Muon track reconstruction and muon energy estimate in the KM3NeT/ARCA detector

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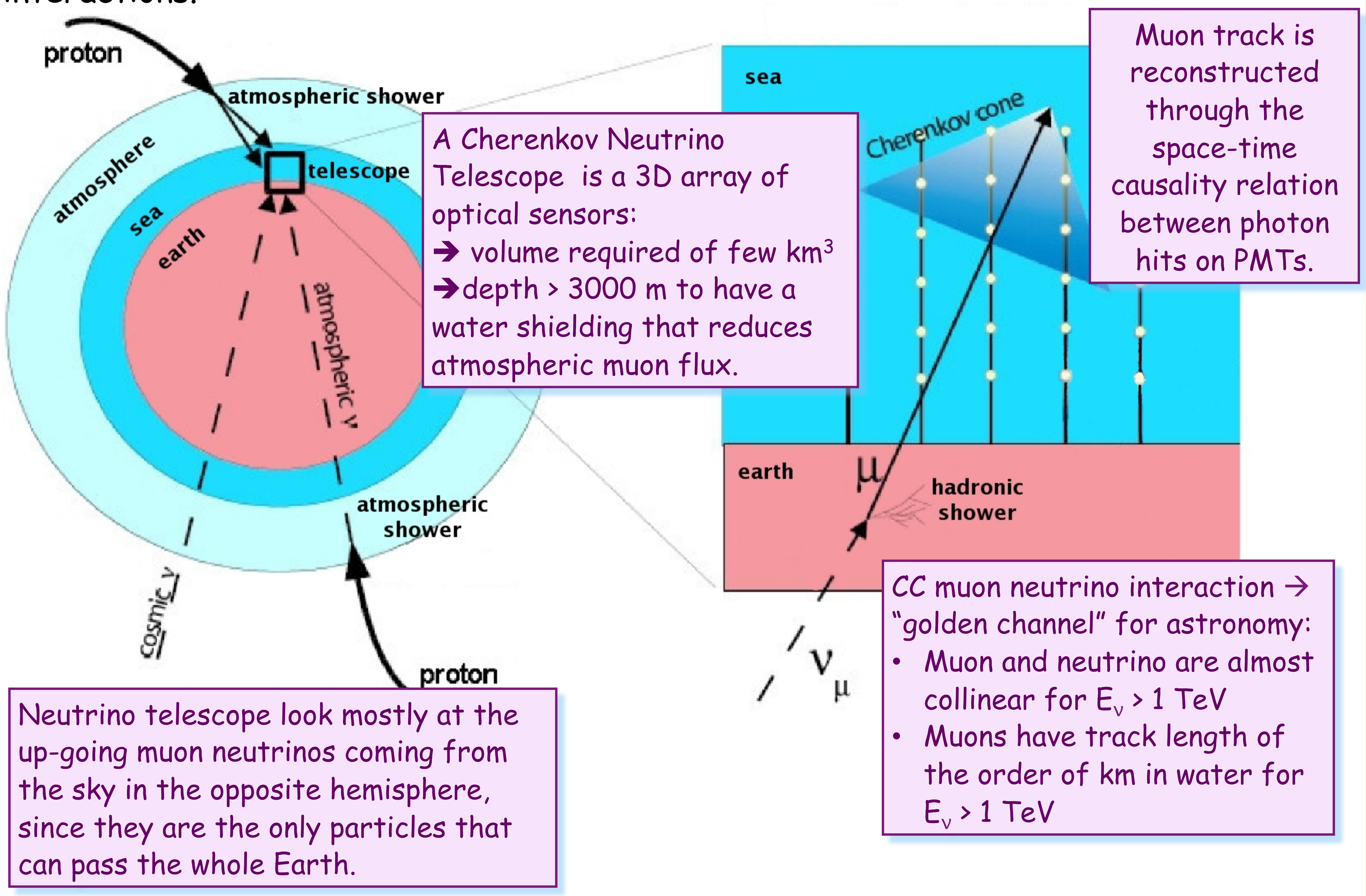
Introduction

The main goal of neutrino telescope experiments is the observation of high energy neutrinos from cosmic sources. Neutrinos are detected indirectly through optical Cherenkov radiation emitted by charged particles produced in weak neutrino interactions.



