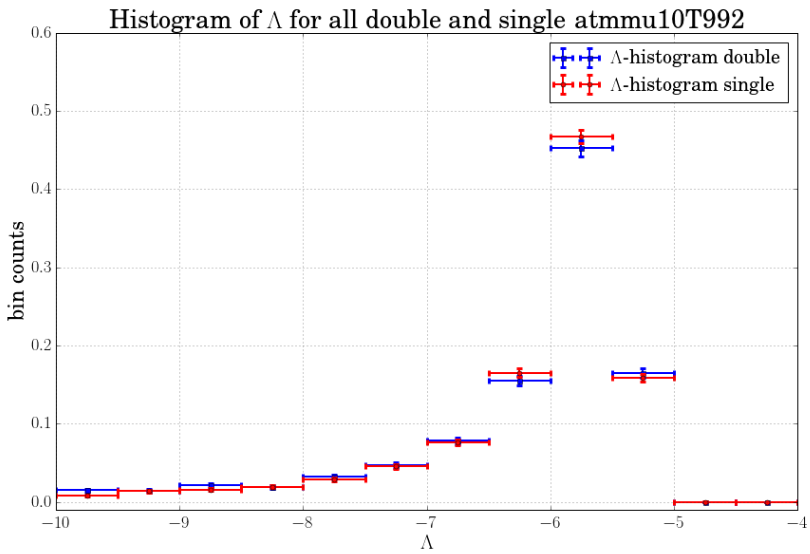



**Figure 5.4:** Histogram of all Λs for a twofold MUPAGE MC set (blue) and single MUPAGE events (red). The distribution is normalised. For both single and coincident events the distributions are nearly alike.

In Figure 5.5 a cut on $\Lambda > -5.6$ is applied, in order to take a closer look at the part of the events that are reconstructed very well. My initial assumption is that the number of well reconstructed events decreases when a second MUPAGE event is present due to the interference of the lightcones.

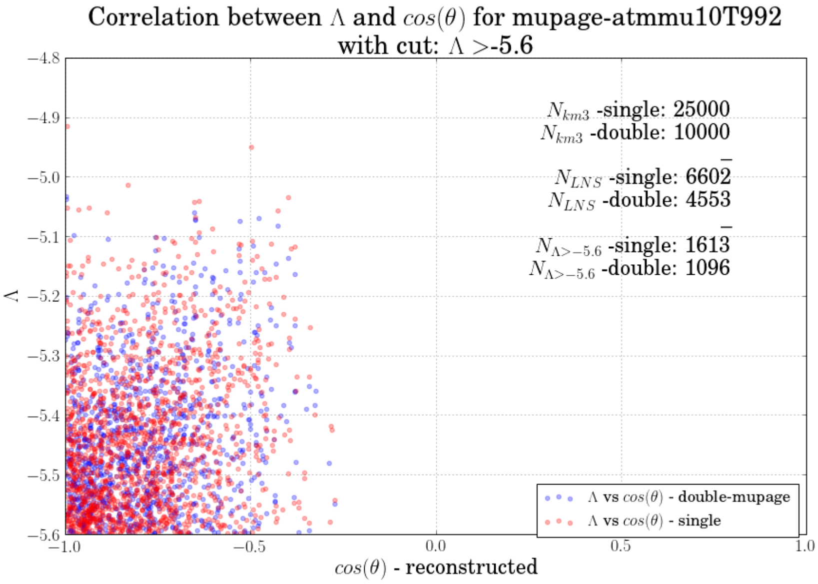



**Figure 5.5:** $\Lambda$ over the zenith angle of the reconstructed tracks of a single (red) or two coinciding(blue) MUPAGE events with a $\Lambda > -5.6$.

However, the fraction of well reconstructed events found in Figure 5.5 is equal for the double coincident events. For all 10 MC productions of 10000 coincident events at km3 stage (as in this example of Figure 5.6) these values account to:

$$\text{double}: \quad F_{\Lambda>-5.6} = \frac{N_{\Lambda>-5.6}}{N_{\text{LNS}}} = 0.25 \pm 0.003 \tag{5.28}$$

and

$$\text{single}: \quad F_{\Lambda>-5.6} = \frac{N_{\Lambda>-5.6}}{N_{\text{LNS}}} = 0.25 \pm 0.003\,. \tag{5.29}$$

