P2.025

Earth Tomography with KM3NeT-ORCA

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ABSTRACT

KM3NeT-ORCA is a future water-Cherenkov neutrino detector designed for studying the oscillations of atmospheric neutrinos, with the primary objective of measuring the neutrino mass ordering. ORCA will be deployed in the Mediterranean Sea, offshore Toulon, at a depth of 2450m. It will be able to reconstruct interacting neutrinos of all flavours with a large range of baselines and energies, and an effective mass of several megatons.

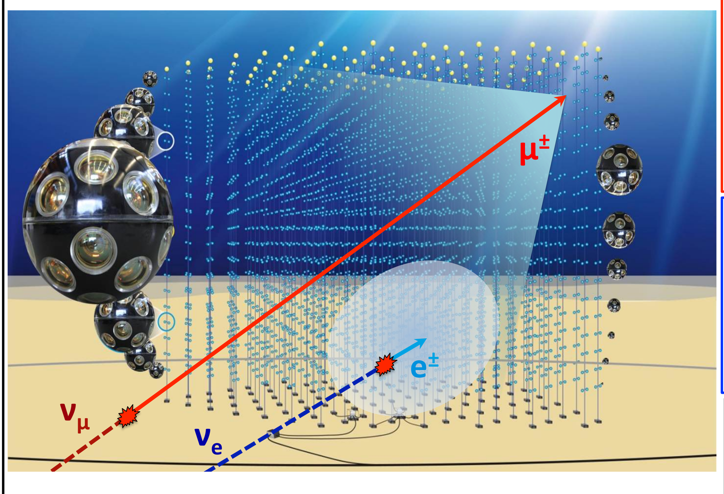
Neutrinos crossing the Earth undergo matter effects, modifying the pattern of their flavour oscillations. The study of the angular and energy distribution of neutrino events in ORCA can therefore provide tomographic information on the Earth interior with an independent technique, complementary to the standard geophysics methods.

We study here the sensitivity to the electron density for two distinct layers of the Earth: mantle and outer core. A full Monte Carlo simulation of ORCA, event reconstruction and flavour classification, is used to model the detector response. A simple statistical analysis is then performed to derive confidence intervals for the measurement of the electron density in these two layers.

DETECTION PRINCIPLE

Cherenkov light produced by secondary particles emerging from neutrino interactions is detected by multi-PMT Digital Optical Modules (DOM). The DOMs are attached to vertical strings anchored to the seabed.

- 9m vertical spacing of DOMs
- 20m average horizontal spacing of lines
- 115 lines × 18 DOMs × 31 PMTs = **5.7 Mton** water instrumented



Track signature:
- $\nu_\mu, \overline{\nu_\mu}$ CC events
- $\nu_\tau, \overline{\nu_\tau}$ CC with $\tau \to \mu$
- $\mu_{\rm atm}$ contamination

Cascade signature:
- $\nu_e, \overline{\nu_e}$ CC events
- $\nu_\tau, \overline{\nu_\tau}$ CC, $\tau \to had./e$
- NC events

No $\nu/\overline{\nu}$ event-by-event separation

EARTH MODEL BASIS

Proportionality factor between electron density and matter density depends on chemical & isotopic composition:

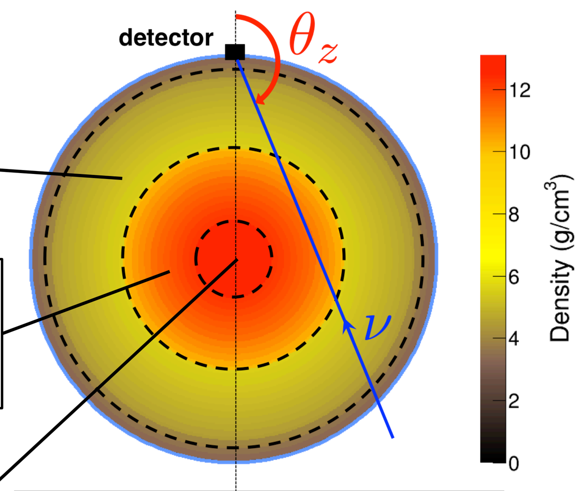
$$\frac{Z}{A} = \frac{\sum x_i Z_i}{\sum x_i A_i} = \sum w_i \frac{Z_i}{A_i} \Rightarrow n_e = \frac{N_A}{m_n} \times \frac{Z}{A} \times \rho_{\rm matter}$$

