Status and prospects of the IceCube neutrino telescope

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Abstract

The IceCube neutrino observatory, under construction at the South Pole, consists of three sub-detectors: a km-scale array of digital optical modules deployed deep in the ice, the AMANDA neutrino telescope and the surface array IceTop. We summarize results from searches for cosmic neutrinos with the AMANDA telescope and review expected sensitivities for IceCube at various installation phases. Reliability and robustness of installation at the South Pole has been demonstrated during the past four successful construction seasons. The 40 installed IceCube strings are working well. We are developing detailed plans for the final construction of IceCube, including extensions optimized for low and high energy. We describe the IceCube Deep Core project which will extend the low energy response of IceCube.

Key words: IceCube, Astroparticle physics, Deep Core, Low energy
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1. Introduction

IceCube, the largest neutrino telescope in history is rapidly becoming a reality after four successful construction seasons. IceCube searches primarily for neutrinos in the GeV-PeV energy region expected to be produced at acceleration sites of high energy cosmic rays (1) (2). The IceCube design (3) employs 80 uniformly spaced strings, each one equipped with 60 digital optical modules (DOMs) (4). Among the strings of this "in-ice" array, 40 have already been deployed at depths between 1.5 and 2.5 km in the icecap of the South Pole. Moreover, an additional installation in the center-bottom part of the detector of an inner core array (the so-called IceCube Deep Core) composed of additional strings has been financed and recently approved. The AMANDA-II neutrino telescope (5) - the predecessor of IceCube - is maintained in operation. AMANDA-II is completely embedded in the IceCube instrumented volume, and the hits registered by AMANDA and IceCube are merged together into combined events (6). The third fundamental component of the neutrino observatory is also under construction: the IceTop air shower detector (7). Combining IceTop data with data from the deep-ice array provides a unique opportunity to study cosmic ray composition in the region of the "knee" extending earlier measurements performed using the combination of the SPASE and AMANDA detectors (8) (9). The PMT pulses of the IceCube DOMs are first converted into digital waveforms. Every time the DOM triggers, the waveform is digitized, read out and time stamped. The digitized PMT pulses from different DOMs are sorted into a time-ordered stream. The trigger is accomplished entirely via software. Single majority triggering (SMT) is applied in the in-ice array and in the IceTop array. For the in-ice, it requires the coincidence of hits in eight or more DOMs within a time window of 5μsec and for IceTop six or more DOMs hit in a time window of the same size. Details about the data acquisition can be found in (10). There are two primary detection channels consid-

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Track-like Events	IceCube	AMANDA
Rel. Time Resolution [nsec]	2	5-7
Angular Resolution	$< 1°$	$2° - 3°$
Energy Resolution ($\log_{10}E$)	0.3-0.4	0.3-0.4
Field of view	2π	2π
Cascade-like Events		
Rel. Time Resolution [nsec]	2	5-7
Energy Resolution ($log_{10}E$)	0.18	0.18
Field of view	4π	4π

Table 1
Best values obtained for AMANDA and expected for IceCube observables.

ered for the study of high energy neutrinos: *track-like events* from upward through-going muons induced by charged-current ν_μ interactions and *cascade-like events* from charged-current (CC) interactions of ν_e, ν_τ and neutral-current interactions of neutrinos of all flavor. A third channel concerns composite events in which tracks and cascades from high energy CC interactions are observed together (11). Three *observables* are available for each detection channel: the time of an event which is known with a relative time resolution (18), the incoming direction characterized by the angular resolution (2) and finally the estimated energy of the event characterized by the energy resolution. Average values of these observables for the track-like and cascade-like detection channels are reported in Table 1.

The first level processing sorts events by detection channel or by specific low level analysis channel. Successive higher level processing is progressively more specific for various physics analyses. For example, track-like events are selected for the search for neutrinos from point-like sources (12), from Gamma-Ray-Bursts (GRBs) (13), from annihilation of WIMPs in the Sun (14) and from a diffuse flux (15). Cascade-like events are considered for the search of a diffuse neutrino flux (16) and as an additional channel for neutrinos from GRB explosions (17). The data taking of the IceCube observatory started in 2006 with 9 strings (IC-9) and continued in 2007 with 22 strings (IC-22). The new physics run with 40 strings started in April 2008 and will continue until March 2009. The data taking demonstrated excellent stability and for the first time, operated successfully during drilling operations. As a result, the overall live time of IC-22 has been maximized. The procedures for installation, drilling operation and detector operation have been consolidated during the four deployment seasons, delivering a stable detector that performs as expected or even better without significant problems.