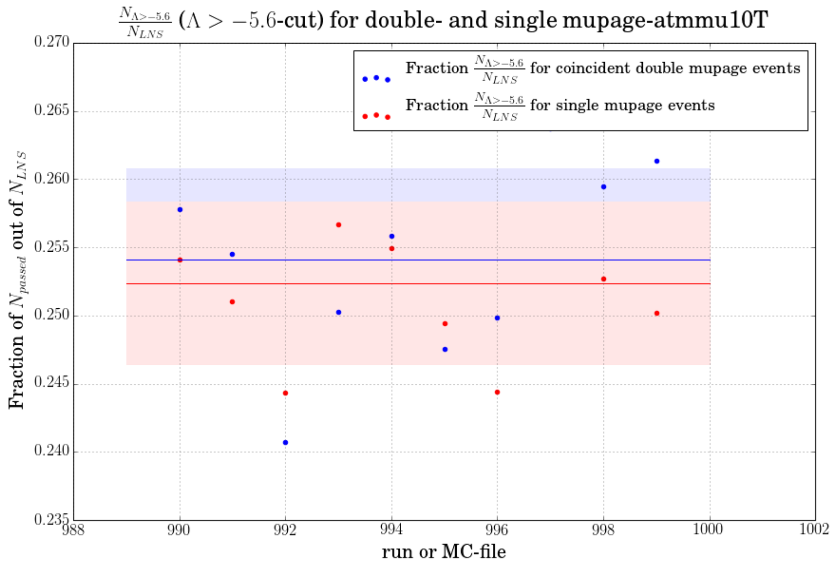



**Figure 5.6:** Fraction of events $N_{\text{passed}}$, that passed the $\Lambda$-cut, of all reconstructed events of the MC productions for single (red) and double (blue) MUPAGE events with $E > 10\,\text{TeV}$. The highlighted areas correspond to the standard deviation $s$. The statistical error is again $\Delta F = \frac{s}{\sqrt{10}}$.

A well reconstructible event appears to be still well reconstructible after adding a few hits of another muon bundle. This seems to be a big advantage of the hit selection.

Anyway, due to the very large livetime of the double events these cases will, of course, still make up only a tiny fraction of the well reconstructed events. Roughly, only

$$\frac{1}{80000\,\text{s}}\left[\frac{1096\,\text{evts}}{9.1\cdot 10^{7}\,\text{s}}\right] \quad \text{for twofold MUPAGE events} \tag{5.30}$$

vs.

$$\frac{1}{5\,\text{s}}\left[\frac{1613\,\text{evts}}{7540\,\text{s}}\right] \quad \text{for single MUPAGE events} \tag{5.31}$$

are reconstructed well.

Having two coinciding MUPAGE events implies different effects on the quality of the reconstruction:

- Obviously, if two tracks are sending Cherenkov light in the detector the accuracy of the track reconstruction should get worse. The more hits that do not belong to the reconstructed track, the worse the reconstruction algorithm works. This can also be observed for cases of a higher frequency of the background.

- The pre-selection of correlated hits happens before the actual reconstruction. Thus, it might happen that events profit from hits from another atmospheric muon bundle that also pass the hit selection. $\Lambda$ is calculated as in Equation (3.1). Therefore, $\Lambda$ is increased by having more data points in the final fit. I assume that this scenario is very unlikely, since the hit selection has a quite narrow selection to search for causally related hits in the DOMs.
- However, the pre-selection – after having chosen these hits – discards the rest. Hence, if the reconstruction algorithm has correctly selected the hits belonging to one specific event, the fit of this track should not depend on a second muon bundle or its photon emission, after all.

It is worth noting, that adding a second event can actually have a positive effect on the reconstruction of a track. This is observed in the case that one event of the coincident MC file has a better $\Lambda$ value than all $\Lambda$'s of the single events and, hence, the reconstruction must have improved compared to the original, single events. One example can be seen in Figure 5.13 later in this chapter.

This, in return, means that in some other cases the reconstruction quality of double MUPAGE events decreases, which is consistent with the results in the preliminary investigation and the initial assumption.

**Impact on falsely reconstructed upgoing tracks**

As stated before, there is a number of events that are clearly misreconstructed with upwards pointing tracks ($\cos(\theta) > 0$), which corresponds to the events on the right side of the plot in Figure 5.1. A minor worry of the collaboration is whether this number or the reconstruction quality of these events increases for twofold atmospheric muon bundles.

Satisfyingly, the results show that the reconstruction quality of the misreconstructed events is not increasing for the twofold MUPAGE events. Figure 5.7 shows the histogram of all upwards pointing reconstructed tracks. For both the single and the twofold MUPAGE sets, these normalised distributions look roughly the same. The reconstruction quality of the upwards reconstructed tracks even seems to decrease slightly for two coincident muon bundles. The reconstructions in Figure 5.7 of the coincident events have less events with $\Lambda \in [-8, -6]$. Hence, they are, in general, reconstructed worse. This again is compatible for all tested MC sets.

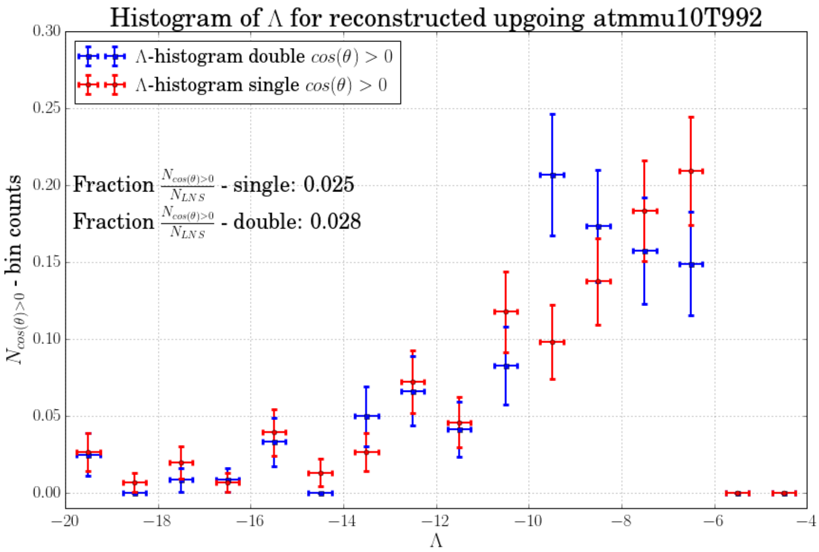



**Figure 5.7:** Histogram of Λ for all upwards reconstructed tracks ($cos(\theta) > 0$) for twofold and single MUPAGE events.

The fraction of all events (no Λ-cut) that are misreconstructed upwards, if a second MUPAGE event is coincidentally in the detector, is not significantly increasing either. In general, this fraction is only about 3% for the atmospheric muon bundles with $E > 10\,\text{TeV}$. For all 10 produced MC sets the averaged fractions of upwards reconstructed events are:

$$\text{single}: \quad F_{\cos(\theta)>0} = \frac{N_{\cos(\theta)>0}}{N_{\text{LNS}}} = (2.76 \pm 0.07)\% \qquad (5.32)$$

and

$$\text{double}: \quad F_{\cos(\theta)>0} = \frac{N_{\cos(\theta)>0}}{N_{\text{LNS}}} = (2.91 \pm 0.13)\%\,. \qquad (5.33)$$

Performing a standard t-test again, the hypothesis that the fractions of reconstructed up going events are the same for double and single is disfavoured with $t \approx 1$. Hence, the small increase of the fraction is statistically approved.

Anyway, none of the MC productions of twofold MUPAGE events showed a significantly improved reconstruction or number of misreconstructed events compared to the reconstruction of single muon bundles.

### 5.2.2 Analysis of MC files containing $\nu_\mu$-events coinciding with atmospheric muon bundles

In Section 5.1.2 I have presented the production of the MC files of coincident $\nu_\mu$-events and atmospheric muon bundles. This section continues with the analysis of these MC files. Five MC sets of cosmic neutrino events coinciding with atmospheric muon bundles with energies $E > 10\,\text{TeV}$ have been generated and are used to evaluate the response of the reconstruction algorithm.

**Impact on the quality of the reconstruction**

Analog to the analysis in the preliminary investigation, for this type of coincidence the neutrino is supposed to be reconstructed well and with good accuracy of the direction. This is why the angular resolution of the reconstructed track is identified to evaluate the performance of the algorithm.

Figure 5.8 and a close-up in Figure 5.9 (with all $\Lambda > -8$) show the correlation between the quality parameter $\Lambda$ and the reconstructed angular resolution $\alpha = \cos^{-1}(\vec{v}_{\text{recon}} \cdot \vec{v}_{\nu-\text{initial}})$, with the normalised direction vectors $\vec{v}_{\text{recon}}$ and $\vec{v}_{\nu-\text{initial}}$, for one MC set (blue) of coincident $\nu_\mu$-events and atmospheric muon bundles. For comparison the original neutrino MC set (red) with the same number of events at km3 stage (roughly 4000) is shown.

Most reconstructed tracks of the single neutrino event have a very good angular resolution, i.e. small $\alpha$, regardless of $\Lambda$. Especially, for $\Lambda > -8$ just a few reconstructed tracks of the single neutrino events deviate by more than $\alpha > 0.25$ from the initial neutrino direction.

However, with an atmospheric muon bundle coincident, a large fraction of reconstructed tracks does not match the corresponding neutrino directions. In these cases either the atmospheric muon bundle is reconstructed instead of the neutrino event or the reconstruction is disturbed by its Cherenkov light.

Again, it is helpful to take a look at the distribution of $\Lambda$ for all reconstructed events (Figure 5.10) with the single $\nu_\mu$ events in red and the coincident in blue.

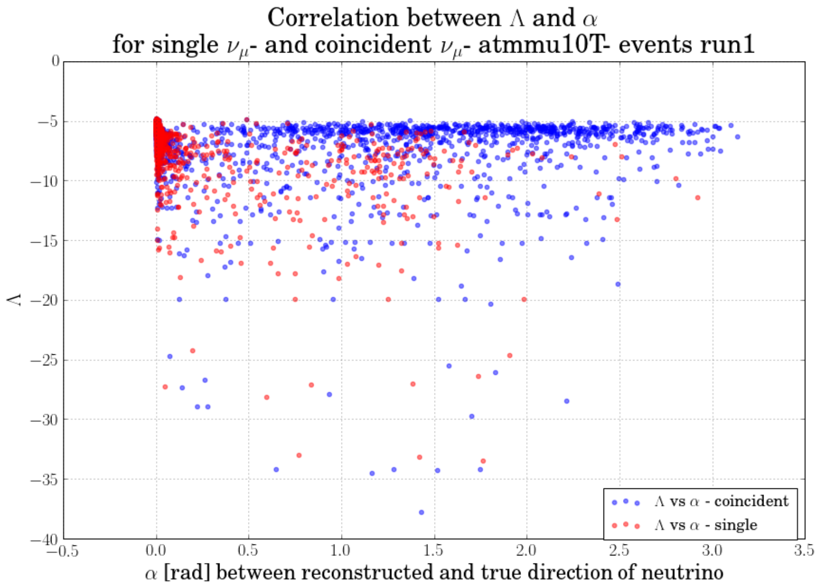



**Figure 5.8:** Correlation between $\Lambda$ and $\alpha$ [rad] for one MC set of coincident neutrino and atmospheric muon bundle ($E > 10\,\text{TeV}$) events (blue) and for the comparison of the same single neutrino events (red)

