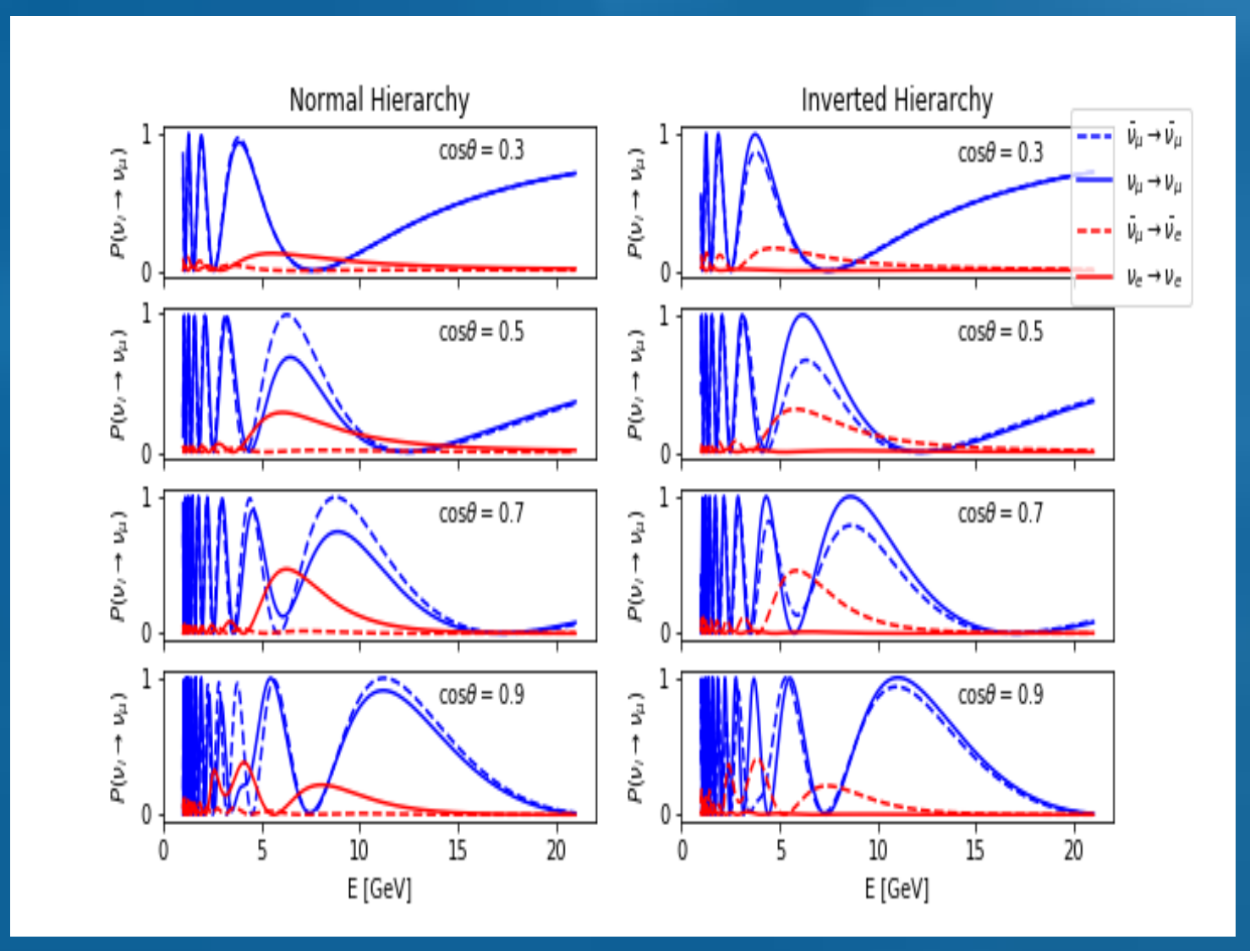
Determining the Neutrino Mass Ordering and oscillation parameters with KM3NeT/ORCA

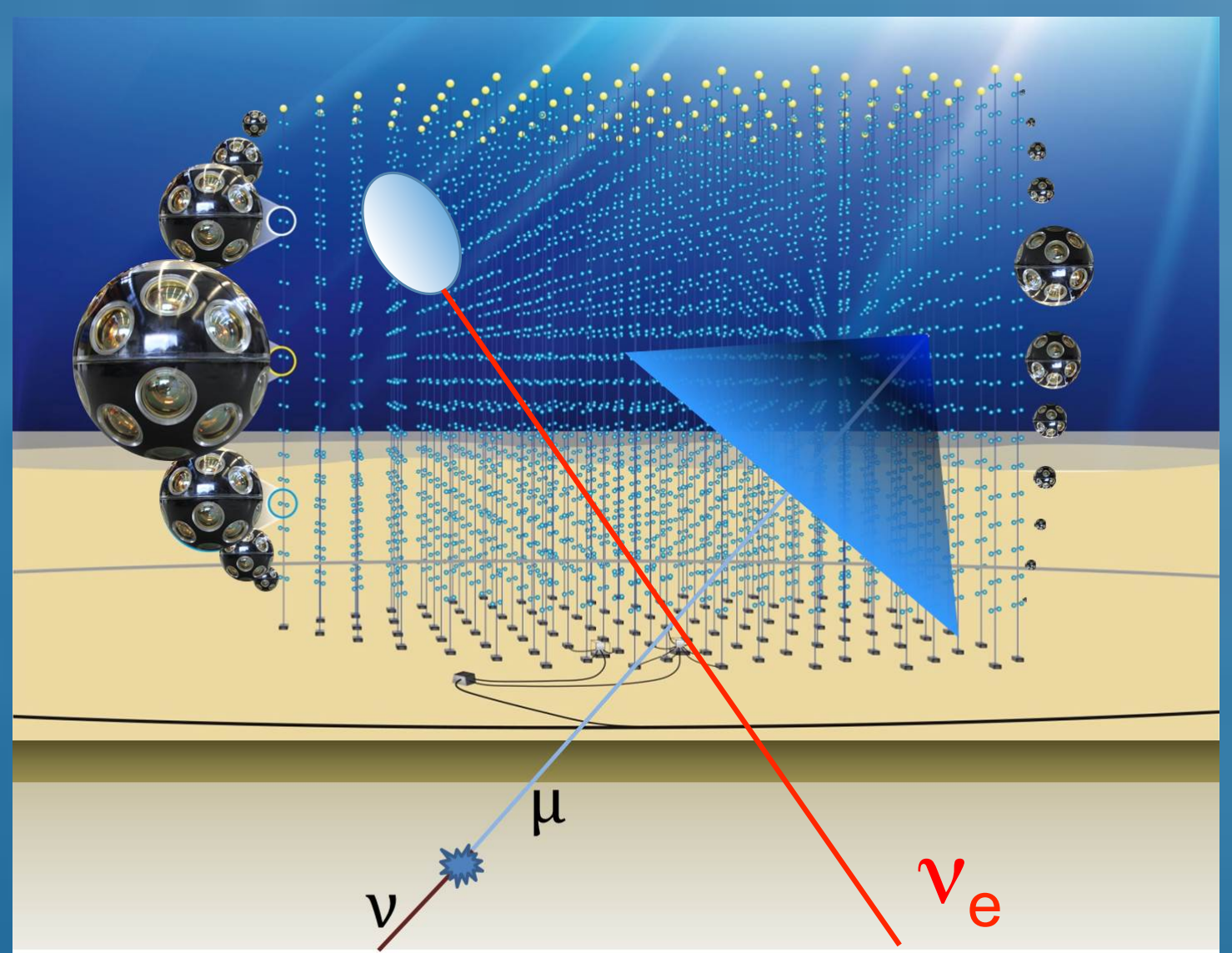
Simon Bourret*[1], Liam Quinn[2] for the KM3NeT collaboration

