Oscillation Physics with KM3NeT-ORCA

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on behalf of the KM3NeT collaboration

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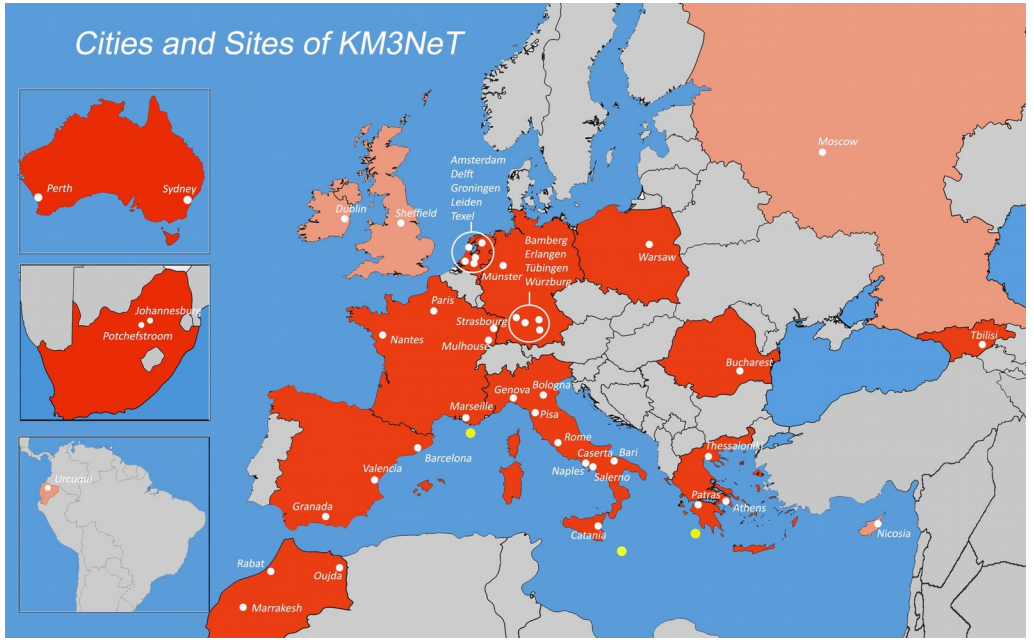
WIN 2019, Bari, Italy

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)
- **Deployment and Current Status**
- **Future Upgrade Study:**
  - Protvino to ORCA (P2O)
- **Summary**

KM3NeT Collaboration Map



Oscillation
Research
with **C**osmics
In the **A**byss

Astroparticle
Research
with **C**osmics
In the **A**byss

ORCA : low energy physics (neutrino oscillations)

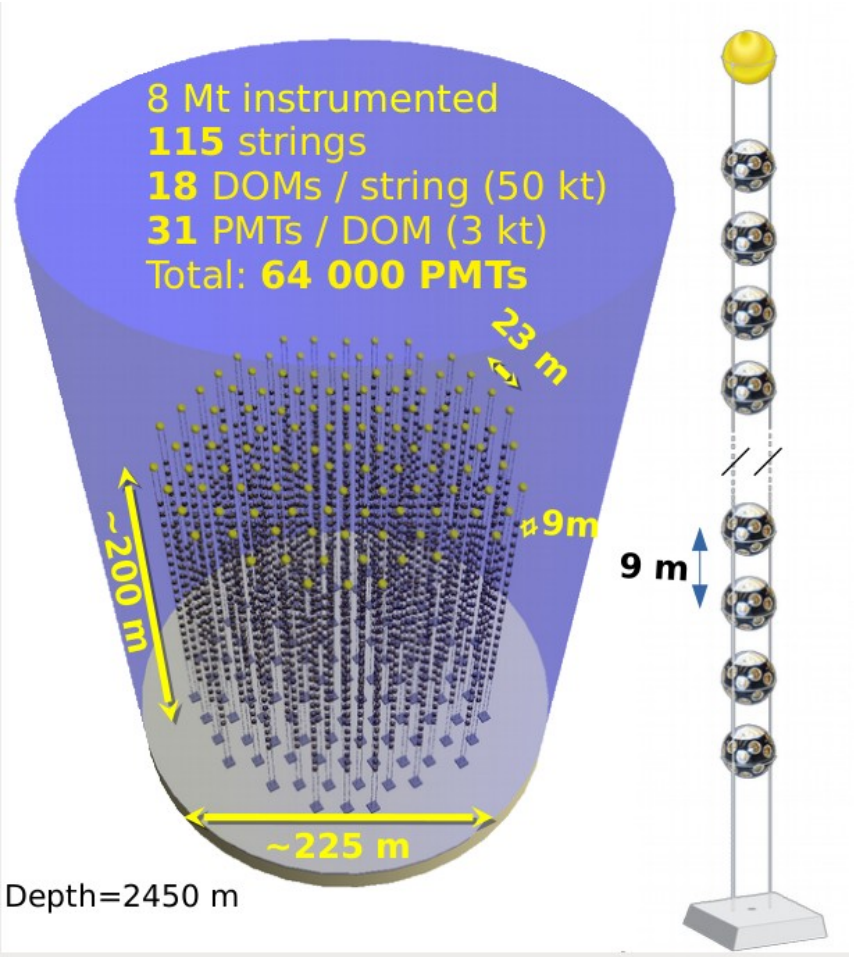
ARCA : high energy physics (astrophysical neutrinos, dark matter search)

