Measurement of the atmospheric muon neutrino flux with KM3NeT/ORCA6

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Advancing Searches for New Physics

Dimitris Stavropoulos*, PhD candidate
National Center for Scientific Reasearch "Demokritos"
National Technical University of Athens

*dstavropoulos@inp.demokritos.gr

Work carried out in the context of the program “Intelligent, Specialized Environmental Observatory in Messinia” (ISEO), funded by the Operational Program “Peloponnesos” 2014-2020, of NSRF (2014-2020).

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

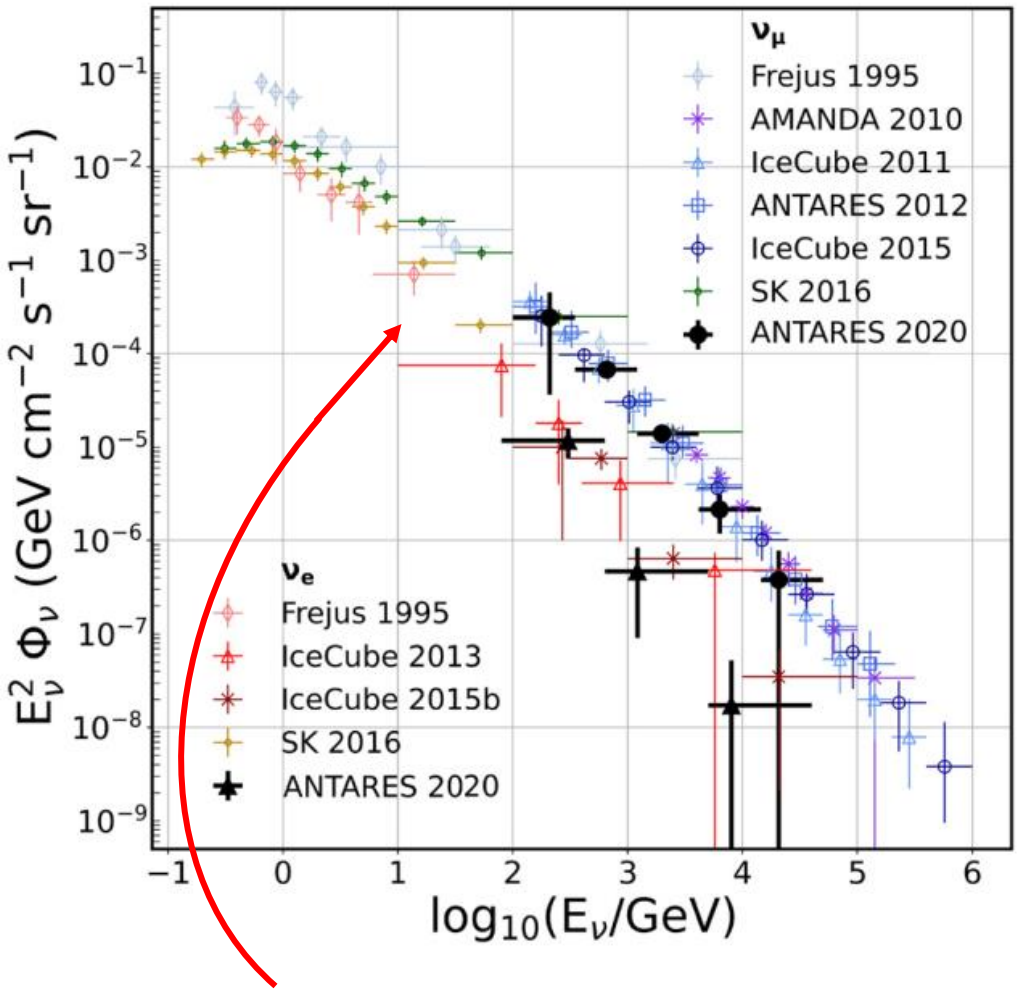
Wide energy range, from ~100 MeV to PeV scale

