

# Particle Physics with AMANDA and IceCube

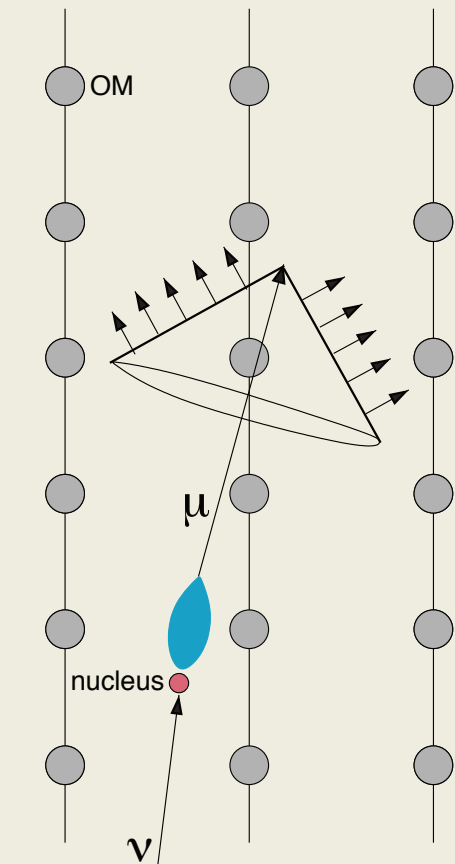
Jens Ahrens<sup>a</sup> and Henrike Wissing<sup>b</sup> for the IceCube Collaboration

<sup>a</sup>Institute of Physics, Mainz University, Staudinger Weg 7, D-55099 Mainz, Germany

<sup>b</sup>III Physikalisches Institut, RWTH Aachen University, D-52056 Aachen, Germany

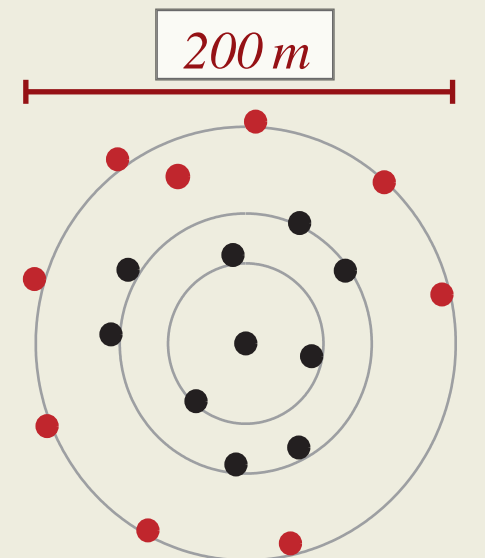
## Introduction

AMANDA-II [1] and its successor IceCube [2], are neutrino telescopes embedded 1.5 km deep in the transparent and inert ice under the geographic South Pole. While the IceCube detector is still under construction, AMANDA-II in its final configuration has been taking data since the beginning of the year 2000. Cherenkov light from charged particles produced in neutrino-nucleon interactions is mapped with a 3-dimensional grid of optical sensors. Muons from high energy  $\nu_\mu$ -interactions can be reconstructed directionally with degree-accuracy. Therefore, muons entering the detector from below