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

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

See talk on ANTARES and ARCA by Pasquale Migliozzi

ORCA Schematics



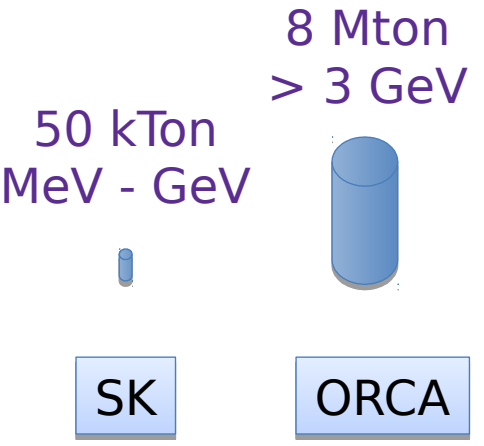
Digital Optical Module

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

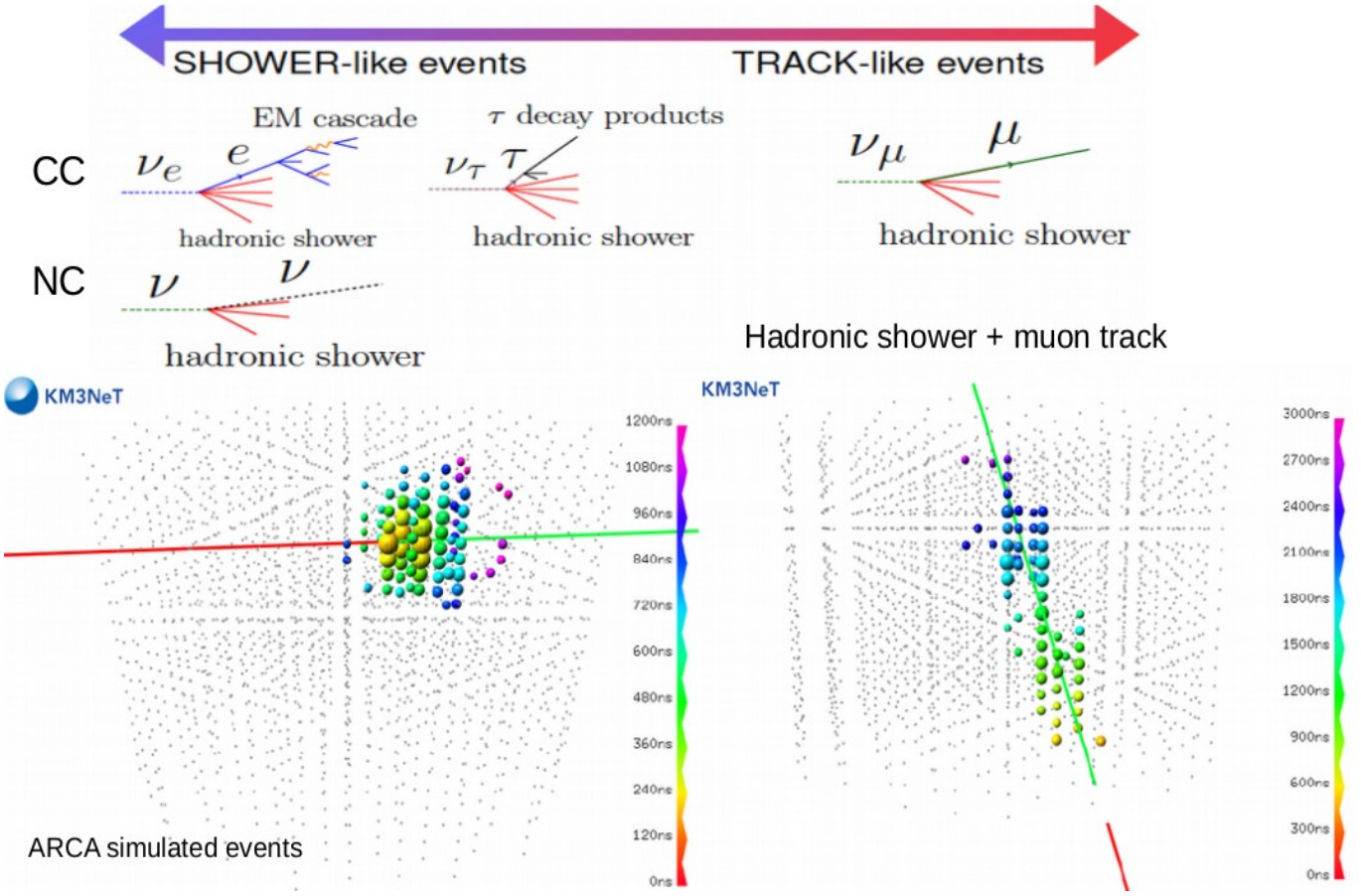
✔ Uniform angular coverage
✔ Directional information
✔ Digital photon counting
✔ All data to shore

photocathode area similar to a 17” PMT

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

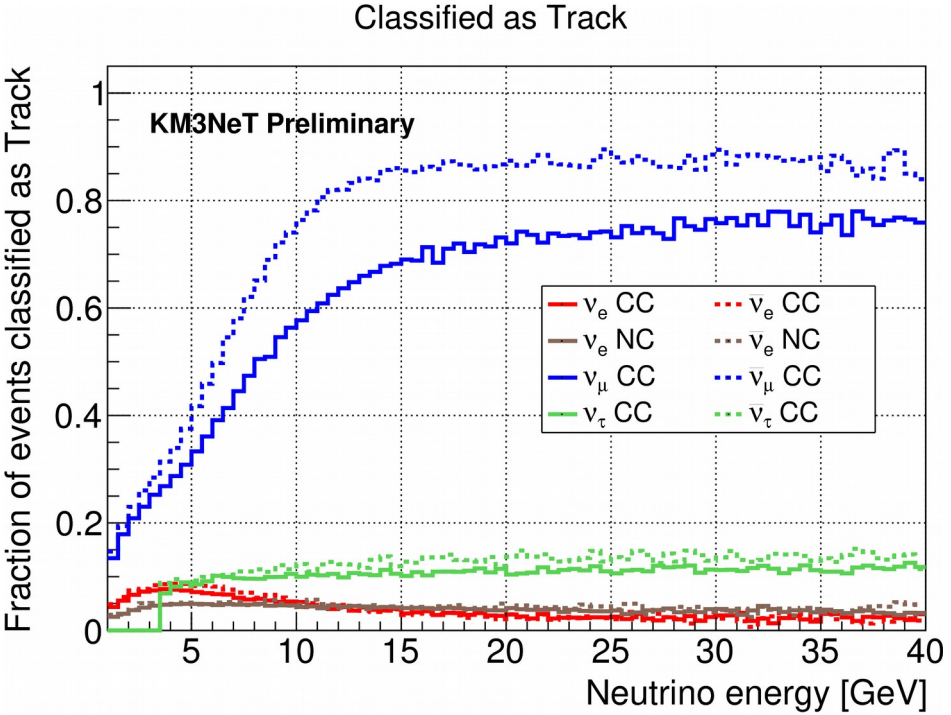


Event Topology in ORCA



- Different reconstruction algorithms for track and shower events
- Studies are underway to use Bjorken y in future, which are expected to improve oscillation parameter sensitivities

PID(Event Topology) Classification

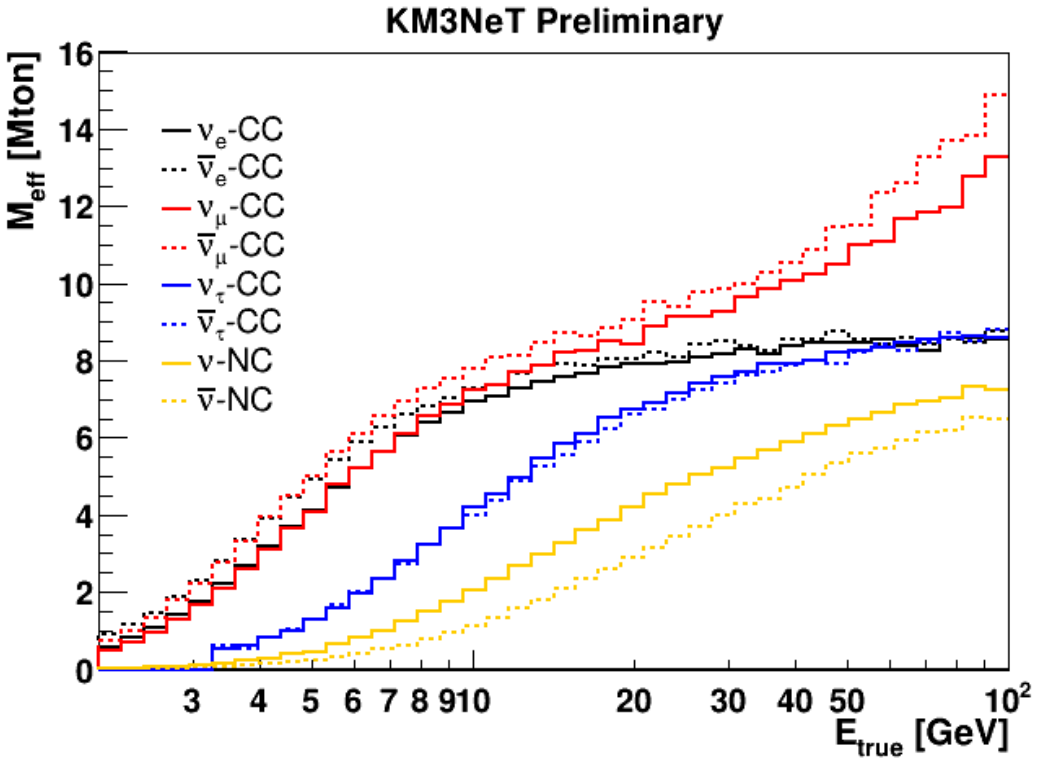


Random Decision Forests used to classify the event topology.