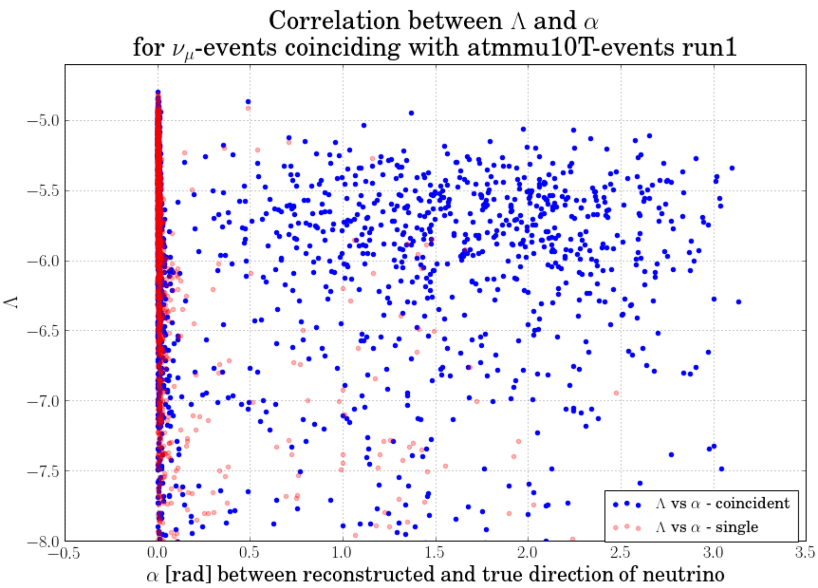



**Figure 5.9:** Correlation between $\Lambda$ and $\alpha$ [rad] for one MC set of coincident neutrino and atmospheric muon bundle ($E > 10\,\text{TeV}$) events (blue) and for the comparison of the same single neutrino events (red) with a cut of $\Lambda > -8$.

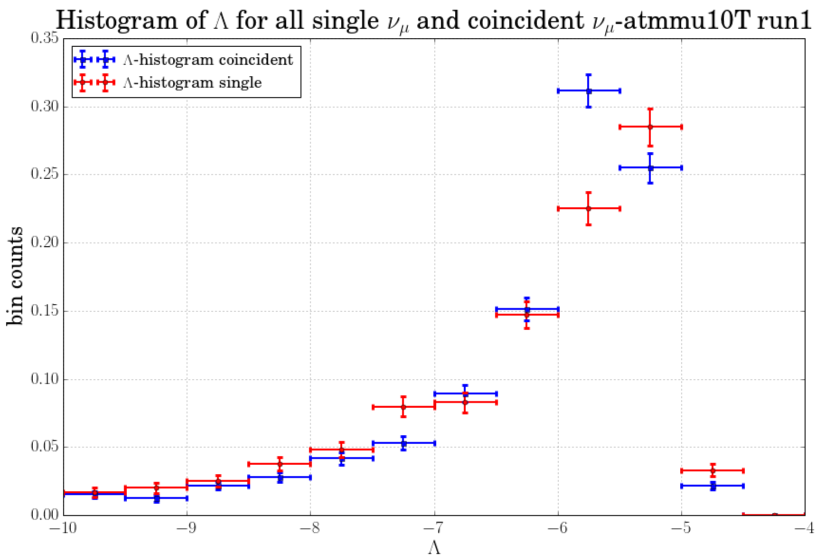



**Figure 5.10:** Histogram of Λ for all events of one MC set of coincident neutrino and atmospheric muon bundle ($E > 10\,\mathrm{TeV}$) events (blue) and for the comparison of the same single neutrino events (red). The histogram is normalised.

The normalised histograms in Figure 5.10 show approximately the same distribution for single and coincident events except for some fluctuations around $\Lambda \in [-6, -5]$. The explanation for these is the good reconstruction of the atmospheric muon bundles instead of the neutrino events. The average $\Lambda$ for all 5 MC files is nearly equal for both the single and the coincident MC files, with

$$\bar{\Lambda}_{\text{single}} = -6.981 \pm 0.012\,, \tag{5.34}$$
$$\bar{\Lambda}_{\text{coin}} = -6.990 \pm 0.022\,. \tag{5.35}$$

A decrease of only 0.1 for $\bar{\Lambda}_{\text{coin}}$ (i.e. $\bar{\Lambda}_{\text{coin}} = \bar{\Lambda}_{\text{single}} - 0.1$) due to coincidences, which I have found for the twofold MUPAGE events before, is disfavoured with $\sigma \approx 3.6$ for coincident neutrino events.

That is to say, in general, the algorithms quality parameter of the reconstruction $\Lambda$ does not suffer from atmospheric muon background. Obviously, this statement is not relevant, if one is interested in reconstructing the $\nu_\mu$-event only.

