Oscillation Physics with KM3NeT-ORCA

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on behalf of the KM3NeT collaboration

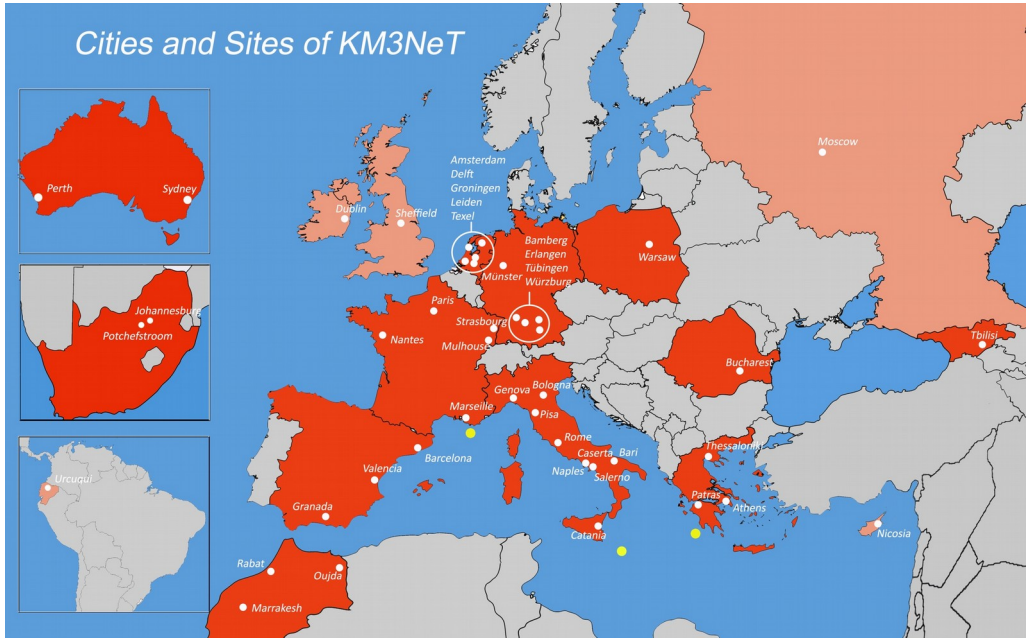
October 8, 2019

4th Uppsala Workshop on Particle Physics with Neutrino Telescope, Uppsala

Outline

- **The KM3NeT-ORCA neutrino telescope and detector performance**
- **Oscillation Physics Sensitivities**
  - Neutrino Mass Ordering (NMO)
  - Atmospheric oscillation parameters measurement
  - ν_τ appearance
  - Sterile Neutrinos
  - Non-Standard Interactions (NSI)
  - Neutrino Decay Constrains
- **Deployment and Current Status**
- **Future Upgrade Study:**
  - Protvino to ORCA (P2O)
- **Summary**

KM3NeT Collaboration Map



Oscillation Research with Cosmics In the Abyss

Astroparticle Research with Cosmics In the Abyss

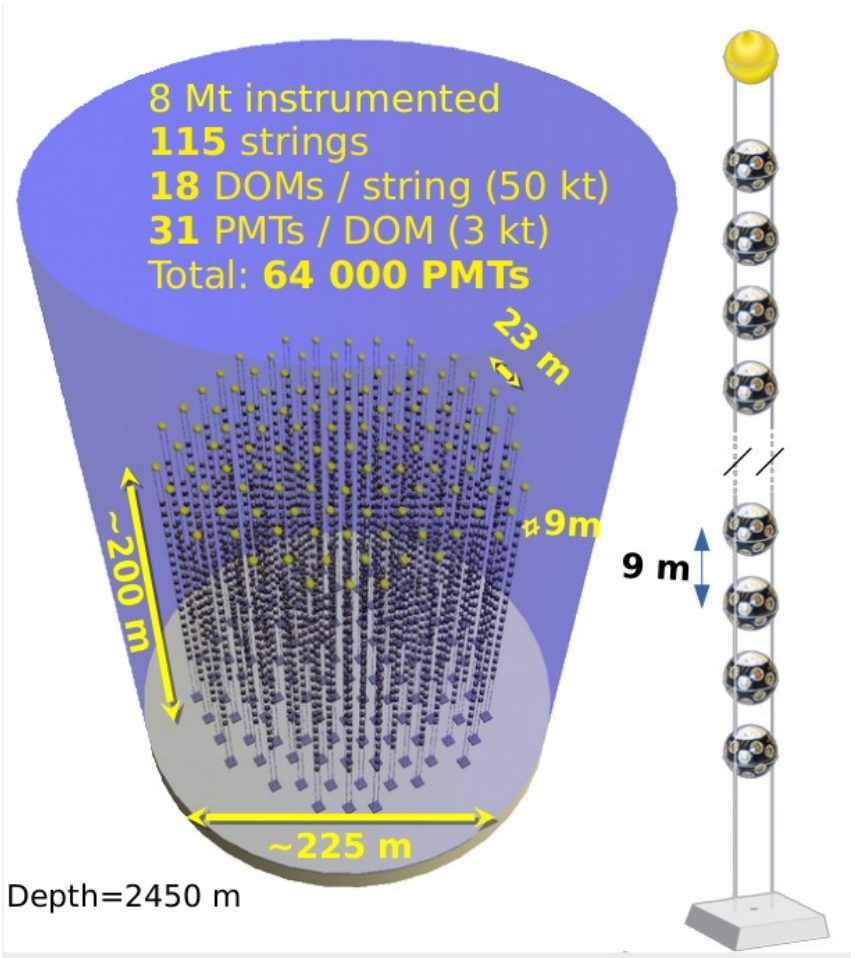
ORCA : low energy physics (neutrino oscillations)

ARCA : high energy physics (astrophysical neutrinos, dark matter search)

KM3NeT 2.0 : Letter of Intent
J. Phys. G, **43** (2016) 084001

KM3NeT is built upon the technology proven for the ANTARES neutrino telescope.

ORCA Schematics



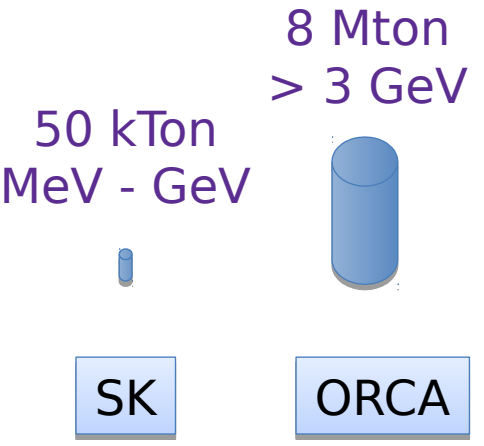
Digital Optical Module

- 31 x 3” PMTs
- PMT HV
- LED & piezo
- FPGA readout
- DWDM

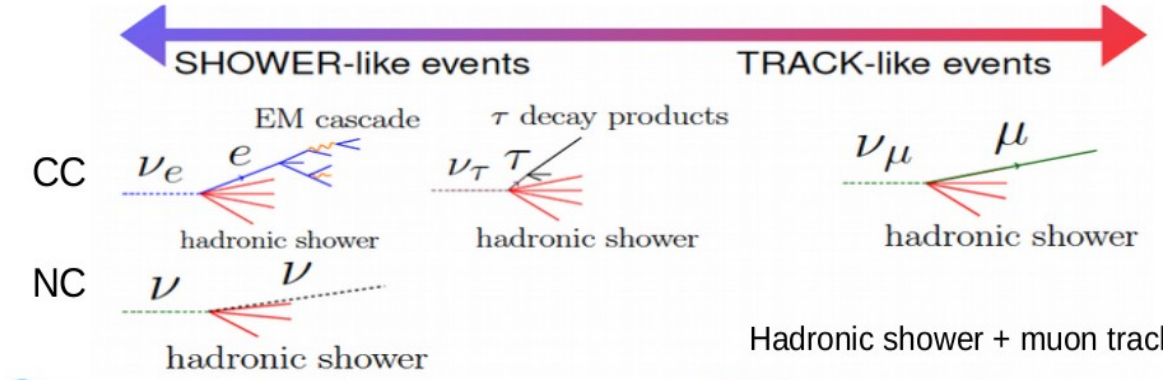
✔ Uniform angular coverage
✔ Directional information
✔ Digital photon counting
✔ All data to shore

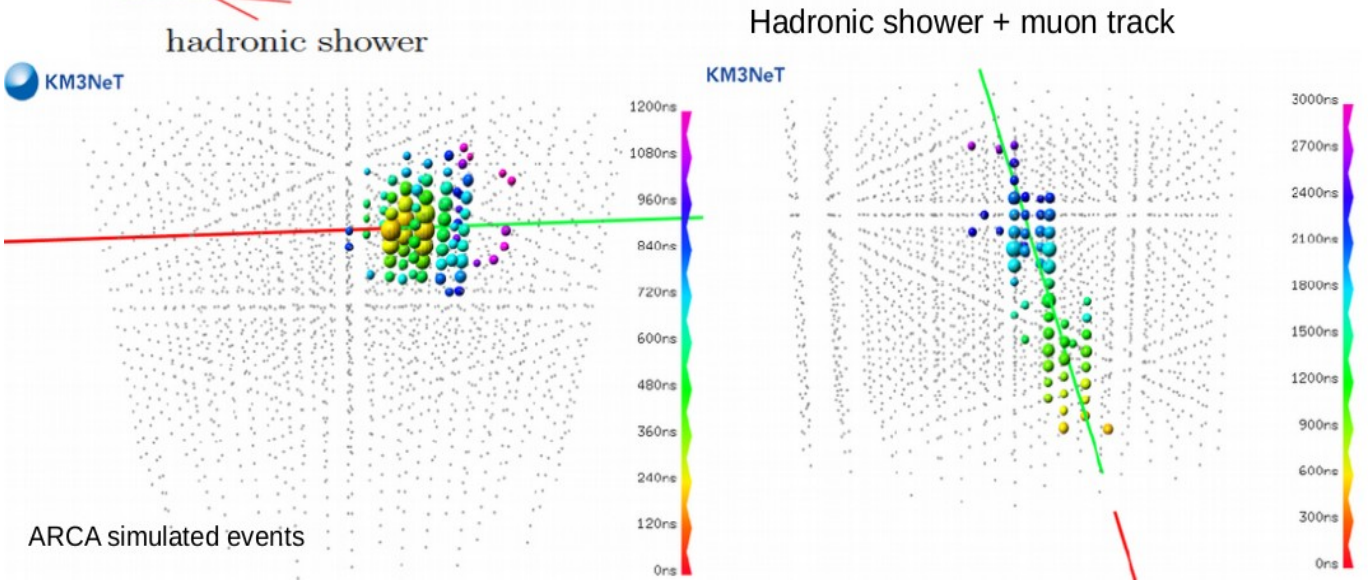
photocathode area similar to a 17” PMT

Water Cherenkov detection for the outgoing particles produced in a neutrino interaction



