# Super-PINGU for Leptonic CP Phase using Atmospheric Neutrino Flux

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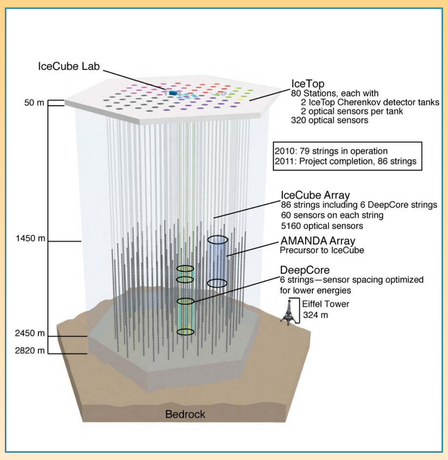
## Motivation

A large underground/under-ice detector (few Mt effective volume with 0.5-1.0 GeV neutrino energy threshold) can measure leptonic CP phase using atmospheric neutrino fluxes. This can also be used to search for proton decay.

Currently proposed PINGU detector within the IceCube DeepCore array can be further instrumented with more strings and phototubes in near future to achieve this goal. This upgraded detector is referred to as super-PINGU here.

$$\rho V_{\rm eff}(E_\nu) = 2.6\,[\log(E_\nu/{\rm GeV}) + 1]^{1.32}\ {\rm Mt},$$

- **Super-PINGU:** 1.6 Mt at 0.5 GeV and 2.6 Mt at 1 GeV
- **PINGU:** 1.0 Mt at 1.5 GeV and 1.9 Mt at 3 GeV




**IceCube Neutrino Observatory**

## Methodology

Calculate oscillation probabilities $P_{\alpha\beta}$ along different trajectories with angle $\theta_z$ to the detector using the PREM density profile of the Earth and $\nu$ mixing parameters for different CP phase $\delta$=0, $2\pi$

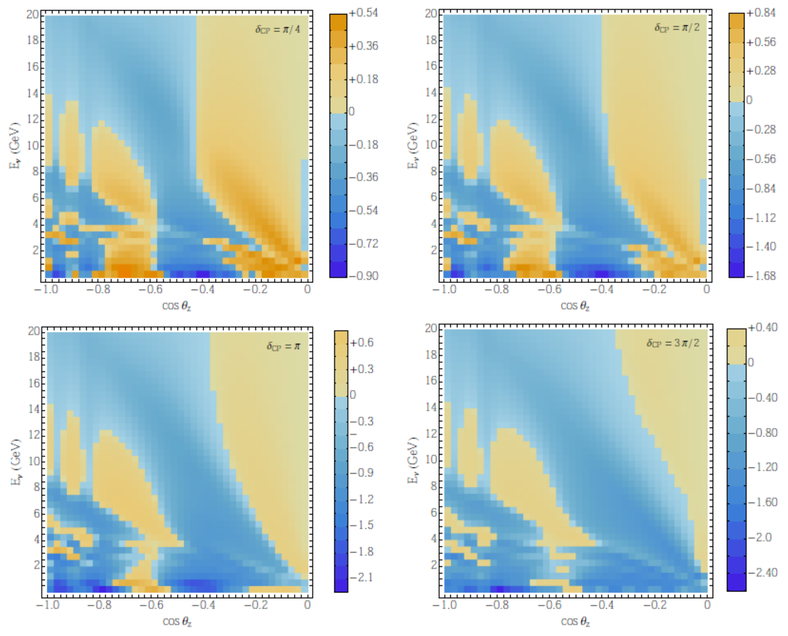
Calculate nm track events and ne cascade events in the detector using the probabilities, atmospheric n flux models and super-PINGU effective volume.

Define a measure of the distinguishability between two CP phase values from neutrino events in the $E_\nu - \cos\theta_z$ plane. The total distinguishability can be interpreted as statistical significance.

$$S_{ij} = \frac{N^\delta_{ij} - N^0_{ij}}{\sigma_{ij}},$$

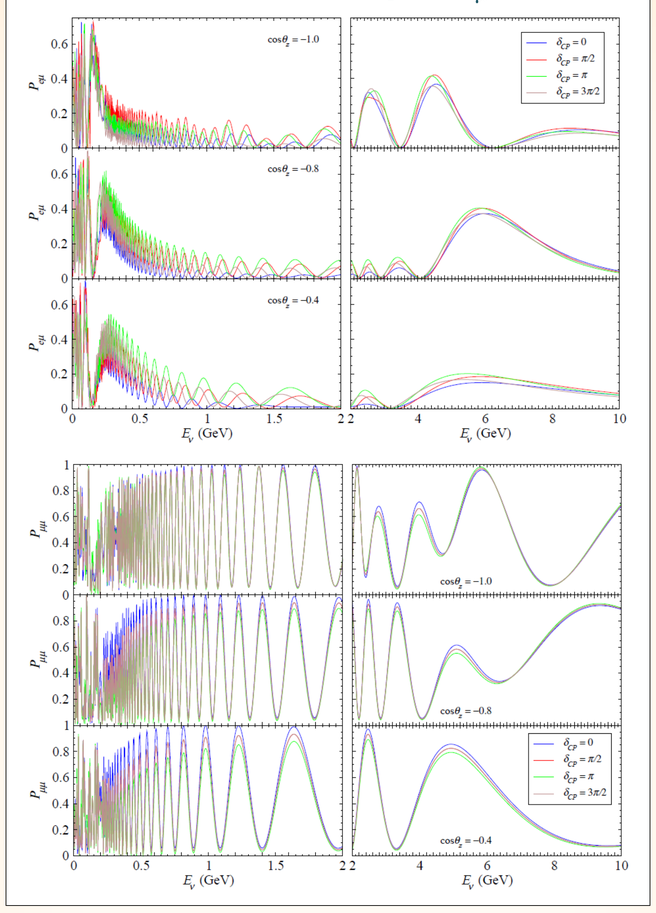
$$S^{tot} = \sqrt{\sum_{ij} S^2_{ij}} = \sqrt{\sum_{ij} \frac{(N^\delta_{ij} - N^0_{ij})^2}{\sigma^2_{ij}}},$$

## Distinguishability of $\nu_\mu$ Track Events with 1 yr Data




Distributions using true neutrino energy and directions

## Probabilities for $\nu_e$ and $\nu_\mu$




A systematic upward shift of probabilities with increasing CP phase from 0 at low energies (<2 GeV) is crucial to its measurement. Requires large effective volume at low energies

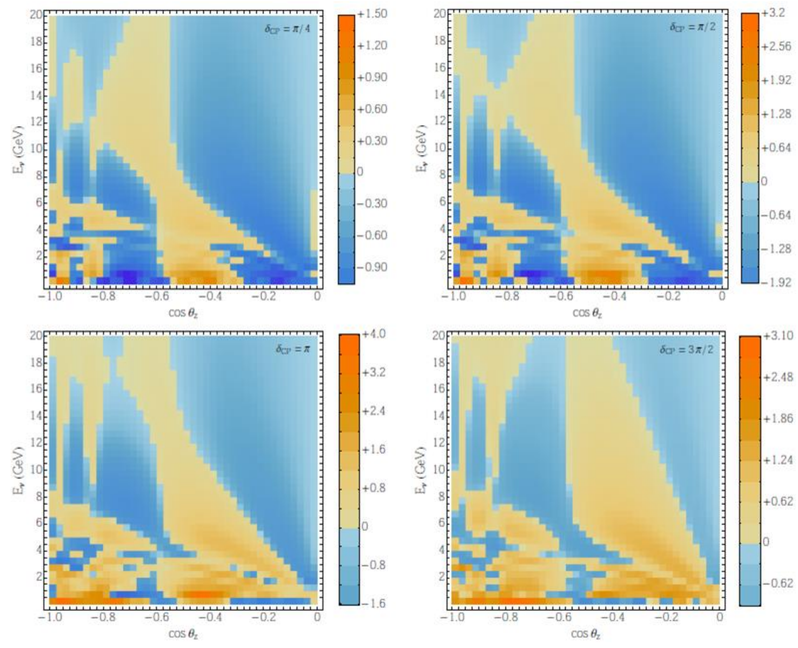
Both $\nu_\mu$ and $\nu_e$ carry CP information. Important to measure and distinguish both muon track events and electron cascade events

Information on neutrino mass hierarchy is separated from CP in the energy and angular plane. PINGU will measure mass hierarchy before CP phase measurement is possible.

The domain structure of the event distributions in the $E_\nu - \cos\theta_z$ plane is largely described by the solar, atmospheric and interference magic lines

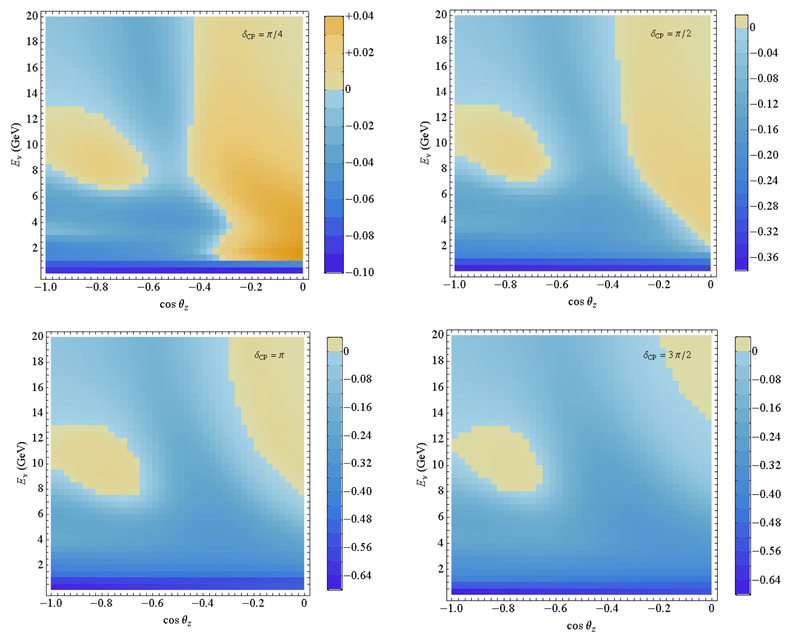
Reconstructed neutrino energy and direction are calculated after smearing the true energy and direction with Gaussian functions of widths $\sigma_E = 0.2E$ and $\sigma_\theta = 0.4(m_p/E_\nu)^{0.5}$

## Distinguishability of $\nu_e$ Cascade Events with 1 yr Data



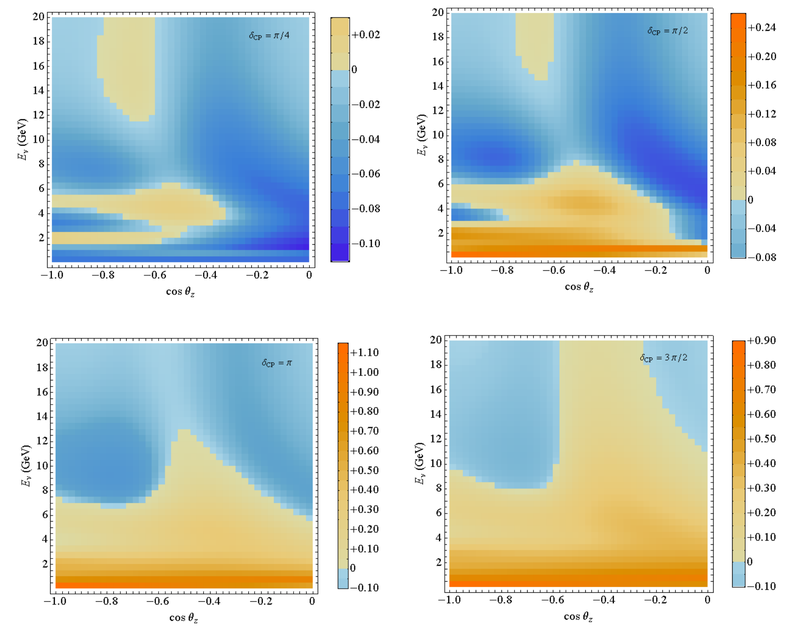

Distributions using true neutrino energy and directions

## Distinguishability after Smearing of $\nu_\mu$ Track Events




Distributions using reconstructed neutrino energy and directions

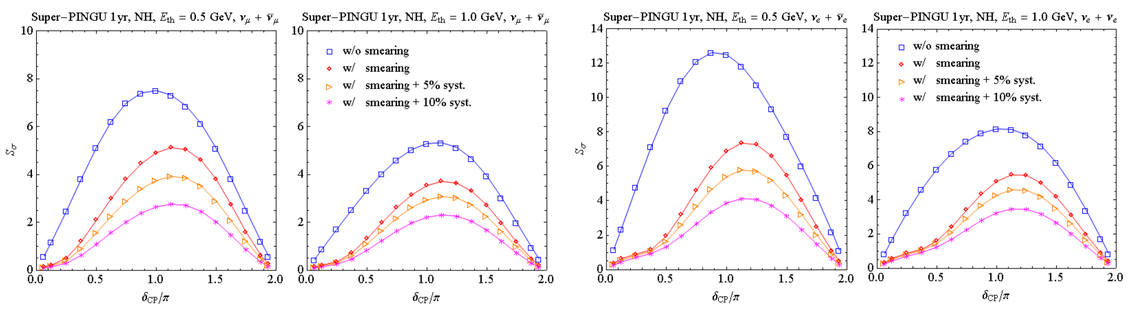
## Distinguishability after Smearing of $\nu_e$ Cascade Events




Distributions using reconstructed neutrino energy and directions

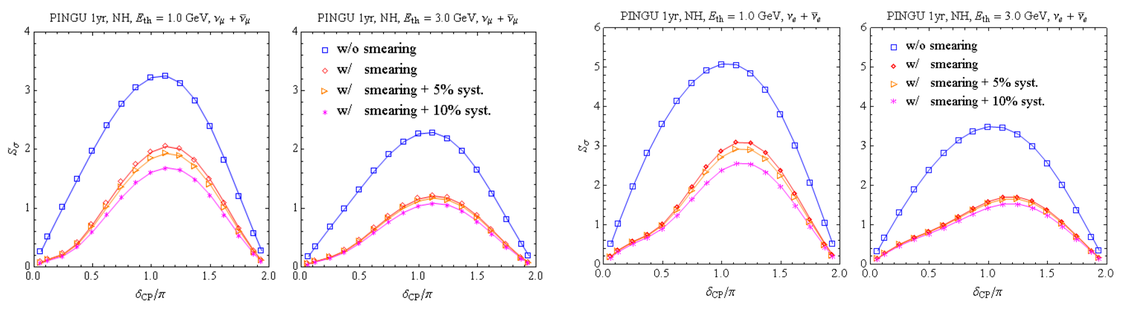
## CP Measurement Prospects

### Total Distinguishability of $\nu_\mu$ Track and $\nu_e$ Cascade Events – super-PINGU




Super-PINGU with 5% systematics can discriminate between CP phase 0 and $\pi$ with 9$\sigma$ in 4 years
Can measure CP phase with $\pm\pi/4$ accuracy in 4-6 years

### Total Distinguishability of $\nu_\mu$ Track and $\nu_e$ Cascade Events – PINGU




Sensitivity of PINGU to CP is marginal because of a higher threshold and smaller volume
Statistical separation of muon neutrinos and antineutrinos can help

References: S. Razzaque and A. Yu. Smirnov, arXiv:
E. Kh. Akhmedov, S. Razzaque and A. Yu. Smirnov, arXiv:1205.7071
M. G. Aartsen et al. [IceCube-PINGU Collaboration], arXiv: 1401.2046

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