2. The Past: AMANDA

The idea to take advantage of the clear optical characteristics of the Antarctic ice for a neutrino telescope goes back to 1990 (19) (20). The first demonstration of the possibility to detect the Cherenkov light generated by muons produced by cosmic neutrinos was obtained with the prototype string deployed in January 1992 at the South Pole (21). In parallel to the progressive understanding of experimental issues like optical properties of the deep ice (22), optical coupling between optical modules and refrozen ice, stability of the equipment during refreezing, drilling of vertical and deep holes etc., the study of the physics of non-thermal sources demonstrated the need for an effective area of the order of 1 km^2 since the very early stages (23). After the installation of 4 shallow strings (AMANDA-A) (24) (25) (26) and the observation of the scattering effect produced by air bubbles, the installation of ten strings at deeper depth (AMANDA-B10) was completed in 1997 (37). First performance of the 10-string array demonstrated that the site is adequate for a neutrino telescope (27). The South Pole seasons 1998-1999 and 2000 saw the final installation of AMANDA-II, which is still taking data in its final configuration (19 strings). We report here a limited selection of results obtained during more than 10 years of AMANDA operation.

2.1. *The Point Source Search*

Downward-going atmospheric muons are the primary background in a high energy neutrino telescope. These are produced in the upper part of the atmosphere from the decay of charged pions and kaons which are generated in the interactions of high energy cosmic rays with atmospheric nuclei. Highly energetic muons can penetrate a few kilometers of matter. As a result, downward-going atmospheric muons arrive at the detector site at high rates. To eliminate the contamination from atmospheric muons, neutrino telescopes typically focus on neutrino-induced upward or horizontal-going muons (28). This limits the field of view of a neutrino telescope to half of the sky; i.e. the opposite hemisphere with respect to the geographical posi-

Detector Years	Energy (TeV)	Live time (days)	$E_\nu^2 \frac{d\Phi_{\nu_\mu}}{dE}$ $(\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1})$
AMANDA B-10 (1997-1999)	1-1000	623	$4.0 \cdot 10^{-10}$
AMANDA II (2000-2004)	1.6-2600	1001	$5.5 \cdot 10^{-11}$
AMANDA II (2000-2006)		1387	$2.0 \cdot 10^{-11}$
IC 22	5 - 5000	270	$1.0 \cdot 10^{-11}$
IC 22+AMANDA	0.1 - 10		specific scenarios
IC 80	1 - 5000	3 years	$2.0 \cdot 10^{-12}$

Table 2
Summary of the best limits achieved for the point source search using AMANDA data and expected sensitivity for IceCube analysis. The energy range corresponds to that for 90% of the events, assuming an E^{-2} spectrum. Details about AMANDA B-10 analysis for the 3 years 97-98-99 are reported in (38). The 5 years analysis of AMANDA II is described in (12) (40) and the latest analysis of the 7 years of AMANDA II is reported in (39).

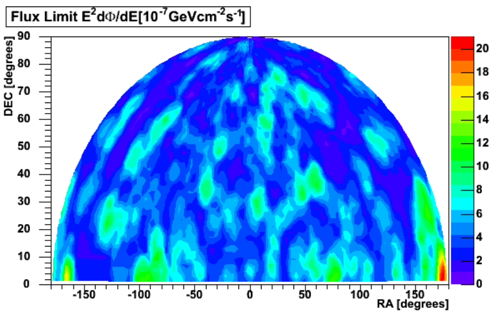

Fig. 1. Limit on the extraterrestrial neutrino flux for different position in the sky based on AMANDA data collected during 1997-1999 (38).

tion of the detector. Moreover, atmospheric neutrinos can also induce upward-going muons which are an irreducible background for extra-terrestrial neutrino searches. The search for point sources is then realized by looking for localized excesses over the near-isotropic background of atmospheric neutrinos. Candidate sources are selected a priori, like active galactic nuclei or Supernova remnants. The full northern sky is also scanned for unknown sources. Results are reported in Table 2 and Fig. 1, Fig. 2. Methods have been implemented in order to search for variable sources and coincidences with X- and γ-ray flares (29), (30).

