Friedrich-Alexander-Universität
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ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Feasibility study of a tau appearance measurement with the ANTARES neutrino telescope

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Motivation

- Tau neutrinos are one of the least well measured particles in the Standard Model.
  - Studies into tau neutrino cross section
  - Investigate into unitarity of PNMS matrix
- Studies performed or being performed already by OPERA, IceCube/DeepCore, Super-Kamionkande and KM3NeT
- Possibility of adding statistics to the already ongoing analysis by KM3NeT **(check T 87.6 by N. Geisselbrecht)**
- Analyze ANTARES data for particle physics: beyond its original purpose

Challenges:

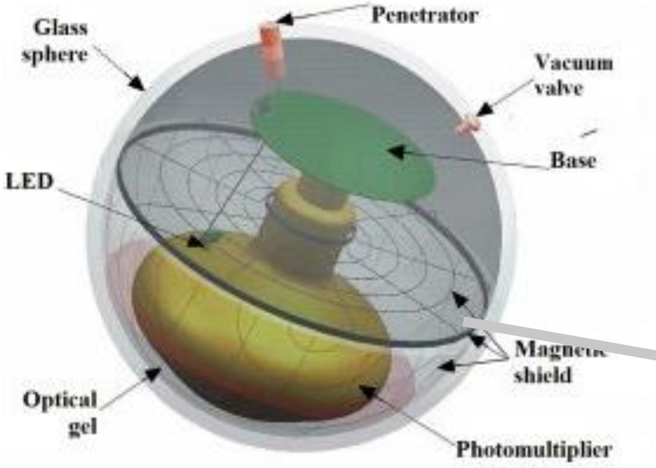
- Signal region of the analysis very close to the energy threshold of the detector.

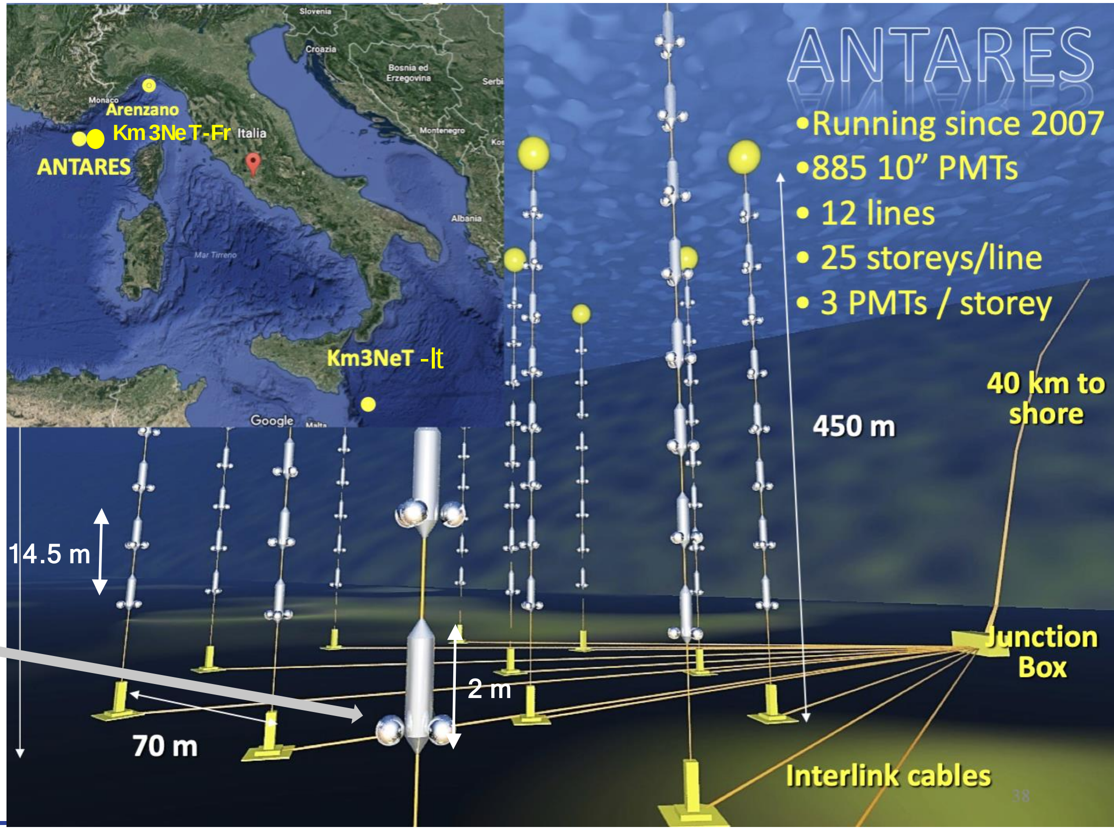
[Most recent results:10.1103/ PhysRevLett.120.21180, 10.1103/PhysRevD.99.032007, 10.1103/PhysRevD.98.052006, 10.22323/1.444.1107]

ANTARES detector
Neutrino Telescopes

Key Points:

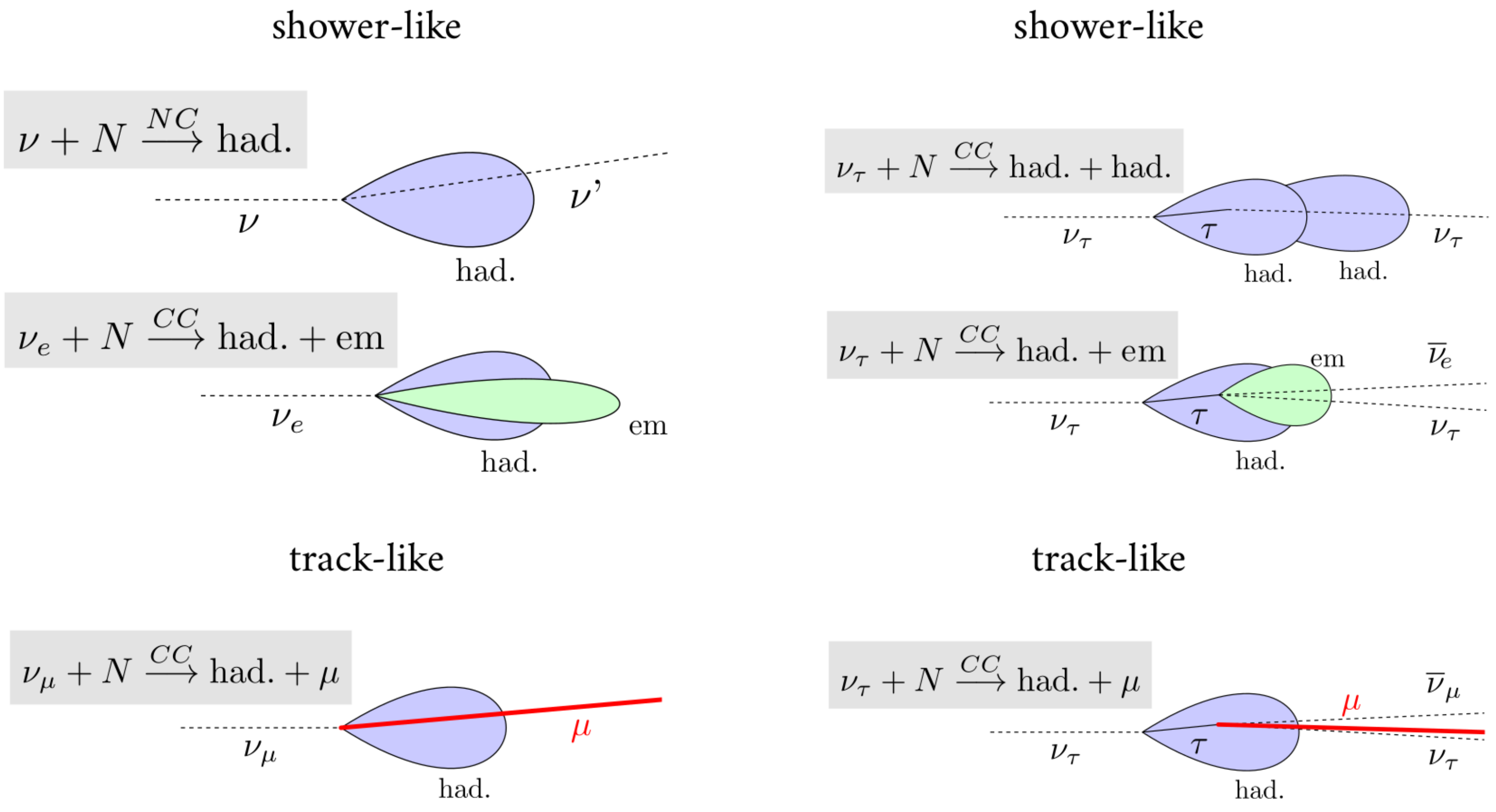
- **Goal:** study neutrinos from GeV → PeV neutrinos (astrophysics, astronomy, particle physics)
- **Detection Principle:** measurement of Cherenkov radiation of secondary charged particles
- Located 40km off **Toulon, France**
- Sea depth: ~2500m
- Active: 2007 - 2022
- Energy threshold: 10 GeV





Nucl. Instrum. Meth. A 656 (2011) 11-38

Topology of Neutrino Events



- No event-by-event identification for tau neutrino interactions
- Tau neutrinos result in both **tracks** and **showers signatures!**

$\tau^- \rightarrow e^- \overline{\nu}_e \nu_\tau$	(17.8%)	**leptonic**	**(35.2%)**
$\tau^- \rightarrow \mu^- \overline{\nu}_\mu \nu_\tau$	(17.4%)		
$\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$	(25.5%)	**hadronic**	**(64.8%)**
$\tau^- \rightarrow \pi^- \nu_\tau$	(10.8%)		
$\tau^- \rightarrow \pi^- \pi^0 \pi^0 \nu_\tau$	(9.3%)		
$\tau^- \rightarrow \pi^- \pi^- \pi^+ \nu_\tau$	(9.0%)		
$\tau^- \rightarrow \pi^- (> 2\pi)\, \nu_\tau$	(9.0%)		

Hallmann, Steffen (Jan 2021). Sensitivity to atmospheric tau-neutrino appearance and all-flavour search for neutrinos from the Fermi Bubbles with the deep-sea telescopes KM3NeT/ORCA and

Tau Appearance

Atmospheric neutrinos from the decay of $\pi^{\pm}$ and $K^{\pm} \rightarrow$ only ν_e and ν_μ for these energies!

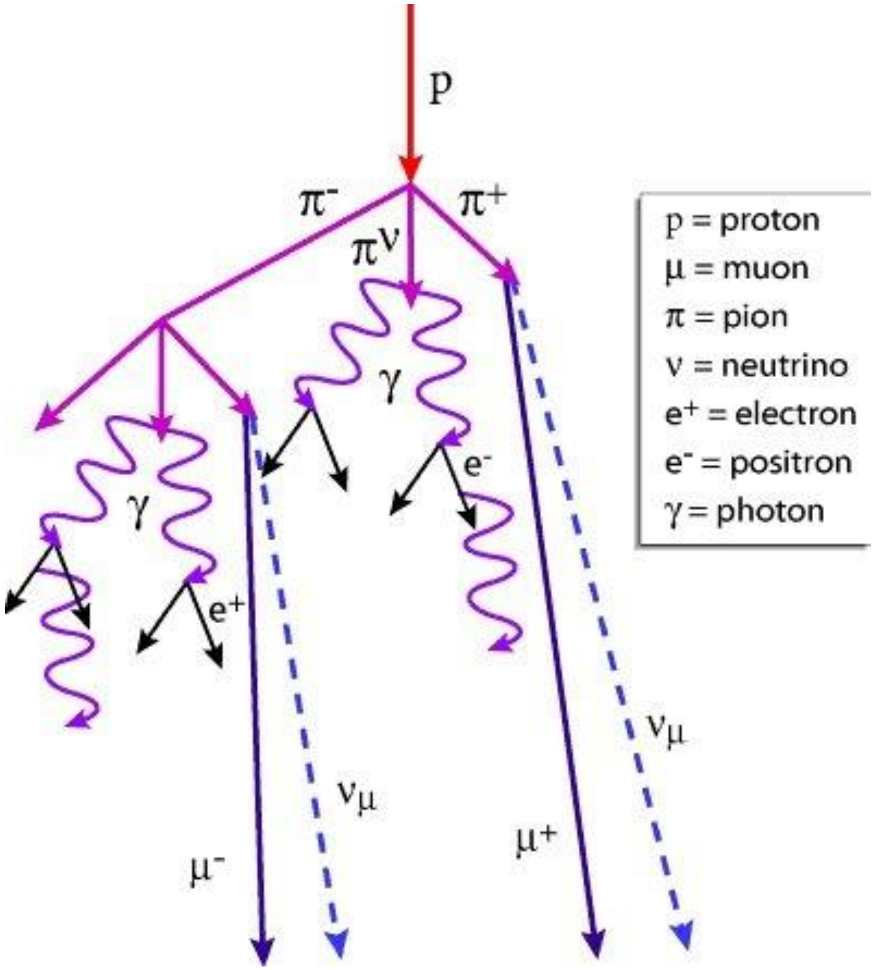
Tau events **only** product of **neutrino oscillations:**

- deficit of muon neutrino events (track-like events)
- excess of shower events

Tau normalization measurement:

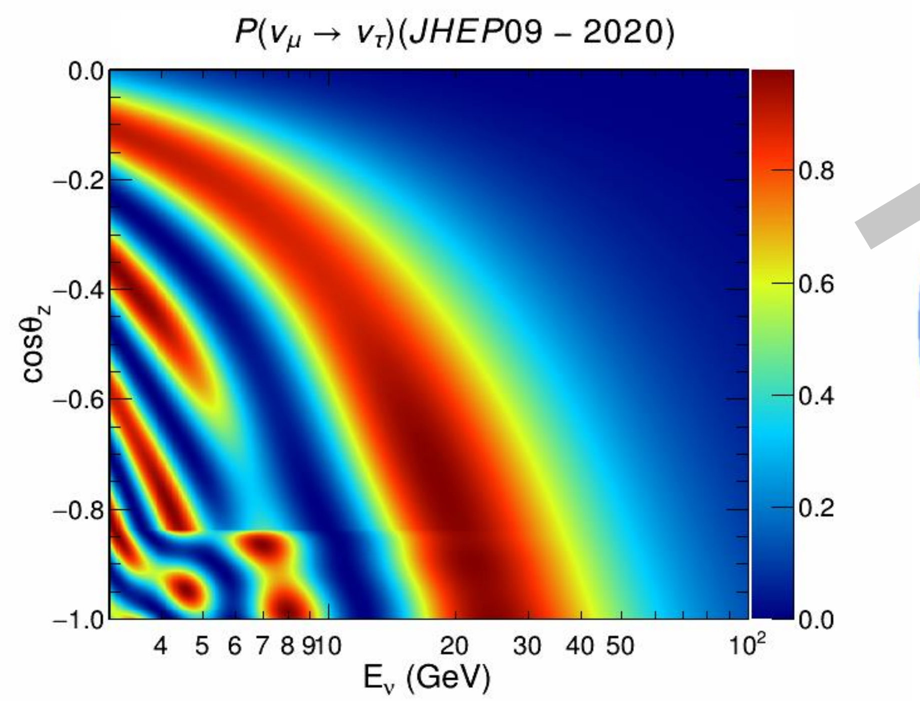
$$n_\tau = \frac{N_{\tau,\mathrm{measured}}}{N_{\tau,\mathrm{expected}}}$$

- n_τ = 1: expected case
- n_τ = 0: no-tau case

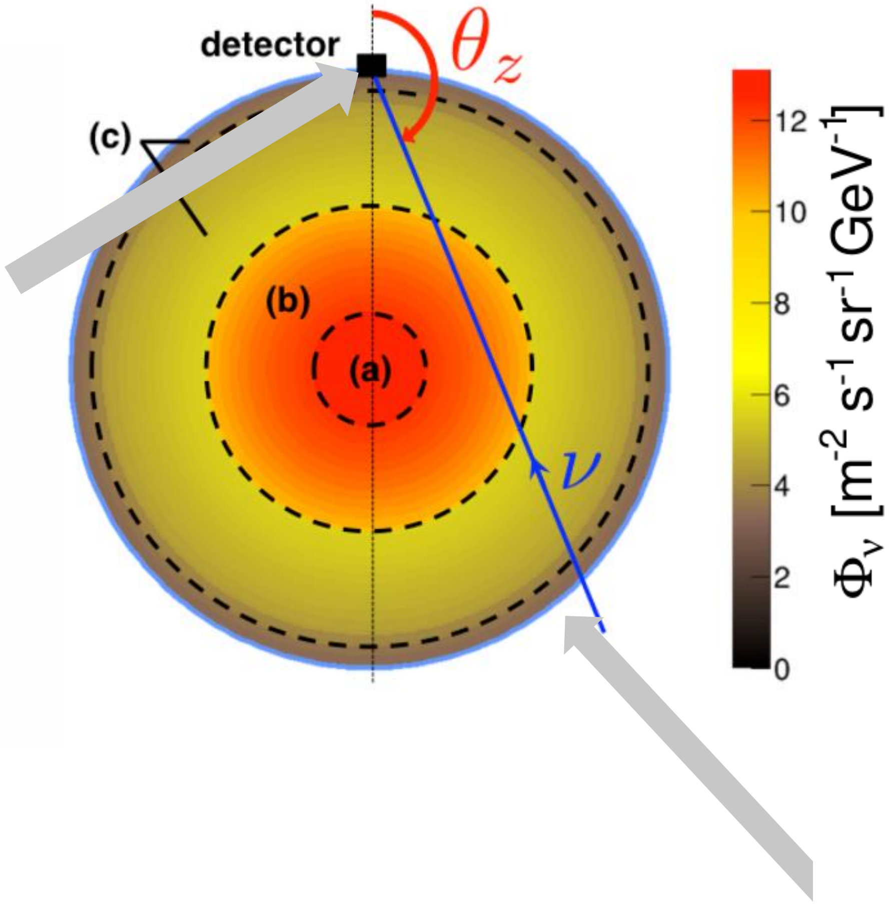


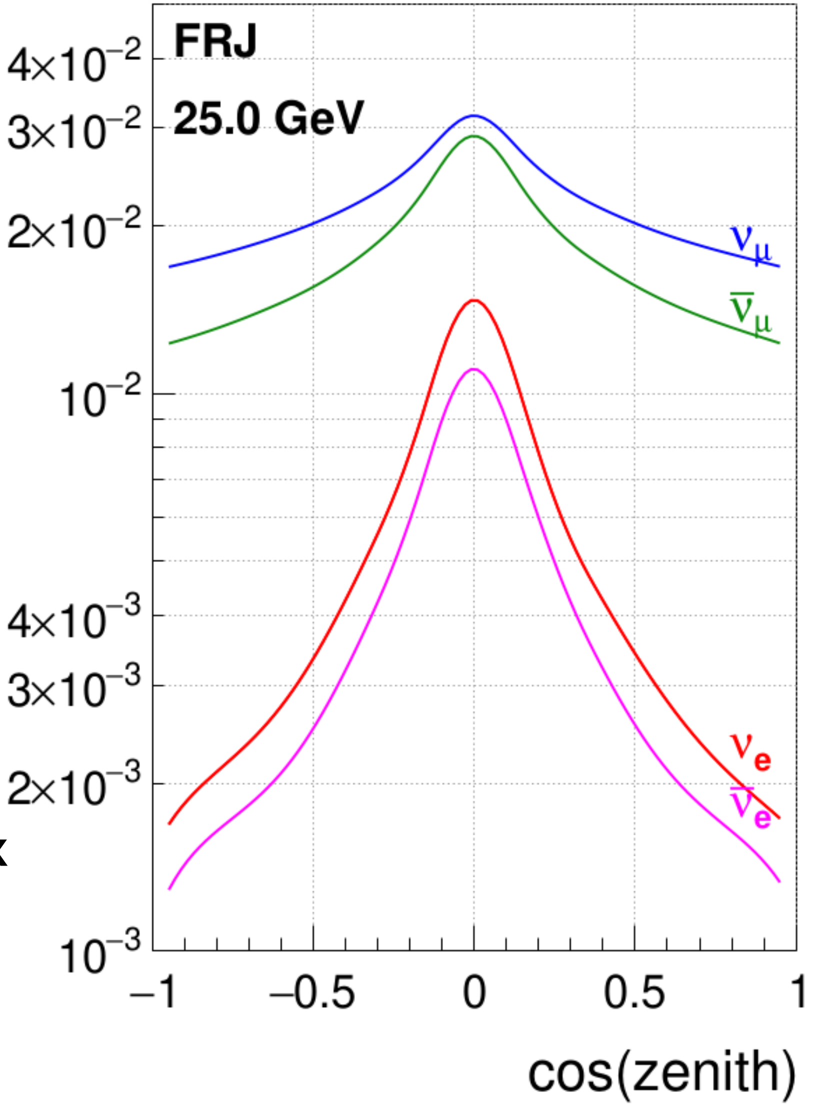
http://www-rccn.icrr.u-tokyo.ac.jp/mhonda/public/nflx2014/index.html

