Neutrino mass hierarchy with ORCA

Thomas Eberl
on behalf of the KM3NeT collaboration

Beijing, August 21st 2013
International Workshop on Neutrino Factories, Super Beams and Beta Beams

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ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS
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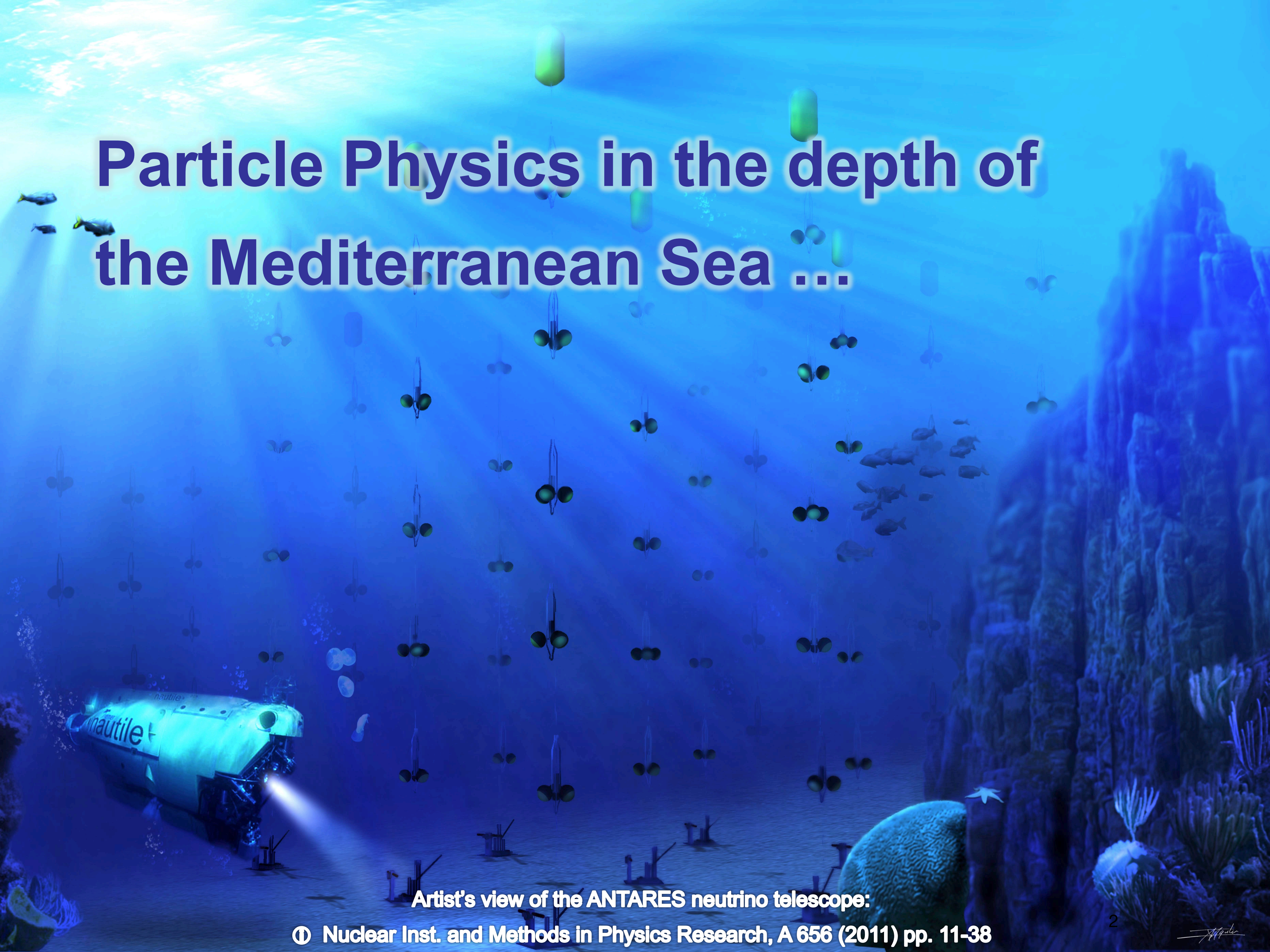
Particle Physics in the depth of the Mediterranean Sea …



Artist's view of the ANTARES neutrino telescope:

Nuclear Inst. and Methods in Physics Research, A 656 (2011) pp. 11-38

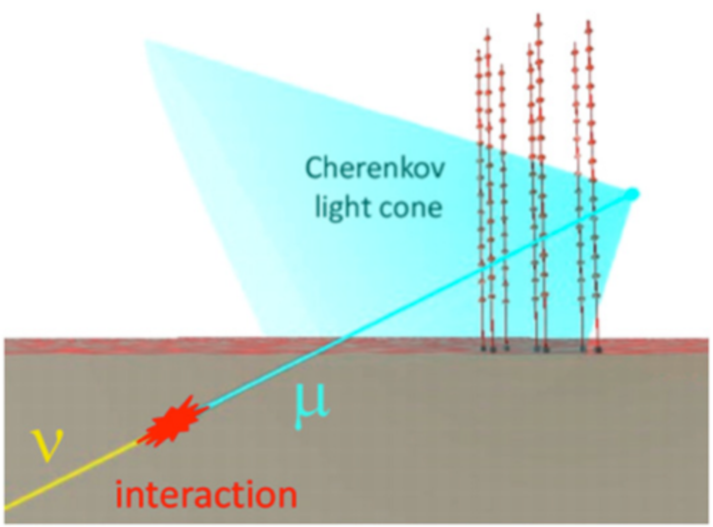
… with megaton water Cherenkov detectors

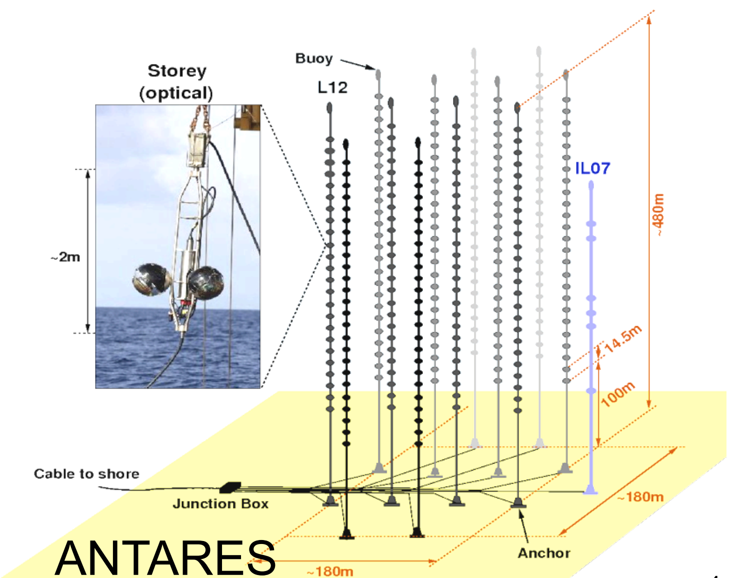
Artist's view of the ANTARES neutrino telescope:

ⓘ Nuclear Inst. and Methods in Physics Research, A 656 (2011) pp. 11-38

Measuring neutrinos with neutrino telescopes

- Neutrino telescopes in water or ice: large 3D arrays of PMTs measure Cherenkov light from secondary charged particles, allow reconstruction of neutrino direction and energy
- Main focus on neutrino energies $> \mathcal{O}(1\ \mathrm{TeV})$
- Goal: Discover neutrino fluxes from astrophysical sources
- Current instruments, ANTARES and IceCube DeepCore sensitive down to ~10 GeV





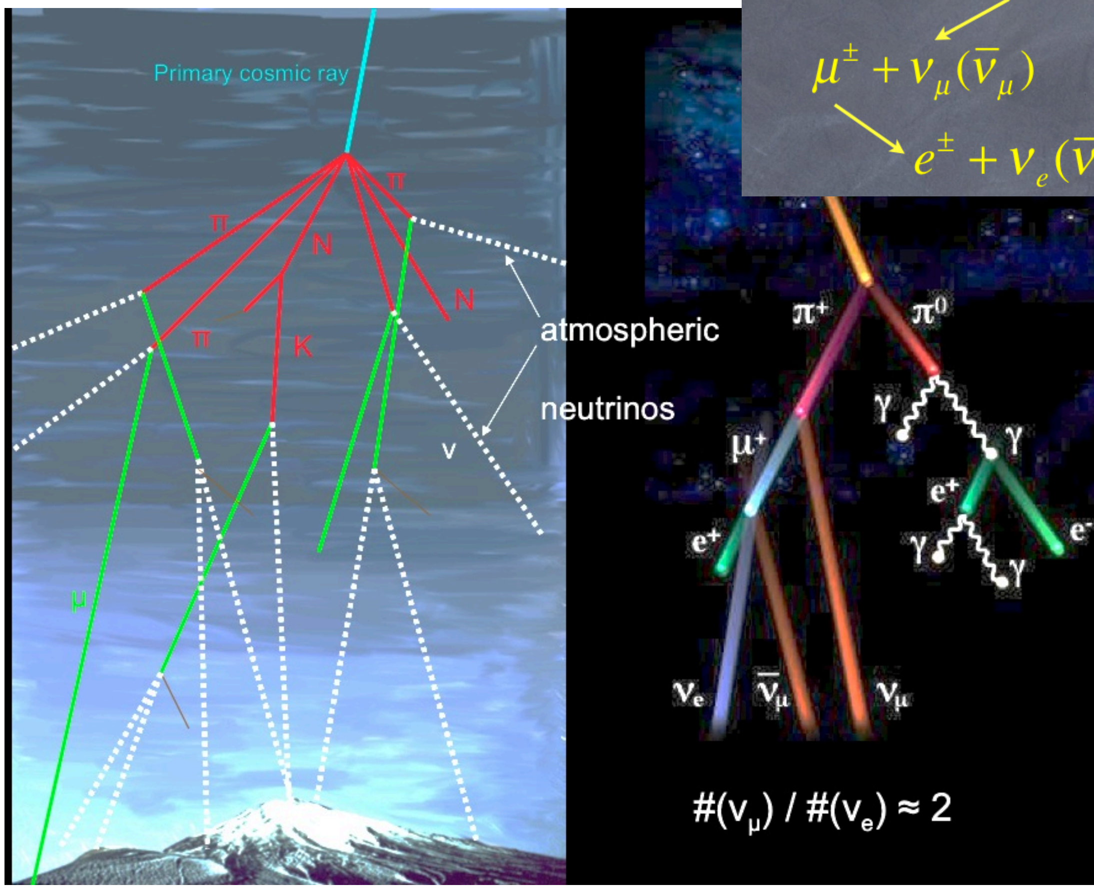
ANTARES

Production of Atmospheric Neutrinos

$$p + X \rightarrow \pi^{\pm} / K^{\pm} + Y$$

$$\mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

$$e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$



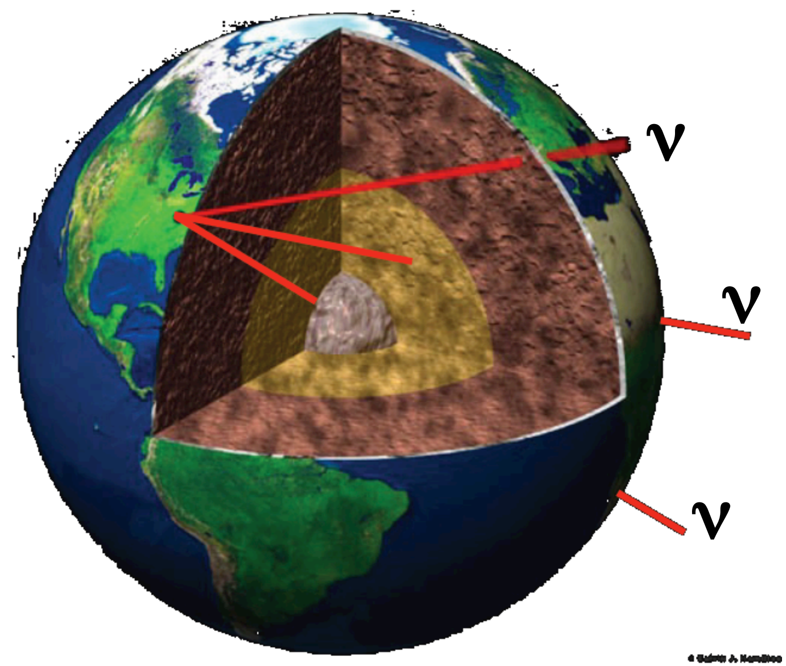
Oscillations of Atmospheric Neutrinos

- Neutrinos oscillating over one Earth diameter have a ν_μ survival minimum at ~25 GeV
  - Hierarchy-dependent matter effects below ~10-20 GeV

- Neutrinos are available over a wide range of energies and baselines

  - Comparison of observations from different baselines and energies is crucial for controlling systematics

  - Essentially, a generalization of the up-down ratio approach

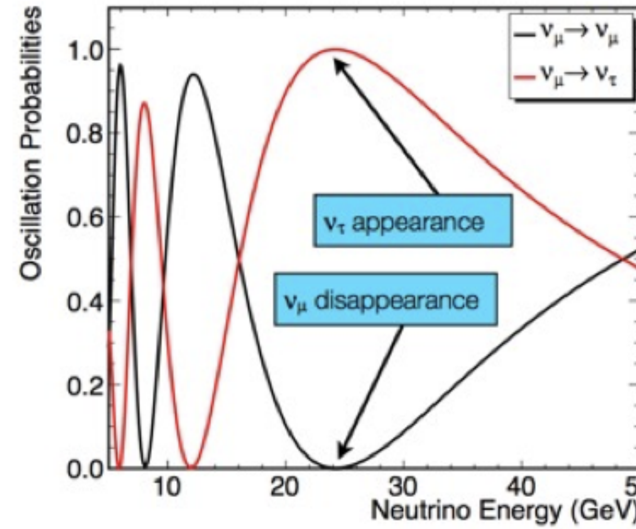


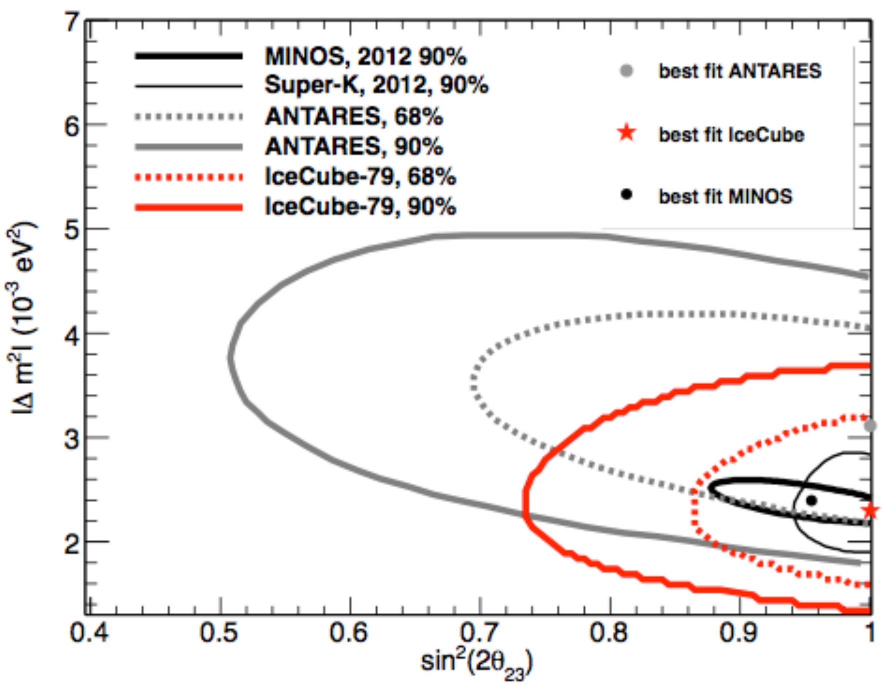
First Neutrino Oscillation Results from Neutrino Telescopes

