KM3NeT/ORCA calibration procedures and capabilities

Antonio De Benedittis - on behalf of KM3NeT Collaboration

NuFact: July 31st - Aug. 6th, 2022

INFN NAPOLI
Istituto Nazionale di Fisica Nucleare
Sezione di Napoli

KM3NeT

Outline

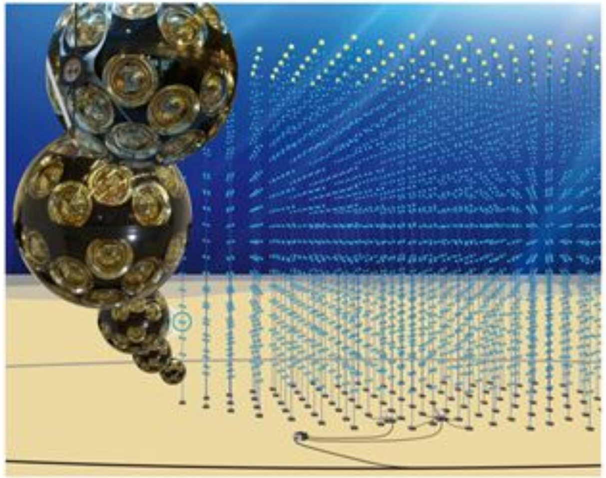
- **KM3NeT experiment**
- **ORCA Detector**
- **Calibration**:
  - Time calibration
  - PMTs efficiency/gain evaluation
  - Positioning
  - Dynamic calibration
  - Sun/Moon shadow
- **Summary**

KM3NeT Experiment

- 2 neutrino telescopes: **ARCA** and **ORCA**
- Same technology: based on the *Digital Optical Module* (**DOM**), hosting 31 PMTs. Arranged in 3D array
- Different location:
  - **ARCA:** Off the coast of Sicily (Capo Passero) – *~3.5 km of depth*
  - **ORCA:** Off the coast of France (Toulon) – *~2.5 km of depth*
- Different aims:
  - **ARCA:** studies on astrophysical neutrino sources
  - **ORCA:** studies on neutrino oscillations and mass ordering

Principle

Instrumenting a large volume of water to exploit the production of Cherenkov light induced by charged particles produced by the interaction of neutrinos

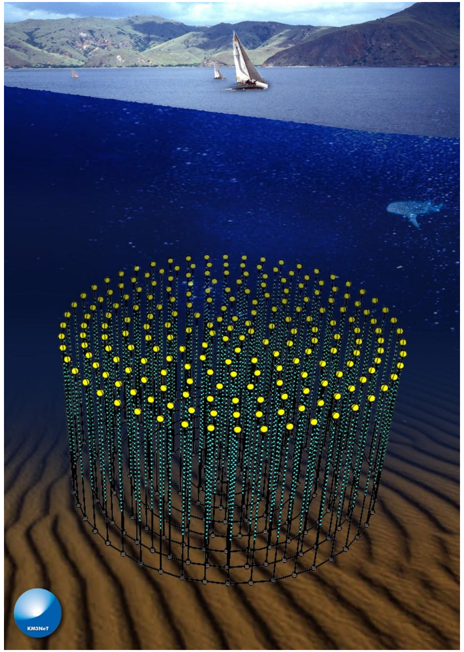


ORCA Detector

ORCA consists of a *Building Block* (BB) of 115 *Detection Units* (DU) with 18 DOMs

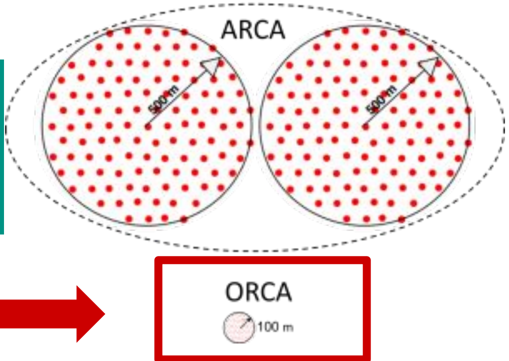
Dense configuration compared to ARCA for low energy reach (GeV), ideal for studying atmospheric neutrino oscillations

Distance of strings = 20m (90m) ORCA (ARCA)
Distance of DOMs = 9m (35m) ORCA (ARCA)



- Stable data taking from mid-2019, starting with 4 lines
- In june lines grew by up to 11

1xBB ->64170 PMTs



Technology

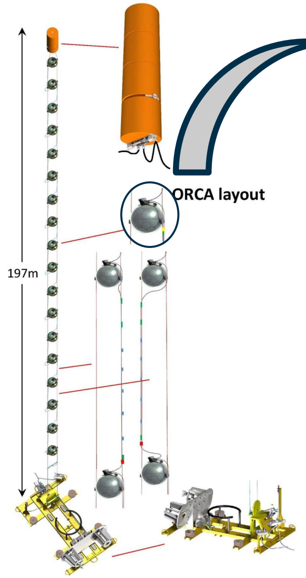
Detection of Cherenkov radiation⇒**neutrino interaction**