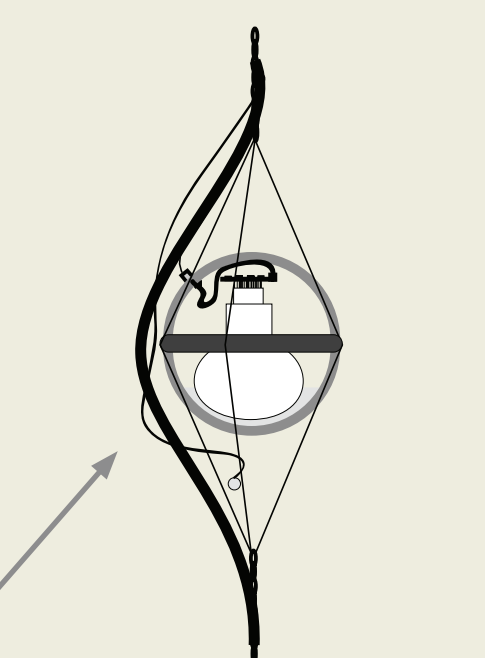


the horizon are the fundamental neutrino detection channel: The background of down-going muons from cosmic ray interaction in the atmosphere above the detector are eliminated by the directional criterion. Apart from the main science objective, the search for extraterrestrial high energy neutrinos, neutrino telescopes have the potential to address open questions in particle physics. Here, we present two analyses performed on data collected with AMANDA-II: (1) **Tests of alternative models for neutrino oscillations using atmospheric neutrino data**, and (2) **Search for relativistic magnetic monopoles**.

AMANDA-II consists of 677 optical modules on 19 vertical strings, arranged in three concentric circles. Signals are transmitted to the surface through electrical cables or optical fibers.



Arrangement of the AMANDA strings in the horizontal plane. Optical modules located on the outer circle (red) are read out via fiber optics, while the inner strings are read out electrically.

