Neutrino oscillation measurement with KM3NeT/ORCA

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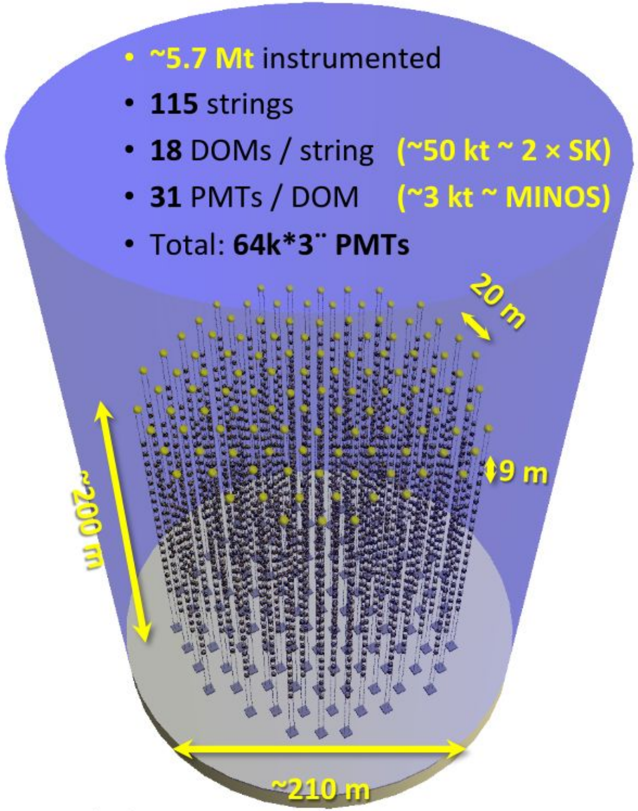
6/12/2021

The KM3NeT Detector

KM3NeT Detector ORCA

- ORCA, **O**scillation **R**esearch with **C**osmics in the **A**byss, is the low energy KM3NeT neutrino underwater detector, located in the French Mediterranean sea.
- ORCA comprises a dense array of optical modules designed to detect the Cherenkov light emitted from charged particles resulting from neutrino interactions in the vicinity of the detector.
- **Physics goal** : determination of the neutrino oscillations parameters.

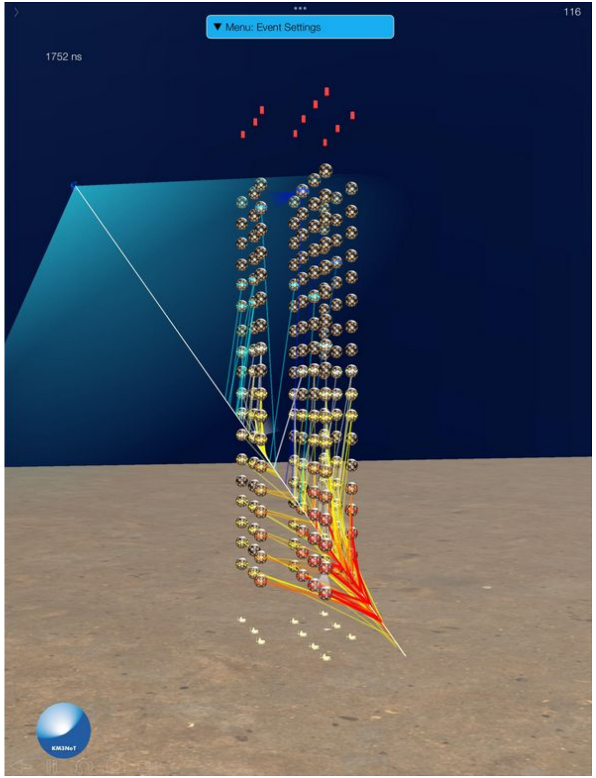


Depth=2475m

Overview of the KM3NeT design building block, composed of 115 detection units, with a zoom on the Digital Optical Modules, the fundamental constituent of the detector.