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

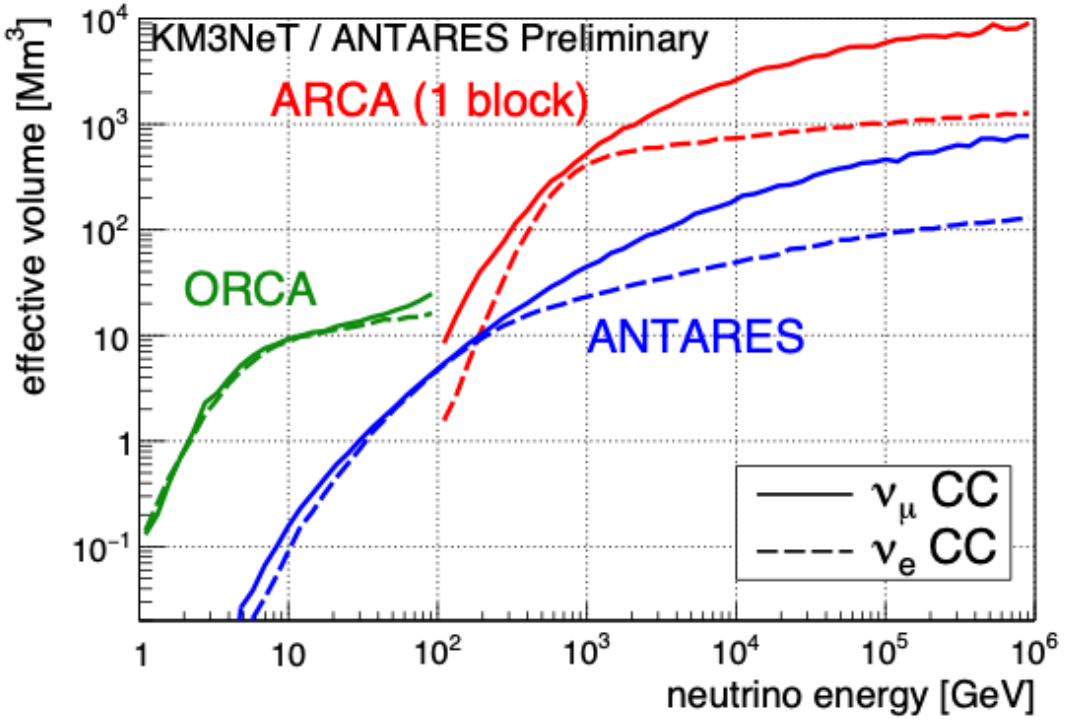
ν_τ CC: 2 900

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

NC: 6 800

Large event statistics drives measurements of oscillation parameters.