→ **3 chemically distinct layers**
→ **Z/A uniform in each layer**

Mantle: $R_{\rm ext}$ ≈ 6300 km
pyrolite (rock model)
Z/A = **0.496**

Outer core: $R_{\rm ext}$ ≈ 3480 km
pure Fe (+ 5% Ni)
Z/A = **0.4656** (0.4661)

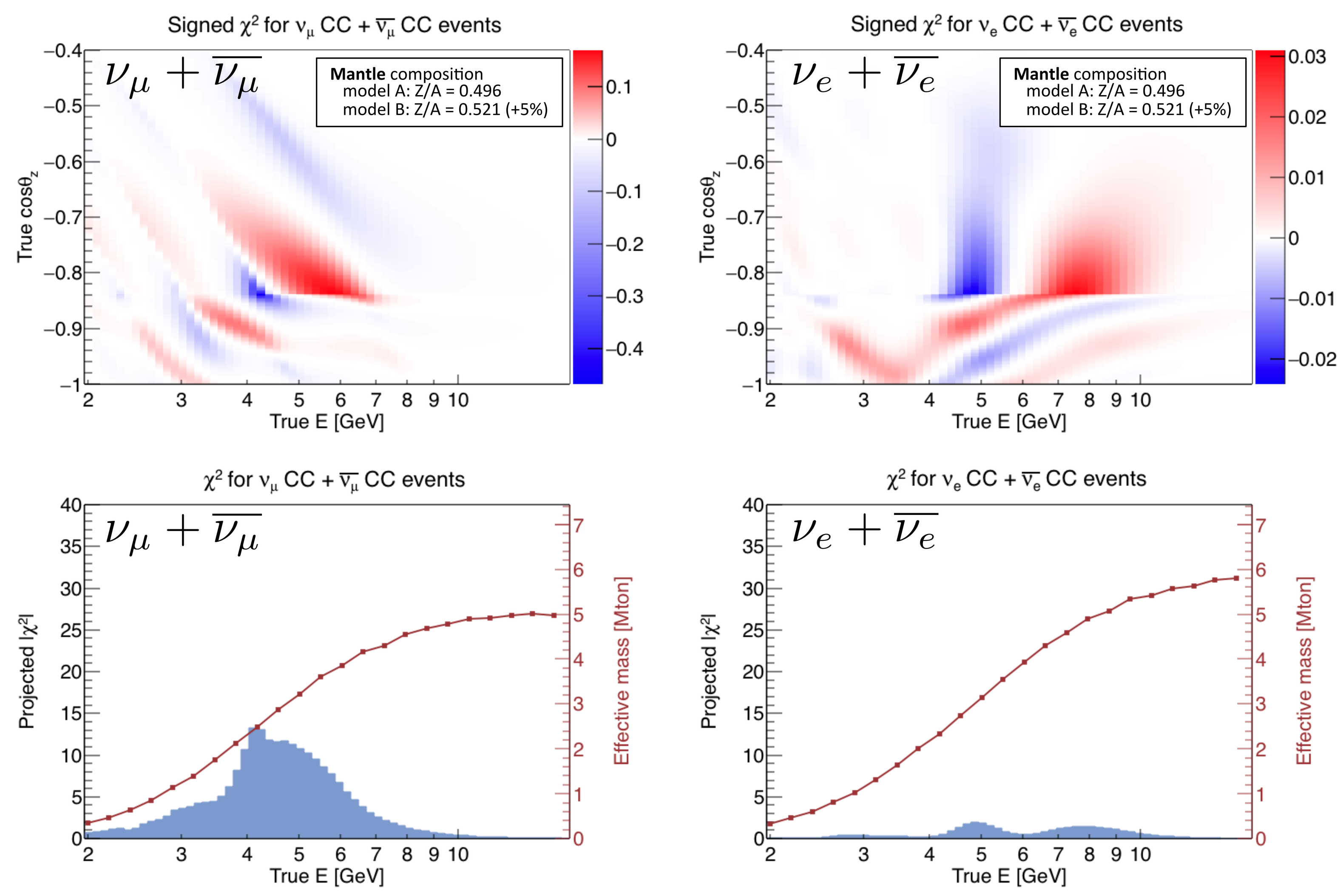
Inner core: $R_{\rm ext}$ ≈ 1220 km
pure Fe
Z/A = **0.4656**



