KM3NeT/ORCA sensitivity to atmospheric tau-neutrino appearance

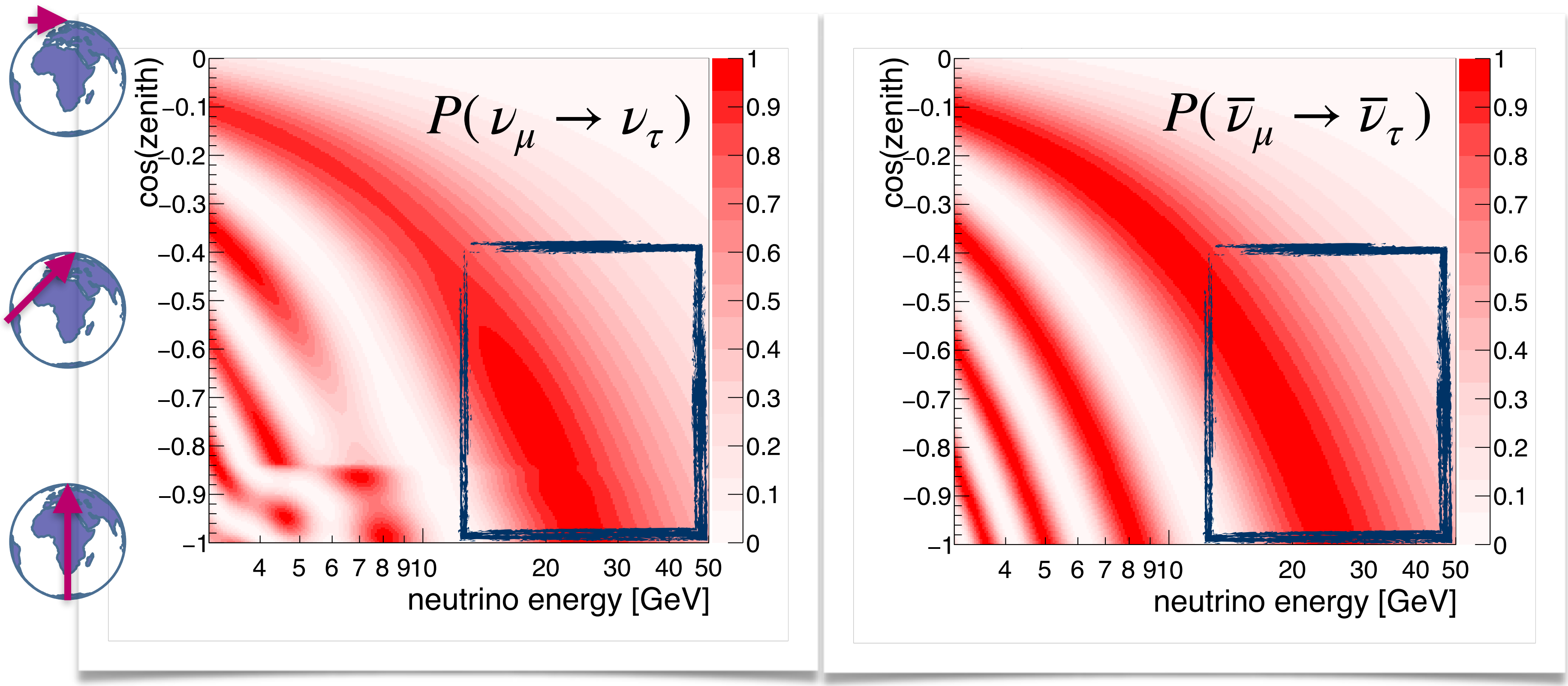
Steffen Hallmann (steffen.hallmann@desy.de)
on behalf of the KM3NeT Collaboration

NuTau2021, 10/01/2021

KM3NeT
Opens a new window on our universe

Atmospheric ν_τ appearance

[OscProb, https://github.com/joaoabcoelho/OscProb]



- oscillation from a pure ν_μ and ν_e atmospheric flux into ν_τ channel
- large oscillation maximum: complete $\nu_\mu \rightarrow \nu_\tau$ conversion at ~25 GeV and upward going
- well above few-GeV detection threshold of KM3NeT/ORCA (optimized to measure neutrino mass ordering)

Neutrino detection in KM3NeT/ORCA

- KM3NeT: Astroparticle (ARCA) and Oscillation (ORCA) Research facility in the Mediterranean Sea

- 3D array of **Digital Optical Modules** (**DOMs**)

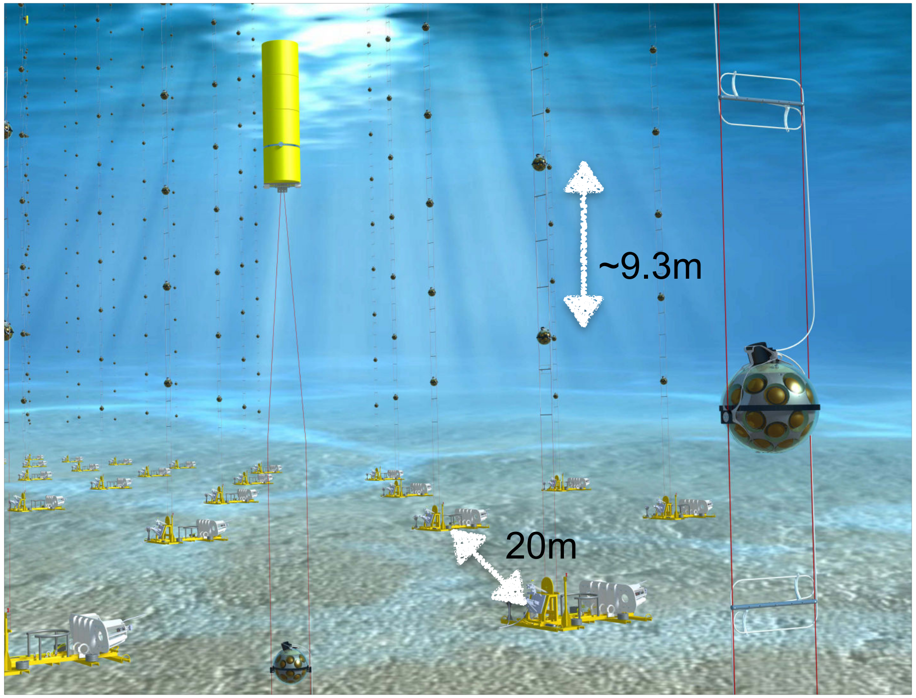
31 × 3” PMT

Neutrino detection in KM3NeT/ORCA

- KM3NeT: Astroparticle (ARCA) and Oscillation (ORCA) Research facility in the Mediterranean Sea

- 3D array of **Digital Optical Modules (DOMs)**

31 × 3” PMT



KM3NeT/ORCA

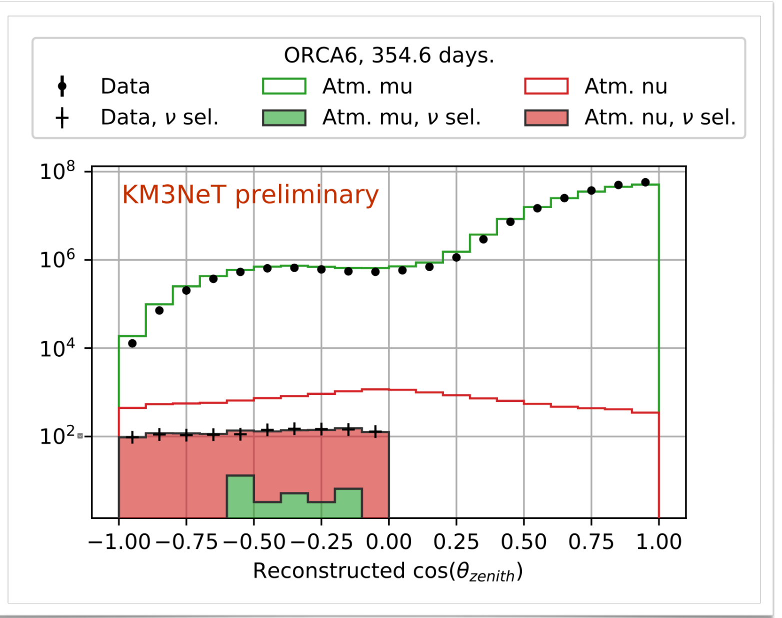
- 20m horizontal /
  9.3m vertical spacing between 2070 DOMs
- instrumented mass ~6.7 Mt
- under construction,
  6 out of 115 strings (“Detection Units”, DUs) installed and operating since > 1 year

