Appendix 3

Atmospheric Neutrinos in 97 Data
(Summary of the DESY analysis)

Abstract

This document describes the results of the analysis of atmospheric neutrinos at DESY and is a compressed version of the corresponding AMANDA Internal Report[1]. The filtering and determination of the final neutrino cuts are explained. The application of these cuts results in a sample of 223 neutrino candidates for 130 days of live-time.

These final neutrino events are compared to the expectations from atmospheric neutrinos. They agree in their characteristic observables and pass various plausibility checks. Different methods to estimate the background lead to an estimation of about 10–20 background events in the final sample.

The systematic uncertainties from the signal expectation, the event overlap with other analyses and a potential celestial clustering are studied.

1 Introduction

The measurement of high energy atmospheric neutrinos is an important step in the analysis of the AMANDA neutrino telescope. It can be considered a proof of method of the detection techniques as well as a calibration of its sensitivity to neutrinos in general. Several analyses have been performed to identify atmospheric neutrino events in the AMANDA-B10 data of 1997 – each with an increased efficiency. An overview is given in table 1.
A first analysis in the beginning of 1999 showed that a separation of neutrino events is possible. Two analysis groups at the University of Wisconsin at Madison, and at DESY-Zeuthen have been working separately, since. The next analyses aimed at an increased signal efficiency and achieved a relatively high neutrino statistics (1999). They used a first MC simulation mass production. Additional simplification efforts and a better systematic understanding of the analyses were achieved in 2000. Their results led to a second joint background MC mass production, yielding more than 90 million triggers from downward going atmospheric muons. Two DESY analyses in the second to last block in table 1 rely on that improved simulation. This document represents a summary of the full technical report[1] (DESY-IIIc) which includes additional sophisticated event reconstructions, an optimized cut evaluation, an elaborate background estimation and a detailed investigation of systematic effects and uncertainties in the final neutrino sample.

[1]available at http://www-zeuthen.desy.de/nuastro/ice3_proposal/

	date	N_ν^{cand}
UW-I	Jan-1999	17
DESY-I	Sep-1999	116
UW-II	Dec-1999	195
DESY-IIa	Mar-2000	135
DESY-IIb	Apr-2000	155
UW-III	May-2000	188
UW-IVa	Sep-2000	154
DESY-IIIa	Sep-2000	218
DESY-IIIb	Oct-2000	209
UW-IVb	Mar-2001	159
UW-IVc	Mar-2001	204
DESY-IIIc	Apr-2001	223

Table 1: Overview and acronyms of atmospheric neutrino analyses of 1997 data.

2 Data Analysis

The data in this report has been processed through 3 levels of cuts until the number of events was reduced to a manageable size for the final cut evaluation.
Before filtering started, a run selection and a hit cleaning procedure was applied to all data removing unstable runs and probable noise hits. Filter level 1 was based on a fast fit algorithm called the "line fit" (abbr. "lf"). With 5% of the remaining data, a first full likelihood reconstruction was performed which basically fitted the arrival times. Cuts on the zenith angle, the number of un-scattered photons and the likelihood were applied (level 2). A consecutive filter level 3 used the results of an iterative likelihood reconstruction with varying starting values, a fit based on the hit probabilities and a reconstruction fitting a point source hypothesis. Additional cuts on the topology of the events were applied. All hitherto applied cuts were simple and set to weak values, details can be found in the full report and references therein.
Before the final cut optimization a last, most elaborate reconstruction was applied using multi-photon statistics derived from the amplitude information (abbr. "mpe"). A cut on its reconstructed zenith angle left less than 10^4 events in the data. In order to optimize the final stage of filtering, a new method (CutEval) was developed which takes into account that the cut parameters are not independent and have individual but correlated efficiencies. The principle of the CutEval method is to numerically optimize the signal to background efficiency by a variation of the cut-parameters within the allowed parameter boundaries. The explicit usage of parts of the experimental data as well as different MC simulations within the optimization procedure allows for a detection and comparison of systematic differences between the samples and the cut parameters used.
The final cuts as proposed by the CutEval procedure are described in the following. Again, a more detailed description of the parameters is given in the full report and references therein.

$|S^{van}| < 0.28$: The pure ("vanilla") smoothness measures the homogeneity of the distribution of hits along the track. Exact equidistance of the hits would give $S^{van} = 0$, all hits at the starting point of the track $S^{van} = +1$ and all hits at the endpoint $S^{van} = -1$. This cut is motivated by the fact that Čherenkov light is emitted continuously.