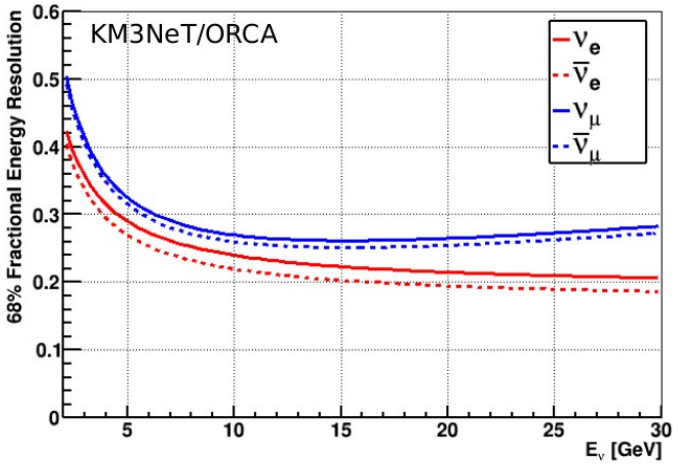
Comparison of Effective Volumes



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

Energy and Zenith Angle Resolutions

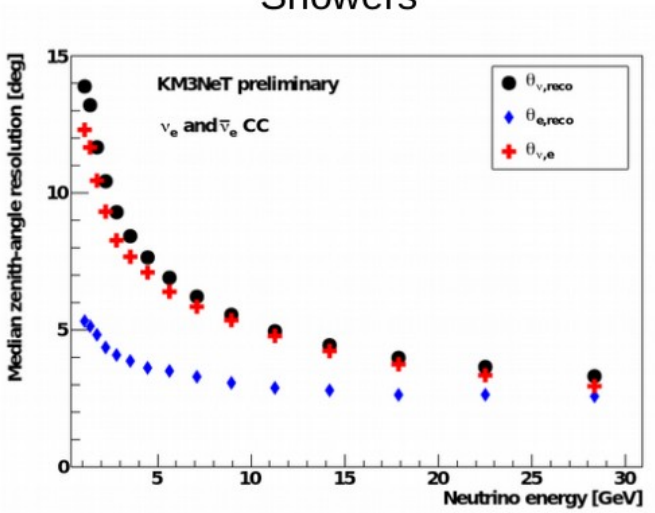
Energy Resolutions



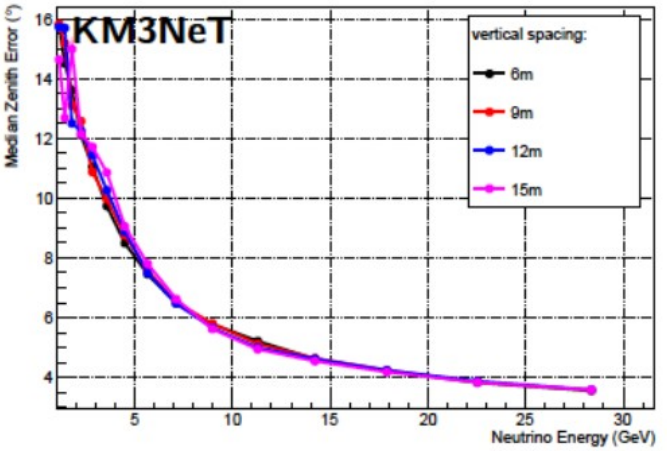
Energy resolution ~ 25% at 10 GeV

Direction resolution ~ 5 degrees at 10 GeV

Showers

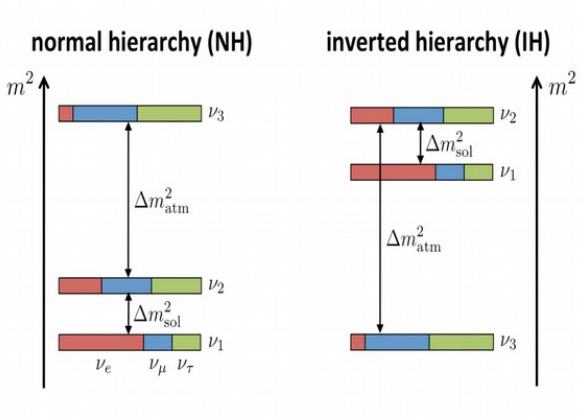


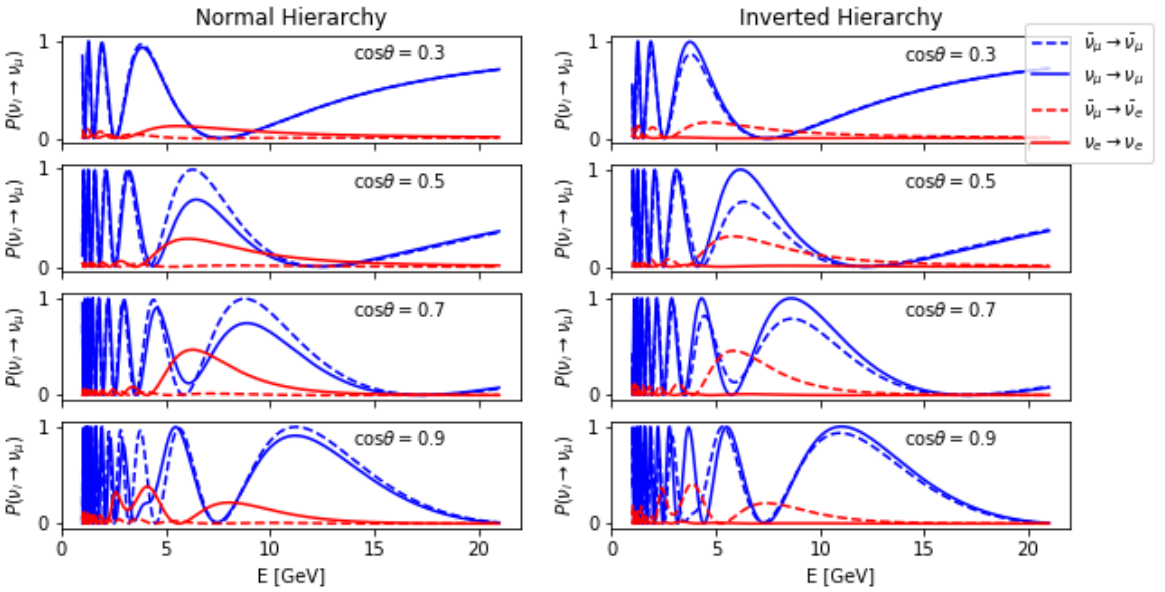
Tracks



Direction resolutions

Oscillation Probabilities



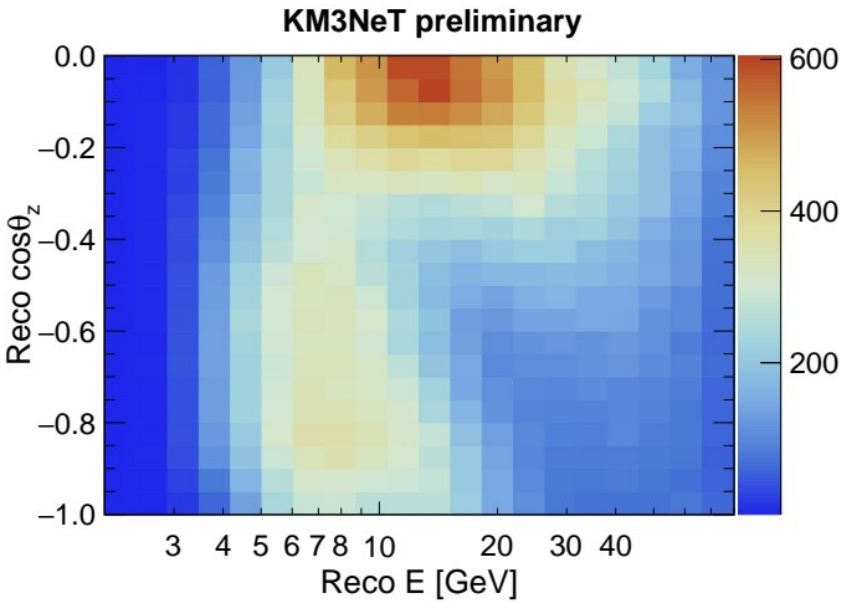


Due to the MSW resonance effect, oscillation probabilities for the Normal and Inverted mass ordering are different, as neutrinos travel through the earth matter.

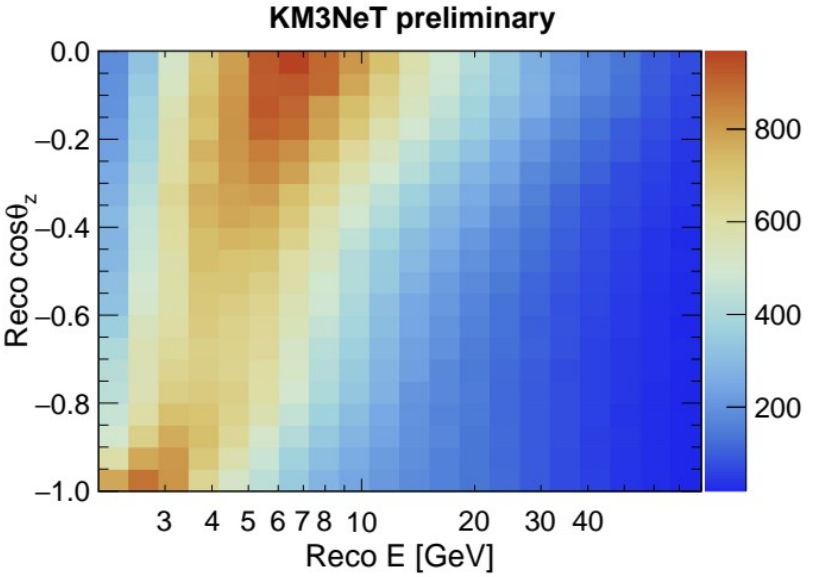
This is reflected in the (E,cos θ_z) distributions observed at the detector.

Event Distributions

Tracks



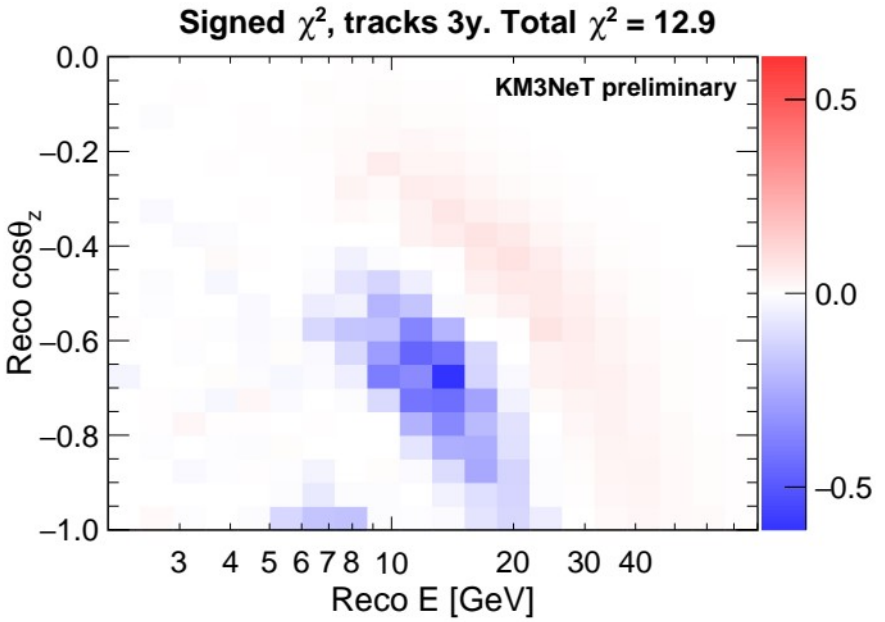
Showers

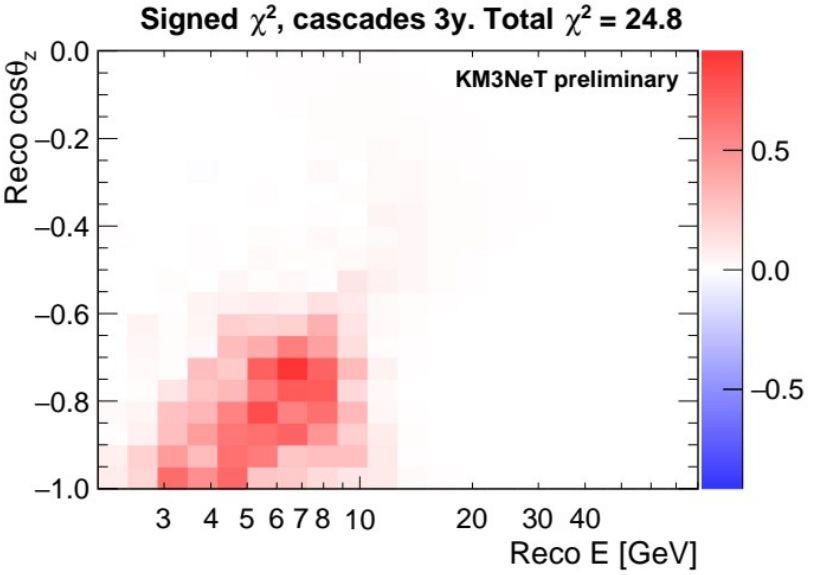


The event distributions are obtained after folding-in :

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.