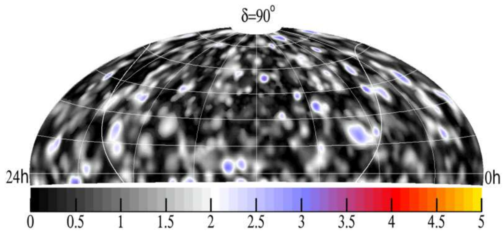

Fig. 2. "Sky map" (significance in number of sigmas) of AMANDA data collected during 2000-2006. The maximum significance obtained is 3.38σ near 11.4h, $+54°$. Out of 100 sets of data randomized in right ascension, 95 have a maximum significance equal to or greater than 3.38σ.

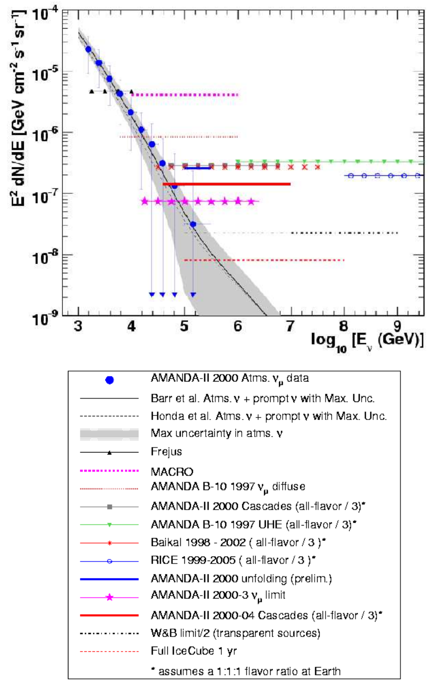

Fig. 3. Summary of existing experimental limits on the diffuse neutrino flux versus the logarithm of neutrino energy (15).

2.2. *The Diffuse Search*

Since the very early time of neutrino astronomy, the existence of a diffuse flux of neutrinos coming from the sum of faint active galaxies has been discussed (31). Limits on the diffuse flux have been reported by the Frejus experiment (32) and the Baikal experiment (33). Up-going neutrinos have been detected with AMANDA B-10 and AMANDA-II. The latest results using AMANDA data are reported in Fig. 3 and in (34).

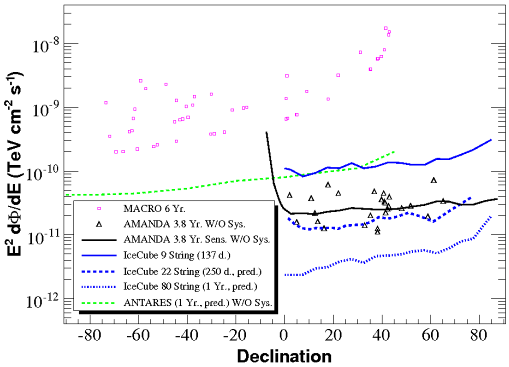

Fig. 4. Average (over right ascension) sensitivities vs declination for all sky point source searches and upper limits for specific sources. E^{-2} differential spectra are assumed. For references see (45).

3. The Present: 22 IceCube Strings and AMANDA

In its 2007 configuration, IceCube consisted of 22 strings in operation with 60 digital optical modules each. Details of the performance of the 22-string array are reported in (35). The sensitivity to point sources provided by the IC22 array is reported in Fig. 4. We discuss here in particular the use of AMANDA as an integrated compact core in IceCube.

3.1. *AMANDA: The First Generation Low Energy Core*

During the two South Pole seasons 2003-2004 and 2004-2005, the data acquisition system (DAQ) of AMANDA was significantly upgraded to provide nearly dead-timeless operation and full digitization of the electronic readout (36). This was achieved by using Transient Waveform Recorders (TWR). The new DAQ system allowed the reduction of the multiplicity trigger threshold and, consequently, of the energy threshold below 50 GeV. Hence AMANDA was seen to be a complement to IceCube at low energies and worth a full integration into IceCube. During the 2006-2007 South Pole season, the following items were deployed in order to realize an integrated AMANDA-IceCube detector: a common run control unit, triggering and event building systems, and on-line filtering algorithms (6). Every time the AMANDA detector is triggered, a readout request is sent to the IceCube detector. The Joint Event Builder (JEB) merges the events coming from both

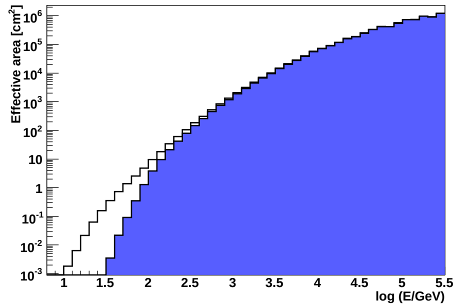

Fig. 5. Monte Carlo estimation of the muon neutrino effective area at high filter level (L3). In blue the effective area of IC22 is reported and in white the one for IC22 and AMANDA.

