Friedrich-Alexander-Universität
Erlangen-Nürnberg

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

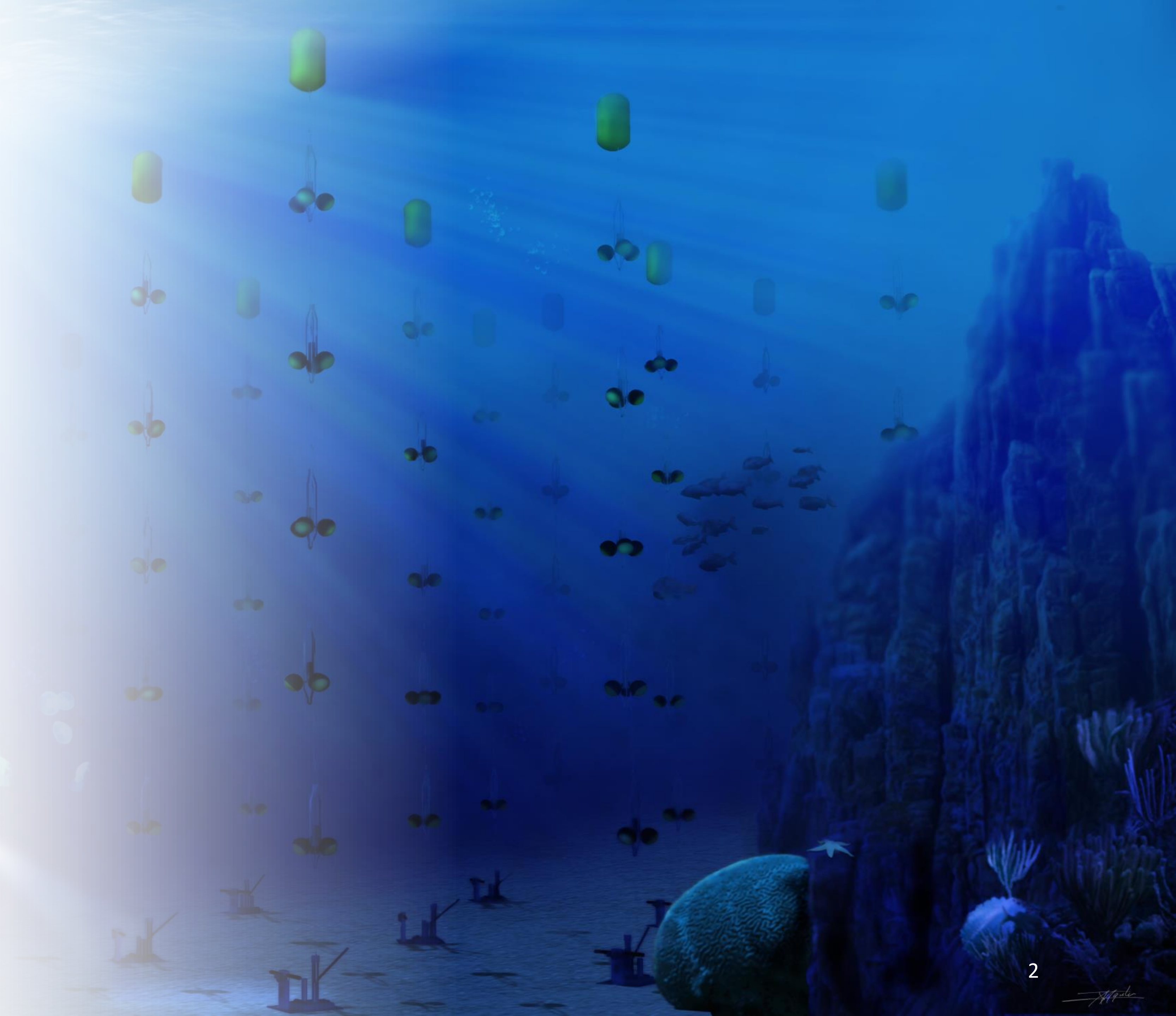
Detection of low-energy tau neutrinos with the ANTARES neutrino telescope - a feasibility study

Michael Chadolias

Erlangen, 22nd of January 2025

M.Sc. Colloquium

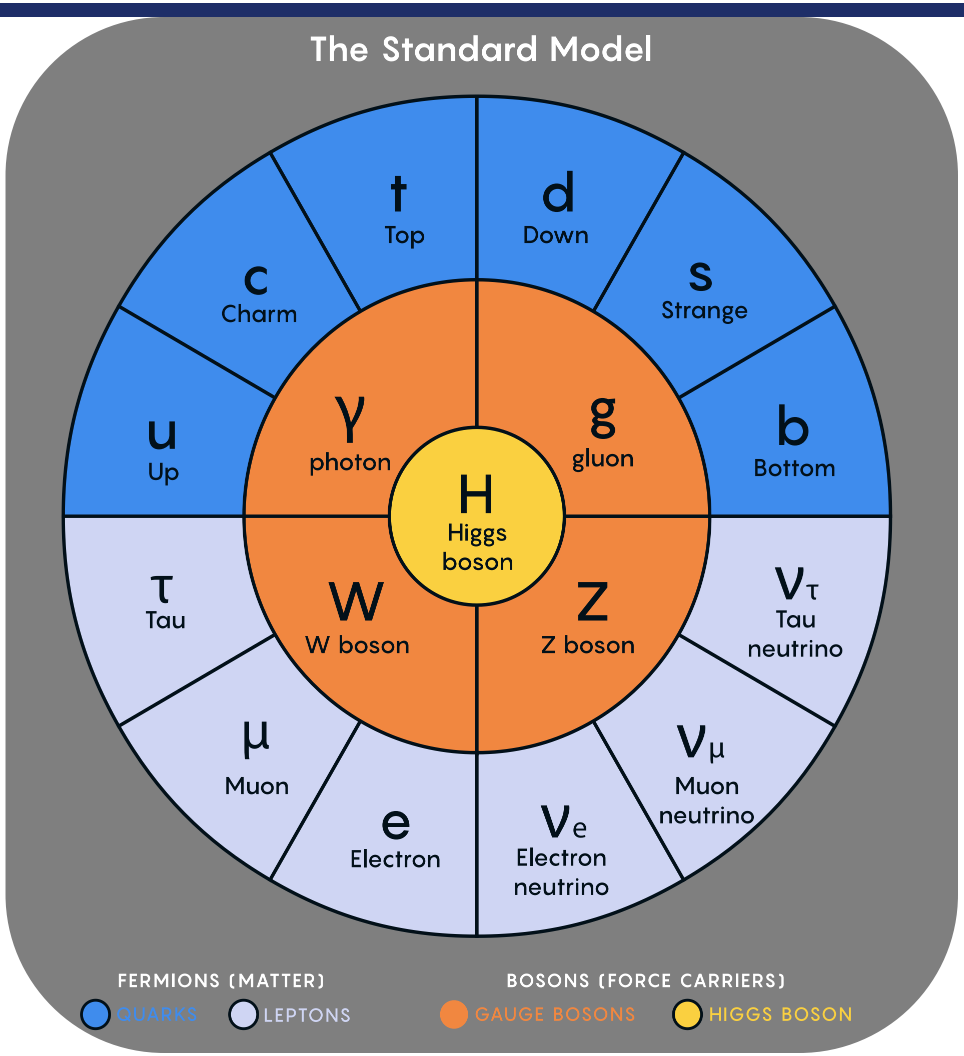
Contents



Neutrinos

Neutrinos

- Lightest particle of the fermionic family of the standard model of particle physics
- There are 3 known flavors
- Interacts under the following forces:
  - Weak nuclear force
  - Gravity
- Neutrinos can undergo oscillations transforming into another flavor



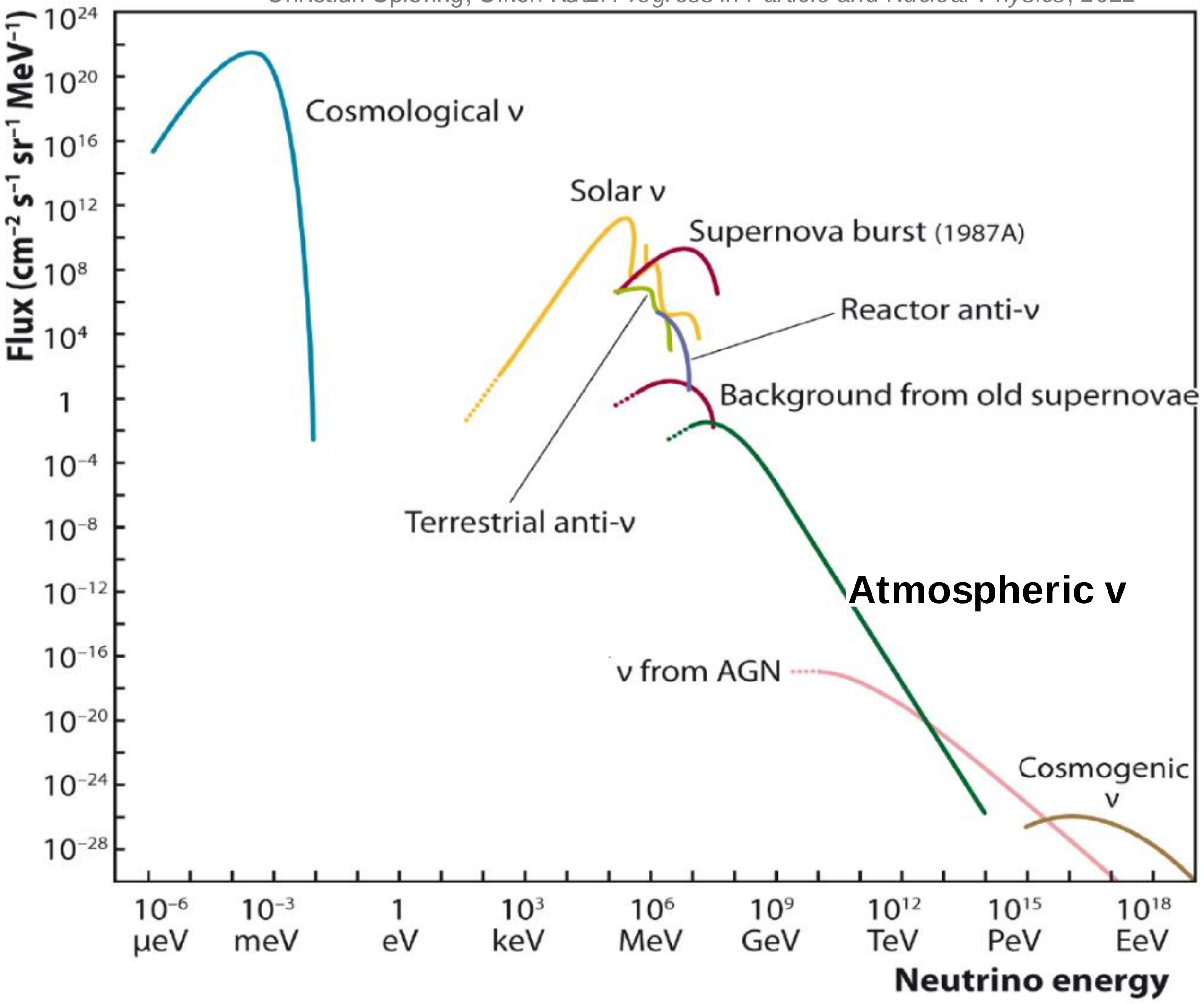
From Quanta magazine

Neutrinos

Sources

- Sources are both natural and artificial
- Large energy range from μeV to EeV
- Ubiquity across scales from 10^{-28} to 10^{24}

Christian Spiering, Ulrich Katz. *Progress in Particle and Nuclear Physics*, 2012



Neutrinos

Atmospheric Neutrinos

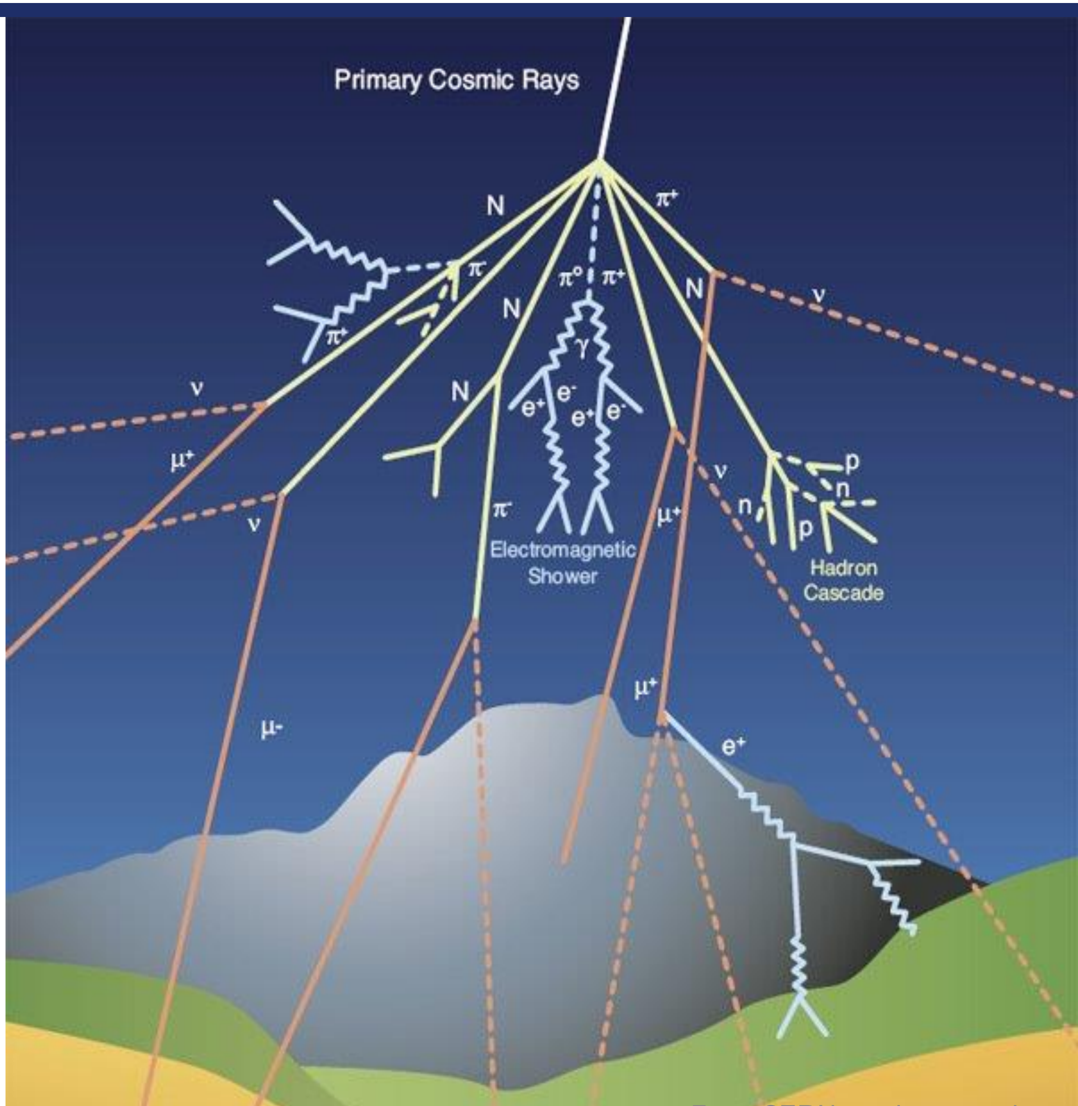
- Originate from collisions of cosmic rays in Earth's atmosphere
  - Unstable kaons and pions are produced, decaying into:

$$\pi^+/K^+ \to \mu^+ + \boxed{\nu_\mu} \qquad \pi^-/K^- \to \mu^- + \boxed{\bar{\nu}_\mu}$$

$$\mu^+ \to e^+ + \boxed{\nu_e} + \boxed{\bar{\nu}_\mu} \qquad \mu^- \to e^- + \boxed{\bar{\nu}_e} + \boxed{\nu_\mu}$$

- Only **electron** and **muon** neutrinos are originally produced in the GeV energy range!
- How is a tau neutrino flux observed?

➡ **Neutrino Oscillations!**



From CERN courier magazine

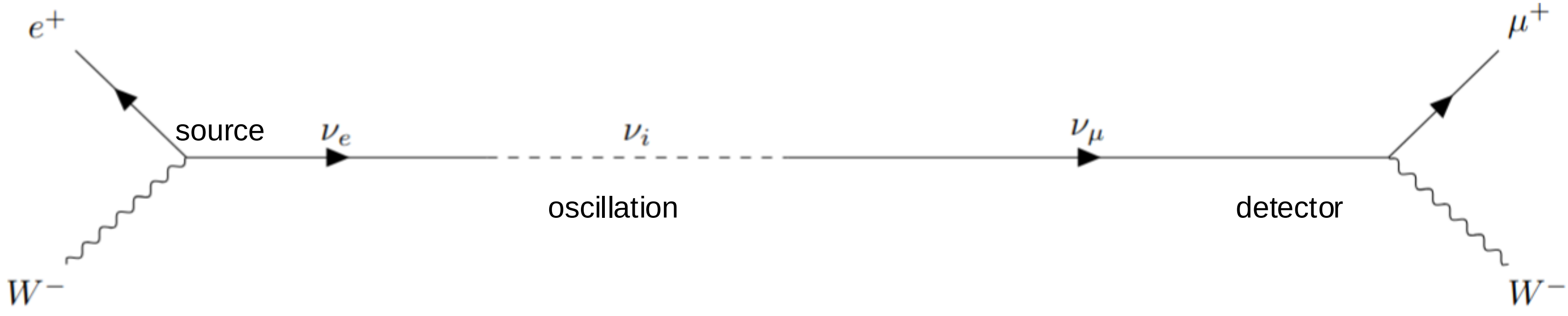
Neutrino

Neutrino Oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$|\nu_e\rangle = U^*_{\mathrm{e}1}\,|\nu_1\rangle + U^*_{\mathrm{e}2}\,|\nu_2\rangle + U^*_{\mathrm{e}3}\,|\nu_3\rangle$$

- Neutrino mixing matrix
- Phenomenology for the 3-flavor case defined with 4 parameters
  - 3 mixing angles: θ_{ij}
  - 1 CP-violating phase: δ_{ij}



Neutrino

Neutrino Oscillations

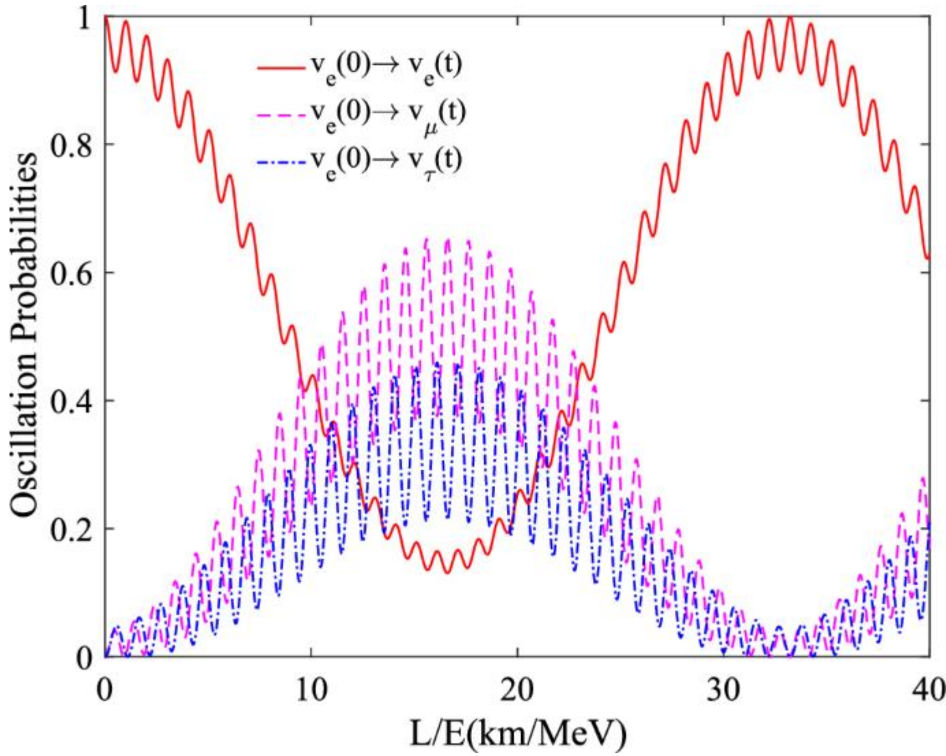
- Oscillation probability for a neutrino from flavor α→β in vacuum

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum Re[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}]\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum Im[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}]\sin\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$

For a given L/E, oscillations are dominated by only one Δm^2 !

