Analysis of Angular Correlations from AMANDA Data 2000-2003

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This work describes an analysis of AMANDA data looking for neutrino point sources. This is made by using a correlation function based on separation angles and it is improved by taking into account energy estimates for reconstructed neutrino candidates.

1 Introduction

My project as a DESY summer student was to analyse data from the AMANDA detector and search for neutrino point sources in the sky among all this data. This is a continuation of the work done in [1]. AMANDA (Antartic Muon And Neutrino Detector Array) is located at the South Pole. AMANDA is essentially a telescope which instead of sensing light responds to charged leptons created in neutrino-nucleon interactions. Astrophysical Neutrinos bring special information that cannot be carried by light or other electromagnetic radiation. For that purpose it is necessary to make a distinction between signals coming from the Earth's atmosphere and those which are extraterrestrial neutrinos. A skyplot of AMANDA data corresponding to 2000-2003 period, which contains 3369 events is shown in figure 1.

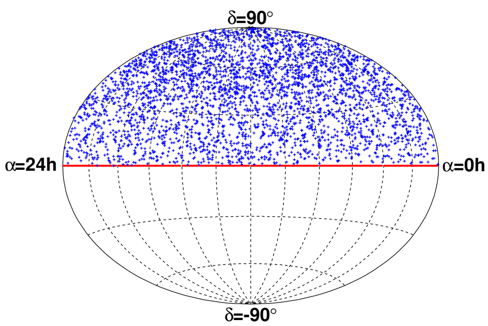

Fig. 1: *Skyplot of AMANDA data from 2000 to 2003. δ and α are declination and right ascension values respectively.*

A direct search for isolated point sources did not reveal any significant signal. However this method is not sensitive to many weak point sources. The distribution of events is approximately uniform in right ascension but not in declination. This uniformity in the right ascension values is due to the rotation of the Earth around the detector's axis which levels out azimuth dependent fluctuations of the detector's acceptance.

For that reason simulation of background samples is done by taking events with declination values from real data and random right ascension values. The analysis is improved by considering weighting for energy values.

2 Separation Angle

A good way for looking for neutrino sources from the sky is to calculate separation angles between any two events. An excess of events with small separation angles might be related to hidden neutrino sources. By calculating all possible combinations of events, a distribution of angle values Ψ can be obtained. An accumulation of low angle values is an indication of point sources. These values must be of the order of the angular resolution of the detector, which is the range over which events from one point source could be smeared out.

We restrict declination values to be $5^\circ < \delta < 85^\circ$ because close to the pole events are not sufficiently separated by randomization and at low declinations an increasing background of misreconstructed atmospheric muons from the southern hemisphere would hide contributions from point sources.

For two neutrino events with declinations δ_1, δ_2 and right ascensions ϕ_1 and ϕ_2 the separation angle can be calculated by:

$$\begin{aligned}\Psi &= \arccos(\cos(\phi_1)\cos(\delta_1)\cos(\phi_2)\cos(\delta_2)\\ &\quad+\sin(\phi_1)\cos(\delta_1)\sin(\phi_2)\cos(\delta_2)\\ &\quad+\sin(\delta_1)\sin(\delta_2))\end{aligned}$$

The distribution of these separation angles Ψ is shown in figure 2.

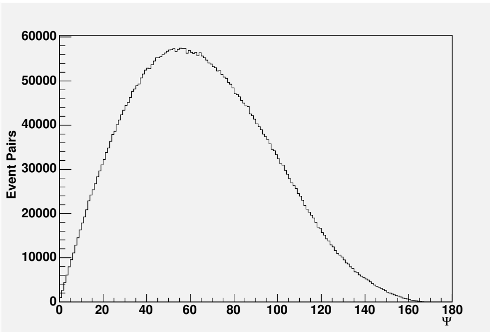

Fig. 2: *Distribution $n(\Psi)$ of event pairs versus separation angles.*

We look for low angle values where the real data might have higher values than the simulated random background as an indication of point sources. Most of the simulated events are close to the real data distribution, as can be seen in figure 3.