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

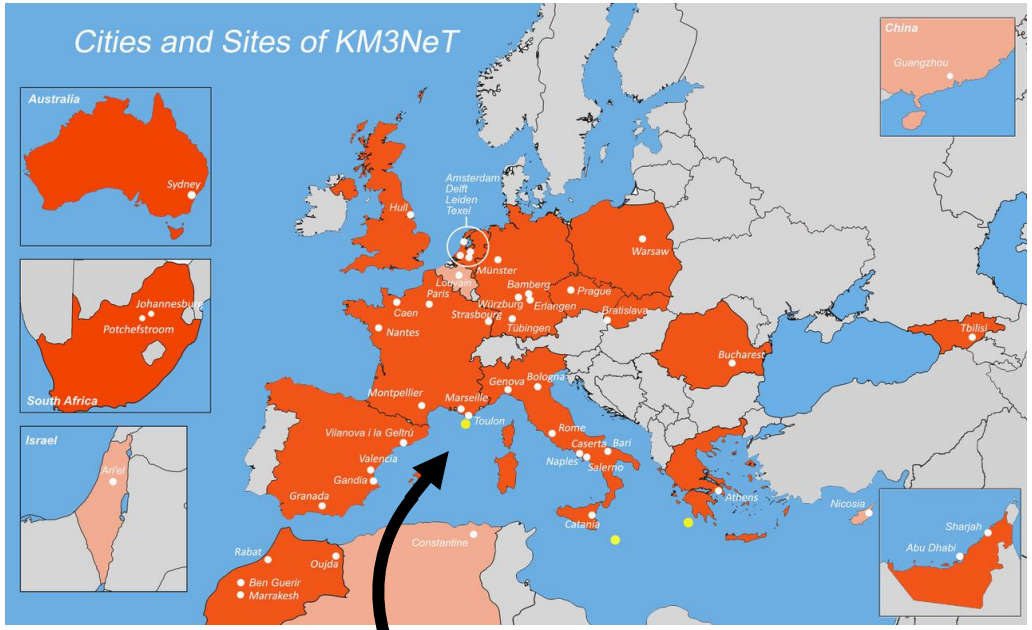


Limited experimental information between 1-100 GeV

The KM3NeT/ORCA detector

Main goal: Determine the neutrino mass hierarchy

But a*lso BSM, dark matter and other studies...*



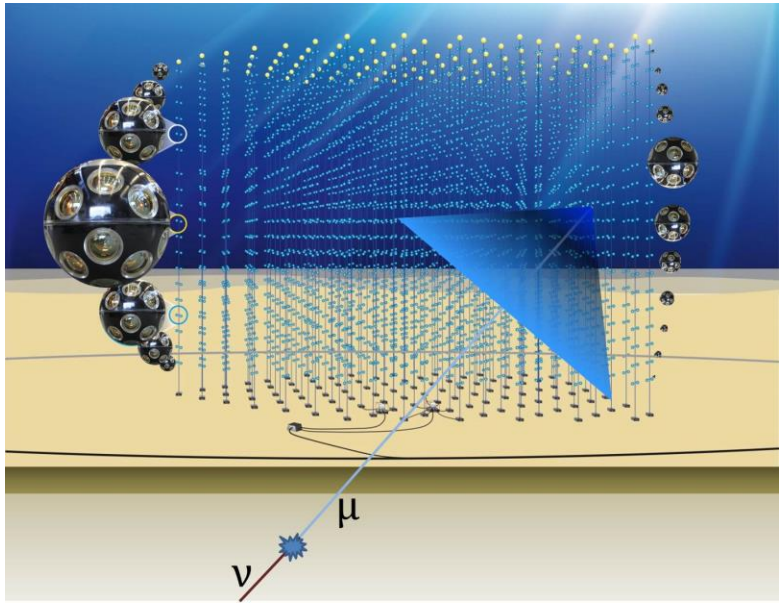
KM3NeT/ORCA site ~40 km offshore Toulon at a ~ 2450 m sea depth.

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 **555.7 days**.

~84% time efficiency with respect to the ORCA6 total running period!

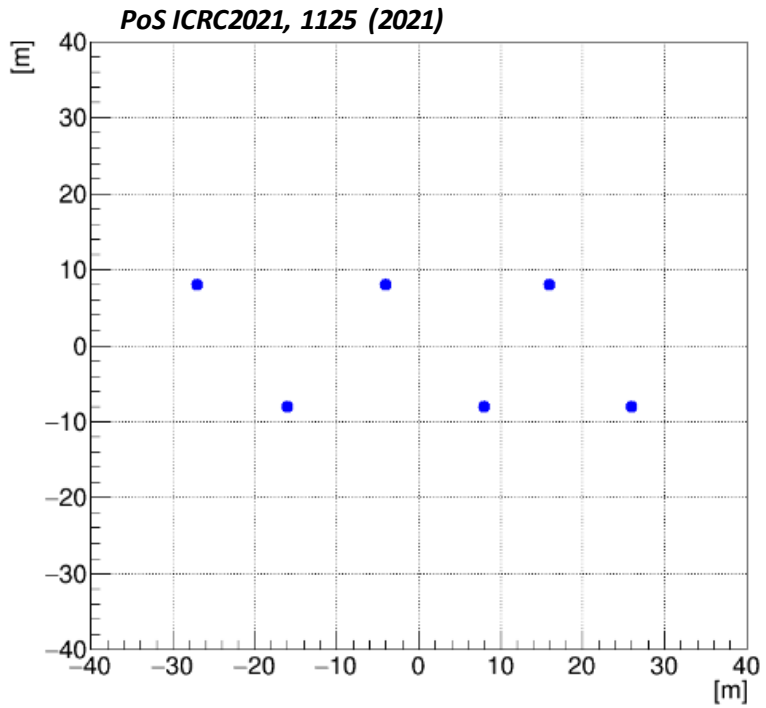
MC simulation:

- Atmospheric muons simulated with the MUPAGE software
- Atmospheric neutrinos, gSeaGen:

$$\begin{cases} \nu_e + \bar{\nu}_e \ \mathrm{CC} & : 1\ \mathrm{GeV} < E < 10\ \mathrm{TeV} \\ \nu_\mu + \bar{\nu}_\mu \ \mathrm{CC} & : 1\ \mathrm{GeV} < E < 10\ \mathrm{TeV} \\ \nu_\tau + \bar{\nu}_\tau \ \mathrm{CC} & : 3\ \mathrm{GeV} < E < 500\ \mathrm{GeV} \\ \nu + \bar{\nu}\ \mathrm{NC} & : 1\ \mathrm{GeV} < E < 10\ \mathrm{TeV} \end{cases}$$

