ORCA - ν Oscillation Research with Cosmics in the Abyss within KM3NeT

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27-28 November KM3NeT-Italia Collaboration Meeting

KM3NeT Strategy

- Multi-site experiment
  - High Energy ν astronomy offshore Capo Passero
  - ORCA Neutrino Mass Hierarchy offshore Toulon
- KM3NeT Phase 1 -> funded
  - 24 strings + 8 towers to be installed and operational off-shore Capo Passero in 2015-2016
  - 6 strings for ORCA feasibility study off-shore Toulon ->2016
- KM3NeT Phase 1.5 -> not funded, application for new ESFRI proposal
  - Two blocks of 115 strings (1-2km^3) LoI to be released in January 2015 see R. Coniglione talk
  - ORCA one block of 115 strings i.e. 4 Mton - LoI in preparation to be released at beginning 2015
- KM3NeT Phase 2 see R. Coniglione talk

Outline

- Motivation
- Aim of the experiment
- Detector design
- Preliminary telescope performances (only official plots)
- First preliminary results on sensitivity (only official plots)
- Conclusions and perspectives

Neutrino properties

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

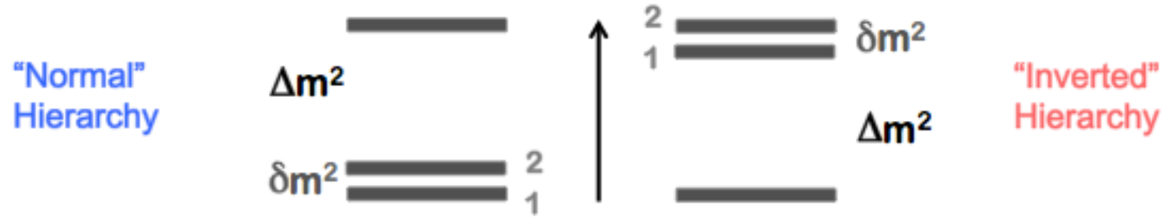
$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\beta/2} \end{bmatrix}$$

[only if Majorana]

Mixing angles θ_{23}, θ_{13}, θ_{12} : known ✔

CP-violat. phase(s) δ (α, β) : unknown ✗

Mass-squared spectrum (up to absolute scale)



[+ contribution in matter ~ $G_F \cdot E \cdot$ density]

δm^2, Δm^2: known ✔

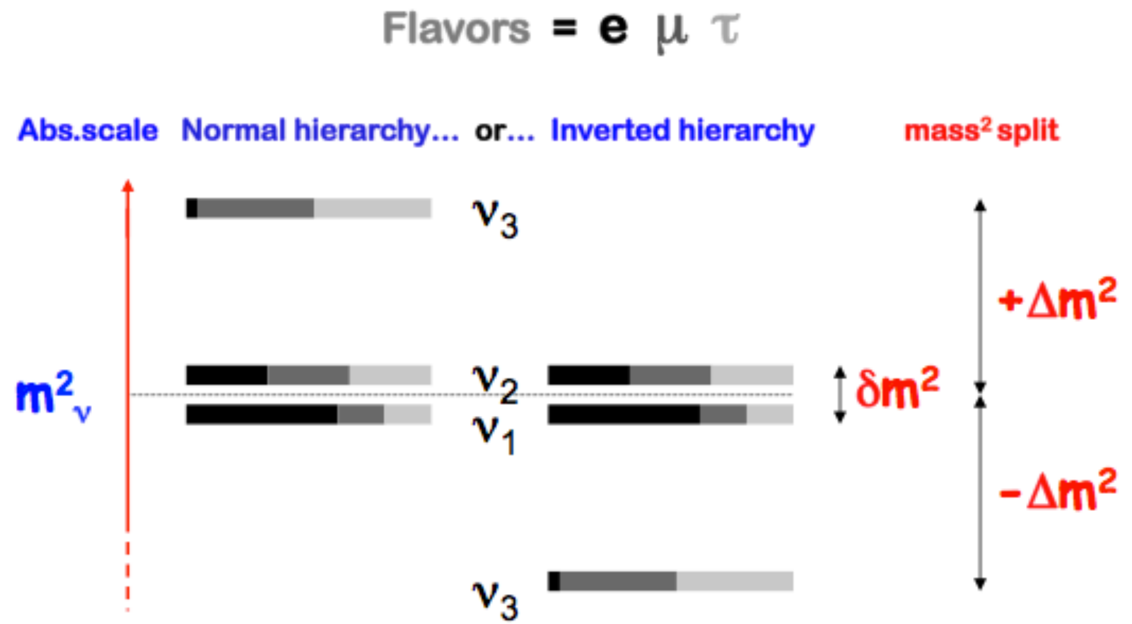
Matter effects (solar ν): ✔

Hierarchy : unknown ✗

E. Lisi ICFA 2014, Beijing, 27/10/14

Neutrino Mass Hierachy

Current 3ν picture in just one slide (with 1-digit accuracy)



Terra Cognita:

$\delta m^2 \sim 8 \times 10^{-5}$ eV^2
$\Delta m^2 \sim 2 \times 10^{-3}$ eV^2
$\sin^2\theta_{12} \sim 0.3$
$\sin^2\theta_{23} \sim 0.5$
$\sin^2\theta_{13} \sim 0.02$

Terra Incognita:

δ (CP)
sign(Δm^2)
octant(θ_{23})
absolute mass scale
Dirac/Majorana nature

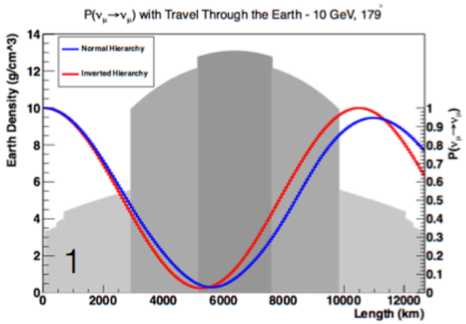
E. Lisi ICFA 2014, Beijing, 27/10/14

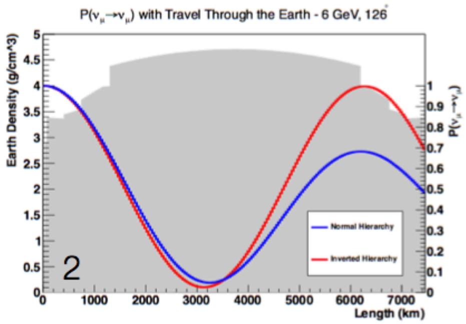
Method

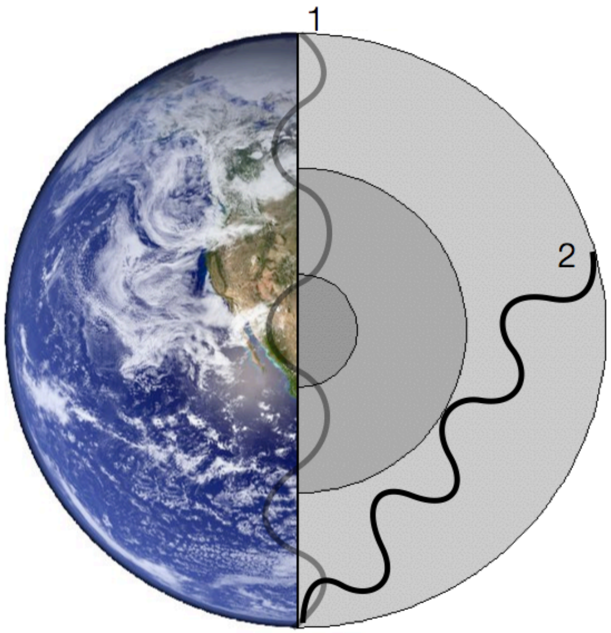
- Smirnov at Neutrino 2012 => PINGU (IceCube)
- Measuring the Neutrino Mass Hierarchy (NMH) with atmospheric neutrinos in a Mton scale ice/deep sea Cherenkov detector at GeV energy
- MSMW effect on up-going neutrinos passing through Earth modify oscillation pattern allowing to disentangle NMH sign
- Exploit ν_μ, ν_e oscillation $P_{\mu e}$ <-> $P_{e\mu}$ in atmospheric up-going events