[1]Astroparticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Obs. de Paris, Sorbonne Paris Cité, France
[2]Aix-Marseille Université, CNRS/IN2P3, CPPM UMR 7346, 13288, Marseille, France

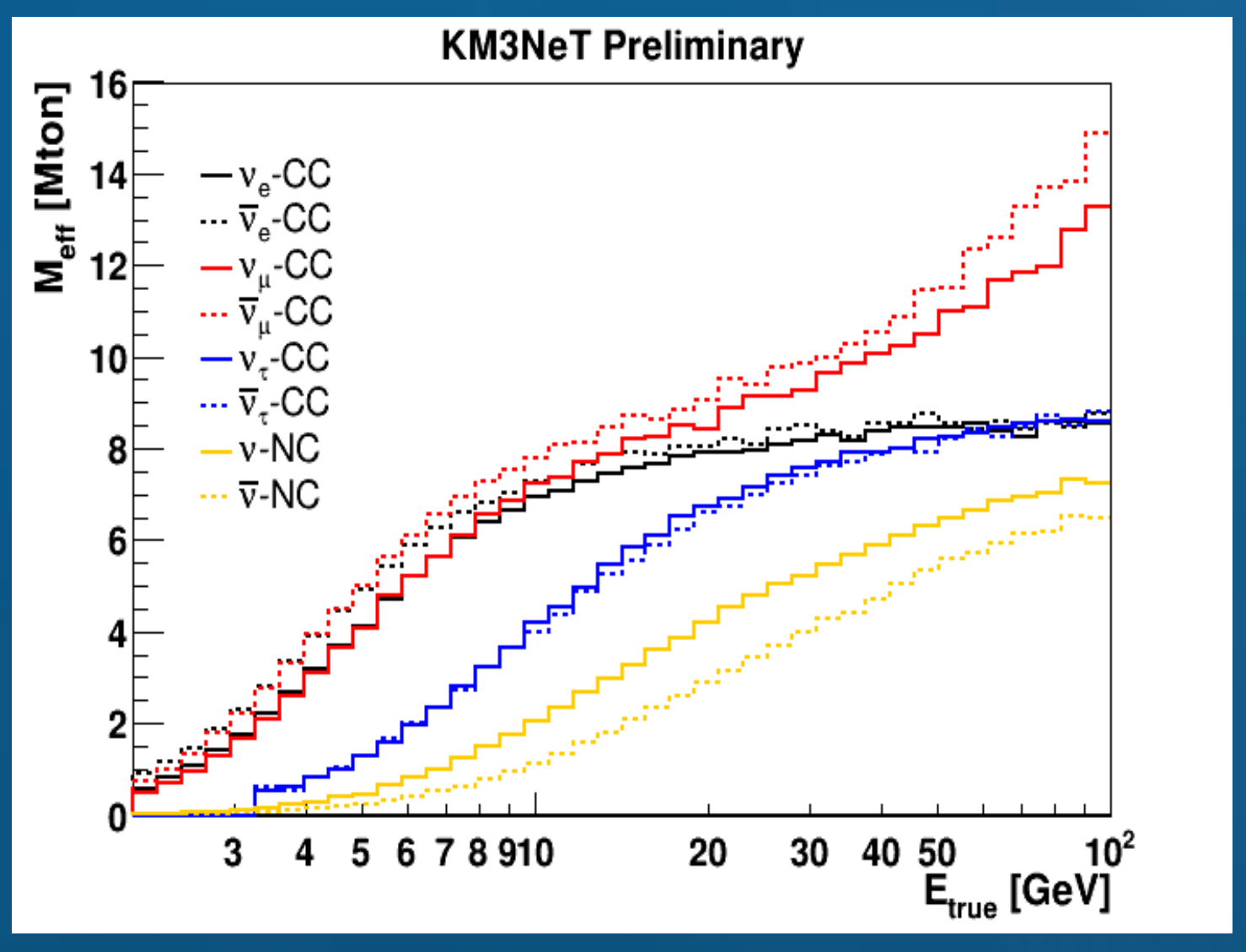
Contact: bourret@apc.in2p3.fr (*presenter), quinn@cppm.in2p3.fr



In the few GeV range, matter effects introduce a resonance into the oscillation probabilities: ν_e appearance is enhanced for a normal mass ordering (NO) and $\overline{\nu}_e$ appearance is enhanced for an inverted mass ordering (IO). The exact energy range for this enhancement depends on the baseline, matter density profile and hence zenith angle of the neutrino as it crosses the Earth.