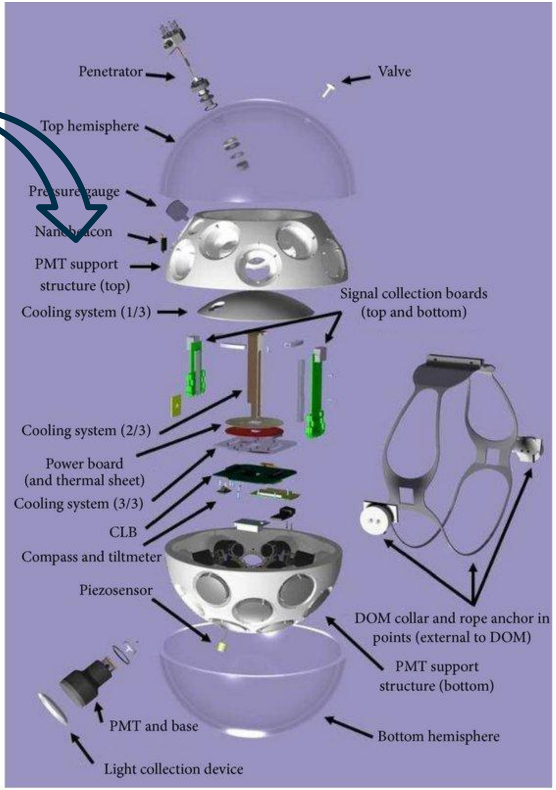
Reconstruction of:
- **Energy**
- **Direction**

Of the incoming particle

Calibration in position:
- Accuracy level ~ **10 cm**

Calibration in **time:**
- Accuracy level ~**ns**





N.B. Timestamping on the **Central Logic Board (CLB)** *inside the DOM*
N.B. Clock distribution based on a fiber-optic broadcast by implementation of the **White Rabbit (WR)** *technology for distribution of absolute time from GPS on shore to the nodes*

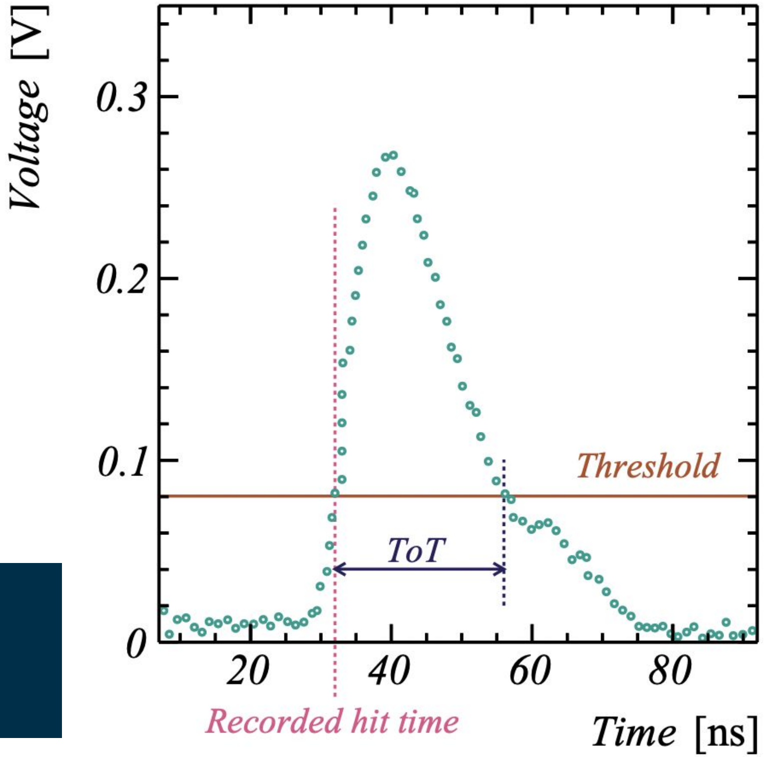
Time over Threshold

Recorded signals are characterised by two quantities:

- the time at which the PMT waveform passes the *threshold* (the hit time)
- the period it stays above the threshold, called the **time over threshold** (**ToT**)

ToT -> **0.3 photo-electron equivalent**

ToT gives a measurement of the amplitude of the signal and it is related to the PMTs gain and relative efficiency



Time Calibration

The hit time distributions need to be calibrated (***PMT time offset***):

- relative time delay between PMTs of the same DOM (PMT transit time and propagation delays)
- absolute calibration of the DOM's CLB (the CLB clocks are syntonized, but not necessarily synchronised)

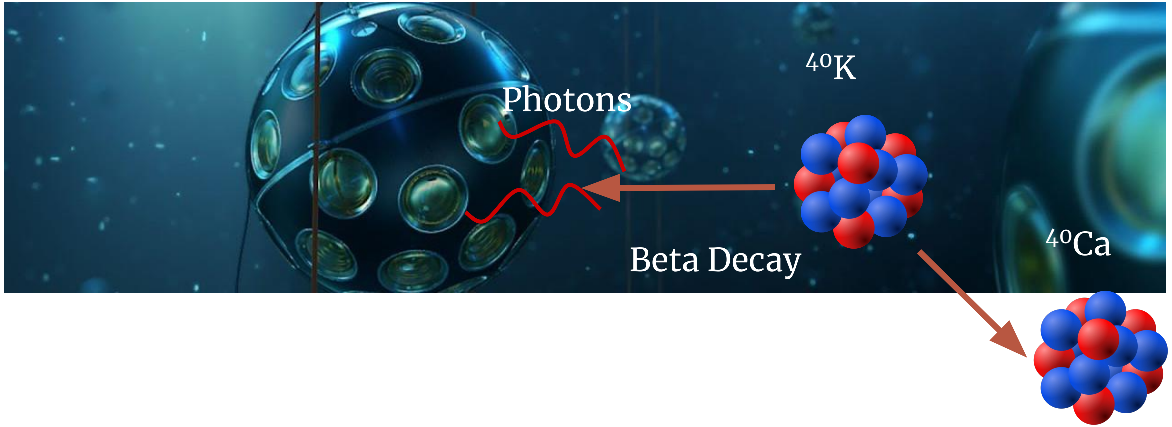
Time Calibration

The hit time distributions need to be calibrated (***PMT time offset***):