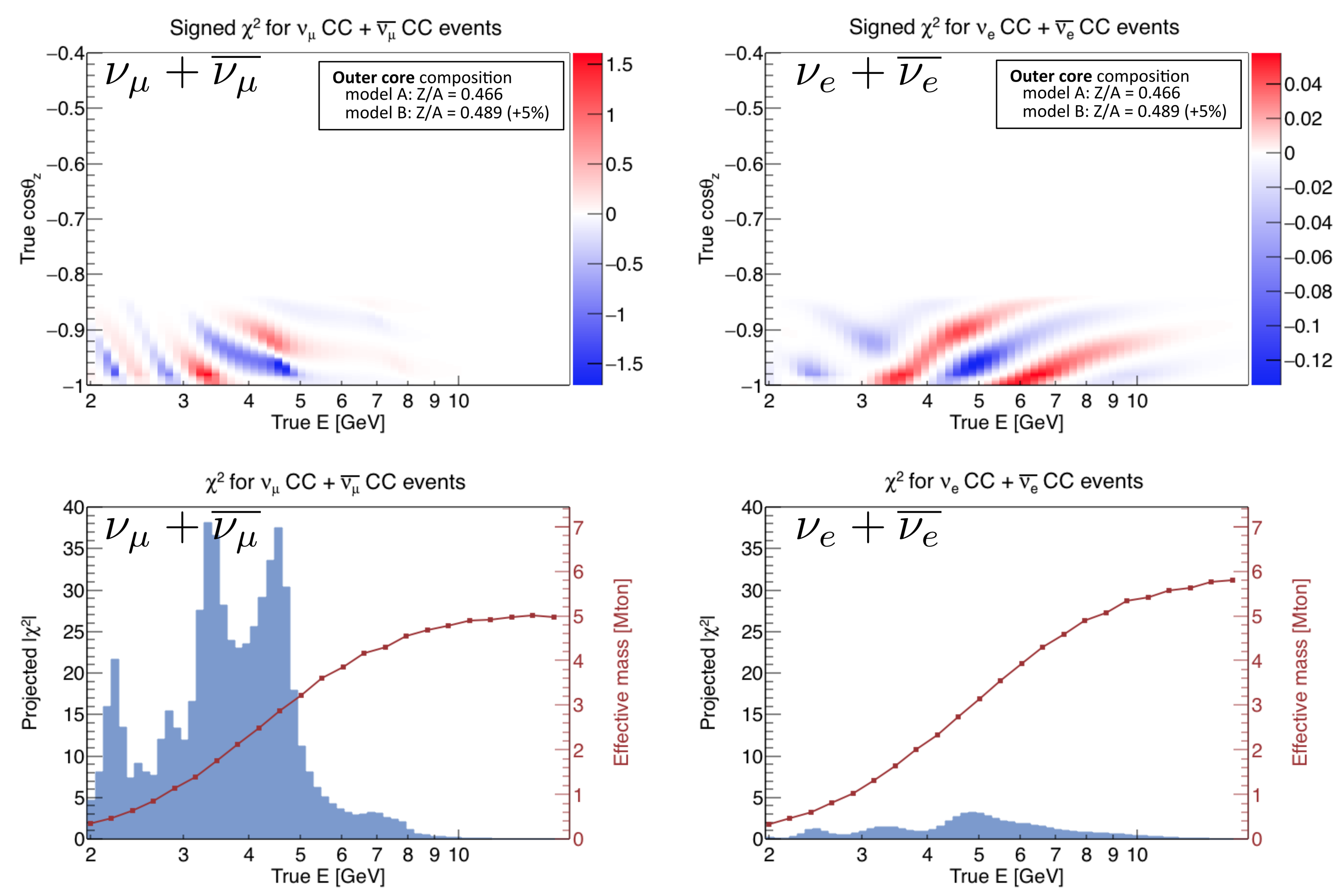
42-steps PREM model

$\nu + \overline{\nu}$ SIGNAL – INTERACTING EVENTS WITH NO DETECTOR EFFECTS – ORCA 10 YEARS (570 MTON.YRS)

Z/A varied by 5% in **mantle** only



Z/A varied by 5% in **outer core** only



- A = base model value – B = Z/A increased by 5%
- Top plots: signed $\chi^2(\text{bin } i) = \frac{(n_A^i - n_B^i) \times |n_A^i - n_B^i|}{n_A^i}$
- Bottom: 1-D projection of absolute value $|\chi^2(\text{bin } i)|$
- Channel-specific ORCA effective mass superimposed

→ theoretical signal is more pronounced in muon channel (*i.e.* Tracks)

→ outer core shows higher asymmetry, but concentrated in fine-grained pattern at low energy: challenging measurement

Ingredients for calculating rates of interacting events:
- Flux data tables: *Honda et. al* [3]
- Cross-sections: GENIE event generator [4]
- Earth Model basis = 42-steps PREM model [2]
- Oscillation Probabilities: OscProb calculator, *J. Coelho* [6]
- Oscillation parameters taken from NuFit website [5], δ_{CP}=0
- Normal mass ordering assumed
- Exposure: ORCA instrumented vol. × 10 years = 570 Mton.yrs

DETECTOR RESPONSE

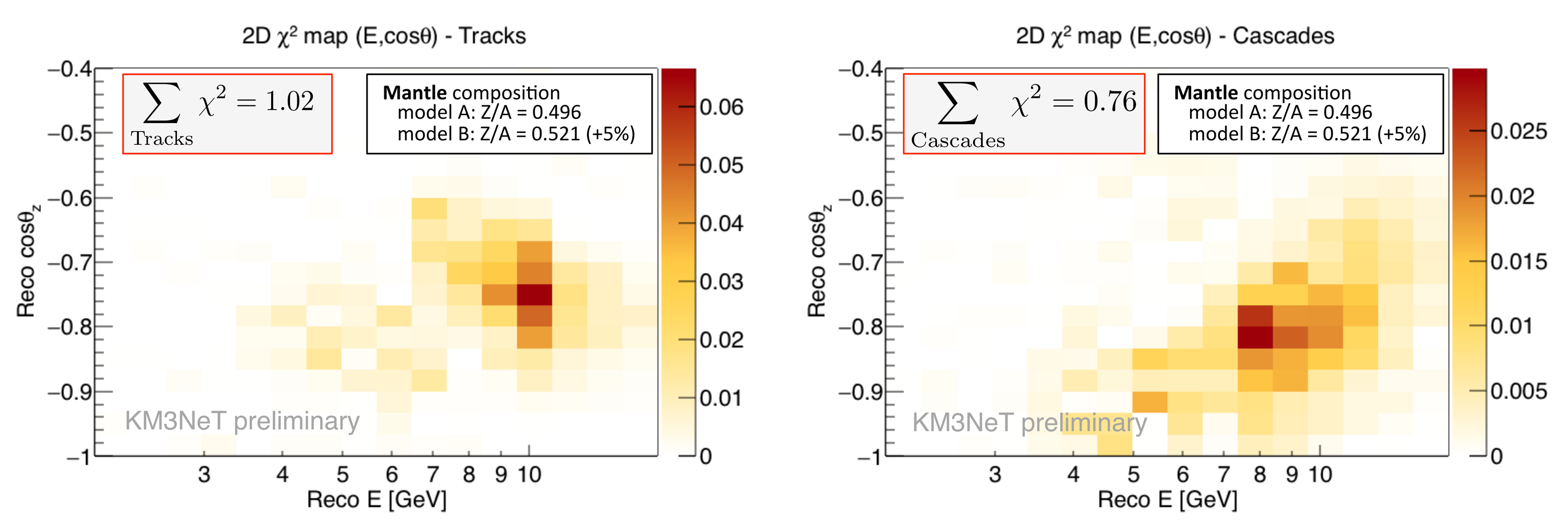
- Response in neutrino energy, zenith angle (cosθz<0 for upgoing), and inelasticity $Y_{\rm Bjorken} = 1 - \frac{E_{\rm lepton}}{E_\nu}$
- Dedicated reconstruction algorithms for Track and Cascade channels [1]
- Event classification and atmospheric muon rejection handled by Random Decision Forest technique