Vacuum neutrino oscillations:

- ν_μ disappearance at ~25 GeV (Earth diameter),
- event reconstruction down to $E_\nu \sim 10$ GeV

Mena et al. PR D78 2008





Oscillation parameters measured with atmospheric muon neutrinos:

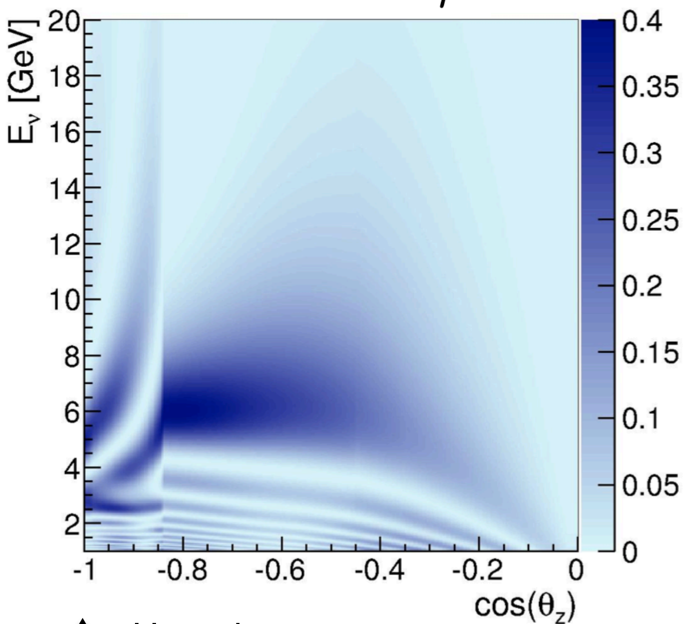
IceCube: arXiv:1305.3909
ANTARES: Phys.Lett. B714 (2012)

→ demonstrates potential of megaton water / ice Cherenkov detectors

Oscillograms for propagation through Earth

Appearance and survival probability of upgoing muon neutrinos

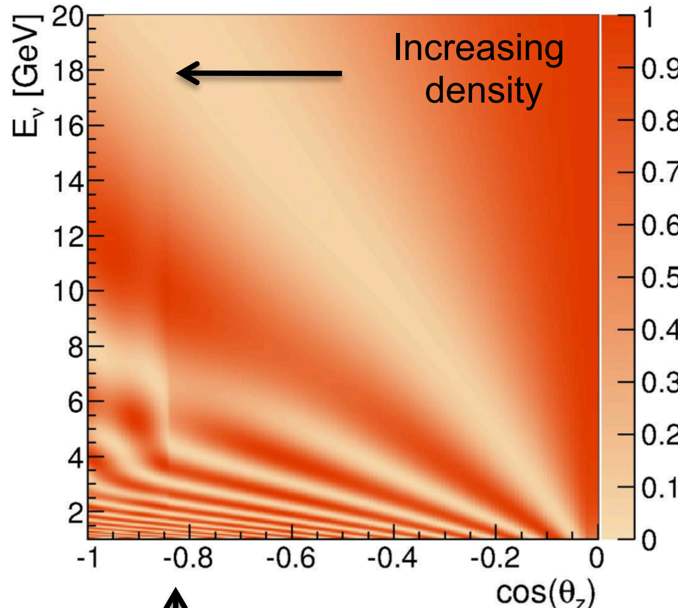
$\nu_e \rightarrow \nu_\mu$



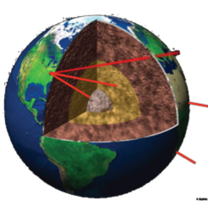
Up-going

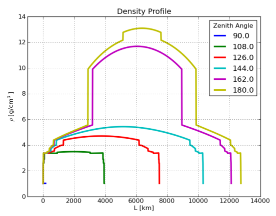
horizontal

$\nu_\mu \rightarrow \nu_\mu$



Outer core



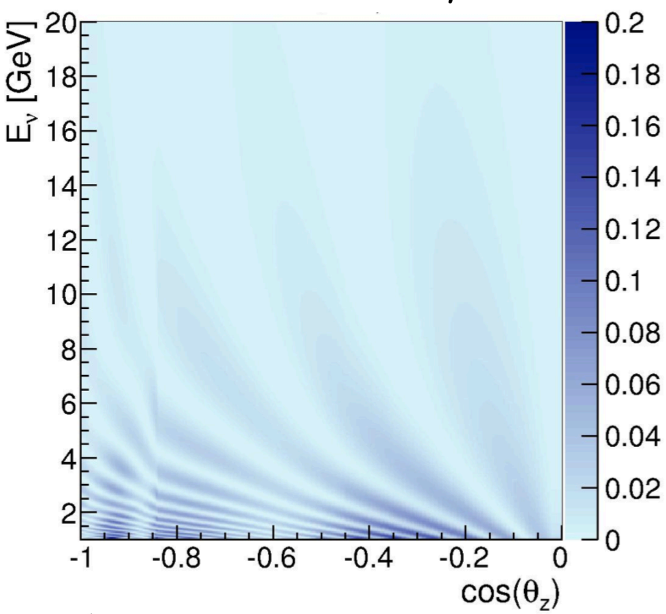


- neutrinos, **normal** hierarchy
- earth density profile: PREM
- oscillation parameters from Fogli, PRD 86(1), p.013012, 2012

Oscillograms for propagation through Earth

Appearance and survival probability of upgoing muon neutrinos

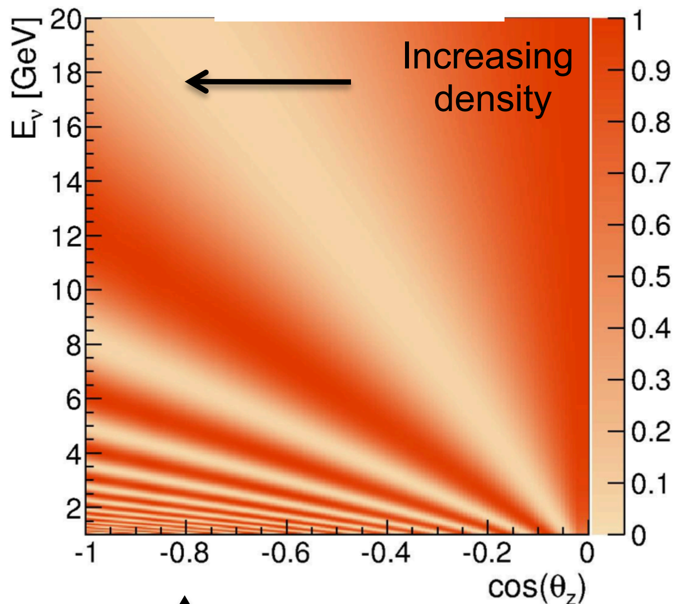
$\nu_e \rightarrow \nu_\mu$



Up-going

horizontal

$\nu_\mu \rightarrow \nu_\mu$



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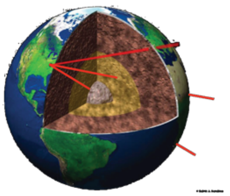
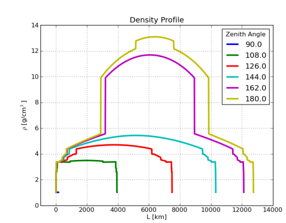


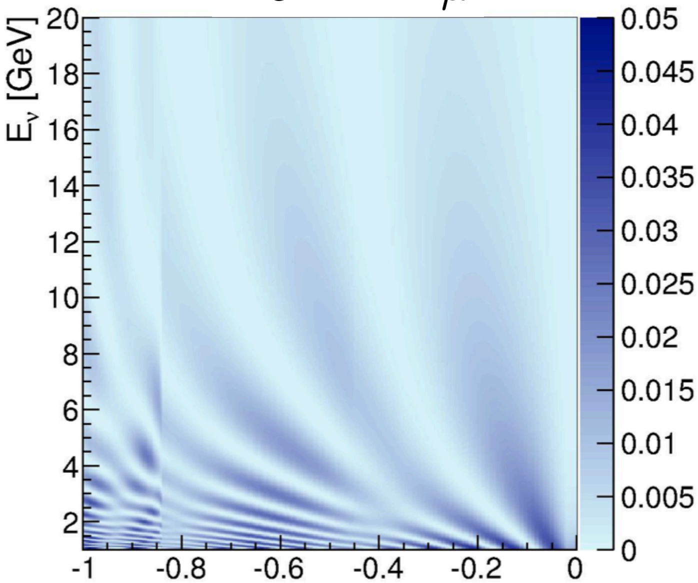


- neutrinos, **inverted** hierarchy
- earth density profile: PREM
- oscillation parameters from Fogli, PRD 86(1), p.013012, 2012

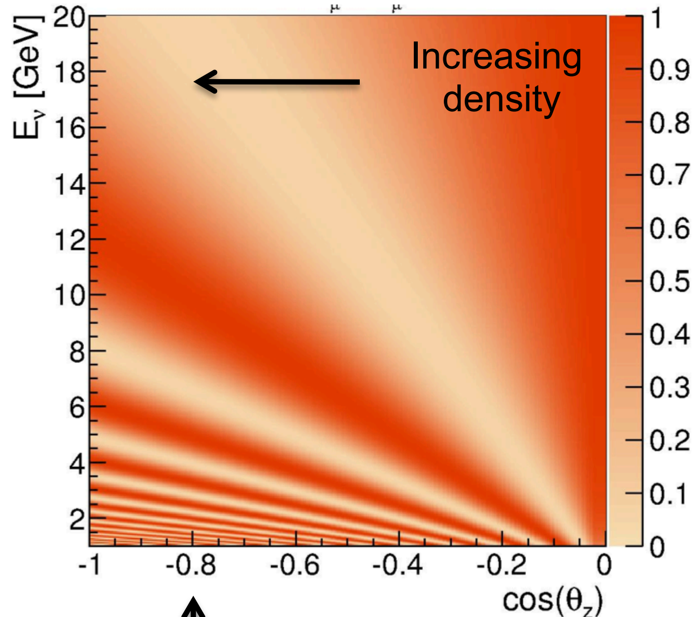
Oscillograms for propagation through Earth

Appearance and survival probability of upgoing muon antineutrinos

$\overline{\nu}_e \rightarrow \overline{\nu}_\mu$



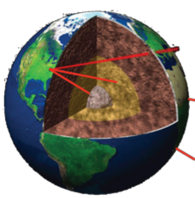
$\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu$

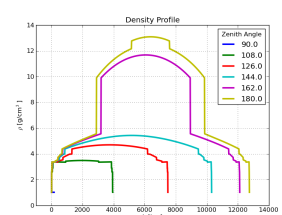


Up-going

horizontal

Outer core

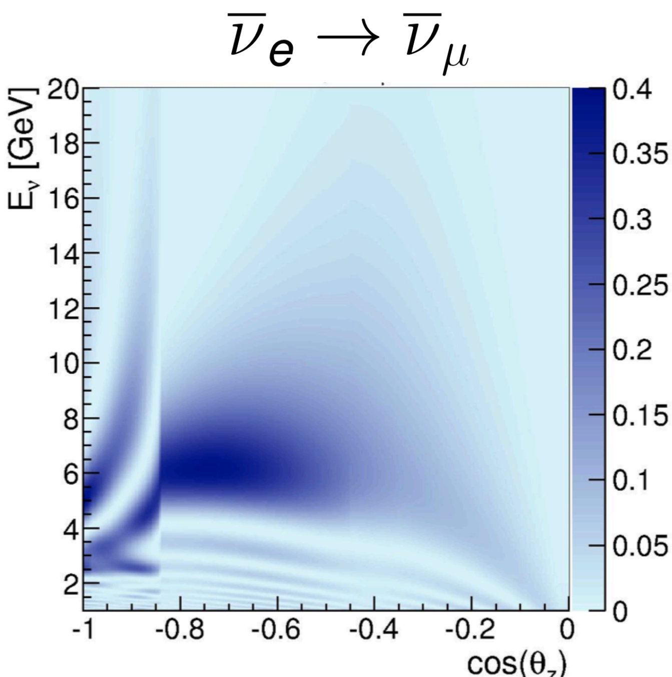


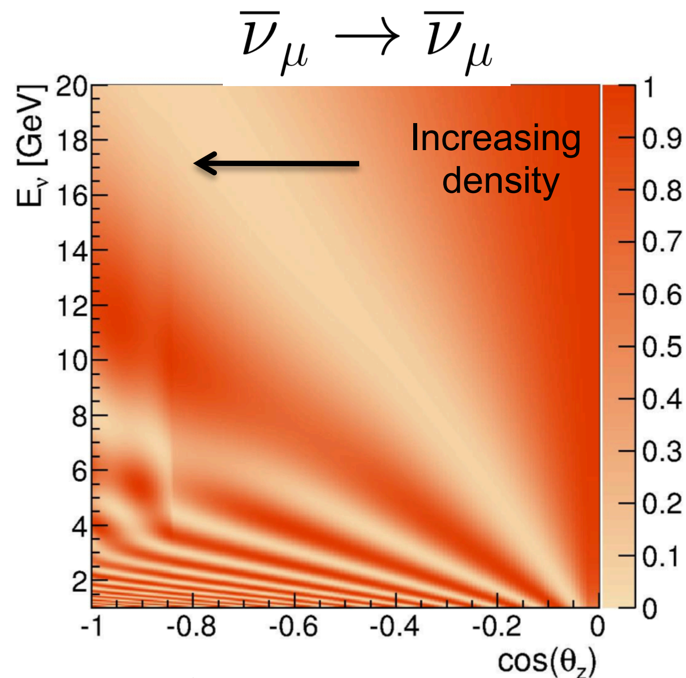


- antineutrinos, **normal** hierarchy
- earth density profile: PREM
- oscillation parameters from Fogli, PRD 86(1), p.013012, 2012

Oscillograms for propagation through Earth

Appearance and survival probability of upgoing muon antineutrinos

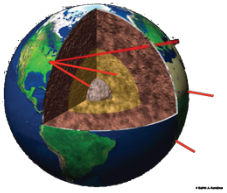


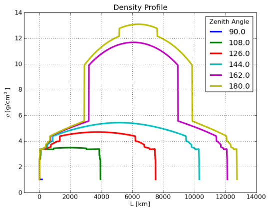


Up-going

horizontal

Outer core





- antineutrinos, **inverted** hierarchy
- earth density profile: PREM
- oscillation parameters from Fogli, PRD 86(1), p.013012, 2012

MSW: resonant neutrino oscillations in matter

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- 3-flavour oscillations of ν_e <-> ν_μ in matter show resonance for neutrinos in normal hierarchy and antineutrinos in inverted hierarchy
- Effect in principle usable to determine the sign of Δm_{31}^2, i.e. the neutrino mass hierachy!
- Resonance condition in Earth: $E_\nu \approx 30\,\mathrm{GeV}/\rho[\mathrm{g\,cm^{-3}}]$
  i.e. for neutrino energies $E_\nu \sim 3\text{–}10\,\mathrm{GeV}$
- Note however: effect cancels if neutrinos and anti-neutrinos have equal fluxes and cross sections, and if the detector cannot distinguish μ^+ and μ^-.

