ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Neutrino Mass Hierarchy Studies with ORCA

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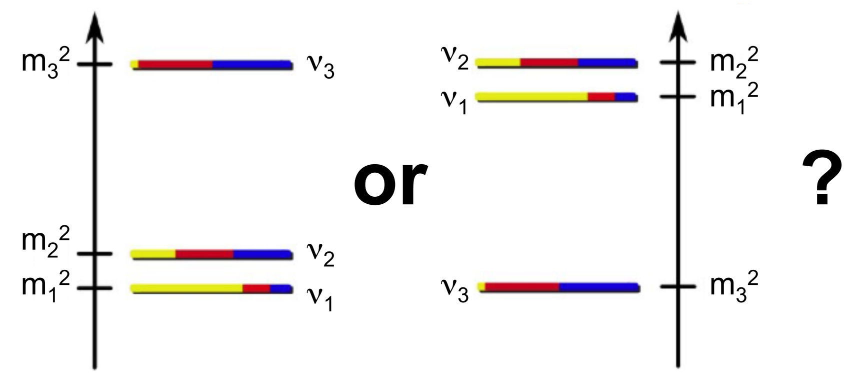
Abstract

ORCA (Oscillation Research with Cosmics in the Abyss) is a possible future megaton-scale water Cherenkov neutrino detector in the Mediterranean Sea. The idea is to use KM3NeT [1] technology to install a dense array of optical modules, each containing 31 photomultiplier tubes (PMT).
Recent studies [2] indicate that with such a detector the neutrino mass hierarchy might be determined by precisely measuring the energy and zenith angle of upgoing atmospheric neutrinos in the energy range of 1–20 GeV. The determination of the neutrino mass hierarchy, i.e. normal or inverted, is based on differences (due to the MSW effect and other effects) in the energy and zenith-angle dependence of the oscillation probabilities of neutrinos and antineutrinos traversing the Earth.

Motivation

The neutrino mass hierarchy is:

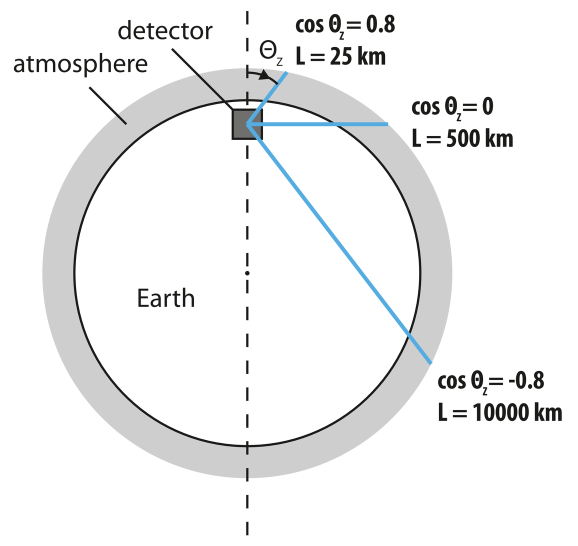
- a fundamental parameter of nature
- essential to interpret the results of other experiments (e.g. neutrino beam experiments)