A Cherenkov Neutrino Telescope is a 3D array of optical sensors:
- ➔ volume required of few km^3
- ➔ depth > 3000 m to have a water shielding that reduces atmospheric muon flux.

Muon track is reconstructed through the space-time causality relation between photon hits on PMTs.

CC muon neutrino interaction → "golden channel" for astronomy:
- Muon and neutrino are almost collinear for E_ν > 1 TeV
- Muons have track length of the order of km in water for E_ν > 1 TeV

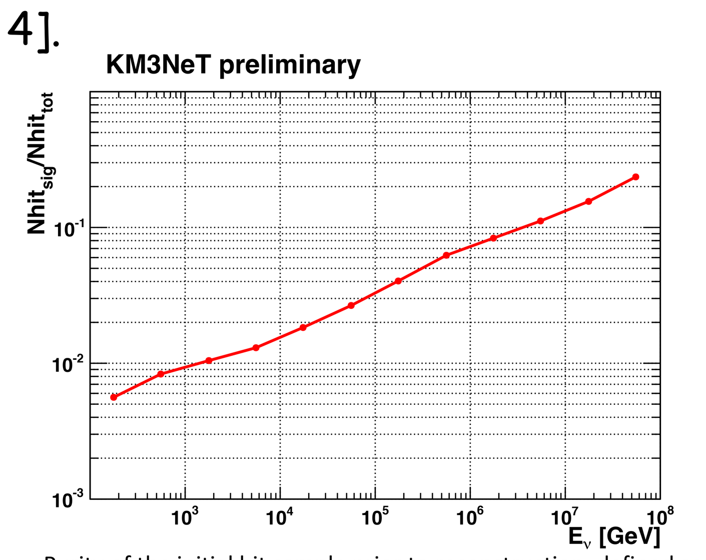
Neutrino telescope look mostly at the up-going muon neutrinos coming from the sky in the opposite hemisphere, since they are the only particles that can pass the whole Earth.

Muon track reconstruction

The track reconstruction algorithm permits to estimate the muon direction, and consequently to infer the neutrino direction, using the information of the PMT spatial positions and the Cherenkov photon arrival times [3, 4].

Initial hit selection:

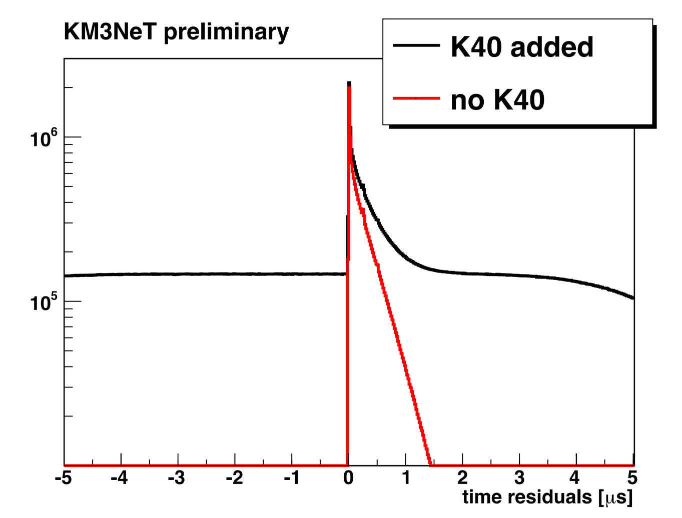
- ➢ Optical background (bioluminescence and ^{40}K decays) gives spurious, mostly uncorrelated, signals on the optical sensor
- ➢ Hit selection based on space-time correlations between hits is performed and only selected hits are used for the reconstruction procedure



Purity of the initial hit sample prior to reconstruction, defined as the ratio between the signal hits and the total number of hits.