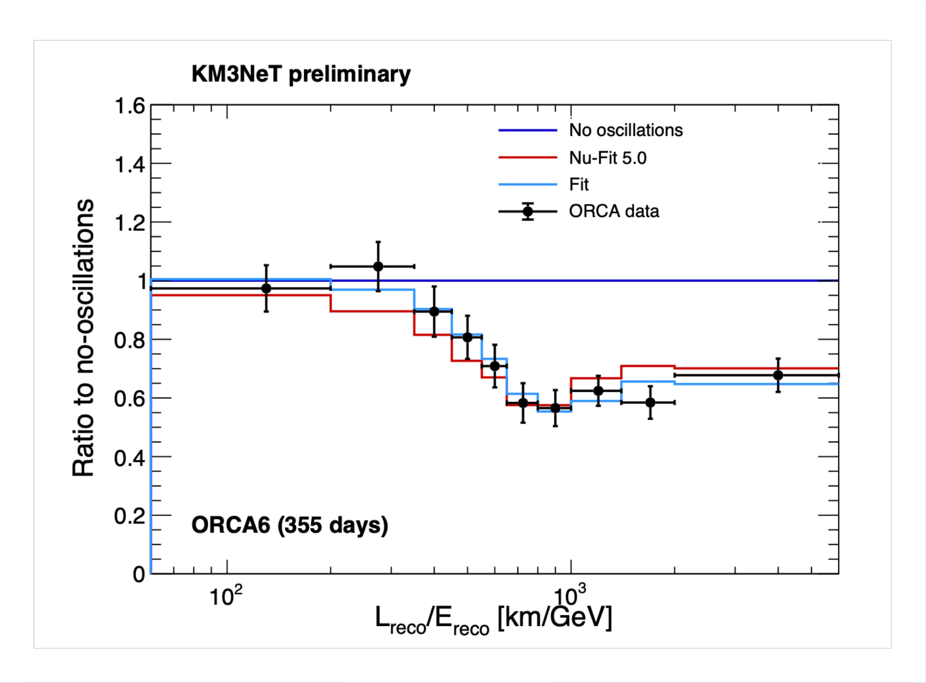
- arXiv:2103.09885, submitted: update to the Letter of Intent, including **sensitivity to ν_τ-appearance**
- PoS(ICRC2021)1123: first oscillation analysis with KM3NeT/ORCA

First oscillation measurement with KM3NeT/ORCA

- first oscillation measurement: ν_μ disappearance mode
- analysed dataset: 355 out of 386 days taken with 6 DUs
- 'clean' neutrino sample

- atmospheric oscillation via **L/E** measurement
  - **L:** from reconstructed direction
  - **E:** from muon track length
- 5.9σ preference for oscillation





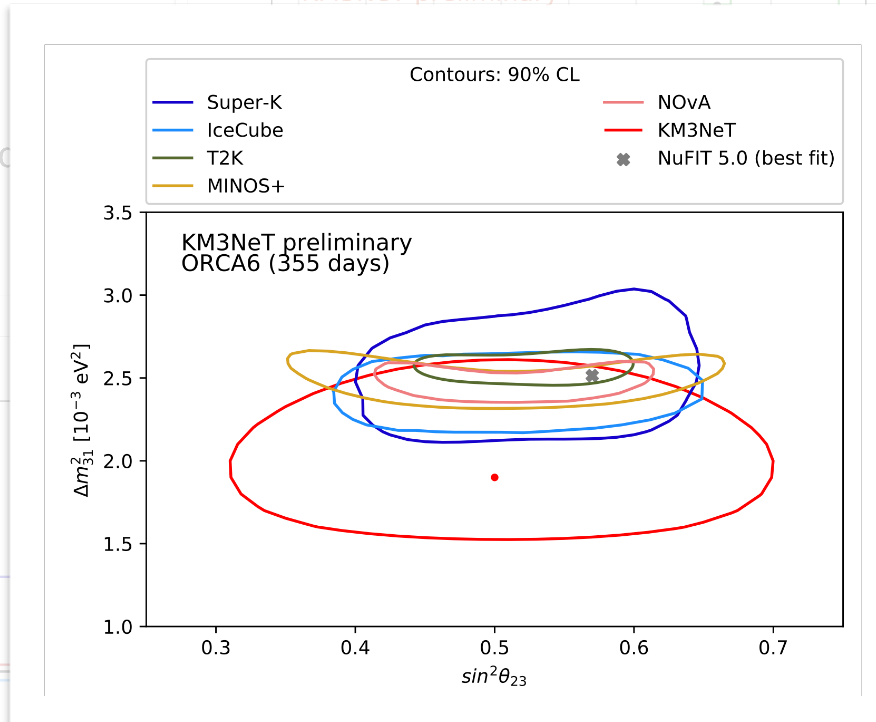
[PoS(ICRC2021)1123]

KM3NeT/ORCA can already measure oscillation

- first oscillation measurement: ν_μ disappearance mode
- analysed dataset: 355 out of 386 days taken with 6 DUs
- ‘clean’ neutrino sample

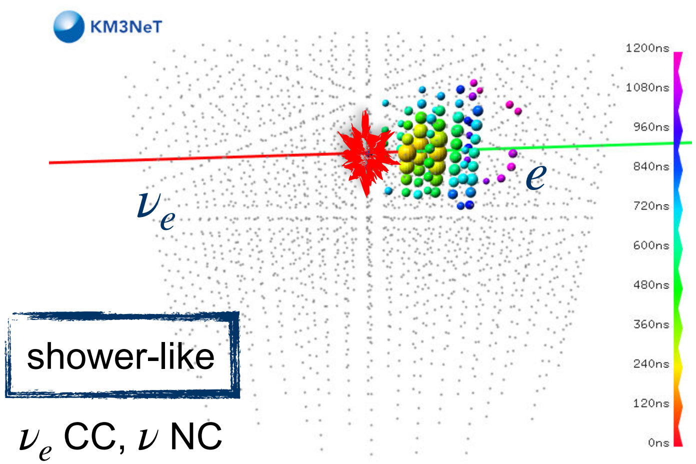
- atmospheric oscillation via L/E measurement
  - traversed path length L from reconstructed d
  - energy E from muon track length

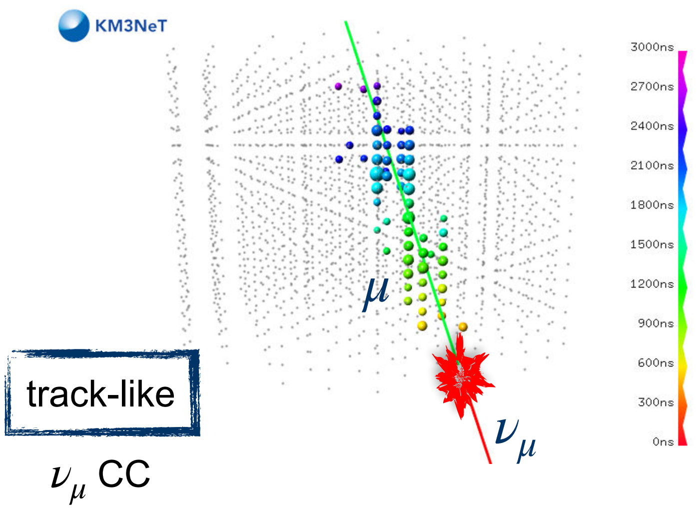
- KM3NeT/ORCA soon competitive in measuring atmospheric oscillation parameters
- next on ticklist:
  measure oscillation in shower channel