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

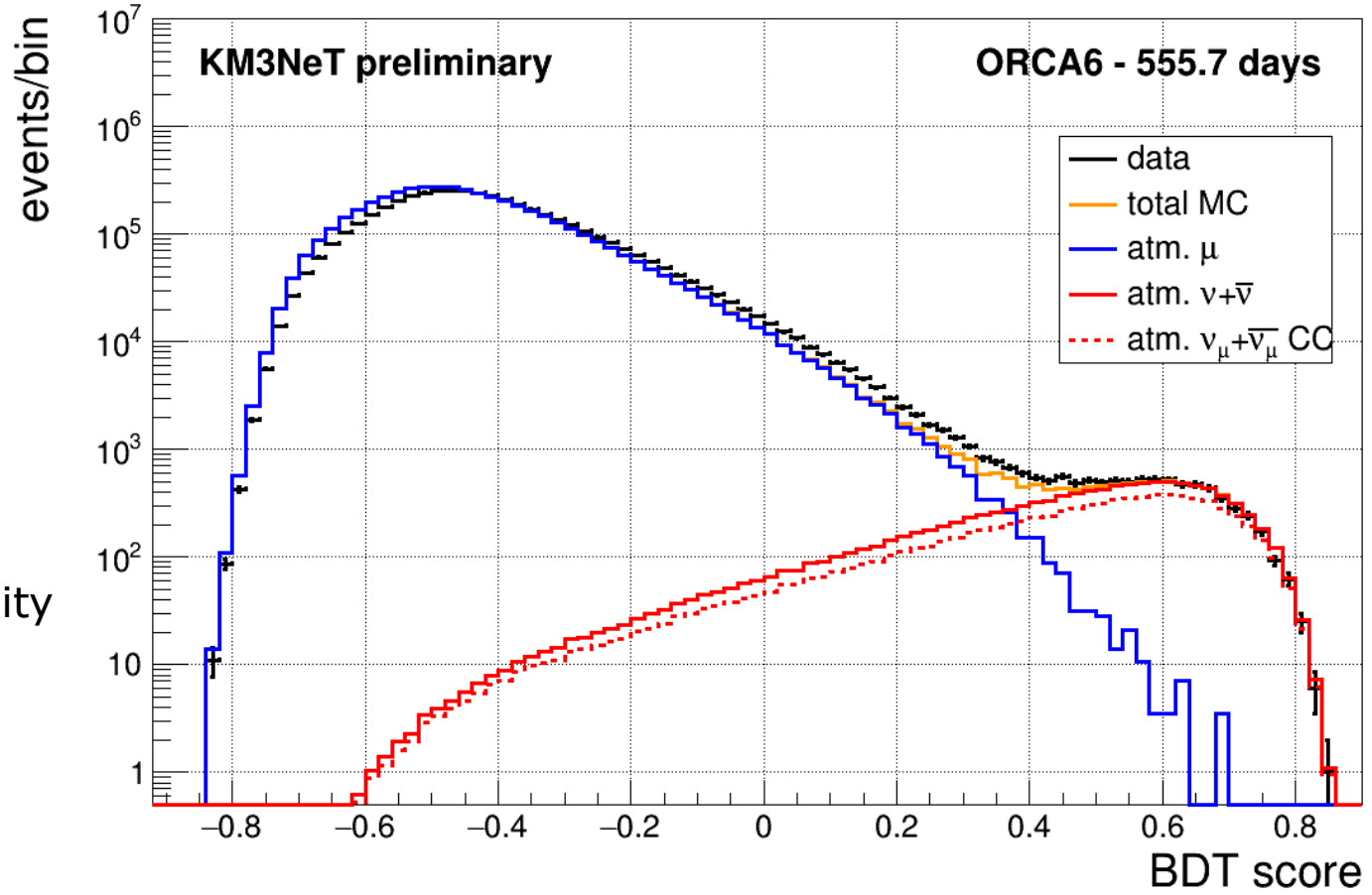
- Application of an Adaptive BDT classifier (*TMVA*):

BDT score cut at 0.56:

Data: 4197 events
Atm neutrinos: 4196.1 events
Atm muons: 28.1 events

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

- Signal-like hits
- Event topology
- Reconstruction quality



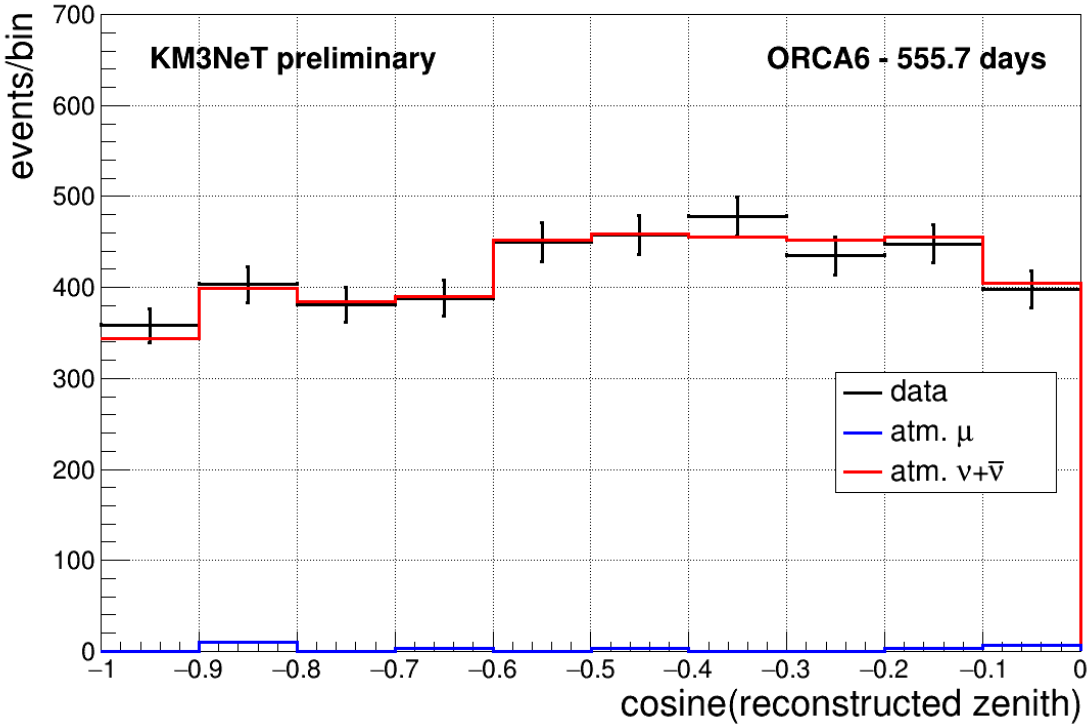
~7.5 events/day

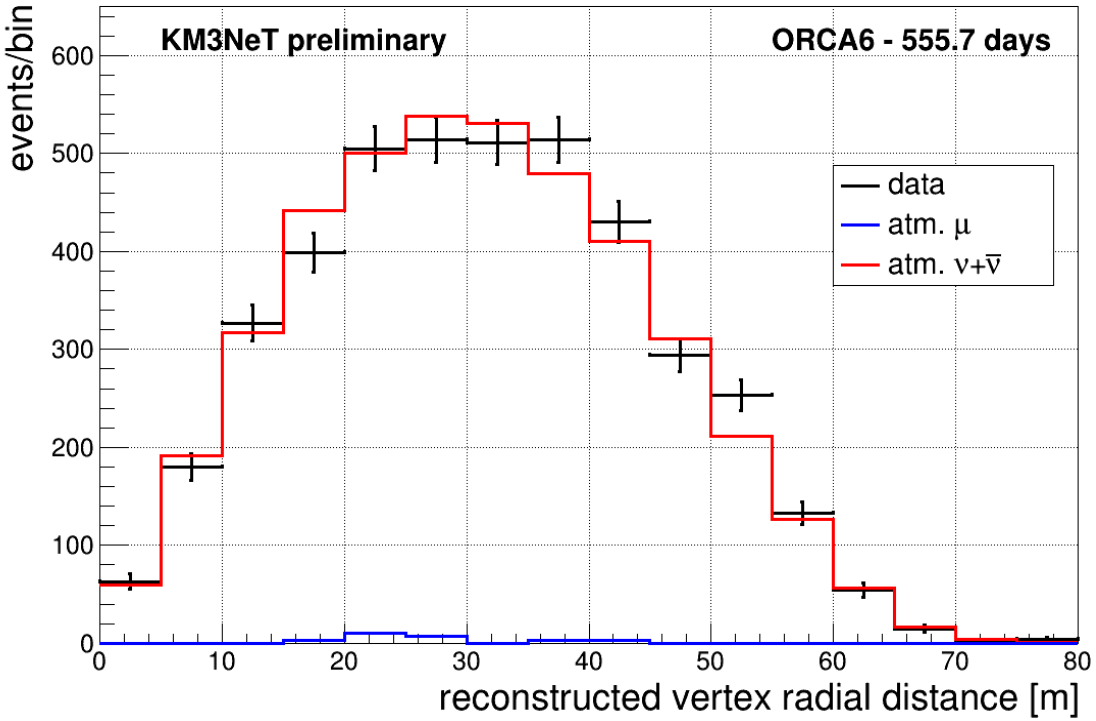
~0.6% muon contamination

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

Event selection: reconstructed direction and position

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





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Unfolding - Reconstructed energy

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

Measured data spectrum (reco phase space)

True spectrum (unfolding result)

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

Response matrix (reco phase space vs true phase space)

MC reco energy of background source (or sources)