- Two flavor case:
  - Amplitude depends on: θ
  - Frequency depend on: L/E, Δm^2

$$P(\nu_\alpha \to \nu_\beta) = \underbrace{\sin^2(2\theta)}_{\text{Amplitude}}\underbrace{\sin^2\left(\frac{\Delta m^2 L}{4E}\right)}_{\text{Frequency}}$$



Motivation for this analysis

- Tau neutrinos are one of the least well measured particles in the standard model of particle physics
  - Reduce the uncertainties in the charged-current cross section
  - Investigate the unitarity of the neutrino mixing matrix

Tau appearance measurement

- Relevant results from OPERA, IceCube/DeepCore, Super-Kamiokande and KM3NeT

- Is a potential combined analysis with KM3NeT possible?

  ➡ First usage of ANTARES pseudo-data with KM3NeT tools!

- Additional goal for ANTARES data beyond its main objective?

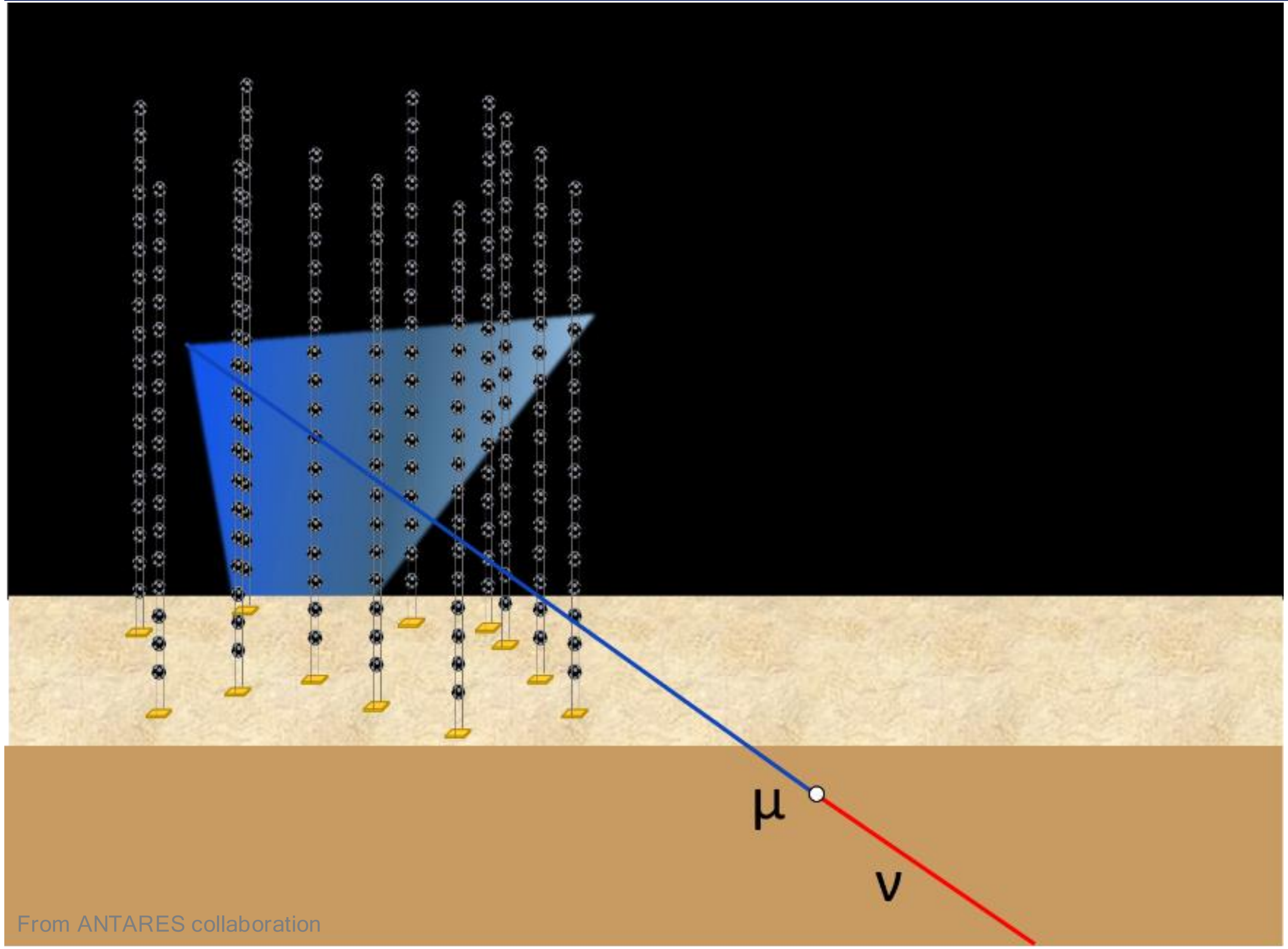
  ➡ A preliminary feasibility analysis necessary

[Most recent results: (Opera collaboration, Physical Review Letters, 2018), (IceCube collaboration, Physical Review D, 2019), (SK collaboration, ICHEP, 2022), (KM3NeT collaboration, ICRC, 2023)]

Neutrino Telescopes

Neutrino Telescopes

Introduction to Neutrino Telescopes

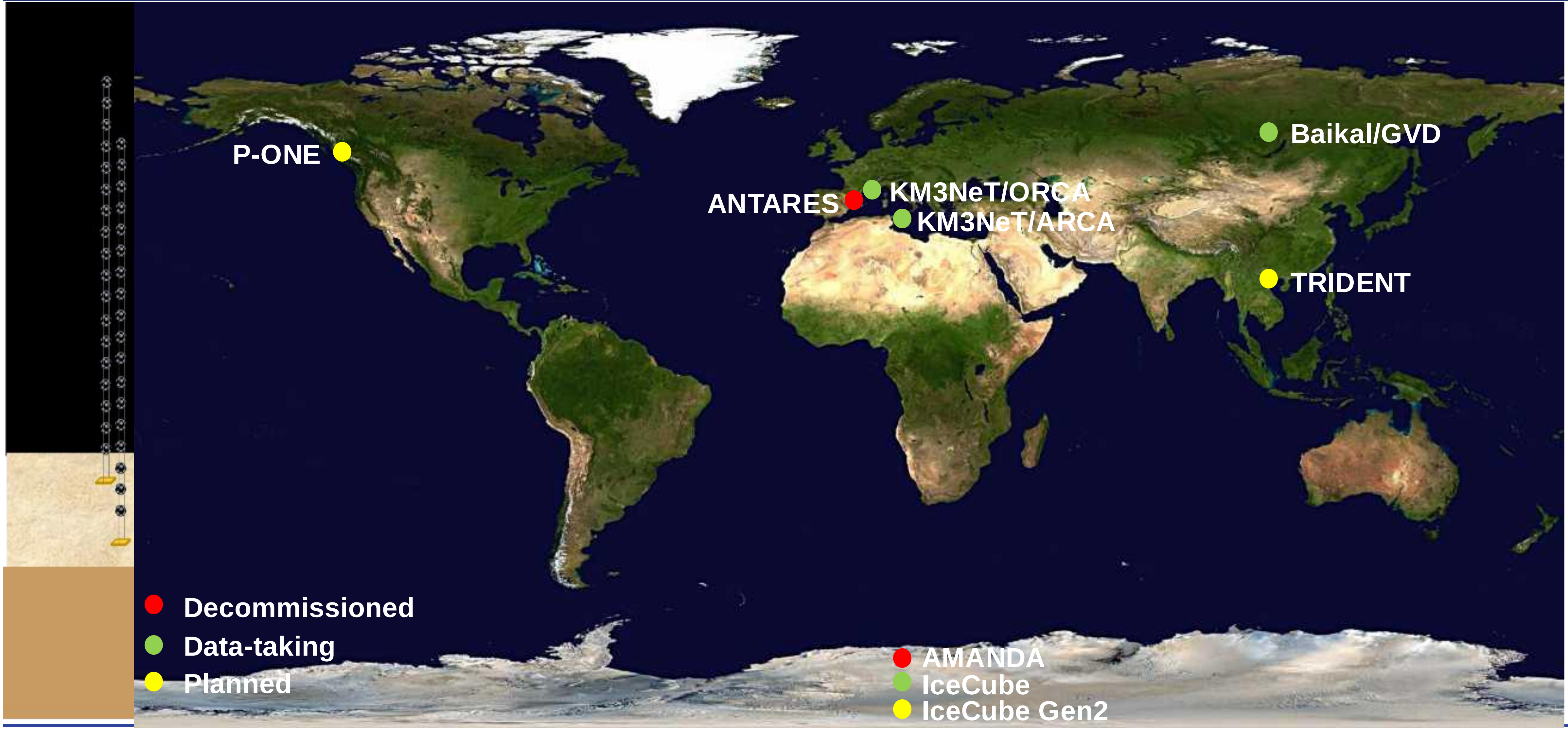


Applications:

- Study of neutrino properties (e.g., oscillations).
- Investigation of astrophysical phenomena (e.g., supernovae, AGNs).
- Search for dark matter and exotic particles.

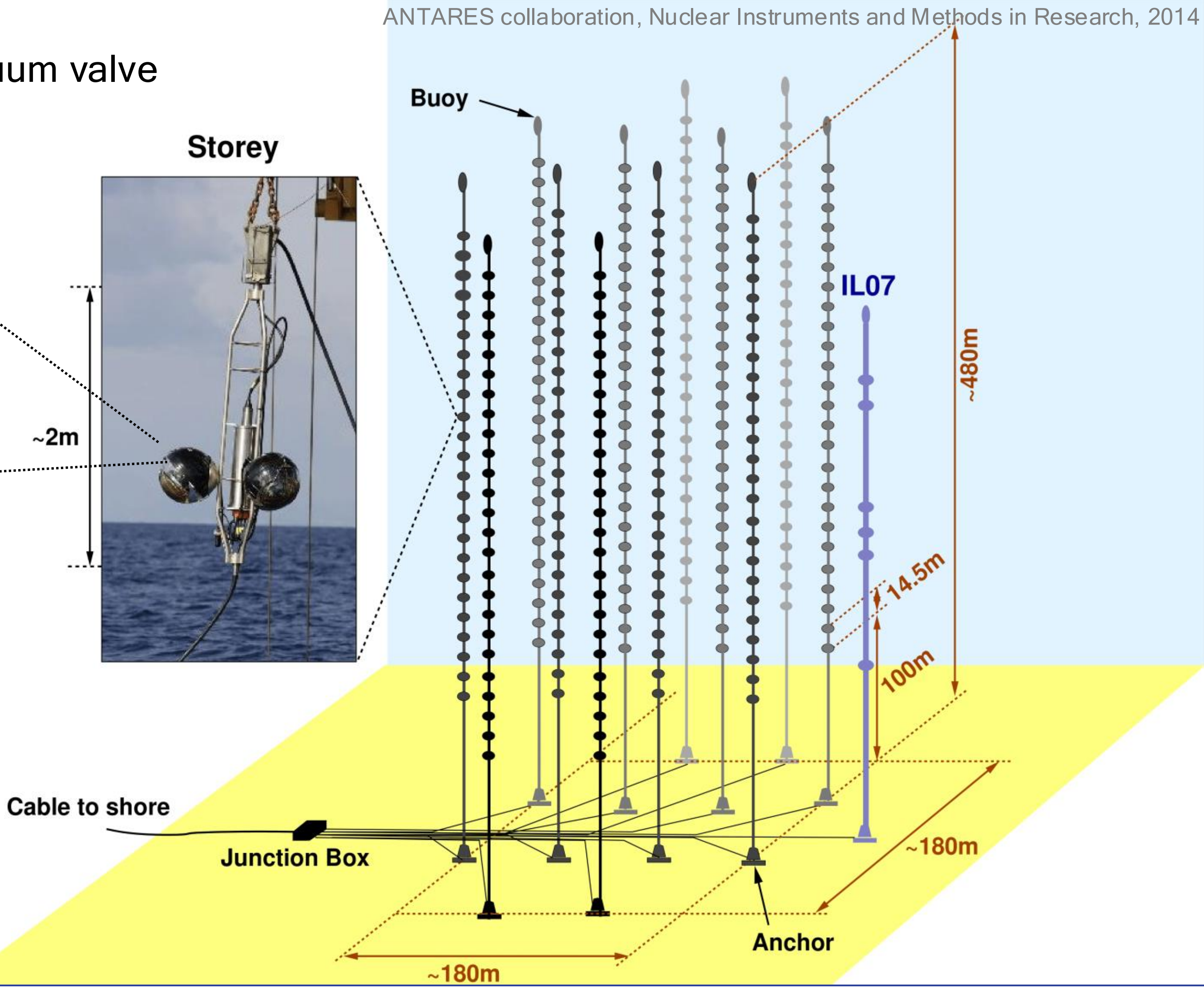
Neutrino Telescopes

Introduction to Neutrino Telescopes



Neutrino Telescopes

ANTARES Detector

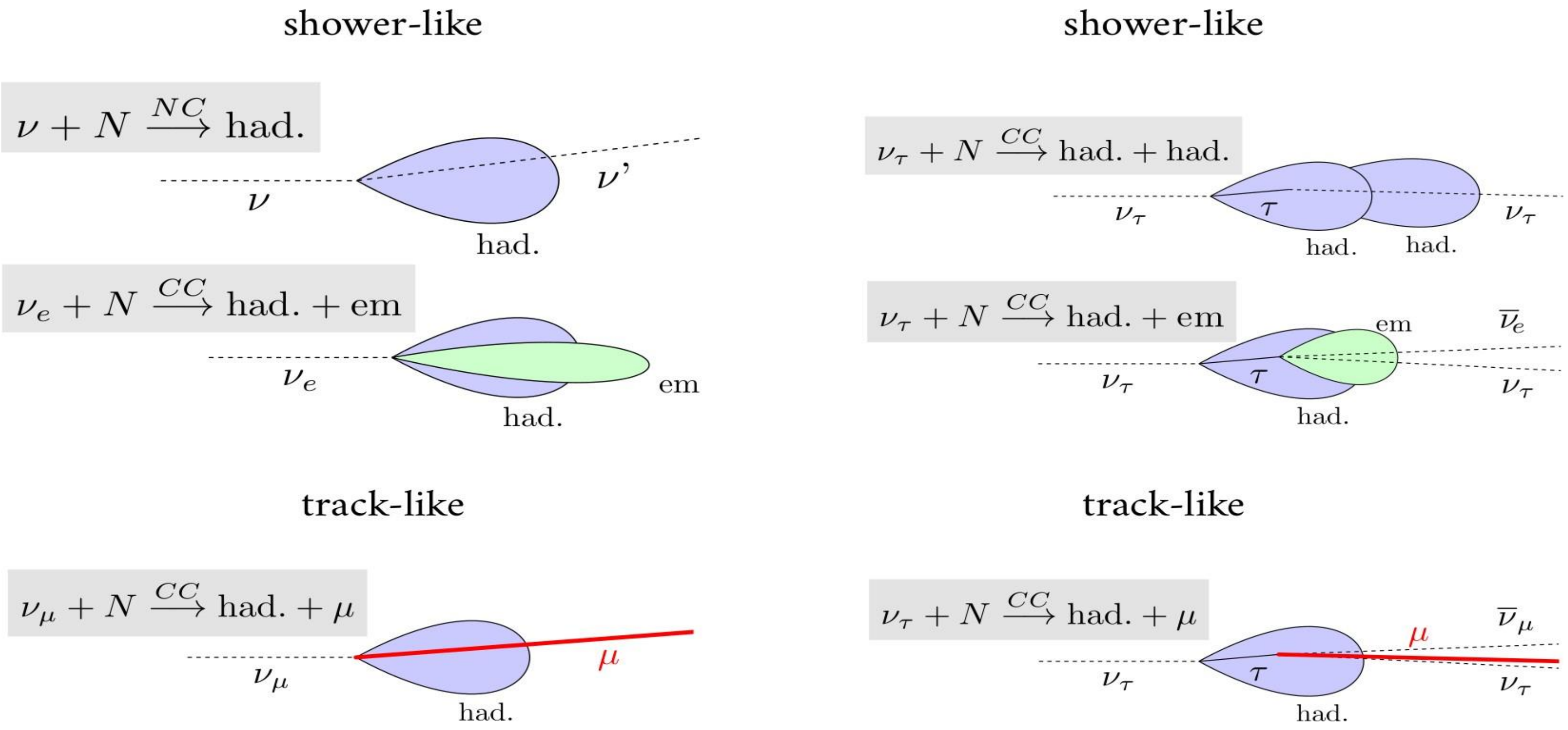


- Located 40 km off Toulon, France
- Sea depth: ~2500m
- Detector volume: ~0.03 km^3
- Active: 2007 - 2022
- Energy threshold: 10 GeV

Neutrino Telescopes

Topology of neutrino events

Non-tau channel **Tau channel**



Hallmann, Steffen, PhD Thesis, 2021

- No event-by-event identification for tau neutrino interactions!
- Tau neutrinos result in **both tracks** and **showers** signatures!
- Event topology depends on the decay channel.