True	Reconstruction & Classification	Reco
• True $(E, \cos\theta_z, Y_{\rm Bj})$ • True channel: → CC $\nu_e/\overline{\nu_e}$, $\nu_\mu/\overline{\nu_\mu}$, $\nu_\tau/\overline{\nu_\tau}$ → NC $\nu/\overline{\nu}$	⇒	• Reco $(E, \cos\theta_z, Y_{\rm Bj})$ • Event classification ("flavour ID"): → Track / Cascade / $\mu_{\rm atm}$

- Full sample of Monte Carlo events is used to fill a binned response matrix = (6+1)-dim sparse histogram
- Takes into account all efficiencies, resolutions and misidentification probabilites, with all correlations
- Validity of full Monte-Carlo approach has been checked for simple 2-D analysis presented here

→ Both channels contribute significantly to the sensitivity

Reconstructed signal in Track and Cascade channels – **mantle** only – ORCA 10 years



SENSITIVITY EVALUATION

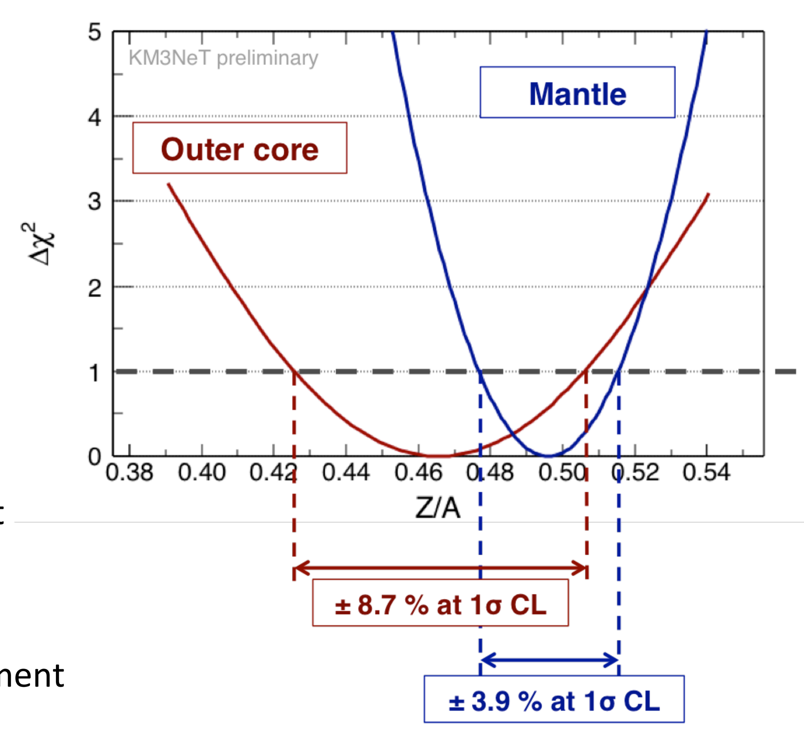
$$\Delta\chi^2 = -2\log\left[\frac{L(x|B)}{L(x|A)}\right]$$