Fitting procedures:

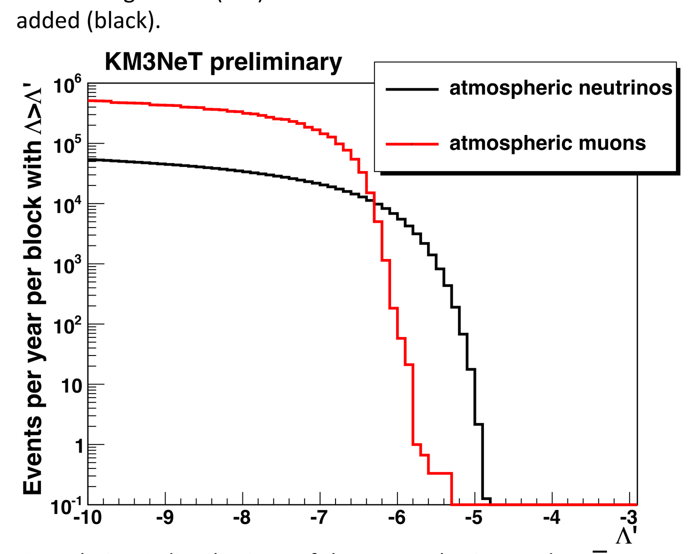
- ➢ Consecutive fitting steps, each using the result of the previous one as starting point.
- ➢ First step: prefit → linear fit
- ➢ Maximum likelihood method and use a probability density function (PDF) for the ***time residuals***, defined as the difference between the expected time of arrival of the Cherenkov photon on the PMT and the recorded hit time.
- ➢ Sky scanning in step of 3°starting from the prefit track. Fitting procedures performed for each of these directions and the solution with the highest likelihood per degree of freedom chosen.



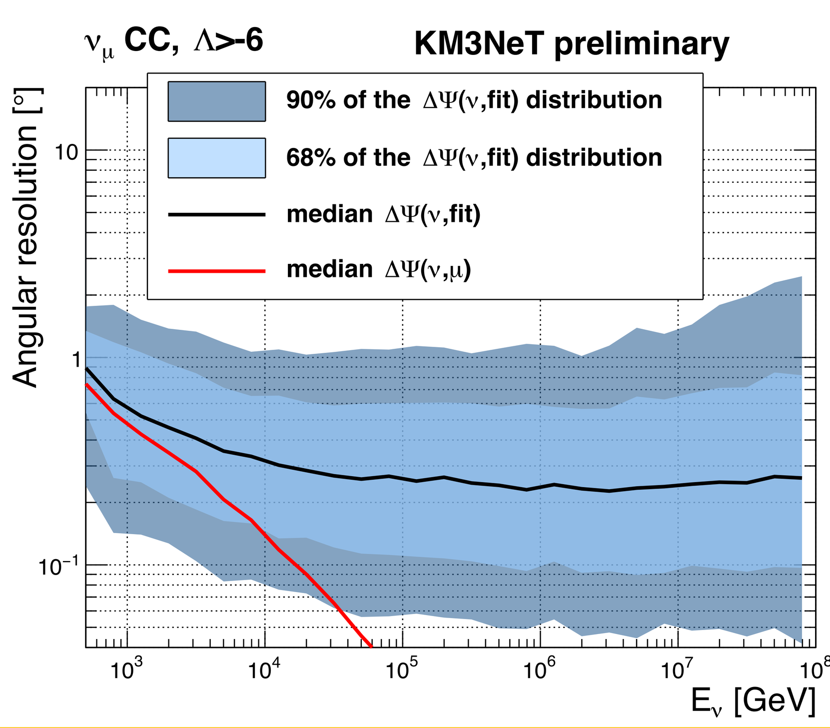
Time residuals distributions with respect to the simulated muon track for signal hits (red) and for events with the ^{40}K contribution added (black).

Results:

The reconstruction output is the reconstructed track and an estimator of the fit quality, Λ, calculated as the maximum log-likelihood value per degree of freedom found in the fit. This variable is used to reject badly reconstructed events. A cut Λ>-6 will remove most of the atmospheric muons misreconstructed as upgoing.



Cumulative Λ distributions of the atmospheric μ and $\nu_\mu+\bar{\nu}_\mu$ reconstructed as upgoing.



The neutrino angular resolution is defined as the median of the angular distance between the simulated neutrino and the fitted track (black line). It reaches about 0.2° above 10 TeV.

Neutrino angular resolution (black line). The light and dark blue bands indicate the 68% and the 90% quantiles, respectively. For reference also the median of the intrinsic angle, the angular distance between the simulated neutrino and the corresponding muon, is reported with a red line. A cut Λ>-6 is applied both for the calculation of the angular resolution and of the intrinsic angle.