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

Tau appearance

Tau Appearance

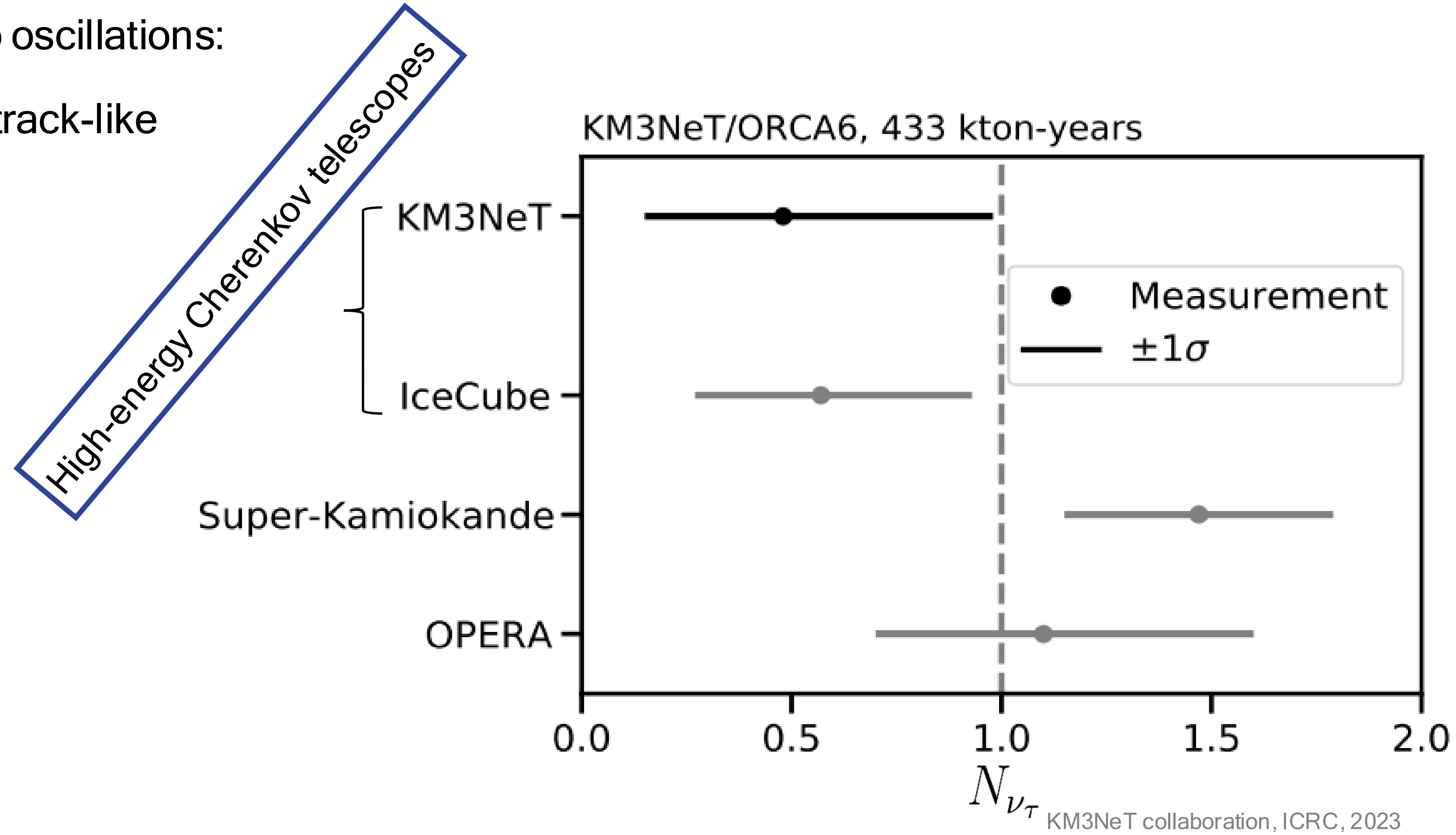
Tau events only product of neutrino oscillations:

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

$$\boxed{N_{\nu_\tau} = \frac{N_{\tau,\text{measured}}}{N_{\tau,\text{expected}}}}$$

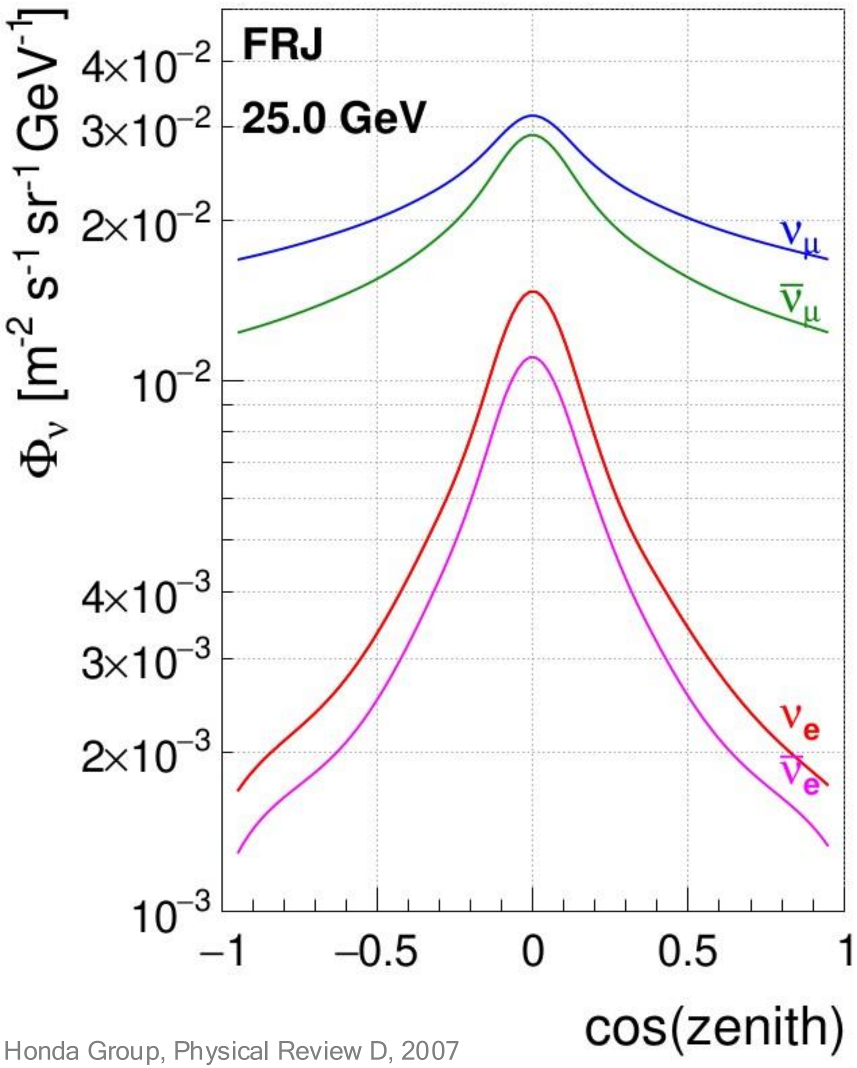
Tau normalization measurement:

- N_{ν_τ}= 1: expected case
- N_{ν_τ}= 0: no-tau case

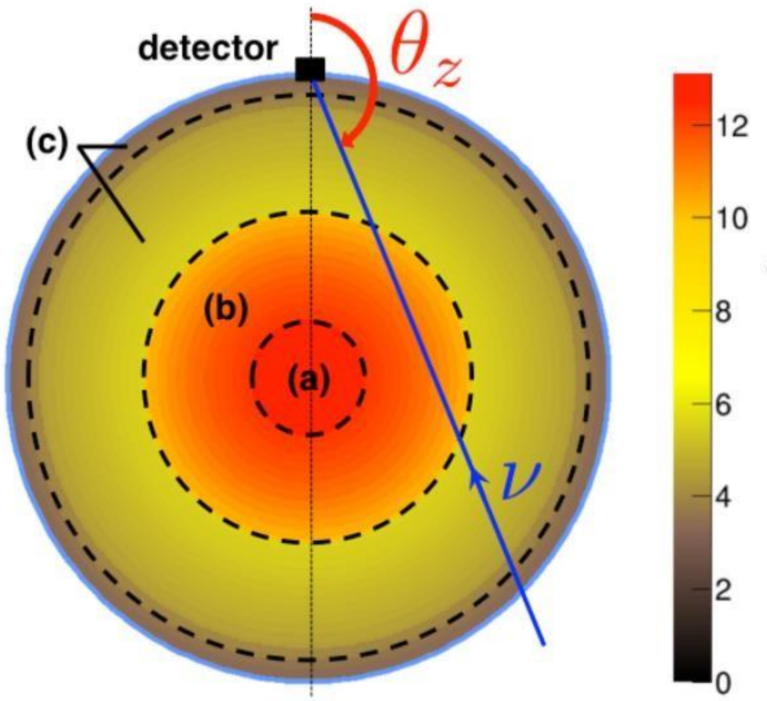


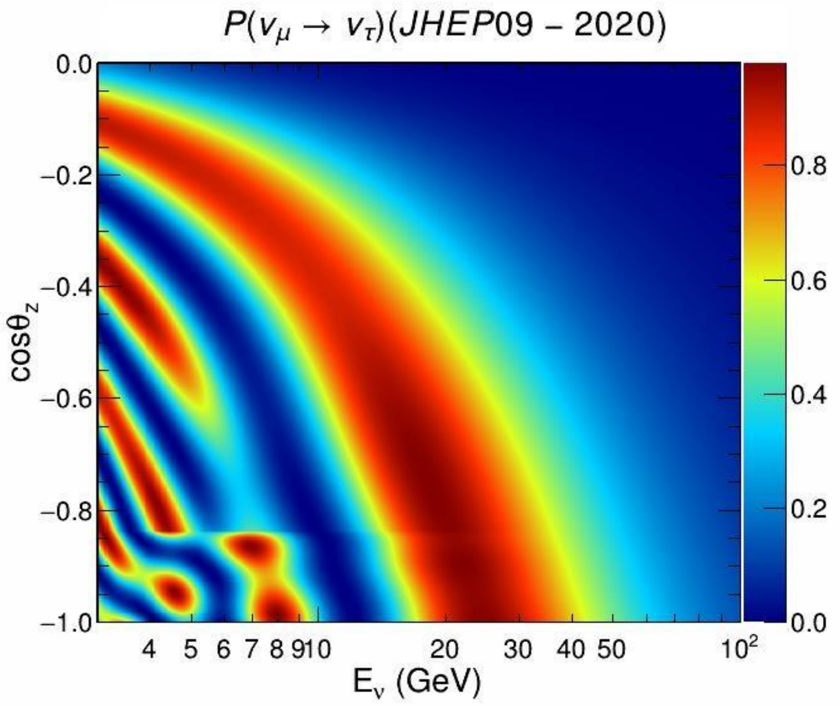
KM3NeT collaboration, ICRC, 2023

Tau Appearance



Honda Group, Physical Review D, 2007





Honda flux

Oscillation probability

Cross section

$$N_{\nu_\beta}(E_\nu, \theta_\nu) = \Phi(E_\nu, \theta_\nu) \times P(\nu_\alpha \to \nu_\beta)(E_\nu, \theta_\nu) \times \sigma(E_\nu) \times \text{Detector Efficiency}$$

Tau Appearance

Sensitivity Calculation for the Tau Normalization Parameter

1. Fill 2D histograms (E, cos(θ)), for data and model

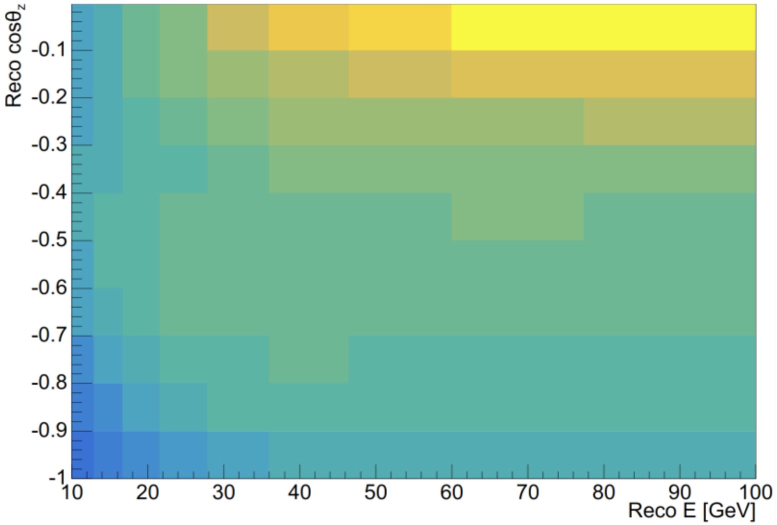
2. Obtain the negative log likelihood distribution, χ^2

$$\chi^2 = 2\sum_{ij}\underbrace{\left(n_{ij}^{model} - n_{ij}^{data} + n_{ij}^{model}\log\left(\frac{n_{ij}^{data}}{n_{ij}^{model}}\right)\right)}_{\text{Statistical part}} + \underbrace{\sum_{\alpha}\left(\frac{\alpha_{exp} - \alpha_{obs}}{\sigma_a}\right)^2}_{\text{Systematics part}}$$

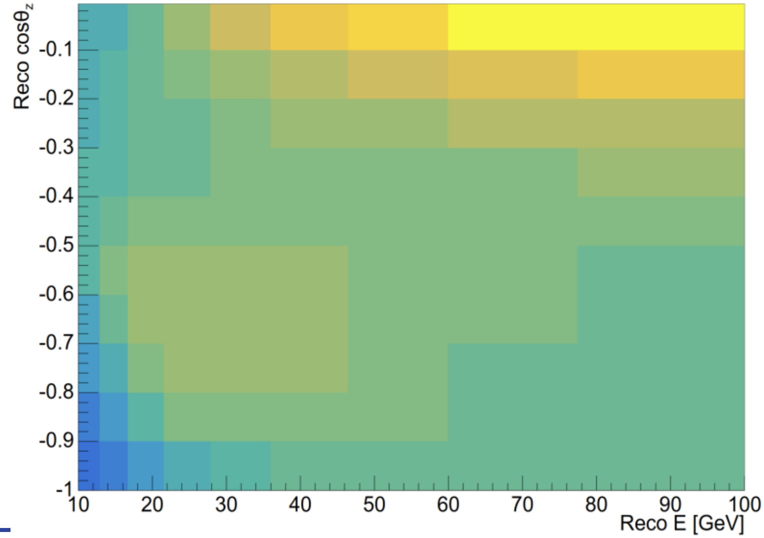
Systematics:
- Oscillation parameters
- Cross section
- Background
- Detector response
- Flux parameters

A total of 17 parameters included!

Model Showers



Data Showers



Tau Appearance

Sensitivity Calculation for the Tau Normalization Parameter

3 Calculate the square difference between the hypothesis and best-fit model

$$\Delta\chi^2 = \chi^2_{\text{hypothesis}} - \chi^2_{\text{best-fit}}$$

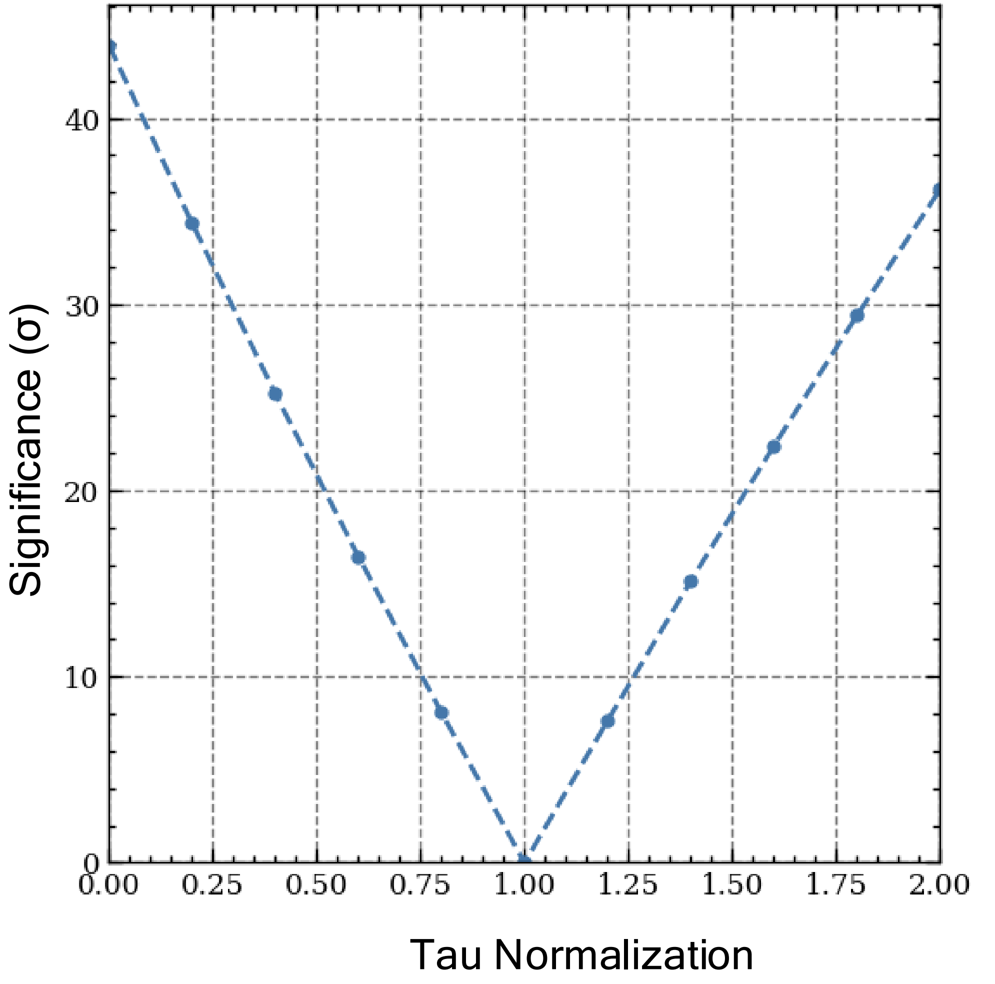
"best-fit":

Let the fit find the value of the Tau Normalization that corresponds to our data

"fixed hypothesis":

Calculate the likelihood of rejection for a certain fixed value of the Tau Normalization

Significance approximated as $\sigma = \sqrt{\Delta\chi^2}$



ANTARES Monte-Carlo

ANTARES Monte-Carlo

Open Analysis Questions

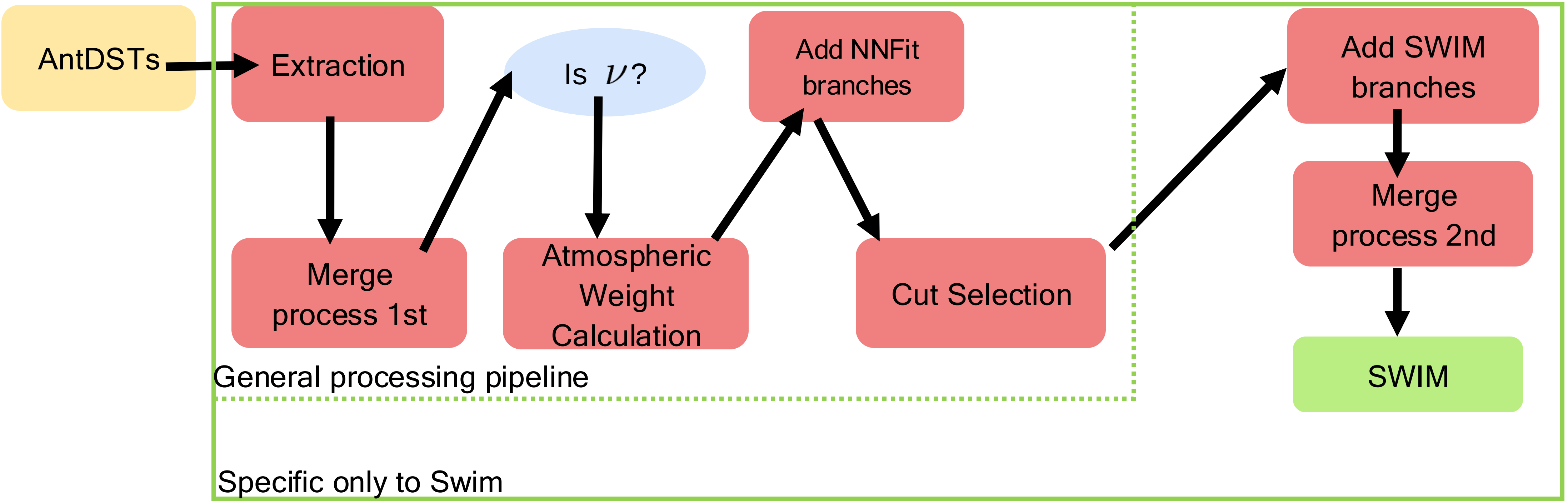
1. How many ν_τ are expected?

