# A search for the extremely high energy cosmogenic neutrinos with the IceCube 2010-2011 data


**K. Mase for the IceCube collaboration**

Chiba University, *Yayoi-cho 1-33, Inage-ku, Chiba-shi,* Chiba, Japan


## Search for Extremely High Energy Neutrino

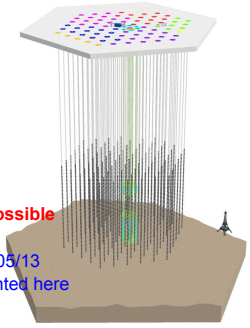
- ✓ Extremely high energy (EHE) neutrinos (>$10^7$ GeV) generated from EHE cosmic rays (EHECRs)
- ✓ Can shed light on the origin of EHECRs
- ✓ The expected EHE neutrino rate is low: 1 event / year / km$^3$
- ✓ Major background is atmospheric muons

## The IceCube Detector

- ✓ Deployed in the Antarctica glacier
- ✓ In-ice + IceTop + DeepCore
- ✓ 86 strings (completed at the end of 2010!)
- ✓ ~ 5,000 Digital Optical Modules (DOM)
- ✓ Detector volume: ~ 1 km$^3$

**→ make the EHE cosmogenic neutrino search possible**

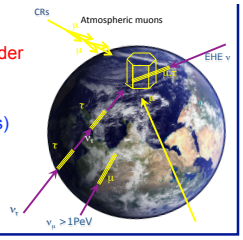
The results based on data taken in 2010/5/31-2011/05/13 (319.2 days) with 79 strings configuration are presented here



## Search Principle

The zenith angle and energy information is used in order to separate neutrino signals from backgrounds

- ✓ EHE cosmogenic neutrino (GZK) signal (all flavor)
  - ✓ horizontal (The earth is opaque for HE neutrinos)
  - ✓ high energy (> $10^7$ GeV)
- ✓ Atmospheric muon background
  - ✓ down-going
  - ✓ low energy (the energy spectrum is steep (E$^{-3}$))

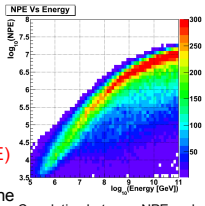



## Energy estimator

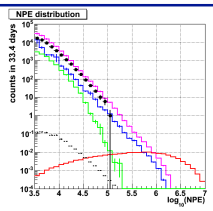
The integral number of photo-electrons (NPE) observed by each optical module for an event is used as the energy estimator in this analysis.

- ✓ Correlated with energy
- ✓ Robust (low energy event can not produce high NPE)

The NPE distributions are shown at right. As seen from the plot, the GZK signals have high NPE value compared to the background.




Correlation between NPE and energy for muons derived from neutrinos. The energy is estimated at a point 880 m from the detector center.




NPE distributions (Number of DOM (NDOM) > 300). Black: one tenth of observation test data, magenta and blue: atmospheric muon MC (pure iron and proton respectively), green: atmospheric coincident muon MC, dashed black: atmospheric neutrino MC (Bartol (2004)) and red: GZK signal MC (S. Yoshida et al. [1])

## Zenith Angle Reconstruction

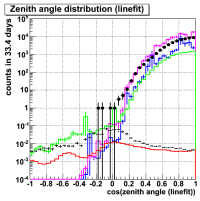
The zenith angle of events can be used to separate signal from background.

First, a first guess chi-square fit assuming a plane wave propagation was applied.

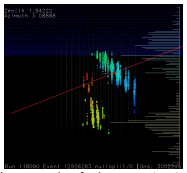
As seen in a right plot, several events are mis-reconstructed as up-going. Two categories of mis-reconstruction were found.

- ✓ Coincident events
- ✓ Corner clipping events

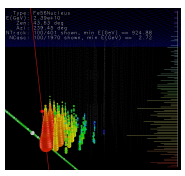
In order to reconstruct / remove those events, several method were developed and performed.




Zenith angle distributions (Number of DOM (NDOM) > 300). A simple algorithm of linefit is used. The color definitions are same as above.



An example of mis-reconstructed event due to a coincident event (obs. data)



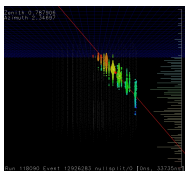
An example of mis-reconstructed event due to a corner clipping event (atmospheric muon MC)

- ✓ Isolated DOM cleaning
- ✓ Maximum log-likelihood reconstruction based on a track hypothesis (SPE with 12 iterations (SPE12))
- ✓ Quality of reduced log-likelihood value of SPE12

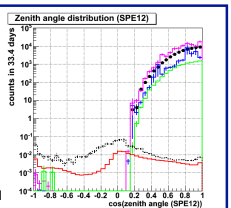
The isolated DOM cleaning removes DOMs that do not have additional hits within a certain radius (150m) and time range (1 μs). This cleaning is useful to keep the larger event in a coincident event.