- relative time delay between PMTs of the same DOM (PMT transit time and propagation delays)
- absolute calibration of the DOM's CLB (the CLB clocks are syntonized, but not necessarily synchronised)

Synchronisation of PMTs in the same DOM (intra-DOM)

Cherenkov radiation coming from electrons produced by the decay of **^{40}K (constant rate)** in the sea water is measured on PMTs. Time delays between pairs of PMTs are computed



Time Calibration

The hit time distributions need to be calibrated (***PMT time offset***):

- relative time delay between PMTs of the same DOM (PMT transit time and propagation delays)
- absolute calibration of the DOM's CLB (the CLB clocks are syntonized, but not necessarily synchronised)

Synchronisation of PMTs in the same DOM (intra-DOM)

Cherenkov radiation coming from electrons produced by the decay of ^{40}**K (constant rate)** in the sea water is measured on PMTs. Time delays between pairs of PMTs are computed

Synchronisation of DOMs in the same DU (inter-DOM)

A LED on the top of the DOM, illuminate DOMs above. Knowing the distances between the DOMs, computation of time delays between DOMs of the same DU can be computed

Time Calibration

The hit time distributions need to be calibrated (***PMT time offset***):

- relative time delay between PMTs of the same DOM (PMT transit time and propagation delays)
- absolute calibration of the DOM's CLB (the CLB clocks are syntonized, but not necessarily synchronised)

Synchronisation of PMTs in the same DOM (intra-DOM)

Cherenkov radiation coming from electrons produced by the decay of ^{40}**K (constant rate)** in the sea water is measured on PMTs. Time delays between pairs of PMTs are computed

Synchronisation of DOMs in the same DU (inter-DOM)

A LED on the top of the DOM, illuminate DOMs above. Knowing the distances between the DOMs, computation of time delays between DOMs of the same DU can be computed

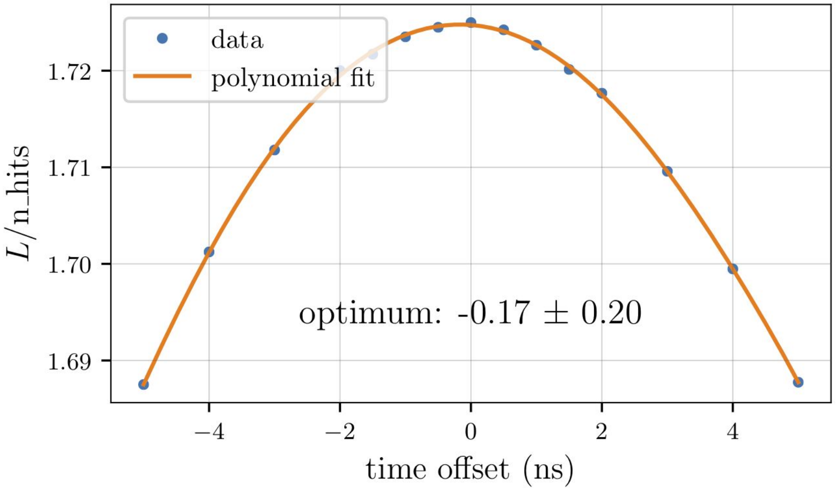
Synchronisation of DUs between them (inter-DU)

Reconstruction of down-going atmospheric muons with different detector geometries and time offsets: allowing the evaluation of average quality of the fit, L and the determination of a optimal value

Time Calibration

The hit time distributions need to be calibrated (***PMT time offset***):

- relative time delay between PMTs of the same DOM (PMT transit time and propagation delays)
- absolute calibration of the DOM's CLB (the CLB clocks are syntonized, but not necessarily synchronised)



Synchronisation of DUs between them (inter-DU)

Reconstruction of down-going atmospheric muons with different detector geometries and time offsets: allowing the evaluation of average quality of the fit, L and the determination of a optimal value

Time Calibration

DOM is correctly calibrated

↓

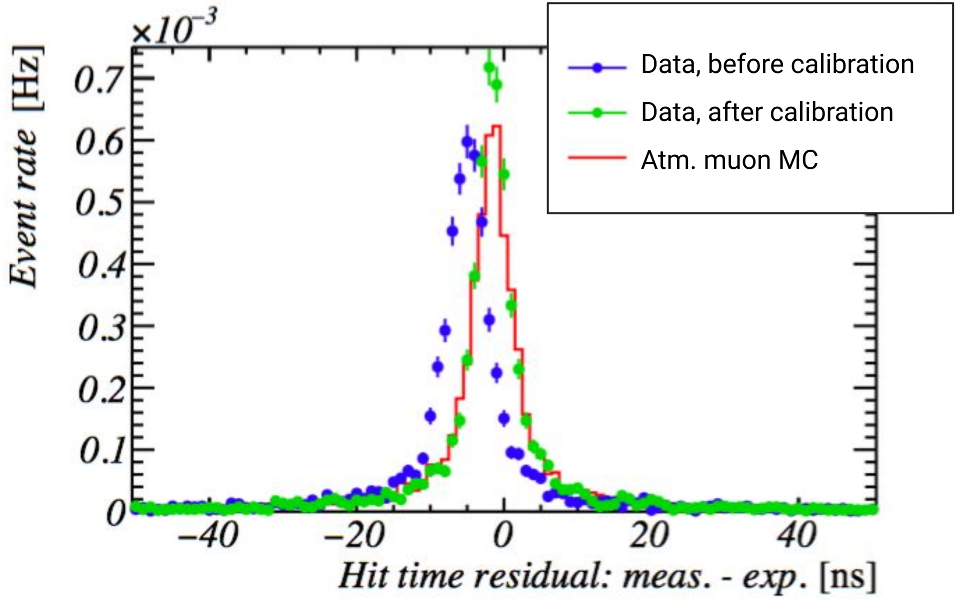
distribution of the hit time residuals of a given PMT pair peaks at zero