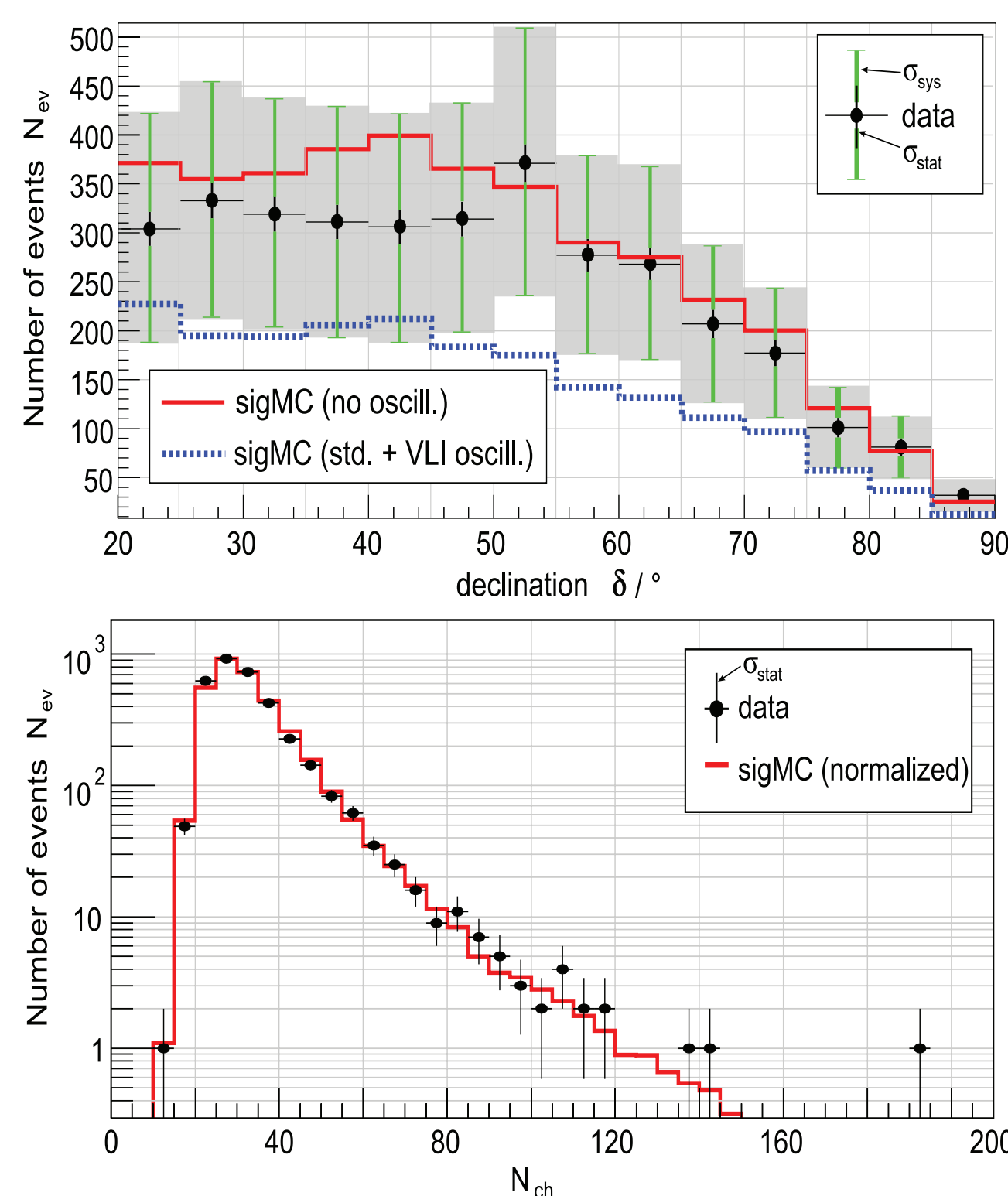


An Optical Module consists of a photomultiplier tube and its supporting electronics in a transparent pressure housing.

## Alternative oscillations

While standard mass-induced atmospheric neutrino oscillations are negligible in AMANDA's energy range (above 50 GeV), oscillation patterns at higher energies may appear in some models of quantum gravity. Violation of Lorentz invariance can introduce a third set of eigenstates with characteristic maximal attainable velocities  $c_n$ , differing by  $\delta c/c$  [3]. Violation of the weak equivalence principle creates a similar oscillation pattern, with additional gravitational neutrino eigenstates characterized by different couplings  $\gamma_n$  to the local gravitational potential  $\phi$  [4]. The resulting oscillations are parametrized by  $\delta c/c$  or  $2\delta\gamma|\phi|$ , an additional mixing angle  $\Theta$ , and a complex phase  $\eta$ .

Neutrinos were separated from background atmospheric muons by selecting particles that traverse the earth with angles at least 20 degrees below the horizon. These tracks were required to carry good angular resolution and low background likelihood. With a total exposure of 807 days, 3401 neutrino candidates survived the selection criteria. The remaining level of wrongly reconstructed cosmic muons was estimated to be below 4%. A  $\chi^2$  test, incorporating penalty terms to account for systematic errors, was applied to the distributions of the declination  $\delta$  and an energy related variable, the number of triggered optical modules  $N_{ch}$ . The neutrino flux and the ratio of kaons to pions were assumed to be known with uncertainties of 30% and 6%, respectively. The average optical module sensitivity uncertainty was estimated from the data to be 11.5%.