Neutrino-nucleon cross sections

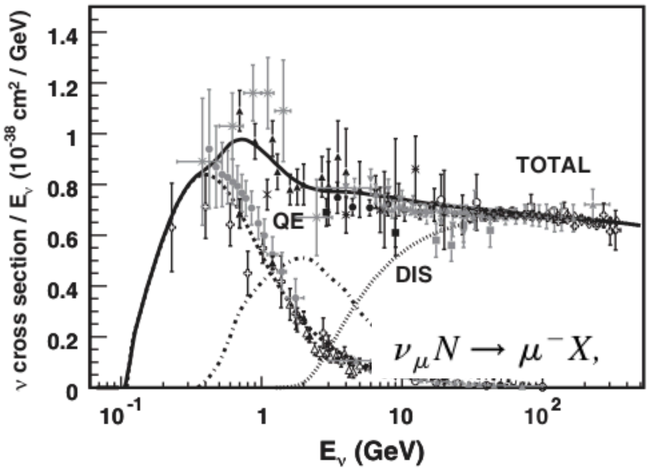
Formaggio, Zeller, Rev. Mod. Phys., 84(3), pp.1307–1341 (2012)

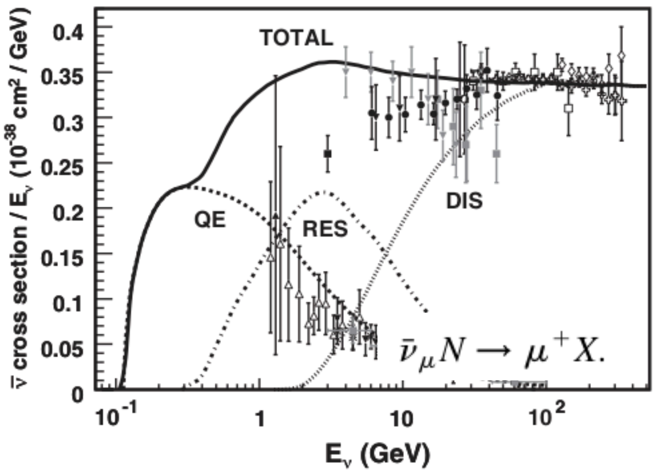
Neutrino

and

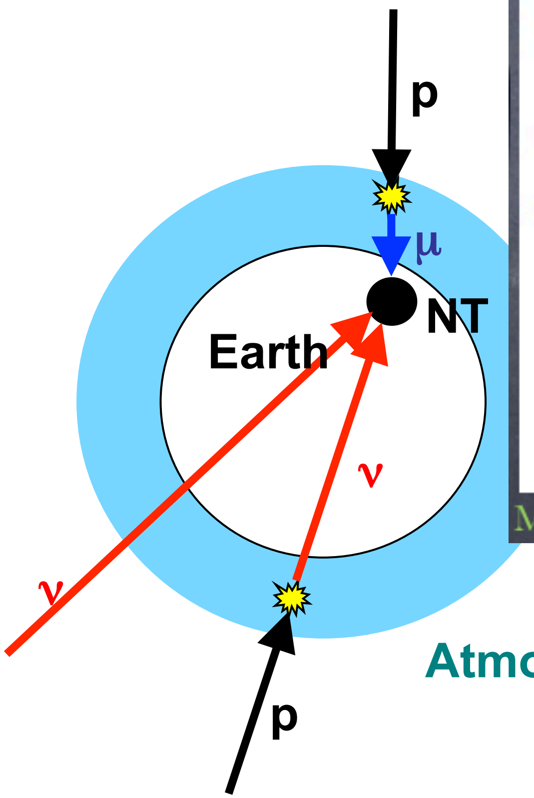
Antineutrino

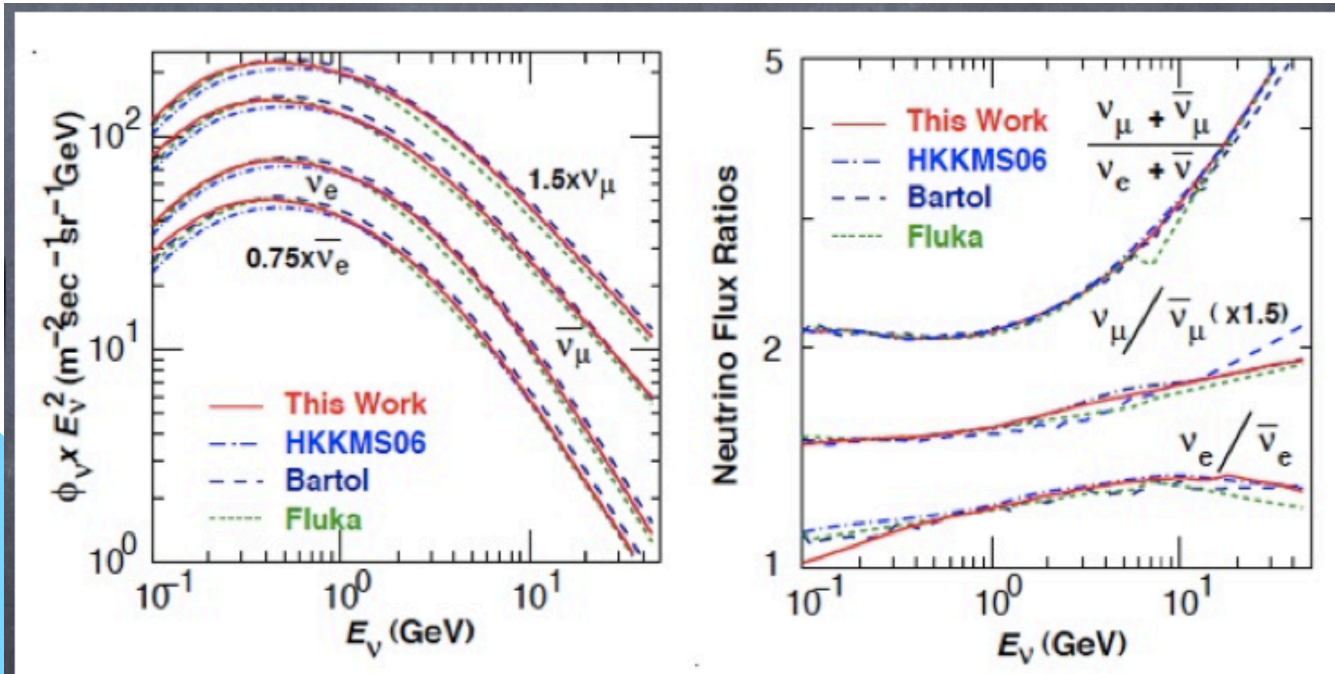
cross sections on the nucleon are different!





Atmospheric neutrino fluxes



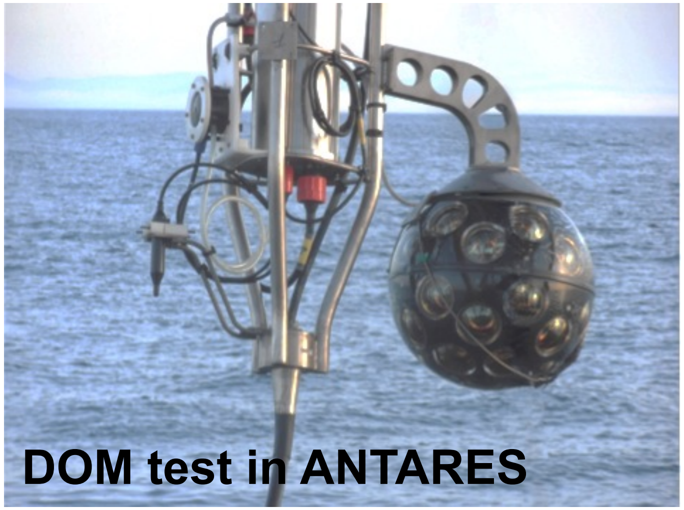


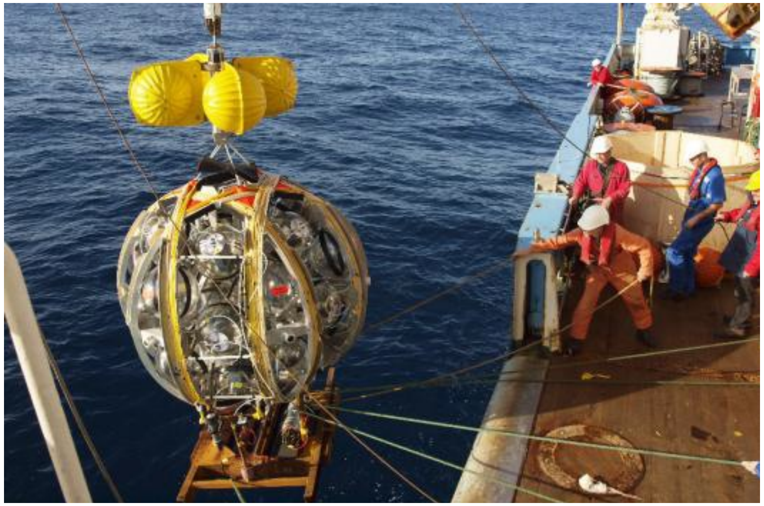
M. Honda, T. Kajita, K. Kasahara and S. Midorikawa, *Phys. Rev.* D83:123001, 2011

Neutrino and anti-neutrino fluxes different!

ORCA and KM3NeT

- ORCA (Oscillations with Cosmics in the Abyss) is an ongoing feasibility study towards a measurement of the neutrino mass hierarchy within the KM3NeT collaboration.
- KM3NeT will be the future very large volume (several cubic kilometer) neutrino telescope in the Mediterranean Sea.
- Start-up funds (40M€) are available for phase-1 and the construction has started with deployment and hardware tests.


DOM test in ANTARES



KM3NeT

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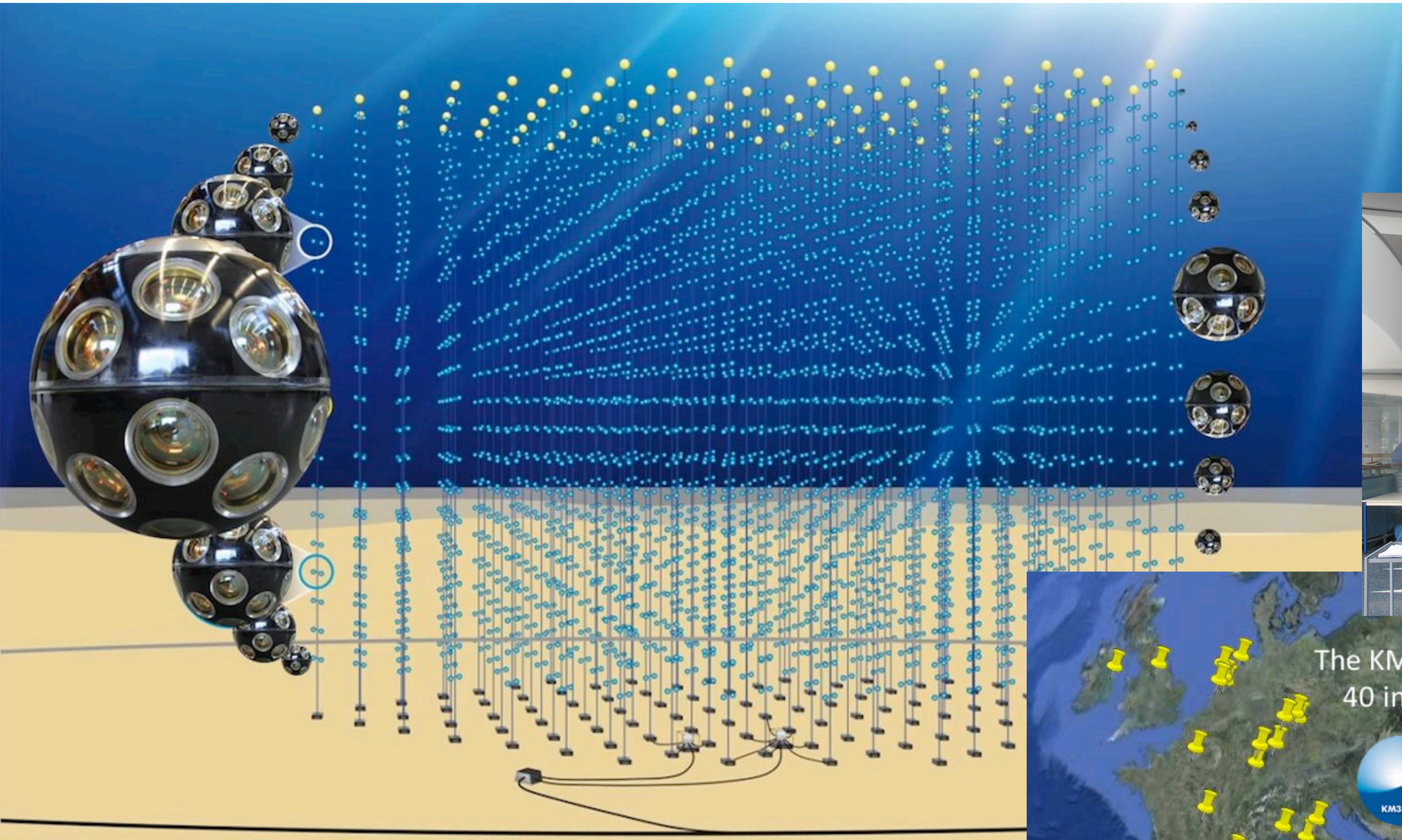
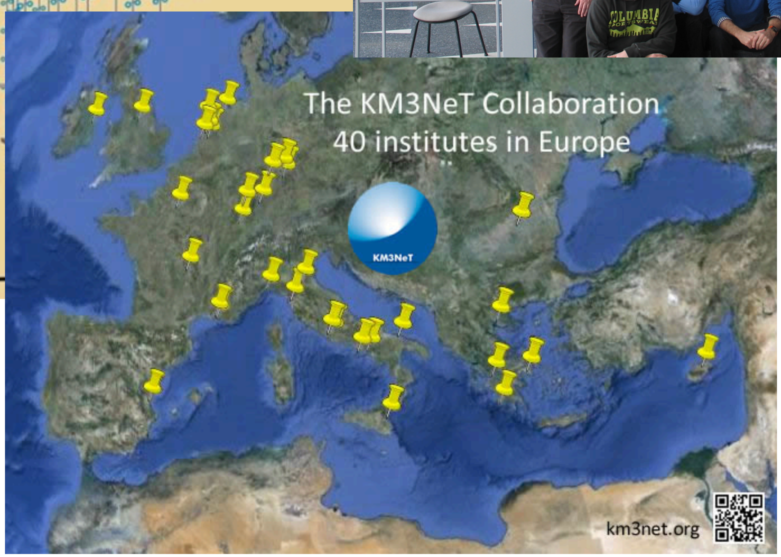
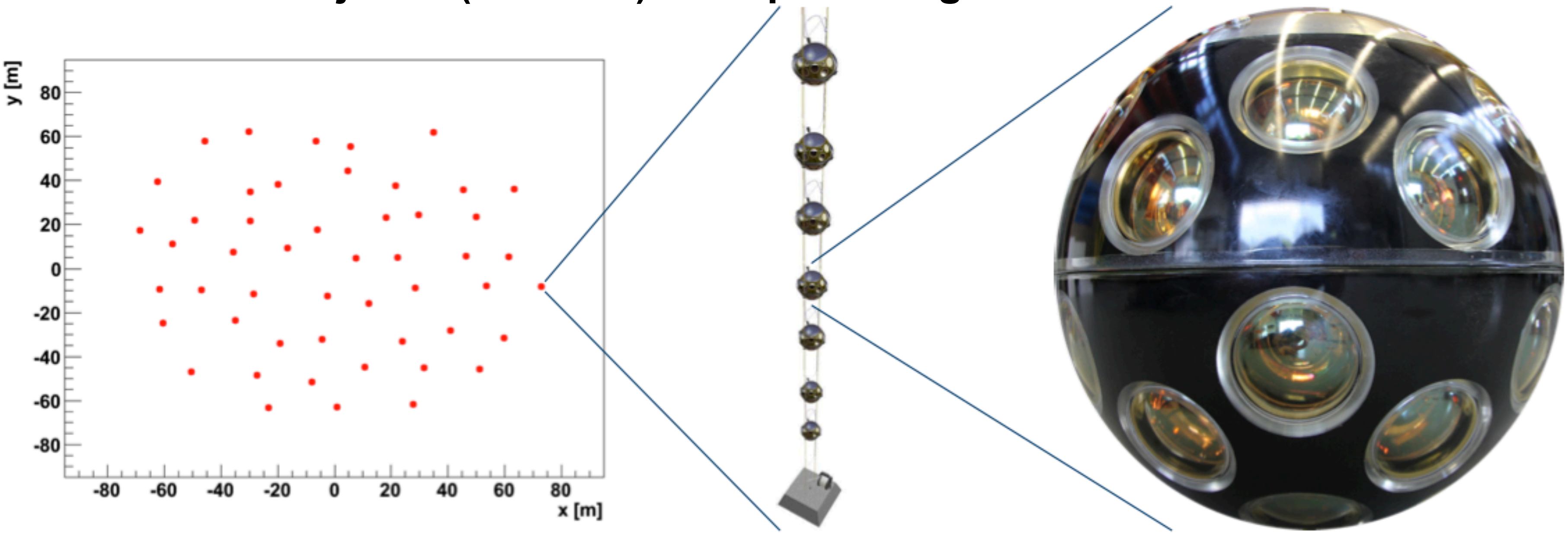