Current status of ORCA

- ORCA has been operating with **10 Detection Units** (DUs) since late **November 2021**.
- Each DU is a vertical string composed of 18 multi-PMT Digital Optical Modules (DOMs).
- More DUs are planned to be deployed in early 2022.
- The final ORCA detector will be composed of 115 DUs, over a volume of ~8 Mton.

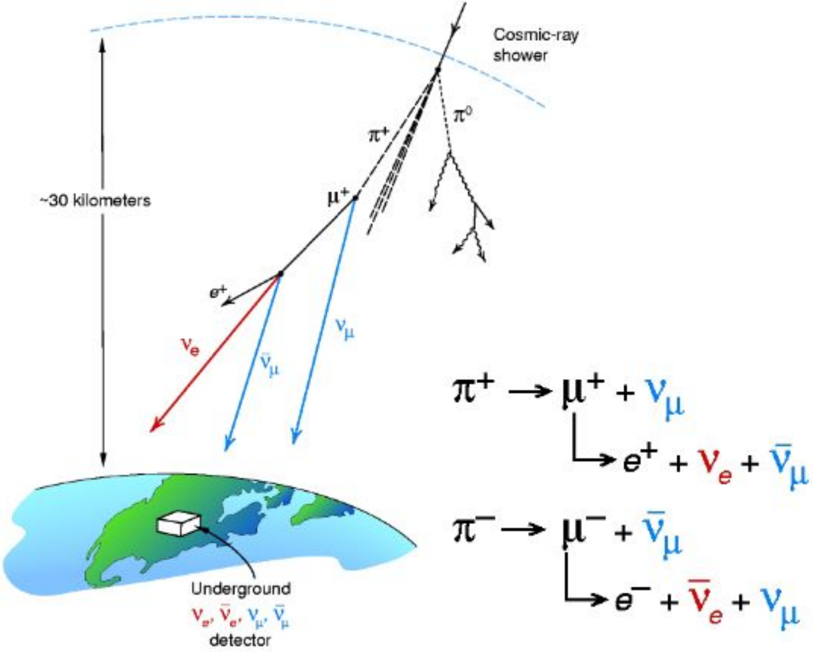


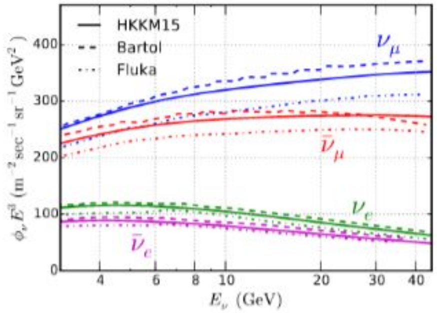
3-D event display of an event passing through the ORCA-10DUs detector.

Physics background

Atmospheric neutrinos

- Cosmic rays reach Earth in all directions and interact with nuclei in Earth atmosphere, producing a an air shower.
- During these interactions, charged mesons (π) are produced and decay after their production to muons and muon neutrinos.
- Finally, the produced muons decay producing electron neutrino and additional muon neutrino.
- Atm neutrino flux follows a **power law**, with a spectral index ≈3.
- There is a dependence on the energy and the zenith angle.
- the absolute flux normalisation differs between flux models by ≈15% -> effects the physics analysis.





Neutrino Oscillations

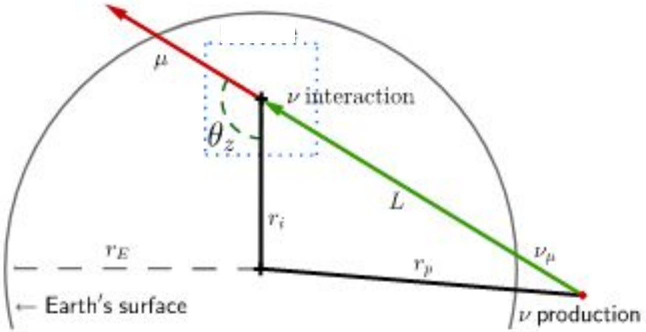
Neutrinos exist in 3 flavours: ν_e, ν_μ and ν_τ

These flavour eigenstates are a mixture of the 3 unequal mass eigenstates -> neutrinos oscillate, i.e neutrinos change flavour eigenstate when travelling over macroscopic distance.

