Reconstruction in KM3NeT

WCD 2025, Kraków

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Reconstruction

Overview

- Introduction
  - Reconstruction General
  - KM3NeT Infrastructure
  - KM3NeT Detector Calibration
- PDFs of the Arrival Time of Light
- Muon Track Reconstruction
- Shower Reconstruction
  - ORCA
  - ARCA
- Beyond the Standard Reco
- Reconstruction of an UHE neutrino by KM3NeT

General

Reconstruction in Water Cherenkov Detectors

- Fitting a model to data
- Model: event hypothesis which should accurately describe the signal induced in the detector
- Estimate the direction and energy of the event as accurately as possible

- For neutrino experiments such as KM3NeT, an accurate reconstruction increase the discovery potential of a detector to astrophysical neutrino sources, or improves the sensitivity and measurement of neutrino oscillation parameters and the neutrino mass ordering (NMO)

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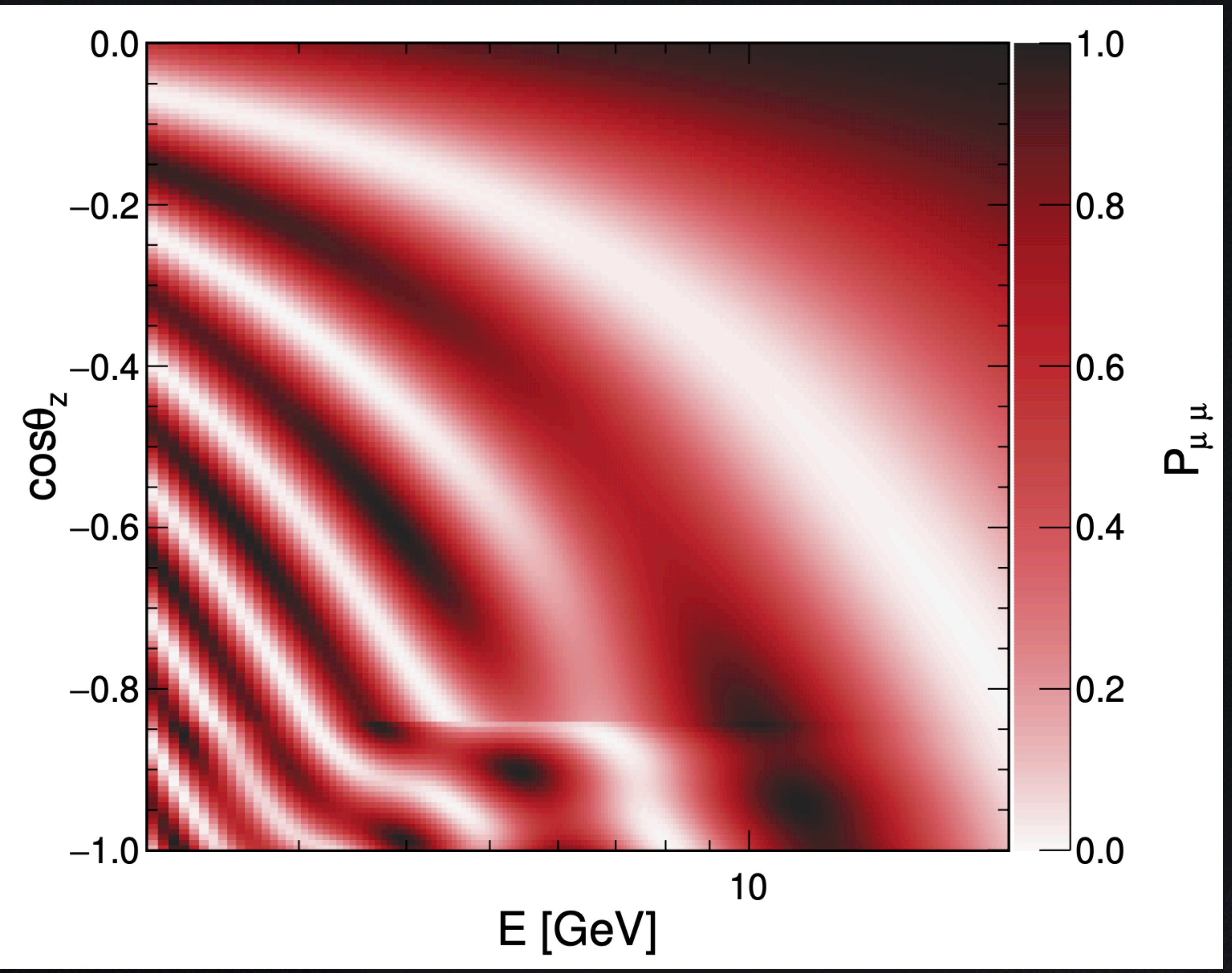
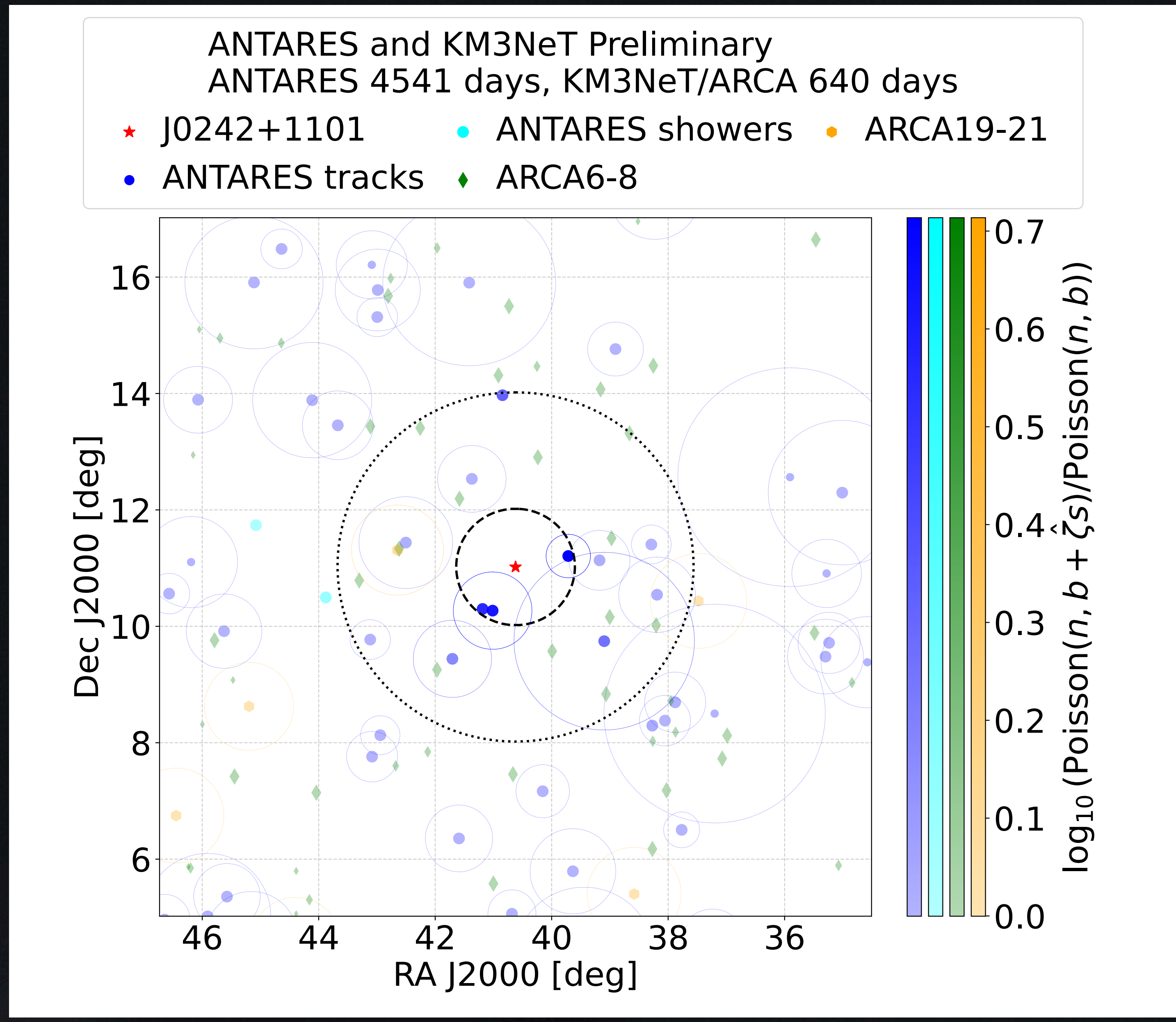


Measurement of neutrino oscillation parameters with the first six detection units of KM3NeT/ORCA, KM3NeT Collaboration (2024)



Combined KM3NeT-ARCA and ANTARES searches point-like neutrino emission, KM3NeT Collaboration (2025)

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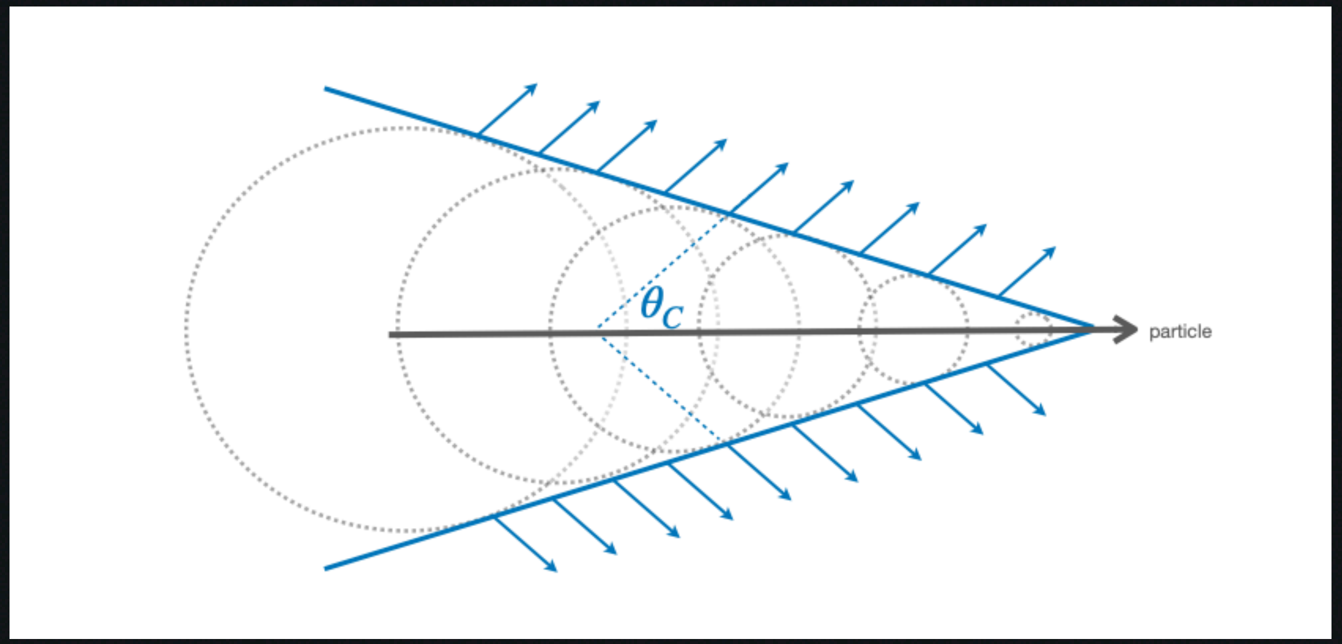
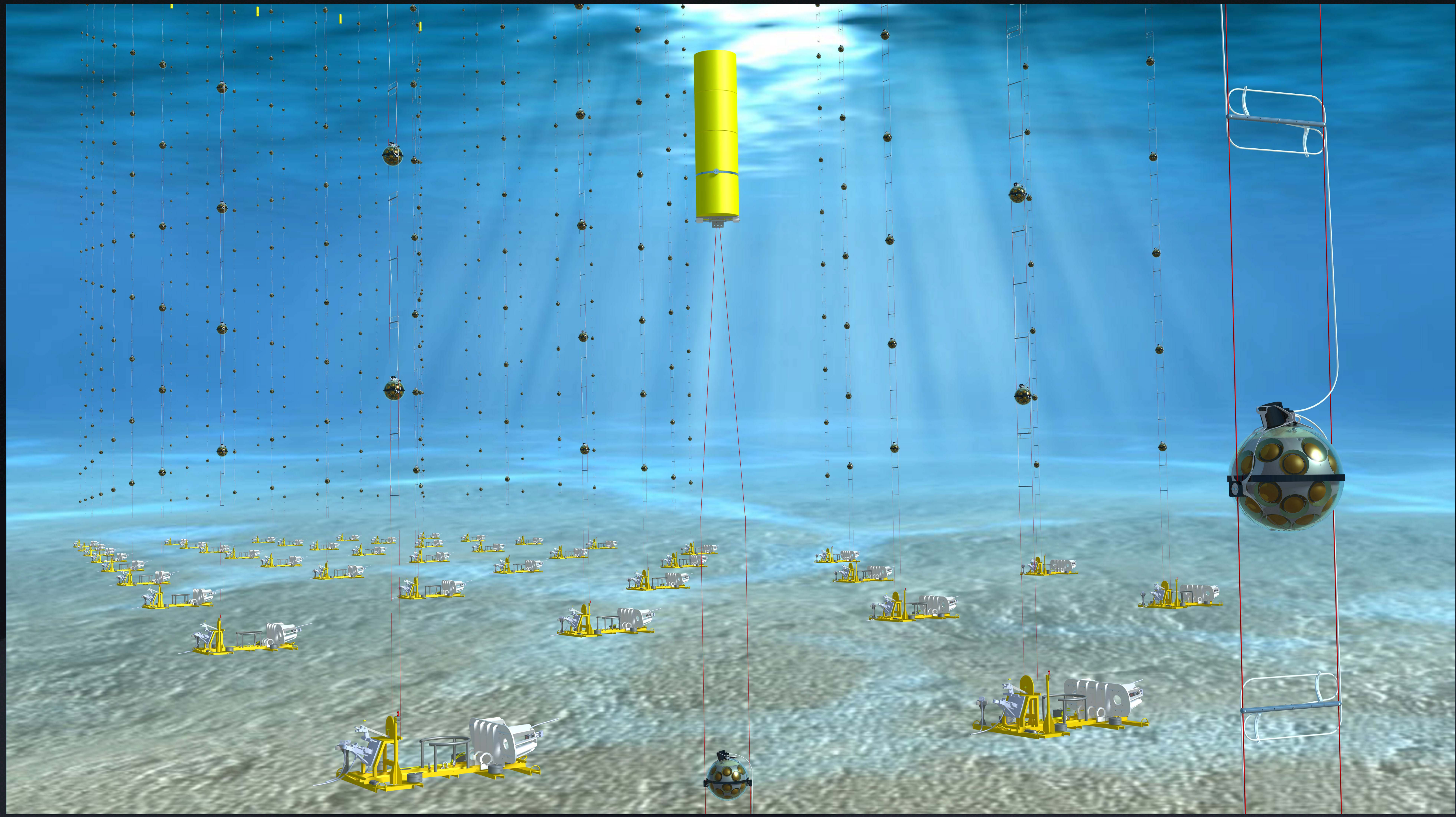
General