detectors and provides the data to the on-line filtering. The on-line filters process the joint events and filter out the interesting ones, which are then transferred via satellite to the Northern Hemisphere for physics analysis. The study of AMANDA as a nested array in IceCube reveals that:

- because of the additional hits in adjacent IceCube strings, a larger fraction of AMANDA triggered events can be better reconstructed and survive at higher analysis level as compared to AMANDA alone;
- the 1 km long IceCube strings provide a longer lever arm that translates directly into an improved angular resolution of AMANDA events;
- the combined detector shows an increased effective area at low energy for events below 1 TeV down to 10-50 GeV as compared to IceCube alone (Fig. 5, Fig. 6).

These benefits are used in order to improve the search for neutrinos from point sources and from dark matter annihilation in the Sun. Effective volumes for WIMPs are reported in Fig. 7 and expected sensitivities in (41). Moreover, studies of atmospheric neutrinos with higher statistics are also conceivable. In Section 4, we describe in detail the physics content at lower energies.

The use of AMANDA as a low energy core is limited by different factors:

- the position of AMANDA is not optimal inside the IceCube array, being in the higher part of the instrumented volume and in a corner of the array;
- the AMANDA electronics is housed in the MAPO building at the South Pole and the snow accumulation is a threat to the building;
- the AMANDA electronics is different from IceCube electronics and needs special software and service.

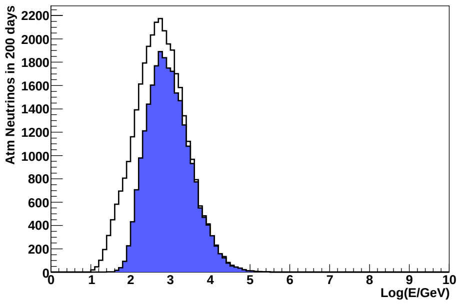

Fig. 6. Monte Carlo estimation of the atmospheric muon neutrino event rates per 200 days exposure at high filter level (L3). With IceCube-22 alone, 25000 events are observed. With AMANDA included the total rate rises to 34000.

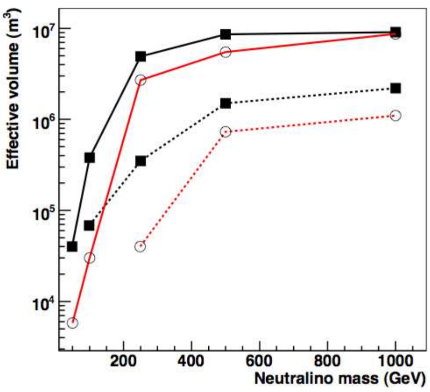

Fig. 7. Effective volumes as function of neutralino mass for interacting neutrinos from neutralino annihilation in the Sun, for IceCube-22 alone (circles) compared with the combined detector of IceCube-22 plus AMANDA (squares). Solid and dashed lines correspond to hard and soft annihilation channels, respectively (41).

For these reasons, the IceCube collaboration is planning to replace AMANDA with a sub-array composed of additional strings in the center-bottom part of the detector: the IceCube Deep Core.

4. The Future: IceCube 80, On-line, Deep Core, High Energy Extension

The potential of the 80 string array is described in (2). Here we summarize methods for the exploitation of IceCube physics program. As soon as IceCube reaches the sensitivity level to detect short bursts of neutrinos from AGN flares, GRB or Supernovae the possibility to send timely alerts to telescopes or satellites will be of primary importance. This requires the development of on-line analysis, prompt alerting systems and the establishment of collaboration among IceCube and photon-based telescopes. Details can be found in (46) and in (47). The IceCube geometry has been optimized for the neutrino region around 10 TeV. It is desirable, however to improve the performance at lower energies and higher energies. At higher energies, we are looking into extensions of IceCube using radio or acoustic technology and also investigating the optimal position of the remaining IceCube strings. To detect neutrino fluxes with EeV energies, such as the guaranteed GZK neutrino flux, a fiducial volume of approximately 100 km^3 is required. Optical Cherenkov technology does not allow the construction of such an array at a reasonable cost, owing to the relatively short attenuation length of light. However, the absorption length of radio and acoustic waves in the ice may be as long as 1 km, so a sparse array of the required scale might be feasible. At the lowest energies, the funding for the IceCube Deep Core subarray has been approved. We report in some detail the status of the Deep Core design.