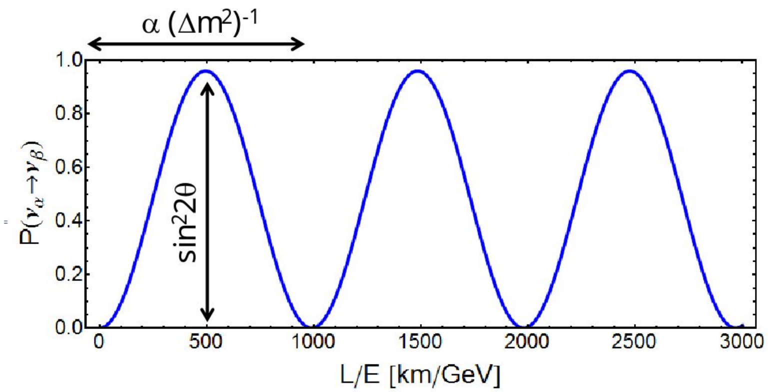
Neutrino Observables

- Neutrino energy **E**.
- Neutrino baseline L, i.e the length of neutrino trajectory.

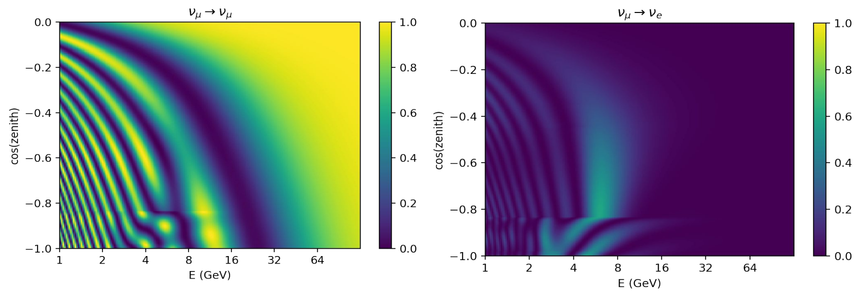
More complex picture in the case of 3 flavours.



$$\boxed{P(\nu_\alpha \to \nu_\beta) \approx \sin^2 2\theta \times \sin^2\left(1.27 \times \Delta m^2\ [\mathrm{eV}^2] \times L/E\ [\mathrm{km/GeV}]\right)}$$



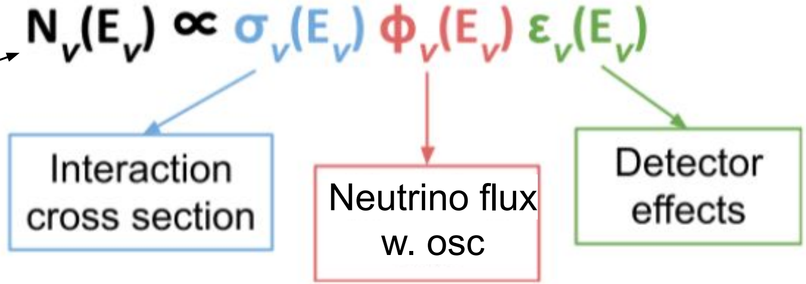
*Oscillation probability under the assumption of **2** neutrino flavours*

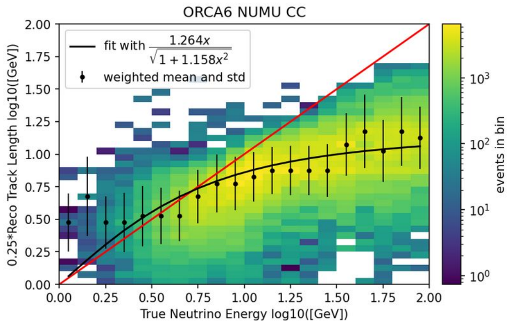


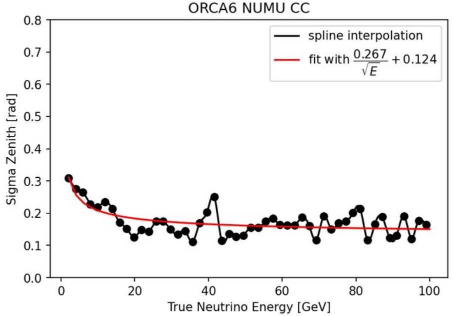
*Oscillation probability under the assumption of **3** neutrino flavours*