References

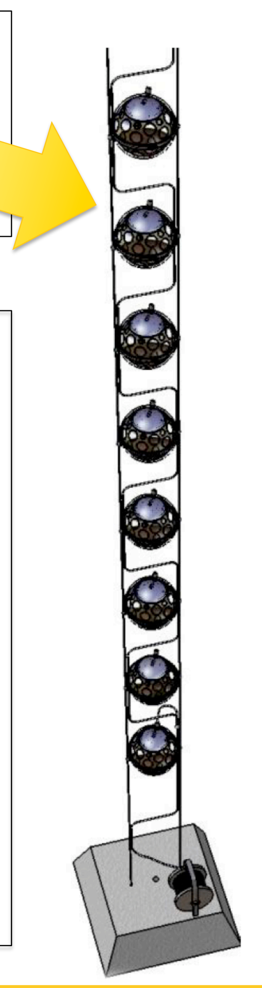
[1] P. Piattelli et al. (KM3NeT Collaboration), these proceedings (ID=1158).
[2] A. Hoecker et al. TMVAUsersGuide (2013).
[3] A. J. Heijboer, PhD thesis, Universiteit van Amsterdam (2004).
[4] A. Trovato, PhD thesis, Università degli studi di Catania (2013).

KM3NeT/ARCA detector [1]

The KM3NeT detector will consist of three-dimensional arrays of 17 inch diameter pressure resistant glass spheres, the so-called DOMs (Digital Optical Modules).

A DOM contains 31 three-inch photomultipliers (PMTs) and their readout electronics.

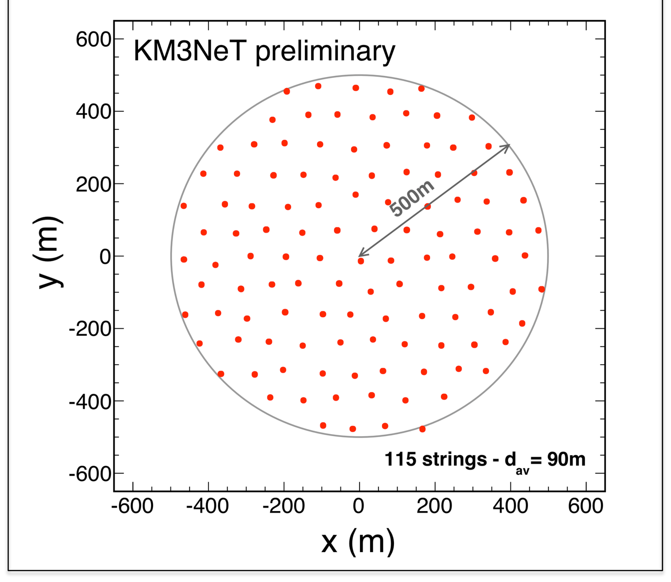
The DOMs will be arranged in detection units (DU):
- ➢ 18 DOMs/DU
- ➢ 36 m DOM spacing



The detector array will be subdivided into building blocks of 115 detection units each (volume about 0.5 km^3).

KM3NeT/ARCA will consist of 2 building blocks installed at the CapoPassero site (Italy) at a depth of 3500 m

Detector footprint:



Muon energy estimate

The muon energy can be estimated from the light collected inside the instrumented detector volume.

Muon energy loss:

- $-dE/dx = a(E) + b(E)\,E_\mu$

  ionisation *stochastic energy loss*
- Muons with E > 1 TeV lose energy stochastically, while for lower energies ionisation dominates.

Containment selection:

- Muons have to travel an adequate distance inside the instrumented volume to permit the energy estimate.
- A reference distance traveled inside the instrumented volume, **L**, is estimated in the code as a function of the reconstructed zenith angle.
- For each event the distance **L_{rec}** between the first and the last PMT position along the track is calculated
- The event is accepted if **L_{rec} >0.3L** → The fraction of the reconstructed events with Λ>-5.8 that survive this selection is greater than 90% for 1 TeV < E_μ < 100 PeV