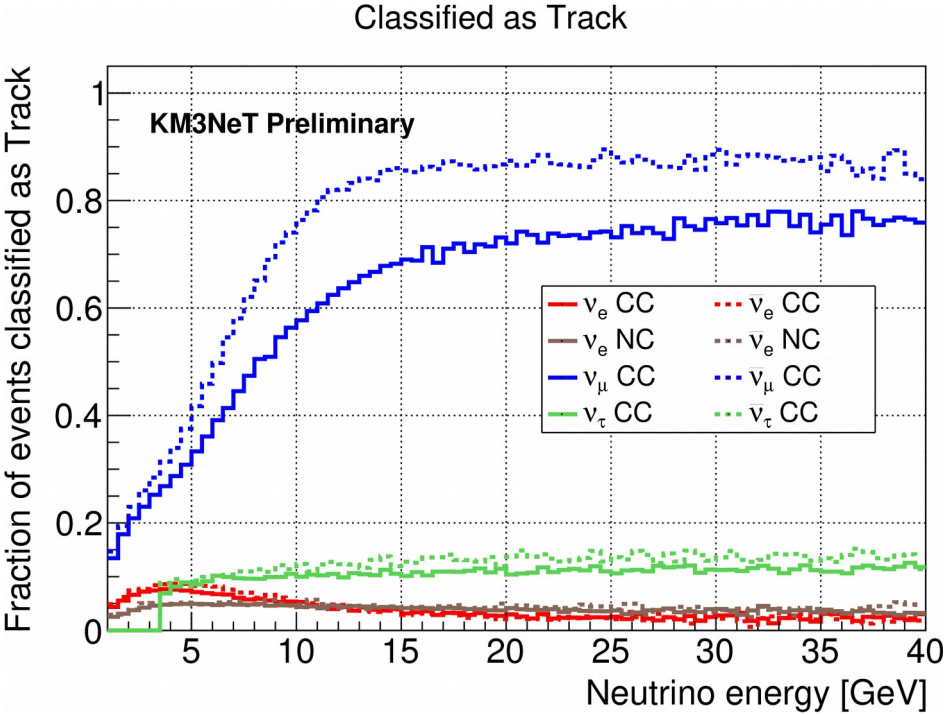
Event Topology in ORCA





- Different reconstruction algorithms for track and shower events
-
- Studies are underway to possibly use multiple PID (topology) classification over current 2 classes

PID(Event Topology) Classification

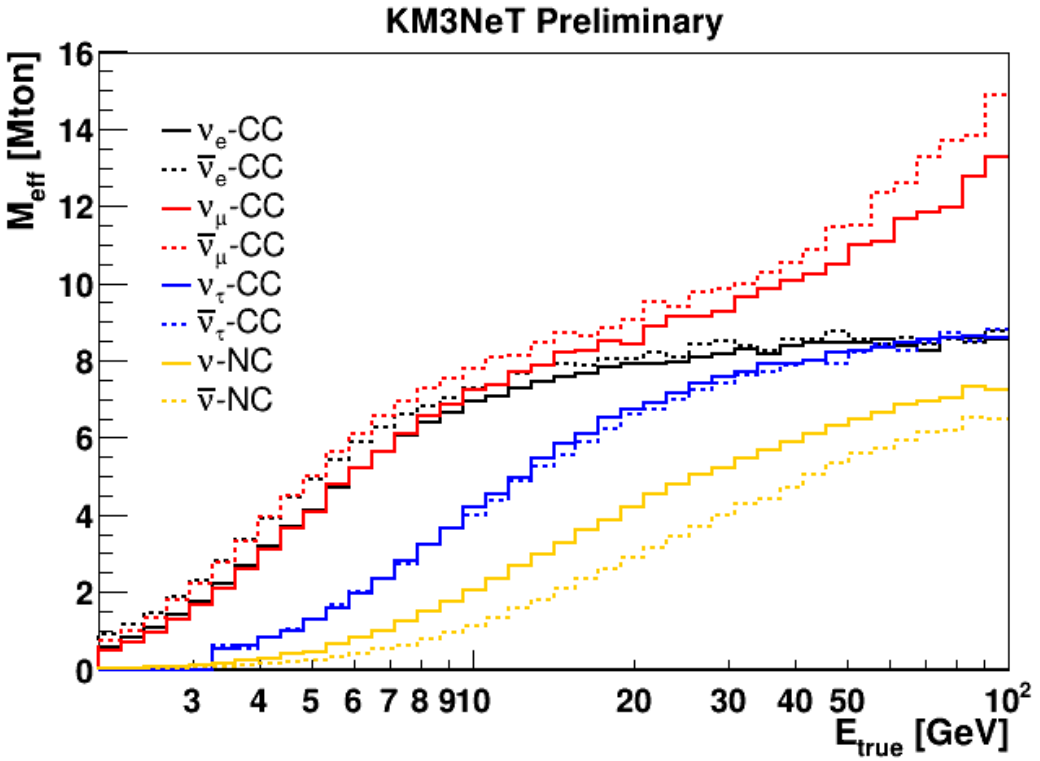


Random Decision Forests used to classify the event topology.

Deep learning techniques are also being explored. They are expected to improve the classification efficiency.

As expected, most CC ν_μ events are classified as tracks, and all others as showers.

Effective Mass and Expected Event Rates



Atmospheric neutrino events / year:

ν_e CC: 14 700

$\overline{\nu}_e$ CC: 5 700

ν_μ CC: 21 300

$\overline{\nu}_\mu$ CC: 9 900

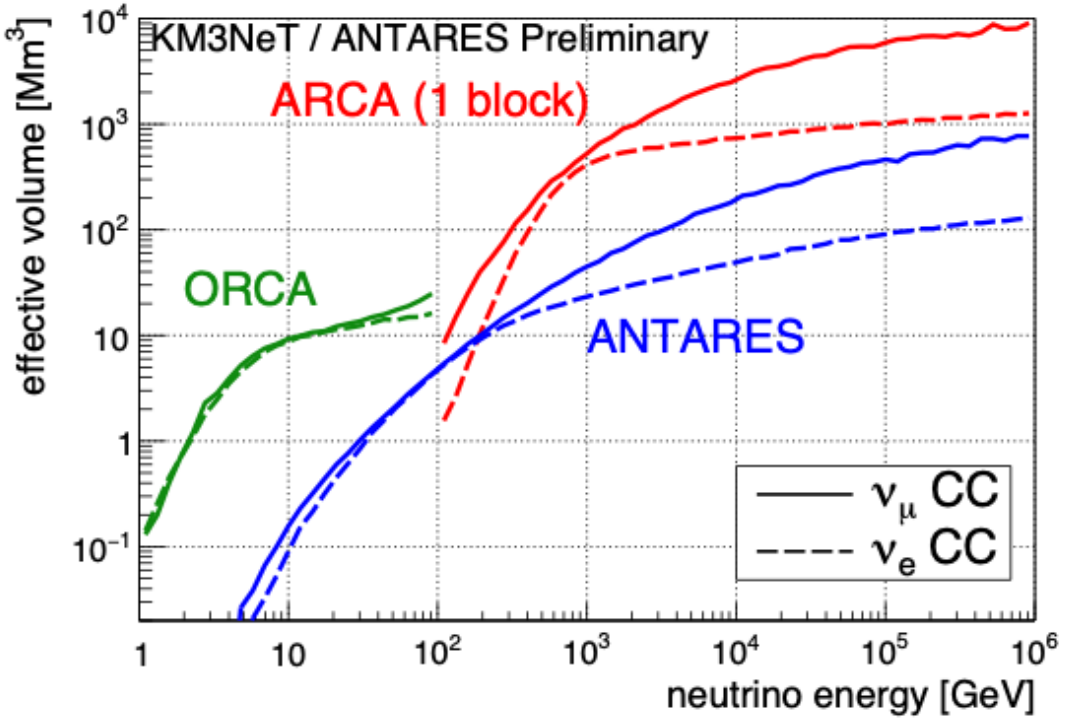
ν_τ CC: 2 900

$\overline{\nu}_\tau$ CC: 1 300

NC: 6 800

Large event statistics drives measurements of oscillation parameters.