Measurement of the Neutrino Mass Hierarchy with atmospheric ν

- Broad range of baselines (50 -> 12800 km) and energies (GeV -> O(100 TeV)
- Oscillation signal enhanced at resonance energy in matter







$$P_{e\to\mu} \approx P_{\mu\to e} \approx \sin^2\theta_{23}\sin^2(2\theta_{13}^{\text{eff}})\sin^2\left(\frac{\Delta_{13}^{\text{eff}}L}{2}\right)$$

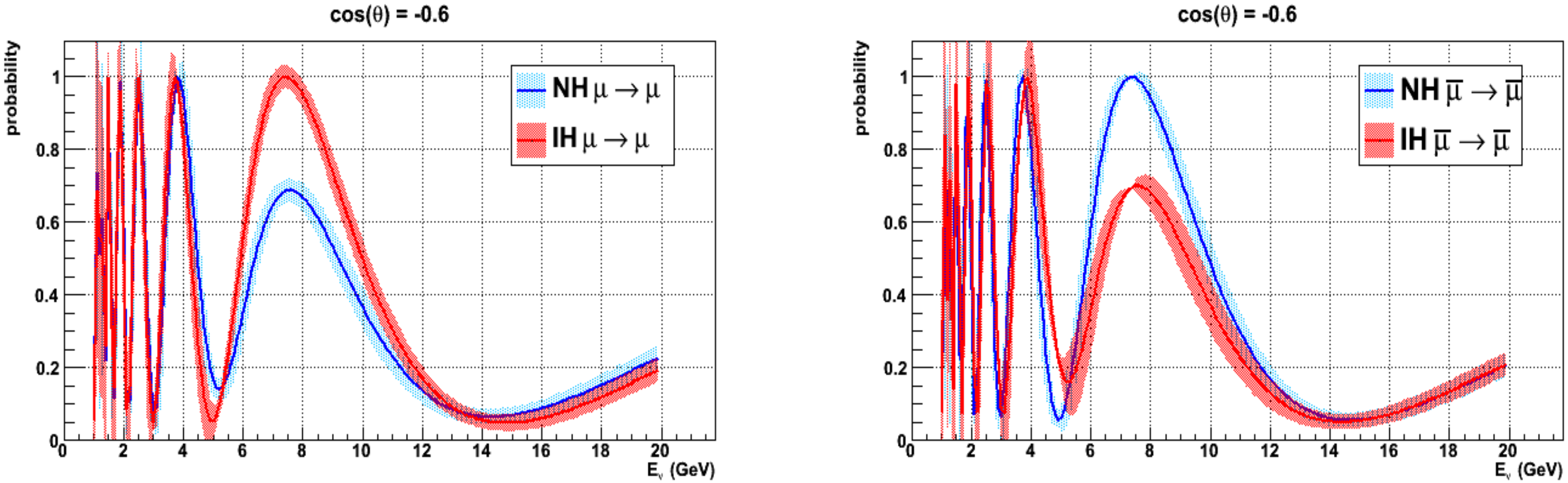
$$\Delta_{13} = \frac{\Delta m_{13}^2}{2E_\nu} \qquad \sin^2(2\theta_{13}^{\text{eff}}) = \frac{\Delta_{13}^2\sin^2(2\theta_{13})}{\Delta_{13}^{\text{eff}}L}$$

$$\Delta_{13}^{\text{eff}} = \sqrt{[\Delta_{13}\cos(2\theta_{13}) - A]^2 + \Delta_{13}^2\sin^2(2\theta_{13})}$$

$$A = \sqrt{2}G_F N_e \text{ for } \nu \text{ and } A = -\sqrt{2}G_F N_e \text{ for } \bar{\nu}$$

$$E_\nu^{\text{res}} = \pm\frac{\Delta m_{13}^2\cos(2\theta_{13})}{2\sqrt{2}G_F N_e}$$

ν_μ oscillation probability



neutrinos and anti-neutrinos have opposite behaviour and contributions will cancel if summed, but

- different cross section
- different flux

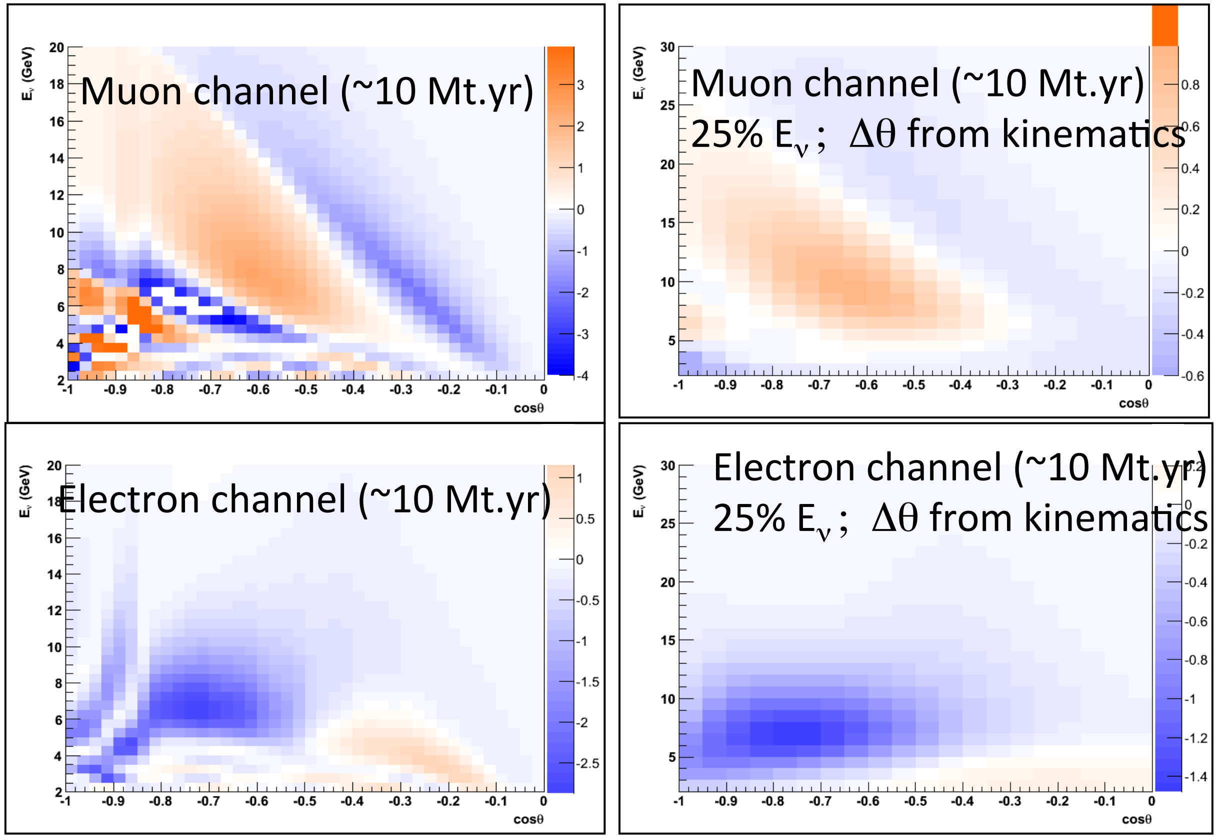
A very challenging experiments

- Relatively low statistics for energy above 2-3 GeV
- Presence of both neutrinos and anti-neutrinos in the atmospheric flux
  - no magnetic field
  - speculation about experimental access to inelasticity in order to disentangle between neutrinos and anti-neutrinos
- Flavour (mis) identification
- Neutral current vs Cascade events
- Smearing of signal over energies and zenith angles due to experimental resolutions
- Uncertainties due to poor knowledge of
  - neutrino cross sections
  - flux and shape of atmospheric neutrino spectra
  - …
  - neutrino properties