Artistic view of 1 of several building blocks

ORCA: simulation detector layout

Note: This is just a (scalable) example configuration

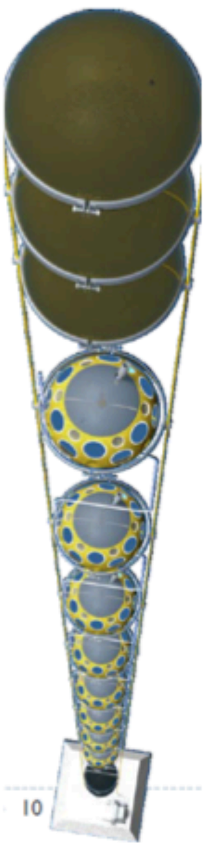


- instrumented volume: 1.75Mton sea water
- 50 detection units (strings)
- 20 optical modules (OM) each
- height 114m, diameter 140m
- 20m (mean) horizontal string distance
- 6m vertical distance between OMs

KM3NeT OM design:

- 17-inch glass sphere
- 31 3-inch PMTs / OM (19 ↓,12 ↑)
- photo cathode area ~3x10” PMTs
- directionality

Detector simulation

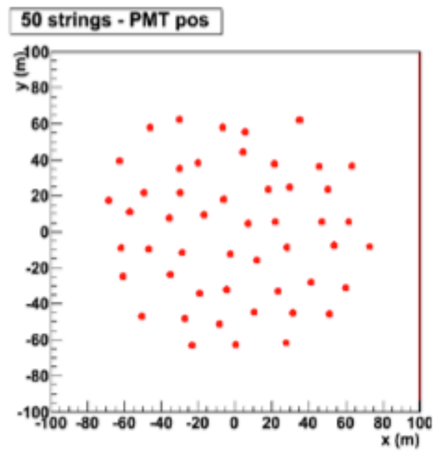


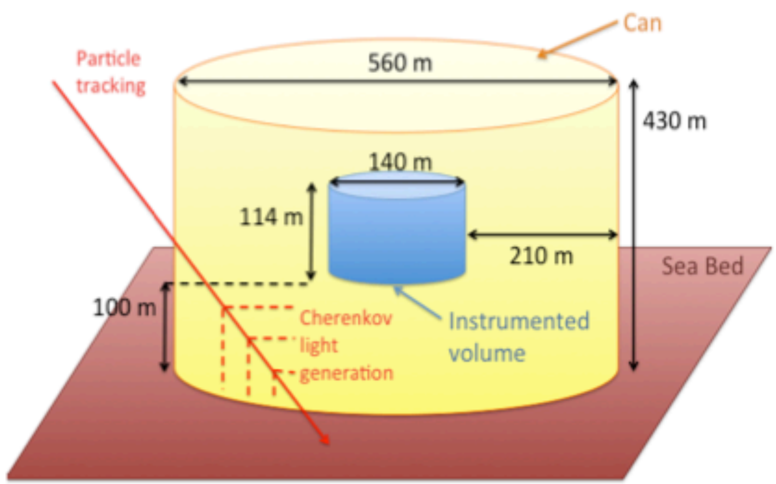
ORCA reference detector

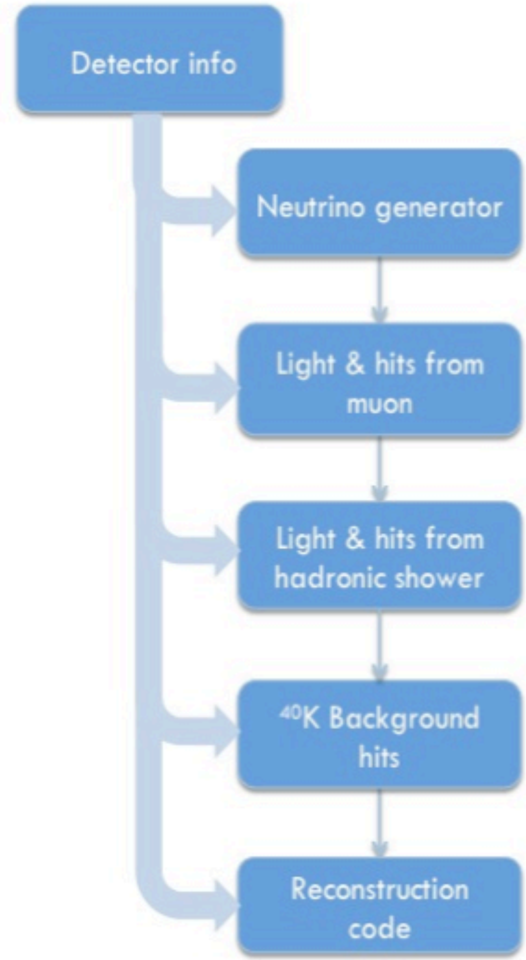
- 50 strings 20m spaced
- 20 DOM/string spaced 6m

Instrumented volume:

$\Pi \times 70^2 \times 114 = 1.75$ Mt

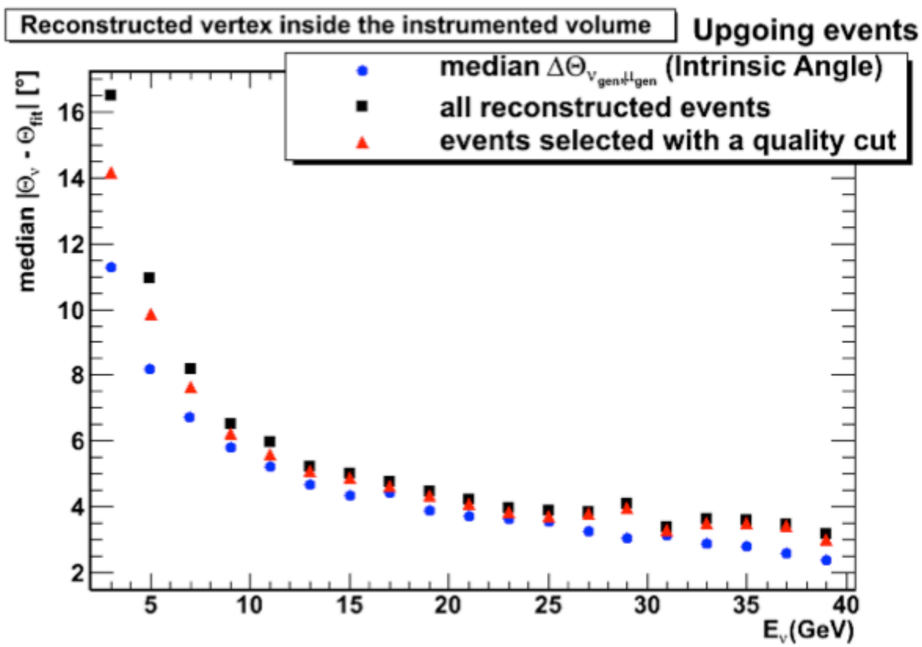






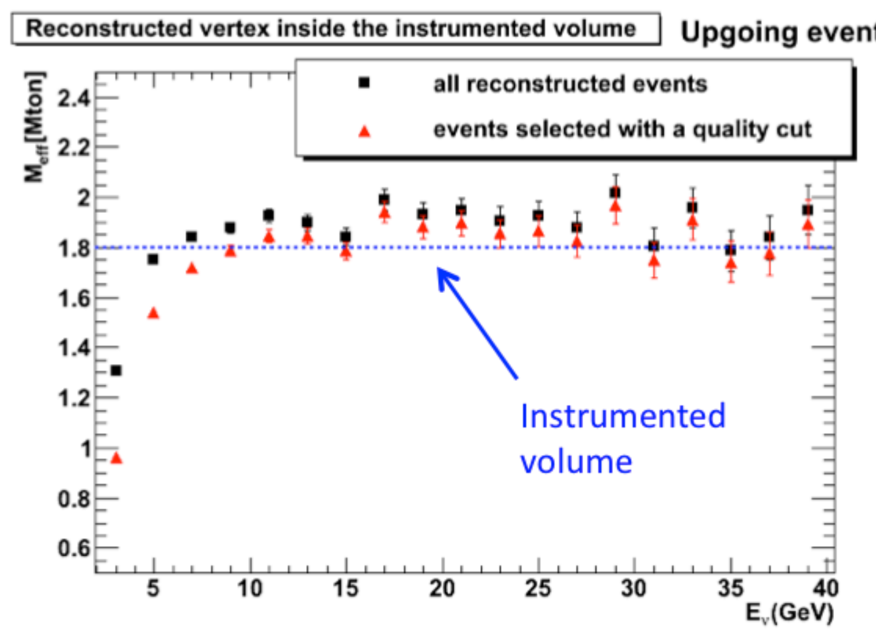
Muon reconstruction: direction

ANGULAR RESOLUTION



better than 10° for $E_\nu \geq 5$ GeV

EFFECTIVE VOLUME

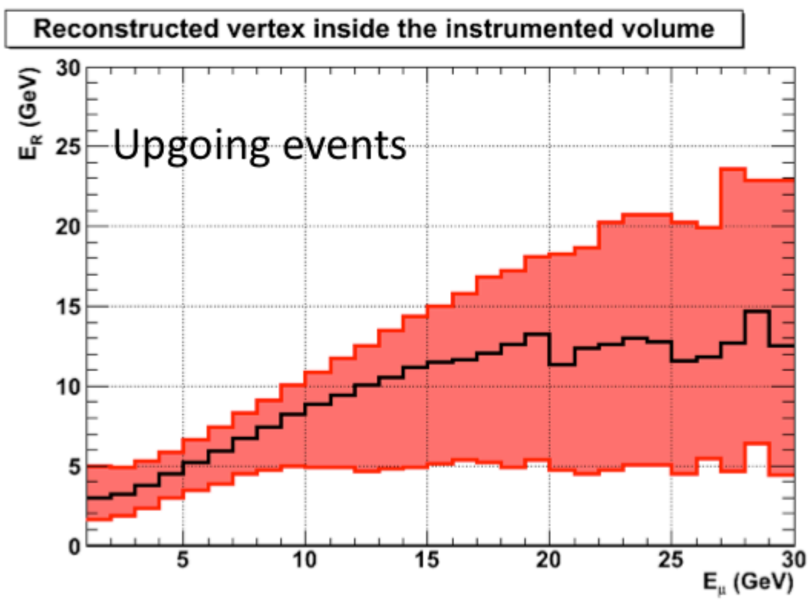


almost flat for $E_\nu \geq 8$ GeV

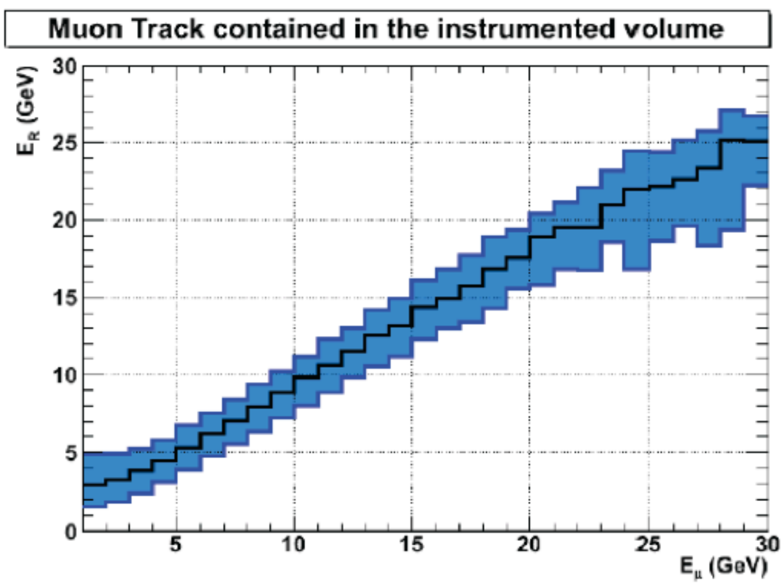
Muon reconstruction: energy

- Muon energy inferred from measurement of track length
- Median per energy bin, color band shows 1σ range
- Muon energy estimate most reliable for fully contained tracks
- Estimation of shower energy (inelasticity) in progress