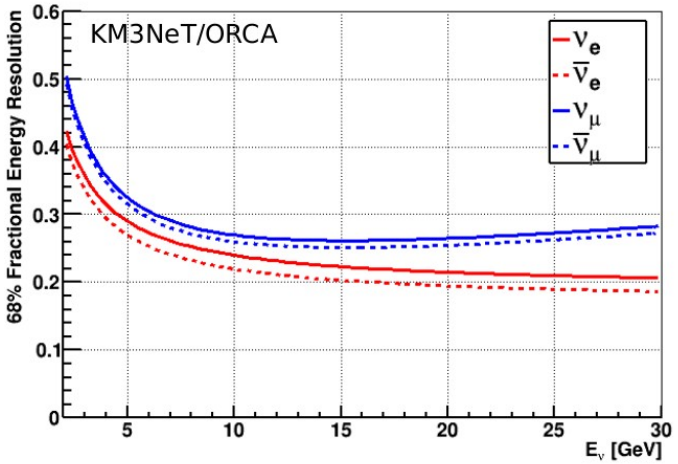
Comparison of Effective Volumes



Interplay of energy/direction resolutions, statistics, energy range of interest

Energy and Zenith Angle Resolutions

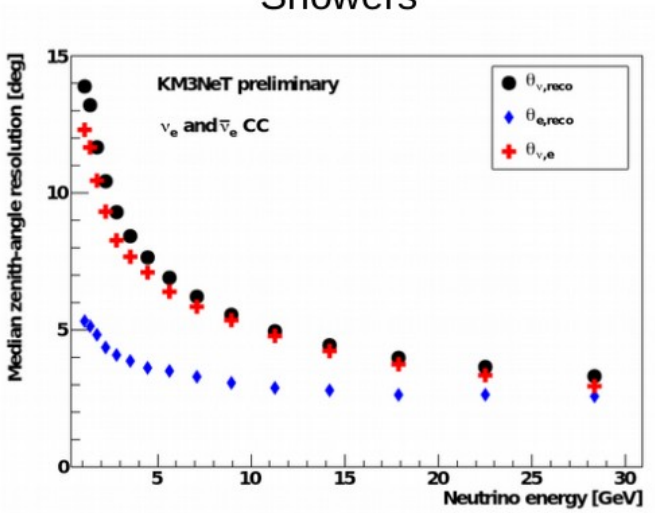
Energy Resolutions



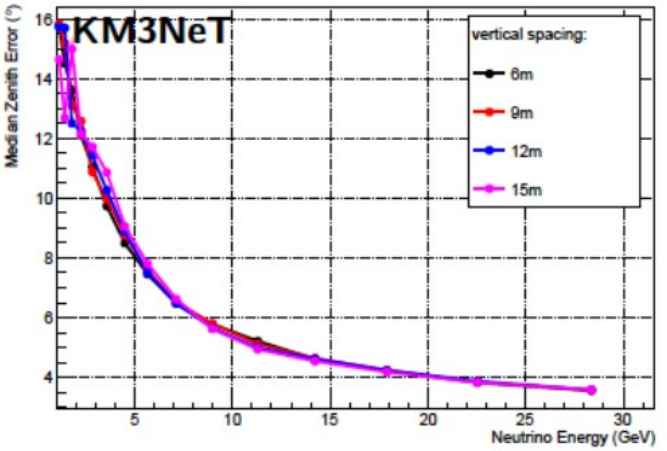
Energy resolution ~ 25% at 10 GeV

Direction resolution ~ 5 degrees at 10 GeV

Showers

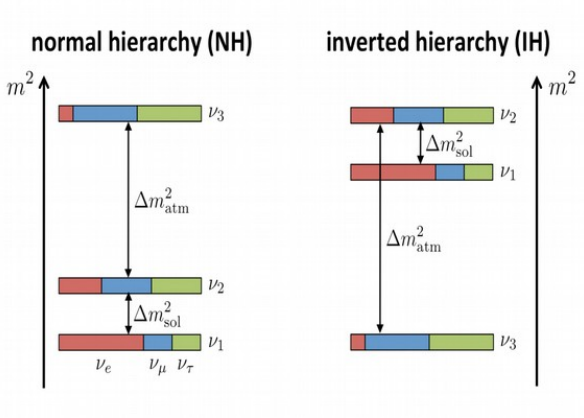


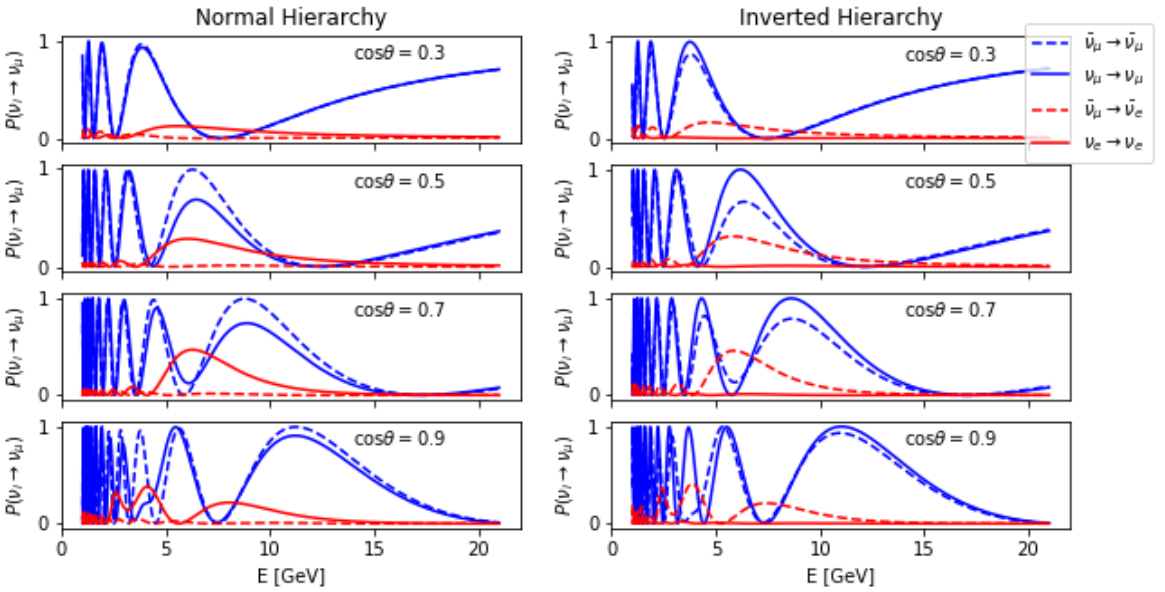
Tracks



Direction resolutions

Oscillation Probabilities



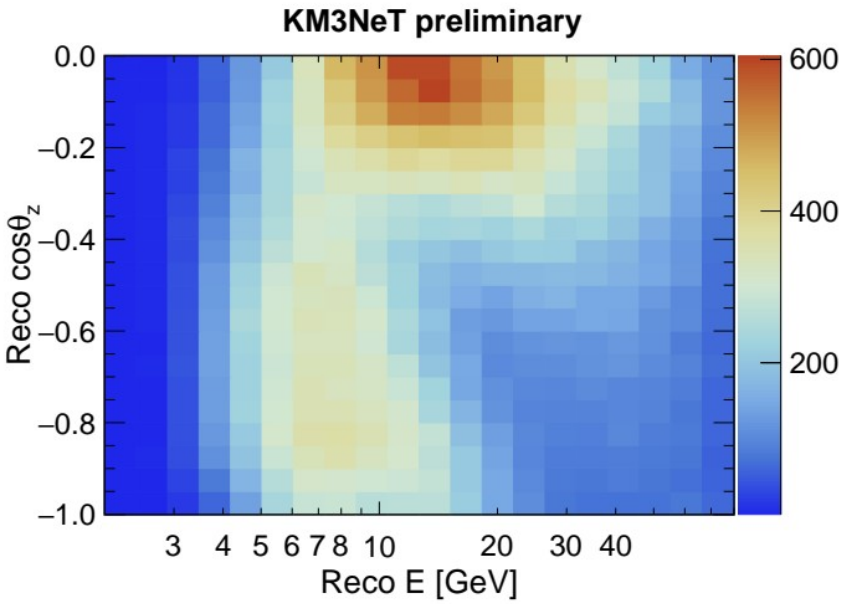


Due to the MSW resonance effect, oscillation probabilities for the Normal and Inverted mass ordering are different, as neutrinos travel through the earth matter.

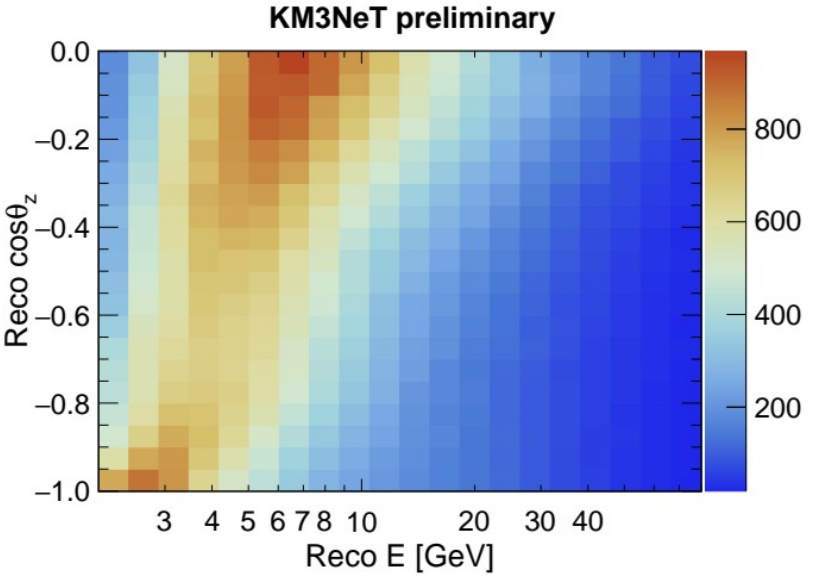
This is reflected in the (E,cos θ_z) distributions observed at the detector.

Event Distributions

Tracks



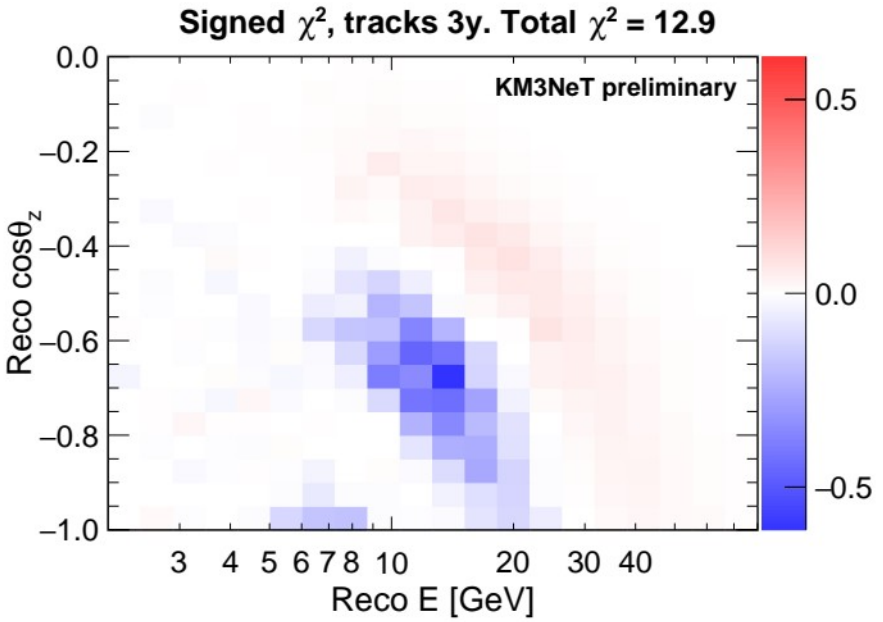
Showers

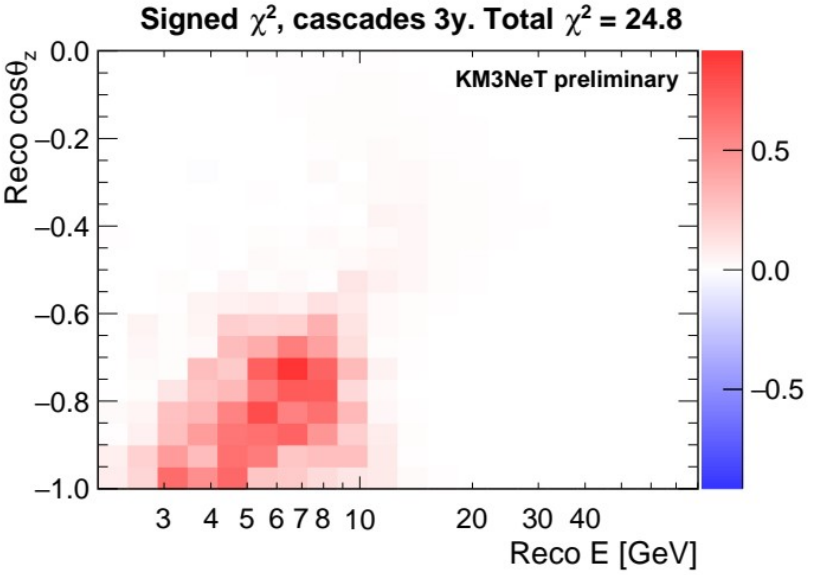


The event distributions are obtained after folding-in :

Atmospheric neutrino flux, oscillation probabilities, interaction cross sections,
Effective masses, resolutions and the PID classification efficiency

X^2 Distributions (NMO Sensitivity)





The track channel brings NMO sensitivity in the energy range [7-20] GeV.

In the shower channel, NMO sensitivity arise in the energy range [4,10] GeV.