4.1. *The IceCube Deep Core*

A dedicated IceCube effort towards an improved sensitivity at low energy, the so called IceCube Deep Core (IC-DC) project, was proposed for the first time in spring 2007. To have a denser array in the clean ice at great depth, below the center of the IceCube array has several advantages compared with AMANDA:

– *Natural shield*: the larger overburden reduces the background of atmospheric muons.
– *Muon veto*: the central location allows the use of outer rings of IceCube strings, as well as all of the instrumented ice between 1450 m and 2000 m, to achieve additional atmospheric muon veto allowing observations of neutrinos from above the horizon.
– *Ice properties*: the increased transparency of the ice at greater depth implies less scattering of Cherenkov photons and hence better reconstruction efficiency and better angular resolution.

At the moment, the baseline for IC-DC calls for six strings centered around one of the central IceCube strings (Fig. 8). The spacing among the IC-DC strings and the seven closest IceCube strings is 72 m as opposed to the 125 m standard IceCube string spacing. Each string will be equipped with 60 IceCube DOMs (Fig. 10). Below the so called

"dust layer", an ice layer at 2100 m with reduced optical transparency, 50 DOMs will be deployed in the very transparent ice with 7.0 m spacing (IceCube standard is 17 m spacing) and above the dust layer an additional 10 DOMs will be deployed in the transparent ice with 10 m spacing. IceCube is optimized for the search of cosmic ray sources able to accelerate up to PeV energies. This translates into neutrino energies of the order of few TeV. However, for several topics in particle physics and astrophysics, the detection of lower energy neutrinos is absolutely crucial. Some examples are:
- *Dark matter:* neutrinos from neutralino (mass m_χ) annihilation in the Sun and the Earth are expected to have low energy. The muon energy from these neutrino interactions in the detector would have mean $E \sim m_\chi/3$ for hard and mean $E \sim m_\chi/6$ for soft annihilation channels (Fig. 9). One difficulty in the analysis of neutrinos coming from the Sun is that their incoming direction is very close to the horizon (a maximum of 23° below the horizon at the South Pole) where the background of badly reconstructed atmospheric muons is highest. The possibility to observe neutrinos from above the horizon will permit an increase in exposure time for neutrinos from dark matter annihilations up to the entire year.
- *High energy galactic sources:* Muon neutrinos produced in the decay chain $\pi \rightarrow \mu\nu_\mu \rightarrow e\nu_\mu\nu_\mu\nu_e$ peak at an energy that is a factor of 2-5 lower than the gamma rays from $\pi^o \rightarrow \gamma\gamma$ decays (44). In the scenario in which gamma rays are of hadronic origin, features such as cutoffs observed in gamma ray spectra would be expected in neutrino spectra at around half the energy. Recently the gamma-ray telescopes HESS, VERITAS and MAGIC have observed a population of galactic sources characterized by steep spectral indices. Moreover, several sources show evidence of an exponential cutoff in the source spectrum at energies of 10 TeV or so, implying that sensitivity at low energy will be essential for observing these sources. The sources recently discovered are concentrated in the region of the inner Galaxy, most of them in the Southern Hemisphere, i.e. outside the nominal field of view of IceCube. The southern sky is a prime target for observations by Mediterranean telescopes such as ANTARES. AMANDA and IceCube searches for point sources have focused on the Northern Hemisphere, using the Earth to filter out atmospheric muons. With IceCube Deep Core we aim not only to lower the threshold of IceCube but also to access the Southern Hemisphere using part of IceCube as

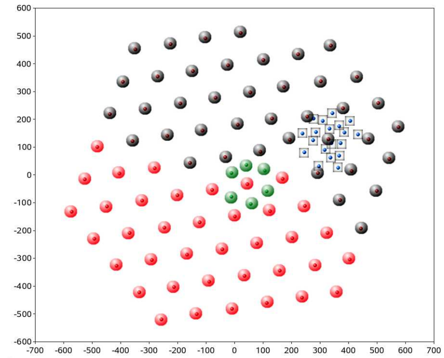

Fig. 8. Overhead view of the in-ice detector. The black spots represent the 40 strings already deployed. The squares mark the positions of AMANDA strings. The red and green spots correspond to the planned IceCube and Deep Core string positions.