$|S^{phit}|/(\theta - 90°) < 0.01$: This cut parameter compares the reconstructed zenith angle to the "phit" smoothness (the above mentioned smoothness, where every hit is weighted with its hit probability). This cut is particularly effective due to the asymmetry of the detector acceptance with respect to the reconstructed zenith angle.

$(N_{dir}(-15:75) - 2) \cdot L_{dir}(-15:75) > 750\text{m}$: The number of OMs hit by un-scattered photons (reduced by 2), multiplied with the largest distance between any two of these OMs is required to exceed 750 m. We interpret this observable as the lever-arm of the fit times the number of strong supporting points in between. Here, the definition of un-scattered photons is such that they arrive at most 15 ns too early or 75 ns too late as compared to the expectation for un-scattered photons.

$\log(\mathcal{L}_{up}/\mathcal{L}_{down}) > 7.7$: The ratio of likelihoods of the reconstruction between the best upward moving and the best downward moving track hypothesis has to be larger than 7.7.

$\Psi(mpe, lf) < 35°$: The space angle between the multi-photon reconstruction and the line fit must not exceed 35°. It turned out that this cut efficiently removes residual cross-talk features in the data which were not simulated by the MC. The effects and properties of this un-simulated background has been studied in detail during the past two years.

$\sqrt{S^{van}_{dir}(-15:75)^2 + S^{phit}_{dir}(-15:75)^2} < 0.55$: A cut on the "radius" of the two flavors of smoothness, this time only calculated for un-scattered hits. This cut effectively removes residual coincident muon events from independent air showers.

3 Results

Once the minimum set of observables is found, the optimum cut values can be calculated under variation of a pre-defined number of allowed residual background events N_{BG}. The optimum cut values are parameterized as function of the allowed background contamination. The result is a path through the cut parameter space which yields the best signal efficiency as function of a given N_{BG}.
Using these parameterizations it is possible to calculate the numbers of events passing the cuts as function of N_{BG} for the signal and background MC and compare them to the experimental values. This is shown in figure 1 with N_{BG} varying from the trigger level to the highest possible quality selection.
One observes that the background expectation falls quickly with smaller values of N_{BG}. Below values of 10^2 to 10^3, the signal starts to dominate the expected event rate: It has the necessary flatter slope than the background. The experimental curve follows the expectation from the sum of background and signal MC: For large values of N_{BG}, the experimental event rate follows the background expectation. Towards smaller values, the experimental shape turns over into the signal expectation and follows it nicely up to the highest quality events (smallest value of N_{BG}). The difference between the two signal Monte Carlos will be explained in section 4.
Table 2 lists the cut efficiencies for the atmospheric neutrino simulation (with and without the implementation of the angular sensitivity of the OMs, see section 4), the background simulation of atmospheric muons from air showers and the obtained numbers from the experiment. Again, the experimental numbers agree well with the background simulation up to the first two filter

levels. Later, the MC underestimates the experimental passing rates slightly. The last two rows show the expected numbers of events for the last stage of filtering, with and without neutrino oscillations. A total of 223 neutrino candidates is found. The experiment favors the "ang. sens." MC. The oscillation scenario describes the experiment best. However, the 10% effect due to oscillation are smaller than our systematic uncertainty.

Figure 2 shows a typical neutrino event in the AMANDA event display.

Figure 3 shows the luminosity of the AMANDA detector. The cumulative number of neutrino events is plotted versus the day number as well as the cumulative number of event triggers. One can observe that the neutrino events follow the number of triggers albeit with a small deficit in