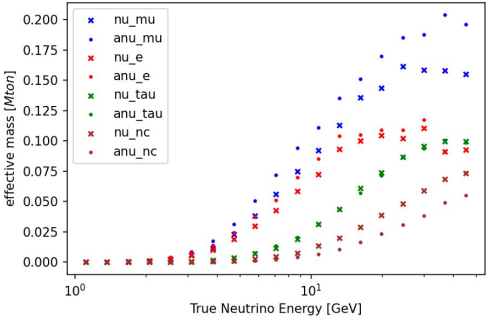
Neutrino events seen in KM3NeT - detector effects

Number of neutrino events









- Detector needs to see enough light to trigger/reconstruct a neutrino.
- More energy -> more light. At low energies efficiency drops.
- In KM3NeT, we quantify the detector efficiency using the effective mass/volume.
- Energy/zenith resolution impacts our ability to see oscillations.
- Light capture is limited by the size and the shape of detector.
- The shape of ORCA6 detector is "very vertical" -> saturation in the reconstructed energy.

-> Detectors effects need to be included for oscillation measurements.

Analysis pipeline

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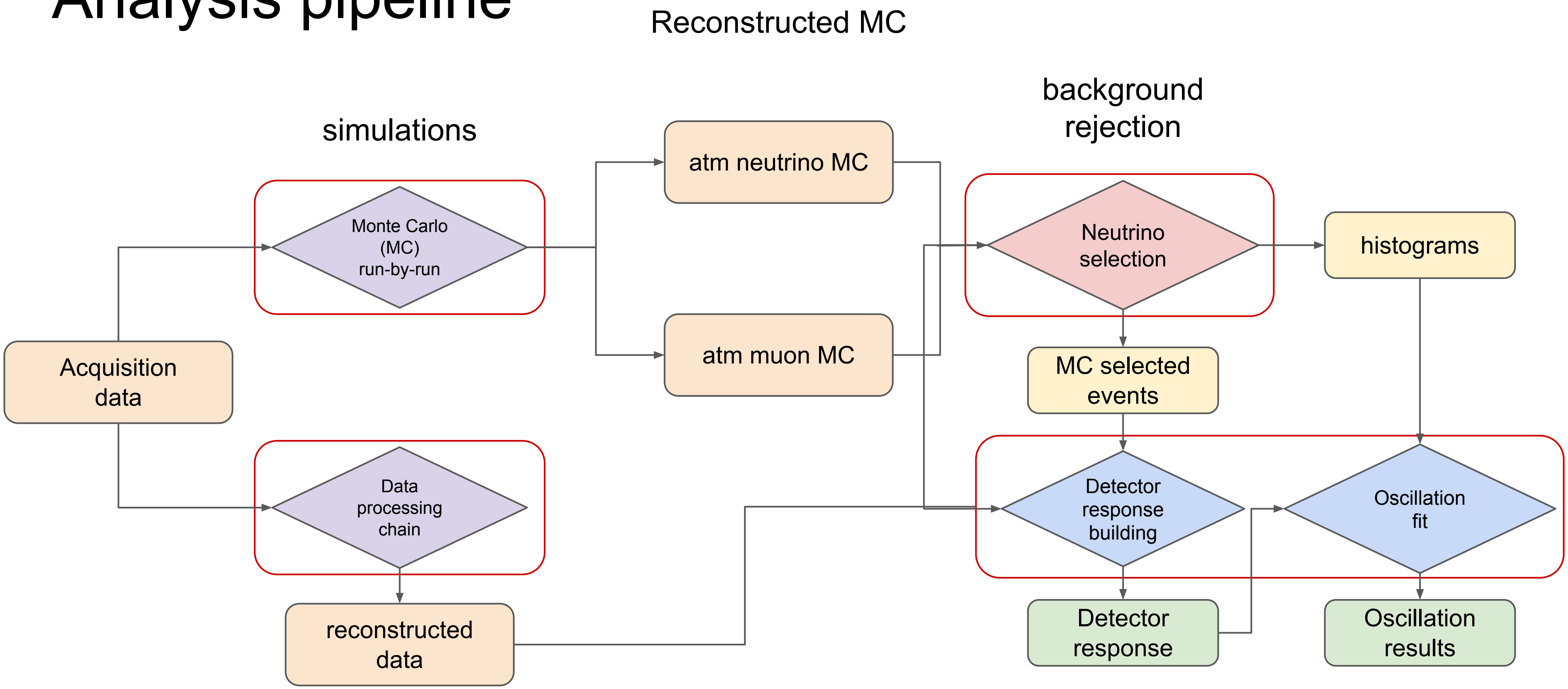


