Atmospheric neutrino oscillations with PINGU

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Abstract. Measurements of atmospheric, solar, reactor and accelerator neutrinos (see e.g. [1, 2, 3, 4]) have shown that neutrinos undergo flavour-changing oscillations and hence have mass. The cubic-kilometre neutrino detector IceCube [5] with its more densely instrumented inner region DeepCore [6] has studied oscillations of atmospheric neutrinos at energies above $\sim 10$ GeV [7, 8, 9]. The Precision IceCube Next Generation Upgrade (PINGU) [10] is a proposed extension of IceCube with the goal to perform precise measurements of atmospheric neutrino oscillations down to a few GeV and to determine the neutrino mass hierarchy (NMH).

1. Introduction

Neutrino oscillations can only exist if neutrinos have mass, and the probability to change flavour depends on the squared mass difference and the mixing angles. The ordering of the neutrino masses is however not fully resolved yet as the sign of $\Delta m^2_{\text{atm}}$ is still unknown. The third neutrino mass eigenstate may thus either be the heaviest (normal mass hierarchy) or the lightest (inverted mass hierarchy). The determination of the mass hierarchy will constitute a large step towards the full knowledge of the PMNS neutrino mixing matrix and its potentially non-zero CP-violating phase. It is also an important input for the interpretation of $0\nu$2$\beta$-decay experiments.

2. The IceCube detector

IceCube [5] is a cubic-kilometre neutrino detector at the South Pole, consisting of 5160 optical light sensors at depths between $\sim 1.5$ and $\sim 2.5$ km below the surface which detect the light generated by charged particles produced in $\nu$ CC and NC interactions. The majority of the optical modules are deployed with a vertical spacing of 17 m and a horizontal spacing of 125 m. To increase the sensitivity in the energy range from $\sim 10$ GeV to $\sim 100$ TeV, a region of denser instrumentation called DeepCore [6] is located in the lower part of the detector center.

Among other detection channels, IceCube and DeepCore record atmospheric $\nu_\mu$ CC interactions at neutrino energies $E$ between $\sim 10$ GeV and $\sim 100$ TeV. Outgoing muon tracks with lengths of $O(50m)$ and more allow to distinguish these events from other interactions, and facilitate the reconstruction of the neutrino direction and thus the propagation length $L$. Thanks to the large field-of-view and energy range of IceCube, a large range of values of $L/E$ can be probed. Muon neutrino disappearance has been observed in energy and energy vs zenith distributions using data from the complete and almost complete IceCube detector [7, 8, 9].

1 http://icecube.wisc.edu/collaboration/authors/pingu
Figure 1. Illustration of impact of the neutrino mass hierarchy on the distribution of track-like (left) and cascade-like (right) events in PINGU, for 1 year of data with 2400 PINGU optical modules. The figures include the effects of reconstruction and particle classification. From [10].

3. PINGU as an extension of IceCube
PINGU is a proposed extension of the IceCube detector. The installation of additional optical modules in the deep center of IceCube with vertical spacing of $O(5m)$ and horizontal spacing of $O(20m)$ will lower the energy threshold to a few GeV. The location inside IceCube will allow to use the existing array as an active veto against the $\sim 6$ orders of magnitude larger background of down-going atmospheric muons. Methods to efficiently reject muon events based on the light detected in the outer parts of the detector exist and achieve a background rejection of $10^7$ [11].

The new sensors can be deployed within a very short time frame of 2-3 years; for IceCube up to 1200 optical modules were installed at 20 different horizontal positions in a single Antarctic summer. The full integration of PINGU into IceCube’s on-line and off-line software systems implies minimal cost for software development, a seamless combination of the data and a fast turnaround in the analysis of the data. The design studies for PINGU use the simulation framework of IceCube and are thus able to fully include the optical properties of the ice, the data acquisition, the topology of the expected events and the most important systematic uncertainties.

PINGU may also provide a positive feedback to IceCube. The design and analysis of data from DeepCore have for example resulted in advanced noise cleaning algorithms [12] and extensions of the simulation. The first evaluation of an atmospheric neutrino veto [14], a result that is now also used at very high energies [13], was inspired by DeepCore. PINGU will also provide the opportunity to install new calibration devices in the center of IceCube.

4. PINGU and the neutrino mass hierarchy
As atmospheric neutrinos travel through the Earth, their oscillation patterns are changed by matter effects which depend on the NMH. The Mikhaev-Smirnov-Wolfenstein effect [15, 16] and parametric resonances [17] at the core-mantle boundary enhance the $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) probability at certain $L/E$ in the normal (inverted) hierarchy. PINGU will measure the sum of $\nu$ and $\bar{\nu}$ interactions as a function of zenith angle and energy distinguishing between events with and without evidence of a track (track-like vs cascade-like). Due to differences in the atmospheric flux and the cross-sections of $\nu$ and $\bar{\nu}$, there will be an imprint of the NMH in the distribution of the detected events. Figure 1 (from [10]) shows the difference in the expected number of events under the normal ($N_{NH}$) and inverted hierarchy ($N_{IH}$) after one year, normalized to $\sqrt{N_{NH}}$. 2400 additional optical modules at 40 horizontal positions with a vertical spacing of 5 m were simulated. A reconstruction of arrival direction, energy and vertex position was applied and the vertex was required to be within or below the instrumented volume of PINGU. A parametrization of PINGU’s expected capability to distinguish track- and cascade-like events was used. The left plot shows track-like events (mostly $\nu_\mu$ and $\bar{\nu}_\mu$ CC events) while the right plot shows cascade-like events.
events. The NMH leaves a clear imprint in these distributions.

Figure 2 (from [10]) shows for the same detector configuration and event selection the estimated median significance for the rejection of the normal hierarchy as a function of time, assuming that the inverted hierarchy is realized in nature and that $\Theta_{23}$ is in the first octant. A full analysis of the PINGU data will be a likelihood analysis of the two-dimensional event pattern including systematic uncertainties as nuisance parameters. The sensitivity shown here has been obtained with a faster approach based on the Fisher matrix [18]. It has been shown that this approach yields similar although slightly lower sensitivities than the full likelihood analysis [10]. The estimated significance takes an energy scale uncertainty and an energy-dependent uncertainty of the effective area into account. Also a 15% uncertainty on the $\nu/\bar{\nu}$ cross-sections and uncertainties on the oscillation parameters $\Delta m_{31}^2$, $\Theta_{31}$ and $\Theta_{23}$ are included.

PINGU’s configuration can be optimized for the measurement of the NMH. Advanced particle identification and reconstruction methods may in the future further improve the sensitivity, as well as improved measurements of the neutrino cross-sections and oscillation parameters. Beyond the NMH measurement, PINGU will also measure the atmospheric oscillation parameters at high precision and improve IceCube’s sensitivity to dark matter and supernovae [10].

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