[PoS(ICRC2021)1123]

Event signatures





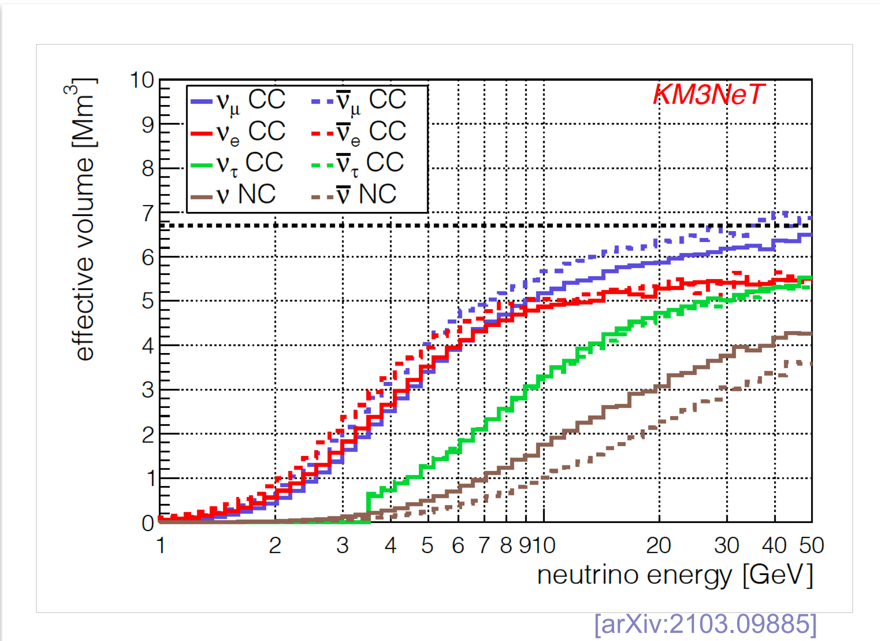
@ GeV energies:

- ~4m / GeV muon length
- ~15 detected photons / GeV in ORCA
  → **track/shower distinction using machine learning techniques**

[arXiv:2103.09885; JINST 15 P10005 (2020)]

ν_τ CC interactions

- τ mass $\approx 1.78\,\mathrm{GeV}/c^2$
  - cross section suppressed, threshold: 3.4 GeV

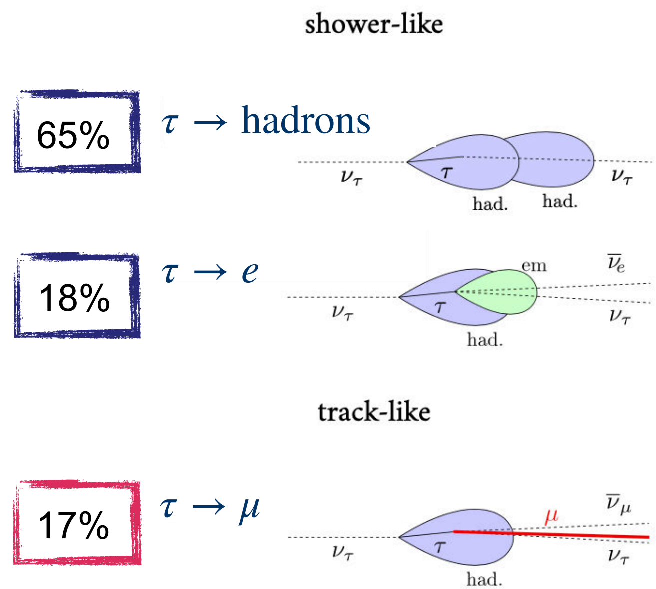


[arXiv:2103.09885]

strength of KM3NeT/ORCA: ν_τ statistics

- >3000 detected oscillated ν_τ CC / year !

- τ decay after $\mathcal{O}$(mm):
  - no event-by-event identification possible in KM3NeT/ORCA
  - **ν_τ appearance on statistical basis**



Event classification

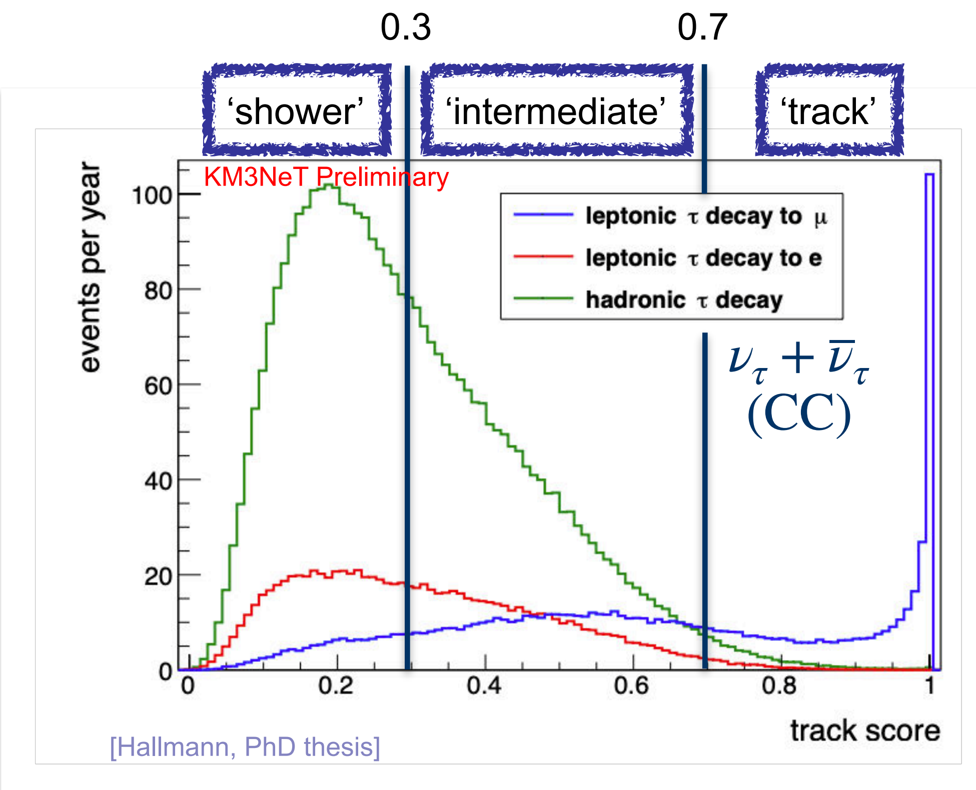
- Random Decision Forest used, trained on binary decision problems:
  track ↔ shower,
  neutrino ↔ atm. muon, neutrino ↔ pure noise (^{40}K) → can be suppressed to few-% level

- uses **high-level features** from - track/shower reconstruction algorithms &
  - hit distributions expected for ν_μ (track) or ν_e (shower) (LLH ratio based)

- Deep learning classifier trained directly on photon "hit" distribution yields consistent results