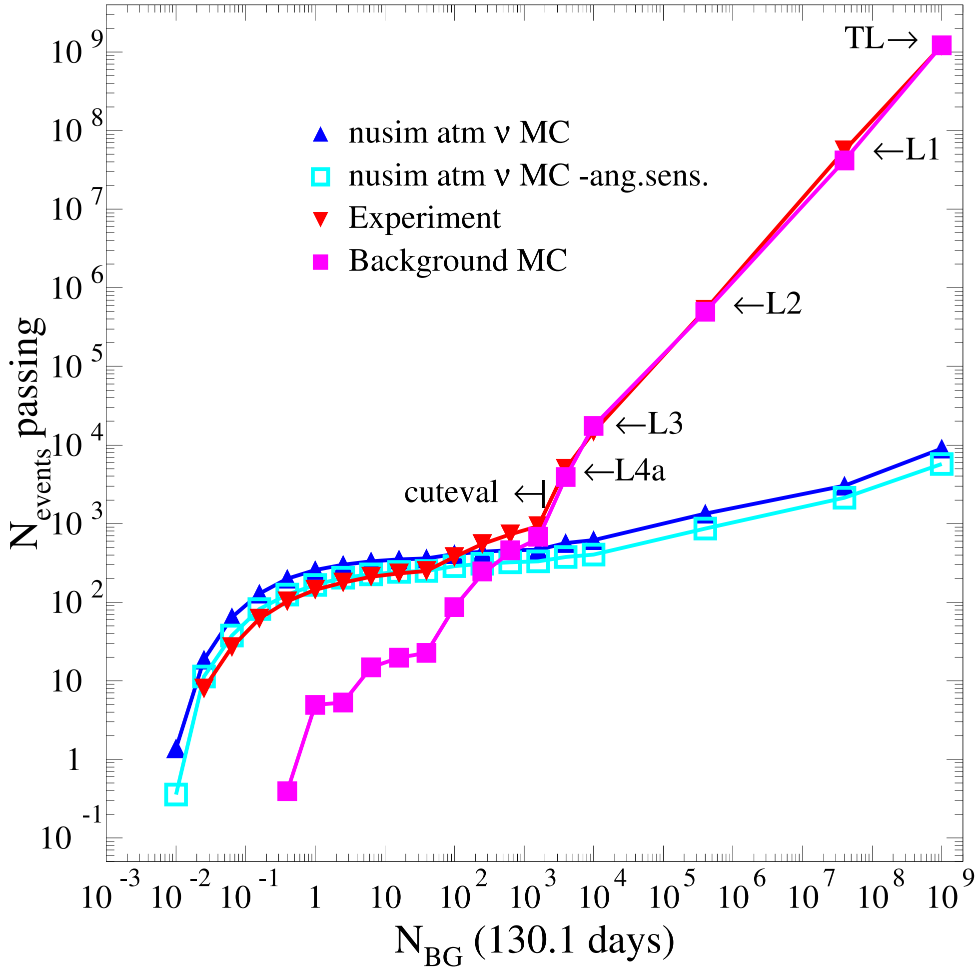

Figure 1: Number of events versus background parameter N_{BG}. The figure shows the number of events of the experiment, the neutrino MC nusim, with and without the angular sensitivity model and the background MC, which pass the cuts corresponding to the value N_{BG}. Smaller values of N_{BG} correspond to tighter cuts. Up to $N_{BG} = 1500$, the CUTEVAL parameterization was used to calculate the cut values. For larger values of N_{BG}, the data points correspond to the cuts from the filter levels: level 4a ($\equiv$ only the zenith angle cut of cut level 4), levels 1-3 (L1, L2 and L3) and the trigger level (TL). The final level 4 cuts correspond to $N_{BG} = 10$.

Filter level	atm. ν MC	atm. ν MC (ang. sens.)	atm. μ BG MC	experiment
Trigger	8978.8	5759.1	$9.03 \cdot 10^8$	$1.18 \cdot 10^9$
ϵ Level 1	0.34	0.37	$0.4 \cdot 10^{-1}$	$0.5 \cdot 10^{-1}$
ϵ Level 2	0.15	0.15	$0.4 \cdot 10^{-3}$	$0.4 \cdot 10^{-3}$
ϵ Level 3	$0.7 \cdot 10^{-1}$	$0.7 \cdot 10^{-1}$	$0.7 \cdot 10^{-5}$	$0.1 \cdot 10^{-4}$
ϵ Level 4 (just zenith angle cut)	$0.6 \cdot 10^{-1}$	$0.6 \cdot 10^{-1}$	$0.1 \cdot 10^{-5}$	$0.4 \cdot 10^{-5}$
ϵ Level 4 (final)	$0.4 \cdot 10^{-1}$	$0.4 \cdot 10^{-1}$	$0.5 \cdot 10^{-8}$	$0.2 \cdot 10^{-6}$
# events final level (without osc.)	362.3 ± 3.9	236.9 ± 5.5	7.5 ± 4.8 (130 days)	-
# events final level (with osc.)	335.3 ± 3.4	219.3 ± 4.3	7.5 ± 4.8 (130 days)	223

Table 2: The cut efficiencies of the atmospheric neutrino MC, the atmospheric muon background MC simulation and the experimental data for 130 days detector life time. Shown are the numbers of triggers, the different filter levels as well as the number of events after application of the final cuts. The last two rows give the expected numbers of events for the cases without and with neutrino oscillations (in the case of BG these numbers are normalized to the total life-time). The differences between the two signal MCs will be discussed in section 4.4.

the winter (the summer in the northern hemisphere). This deficit is consistent with statistical fluctuations.
Figure 4 shows the celestial distribution of the 223 events in galactic coordinates. We performed a binned analysis and a cluster analysis and found that the data was consistent with a random distribution.

4 Systematics

An open detector like AMANDA is conceptually challenging to run. It uses its natural environment as an inherent part of the detector. This "part" cannot be calibrated and tested under laboratory conditions. A thorough investigation of systematic effects is thus of crucial importance.

4.1 Inspection of characteristic distributions

The most basic investigation of our systematics consists of the inspection of various distributions. In the following, we describe the use of four classes of distributions: *cut observables*, *unbiased variables*, $N-1$ *cuts* and *low level distributions*.
An obvious test is the investigation of distributions of the final neutrino sample. Here, the experimental events follows the MC signal expectations nicely - for both: *observables which have been cut upon* and *unbiased ones*. Some deviations are observed, especially the number of hit OMs and the speed of the line fit. There, a deviation between experiment and MC can be seen. The full report discusses these deviations in detail and can resolve it by application of the angle-dependent OM sensitivity model in the MC (essentially reducing the sensitivity in forward illumination).
The $N-1$ *test* is particularly powerful to evaluate the final cuts and to obtain an estimate of the background contamination in the final sample. One applies all final cuts except for one and plots the data in this variable. One expects that the observed experimental events follow the expected background shape at one end of the distribution and turn over into the signal shape

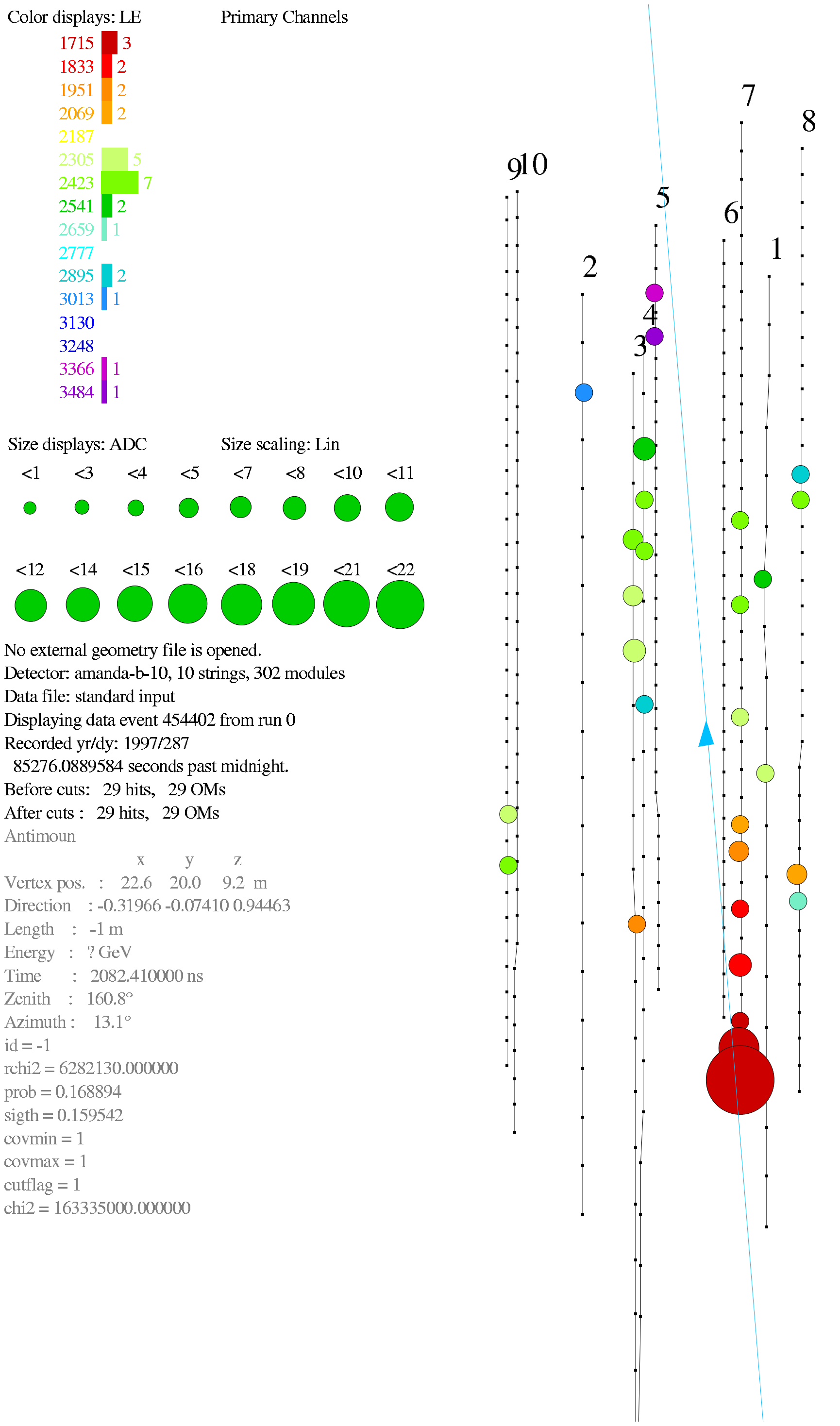

Figure 2: Experimental neutrino event. The circles represent hit OMs, their color (greyscale) codes the light arrival times (bottom early, top late) and their size represents their amplitude. The diagonal line indicates the reconstructed track, the vertical lines indicate the detector strings.)