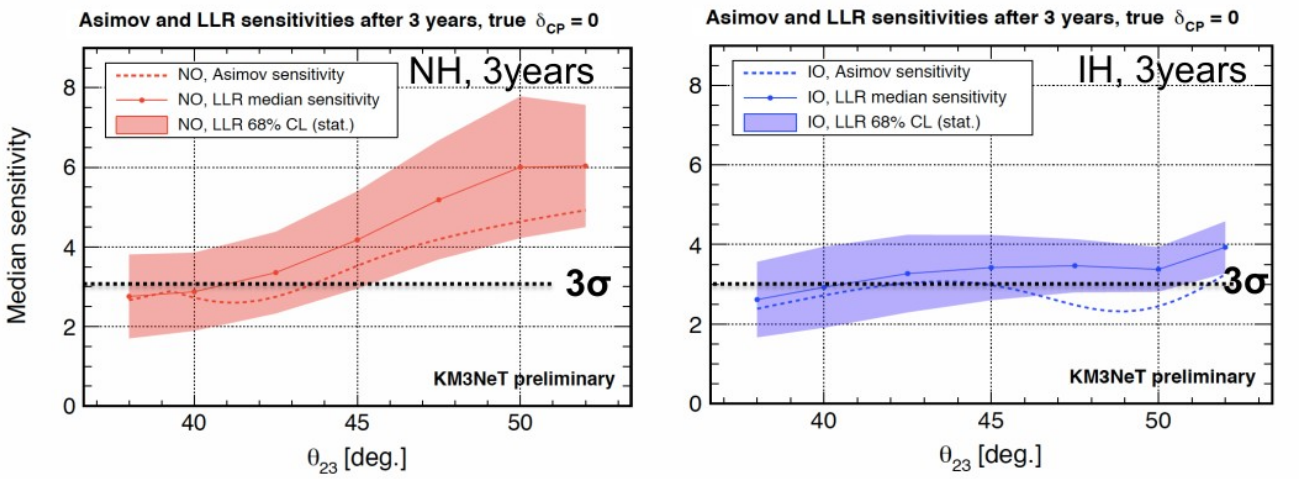
NMO Sensitivity Study

osc. parameters

param.	treatment	true value	prior
ΔM^2	fitted	$2.48\ 10^{-3}$ eV^2	free
Δm^2_{21}	fix	$7.53\ 10^{-5}$ eV^2	–
θ_{13}	fitted	8.42°	0.26
θ_{12}	fix	33.4°	–
θ_{23}	fitted	38° – 52°	free
δ_{CP}	fitted	0 – 2 π	free

Systematics

Parameter	treatment	true value	prior
Flux spectral tilt	fitted	0	free
ν/ν̄ skew	fitted	0	0.03
Track normalization	fitted	1	free
Cascade normalization	fitted	1	free
NC events normalization	fitted	1	0.1



Median sensitivity study with fake data sets

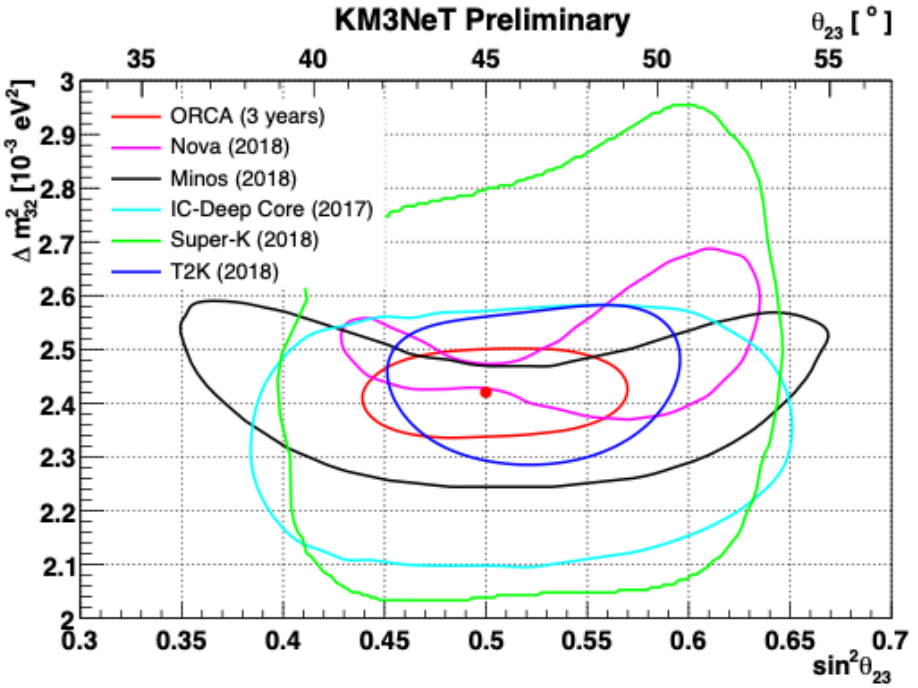
ORCA will determine the mass hierarchy with a significance of (2.2-5)σ with 3 years of operation

Currently systematics on the atmospheric flux model and normalizations have been included.

Incorporation of additional systematics into analysis is under progress.

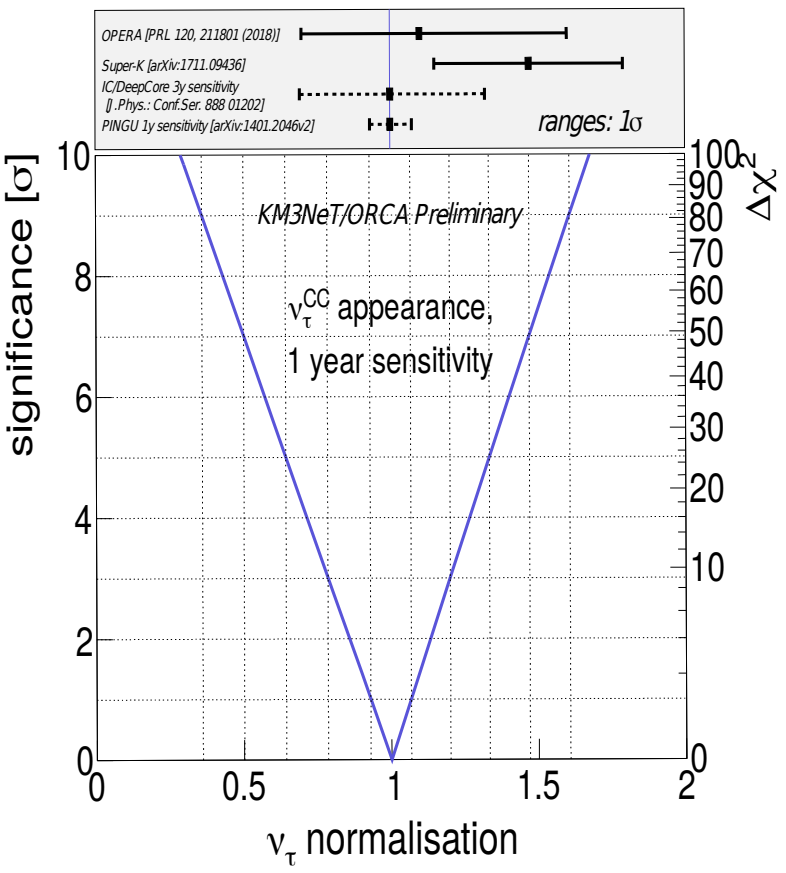
DOI:10.5281/zenodo.1300771

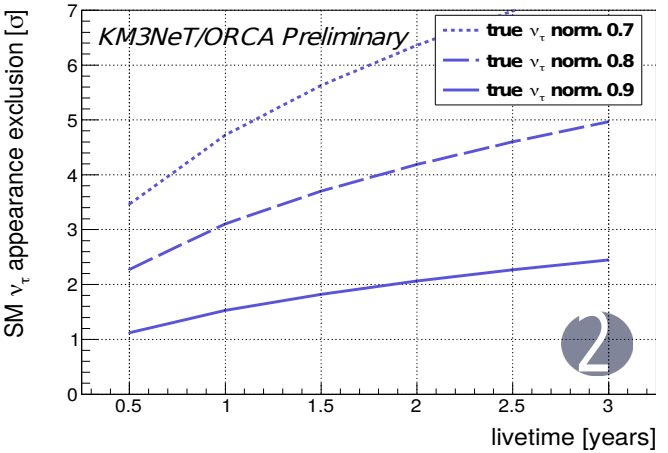
Atmospheric Parameters Measurement



With 3 years of run time, ORCA has strong sensitivity to the parameters ($\sin^2 \theta_{23}$, Δm^2_{31}) compared to current T2K and NOvA allowed regions.

ν_τ appearance and neutrino unitarity test



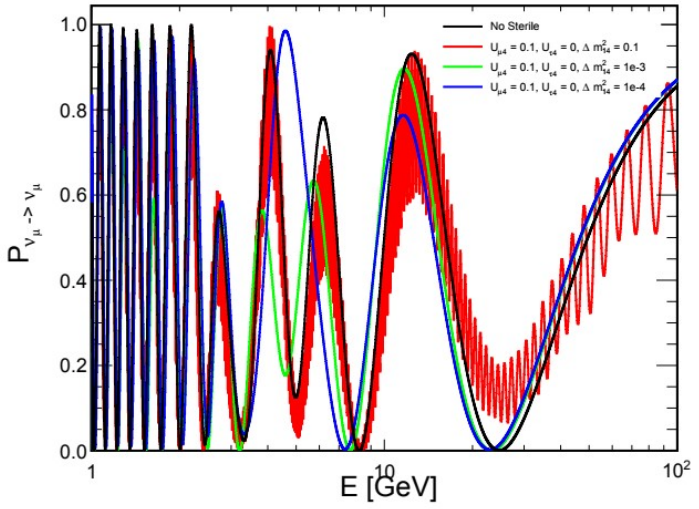


ν_τ appearance signal is expected at 10 – 30 GeV as excess events in the shower channel.