Data samples and neutrino events selection

Data sample

Steady data taking since 2019 with 4 Detection Units (ORCA4), and 6 DUs from early 2020 (ORCA6).

ORCA6: 385.8 total days of exposure.

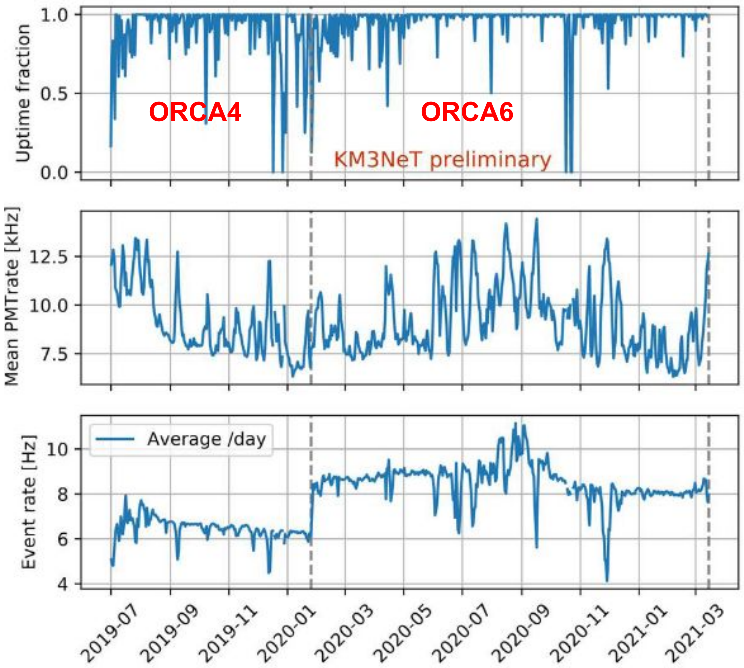
Run selection:

- Physics runs, with duration higher than 2h.
- Stable data acquisition conditions.
- Detector hardware functioning within acceptable margins (PMT rates nominal, clocks are synced, etc..)

~356 days valid for physics analysis

Efficient data taking:

- 96% uptime
- 92% survive the run selection



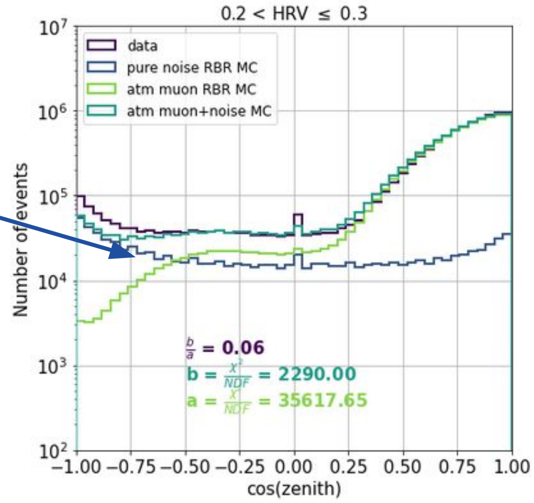
Time evolution of the Uptime fraction, Mean PMT rate and Event rate of ORCA detector from 2019 to early 2021

Neutrino events selection: Pure noise rejection

Background rejection: **Pure noise**.