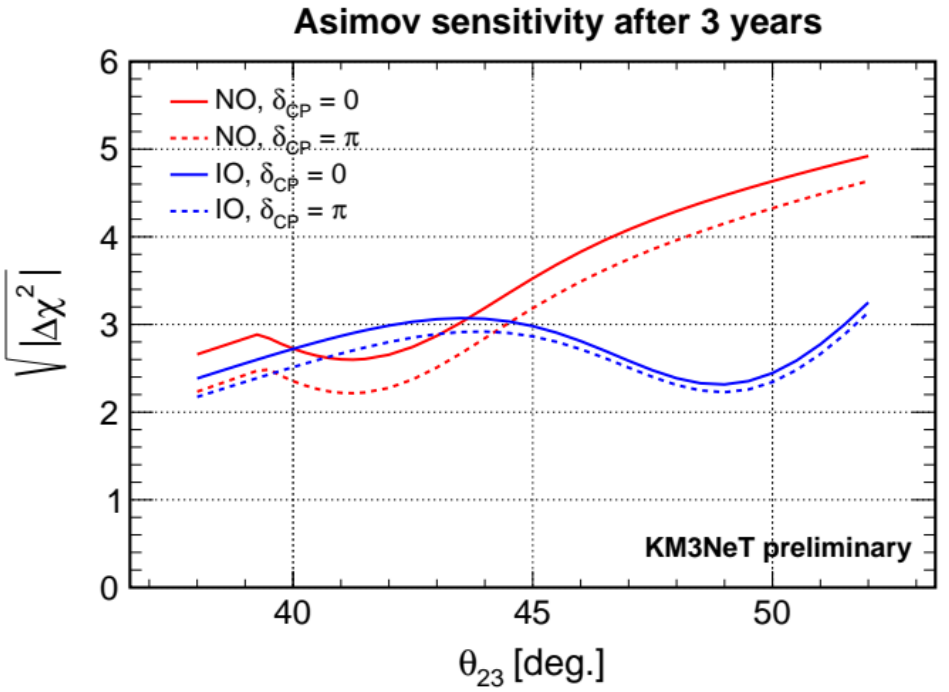
NMO Sensitivity Study

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

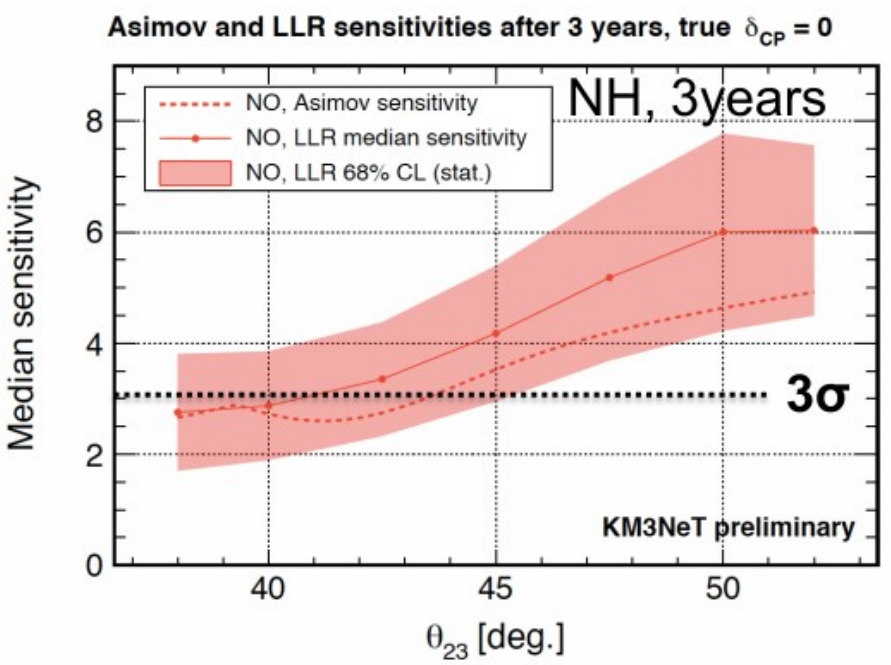


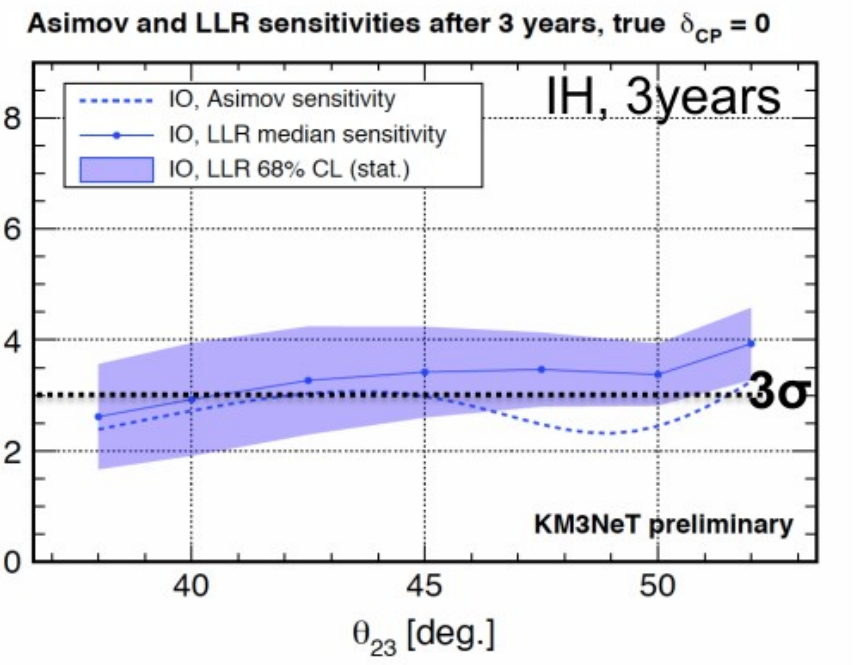
ORCA will determine the mass hierarchy with a significance of (2.2-5)σ with 3 years of operation

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

Incorporation of additional systematics into analysis is under progress.

