PROCEEDINGS OF SCIENCE

IceCube

Albrecht Karle*, **for the IceCube Collaboration**
Department of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin-Madison, Madison, WI 53706, USA
E-mail: karle@icecube.wisc.edu

In May 2011, the IceCube neutrino observatory with one cubic kilometer instrumented volume started full operation with 5160 sensors on 86 strings and 324 sensors on 162 IceTop detectors. The fine-tuning of operation and calibration of the detector is still in progress while a very high uptime of well above 98% is obtained. New analysis techniques rely on veto techniques for enhanced rejection of atmospheric muon and neutrino backgrounds. We will give an overview of recent results including the techniques of searching for starting tracks and some comments on the reported evidence of astrophysical neutrinos at energies above 30 TeV.

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1. IceCube completion and operation

In May 2011, IceCube, a neutrino telescope with one cubic kilometer instrumented volume started full operation with 5160 sensors on 86 strings and 324 sensors in 162 IceTop detectors. The plan to build an experiment of this scale was based on a decade of research and the demonstration that ice was a suitable medium. First, in the 1990s, the Antarctic Muon and Neutrino Detector Array (AMANDA) was built. Then, based on AMANDA as a proof of concept, the full kilometer-scale IceCube neutrino telescope was constructed and completed by 2010 (see Fig. 1). Today, the South Pole has become a premier site for neutrino astronomy.

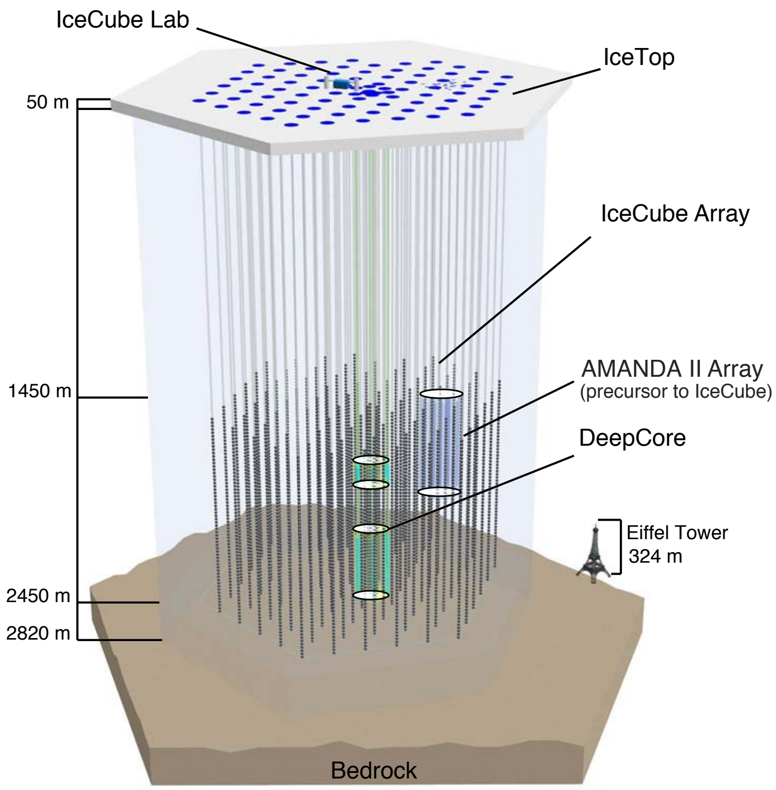

Figure 1: Schematic view of IceCube.

In the 1990-91 austral summer, the first exploratory effort was made at the South Pole to deploy photomultipliers in ice at a shallow depth. This would be the first of 13 polar seasons that involved hot water drilling with the goal of deploying photomultipliers in ice and advancing AMANDA and later IceCube. It was preceded by an important exploration of the idea to deploy PMTs in natural ice in Greenland in 1990. The result, the “Observation of muons using the polar ice cap as a Cerenkov detector" was published in [1] and marks an important milestone. The authors concluded: “Our results suggest that a full-scale Antarctic ice detector is technically quite feasible," and started making preparations for an exploration at the South Pole. While the conclusion may have sounded far fetched, exactly 20 years later a cubic kilometer detector was indeed in operation.