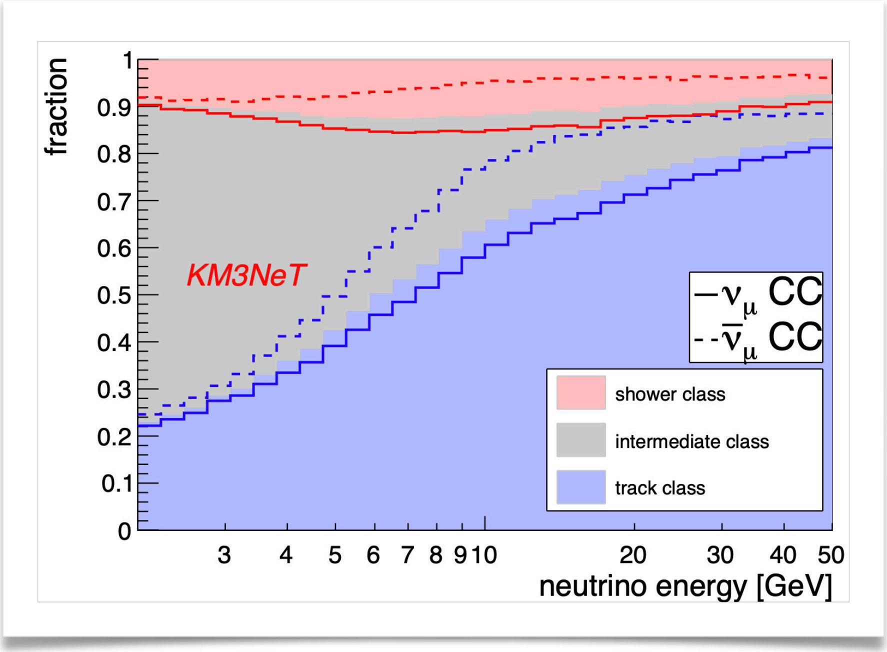
[JINST 15 P10005 (2020)]

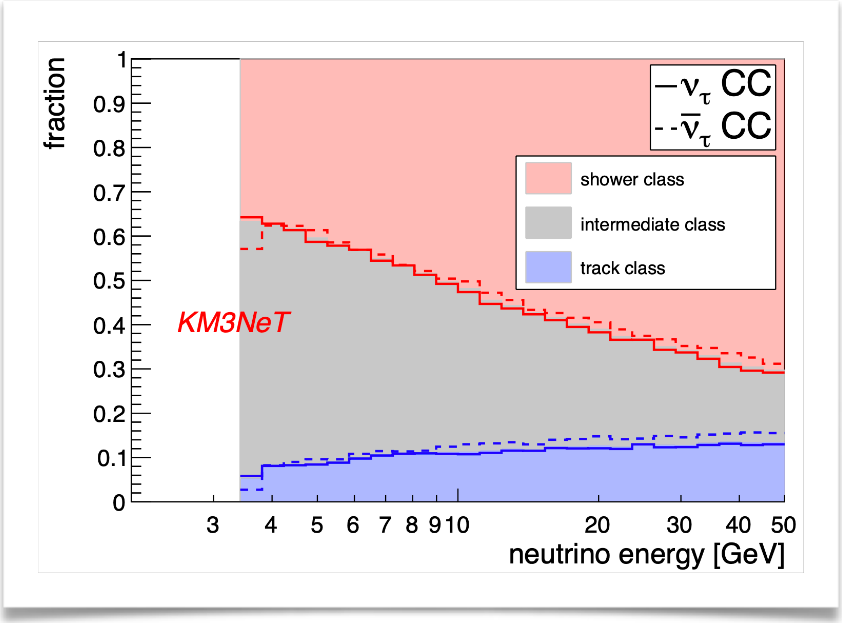
- use **3** event classes for analysis
  'track' → track reco algorithm
  'shower', 'intermediate' → shower reco algorithm

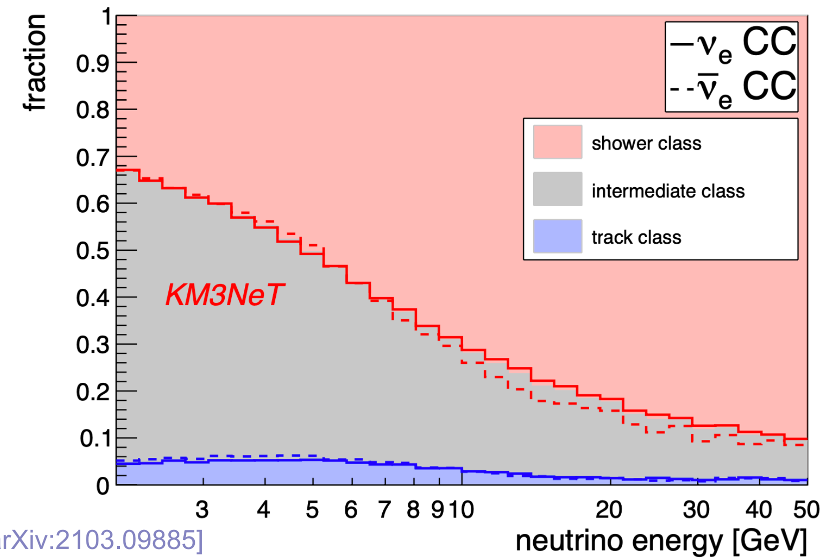


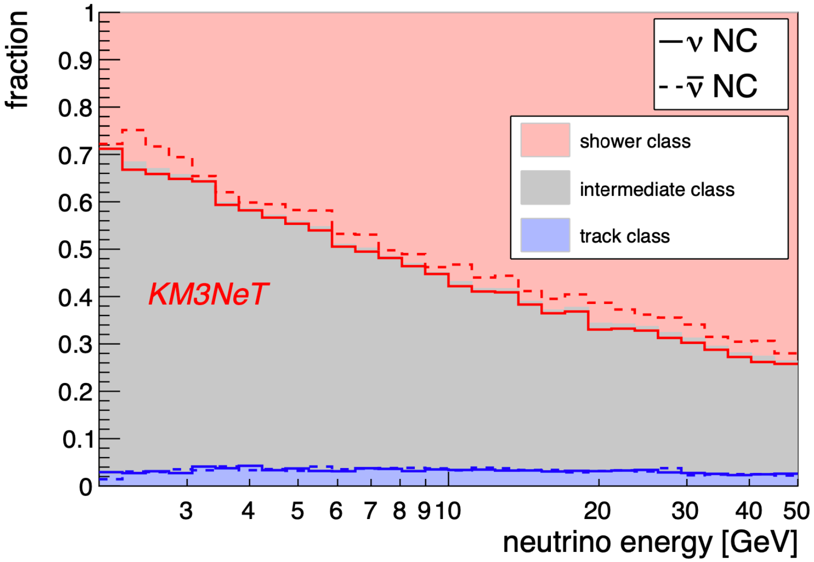
[Hallmann, PhD thesis]

Track ↔ shower classification





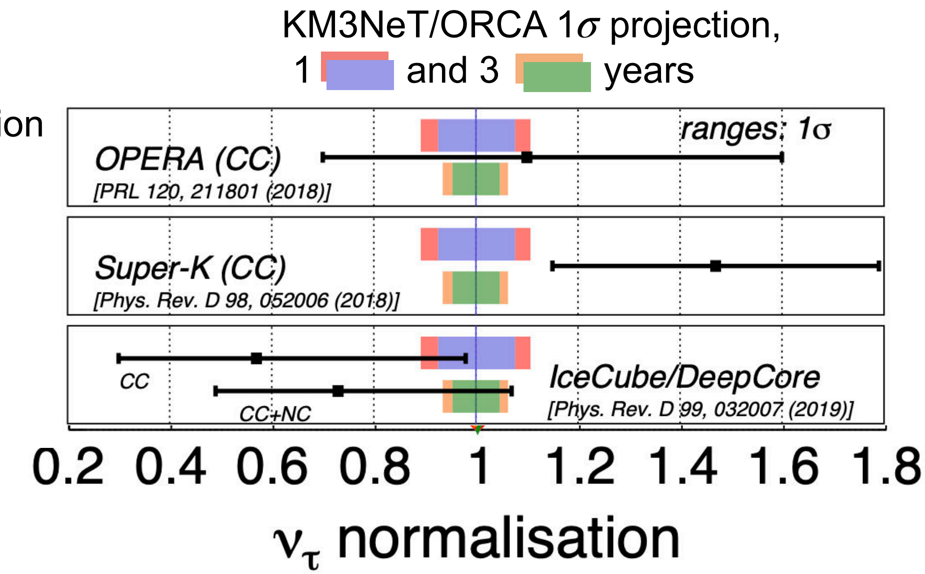




[arXiv:2103.09885]