Median Sensitivity

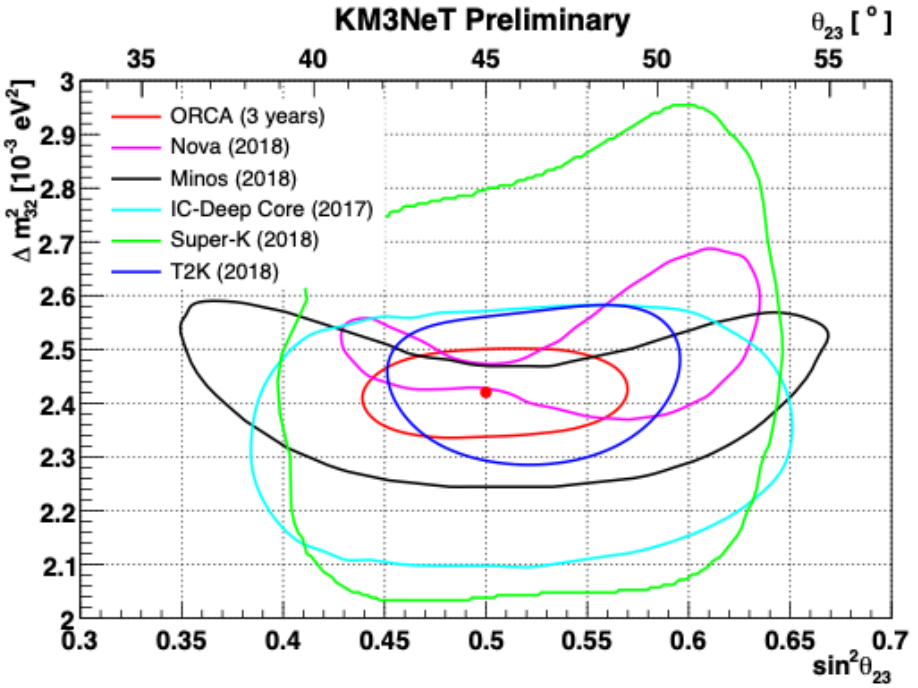




DOI:10.5281/zenodo.1300771

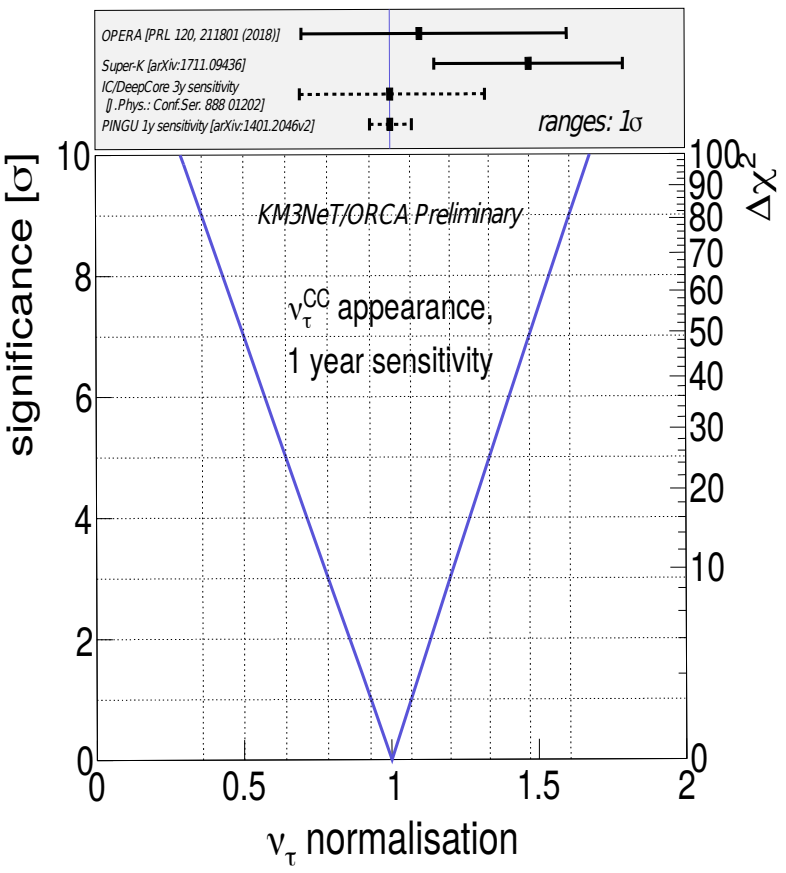
Median sensitivity study with fake data sets

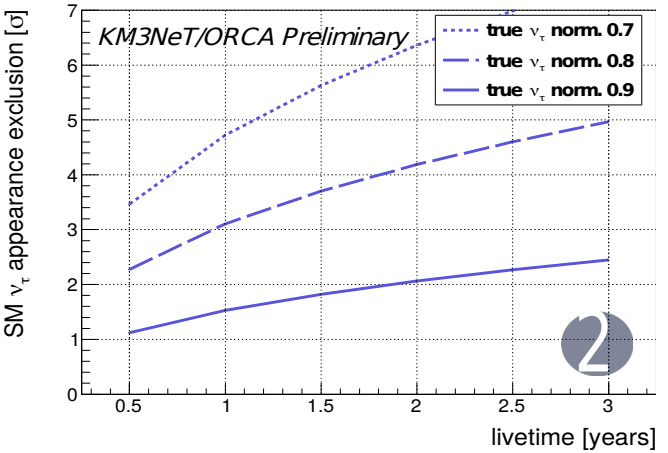
Atmospheric Parameters Measurement



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



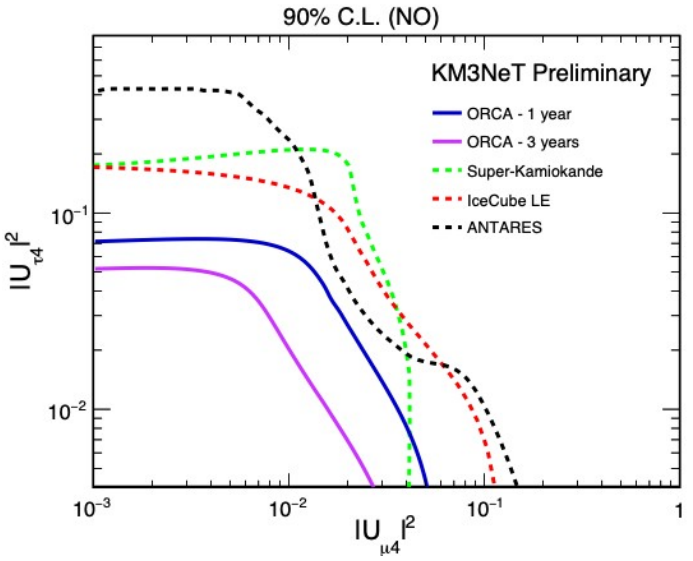


ν_τ appearance signal is expected at 10 – 30 GeV as excess events in the shower channel.

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 has competitive sensitivity to all three mixing elements, U_{e4}, $U_{\mu 4}$, $U_{\tau 4}$.

Non-Standard Interactions (NSI)

NC NSI

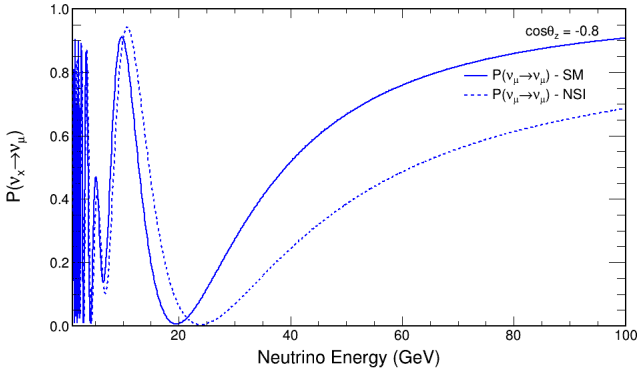
$$H = \frac{1}{2E} U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{bmatrix} U^\dagger + 2\sqrt{2} G_F N_e(x) \begin{bmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau}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

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

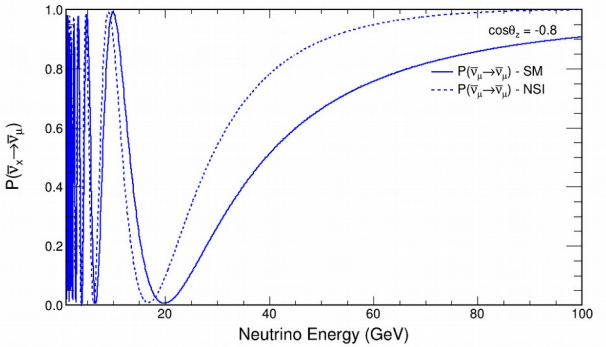
In the presence of NC NSI, neutrino oscillation probabilities can be significantly modified due to the MSW effects.