2. What is the performance of the reconstructions available in the AntDSTs, i.e. ANTARES summary file?

3. What is the performance of NNFit reconstruction?

ANTARES Monte-Carlo

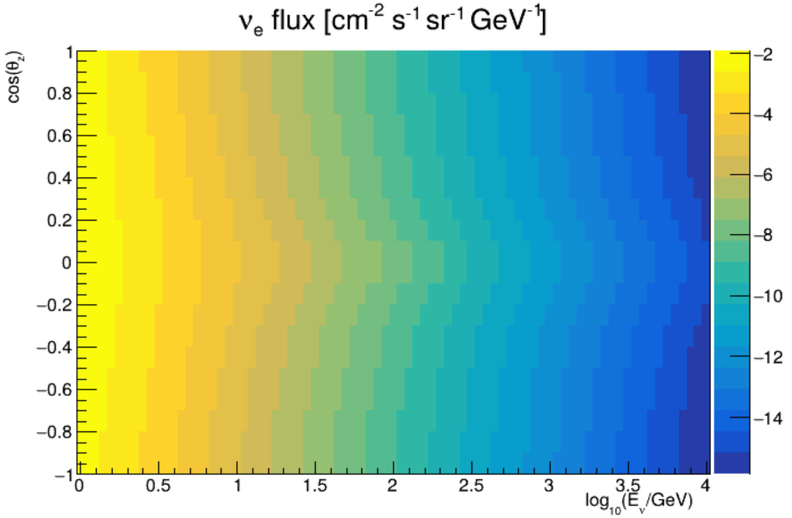
Processing Pipeline



- Applicable in both computing clusters (woody and cc lyon)
- Total computing time: around 4000 CPU hours
- First full lifetime ANTARES dataset with AntDST and NNFit information

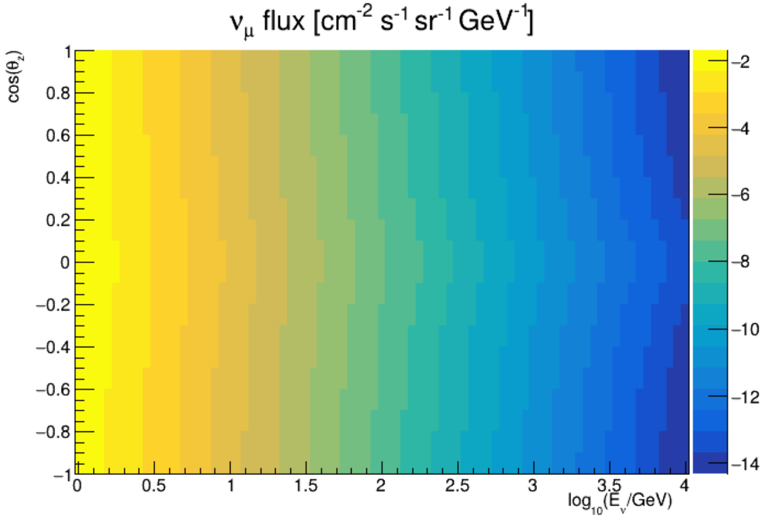
ANTARES Monte-Carlo

Atmospheric weight calculation



ν_e

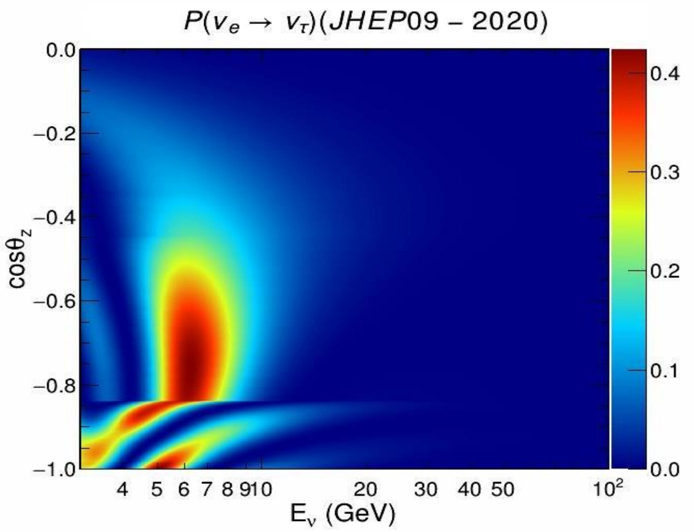
ν_μ

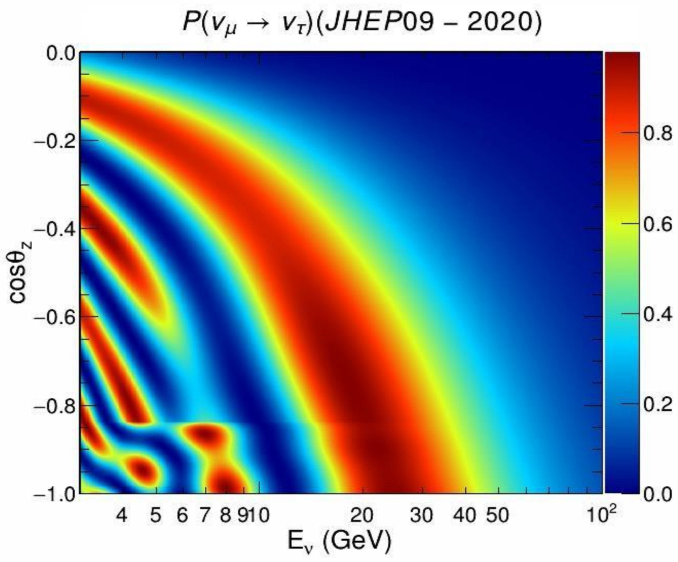


Atmospheric flux

$$w_{\nu_i}^{\text{atm}} \propto \left(\Phi_{\nu_e} P_{\nu_e \to \nu_i} + \Phi_{\nu_\mu} P_{\nu_\mu \to \nu_i}\right) \cdot \text{Time}$$

Oscillation probability





ANTARES Monte Carlo

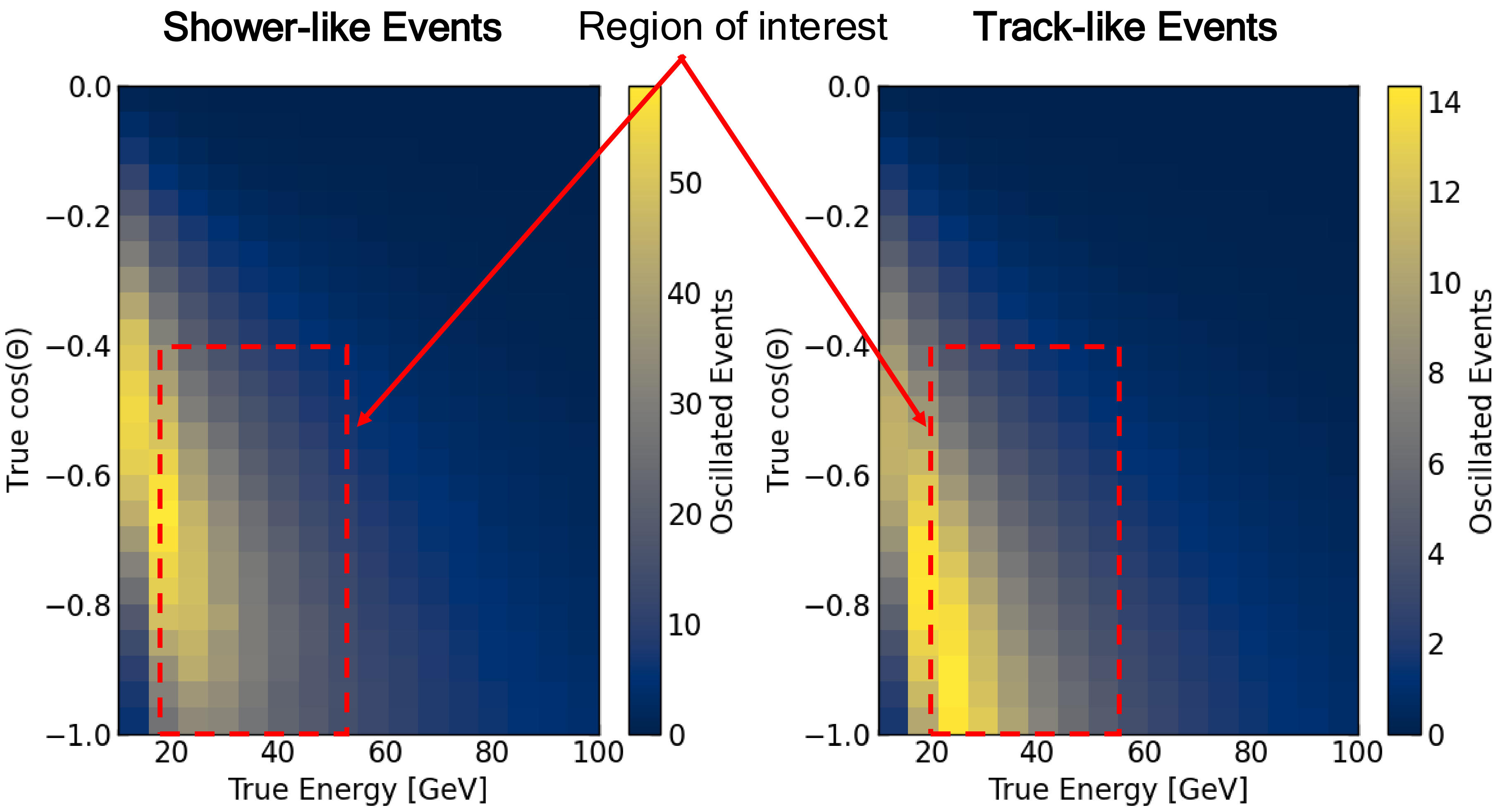
Expected sample - True low energy

- Number of neutrinos for the full duration of the experiment
- Events are **triggered** & **reconstructed**
- Cuts:
  - $10 < E < 100$ GeV
  - $\cos(\theta) < 0$
- Test case assuming perfect "muon" rejection

Category	Events	Percentage (%)
ν_e^{CC}	7773	15
ν_μ^{CC}	41023	81
ν_τ^{CCmu}	1059	2
$\nu_\tau^{CCshower}$	3355	7
ν^{NC}	4127	8
Total	**57338**	

ANTARES Monte Carlo

Expected sample - full upgoing



Region of interest:

- Expected majority of events
- Maintains 90% of the sample
- Transition probability from $\nu_\mu \rightarrow \nu_\tau$ the highest

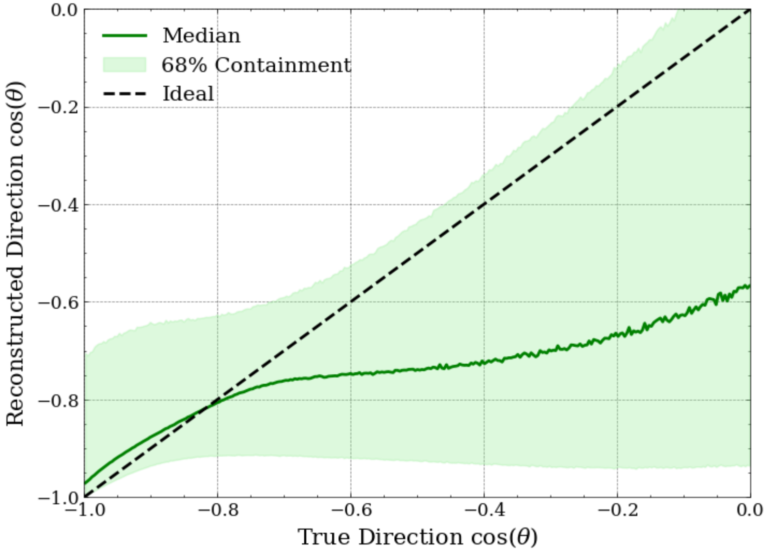
ANTARES Monte Carlo

Reconstruction performance - AAFit

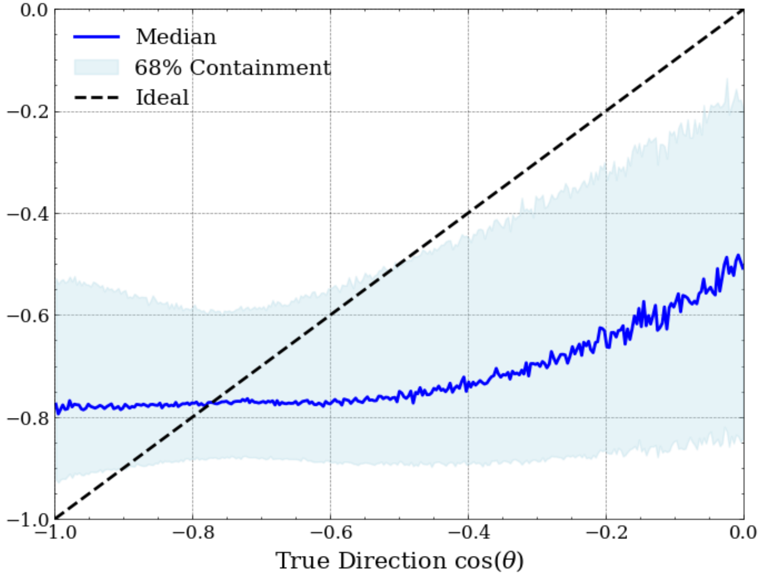
AAFit:

- Maximum likelihood method
- Aims to reconstruct high energy events
- **Advantages:**
  - Reconstruction efficiency: almost 70%
  - Direction reconstruction for up-going tracks
- **Disadvantages:**
  - Direction reconstruction for showers

Tracks



Showers

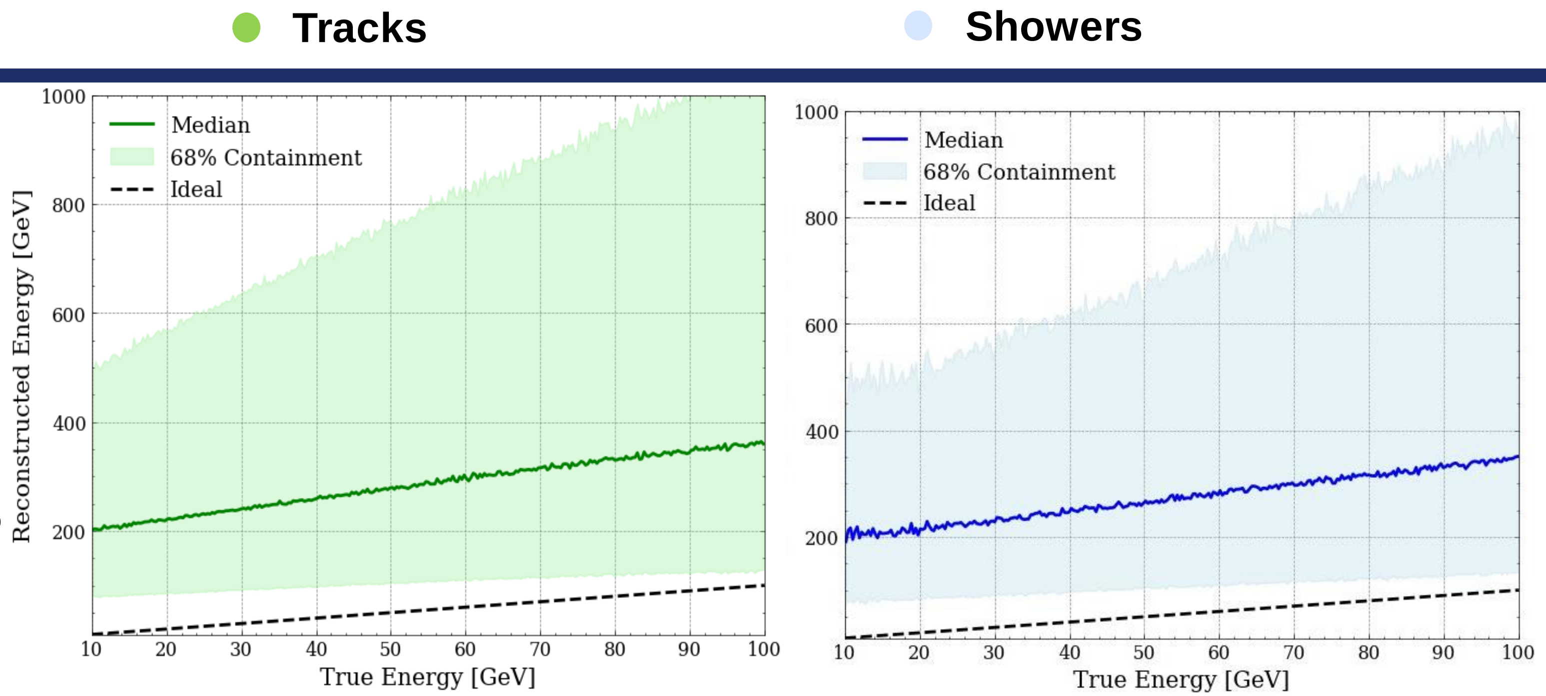


ANTARES Monte Carlo

Reconstruction performance - AAFit

AAFit:

- Maximum likelihood method
- Aims to reconstruct high energy events
- **Advantages:**
  - Reconstruction efficiency: almost 70%
  - Direction reconstruction for up-going tracks
- **Disadvantages:**
  - Direction reconstruction for showers
  - Energy reconstruction for from ideal!
  - Efficiency drop to 10% even with loose quality cuts

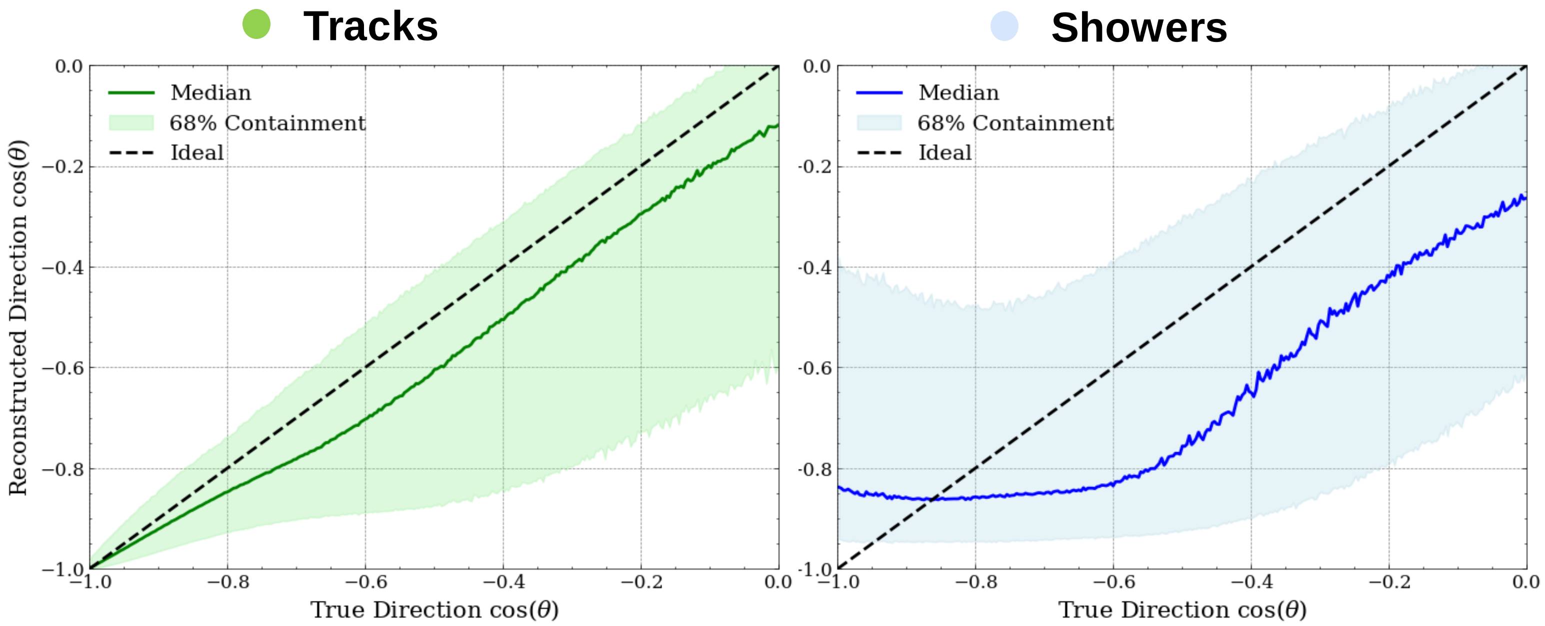


ANTARES Monte Carlo

Reconstruction performance - BBFit

BBFit:

- Maximum likelihood method
- Aims to reconstruct low energy track-like events
- Approximation for shower also exists
- **Advantages:**
  - Direction reconstruction for both topologies better than AAFit
  - Efficiency after quality cuts up to 15%
- **Disadvantages:**
  - Low reconstruction efficiency up to 30%



Direction performance: simple quality cuts

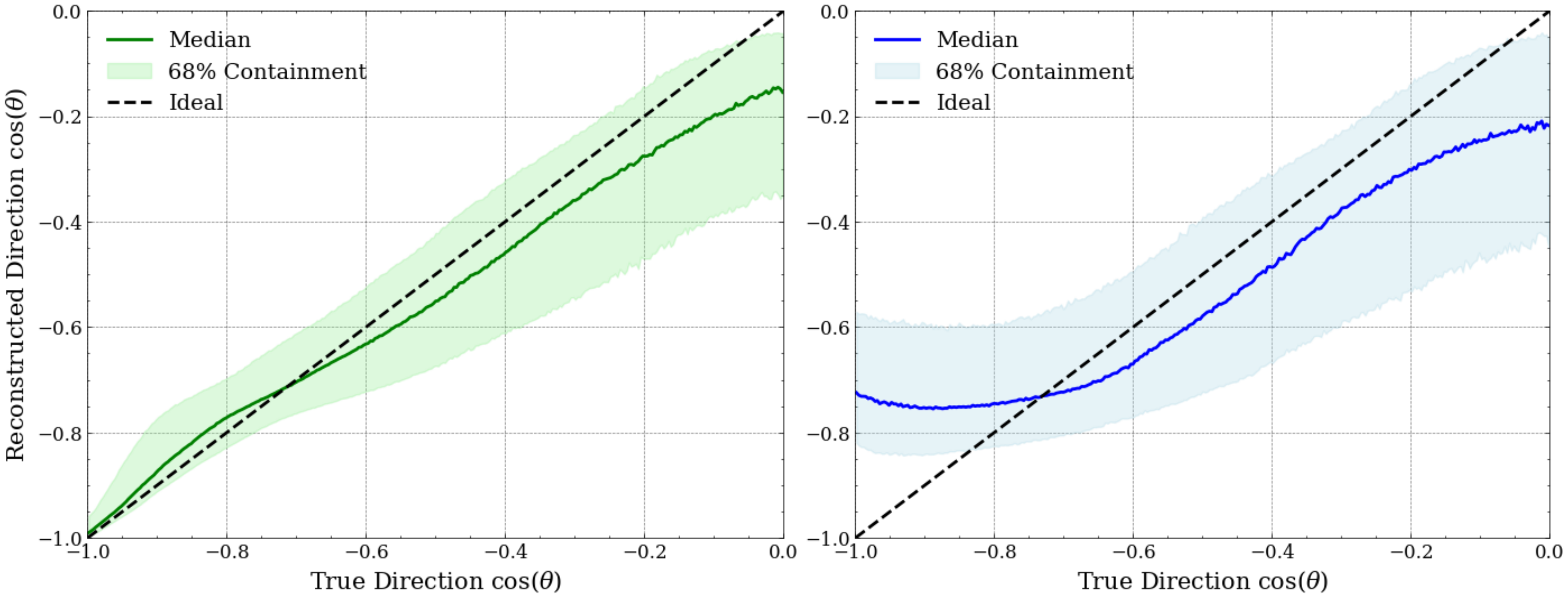
ANTARES Monte Carlo

Reconstruction performance - NNFit

NNFit:

- ML based method
- Aims to reconstruct low energy events
- Two networks developed for both topologies: NNFitTrack, NNFitShower
- **Advantages:**
  - Direction reconstruction for both topologies better than AAFit
  - Efficiency after quality cuts up to 15%
- **Disadvantages:**
  - Low reconstruction efficiency up to 25%

Tracks Showers



Direction performance: simple quality cuts

More information about the reconstruction

J.G. Mendez, S. Ardid, and M. Ardid., ICRC, 2023

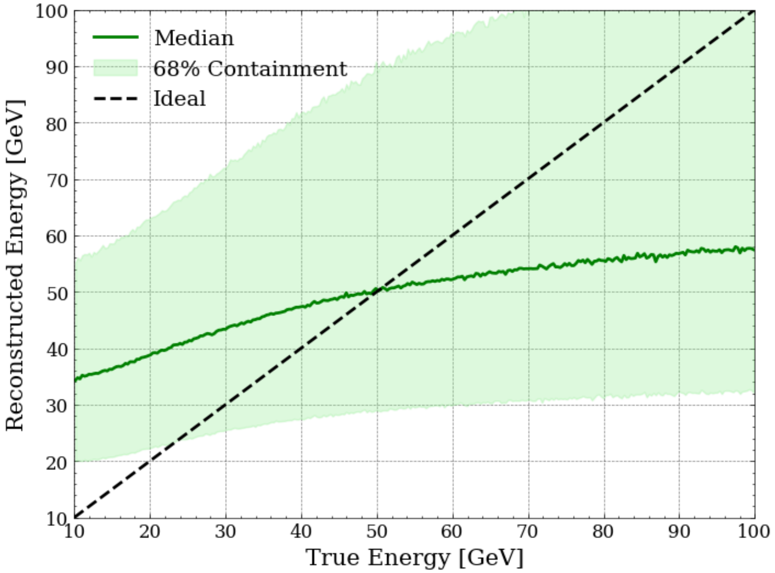
ANTARES Monte Carlo

Reconstruction performance - NNFit

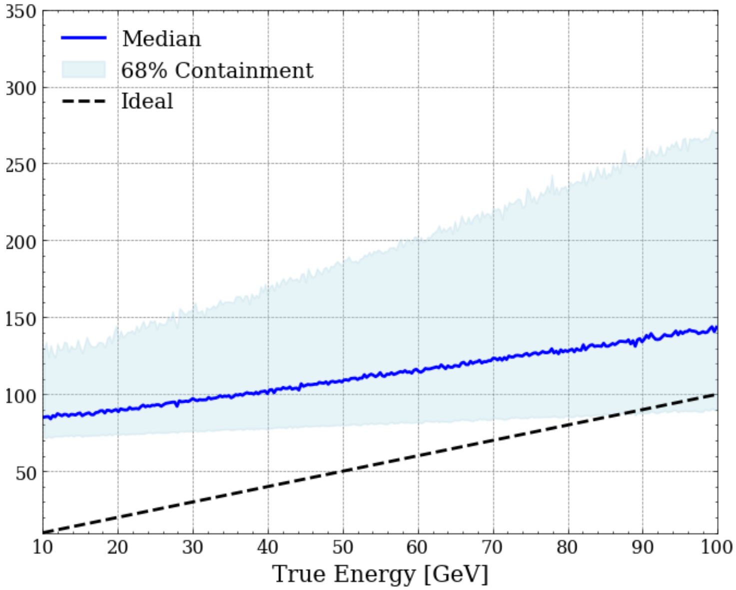
NNFit:

- ML based method
- Aims to reconstruct low energy events
- Two networks developed for both topologies: NNFitTrack, NNFitShower
- **Advantages:**
  - Direction reconstruction for both topologies better than AAFit
  - Efficiency after quality cuts up to 15%
- **Disadvantages:**
  - Low reconstruction efficiency up to 25%
  - Energy reconstruction also not ideal

Tracks



Showers



Energy performance: simple quality cuts

ANTARES Monte Carlo

Expected sample - NNFit quality sample

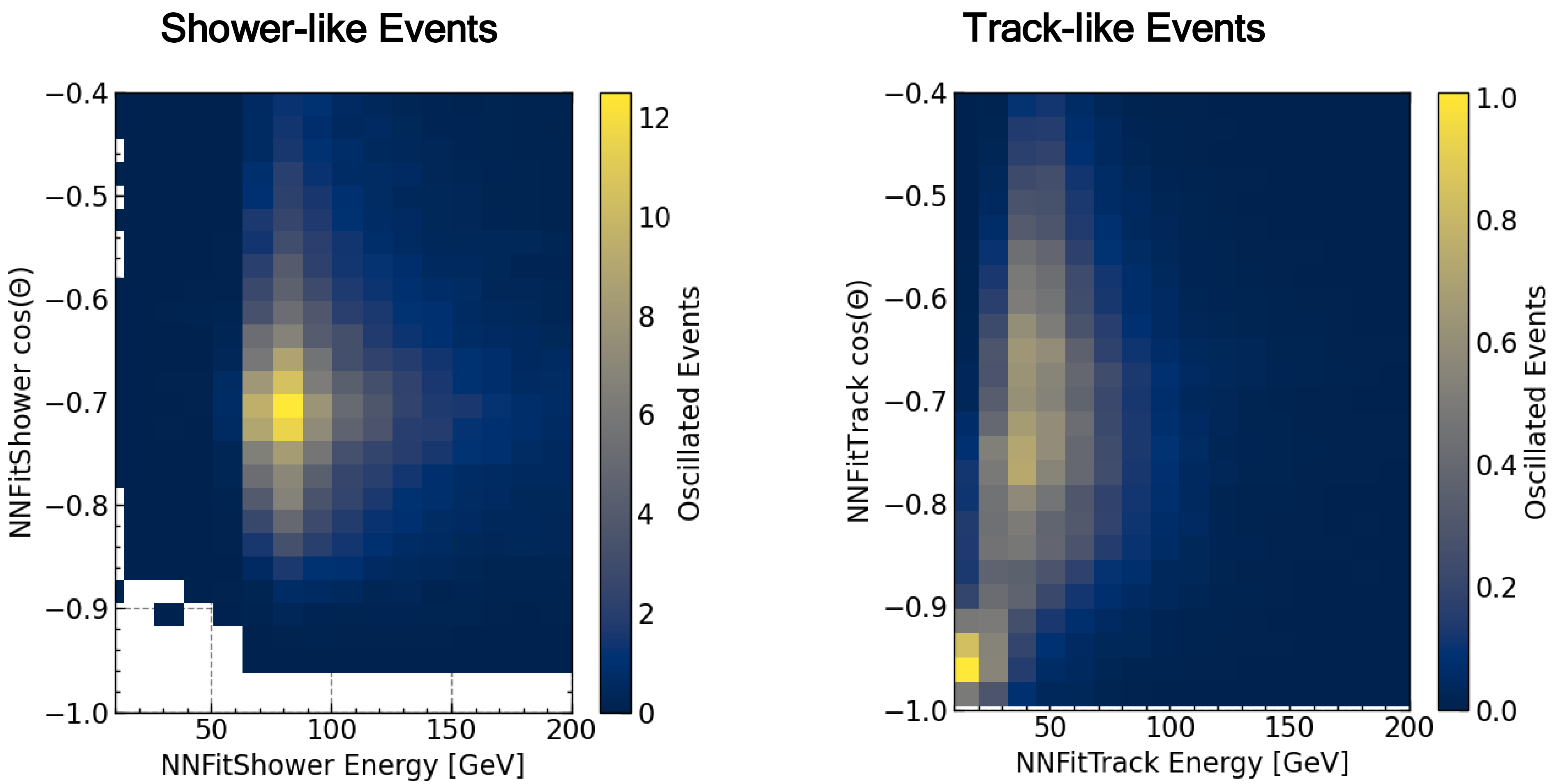
- Number of neutrinos for the full duration of the experiment reconstructed by NNFit with some quality cuts applied
- First iteration of selection criteria, not optimized!
- Assume "perfect" classification
- Cut selection for both topologies
- Tracks:
  - $\sigma_\theta < 8°$
  - $\sigma_R < 10$ m
  - $\sigma_Z < 10$ m
  - $\cos(\theta) < -0.4$
- Showers:
  - $\sigma_R < 10$ m
  - $\sigma_Z < 10$ m
  - $\cos(\theta) < -0.4$

Category	Events	Percentage (%)
ν_e^{CC}	885	13
ν_μ^{CC}	3107	45
ν_τ^{CCmu}	67	1
$\nu_\tau^{CCshower}$	372	5
ν^{NC}	447	7
μ	1982	29
Total	**6860**	

Cut selection focused mainly on the predicted uncertainties from the network!

ANTARES Monte Carlo

Expected sample - NNFit quality sample



ANTARES Monte Carlo

Comparison summary

	AAFit	BBFit	NNFit
Initial efficiency			
Efficiency after cuts			
Energy - Showers		No Data	
Energy - Tracks		No Data	
Direction - Showers			
Direction - Tracks			

Tau Appearance Sensitivity

Tau Appearance - Sensitivity

Scenarios

Sensitivity calculations/scenarios depends on the following, parameters:

- Cut Selection
- Mass Ordering
- Interaction Channel
- Reconstruction
- Systematic Treatment

In total 120 different scenarios!

All sensitivities computed via the *Swim* software!

Detector response

Cut Selection

- True energy
- NNFit reconstructed upgoing
- NNFit reconstructed with quality cuts

Reconstruction

- MC truth
- AAFit
- NNFit

Model parameters

Mass Ordering

- Normal (NO)
- Inverted (IO)

Interaction Channel

- CC
- CC + NC

Systematic Treatment

- fixed
- fitted

Tau Appearance - Sensitivity

Scenarios

Sensitivity calculations/scenarios depends on the following, parameters:

- Cut Selection
- Mass Ordering
- Interaction Channel
- Reconstruction
- Systematic Treatment

In total 120 different scenarios!

All sensitivities computed via the *Swim* software!

Scenarios presented here!

Cut Selection

- True energy
- NNFit reconstructed upgoing
- NNFit reconstructed with quality cuts

Mass Ordering

- Normal (NO)
- Inverted (IO)

Interaction Channel

- CC
- CC + NC

Reconstruction

- MC truth
- AAFit
- NNFit

Systematic Treatment

- fixed
- fitted

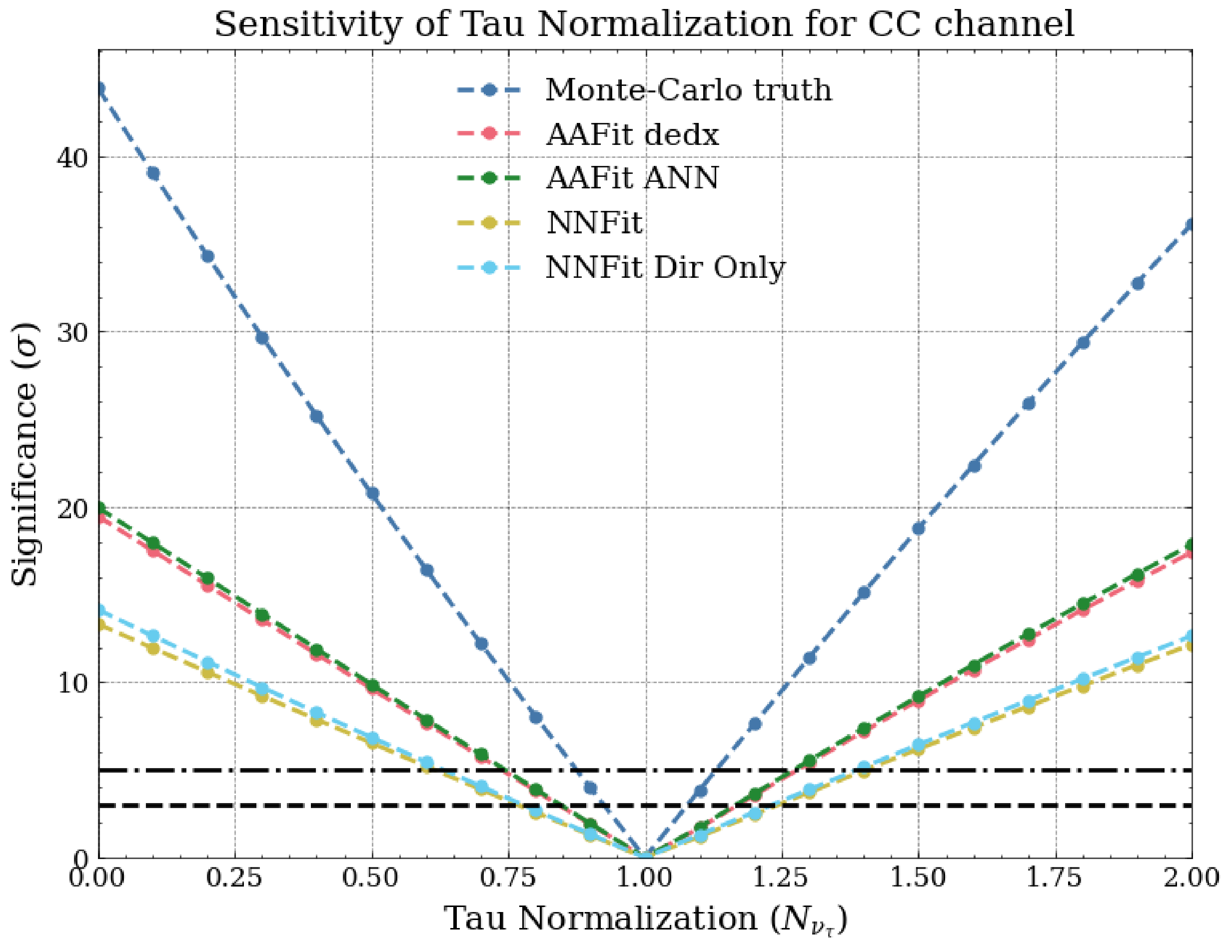
Tau Appearance - Sensitivity

Reconstruction Sensitivities

Scenario chosen:

- "True energy" event sample
- "Charged-current" measurement
- Mass ordering: normal
- **Systematics: fixed**

Reconstruction	Energy	Direction
AAFit	dedX	aafit
AAFit	ANN	aafit
NNFit	NNFit	NNFit
NNFit Dir Only	true	NNFit
MC	true	true



Tau Appearance - Sensitivity

Reconstruction Sensitivities

Scenario chosen:

- "True energy" event sample
- "Charged-current" measurement
- Mass ordering: normal
- **Systematics: fitted**

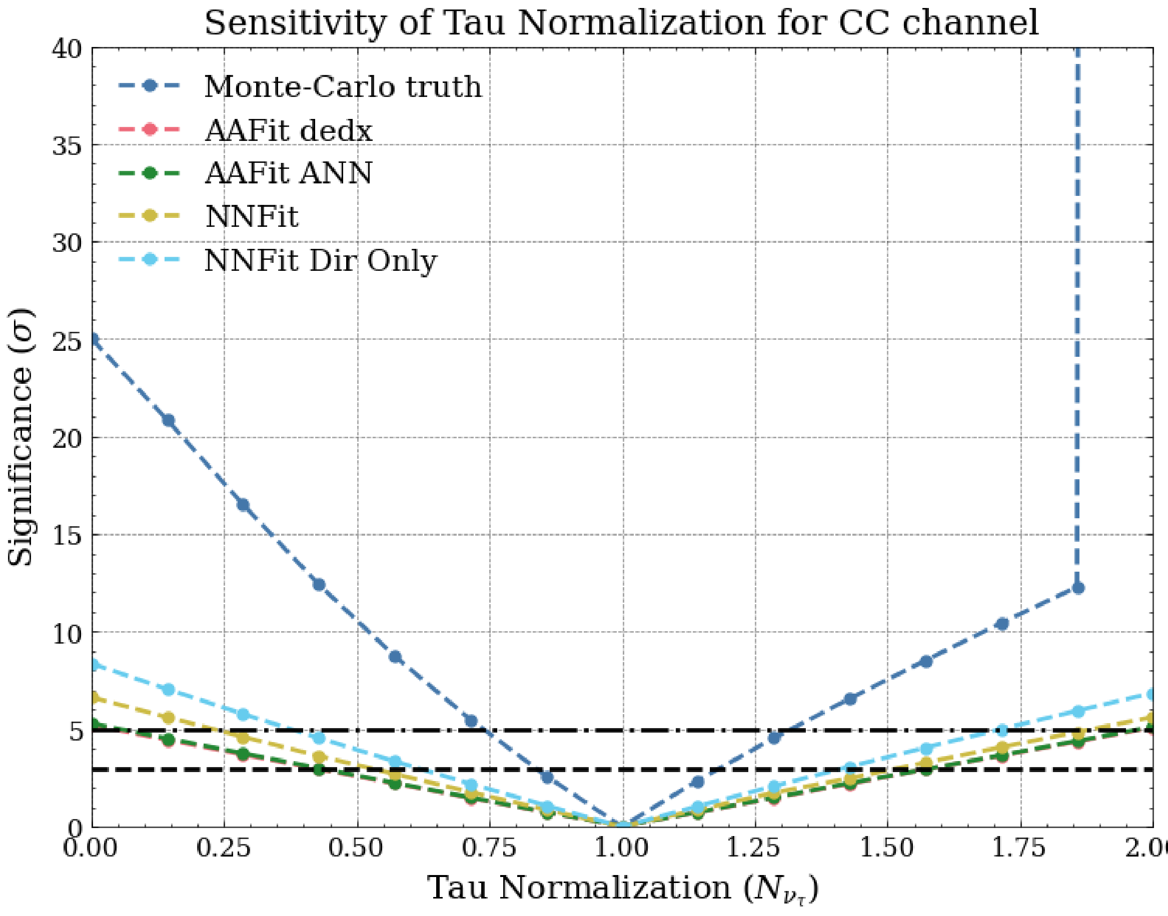
Same treatment as the KM3NeT study

Remarks:

- NNFit exhibits the best performance
- AAFit: both energy estimators have similar performance

<u>Hypothesis – 1st clue</u>

There is a correlation between the variance of the reconstruction performance and the way the systematics are treated!



