Measurement of the atmospheric muon neutrino flux with KM3NeT/ORCA6

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Introduction

- Atmospheric neutrinos; why are they interesting?
- KM3NeT/ORCA detector
- ORCA6 configuration; data and MC simulation
- Atmospheric neutrino event selection for ORCA6
- Unfolding of the energy spectrum
- Flux measurement

Atmospheric neutrinos

Produced when cosmic rays interact with the Earth's atmosphere, from secondary particle decays:

K, π mesons ⟶ Conventional Flux

D mesons ⟶ Prompt Flux

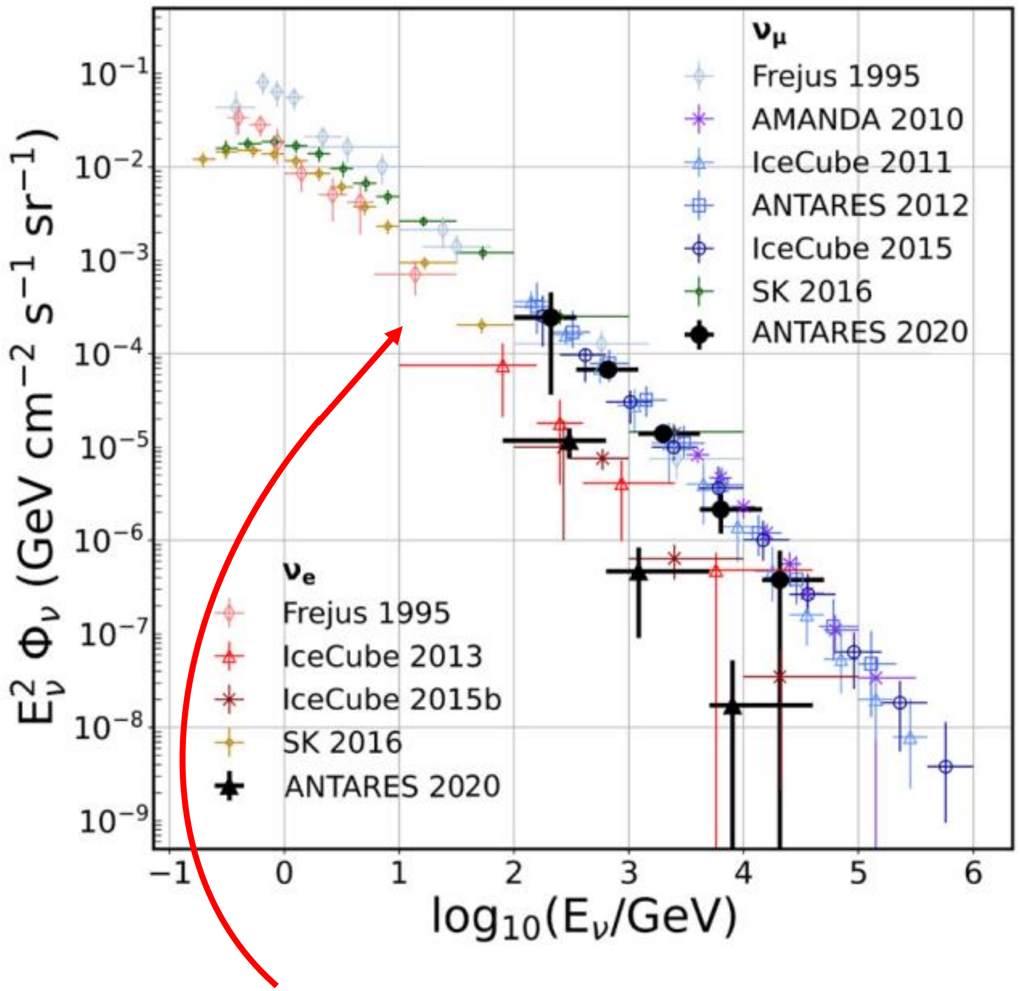
Wide energy range, from ~100 MeV to PeV scale

Why are they interesting?

- Testing of the Cosmic Ray models
- Lower part of energy spectrum suitable for studying phenomena associated with neutrino oscillations
- Irreducible background in neutrino astronomy

Current experimental status:

Phys. Lett. B 816, 136228

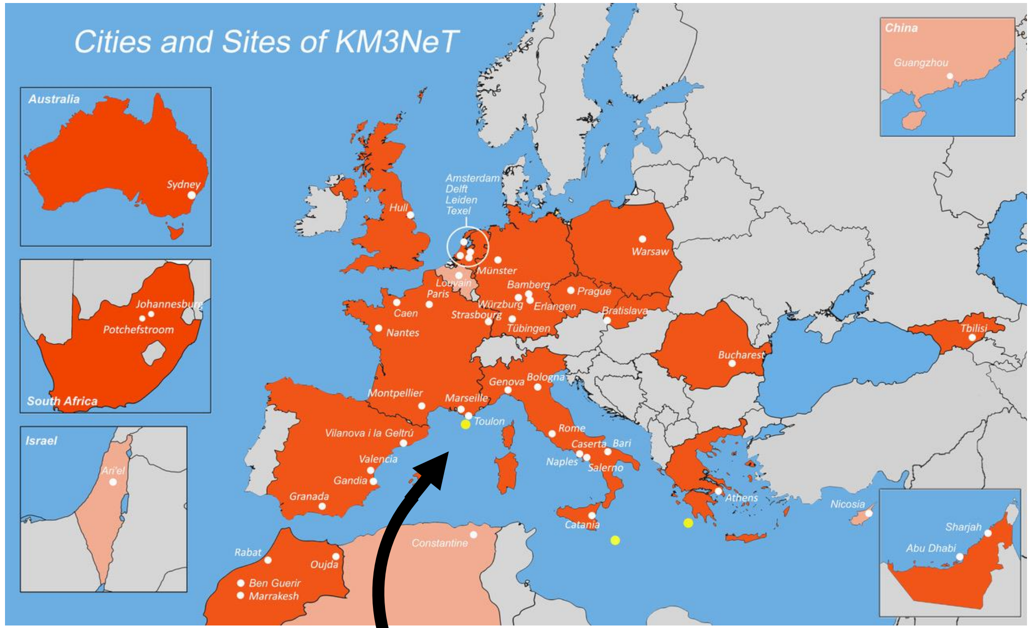


Limited experimental information between 10-100 GeV

The KM3NeT/ORCA detector

Main goal: Determine the neutrino mass hierarchy

But *also BSM, dark matter and other studies...*



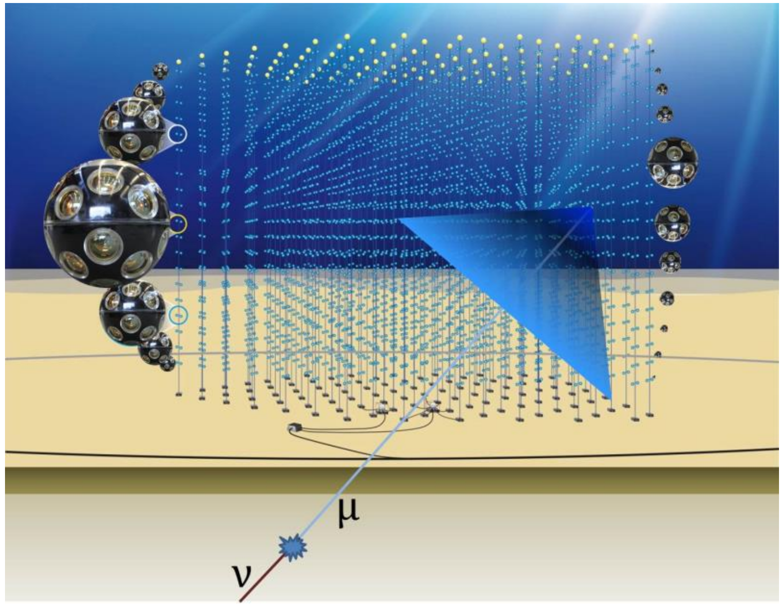
KM3NeT/ORCA site ~40 km offshore Toulon at a ~ 2450 m sea depth.

ORCA is currently operating with 18 Detection Units!

Detection Unit (DU)

18 Digital Optical Modules (DOMs)

1 Building Block = 115 DUs



31 PMTs

KM3NeT/ORCA6 configuration: Data & MC simulation

Data collected from February 2020 to November 2021 with 6-DUs (**ORCA6**): livetime equal to **510 days**.

~77% time efficiency with respect to the ORCA6 total running period!

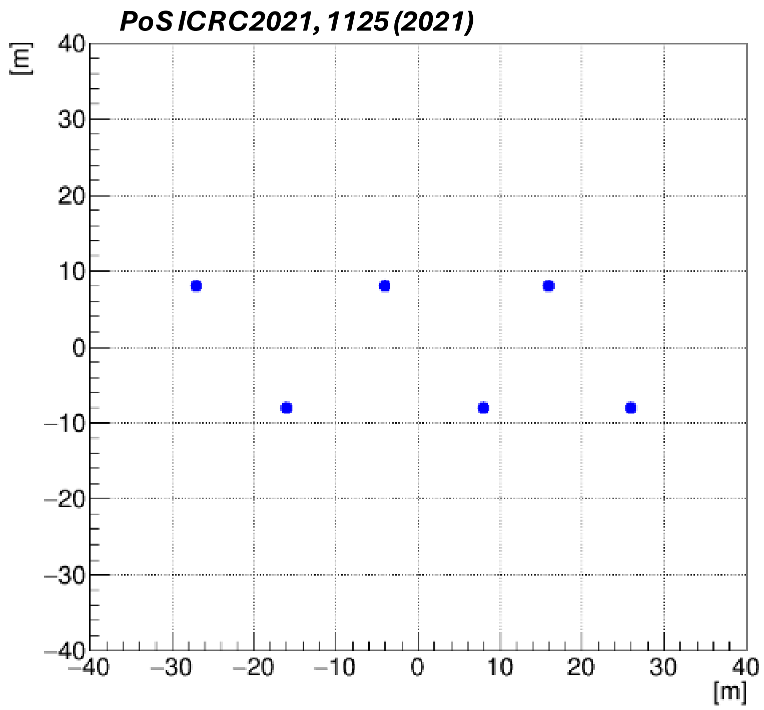
MC simulation:

- Atmospheric muons simulated with the MUPAGE software

- Atmospheric neutrinos, gSeaGen:
  - $\nu_e + \bar{\nu}_e$ CC : 1 GeV < E < 10 TeV
  - $\nu_\mu + \bar{\nu}_\mu$ CC : 1 GeV < E < 10 TeV
  - $\nu_\tau + \bar{\nu}_\tau$ CC : 3 GeV < E < 500 GeV
  - $\nu + \bar{\nu}$ NC : 1 GeV < E < 10 TeV

Atmospheric neutrino events weighted using the HKKM14 conventional flux model for the Frejus location and oscillation probabilities (NuFIT v5.2) assuming Normal Hierarchy

ORCA6 DU footprints:



Atmospheric neutrino event selection

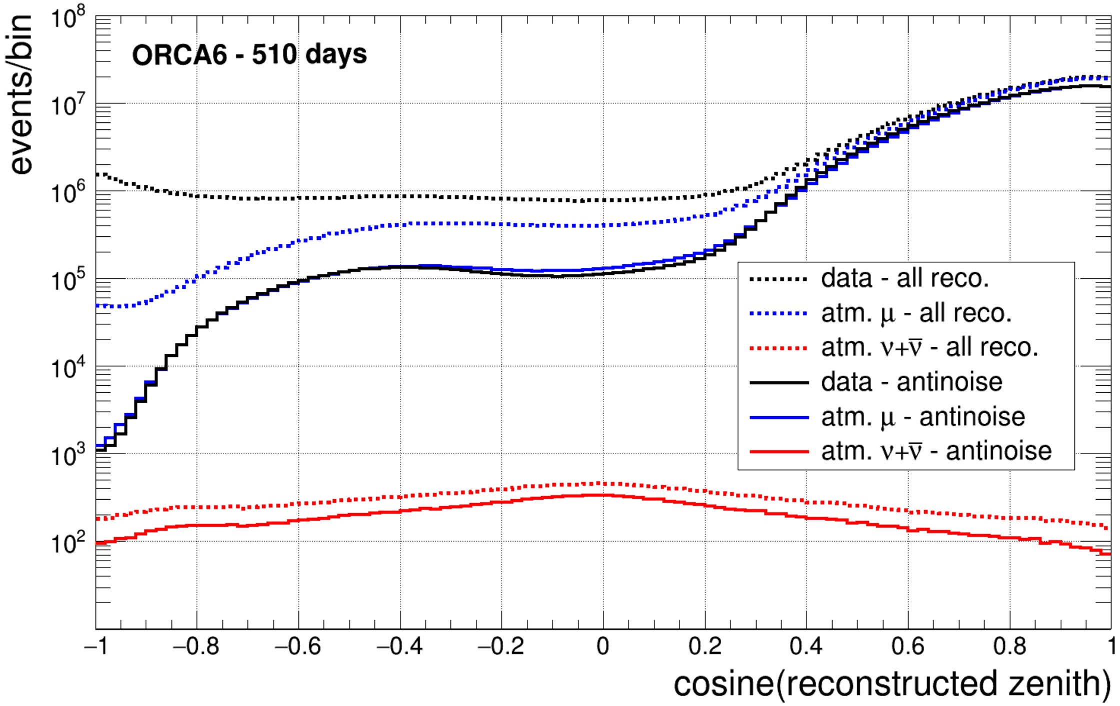
- Simple precuts to reject the contribution of random noise events
- Selection of events reconstructed as upward-going

} *precuts*

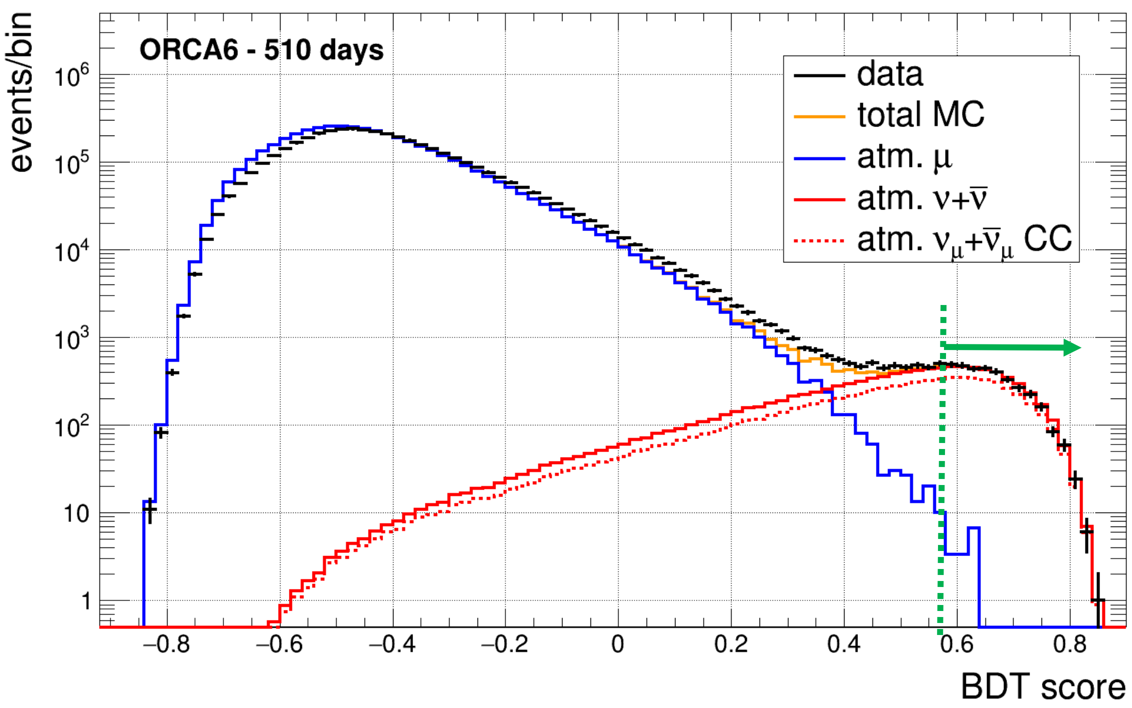
Application of an Adaptive BDT classifier (*TMVA*):

Event variables created and used as BDT features, based on:

- Signal-like hits
- Event topology
- Reconstruction quality



BDT score distribution for events surviving the preselection; cut @ 0.56:



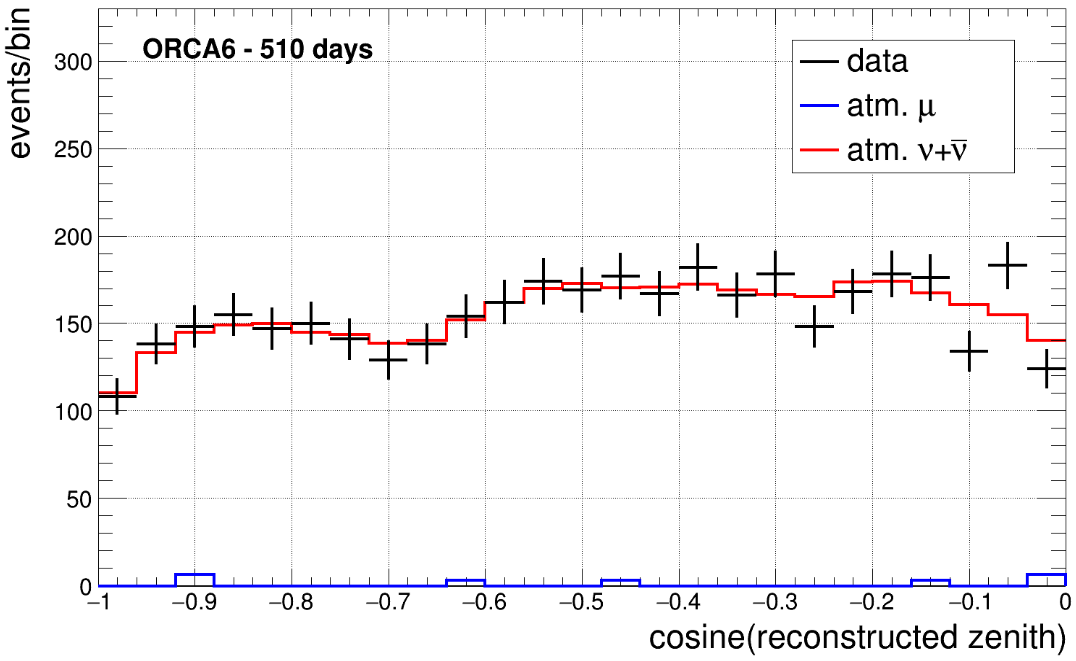
Event selection: reconstructed direction and position

