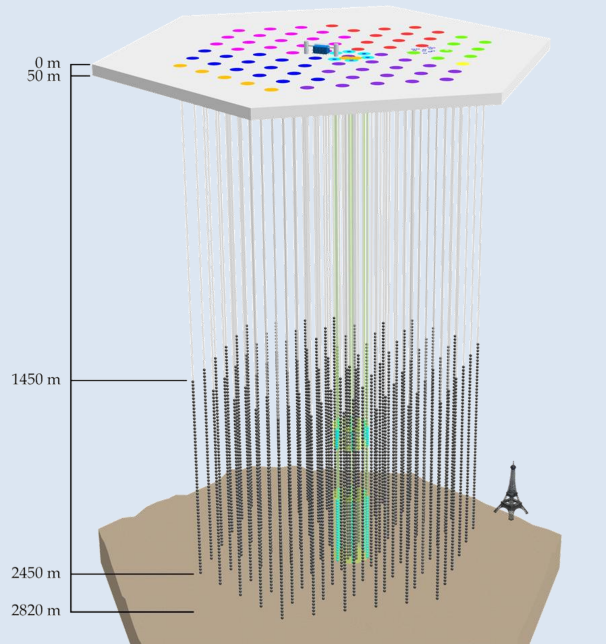
Atmospheric Neutrino Oscillation Physics with IceCube

The IceCube collaboration

Corresponding authors: Christopher Wiebusch[1], Sebastian Euler[1], Andreas Groß[2], Marius Wallraff[1], Juan Pablo Yáñez[3]

[1]III. Physikalisches Institut, RWTH Aachen University, Germany,
[2]Technische Universität München, Germany,
[3]DESY, Zeuthen, Germany

The IceCube Neutrino Observatory



IceCube is a Cherenkov detector, located two kilometers below the surface of the Antarctic ice at the Amundsen–Scott South Pole Station. The detector consists of 5160 optical sensors, which are arranged along 86 strings and instrument a volume of one cubic kilometer of ice (see sketch). 8 central strings have been deployed with smaller spacing and form together with the surrounding IceCube strings the DeepCore detector (marked in green), which has a lower energy threshold. The construction of the full detector was completed in December 2011. However, data was also taken in earlier stages of the installation.

Atmospheric muon neutrinos can be measured by detection of muons from charged-current interactions above an energy of about 10 GeV. IceCube triggers more than 200000 atmospheric muon neutrinos per year, most of them in DeepCore.

Measurement of the Disappearance of ν_μ

The measurement of the disappearance maximum of ν_μ as a function of the zenith angle is a direct verification of the oscillation hypothesis and an important test because oscillations have not been observed at these high energies before. A goal is also to precisely measure the oscillation parameters Δm^2_{32} and θ_{23}, based on the clear zenith and energy dependence of the oscillation signature. Several experimental observables are currently tested for these measurements.

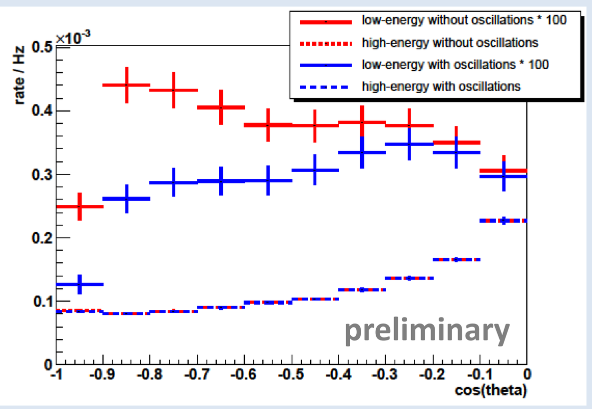


Fig. 4: Event rates vs. zenith angle for a high-energy and a low-energy neutrino sample, without and with oscillation effects (Δm_{32}^2 = 2.4e-3, θ_{23} = 45°).

An intuitive approach is to compare the zenith dependence of atmospheric neutrinos for high energies compared to low energies (fig. 4). In particular, when taking the ratio of the high-energy to low-energy rates, the effect of oscillations becomes obvious (fig. 5).