Sensitivity to tau neutrino appearance with KM3NeT/ORCA

Sensitivity to ν_τ appearance



- compare measured signal strength of ν_τ contribution with physics model assumption

$\boxed{\nu_\tau \textbf{ normalisation} \text{ measurement}}$

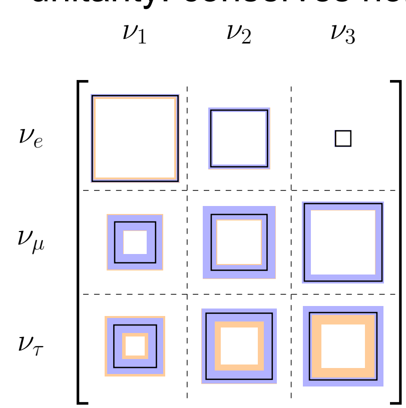
- similar approach also in Super-K / DeepCore
- currently: non-appearance excluded, **but**:
- **normalisation barely constrained**

- **normalisation $\neq$ 1:** deviation from assumed physics model

$\boxed{\text{“model independent”}}$

- **cross section wrong?** $\mathcal{O}(10\%)$? uncertainties in calculations due to τ mass
- **additional interactions?**
- **3 neutrino picture complete?** $\leftrightarrow$ unitarity: conserves normalisation

$$\left|\begin{pmatrix} \mathcal{U}_{e1} & \mathcal{U}_{e2} & \mathcal{U}_{e3} & ? \\ \mathcal{U}_{\mu1} & \mathcal{U}_{\mu2} & \mathcal{U}_{\mu3} & ? \\ \mathcal{U}_{\tau1} & \mathcal{U}_{\tau2} & \mathcal{U}_{\tau3} & ? \\ ? & ? & ? & ? \end{pmatrix}\right| =$$



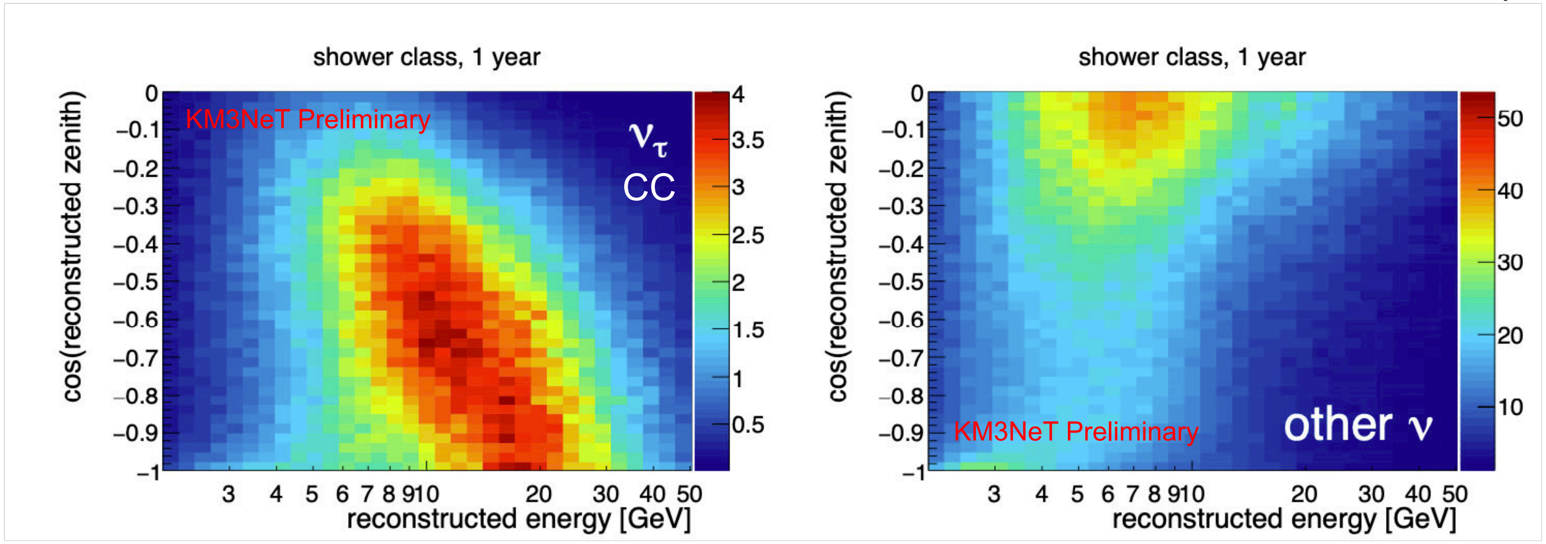
with unitarity:
%-level precision on most oscillation parameters from experiment

without unitarity:
$\leftarrow$ large uncertainties in ν_τ row !

Event distributions in analysis

- events binned in energy & cos(zenith angle)
  - rate of interacting neutrinos $R_a = \frac{\rho_{\text{water}}}{m_{\text{nucleon}}} \cdot \sum_{b = \{\nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu\}} \sigma_a(E) \cdot P^{\text{osc}}_{b\to a}(E, \theta_z) \cdot \Phi^{\text{atm}}_b(E, \theta_z)$
  - × detector effective volume
  - × classification: track / shower / intermediate
  - × detector resolutions (smearing):

direction: limited by intrinsic fluctuations from ν-lepton scattering
energy: limited by shower-to-shower fluctuations (all flavours), detector size (high E μ-tracks)

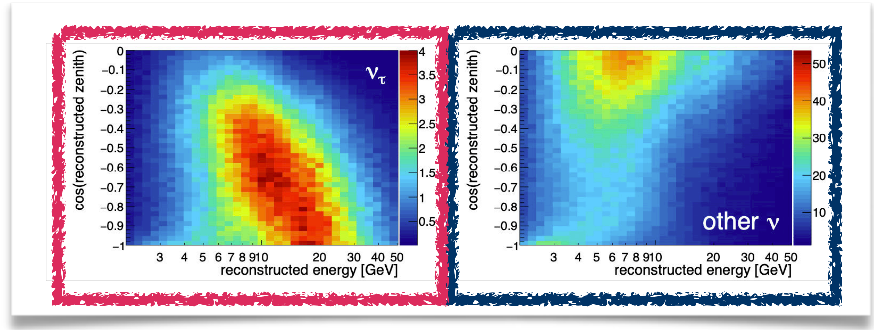


[Hallmann, PhD thesis]

- events per year in analysis sample:

	shower	middle	track
$\nu_\tau + \overline{\nu_\tau}$ CC	2.0×10^3	0.85×10^3	0.43×10^3
other ν	2.0×10^4	1.8×10^4	2.0×10^4

Significance evaluation

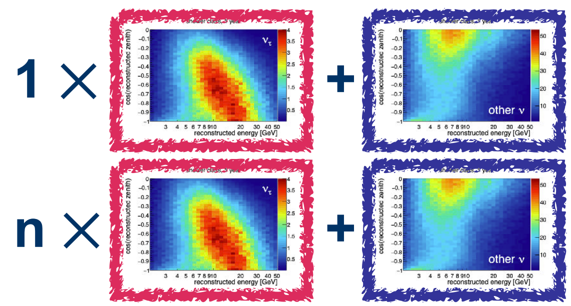


- fit one **average** data set (Asimov approach)

- hypothesis test:

  H0: ν_τ norm = 1, parameters fixed

  H1: ν_τ norm $\neq$ 1, free parameters fitted

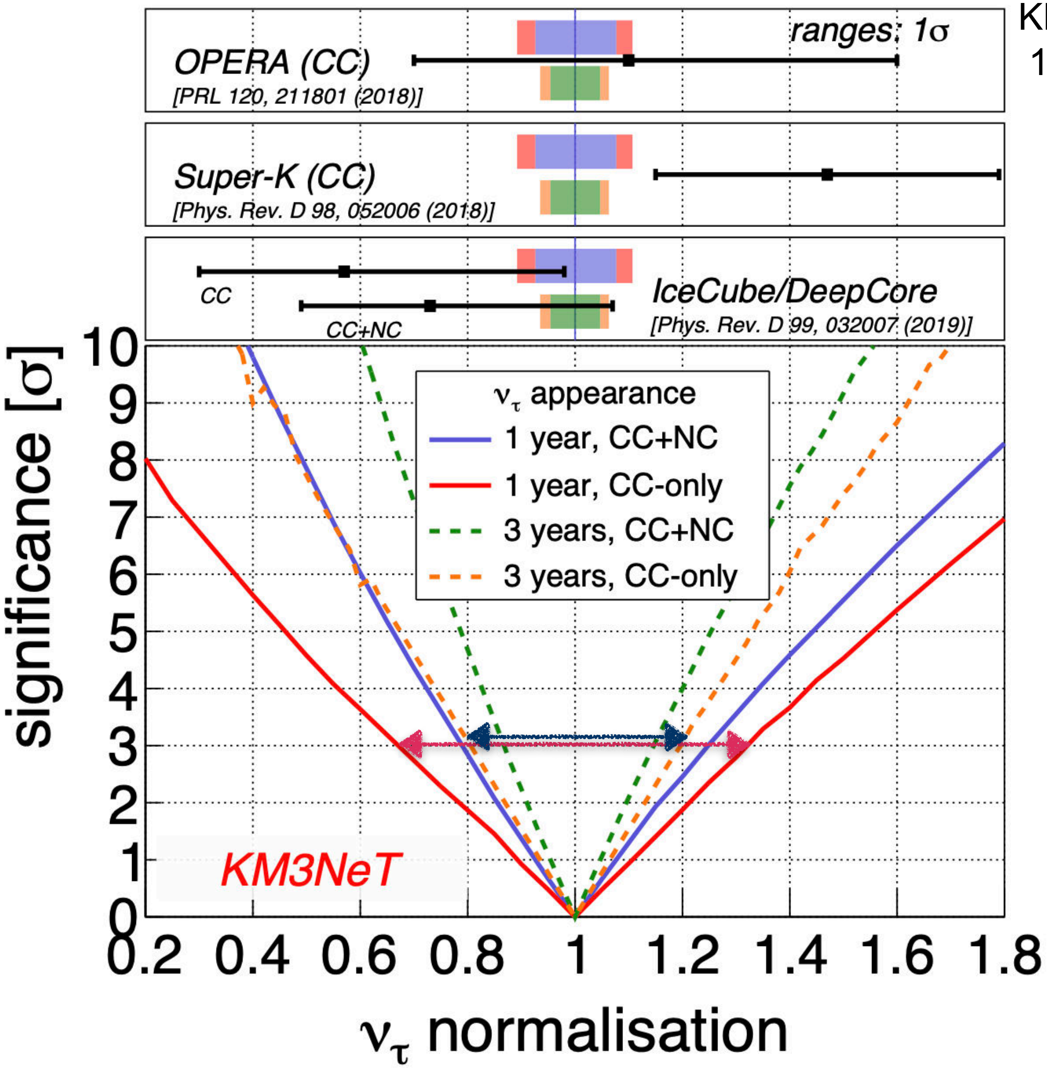


- scale either CC-only or CC+NC contribution

  (barely any sensitivity to distinguish non-unitary CC-only from CC+NC case)

- account for
  - oscillation parameter uncertainties (4 free parameters)
  - flux / interaction / detection systematics (12 free parameters)

KM3NeT/ORCA sensitivity for 1 & 3 years of data taking



KM3NeT/ORCA 1σ projection,
1 and 3 years

- constraints at 3σ CL (CC-only case):

$\pm 30\,\%$ after 1 year

$\pm 20\,\%$ after 3 years

- after <2 months:
  5σ exclusion of ν_τ norm = 0

- KM3NeT/ORCA competitive already at early construction stage
  [PoS (ICRC2019) 1019]

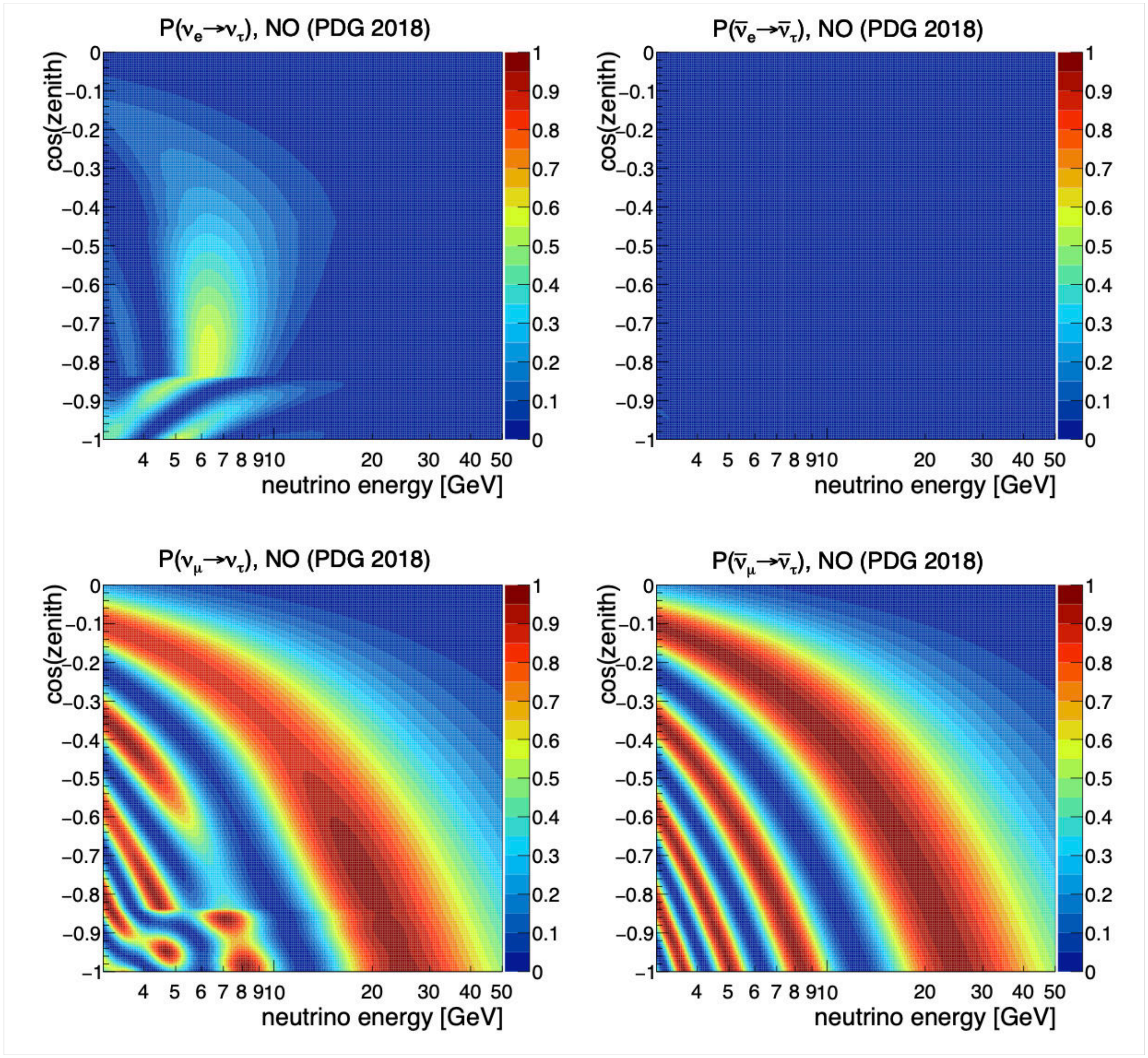
[arXiv:2103.09885]