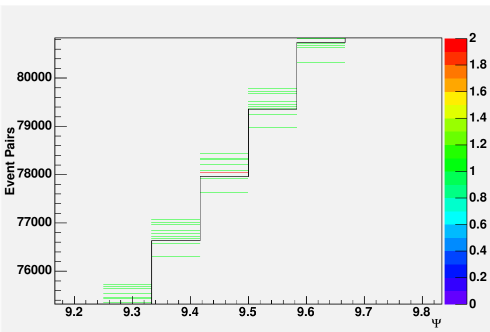

Fig. 3: *Separation angle distribution $n(\Psi)$ for real data (solid line) and simulated data.*

3 Correlation function

Summing over all the values of event pairs separated by a space angle less than Ψ defines the accumulative number $N(\Psi)$. By taking declination values from the real data and randomizing right ascension we create a background distribution $N_{rand}(\Psi)$ which is averaged over a large number N_{bg} of events sets. This background distribution $N_{rand}(\Psi)$ is defined as the average of the distributions $N_{k,bg}(\Psi)$ calculated for event samples k=1,2,3...N_{bg} in the same way as $N(\Psi)$ for real data.

$$N_{rand}(\Psi) = \frac{1}{N_{bg}}\sum_{k=1}^{N_{bg}} N_{k,bg}(\Psi)$$

The correlation function is defined by

$$W(\Psi) = \frac{N(\Psi)}{N_{rand}(\Psi)} - 1$$

We select the range of interest where separation angles are below 15 degrees where we would expect an indication of point sources. $W_{min}(\Psi)$ and $W_{max}(\Psi)$ are functions which bound $W(\Psi)$ to be between a 68% of all randomized event sets, corresponding to the "one sigma" range of the background distribution. Any point source will make a significant deviation from $W(\Psi) \approx 0$ outside this range.

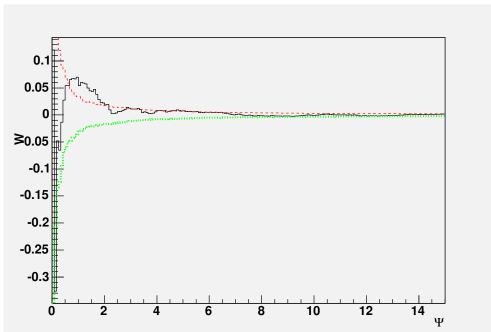

Fig. 4: *Correlation function which relates the number of event pairs to the number of event pairs in the randomized event sets. The dashed line represents $W_{min}(\Psi)$ and the pointed line represents $W_{max}(\Psi)$ which approximately bound the $W(\Psi)$ function (solid line) that represents the real data.*

4 Point Sources

Simulated point sources are added to the real data to see the effect in the correlation function. For each source, some related events are added. The positions of the sources are random. The corresponding events are established by using a gaussian distribution around each source with resolution $\sigma_\Psi = 2,1\,^\circ$ as obtained from the detector simulation. An example of this can be seen in Figure 5.

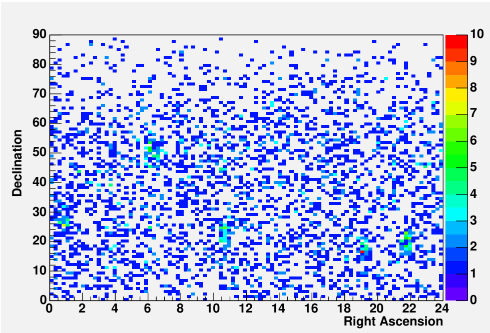

Fig. 5: *Point sources are added to the AMANDA data. Here are 5 sources with 50 events each.*