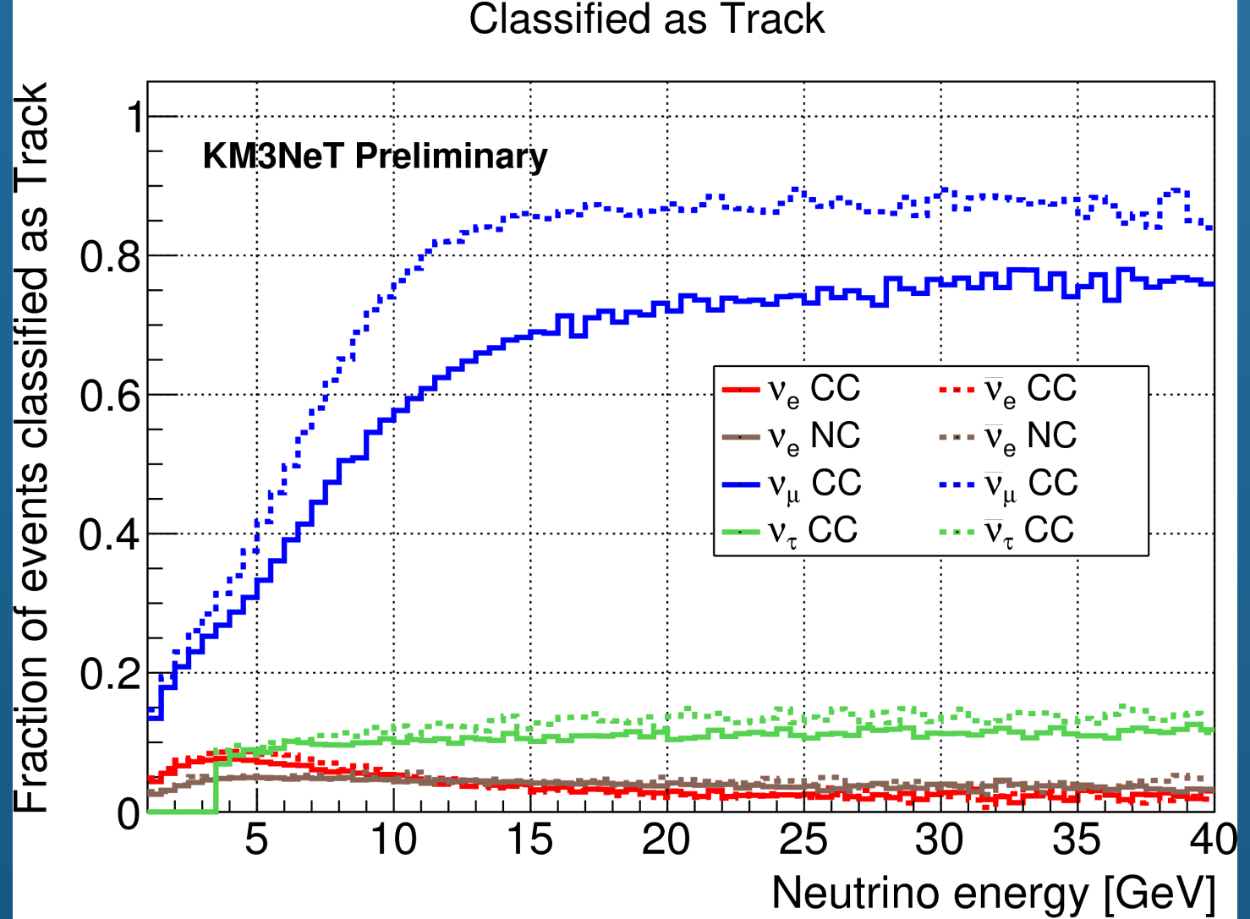


The KM3NeT/ORCA detector [1] will consist of an array of 2070 glass spheres, each containing 31 3" photomultiplier tubes, installed at a depth of 2450 m below the Mediterranean Sea. The energy and direction of atmospheric neutrinos can be determined by exploiting the Cherenkov signatures of secondary charged particles. On the left, an artist's impression of the detector is shown, as well as the distinct event topologies of ν_e and ν_μ charged current interactions.



Left: detector effective mass in megatons for each interaction channel.
Below: count of selected upgoing events in the 2-100 GeV energy range (3 years)

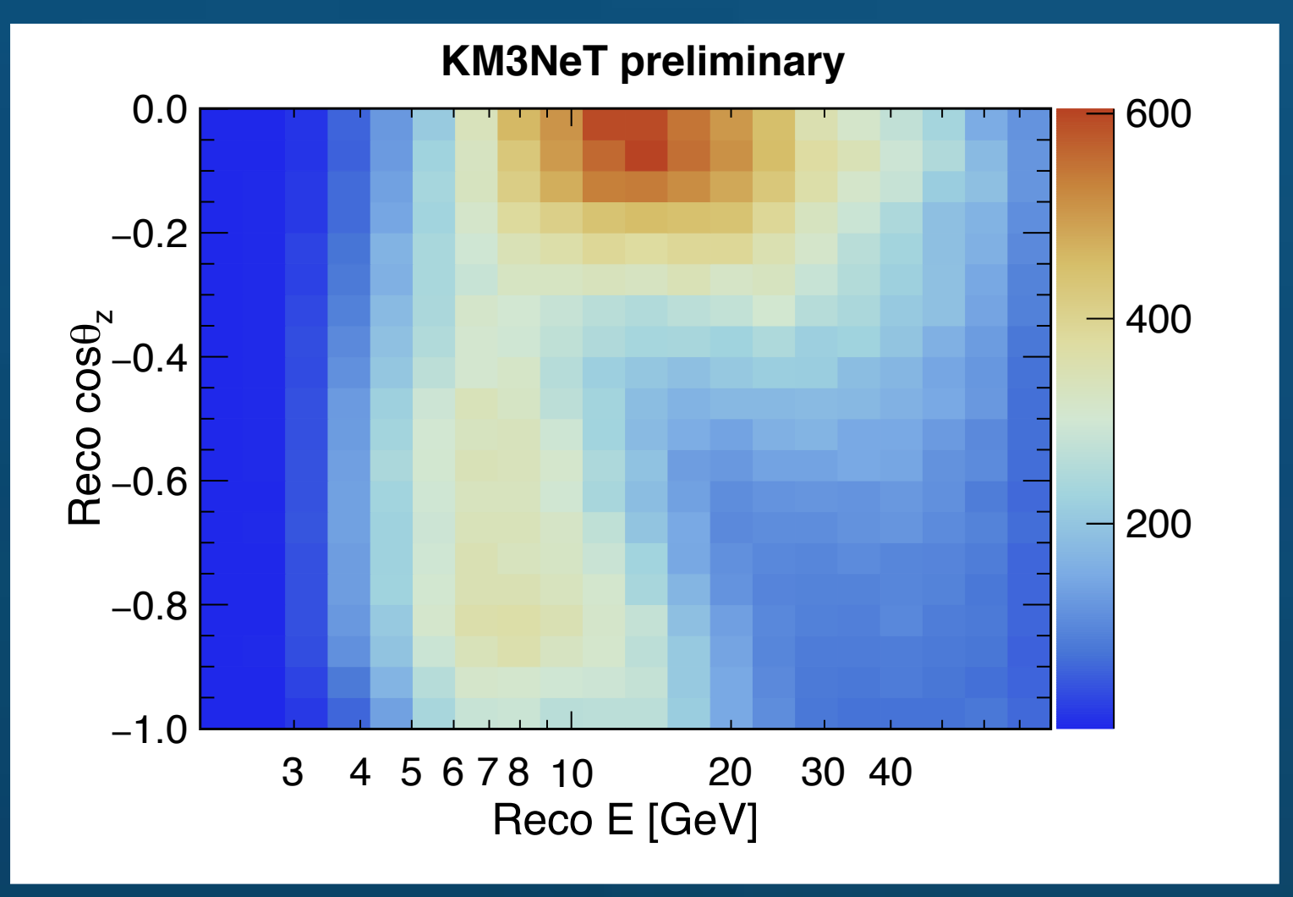
channel	events/y	channel	events/y
ν_e CC	14700	ν_τ CC	2900
$\bar{\nu}_e$ CC	5700	$\bar{\nu}_\tau$ CC	1300
ν_μ CC	21300	ν NC	5300
$\bar{\nu}_\mu$ CC	9900	$\bar{\nu}$ NC	1500