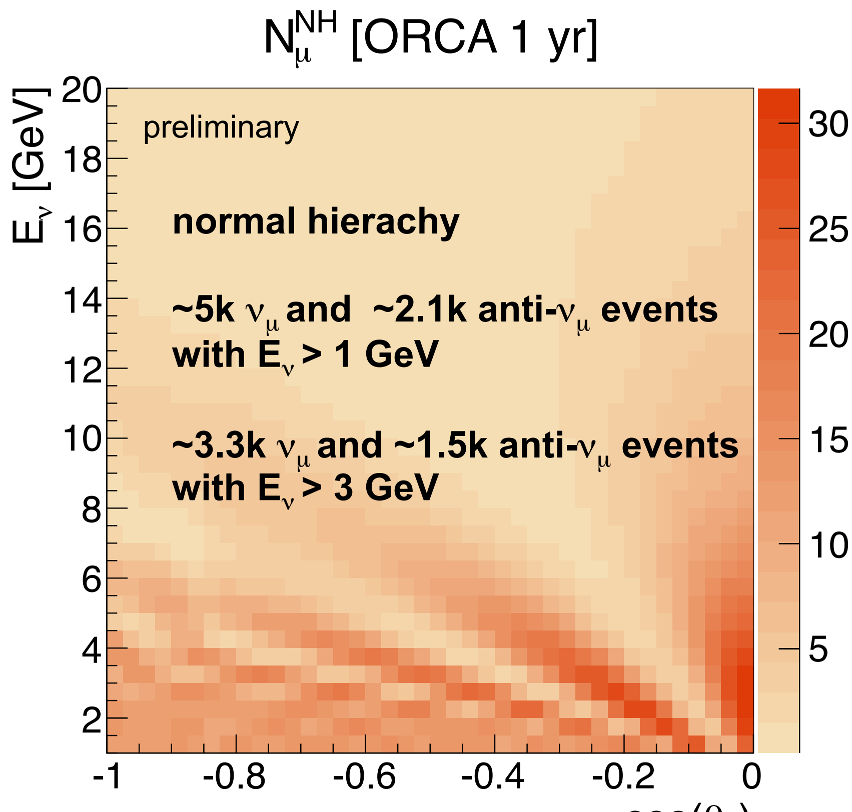
VERTEX CONTAINED

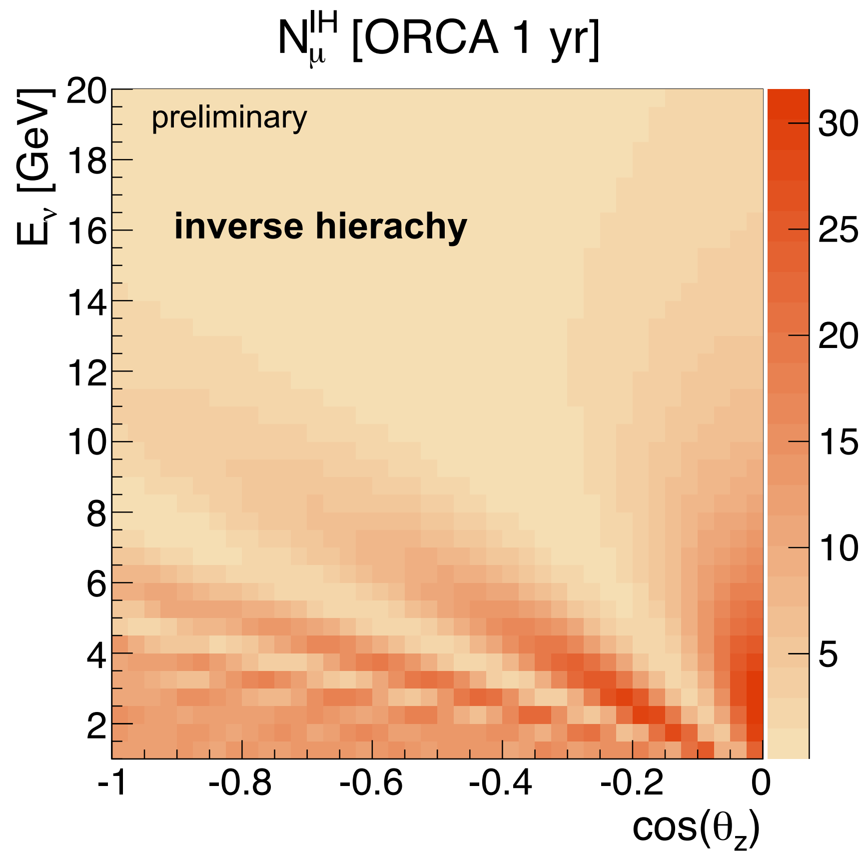


TRACK+VERTEX CONTAINED



Muon event rates in ORCA for 1 year



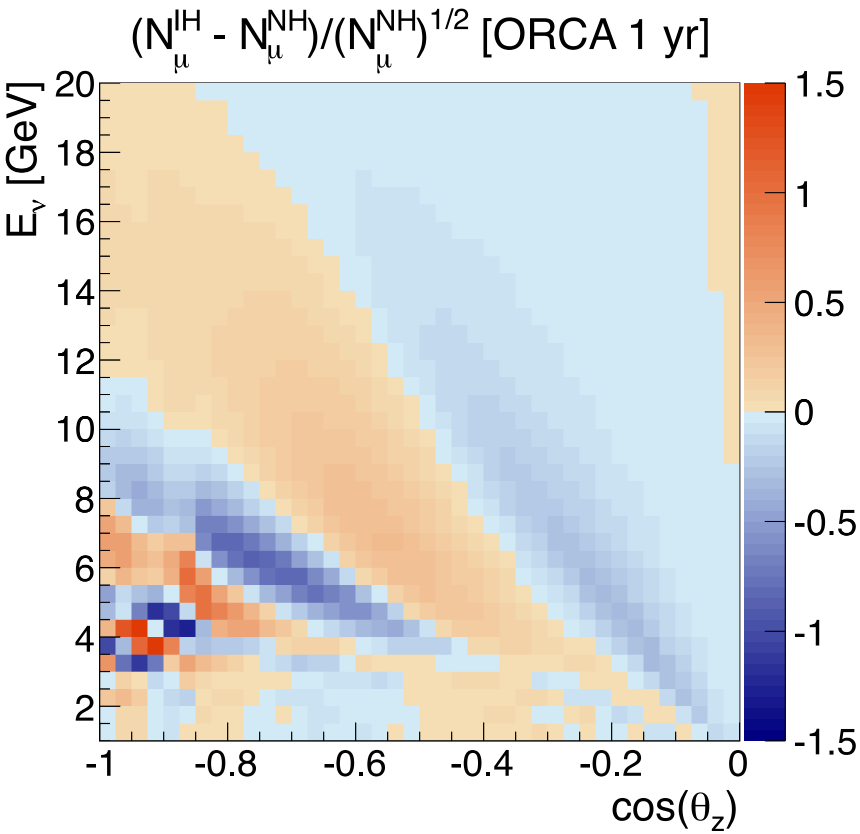


assumptions:

- contained events, 10 PMT hits from muon
- 100% tagging efficiency (upgoing ν_μ + anti-ν_μ CC)
- no atmospheric muon background

Experimental Signature of Mass Hierarchy

- Binned counting experiment in energy and zenith angle plane
- Compare difference in expected number of events for normal vs. inverted hierarchy due to mass effects
- Useful metric is significance estimate of Akhmedov, Razzaque & Smirnov [arXiv:1205.7071]



$$S_{tot} = \sqrt{\Sigma_{ij} \frac{(N_{ij}^{IH} - N_{ij}^{NH})^2}{N_{ij}^{NH}}}$$

$$\begin{aligned} i &= \cos(zenith) \\ j &= energy \end{aligned}$$

Experimental Signature of Mass Hierarchy

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

- Binned counting experiment in energy and zenith angle plane
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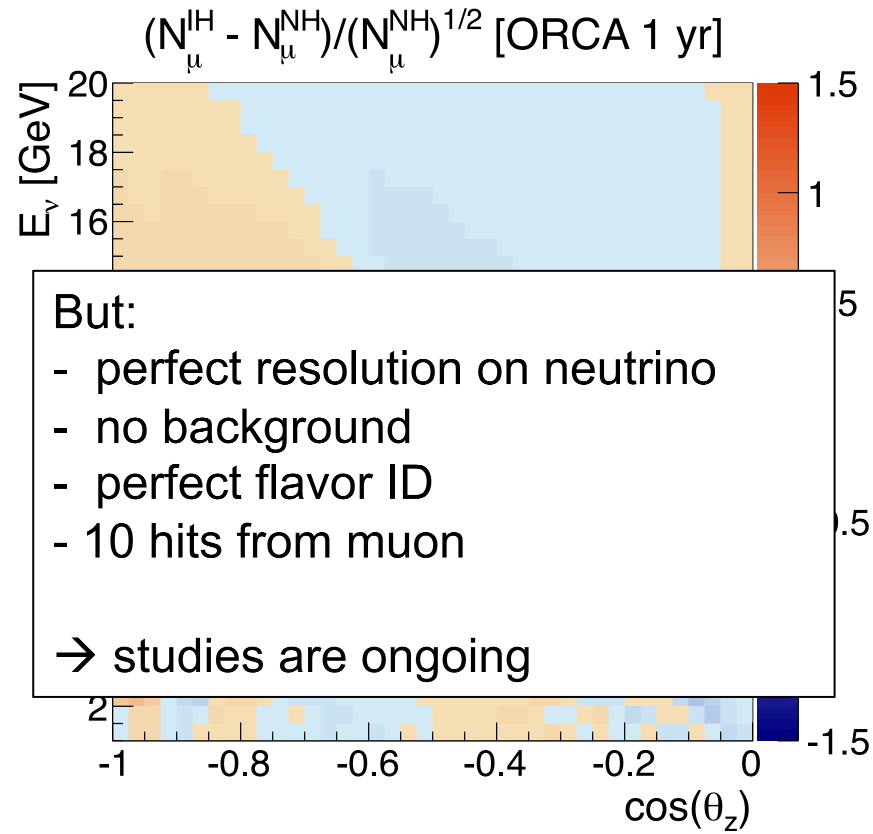


But:
- perfect resolution on neutrino
- no background
- perfect flavor ID
- 10 hits from muon

→ studies are ongoing

$$S_{tot} = \sqrt{\Sigma_{ij} \frac{(N_{ij}^{IH} - N_{ij}^{NH})^2}{N_{ij}^{NH}}}$$

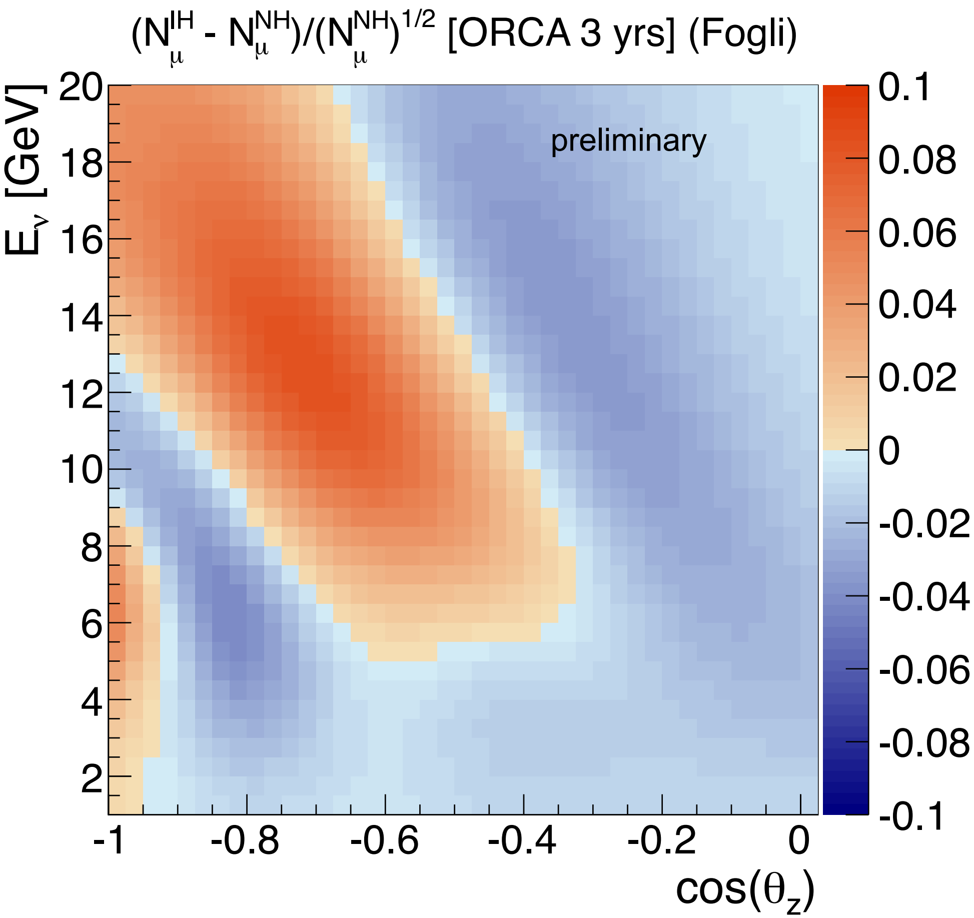
$$\begin{aligned} i &= \cos(zenith) \\ j &= energy \end{aligned}$$

Hierarchy asymmetry with example detector resolution

- energy dependent angular smearing due to neutrino interaction kinematics

- average angular resolution on muon: 5 degrees

- energy resolution: 1GeV (muon) + **0.2** * E_ν



Pseudo-experiment generation

- assume rate of muon-like events is Poisson-distributed in each bin
- mean μ given by calculated rate

- log-likelihood ratio with *k* muon-like events in bin *i*:

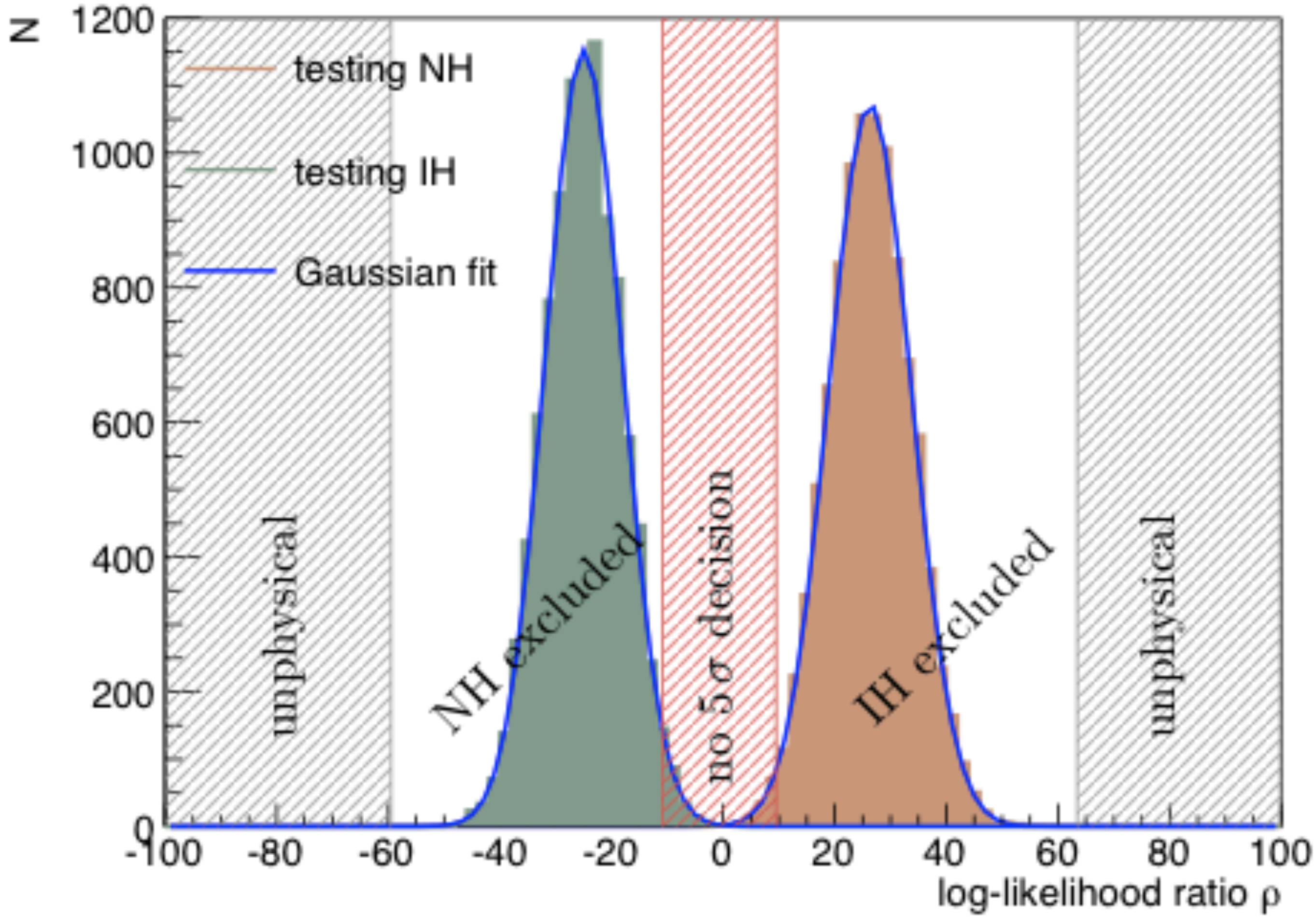
$$\rho_i = \ln\left(\frac{(\mu_{i,NH})^k \exp(-\mu_{i,NH})}{k!}\right) - \ln\left(\frac{(\mu_{i,IH})^k \exp(-\mu_{i,IH})}{k!}\right)$$