Oscillation pattern and sensitivity in the muon and electron channel

- Sensitivity and detector resolution effects:

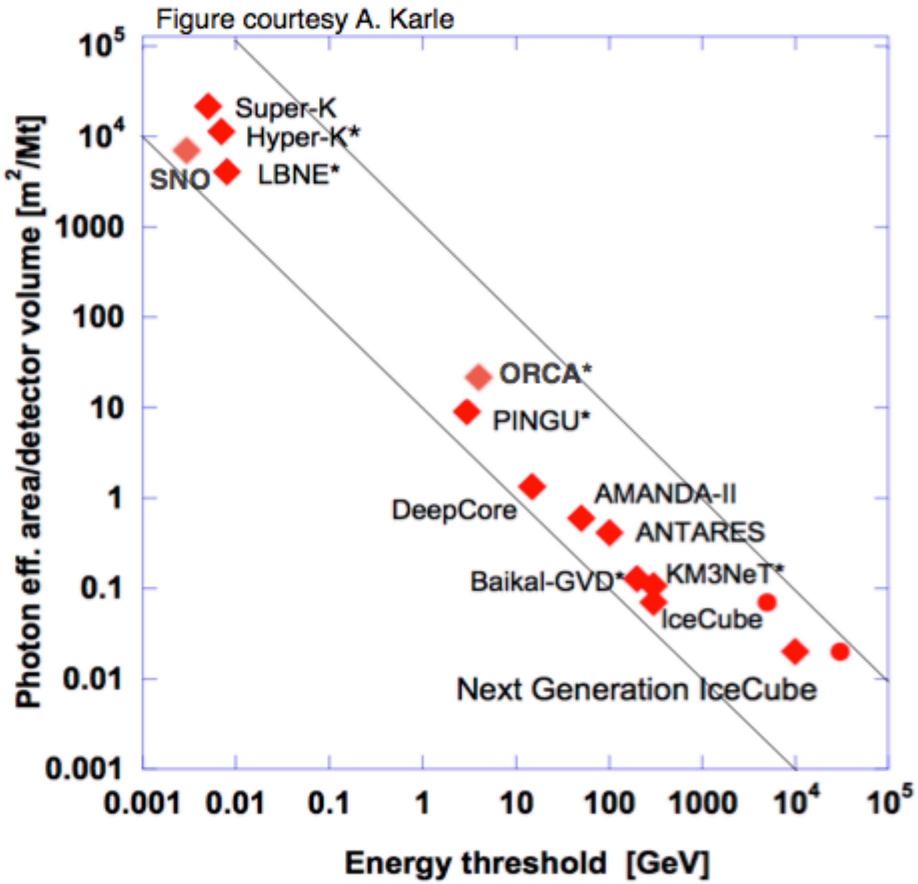
$(N^{IH} - N^{NH}) / (N^{NH})^{1/2}$ $(N^{IH} - N^{NH}) / (N^{NH})^{1/2}$



- Maximum sensitivity between 5 GeV and 10 GeV

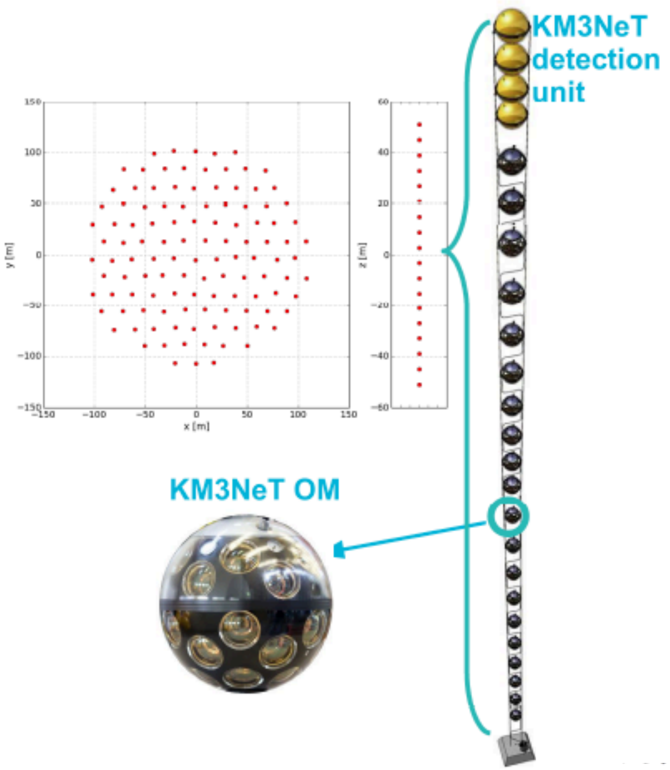
Detector "granularity"

- ✓ Detection threshold decreases with increasing photocathode area density



ORCA detector

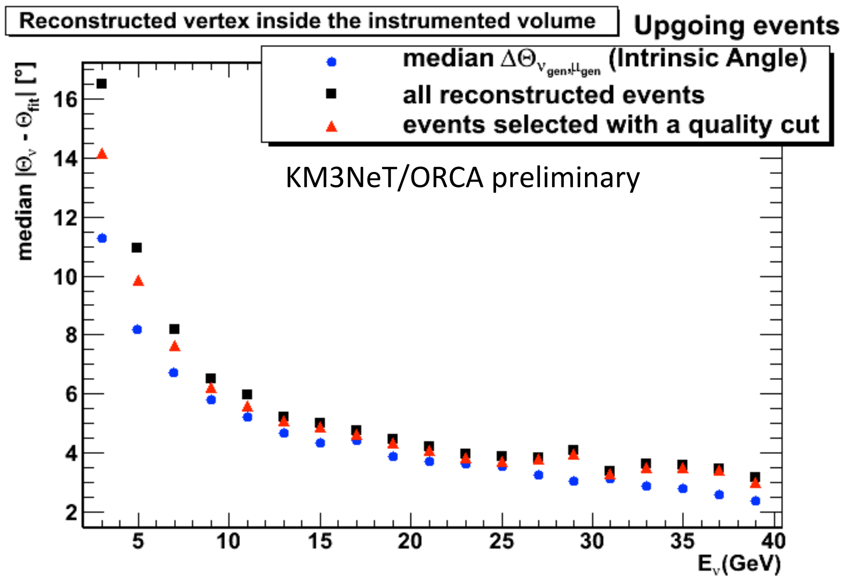
- ORCA is part of the KM3NeT research infrastructure
  - A different detector with same technology, but Mton instead of Gton scale
  - Few GeV signal => more compact detector (75 times denser!)

