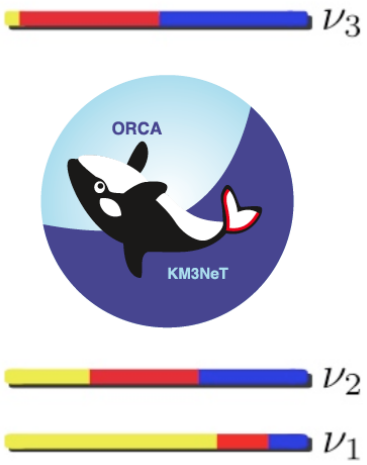
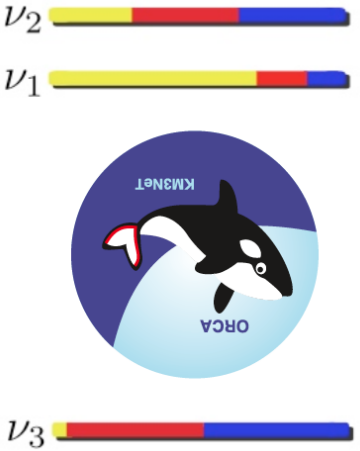




KM3NeT/ORCA: Oscillation Research with Cosmics in the Abyss

Salvatore Galatà

APC, Paris

1st International Workshop for Neutrino Oscillation Tomography

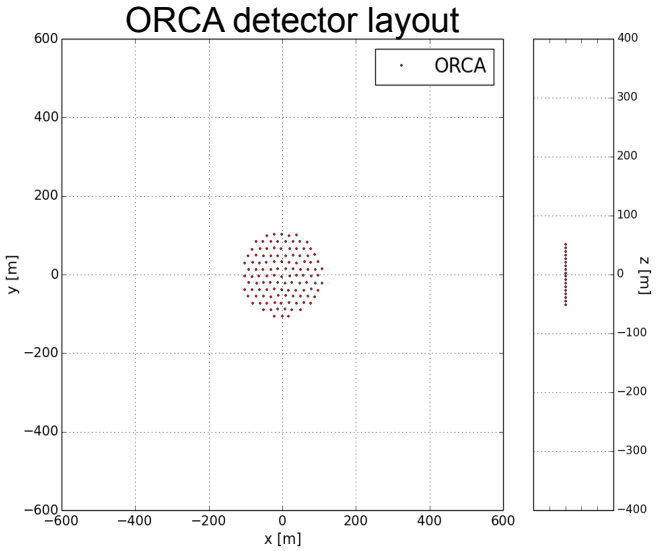
Earthquake Research Institute, Tokyo

08.01.2016

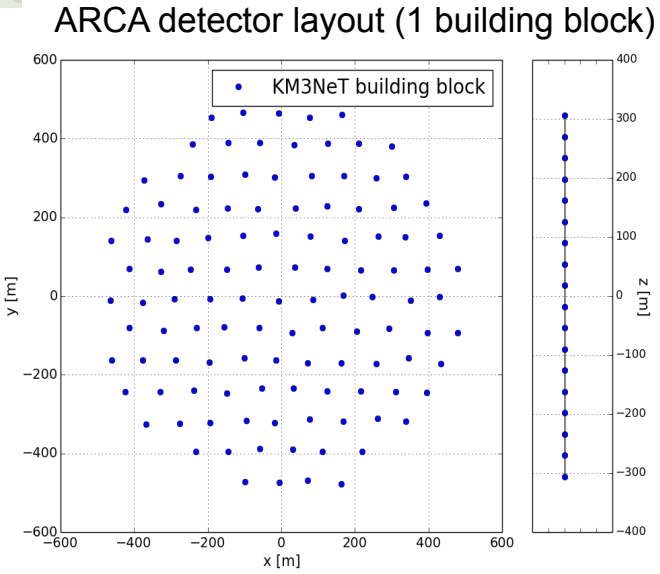
The KM3NeT infrastructure

An infrastructure for “Research with Cosmics in the Abyss”

ORCA



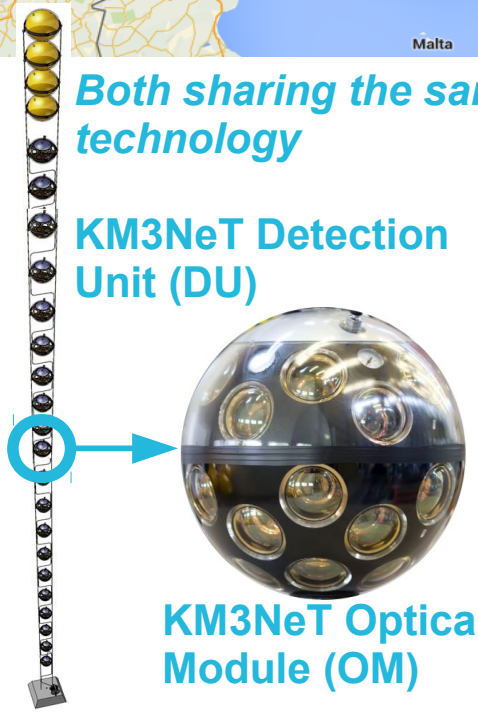
ARCA



Both sharing the same technology

- Neutrino physics: mass hierarchy, dark matter,...
- Optimised for neutrinos from a few GeV up to ~100 GeV
- Will be located offshore the Southern coast of France

KM3NeT Detection Unit (DU)

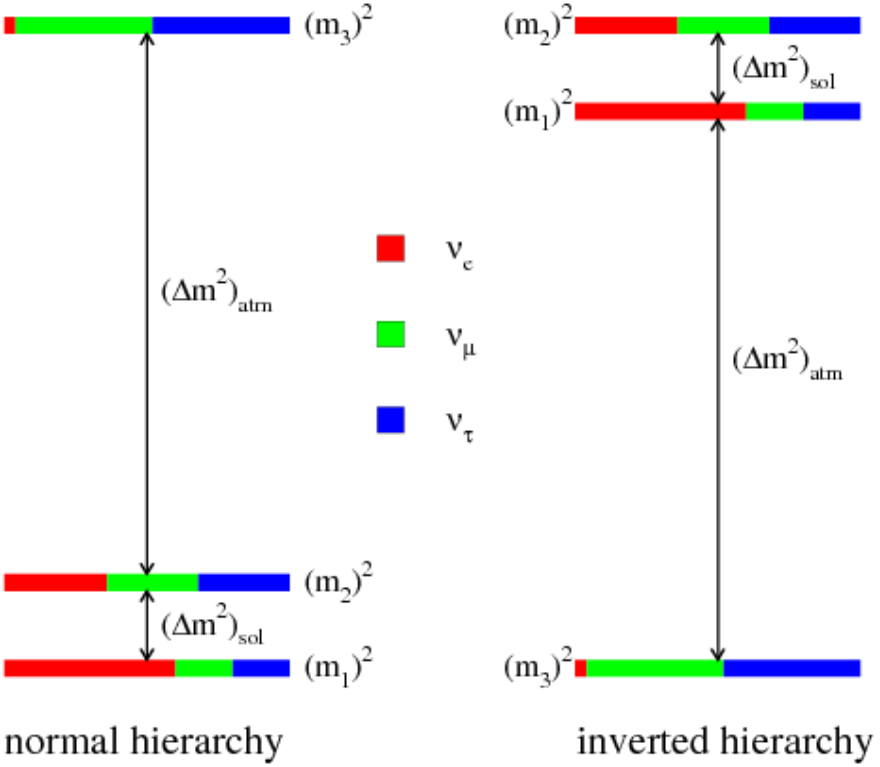


KM3NeT Optical Module (OM)

- Neutrino astrophysics: newly born after IceCube detection
- Optimised for neutrinos from ~100 GeV on
- Will be located offshore the Southern coast of Italy (Sicily)