Reconstruction in Water Cherenkov Detectors

- M. Markov proposed an idea
  "to install detectors deep in a lake or a sea and to determine the direction of charged particles with the help of Cherenkov radiation."
- KM3NeT in sea water - make use of our excellent understanding of optical properties of water
- Naturally-occurring detection medium, water overburden and surrounding volume offers shielding against background signals
- Offers its own challenges too: in sea water we have ^{40}K background radiation, sedimentation, bioluminescence, dynamic environment in which to operate a detector

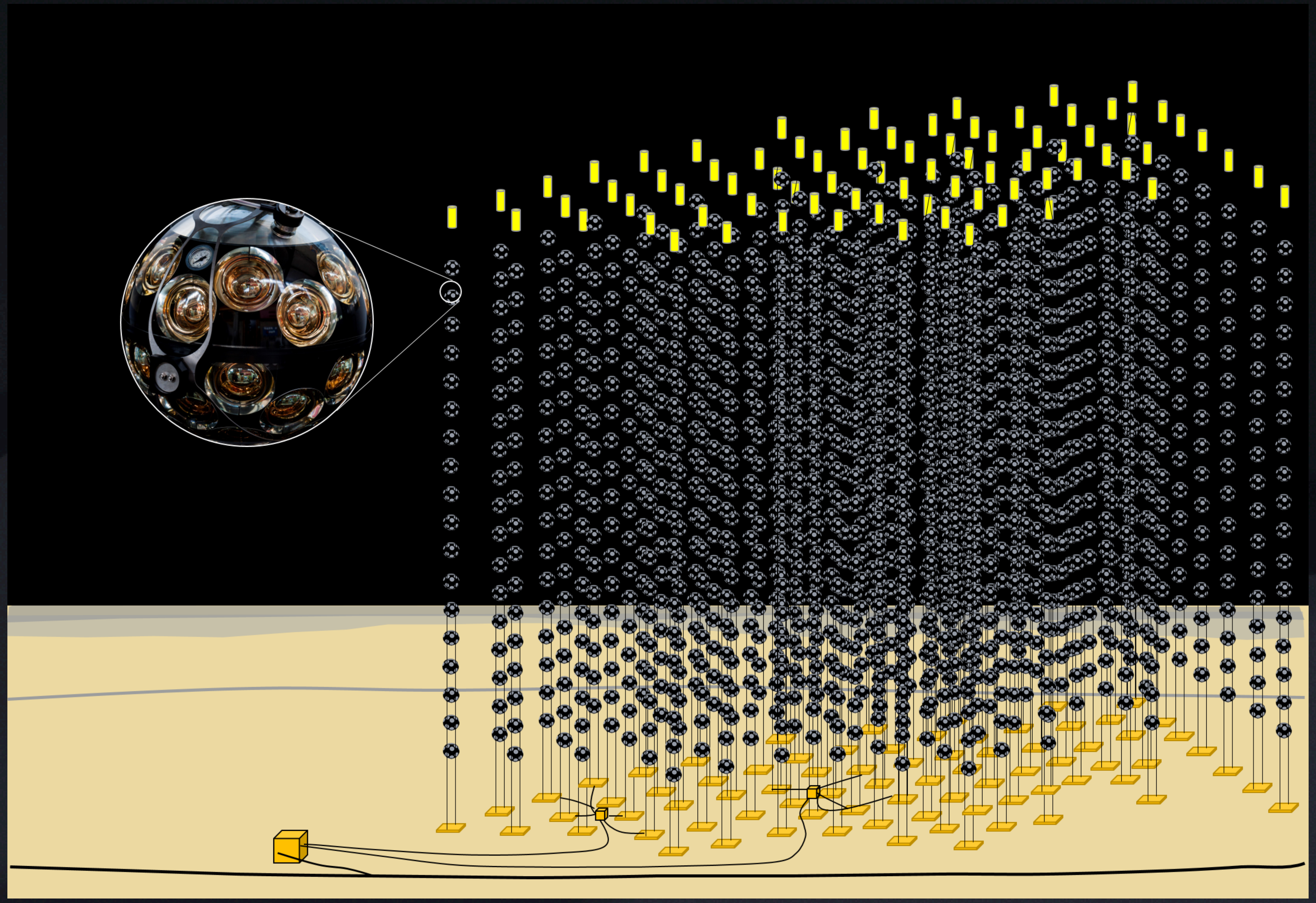




KM3NeT

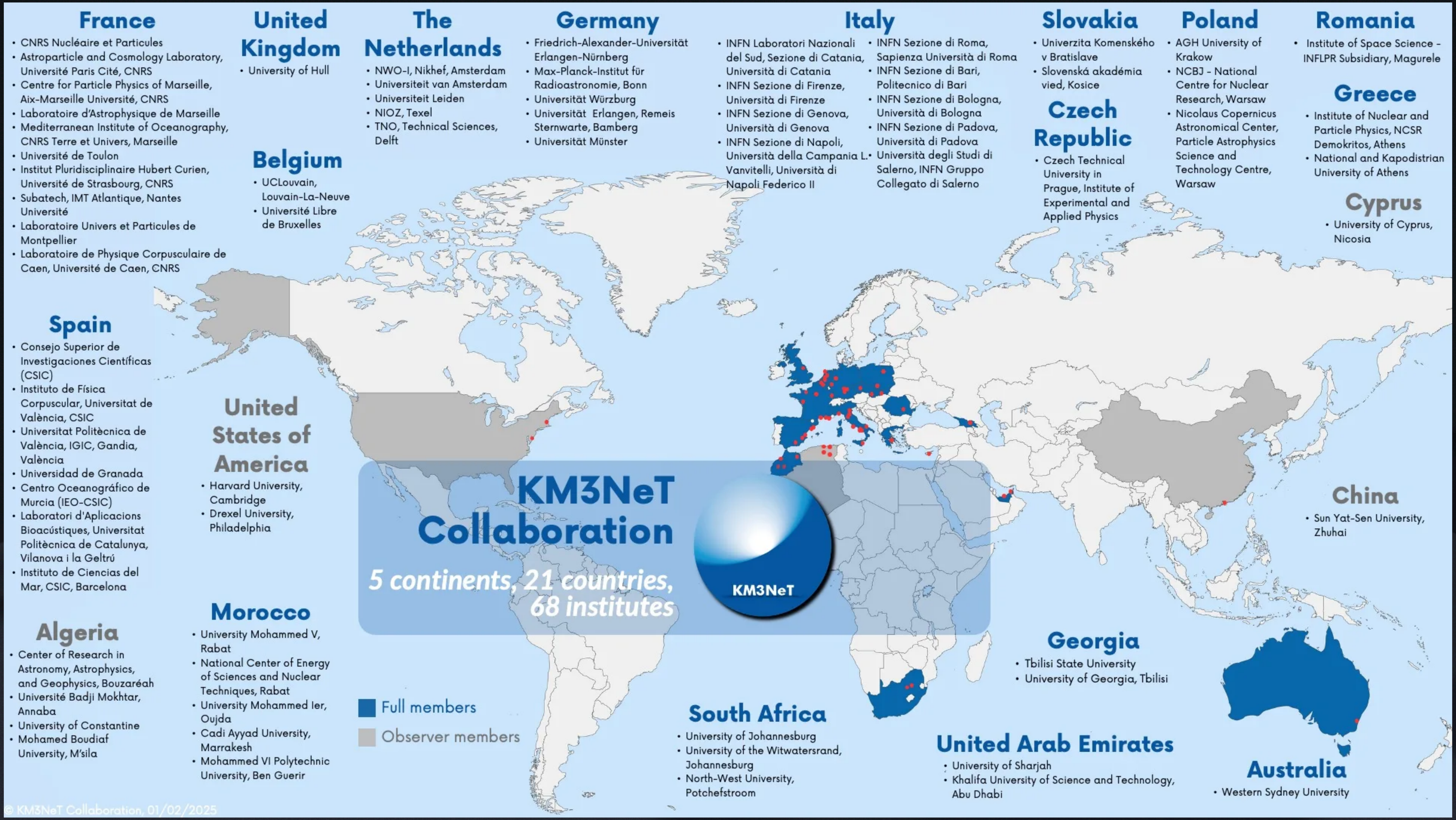
Infrastructure

- Two detector sites.
  - KM3NeT/ORCA
    ~2.5 km below sea level, ~40 km from Toulon, France
  - KM3NeT/ARCA
    ~3.5 km below sea level, ~100 km from Porto Palo di Capo Passero, Italy
- 31 PMTs -> 18 digital optical modules (DOMs) -> 115 detection units -> 1 building block
- ORCA foresees 1 building block - currently installed 28/115 detection units
  ARCA foresees 2 building blocks - currently installed 51/230 detection units
- Same technology optimised for different ν energy ranges, by modifying the detector geometry
- These alternate geometries allow for different reconstruction techniques due to differing event signatures