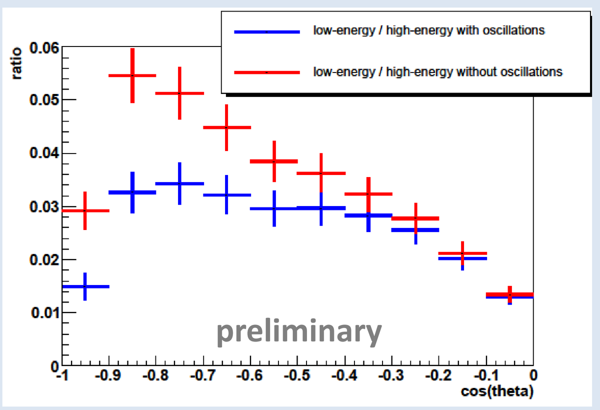


Fig. 5: Ratios of the rates of low- to high-energy neutrinos from fig. 4 without and with oscillation effects.

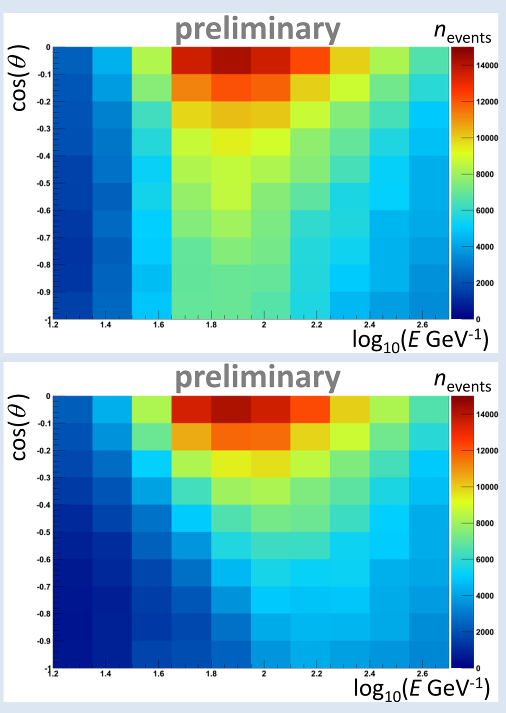


Fig. 6: Events per year vs. energy and zenith angle, without reconstruction effects; without (top) and with (bottom) oscillation.

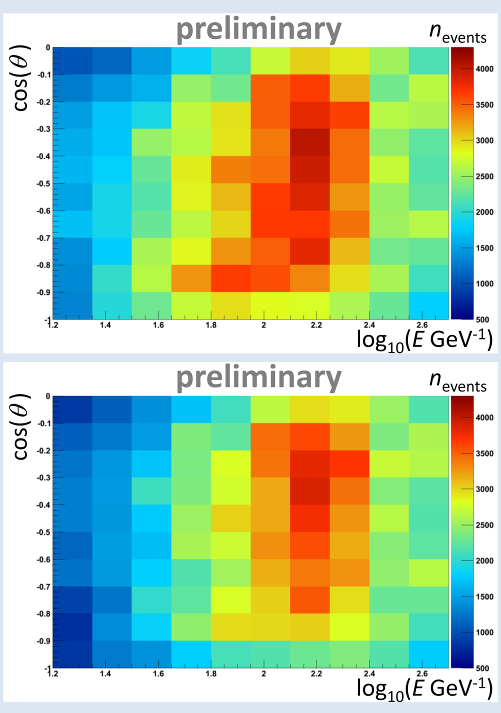


Fig. 7: Same as fig. 6, but now with reconstruction effects; without (top) and with (bottom) oscillation effects.

With a higher-statistics event selection it becomes possible to investigate oscillation effects two-dimensionally in energy and zenith. Fig. 6 shows the expected signature for one simulated year of data without taking into account reconstruction resolution. If these are taken into account (fig. 7), the signature gets washed out, but remains clear enough to allow a highly sensitive likelihood test. The result for such a test shows that the simulated oscillation parameters can be recovered with high significance (fig. 8).

However, systematic uncertainties are found to strongly bias the result.

