PINGU (Precision IceCube Next Generation Upgrade)

The IceCube and PINGU Collaborations

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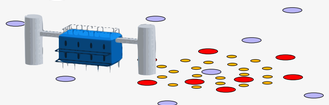
Introduction



IceCube: is the largest neutrino telescope in the world and it is based at the South Pole. It is optimized for the detection of neutrinos of different flavors with energies in the rage between 10 GeV up to the PeV, or even EeV scale.
DeepCore: a dedicated set of strings has been deployed in the center-bottom part of the detector obtaining a nested array for low energy neutrinos in the region 10 GeV up to circa 200 GeV.

PINGU: a further extension of IceCube for the energy region between few GeV to 50 GeV is here motivated. The primary physics goal of PINGU is the study of the **neutrino mass hierarchy**. For this challenging goal, an improvement in energy resolution and a reduction of systematic uncertainties are mandatory. The road map to precise atmospheric neutrino studies with PINGU is discussed here.

From IceCube to DeepCore

The IceCube Neutrino Observatory includes a compact inner array in the deepest ice, called DeepCore. DeepCore provides access to low-energy neutrinos with a sizable surrounding cosmic ray muon veto.
Principle science goals: dark matter indirect searches, atmospheric neutrino studies in the energy region [10 GeV - 500 GeV].

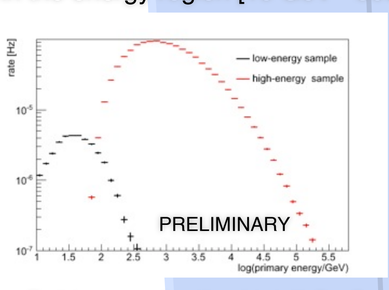


Fig. 1: true energy of neutrinos detected in DeepCore (low-energy, black) and in IceCube (high-energy, red).

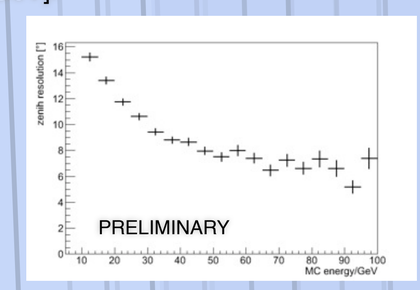


Fig. 2: zenith resolution vs true energy of atmospheric neutrinos collected in DeepCore.

see also A. Gross for IceCube, this conference; "Particle Physics in Ice with IceCube DeepCore", *T. DeYoung (IceCube)*, arXiv:1112.1053, 2011. 3rd RICAP.

From DeepCore to PINGU

Principle science goal: measurement of the **neutrino mass hierarchy asymmetry.**
PINGU can exploit parametric resonances of earth-crossing atmospheric neutrinos to gain enhanced sensitivity to the hierarchy. Here the **N**ormal - **I**nverted hierarchy asymmetry as defined in [E. Kh. Akhmedov, S. Razzaque, A. Y. Smirnov in preparation]

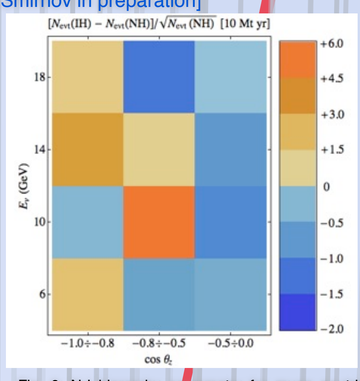


Fig. 6: N-I hierarchy asymmetry for muon neutrino induced events in PINGU, 1 year. The binning chosen considers possible experimental resolutions.

No. track-like events, PINGU-20, 1 year, IH

No. track-like events, PINGU-20, 1 year, NH

$$A^{N-I}_{\mu,ij} \equiv \frac{N^{IH}_{\mu,ij} - N^{NH}_{\mu,ij}}{\sqrt{N^{NH}_{\mu,ij}}}.$$

Experimental resolution of the energy and direction have to be taken into account in order to estimate a possible sensitivity.
Here considered:
- Energy res., range: 4 GeV, [2-20 GeV]
- Angular accuracy: ~0.3 in cos(zenith)

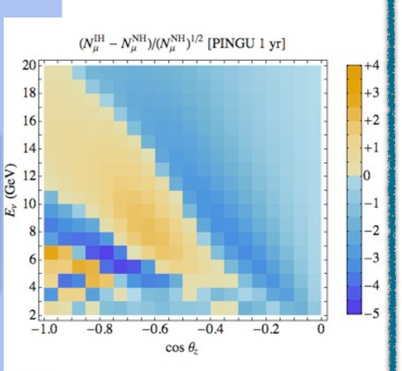


Fig. 7: N-I hierarchy asymmetry for muon neutrino induced events in PINGU, 1 year. The binning chosen is very fine for illustration purposes.

Atmospheric Neutrinos: ~100 GeV
atmospheric neutrino-induced CASCADES

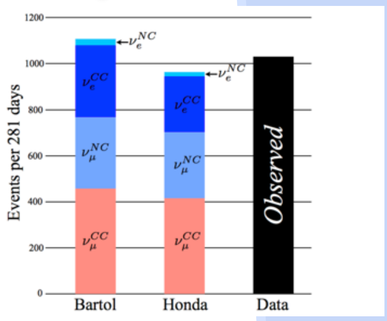


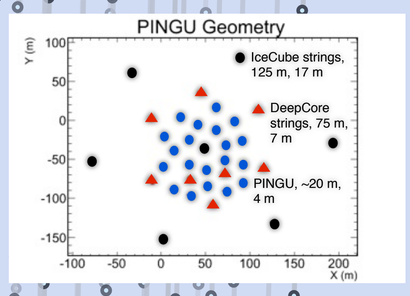
Fig 3: expected contributions of muon and electron neutrino interactions with two atmospheric flux models (Bartol [1] and Honda [2]) and the observed data rate. No systematic errors are included here.

Charged-current electron, tau neutrino as well as neutral-current of neutrino interactions create spherically-symmetric light distributions in ice, also called cascade-like events. The primary background for the identification of cascade-like events is produced by stochastic energy losses of atmospheric muons. Via a **veto** strategy cosmic ray muon background is reduced by about 10^8. Here, the observation of atmospheric neutrino-induced cascade events in IceCube is obtained on events detected in DeepCore. The **mean cascade energy of electron neutrinos is 180 GeV**.

see also "The First Year IceCube-DeepCore Results", *Chang Hyon Ha (IceCube)* arXiv:1201.0801, 2012. TAUP 2011.
[1] G. D. Barr et al., Phys. Rev. D70, 023006 (2004)
[2] M. Honda et al., Phys. Rev. D75, 043006 (2007)

PINGU: Geometry and Effective volume

We have simulated a total of 20 additional strings to be deployed inside DeepCore. The DOM-to-DOM spacing is 4 m. Each DOM is equipped with a high quantum efficiency PMT.



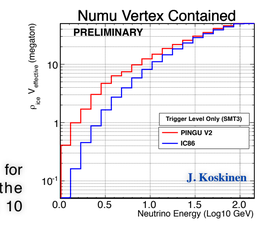


Fig. 8: effective volume for PINGU. At 10 GeV, the effective volume is about 10 Megaton.

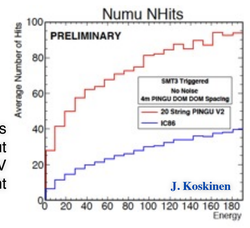


Fig. 9: number of hits collected with and without PINGU. For a 20 GeV neutrino, a factor 4 more light is collected with PINGU-20.

Atmospheric Neutrinos: ~10-50 GeV
standard neutrino oscillation

see A. Gross for IceCube, this conference

IceCube, during the year 2010-2011, has collected data in 79-strings configuration. The atmospheric neutrinos extracted from the data collected have been recently analyzed for the search of standard neutrino oscillation.

Two streams have been used, a low-energy one composed by data collected by DeepCore, and a high-energy one from IceCube. The use of the two streams allow the mitigation of the correlated systematic uncertainties. Atmospheric neutrino oscillation is clearly visible in the low-energy data stream.

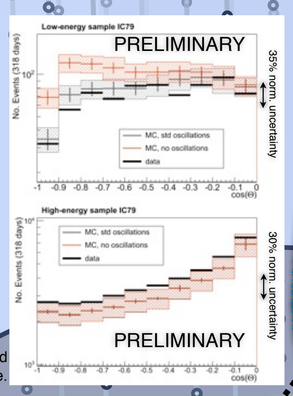


Fig 4, 5: zenith distribution of the low-energy and high-energy neutrinos collected in IceCube.

PINGU: Anticipated requirements

Performances required for PINGU in order to access precision measurements like the neutrino mass hierarchy:

- Effective volume: ~ Megaton (at few GeV) ✓
- Neutrino energy region: [few - 50 GeV] ✓

To be demonstrated in on-going feasibility studies:
- Neutrino energy resolution: ~ 5 GeV (under study)
- Neutrino zenith resolution: < 20° (under study)
- Neutrino flavor identification: electron/tau vs muon (under study)
- Non correlated systematic uncertainties: < 10% (under study)

Calibration Program:

The deep ice will be sampled by PINGU at much shorter distances respect the one sampled by IceCube. For this reason, dedicated calibration devices are under design in order to improve the measurement of the ice properties and the Digital Optical Module sensitivity, the two primary systematic uncertainties of IceCube.

- LED flashers will be deployed with every DOM. Under study are the width(s) and rise times of the LED and how well the brightness and orientation need to be known.

- Optical camera equipped with laser to monitor the refreezing process of the hole.

Systematic Uncertainties

Systematic uncertainties affects the precision of the measurement performed by IceCube and DeepCore. We distinguish between theoretical and experimental systematic uncertainties.

- Theoretical uncertainties: cosmic ray normalization (25%), cosmic ray index (3-7%); atmospheric neutrino flux model (4-8%), neutrino cross section extrapolation (3%)
- Experimental uncertainties: ice model (5-20%), DOM sensitivity (5-15%)

Various of these systematic effects are **strongly correlated** among different energy regions. Hence, their direct effect on final measurements can be mitigated via analysis.

Acknowledgments

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