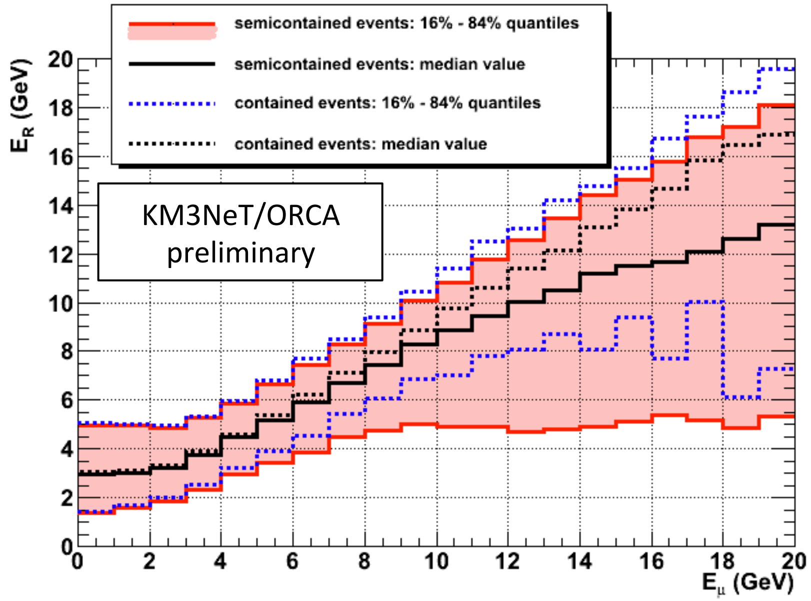


- 115 detection units, 20m spacing
- 18 Optical Modules (DOMs) per detection unit
- 6m vertical distance between DOMs
- 31 3” PMTs/DOM
- Instrumented volume 3.75 Mtons
- Estimated cost 40 M€ (conservative)
- Geometry optimisation study ongoing

ORCA resolution: muon channel

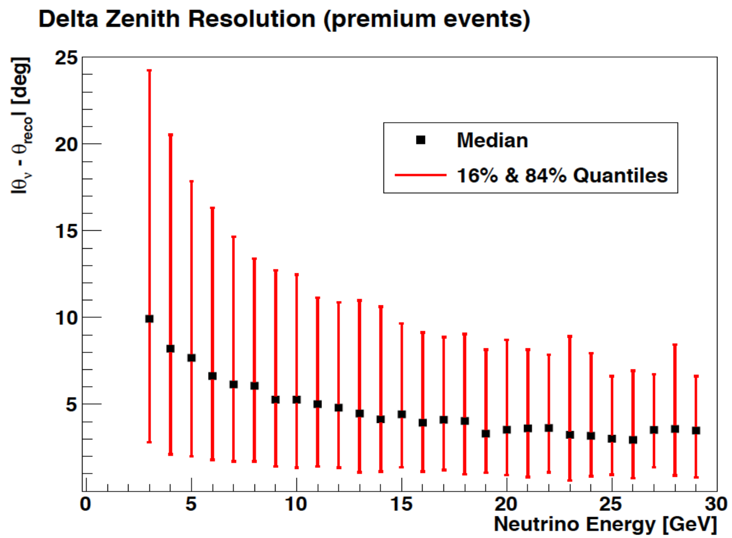
- Results obtained with the “reference detector”: 50 strings, 20 DOM, 20 m spaced, 6 m spacing between DOMs
- Resolutions on ν_μ CC events with E_ν > 5 GeV:
  - Zenith angle resolution: about 5° in the 5-10 GeV energy range
  - Track length as energy estimator, hadronic shower at vertex not included => Energy resolution: better than 35%

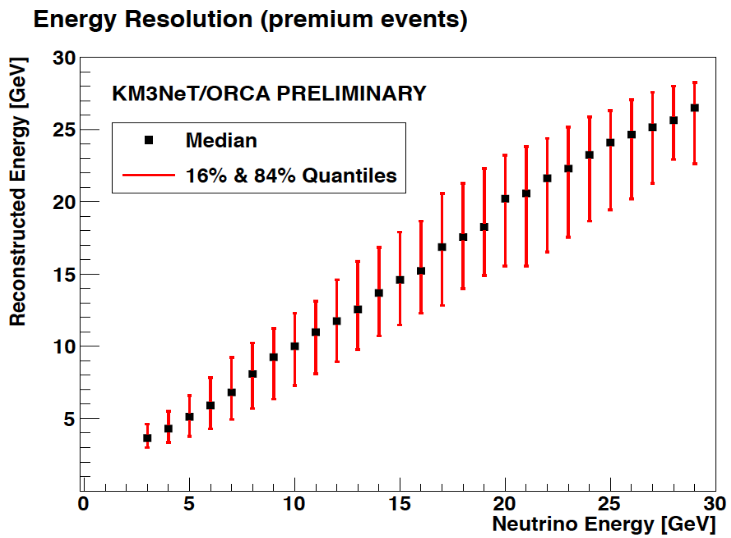




ORCA resolution: electron channel

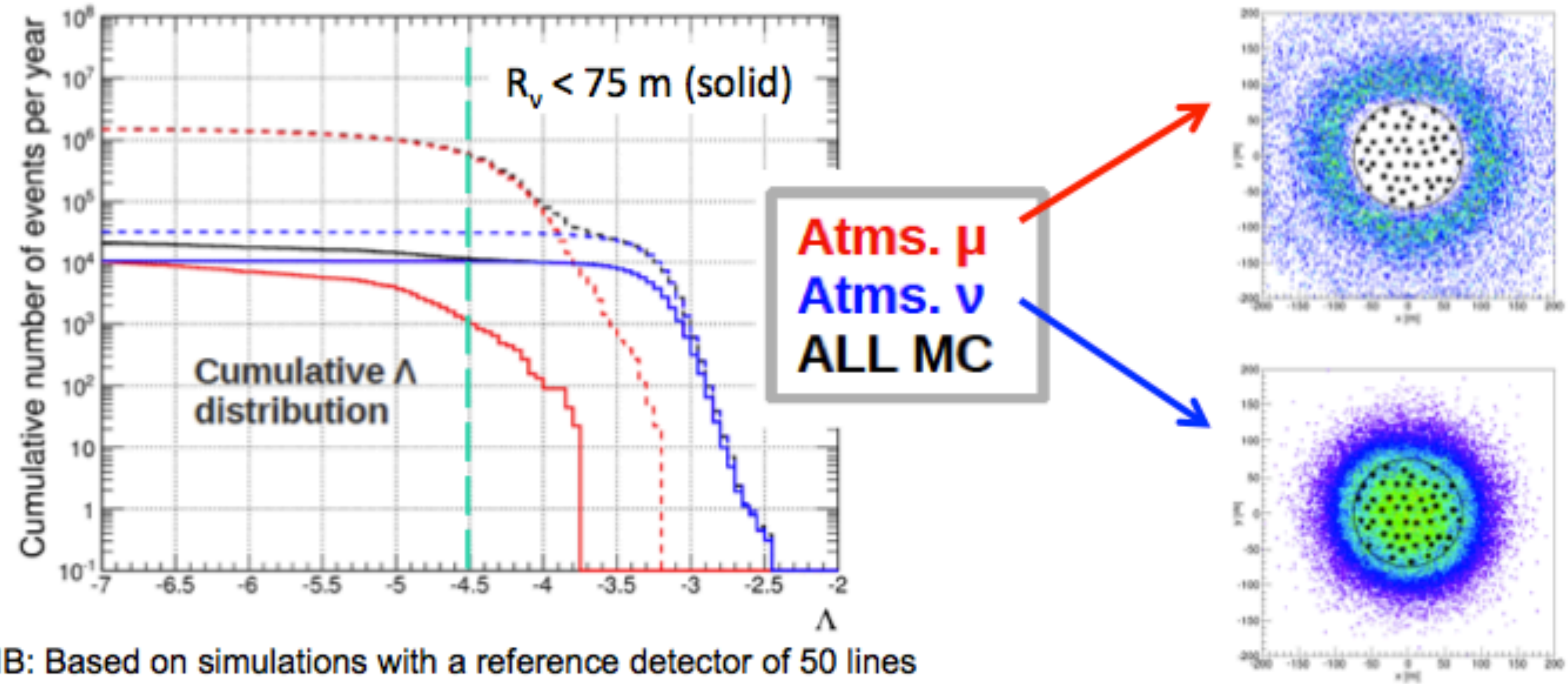
- Results obtained with the reference detector: 50 strings, 20 DOM, 20 m spaced, 6 m spacing between DOMs
- Selection of golden events
- Resolutions on ν_e CC events with E_ν > 5 GeV:
  - Zenith angle resolution: better than 10º
  - Energy resolution: better than 30%