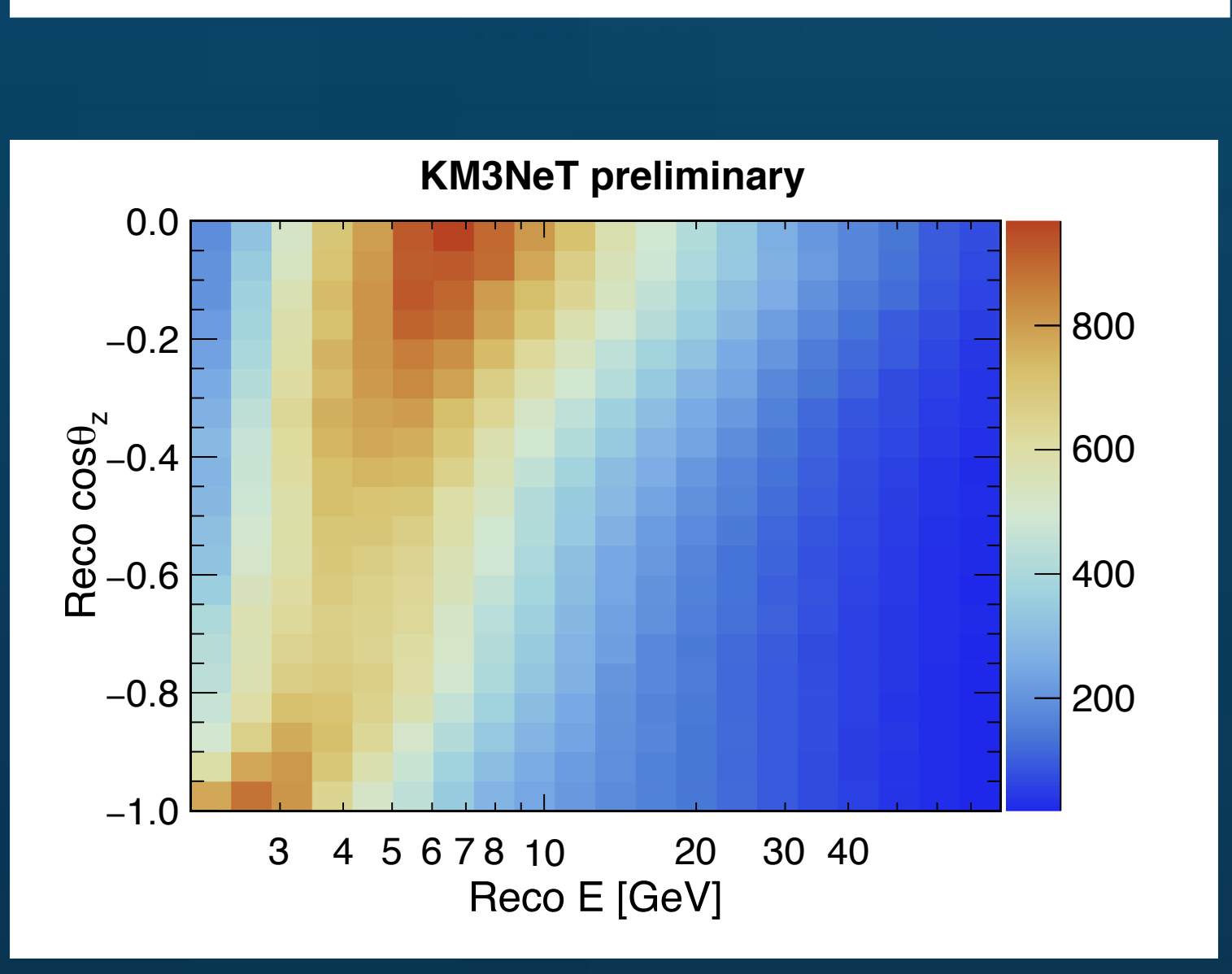


Random decision forests are used to reject background (optical, atmospheric muons) and categorise events as either:

- track-like (events with an outgoing μ)
- cascade-like (all other channels)

Using this method, ORCA is able to achieve a partial statistical separation between ν_e and ν_μ charged current events. The classification performance is shown on the left. Event classes are defined by a cut on the classification score, which is optimised with respect to the NMO measurement.





Calculation of the rate of interacting events: The HKKM 2014 flux tables (Gran Sasso site) [2] are interpolated in $\log_{10}$(E) and cosθ. Oscillation probabilities are calculated with the OscProb package [3], using a 42-layers radial Earth model based on the PREM [4], including realistic values of Z/A (chemical composition), neutrinos being produced at a fixed height of 15 km.

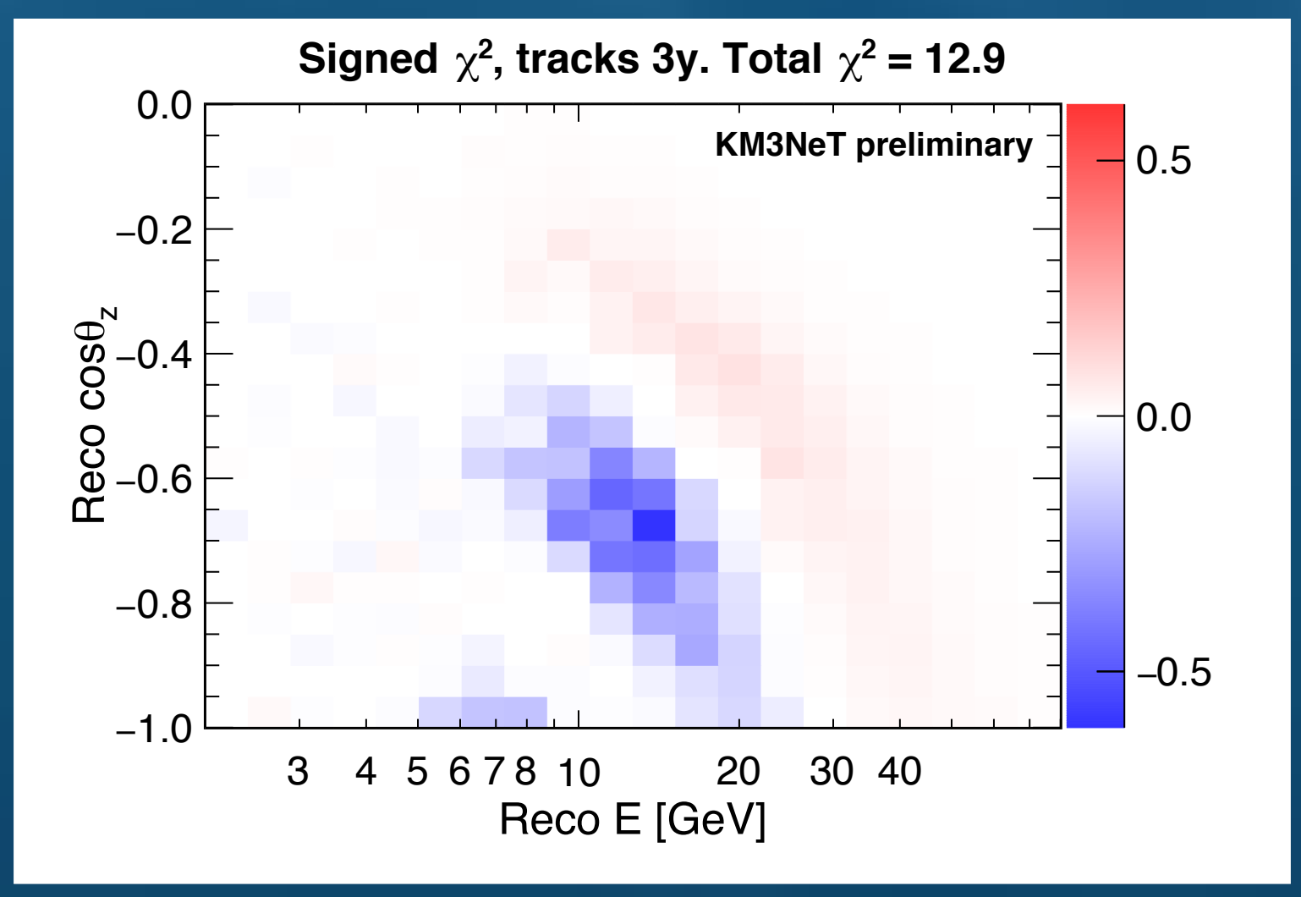
Detector response: A multi-dimensional response matrix is built from MC events, modeling detection and selection efficiency, classification probabilities and correlated smearing of reconstructed energy and zenith angle.