If not

↓

Fit on time offsets of all PMT pairs in each DOM

Determination of individual time offsets for each PMT



Hit time residuals distribution of a given PMT pair

^{40}K – Gain and Efficiency

The intra-DOM calibration exploits the ToT distribution of single photo-electron hits from Cherenkov photons originating from the ^{40}K decay to evaluate efficiency and gain of PMTs

The PMT **gain** calibration exploits the ToT distribution of single photoelectron hits

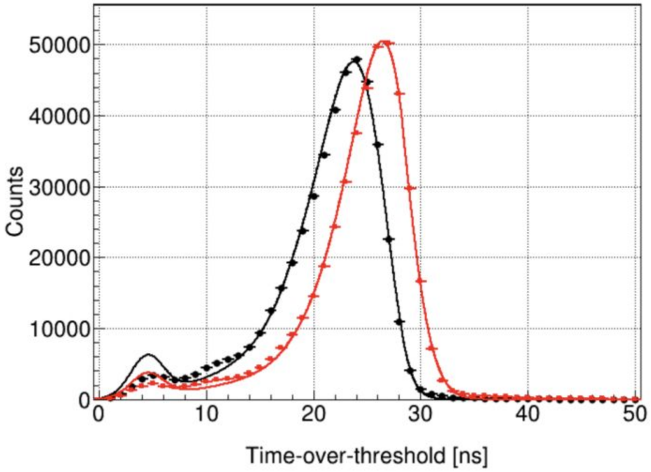
Inference from the statistical behaviour of the ToT

Model based on conversion of the measured ToT values in charge

A regular tuning of the high voltage (HV) supplied to the PMTs is needed to equalize the gains of the PMTs

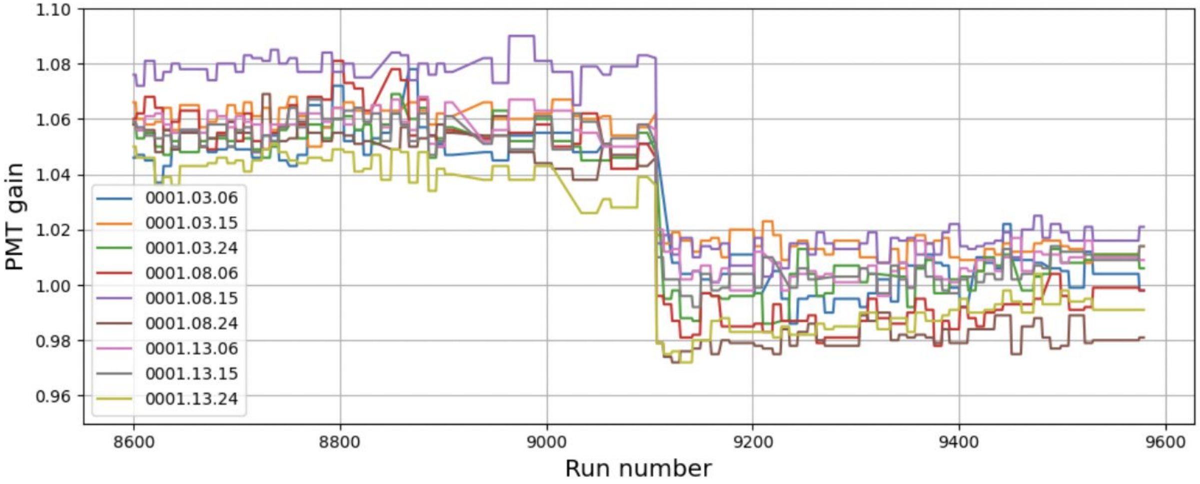
$$G = A \times HV^{kN}$$

A, k, N constants related to the dynode system of PMTs



ORCA PMTs
HV = −1130 V
HV = −1180 V

^{40}K – Efficiency and Gain



*The stability over time of the fitted PMT **gains** of 9 PMTs selected in the period between* **September 2020** *and* **March 2021.** A discontinuous jump around run 9100 shows the effect of a gain-calibration campaign

^{40}K – Gain and Efficiency

The intra-DOM calibration exploits coincident hits in multiple PMTs of the same DOM from Cherenkov photons originating from the ^{40}K decay to evaluate efficiency and gain of PMTs

