

ORCA (Oscillation Research with Cosmics in the Abyss): a feasibility study of measuring the neutrino mass hierarchy with an underwater Cherenkov detector within the KM3NeT framework

Jannik Hofestädt (ECAP & University Erlangen-Nürnberg) on behalf of the **KM3NeT Collaboration**



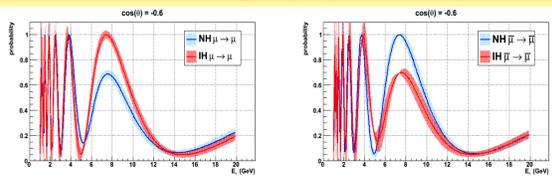
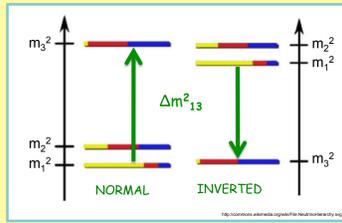
Measuring the neutrino mass hierarchy with atmospheric neutrinos

The values of all neutrino oscillation parameters can be extracted from global fits of now available data with a precision better than 15%. The largest uncertainty remains on θ_{23} and its octant. The relatively large value of θ_{13} (which drives the $\nu_e \leftrightarrow \nu_\mu$ oscillation) is beneficial for the determination of the remaining unknown neutrino parameters: the value of the CP-violating phase δ_{CP} and the **neutrino mass hierarchy** (NMH: normal or inverted, see right plot).

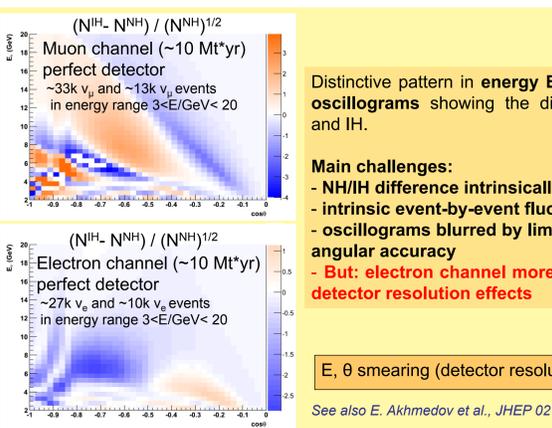
Standard strategy for NMH determination: probe $\nu_e \leftrightarrow \nu_\mu$ oscillation in presence of matter effects which allows to resolve the sign of Δm^2_{13} :

The oscillation enhancement is maximal at the resonant energy:

$$E_{res} \sim 30 \text{ GeV} / \rho \text{ [g cm}^{-3}\text{]} \quad E_{res} \approx \text{few GeV for Earth matter density: good prospects for atmospheric neutrinos!}$$



But: $P(\nu_\mu \rightarrow \nu_\mu, NH) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu, IH)$
 other ingredients are needed to create a difference in the number of events for IH vs. NH:
 - (anti-)neutrino cross-section: $\sigma_{\nu N} \approx 2\sigma_{\bar{\nu} N}$
 - atmospheric ν_e & ν_μ (anti-)neutrino fluxes
 - matter effects in the Earth (different baselines)



Distinctive pattern in energy E_ν and zenith θ_ν oscillograms showing the difference for NH and IH.

Main challenges:
 - NH/IH difference intrinsically small
 - intrinsic event-by-event fluctuations
 - oscillograms blurred by limited energy and angular accuracy
- But: electron channel more robust against detector resolution effects

E, θ smearing (detector resolution)

See also E. Akhmedov et al., JHEP 02 (2013), 082

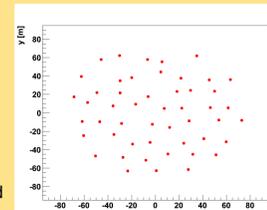
ORCA: an undersea neutrino Cherenkov detector within the KM3NeT framework

