Carla Distefano

for the NEMO Collaboration

Measurement of the atmospheric muon flux at 3500 m depth with the NEMO Phase-2 detector

- The NEMO collaboration conducted an R&D activity for more 10 years towards the construction of a Mediterranean km3 neutrino telescope.

- Activity ended with the construction of the NEMO Phase-2 tower: the second prototype of the detection unit proposed for the km3 project.

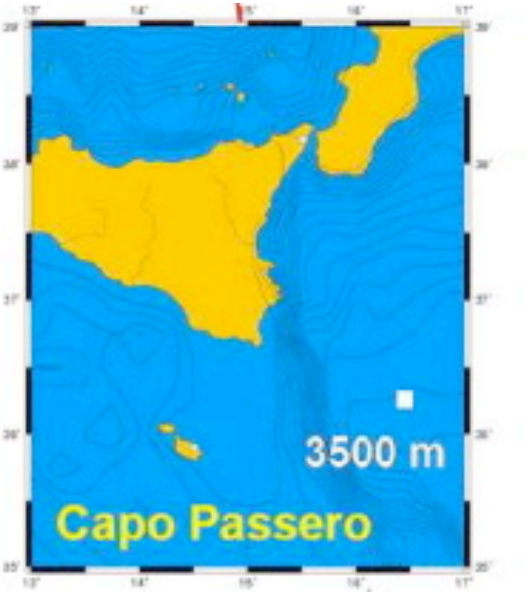
- The tower was deployed in the Capo Passero site;

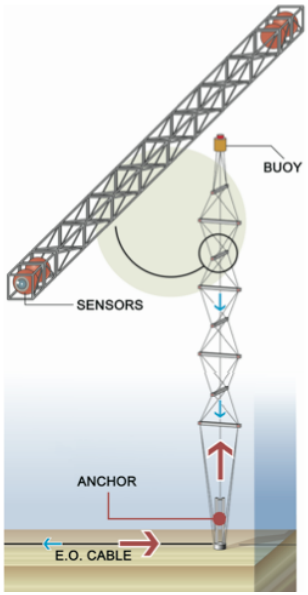
- NEMO is now part of the KM3NeT Collaboration (see G. Riccobene's talk).

In this talk:

- The NEMO Phase-2 tower: lay-out and operation;
- Muon data-taking and analysis;
- Atmopsheric muon flux measurement.

The Capo Passero Site infrastructure





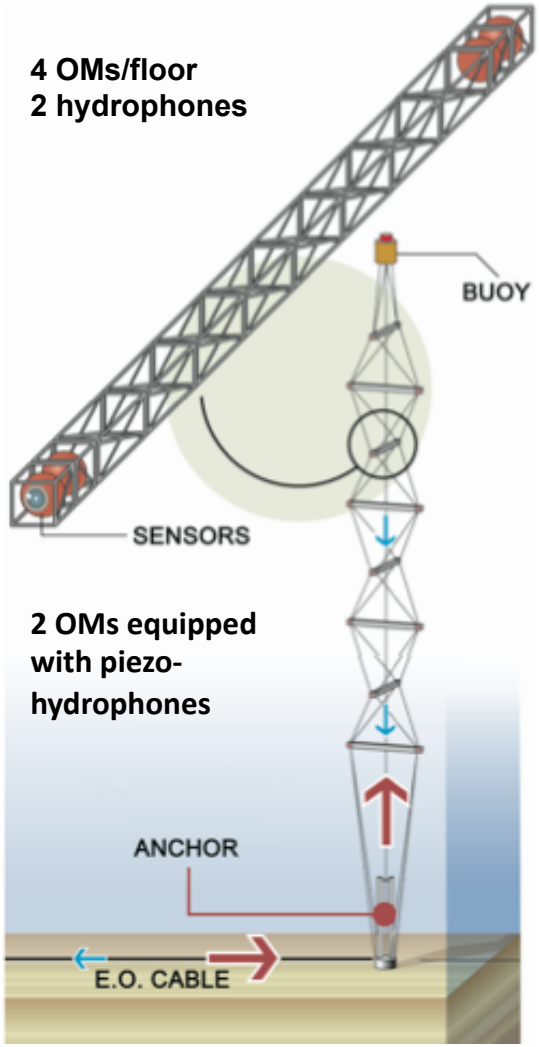
Shore Laboratory:
Electronics Labs
Data Acquisition Room
Control Room
Guest House 4 rooms
Power Feeding Equipment (UPS protected)
1Gb/s (upto 10) Optical-fibre link GARR-X

Submarine cable and infrastructure:
96 km
20 fibres ITU655-NZDSF
Single conductor with DC-sea return
Cable Termination Frame:
Medium Voltage Converter: 10kV to 375V
3 ROV-mate e.o. output connectors