Disclaimer: Fit of the last point failed!

Tau Appearance - Sensitivity

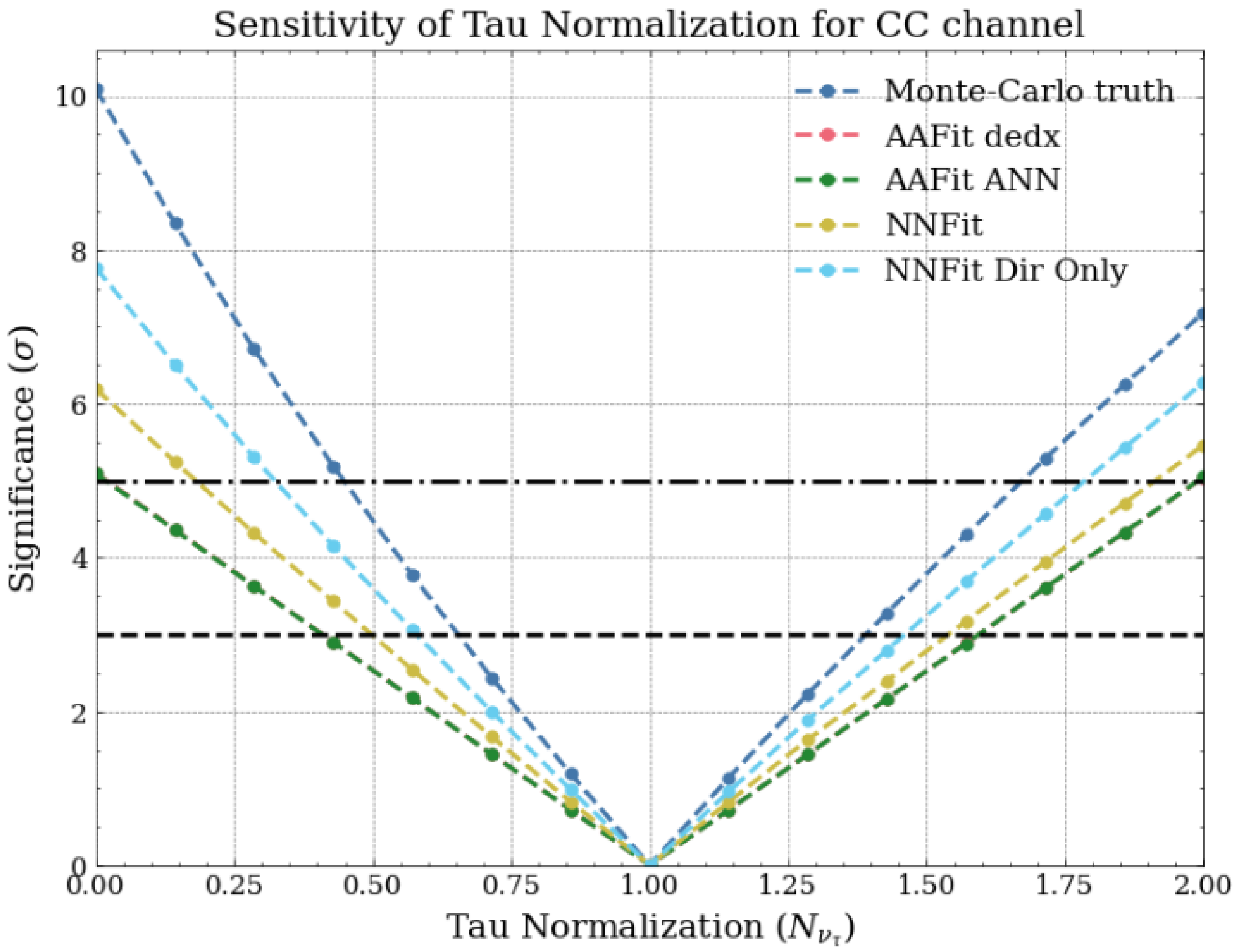
Reconstruction Sensitivities

Scenario chosen:

- NNFit reconstructed events with quality cuts
- "Charged-current" measurement
- Mass ordering: normal
- Systematics: fitted

Remarks:

- NNFit reconstruction can provide up to 6σ
- Loss of 2σ due to imperfect energy reconstruction



Tau Appearance - Sensitivity

Resolution simulation, aka smearing method

Next step: Smearing the MC-truth events

- **Goal:** Find at which level of smearing NNFit reconstruction currently stands
- **Two Methods:**
  - "constant" smearing: smearing events proportional to their true values
  - "resolution" smearing: smearing that mimics the directional & energy resolution of NNFit

Smearing Options:

- 10% smearing
- 30% smearing
- 100% smearing

- ANTARES
- ORCA 6 DUs
- ORCA 115 DUs

Comparison with median performance of ORCA

Tau Appearance - Sensitivity

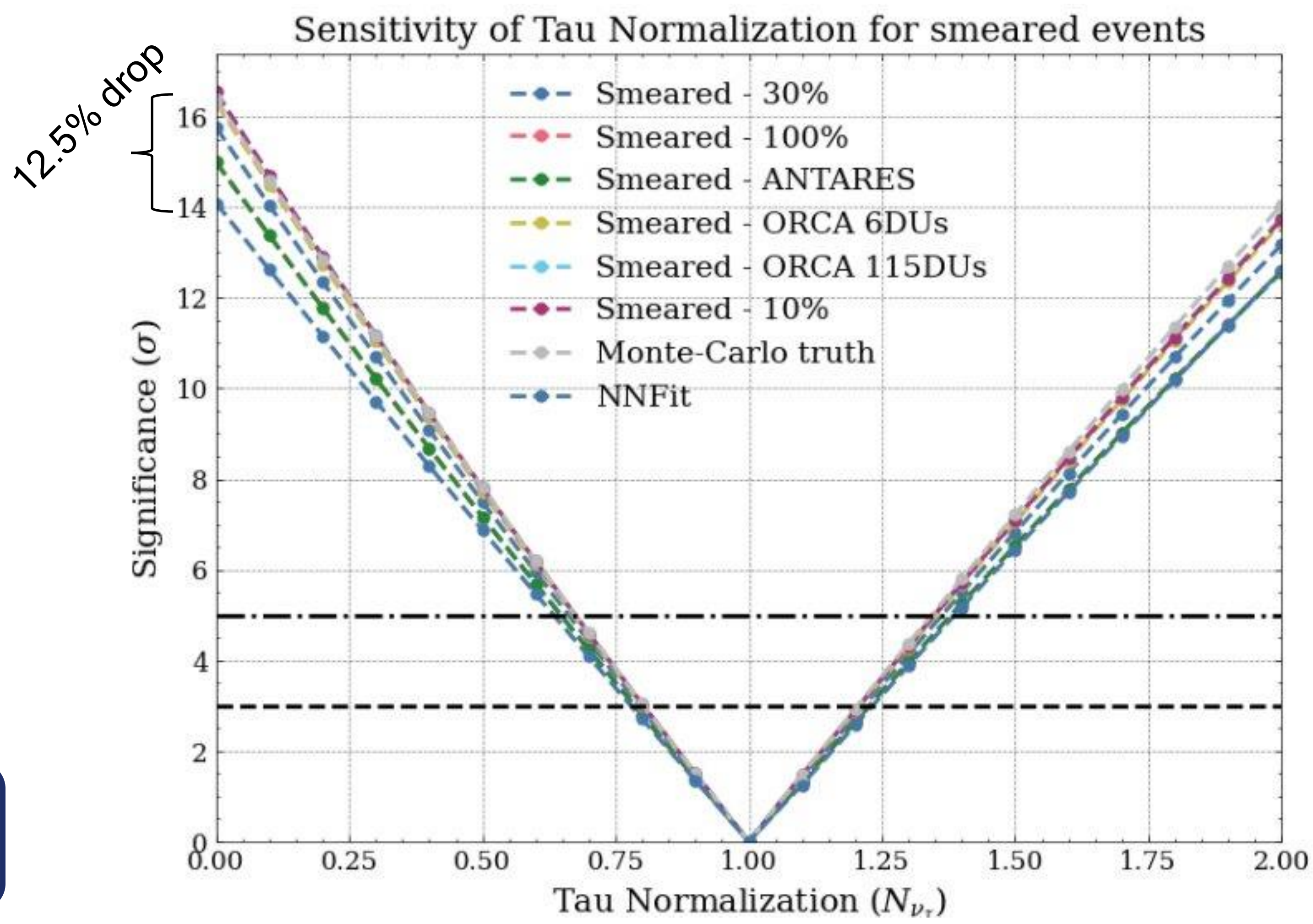
Smearing Sensitivity - Systematic fixed scenario

Remarks:

- Best performing scenarios very close with the unsmeared events
- No improvement detected between ORCA 6 & 115 DUs
- Current "resolution" level almost the same as 100% constant smearing

Why NNFit and Smeared-ANTARES don't have the same sensitivity?

➡ NNFit has a significant variance in the energy reconstruction!

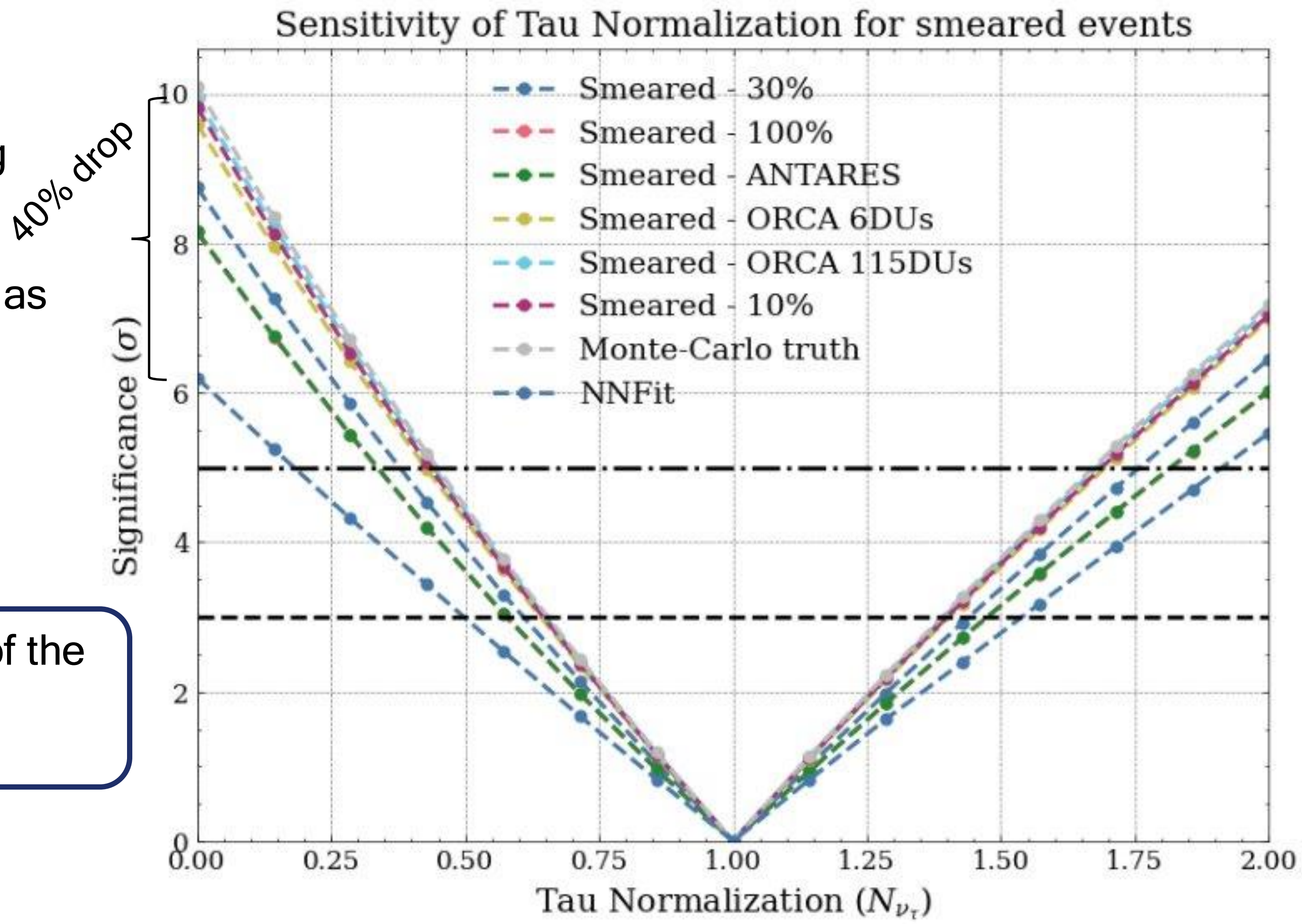


Tau Appearance - Sensitivity

Smearing Sensitivity - Systematics fitted scenario

Remarks:

- Slight differences between best performing scenarios detected!
- Current "resolution" level almost the same as 100% "constant" smearing



Hypothesis - 2nd clue

There is a correlation between the variance of the reconstruction performance and the way the systematics are treated!

Tau Appearance - Sensitivity

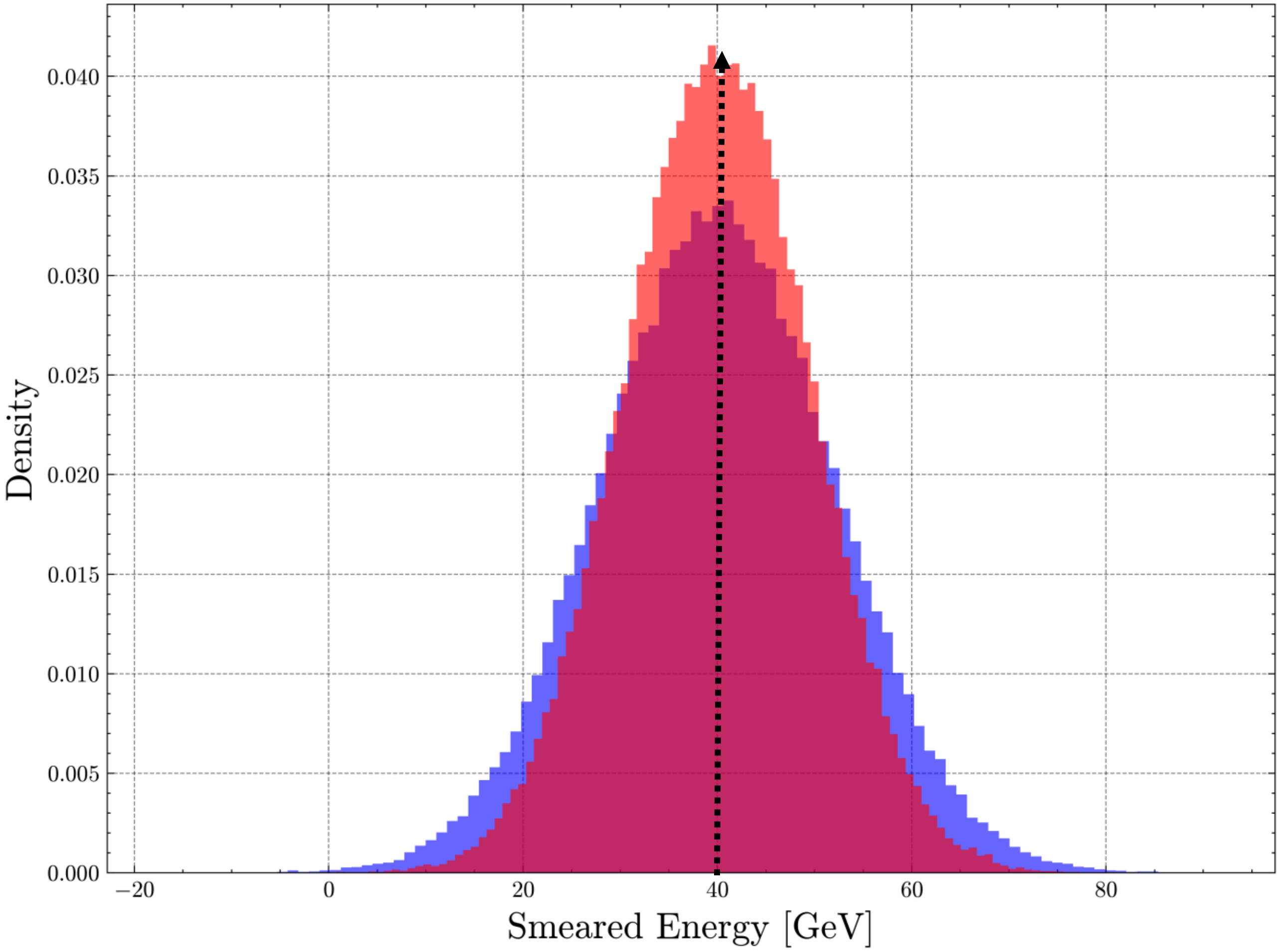
Reconstruction algorithm improvement

Investigation of a potential improvement to an algorithm with performance comparable to NNFit

Potential improvements investigated:

- 40% on the energy reconstruction
- 40% on the direction reconstruction
- 20% on both tasks

Strategy is similar to the "constant"- based smearing method!