Table 1 summarizes the chronological development of string installation and some performance measures from AMANDA to the completion of IceCube.

Season	**Campaign**	**Sensors** cumulative	**Strings** season/cum.	**Depth** (m)	**Neutrinos** per day	**Resol.** @100TeV
1991-1992	exploratory	few		shallow	-	
1992-1993						
1993-1994	AMANDA-A	80	4	800-1000	-	
1994-1995						
1995-1996	AMANDA-B4	86	4	1500-1950	~ 0.01	
1996-1997	AMANDA-B10	206	6/10	1500-1950	~ 1	4°
1997-1998						
1998-1999	AMANDA-II-13	306	3/13	1500-2300		
1999-2000	AMANDA-II-19	677	6/19	1500-1950	~ 5	2°
2001-2002						
2002-2003						
2003-2004	IceCube prep.					
2004-2005	IceCube 1	60	1/1	1450-2450	0.01	
2005-2006	IceCube 9	540	8/9	1450-2450	2	
2006-2007	IceCube 22	1320	13/22	1450-2450	18	1.5°
2007-2008	IceCube 40	2400	18/40	1450-2450	40	0.8°
2008-2009	IceCube 59	3540	19/59	1450-2450	120	0.6°
2009-2010	IceCube 79	4740	20/79	1450-2450	180	0.4°
2010-2011	IceCube 86	5160	7/86	1450-2450	>200	0.4°

Table 1: The table summarizes the deployment of optical sensors at the South Pole. The cumulative number of sensors deployed per year is shown (324 IceTop sensors deployed with IceCube are not included). The angular resolution is shown for the reference analysis for point source searches.

The reliability and successful installation of the sensors was a critical requirement. About 80 sensors out of 5484 did not commission successfully after the installation. The reliability after commissioning has been very high. In total 6 sensors failed since the regular science run of the full IceCube detector started in May 2011. In October 2013 98.5% of the deployed sensors are in regular data taking mode. Of the 323 IceTop DOMs only one channel failed. The table summarizes the numbers of operational DOMs. The failure rates in the last two years since construction has finished are very small indeed, with loss rates at a level of about $0.5 \cdot 10^{-3}$/year.

Total number of sensors (DOMs) deployed	5484
DOMs in regular readout at start of full IceCube (May 2011)	5400
DOMs in regular readout (October 2013)	5397

The detector has been running very stably with little downtime. During the most recent science run, 5/2012 - 5/2013, the data acquisition systems of the detector recorded an uptime of 98.5%. Standard physics analyses use a data set with additional quality criteria, which led to a standard

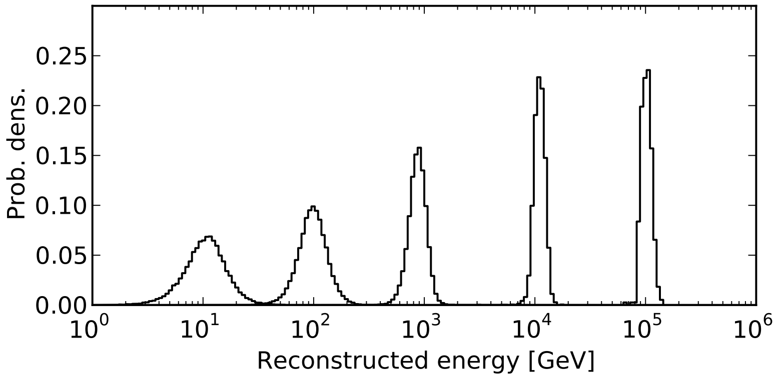

Figure 2: Reconstructed-energy distribution of simulated cascade events with a fixed true total energy depositions of $10^1, 10^2, 10^3, 10^4$, and 10^5 GeV.

physics uptime of about 96.3%. The remaining data could be mined in case of an astronomical event, such as a supernova. A science run refers to a fixed detector configuration of typically 1 year during which trigger and filter settings and any other detector configuration parameters are kept constant or only minor changes are performed that will not affect the event selection.