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

neutrino



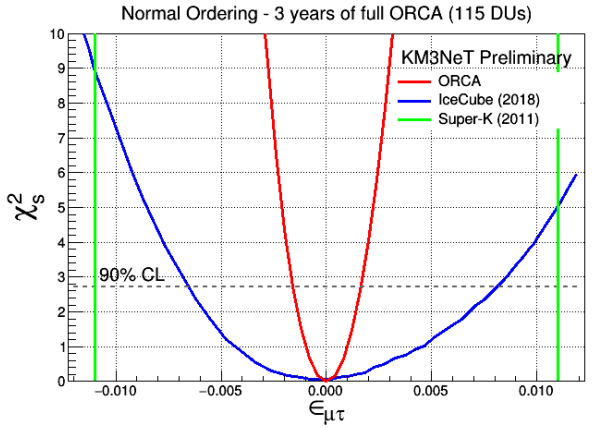
anti-neutrino

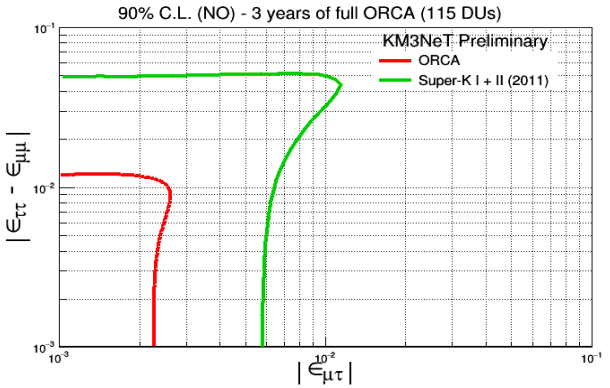


ν_μ survival probability for $\epsilon_{\mu\tau}$ = 0.01 and standard oscillations

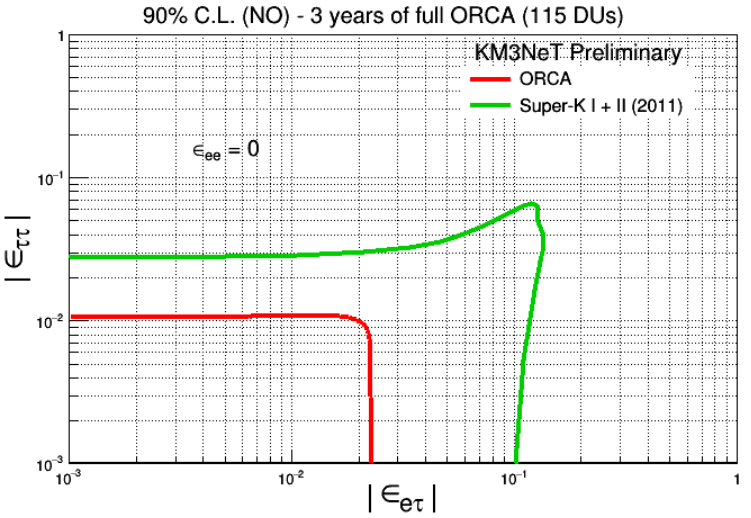
NSI : Hybrid model sensitivity

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)



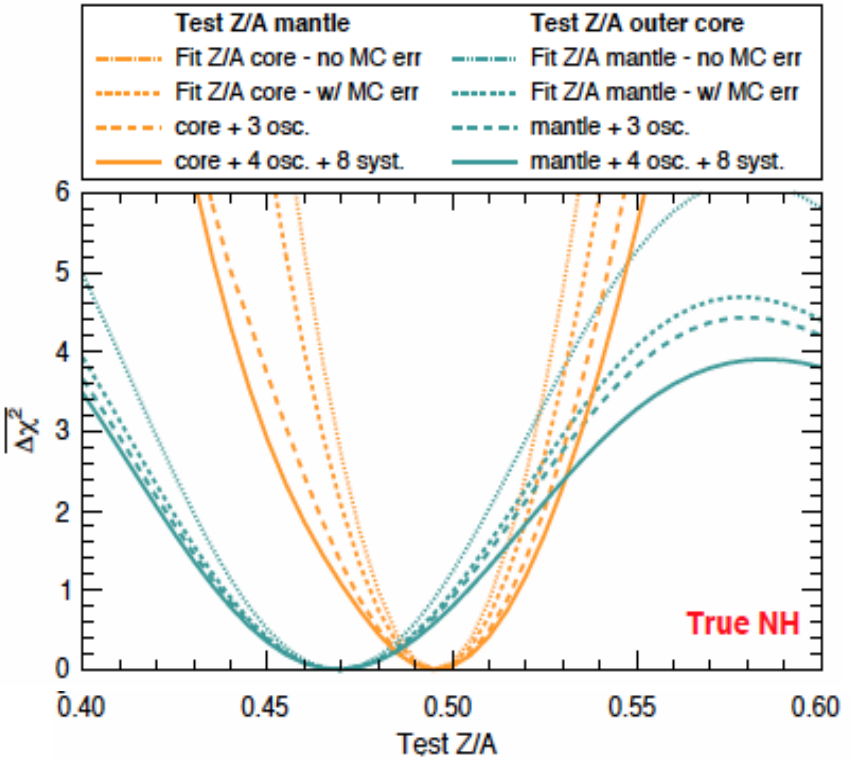
Study is under progress for the full 3 flavor NSI model.

NSI d-quarks couplings

Other Exotic Physics Topics with ORCA

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

- 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

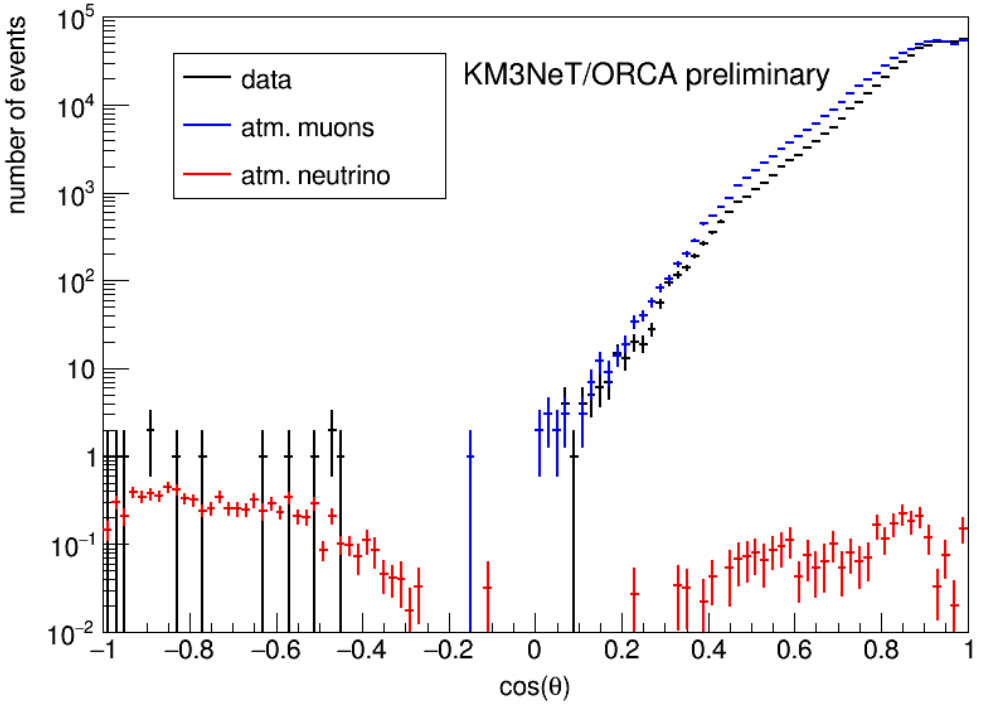
- **Phase 2** : 115 ORCA strings

  Full atmospheric oscillation physics program

Current Status

- The first ORCA string was deployed in September 2017.
- As of May, 2019, two strings are operational.
- Four new strings are ready to be deployed.