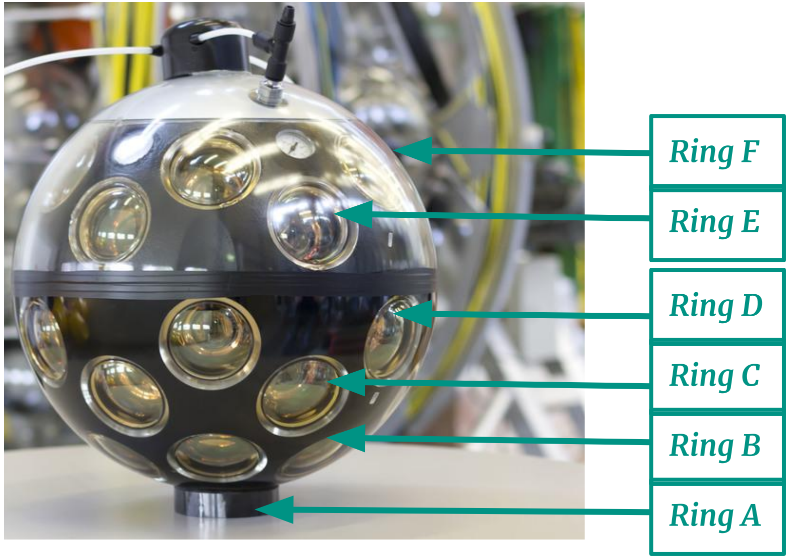
The probability to detect a single photon is referred as the **collective efficiency** of the PMT

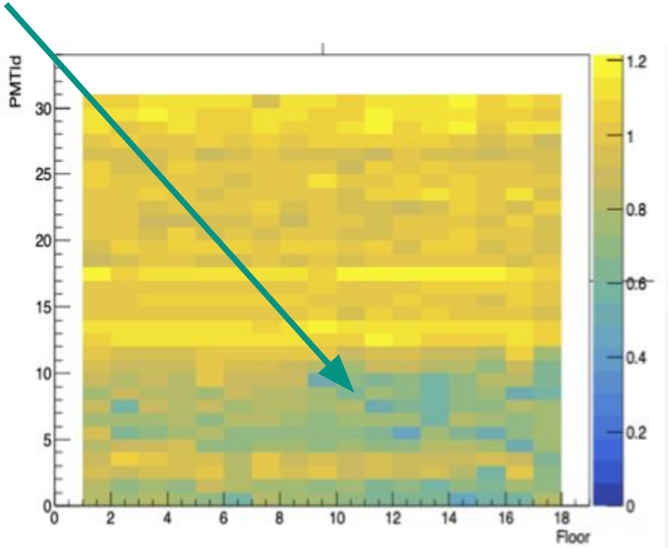
The probability that the analogue pulse from the PMT passes the threshold depends on the gain and the gain spread of the PMT.

The determined PMT efficiencies are accurate enough to monitor the effects of sedimentation on the top of each DOMs

^{40}K – Efficiency and Gain

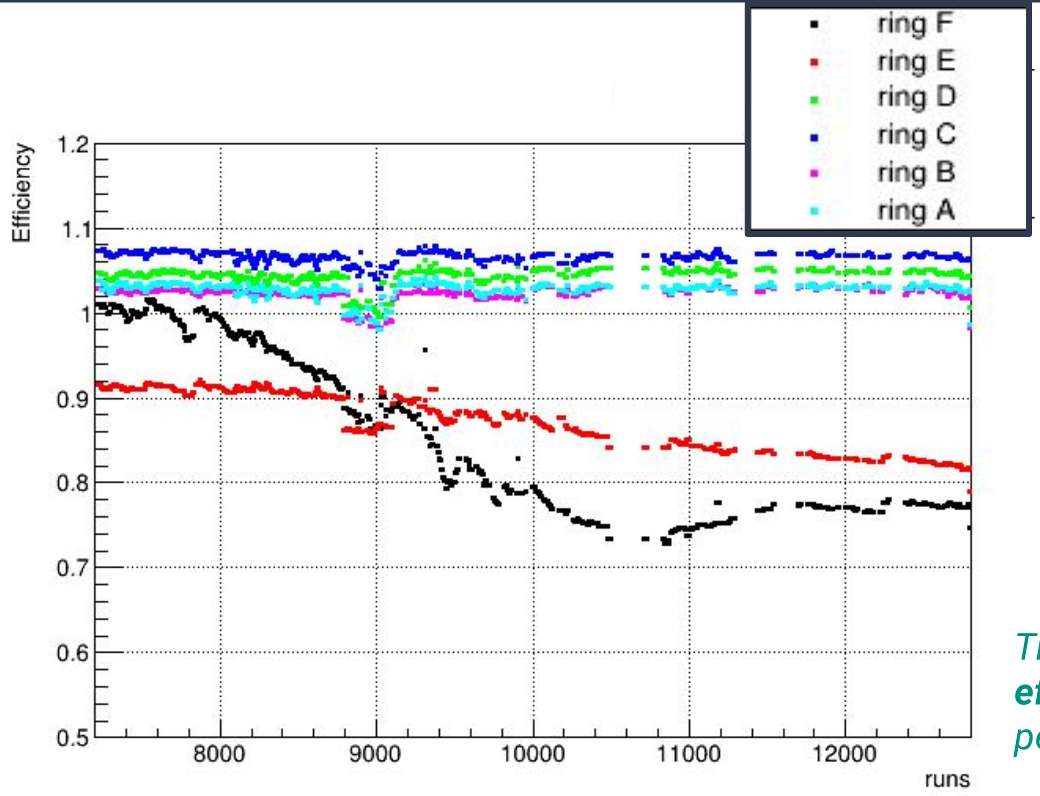
Effects of the sedimentation on upper hemisphere PMTs