Efforts are still continuing to optimize the data acquisition and filtering. One significant change in January 2013 was the implementation of a system that buffers all photomultiplier signals for several hours on disk. Normally only triggered events and scaler rates are recorded. The scaler rates (2 ms binning) allow the search for Supernova neutrino bursts. A galactic supernova would record a huge burst with time structures on a ms scale. The new system, referred to as Hit-spooling, will allow to extract all single photoelectrons from disk up to several hours after a trigger took place. That means all possible information will be kept for secondary fine-tuned analysis beyond the regular online supernova trigger system. This feature also provides a measure to mitigate against a DAQ crash in case of an extremely close (<0.5 kpc) and therefore extremely strong neutrino burst. The technology may also be used as a basis for improved extraction of long duration events as expected from slowly moving exotic particles, for example magnetic monopoles.

As the statistics of recorded neutrinos increases at a rate of more than 50,000 neutrinos/year statistical errors shrink rapidly. The optical properties of the ice are known to better than 10% as a function of depth [2]. However, closer inspection has revealed more subtle features that have consequences for some analyses. This includes the tilt of dust layers of as much as 60 m vertical variation over a horizontal distance of 1 km. Another confirmed feature is the observation that light scatters about 10% less in one horizontal direction than perpendicular to that direction. The direction of reduced scattering coincides with the direction of the glacial flow, likely not a coincidence. The effect is noticeable for high energy cascade event reconstruction. In muons, which are triggering IceCube at a rate of 3 kHz, the moon shadow is seen on a monthly basis. An analysis with a deficit of 8700 events (14σ) in one year agrees with predictions [3]. The center of the moon shadow confirms the absolute pointing to within the error of 0.1° after applying a correction of 0.05° to account for Earth's magnetic field.

Event reconstruction continues to be an area of ongoing development. Single muon event reconstruction results in an angular resolution at the level of 0.4° at energies of 100 TeV. We expect significant further improvements for events at this energy and above. Figure 2 shows the energy resolution of cascades as a function of energy [4]. At energies above 10 TeV the energy resolution for neutrino induced cascades is below 10% of the deposited energy. The absolute energy calibration is constrained by a variety of methods using both muons and artificial light flashers to a level of better than 10%. Significant progress has been made with unfolding the stochastic energy losses of energetic muons above 100 TeV. However, even at a sampling length of 1 km along the track, the relation between energy loss and muon energy remains moderate at the level of 0.3 in log(energy), due to the stochastic nature of the energy losses. For throughgoing muons the relation to the neutrino energy is further constraint. These methods however will allow to identify tau neutrino double bang events readily at decay lengths of 50 m and possibly less. They also help provide tools to classify single muons in the background of high energy muon bundles. Equally important they form the basis for further improvements in the angular resolution.