KM3NeT

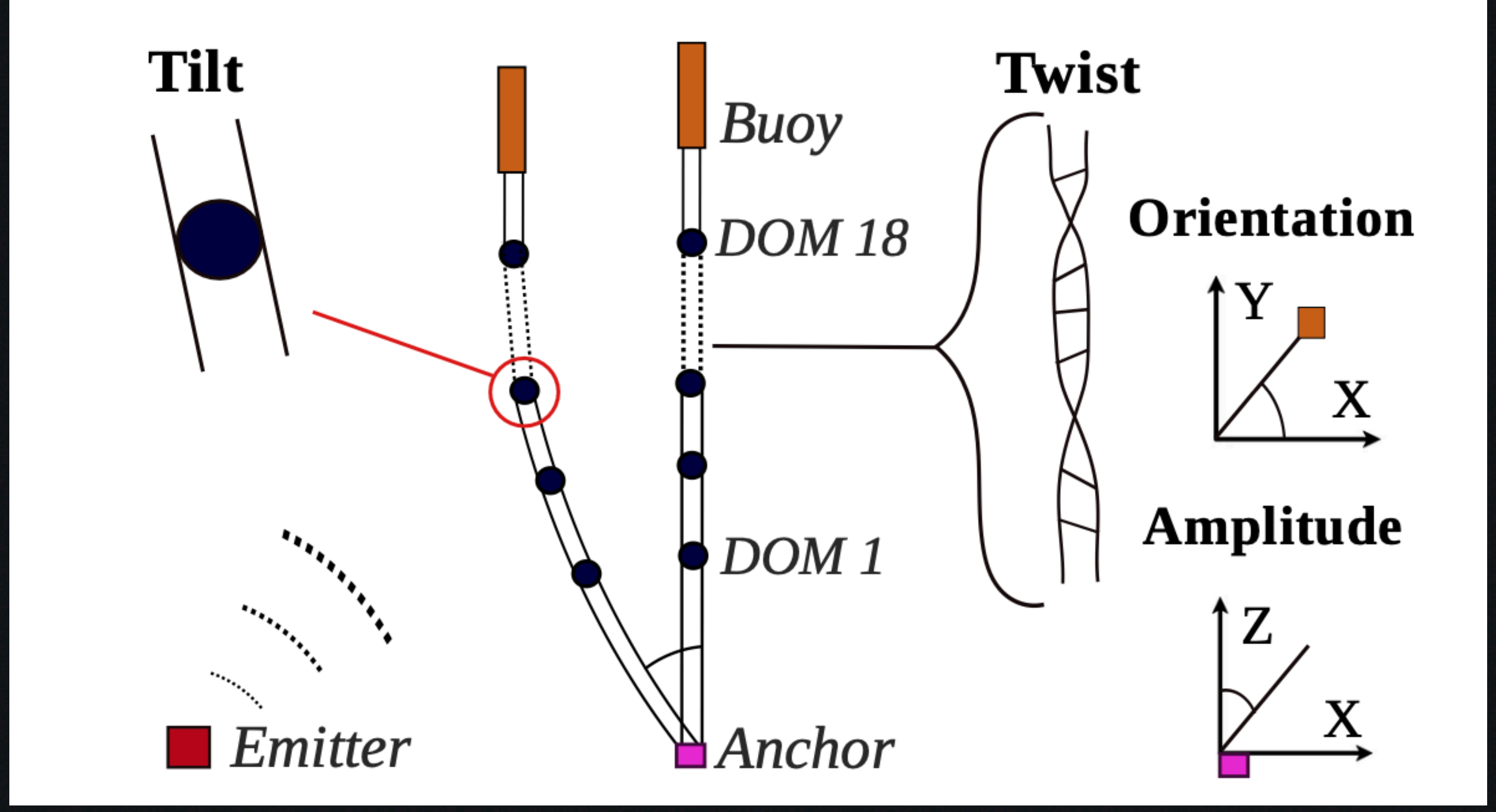
Collaboration

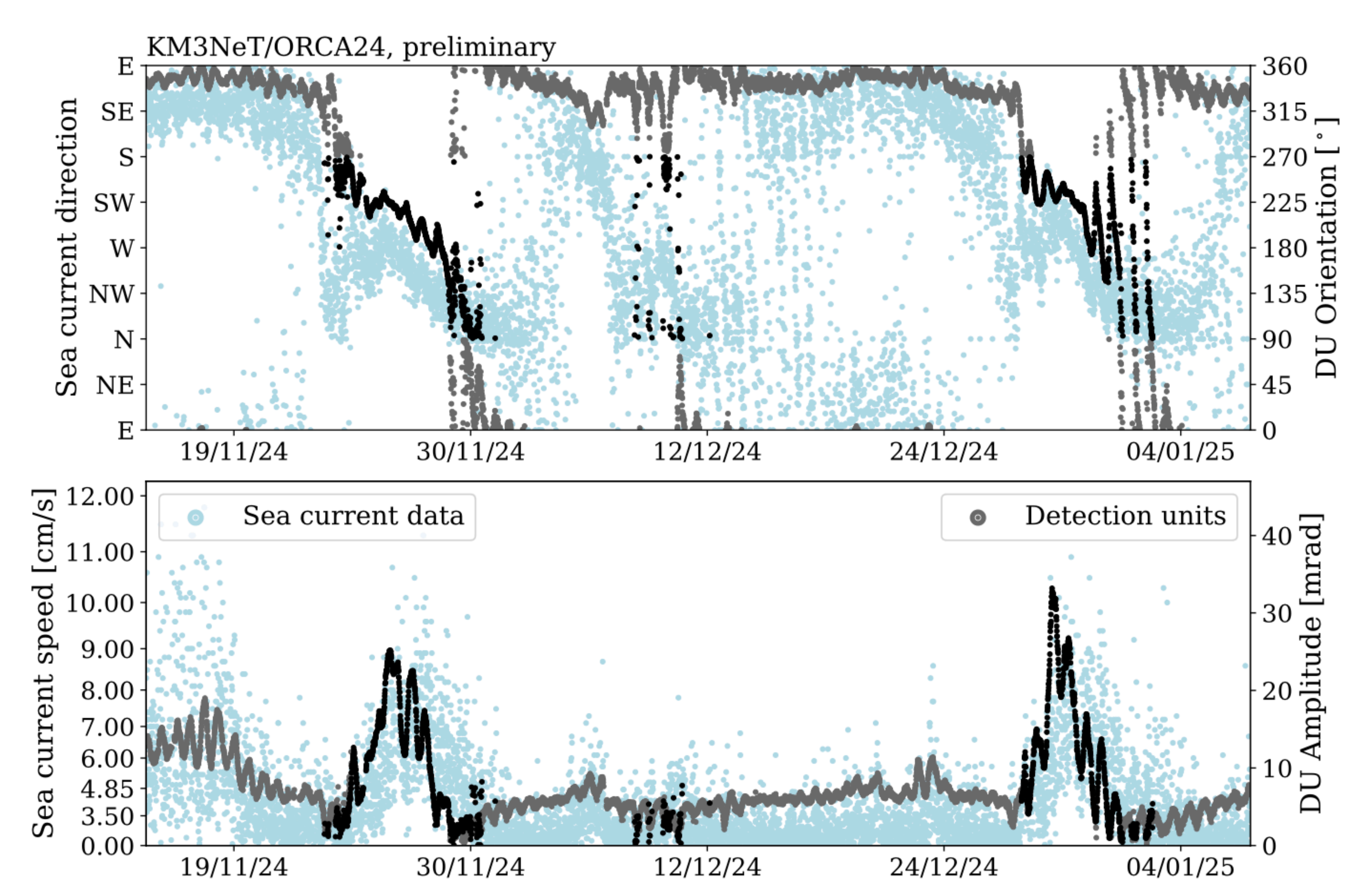


KM3NeT

Detector Calibration

- For an angular resolution of 0.05° in ARCA, the positional resolution must be of the order ~20 cm, and tilt/rotational accuracy of < 3°
- Within the infrastructure are autonomous beacons which emit pings, received by piezo sensors on the DOMs
- This allows for an acoustic calibration procedure to be carried out: global fit procedure of the acoustic data
- Without this calibration procedure, any reconstruction of events would be without reason
  -> the true position and direction of event needs to be determined, not affected by a skewed or mis-oriented detector





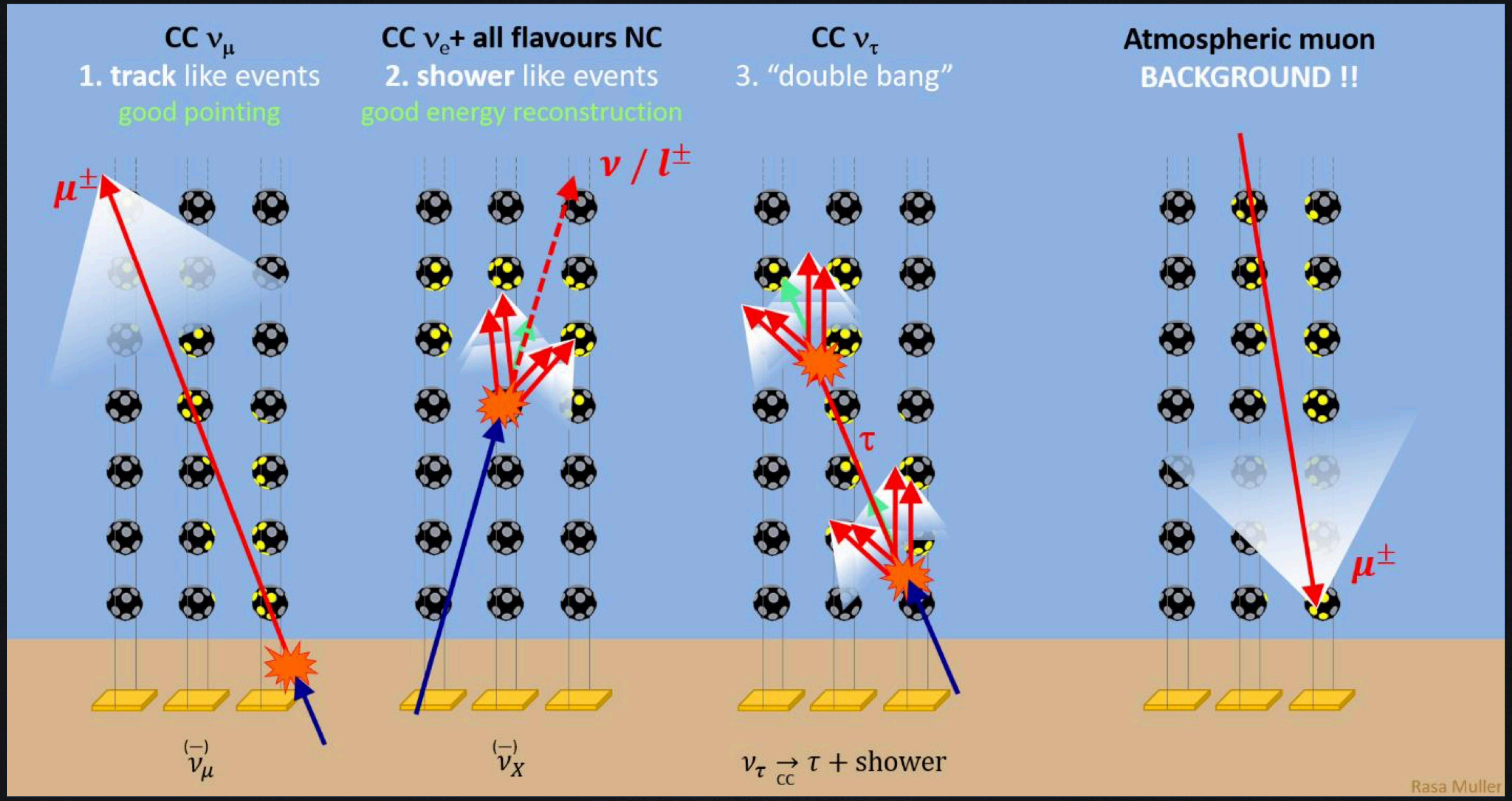
Dynamic positioning and orientation calibration for the KM3NeT detectors, Lessing, N. (2025)

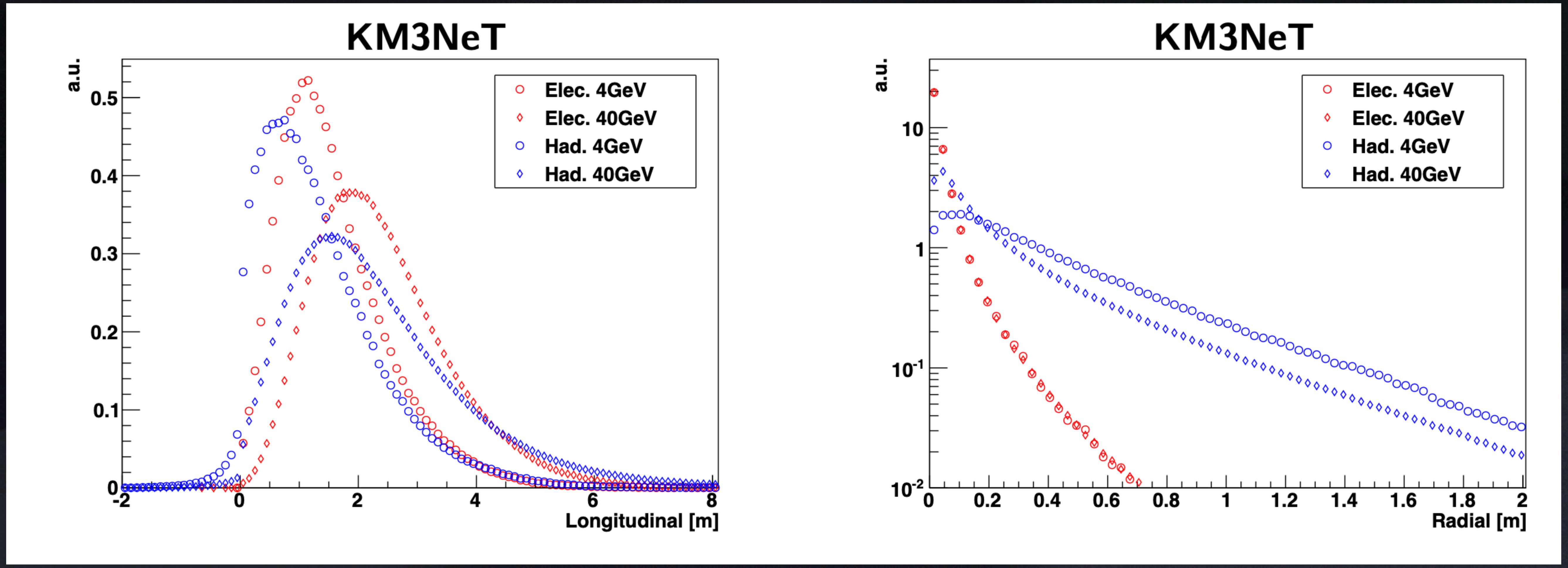
Event Signatures

Topologies

- Various event topologies can be distinguished in the detector, due to the different 3-D patterns of signal position and times induced in the detector
- Track-like events:
  - induced by μ tracks (or τ tracks, although shorter lived), results in a 'straight line' of light deposit in the detector
- Shower-like events:
  - induced by all ν flavours in the detector, can be induced by hadronic particle showers or electromagnetic ones

    These result in localised bursts of light in the detector, with elongation features which depend on the particle types and energies
- The different profiles of hadronic particle showers or electromagnetic showers result in features to be exploited by reconstruction techniques





KM3NeT Letter of Intent, KM3NeT Collaboration (2016)

Photon Arrival Time Distributions

PDFs of the Arrival Time of Light

- At present, some reconstruction techniques in KM3NeT make formidable use of 'light PDFs', which can be calculated from first principles for track or shower-like event signatures.

- Presented in The probability density function of the arrival time of Cerenkov light, de Jong, M., van Campenhout, E. (2023)

- Descriptions of the
  -instantaneous
  -cumulative
  -total
  expected number of photo-electrons per second on the PMT, as a function of the arrival time, can be calculated for a set of event parameters: (E, R, θ, ϕ, t)

- These calculations take the detector response into account, with the PMT Q.E., the light collection efficiency, and optical properties of light included

- These PDFs can be calculated for light emitted directly from the event and reaching a PMT, for scattered light, and radiation emitted by delta rays or secondary electromagnetic shower emission along the track.