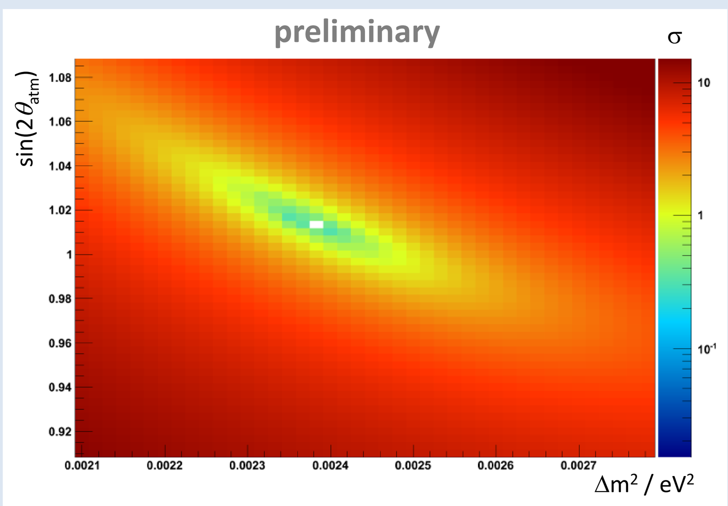


Fig. 8: Example of a likelihood landscape relative to the best fit result for Δm_{32}^2 = 2.4e-3 and θ_{23} = 45° (in units of σ = sqrt(2Δln($\mathcal{L}$)). No systematical errors.have been considered.

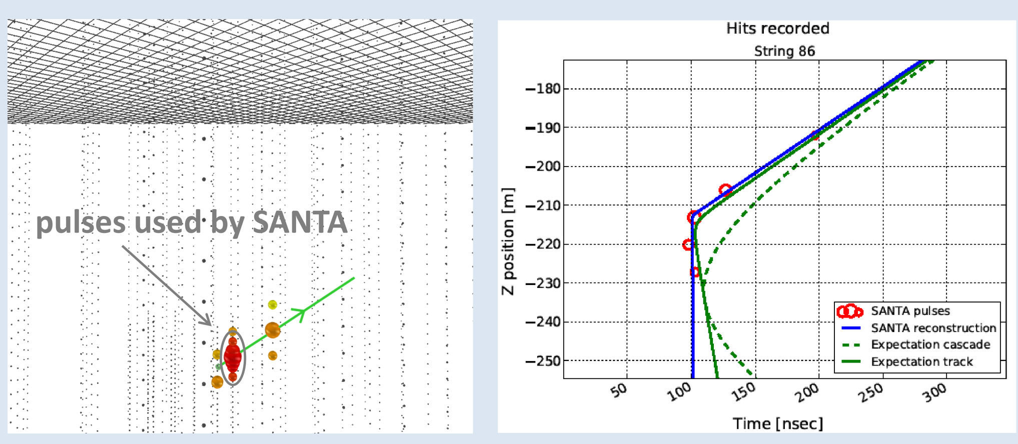


Fig. 9: Example event (57 GeV muon neutrino) and illustration of the corresponding SANTA reconstruction.

To further improve the results, new reconstruction methods are developed. One example is the SANTA reconstruction, based on a method used by ANTARES.[3] It fits the arrival direction based on the time distribution of early hits on a single string (fig. 9). Fig. 10 shows sensitivity regions for oscillation parameters for different benchmark analyses; atmospheric muon contamination and systematic errors are not included. From left to right: using the Monte-Carlo truth for the arrival direction; with arrival direction taken from SANTA; with bias by not considering all flavors in expectations; result for including the zenith fit and all flavors. It is expected that these results will change once all systematic uncertainties are taken into account.

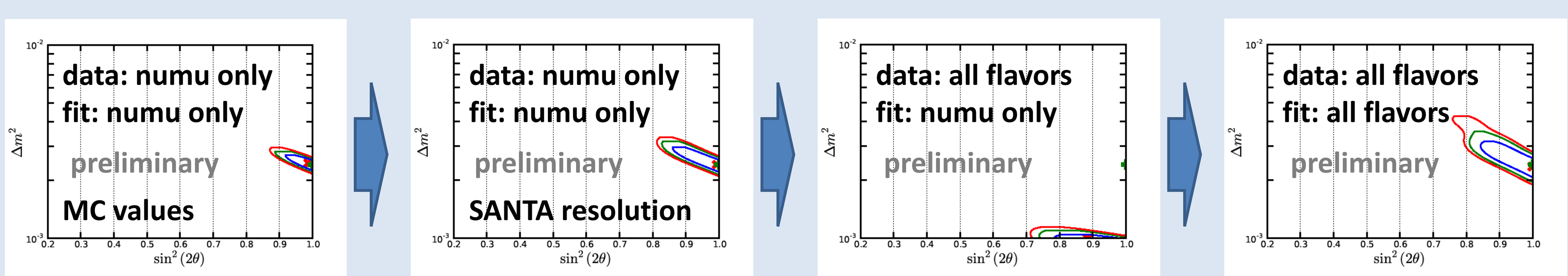


Fig. 10: Simulation study of the bias, related to the experimental resolutions and the analysis methods, on the measurement of oscillation parameters. Shown are confidence regions, MC truth (green plus), and best fit (red cross).