DOI:10.5281/zenodo.1292823

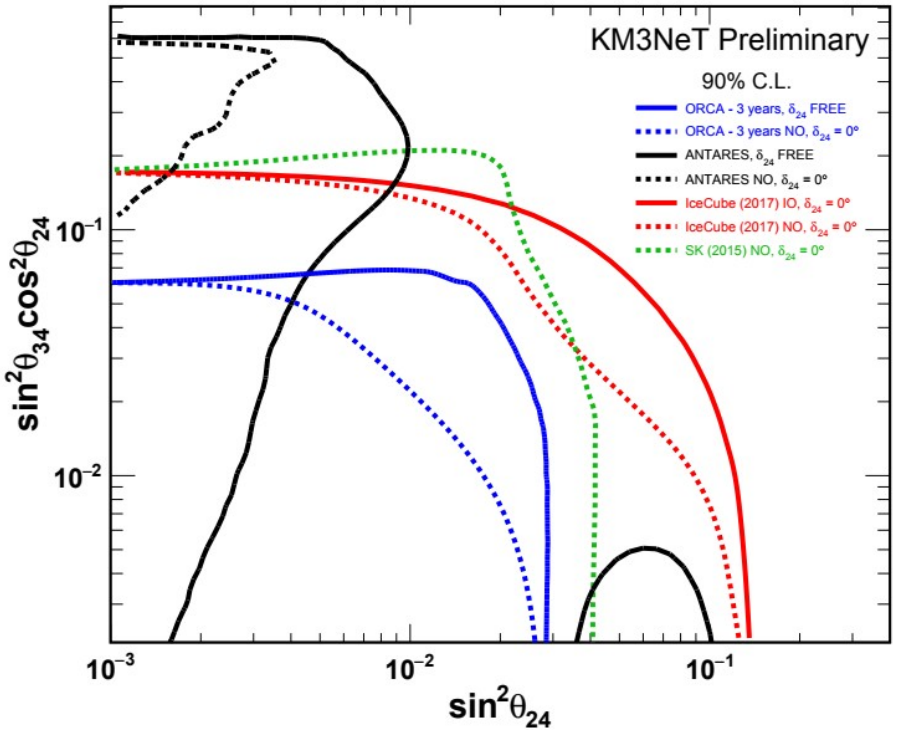
Sterile Neutrinos

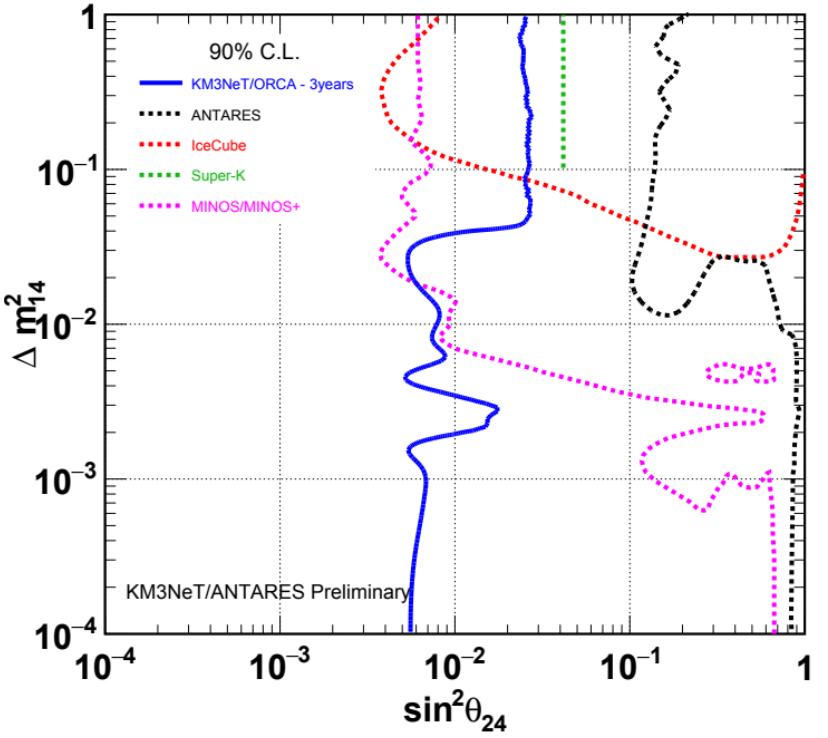
$$U \equiv \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$



- ORCA is able to constrain (3+1) model over a large range of Δm^2_{41}, thanks to broad L/E range.
- At $\Delta m^2_{41} \sim 1$ eV^2, ORCA will improve constrains on $U_{\tau 4}$.
- Further study is under progress for low Δm^2_{41}, where ORCA can constrain three mixing elements, U_{e4}, $U_{\mu 4}$, $U_{\tau 4}$ simultaneously with atmospheric neutrinos.
- Matter effect play an important role at $\Delta m^2_{41} \sim 10^{-3}$ eV^2

Sterile Neutrino Constrains





Sensitivity plots for U_{e4} and $U_{\tau 4}$ constrains coming in near future.

Non-Standard Interactions (NSI)

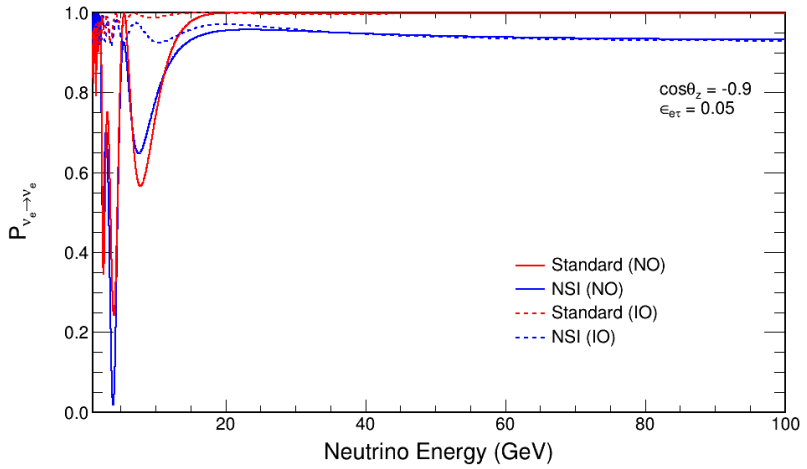
NC NSI

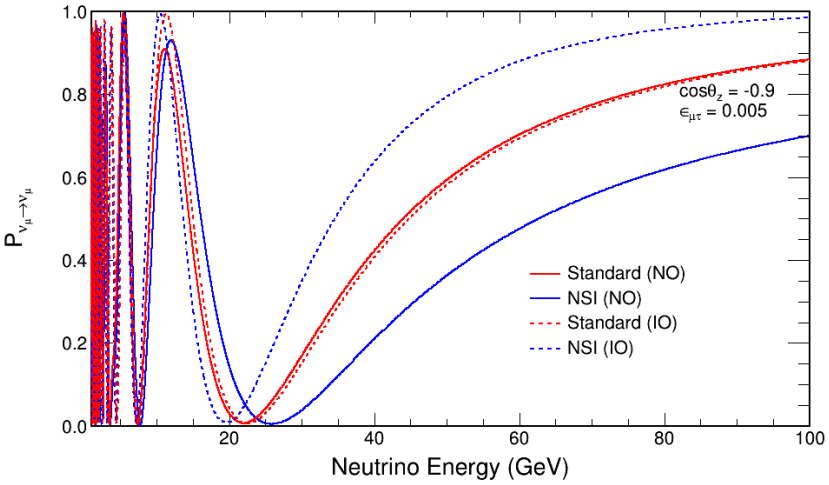
$$H = \frac{1}{2E} U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{bmatrix} U^\dagger + 2\sqrt{2} G_F N_e(x) \begin{bmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{bmatrix}$$

Neutrino telescopes are an ideal setup to constrain Neutral Current(NC) NSI in propagation.

In the presence of NC NSI, neutrino oscillation probabilities can be significantly modified due to the MSW effects.

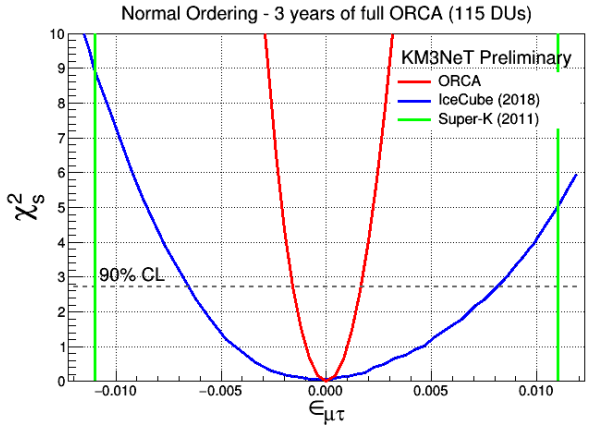
ORCA will improve constrains on most NSI parameters by an order of magnitude

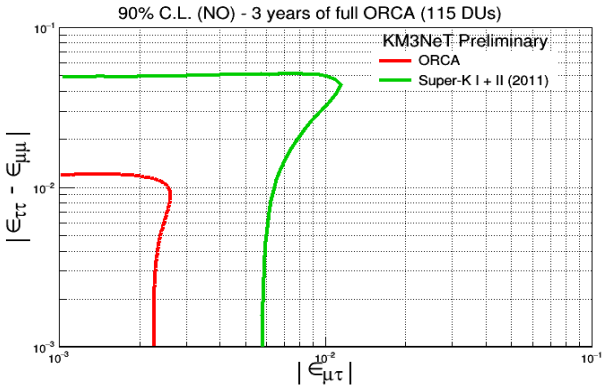




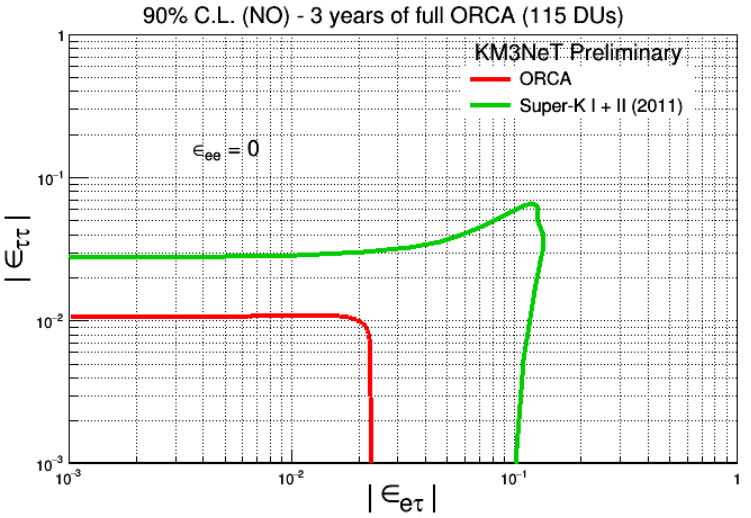
NSI : Hybrid model sensitivity

2 flavor hybrid model :
$\sin^2\theta_{12}=0$, $\Delta m^2_{21}=0$, $\sin^2\theta_{13}=0$
Oscillations only in the $\nu_\mu - \nu_\tau$ sector



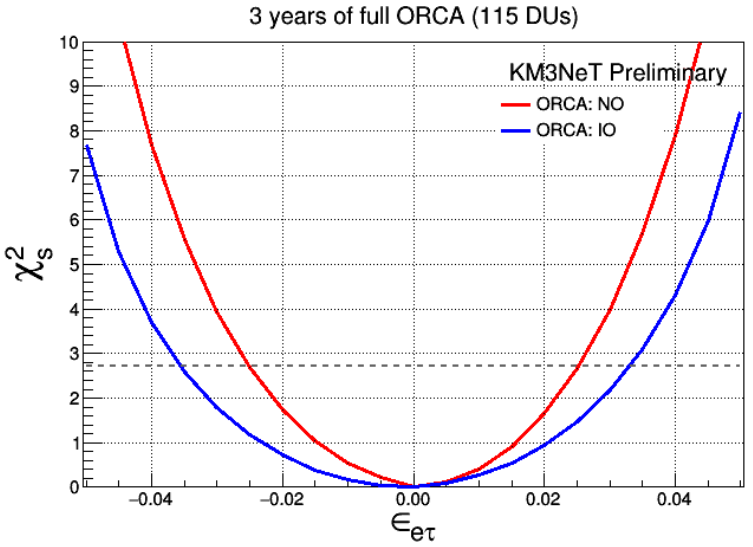


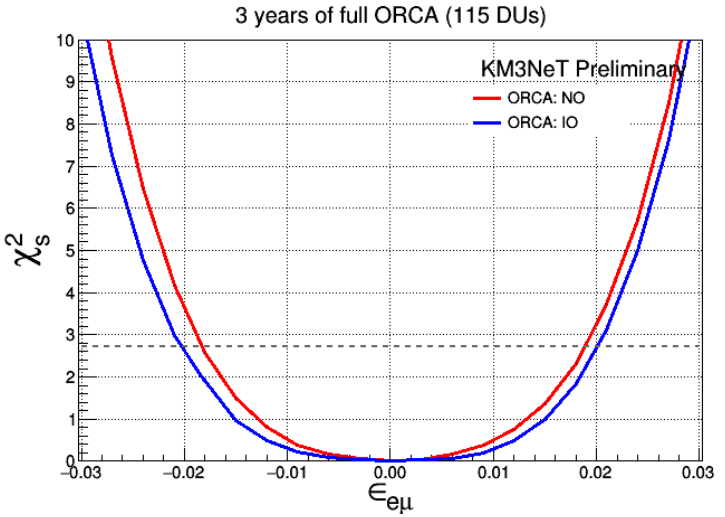
3 flavor hybrid model :
$\sin^2\theta_{12}=0$, $\Delta m^2_{21}=0$, $\sin^2\theta_{13}=0$
Oscillations via $\nu_\mu - \nu_\tau$ (standard) and $\nu_e - \nu_\tau$ (NSI)