Off-shore Laboratory (Depth=3458 m):
NEMO Phase-2 tower 23 March 2013 – 4 August 2014
PPMDU May 2014 (S. Biagi's talk)

The site will host KM3NeT Phase-1 (G. Riccobene's talk)

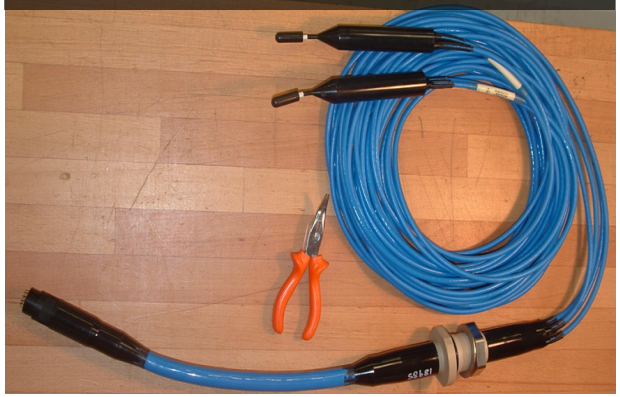
The NEMO Phase-2 tower: main components



- 8 floors
- 8 m bars, vertical dist. = 40 m, H_{tot} = 450 m
- 32 OM, 14 acoustic receivers
- oceanographic instrumentation

The OM: 10" Hamamatsu R7081, Front End Module, Time Calibration, LED beacons

Hydrophones: acoustic positioning and bioacustics



Instrumentation on board the tower

Floor	Acoustics	Calibration and environmental instrumentation
8	OAM *(ECAP, Erlangen)* [on OM 2 and 3 (downlooking)] OK	Porfido [on OM 1 and 4 (horizontal)]
7	FFR *(UPV, Valencia)* OK	Porfido [on OM 1 and 4 (horizontal)] Conductivity – Temperature – Depth (CTD) probe
6	OK	
5	Not integrated	Doppler Current Sensor (DCS)
4	OK	Cstar Nano-B 400 nm [on OM 2 and 3 (downlooking)]
3	OK	Nano-B 440 nm [on OM 2 and 3 (downlooking)]
2	OK	Nano-B 470 nm [on OM 2 and 3 (downlooking)]
1	OK	Conductivity – Temperature – Depth (CTD) probe Nano-B 470 nm [on OM 2 and 3 (downlooking)]
0	Monitoring station Not integrated	ACSA beacon Laser Beacon *(IFIC, Valencia)* Acoustic Beacon *(UPV, Valencia)*

The tower deployment

The tower on the “Nautical Tide”

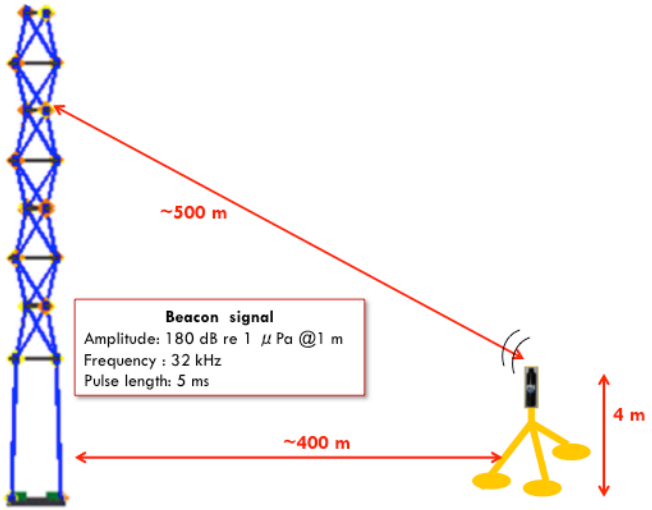
Deployment from the “Nautical Tide”

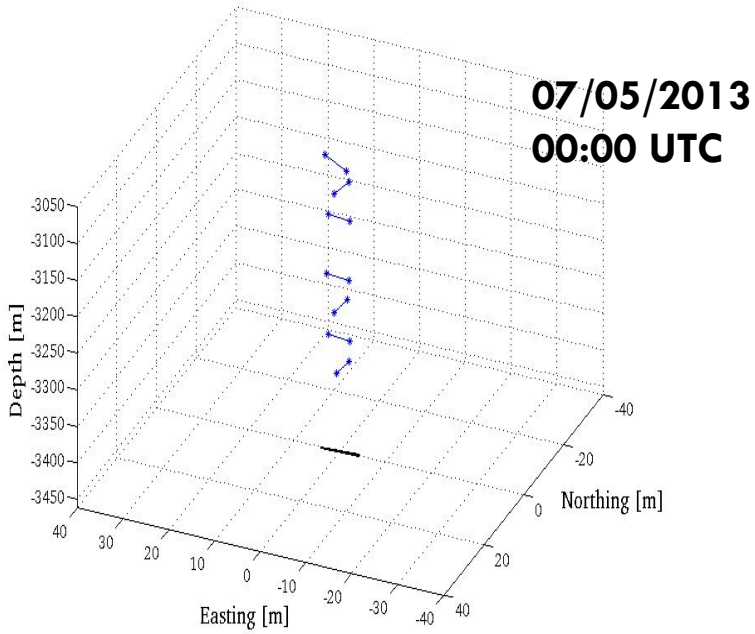
The tower touches the sea-bottom at 3500m depths