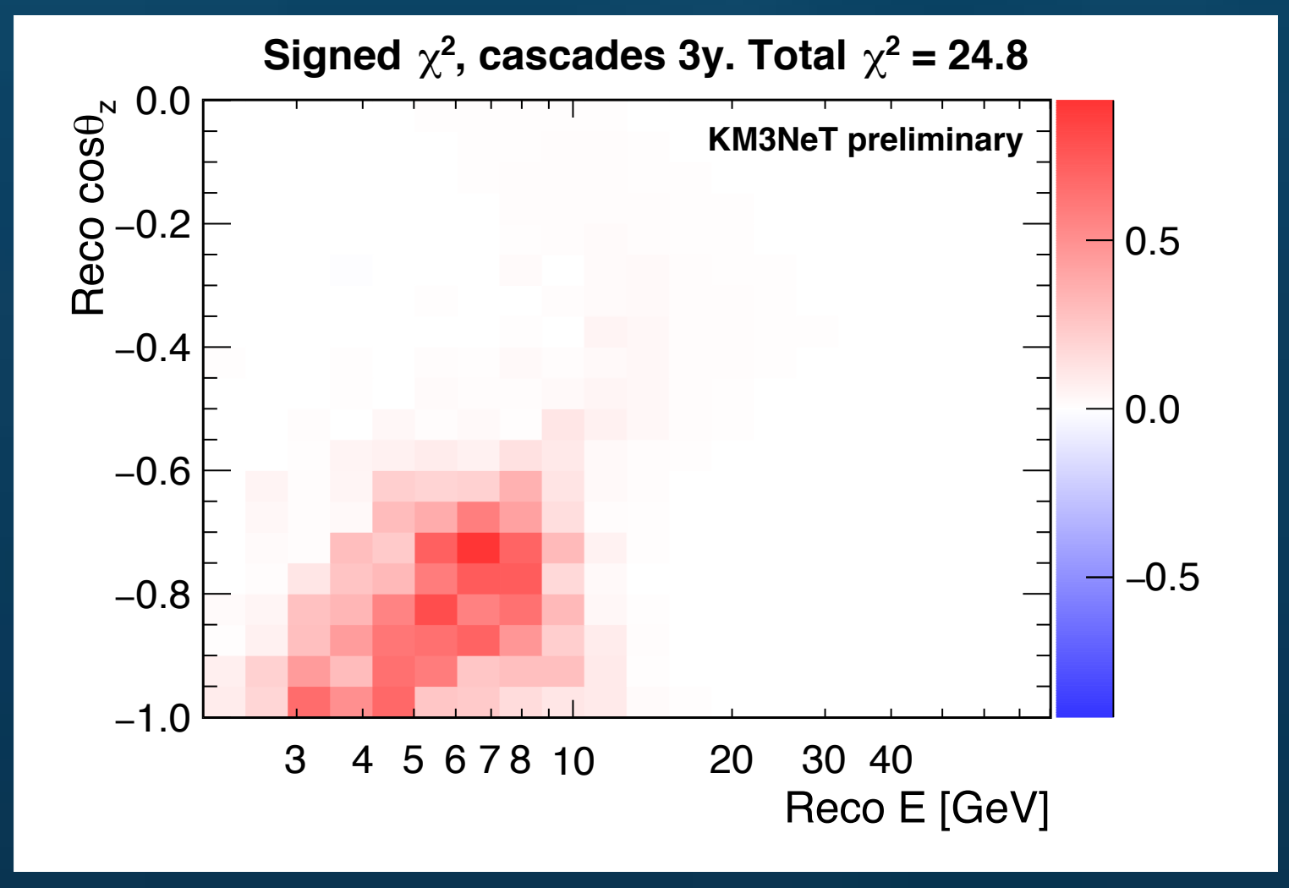
$$\text{true }(E, \cos\theta_z, y) \rightarrow \text{reco }(E, \cos\theta_z)$$

$$\{\text{CC}\,\nu_e, \overline{\nu}_e, \nu_\mu, \overline{\nu}_\mu, \nu_\tau, \overline{\nu}_\tau, \text{NC}\,\nu, \overline{\nu},\ \text{bkg}\} \rightarrow \{\text{track}, \text{cascade}\}$$

Left: Number of neutrino events classified as track-like (top) and cascade-like (bottom) for 3 years of operation, shown as function of the reconstructed E_ν and $\cos\theta_\nu$. Normal ordering is assumed.