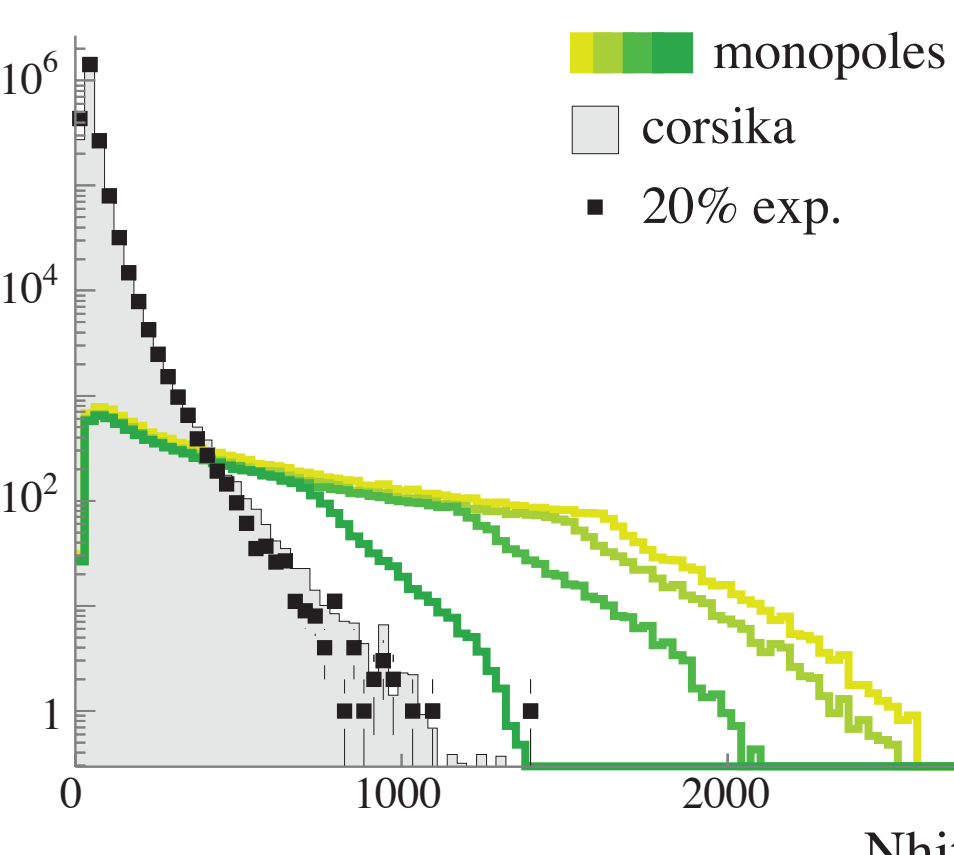
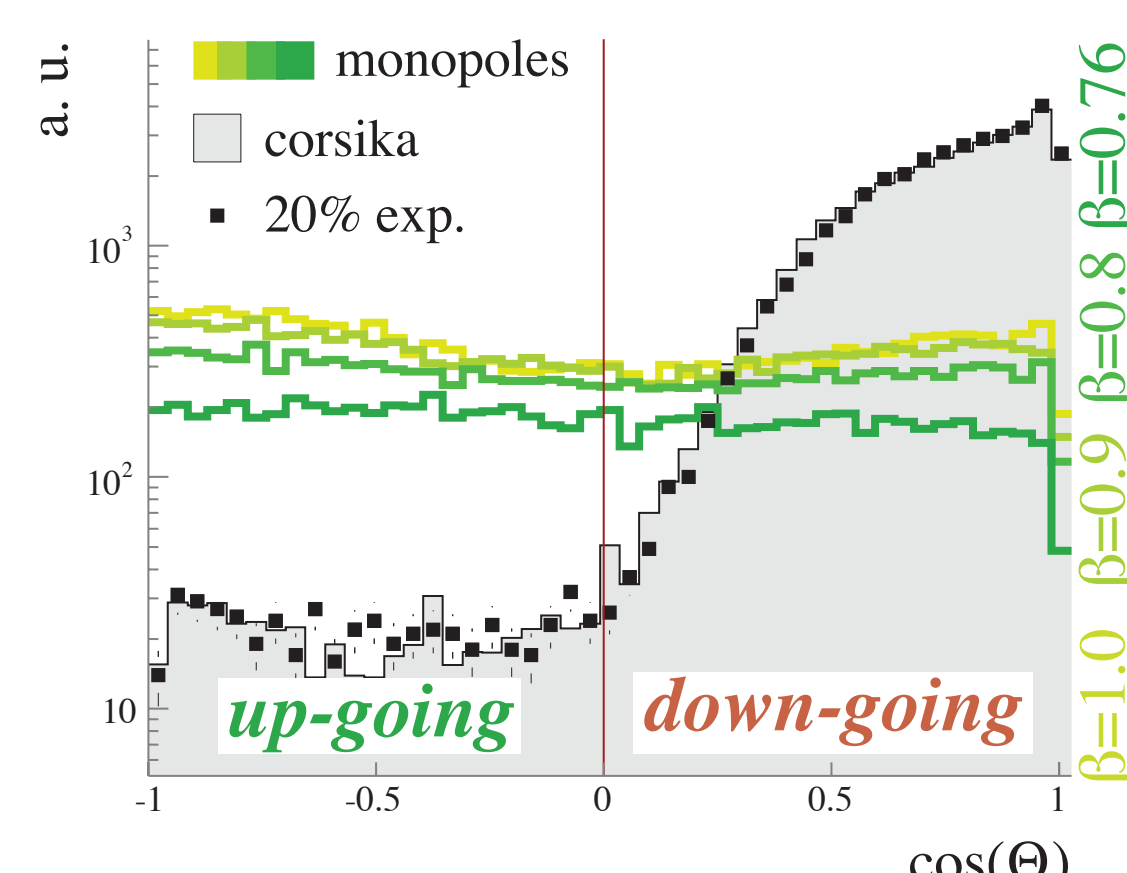