Tower inspection after the unfurling

Acoustic positioning

- Distance derived from TOA differences using sound velocity measured by CTDs.
- Distances between hydrophones on the same floor are known.
- Monitoring station not integrated: not-stardard position reconstruction



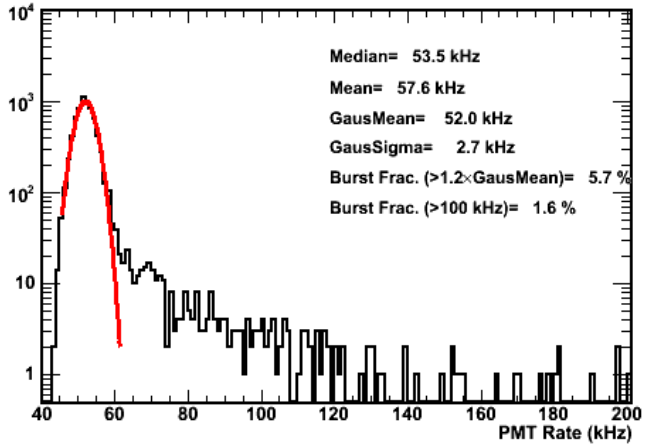


But from acoustic system and floors 1 and 7 depth info from CTDs:

- Geometry reconstruction possible with accuracy O(1m).
- Max tower inclination: a few degrees (negligible with respect intrinsic angular resolution).
- During the muon reconstruction procedure, the nominal tower geometry is assumed.

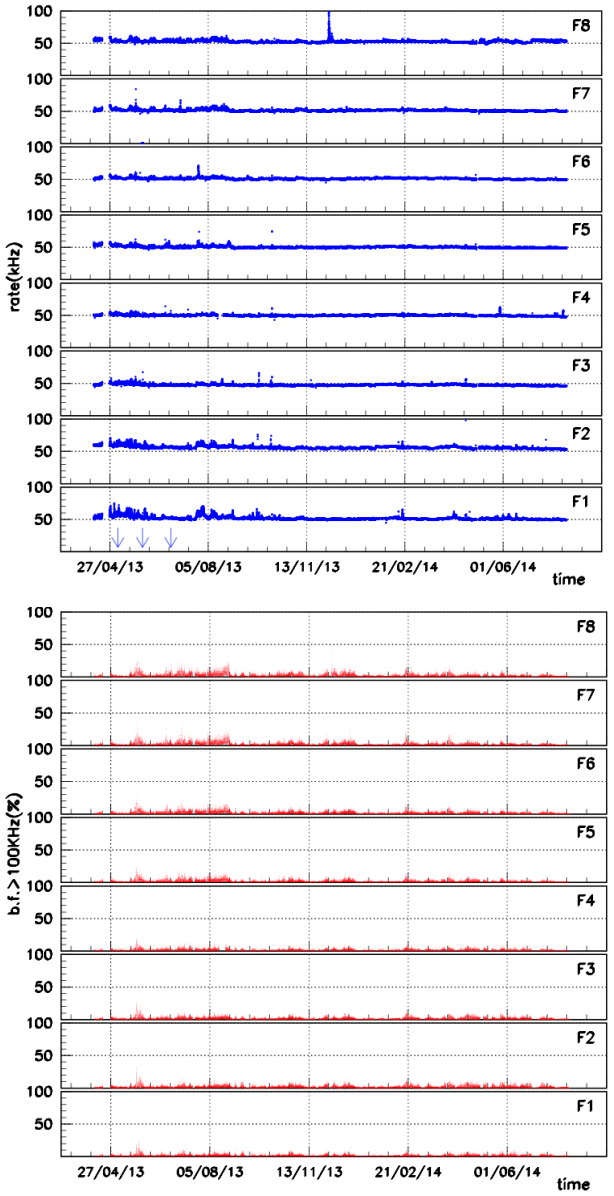
PMT Rate Monitoring

- The rate is sampled once per second by the PMT Front-End electronics;
- Rate is measured in a time window Δt=10 ms;