- total log-likelihood given by sum over bins

$$\rho = \sum_{\text{bins } i} \rho_i$$

- repeat this pseudo-experiment many times

Log-likelihood ratio distribution



Preliminary results of toy analysis

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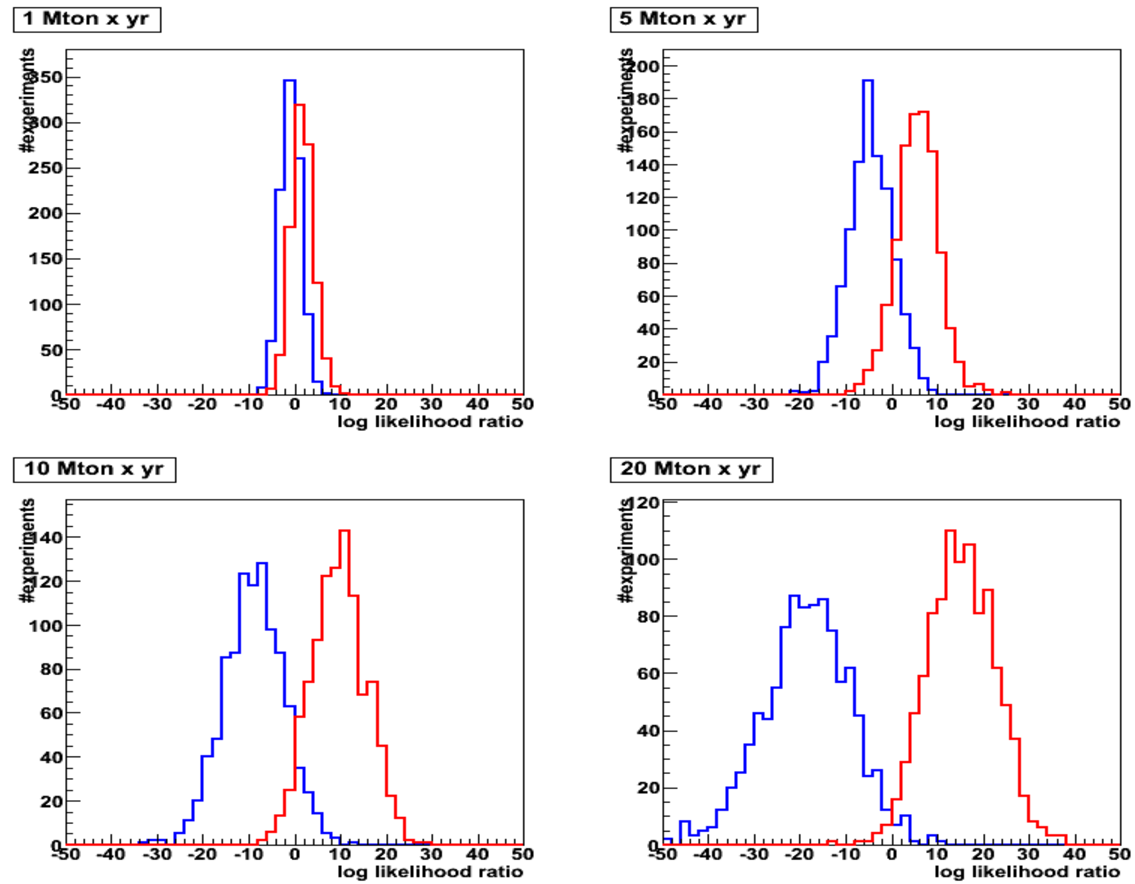
- Neutrino vertex in detector volume, true μ direction, $\sigma(E_\nu) = 0.2E_\nu$
- Distribution of log-likelihood ratio NH/IH for toy experiments
- Experimental determination of mass hierarchy at 4-5σ level requires ~20 Mton-years
- Improved determination of Δm^2_{23} and θ_{23} seems possible



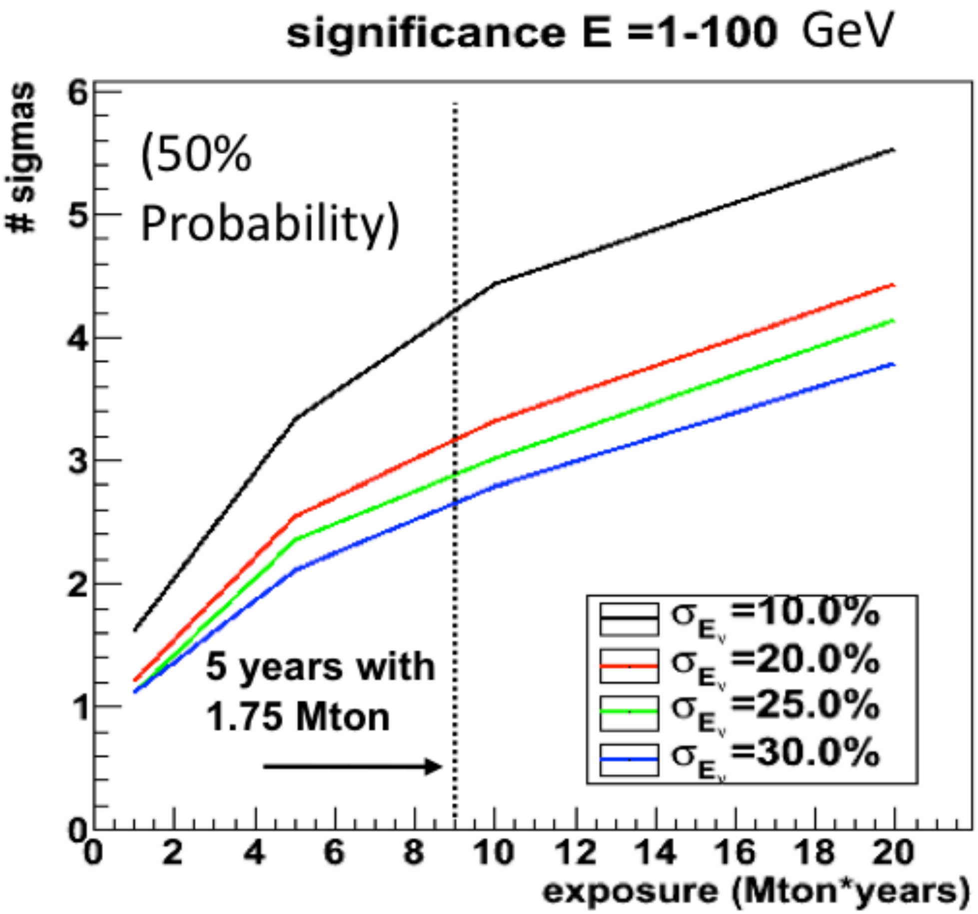
Significance of mass hierarchy determination

Results of a preliminary study without reconstruction effects

Assumptions:

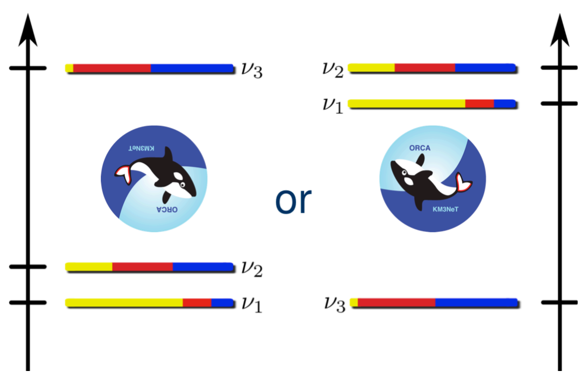
- Perfect muon zenith angle resolution
- True neutrino vertex contained
- 15 PMT hits (from Geant4 simulation)

ⓘ 2.5σ → 4σ in 5 years with reference detector, strong dependence on reconstruction performance



Summary and Outlook

- ORCA: feasibility study within KM3NeT towards neutrino mass hierarchy determination in progress.
- Fast progress by small number of (very) active participants, but no conclusion on feasibility yet.
- Development of reconstruction algorithms in progress.
- Evaluation of detector performance, backgrounds, flavor ID and systematics by means of toy-MC sensitivity study.
- Detector optimization studies have started.



Thank you for your attention!

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Bundesministerium für Bildung und Forschung

ORCA KM3NeT

KM3NeT

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Backup Slides

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Earth Density Profile

- Preliminary Reference Earth Model

A.M. Dziewonski, D.L. Anderson, Phys. Earth Planet. Inter., 25 (1981) 297-356

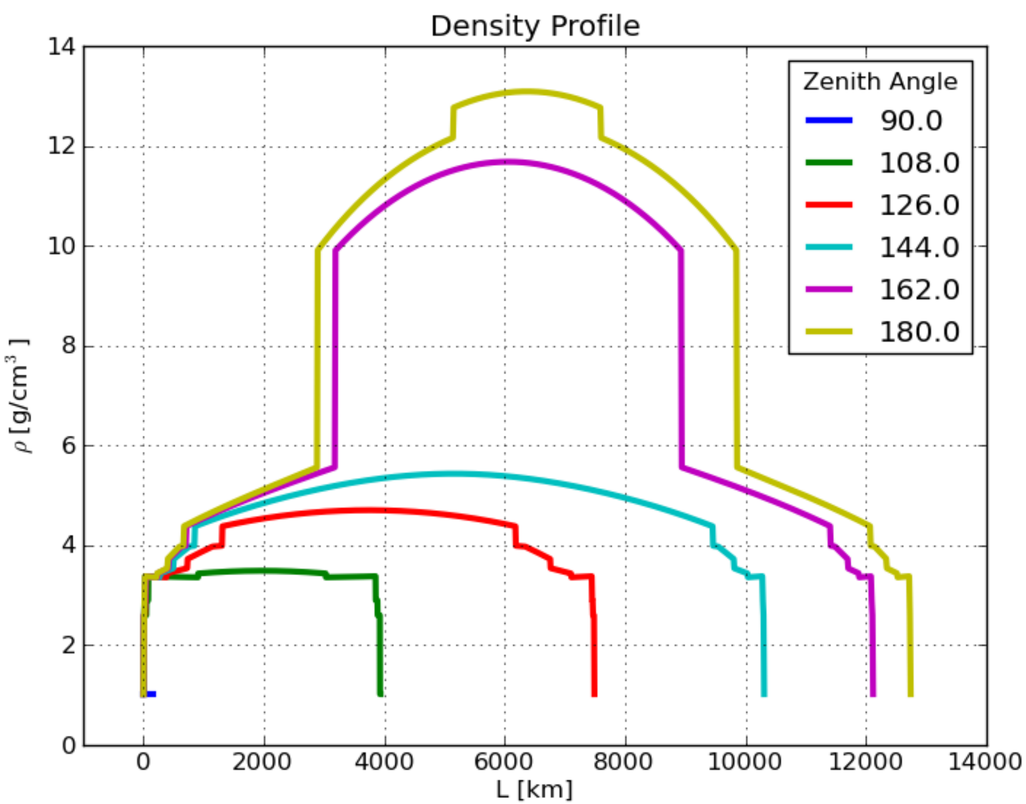
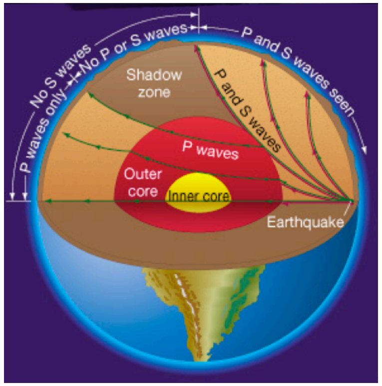
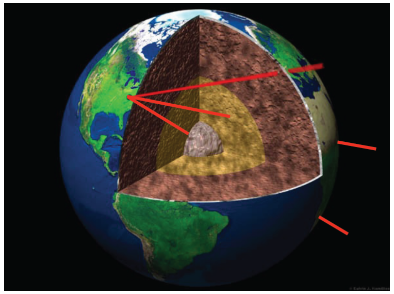


figure courtesy P. Toale





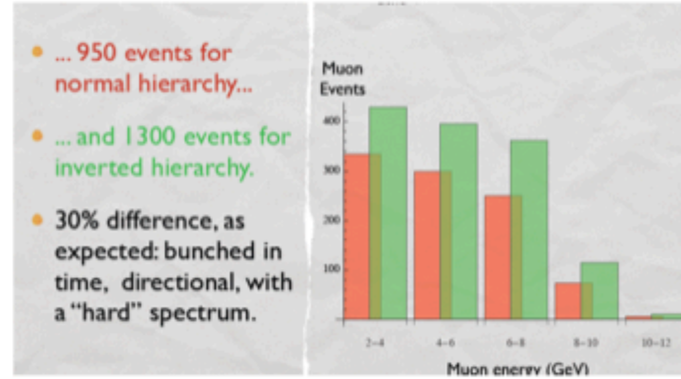
relevant neutrino energies:

$E_\nu \sim$ 3–10 GeV

A neutrino beam to ORCA ?

F. Vissani (Paris Workshop & arXiv:1301.4577):

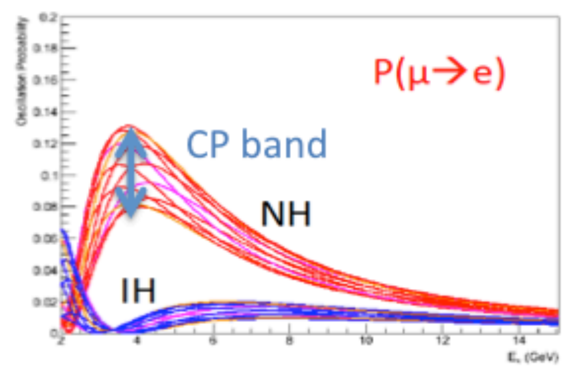
- The matter (MSW) effect indicates 6-8 GeV as optimal energy.
- A large enough oscillation phase dictates distances of 6000-8000 km as optimal.



use nu_mu beam ? (Fermilab → Sicily: 7800 km)

J. Brunner (Paris Workshop & arXiv:1304.6230v2):

nu_e appearance at shorter baseline: a nu_mu beam from Protvino → ORCA ?