Upper plot: Distribution of the declination compared to the expectation without alternative oscillations and a distribution with oscillations included for  $\delta c/c = 10^{-24}$ . Lower plot: Comparison of  $N_{ch}$  between data and atmospheric neutrino Monte Carlo, normalized to the number of events in the data.

## Search for relativistic magnetic monopoles

The existence of magnetic monopoles with masses of  $10^9$  to  $10^{19}$  GeV is mandatory in a large class of Grand Unified Theories [8]. Such super-heavy particles would have been produced in the very early universe and should still be present in cosmic radiation. Monopoles with masses up to  $10^{14}$  GeV should have acquired relativistic velocities in large scale magnetic fields [9]. The intensity of the Cherenkov light emitted from a minimally charged relativistic magnetic monopole passing through ice exceeds the one emitted from a muon by a factor 8300 [10]. Depending on their initial kinetic energy, monopoles with masses above  $10^6$  to  $10^{11}$  GeV can cross the entire Earth and can be detected in AMANDA as up-going particle [11,9].

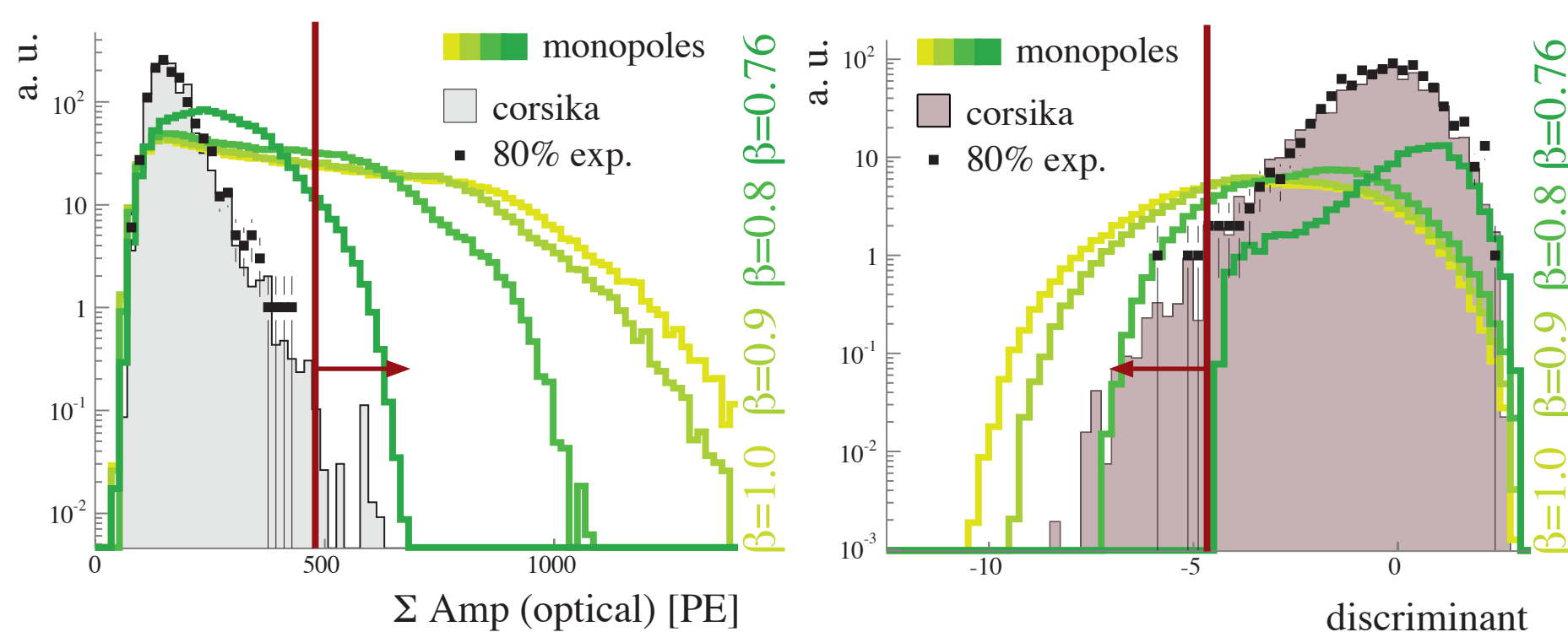
We have searched for monopole Cherenkov signatures in data taken during the year 2000 (194 days effective livetime). Following a blind analysis procedure [12], only 20% of the data were used to set up the analysis chain. The final analysis was applied to the remaining 80%, which were kept blind. Data were filtered using both directional criteria and observables sensitive to the light yield (e.g., the number of pulses recorded for all photomultiplier tubes, *Nhits*). Cuts were optimized separately for events which were reconstructed as particles entering from above or below the horizon (up- and down-going), respectively.