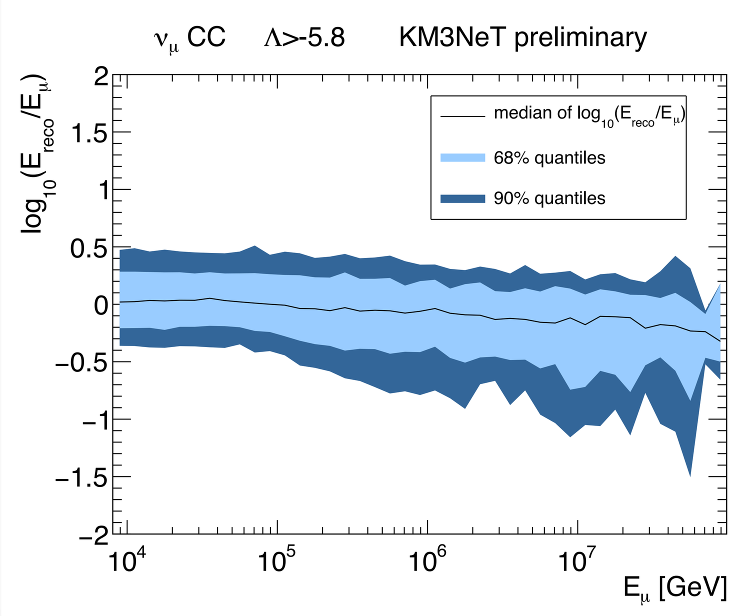
Neural network:

- An artificial neural network is used, specifically a Multi-Layer Percepton (MLP) Neural Network [2].
- Quantities used to feed the Neural Network:

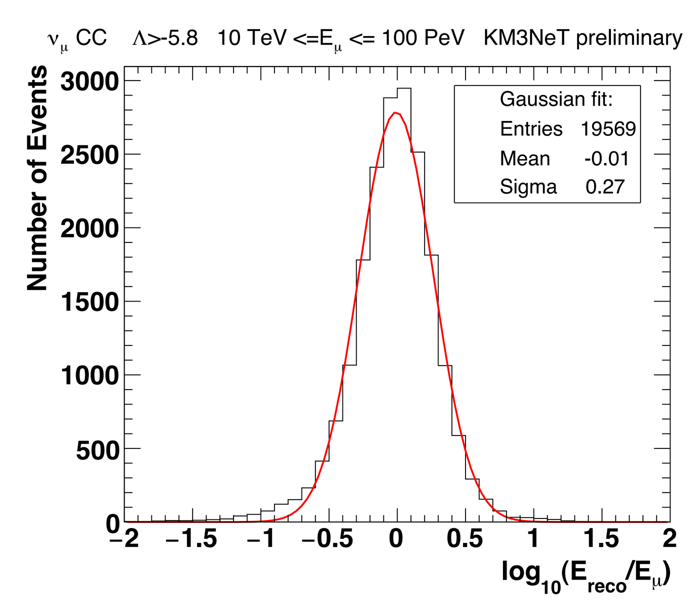
i. Number of DOMs with hits used for the track direction reconstruction.
ii. Number of hit PMTs, N_{PMT}, weighted according to the vertical distance from the track.
iii. Ratio of N_{PMT} over the number of PMTs where a signal was expected but not recorded
iv. Total time over threshold (ToT) of all PMTs used in the track direction reconstruction.

Results:

Energy resolution for all events with Λ>-5.8 of about 0.3 in units of $\log_{10}E_\mu$ for E_μ > 10 TeV



Median of $\log_{10}(E_{reco}/E_\mu)$ with 68% and 90% quantiles for events that satisfy the containment selection.
- ✓ E_{reco} → reconstructed energy
- ✓ E_μ → MC muon energy



Distribution of $\log_{10}(E_{reco}/E_\mu)$ for events with E_μ> 10 TeV that satisfy the containment selection and a gaussian fit. The energy resolution corresponds to about 0.27 in units of $\log_{10}E_\mu$

Conclusions

- ✧ The algorithms described to reconstruct the muon direction and energy of events recorded by the KM3NeT/ARCA detector reach a median angular resolution of about 0.2° (for E_ν > 10 TeV) and an energy resolution of about 0.3 in $\log_{10}E_\mu$ (for E_μ > 10 TeV).
- ✧ Performance tested also for detector configuration corresponding to larger average horizontal distance between strings
  - ✓ For a distance of 120 m instead of 90 m corresponding to a volume of about 0.8 km^3 per block:
  - ➢ performance almost unchanged both for the median angular resolution and for the energy resolution