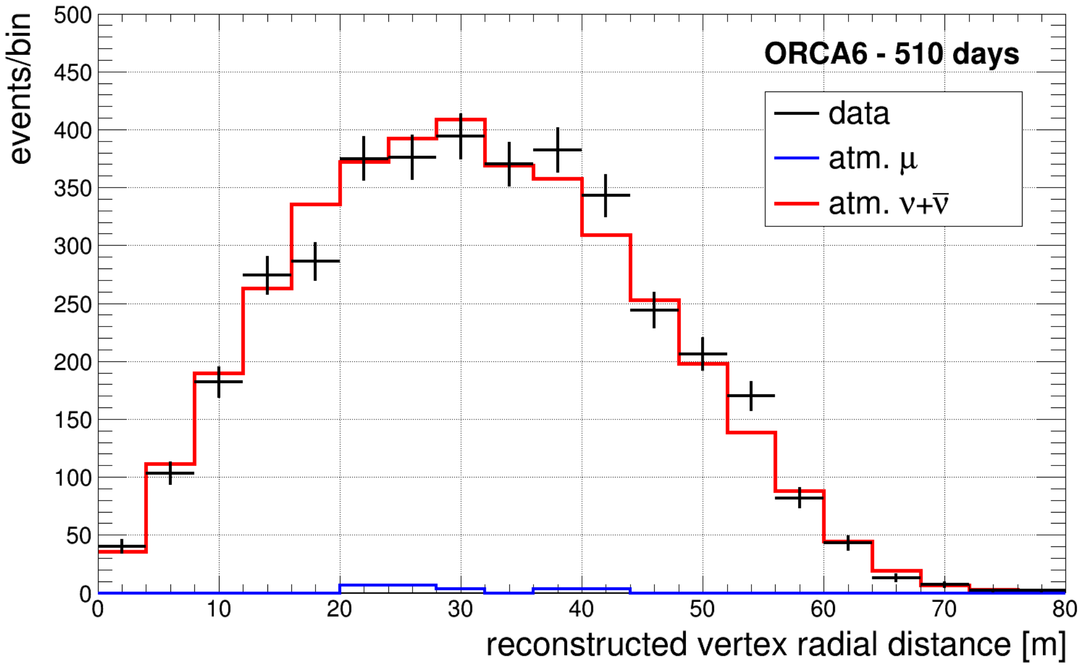
Data/MC ~ 0.994

3894 data events, ~7.5 events/day

~0.6% muon contamination

~25.0% neutrino efficiency with respect to the total number of neutrino events reconstructed as upgoing





The distributions of the reconstructed cosine zenith and the reconstructed vertex position (radial position) illustrate good data/MC agreement

Unfolding - Reconstructed energy

Unfolding: Deconvolution of a *true* spectrum from the experimentally measured one

Unfolding of the $\nu_\mu + \bar{\nu}_\mu$ CC energy spectrum from the reconstructed energy distribution

Measured data spectrum (reco phase space)

True spectrum (unfolding result)

$$y_i = \sum_{j=1}^{m} A_{ij} x_j + b_i, 1 \le i \le n$$

Response matrix (reco phase space vs true phase space)

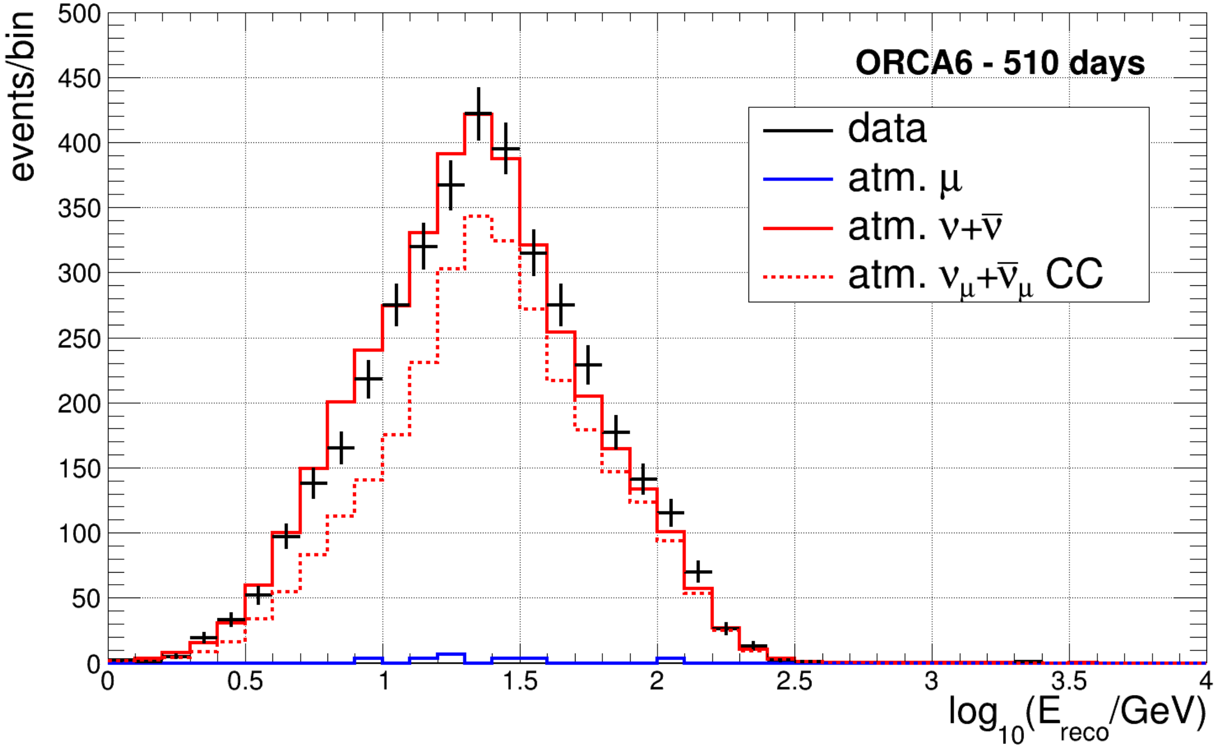
MC reco energy of background source (or sources)