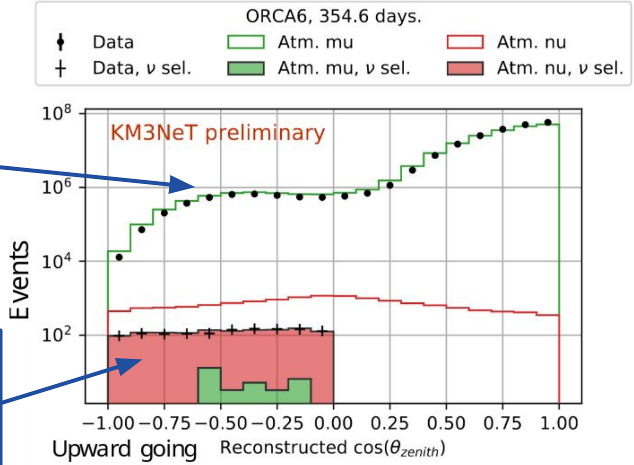
- Goal: select a “pure” neutrino sample by rejecting background events.
- Pure noise events are reconstructed as up going events in all HRV regimes.
- Pure noise rejected by limiting the number of triggered DOMs.

Pure noise mostly reconstructed as upgoing



Good data/atm muon MC agreement after pure noise cut

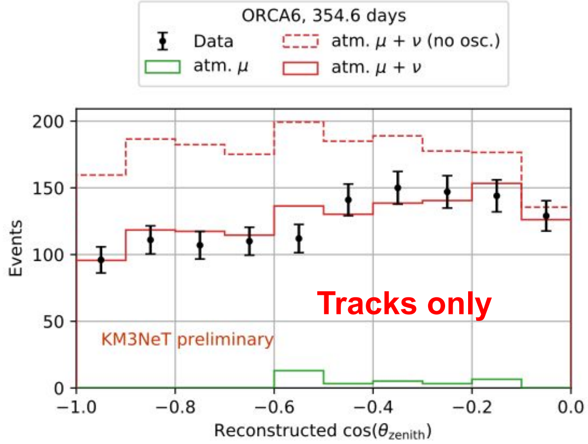
“Pure” neutrino sample



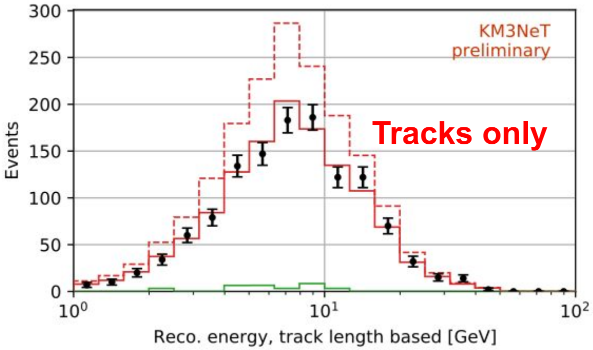
Neutrino events selection, rejection of atm muons - 3.5 neutrino/day

Background rejection: **atm. Muons rejection**.

- **zenith angle**: up-going events only.
- **event reconstruction quality**:
  - criteria for fit quality: the maximum-likelihood fit and the relative likelihood value per hit (L/N_{hit}).
- **up/down ambiguity**:
  - Exclude events with up and down-going reconstruction solutions with similar likelihoods.
- **number of signal-like hits:**
  - signal-like hits have a small time residual and are recorded by nearby DOMs with a not too large photon travel distance from the expected Cherenkov photon emission position along the muon track to the PMT.
- **Containment**:
  - Interaction vertex close to detector center in x-y-plane to select events fully contained within the detector volume.



