RECONSTRUCTION OF ATMOSPHERIC NEUTRINOS WITH THE BAIKAL NEUTRINO TELESCOPE NT-96

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We describe the track reconstruction procedure for events recorded with the Neutrino Telescope NT-96. After having identified 2 neutrino candidates close to the opposite zenith with the small prototype telescope NT-36, we present here results of the reconstruction of \(5.3 \times 10^6\) muons, recorded with NT-96 during its first 18 days lifetime. We have separated 3 neutrino candidates, compared to 2.3 events expected from MC calculations.

1 Introduction

A primary challenge for deep underwater detectors is the identification of upward muons generated in neutrino interactions. Taking into account that the flux of downward muons at 1 km depth is about 6 orders of magnitude larger than the flux of upward muons, this task is extremely difficult with small detectors.

Data obtained with the 36-PMT array NT-36 showed good agreement of the observed zenith angle distribution with that expected for atmospheric muons. Also, the rate of fake events (i.e. downward muons being reconstructed as upward muons) was similar to MC calculations: \(S/N \approx 1/40\) for both experimental data and the MC, with \(N\) being the fake rate, and \(S\) the rate for events from true upward moving muons. The agreement between NT-36 data and MC gave confidence in extrapolation of the results towards larger arrays. However, with \(S/N = 1/40\), clear neutrino signatures were out of the range of NT-36 – apart from a narrow cone around the opposite zenith.

In 1996, the four-string array NT-96 with 24 optical modules (OMs) at each string was deployed. With 72 m height, this detector surpassed NT-36 considerably, as well in the number of OMs as in the lever arm for track fitting. The OMs were grouped in pairs along the string, with the two PMTs switched in coincidence. The orientation of the OMs was changed compared to the symmetric NT-36. Only two of the twelve layers of NT-96 (the
second and the eleventh) had upward looking OMs, all others pointed down. The strings were placed at the edges of a trapezoid with side lengths of $3 \cdot 18.5$ m, and $10.2$ m.

2 Reconstruction procedure

The reconstruction algorithm is based on the assumption that the light radiated by the muons is emitted exactly under the Cherenkov angle (42 degrees) with respect to the muon path. This "naked muon model" is a simplification, since the direction of shower particles accompanying the muons is smeared around the muon direction. The reconstruction procedure consists of the following steps:

1. A first quality analysis of the event which
   a) excludes events far from being described by the model of a "naked muon", and
   b) finds a first guess for the $\chi^2$ minimization.
2. Determination of the muon trajectory based on the minimization of the function

   $\chi^2_t = \sum_{i=1}^{N_{hit}} \frac{(T_i(\theta, \phi, u_0, v_0, t_0) - t_i)^2}{\sigma_{ti}^2}$ (1)

   Here, $t_i$ are the measured times and $T_i$ the times expected for a given set of track parameters. $N_{hit}$ is the number of hit channels, $\sigma_{ti}$ are the timing errors. A set of parameters defining a straight track is given by $\theta$ and $\phi$ – zenith and azimuth angle of the track, respectively, $u_0$ and $v_0$ – the two coordinates of the track point closest to the center of the detector, and $t_0$ – the time the muon passes this point.
3. Rejection of most bad reconstructed events with the help of final quality criteria.

   In the initial quality analysis (step 1), an event has to pass the following criteria:
   a) The time difference $\Delta t_{ij}$ must obey the following condition: $|\Delta t_{ij}| \cos \eta < R_{ij}/c + \delta$, here are $\eta$ the Cherenkov angle and $R_{ij}$ the distance between channels. $\delta = 5$ns.
   b) For any two channels on the same string, a zenith angles region $\theta_{min} - \theta_{max}$ is determined which is allowed by the observed time differences:

   $\cos(\theta_{min} + \eta) < \cos \frac{c \cdot \Delta t_{ij}}{z_j - z_i} < \cos(\theta_{max} - \eta)$ (2)

   Here $z_i, z_j$ are z coordinates of the channels. If the regions of possible zenith angles for all pairs along a string do not overlap, the event is excluded.
   c) Assuming the event is caused by a naked muon, for every channel one can define a range of distances to the muon depending on the measured amplitude $A$ of the channel. For every channel pair one can define the minimal ($\Delta t_{min}$) and maximal ($\Delta t_{max}$) allowed time difference, in dependence on the distance between the channels and the amplitudes. If for any pair the condition $\Delta t_{min} < t_{exp} < \Delta t_{max}$ is violated, the event is rejected.