From preliminary studies: 10^{21} pot (3 yr) → 7σ (stats), 3σ with 3-4% systematics (no assumption on energy reconstruction)

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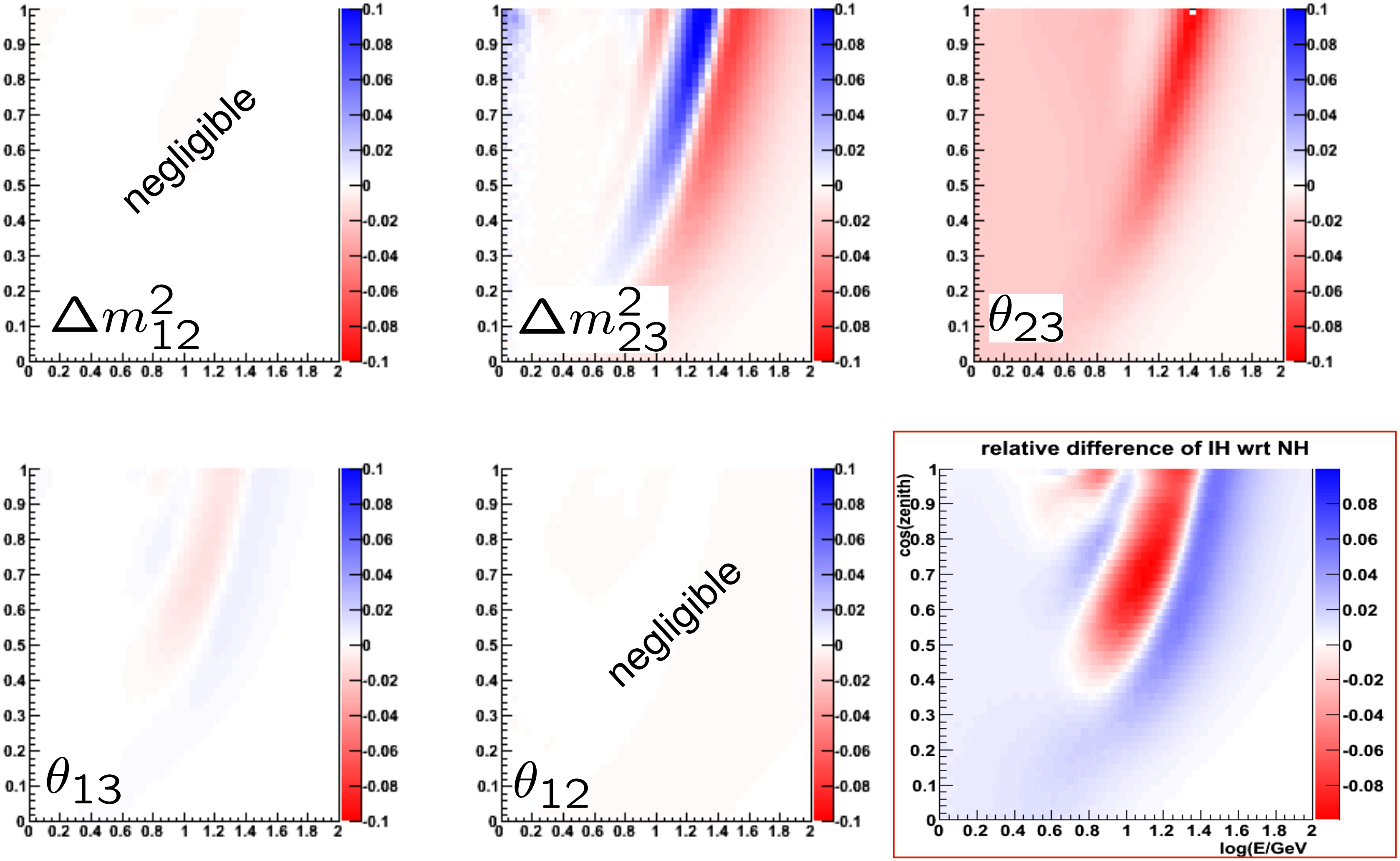
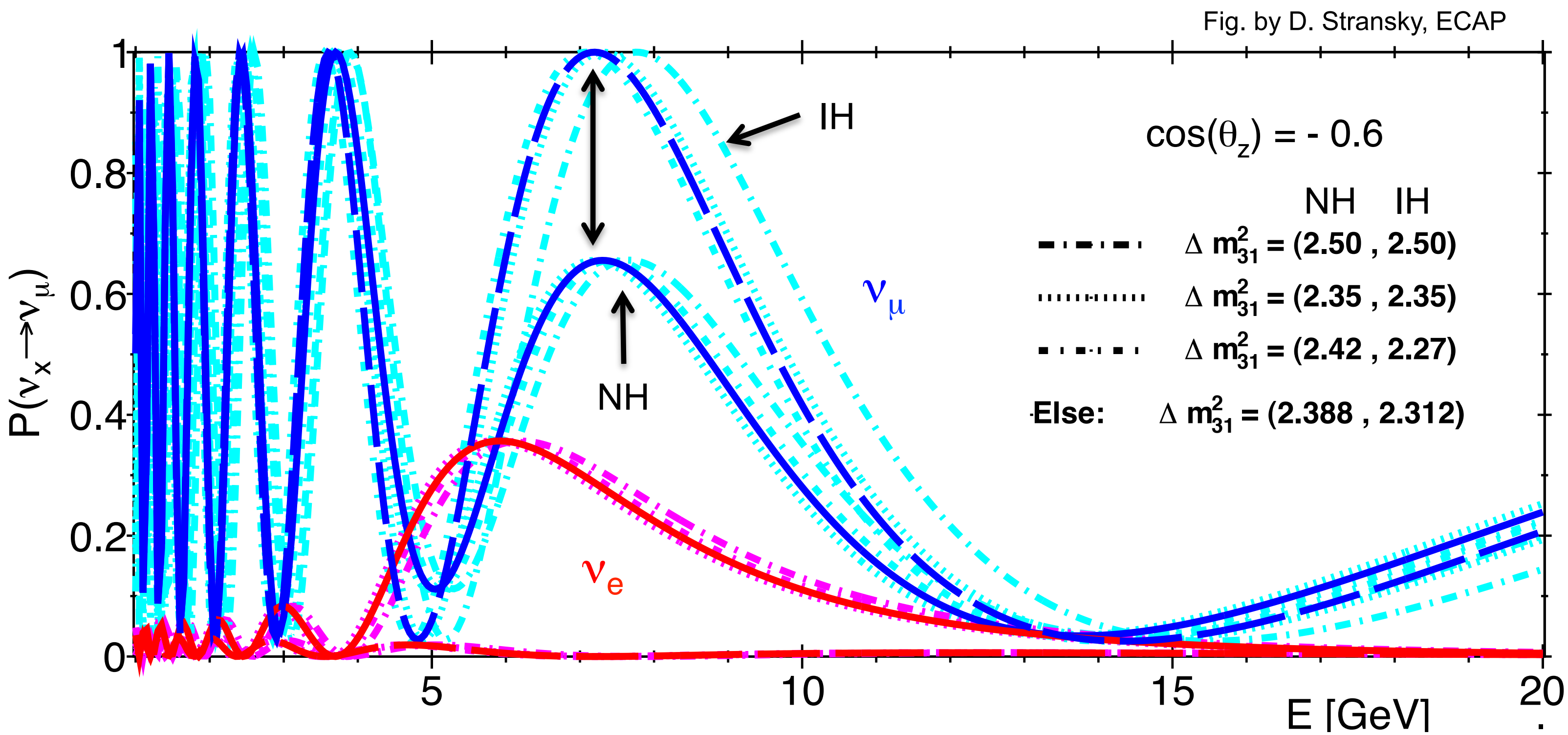
Impact of oscillation uncertainties

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS



Hierarchy discrimination

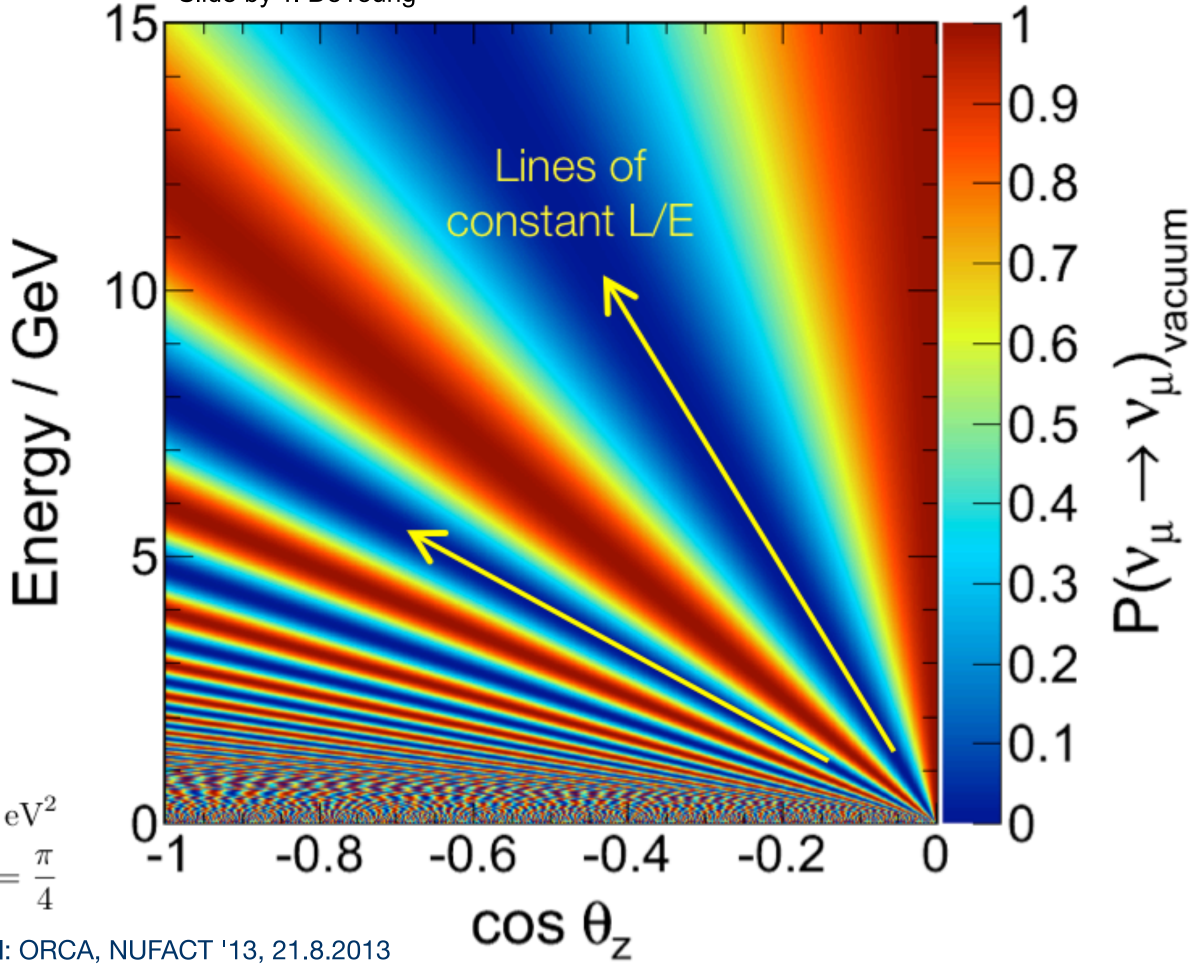


Maximum difference for zenith = 130 deg at 7 GeV

Neutrino oscillations in vacuum

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Slide by T. DeYoung

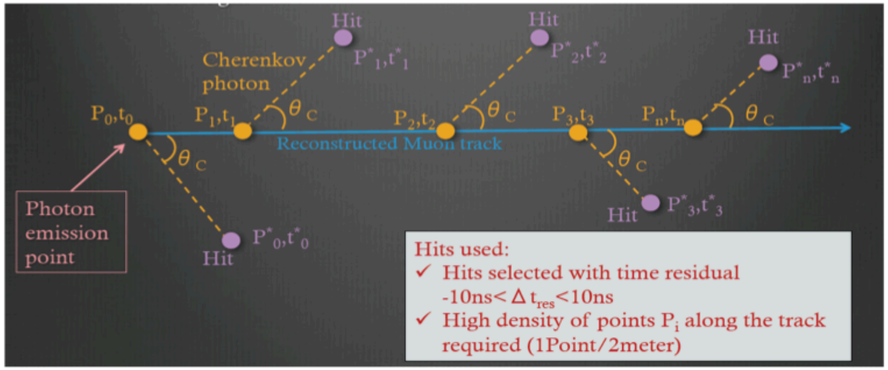


$$\Delta m^2_{32} = 2.32 \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2(2\theta_{23}) = \frac{\pi}{4}$$

Muon track and vertex reconstruction

ANTARES-inspired reconstruction (Aart's strategy)

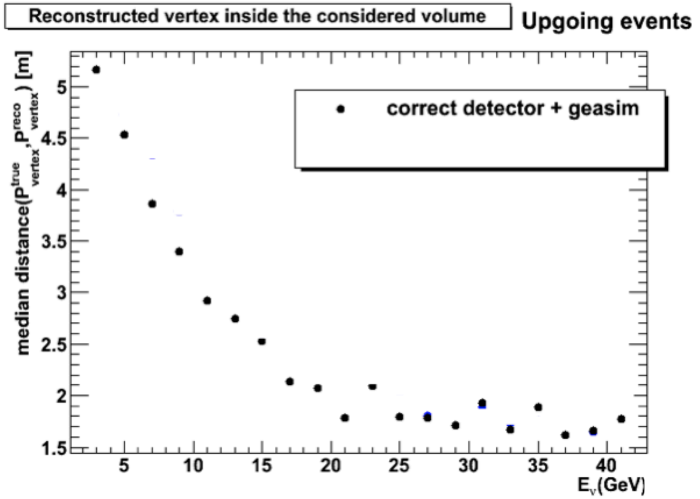


1) Muon track reconstruction and track length estimation (first/last emission point)

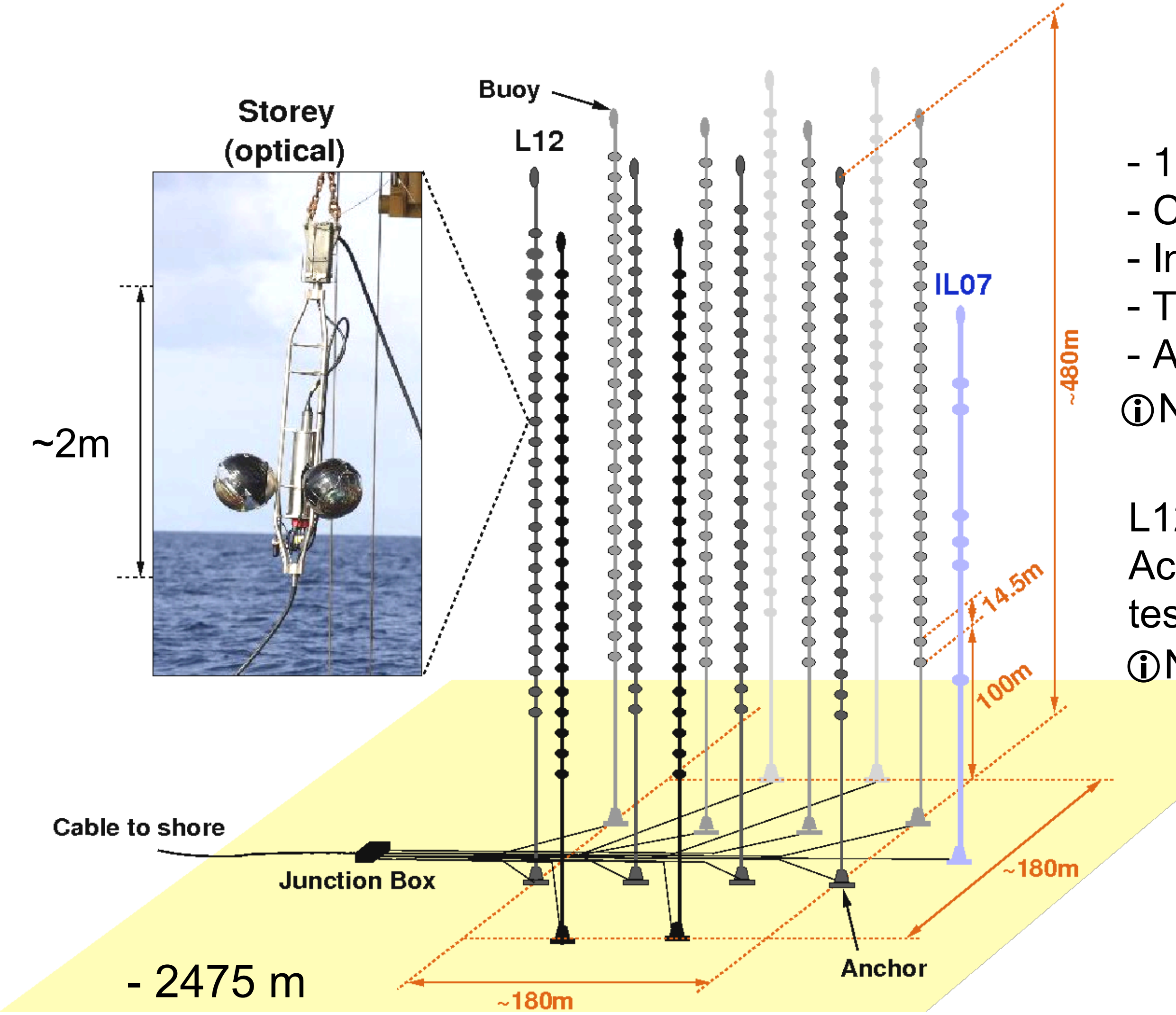
2) Identification of hits belonging to hadronic shower

3) Re-estimation of vertex position (assuming spherically expanding shower)

➡ improved vertex identification
➡ improved track length estimate



The ANTARES neutrino telescope



- 12 Lines (885 PMTs) + IL.
- Complete since 05/2008.
- Instrumented Volume: ~0.01km^3.
- Time resolution: ~0.5ns.
- Acoustic positioning: < 10cm.