http://commons.wikimedia.org/wiki/File:NeutrinoHierarchy.svg

Principle of Measurement

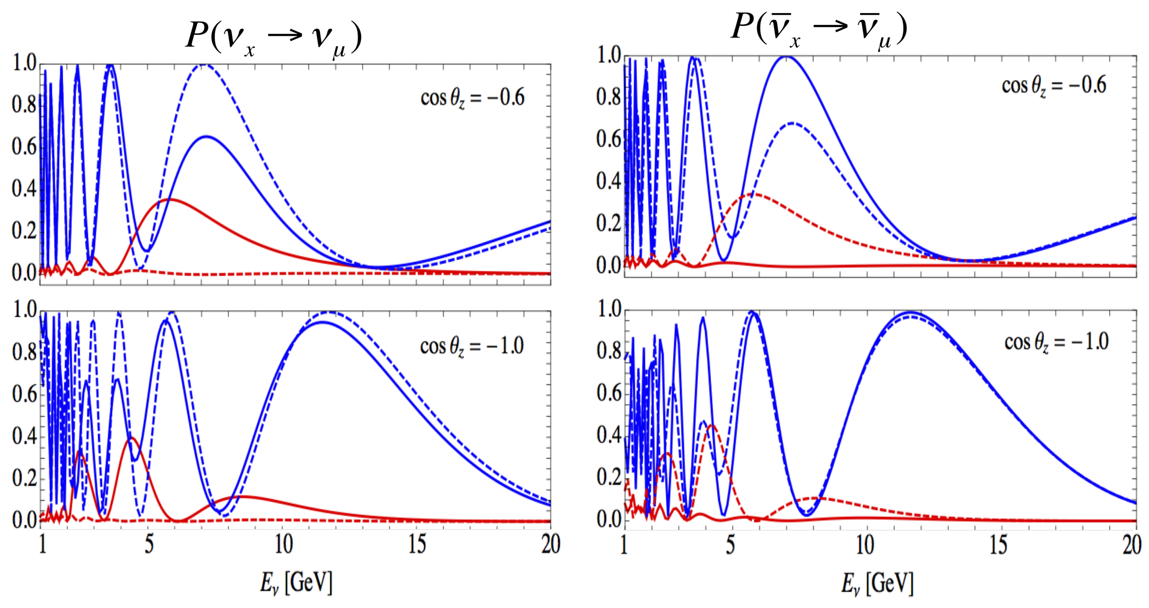
Oscillation probabilities of atmospheric neutrinos propagating through the Earth are modified due to matter effects (MSW effect, parametric enhancement). Thus, the oscillation probabilities are different for normal hierarchy (NH) and inverted hierarchy (IH). However, the oscillation probabilities for neutrinos under the normal hierarchy are very similar to that for antineutrinos for the inverted hierarchy, and vice versa.
In an experiment with nearly the same number of incident neutrinos and antineutrinos, as is the case for the atmospheric neutrino flux, this ambiguity is broken by the different cross-sections for neutrinos and antineutrinos.



Oscillation Probabilities depend on:

- neutrino oscillation parameters
- neutrino energy E_ν
- zenith angle θ_Z determining the trajectory through the Earth
- model of the Earth density profile [3]

Strongest modifications for E_ν = ~(4 - 8) GeV due to MSW resonance in the Earth mantle.



Probabilities of oscillation of neutrino (ν_e in blue and ν_μ in red) to ν_μ vs. E_ν for two different zenith angles θ_Z. The solid and dashed lines are for NH and IH, respectively. Left panel is for neutrinos and right panel is for antineutrinos. Taken from [2].

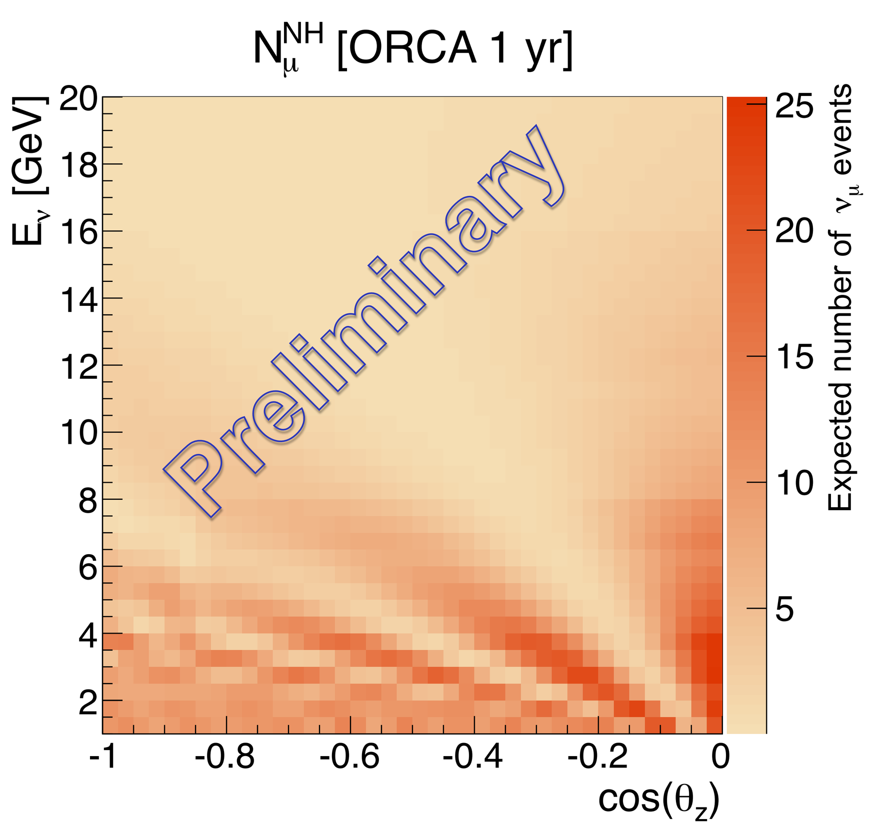
Expected Signal in the ORCA Detector

Input:

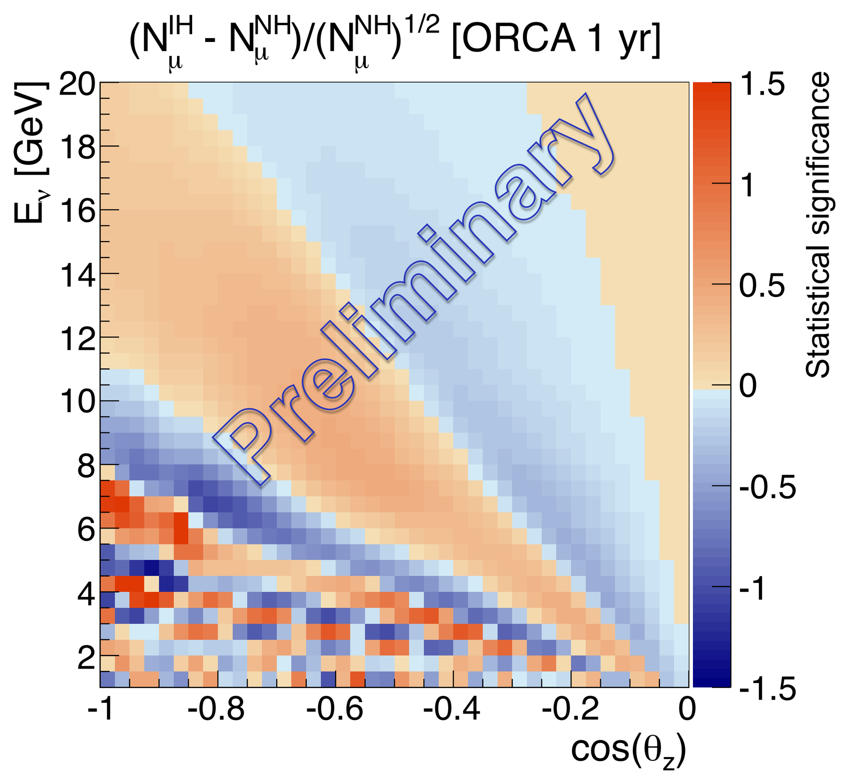
- oscillation probabilities (see above)
- model of the Earth density profile [3]
- atmospheric neutrino flux [4]
- neutrino-nucleon cross sections [5]
- detector acceptance and reconstruction efficiencies

Output:

- Expected number of detected neutrino events in E_ν and θ_Z for both hierarchies (below: for muon (anti-)neutrino events, NH and 1 year exposure time)



(for both plots: minimum 10 hits from a muon track fully contained in the instrumented volume are required and no smearing in neutrino energy and angular resolution is applied)