Neutrino Oscillations

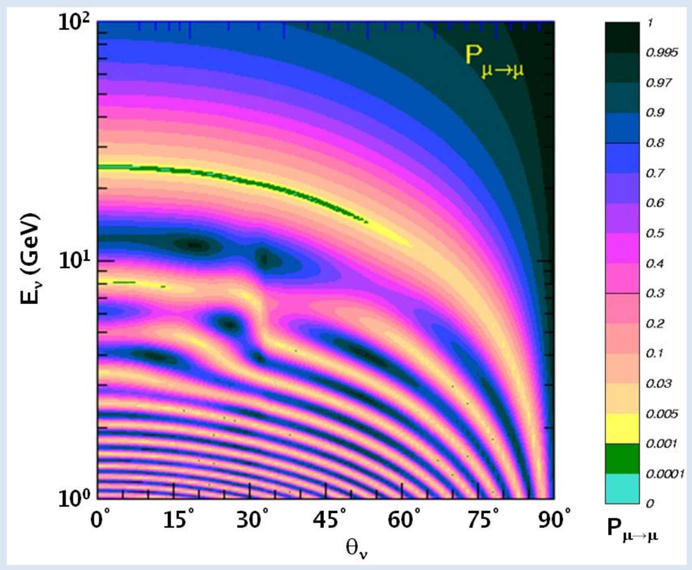


Fig. 1: Survival probability of muon neutrinos on their path through Earth.[1]

While atmospheric neutrinos propagate to a detector, they can change their flavor due to neutrino oscillations. The propagation of flavors in vacuum is described by

$$i\frac{d}{dx}\begin{pmatrix}\psi_e\\ \psi_\mu\\ \psi_\tau\end{pmatrix} = 1.267\,\frac{1}{E_\nu}\frac{\mathrm{GeV}}{\mathrm{eV}^2}M^2\begin{pmatrix}\psi_e\\ \psi_\mu\\ \psi_\tau\end{pmatrix}, \quad M = U\,\mathrm{diag}(m_1, m_2, m_3)\,U^\dagger$$

where m_i are the masses, and U is the PMNS mixing matrix. Effectively, the flavor change during propagation depends on the three mixing angles θ_{ij}, the squared mass differences Δm^2_{ji}, and the L/E_ν ratio, where L is the travelled distance. In order to account for matter effects, the PMNS matrix is modified with densitiy-dependent effective mixing angles.

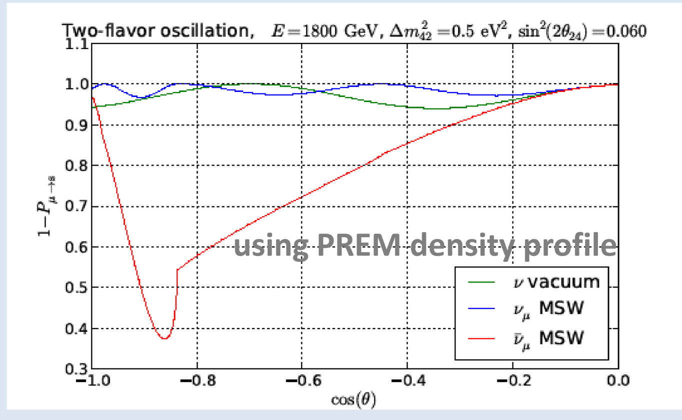
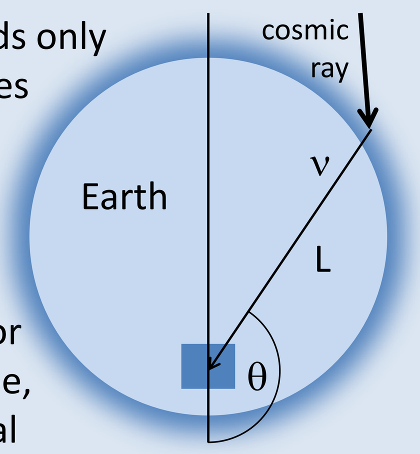


Fig. 2: Example of the survival probability of (anti-)muon neutrinos at 1.8 TeV on their path through Earth with and without matter effects, assuming a specific model with one flavor of sterile neutrinos.