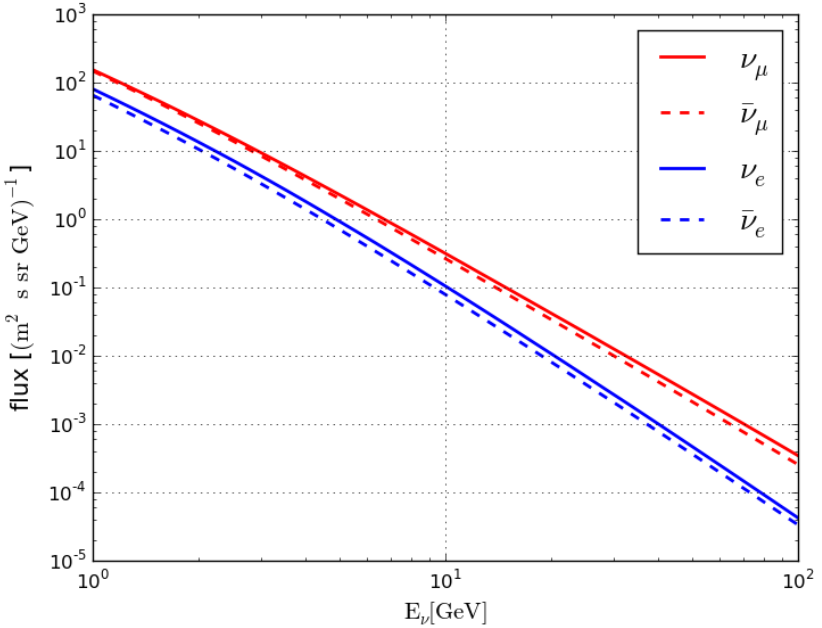
Neutrino Oscillations and Mass Hierarchy

- Neutrinos can change flavour
- Relevant parameters:
  - Mixing angles $\theta_{23}, \theta_{13}, \theta_{12}$
  - CP violating phase δ_{CP}
  - Mass-squared differences:
    $\Delta m^2_{ij} = m^2_i - m^2_j$
    (actual masses are unknown)
- Vacuum oscillation only depends on distance, energy and mass-squared differences: it tells us $\Delta m^2_{21} << |\Delta m^2_{32}|$
- Oscillation is different in matter (MSW-effect): this can be used to measure the neutrino mass hierarchy and for the Earth tomography

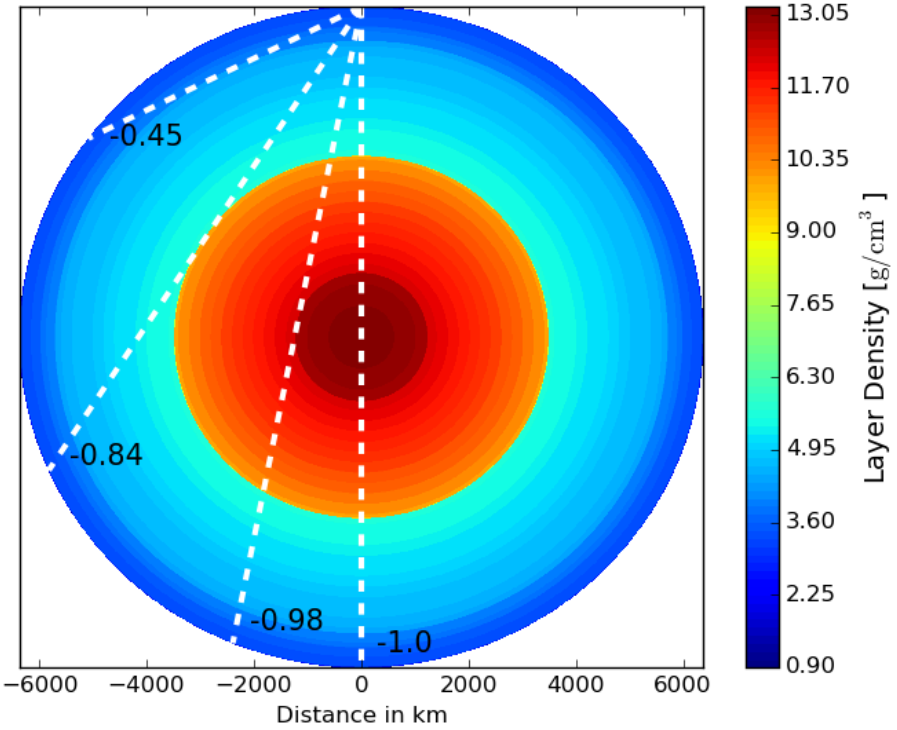


Atmospheric neutrinos

- Produced by the interaction of cosmic rays with the atmosphere
- A free source of neutrinos with a wide energy range
- cos(Zenith) defines the propagation length and the density profile



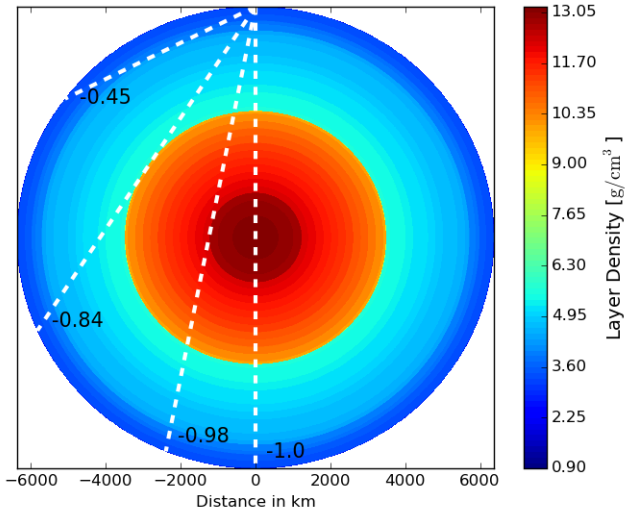
Honda 2014 neutrino flux

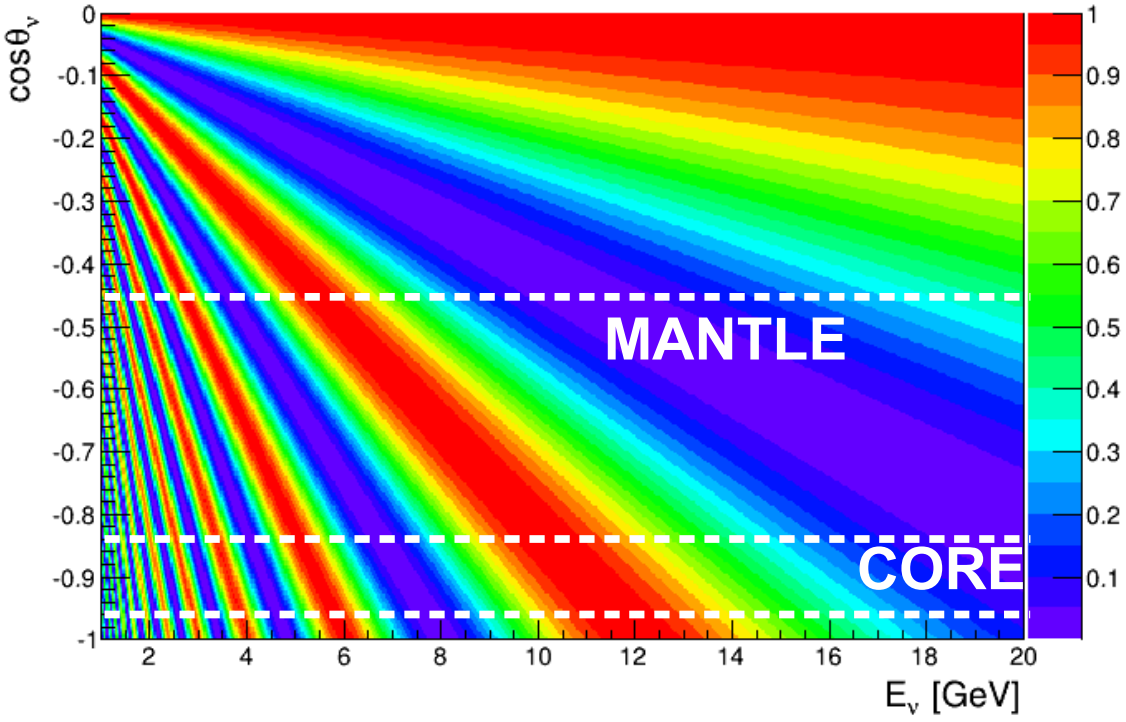


PREM density profile with a few representative neutrino trajectories

Oscillation probability and matter effects

- Here represented as an “oscillogram” cos(Zenith) vs Energy
- Resonance conditions for matter effects (or MSW effect): $2.5 < E_\nu < 6$ GeV for mantle and core densities
- Atm. neutrinos in Earth provide a suitable combination





