Mass Hierarchy Measurement with KM3NeT/ORCA

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Introduction

KM3NeT/ORCA

"Oscillation Research With Cosmics in the Abyss"

- Part of KM3NeT
- Measurement of neutrino mass hierarchy (NMH)
- Using atmospheric neutrinos
- Underwater Cherenkov detector in the Mediterranean

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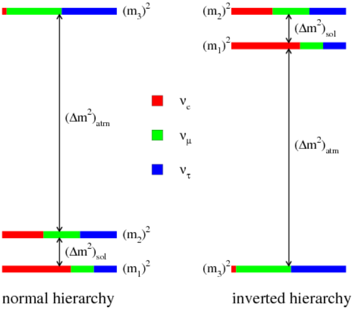
Oscillation and Neutrino Mass Hierarchy

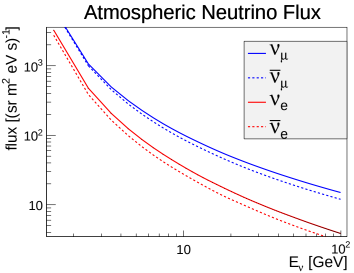
- Neutrinos can change flavour
- Relevant parameters
  - Mixing angles θ_{23}, θ_{13}, θ_{12}
  - CP-violating angle δ_{CP}
  - Mass-squared differences $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$ masses themselves are unknown
- Normal ('vacuum') oscillation depends only on distance, energy and mass-squared differences. It tells us $\Delta m_{21}^2 \ll |\Delta m_{31}^2|$ (sign of latter unknown)
- Oscillation is different in matter (MSW-effect) this is what we will use to **measure the hierarchy**.



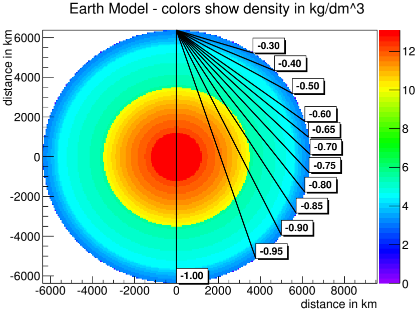
The two possibilities for the relative ordering of the neutrino masses.

Atmospheric Neutrinos

- Free neutrino source
- From atmospheric cosmic ray interactions
- Zenith angle $\theta \leftrightarrow$ distance and density profile

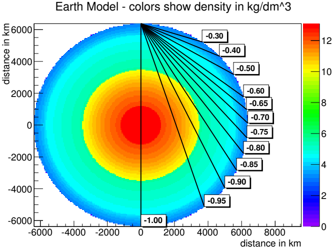


Atmospheric neutrino flux (from HKKM2014 flux tables)

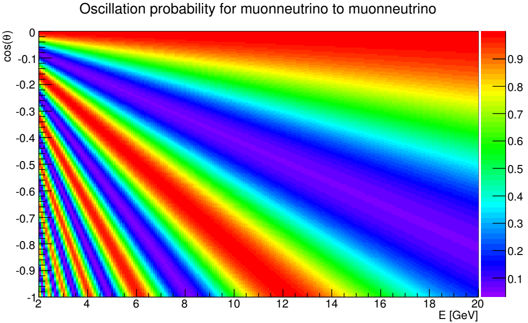


Earth density profile with neutrino trajectories under various zenith angles. The boxes show $\cos(\theta)$.

Neutrino Oscillation in an Oscillogram



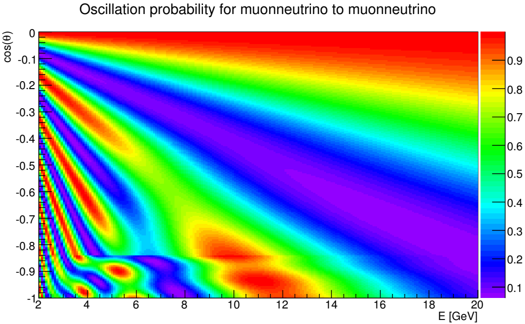
Again the neutrino trajectories through Earth.