Atmospheric muon rejection

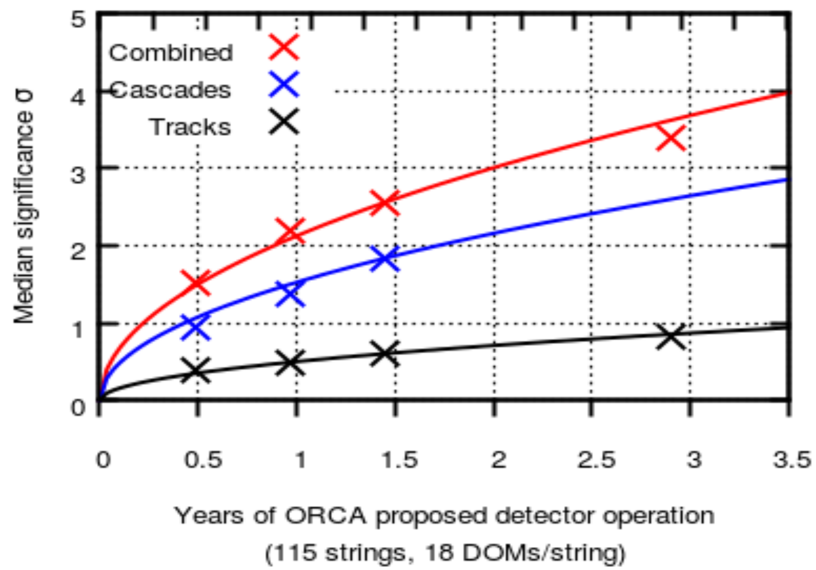
- No active veto needed



NB: Based on simulations with a reference detector of 50 lines

ORCA sensitivity
Very Preliminary results!!!

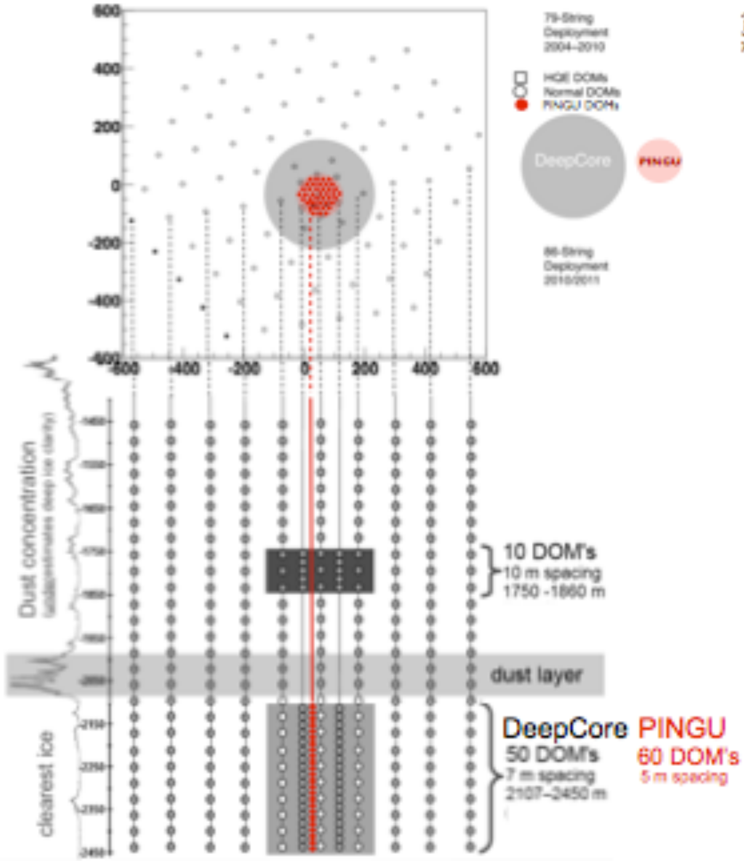
- Goal: Neutrino Mass Hierarchy determined at 3σ level after about 3 years of data taking with 115 detection units
- Fit θ_{23}, $\Delta M2$ and δ
- 1° octant assumed for θ_{23}
- Fit on oscillation parameters
- State of art E-θ resolution included
- Channel misindentification tracks vs cascades included, but not optimal
- NC not included
- Analysis very preliminary, a lot of work in progress

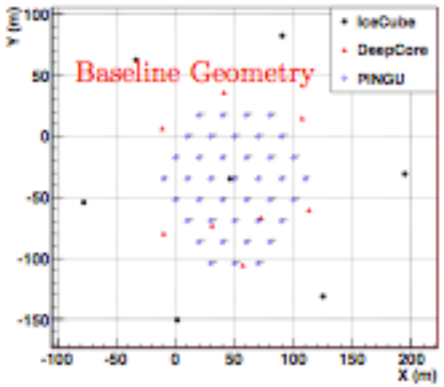


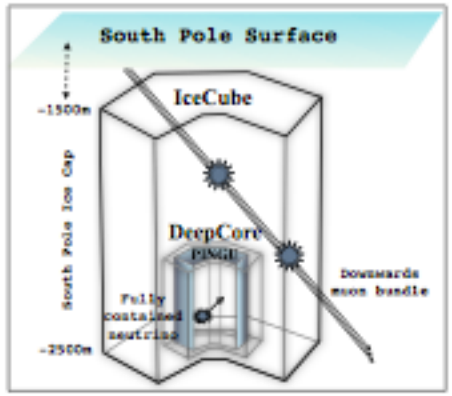
Comparison ORCA-PINGU

- Caveat: direct comparison not straight forward, different methods and ingredients
- A very accurate comparison in progress with a common work in the two collaboration, final results expected soon