Neutrino Oscillations



https://github.com/joaoabcoelho/OscProb





Honda Flux

Tau Neutrino Production:

- From atmospheric: ν_e / ν_μ $\rightarrow \nu_\tau$
- Main channel for ANTARES: from **muon neutrino**

Expected number of events from full dataset

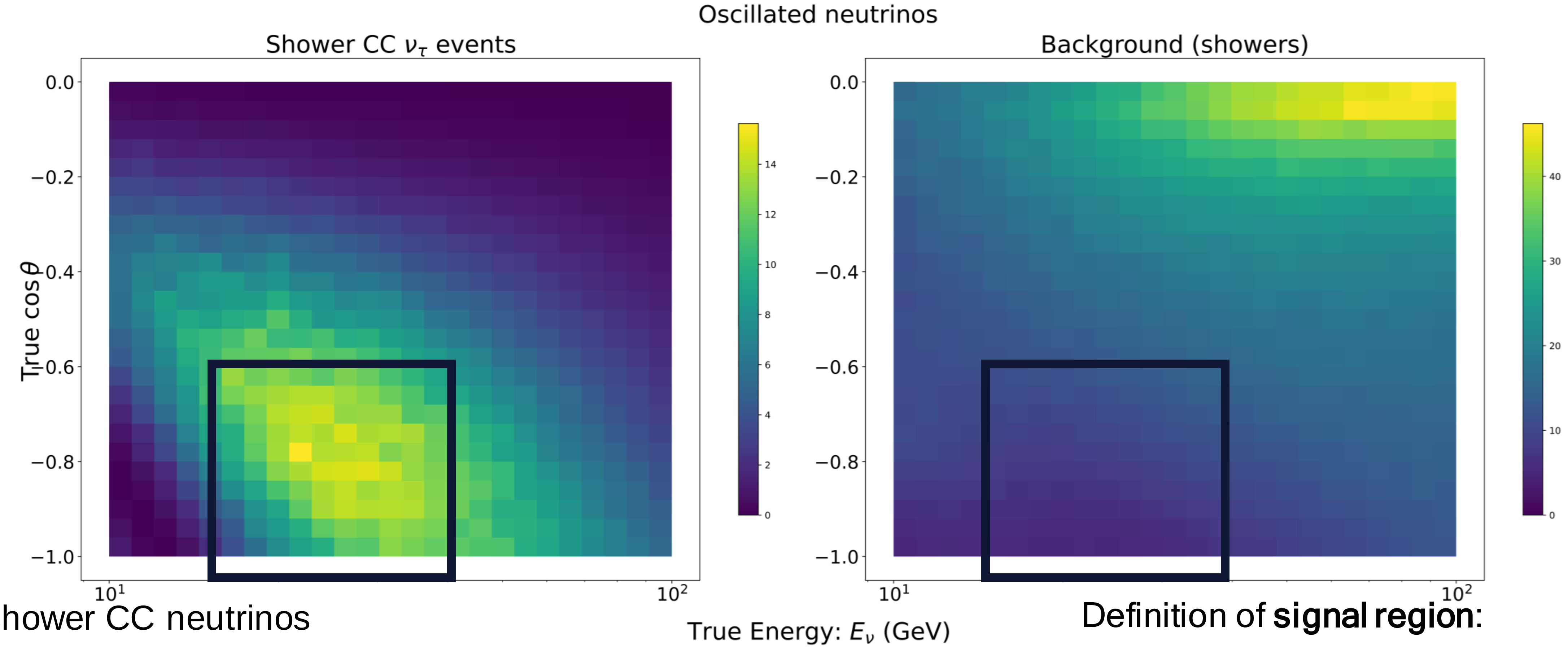
MC neutrino low-energy & upgoing sample

Type	Charge	Event Type	Percentage (%)	Num. Event
ν_e	CC	shower	13.6	7765
ν_μ	CC	track	71.6	40961
$\nu_\mu + \nu_e$	NC	shower	6.2	3047
ν_τ	CC	shower	5.8	3340
ν_τ	CC	track	1.8	1056
ν_τ	NC	shower	1.9	1072
Total MC				57241

- Already applied cut in true energy for E_{true}> 10 GeV
  - 10% of tau events discarded
- Monte Carlo sample is **low-energy** & **upgoing** → Sample "free" of muons!
- **Triggered & reconstructed** by at least one reconstruction algorithm!

Neutrino sample - 2

Distribution of events



Keeping:

- 75% of shower CC neutrinos
- Content of shower increased:
  - CC 5.8% → 10%

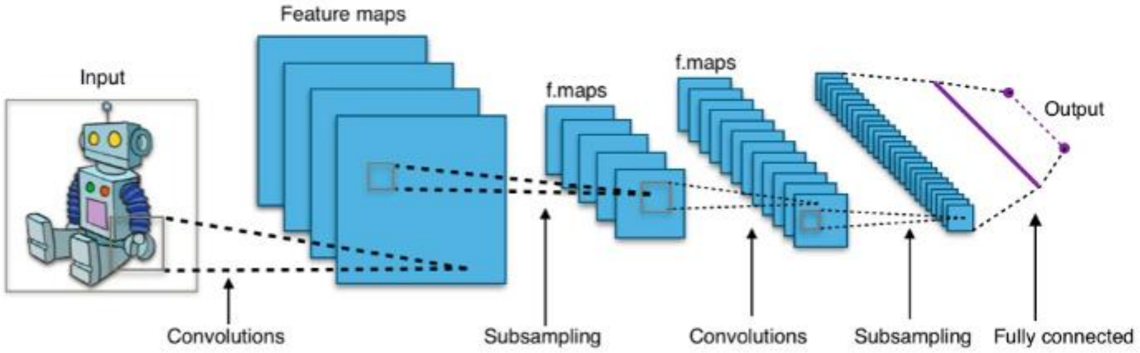
Definition of **signal region**:

- cos(θ) < - 0.6
- E_{true} in [15, 40] GeV

Reconstruction Algorithms

NNFit by J.G. Mendez @ IFIC Valencia

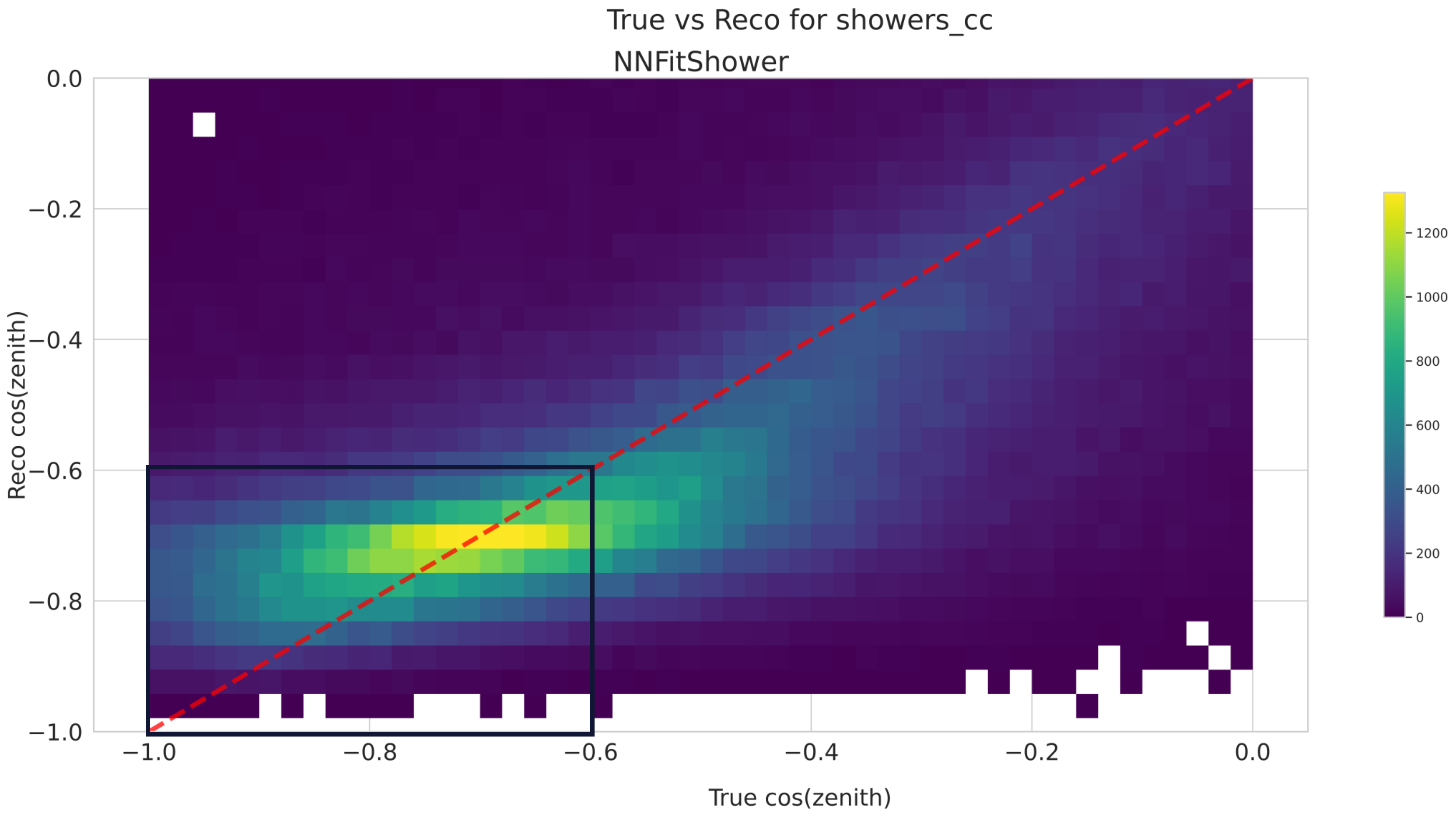
- Deep learning reconstruction method for ANTARES
  - Deep Convolutional Networks (DCNs) + Mixture Density Networks(MDNs)
- Developed for **low-energy** events (E_{true} < 150 GeV)
- **Single-line** event detection
- 2 models provided
  - NNFitTrack
  - NNFitShower
- Reco Variables:
  - Zenith, azimuth, energy, interaction vertex



Garcia-Mendez, J., Ardid, S., & Ardid, M. (2023). Dark matter search towards the Sun using Machine Learning reconstructions of single-line events in ANTARES. *PoS, ICRC2023, 1443.*