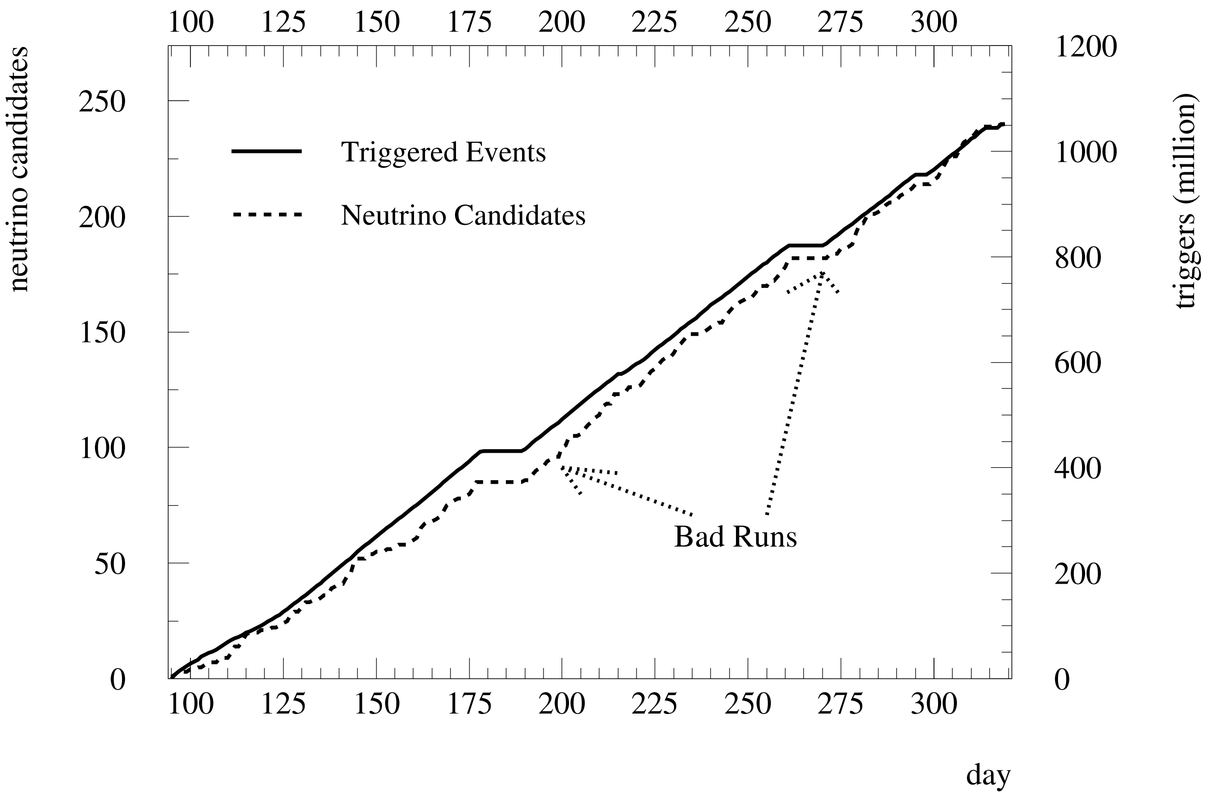

Figure 3: The luminosity of the AMANDA detector 1997. The figure shows cumulative numbers of event triggers (solid line) and the number of neutrino events (dashed line) versus the day number (year 1997). The times marked as bad runs correspond to times of unstable detector operation.

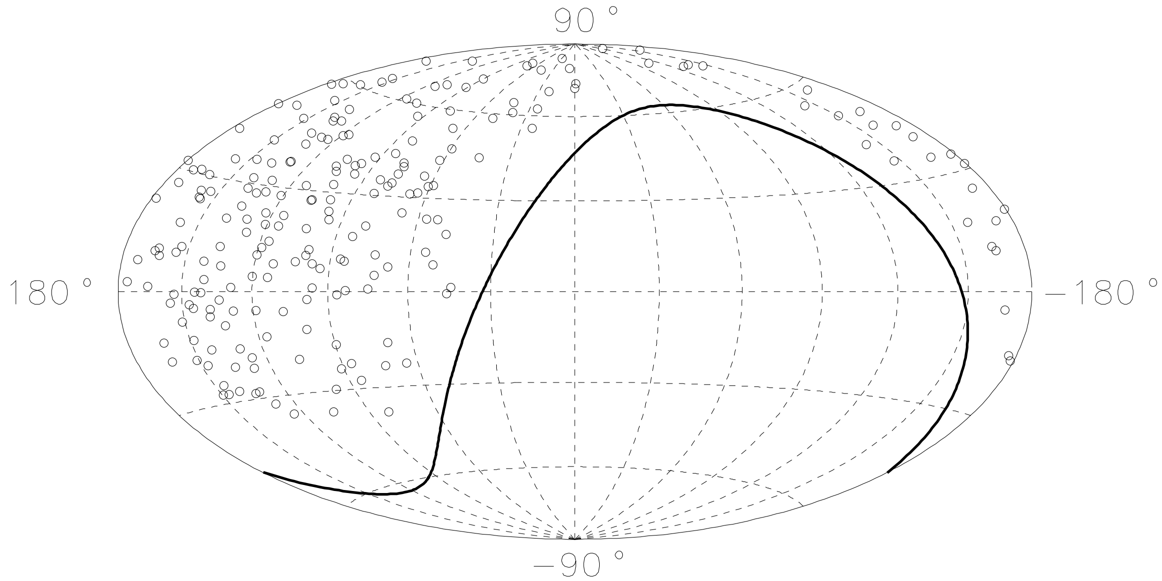

Figure 4: The celestial distribution of the sample of detected neutrino candidates in galactic coordinates. The curve represents the detector horizon.

at the other end. An appropriately placed cut is then expected on the signal side, close to the transition region. This technique requires the appearance of background events and thus uncorrelated cuts. All our cuts satisfy this test: The distributions agree on both sides of the applied cuts.

In order to account for possible pathological *low level* features in the data sample (especially cross-talk), we investigated basic ADC and TOT distributions and re-fitted all events after a dedicated cross-talk hit-cleaning procedure. These distributions and the thus reconstructed zenith angles show no significant deviation from the previous ones. No cross-talk features are found in the resulting neutrino sample.

Finally, a *visual inspection* of the full neutrino sample was performed. This led to the discovery of a small contamination of events arising from coincident independent air showers - a class of un-simulated background. The last cut mentioned in section 2 was developed and enters the cut optimization as a dedicated cut, capable of removing most of this background. The visual inspection gives consistent results with the other methods of background estimation and yields an upper limit on the background contamination of muons from coincident air showers.

4.2 Background estimation

An elaborate background estimation was performed, the results of which can be seen in table 3. First, the background MC itself gives an estimate (see also table 2). Because the passing rates differ slightly between the experiment (higher) and the background MC (lower), we made the conservative choice to re-normalize the background MC to the level 3 experimental passing rate. This gives an estimate of about 16 background events in our final sample.