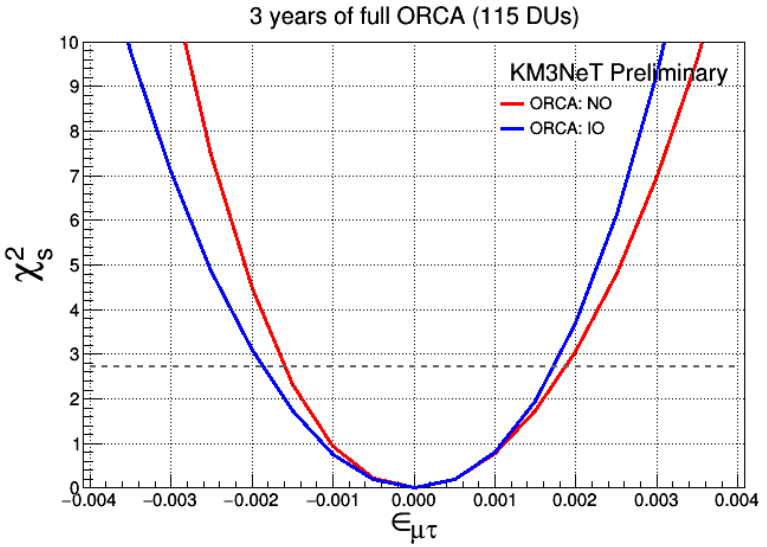


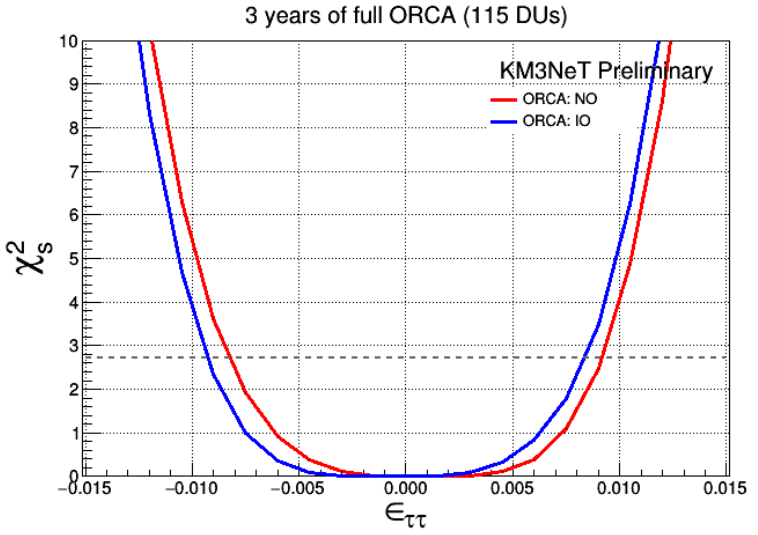
NSI d-quarks couplings

Sensitivities in the Full 3 flavor model

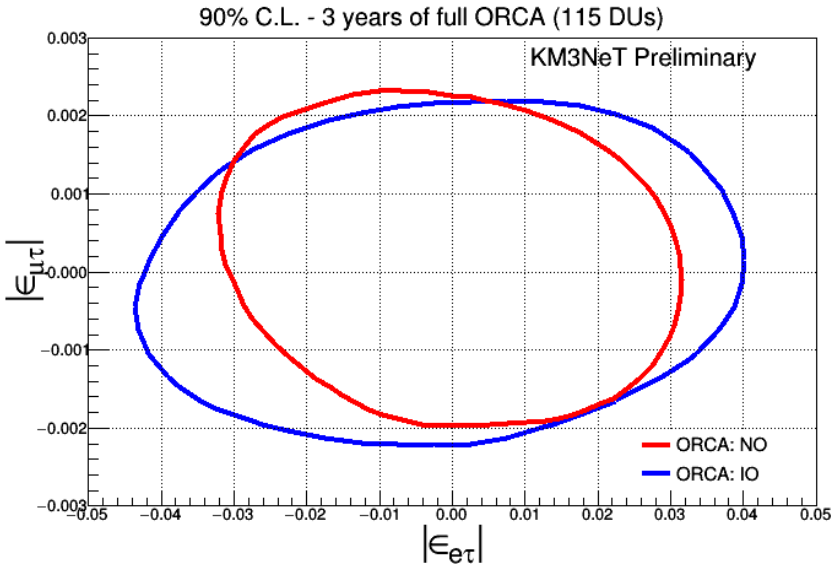


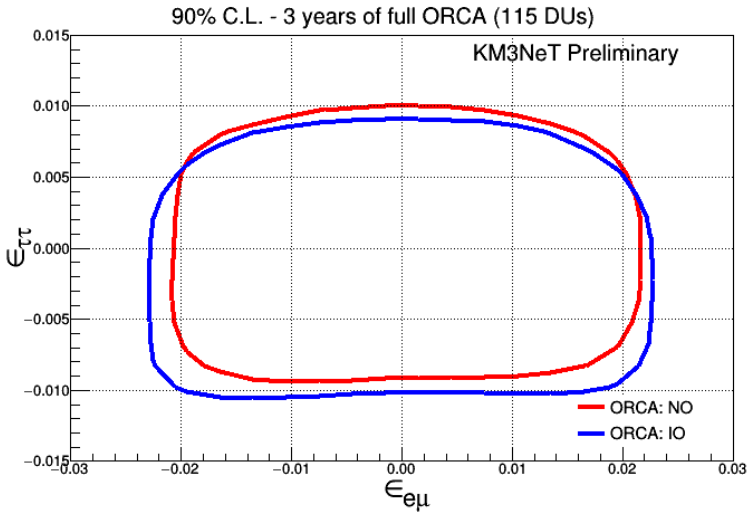


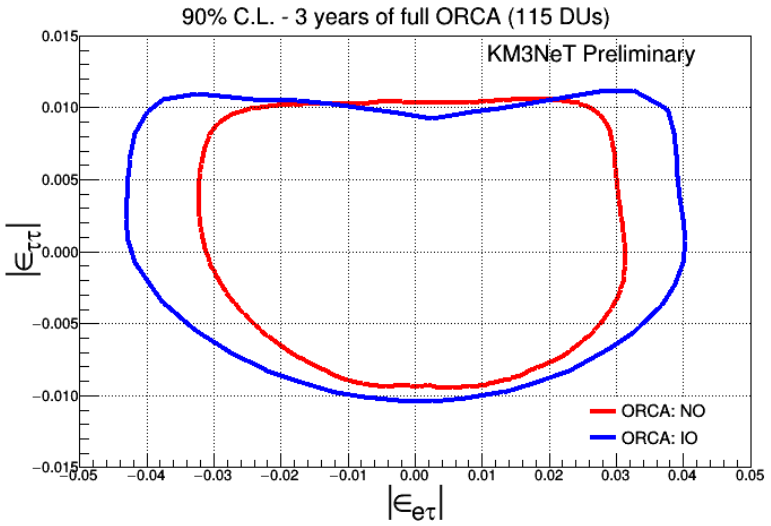


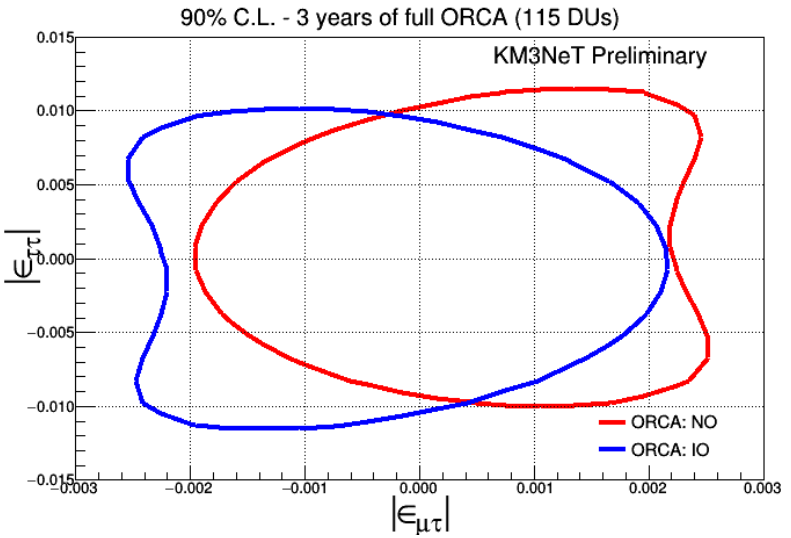


Correlated NSI Sensitivity Plots









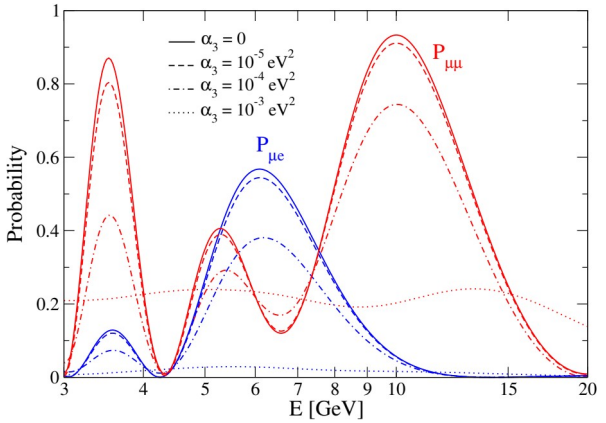
Neutrino Decay Constrains

$$H = \frac{1}{2E}\left[H_0 + H_m + H_D\right]$$

$$H_D = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -i\alpha_3 \end{pmatrix} U^{\dagger}$$

$$\alpha_3 = m_3/\tau_3$$

A decay term is added to the standard Hamiltonian.