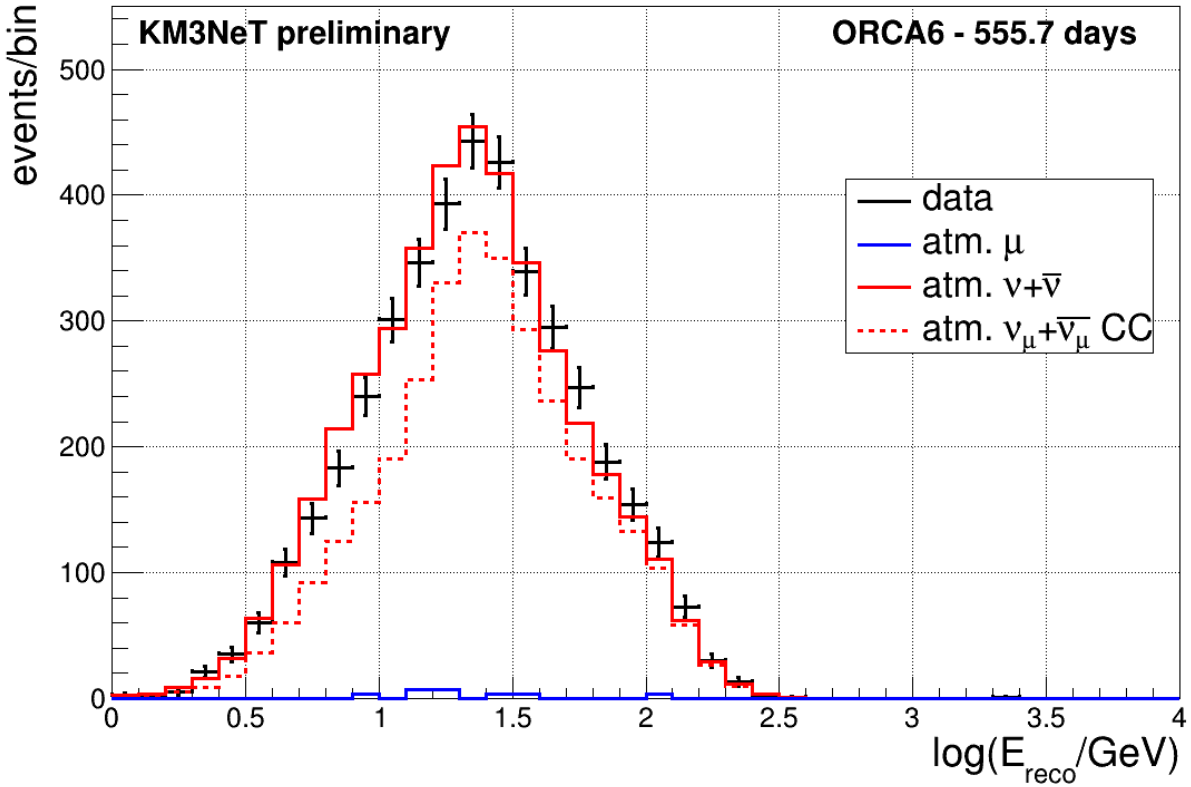
Unfolding of the $\nu_\mu + \bar{\nu}_\mu$ CC energy spectrum from the reconstructed energy distribution

The TUnfold software used.
Subtraction of background:

- Remaining atm. Muons
- Shower-like events $\begin{cases} \nu_e + \bar{\nu}_e \text{ CC} \\ \nu_\tau + \bar{\nu}_\tau \text{ CC} \\ \nu + \bar{\nu} \text{ NC} \end{cases}$
- To account for the limitted instrumented volume:

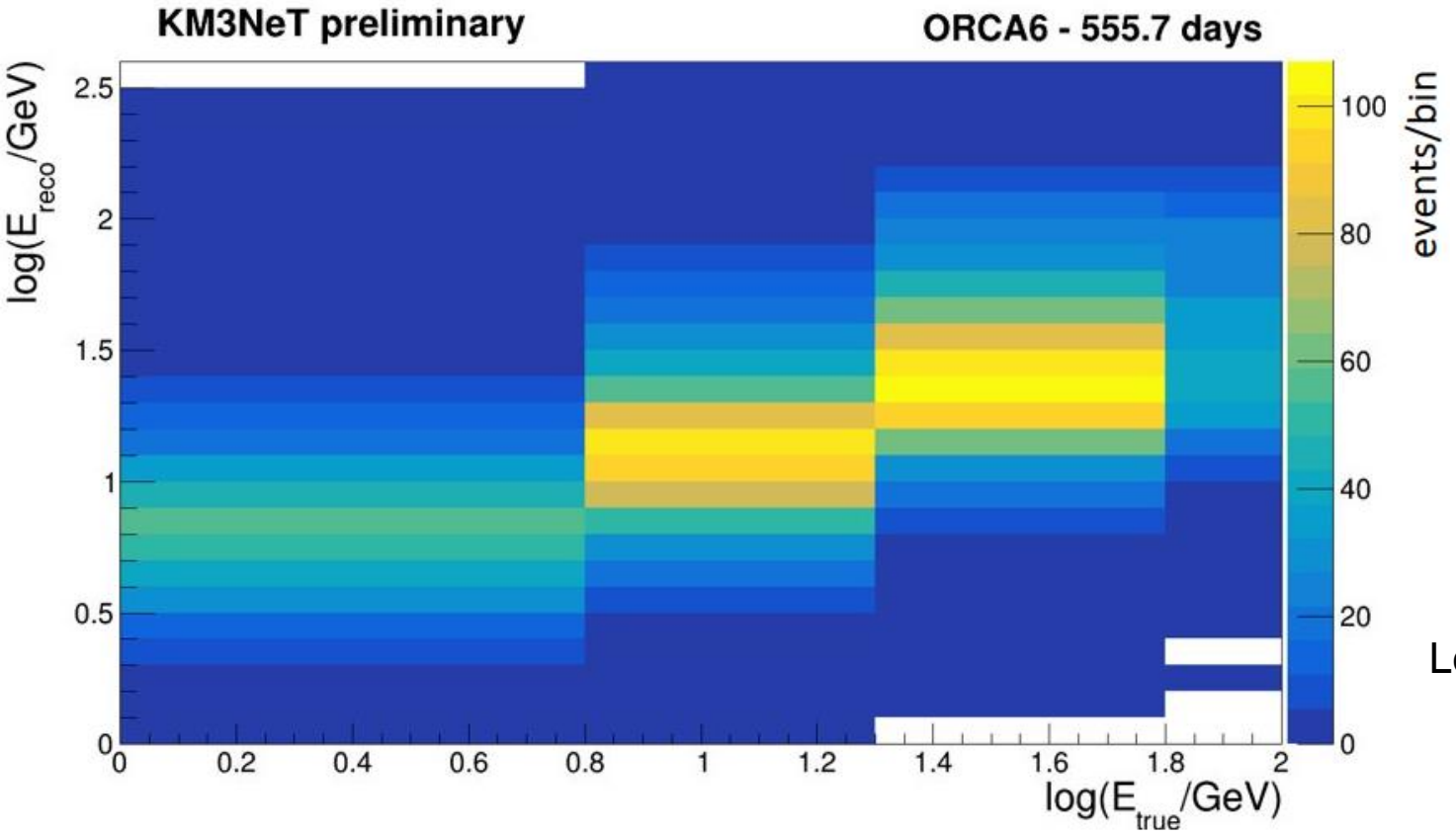
$$\nu_\mu + \bar{\nu}_\mu \text{ CC with } E_{true} > 100 \text{ GeV}$$