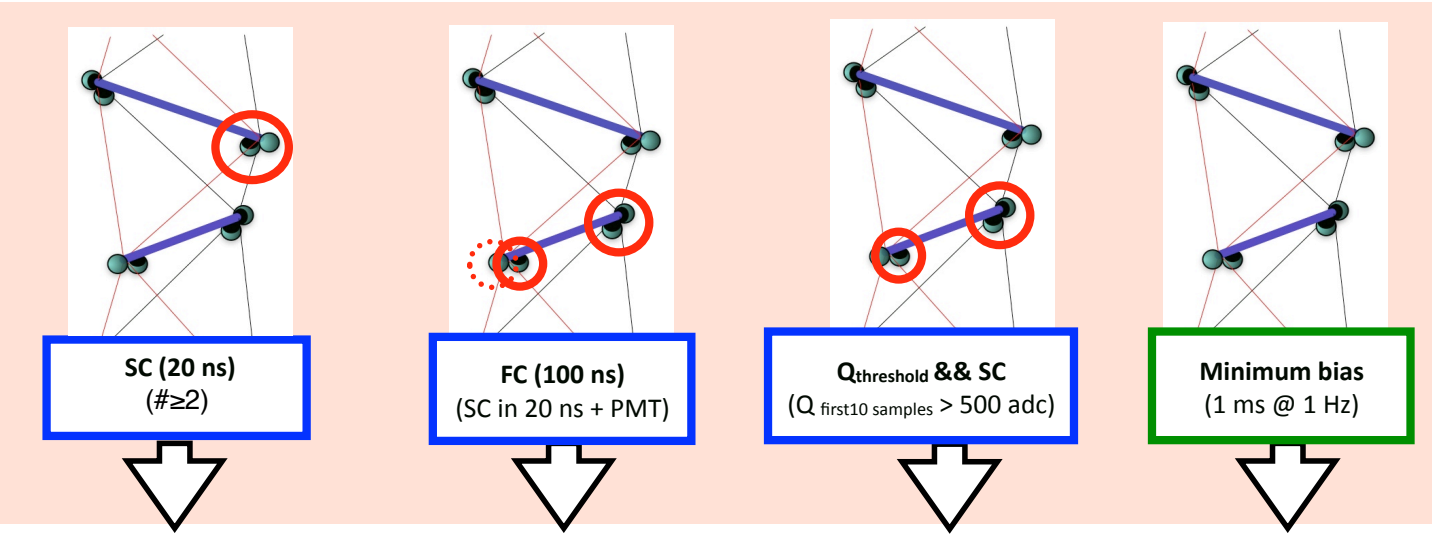
- The rate was stable over more than 1 year at 50-55 kHz on all PMTs;
- Measured rates are consistent with expected background from 40K decay with a low contribution of burst activity (a few percent);
- Simulation input in this analysis (noise generation).

Down-looking PMTs

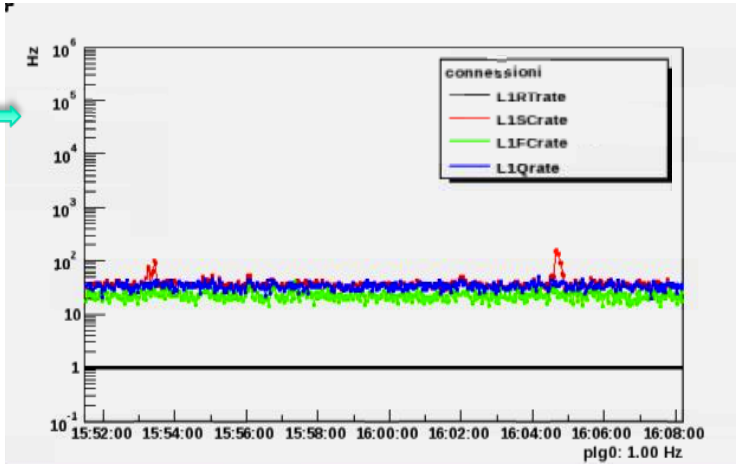


See M.G. Pellegriti's poster.