The ORCA workhorse: the zenith-energy plot. This one shows the $\nu_\mu \rightarrow \nu_\mu$ **vacuum** *oscillation probability as a function of neutrino energy and zenith angle.*

Neutrino Oscillation in an Oscillogram

- Resonances occur only for neutrinos/antineutrinos depending on the hierarchy.



Zenith-energy plot of the $\nu_\mu \rightarrow \nu_\mu$ oscillation probability **with the MSW-effect**.

Measurement

Main mechanism

- Measure atmospheric neutrino energy and zenith
- Map oscillation pattern for different flavours
  - Resonances either for ν or $\bar{\nu}$ in NH/IH

Complicating factors

- Cannot distinguish $\nu/\bar{\nu}$ (except through Bjorken y)
  - natural $\nu/\bar{\nu}$ asymmetry
- Multiple initial and final flavours
  - Oscillation patterns merge
  - Need flavour ID
- Detector resolution
- Background (atmospheric muon, NC)
- Systematics

Neutrino Interactions

Charged Current (CC)

$$\nu_\ell + X \xrightarrow{\text{via } W^\pm} \ell + \text{hadronic cascade}$$

- $\ell = e \Rightarrow$ electromagnetic **cascade**
- $\ell = \mu \Rightarrow$ several meters long **track**
- $\ell = \tau \Rightarrow$ immediately decays (strongly suppressed) **cascade**

Neutral Current (NC)

$$\nu_\ell + X \xrightarrow{\text{via } Z^0} \nu_\ell + \text{hadronic cascade}$$

- No way to determine neutrino flavour
- Background
- **cascade**

Particle ID by distinguishing 'track-like' events from 'cascade-like' events.

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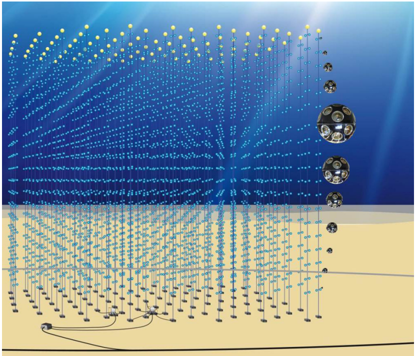
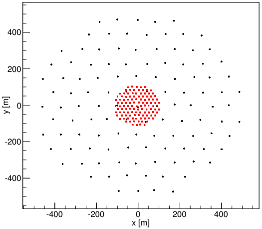
Layout



Artist's impression of a KM3NeT building block: 115 strings of 18 DOMs.

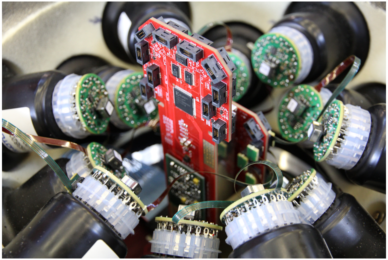


Detector footprint of ORCA (red) and ARCA (black)

- ORCA: low energy, 20m inter-string spacing, approx. 3.8 Mton
- ARCA: high energy, 90m inter-string spacing, multiple building blocks

Digital Optical Module (DOM)

- For both ORCA and ARCA
- 17 inch pressure-resistant glass sphere
- 31 3 inch photomultiplier tubes (PMTs)
- single photon counting
- directional sensitivity
- Multi-wavelength optical communication



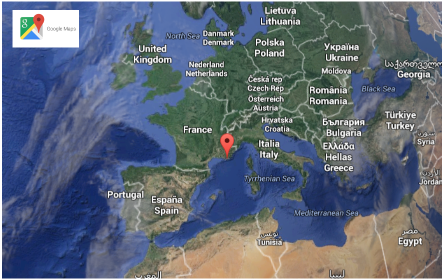
DOM Interior

The KM3NeT Digital Optical Module.

Current Status

Second completed KM3NeT string at Nikhef.

- Prototypes successfully deployed: single DOM and 3-DOM line



ORCA site off the coast of Toulon, France.