ⓘNIM A 656 (2011) 11-38

L12+ IL host AMADEUS: Acoustic neutrino detection test system.

ⓘNIM A 626-627 (2011) 128-143

Rate estimation

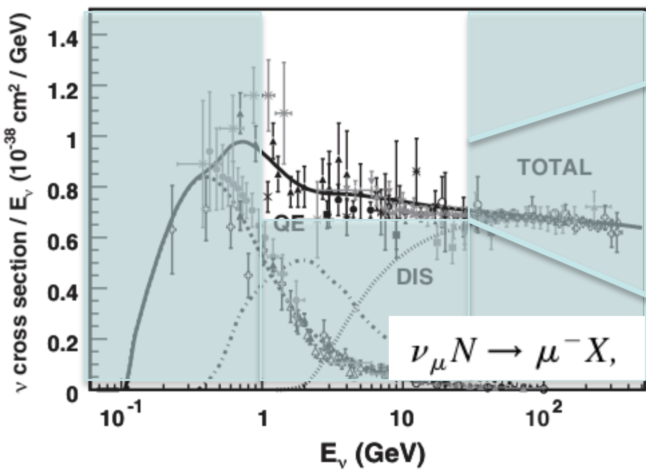
- Calculating number of events per bin N_{bin} in energy - zenith angle plane:

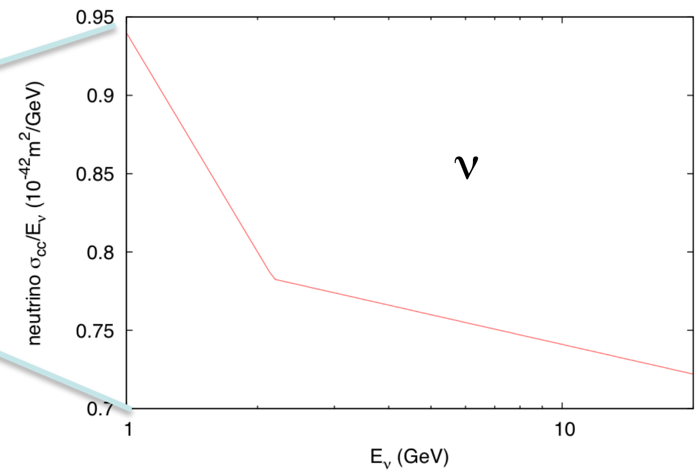
$$\frac{\mathrm{d}\,n(E,\cos(\theta_z))}{\mathrm{d}\,t} = 2\pi N_A\,\rho\,m_{\mathrm{mol}}^{-1}\;\Phi(E,\cos(\theta_z))\cdot\sigma(E)\cdot V_{\mathrm{eff}}(E)$$

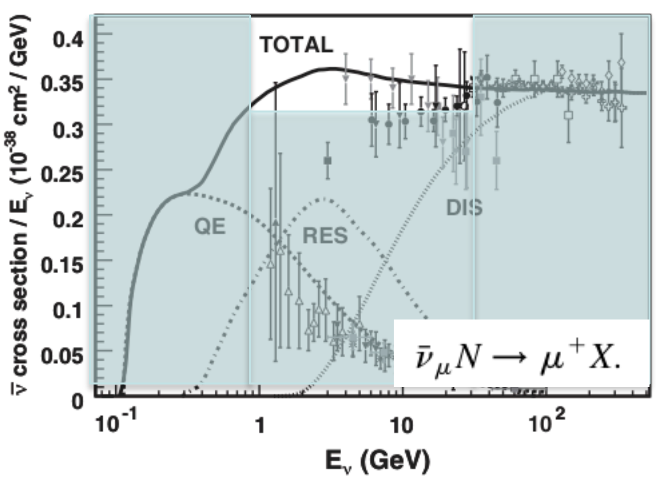
$$N_{\mathrm{bin}} = \int_{E(low)}^{E(up)} \mathrm{d}\,E \int_{\cos(\theta_z)(low)}^{\cos(\theta_z)(up)} \mathrm{d}\cos(\theta_z)\;P_{i\to j}^{H}\cdot\frac{\mathrm{d}\,n(E,\cos(\theta_z))}{\mathrm{d}\,t}\Delta\,t$$

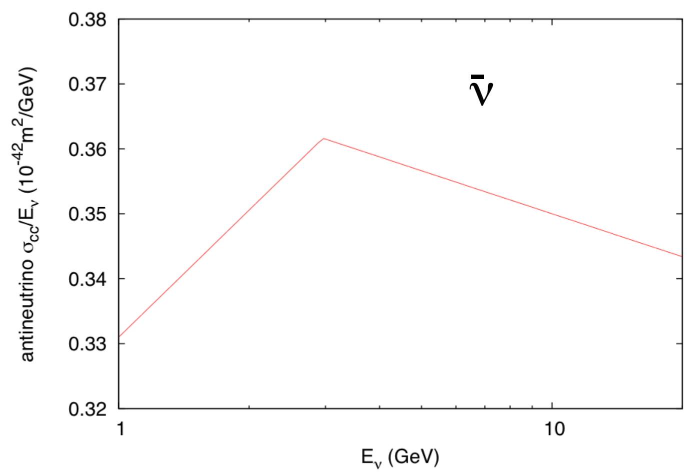
Neutrino-nucleon cross sections

Formaggio, Zeller, Rev. Mod. Phys., 84(3), pp.1307–1341 (2012)



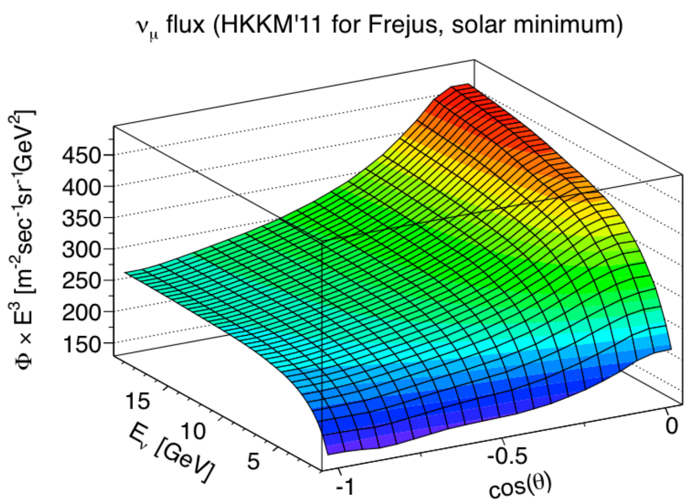






Atmospheric neutrino fluxes

- Atmospheric neutrino flux table: $\Phi(E, \cos(\theta_z))$
  - Honda et al., Phys. Rev. D83, 123001 (2011)
  - data from: http://www.icrr.u-tokyo.ac.jp/~mhonda/nflx2011/index.html
  - table for Frejus, solar minimum, azimuth averaged



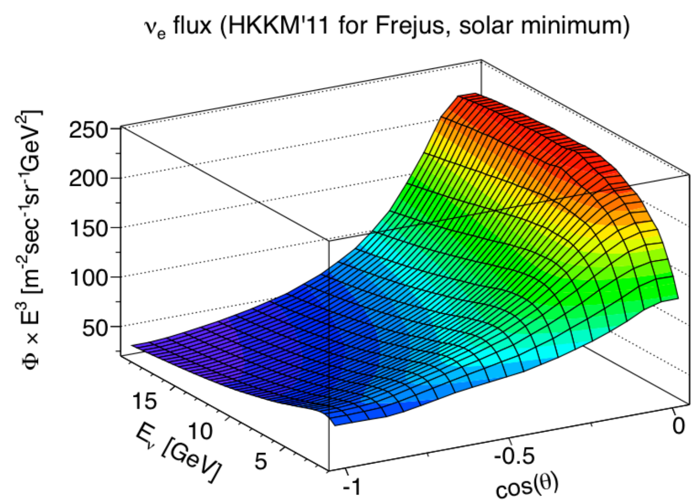


fig. S. Hallmann, B.Sc. thesis, ECAP 2013

Containment volume for muons in ORCA

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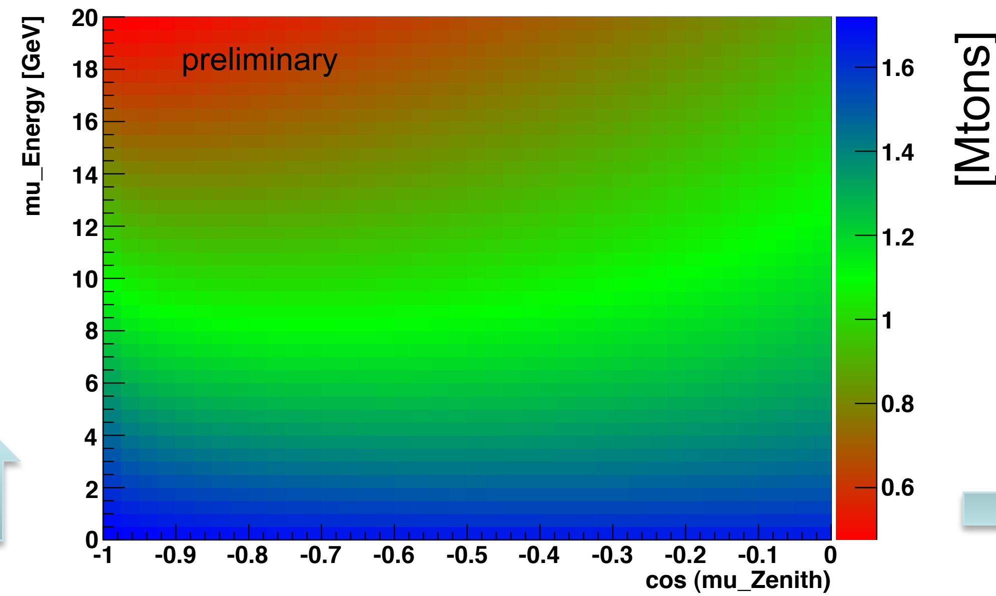
Assumption: detector has a cylindrical shape
D: detector diameter
h: detector height
R: average muon range

$$V = \frac{1}{2} h D_d^2 \arcsin\left(\sqrt{1 - \frac{R_\mu^2}{D_d^2}\sin^2\theta_Z}\right)\left(1 - \frac{R_\mu}{h}|\cos\theta_Z|\right)$$

formula from Albuquerque, Smoot, Phys. Rev. D64(5), 053008 (2001)



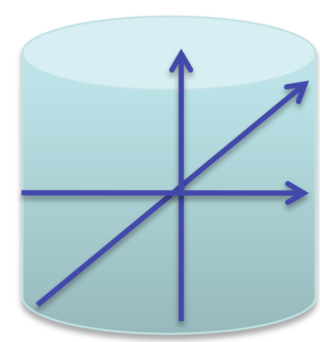
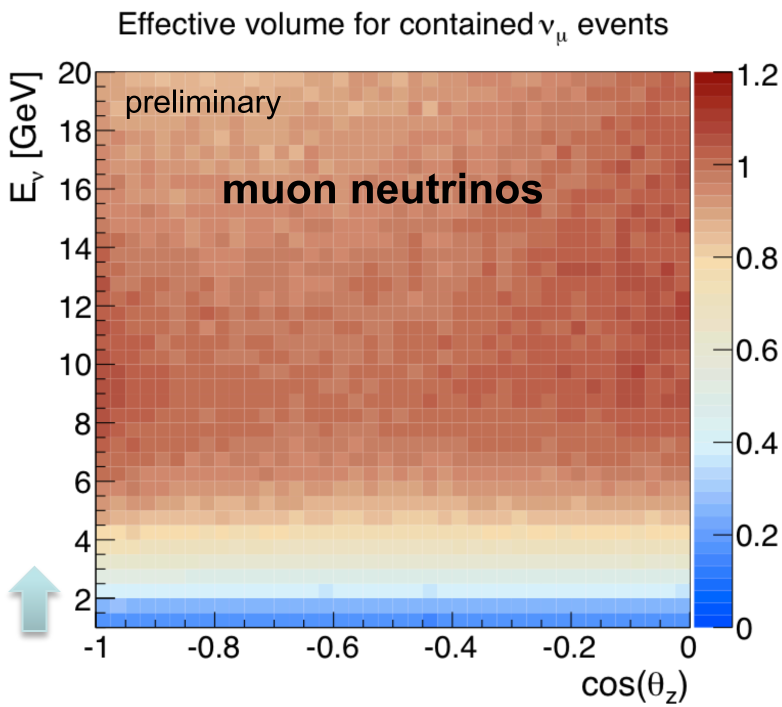


fig. courtesy J. Hofestädt

Effective volume for muon (anti-)neutrinos

- muon tracks fully contained in instrumented volume
- **min. 10 hits on PMTs from muon**



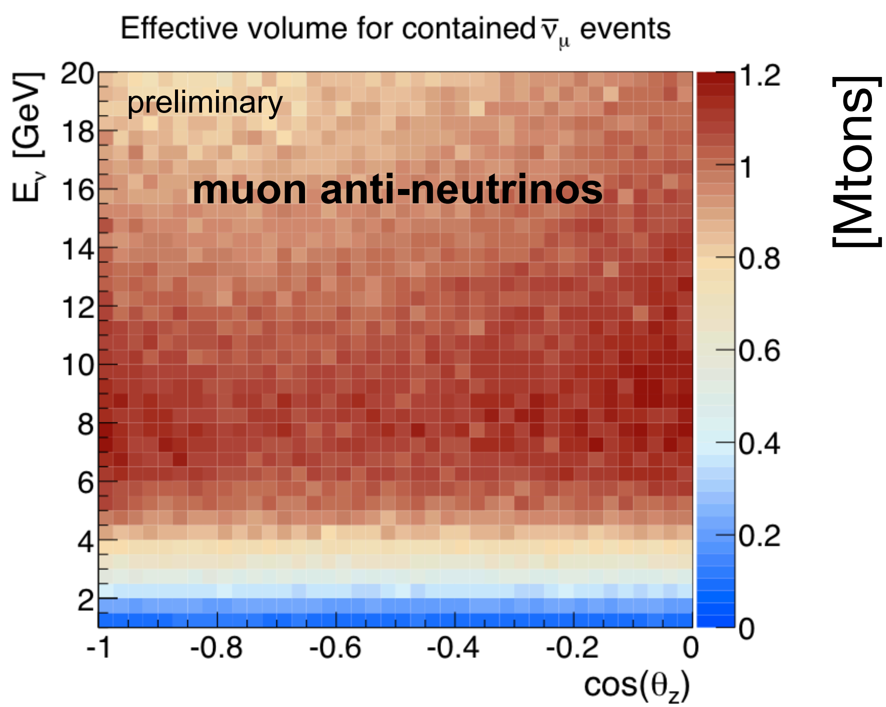


fig. S. Hallmann, B.Sc. thesis, ECAP 2013