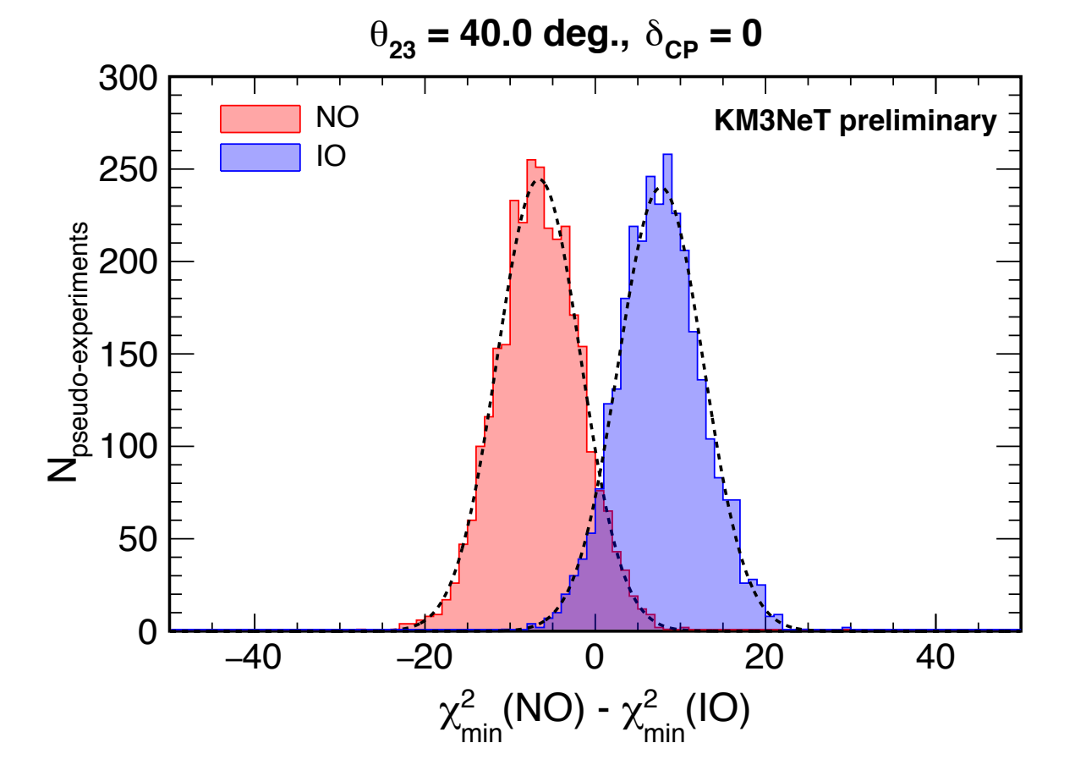
Right: Signed $\chi^2 = (N_{NO} - N_{IO})\,|N_{NO} - N_{IO}| / N_{NO}$ shown as a function of reconstructed neutrino energy and cosine zenith for track-like events (top) and cascade-like events (bottom). An overall larger statistics-only sensitivity is observed for cascades.

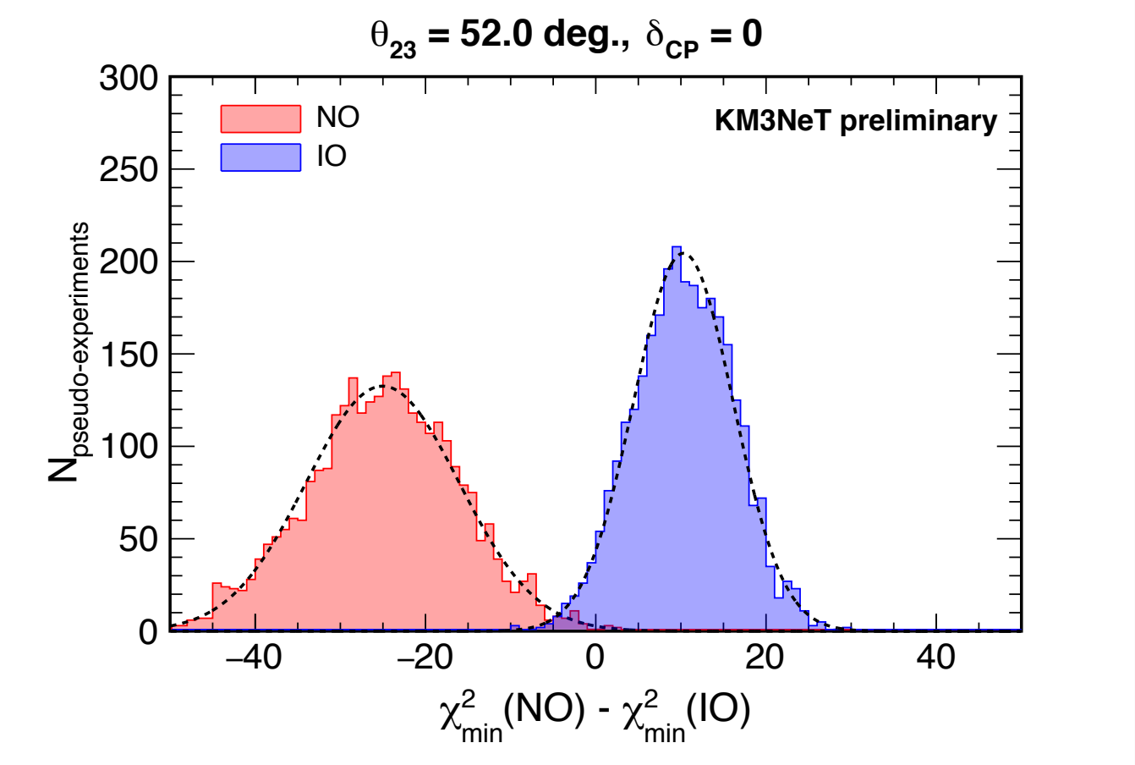




Statistical methods: We report the median sensitivity to exclude the wrong ordering, based on the study of a log-likelihood ratio (LLR) test statistic:

$$TS = -2 \cdot \ln \frac{\max \mathcal{L}_{\text{NO}}}{\max \mathcal{L}_{\text{IO}}} = \chi^2_{\min}(\text{NO}) - \chi^2_{\min}(\text{IO})$$