From the $N-1$ – distributions we could get an alternative approximation of the residual background. To do so, we re-normalized both signal and background MCs in the background region to fit the number of experimental events in the background region. The number of re-normalized background MC events in the signal region is then a background estimate. This was performed N times (once for each $N-1$ – distribution). The combined average for all N estimations yields about 14 estimated background events.

Because previous analyses have found that un-simulated experimental background due to cross-talk causes a characteristic triple-peak structure in the distribution of the vertical component of the center of gravity of hits (z_{cog}), this distribution was studied in detail. No statistically significant excess can be found for the experimental data in the previous peak regions with respect to the atmospheric neutrino MC prediction. Therefore, an upper limit of this special kind of background was derived and yields < 35 events.

A conservative estimation of the background by visual inspection - using blind tests of signal and background MC - yields about 16 events plus an upper limit of 14 events due to coincident muons from random independent air showers.

The expected background is approximately between 4% and 10% of the 223 experimental events.

4.3 Event overlap with the UW-analysis

A comparison of this analysis with other recent ones was performed, especially the one called UW-IVc in table 1. The comparison is interesting since the UW-analysis is relatively independent to this one. An event overlap of 102 experimental events is observed as well as a predicted overlap

BG estimation method	estimation	upper limit
BG MC	16.2 ± 7.6	-
$N-1$-cuts	14.1 ± 4.3	-
z_{cog} distributions	0	< 35
Visual inspection - fakes	9 ± 9	-
Visual inspection - Coincident muons	7	< 14

Table 3: Various background estimations for the experimental data sample of 223 neutrino candidates.

of 119 ± 13 from the atmospheric neutrino MC. Comparing the ratio $\kappa \equiv \frac{A \cap B}{A \cup B}$ of shared event numbers to the combined event numbers between experiment and MC, one finds $\kappa_{exp} \approx 1/3$ compared to the expectation of $\kappa_{MC} \approx 1/5$.

Usually, one would expect a smaller experimental overlap than expected from the MC, e.g. due to background or to undetected efficiency losses. Note however that the fraction of MC events found in this analysis but *not* in the UW-sample is twice as high as the fraction of MC events found in UW but not here. Furthermore, the UW-analysis sees an unexplained excess of experimental "high-quality events" with respect to the signal MC prediction.

4.4 Signal uncertainties

In the previous sections we have concentrated on proving that the observed neutrino candidates are in fact neutrino events by inspecting their properties and studying the backgrounds. This section investigates the systematics and uncertainties of the signal from atmospheric neutrinos. In particular, we discuss the discrepancies observed between the experiment and the MC.

One major uncertainty comes from the generation of neutrino events. Here one has to differentiate between: the uncertainties in the neutrino flux, the interaction cross section and the atmospheric neutrino oscillations. The uncertainties in the prediction of the neutrino flux are estimated to be smaller than $\pm 30\%$ (actual calculations differ by less than 10%). This is the dominant uncertainty. The effect of different simulation techniques and interaction models were studied via the comparison of two independent signal MCs. They predict slightly different total event numbers (5%), but the shapes of the angular distributions are compatible with each other. Concerning neutrino oscillations, the Super-Kamiokande results have been included a posteriori by re-weighting the MC-events. They reduce the event numbers by 10% and only change the shape of energy sensitive variables.

Incorrect assumptions on the energy losses of the muons may produce additional light and limit the range of the muon (or vice versa). The additional (less) light influences the trigger and the cut efficiency. The muon range defines the effective volume. Measurements of the muon energy loss are relatively accurate at low energies (below ~ 600 GeV, where ionization losses dominate), but depend on theory and extrapolations at higher energies (where radiative processes like pair-production and bremsstrahlung become the major source of the energy loss). The uncertainties at the high energies might be relevant for the atmospheric muon background simulation, but the atmospheric neutrino events are mostly low energy events. So even assuming uncertainties of the order of 10% at high energies, the total error is nevertheless dominated by the low energy events. We assume the total error for this analysis to be less than 5%.

The quality of simulation of the light propagation and optical properties of the ice was significantly improved over the past years (e.g. by including their depth dependency into the MC). We estimated the magnitude of the effect by comparing the results of different simulations. Vertical ice-structures seem to reduce the neutrino efficiency. The shapes of the characteristic distributions however remains unchanged. The relative uncertainty of the absolute event rate for the current model should be smaller than the change from the current model to the `bulk` ice model: 15%.