L1 triggers



Trigger rates



Event trigger rate: ~100 Hz

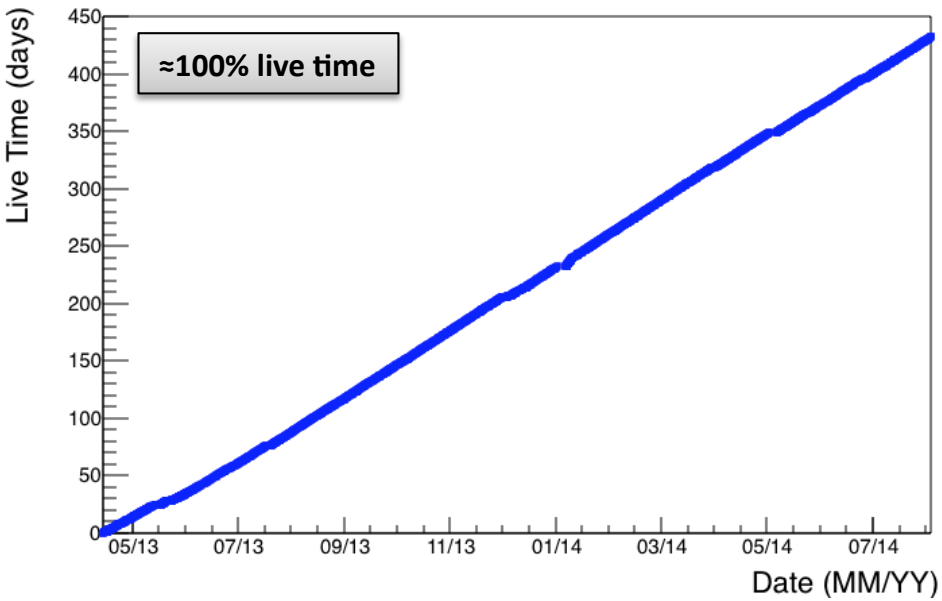
Expected (simulation): ~0.1 Hz

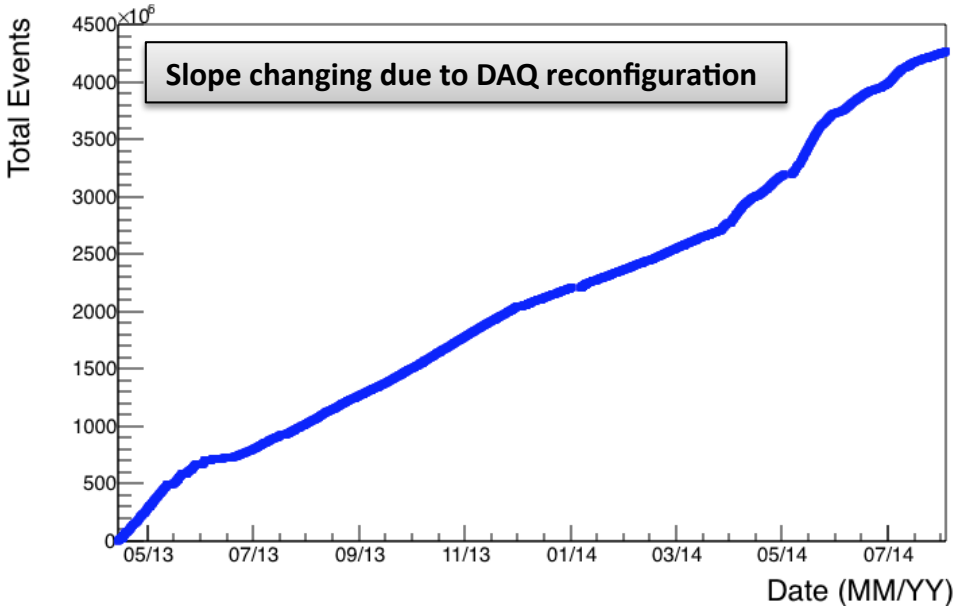
Signal dominated by noise, rejected during the off-line analysis.

Live time and accumulated events

Deployment:	**23 March 2013**
Detector turning off:	**4 August 2014**
Detector operation time:	**500 days**
Total live time:	**432.3 days**
Total accumulated events:	**4.3E9**

(since 16 April 2013, commissioning phase ending)





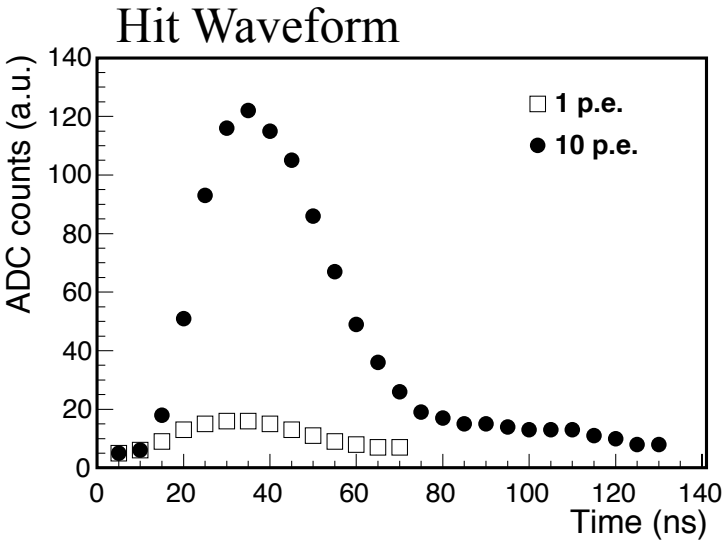
PMT DATA Features:

Signal Digitization Sampling ~ 200 MHz

Time resolution ~ 5 ns

Charge Threshold ~ 0.3 s.p.e.