Reconstructed energy for the event selection:



Unfolding – Define binning and response matrix

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



Study on MC simulated events:

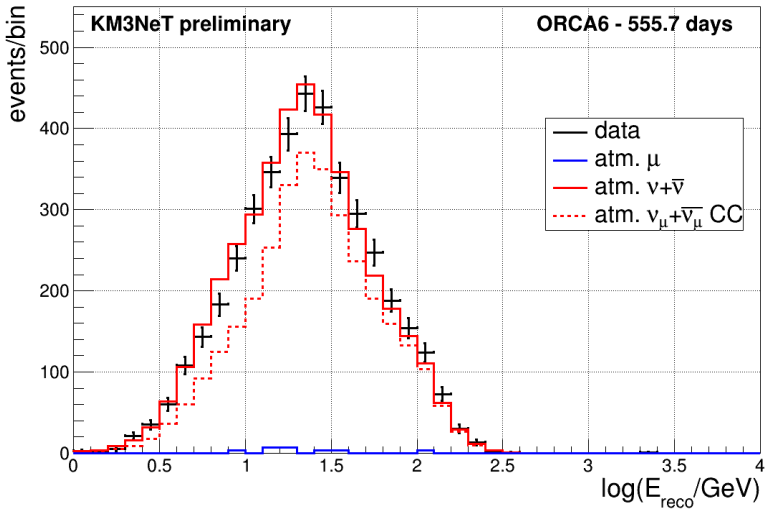
- Purity of the energy bins: Percentage of events with reconstructed energy within the true energy bin
- MC consistency check: Apply the unfolding using the MC reco energy to ensure consistency
- Robustness check: "toy" unfolding experiments (1k) performed using pseudo-data

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

$Log(E_{true}/GeV)$: {0.0, 0.8, 1.3, 1.8, 2.0}

Unfolding – Result

Reconstructed energy:

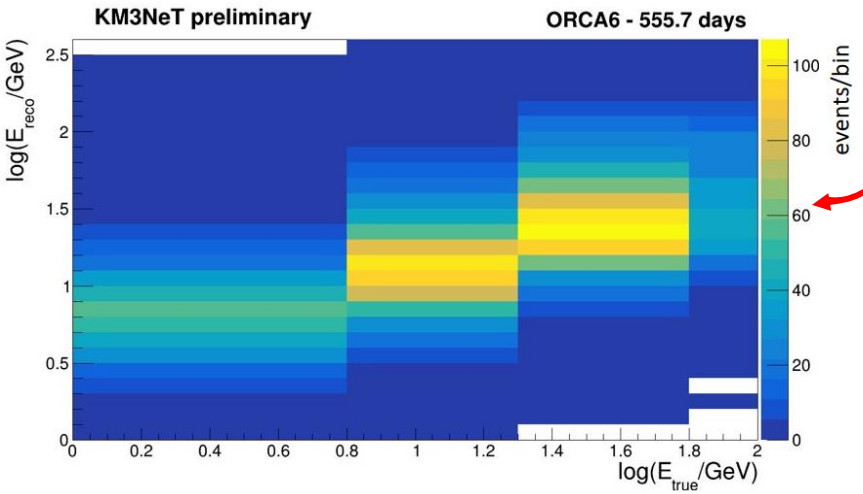


MC estimation of background sources subtracted

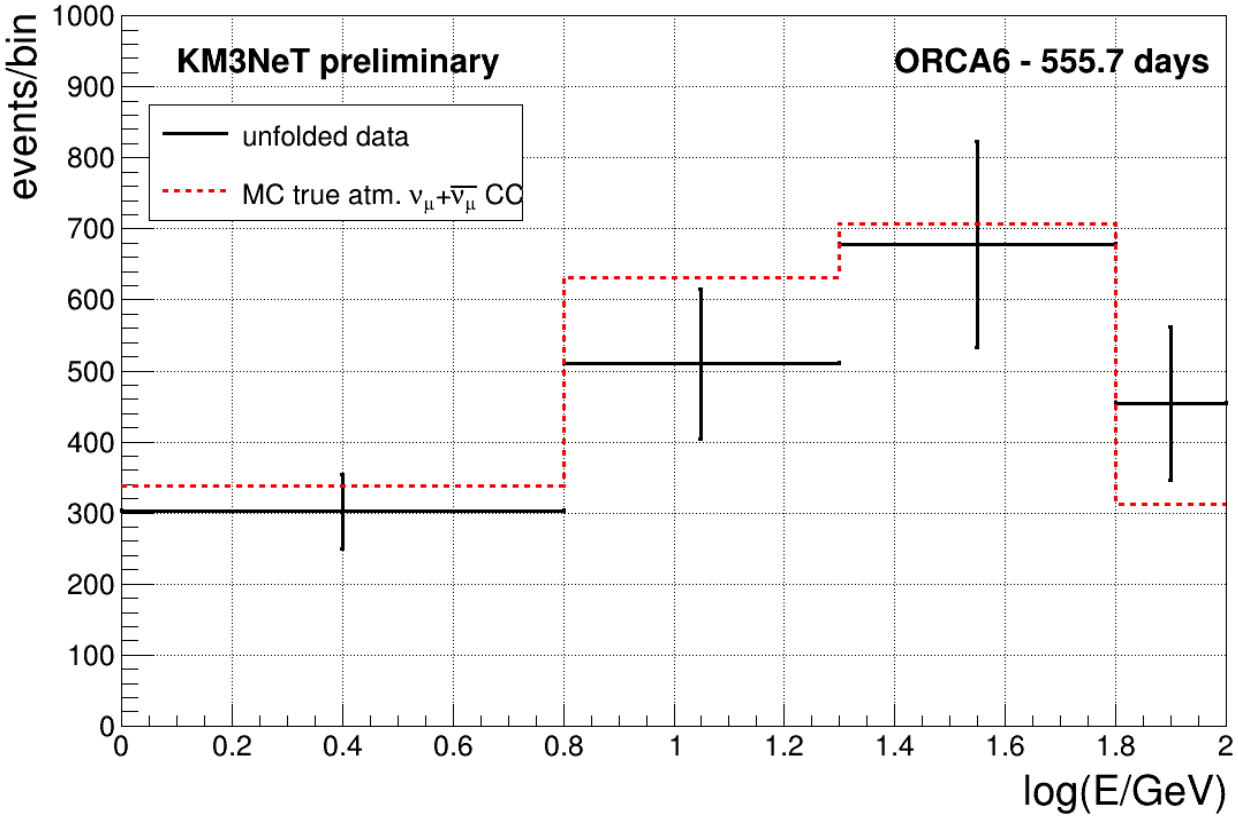
$$y_i = \sum_{j=1}^{m} A_{ij} x_j + b_i, 1 \leq i \leq n$$

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

Response matrix:



Unfolding result:



Procedure to extract flux values

Measured value in bin i

$$\Phi_i = \Phi_i^{MC} \cdot \frac{N_i^{unf}}{N_i^{MC}}$$

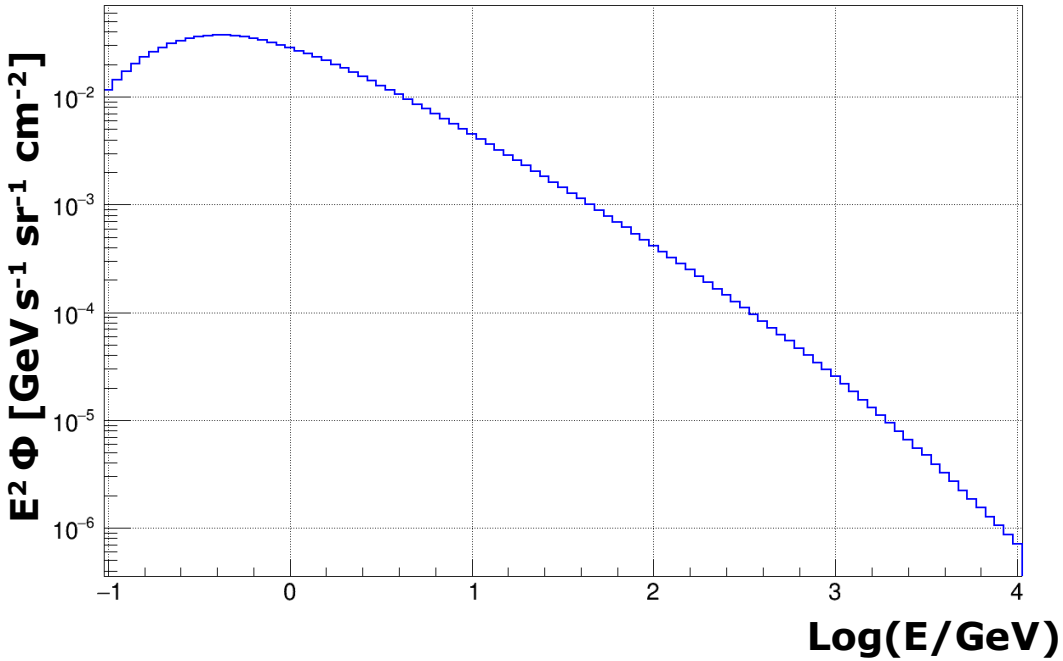
N_i^{unf}: # of unfolded data events in bin i

N_i^{MC}: # of events in bin i for $\nu_\mu + \bar{\nu}_\mu$ CC MC

By interpolating the 4π integrated flux for the bin weighted energy

$$\Phi_{MC}^{\nu_\mu+\bar{\nu}_\mu}(E_\nu) = \int_{4\pi} d\Omega \Big\{ \Phi_{MC}^{\nu_e}(E_\nu,\theta)\cdot O^{\nu_e\to\nu_\mu}(E_\nu,\theta) + \Phi_{MC}^{\bar{\nu}_e}(E_\nu,\theta)\cdot O^{\bar{\nu}_e\to\bar{\nu}_\mu}(E_\nu,\theta) + \Phi_{MC}^{\nu_\mu}(E_\nu,\theta)\cdot O^{\nu_\mu\to\nu_\mu}(E_\nu,\theta) + \Phi_{MC}^{\bar{\nu}_\mu}(E_\nu,\theta)\cdot O^{\bar{\nu}_\mu\to\bar{\nu}_\mu}(E_\nu,\theta) \Big\}$$