- Original density distribution
- Improved density distribution

Tau Appearance - Sensitivity

Reconstruction algorithm improvement

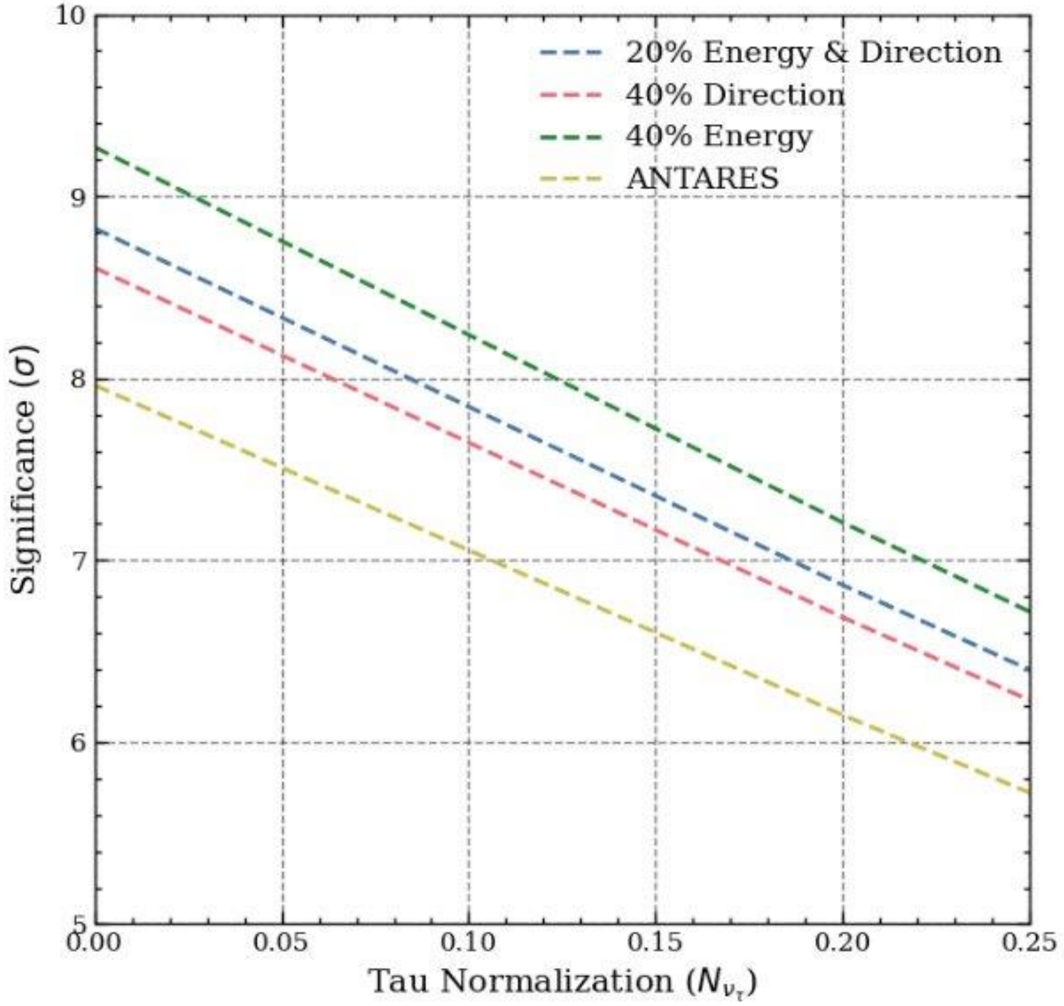
Scenario:

- Systematic treatment: fitted scenario
- Cut selection: NNFit reconstructed with quality cuts

➡ 15% of the sample

Remarks:

- Energy reconstruction task offers the biggest improvement
- Less improvement in both tasks still preforms better than direction alone



Conclusion

Summary

- **Processing pipeline developed for MC ANTARES files**
  - 300k AntDST files processed
  - Full sample from the entire detector sample offered
  - First pipeline to include NNFit for the purpose of *Swim*

- **Tau appearance study with ANTARES**
  - First sensitivity analysis with ANTARES
  - Most suitable reconstruction: NNFit
  - With "perfect" classification and muon rejection, the non-tau scenario can be excluded with a 6.6σ

- **Reconstruction performance**
  - NNFit not optimized for these energies!
  - Proposed focus: the energy reconstruction task
  - Potential improvement of 0.6 up to 1.5σ

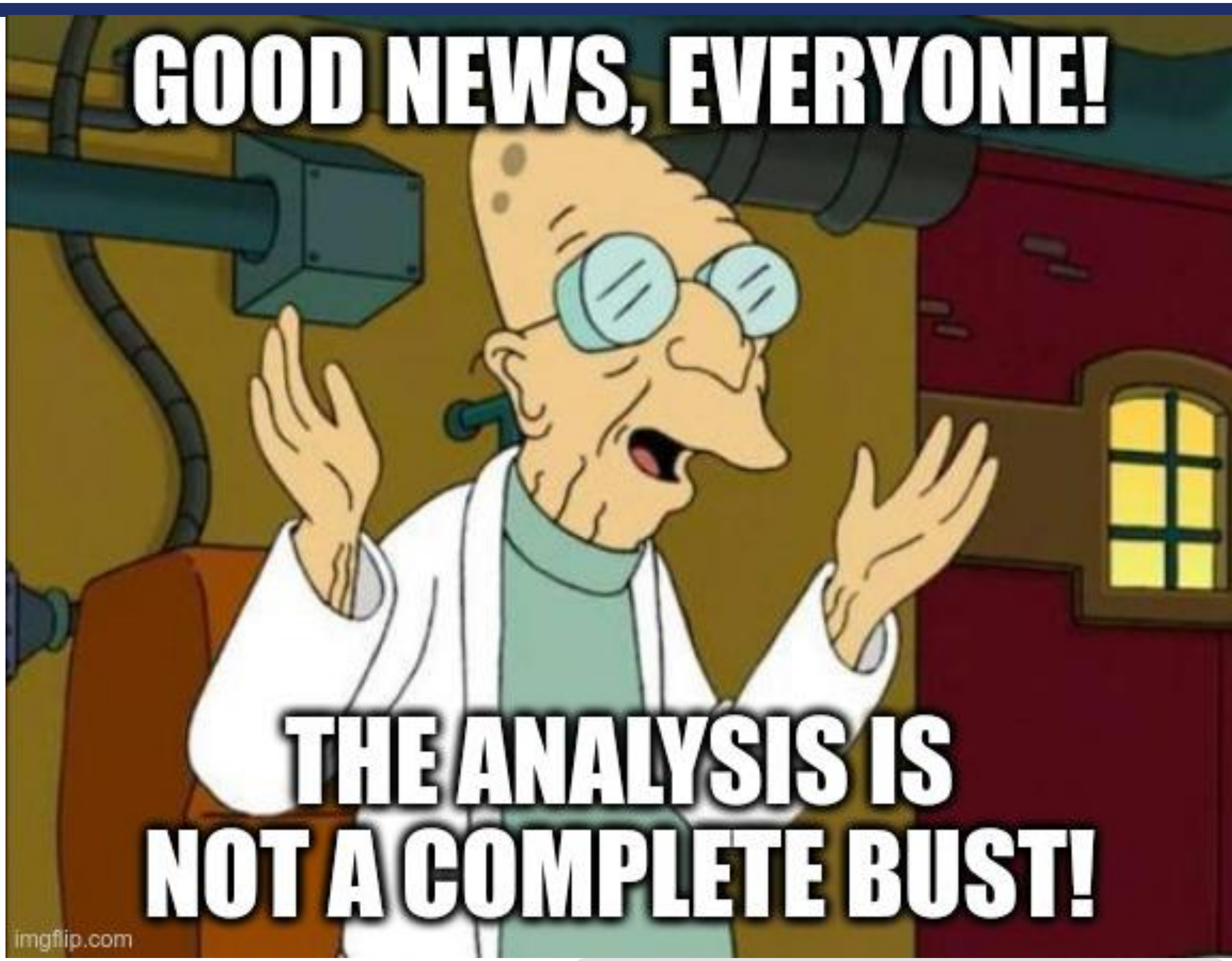
- **Open Question:**
  - Is there an underlying influence between the reconstruction performance and the treatment of systematics?

Conclusion

Outlook

- **Potential improvement**
    - Enlarge the event sample by combining BBFit & NNFit reconstructions
    - Optimize cut selection criteria & binning

- **Make the analysis more realistic**
    - Use of newly developed classifier based on NNFit
    - Study differences in parameters specific to the detector, compared to the KM3NeT/ORCA case



Thank you for your time!

Thank you very much for your attention!

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Back-Up Slides

NuFit Parameters

NuFIT 5.3 (2024)

without SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$
$\theta_{12}/^\circ$	$33.66^{+0.73}_{-0.70}$	$31.60 \to 35.94$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$
$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.407 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00058}$	$0.02029 \to 0.02391$	$0.02219^{+0.00059}_{-0.00057}$	$0.02047 \to 0.02396$
$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.11}$	$8.19 \to 8.89$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.90$
$\delta_{CP}/^\circ$	197^{+41}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.511^{+0.027}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.024}$	$-2.581 \to -2.409$

with SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.1$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$
$\theta_{12}/^\circ$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$
$\sin^2\theta_{23}$	$0.454^{+0.019}_{-0.016}$	$0.411 \to 0.606$	$0.568^{+0.016}_{-0.021}$	$0.412 \to 0.611$
$\theta_{23}/^\circ$	$42.3^{+1.1}_{-0.9}$	$39.9 \to 51.1$	$48.9^{+0.9}_{-1.2}$	$39.9 \to 51.4$
$\sin^2\theta_{13}$	$0.02224^{+0.00056}_{-0.00057}$	$0.02047 \to 0.02397$	$0.02222^{+0.00069}_{-0.00057}$	$0.02049 \to 0.02420$
$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.13}_{-0.11}$	$8.23 \to 8.95$
$\delta_{CP}/^\circ$	232^{+39}_{-25}	$139 \to 350$	273^{+24}_{-26}	$195 \to 342$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.505^{+0.024}_{-0.026}$	$+2.426 \to +2.586$	$-2.487^{+0.027}_{-0.024}$	$-2.566 \to -2.407$

ANTARES Monte-Carlo

ANTARES Summary files (AntDSTs)

- Final stage files of ANTARES Monte-Carlo chain
- Contains **only** high-level variables
  - run information
  - reconstructed information
  - "true" information

Aim: Suitable for a physics analysis!

- Summary

➡ For each run there are $8\nu_e$, $8\nu_\mu$, $12\nu_\tau$ and one μ files

AntDST

RecEvent

- run and customized event-ID
- event time
- reconstruction quality
- a list of reconstructed particles

MCEvent

- GenHen ➡ ν
- Mupage
- Corsika

$\}$ ➡ μ

Event

ANTARES Monte-Carlo

ANTARES Summary files (AntDSTs)

- Naming convention:

Particle type:
- neutrinos
  - (a)nue
  - (a)numu
  - (a)nutau
- muons

Run-ID

Example: MC_068813_numu_a_CC_reco.root

Energy range:
- a for 5 GeV to 20 TeV
- b for 20 TeV to 100 PeV

Interaction type:
- CC
- NC
- CCmu
- CCshow

Attention: Second row only for tau neutrinos!

- Summary

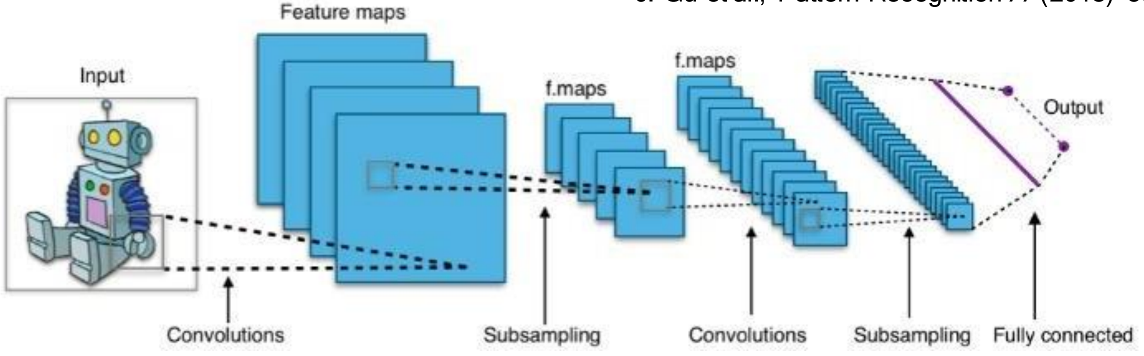
➡ For each run there are $8\nu_e$, $8\nu_\mu$, $12\nu_\tau$ and one μ files

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

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



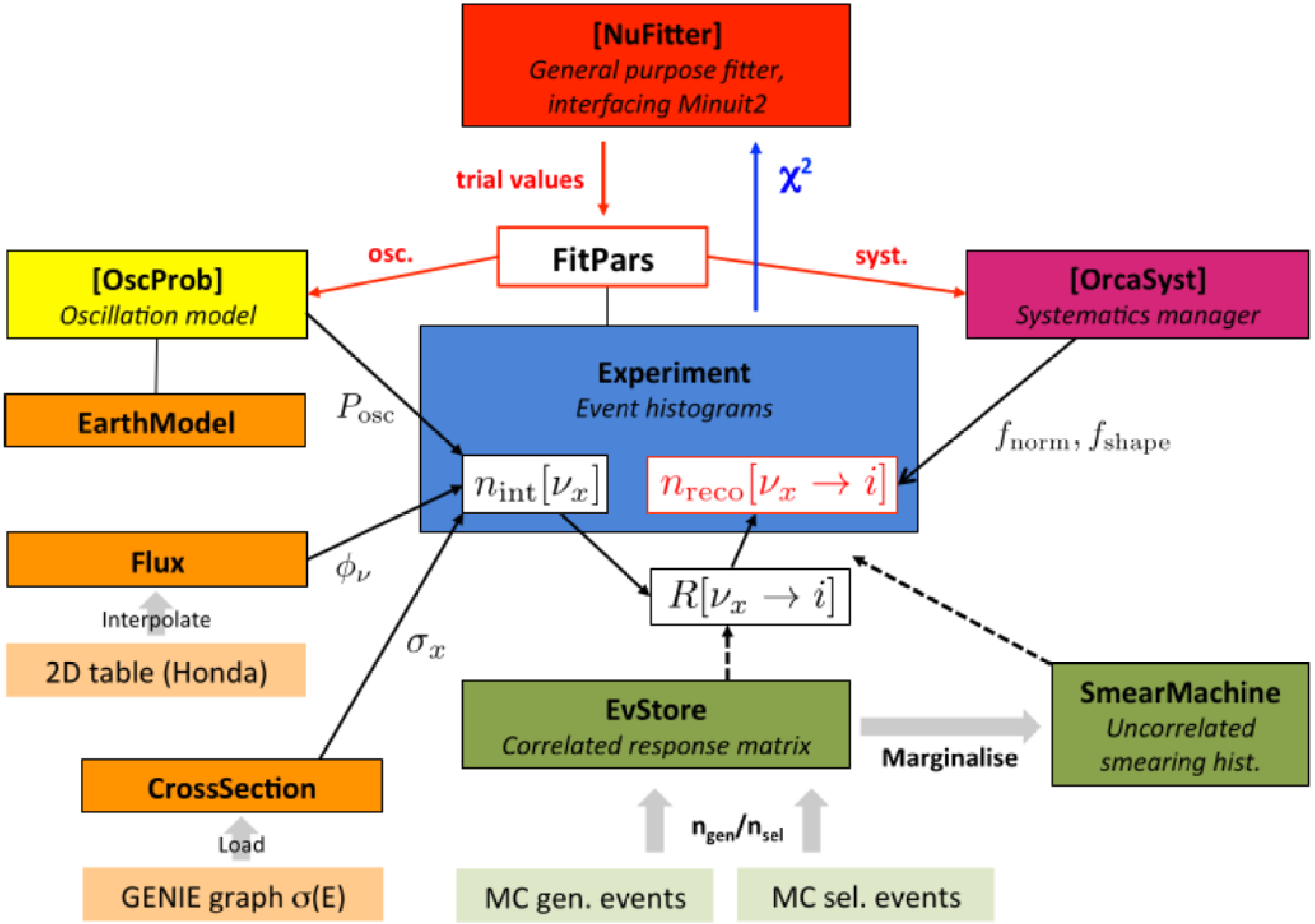
Garcia-Mendez, J., Ardid, S., & Ardid, M. (2023). Dark matter search towards the Sun using Machine Learning reconstructions of single-line events in ANTARES. PoS, ICRC2023, 1443.

Tau Appearance - Sensitivity

Swim software

Swim:

- Internal software for the oscillation WG of KM3NeT
- Framework based on ROOT & C++
- Provides methods for sensitivity calculation in various analyses (SM & BSM)
- Main packages:
  - OrcaSim: Simulate experiments
  - OscProb: Oscillation probabilties
  - OrcaDet: Simulate detector response
  - NuFitter: Minimization class (Minuit)
  - OrcaSyst: Systematics handler



Tau Appearance - Sensitivity

Analysis systematics

Systematic fixed scenario

Parameter	Initial value	Prior
θ_{12}	33.44 (NO) 33.45 (IO)	fixed
θ_{13}	8.57 (NO) 8.60 (IO)	fixed
θ_{23}	49.2 (NO) 49.3 (IO)	fixed
Δm_{31} [eV^2]	2.517e-03 (NO) -2.4238e-03 (IO)	fixed
Δm_{21} [eV^2]	7.42e-05	fixed
δ_{CP}	197.0 (NO) 282.0 (IO)	fixed
Energy Slope	0	10%
Zenith Slope	0	2%
ν_μ skew	0	5%
ν_e skew	0	7%
flavor skew	0	2%
NC scale	1	20%
Energy scale	1	9%
FluxNorm	1	free
TrackNorm	1	fixed
ShowerNorm	1	fixed
MuonNorm	1	fixed

Systematics fitted scenario

Parameter	Initial value	Prior
θ_{12}	33.44 (NO) 33.45 (IO)	fixed
θ_{13}	8.57 (NO) 8.60 (IO)	fixed
θ_{23}	49.2 (NO) 49.3 (IO)	free
Δm_{31} [eV^2]	2.517e-03 (NO) -2.4238e-03 (IO)	free
Δm_{21} [eV^2]	7.42e-05	fixed
δ_{CP}	197.0 (NO) 282.0 (IO)	fixed
Energy Slope	0	10%
Zenith Slope	0	2%
ν_μ skew	0	5%
ν_e skew	0	7%
flavor skew	0	2%
NC scale	1	20%
Energy scale	1	9%
FluxNorm	1	free
TrackNorm	1	free
ShowerNorm	1	free
MuonNorm	1	free

Tau Appearance - Sensitivity

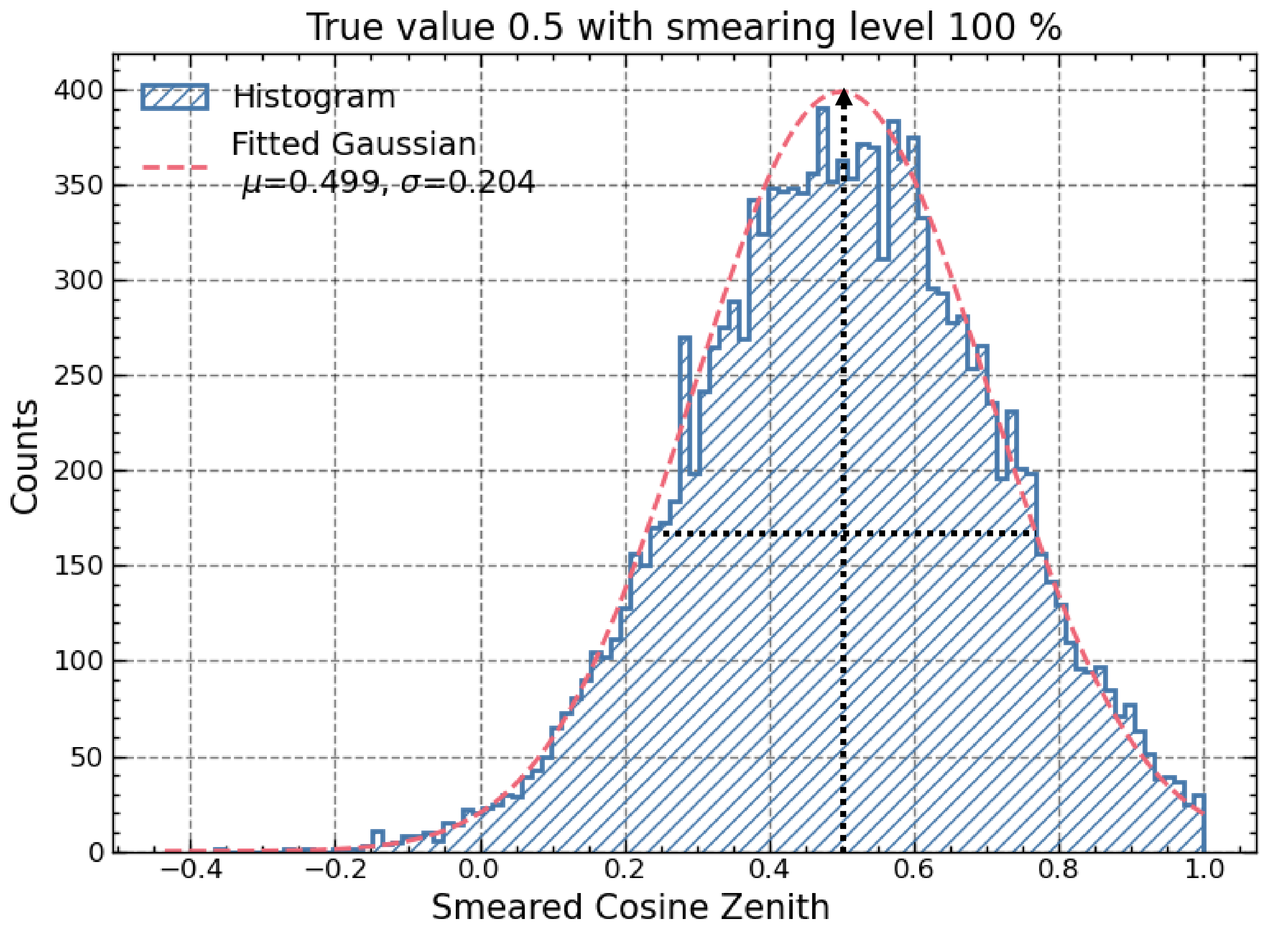
Smearing Method - Example

Steps:

1. Create a Gaussian with mean the true value and error proportional to the true value
2. Randomly sample a new value from the generated distribution
3. If new value, physically impossible repeat step 2

For each event smear both direction and energy branch!