2. Searches for astrophysical neutrinos

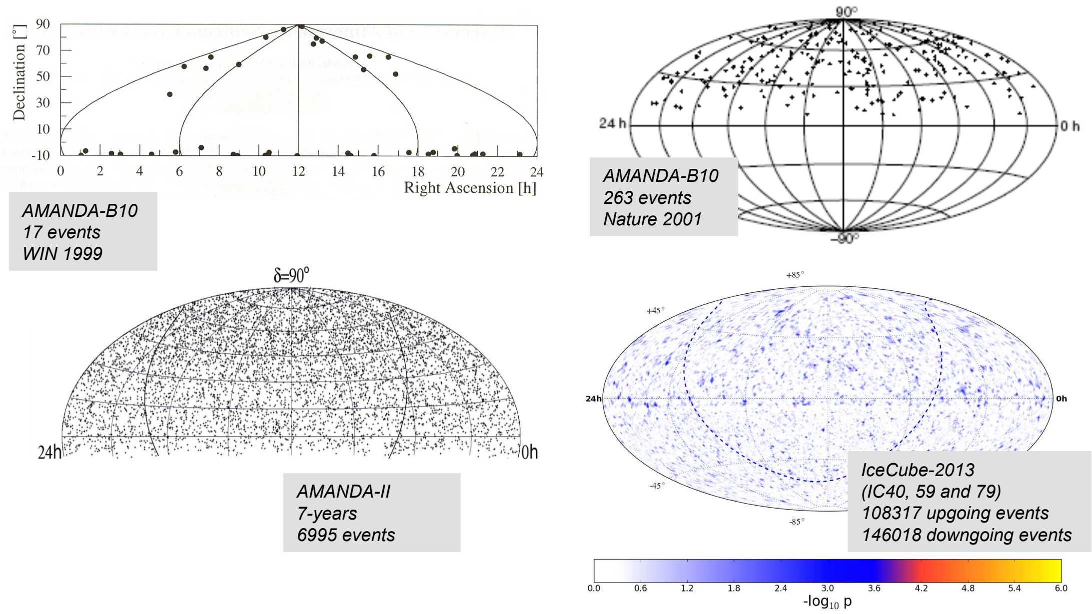

Figure 3: Neutrino sky maps generated by several generations of neutrino detectors at the South Pole from AMANDA to IceCube.

The classical detection channel for neutrino astronomy is muon neutrinos with the goal of point source searches because of the superior angular resolution of muons compared to cascade events. To complement the brief construction review in the previous section, we illustrate the progress in point source searches over the years in Fig. 3, which includes skymaps from the first map with AMANDA-B10 containing 17 events to the 3 year combined sky map based on IceCube data from the 40-, 59- and 79-string configuration. The IceCube significance map (IceCube-2013) is based on $1.1 \cdot 10^5$ upgoing neutrinos and $1.46 \cdot 10^5$ downgoing events, the latter ones being largely background from atmospheric muons. The most recent point source results are presented and discussed in a separate paper at this conference [6] and in [7]. The Southern sky searches are primarily sensitive to sources above PeV energies because of the much higher cosmic ray muon background. The Northern sky searches are effective at all energies from TeV to PeV energies where absorption in the Earth begins to attenuate the signal. An alternate strategy for rejecting the down going muon background relies on an event selection that aims to reject throughgoing muons altogether. Several analyses are underway in IceCube that select events with various degrees of cosmic ray muon rejection by requiring that the vertex of down going events or even all events be contained.

2.1 Diffuse searches

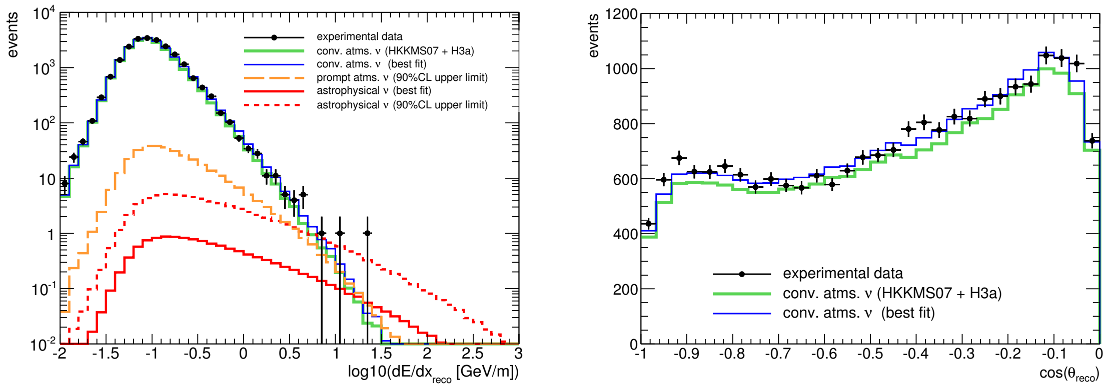

Figure 4: Search for a diffuse neutrino flux with IceCube's 59 string configuration [12]. The observed energy loss distribution of upgoing muons is compared to the best fit of atmospheric and astrophysical neutrino fluxes (left). The best fit includes a non zero astrophysical component. The corresponding zenith distribution is shown in the right panel.

Astrophysical neutrino fluxes are expected at higher energies than the steeply falling spectrum of atmospheric neutrinos. Diffuse searches rely on energy only and to some extent on flavor discrimination. Background determination is more challenging as it must rely to a higher degree on simulations and the modeling of the atmospheric neutrino background at high energies. Diffuse searches can be performed with ν_μ as well as with cascades and depending on energy in one or both hemispheres.