PINGU inside IceCube

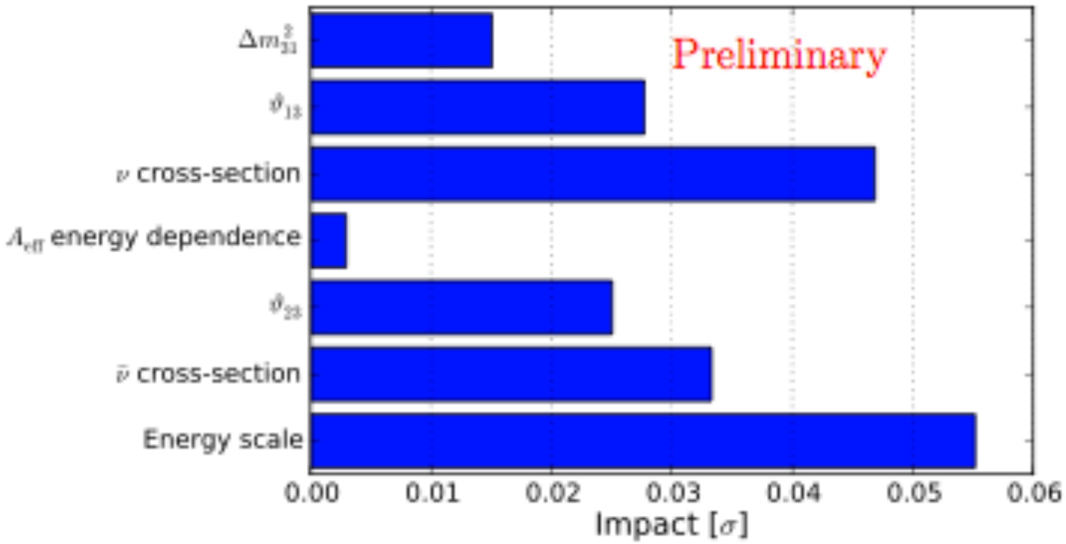




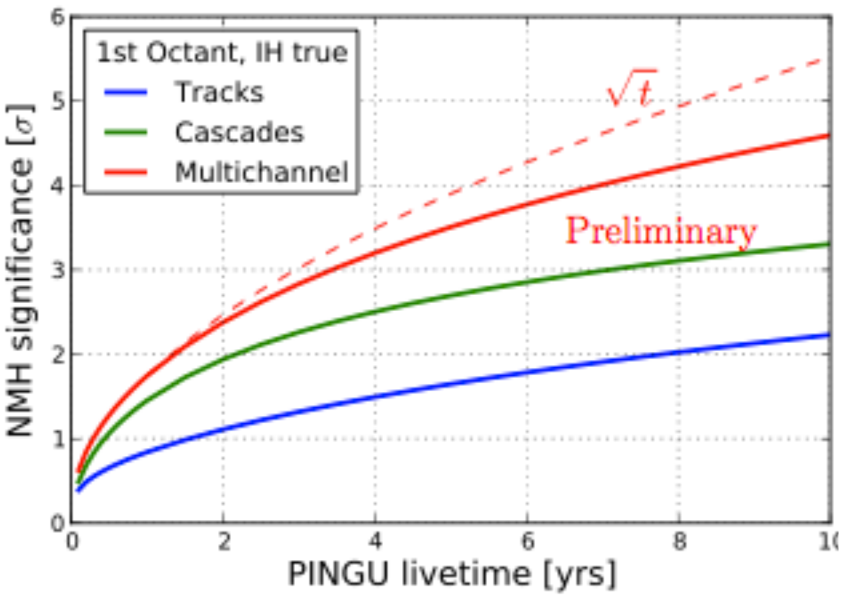


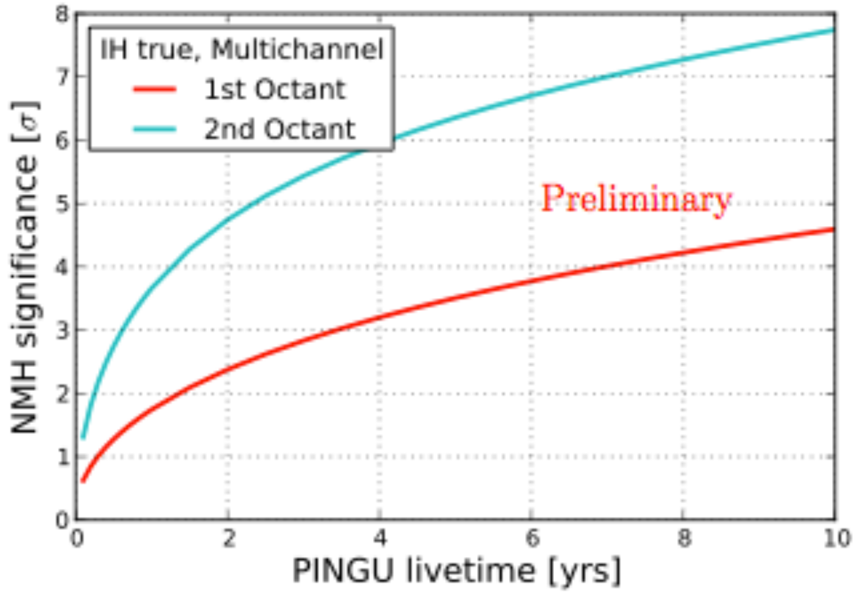
Systematic uncertainties

- Estimates by PINGU collaboration



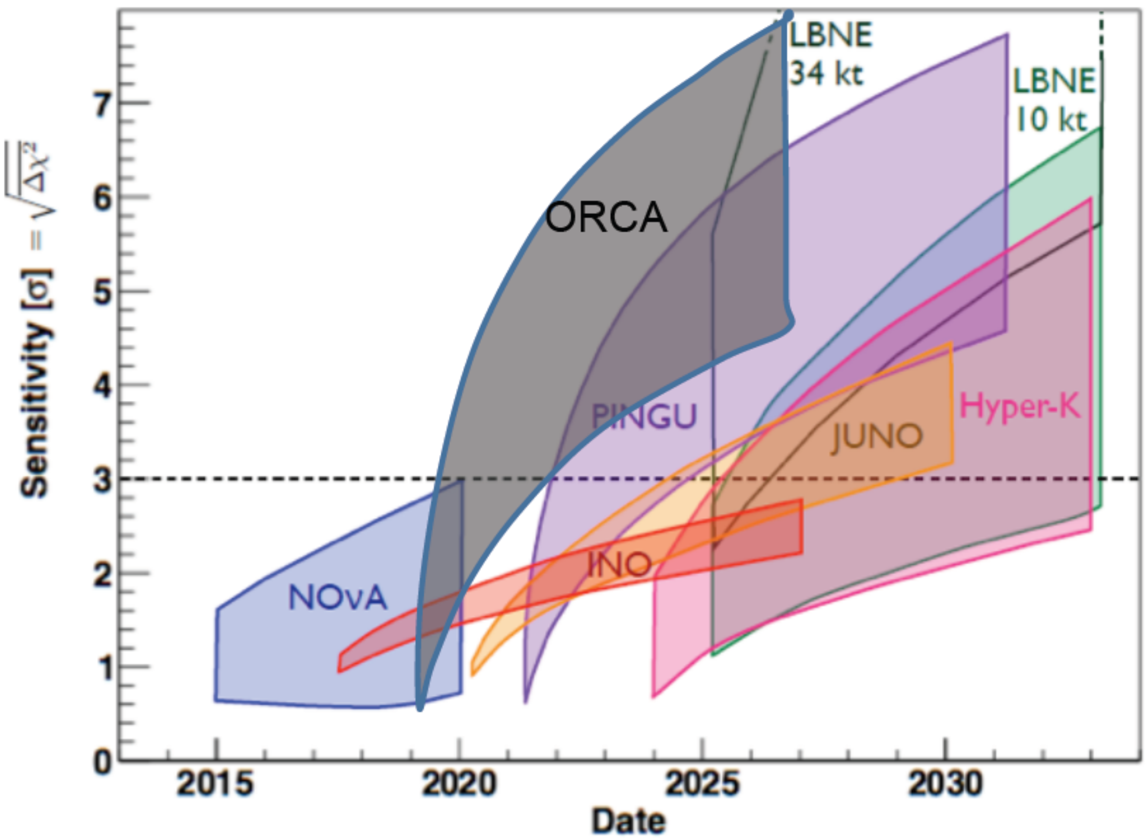
PINGU significance for NMH





Sensitivity of NMH experiments

- We wouldn't like to show this plot, but other people do….



Conclusions and perspectives

- ORCA enforce the KM3NeT case extending the physics case to low energy
  - Focus on Neutrino Mass Hierarchy, but also for Dark Matter indirect search, SuperNovae neutrinos, … are expected to be promising even if not investigated yet
- Competition with PINGU
- LoI to be releasd at beginning 2015
- Demostrator made of 6 strings to be deployed in Toulon in 2016 allow to validate technology and prove feasibility approved in the KM3NeT IB

BACK UP

Sensitivity studies

Global Fit Approach

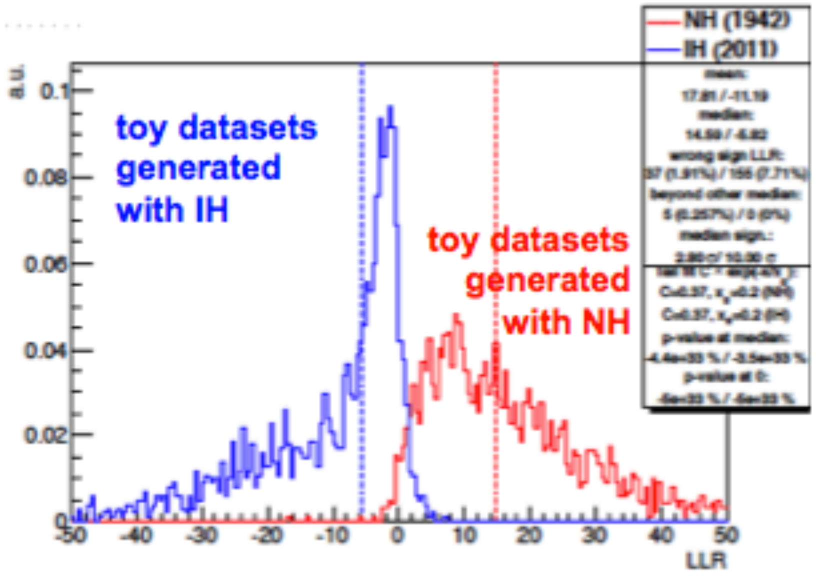
The performance of ORCA for the determination of the NMH is assessed by means of a likelihood ratio test:

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

$\hat{\theta}^{\text{H}} =$ maximum-likelihood estimates for the Δm^2's and angles using both data and constraints from global fit.
nb: constraints are different for H=IH and H=NH

1) fit mixing parameters assuming NH
2) fit mixing parameters assuming IH
3) compute ΔlogL = log(L(NH)/L(IH))

θ_{23} , Δm^2 and δ_{CP} can be fitted from data.