4π-integrated HKKM14 flux accounting for oscillations:

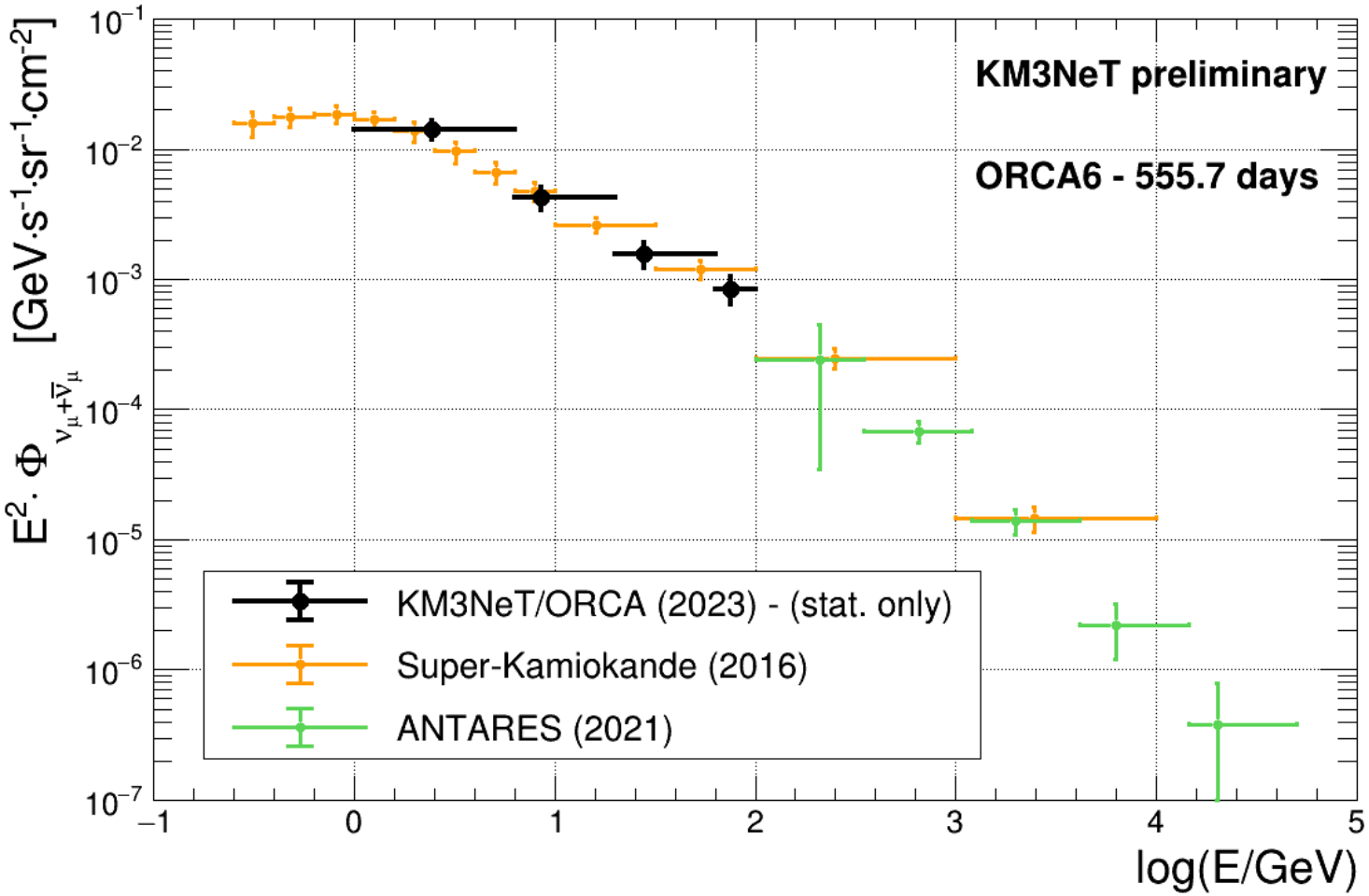


Extracted flux values:

$\Delta log(E_\nu/GeV)$	$\overline{log(E_\nu/GeV)}$	$E_\nu^2\Phi_\nu[GeV\cdot s^{-1}\cdot sr^{-1}\cdot cm^{-2}]$	stat.
0.0-0.8	0.39	$1.43\cdot10^{-2}$	±17%
0.8-1.3	0.93	$4.25\cdot10^{-3}$	±21%
1.3-1.8	1.45	$1.57\cdot10^{-3}$	±21%
1.8-2.0	1.88	$8.46\cdot10^{-4}$	±24%

Statistical errors are extracted by unfolding

Measured flux



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An estimation of systematic errors is ongoing

Outlook

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

- Results and energy range of the measurement are to be improved in future due to the increase of instrumented volume

ORCA is currently collecting data with 18 DUs!

- An estimation of systematic uncertainties is in progress

Thank you for your attention!

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