The TUnfold software used.
(Least Squeare Fit with regularization term)

Subtraction of background:

- Remaining atm. Muons
- Shower-like events: $\nu_e + \bar{\nu}_e$ CC, $\nu_\tau + \bar{\nu}_\tau$ CC, $\nu + \bar{\nu}$ NC
- To account for the limitted instrumented volume: $\nu_\mu + \bar{\nu_\mu}$ CC with $E_{true} > 100$ GeV

Reconstructed energy for the event selection:

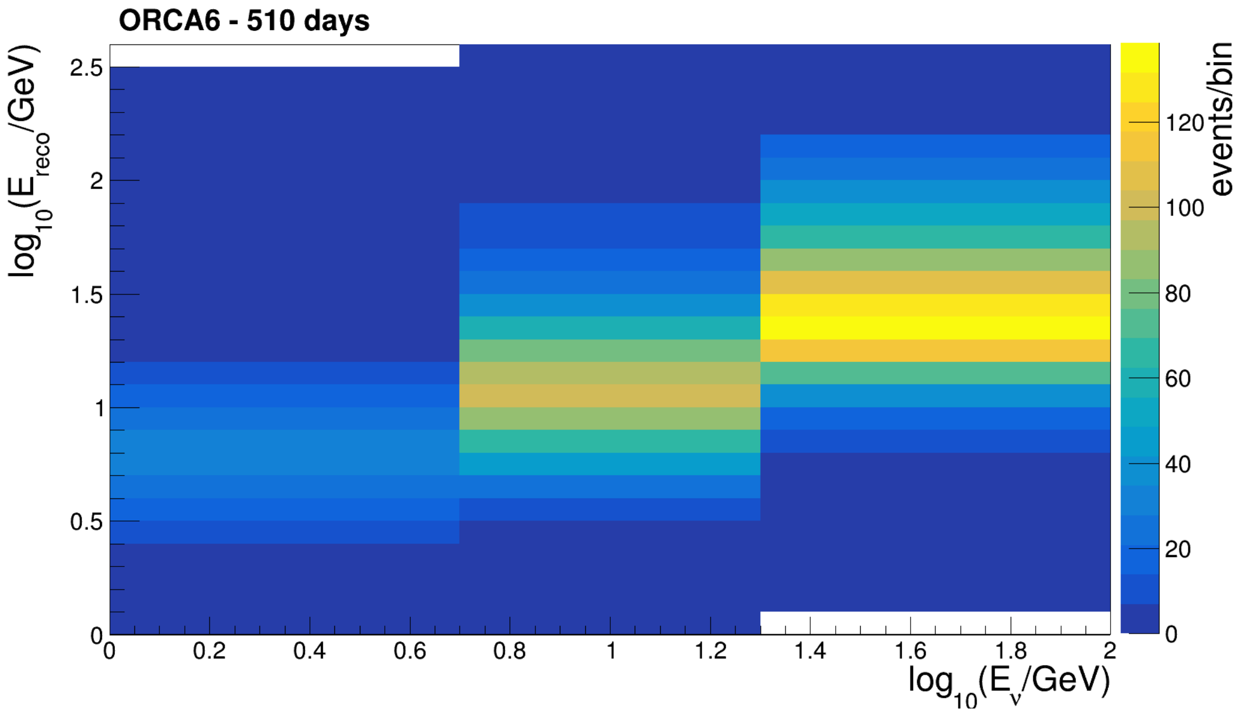


Unfolding – Define binning, response matrix

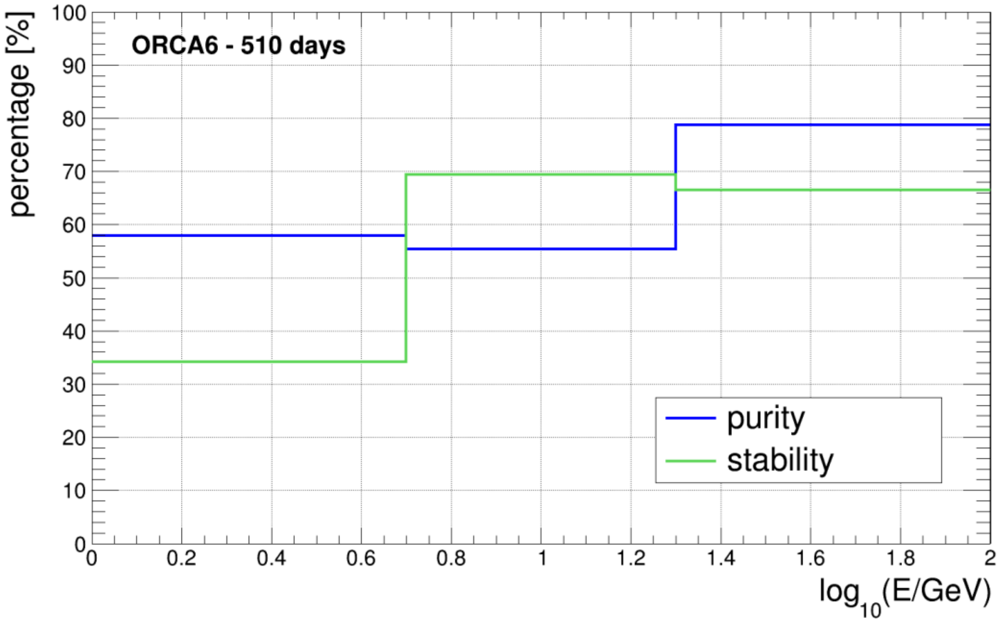
The choice of binning for the true and reco phase spaces is important for the unfolding