Sensitivity studies

Global fit approach to the mass hierarchy discrimination:

likelihood ratio test *with nuisance parameters*

(→ deal with degeneracies by fitting)

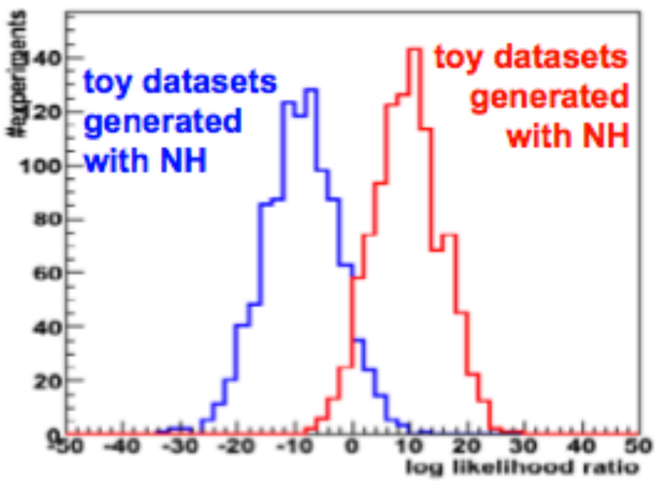
1) fit mixing parameters assuming NH

2) fit mixing parameters assuming IH

3) compute

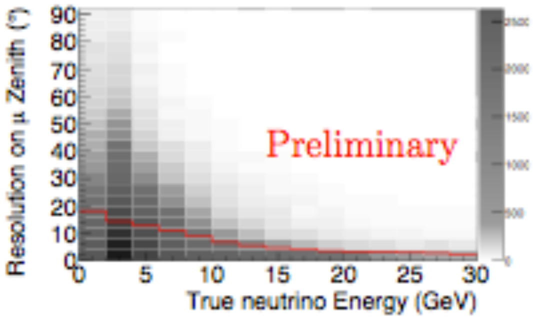
$$\Delta \log(L^{\max}) = \sum_{\text{bins}} \log P(\text{data}|\hat{\theta}^{\text{NH}}, \text{NH}) - \log P(\text{data}|\hat{\theta}^{\text{IH}}, \text{IH})$$

$\hat{\theta}^{\text{H}} =$ maximum-likelihood estimates for the Δm^2's and angles using both data and constraints from global fit.
nb: constraints are different for H=IH and H=NH

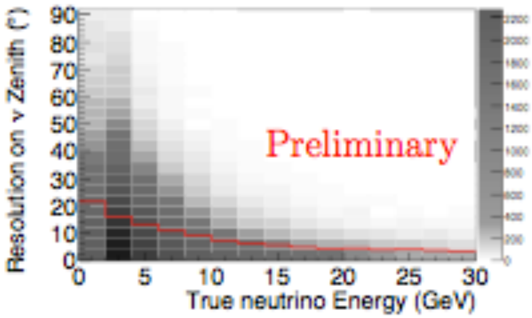


(example shown is for 10 Mt*yr)

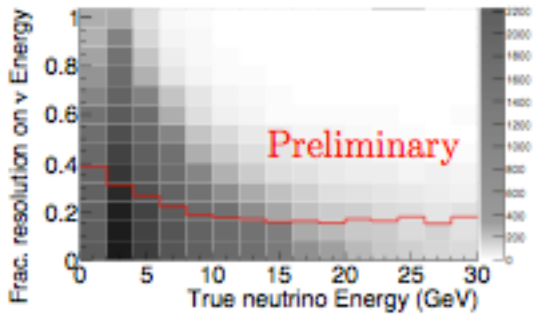
ν_μ



(a) $|\theta_{\mu,\mathrm{true}} - \theta_{\mu,\mathrm{reco}}|$ vs. $E_{\nu,\mathrm{true}}$.

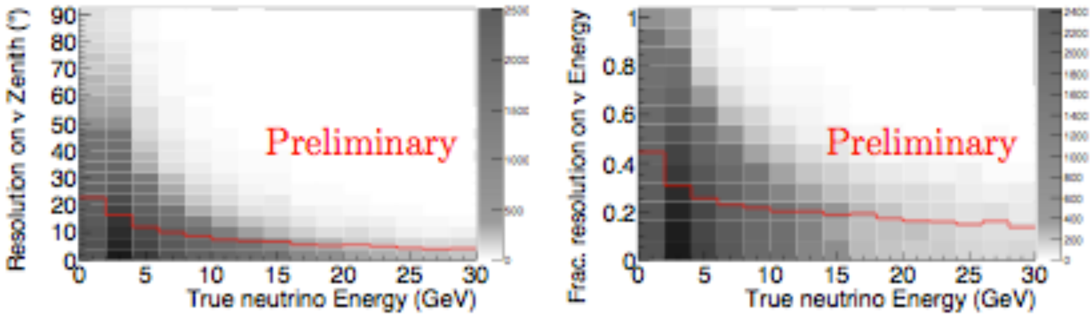


(b) $|\theta_{\nu,\mathrm{true}} - \theta_{\nu,\mathrm{reco}}|$ vs. $E_{\nu,\mathrm{true}}$.



(c) $|E_{\nu,\mathrm{reco}} - E_{\nu,\mathrm{true}}|/E_{\nu,\mathrm{true}}$ vs. $E_{\nu,\mathrm{true}}$.

ν_e



(a) $|\theta_{\nu,\mathrm{true}} - \theta_{\nu,\mathrm{reco}}|$ vs. $E_{\nu,\mathrm{true}}$.

(b) $|E_{\nu,\mathrm{reco}} - E_{\nu,\mathrm{true}}|/E_{\nu,\mathrm{true}}$ vs. $E_{\nu,\mathrm{true}}$.

Figure 8: Zenith angle and fractional energy resolutions for ν_e events with reconstructed vertices within the PINGU fiducial volume. The red line indicates the median value in each bin. The gray scale indicates number of simulated events in each bin. The resolutions for ν_τ and NC events are similar.