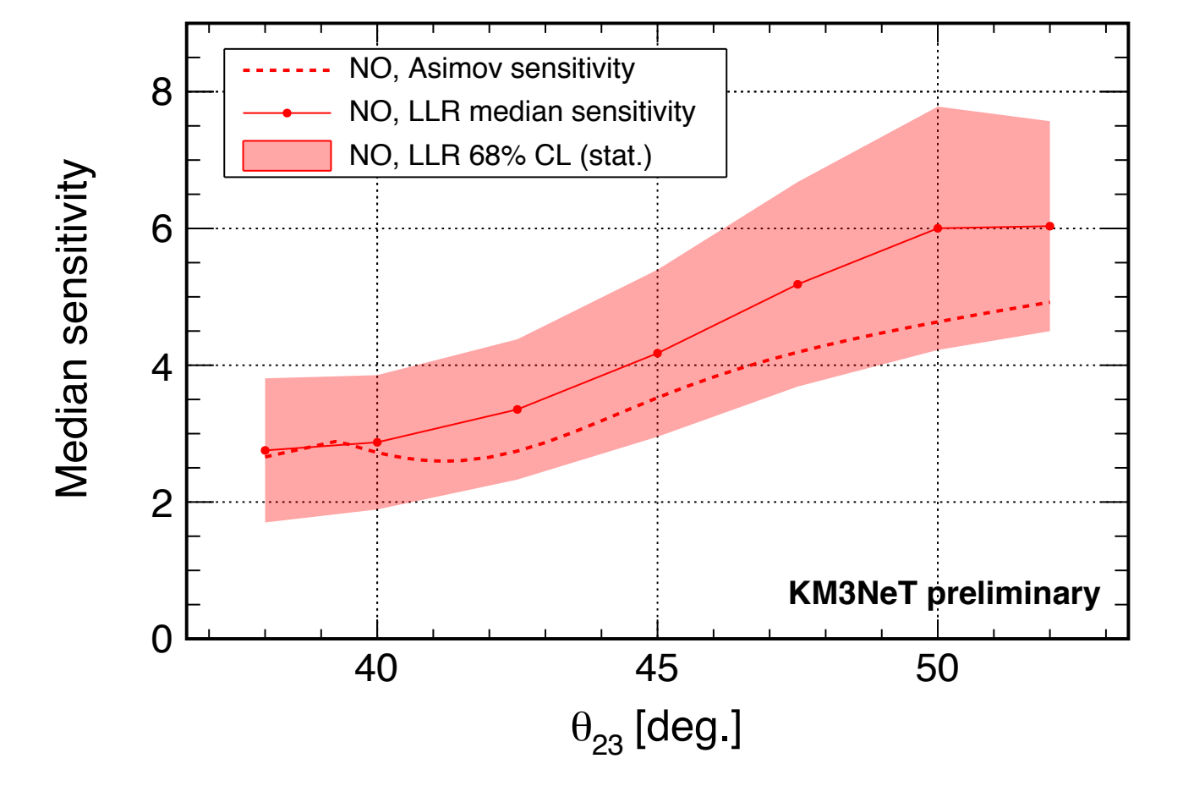


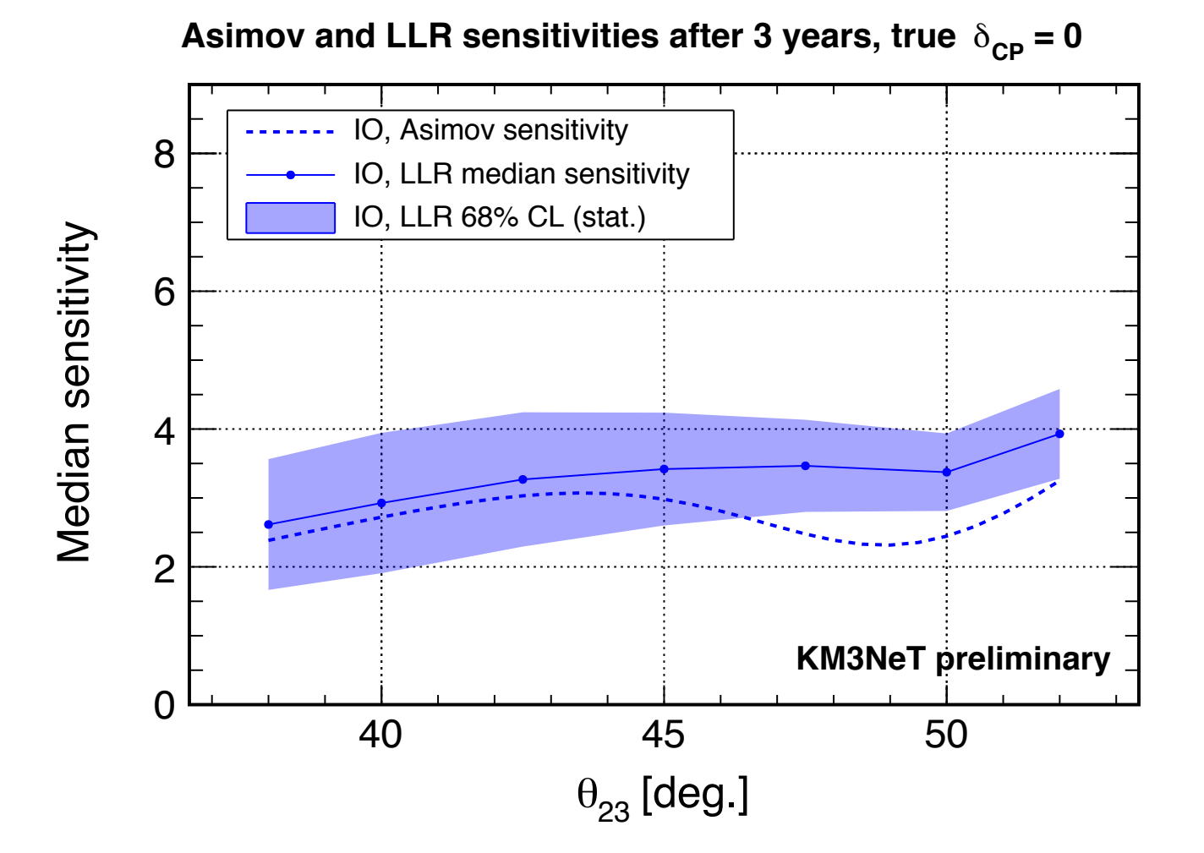


For the NMO study, both likelihoods are maximised over the following ensemble of nuisance parameters, oscillation and systematics:

parameter	*treatment*	*true value*	*prior*
$\|\Delta M^2\|\,(\text{eV}^2)$	fitted	$2.48\,10^{-3}$	free
$\Delta m^2{}_{21}\,(\text{eV}^2)$	fix	$7.53\,10^{-5}$	–
$\theta_{13}\,(^\circ)$	fitted	8.42	0.26
$\theta_{12}\,(^\circ)$	fix	33.4	–
$\theta_{23}\,(^\circ)$	fitted	$38-52$	free
δ_{CP}	fitted	$0, 2\pi$	free
Flux spectral tilt	fitted	0	free
$\nu/\bar{\nu}$ skew	fitted	0	0.03
Tracks normalisation	fitted	1	free
Cascades normalisation	fitted	1	free
NC events normalisation	fitted	1	0.10