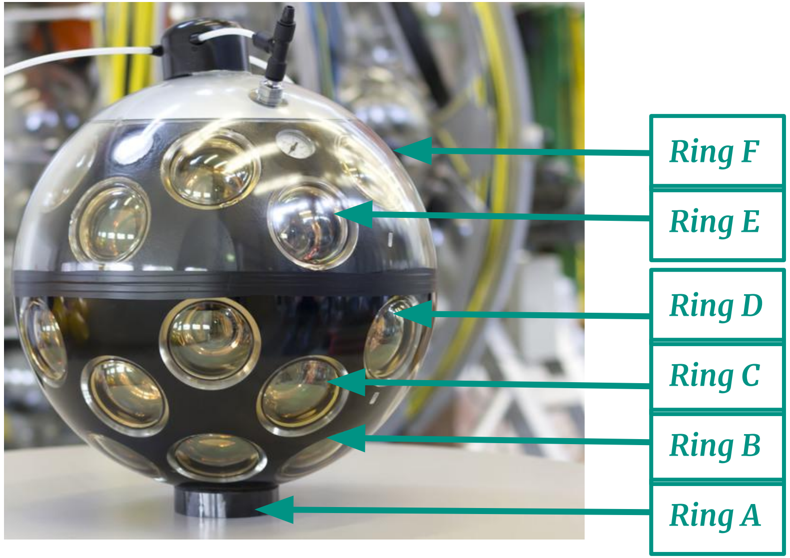




PMT efficiencies of the DOMs belonging to a ORCA DU deployed in September 2017

^{40}K – Efficiency and Gain

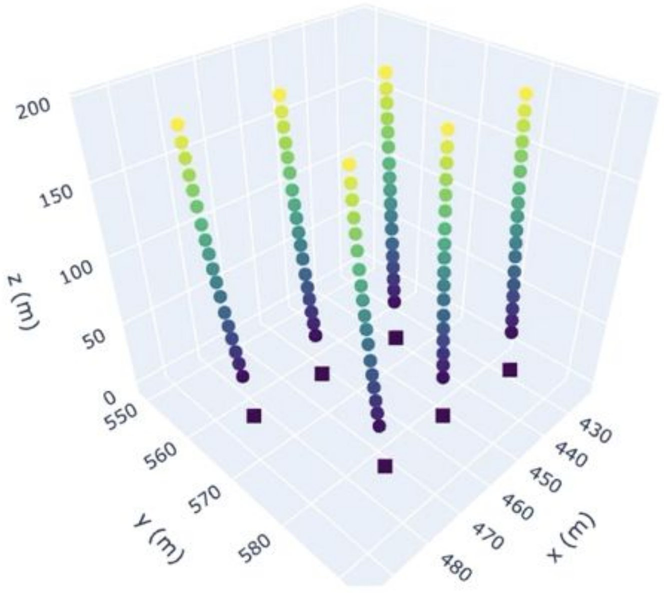




The stability over time of the fitted PMT ***efficiencies*** *of an arbitrarily chosen DU in the period between* **January 2020** *and* **March 2022**

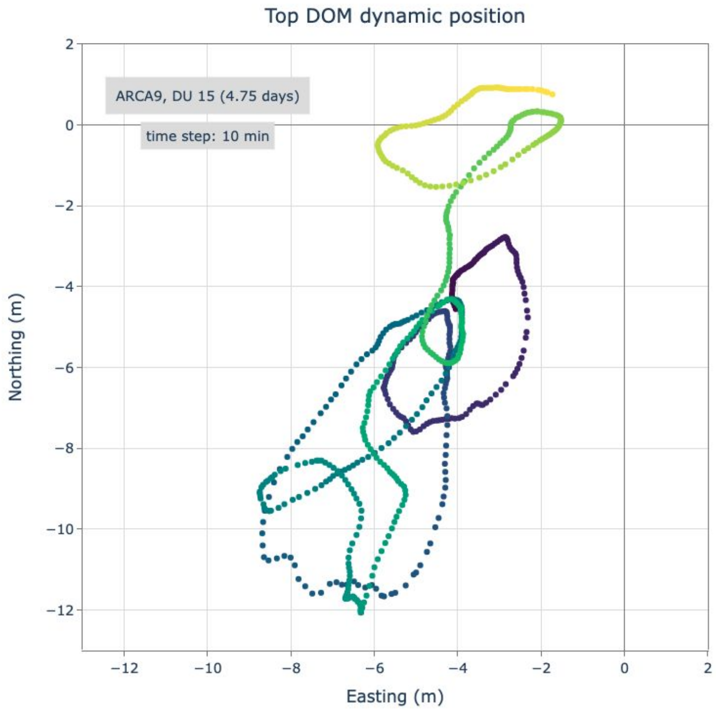
Positioning and dynamic calibration

Sea currents move DUs
A setup is needed to take into account the dynamic positions of strings