Photon Arrival Time Distributions

PDFs of the Arrival Time of Light

- One such example from this paper of the expected number of photo-electrons for unscattered muon radiation

3.1 Direct light from a muon

For direct light from the muon, the zenith angle at which the photons are emitted can be considered fixed ($\theta_0 = \theta_C$). The distribution of the arrival times of the photons is then mainly determined by the dispersion of light in the medium. The probability density function for the distribution of the arrival times can then be expressed as:

$$\frac{d\mathcal{P}}{dt} = \Phi_0(R,\lambda)\,A\left(\frac{\partial t}{\partial\lambda}\right)^{-1}\varepsilon(\cos\theta_\oslash)\,QE(\lambda)\,e^{-d/\lambda_{abs}}\,e^{-d/\lambda_s} \qquad (43)$$

PDFs of the Arrival Time of Light

Detectable flux

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PMT photo-cathode area

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Time derivative w.r.t. wavelength

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Photon Arrival Time Distributions

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QE of PMT

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Photon Arrival Time Distributions

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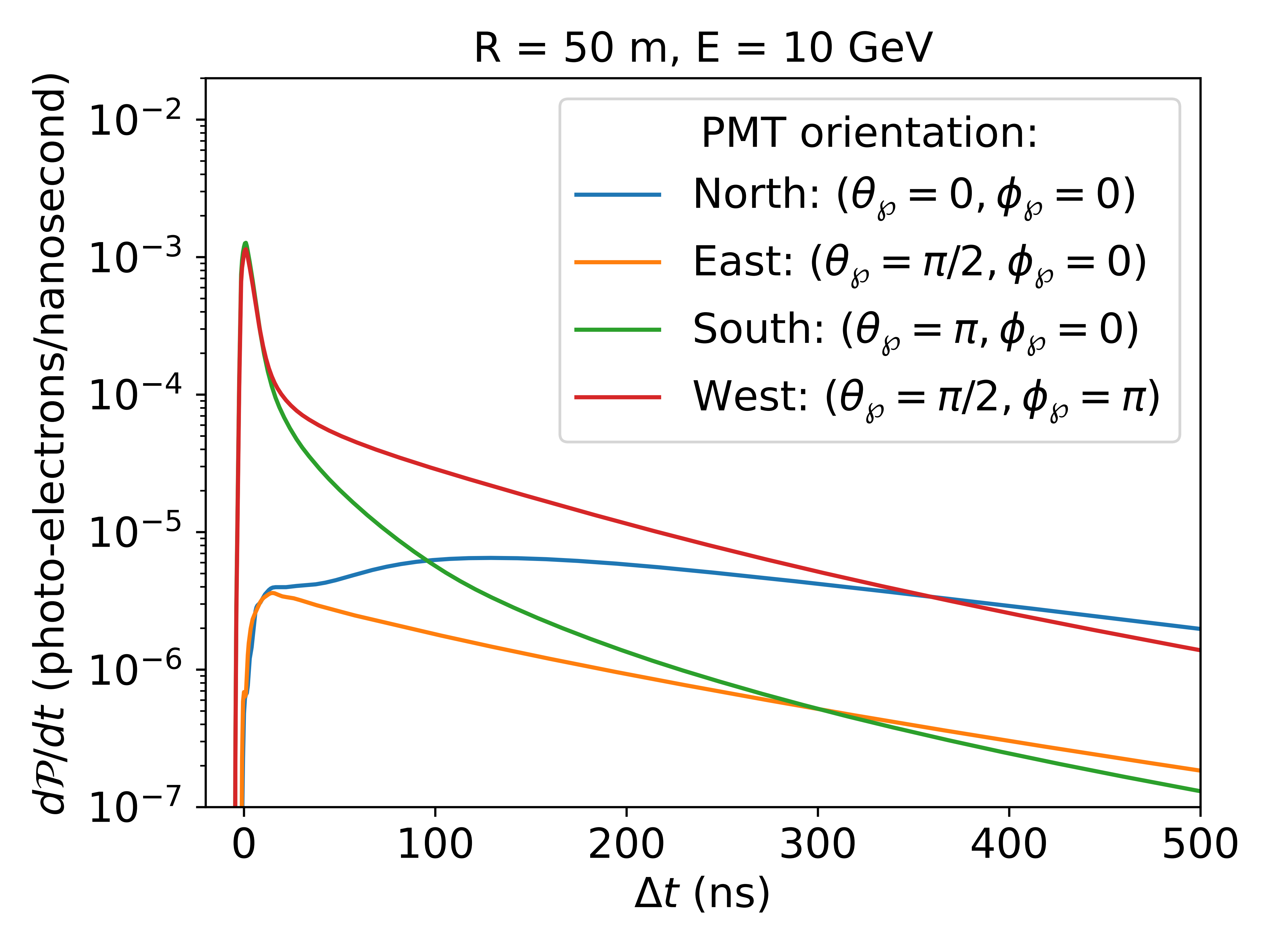
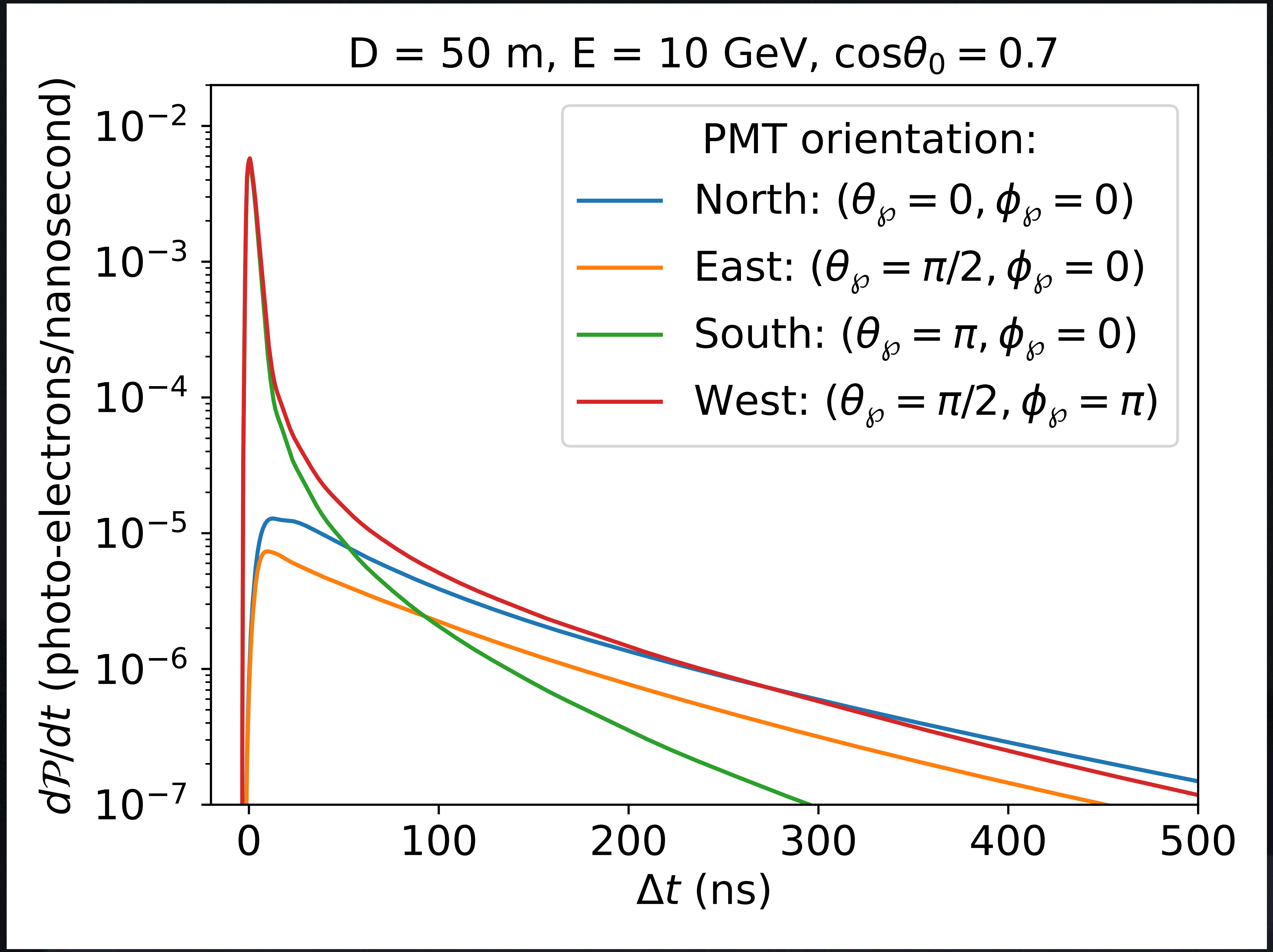
MuonTrack



EM Shower



Following the Light, PhD thesis, Ó Fearraigh, B. (2024)

Event Reconstruction

Likelihood Minimisation

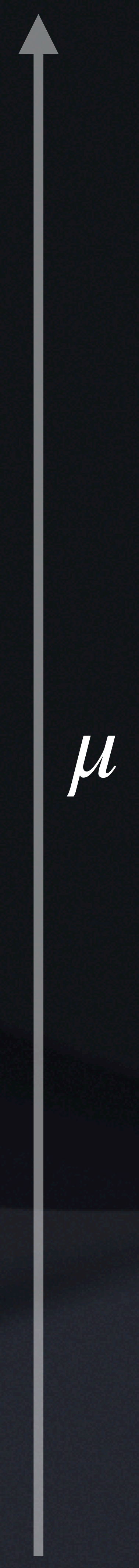
- Using the light PDFs for the appropriate event signatures, parameter estimation techniques can be used in reconstructing the events
- In the following methods, the $-\log \mathscr{L}$ (likelihood) is minimised, given the event model in question. We also make use of the Simplex algorithm, M-estimators, some minimising techniques.
- The same μ track reconstruction algorithms are used for ORCA and ARCA. For shower events, with the differing geometries and shower profiles, distinct procedures are currently employed in their reconstruction between ARCA and ORCA

e.g. see
Statistical Methods in Data Analysis, Metzger, W.J. (2010)

Track Reconstruction

Fit Algorithms

- The track reconstruction procedure in KM3NeT consists of different steps, with distinct fit procedures used to reconstruct the event parameters in sequence.
- The starting value problem is addressed by *linearising* the problem: over a scan of the full sky, thousands of direction are estimated and used estimate that which complies best with the signal. This acts as a 'prefit' stage with a $-\log \mathscr{L}$ to minimise, based on the time residuals of hits



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- Simplex algorithm used to speed up procedure - using an M-estimator

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- Full fit to direction is employed, minimising $-\log \mathscr{L}$, employing the light PDFs and a modified Levenberg-Marquardt method.

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- The track length is determined through the back-projection of signal onto the track, and evaluating the signal falling above or below a pre-defined threshold.

- The energy is determined using the light PDFs and a likelihood minimisation, considering the PMTs with at least one photo-electron hit in the detector

μ

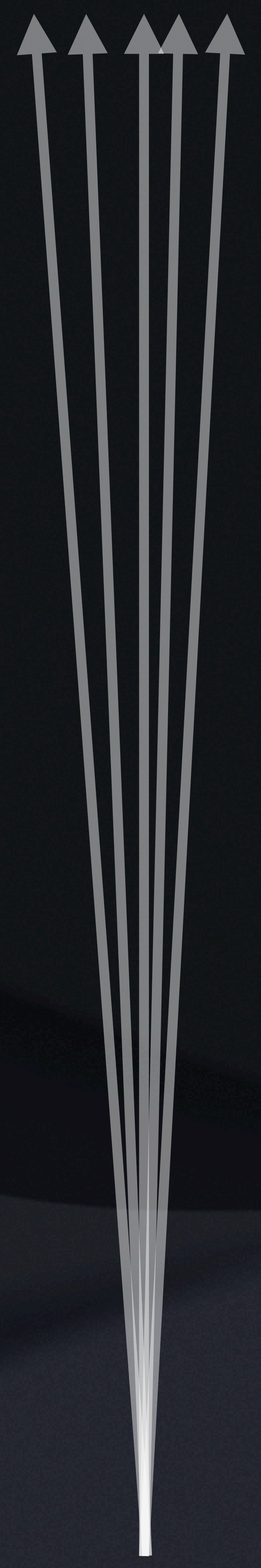
Technical paper in preparation

Recently documented in:
Following the Light, PhD thesis, Ó Fearraigh (2024)

Shower Reconstruction in ORCA

Fit Algorithms

- The shower reconstruction procedure in KM3NeT/ORCA also consists of various fit stages
- A prefit is also carried out here, with the vertex (shower bright point) estimated from the barycentre of hits with a linear fit



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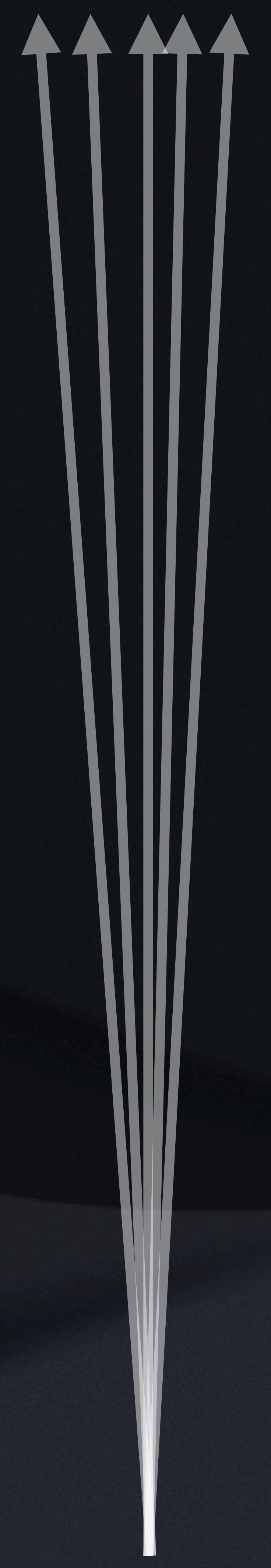

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- Position, energy fit carried out using isotropic shower light PDFs, minimising $-\log \mathscr{L}$ using detector hits

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- Position, energy fit carried out using isotropic shower light PDFs, minimising $-\log \mathscr{L}$ using detector hits

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- Direction, energy prefit carried out with scan over directions, for hit/non-hit PMTs using EM shower PDFs

↓

- Direction, energy fit procedure for direction and energy, minimising $-\log \mathscr{L}$ for all PMTs using EM shower PDFs

Technical paper in preparation

Shower Reconstruction and Sterile Neutrino Analysis with KM3NeT/ORCA and ANTARES, PhD thesis, Domi, A. (2018)

Shower Reconstruction in ARCA

Fit Algorithms

- An expanding sphere of light is used as the model hypothesis.
  Vertex prefit using an M-estimator on coincident hits

  ⇓

  Full shower direction, energy fit, $-\log \mathscr{L}$ minimisation with hit/non-hit PMTs
- Custom MC-based PDFs currently used, although the data tables mentioned above are being introduced
- In development: to include timing information in the likelihood formulation, use elongation of the showers within the PDFs.
- In ARCA, the geometry and energies of interest also allow for a reconstruction of tau neutrinos through 'double bang' events.
  A reconstruction algorithm related to the standard shower reconstruction algorithm has been developed for such events.