Attention: in the "performance" smearing, the error is based on a function parameterizing the behavior of NNFit



Tau Appearance - Sensitivity

Smearing Method - "performance" smearing

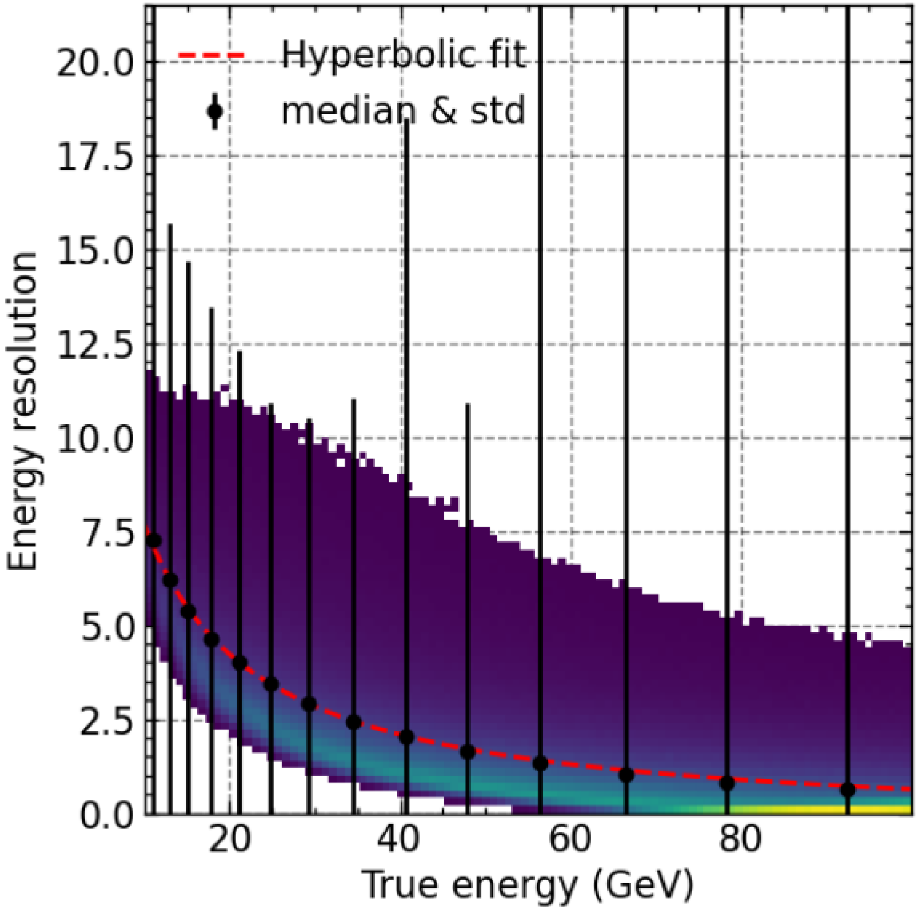
1D parameterization of the reconstruction performance for each variable

- **energy:** assumption to follow a hyperbolic behavior

$$y = \frac{\alpha}{(\beta x + \gamma)} + \delta$$

  - Noticeable variance on each bin
  - Potential influence of event's direction

2D approximation not investigated



Tau Appearance - Sensitivity

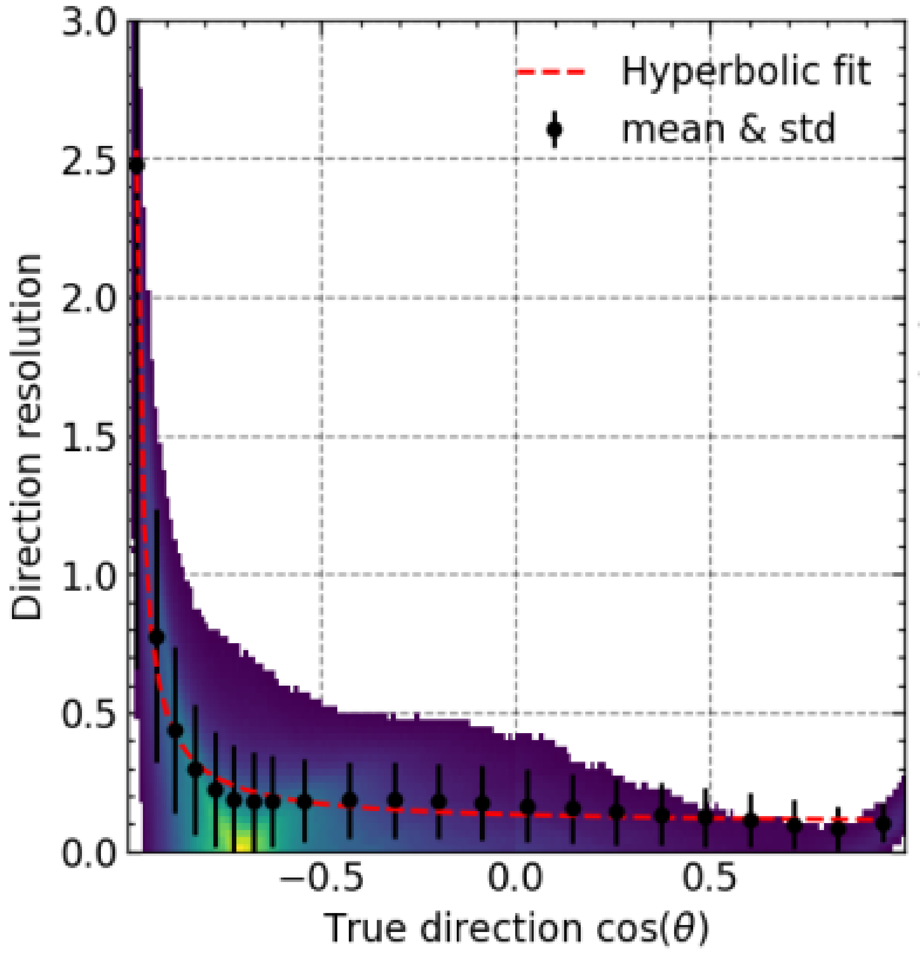
Smearing Method - "performance" smearing

1D parameterization of the reconstruction performance for each variable

- **energy:** assumption to follow a hyperbolic behavior

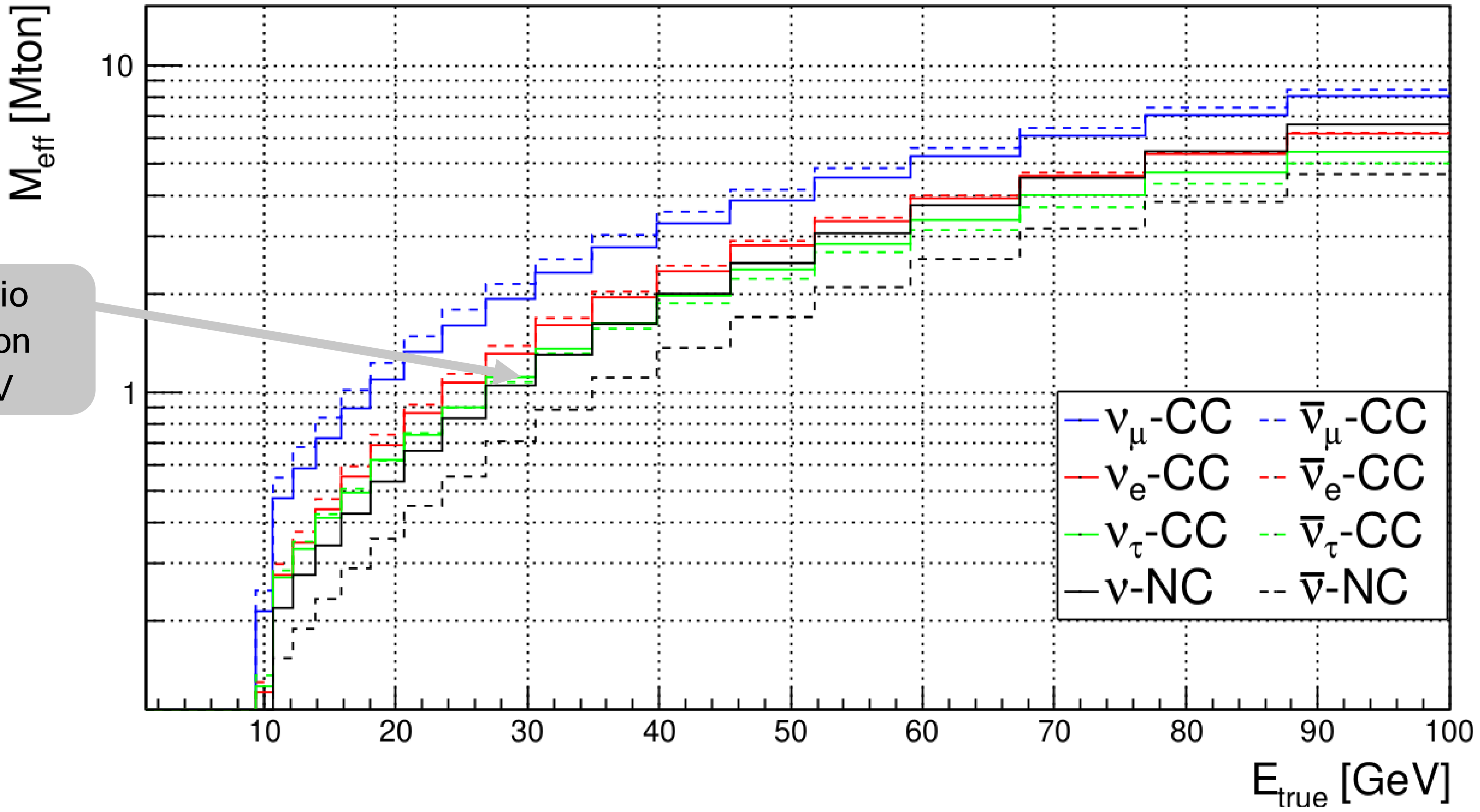
$$y = \frac{\alpha}{(\beta x + \gamma)} + \delta$$

  - Noticeable variance on each bin
  - Potential influence of event's direction → 2D approximation not investigated
- **direction**: hyperbolic function again can describe it
  - No influence of event's energy present
  - 90% event have a resolution less than 40%



Detector effective volume

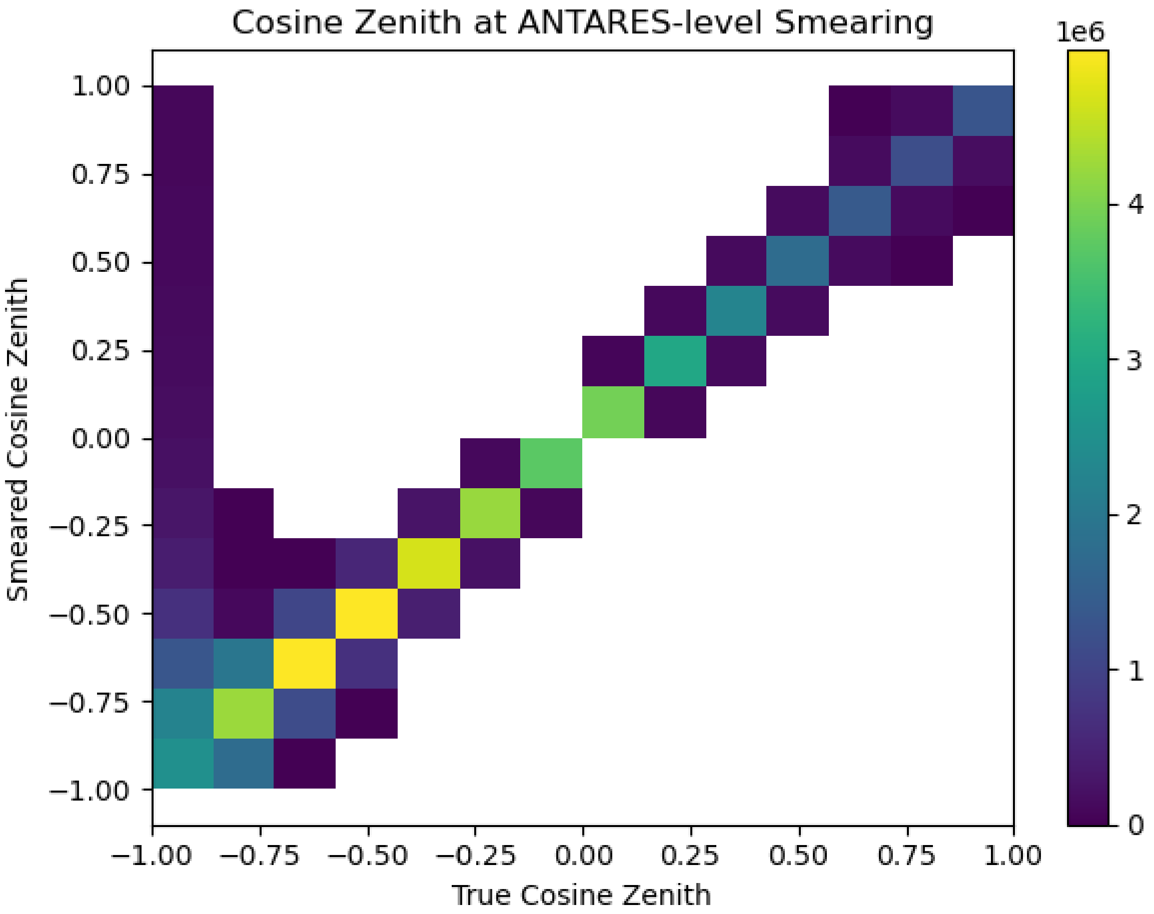
Full detector sample

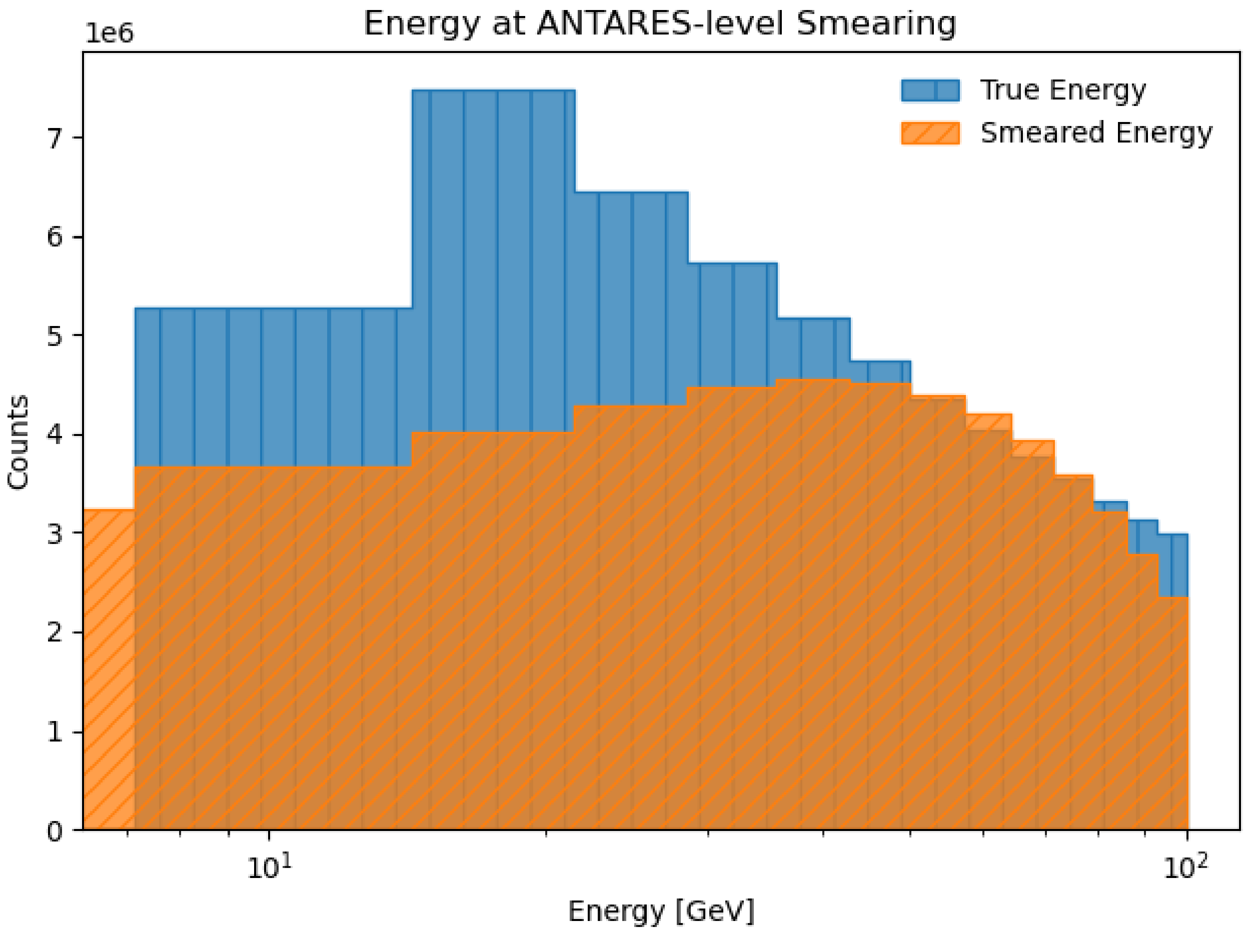


ν_τ CC scenario reaches 1Mton from 30 GeV

Smearing Comparison

"performance" reconstruction





Swim pipeline