ORCA is building on expertise of the **KM3NeT Collaboration**, which aims at the deployment of a multi-km³ neutrino telescope in the Mediterranean to perform high-energy (TeV-PeV) neutrino astronomy: [talk by P. Piattelli](#)

- same detection principle: Cherenkov light emitted by secondary particles produced by the neutrino interaction
- **same technology and detector design** (instrumented lines anchored at the seabed and supporting multi-PMT digital optical modules)
- [poster by T. Chiarusi](#)
- **denser array to lower the energy threshold to ~GeV** neutrino energies
- line spacing and length limited by deployment contingencies

A modest **reference detector** was used for the first stages of the feasibility study:

- 50 strings, 20m spaced
- 20 DOM/string, 6m spaced
- instrumented volume: $\pi \times 70^2 \times 114 \times \rho_{sea} = 1.8 \text{ Mt}$
- ~1% of Cherenkov light is detected

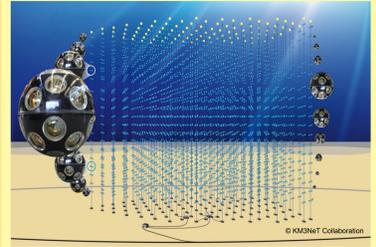
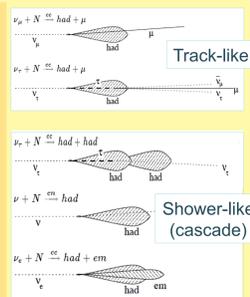


Full optimization is planned to be performed on basis of an over-dense detector with different optical module masking options.

Simulation

- atmospheric $\nu_e + \nu_\mu$ (+anti) flux: Bartol flux, [Agrawal et al. PRD 53, \(1996\) 1314](#).
- neutrino interaction: GENIE, [Andreopoulos et al. Nucl. Instrum. Meth. A614 \(2010\), 87-104](#).
- particle propagation and Cherenkov light emission: GEANT4, [Agostinelli et al. Nucl. Instr. and Meth. A506 \(2003\), 250-303](#).
- down-going atmospheric muon background based on parameterizations, [Carniani et al., Comput. Phys. Commun. 179 \(2008\) 915-923](#).
- optical background (⁴⁰K decay: 5kHz/PMT and 500Hz in-DOM time-correlated)

Event topologies



The proposed ORCA detector

The collaboration now proposes to build a detector of 115 strings with 18 optical modules each. For the same spacing as that of the reference detector, this corresponds to an effective mass of 3.75 Mt.

This proposed detector can be built with an investment budget of 40 M€.

Track reconstruction

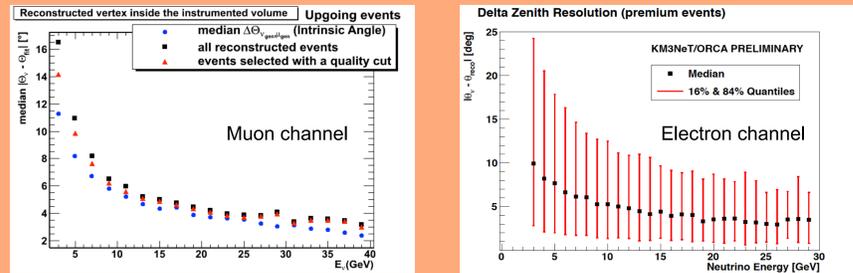
- Likelihood maximization based on the hit time residuals and length estimation on basis of first/last emission points
- Identification of hits belonging to the hadronic shower and re-estimation of the vertex position

Shower reconstruction

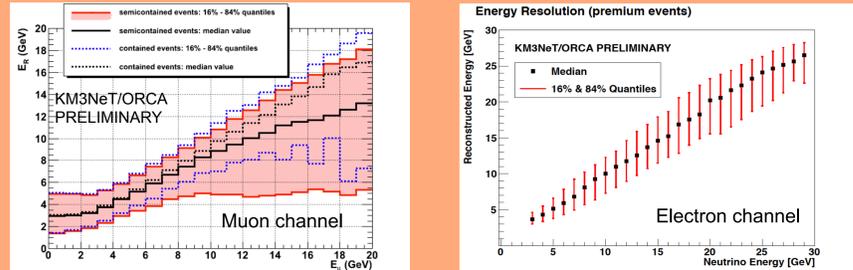
- Vertex: likelihood maximization based on hit time residuals (assuming spherical shower)
- Direction: likelihood maximization based on the probability that detected hits have been created by a certain shower hypothesis
- Energy: counting the number of DOMs which have at least one selected signal-like hit.