Diffuse searches for astrophysical ν_μ-events in AMANDA [8], BAIKAL [9] as well as more recently with ANTARES [10] and an IceCube-40 [11] analysis resulted in upper limits with no indication of a hard component. The flux limits are commonly presented as model tests of reference flux with an energy^{-2} spectrum, which is motivated by a natural spectral index of 2 of high energy cosmic rays generated by shock acceleration. The IceCube-59 data set based on 348 days of live time contained 21,943 events in the final event selection. The neutrino purity of the strictly upgoing event sample (dominated by atmospheric neutrinos) is 98.8%. Figure 4 shows zenith distribution and the energy loss distribution of data compared to atmospheric neutrino backgrounds and an

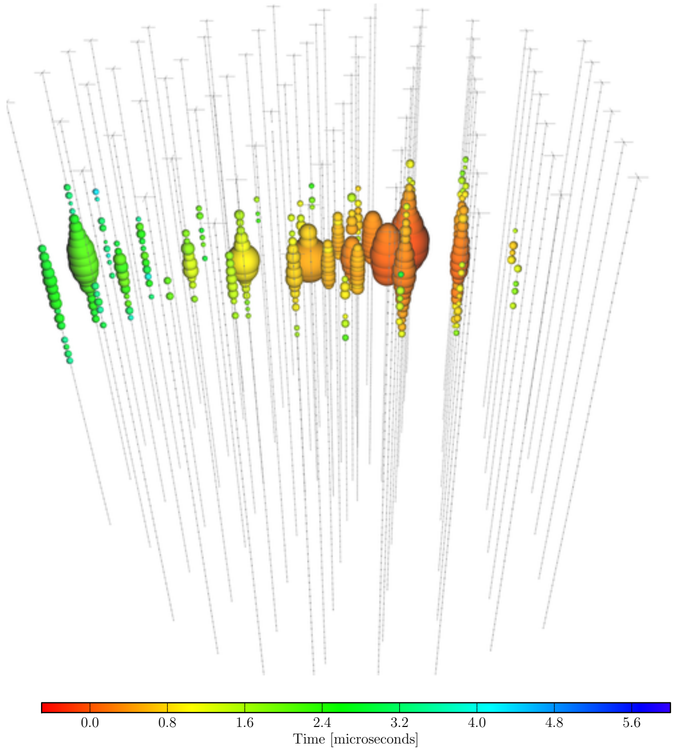

Figure 5: Horizontal muon neutrino event with a contained vertex and an outgoing track. This event has a deposited energy of 71 TeV. Most of the observed events are cascade like events.

astrophysical flux. The final result is in tension with no signal at the 2 sigma level [12] and an upper limit is derived. All known sources of systematic errors were included into the final fit result.

The cascade detection channel focuses on events with contained vertex generated in ν_e and ν_τ charged current interactions and neutral current interactions of all neutrino flavors. Results from a search for cascade-like high-energy events with the IceCube 40-string detector configuration [13] showed an excess of events at a similar level. The significance of that excess is $2.7\,\sigma$ with respect to the expectation of conventional atmospheric and prompt atmospheric neutrinos. The upper limit derived from that analysis is an all-flavor flux of $E_\nu^2\Phi(E_\nu) = 7.46 \cdot 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$ (90% confidence level). Assuming equal mixing of neutrino flavors when arriving at Earth, that flux is compatible with the best-fit flux and the upper limit derived in the IC59 muon neutrino analysis.

3. PeV neutrinos and the search for starting tracks

IceCube reported the observation of two events the energy of 1 PeV above what is generally expected from atmospheric backgrounds and a possible hint of an astrophysical source [14]. These events were found in a search for cosmogenic or GZK neutrino flux and the two events were at the very low end of the energy range that this search was sensitive to. In a follow-up analysis a search was performed for neutrinos at lower energies with interaction vertices well contained within the detector volume, discarding events containing muon tracks originating outside of IceCube. This event selection achieved nearly full efficiency for interacting neutrinos of all flavors above several hundred TeV, with some sensitivity extending to neutrino energies as low as 30 TeV. The event selection relies on relatively simple criteria, essentially requiring that the vertex be well contained and rejecting events where early photons were detected inside the veto region consisting primarily of the outermost strings and sensors. An additional 26 events were found for a total of 28 events including the original two PeV events during a combined live time of 662 days (May 2010 to May 2012). The analysis was presented for the first time in May 2013, after this conference, and was recently published in *Science* [17]. Although there is some uncertainty in the expected atmospheric background rates, in particular for the contribution from charmed meson decays, the energy spectrum, zenith distribution, and shower to muon track ratio of the observed events strongly constrain the possibility that these events are entirely of atmospheric origin. Almost all of the observed excess is in showers which are randomly distributed in the fiducial volume and in direction rather than muon tracks, ruling out an increase in penetrating muon background to the level required. Figure 3 shows an event with a reconstructed deposited energy of 71 TeV. It is easy to see that this event is indeed an event with the vertex inside. No signals have been recorded at all in the outermost layer (on the right side). The good energy resolution for contained events and specifically for cascades (Figure 2) is the basis for the energy spectrum shown in Figure 6, which shows a significant excess over background at higher energies.

The zenith angle distribution in Fig. 6 illustrates the effectiveness of the event selection and background rejection especially in the downgoing hemisphere. In this figure only events with energy above 60 TeV are shown. It can be seen that the atmospheric neutrino background is highly suppressed for zenith angles less than $\approx 60^\circ$. The reason for the suppression of atmospheric neutrinos towards smaller zenith angle is the fact that atmospheric neutrinos at sufficiently high energy will be accompanied by muons generated in the same parent air shower. This mechanism, pointed

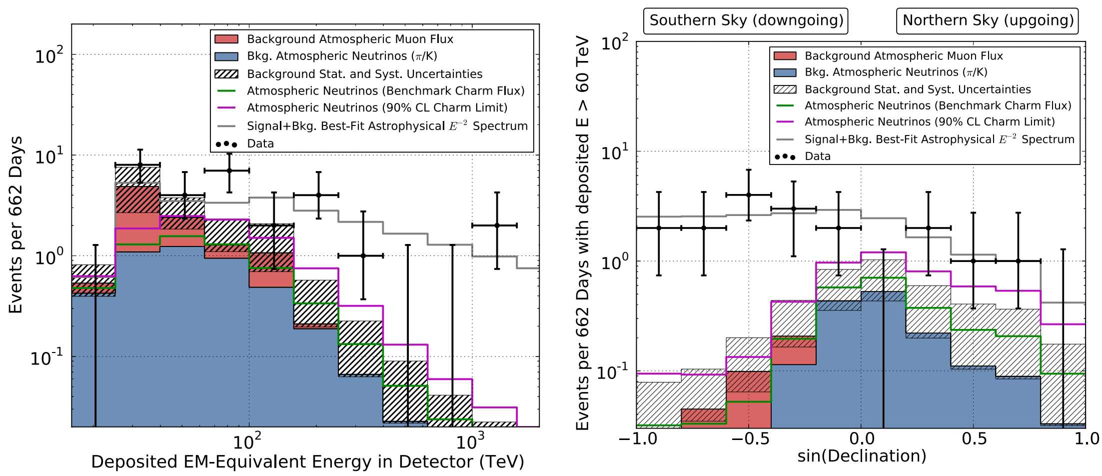

Figure 6: The distribution of the reconstructed energies of 28 events with contained vertex is compared to the best fit for signal and atmospheric background [17](left). The reconstructed zenith angle distribution for events with reconstructed energy greater than 60 TeV is compared to backgrounds and best fit in the right panel.