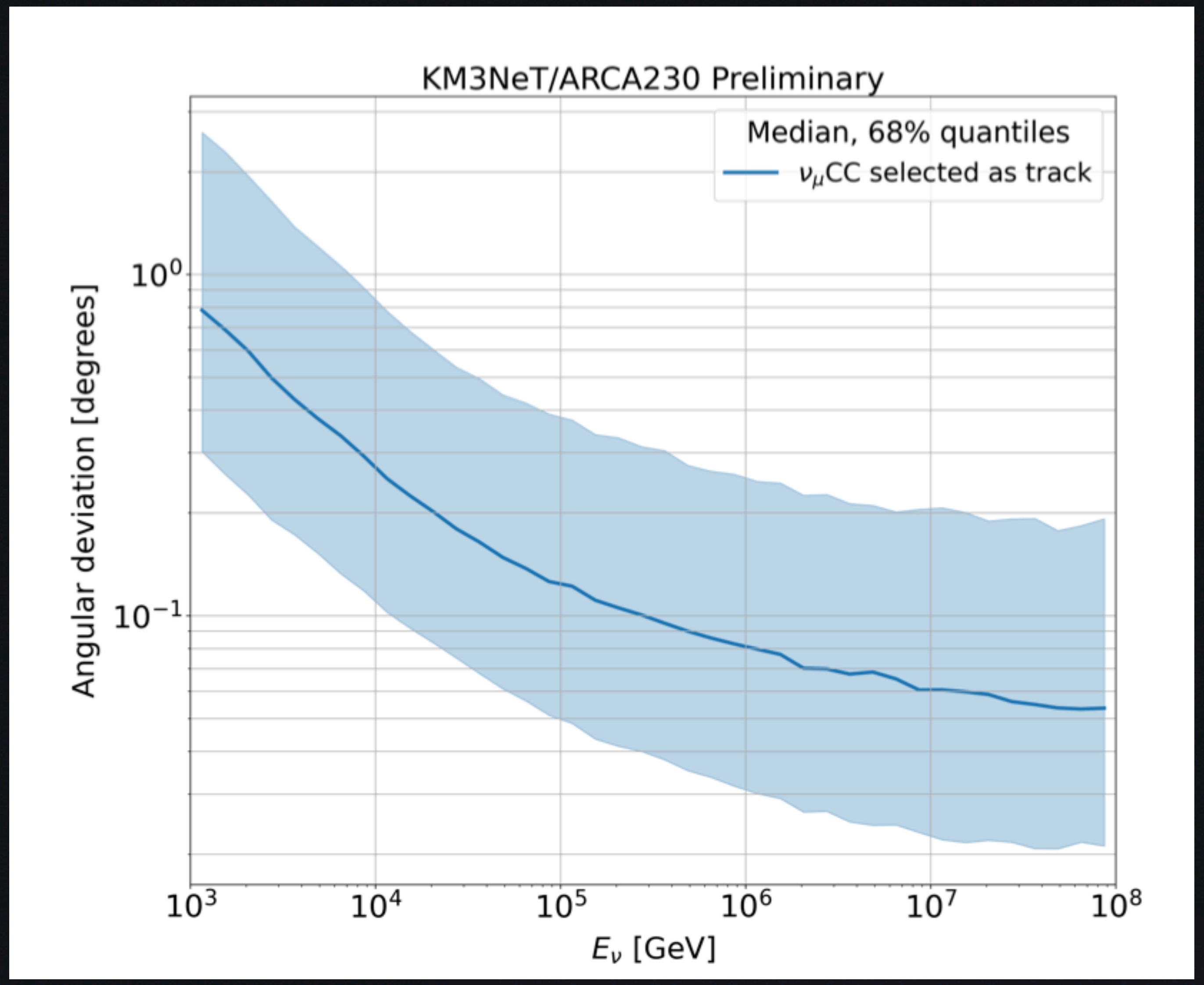
KM3NeT/ARCA Event Reconstruction Algorithms, KM3NeT Collaboration (2017)

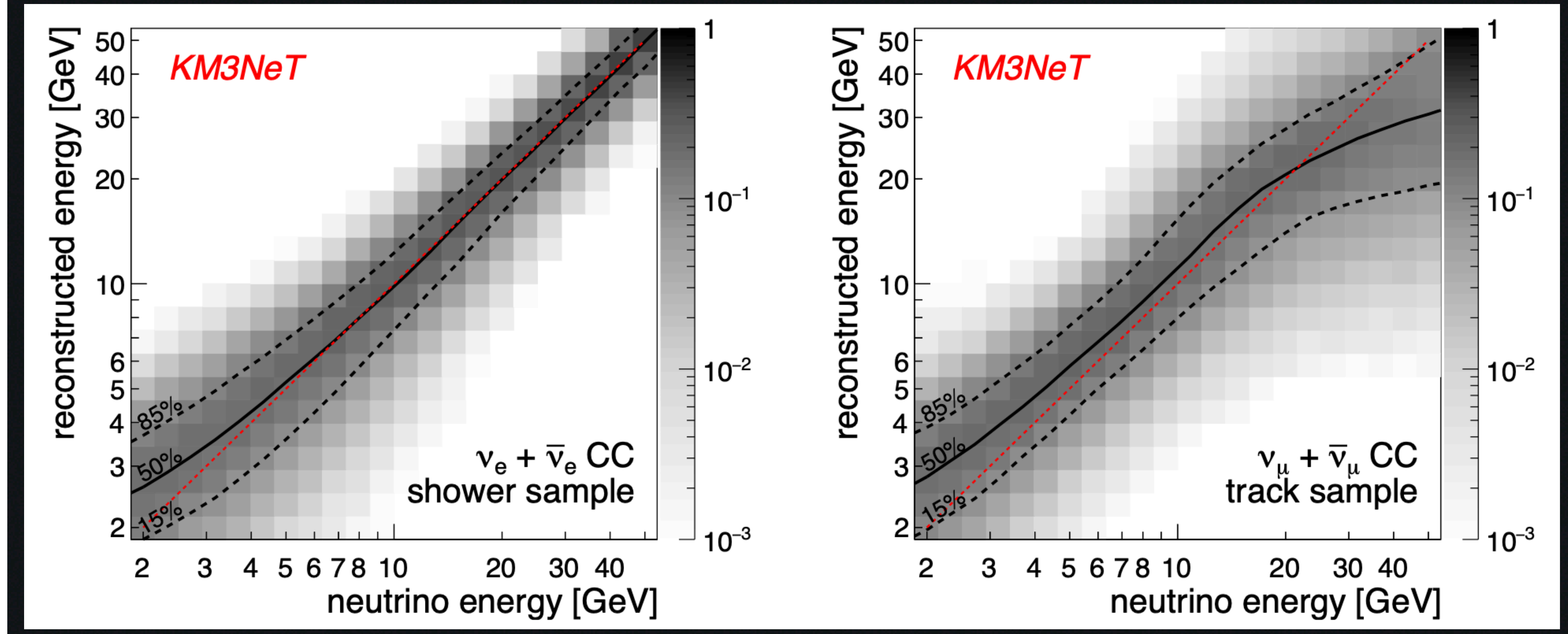
ShineFit: Time-Informed Reconstruction of Cosmic Neutrino Showers, PhD thesis, Seneca, J.A.L. (2024)   Neutrino astronomy with KM3NeT/ARCA, PhD thesis, van Eeden, T.J. (2024)