### Impact on the incorrectly reconstructed $\nu_\mu$-tracks

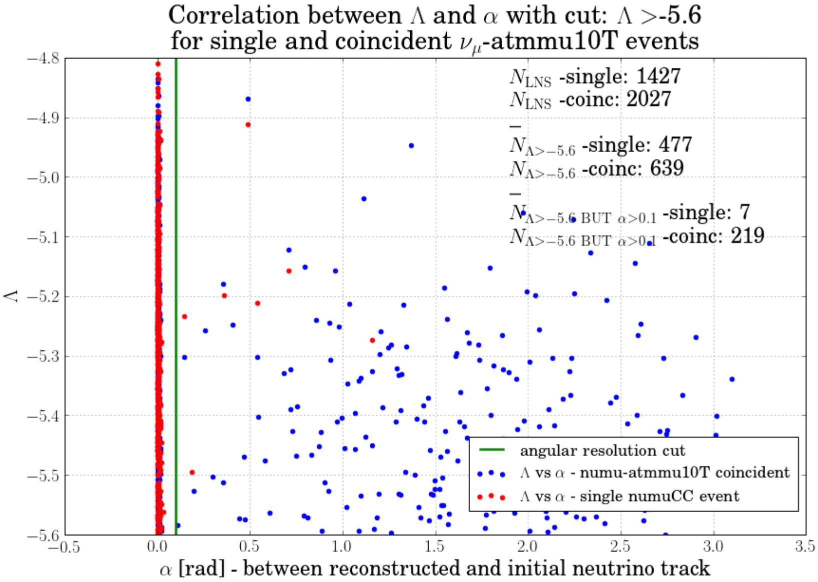



**Figure 5.11:** Correlation of $\Lambda$ and $\alpha$[rad] for a single neutrino (red) and a coincident $\nu_\mu$-atmmu10T (blue) production with cuts to $\Lambda > -5.6$ and an indicated $\alpha < 0.1$ -cut. All events to the right of the green cut-line ($\alpha > 0.1$) are incorrectly labelled as reconstructed well ($\Lambda > -5.6$) by the algorithm.

The purpose of KM3NeT is to reconstruct the neutrino. Therefore, all reconstructed tracks deviating by a certain angle $\alpha > 0.1$ from the initial neutrino track are here referred to as misreconstructed. I consider these as 'lost' events. However, in order to search for point-sources, the reconstruction algorithm is designed to have an angular resolution that goes up to $\alpha < 0.2°$, i.e. approx. $\alpha < 0.004$. This is why, after analysing the 'lost' events in the first paragraph, I focus on the impact of the muon bundle on the angular resolution for very small angular deviations ($\alpha < 1°$) in the second paragraph.

- **'Lost' events with** $\alpha > 0.1$

Figure 5.11 shows the number of 'lost' events, which are labelled as well reconstructed with $\Lambda > -5.6$, although they deviate by more than $\alpha > 0.1$, i.e. $\alpha > 5.7°$, from the neutrino direction. Naturally, this fraction of incorrectly well reconstructed $\nu_\mu$ events should be relatively small, as it makes interpretations difficult. For the coincident events this fraction increases vastly, though. Obviously, in many cases the muon bundle is reconstructed instead of the neutrino making large angular deviations from

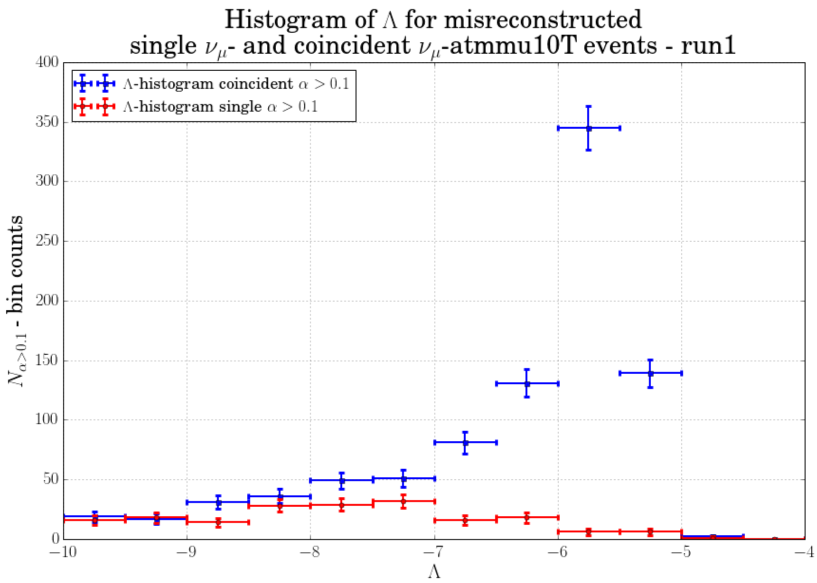



**Figure 5.12:** Histogram of $\Lambda$ for all events with an angle between reconstructed and initial neutrino track of $\alpha > 0.1$ for a single $\nu_\mu$-MC set and a set of coincident $\nu_\mu$ and atmospheric muon bundle events. The error is estimated via the normalised $\Delta N_{\text{bin}} \approx \sqrt{N_{\text{bin}}}$.

the neutrino with good $\Lambda$ more likely.

For single $\nu_\mu$-events this fraction of 'lost' events

$$F_{\Lambda>-5.6,\text{ but }\alpha>0.1} = \frac{N_{\Lambda>-5.6,\text{ but }\alpha>0.1}}{N_{\Lambda>-5.6}} = 0.011 \pm 0.001 \tag{5.36}$$

is negligible.

