IceCube – Astro- and Astroparticle Physics at the South Pole

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Abstract: The IceCube Neutrino Observatory at the South Pole has been completed in December 2010. In this paper we describe the final detector and report results on physics and performance using data taken at different stages of the yet incomplete detector. No signals for cosmic neutrinos from point sources and diffuse fluxes have been found. Prospects of these searches, including the setup of multi-messenger programs, are discussed. The limits on neutrinos from GRBs, being far below model predictions, require a reevaluation of GRB model assumptions. Various measurements of cosmic ray properties have been obtained from atmospheric muon and neutrino spectra and from air shower measurements; these results will have an important impact on model developments. IceCube observed an anisotropy of cosmic rays on multiple angular scales, for the first time in the Southern sky. The unique capabilities of IceCube for monitoring transient low energy events are briefly discussed. Finally an outlook to planned extensions is given which will improve the sensitivities both on the low and high energy side. The IceCube contributions to this conference (ICRC 2011) can be found in \cite{1}.

Keywords: Cosmic neutrinos, cosmic rays, IceCube, DeepCore, IceTop

1 Introduction

The main component of the IceCube Neutrino Observatory at the geographic South Pole is a 1-km\(^3\) detector instrumented with optical sensors in the clear ice of the polar glacier at a depth of about 2000 m. The installation of IceCube with all its components was completed in December 2010. The main purpose of IceCube is the detection of high energy neutrinos from astrophysical sources via the Cherenkov light of charged particles generated in neutrino interactions in the ice or the rock below the ice.

The basic motivation for the construction of IceCube is to contribute to answering the fundamental, still unanswered question of the origin of cosmic rays. If cosmic rays are accelerated in astronomical objects, like Supernova Remnants (SNR), Active Galactic Nuclei (AGN) or Gamma Ray Bursts (GRB), one expects the accelerated particles to react with the accelerator environment leading mainly to pion production. The principle of such a reaction of an accelerated hadron \(N\) with an ambient hadron or photon is:

\[ N + N' \rightarrow X + \left\{ \begin{array}{ll} \pi^+ & \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_e \nu_\nu \text{ (+c.c.)} \\
\pi^0 & \rightarrow \gamma \gamma \end{array} \right. \] (1)

While neutral pions decay to gammas which can be detected by satellite gamma detectors up to several 100 GeV and by Cherenkov gamma ray telescopes in the TeV range, the charged pion decays or other weak decays such as kaon decays lead to neutrinos with a similar energy spectrum. If the pion production happens in or near the accelerator one expects to observe neutrino point sources. Interactions on the interstellar or intergalactic radiation background would lead to a diffuse flux of neutrinos. Also the summed flux of many faint sources could be seen as diffuse flux. The high-est energies in the diffuse flux are expected to be in the EeV range stemming from interactions of the highest energy cosmic rays with the photons of the Cosmic Microwave Background (CMB). The observation of these neutrinos could confirm that the cosmic rays are limited at energies of about 10\(^{20}\) eV by the so-called "Greisen-Zatsepin-Kuzmin limit" (GZK cut-off). The importance of the observation of neutrinos from astrophysical sources to prove or disprove theoretical models was stressed in various talks at this conference, for example \cite{2}.

In the lowest part of the IceCube detector a subvolume called DeepCore is more densely instrumented lowering the energy threshold from about 1 TeV in most of the detector to about 10 GeV. This addition to the original detector design extends appreciably the physics reach of the observatory to atmospheric neutrino oscillation phenomena, WIMP searches at lower masses and improves the sensitivity for the detection of transient events like supernovae and GRBs.

IceTop, the surface component of IceCube, is an air shower array covering an area of 1 km\(^2\). With this detector air-showers from primary particles in the energy range from about 300 TeV to above 1 EeV can be measured. The
Table 1: List of the years when a certain configuration of IceCube (IC), IceTop (IT) and DeepCore (DC) became operational. The DC strings are also included in the numbers for IC. In this paper we will use abbreviations like IC40, IT40 for the constellation in 2008, for example.

<table>
<thead>
<tr>
<th>Year</th>
<th>IC strings</th>
<th>IT stations</th>
<th>DC strings</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>9</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>2007</td>
<td>22</td>
<td>26</td>
<td>-</td>
</tr>
<tr>
<td>2008</td>
<td>40</td>
<td>40</td>
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<tr>
<td>2009</td>
<td>59</td>
<td>59</td>
<td>-</td>
</tr>
<tr>
<td>2010</td>
<td>79</td>
<td>73</td>
<td>6+7</td>
</tr>
<tr>
<td>2011</td>
<td>86</td>
<td>81</td>
<td>8+12</td>
</tr>
</tbody>
</table>

Figure 1: The IceCube detector with its components DeepCore and IceTop in the final configuration (January 2011).

In the following I will describe the IceCube detector with its sub-components DeepCore and IceTop. During the construction time from 2004 to the end of 2010 data have been taken with the still incomplete detector, see Table 1.

Trigger and data acquisition: To initiate the full readout of DOMs, a so-called ‘hard local coincidence’ (HLC) is required. In IceCube at least one of the two nearest neighbours of a string must have signals above threshold within \( \pm 1 \mu s \), reducing the single-DOM noise rate of about 400 Hz to a rate of about 20-40 Hz per DOM. In IceTop the HLC requirement is a coincidence of the two high gain DOMs of a station. This results in a launch rate of high energy cosmic ray showers.

Ice Properties: At the depth of the detector the ice is very clear with an absorption length reaching about 100 m. Scattering and absorption show a depth dependence, which follows the dust concentration in the polar glacier. The most prominent feature is a dense dust layer at a depth around 2000 m. The measurement and modelling of the ice properties for reconstruction and simulation is discussed in [5].

DeepCore: In the lower part of the detector a section called DeepCore is more densely instrumented. The DeepCore subarray includes 8 (6) densely instrumented strings optimized for low energies plus the 12 (7) adjacent standard strings (the numbers in parentheses apply to the DeepCore Core subarray). The DeepCore strings (the numbers in parentheses apply to the DeepCore Core subarray) include 8 (6) densely instrumented strings optimized for low energies plus the 12 (7) adjacent standard strings (the numbers in parentheses apply to the DeepCore Core subarray) include 8 (6) densely instrumented strings optimized for low energies plus the 12 (7) adjacent standard strings (the numbers in parentheses apply to the DeepCore Core subarray).
gain DOMs of 2-4 Hz compared to about 1600 Hz of a single high gain DOM at a threshold of about 0.2 VEM.

In the counting house at the surface, triggers are generated from the HLCs deciding if the data are written to a permanent storage medium to make it available for later analysis. The basic in-ice trigger, for example, requires that at least 8 DOMs are launched by an HLC leading to a rate of about 2 kHz. A very loose trigger requirement is applied to the DOMs in the DeepCore fiducial region (below the dust layer) by requiring 3 or more HLC hits within a 2.5 µs time window. The basic trigger for IceTop is issued if the readouts of 6 or more DOMs are launched by an HLC leading to a rate of 30 to 40 Hz. For all detector components HLC hits are always stored in case of a trigger issued by another detector component.

For each DOM above threshold, even without a local coincidence, condensed data, so-called SLC hits (soft local coincidence), are transmitted. These data contain only the time and amplitude of the PMT waveform peaks (for in-ice DOMs) or the time and integrated charge (for IceTop DOMs). The SLC hits are, for example, used for detecting transient events and to generate vetos for special event signatures. In the case of IceTop they are useful for detecting single muons in showers where the electromagnetic component has been absorbed (low energies, outer region of showers, inclined showers).

For monitoring transient events via rate variations, the time of single hits are histogrammed. In IceTop the single hits in different tanks are obtained with various thresholds (scaler rates) for heliosperic physics.

Triggered events which fulfill certain filter criteria for various event classes (muon, cascade etc.) are sent via a satellite to the IceCube Computing Center in Madison. In addition fast online processing produces alerts for other telescopes in case of significant neutrino accumulations (see Section 4.5 on follow-up programs).

### 3 Detection Methods and Performance

**IceCube Performance:** For point source searches muon neutrino detection is best suited because they generate tracks from muons which provide a good direction information. This allows to determine the muon energy in the order of 1° and better (see the moon shadow energy due to bremsstrahlung, pair production and nuclear interactions from atmospheric muons which provide a good direction information). IceCube is designed to detect first order interactions from neutral currents in the earth, the muon energy yields only a very coarse proxy for the neutrino energy which is only partially against the large background of high energy muons from transferred to the muon. The angular resolution for muon cosmic rays. However, because the neutrino cross section increases with energy the Earth becomes opaque for neutrinos above about 1 PeV. This can be seen in Fig. 2 where the muon neutrino fluxes if they generate an electromagnetic or hadronic cascade in the ice. Electron and tau neutrinos can generate cascades of different zenith angles. The effective area is defined as the target area which yields the observed muon neutrino fluxes if they generate an electromagnetic cascade in charged current interactions, as the target area which yields the observed muon neutrino fluxes.

Since at high energies the background from down-going IceCube as nearly spherical isotropic light sources, so that

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1. The term ‘neutrinos’ usually includes anti-neutrinos.
IceTop will cover a primary en-
IceTop performance: confirms the performance expectations. of a sizeable number of cascade event in DeeepCore [10] year, thus allowing oscillation studies [9]. The observation unprecedented statistical samples of atmospheric neutrinos,
of about 0.3 sr; the event rate is sufficient for a composition angle range is more limited yielding an angular coverage which makes the neutrino effective area about an order of magnitude smaller than in the muon case.

DeepCore performance: The main improvement added by DeepCore is the decrease of the energy threshold to about 10 GeV. Using the surrounding IC strings as veto, one can identify low energy neutrino interactions inside or near the DC volume. In this way, atmospheric neutrinos can be collected over an angular range of $4\pi$ sr, yielding unprecedented statistical samples of atmospheric neutrinos, about 150,000 triggered atmospheric muon neutrinos per year, thus allowing oscillation studies [9]. The observation of a sizeable number of cascade event in DeepCore [10] confirms the performance expectations.

IceTop performance: IceTop will cover a primary energy range from about 300 TeV to 3 EeV for zenith angles up to about 65°. In coincidence with IceCube the zenith angle range is more limited yielding an angular coverage of about 0.3 sr; the event rate is sufficient for a composition analysis up to about 1 EeV.
The following resolutions have been obtained for 10 PeV (100 PeV) and for zenith angles smaller than 30° [11]: core position 7 m (8 m), zenith angle 0.5° (0.3°), energy resolution 0.05 (0.04) for $\log_{10} E$/PeV.

4 Neutrino Point Sources

4.1 Search Strategy
The neutrino point source search relies on the good direction information from muons generated by muon neutrinos interacting in the ice in and around the detector or the Earth crust below the detector. Figure 3 shows a skymap of arrivals directions of neutrino candidates. The plot contains 57460 up-going and 87009 down-going neutrino candidates selected from 723 days of data taken with the 40 and 59 string configurations during 2008 and 2009 (IC40+59).

252 In a basic approach one searches in the full considered data set for a significant accumulation of events in an angular range compatible with the angular resolution. For that purpose a likelihood function is defined which takes into account a possible signal and background:

$$L(n_s, \gamma) = \prod_{i=1}^{N} \left[ \frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i \right] \quad (2)$$

For a given direction on the sky $S_i$ and $B_i$ are the probabilities for the event $i$ to be signal or background, respectively; $N$ is the number of events which is looped over and $n_s$ is the number of most likely signal events. The likelihood function depends also on the energy via a spectral index $\gamma$ which is estimated in the search procedure. The search has to be done in a fine grid of directions, here at about 100000 points which reduces appreciably the “pre-trial” significance for a point source to a “post-trial” significance. The significances are evaluated defining a test statistics which compares the most likely values $\hat{n}_s, \hat{\gamma}$ with the null hypothesis. Using simulations the distribution of the test statistics for the case of no signal is evaluated yielding a p-value which is the probability to reach the observed or a higher significance for a result $\hat{n}_s, \hat{\gamma}$ if there is no sig-
In the analysis of the IC40+59 data the hottest spot at (Ra, Dec) = (75.45°, −18.15°) has a pre-trial p-value of 4.4 × 10^{-4.65}, corresponding to an about 4 sigma significance, but a post-trial p-value of 0.67, indicating a high compatibility with the null hypothesis. This means that no significant point source observation can be reported from this search.

An overview of limits obtained from time integrated point source searches is given in Fig. 4. The IceCube 40+59 results are compared to previously published limits from IceCube and other experiments. The recently published IC40 results [12] include also limits for specific source candidates which had been selected before looking at the data. It is interesting to note that with these IceCube measurements the limits decreased by about a factor 1000 over the last 15 years.

The IC40+59 limits reached already the projected sensitivities obtainable by the full detector in one year. However, sensitivities below about 10^{-44} J suggest that a large fraction of the extragalactic cosmic rays at the highest energies could be accelerated in GRBs. GRBs are usually modeled as explosions of very massive stars which eventually collapse to a black hole. In such models the observed gamma rays stem from synchrotron radiation and/or inverse Compton scattering of electrons accelerated in shock fronts in the collimated explosive outflow. It was proposed that in the same way also protons are accelerated [15, 16]. These protons would undergo interactions with the surrounding photon field in the fireball and thus generate neutrinos according to (1). With their preferred parameters the models predict that GRB neutrinos be detectable by IceCube within not more than a year.

At this conference a search using IC59 data was reported [17]. The search was based on a list of 98 GRB observations reported from satellites during times when IceCube was taking data. The neutrino search was done similarly to the point source searches, using a likelihood like (2) with an additional term for the time included. The time probability density function was flat in the interval were the first and last gamma rays were observed falling off smoothly to both sides. In the point-spread function the uncertainty in the GRB coordinates as obtained from satellites was included.

No neutrino candidate was observed in the space-time windows. The analysis sets a limit far below the predicted sensitivity, but a post-trial p-value of 1.4% (corresponding to about 2.3 sigma) which is not sufficiently significant for claiming a neutrino flare discovery.

### 4.4 Gamma Ray Bursts

#### 4.3 Time-dependent Searches for Point Sources

The statistical significance can be improved by including time dependence in the likelihood function (2) since sources such as AGN can exhibit significant time variability in photon fluxes, which might be also visible in neutrinos, while the atmospheric background is roughly constant.

An example for an 'untriggered' search, i.e. without a priori time information, was presented at this conference [13] using the IC40+59 data as for the time-independent search (the IC40 analysis has recently been published [14]). The time-dependent likelihood term for this search is a Gaussian function, with its mean and width as free parameters.

Scanning for flares of all durations from 20 seconds to 150 days the likelihood maximization returns the most significant flare from a particular direction. The strongest deviation from background was found in the IC59 data in a direction (Ra, Dec) = (21.35°, −0.25°), centered on March 4 with a FWHM of 13 days (Fig. 5). An excess of 14 events is seen with a soft spectrum of E^{-3.9}, i.e. with no discrimination against the atmospheric spectrum. The post-trial p-value is determined to be 1.4% (corresponding to about 2.3 sigma) which is not sufficiently significant for claiming a neutrino flare discovery.

#### 4.4 Gamma Ray Bursts

![Figure 4: Neutrino point source limits (90% c.l.) for an E^{-2} spectrum. The currently most stringent limit from IC40+59 data is compared to previous and expected limits.](image1)

![Figure 5: IC59: The time distribution of the signal-to-background ratio of events from the location of maximum significance. The curve is the fitted gaussian for the most significant flare.](image2)
model flux (Fig. 6). Combining the results from IC40 [18] and IC59 our data lie a factor 5 below the model curve. This leads to the conclusion that either the model picture of GRBs is wrong or the chosen parameter values are not correct. Important model parameters are the Lorentz boost factor $\Gamma$ of the collimated outflow of the exploding star and the typical time scale $t_{\text{coll}}$ of subsequent collisions of internal shocks. In [17] the limits obtained for the combination of these parameters are presented.

4.5 Follow-Up Programs

A special feature of the IceCube detector is that it is able to monitor the whole sky (though with different energy sensitivities, see Section 3). This can be exploited to send alerts to other telescopes with narrow fields of view (optical, X-ray, gamma-ray) if in a certain space-time window an absence of neutrinos above background is observed with a pre-defined significance. The alerted telescopes can then make follow-up observations on these ‘targets-of-opportunity’ which would lead to a significance enhancement if a positive correlation between different messenger signals are observed. The alert decisions have to be made fast, i.e. online at Pole and reported via satellite, and have to be tuned in a way that the alert rate is tolerable for the alerted partners.

The IceCube collaboration has follow-up programs established with several telescopes:

- Search for GRB and core-collapse supernovae: neutrino multiplets in a short time window, $< 100$ s, generate alerts for optical follow-up by the Robotic Optical Transient Search Experiment (ROTSE) and the Palomar Transient Factory (PTF), see [19]. Furthermore an X-ray follow-up by the Swift satellite of the most significant multiplets has been set up and started operations in February 2011 [20].

- Search for neutrinos from TeV-gamma flares: a follow-up program with the MAGIC telescope has been tested with the IC79 setup and should become active for the IC86 running [21].

5 Diffuse Flux of Neutrinos

If there are many point sources, each with an unobservably low flux, then the aggregate flux may still be observable as a diffuse flux. Interactions of the cosmic rays with the matter and radiation near the source or somewhere else on their path through the space would lead, according to eq. (1), to meson production and the subsequent weak decays to a diffuse flux of neutrinos.

The identification of diffuse cosmic neutrinos relies on the assumption that they have a harder spectrum, e.g. $E^{-2}$ compared to about $E^{-3.7}$ for atmospheric neutrinos. The 'prompt' component of atmospheric neutrinos from decays of heavy flavour hadrons, which are produced predominantly in the first interactions in the atmosphere, is predicted to be harder than the ‘conventional’ neutrino flux.

This introduces some additional uncertainty in the transition region where the cosmic flux is expected to become dominant. The experimental limits tell us that this transition is well above 100 TeV neutrino energy (see Fig. 7).

5.1 Diffuse Muon Neutrino Flux

Figure 7 shows the currently best limit obtained from IC40 data of up-going muons [22]. The points are the atmospheric neutrino spectrum determined by unfolding the measured muon energy depositions to obtain the flux as a function of the neutrino energy. The limit is now below the Waxmann-Bahcall bound [24] which gives a guideline of how much flux can be at most expected if cosmic neutrinos are generated in or near the accelerating sources (AGN, GRB, ...) via meson production as in (1).

5.2 Cascades and all-flavour neutrino flux

The interaction of electron neutrinos in IceCube generates an electromagnetic cascade which shows up in the detector as a nearly spherical source of light with little information about the direction. To this ‘cascade channel’ also neu-
The current best limit from cascades as derived in a more conservative analysis of the IC40 data for an energy range between about 90 TeV and 20 PeV is shown in Fig. 8.

5.3 Extremely-high energy neutrinos

Interactions of the highest energy cosmic rays with the photons of the Cosmic Microwave Background (CMB) are predicted to generate a diffuse neutrino flux in the EeV range. The observation of these neutrinos could confirm that the cosmic rays are limited at energies of about 10^{20} eV by the "GZK cut-off", at the point where the $\gamma_{CMB} - \nu$-nucleon system surpasses the threshold for pion production (with a strong enhancement due to the $\Delta$-resonance close to threshold). Since all involved processes and particles are well known this GZK process could be considered a "guaranteed" source of cosmogenic neutrinos. However, in detail the theoretical predictions for the fluxes vary by about 3 orders of magnitude, depending mostly on the assumed primary composition and the distribution of cosmic ray sources.

At this conference preliminary results for ‘Extremely-High Energy’ (EHE) neutrinos have been presented [27] using the IC40 detector. The analysis aims at finding down-going neutrinos generating very bright events in the detector. However, the large atmospheric muon background restricts the search to events coming from near the horizon where neutrinos have also the largest interaction probability. The obtained EHE neutrino flux limits are shown in Fig. 8. Up to about 10 EeV IceCube has the best upper limit. The comparison with predictions shows that a positive observation of GZK neutrinos might still take some years.

On the other hand improvements in the analysis procedure could increase the detection efficiency [28]. For example a scheme is currently investigated to use single-tank hits in IceTop for a veto against the overwhelming background from down-going muons [29].

6 Exotics

An essential part of the IceCube physics program deals with generic Particle Physics problems such as the search for new particles beyond the Standard Model, called ‘exotic particles’. Such particles include Dark Matter candidates such as proposed by Supersymmetry (SUSY) or by Kaluza-Klein models. The breaking of larger symmetries, as postulated by ‘Grand Unified Theories’, implies the generation of topological defects such as monopoles which can also be searched for with IceCube.

6.1 WIMP Search

It is now experimentally well established that ‘Dark Matter’ (DM) exceeds normal, baryonic matter by about a factor 5. In most common scenarios the DM consists of Weakly Interacting Massive Particles (WIMPs) which remained from the Big Bang after the expansion rate of the Universe surpassed their annihilation rate. A promising WIMP candidate is the lightest supersymmetric particle, in most SUSY variants the neutralino $\chi$. In the searches reported below parameters have been investigated within the MSSM (‘Minimal Supersymmetric Model’).

There are three general DM search strategies: In direct searches one looks for elastic WIMP scattering off nuclei; in indirect searches one tries to detect WIMP annihilation products, such as gammas or neutrinos, with astroparticle detectors and finally in accelerator experiments one...
Neutrino excess from the galactic center and halo was reported. Using IC40 data (367 days) preliminary limits for \( \langle \sigma_{\text{ann}} v \rangle \) as a function of the WIMP mass in the range \( 10^{-22} - 10^{-23} \text{cm}^3 \text{s}^{-1} \) have been obtained. The ‘natural scale’, given by the above mentioned relation to cosmological parameters, is about \( 3 \times 10^{-25} \text{cm}^3 \text{s}^{-1} \). The limits depend strongly on the assumed model for the WIMP density and on the annihilation channel.

The IceCube observatory offers a variety of possibilities to measure cosmic rays, analyse composition and determine the spectrum which can be used to tune the models of Grand Unified Theories and inflationary fields. The non-observation of monopoles constrains the possible abundance of monopoles exploiting that the acceleration of monopoles by magnetic fields would damp those fields. The non-observation of monopoles constrains the combinations of Grand Unified Theories and inflationary scenarios.

Origin, composition and spectrum of high energy cosmic rays are still not well understood. In particular above some 100 TeV, up to which direct measurements with balloons and satellites are possible, the experimental situation is far from being satisfactory. The understanding of the muon fluxes from cosmic ray initiated air showers is also essential for IceCube because they are the major background in the search for extraterrestrial neutrinos and exotic particles.

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At high energies the muons. Laterally separated muons: of the leading muon by exploiting cascade-like stochastic composition in the knee region which is otherwise difficult to tackle. For the analysis new methods had to be developed, for example a method for determination of the energy of the leading muon by exploiting cascade-like stochastic energy losses [34].

Laterally separated muons: At high energies the muons reach the in-ice detector in bundles which are, for primaries above about 1 PeV, collimated within radii of the order of some 10 m. Most of the muons stem from the soft peripheral collisions with little transverse momentum transfer. Perturbative QCD calculations, however, predict the occurrence of muons with higher transverse momenta in some fraction of the events. A first analysis of the IC22/IT26 data [36], where the muon bundle was measured together with the shower energy in IceTop, demonstrated that separations of single muons from the bundle by more than about 100 m, corresponding to transverse momenta above about 6 GeV, could be detected. A better understanding of the remaining background from uncorrelated multiple events and an unfolding from the lateral separation to transverse momentum distributions is currently pursued. With a larger muon bundle (muon threshold about 500 GeV), originating from the first interactions in the atmosphere, has a strong sensitivity to composition. Here IceCube offers the unique possibility to clarify the cosmic ray composition and spectrum in the range between about 300 TeV and 1 EeV, including the ‘knee’ region and a possible transition from galactic to extra-galactic origin of cosmic rays.

7.1 Cosmic Ray Physics with Muons in IceCube

Atmospheric muon spectra: Atmospheric muon and neutrino spectra measured with IceCube probe shower development of cosmic rays with primary energies above about 10 TeV. In a contribution to the conference [34] it was shown that with an accurate measurement of the muon spectra one can discriminate between different composition models (Fig. 10). At the current stage of the investigation a smoother transition of the different element contributions in the knee region (than for example suggested by the polygonato model [35]) is preferred. With additional systematic studies a clarification should be reached about what energy dependence of composition has to be used in simulation models.

This is a completely new approach to analyse cosmic ray composition in the knee region which is otherwise difficult to tackle. For the analysis new methods had to be developed, for example a method for determination of the energy of the leading muon by exploiting cascade-like stochastic energy losses [34].

Seasonal variations of the muon rate: IceCube observed a ±8% seasonal variation of muon rates in the ice. This modulation is strongly correlated with the variability of the temperature, and thus of the density, in the upper atmosphere at heights corresponding to pressures around 10 to 100 hPa. The convolution of the density profile with the production cross section for muons defines the effective temperature $T_{\text{eff}}$. The relation between the effective temperature change and the rate change, assumed to be linear,

$$\frac{\Delta R_{\mu}}{\langle R_{\mu}\rangle} = \alpha_T \frac{\Delta T_{\text{eff}}}{T_{\text{eff}}}$$

depends on the $K/\pi$ production ratio. From the coefficient $\alpha_T$ measured over 4 years on a sample of 150 billion events a preliminary result is reported in [37] which indicates that the currently assumed $K/\pi = 0.15$ has to be lowered to about 0.1. If confirmed this would lead to modifications of the models for air shower simulation.

7.2 Atmospheric neutrino spectra

Muon neutrinos: IceCube has the most precise determination of the atmospheric muon neutrino spectrum at high energies (Fig. 7). This spectrum has to be unfolded from the measured muon energies to the neutrino energies. A measurement of cascades from electron neutrinos and charged current interactions of all flavours would yield a better energy determination. This is important especially at the high energy end where signals from diffuse neutrino fluxes are searched for. The potential transition region is still theoretically uncertain due to missing information about composition and about the uncertainty in the prompt contribution from heavy quark production.

Cascade analysis with DeepCore: In a first analysis of data taken with the DeepCore detector in the IC79 configuration (2010/11) cascades from atmospheric neutrinos
have been searched for. In the DeepCore detector 1029
cascade candidates have been observed with a medium en-
ergy around 180 GeV for 281 days of data [10] while 1104
were predicted from simulations using the Bartol model
[38]. Of the predicted events 59% are cascades with about
equal amounts of $\nu_e$ CC and $\nu_\mu$ NC events. The remain-
ing 41% is background from muon tracks from up-going
$\nu_\mu$; background from down-going atmospheric neutrinos is
still under investigation. A final conclusion about the quan-
titative comparison with model predictions would be pre-
mature because systematic uncertainties are still evaluated
[10].

This is a nice, surprisingly early result from the newly com-
missioned DeepCore detector and supports the expecta-
tions for the performance of the detector (Section 3). The
physics goals of measuring neutrino oscillations [9], de-
creasing the mass range for the WIMP search and enhanc-
ing the sensitivity for supernovae detection become very
realistic.

### 7.3 Cosmic Ray Anisotropy

IceCube has collected a huge amount of cosmic ray muon
events, about $10^{11}$ events between 2007 and 2010, and ev-
ery year of running with the full detector will increase this
number by about the same amount. These events have been
used to study cosmic ray anisotropies, for the first time in
the Southern sky. The observation of anisotropies on mul-
tiple angular scales has been previously reported [39, 40],
At this conference, analyses of anisotropies using $33 \cdot 10^9$
events from IC59 data were presented with preliminary re-
results on energy and angular scale dependencies as well as
various stability tests of the analyses [41, 42, 43].

Figure 11 shows skymaps of relative intensities for selec-
tions of muon energies resulting in primary energy distri-
butions which center around 20 TeV and 400 TeV. In the
20-TeV right ascension projection a clear structure dom-
inated by a dipole and quadrupole contribution is visible
while the most significant feature in the 400-TeV data set
is a deep deficit with a completely different phase than the
dip in the 20-TeV data. For more details see [41].

In addition to large-scale features in the form of strong
dipole and quadrupole moments, the data include several
localized regions of excess and deficit on scales between
$10^\circ$ and $30^\circ$ (Fig. 12). Angular decomposition into speri-
cal harmonics exhibits significant contributions up to $l=15$.
More details can be found in [42].

As yet the anisotropies observed on multiple angular scales
and at different energies have not found an explanation.
One could expect an effect due to the movement of the solar
system relative to the Milky Way, the so-called Compton-
Getting effect. This effect which results in a dipole compo-
ment in the cosmic ray intensity distribution cannot, at least
not fully, explain the data. Theoretical explanations like lo-
cal magnet fields affecting the cosmic ray streams and/or
nearby sources of cosmic rays are discussed. The deter-
mination of the energy dependence of anisotropies will be
crucial for scrutinizing models. For this reason an analysis
using IceTop with a better energy resolution and an exten-
sion to the PeV range for the primary cosmic rays has been
started.

### 7.4 Cosmic Ray Composition

As mentioned above, the combination of the in-ice detector
with the surface detector offers a unique possibility to de-
termine the spectrum and mass composition of cosmic rays
from about 300 TeV to 1 EeV.

The first analysis exploiting the the IceTop-IceCube corre-
lation was done on a small data set corresponding to only
one month of data taken with about a quarter of the final
The zenith angle dependence of shower size [11], muon rates induced by including different mass sensitive variables, like systematic uncertainties related to the models can be reduced by employing multi-messenger methods and following developing methods to enhance significances, for example by employing optical, X-ray and \( \gamma \) -ray telescopes. The hope is to accelerate the progress by further developing methods to enhance significances, for example by employing optical, X-ray and \( \gamma \) -ray telescopes. The limits on diffuse cosmic neutrino fluxes are now a factor of 4 below the Waxman-Bahcall bound, indicating that the IceCube-IceTop combination has also been used to identify high-energy photons as IceTop showers with no muons in the ice [46].

8 Transient rate monitoring

Transient events such as supernovae, GRBs or sun flares, if they generate very high fluxes of low energy particles, could be observed as general rate increases above the noise level in the DOMs even if they could not be detected individually by IceCube or IceTop. Supernova explosions in our and nearby galaxies would be observable by IceCube via a rate increase in all DOMs due to a high interaction rate of low energy neutrinos. With a rather low average noise of 286 Hz per DOM IceCube is particularly suited to emit supernova alerts, specifically important when the supernova is obscured by dust or stars in a dense region. Measurements would be sensitive to the supernova parameters such as the progenitor star mass, neutrino oscillations and hierarchy. In the contribution [47] possibilities for improving the current sensitivities, including also DeepCore, are discussed.

IceTop is able to monitor cosmic ray products from transient events such as from Sun flares, as demonstrated with the observation of the Dec 13, 2006 Sun flare event [48]. The detector readout has since then been setup such that counting rates could be obtained at different thresholds allowing to unfold cosmic ray spectra during a flare. At this conference the observation of a Forbush decrease in February 2011 was reported [49].

9 Summary and Outlook

The energy was restricted to 1 to 30 PeV. A neural network was employed to determine from the measured input variables shower size and muon energy loss the primary energy and mass (Fig. 13). The resulting average logarithmic mass is shown in Fig. 14. These results are still dominated by systematic uncertainties, such as the energy estimates or are sometimes seriously challenging models. Most scale of the muons in IceCube and of the effects of snow accumulation on the IceTop tanks.

A first look into the IC79/IT73 data set taken in 2010 showed that there will be enough statistics for composition analysis, six up to at least 1 EeV [45]. An estimation yields about 150 event with energies larger than 300 PeV and 15 events larger than 1 EeV in 1 year of data taking with the full detector.

In the near future we will concentrate on understanding the systematic uncertainties in the coincident analysis. The systematic uncertainties related to the models can be reduced by including different mass sensitive variables, like zenith angle dependence of shower size [11], muon rates in the surface detector and shower shape variables, and checking for consistency.

The IceCube-IceTop combination has also been used to identify high-energy photons as IceTop showers with no muons in the ice [46].

Figure 13: Simulated correlation between the energy loss of the muon bundles in the ice (K70) and the shower size at the surface (S125) for proton and iron showers. The shading indicates the percentage of protons over the sum of protons and iron in a bin. The lines of constant primary energy are labelled with the logarithms of the energies.

Figure 14: Average logarithmic mass of primary cosmic rays measured with IC40/IT40.
I would like to thank the many people in the IceCube Collaboration who helped prepare the talk and the proceedings.

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[3] IceCube Collab., paper 807, these proceedings.
[5] IceCube Collab., paper 333, these proceedings.