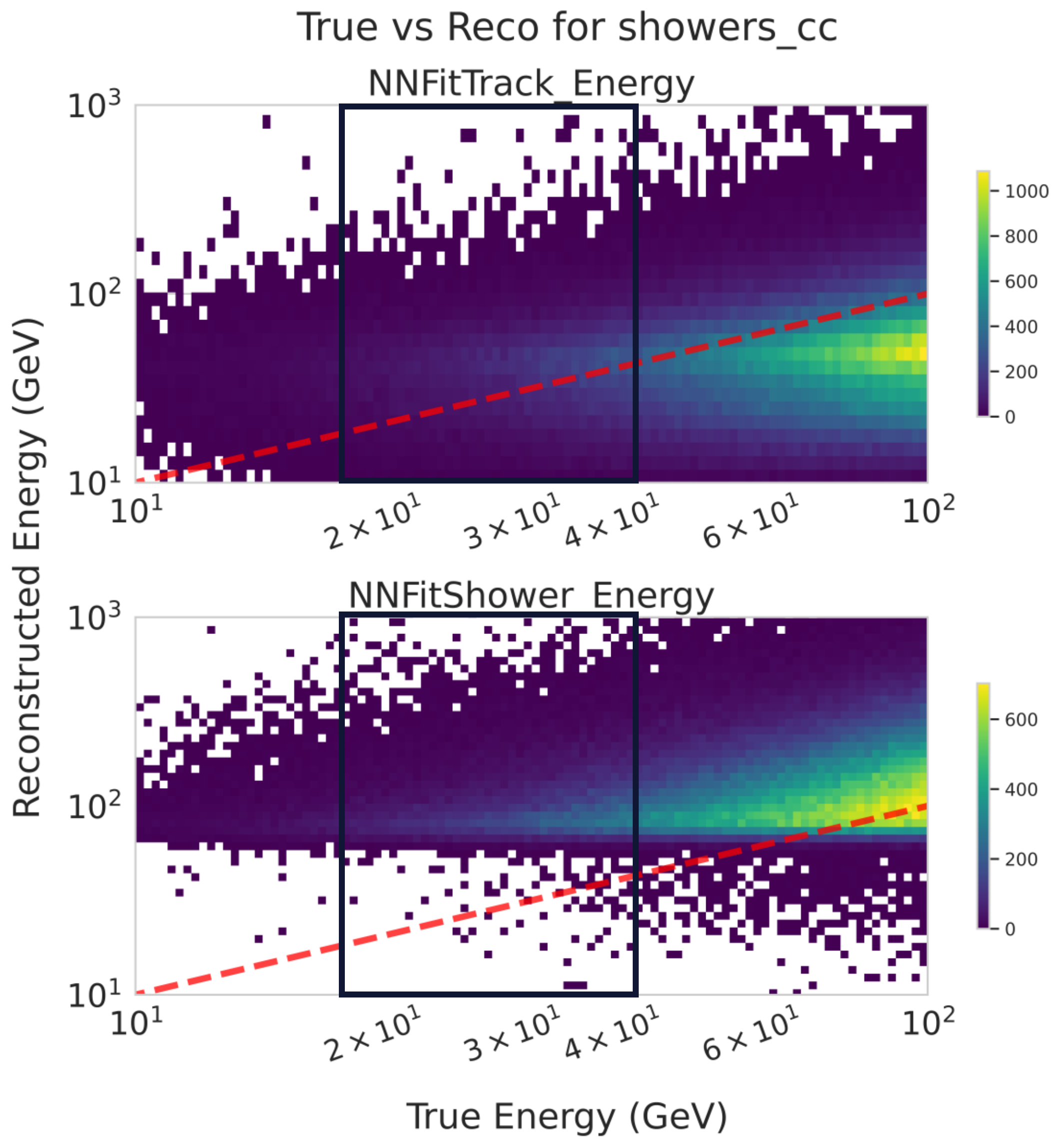
J. Gu et al., Pattern Recognition 77 (2018) 354.

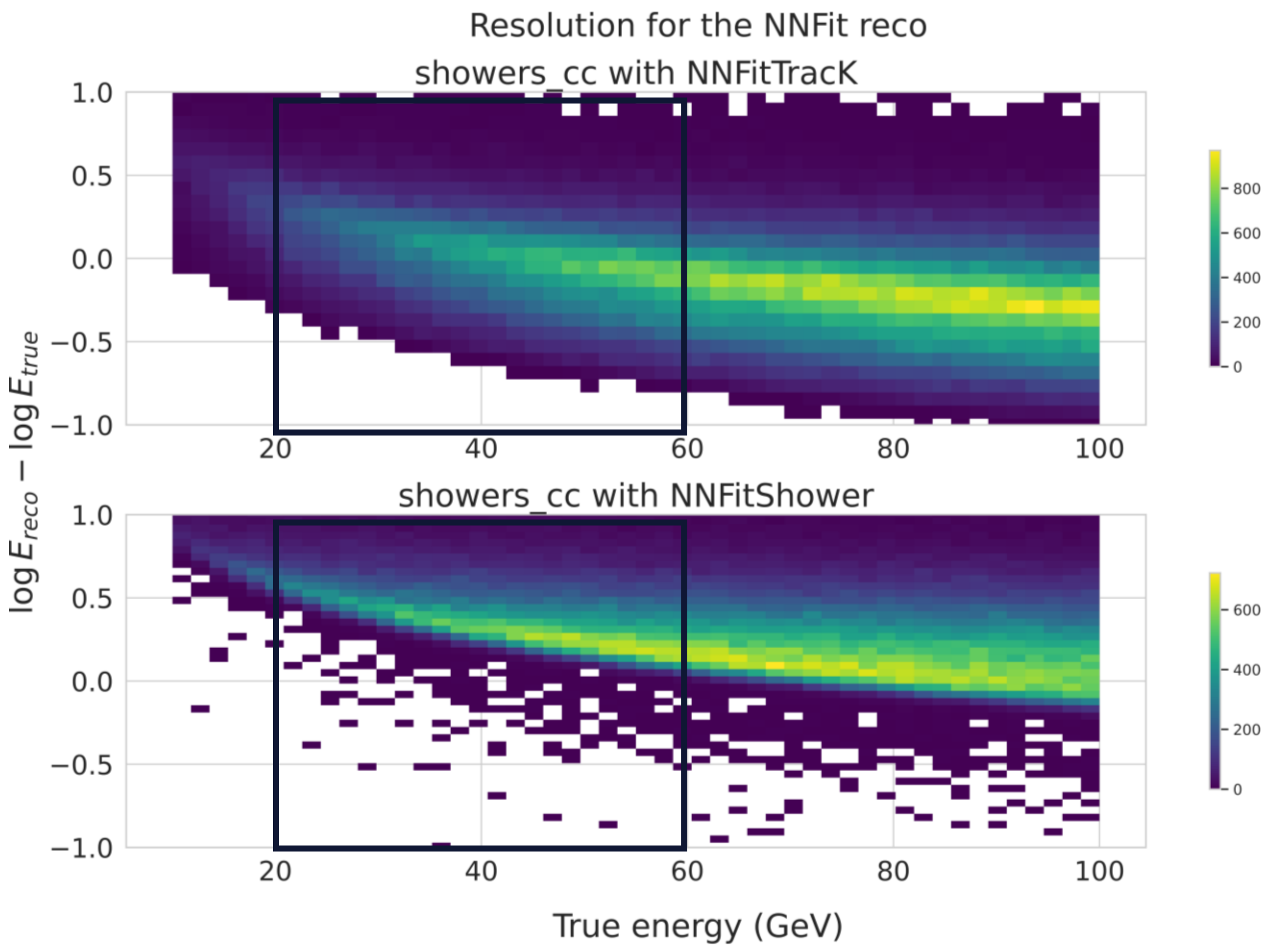
Reconstruction Performance - 1
Direction Reconstruction