With a coincident MUPAGE event the fraction increases to roughly a third averaged over all 5 produced MC sets and yields

$$F_{\Lambda>-5.6,\text{ but }\alpha>0.1} = 0.350 \pm 0.007\,. \tag{5.37}$$

Furthermore, the histogram in Figure 5.12, which includes all misreconstructed events ($\alpha > 0.1$), shows that many of the misreconstructed tracks of the coincident files are labelled as well reconstructed. For single $\nu_\mu$-events the number of misreconstructed events strongly decreases when $\Lambda$ improves, which is what $\Lambda$ is designed to do. This does not hold for neutrino events with coincident atmospheric muon background anymore.

Taking all reconstructed events into account the track direction of one out of two events are misreconstructed for the coincident events, compared to only one out of five single $\nu_\mu$-events. The averaged fraction for the single events is

$$\text{single}: \quad F_{\text{tot},\ \alpha>0.1} = \frac{N_{\alpha>0.1}}{N_{\text{LNS}}} = 0.200 \pm 0.002 \tag{5.38}$$

and for the coincident MC productions

$$\text{coinc}: \quad F_{\text{tot},\ \alpha>0.1} = 0.525 \pm 0.003\,. \tag{5.39}$$

In order to evaluate the relevance of this result, I have calculated how often a well-reconstructed event is actually misreconstructed, i.e. how many incorrectly accepted reconstructions appear per time unit in the detector. Dividing the number of misreconstructed $\nu_\mu$ events (with $\Lambda > -5.6$) by the livetime of the related MC file yields, roughly,

$$\begin{aligned} \text{single}: \quad R_{\Lambda>-5.6,\ \text{but}\ \alpha>0.1} &\approx \frac{7 \pm 3}{3.87 \cdot 10^4\,\text{s}} \\ &= (1.8 \pm 0.7) \cdot 10^{-4}\,\frac{1}{\text{s}} \\ &\approx \frac{5654\,\text{evts}}{\text{yr}} \end{aligned} \tag{5.40}$$

for all single files and

$$\begin{aligned} \text{coinc}: \quad R_{\Lambda>-5.6,\ \text{but}\ \alpha>0.1} &\approx \frac{219 \pm 15}{5.8 \cdot 10^8\,\text{s}} \\ &= (3.8 \pm 0.25) \cdot 10^{-7}\,\frac{1}{\text{s}} \\ &\approx \frac{1.2\,\text{evts}}{\text{yr}} \end{aligned} \tag{5.41}$$

for the coincident $\nu_\mu$ and atmospheric muon background productions. Hence, due to the much larger livetime the misreconstructed single events still dominate by three orders of magnitude.

- **Angular resolution for angles** $\alpha < 0.1$

So far, I have analysed the events that were clearly misreconstructed with directions deviating from the initial neutrino by more than 5°. In the following I analyse the impact of the coincident atmospheric muon bundle on the angular resolution and the reconstruction quality in the crucial area of $\alpha < 0.1 \approx 5.7°$ and good reconstruction quality of $\Lambda > -5.6$. This is the upper part on the left side of the green line in Figure 5.11, which is shown as a close-up in Figure 5.13. To simplify the discussion, I switch to the unit degrees for the angular resolution $\alpha$. In order to study the exact reconstruction of the direction I use an even finer cut at $\alpha < 1°$. However, only very few events with angular resolution between 1° and 5° are reconstructed, anyway. For KM3NeT a resolution of roughly $\alpha < 0.2°$ is desired.

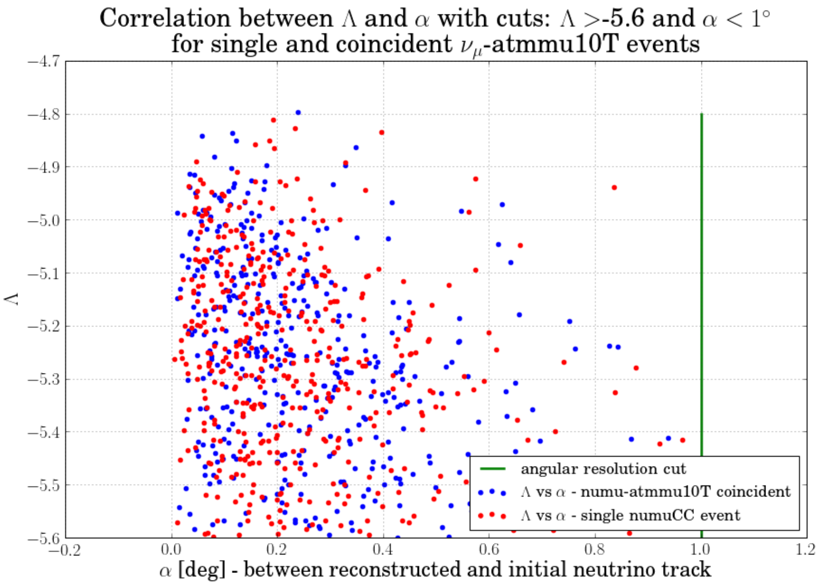



**Figure 5.13:** Correlation of $\Lambda$ and $\alpha$ [deg] for a coincident $\nu_\mu$- MUPAGE-event with cut $\Lambda > -5.6$ and $\alpha < 1°$ (green line).