active muon veto. Later in the text more details about a first implementation of the veto in IceCube are reported.
- *Atmospheric neutrinos:* The ability of the Deep Core array to push the neutrino energy threshold down to $\sim$ 10 GeV also confers benefits on the study of atmospheric neutrinos. Their energy spectrum has been measured by AMANDA for energies above a few hundred GeV. With an instrumented physical volume of roughly 20 megatons, simulations show that Deep Core will trigger on about 60,000 atmospheric-neutrino-induced events per year, using a simple majority trigger set at six hits in a 5 μs window and requiring hits on at least three strings. Roughly 8% of these events are in the 1-10 GeV energy bin, 45% in the 10-100 GeV bin, and 45% in the 100 GeV - 1 TeV bin. The measurement of the energy spectrum and angular distribution of atmospheric muon neutrinos in the region 10 GeV to 1 TeV is particularly interesting for the study of the transition from pion decay to kaon decay production and for neutrino oscillation study. Another aim of Deep Core is to make a first measurement of the flux of electron neutrinos at energies overlapping with and extending that of Super-Kamiokande (42).

IceCube offers for the first time the possibility to enlarge the field of view of the neutrino telescope using part of the instrumented volume as *active veto*. The performance in this respect has been investigated using Monte-Carlo simulation. In order to perform a search for neutrinos from above, muons have to be rejected by a factor of 10^6. We have divided the detector in two regions: Fiducial Volume (FV) and Veto Volume (VV). The FV is the most shielded

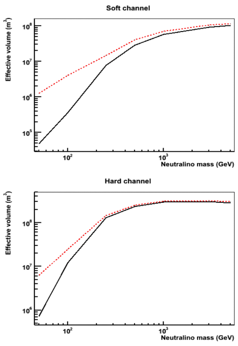

Fig. 9. Effective volume as function of neutralino mass for muons from interactions of ν_μ from neutralino annihilation in the Sun during the six months it is below the horizon. The dashed line corresponds to full IceCube augmented by the six Deep Core strings. The full-drawn line corresponds to full IceCube without a deep core array.

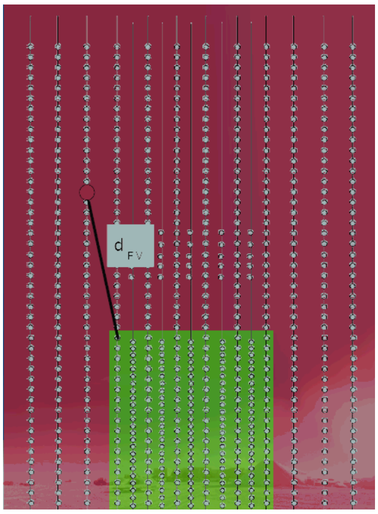

Fig. 10. Schematic view of the IceCube neutrino observatory and the proposed deep core array. The Veto Volume (red) and Fiducial Volume(green) are also shown. The distance d_{FV} of the veto hits from the FV is used as parameter to separate the cosmic ray muon population from the neutrino-induced muons

region of the detector i.e. the central and bottom part of the detector where the deep core strings will be deployed. Events with their interaction vertex in this region are considered signal events. The VV corresponds to the part of the instrumented volume required to reject the bulk of the downward atmospheric muons. The top 36 DOMs and three layers of strings around the FV are used as VV (Fig. 10). In order to separate contained and not contained events, we consider that a hit far away from the FV has a very low probability to be associated to an event in the FV. In order to use this information, we penalize the hits proportionately to their distance (d_{FV}) from the FV, giving them an extra weight. Counting hits in the FV and using geometrically-penalized hits in the VV, we succeed in rejecting downward going muons by four orders of magnitude, while still preserving the neutrino signal. In a second step, a dedicated algorithm determines the most probable interaction vertex of the surviving events (43). The x,y,z distributions and likelihood of the reconstructed vertex differ significantly from the neutrino induced muons and downward through-going muons leaking in. The final selection of neutrino induced events is made by requiring that the reconstructed vertex of the neutrino interaction is inside the FV. This allows the rejection of muons by two additional orders of magnitude. This two-levels analysis proves that IceCube is an efficient muon veto and fully contained events which trigger IC-DC can be identified with an efficiency between 20% and 30%.

5. Conclusions

We have reported the principal steps in the development of high energy neutrino astronomy at the South Pole. Although so far high energy astronomical neutrinos have not been identified, the fast growing IceCube detector together with a well tested technology and advanced methods in data analysis and simulation provide the best opportunity ever to perform high energy neutrino astronomy. The integration of the AMANDA detector and the recent approval of IceCube Deep Core enhance the capability of the IceCube array at lower energies and open new physics opportunities.

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