Reconstruction Performance - 2

Energy Reconstruction



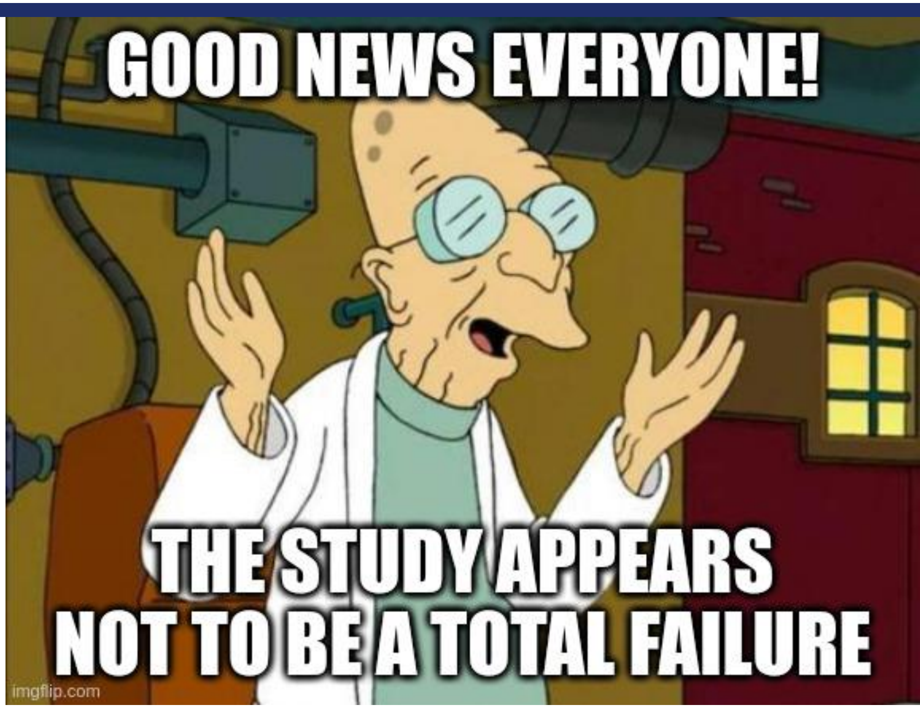


- Better approximation of "low-energy" showers as tracks
- Network was trained for higher energy showers

Summary & Next Steps

Summary:

- Tau neutrinos are still apparent after weighting
- Maximum likelihood reconstructions not helpful in this energy range
- Deep learning seems to be a viable candidate for reconstruction

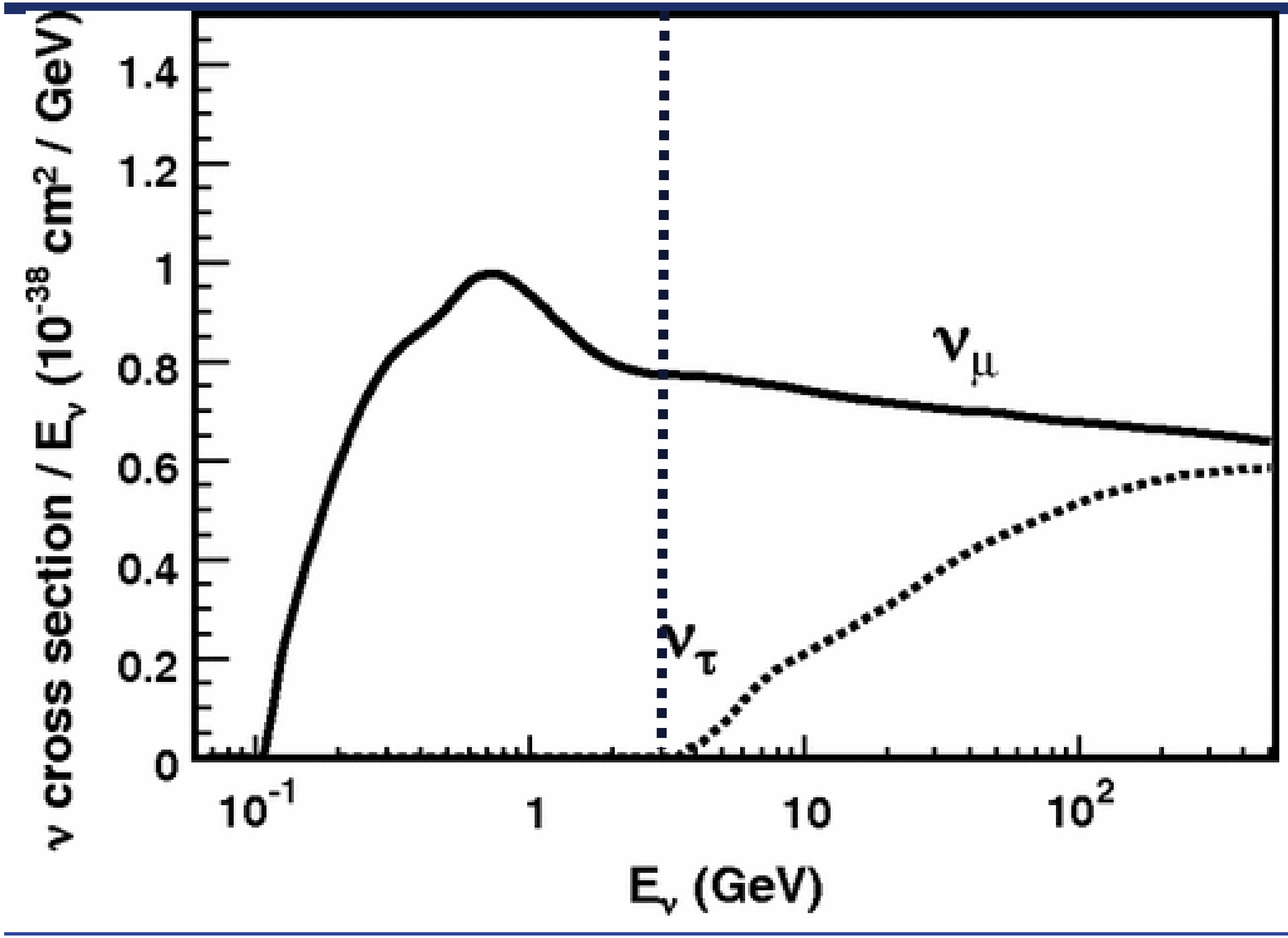


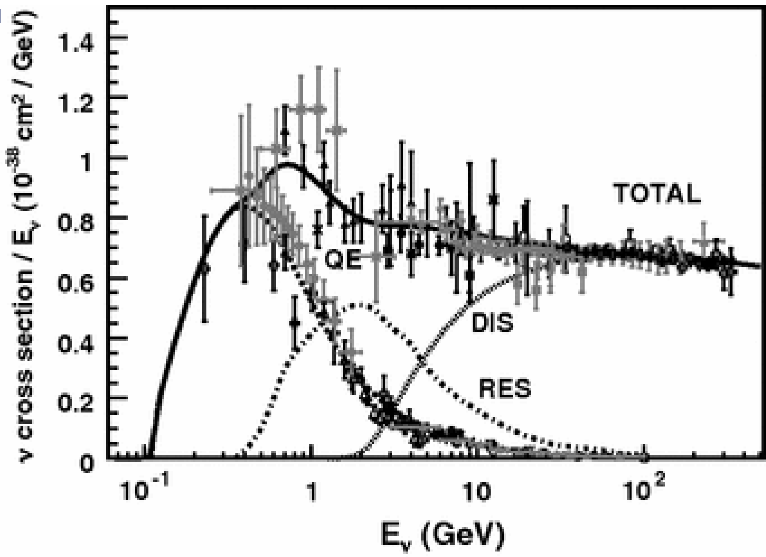
Next Steps for the ongoing investigation:

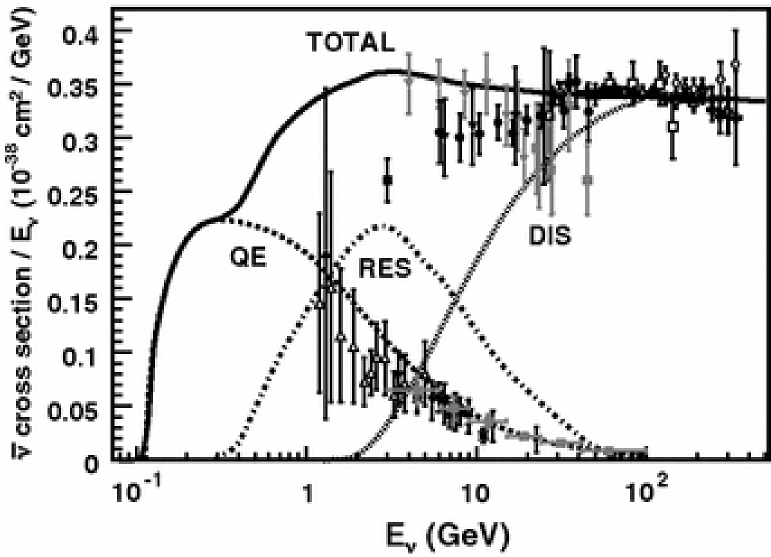
- χ^2 analysis of tau normalisation parameter with/out systematics in the sensitivity study
- Use reconstructed variables from NNFit
- Study extra scenarios (IO, CC+NC)
- Move to a more "realistic" scenario with muons

Back-Up Slides

Neutrino Cross Section



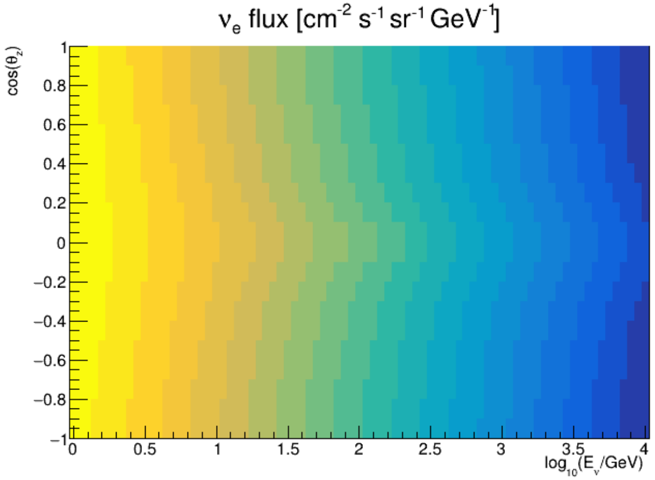


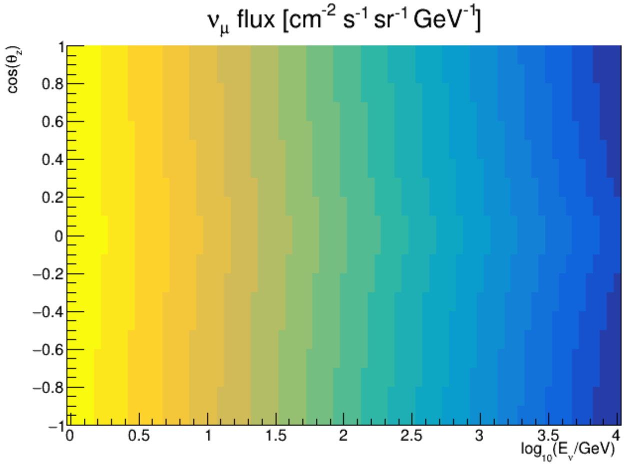


10.1103/RevModPhys.84.1307

Atmospheric Oscillation Weight

The calculation for the oscillated weights are being carried by event-by-event basis:





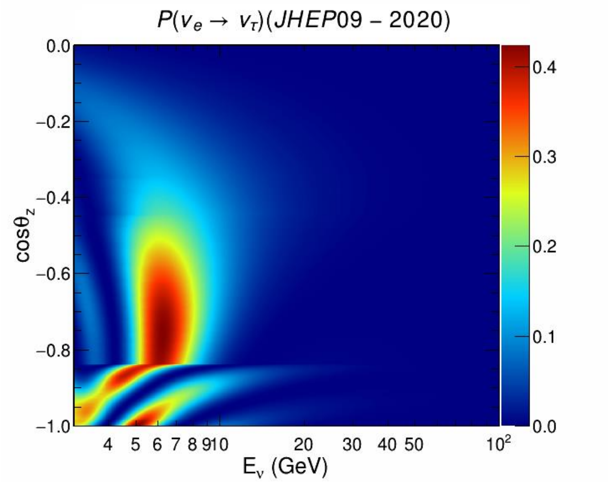
Atmospheric Flux from Honda Group

$$w^{\mathrm{atm}}_{\nu_i} = \frac{w_2}{ngen} \cdot \left(\Phi_{\nu_e} P_{\nu_e \to \nu_i} + \Phi_{\nu_\mu} P_{\nu_\mu \to \nu_i}\right) \cdot \mathrm{rdur}$$

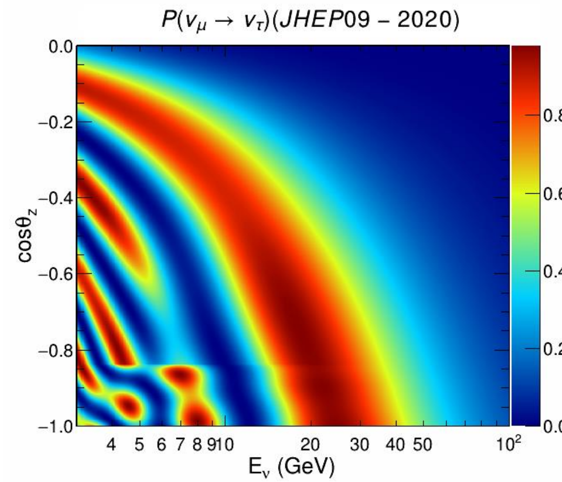
Generated Weight

Oscillation Probability

Run Duration



Calculated with OscProb



https://github.com/joaoabcoelho/OscProb

10.1103/PhysRevD.92.023004

Comparison with other algorithms