Current performances

Zenith resolutions



Energy resolutions



Muon channel (track-like):

Semi-contained events (i.e. with reconstructed vertex inside the instrumented volume) selected with a quality criterion on the track fit provide good angular accuracy: **median $\Delta\theta$ better than 10°** for $E_\nu \geq 5 \text{ GeV}$. The muon energy estimation is most reliable when an additional containment condition is imposed on the full muon track, ensuring that most of the Cherenkov light is detectable. **Using the reconstructed muon energy as a neutrino energy estimator, a median resolution of 35% can be reached at 10 GeV.** Studies are ongoing to evaluate the energy deposited in the hadronic region in order to improve the neutrino energy determination.

Electron channel (shower-like):

Energy and direction resolution have been evaluated on upgoing ν_e CC events, where most of the Cherenkov light is contained in the instrumented volume ('premium events'). Under these optimistic assumptions, **the median $\Delta\theta$ is better than 10°** and the energy resolution better than ~30% for $E_\nu \geq 5 \text{ GeV}$.

Statistical method

The performance of ORCA to the NMH determination is assessed by means of a **likelihood ratio test**:

$$\Delta \log(L^{\max}) = \sum_{bins} \log P(\text{data} | \hat{\theta}^{NH, NH}) - \log P(\text{data} | \hat{\theta}^{IH, IH})$$

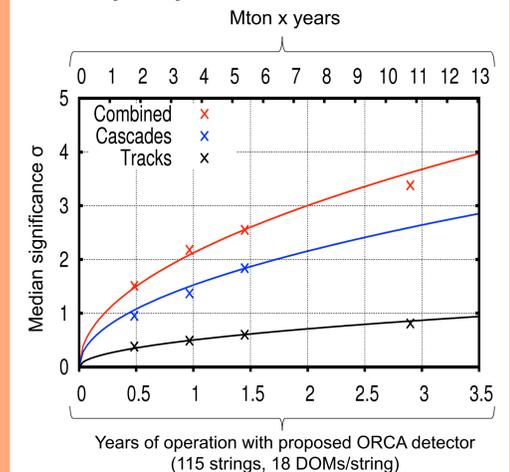
where $\hat{\theta}^{MH}$ = maximum-likelihood estimates for the mixing parameters

For each toy dataset generated with a given hierarchy, the mixing parameters are fitted with either IH or NH and the log-likelihood ratio is computed. The separation of the two resulting distributions is used to compute the significance.

The study does include some misidentification rates based on MC studies.

Note that θ_{23} and Δm^2_{large} can be fitted from data.

Sensitivity study



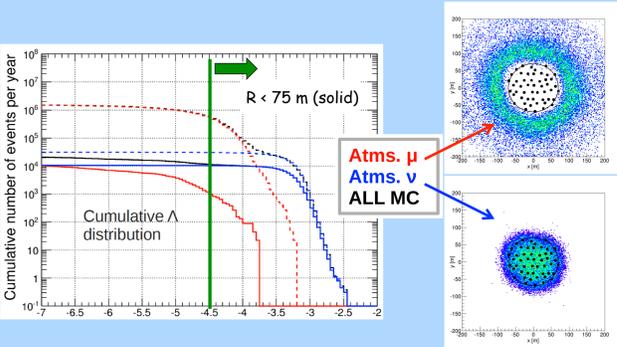
Caveats:

- The sensitivity study does not yet take into account:
 - overall flux uncertainty & cross-section uncertainty
 - NC events
 - altered resolution for misidentified events
 - atmospheric muon background contamination

Muon background rejection capabilities

The main physical background comes from down-going atmospheric muons misreconstructed as upgoing, mimicking a ν_μ CC event. Preliminary studies show that the muon contamination (C_μ) can be reduced efficiently by cuts on the reconstruction parameters, maintaining a high neutrino signal efficiency:

- track fit quality parameter: $\Lambda > -4.5$ to -4
- reconstructed vertex position: $R < 75 \text{ m}$



Impact of systematics

Besides intrinsic detector capabilities, other sources of uncertainties can spoil the NMH measurement by biases in the statistical distributions that may result in a degraded discrimination power or wrong hierarchy determination. Several studies have addressed the impact of systematic errors and identified the most critical among them.

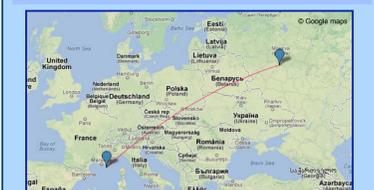
- ❖ **Earth density profile** (PREM model): negligible impact
- ❖ **Atmospheric neutrino fluxes:**
 - moderate impact of the shape uncertainties
 - overall normalization uncertainty can be mitigated by anchoring the fit at $E_\nu > 20 \text{ GeV}$
- ❖ **Neutrino interaction cross-sections:**
 - different uncertainties for neutrinos and anti-neutrinos
 - other measurements, e.g. from MINERvA, will likely reduce these uncertainties
- ❖ **Oscillation parameters:** significant impact of uncertainties in atmospheric sector (Δm^2_{large} , θ_{23} , θ_{13}), in particular θ_{23} octant, while solar sector and δ_{CP} have small impact
- ❖ **ORCA can improve on precision of Δm^2_{large} , θ_{23} through global fit procedure!**

		with proposed detector (3.75 Mton)		
Error on ...	current	1.5 yr	2.5 yr	5 yr
θ_{23} [deg]	1.6*	0.6	0.4	0.3
Δm^2_{large} [10^{-5} eV^2]	8*	7.2	5.8	4.3

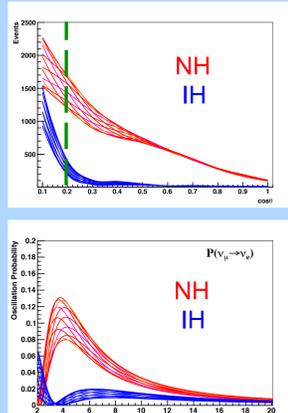
* Capozzi et al., arXiv:1312.2878v1

A neutrino beam to ORCA?

Counting events related to a neutrino beam of given flavour can increase the sensitivity of ORCA to the NMH even with a moderate capability of flavour identification. In the **appearance channel $\nu_\mu \rightarrow \nu_e$** and for a typical ν_μ beam in the energy range of 2-8 GeV, an optimal separation between NH and IH is found for $\cos\theta=0.2$, i.e. a **baseline of 2600 km**. The oscillation probabilities are only marginally affected by the value of δ_{CP} .



A beam with a suitable baseline could be built from **IHEP in Protvino** (near Moscow, Russia) towards ORCA, with a baseline of 2588 km. Assuming $N_{pot} \approx 1.5 \cdot 10^{21}$ within a few years, a **3σ measurement of the hierarchy can be achieved** (3σ with 3-4% systematic uncertainty on event rates).



Channel	Tracks NH	Tracks IH	Cascades NH	Cascades IH
No oscill	8990	26315	8735	1134-1547
Signal	232-329	47-79	1326	1280
ν_e	324-332	351-355	978-998	1057-1068
NC	1992	1992	3640	3640
BG Total	1655-1745	1494-1522	5944-5964	5977-5988
Total	10645-10736	10229-10257	7099-7491	6338-6496

J. Brunner, arXiv:1304.6230