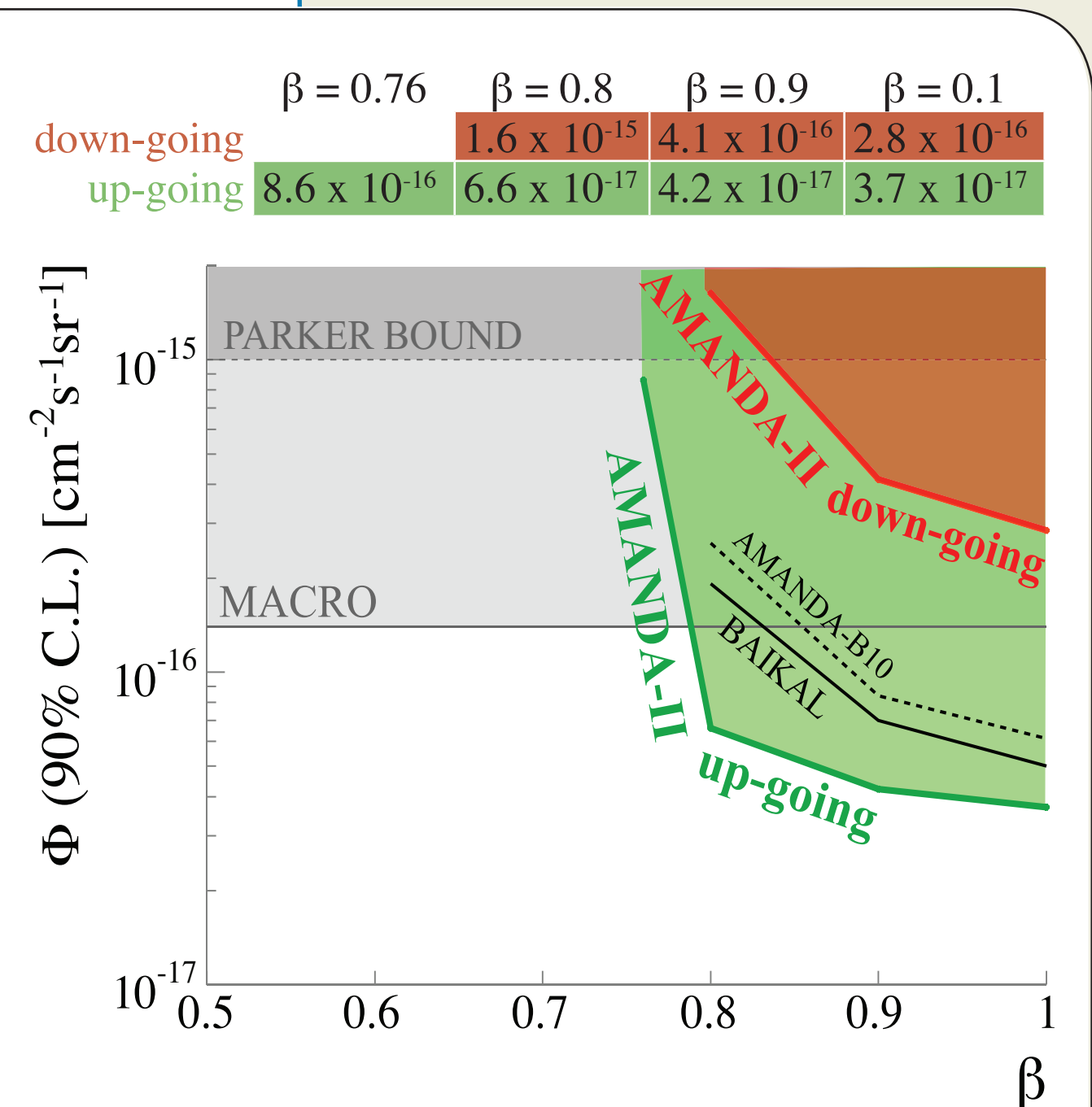
$\Delta$  Number of pulses (*Nhits*) recorded during an event. Experimental data (black markers) agree well with the simulated background of atmospheric muons (generated with CORSIKA [13], full grey histogram). Simulated minimally charged monopoles with speeds  $\beta=0.76$  (darkest green) to  $\beta=1$  (lightest green) yield higher hit-multiplicities.