With these cuts to $\Lambda$ and $\alpha$ the distribution of $\Lambda$, shown in the histogram in Figure 5.14, is roughly the same for single and coincident events. Also the angular resolution, which is shown in the histogram for $\alpha$ [deg] in Figure 5.15, is not affected by the coincident MUPAGE event.

In particular, for cuts to the angular resolution with even smaller tolerance, $\alpha < 0.2°$, which is a typical angular resolution cut for the reconstruction, $\Lambda$ and $\alpha$ of the reconstructed $\nu_\mu$-event are not significantly affected by the coincident MUPAGE event compared to the single $\nu_\mu$-events according to the histograms in 5.14 and 5.15.

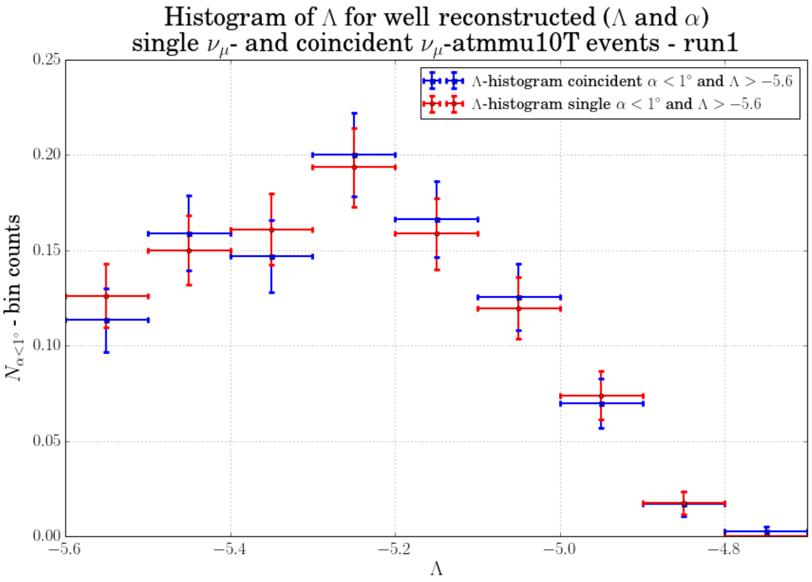



**Figure 5.14:** Normalised histogram for Λ of coincident $\nu_\mu$-MUPAGE events with $\Lambda > -5.6$ and $\alpha < 1°$. The error is estimated via $\Delta N_{\text{bin}} \approx \sqrt{N_{\text{bin}}}$.

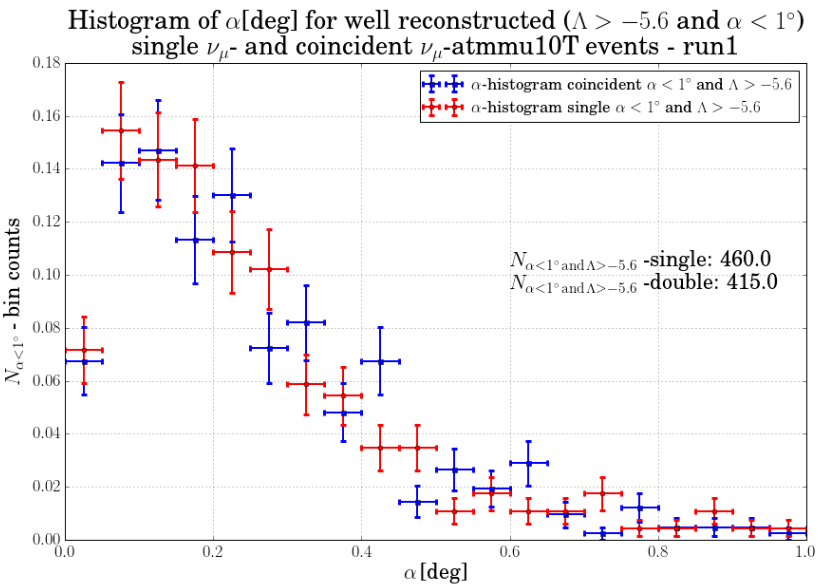



**Figure 5.15:** Normalised histogram for α[deg] of coincident $\nu_\mu$-MUPAGE events with $\Lambda > -5.6$ and $\alpha < 1°$. The error is estimated via $\Delta N_{\text{bin}} \approx \sqrt{N_{\text{bin}}}$.

However, the fraction of the reconstructed events that passes these cuts is smaller for the coincident MC production. For this example in Figure 5.15, the fraction for single events is

$$\begin{aligned} \text{single}: \quad F_{\Lambda > -5.6 \,\text{and}\, \alpha < 1^\circ} &= \frac{460}{1427} \\ &= 0.32 \end{aligned} \tag{5.42}$$

and for the coincident events

$$\begin{aligned} \text{coinc}: \quad F_{\Lambda > -5.6 \,\text{and}\, \alpha < 1^\circ} &= \frac{415}{2027} \\ &= 0.20\,. \end{aligned} \tag{5.43}$$

This decrease of the fraction of well reconstructed events in terms of $\alpha$ for coincident $\nu_\mu$ – MUPAGE events is consistent with the result of the increasing number of misreconstructed events for coincident events from the first part of this section.