- Six ORCA-style strings already funded
- First to be deployed before end of 2016
- String production started: 2 ARCA strings completed
- Deployment December 2015 and early 2016

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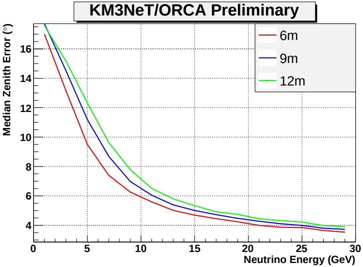
Track Reconstruction

- 7200 starting tracks spanning full sky
- Fitted stepwise with increasing precision
- Final fit of best track
  - maximum likelihood method
  - pdf based on full simulation with background
- Bjorken y from time residual distributions
- Neutrino energy from
  - E_μ (track length)
  - N_{hits}
  - Bjorken y



Median direction resolution for μ-type CC events.

- Finds μ track direction
- Resolution dominated by intrinsic $\nu - \mu$ scattering angle
- ~7° at 10 GeV

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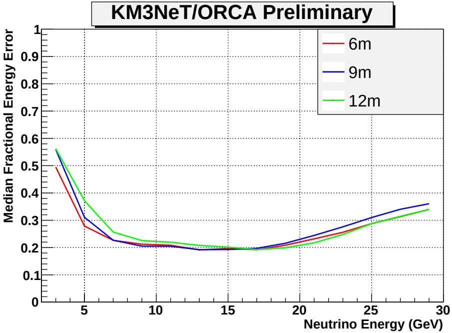
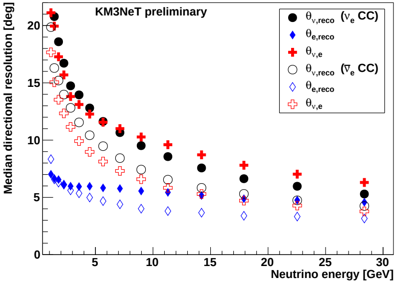


Median fractional energy resolution for ν_μ CC events.

- Median resolution better than 25% in relevant range

Cascade Reconstruction

- First: vertex from time residuals
  Resolution: 0.5-1 m
- Then: E, direction and inelasticity from maximum likelihood fit
- Bjorken y from relative strength of Cherenkov peak

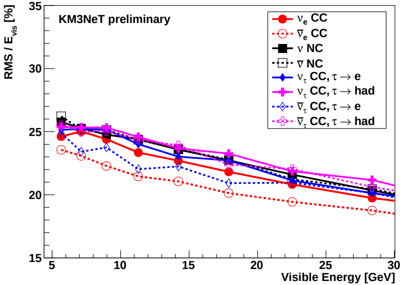


Median neutrino direction resolution for ν_e CC events.

- Finds direction of leading electron
- Resolution dominated by intrinsic $\nu - e$ scattering angle
- ~10° at 10 GeV

Cascade Reconstruction

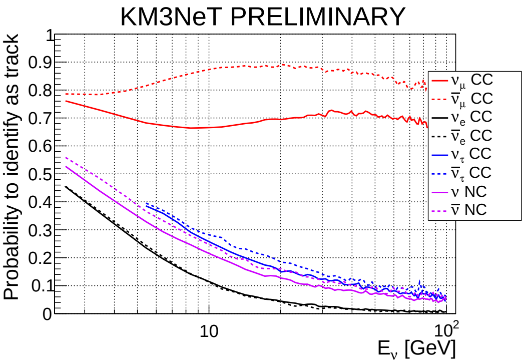
- First: vertex from time residuals
  Resolution: 0.5-1 m
- Then: E, direction and inelasticity from maximum likelihood fit
- Bjorken y from relative strength of Cherenkov peak



Relative energy resolution RMS/E_{vis} as a function of the visible energy Evis for shower-like neutrino interaction channels.

- Better than 25% in the relevant range.

Particle ID



Probability that the PID algorithm identifies an event as a track as a function of the true neutrino energy. The lines denote different interaction types.

- Random Decision Forest
- Many decision trees trained on MC events
- e-like CC events better than 90% above 10 GeV
- mu-like CC events around 80% (better for $\bar{\nu}_\mu$, worse for ν_μ).

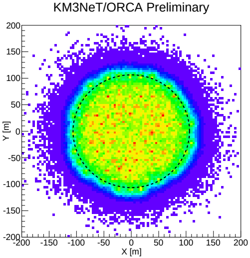
Atmospheric Muon Background

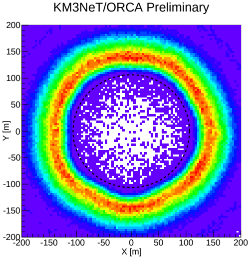
Rejection

- Cut on events reconstructed as upgoing
- Cut on track reconstruction quality parameter
- Cut on pseudo-vertex (see right)
- BDT

Few percent contamination without losing too much signal

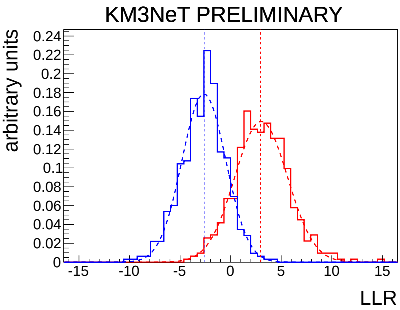
Figures: Reconstructed vertex position in a top view of the ORCA detector for **top:** *muon neutrinos* < 20 *GeV* **bottom:** *atmospheric muons*





Sensitivity Study - Method

- Pseudo-experiments (PEs)
- Fit assuming NH and assuming IH
  - Maximize Likelihood of PE w.r.t. oscillation parameters and systematics
- Log likelihood ratio (LLR) $\log(L_{\mathrm{NH}}) - \log(L_{\mathrm{IH}})$ as discriminating variable
- LLR distributions for NH and for IH
- Figure of merit: median sensitivity $=$ distance in σ's between the medians



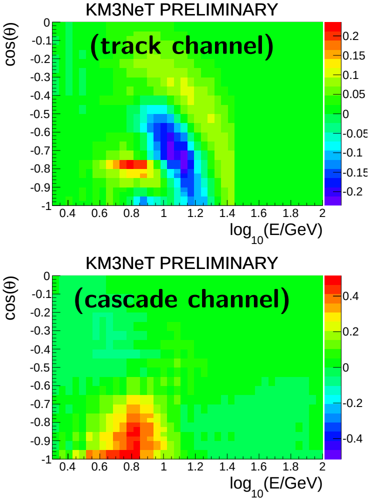
Example LLR distributions with Gaussian fits. Red (blue) shows true NH (IH) pseudo-experiments. The dashed lines indicate the medians.

Sensitivity Study - Detector Model

- Ingredients from full MC simulations
- Steps
  - Atmospheric neutrino flux
  - Interaction cross-sections
  - Detector acceptance
  - PID
  - Detector resolution
- Final output: expected event numbers track and cascade channel as a function of reconstructed E and $\cos(\theta)$.

Figures: 'Mass hierarchy signature'

$$\frac{N_{\mathrm{NH}} - N_{\mathrm{IH}}}{\sqrt{N_{\mathrm{NH}}}}$$

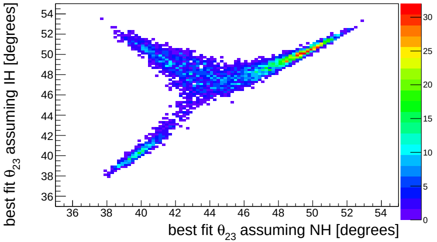


Sensitivity Study - Parameters

- Fitted oscillation parameters
  - Large mass-squared difference ΔM^2
  - θ_{23}
  - CP-violating angle δ_{CP}
  - Rest treated as nuisance parameters
- Systematics
  - $\nu/\bar{\nu}$-ratio
  - μ/e-flavour-ratio
  - overall factor (flux + cross-section)
  - scaling of NC events
  - energy slope (flux + cross-section)
- Large parameter space: minimization using MINUIT

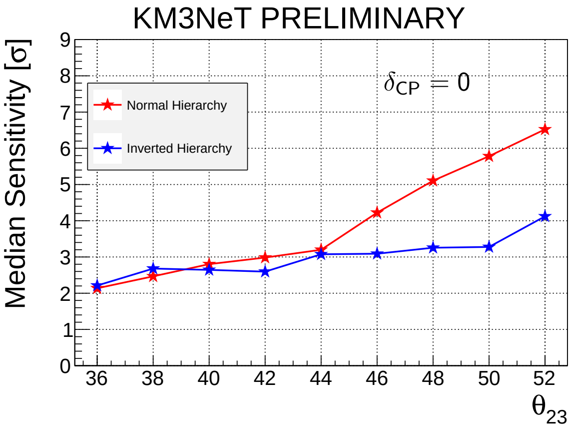
Sensitivity Study - Octant Degeneracy

- Wide range of θ_{23} not excluded yet
- 3σ range $\approx [38^\circ, 53^\circ]$
  Best fit 42.2° (NH), 49.5° (IH)
  (`arXiv:1409.5439v2[hep-ph]`)
- ORCA two likelihood maxima: 'first octant' ($< 45^\circ$) and 'second octant' ($> 45^\circ$)
- Octant correlated to hierarchy
- Simultaneous measurement



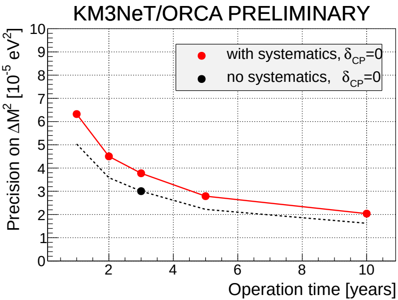
Example: best fit θ_{23} for many PEs assuming NH (horizontal) or IH (vertical). True NH PEs. The wrong hierarchy assumption sometimes leads to a best-fit value in the wrong octant.

Sensitivity Study - Results

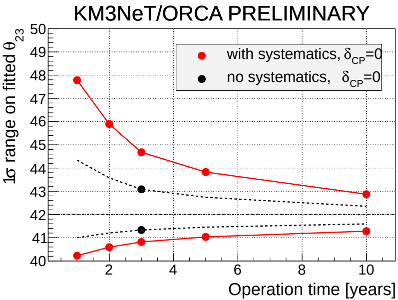


Median mass hierarchy sensitivity as a function of θ_{23} after 3 years of operation time. This includes a fit of ΔM^2, θ_{23} and five systematic parameters. delta$_{CP}$ was fixed to zero.

Sensitivity Study - Results



Expected precision on ΔM^2 as a function of operation time.

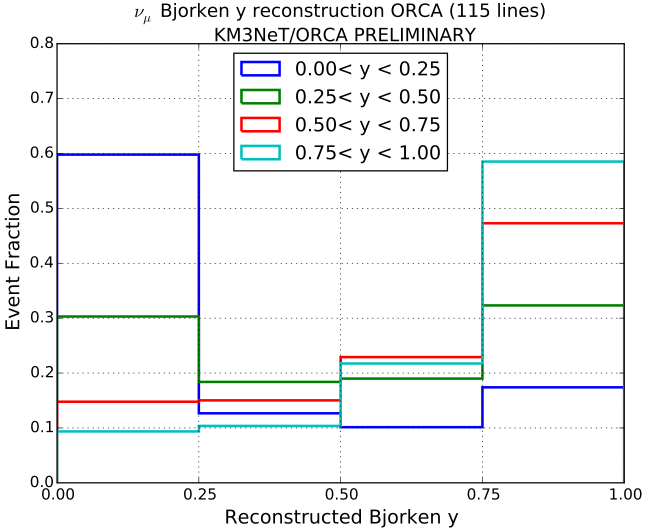


Expected precision on θ_{23} as a function of operation time.

Summary and Outlook

- ORCA can measure the NMH with ~3σ in 3 years of full detector operation
- First 6 ORCA strings funded
  first one to be deployed by end of 2016
- Letter of Intent to be published soon

Backup Slides



Bjorken y sensitivity of the track reconstruction algorithm.