$\triangleleft$  Reconstructed zenith angle. The search for up-going monopoles ( $\cos(\Theta) < 0$ ) has only a very small background from mis-reconstructed atmospheric muons.

Final cuts were optimized to yield the most stringent flux limits [14]. For the monopole search below the horizon, a light yield criterion ( $\Sigma$  Amp) eliminated the entire background: No events were found after unblinding, while the background simulation predicted 0.2 events. In the down-going sample, 3 events passed the final cut (based on a discriminant analysis [15]), consistent with 2.6 events predicted by the simulation. The flux limits obtained from the search for up-going monopoles are the most stringent ones to date. The search above the horizon is less sensitive, but still yields limits below the Parker Bound [16].



Left: The final cut for the up-going analysis requires the registration of at least 476 photo-electrons in the optical modules with optical-fiber read-out. Right: The final cut for the down-going analysis is a linear combination of the cosine of the reconstructed zenith angle and the number of photo-electrons in the optically read-out modules.



Limits on the flux of minimally charged relativistic magnetic monopoles at the 90% confidence level. Systematic uncertainties in detection efficiency and background expectation are accounted for according to [17]. The Parker Bound [16], as well as recent experimental limits set by the MACRO experiment [18] and by the BAIKAL neutrino telescope [19] are shown for comparison.