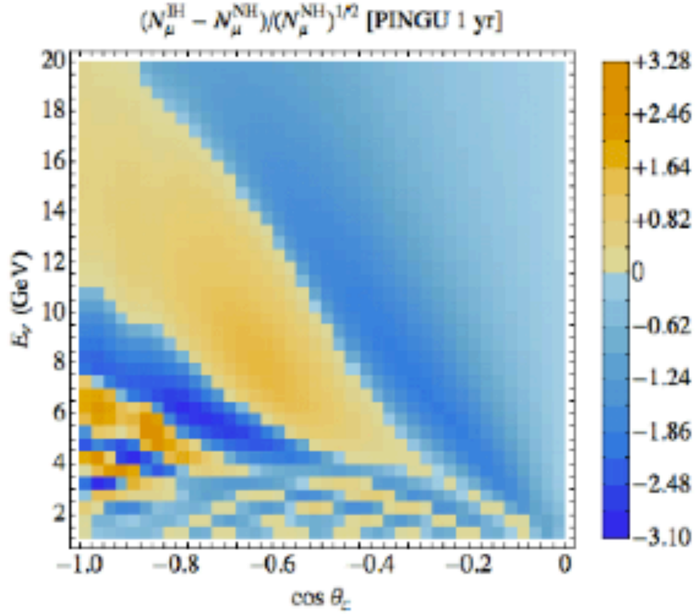
Method

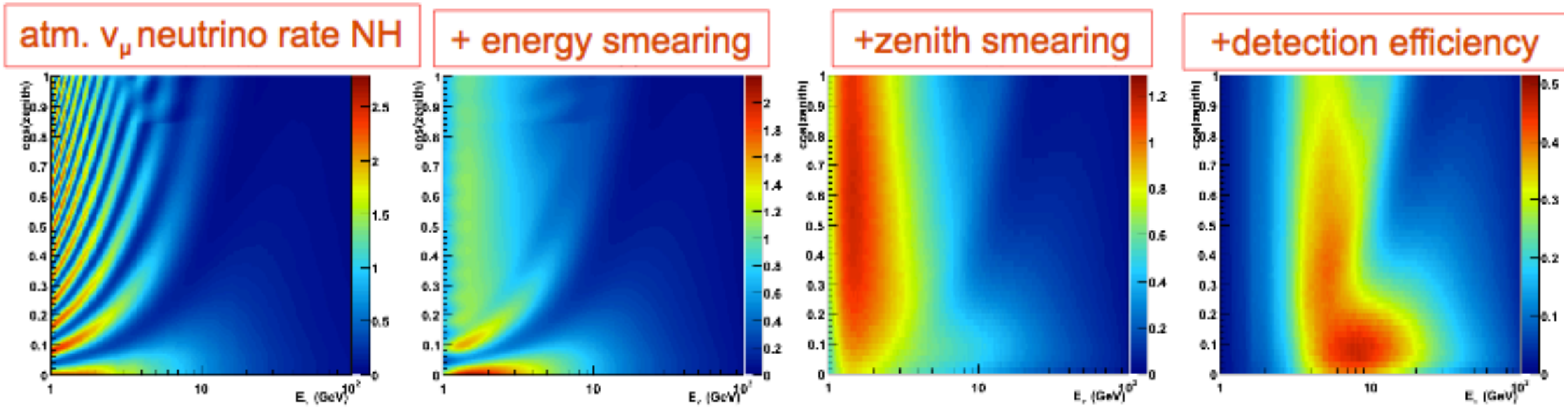
Possible strategy for the determination of NMH: probe $\nu_e \leftrightarrow \nu_\mu$ oscillation in presence of matter effects which allow to resolve the sign of Δm^2_{13}

The oscillation enhancement is maximal

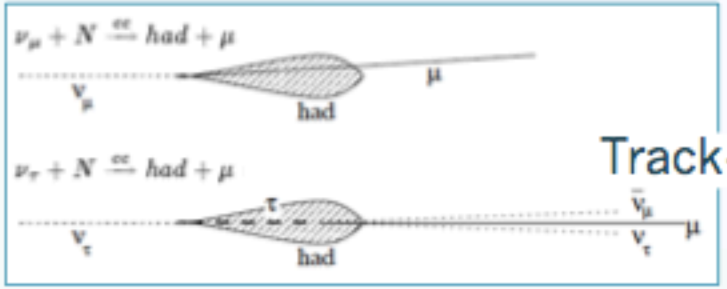
at resonance energy: $$E_\nu^{\mathrm{res}} = \pm\frac{\Delta m^2_{13}\cos(2\theta_{13})}{2\sqrt{2}G_F N_e}$$

Eres ~ few GeV at Earth density

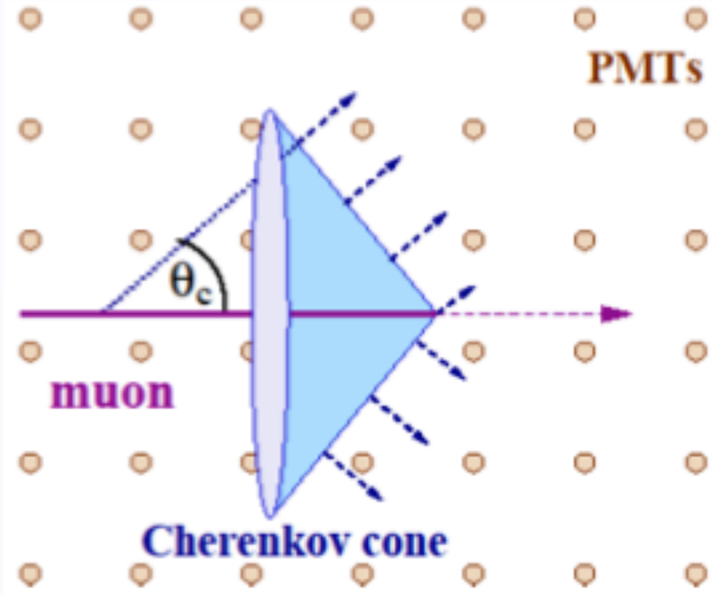




Event topologies

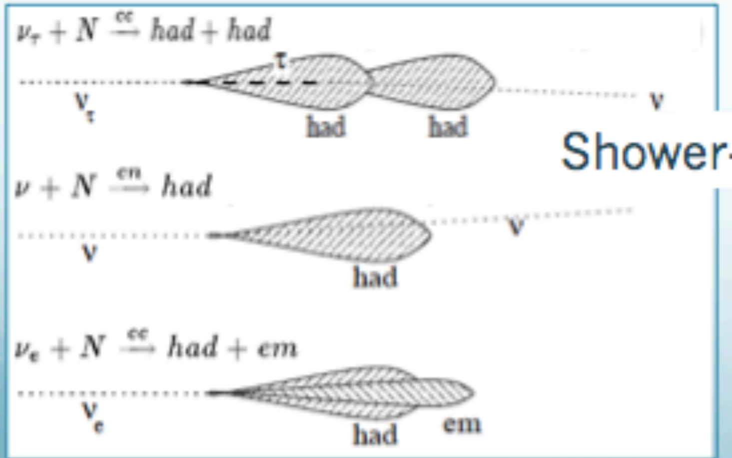


Track-like

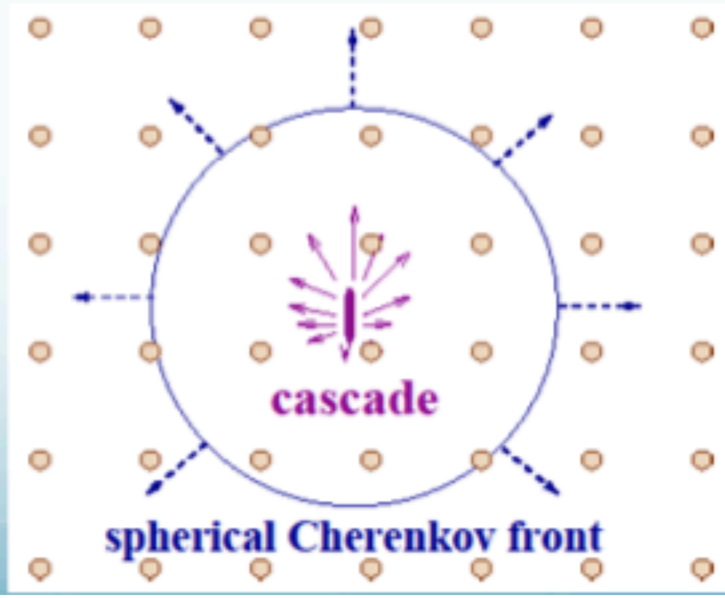


Track-like contains both a cascade and one track

Not to scale



Shower-like



No track is identified