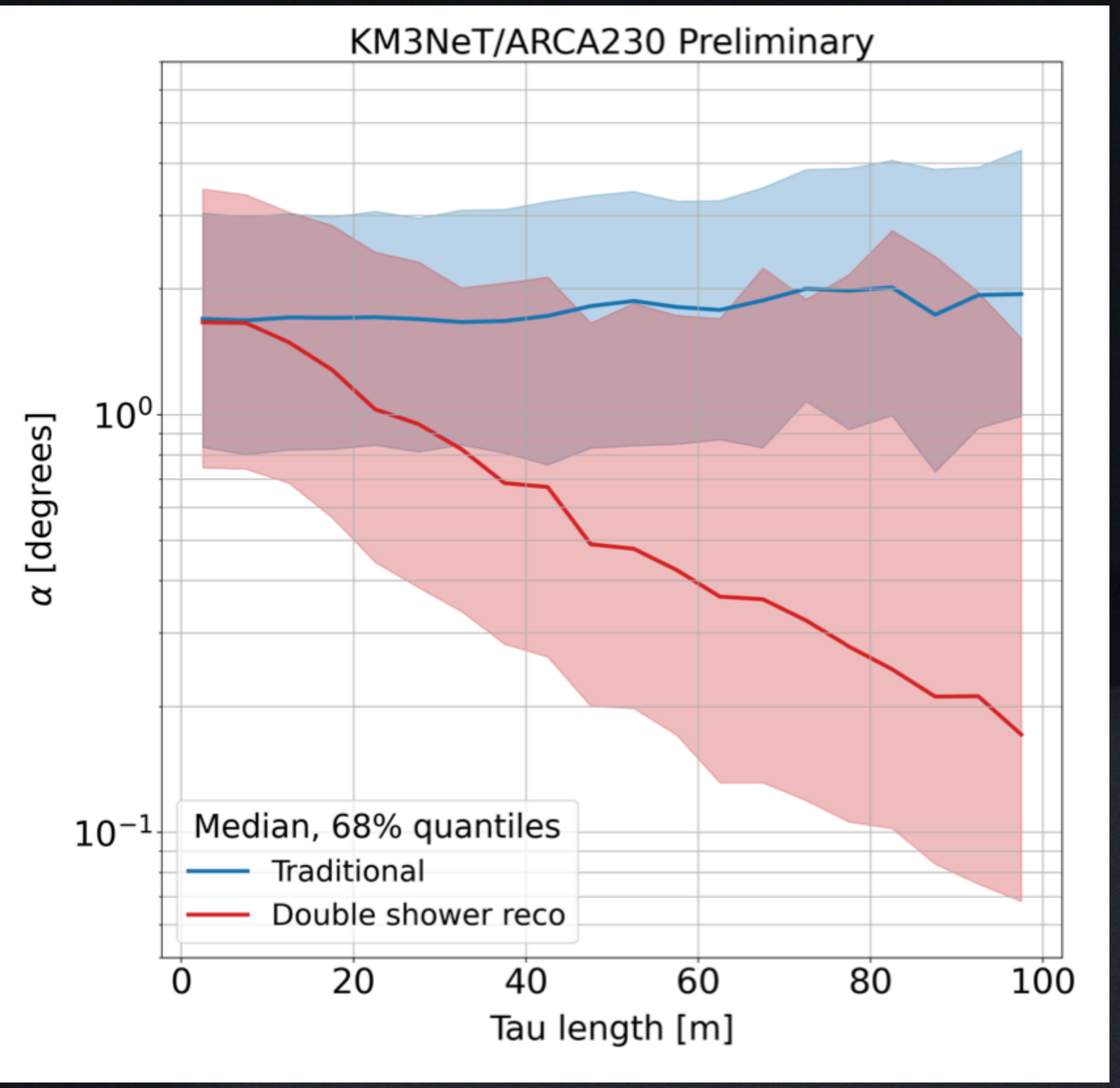
Resolution

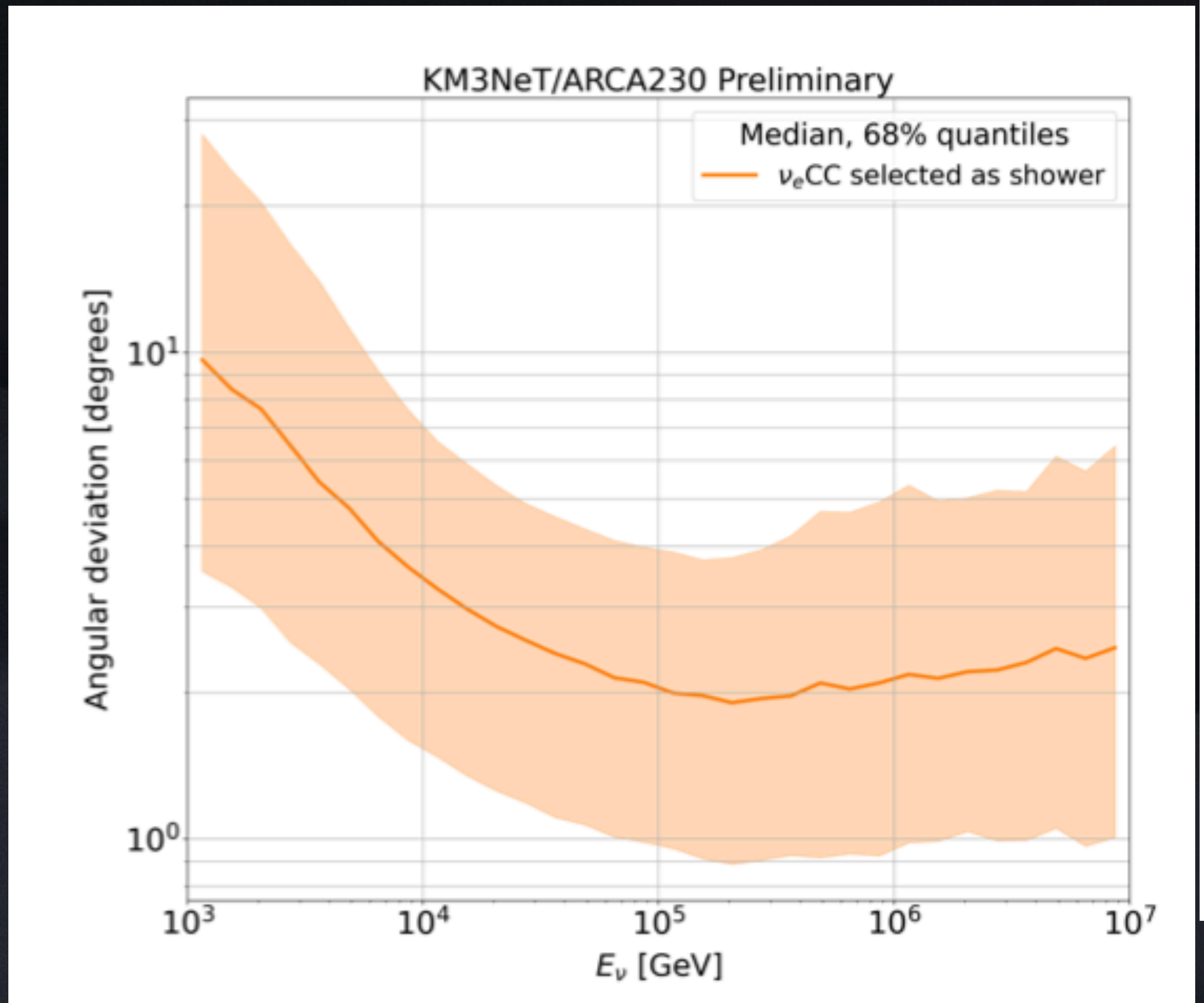
Perfomance Evaluation

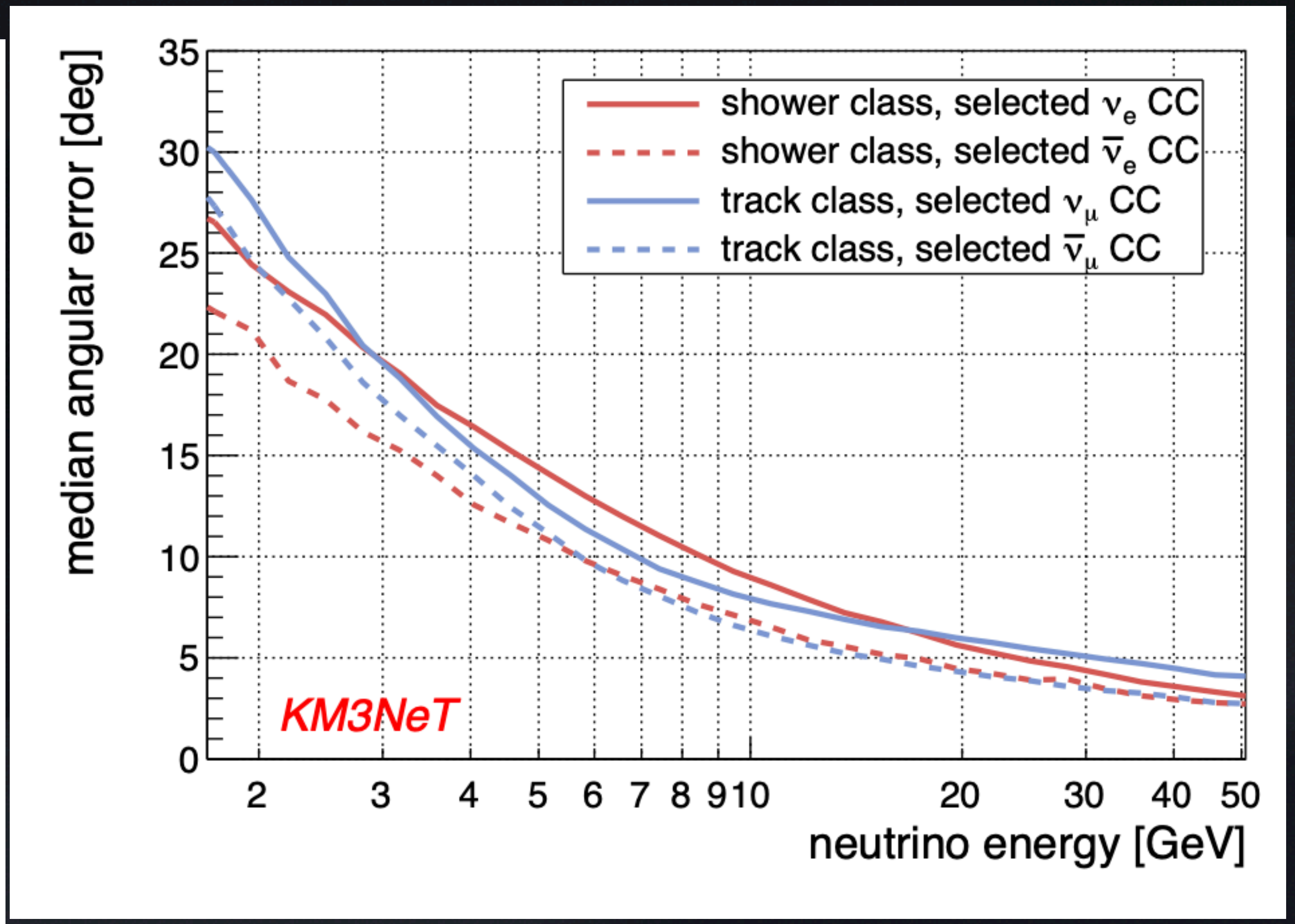
- Angular and energy resolution act as a benchmark of performance; estimate value and error in finding true value
- Competitive track and shower direction/energy resolutions are essential for the physics analyses and experimental goals











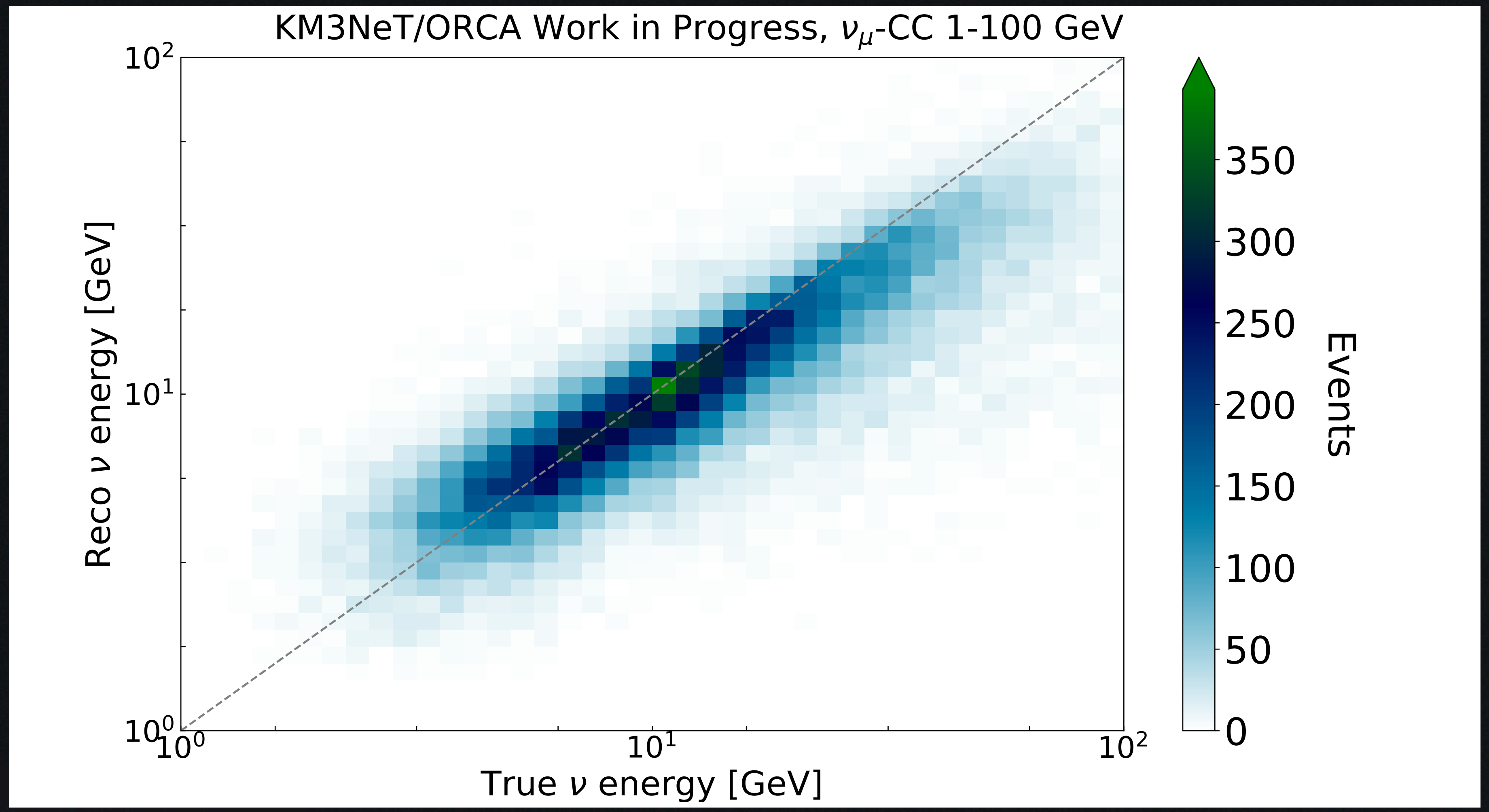
High energy neutrino reconstruction and selections with full KM3NeT/ARCA, KM3NeT Collaboration (2023)

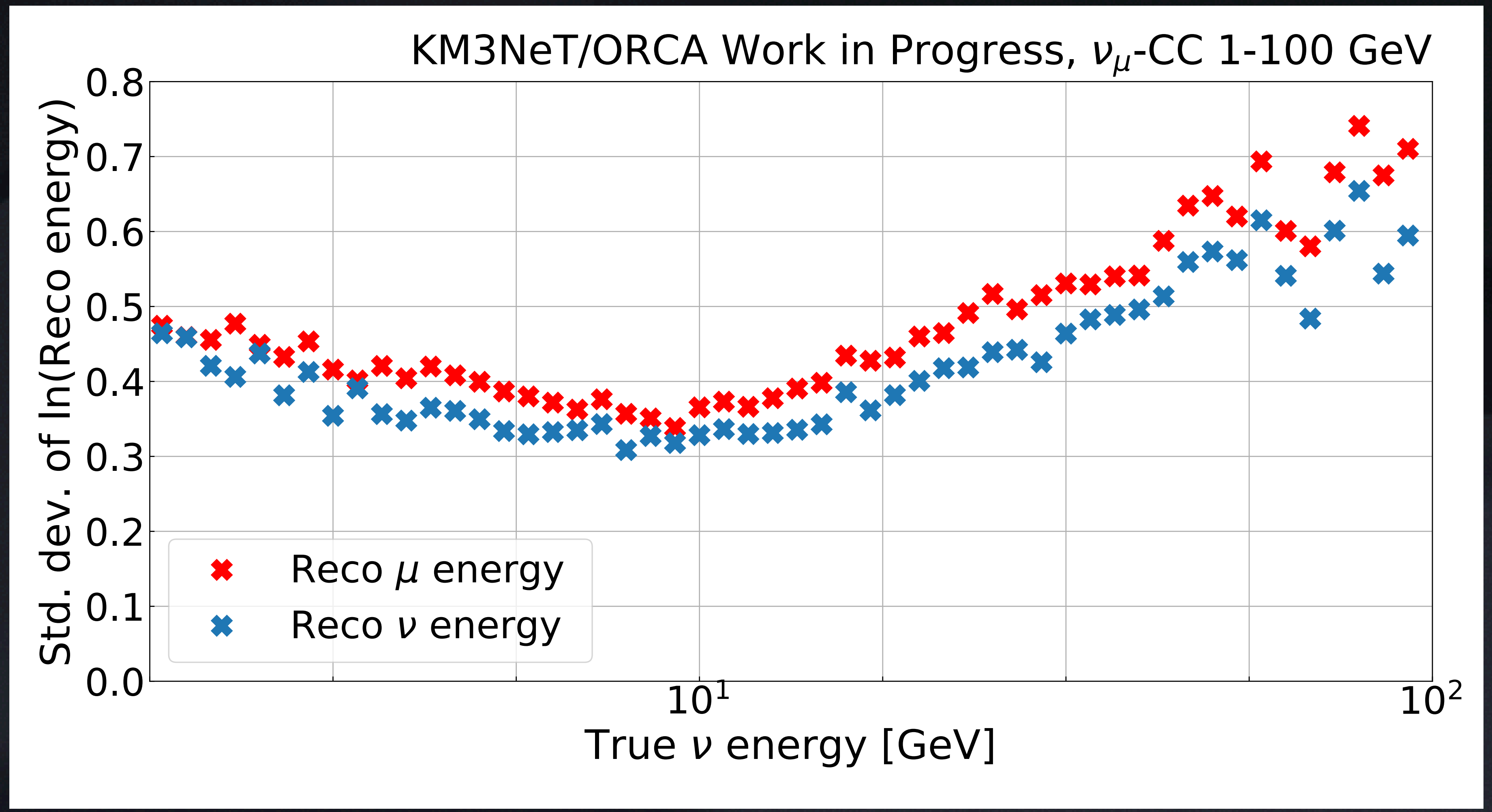
Determining the Neutrino Mass Ordering and Oscillation Parameters with KM3NeT/ORCA, KM3NeT Collaboration (2021)

Beyond the Standard Reconstruction

Other Reconstruction Techniques

- Other developments are being carried out in KM3NeT in reconstructing events.
- One example of such is the reconstruction of events with **both** a **track** and **shower** component, which occurs for all ν_μ-CC interactions
- A method to reconstruct these events has been developed, through the use of the muon + shower PDFs and $-\log \mathscr{L}$ minimisation, using hit and non-hit PMTs
- This complex method involves the determination of the energy and direction of both components, in order to better reconstruct the energy and direction of the neutrino itself.
- Such a procedure would ideally also reconstruct the energy transfer to the nucleon in the interaction





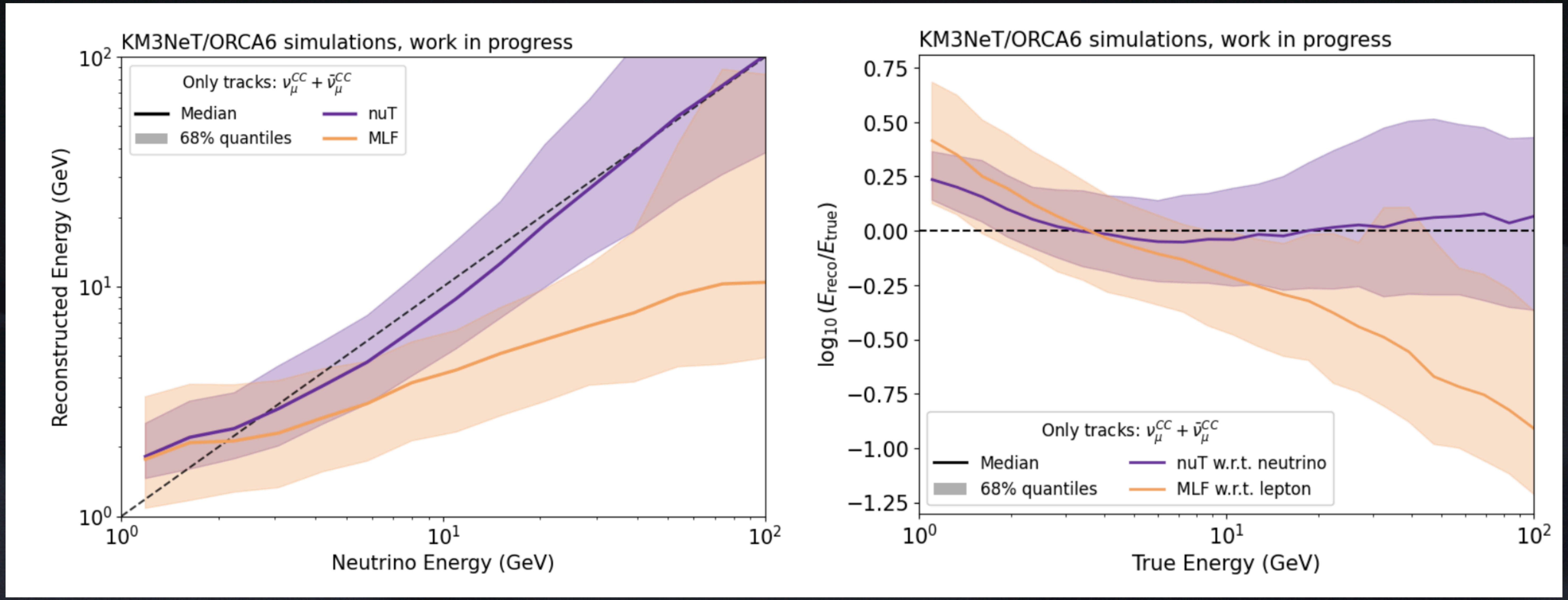
Following the Light, PhD thesis, Ó Fearraigh (2024)