# Chapter 6

# Conclusion

In this thesis the analysis of coincidences of neutrino events with atmospheric muon bundles, as well as, atmospheric muon bundles with themselves in the KM3NeT detector was presented.

In the preliminary investigation a relative maximum time offset of $\Delta t_{\mathrm{max}} = 10\,\mu\mathrm{s}$ was found, for which a second coincident event can severely influence the reconstruction of a single, well reconstructible event in both cases of coincidence. For two events with a relative time offset in this range, the quality parameter $\Lambda$ can drop significantly and the reconstructed track can deviate severely from any of the formerly well reconstructed tracks. Furthermore, for two coincident down going atmospheric muon bundles, also reconstructed up going tracks were found.

With this maximum time offset $\Delta t_{\mathrm{max}}$ Monte Carlo sets of coincident events were produced for both cases.

Having analysed these Monte Carlo productions, a statistically significant impact of the coincidences on the performance of the reconstruction could be quantified.

### Twofold atmospheric muon bundles

A small decrease in the quality of $\bar{\Lambda}$ of $\Delta\bar{\Lambda} \approx 0.11$ for all coincident twofold atmospheric muon bundles events was found with significance $t = 4.91$.

The fraction of well reconstructed events is equal for coincident and single atmospheric muon bundles, indicating a small impact of the coincident events on the reconstruction of these events.
However, due to the small rate the coincident events have no statistical relevance:
Only one coincident event of atmospheric muon bundles is reconstructed well every 8000 s, while one single atmospheric muon bundles is reconstructed with $\Lambda > -5.6$ every 5 s.

Of the twofold coincident down going atmospheric muon bundles a fraction of 0.0291 events are misreconstructed as up going tracks. The fraction for single atmospheric muon bundles is slightly smaller with 0.0276 events. Among these reconstructed up going tracks $\Lambda$ is smaller for coincident events than for single muon bundles.

This result disfavours that a problem of an increase of well reconstructed up going events due to coincidences might occur. All reconstructed event with an up going track were labelled as poorly reconstructed with $\Lambda < -6$ for both single and coincident events.

**Neutrino events with coincident atmospheric muon bundle**

For the neutrino events with a coincident atmospheric muon bundle, the average quality of the reconstruction was found to remain constant. A decrease in $\bar{\Lambda}$ as for the twofold atmospheric muon bundles of 0.1 is disfavoured with $t = 3.6$.

However, the number of the reconstructed tracks that are mistakenly labelled as well reconstructed by quality parameter $\Lambda$, although they clearly deviate from the neutrino track ($\alpha > 0.1$), increases vastly due to the coincident atmospheric muon bundle by a factor of 35. 35% of the coincident neutrino and atmospheric muon bundle events are mistakenly labelled as well reconstructed compared to only 1% for single neutrino events. However, due to the very low rate of the coincident events, the number of mistakenly well reconstructed tracks is still dominated by the single neutrino events.
Roughly one neutrino event per year is mistakenly labelled as well reconstructed due to a coincident atmospheric muon, compared to more than 5000 events per year from single neutrino events.

Looking at the events that were reconstructed well in terms of both $\Lambda > -5.6$ and $\alpha < 1°$, the form of the distribution of $\Lambda$ and $\alpha$ remains the same, but the fraction of the triggered events that pass these cuts decreases from 0.32 for single events to 0.2 for neutrino events with coincident atmospheric muon bundle.

This thesis has shown possible impacts of coincident events on the reconstruction performance. In general, the coincidences do not decrease the average $\Lambda$. Also, due to the low rate of the coincidences the number of misreconstructed events for both cases is statistically not relevant. For further analysis Monte Carlo productions of coincident events for both cases have been produced.

# References

## Literature

Aartsen, M. G. et al. (2013). “Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector”. In: *Science* 342, p. 1242856. arXiv: 1311.5238 [astro-ph.HE] (cit. on pp. 1, 3).

— (2015). “A combined maximum-likelihood analysis of the high-energy astrophysical neutrino flux measured with IceCube”. In: *Astrophys. J.* 809.1, p. 98. arXiv: 1507.03991 [astro-ph.HE] (cit. on p. 4).

Adrian-Martinez, S. et al. (2016). “Letter of Intent for KM3NeT2.0”. In: arXiv: 1601.07459 [astro-ph.IM] (cit. on pp. 1, 6, 11, 14).

Carminati, G., A. Margiotta, and M. Spurio (2008). “Atmospheric MUons from PArametric formulas: A Fast GEnerator for neutrino telescopes (MUPAGE)”. In: *Comput. Phys. Commun.* 179, pp. 915–923. arXiv: 0802.0562 [physics.ins-det] (cit. on p. 7).

Katz, Uli (2003). “The Km3net Project - Design Study For A Deep Sea Facility In The Mediterranean For Neutrino Astronomy And Environmental Sciences”. Presentation. URL: http://ecap.nat.uni-erlangen.de/members/katz/talks/UliKatz_appec_0311.pdf (cit. on p. 3).

Olive, K. A. et al. (2014). “Review of Particle Physics”. In: *Chin. Phys.* C38, p. 090001 (cit. on p. 5).