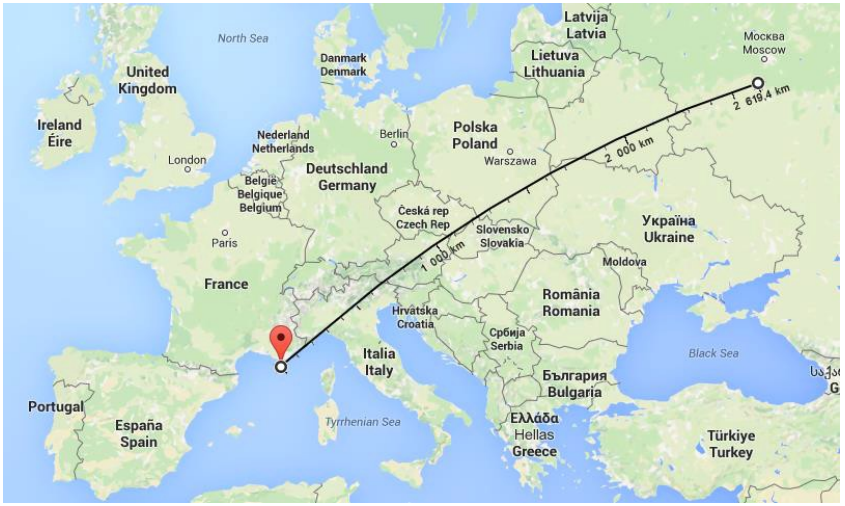
Data from the first ORCA DU

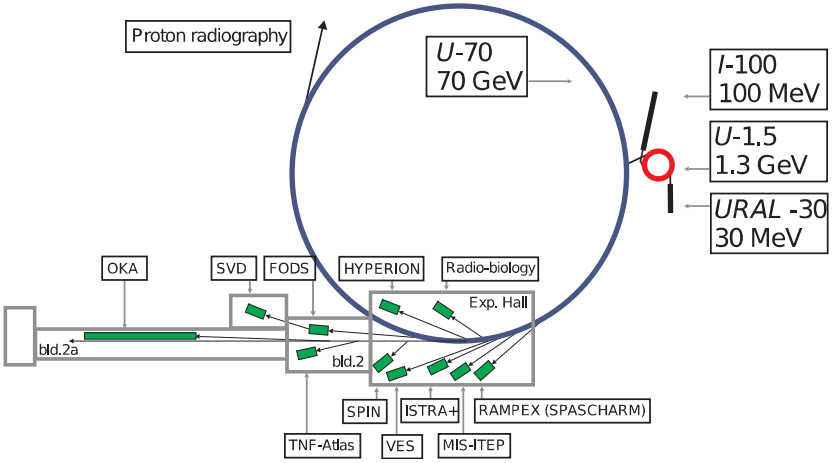


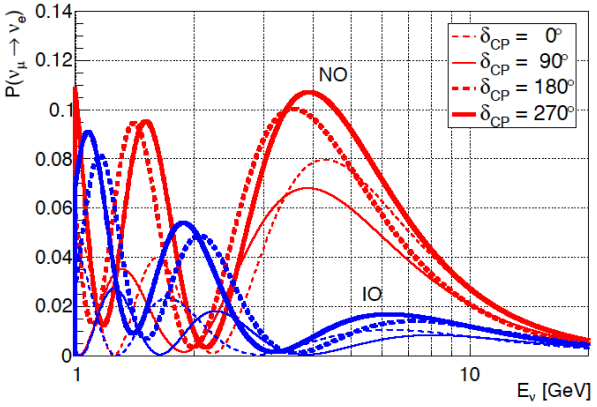
82 days data from DU1

Number of up-going events
MC neutrinos : 8.33
MC muons : 1
Data : 13

P2O (Protvino to ORCA) Neutrino Beam







Baseline : 2590 km

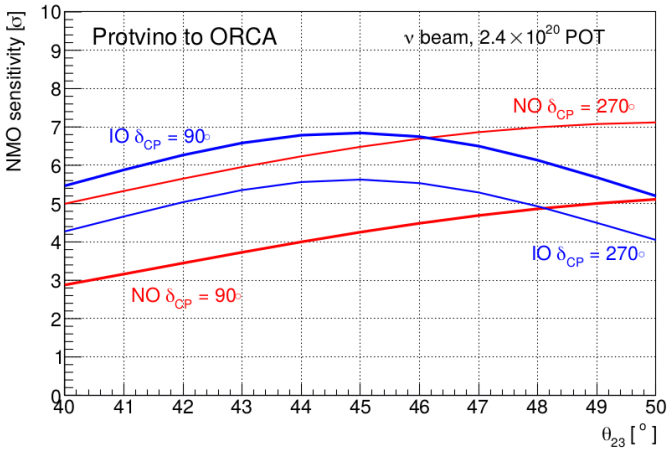
Current beam power : 15 kW,
Up-gradable to 90 - 450 kW

Energy range of interest : 3 - 8 GeV

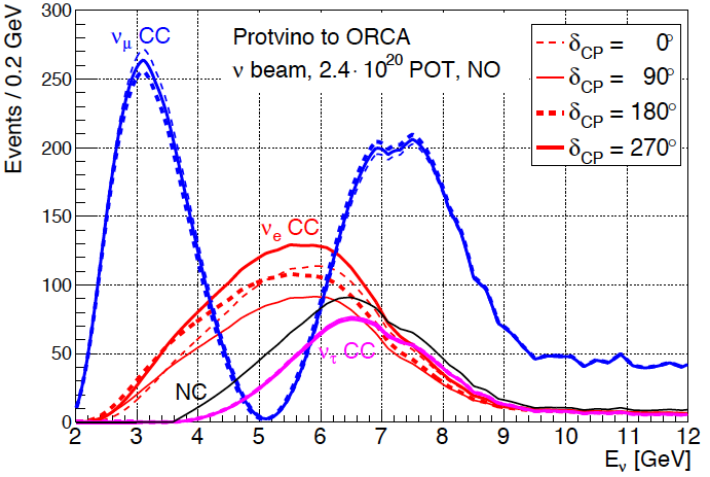
P2O Letter of Interest : arXiv:1902.06083

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

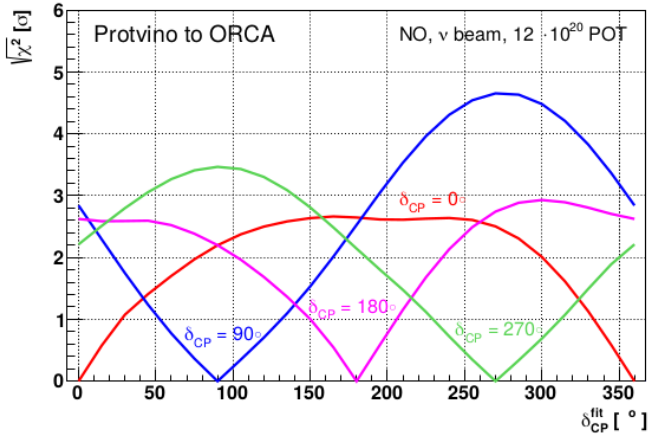
P2O Sensitivity Study



NMO : 90 kW, 3 years



Event Rates (90 kW, 3 years)



CPV : 450 kW, 3 years

Feasibility studies of a denser configuration of ORCA (called as Super-ORCA) are underway. (DOI:10.5281/zenodo.1292936)

In conjunction with the Protvino neutrino beam, Super-ORCA prospects for NMO and CPV discovery are also being explored.

Summary

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

•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 two detection unit 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!