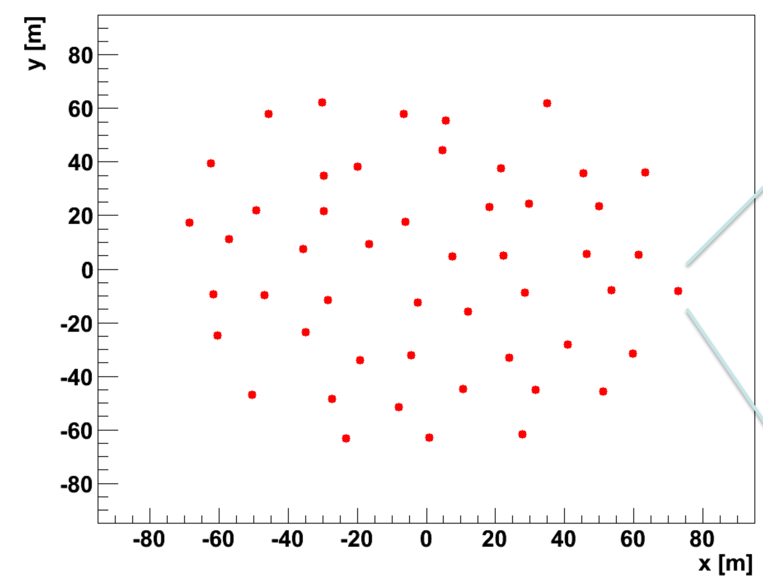


The asymmetry (above) in the expected number of events for NH and IH determines the statistical significance for rejecting one hierarchy hypothesis.
The significance is reduced by the resolution of neutrino energy and direction reconstruction. Therefore, development and optimisation of reconstruction methods is essential.

Possible Detector Configuration

Starting point for detector optimisation:

- use of KM3NeT technology to install a dense array of optical modules
- instrumented volume ca. 1.75 Mt
- Optical modules (OM) placed along vertical strings, 6 m apart with 20 OMs per string, total height 114 m (right)
- 50 strings spaced ca. 20 m apart from each other with irregular footprint (below)



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- multi-PMT OM with 31 3-inch PMTs (below) advantages of multi-PMT layout:
  - increase of photo-cathode area density
  - superior photo-electron counting
  - increased angular acceptance
  - increased directional sensitivity

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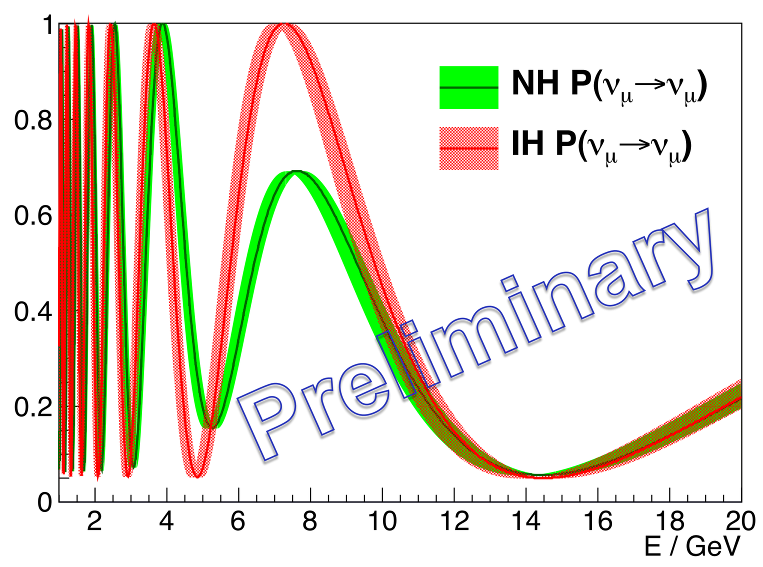
Activities at ECAP

Investigation of uncertainties of neutrino oscillation probabilities due to**:**

- uncertainties of the oscillation parameters
- uncertainties of the Earth density profile



Muon neutrino survival probability as function of the neutrino energy for NH in green and IH in red (for $\cos(\theta_Z) = 0$). The error bands indicate the 1σ uncertainty due to the present knowledge [6] of the large mass splitting Δm_{13}^2.

Reconstruction method development for muon neutrino events:

- adaption of km3net MC simulations to ORCA scientific goals
- muon identification and reconstruction (energy and direction)
- reconstruction of hadronic showers

Evaluation of expected significance:

- influence of uncertainties of atmospheric muon flux and neutrino-nucleon cross sections
- effect of reconstruction efficiencies and resolutions

Hardware development:

- initiate and support the multi-PMT OM development
- measurement of PMT characteristics
- operation understanding and calibration

References

[1] www.km3net.org
[2] E. Akhmedov, S. Razzaque and A. Smirnov, arXiv:1205.7071 [hep-ph]
[3] A. M. Dziewonski and D. L. Anderson, Phys. Earth Planet. Interiors 25 (1981) 297
[4] M. Honda et al., Phys. Rev. D 83, 123001 (2011)
[5] J. A. Formaggio and G. P. Zeller, Rev. Mod. Phys. 84, 1307 (2012)
[6] G. L. Fogli et al., arXiv:1205.5254 [hep-ph]