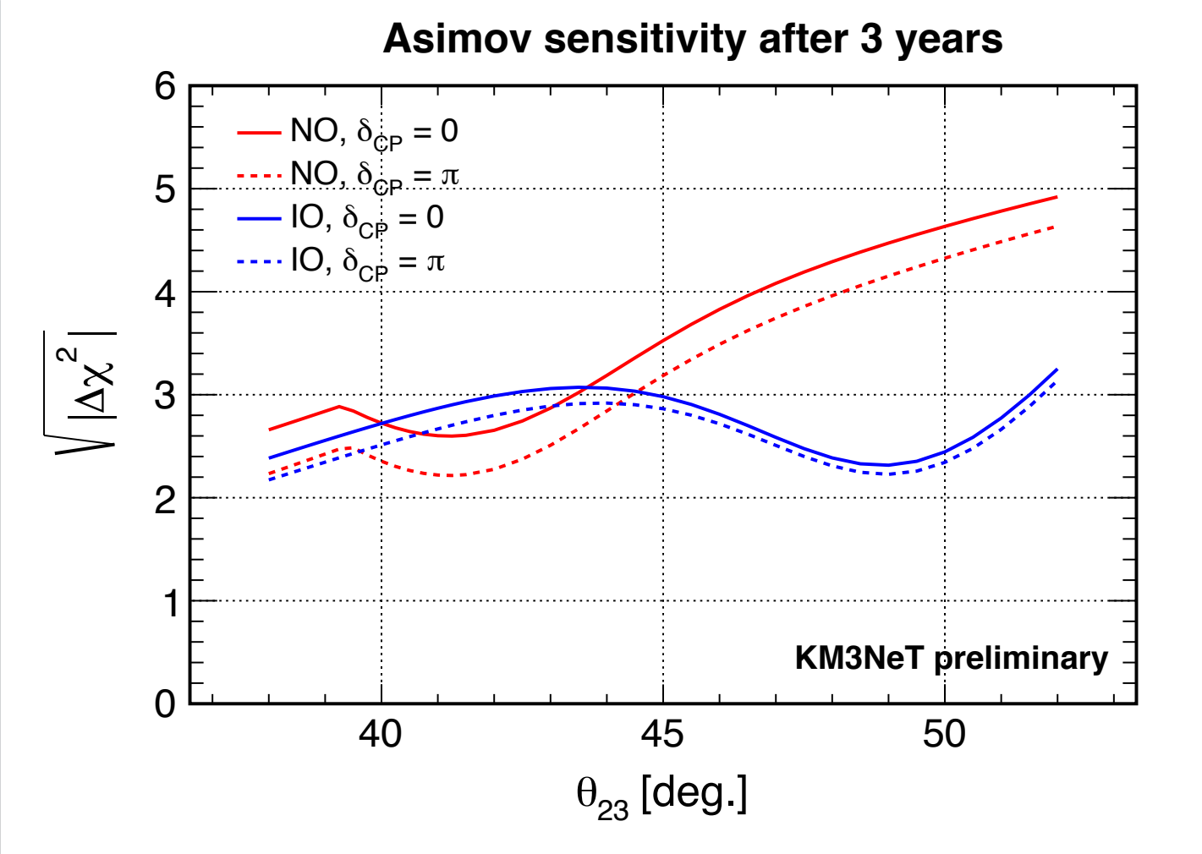
When fixed or constrained, the oscillation parameter values are taken from [5].

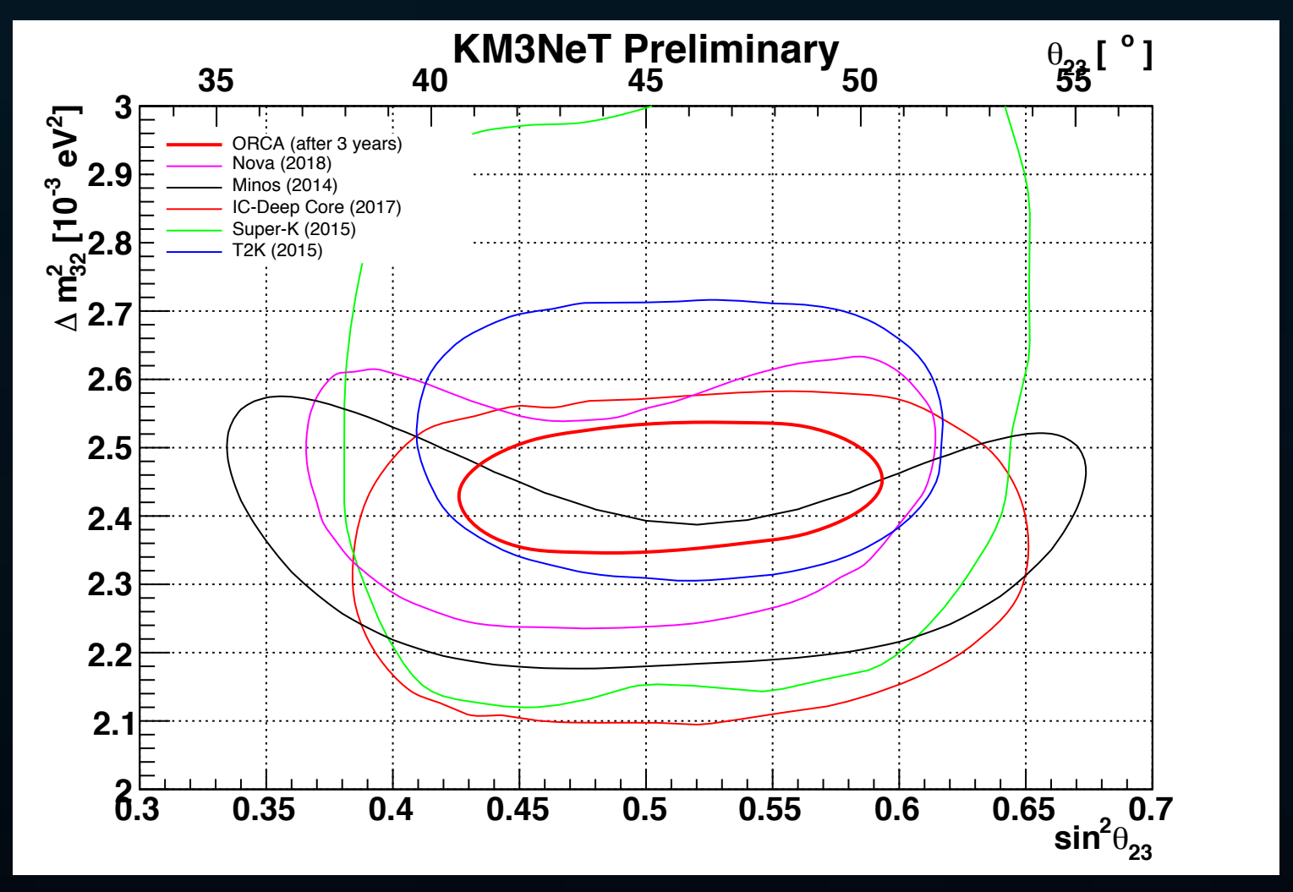




The results of a χ^2 minimisation on the predicted average dataset for the opposite ordering (Asimov method) are also presented below (left) for both orderings and the most favourable and least favourable values of the CP phase.

In addition, we study the sensitivity of ORCA to the combined measurement of θ_{23} and Δm^2_{32}. The resulting 90% CL contour is shown below (right) alongside current results from Minos, Nova, Super-Kamiokande, T2K and IceCube/DeepCore. For this study the detector response is modeled with realistic parametrised response functions, and an additional 10% energy scale systematic (common to all event classes) is applied to all detector functions. The shown contour, also based on the Asimov approach, assumes normal mass ordering (fixed) and δ_{CP} = 0 (fitted).





References:

[1] KM3NeT Collaboration. Letter of intent for KM3NeT 2.0. Journal of Physics G: Nuclear and Particle Physics, 43(8): 084001, 2016.
[2] M. Honda et al., Atmospheric neutrino flux calculation using the NRLMSISE-00 atmospheric model. Phys. Rev., D92(2):023004, 2015.
[3] João A. B. Coelho. OscProb neutrino oscillation calculator. https://github.com/joaoabcoelho/OscProb
[4] Adam M. Dziewonski and Don L. Anderson. Preliminary reference Earth model. Physics of the Earth and Planetary Interiors, 25(4):297–356, 1981.
[5] C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016).