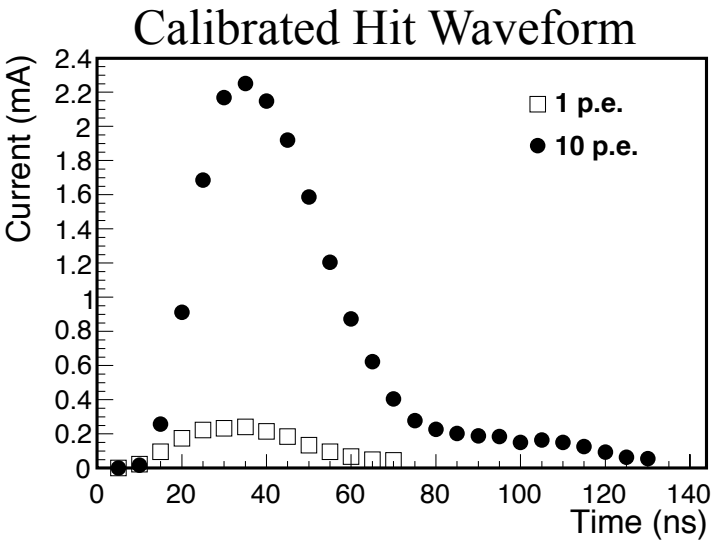
Trigger Window 6 μs



After Hit Calibration:

- **Time resolution ~1 ns**
- **Total Charge determination with σ~0.3 pC**
- **Hit charge converted in p.e.**

  (1 p.e. ~ 8 pC, from fit of s.p.e. charge spectra)



Off-Line Muon Filter and Reconstruction

After hit calibration, we re-checked the "trigger seeds":

1- Simple Coincidence (SC): Coincidence between 2 close hits in the same floor $\Delta T_{CS} \leq 20$ ns

2- Floor Coincidence (FC): Coincidence between 2 hits at the opposite ends of a same floor $\Delta T_{FC} \leq 100$ ns

3- Charge Shooting (CS): A hit exceeding a charge threshold of 2.5 p.e.

Off-Line Filter Condition:

- Ensemble of all hits participating to the Off-Line Trigger seeds
- For each hit, we calculate the number of the other hits in the ensemble causality correlated according to

$$|dt| < dr/v_{light} + 20 \text{ ns}$$

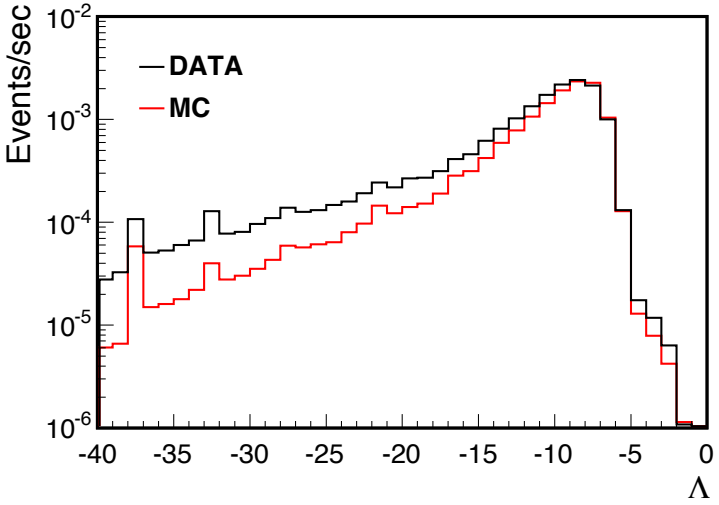
- We calculate the maximun number of causality relations N_{caus}
- We selects all the events having $N_{Caus} \geq 6$: optimized to have a muon purity ≈ 1 at the track reconstruction level (from simulations)

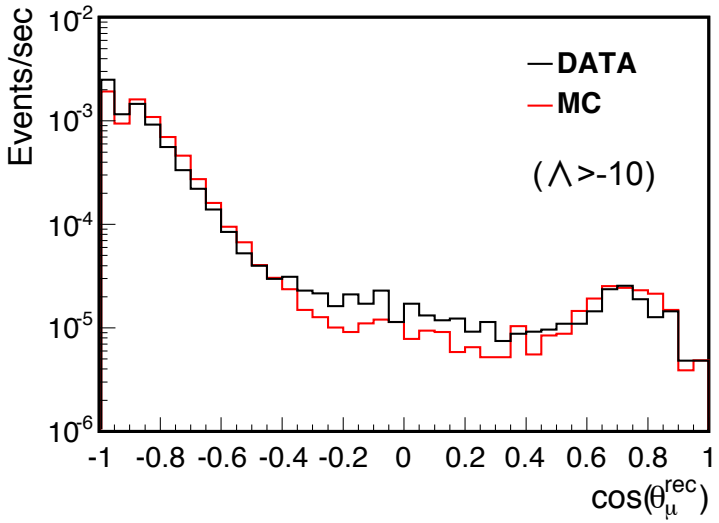
Track reconstruction:

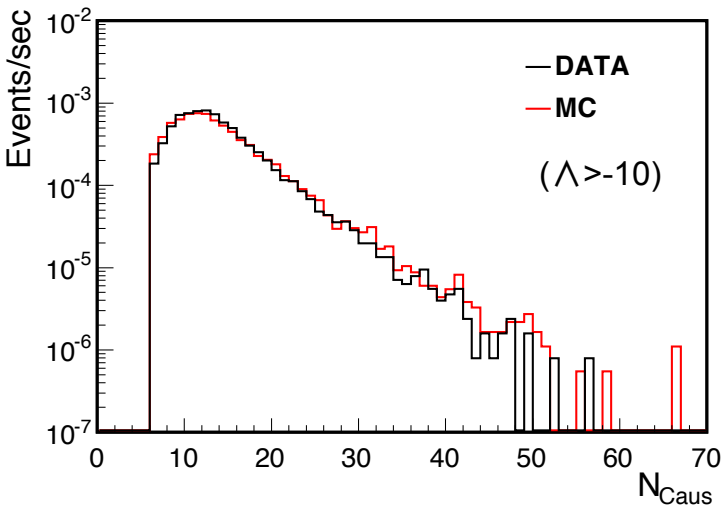
- A Causality Filter is applied to reject background hits in the muon events ($|dt| < dr/v_{light}$ +20 ns)
- Muon events are reconstructed with an algorithm based on the maximization likelihood method (taking into account the Cherenkov features and the possible presence of background hits).

Total live time= 411.1 days

Level	Events	(DATA/MC)
On-line Trigger	$4.0 \cdot 10^9$	$1.3 \cdot 10^4$
Off-line Muon Filter	$1.1 \cdot 10^7$	8.90
Reconstructed	**606546**	**1.23**
Selected (Λ>-10)	269787	1.01







- Monte Carlo simulations were used to evaluate the detector transfer function.
- The transfer function was then used to evaluate the muon flux angular dependence through a deconvolution procedure.
- Systematic uncertainties on environmental and detector parameters were included.

Flux Angular Dependence:

$I(\theta_\mu) = N_\mu(\theta_\mu)\, m(\theta_\mu) / T\, \Delta\Omega\, A^{eff}(\theta_\mu)$

$N_\mu(\theta_\mu)$: number of detected muons (deconvolution)