$\text{Log}(E_{reco}/\text{GeV})$: {0.0, 0.1, 0.2, 0.3, . . . , 2.5, 2.6}

$\text{Log}(E_{true}/\text{GeV})$: {0.0, 0.7, 1.3, 2.0}



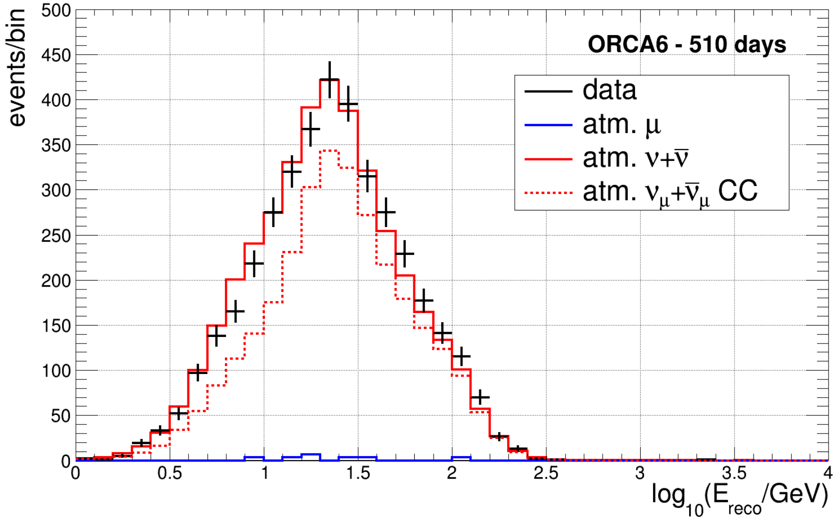
<u>Purity of the energy bins</u>: Percentage of events with reconstructed energy within the true energy bin



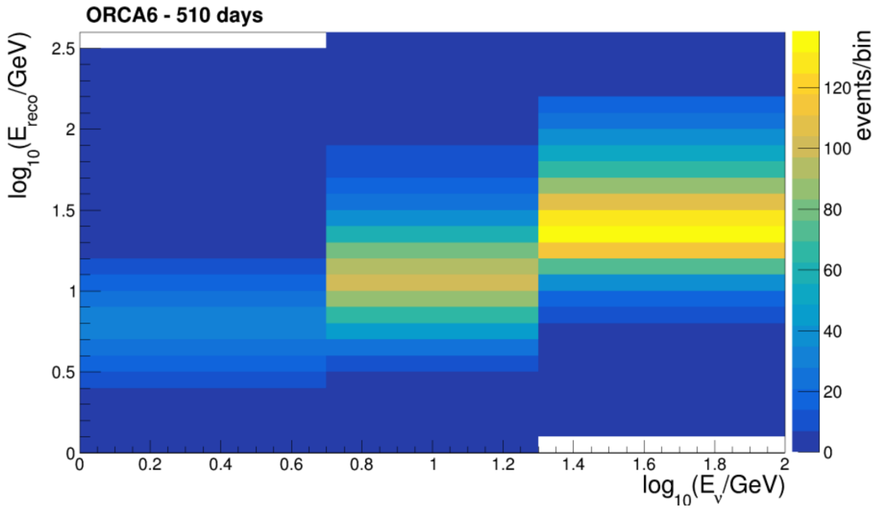
The robustness of the unfolding procedure is checked with toy pseudo-unfolding tests

Unfolding – Result

Reconstructed energy:



Response matrix:

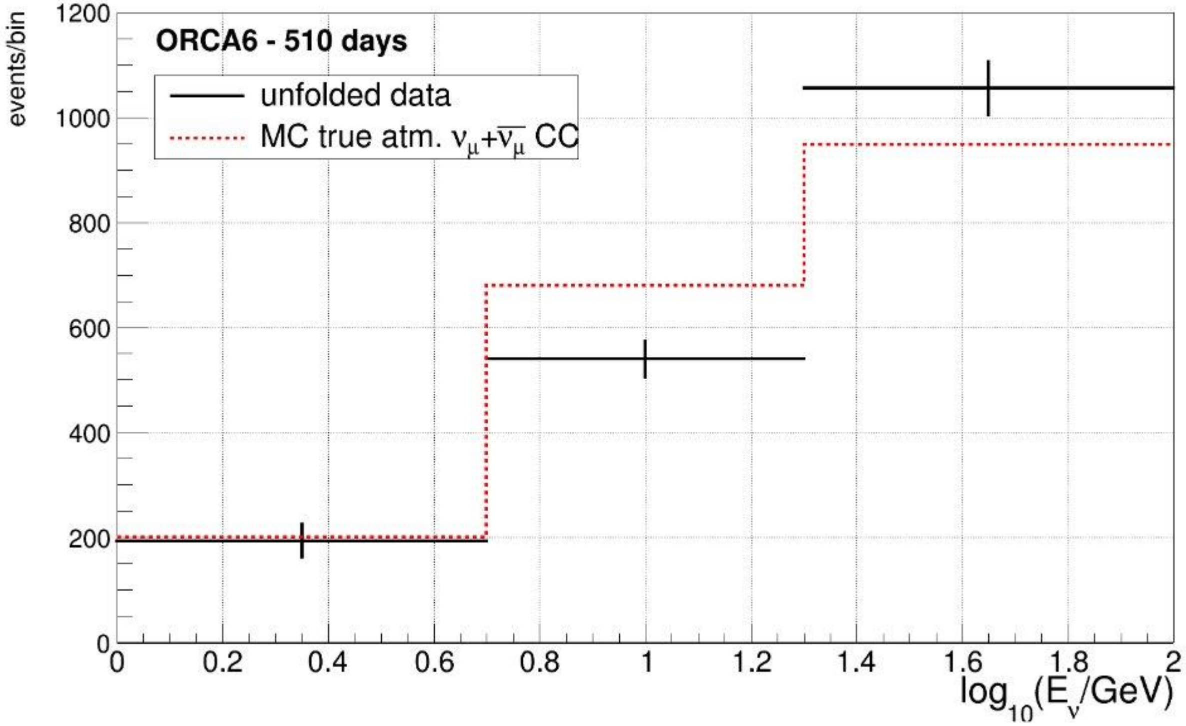


MC estimation of background sources subtracted

$$y_i = \sum_{j=1}^{m} A_{ij} x_j + b_i, 1 \leq i \leq n$$

Eventually the $\nu_\mu + \bar{\nu}_\mu$ CC energy spectrum is unfolded from the data

Unfolding result:



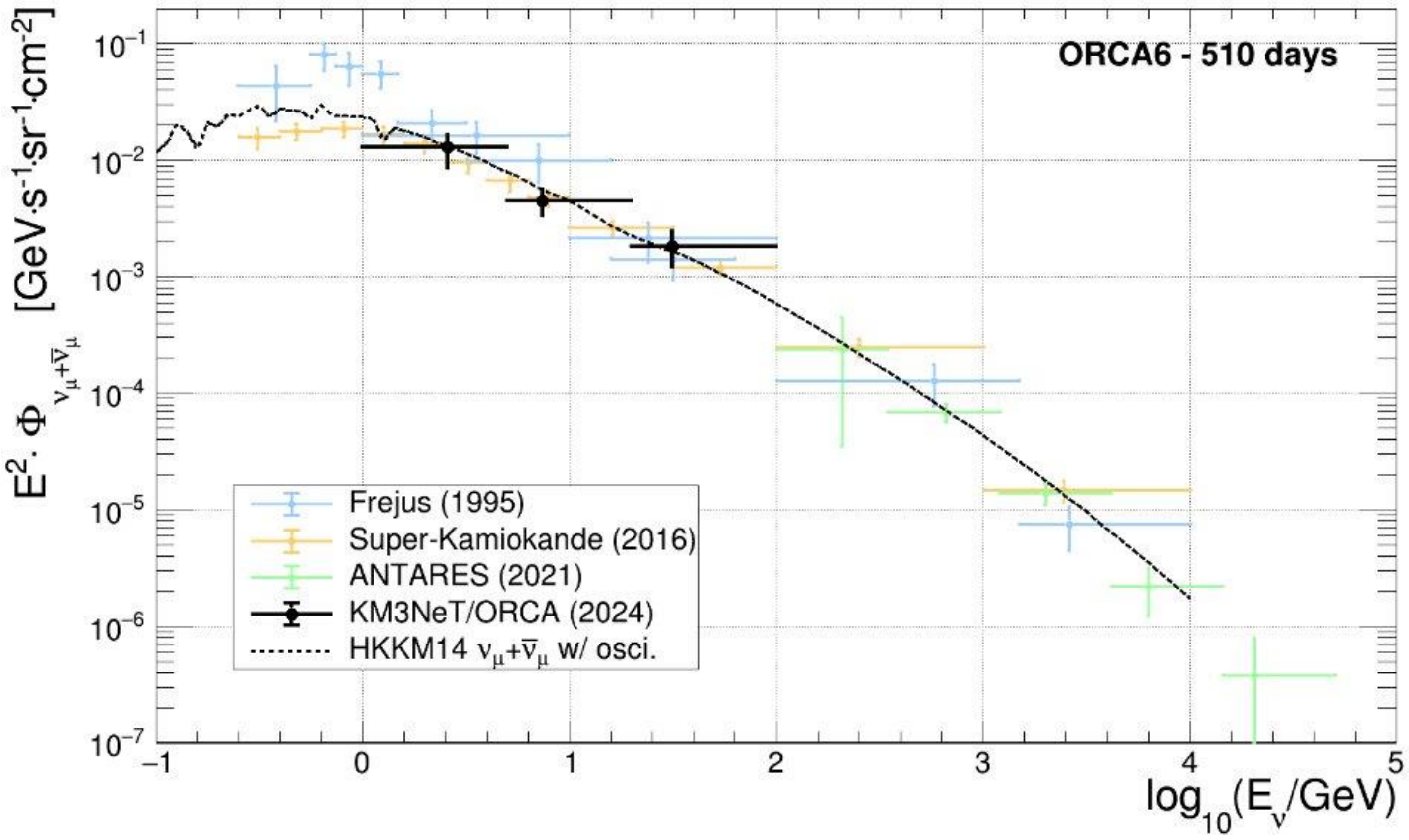
Atmospheric muon neutrino flux measurement - result

Conversion of unfolded energy spectrum to flux using the oscillated HKKM14 as a reference flux:

$$\Phi_i = \Phi_{MC}^{\nu_\mu+\bar{\nu}_\mu}(\tilde{E}_i) \cdot \frac{N_i^{unfolded}}{N_{i,\,MC}^{\nu_\mu+\bar{\nu}_\mu\,CC}}$$

Detailed systematic study has been performed. Uncertainties on:

- Detector response
- Light absorption length in seawater
- Cross sections
- Oscillations
- Unfolding procedure