Summary

- KM3NeT/ORCA optimised in few-GeV region and > 6 Mt instrumented mass
    - >3k ν_τ CC events / year in analysis sample
- tau-neutrino events appear shower-like in KM3NeT/ORCA
- no event-by-event identification feasible; measurement on statistical basis

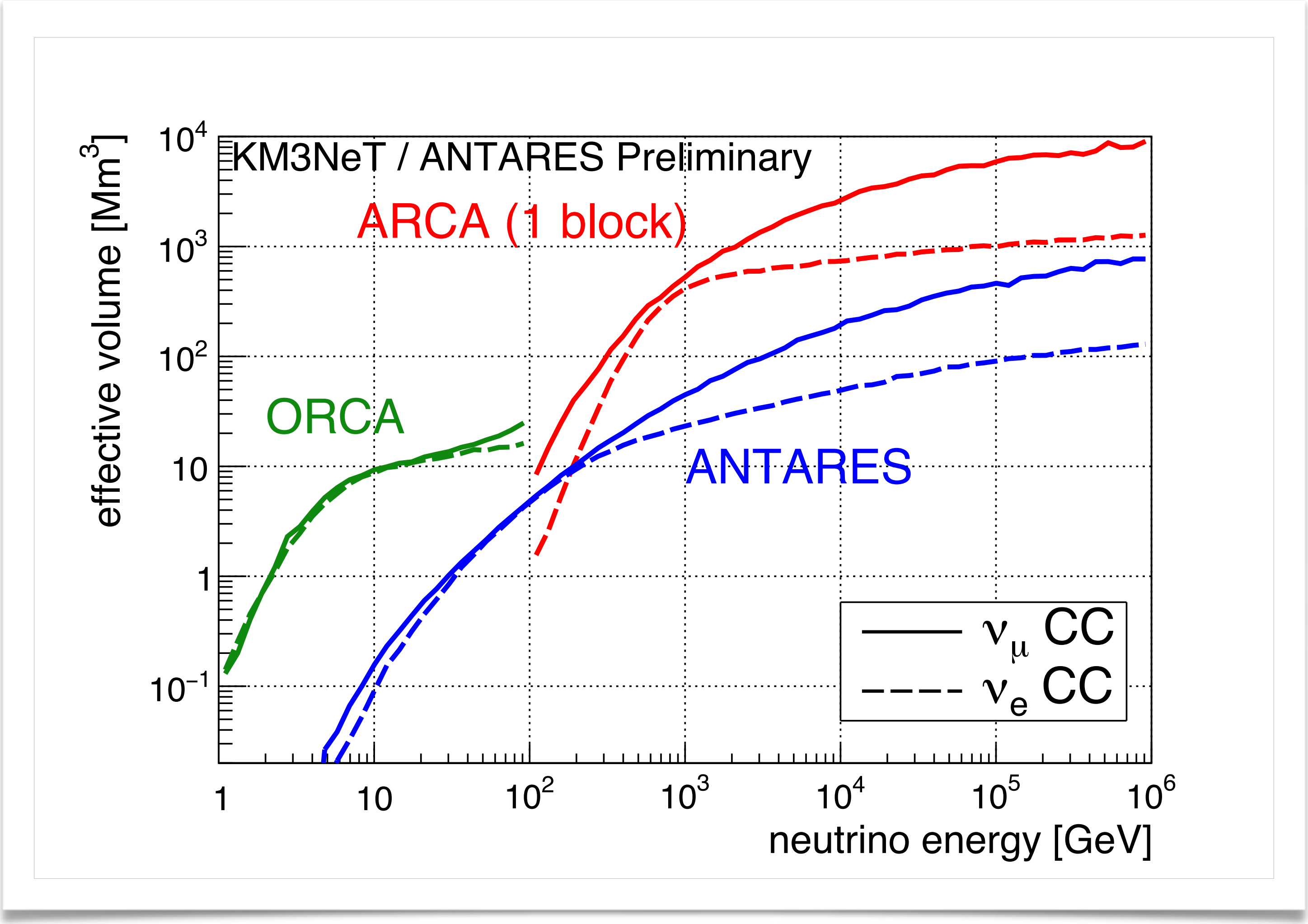
- ν_τ normalisation only weakly constrained (even at 1σ) from current experimental results
- KM3NeT/ORCA is sensitive to constrain normalisation to
  $\pm 20\,\%\,(\pm 30\%)$ after 3 (1) years with 3σ
  and competitive at early construction stage.

Backup



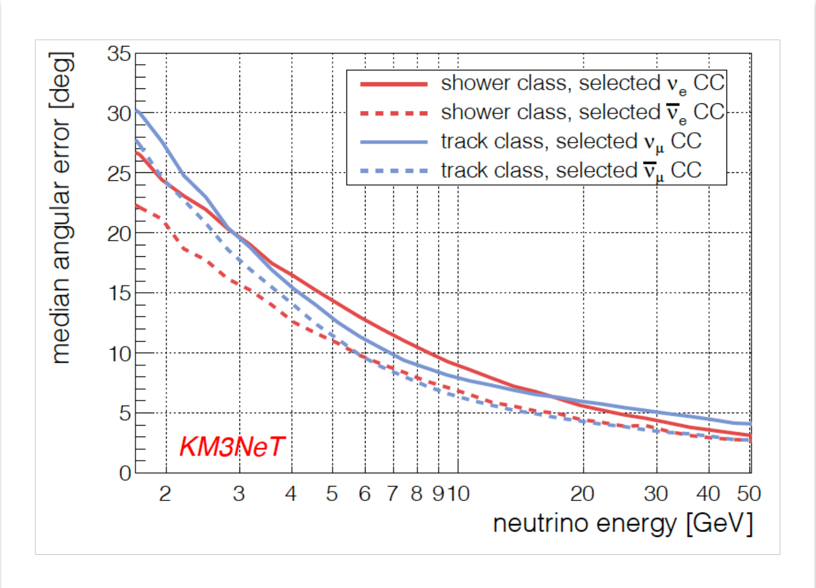
$P(\nu_e \to \nu_\tau)$, NO (PDG 2018)
$P(\bar{\nu}_e \to \bar{\nu}_\tau)$, NO (PDG 2018)
$P(\nu_\mu \to \nu_\tau)$, NO (PDG 2018)
$P(\bar{\nu}_\mu \to \bar{\nu}_\tau)$, NO (PDG 2018)
cos(zenith)
neutrino energy [GeV]