Distribution of the reconstructed zenith angle of the selected neutrino sample



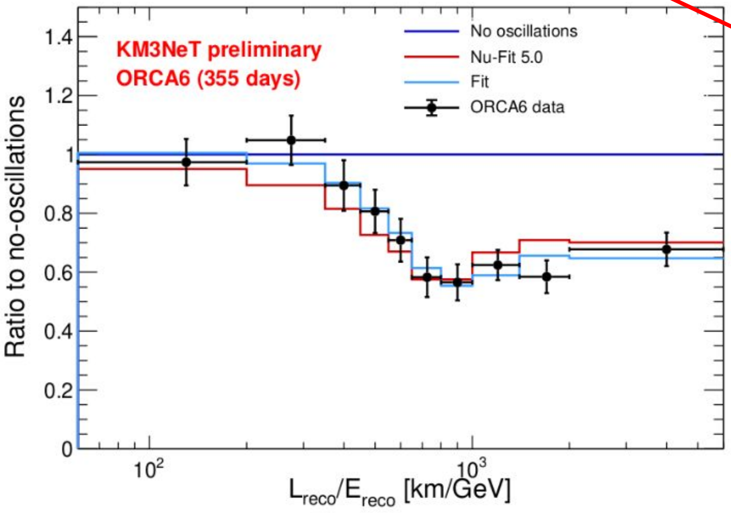
Distribution of the reconstructed track energy of the selected neutrino sample

Neutrino oscillations with the first ORCA data

Sensitivity to neutrino oscillations - 1D

Tracks channel only

- Find oscillations through comparing event distributions
    - No oscillations
    - Oscillations.
- Ratio with respect to 'no oscillations' hypothesis
- Binning is chosen to have similar statistics per bin
- From this $\Delta\chi 2$ for the measured data of ORCA6 is calculated.
- Data has a preference to oscillation with 5.9 σ



Sensitivity to neutrino oscillations - 2D

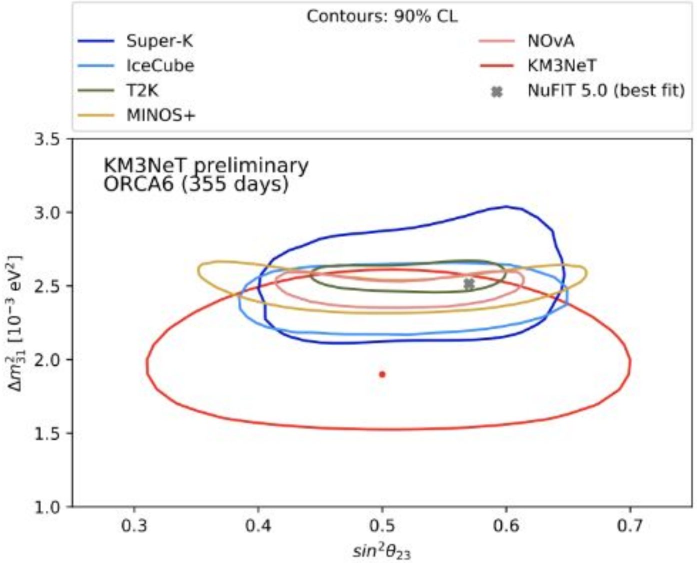
Tracks channel only

- Determine the log-likelihood in the relevant oscillation phase-space. Here it is $\mathbf{\Theta_{23}}$ and $\mathbf{\Delta}M_{31}$.

- Combined data set for ORCA4 and ORCA6

- Systematics include
  - Flux
  - Cross-section
  - Detector systematics
  - Overall normalization

- KM3NeT is soon becoming competitive with other experiments!



Conclusion

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- ORCA detector is growing, and more data is coming in the next few months.
- Neutrino oscillations can already be observed with ORCA6 (in the tracks channel only).
- ORCA sensitivity is becoming competitive with other experiments, with ORCA6 only.