Bin ranges - log(E/GeV)	Log(E/GeV)	$E^2\Phi$ [GeV s^{-1} sr^{-1} cm^{-2}]	Stat. error	Systematic error
0.0 - 0.7	0.41	$1.02 \cdot 10^{-2}$	± 15.7 %	+ 22.9 % / - 30.2 %
0.7 - 1.3	0.87	$3.99 \cdot 10^{-3}$	± 6.3 %	+22.2 % / - 24.6 %
1.3 - 1.8	1.50	$1.87 \cdot 10^{-3}$	± 4.8 %	+ 32.8 % / - 33.5 %

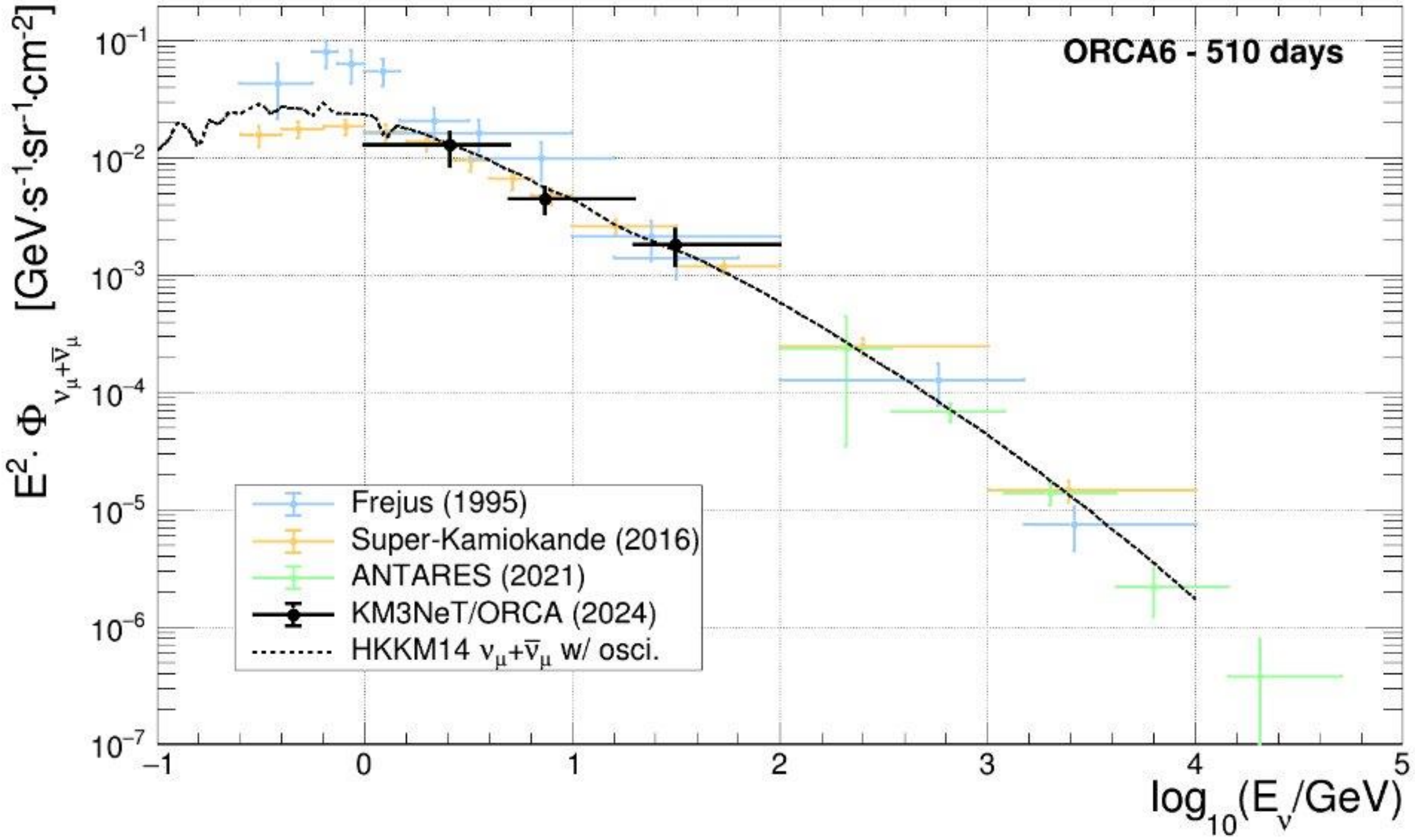
Conclusion

- A measurement of the atmospheric muon neutrino flux has been completed with KM3NeT/ORCA

- KM3NeT/ORCA is able to measure the atmospheric neutrino flux even with a preliminary detector configuration (ORCA6)

- *Publication under preparation!*

- *Thesis writing almost done!*



TUnfold

TUnfold: Calculation of the true spectrum by minimizing the function:

$$\mathcal{L}(\vec{x},\lambda) = \mathcal{L}_1 + \mathcal{L}_2 + \mathcal{L}_3$$

where:

$$\mathcal{L}_1 = (\vec{y} - \hat{A}\vec{x})^T \hat{V}_{yy}^{-1} (\vec{y} - \hat{A}\vec{x})$$ ***(least squares)***

$$\mathcal{L}_2 = \tau^2 (\vec{x} - f_b \vec{x}_o)^T (\hat{L}^T \hat{L}) (\vec{x} - f_b \vec{x}_o)$$ ***(regularization)***

$$\mathcal{L}_3 = \lambda (Y - e^T \vec{x})$$ ***(area constraint)***

The parameter τ^2 defines the strength of regularization

$\mathcal{L}_1$ results in large fluctuations.

$\mathcal{L}_2$ is introduced to limit this effect, but the introduced bias should be checked carefully!

Methods to specify the regularization parameter value:

- **L-curve**

Scan the phase space of the following terms, looking for the maximum curvature point:

$$L_x^{curve} = \log \mathcal{L}_1 \ , \quad L_y^{curve} = \log \frac{\mathcal{L}_2}{\tau^2}$$

- **Minimization of average correlations**

The bias from the regularization term introduces large correlations between the unfolded values

Scan the average correlation coefficient for a range of the regularization parameter values

Straight-forward method; works better in our case

Regularization parameter choice

Minimization of average correlations: