Measuring the neutrino mass ordering with KM3NeT ORCA

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Previous expertise in the Deep-Sea

First Neutrino Telescope in the Sea, complete 2008 – 0.1km²
see http://antares.in2p3.fr/Publications/index.html
ANTARES: world 1st deep-sea NT

Presentation by A. Margiotta on 10th

- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs @ 2475 m depth

- Deployed in 2001
- 40 km
- 14.5 m
- Junction box (since 2002)

Excellent angular resolution (<0.5° muons, ~2° electrons)

8 countries
31 institutes
~150 scientists + engineers

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First achievements on neutrino oscillation

2-flavor approximation analysis with 2008-2010 data

\[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{32} \sin^2 \left( \frac{1.27 \Delta m^2_{32} L}{E_\nu} \right) = 1 - \sin^2 2\theta_{32} \sin^2 \left( \frac{16200 \Delta m^2_{32} \cos \Theta}{E_\nu} \right) \]

Oscillations maximal at 24 GeV for vertical neutrinos (muon range~120m)
Larger effect on low energy (single lines) than higher energy events (multi-lines)

Matter Effects and Mass Hierarchy

Requirements:
• $\Delta m^2_{13} \sim$ A matter potential must be significant but not overwhelming
• L large enough – use atmospheric neutrinos!
• Distinction between neutrinos and anti-neutrinos $\rightarrow$ cross-sections!

$\sigma(\nu) \approx 2\sigma(\bar{\nu})$
Both muon- and electron-channels contribute to net hierarchy asymmetry. The electron channel is more robust against detector resolution effects. (Significances a la Akhmedov et al. JHEP 02 (2013) 082)
KM3NeT is a distributed research infrastructure with 2 main physics topics: Low-Energy studies of atmospheric neutrinos – High-Energy search for cosmic neutrinos.

Talk by P. Migliozzi on Thursday
The ORCA benchmark design

115 lines, 20m spaced, 18 DOMs/line 6m spaced

- 31 3” PMTs
- Digital photon counting
- Directional information

Instrumented volume ~3.8 Mt, 2070 OM
Optical background: 10kHz/PMT & 500Hz coincidence

- Wide angle of view
- More photocathode than 1 ANTARES storey
- Cost reduction compared to ANTARES
Event topologies

Track-like contains both a cascade and one track

Not to scale

Shower-like cascade

No track is identified
Ingredients for NMH measurement

- Efficient and high purity trigger algorithm for neutrino and atmospheric muon events
  - Exploit excellent photon counting of multi-PMT DOMs
  - Use causality of direct photons $\rightarrow$ water almost scattering free for visible photons
- Reconstruction of cascade and track topologies
  - High efficiency down to relevant energies
  - Good resolution in energy and zenith angle
- Topology Identification (track $\leftrightarrow$ cascades)
- Atmospheric muon rejection (no hardware veto)
ORCA shower reconstruction ($\nu_e$)

1. Vertex fit:
   - maximum likelihood method based on time residuals
   - two fits: first robust prefit then more precise fit

2. Energy + direction fit:
   - PDF for number of expected photons depending on:
     $E_v$, Bjorken $y$, emission angle,
     OM orientation, distance(OM,vertex)
   - maximum likelihood method based probability that hits have been created by certain shower hypothesis ($E_v$, Bjorken $y$, direction)

Res. ($\sigma$): 0.5-1 m
Performances $\nu_e$ (cascades)

Excellent angular resolution
Dominated by kinematics

Energy resolution better than 25% in relevant range – close to Gaussian
ORCA Layout Optimization

- Switch off DOMs in proposed 115 line detector
  → 20 m interline spacing imposed by line deployment (sea operations)
  → 6, 9, 12, 18 m vertical spacing inter-DOM

Examples for shower reconstruction

All relevant quantities must be studied in details before adopting an optimum spacing

But substantial improvement possible
Performances $\nu_\mu$ (tracks)

Excellent angular resolution
Dominated by kinematics

Energy resolution better than 25% in relevant range – close to Gaussian
Effective Masses

- Above 10 GeV $M_{\text{eff}}$ close to instrumented volume
- Similar for cascades and tracks
Atmospheric muon rejection

- Simulation based on MUPAGE (Astropart. Phys. 25 (2006) 1) at depth 2475 m
- $\nu_\mu$ reconstruction: cut on the reconstructed pseudo-vertex and quality parameters + BDT

Instrumental veto not mandatory

Tunable few % contamination achievable without too strong signal loss
Flavour (mis)-identification

- Discrimination of track-like (ν_μ^{CC}) and cascade-like (ν^{NC}, ν_ε^{CC}) events
- Classification uses “Random Decision Forest”
- Better than 80% above 10 GeV for all channels but ν_μ^{CC}
Systematic Effects

- Various systematic effects taking into account
  - Oscillation parameters
    - $\Delta m^2$, $\theta_{12}$ fixed; $\theta_{13}$ fitted within its error
    - $\Delta M^2$, $\theta_{23}$, $\delta_{CP}$ fitted unconstrained
  - Flux, cross section, detector related (average fluctuation w.r.t. nominal)
    - Overall normalisation (2.0%)
    - $\nu/\bar{\nu}$ ratio (4.0%)
    - $e/\mu$ ratio (1.2%)
    - NC scaling (11.0%)
    - Energy slope (0.5%)
    - Fitted unconstrained

[Graph showing KM3NeT PRELIMINARY with $\theta_{23} = 42^\circ$ IH, NH]

$\theta_{\nu} = 42^\circ$ 3 yrs
Sensitivity to Neutrino Mass Hierarchy

Dependence of sensitivity on time for fixed $\theta_{23}$ values $\delta_{CP}$ fixed to zero for easy comparison with other experiments

- ✔ Track vs shower event classification
- ✔ Full MC detector response matrices including misidentified and NC events
- ✔ Atmospheric muon contamination
- ✔ Neutral current event contamination
- ✔ Various Systematic uncertainties
Sensitivity to Neutrino Mass Hierarchy

Dependency of sensitivity on $\theta_{23}$ for 3 years
NH easier to determine than IH
Second octant easier than first octant
When fixing $\delta_{\text{CP}}$ to zero sensitivity increases by $\sim 0.5\sigma$

- Track vs shower event classification
- Full MC detector response matrices including misidentified and NC events
- Atmospheric muon contamination
- Neutral current event contamination
- Various Systematic uncertainties
Dependency of sensitivity on $\theta_{23}$ and $\delta_{\text{CP}}$ for NH and 3 years

Best case: large $\theta_{23}$ and $\delta_{\text{CP}} = 0^\circ$

Worst case: small $\theta_{23}$ and $\delta_{\text{CP}} = 180^\circ$
Sensitivity to PMNS parameters

\[ \Delta M^2 - \text{unconstrained fit in conjunction to mass hierarchy hypothesis testing} \]

\[ \rightarrow \text{Significant improvement of precision achievable} \]

\[ \Delta M^2 \text{ – unconstrained fit in conjunction to mass hierarchy hypothesis testing} \]

\[ \rightarrow \text{Significant improvement of precision achievable} \]

KM3NeT/ORCA PRELIMINARY

![Plot showing precision on \( \Delta M^2 \) vs operation time with and without systematics.]

- **With systematics, \( \delta_{CP} = 0 \)**
- **No systematics, \( \delta_{CP} = 0 \)**

**PDG 2014**
Sensitivity to PMNS parameters

$\Theta_{23}$ – unconstrained fit in conjunction to mass hierarchy hypothesis testing
World best measurement after few years of data taking
Modular ring of up to 6 nodes with double connection to shore for up to 120 detection units + Sea Science instruments

Possibility to redirect the ANTARES cable to ORCA

Phase 1 (funded and spent) : deploy a 6-7 string array in the ORCA configuration to demonstrate detection method in the GeV range.

Phase 2 (~40 M€ wo contingency) : 2017 deploy 1 building block 115 strings in French KM3NeT site. Completion by 2020

Requested funds

Soon available : ORCA report document (already ICRC’15 proceedings)
Thank you!

New collaborators are welcome to join the endeavour!
Atmospheric neutrinos measurements

2008-2011 data set

Two different energy estimators:
- \( \frac{dE}{dX} \) as evaluated from total collected charge
- Combined likelihood for hit/no-hit for all OMs

Atmospheric energy spectrum by unfolding measured spectrum averaged in 90°-180° zenith band

\[ Ae = x \]
A: response matrix
E: true distribution
X: measured distribution

\[ dE/dX \approx \rho = \frac{\sum Q_i}{\varepsilon(\bar{x})} \cdot \frac{1}{L_\mu(\bar{x})} \]
L: length
\( \varepsilon \): efficiency

\[ \mathcal{L}(E_\mu) = \frac{1}{N_{OM}} \prod_i L_i(E_\mu) \]
free param

Good understanding of the detector

Smooth operation and data taking since May 2014

Nice Monte Carlo data agreement
ORCA Sensitivity to Inelasticity

- Use PDFs on the time residuals under the track (low-\(y\)) and shower (high-\(y\)) hypothesis
- Select \(y\)-interval corresponding to highest likelihood

"total significance ... may increase by (20 - 50)\%, thus effectively increasing the volume ... by factor 1.5 – 2"

Ribordy & Smirnov PRD, 87. 113007
(muon channel only)

Should be further exploited
PID, NC rejection, neutrinos/anti-neutrinos...
Several studies $\rightarrow$ same conclusions

- D. Franco et al, JHEP 04 (2013) 008
- W. Winter, PRD 88 (2013) 013013

![Graph showing Δm^{2}_{31} correlation](image)

- PINGU LoJXiv1401.2046
  - Impact (increase) on 1year significance (total 1.75 $\sigma$)

![Bar chart showing impact on various parameters](image)

- Capozzi et al. arXiv1503.01999
  - Including E, zenith resolution/shape uncertainties +additional uncorrelated uncertainties
  - Total 5yrs loss in sensitivity from 24% to 40% under very pessimistic assumptions

**Updates coming up in PINGU, suite of systematics being studied in ORCA**
Studies of systematics

\( \sin^2 \theta_{23} \) in \([0.4; 0.6]\)

\( \mu \) and \( e \) indep !?

Shape 1.5%  Residual 1.5%

Total 5yrs loss in sensitivity from 24% to 40%

Worst case \(3\sigma\) in 10 years

Capozzi et al. arXiv1503.01999

PINGU resolutions and effective masses
\( \nu_e^{\text{CC}} \) : median directional resolution

- error bars: 15% and 85% quantiles
- neutrinos and anti-neutrinos
- negligible differences between 5 and 10 kHz single PMT optical background rates
A phased implementation

**PHASE 1:**
Shore and deep-sea infrastructure at KM3NeT-Fr & KM3NeT-It
31 lines deployed by end 2016 (**3-4 x ANTARES sensitivity**)
Proof of feasibility of network of distributed neutrino telescopes and more?
ORCA demonstrator

**2016 PHASE 2:** ARCA (+80-90 M€) and ORCA (+40 M€)
230 lines (2 building blocks in Italy) + 115 lines (1 building block) in France
Investigation of IceCube signal

**2020 KM3NeT NEXT:** Neutrino astronomy
6 building blocks

31 M€ FUNDED ONGOING

ARCA and ORCA Letters of Intent in preparation

220-250 M€ ESFRI Roadmap