$$Probability\ \nu_\mu \rightarrow \nu_\mu\ (\boldsymbol{Vacuum})$$

Oscillation probability and matter effects

- Here represented as an “oscillogram” cos(Zenith) vs Energy
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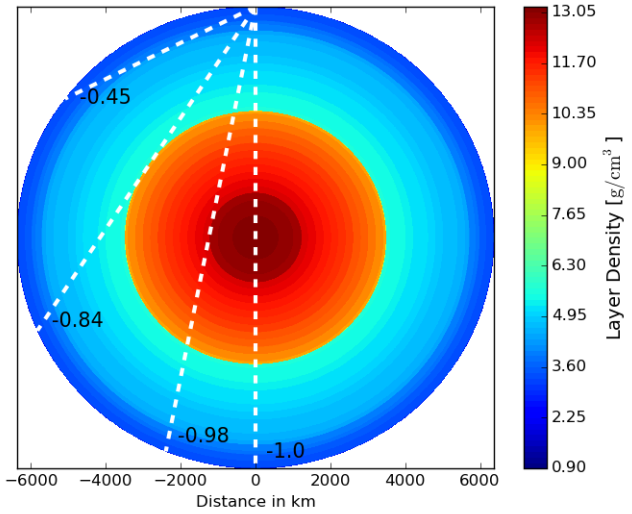
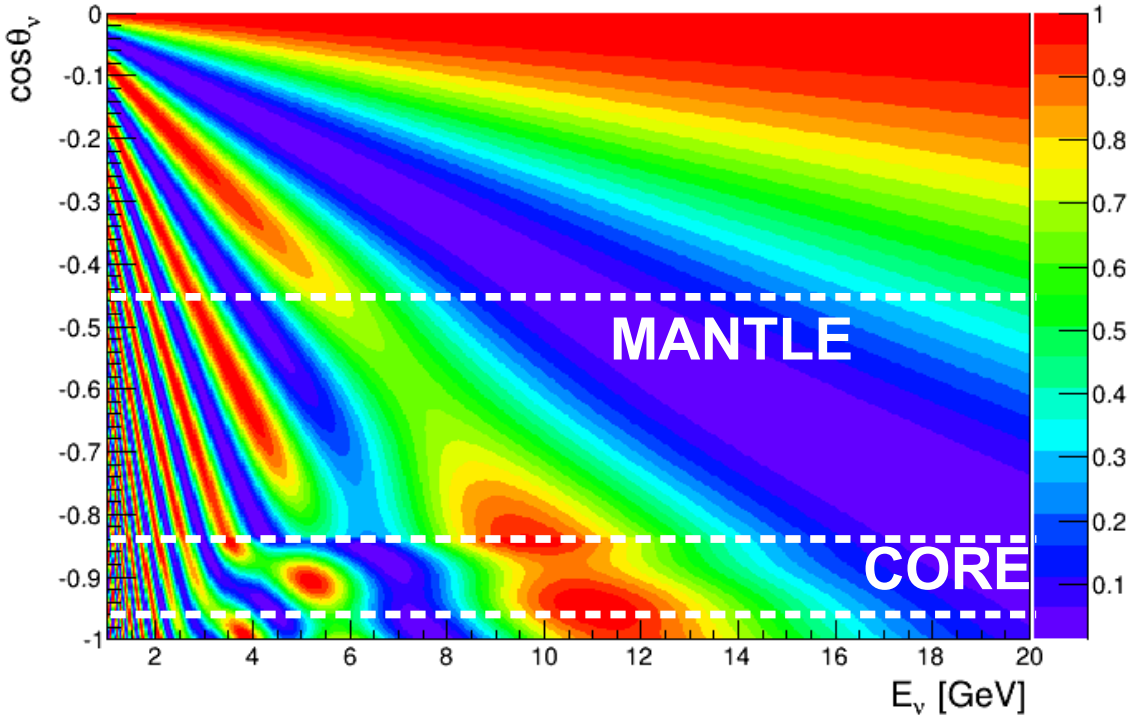
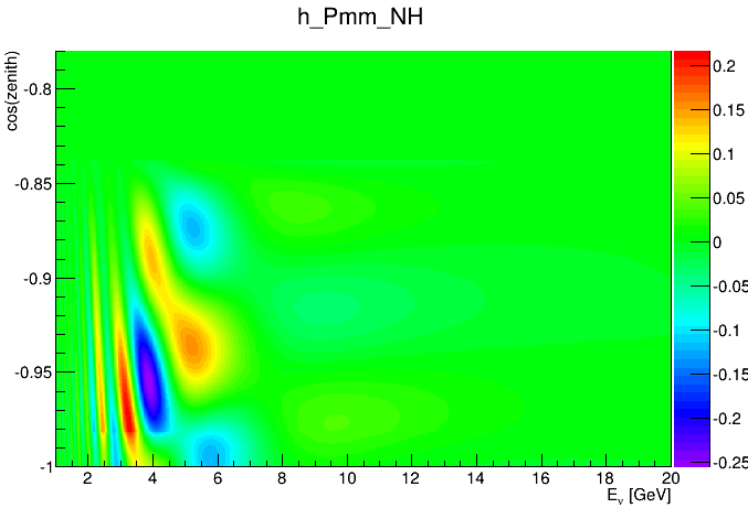




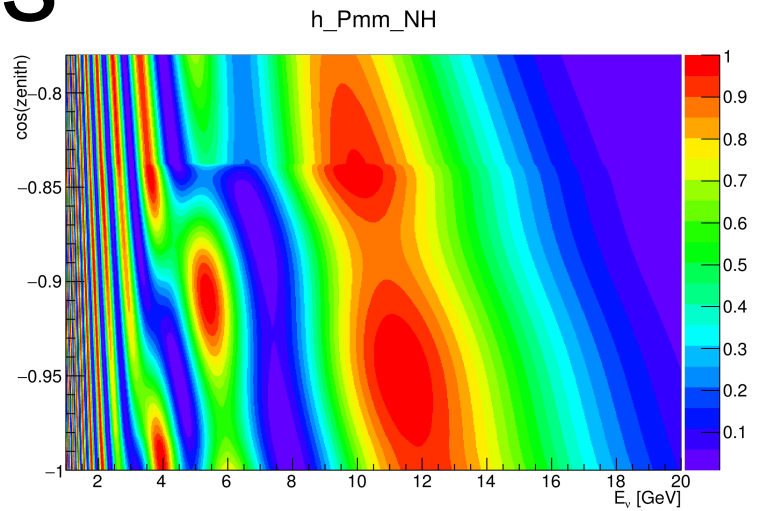
Probability $\nu_\mu \rightarrow \nu_\mu$ ***(Earth density profile)***

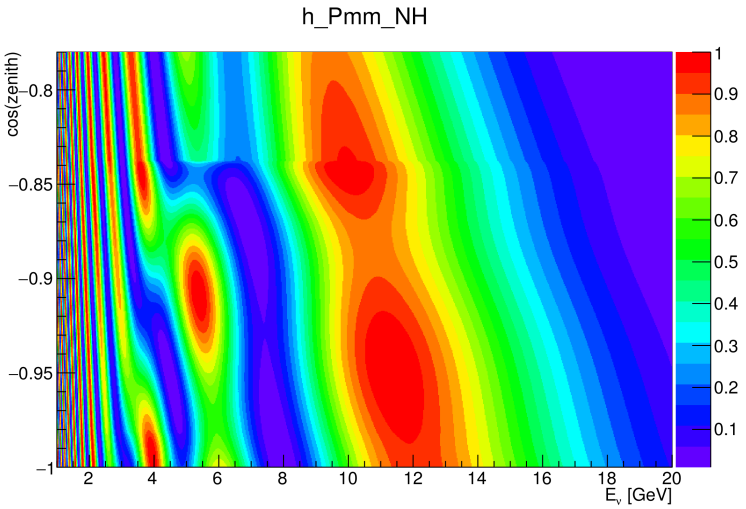
Oscillation probability and matter effects

- Matter effects are sensitive to the electron density $n_e \rightarrow$ can access composition of the Earth layers



Probability difference between the two models





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

top: *outer core is only iron*

bottom: *outer core is iron + 5wt% H*

Neutrino interactions

Charged Current: $\nu_l + X \rightarrow l + hadronic\ cascade$

Neutral Current: $\nu_l + X \rightarrow \nu_l + hadronic\ cascade$

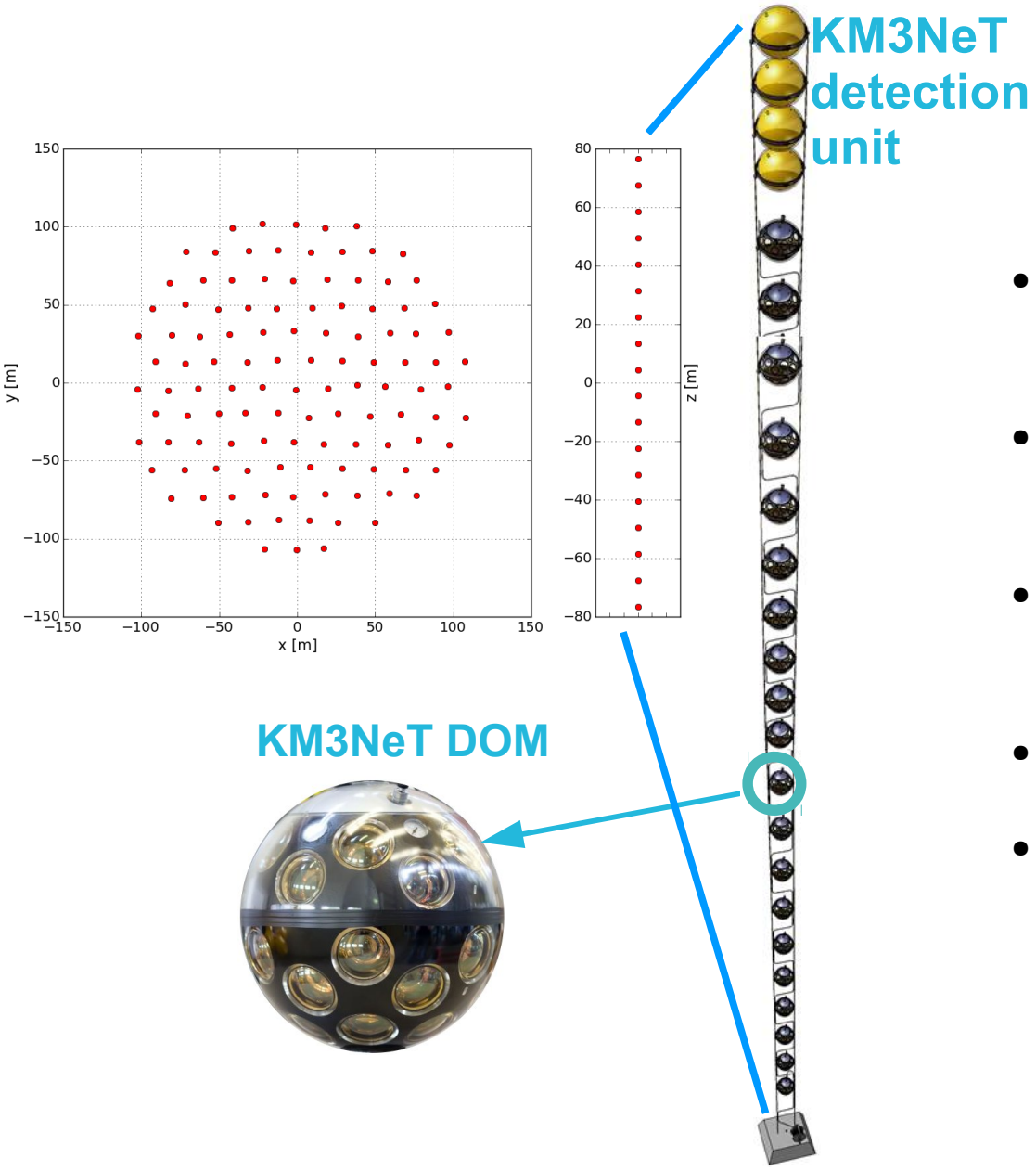
l = leptonic flavour = e, μ, τ
hadronic cascade: *from the disintegration of the struck nucleus*

Corresponding event topologies:

- **track:** all events with a muon in the final state, i.e. υ_μCC and 17% of υ_τCC
- **showers:** υ_eCC, 83% of υ_τCC and all flavours NC

With our PID we can distinguish between these two topologies

The ORCA detector

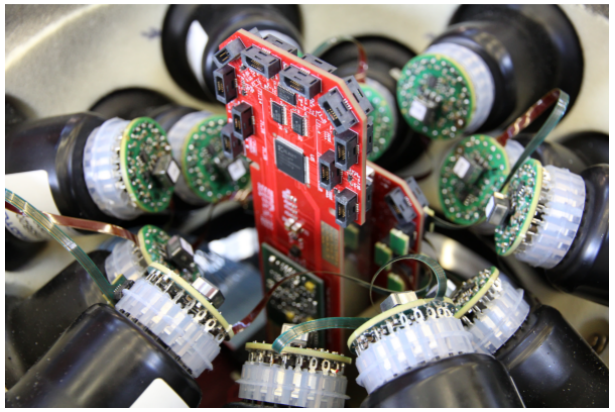


- 115 detection units, 20m spaced horizontally
- 18 Optical Modules (DOMs) per detection unit
- 9m vertical distance between DOMs
- Instrumented volume: ~5.7Mtons
- Estimated cost ~40 M€ (additional)

The KM3NeT DOM

- 17 inch pressure resistant glass sphere
- Hosting 31 photomultipliers, 3 inch each
- Single photon counting
- Maximises photocathode area

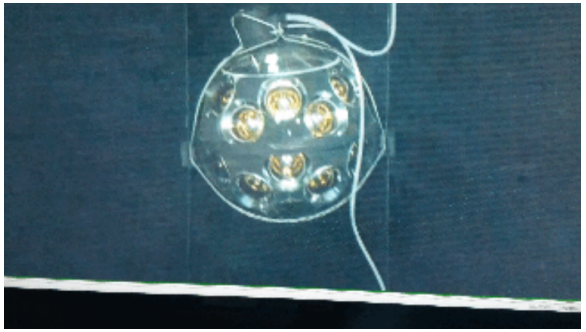
Picture of the multi-PMT Digital Optical Module (DOM)



The interior of the DOM

Current status

- First KM3NeT string successfully deployed last 3/12/2015 @ the ARCA site
- The string is healthy, takes data and reconstructs
- 3 prototypes already deployed and tested
- Another string should be deployed “soon” (few months) @ the ORCA site
- Six ORCA strings already funded

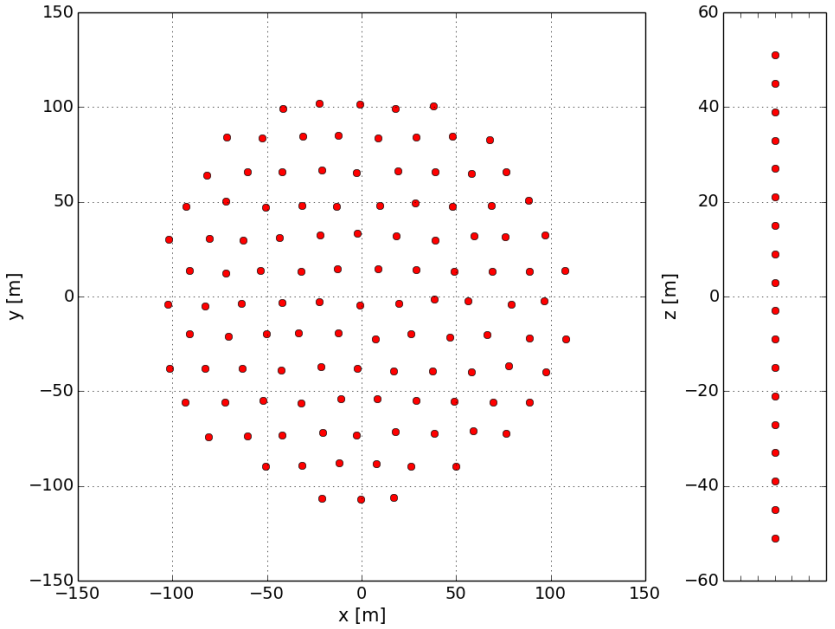


Phases of the deployment of the first ARCA string

Performance evaluation for ORCA

- Evaluated using Monte Carlo simulations
- Relevant quantities for event reconstruction
  - Direction and energy resolution
  - Effective mass
  - Particle identification
  - Atmospheric muon background rejection

Simulation chain



Footprint and z profile of the detector used for this study.
Nota bene: vertical spacing between DOMs is 6m, whereas optimization studies lead to chose 9m (more about this in forthcoming LoI).

- Atmospheric ν_e ν_μ ν_τ (+ anti) → 1–100 GeV
- Neutrino interactions: GENIE, both charged and neutral currents
- For all particles sufficiently close to the detector: tracking + Cherenkov light emission
- Down-going atmospheric muons generated using MUPAGE parameterization (*Carminati et al., Comput. Phys. Commun. 179 (2008) 915-923*)
- Optical ^{40}K background: 10kHz/PMT flat noise + 500 Hz/PMT time correlated
- Realistic trigger applied

Track reconstruction

Direction:

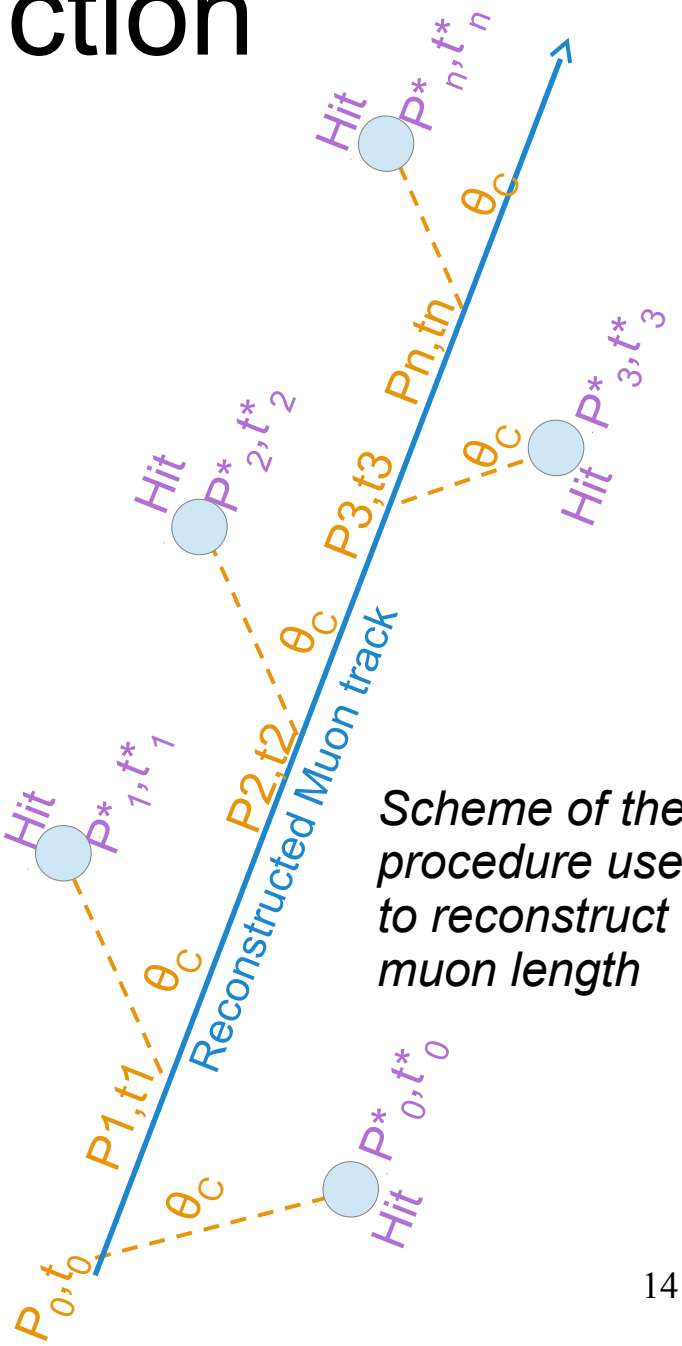
- Scan 7200 directions, chose the best
- Increase precision using a refined PDF of the time residuals (maximum likelihood fit)
- Finds the direction of the outgoing muon

Energy and vertex

- First find the vertex and the muon length, thus E_μ (see figure)
- Obtain the neutrino energy using E_μ and N_{hits}

Bjorken y (inelasticity)

- Use a PDF of the time residuals



Scheme of the procedure used to reconstruct the muon length

Track reconstruction

Direction:

- Scan 7200 directions, chose the best
- Increase precision using a refined PDF of the time residuals (maximum likelihood fit)
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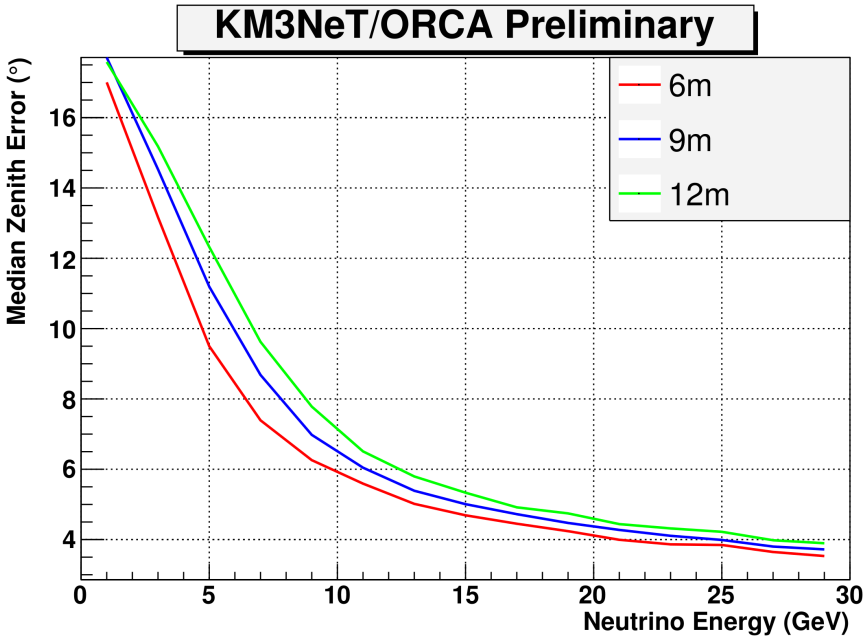

Zenith resolution obtained for ν_μ-CC, as a function of the neutrino energy. Around 10° in the relevant energy range for tomography.

Track reconstruction

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Energy and vertex

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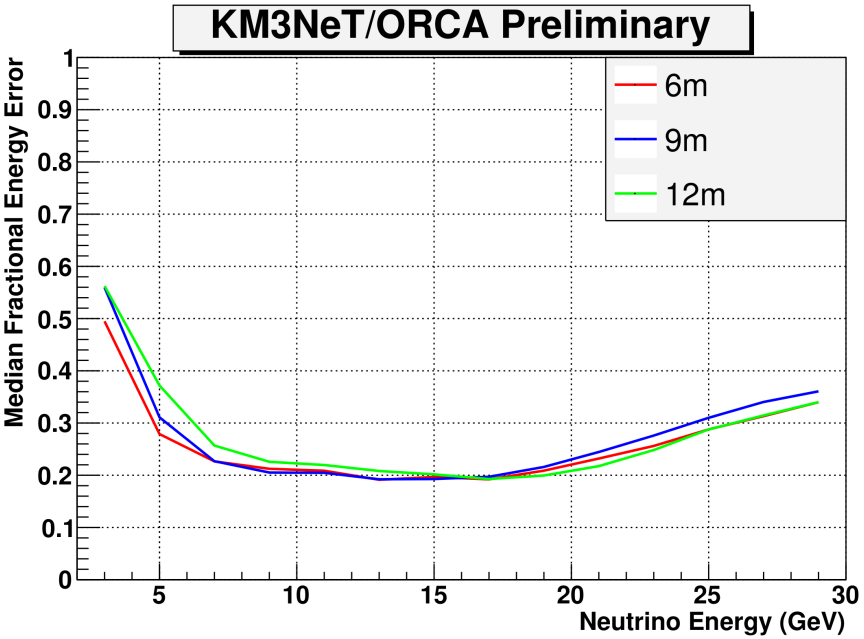

Energy resolution obtained for ν_μ-CC, as a function of the neutrino energy. Around 30% in the relevant energy range for tomography.

Shower reconstruction

Vertex:

- Maximum likelihood fit based on hit times PDF

Direction, energy and Bjorken y

- Joint PDF depending on the number of hits and their distribution in the detector
- Looks for the Cherenkov rings of the electron and/or the hadronic shower (see figures below)
- Reconstructs the direction of the electron (when present)

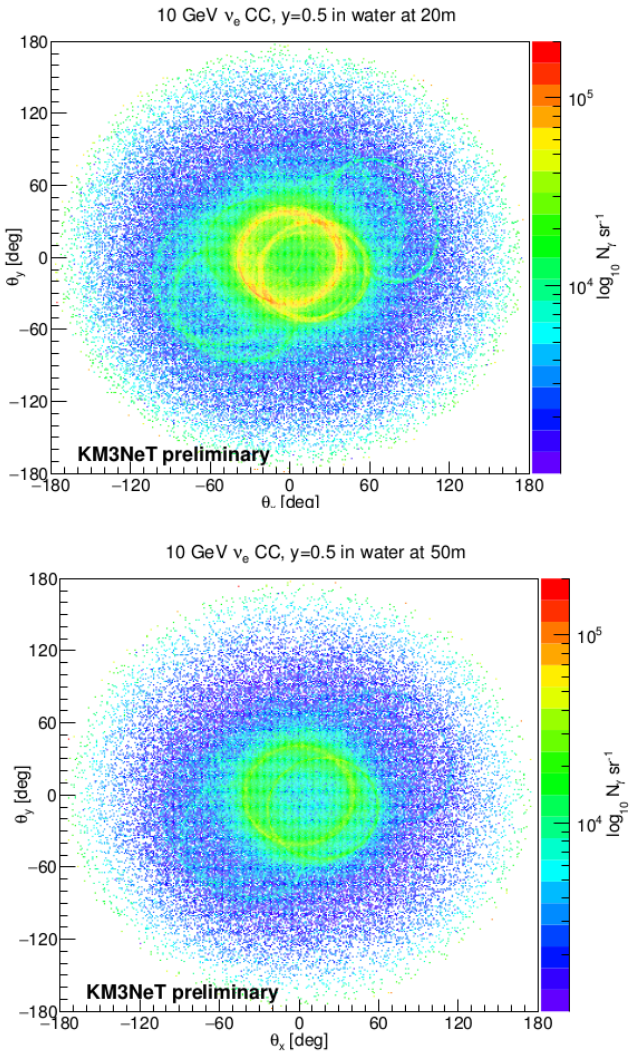

Figure: photon distribution from a ν_eCC event with y = 0.5
***top:** at 20m*
***bottom:** at 50 m*

Shower reconstruction

Vertex:

- Maximum likelihood fit based on hit times PDF

Direction, energy and Bjorken y

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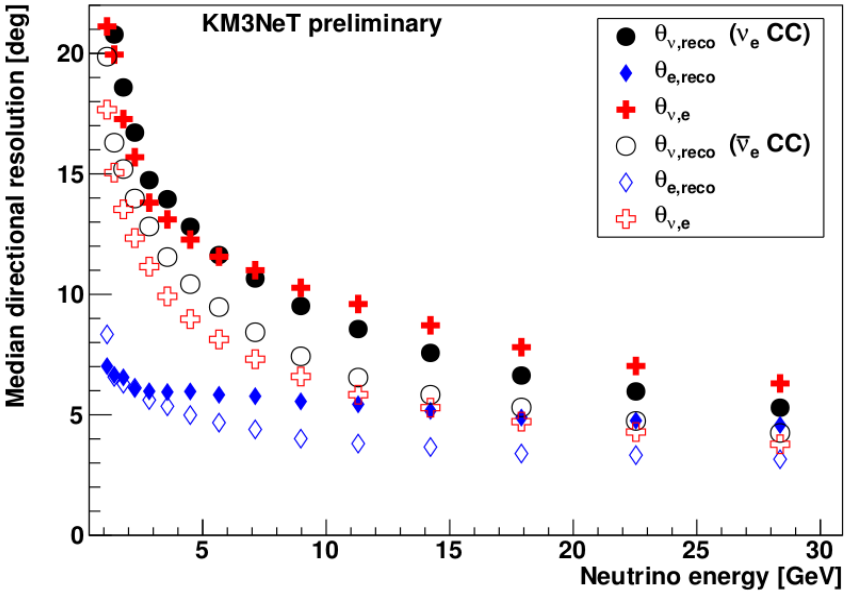


Angular resolution obtained for ν_e-CC, as a function of the neutrino energy. Around 10° in the relevant energy range.

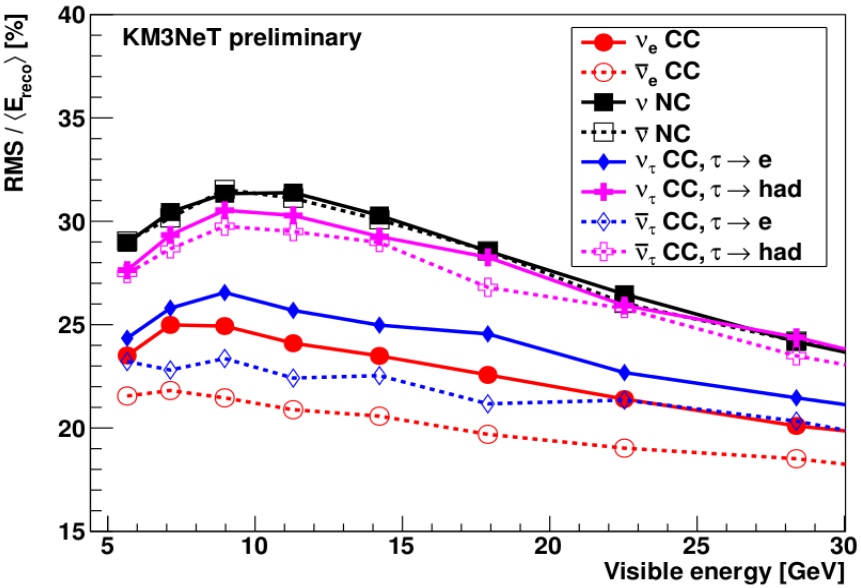
Shower reconstruction

Vertex:

- Maximum likelihood fit based on hit times PDF

Direction, energy and Bjorken y

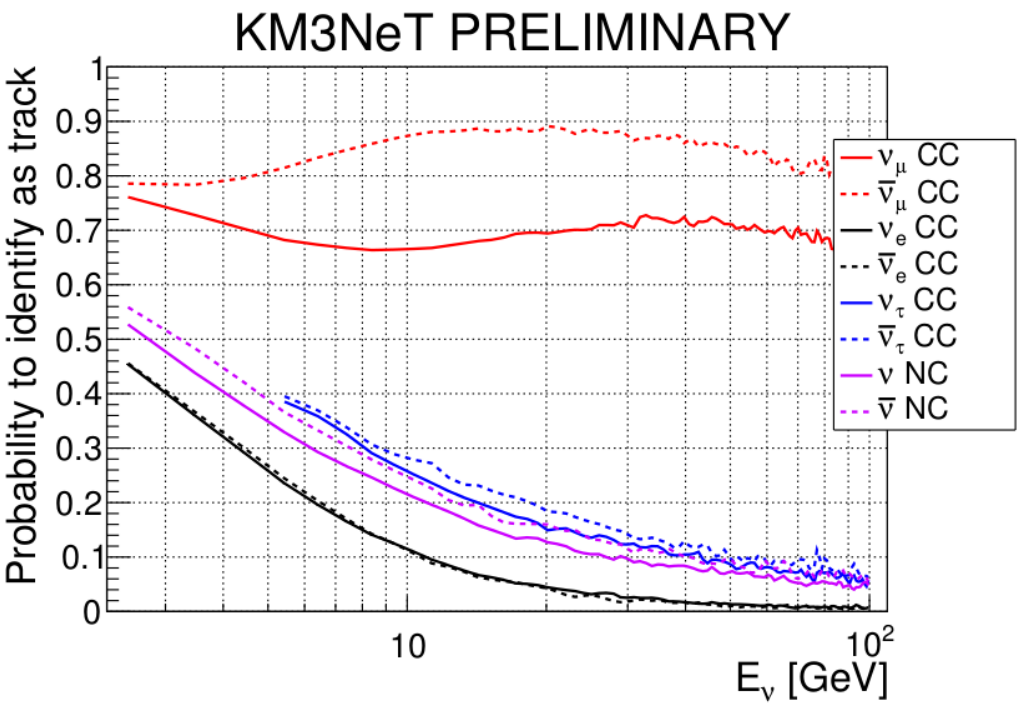
- Joint PDF depending on the number of hits and their distribution in the detector
- Looks for the Cherenkov rings of the electron and/or the hadronic shower (see figures below)
- Reconstructs the direction of the electron (when present)



Energy resolution obtained for shower events, as a function of the neutrino energy. Around 25% in the relevant energy range.

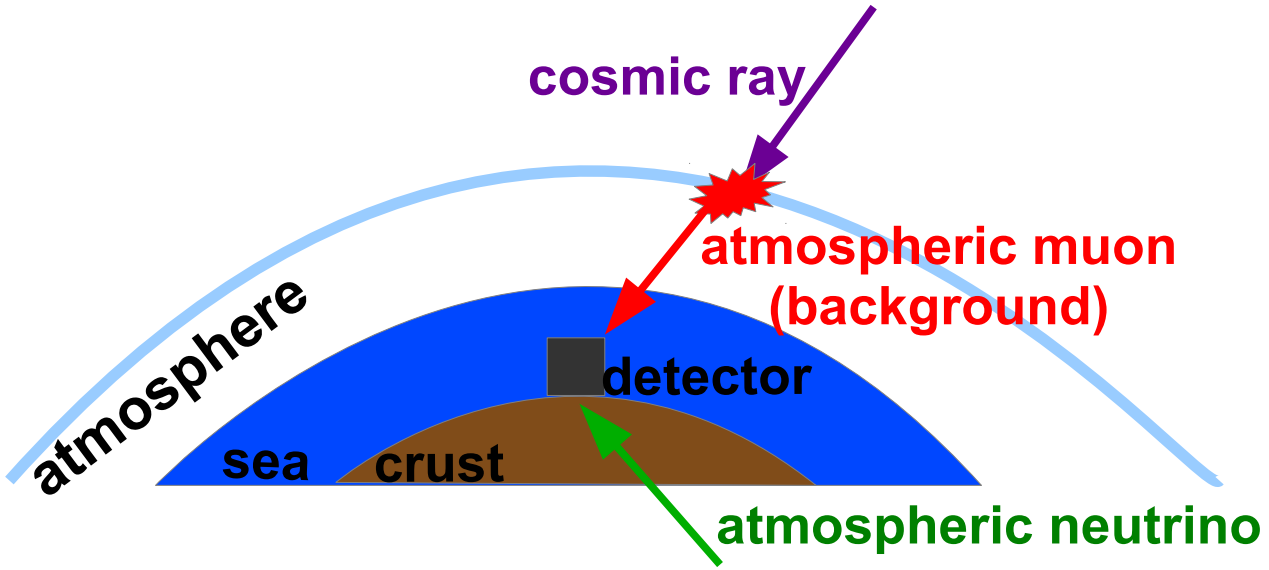
Particle Identification

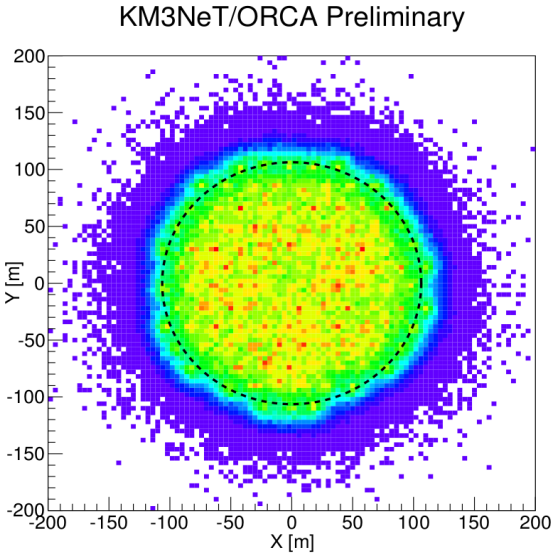
- Discern between track and shower-type events
- Random Decision Forest trained on MC events
- e-like CC events better than 80% above 6 GeV
- μ-like CC events around 80% (better for anti-ν_μ)

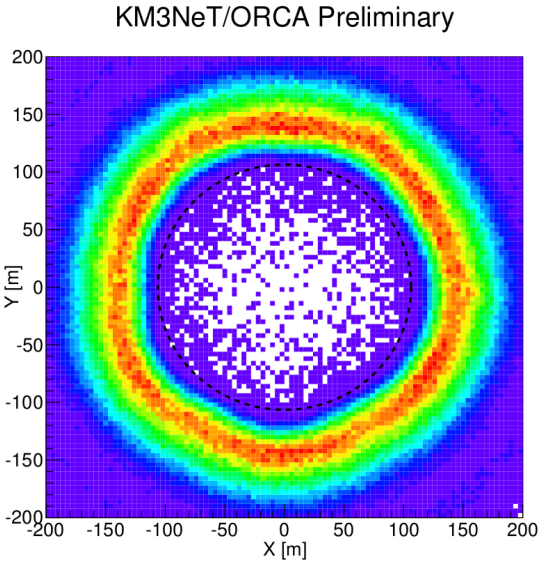


Probability that the PID algorithm identifies an event as a track as a function of the true neutrino energy. The lines denote different interaction types.

Atmospheric muon rejection







- Atmospheric muons can be reconstructed as upgoing → background to the neutrino sample
- Rejection:
  - Select upgoing events
  - Apply quality cuts from reconstruction
  - Pseudo-vertex position (see plots on the right)
  - Boosted Decision Tree
- **A %-level contamination can be achieved without loosing too much signal**

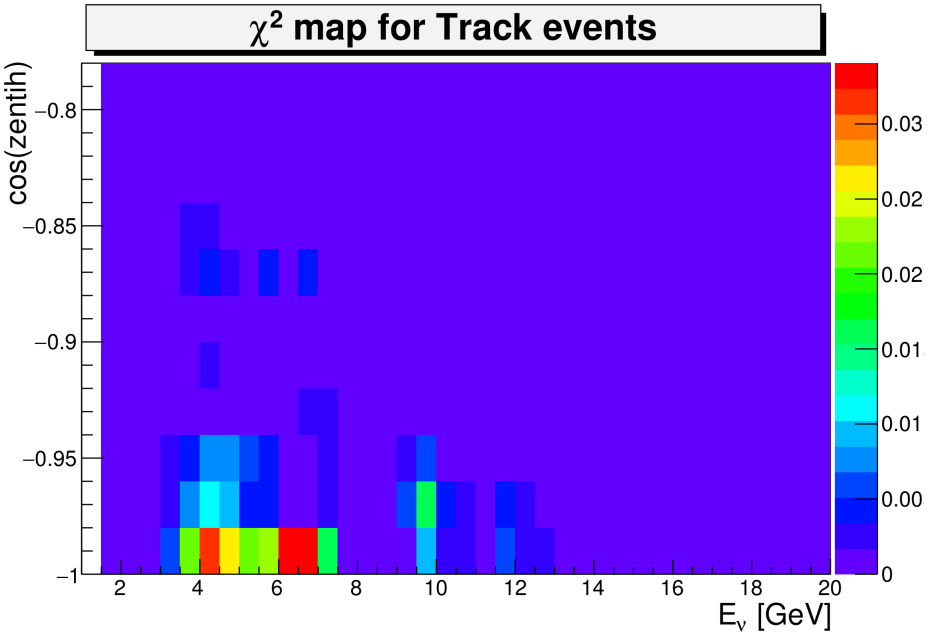
Reconstructed vertex position
top: neutrinos
bottom: atmospheric muons

Application to the Earth tomography

- Used a toy MC tool that can easily create oscillograms of interacting atmospheric neutrinos:
  - Honda flux + GENIE cross sections + GloBES probabilities
  - Applies ORCA resolutions, efficiencies and PID
- Modified PREM Z/A ratios of outer core and compared to the pure iron case

χ^2 map for Track events in the case that:

Model A = pure iron (Z/A =0.4656)
Model B = pure iron + 5wt% H (Z/A =0.4920)



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χ^2 map for Shower events in the case that:

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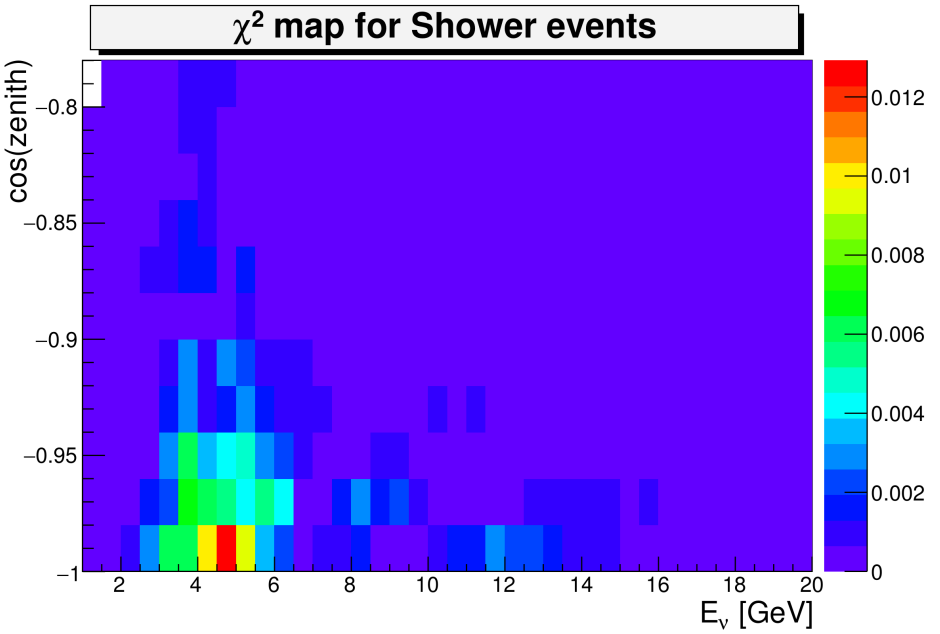
Model B = pure iron + 5wt% H (Z/A =0.4920)



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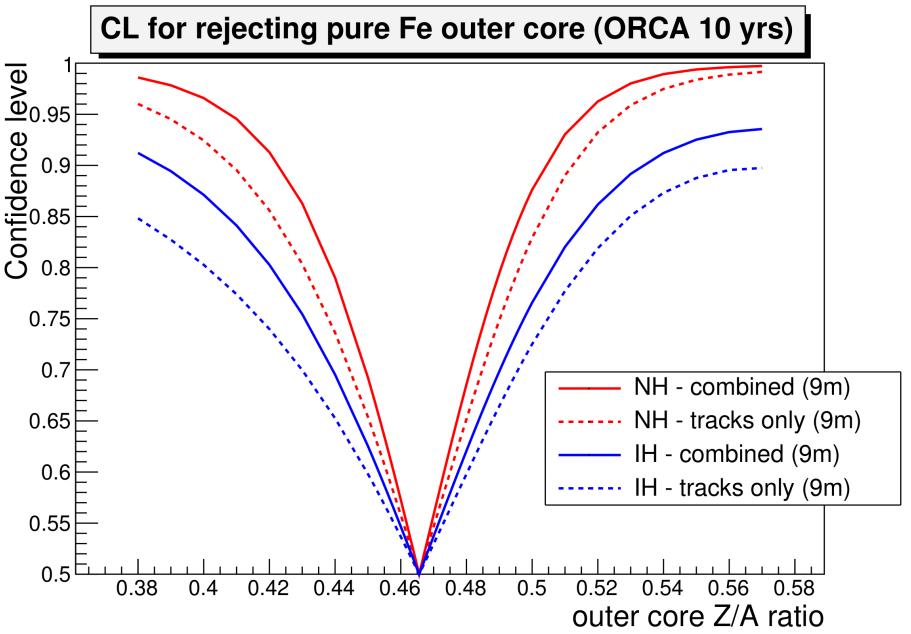
- Modified PREM Z/A ratios of outer core and compared to the pure iron case

Oscillation parameters from:
Gonzalez-Garcia, M.C. et al. JHEP 1212 (2012) 123 arXiv:1209.3023



Summary

- The forthcoming KM3NeT/ORCA will study neutrino oscillations and will have some potential for conducting Earth tomography studies
- The current framework is preliminary and will be improved in the next future: one PhD student (Simon Bourret) and one post-doc (Joao Coelho) on this subject at APC!
  - Implement a new type of analysis based on pseudo experiments
  - Add systematic uncertainties
- Finding out plausible models on the market that can be potentially excluded: also exotic ones, non phi-symmetric, etc.
- Will continue working on this also in collaboration with our colleagues geologists from IPGP in Paris