The maximum log-likelihood based reconstruction uses the arrival time of the first photon in a DOM. SPE12 was found to reconstruct the corner clipping events more accurately.

Finally, the reduced log-likelihood value is used to remove vast numbers of coincident events that have reconstructed poorly.



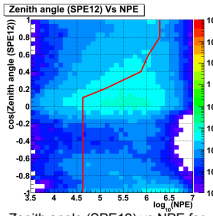
An example of the Isolated DOM cleaning to a coincident event (Same event as shown below left)



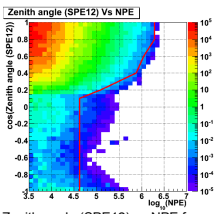

Zenith angle distributions (SPE12) after applying coincidence event cleaning methods. The color definition is same as before.

## Optimization

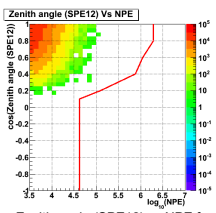
After cleaning mis-reconstructed events, the final optimization was performed by using only MC sets. The model detection potential (MDP) method [2] was used requiring a 4 sigma significance. Five vertices were used to determine the connected final selection criteria. The vertices were moved around and for each combination of vertices the MDP value was calculated. The final selection criteria are shown in following plots.




Zenith angle (SPE12) vs NPE for GZK signal (S. Yoshida et al. [1])



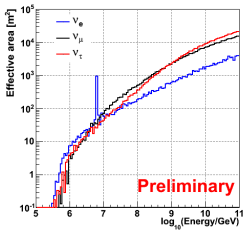

Zenith angle (SPE12) vs NPE for backgrounds (atmospheric muons (pure iron) + atmospheric coincident muons + atmospheric neutrinos (Bartol (2004))

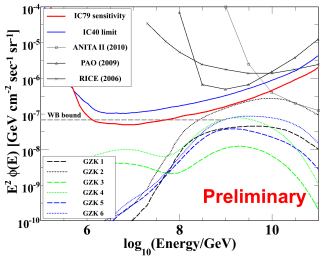



Zenith angle (SPE12) vs NPE for one tenth of observation test data

## Results and Outlook

The effective area and the sensitivity with the final selection criteria are shown below.




GZK1 and 2: S. Yoshida et al. (1997) [1], m=4, $Z_{max}$=4, γ=2, $E_{max}$=10 ZeV and m=4, Zmax=5, γ=1.5, $E_{max}$=10 ZeV, GZK3 and GZK4: Kotera et al. (2010), SFRI and FRII with γ=2.5, $E_{max}$=316 EeV, GZK 5 and 6: M. Ahlers et al. (2010), $E_{min}$=10 EeV, $E_{max}$=1 ZeV best fit with Fermi, m=4.6, $Z_{max}$=2, γ=2.5 and m=4.4, $Z_{max}$=2, γ=2.1

The expected event rate for each model is listed in a right table.

After the final selection criteria were optimized, the full data of year 2010-2011 was searched. There found **no event** above the selection criteria. However, a similar analysis conducted on data taken in 2011-2012 with the complete IceCube detector configuration **found two events** that passed all the selection. We are intensively investigating the two events. **A talk for the analysis is scheduled today afternoon in session 19**.

The largest systematic uncertainty in this analysis comes from the NPE difference between MC and data seen in dedicated calibration measurements with bright laser lights. The difference ((data-MC)/data) is -43.4% and the GZK event rate for GZK1 drops by -17.5%. We are also working to reduce this systematic uncertainties.

**The IceCube detector is capable of detecting EHE cosmogenic neutrinos and most of GZK models will be tested within a few years.**

| model | Event rate (/319.2 days) |
|---|---|
| GZK1 | 0.978 ± 0.005 |
| GZK2 | 3.94 ± 0.02 |
| GZK3 | 0.581 ± 0.037 |
| GZK4 | 2.23 ± 0.09 |
| GZK5 | 0.750 ± 0.005 |
| GZK6 | 1.49 ± 0.01 |
| prompt ν 1 | 0.257 ± 0.002 |
| prompt ν 2 | 0.0954 ± 0.0006 |
| Conv. ν (Bartol) | 0.0382 ± 0.0015 |
| Atmo. μ (iron) | 0.0331 ± 0.0025 |
| Atmo. μ (proton) | 0.00677 ± 0.00129 |
| Atmo. Coin. | 0 ± 0 |
| BG total | 0.0713 ± 0.0029 |

prompt ν1: Enberg et al. (2008), prompt ν2: Martin et al. (2003) MRS

## References


[1] S. Yoshida et al., ApJ, **479**, 547-559, (1997).

[2] G.C. Hill et al., in the Proceedings of PHYSTAT2005, Oxford, England, 2005 (Imperial College Press, London (2006), pp 108–111.