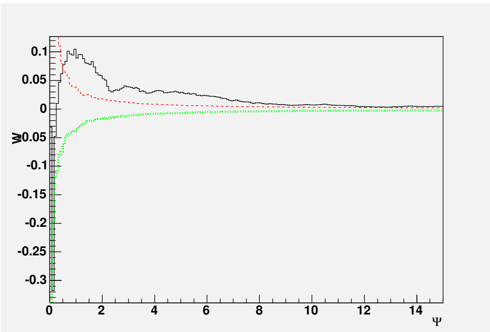

Fig. 6: *Correlation function for data containing 5 sources with 20 events each.*

It can be seen in figure **??** that the $W(\Psi)$ function goes above W_{max} for low angle values up to $\approx 8\,^\circ$ which is the result of the added point sources.

5 Calculating Probabilities

The probability function $\mathrm{P}(\Psi)$ describes the probability to obtain a value $\geq W(\Psi)$ in the absence of point sources. So comparison of the real data and background simulated samples is made by calculating the fraction of background simulations which have $N_{k,bg}(\Psi) > N(\Psi)$ for a given angle separation Ψ. Point source signals are related to low probability values. This can clearly be seen in Fig. 7 and Fig. 8. In the real data, we observe a low probability of about 2% at $\Psi \approx 1,8\,^\circ$, which might be caused by a statistical fluctuation. With the added signal events, even lower probabilities are observed, which extend beyond $\Psi \approx 6\,^\circ$.

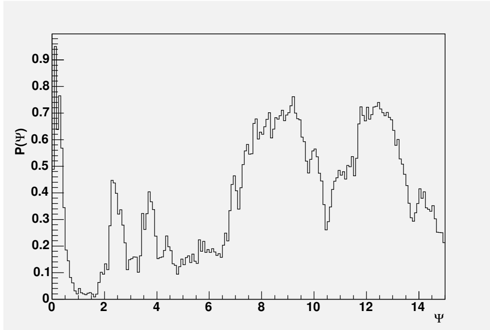

Fig. 7: *Probability function for real data to be background only.*

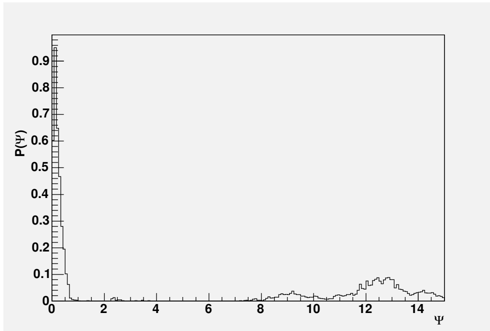

Fig. 8: *Probability function for data containing 5 sources with 20 events each; clearly the probability to be a pure background sample is neglible.*

6 Weighting for Energy Values

Extraterrestrial neutrinos are expected to have on average higher energies than atmospheric neutrinos. Therefore, we can make use of energy estimators to make a distinction between atmospheric and extraterrestrial neutrinos. One such estimator is the number of hit optical modules N_{ch}. Weight factors are assigned to each event based on the ratio $\frac{dN^{signal}/dN_{ch}}{dN^{signal}/dN_{ch}+dN^{data}/dN_{ch}}$ for the distributions of experimental data dN^{data}/dN_{ch} and simulated signal dN^{signal}/dN_{ch}. We approximate this ratio (shown in Fig. 10) by the following function:

$$p(N_{ch}) \equiv \begin{cases} 0 & \text{if } N_{ch} < 7 \\ 1 & \text{if } N_{ch} > 92 \\ (N_{ch}-7)/86 & \text{if } 7 \leq N_{ch} \leq 92 \end{cases}$$

$N(\Psi)$ is defined similarly as before, but each event pair with N_{ch} values N_{ch1} and N_{ch2} contributes only with a weight $P(N_{ch1}) \cdot P(N_{ch2})$ to the acumulative sum.

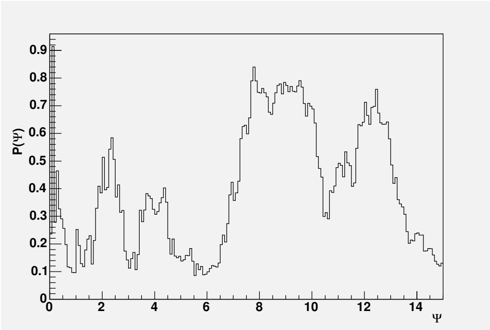

Fig. 9: *Probability function for real data with the energy weighting to be background only.*

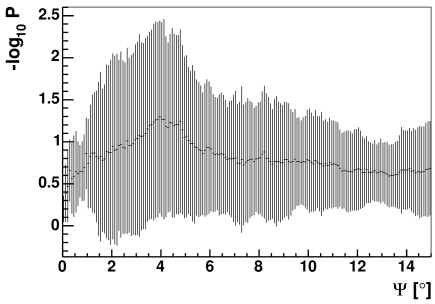

Fig. 11: *Probability distribution of several simulations. Data sample contains 5 sources with 10 events each.*

By using several simulations with the same conditions (number of added point sources and number of events per source) it is possible to obtain a distribution of probabilities with both the N_{ch} dependent weighting or not. This is shown in figures 11 and 12 which plot $-\log_{10} P(\Psi)$. The dots show for each separation angle Ψ the average value of $-\log_{10} P(\Psi)$, while vertical bars indicate the spread (RMS) of these values for the different simulations. In both cases, the maximum significance (lowest average probability) occurs at $\Psi \approx 4\,^\circ$. Since in the case of N_{ch} weighting the maximum significance is much higher (minimum average $P(\Psi) \approx 10^{-2,4}$ compared to $P(\Psi) \approx 10^{-1,3}$) the chance to make a detection with this method is higher. In the $P(\Psi)$ distribution calculated with N_{ch} weighting for real data, shown in Fig. 9, the significance below $2\,^\circ$ is strongly decreased compared to Fig. 7. This indicates that the low probability at $\Psi \approx 1,8\,^\circ$ might just be a statistical fluctuation.

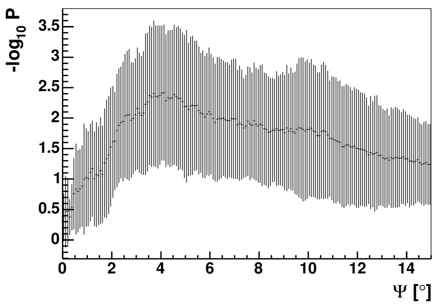

Fig. 12: *Probability distribution of several simulations using N_{ch} dependent weights. Data sample contains 5 sources with 10 events each.*

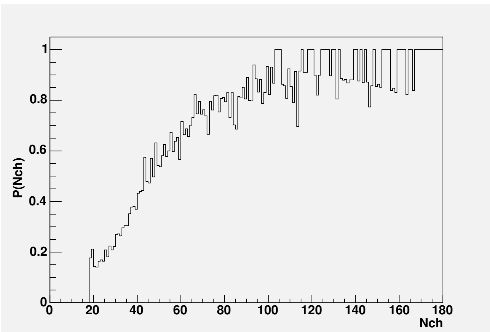

Fig. 10: *Probability values $P(N_{ch})$ for the N_{ch} which is related to the energy of incoming neutrinos.*

7 Conclusions

We analysed AMANDA detector data from 2000 to 2003 with the aim of detecting point sources. For that purpose we searched for a possible indication of several weak point sources, complementary to a standard point source search. A small indication for clustering is found, but not at the expected separation angle, and not confirmed by an improved method. The analysis will be continued by splitting the data sample into smaller periods, varying quality cuts and declination range.

References

[1] Hauschildt, Tonio, *Search for Cosmic Point Sources of High Energy Neutrinos with the AMANDA II Detector*, Ph.D. thesis, Humbuldt Universität zu Berlin (2004).