For atmospheric neutrinos, L depends only on the zenith angle and roughly varies between a few tens of km and the diameter of the Earth. This results in the angular- and energy-dependent survival probability as shown in fig. 1. It can be seen that for E_ν > 10 GeV, as is relevant for IceCube, only the first minimum in the survival probability is observable. This leads to the expectation of a strong disappearance of muon neutrinos, e.g., at about 25 GeV for vertically upgoing neutrinos.



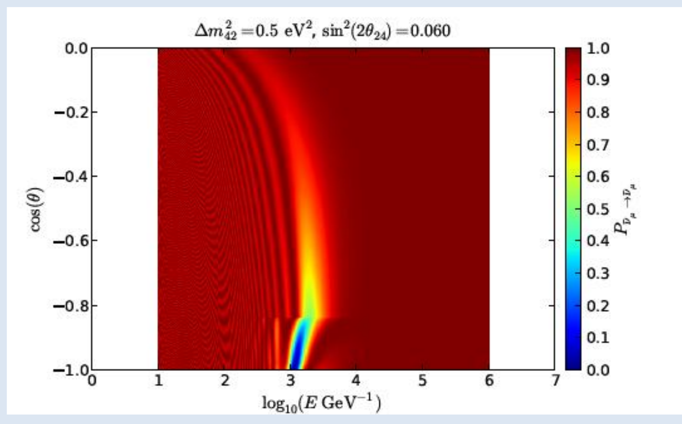


Fig. 3: Survival probability of anti-muon neutrinos as a function of the energy, for the same model as in fig. 2.

The same principles apply if one or more flavors of sterile neutrinos are added. For mass differences on the scale of $\Delta m^2_{42} \approx$ 1 eV^2, strong oscillations due to matter effects are expected for energies on the TeV scale, which can be measured well by IceCube. IceCube's sensitivity on lower-energy effects has been investigated in [2].

Fig. 2 and 3 show the survival probability (in two-flavor approximation) of muon neutrinos which mix with one sterile flavor, with Δm^2_{42} = 0.5 eV^2, $\sin^2(2\theta_{24})$ = 0.06, and normal mass hierarchy.

Search for Light Sterile Neutrinos

Fig. 11 shows the expected signature in IceCube for the disappearance of muon neutrinos in case of the existence of sterile neutrinos with Δm^2_{42} = 0.5 eV^2 and $\sin^2(2\theta_{24})$ = 0.06. It is similar to fig. 3, but it is smeared out due to reconstruction effects and detector acceptance for the sum of muon and anti-muon neutrinos. Only the latter contribute strongly to the disappearance (assuming normal mass hierarchy; compare fig. 2), therefore, the significance of the effect is reduced in the sum.

The pull plot in fig. 12 shows the effect of oscillations compared to no oscillations when both expectations are normalized to the same number of observed events, to accomodate uncertainties in the total flux. Despite the smearing, the shape of the distributions show statistically significant differences. Systematic uncertainties have not yet been included.

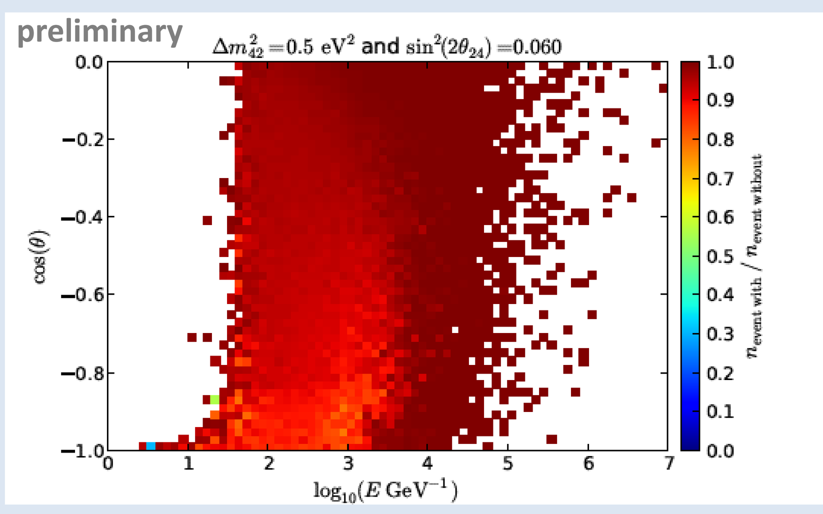


Fig. 11: Survival probability of a mixed muon/anti-muon neutrino sample, smeared out due to reconstruction resolutions and experimental efficiencies, for the example model from fig. 2 and 3.