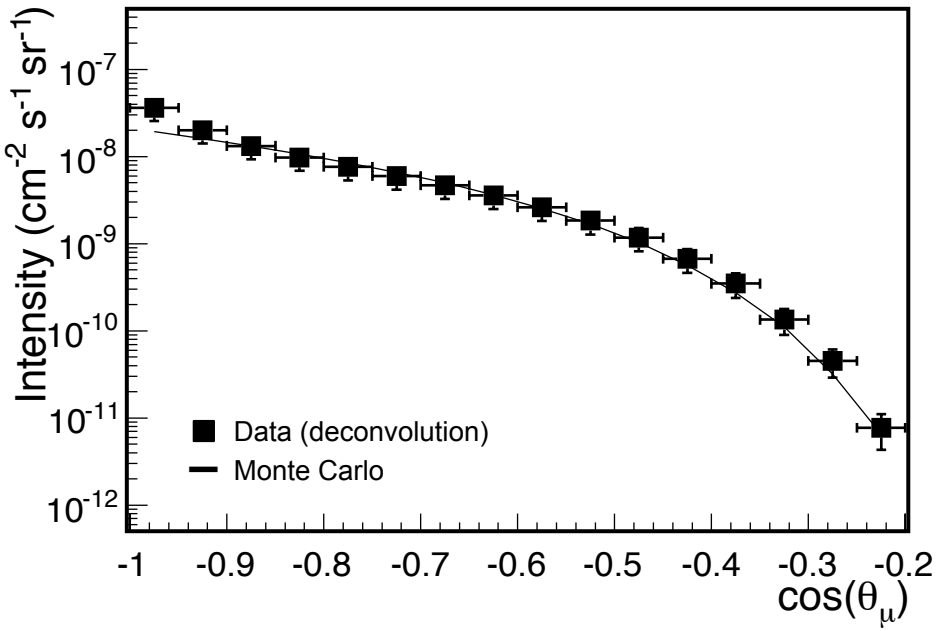
T: livetime

$\Delta\Omega$: solid angle

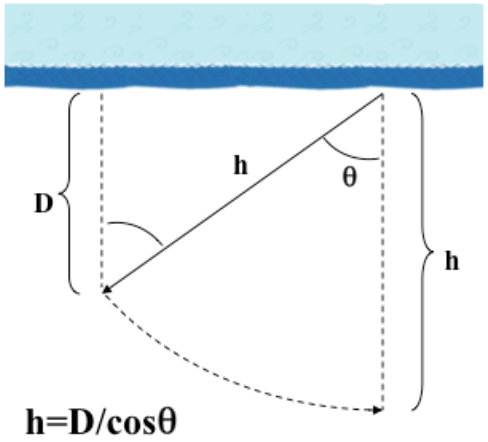
$A^{eff}(\theta_\mu)$: effective area*

$m(\theta_\mu)$: mean multiplicity*

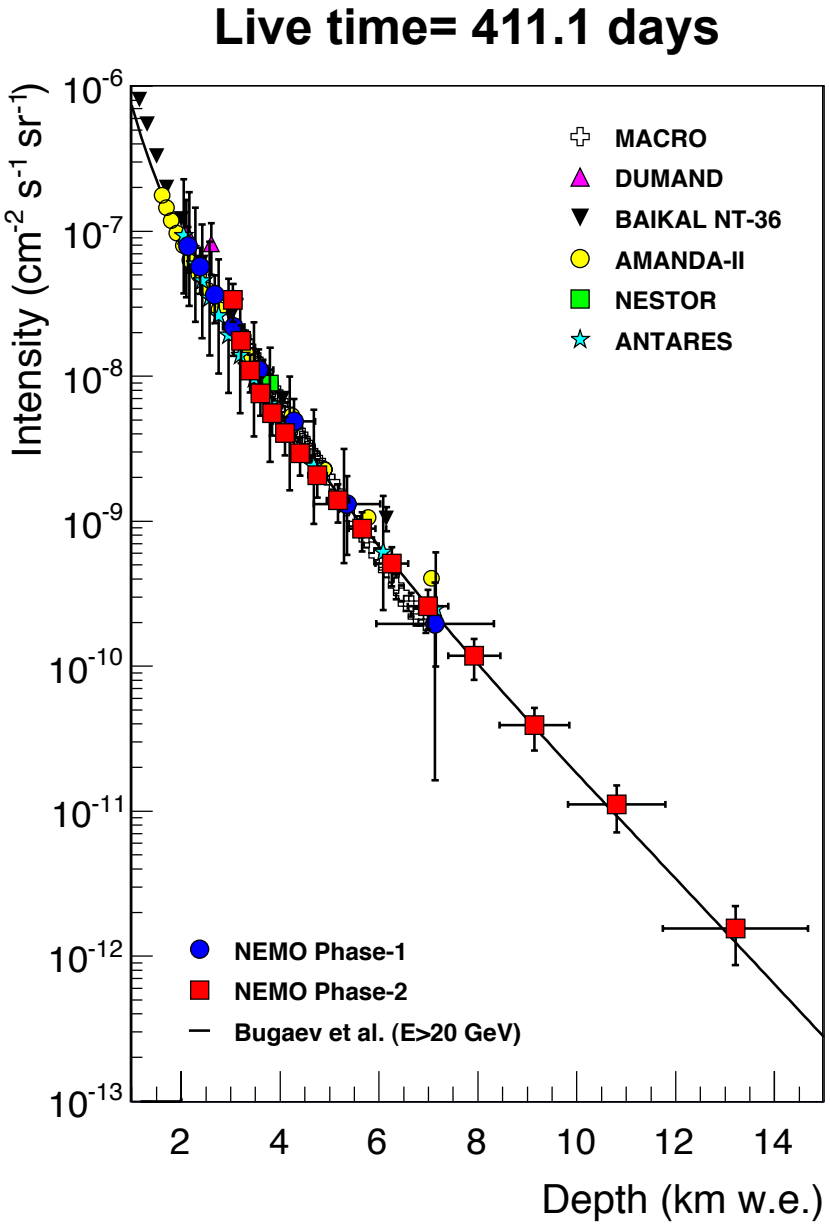
* From Monte Carlo simulations



Vertical Muon Intensity as a function of Depth



DIR extended up to 13 km



Summary

- 8 floor tower deployed on March 23, 2013 (the NEMO Phase-2 tower)
- Continuously in operation up to August 4, 2014 (500 days)
- Atmospheric muon analysis
  - Analyzed Live Time: 411.1 days
  - Atmospheric muons: 606546 reconstructed tracks
  - Angular distributions of atmospheric muons measured
  - Good agreement with simulations
  - Depth Intensity Relation (DIR) measured: in agreement with past experiments
  - DIR extended up to a depth of 13 km and in agreement with expectation