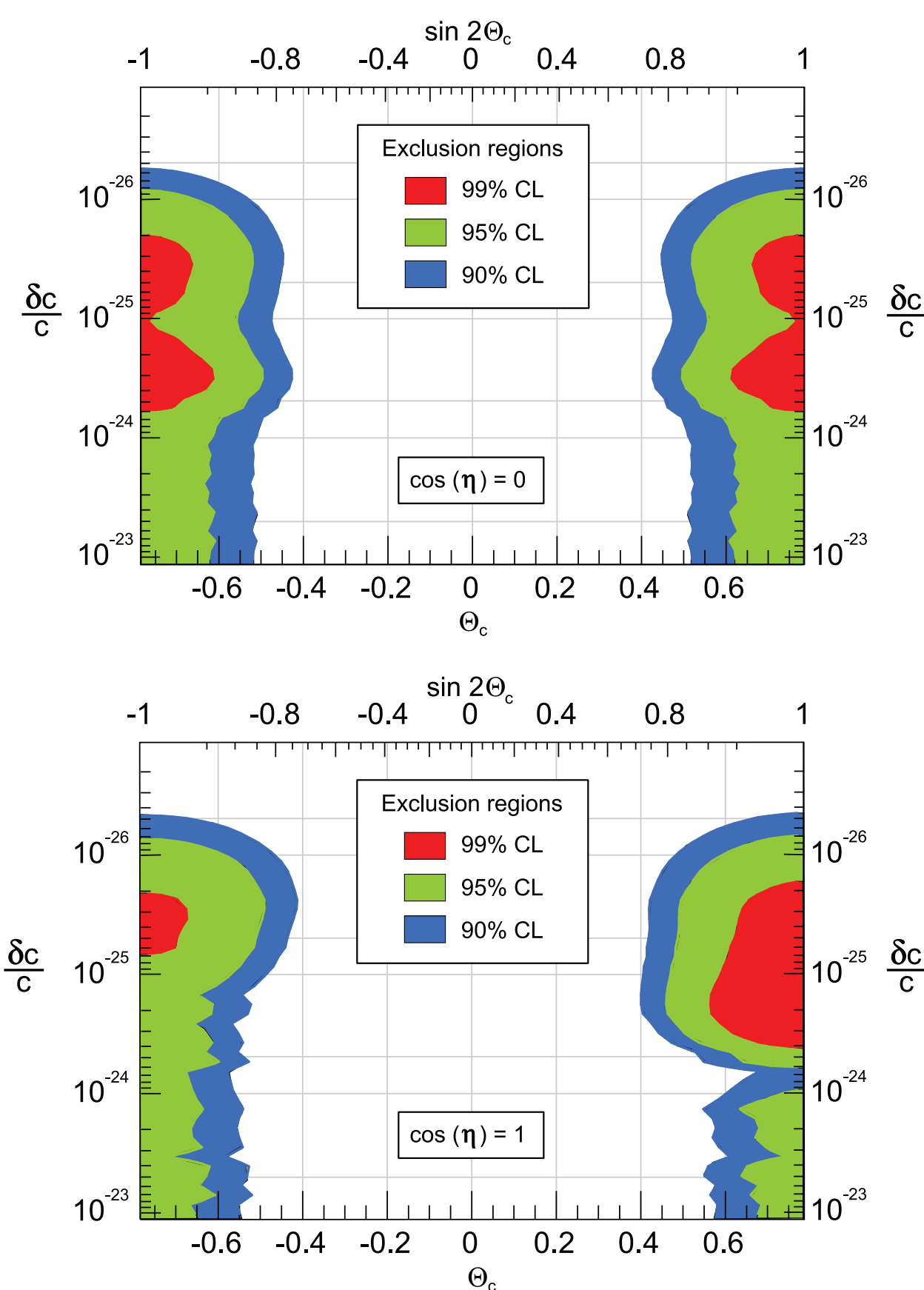
The analysis of sub-sets of available AMANDA data allowed to place limits on new physics phenomena competitive to best existing limits. The km<sup>3</sup> neutrino telescope IceCube, presently under construction, will have substantially improved sensitivity. The full detector, when completed in 2010, will be sensitive to oscillation parameters an order of magnitude below the AMANDA limit [7]. The IceCube configuration as of 2006 (comprising 9 of the 80 foreseen strings) improves the AMANDA sensitivity to relativistic monopoles by a factor of five [20].

## Data selection & analysis

## Results

Bounds on the alternative oscillation variables were deduced from the comparison of the data with Monte Carlo simulations that incorporate oscillation effects. No evidence for alternative oscillations were found (see various exclusion regions in the figures below).

The 90% confidence level limit for maximal mixing angles amounts to a fractional velocity difference  $\delta c/c < 5.3 \times 10^{-27}$ ; the same limit holds for the weak equivalence breaking variable  $2\delta\gamma|\phi|$ . As can be seen from the comparison of the two plots, the dependence on the unknown phase  $\eta$  is weak. The exclusion limits are competitive to those from Super-Kamiokande and MACRO [5]. However, AMANDA is not sensitive to smaller mixing angles due to systematic errors and its high energy threshold. A likelihood analysis of the 2000 - 2006 AMANDA-II data sample is in progress. This analysis will also extend the technique to search for evidence of quantum decoherence resulting from interactions of neutrinos with the background space-time foam [6].



$\triangleleft$  Exclusion regions for various confidence limits as a function of the fractional velocity difference  $\delta c/c$  and the mixing angle  $\Theta$  for two extreme values of the phase  $\eta$ .

## Outlook