Potential improvement of the analysis:

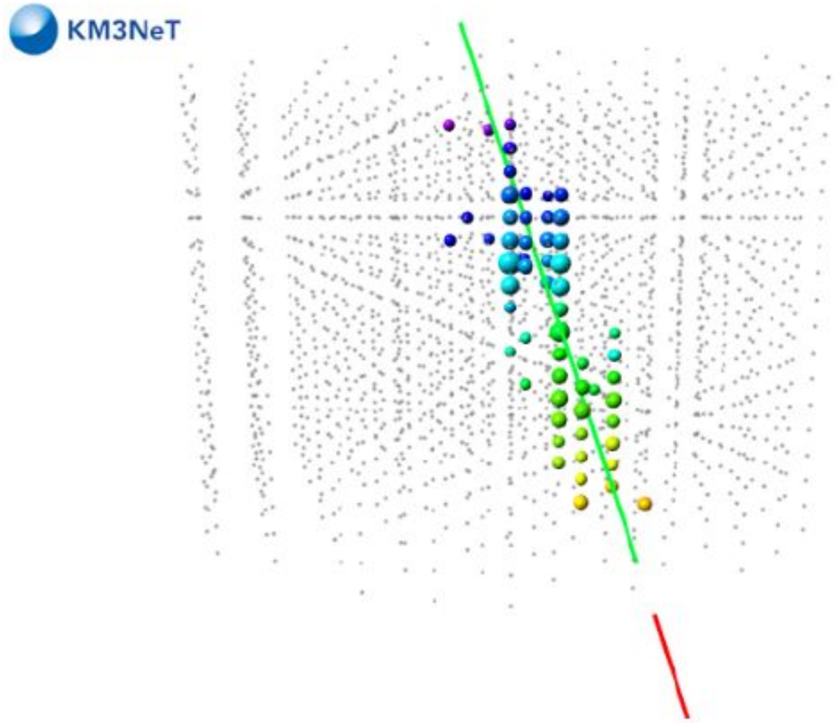
- Include full sample of ORCA6 (almost 2 years of data).
- Include shower reconstruction.
- Add Particle Identification.
- Study the impact of detector resolutions (and other systematics) on the contour.

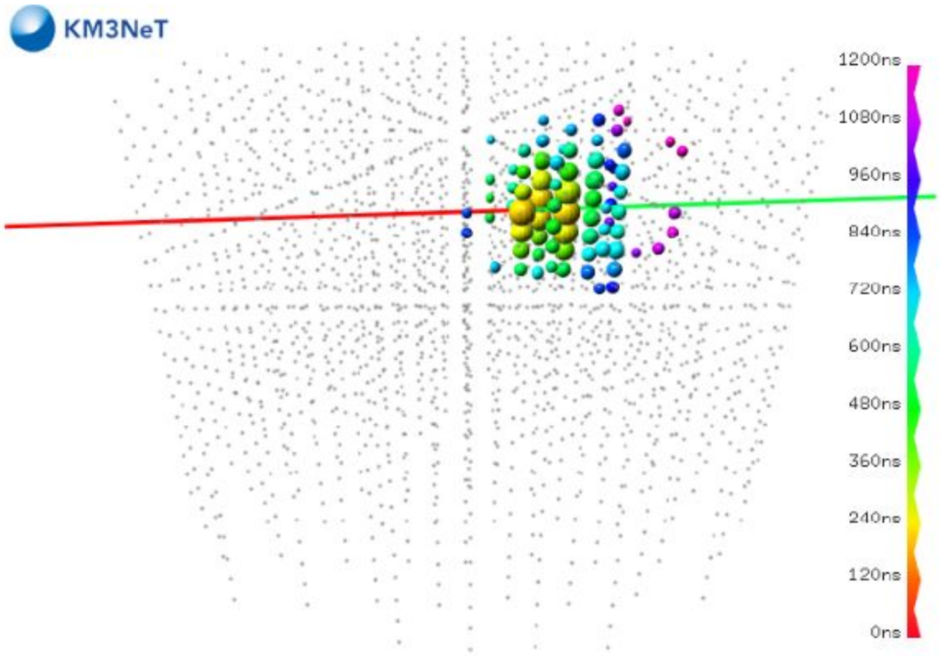
Bonus slides

NuFit 5.0

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
	$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
	$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

Events topology





Events distribution