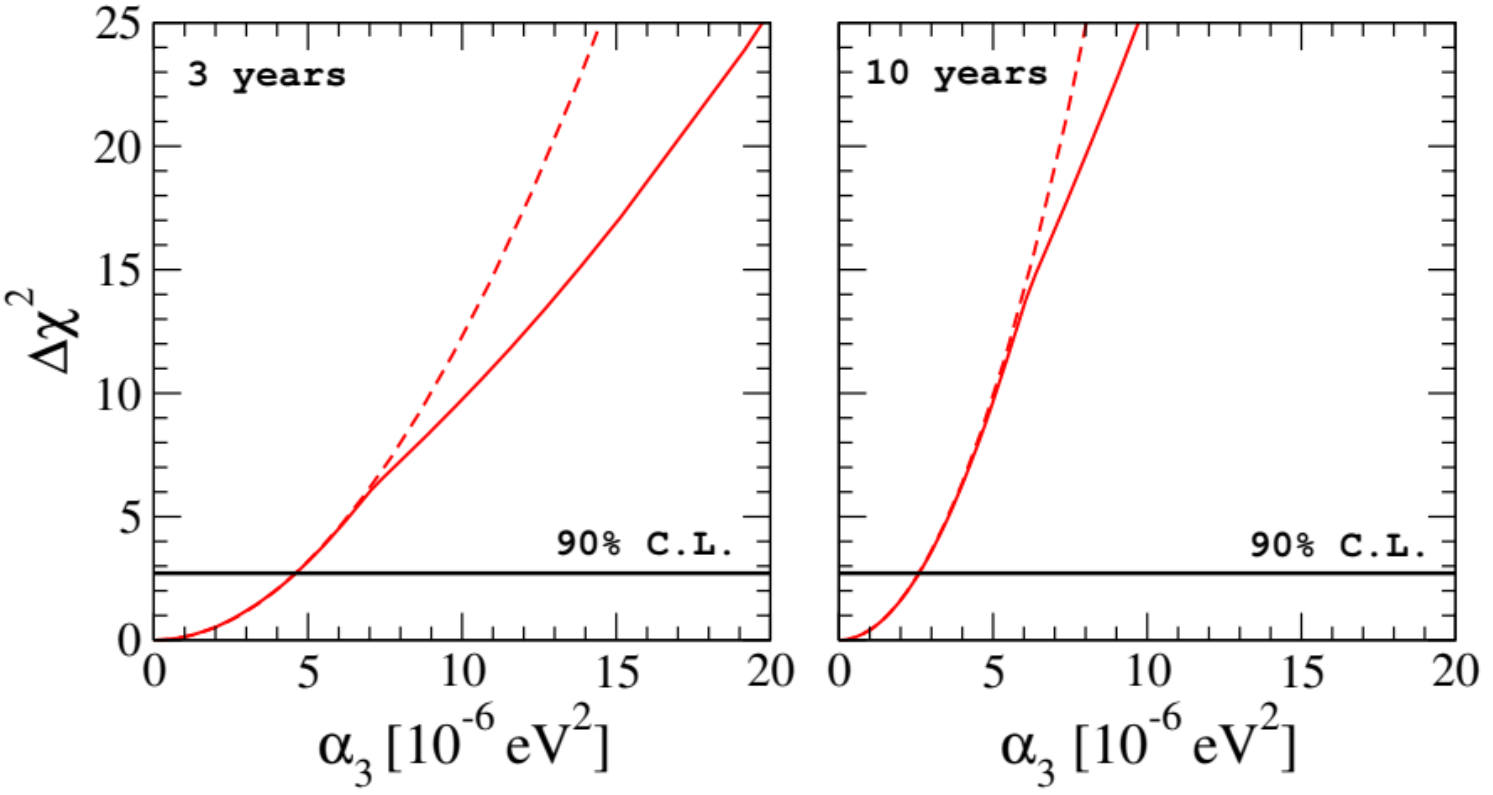


- Neutrino decay originally proposed as a solution to solar and atmospheric neutrino puzzle, but ruled out as the leading order explaination
- However, some models of BSM physics propose visible and invisible neutrino decays.
- We focus on constraining invisible decays.

$$\nu_3 \rightarrow \nu_4 + J$$

- Here, ν_4 is a sterile neutrino, which doesn't mix with the active states.

ORCA Sensitivity to α_3



time	α_3 [eV^2]	τ_3/m_3 [s/eV]
3 years	$< 4.6 \times 10^{-6}$	$> 1.4 \times 10^{-10}$
10 years	$< 2.6 \times 10^{-6}$	$> 2.5 \times 10^{-10}$

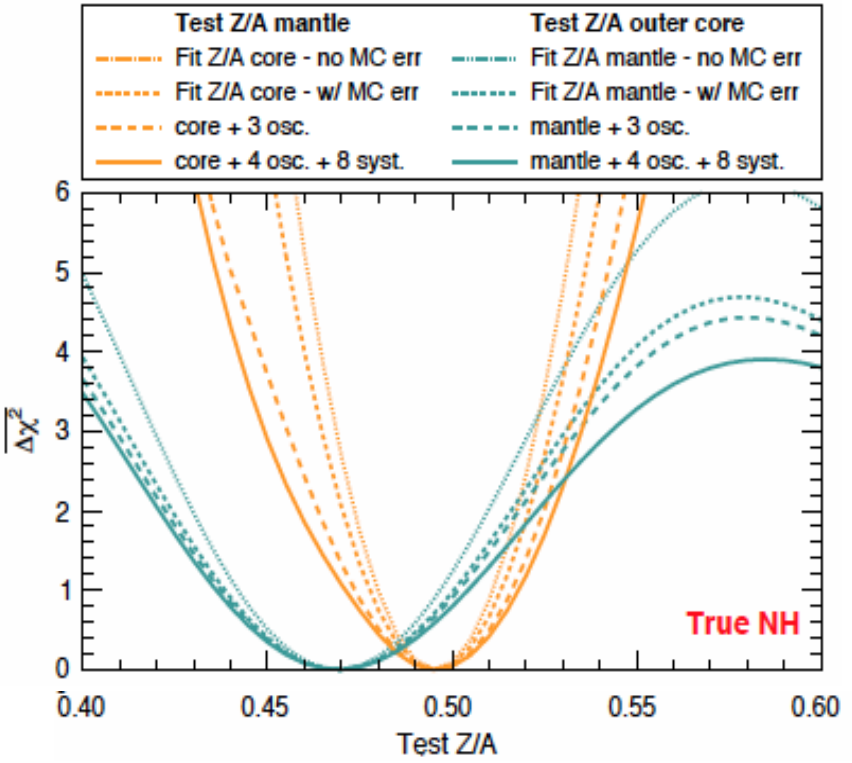
P.F. de Salas, S. Pastor, C.A. Ternes, T. Thakore, M. Tórtola, Phys. Lett.B789, pp. 472 - 479. 2019

Official ORCA analysis under progress

Other Exotic Physics Topics with ORCA

- Dark matter searches
- Earth tomography
- Lorentz Invariance Violation
- Quantum Decoherence

- Thanks to large statistics, ORCA will place competitive limits most of these scenarios.



Earth tomography

Timeline for ORCA Deployment

- **Phase 1** : 6 ORCA strings (fully funded, to be completed in 2019)

  Feasibility tests and first results

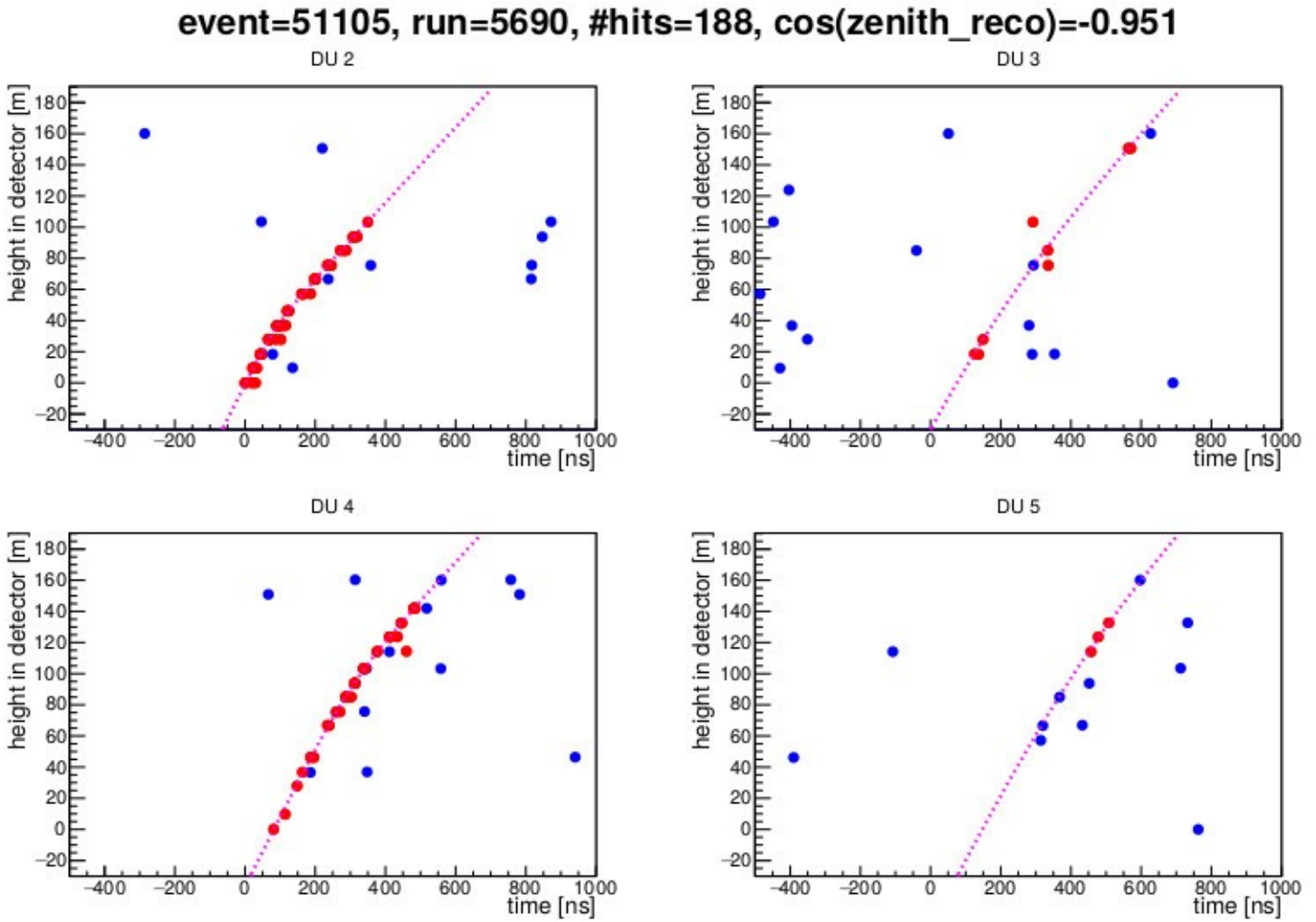
- **Phase 2** : 115 ORCA strings (Partially funded)