x = observed data
A,B = model hypotheses

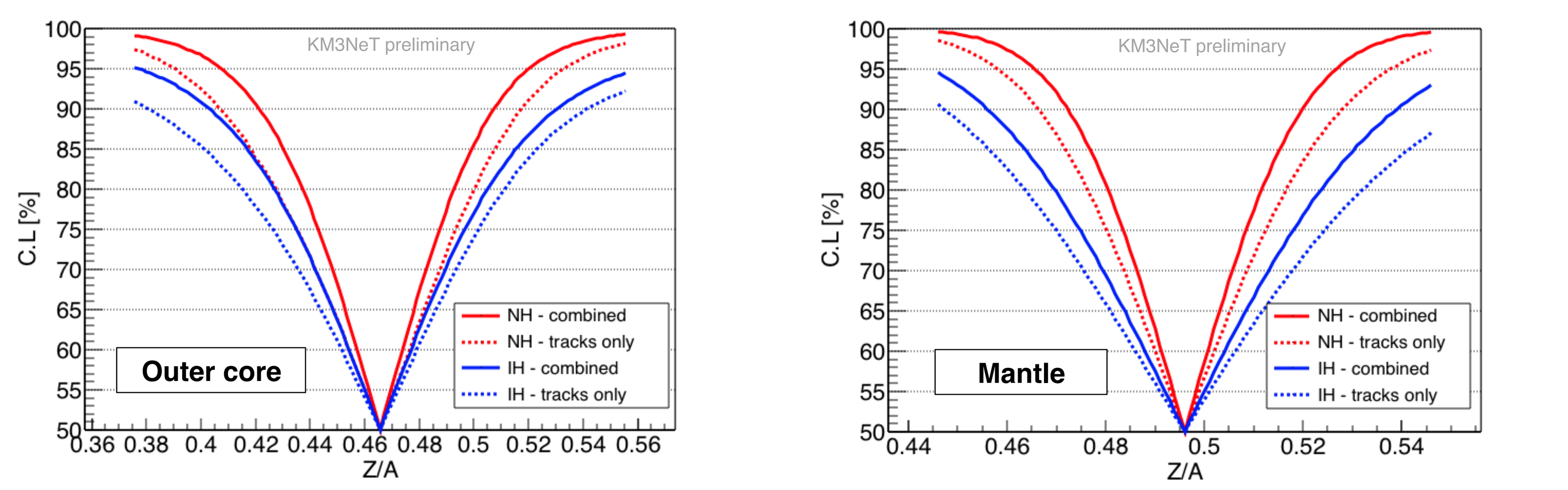
- Simplified method: use « Asimov dataset » instead of pseudo-experiments, then

$$\Delta\chi^2 = \sum_{\substack{\text{Tracks,}\\ \text{Cascades}}} \sum_{\substack{\text{bins } E\\ \text{bins } \cos\theta_z}} 2\left[n_A - n_B + \log\left(\frac{n_B}{n_A}\right)\right]$$

- Sum on 2D bins: reconstructed Bjorken-Y information not included (results under preparation)
- No fitted systematics / oscillation parameters
- Layers considered separately: no simultaneous measurement



Confidence level to reject base Z/A hypothesis in outer core and mantle



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[5] M.C. Gonzalez-Garcia et al., *Updated fit to three neutrino mixing: status of leptonic CP violation*. JHEP 11 (2014) 052. Website: www.nu-fit.org
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SUMMARY AND PROSPECTS

We demonstrate the feasibility of measuring the electron density in the inner layers of the Earth using neutrino oscillation tomography with KM3NeT-ORCA. After 10 years of operation, the proposed ORCA detector can measure the electron density in the Earth mantle to an accuracy of 4% at 1σ confidence level. In the outer core, this performance is reduced to 9% precision. A significant improvement is realised by combining the Tracks and Cascades channels.

Including the reconstructed inelasticity in the analysis has the potential to increase the sensitivity, by allowing to distinguish neutrinos from antineutrinos on a statistical basis. A full analysis quantifying the same performance with improved Bjorken-Y reconstructions is under preparation. Further studies will also include systematic uncertainties and a sensitivity study for simultaneous measurements of several layers.