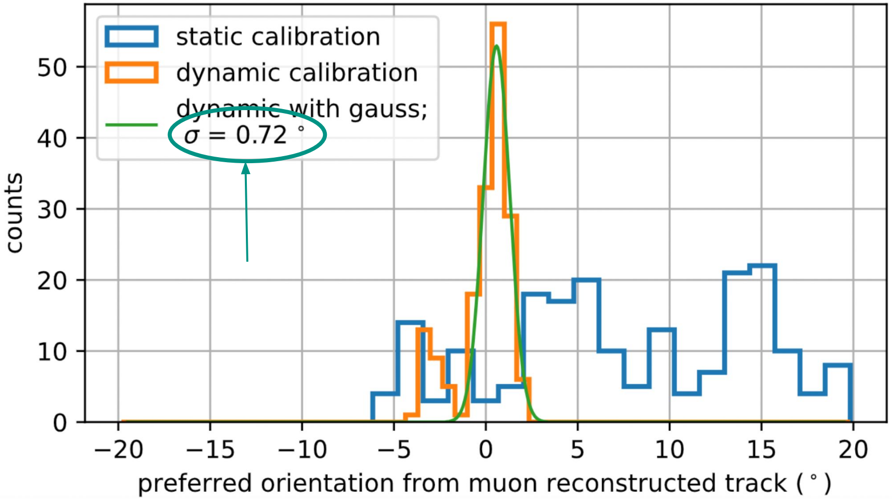
Positioning and dynamic calibration

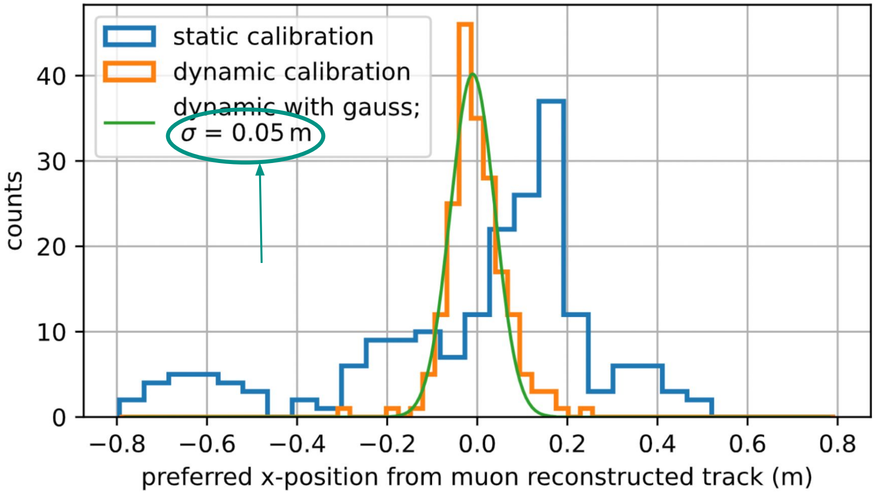
- System of **acoustic emitters** (located in some of DU bases) and **receivers** (located in each DOM and base)
- Acoustic beacons emit a set of pings identified based on their own waveform
- Every 10 minutes a measurement of the arrival time of the acoustic signal is used to determine the position of the detector
- Moreover, each DOM is equipped with a compass and tiltmeter to take into account rotations and tilt



Positioning and dynamic calibration

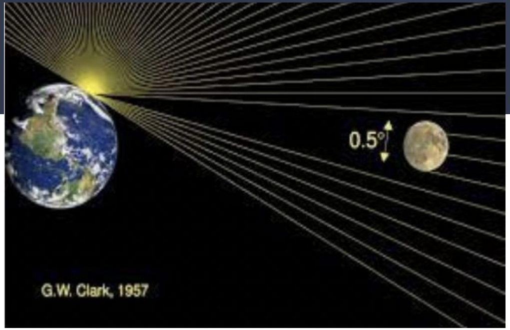
Muon reconstructed track with and without dynamic calibration
In the dynamic case, the position and rotation information is adjusted continuously





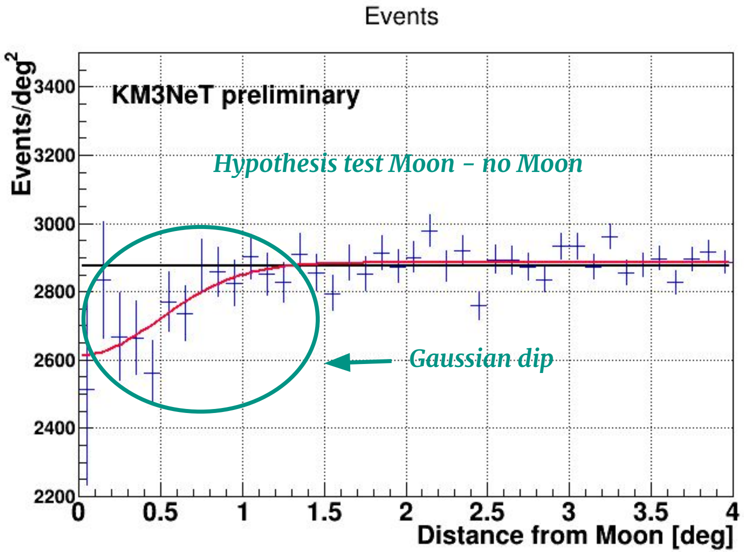
Peak ~0: Excellent agreement between muon calibration and acoustic/orientation calibration