  Full atmospheric oscillation physics program

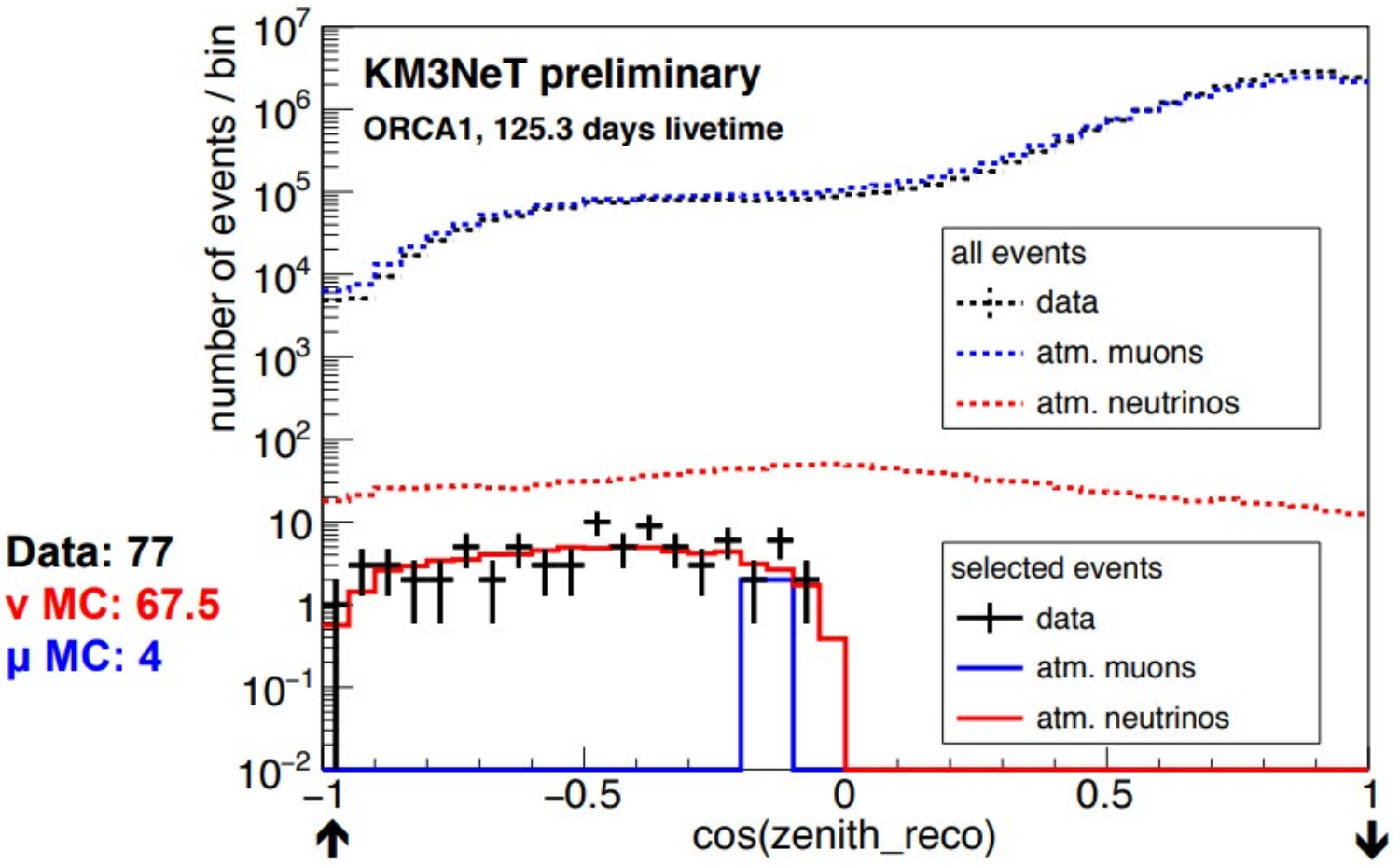
Current Status

- The first ORCA string was deployed in September 2017.
- As of October, 2019, four strings are operational.
- Two new strings are ready to be deployed.

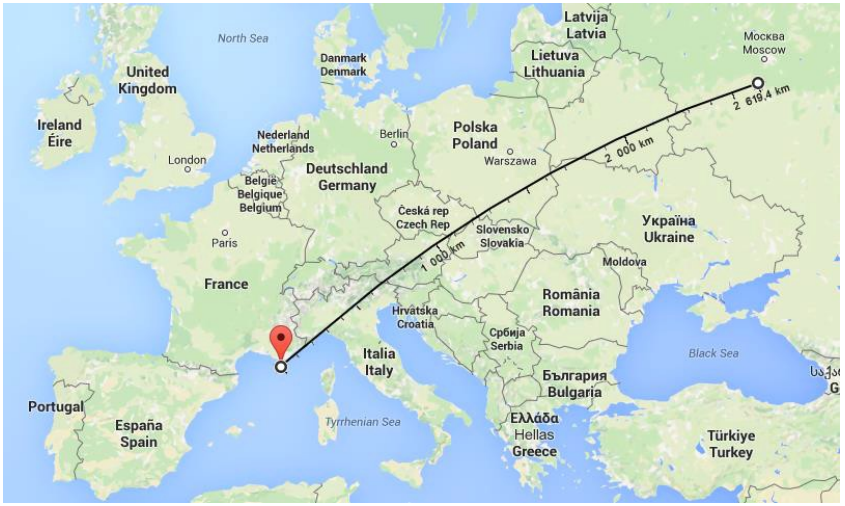
An Up-Going Candidate Event

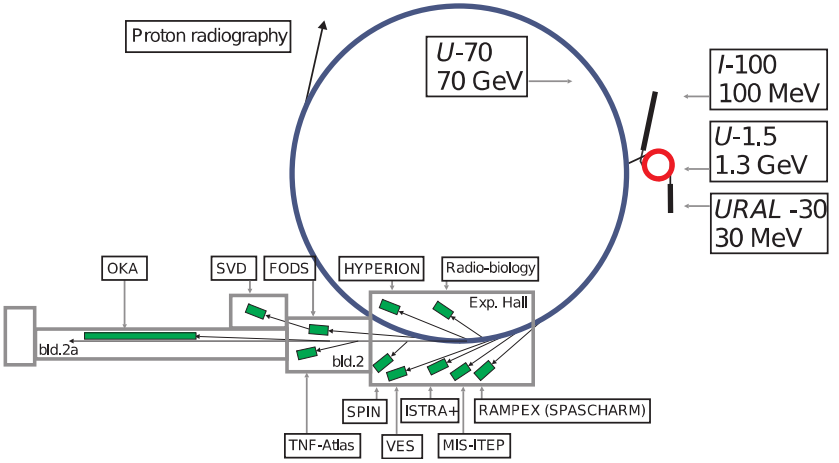


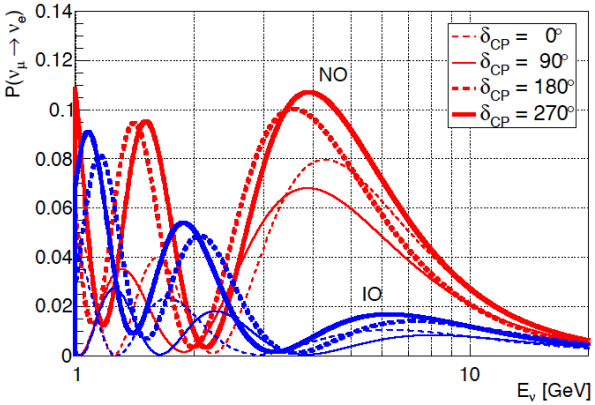
Data from the first ORCA DU



P2O (Protvino to ORCA) Neutrino Beam







Baseline : 2590 km

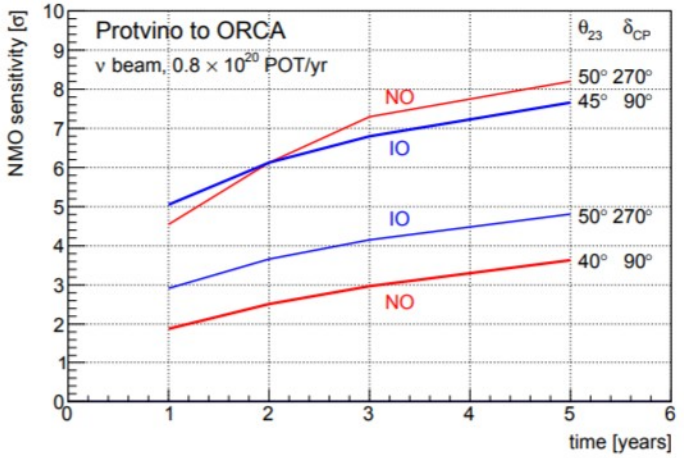
Current beam power : 15 kW,
Up-gradable to 90 - 450 kW

Energy range of interest : 3 - 8 GeV

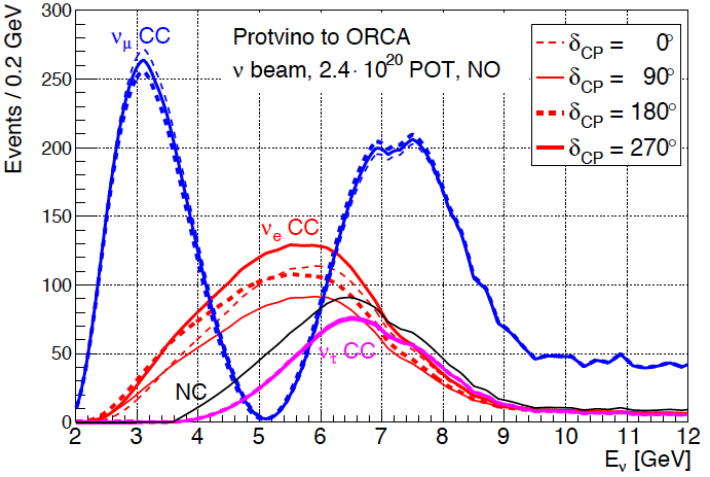
P2O Letter of Interest : Eur.Phys.J. C79 (2019) no.9, 758

Study performed by a subgroup of KM3NeT members and colleagues from Russian institutions.

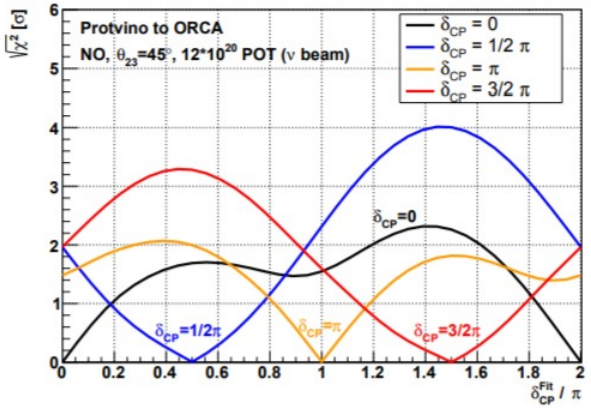
P2O Sensitivity Study



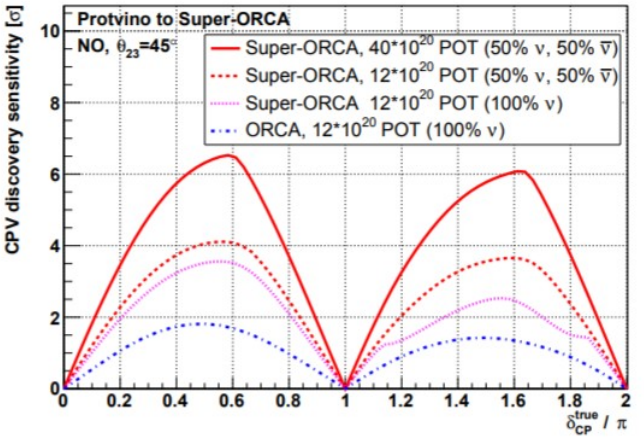
NMO Sensitivity : 90 kW



Event Rates (90 kW, 3 years)



CPV : 450 kW, 3 years



Protvino to Super-ORCA

Summary

•KM3NeT-ORCA will measure oscillation parameters for a number of standard and non-standard physics scenarios with atmospheric neutrinos.

•Matter effects play an important role in most of these measurements.

•ORCA is expected to make a (2.2 - 5)σ determination of the neutrino mass ordering in 3 years, depending on the true values of oscillation parameters.

•The first four lines are already taking data. A total of 6 lines are to expected be deployed by the end of 2019.

•Feasibility of a neutrino beam from Protvino to ORCA is being studied, which will strengthen the NMO determination significance, as well as bring possibilities of the CPV measurement.

Thank You for your attention!