Beyond the Standard Reconstruction

Other Reconstruction Techniques

- Transformer-based model used to reconstruct the neutrino direction, energy, inelasticity for all ν event types , incorporate transfer learning
- Another methodology: reconstructing atmospheric muon bundle properties for the purpose of cosmic ray studies with atmospheric muons

  e.g.
  Cosmic ray composition measurement using Graph Neural Networks for KM3NeT/ORCA, PhD thesis, Reck ,S. (2022)
  The Measurement and Modelling of Cosmic Ray Muons at KM3NeT Detectors, PhD thesis, Kalaczyński, P. (2024)



Enhancing low energy reconstruction and classification in KM3NeT/ORCA with transformers, KM3NeT Collaboration (2025)

UHE Neutrino in KM3NeT

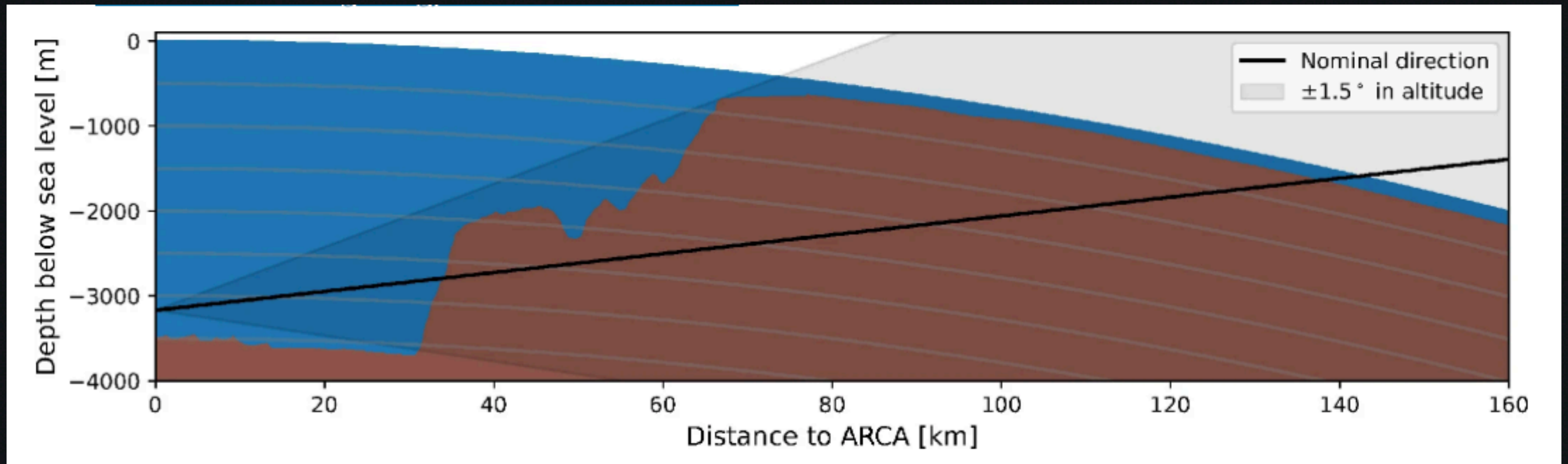
Reconstruction of an Ultra-High-Energy Neutrino Event

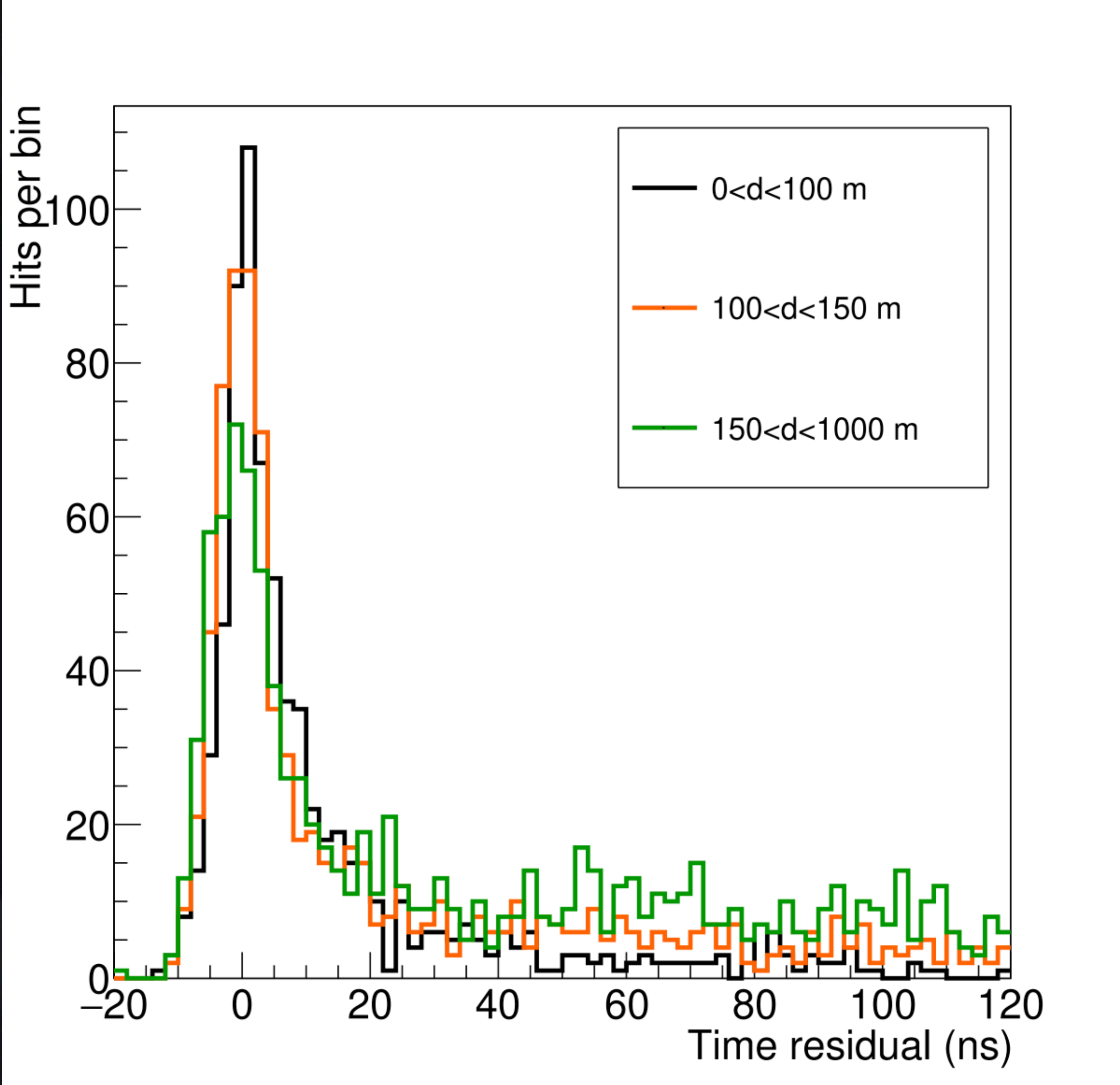
- Further validation of our reconstruction performance comes in the reconstruction of the UHE neutrino event detected in February 2023 with a reconstructed E_μ of 120^{+110}_{-60} PeV

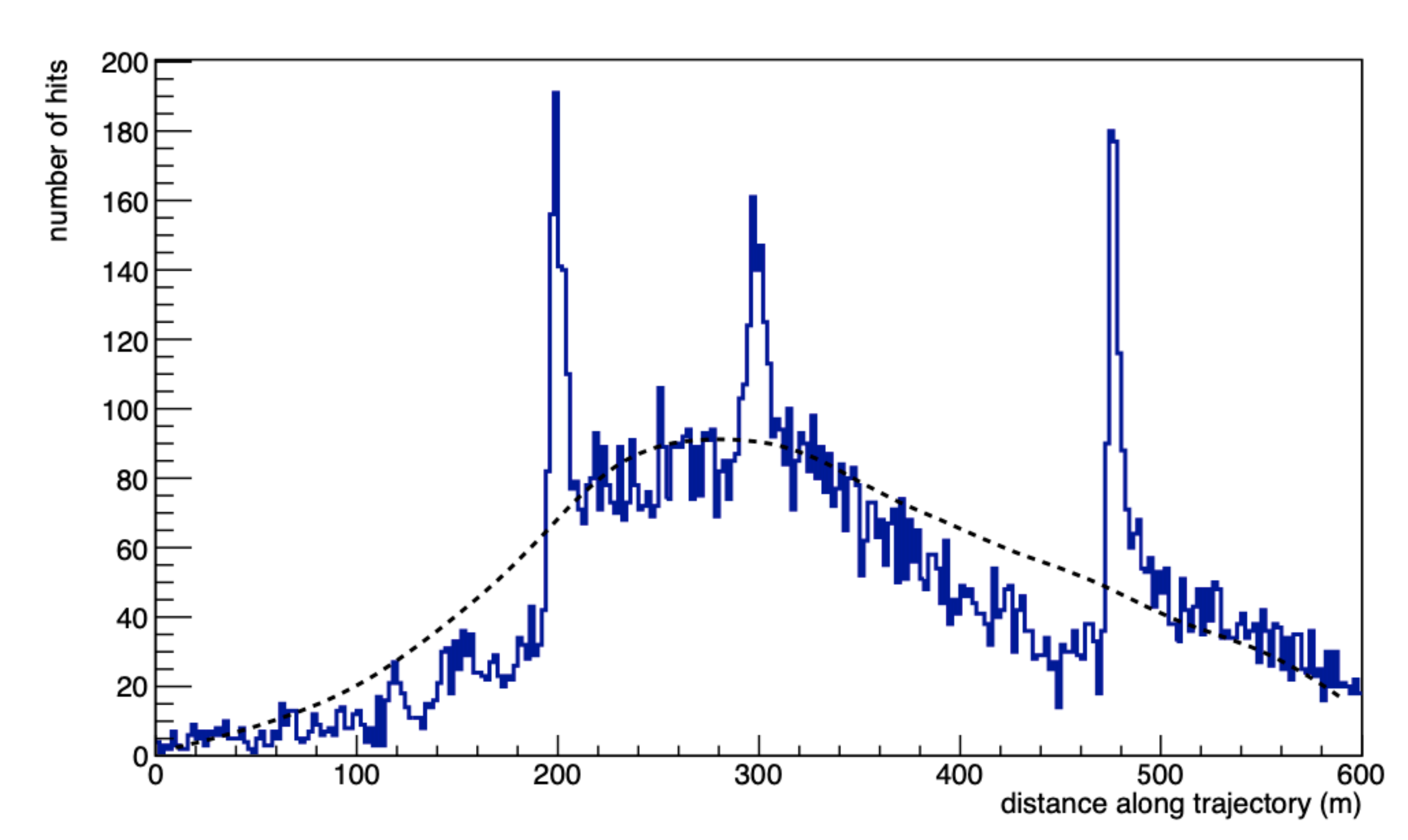
  -> a lower limit for $E_\nu = 220^{+570}_{-110}$ PeV

- Accurate direction reconstruction allowed for the determination of the entry point in the Earth, much reducing the likelihood of the event being due to an atmospheric muon

- The three distinct bremsstrahlung showers emitted along the track profile are also identifiable thanks to exceptional reconstruction methods, and this also allows for further classification of the event