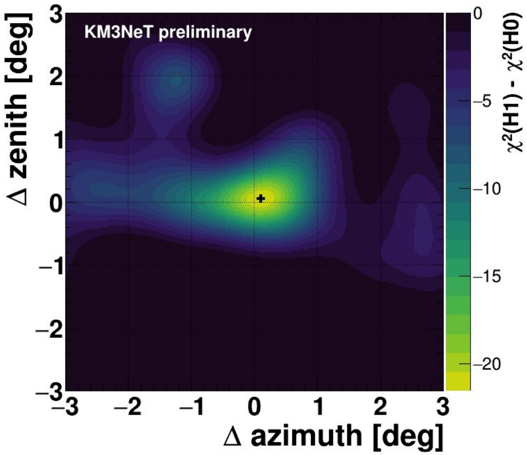
Shadow of Moon/Sun

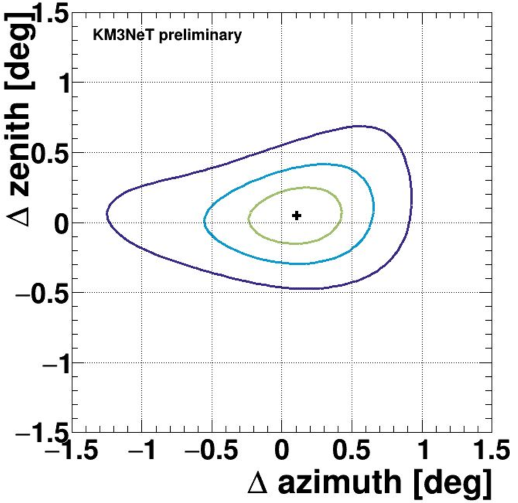


Down-going atmospheric muons direction measurements
Map around nominal moon/sun position

Moon Shadow





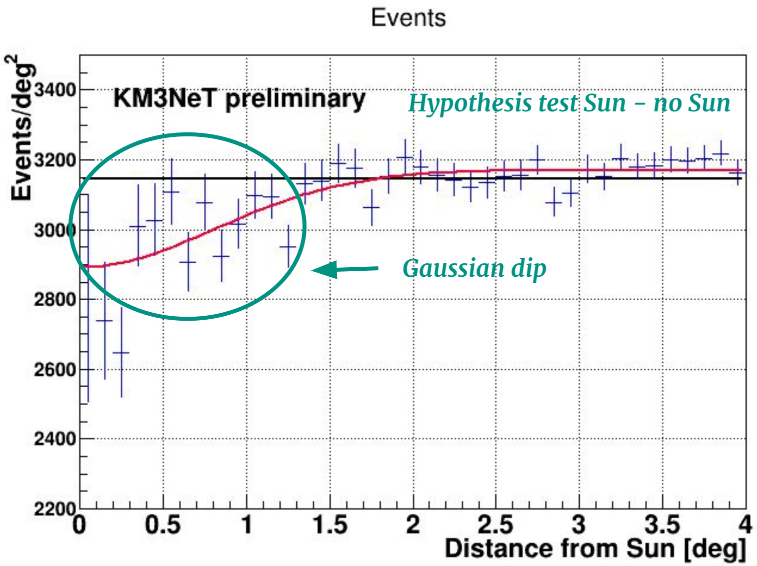


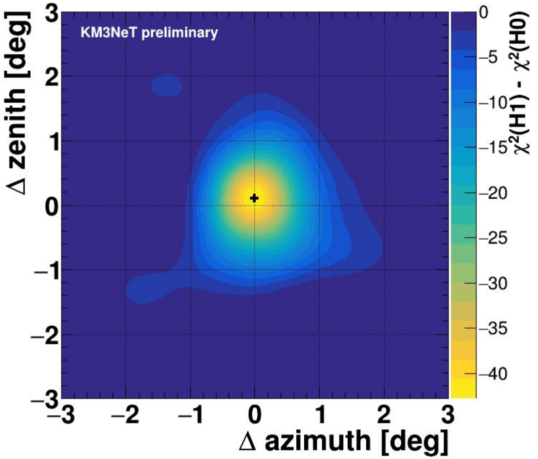
Significance: 4.22 σ *The true position of the Moon is contained within the 68% contour*

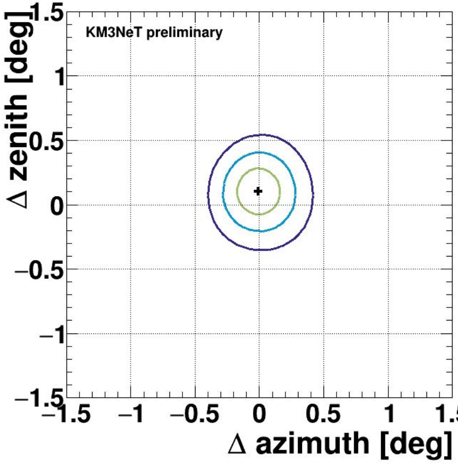
Shadow of Moon/Sun

Down-going atmospheric muons direction measurements
Map around nominal moon/sun position

Sun Shadow







Significance: 6.23 σ   *The true position of the Sun is contained within the 85% contour*

Summary

KM3NeT/ORCA is a detector under construction off the France coast.
Main goal: detection of low-energy atmospheric neutrinos in order to study **oscillations** and **mass hierarchy**.

Accurate calibration procedures have been implemented:

- Time calibration procedures - synchronization of all detector lines and their DOMs: **timing accuracy ~ns**

- Calibration inter-PMTs by exploiting the constant rate of ^{40}K decay to:
  - estimate gain and efficiency
  - verify temporal stability
  - evaluate effects due to sedimentation

- Dynamic calibration using a setup of acoustic emitters and receivers: **positioning accuracy ~ 10 cm**
  - Reconstruction of atmospheric muon tracks shows a spread in position of the order of cm
  - Estimation of the **Moon/Sun shadow** with high statistical significance (**4.2 σ and 6.2 σ**), with a measurement of maximums less than **0.1°** away from the true nominal position

- *Friday, 11.15: "Neutrino oscillation measurement with KM3NeT/ORCA" - J. Schumann (WG1)*