Seventy percent of the triggered events (trigger 6/3, meaning at least 6 hits at 3 strings.) pass these criteria in both the experimental and the MC sample. In the case of MC generated neutrino induced muons, the rate is larger (80%) due to the absence of muon bundles.

We apply final quality cuts after the minimization (see item 3 above). For NT-96 the most effective cuts are the traditional $\chi^2$ cut, cuts on the probability of non-fired channels not to be hit, and fired channels to be hit ($P_{nohit}$ and $P_{hit}$, respectively), cuts on the correlation function of measured amplitudes to the amplitudes expected for the reconstructed tracks, and a cut on the amplitude $\chi^2$ defined similar to the time $\chi^2$ defined above.

To guarantee a minimum lever arm for track fitting, we reject events with a projection of the most distant channels on the track ($Z_{dist}$) below 35 meters. Due to the small transversal dimensions of NT-96, this cut excludes zenith angles close to the horizon, i.e., the effective area of the detector with respect to atmospheric neutrinos is decreased considerably (fig.1).
3 Results

The efficiency of all criteria was tested using MC generated atmospheric muons and upward muons due to atmospheric neutrinos. $1.8 \cdot 10^6$ events from atmospheric muon events (trigger $6/3$) have been simulated, with only 2 of them passing all cuts and being reconstructed as upward going muons. This corresponds to $S/N \approx 1$. Rejecting all events with less than 9 hits, no MC fake event is left, with only a small decrease in neutrino sensitivity (see table). This corresponds to $S/N > 1$ and the lowest curve in fig.1.

Table 1 shows the fraction of events after the final quality criteria, normalized to the number of events surviving pre-criteria and reconstruction, for triggers $6/3$ and $9/3$, respectively.

| Trigger cond. | Experiment | MC atm $\mu$ | MC $\mu$ from $\nu$ |
|---------------|------------|--------------|-------------------|
| 6/3           | 0.19       | 0.21         | 0.20              |
| 9/3           | 0.044      | 0.056        | 0.175             |

With this procedure, we have reconstructed $5.3 \cdot 10^6$ events taken with NT-96 in April/May 1996. The resulting angular distribution is presented in fig.2. Three events were recognized as upward going muons. Fig.3 displays one of the neutrino candidates. Top right the times of the hit channels are shown as as function of the vertical position of the channel. At each string we observe the time dependence characteristically for upward moving particles.
Figure 3: A "gold plated" 19-hit neutrino event. Left: Event display. Hit channels are in black. The thick line gives the reconstructed muon path, thin lines pointing to the channels mark the path of the Cherenkov photons as given by the fit to the measured times. The sizes of the ellipses are proportional to the recorded amplitudes. Top right: Hit times versus vertical channel positions. Bottom right: The allowed $\theta/\phi$ regions (see text).

Applying eq. 4 not only to pairs at the same string, but to all pairs of hit channels, one can construct an allowed region in both $\theta$ and $\phi$. For clear neutrino events this region is situated totally below horizon. This is demonstrated at the bottom right picture of fig. 3. The same holds for the other two events, one of which is shown in fig. 4. Fig. 5, in contrast, shows an ambiguous event giving, apart from the upward solution, also a downward solution. In this case we assign the event to the downward sample.

4 Conclusions

The analysis presented here is based on the data taken with NT-96 between April 16 and May 17, 1996 (18 days lifetime). Three neutrino candidates have been separated, in good agreement with the expected number of upward events of approximately 2.3. Our algorithm
allows to select neutrino events in a cone with about 50 degrees half-aperture around the opposite zenith, and an effective area of $\sim 350m^2$.

With the experimental confirmation that NT-96 can operate as a neutrino detector, we now are searching for additional possibilities to reject fake events with a smaller loss in effective area. The increased transversal dimensions of the future NT-200 (1998) will significantly increase effective area and angular acceptance for reliably separatable up-going events.

References

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