The determination of the in situ OM sensitivity is challenging. Bubbles in the refrozen hole ice lead to a change in the angular dependent OM efficiency. It seems that this effect has been under-estimated in early MC simulations. Thus, the angular sensitivity of the OMs has been modified in the most recent MCs (abbr. "ang. sens."). Table 2 is an example of how much these changes do improve the MC description of the experimental data. The total systematic uncertainties from the OM sensitivity is now estimated to be about 10%.

Other calibration errors do not seem to lead to significant systematic effects: The combined uncertainty of timing and geometry calibration is estimated to be less than 10 ns. It is shown that this is sufficiently small to not worsen our angular resolution. So far, little use is being made of the amplitude information. Errors on the amplitude calibration thus contribute little to final analysis results.

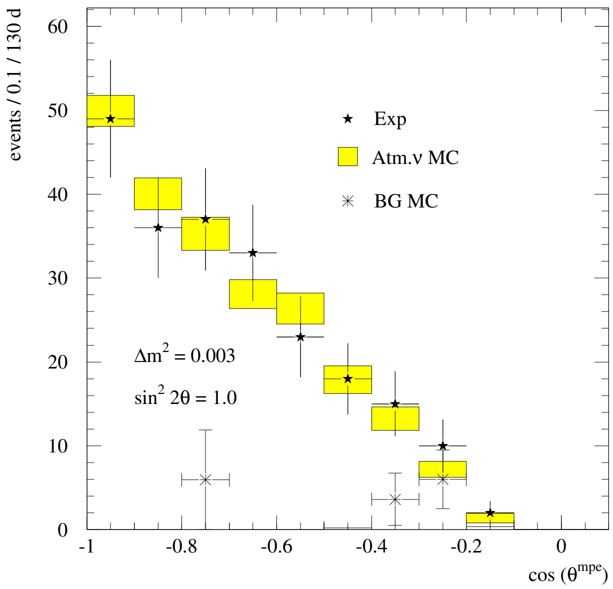

Figure 5: Distribution of the cosine of the reconstructed (mpe) zenith angle. Shown are the experimental data points with the MC expectations for the atm.μ-background and the atm. neutrino simulation *nusim*. The effects of neutrino oscillations have been included as well as the reduced angular sensitivity of the OMs.

Finally, a detailed investigation of those parameters where MC and experiment did not agree, was performed. The earlier mentioned z_{cog} distribution shows the largest discrepancies for the case of mis-reconstructed atmospheric muons. In the neutrino sample, this distribution follows nicely the MC expectations. A few other parameters which do not follow the MC expectations (neither in background nor in signal dominated samples) like the number of hit OMs (N_{OM}) or

the "velocity of the linefit" v_{LF} can be described much better with the "ang. sens." signal MC. As can be seen from table 2, also the expected event numbers agree with the MC. We are not aware of any distribution which is in sharp contrast to our latest MC simulations.
Including all the discussed errors and uncertainties, one obtains the zenith angle distribution presented in figure 5. Within the errors, one notices a good agreement between experiment and MC. The strong angular dependence of the detector is due to the slim shape of the AMANDA−B10 detector. This is expected to change with AMANDA-II and future extensions – like the proposed ICECUBE neutrino telescope.

5 Summary and Conclusions

This document summarized the AMANDA internal report *Analysis of Atmospheric Neutrinos in 97 Data* (available from http://www-zeuthen.desy.de/nuastro/ice3_proposal/). The analysis result in 223 neutrino candidate events in the data set taken with the AMANDA-B10 array during 1997. From various background estimations, we expect about 14 of these to be background events. Including neutrino oscillations, Monte Carlo simulations predict 219.3 ± 4.3 (ang. sens.) or 335.3 ± 3.4 (standard simulation) signal events and 7.5 ± 4.8 background events.
The dominant systematic uncertainty is the 30% total neutrino flux uncertainty. The sum of all other systematic effects are estimated to be less than 20%.
From the Monte Carlo simulation we determine our angular resolution to be 3.1^o. 90% of all Monte Carlo signal events have muon (neutrino) energies between 48 (66) GeV and 1.83 (3.4) TeV. The effective area (volume) for muons at 1 TeV is 3.3×10^3 m^2 (7.8×10^6 m^3). The celestial distribution of the events is compatible with a random distribution.