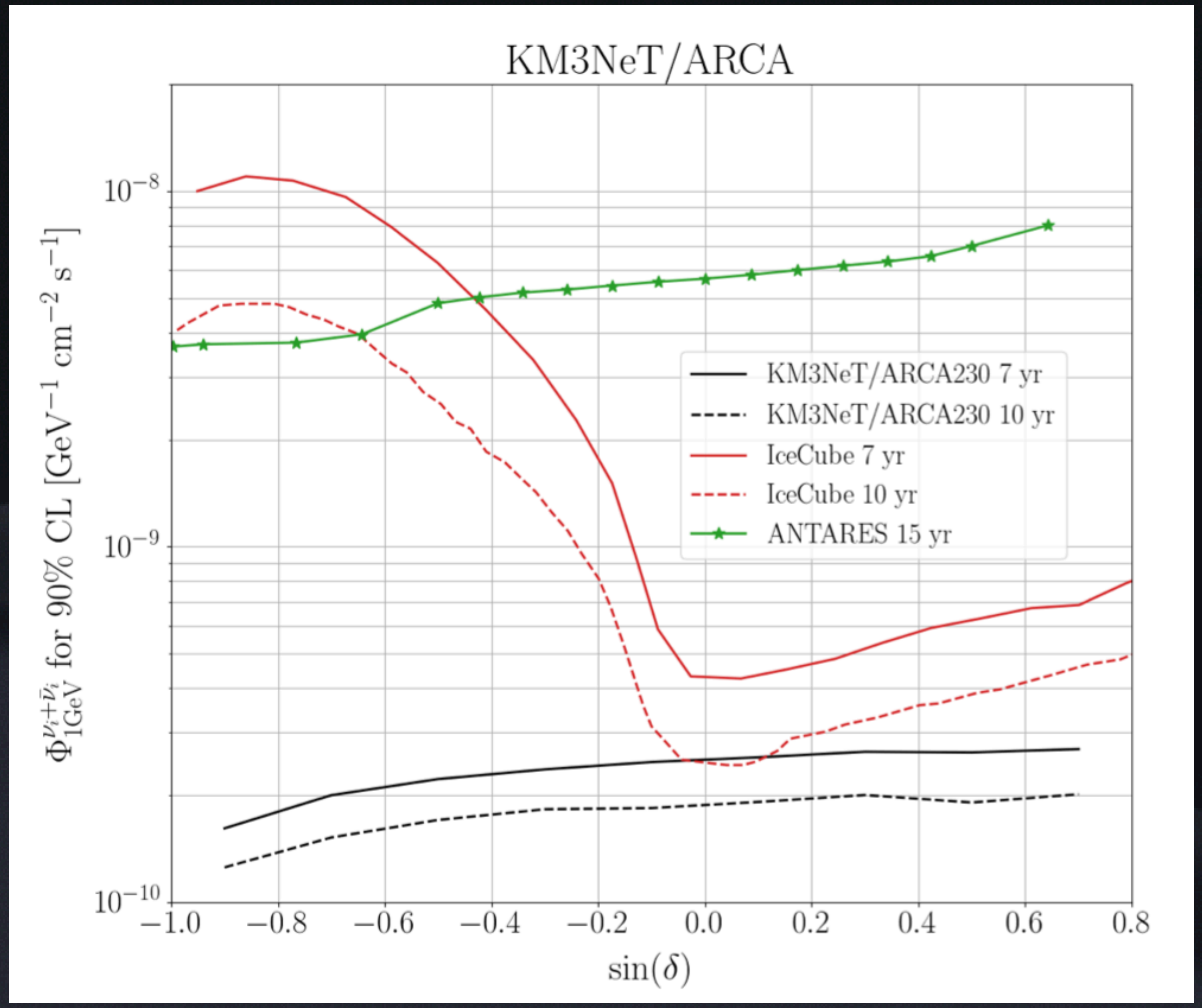


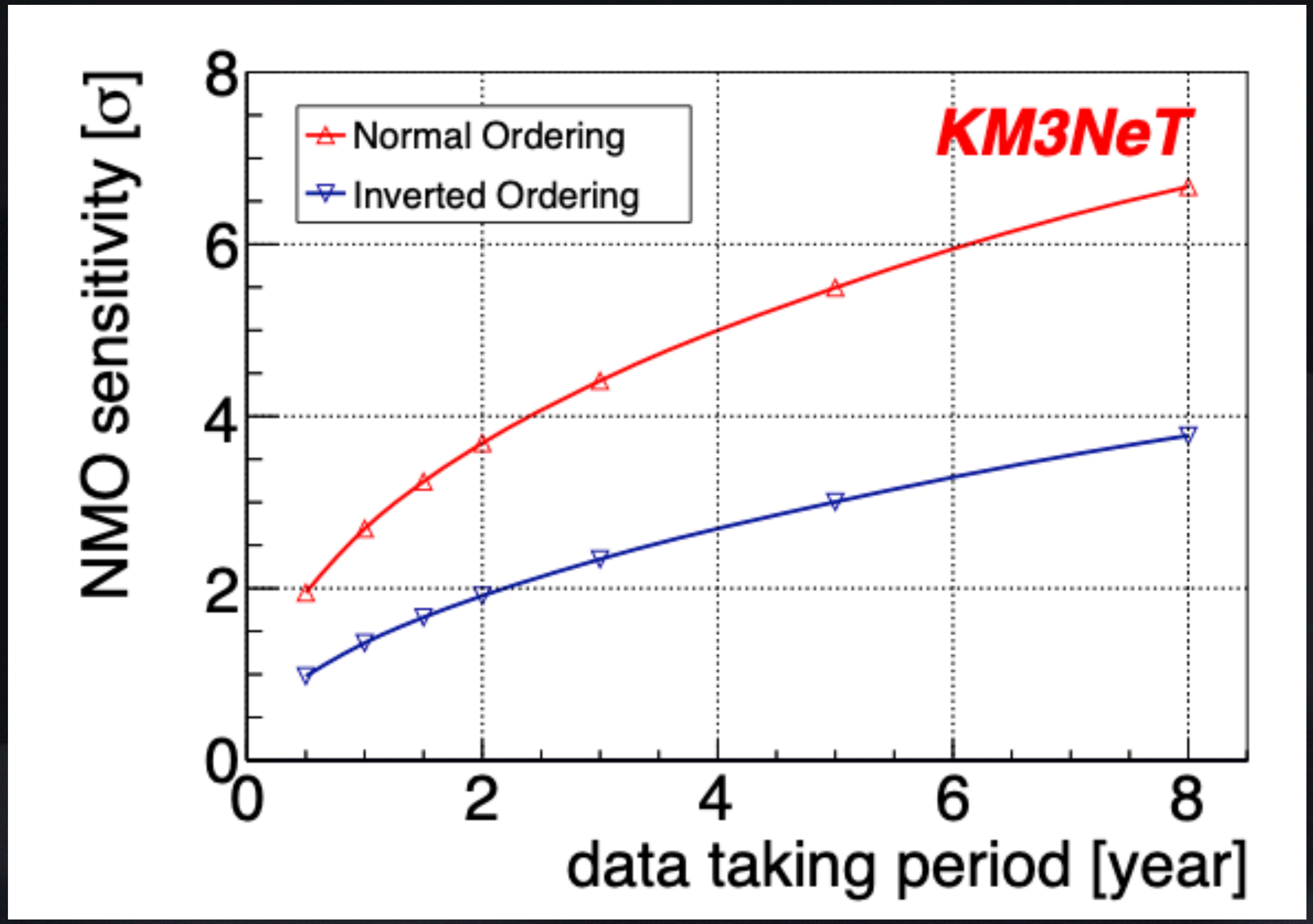
Observation of an ultra-high-energy cosmic neutrino with KM3NeT, KM3NeT Collaboration (2025)

Reconstruction

Why Reconstruction Matters

- An accurate reconstruction is needed to achieve the physics goals of the experiment
- In particular for KM3NeT: NMO determination and discovery potential to astrophysical ν sources

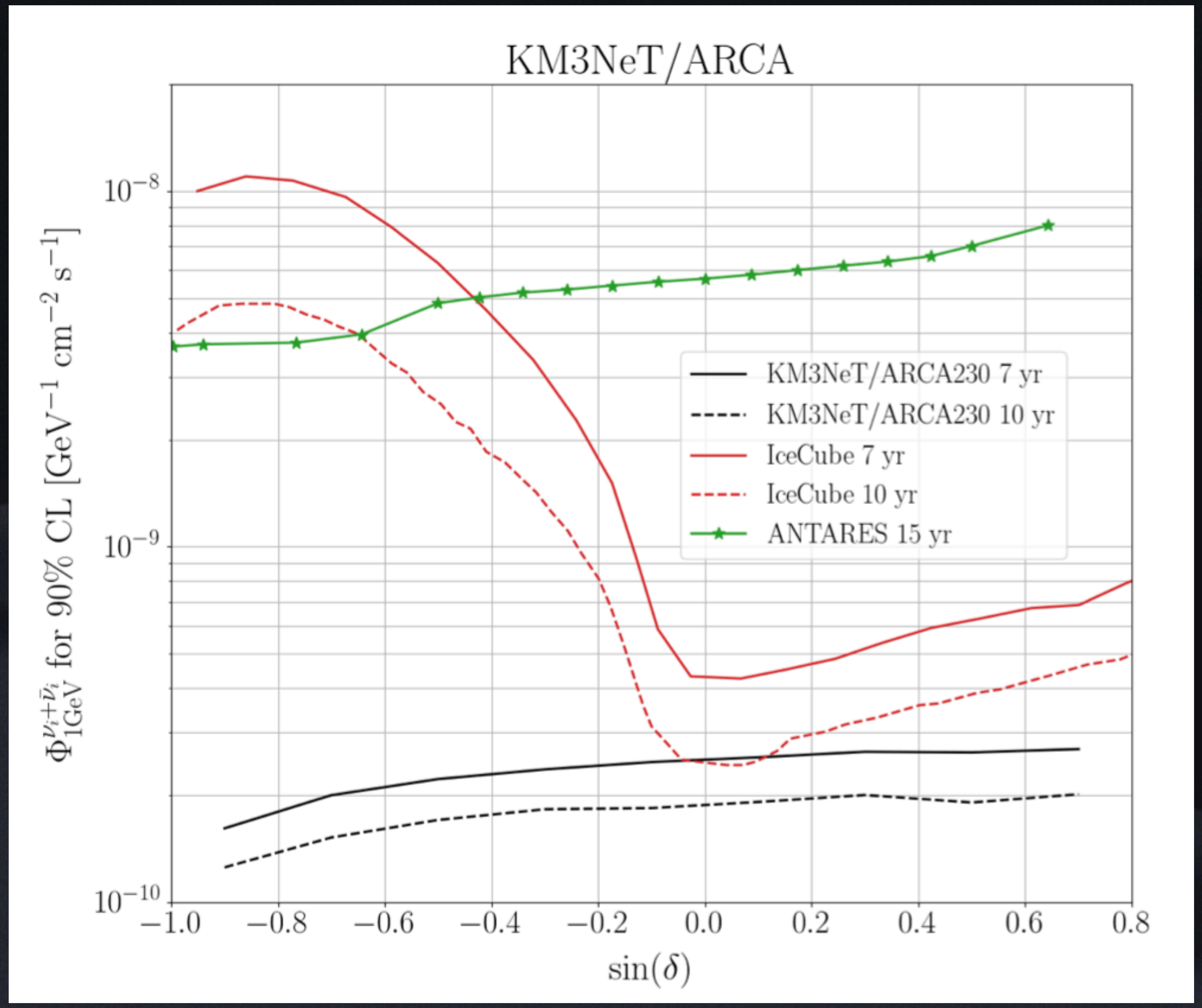


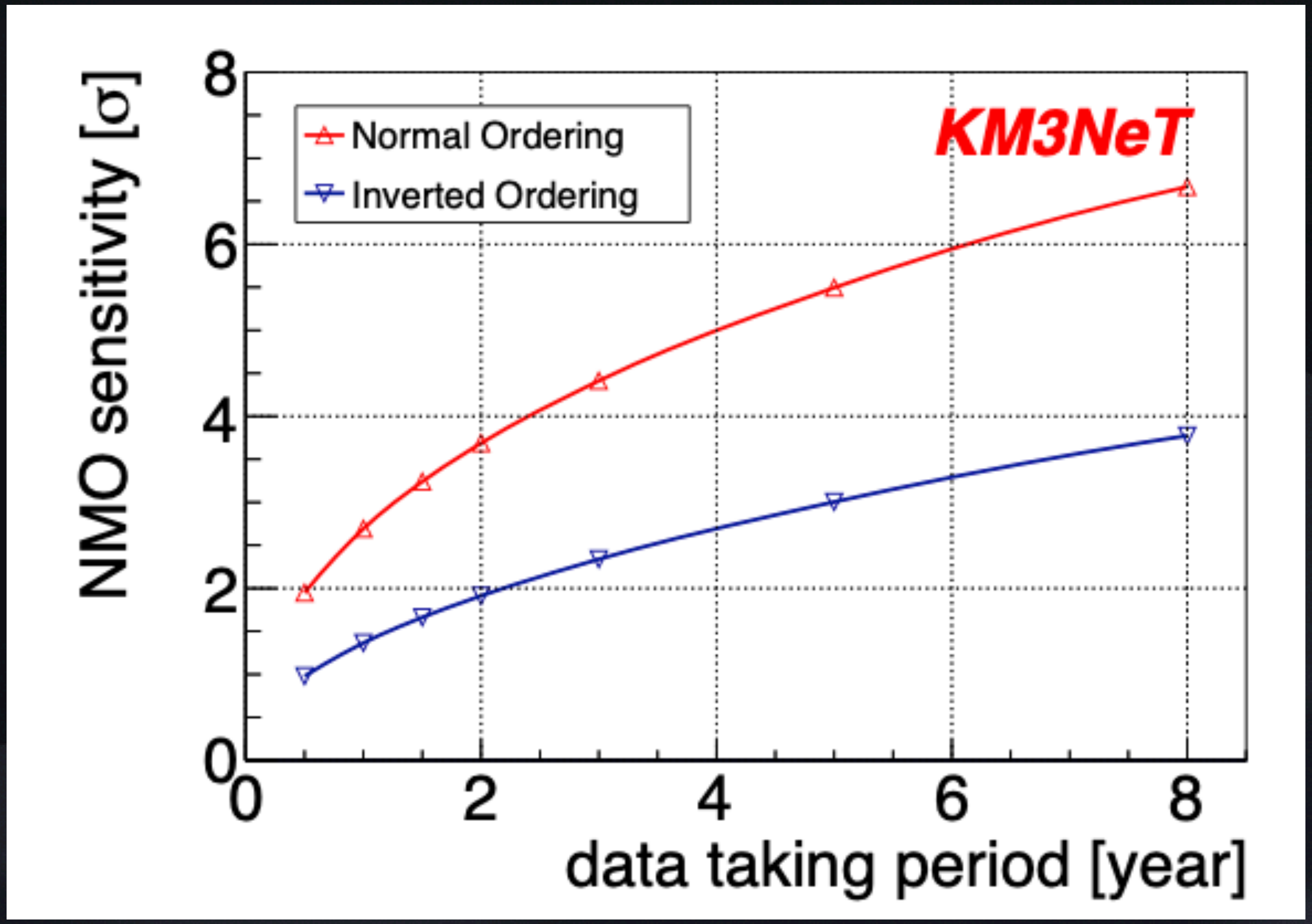


Reconstruction

Why Reconstruction Matters

- Reconstruction allows for exploring computational methods, different algorithms, parameter estimation techniques, and machine learning methods.
- Rich topic which requires knowledge in physics and software.
- Exploration of appropriate cuts for higher level analysis - quantities come directly from the reconstruction and errors.





Thank you for your attention