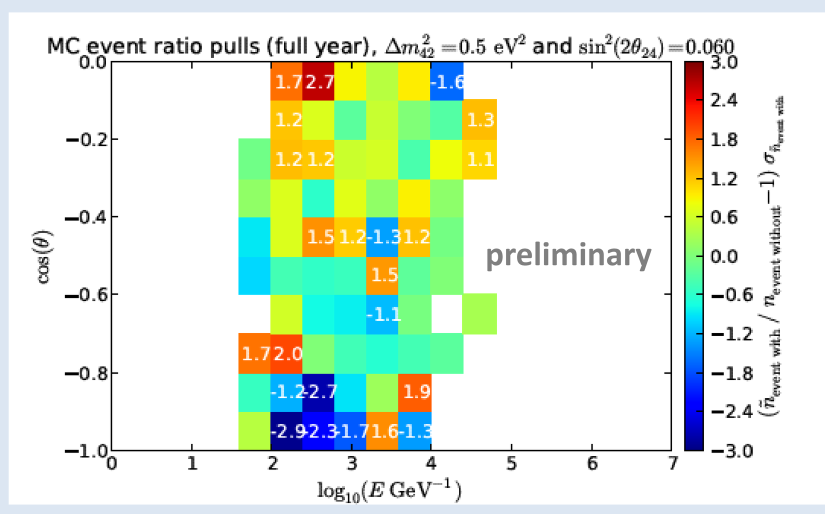


Fig. 12: Example of the significance of deviations of the event rate expected for the model in fig. 11, from the no-oscillation model, for simulated data of one year.

Outlook

IceCube can detect atmospheric neutrinos of all flavors by CC and NC interactions in or close to the detection volume. Improved reconstruction techniques allow to complement disappearance analyses with all-flavor appearance analyses. Fig. 13 demonstrates the capability to detect all flavors. Shown is the number of observed events in IceCube for an analyses of cascade-like events, which arise from NC interactions as well as ν_e and ν_τ CC interactions. The observed number of events cannot be explained by ν_μ CC interactions alone and agrees with the expectation for the sum of all flavors.

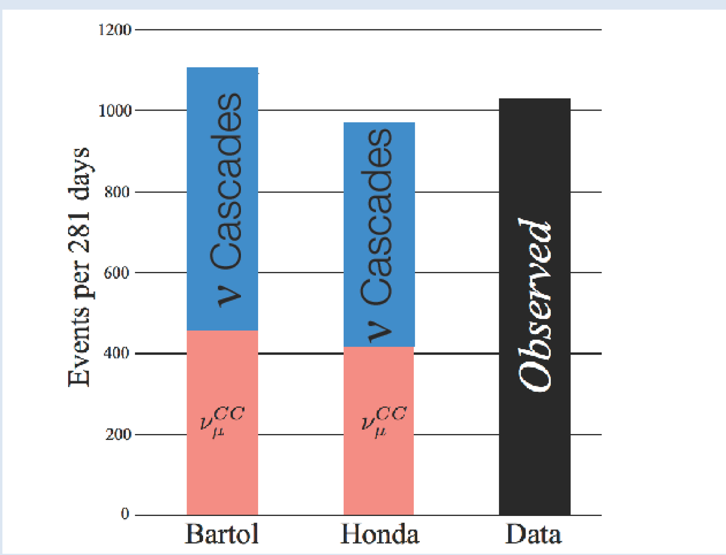


Fig. 13: Comparison of two different atmospheric-rate predictions with all-flavor reconstruction observations.[4]

In conclusion, IceCube is well-suited to measure oscillation parameters due to the excellent statistics. However, the results are limited by systematic uncertainties, and various strategies are currently being developed to determine and reduce them.

[1] Evgeny Kh. Akhmedov, Michele Maltoni, Alexei Yu. Smirnov, **arXiv:0804.1466v4 [hep-ph]** , *private communication*
[2] Soebur Razzaque and A. Yu. Smirnov, **arXiv:1203.5406v2 [hep-ph]**
[3] Jürgen Brunner , *private communication;* see also **10.1016/j.astropartphys.2011.01.003** (ANTARES collaboration)
[4] Chang Hyon Ha and Jason Koskinen for the IceCube collaboration, 32nd ICRC, Beijing 2011, **arXiv:1111.2736v2 [astro-ph.HE]**

Bundesministerium für Bildung und Forschung