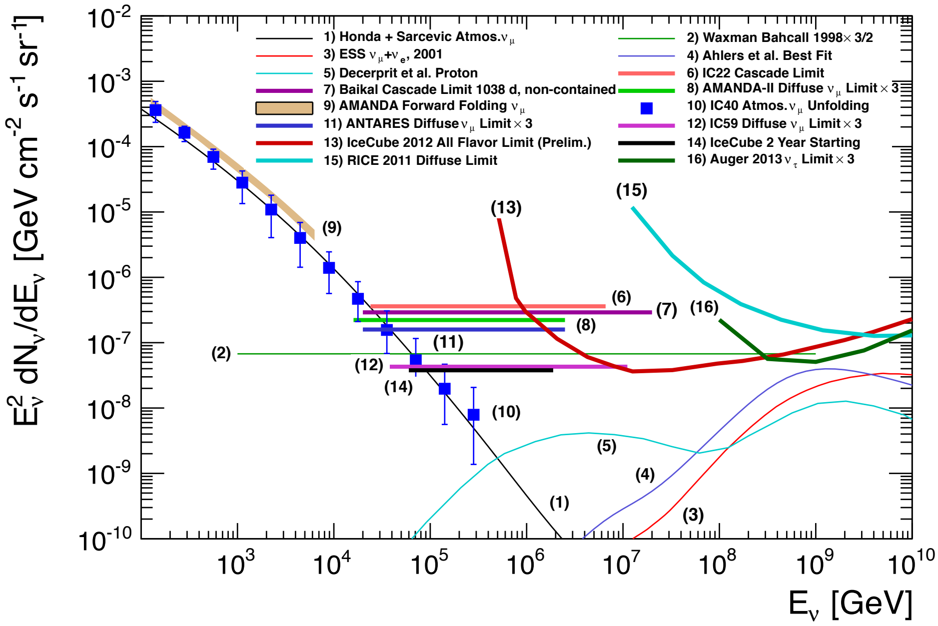

Figure 7: An overview is presented of observed atmospheric neutrino fluxes, upper limits to diffuse fluxes and models. The IceCube 2012 differential upper limit (11) turn up sharply at 1PeV because of observed PeV events. The best fit diffuse flux using starting events in IceCube (12) forms evidence for a diffuse astrophysical flux up to PeV energies above the atmospheric neutrino spectrum extending to a few 100 TeV.

out in [15], becomes very effective above energies of order 100 TeV. These accompanying muons will trigger the muon veto, removing the majority of these events from the sample and biasing atmospheric neutrinos to the northern hemisphere. The majority of the observed events, however, arrive from the south and one of the PeV events in fact is reconstructed at a zenith angle of only 23° with an angular error of 11°. A search was performed for clustering of these events, which did not leave any significant evidence for a point source in this sample.

In a global fit that allows the normalization of the atmospheric neutrino backgrounds to float, the data in the energy range between 60 TeV and 2 PeV are well described by an E^{-2} neutrino spectrum with a per-flavor normalization of

$$E^2\Phi(E) = (1.2 \pm 0.4) \cdot 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}.$$

The absence of events at higher energies may be an indication for a break of the energy spectrum. The result is inconsistent with zero astrophysical flux at the 4 sigma level. Figure 7 shows some of the observations of high energy neutrino fluxes. Atmospheric neutrino fluxes have been measured by IceCube up to energies where an indication for a hardening of the energy spectrum is observed in several analyses. For reference, the atmospheric neutrino flux expectation is shown for Honda [18], and the upper bound for an astrophysical E^{-2} neutrino spectrum based on the observed energy in high energy cosmic rays derived by Waxman and Bahcall [19]. The observed results and upper limits in muon and cascade analyses of IceCube ([17, 11, 12, 16] and some earlier results) are in reasonable agreement with the first observed evidence at the 4 sigma for an astrophysical flux in the starting track analysis [17]. Next steps in the diffuse searches will include the inspection of several years of diffuse muon neutrinos as well as cascade searches with the full detector. The IC59 analysis may be seen as a hint toward an astrophysical muon neutrino flux in the Northern hemisphere at a level compatible with the flux reported in the starting track analysis. If this is confirmed, the observed diffuse flux can be put in perspective of the point source searches already under way since several years.

4. Concluding remarks

The IceCube detector is operating well with high uptime and exceeding original performance parameters. First evidence is emerging for an astrophysical neutrino flux in an analyses relying on events with contained vertex. Many other physics results were not discussed in this report. A detailed discussion of point source results was presented by J. Aguilar [6]. At low energies intense efforts are underway using the DeepCore in fill detector to search for dark matter above 10 GeV and determine oscillation parameters using atmospheric neutrinos. For these results and an outlook for future upgrades we refer to the presentation by M. Kowalski at this conference [20].

5. Acknowledgments

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