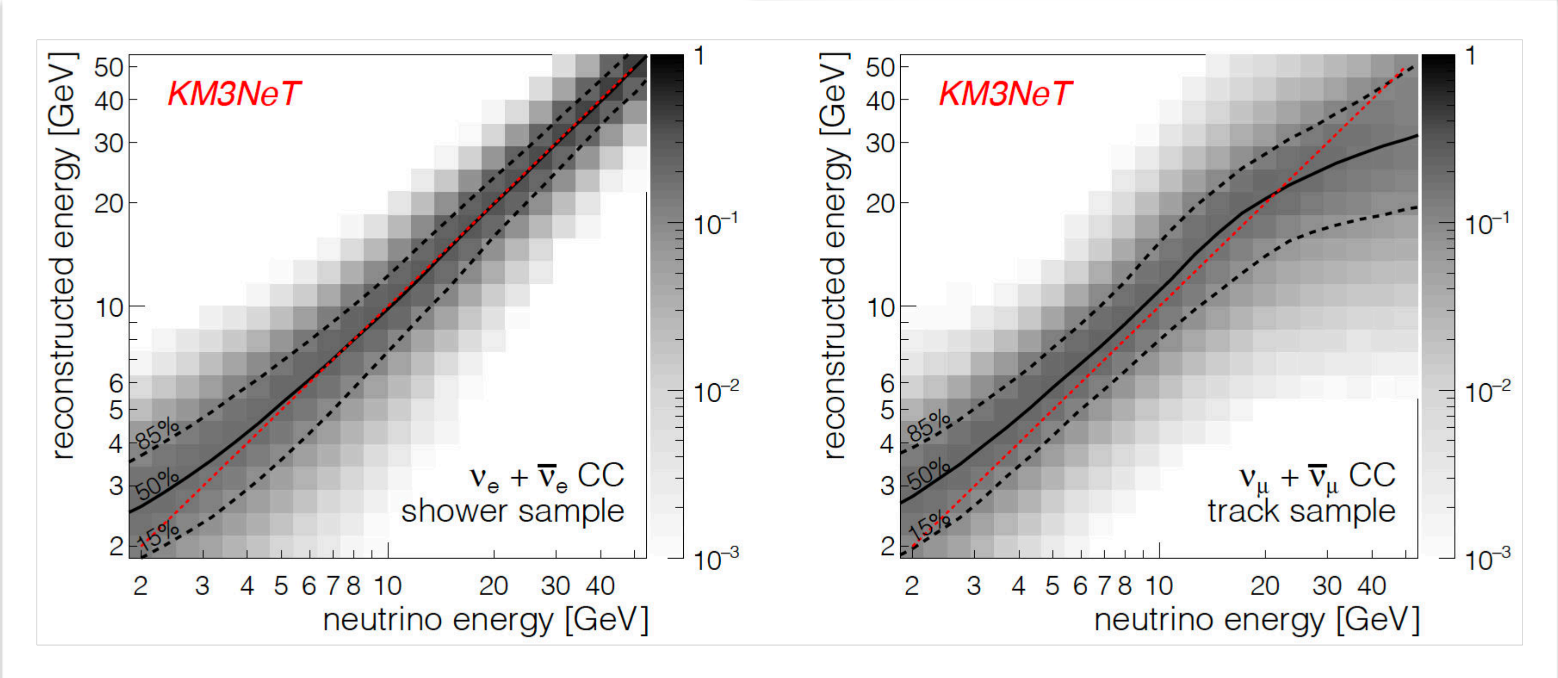
Trigger effective volume



Detector performance

[arXiv:2103.09885]





Included systematics

$$I(\vartheta) = \frac{n_\tau(3\sigma|n_\tau > 0, \vartheta \text{ fitted}) - n_\tau(3\sigma|n_\tau < 0, \vartheta \text{ fitted})}{n_\tau(3\sigma|n_\tau > 0, \vartheta \text{ fixed}) - n_\tau(3\sigma|n_\tau < 0, \vartheta \text{ fixed})} - 1$$

parameter	*null* hypothesis value NO	*null* hypothesis value IO	prior
θ_{12}	33.82°		fixed
Δm^2 [eV^2]	7.39×10^{-5}		fixed
θ_{13}	8.60°	8.64°	$\pm 0.13^\circ$
θ_{23}	48.6°	48.8°	free
ΔM^2 [eV^2]	2.528×10^{-3}	2.436×10^{-3}	free
δ_{CP}	221°	282°	free

Importance evaluation:
impact on allowed 3σ range when fixing individual (groups of) parameters

shifts position of oscillation maximum

parameter	initial value	prior
$\nu_e/\bar{\nu}_e$ flux ratio	0	$\mu = 0\,,\ \sigma = 7\%$
$\nu_\mu/\bar{\nu}_\mu$ flux ratio	0	$\mu = 0\,,\ \sigma = 5\%$
$\overset{(-)}{\nu}_e/\overset{(-)}{\nu}_\mu$ flux ratio	0	$\mu = 0\,,\ \sigma = 2\%$
spectral tilt	0	$\mu = 0\,,\ \sigma = 5\%$
$\cos(\theta)$ tilt	0	$\mu = 0\,,\ \sigma = 2\%$
$\nu/\bar{\nu}$ ratio	0	$\mu = 0\,,\ \sigma = 3\%$
NC scale	1	$\mu = 1\,,\ \sigma = 10\%$
E-scale shift EM shower	0	$\mu = 0\,,\ \sigma = 5\%$
E-scale shift hadronic shower	0	$\mu = 0\,,\ \sigma = 6\%$
track channel norm	1	free
shower channel norm	1	free
middle channel norm	1	free

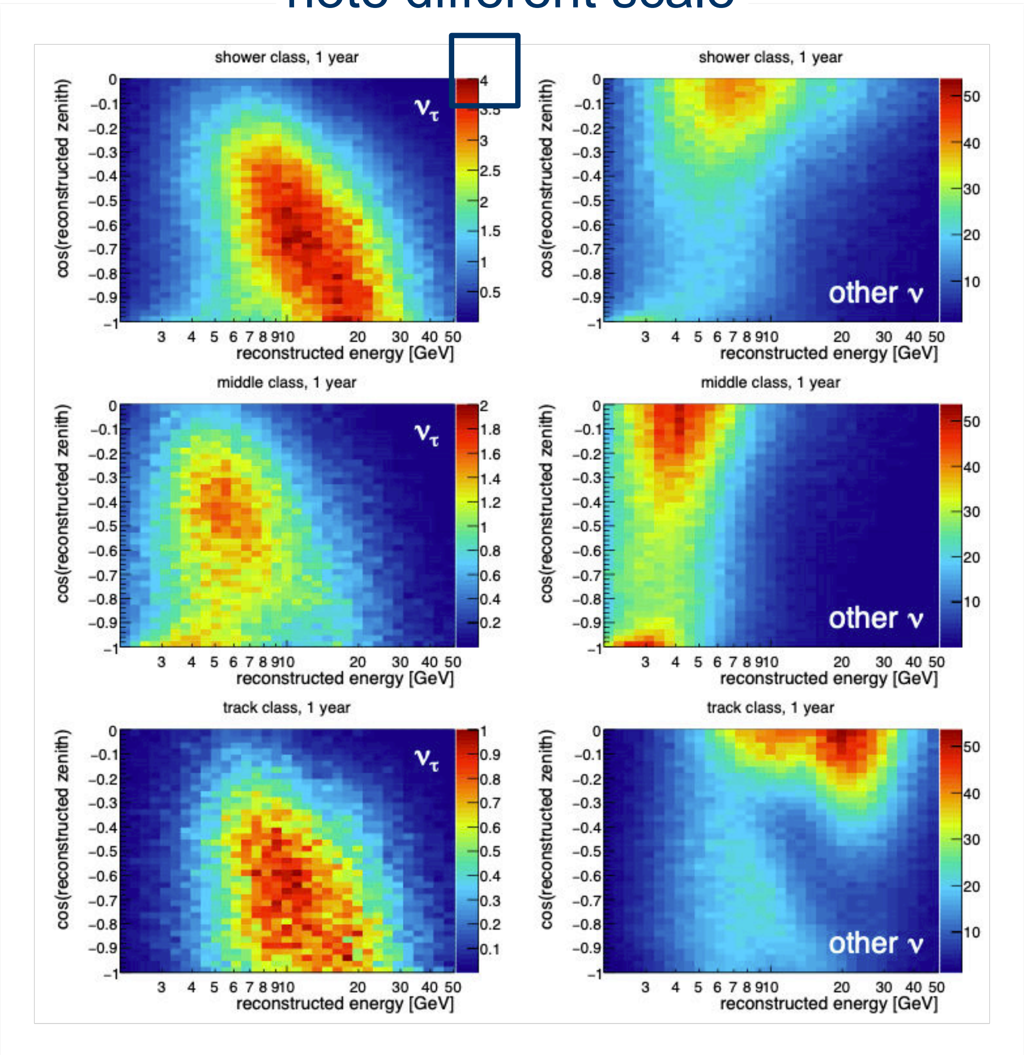
tilts flux spectrum in cos(zenith)

PMT efficiency / water properties
light yield of hadronic part of cascade

[Hallmann, PhD thesis, arXiv:2103.09885]

Event distribution, all classes

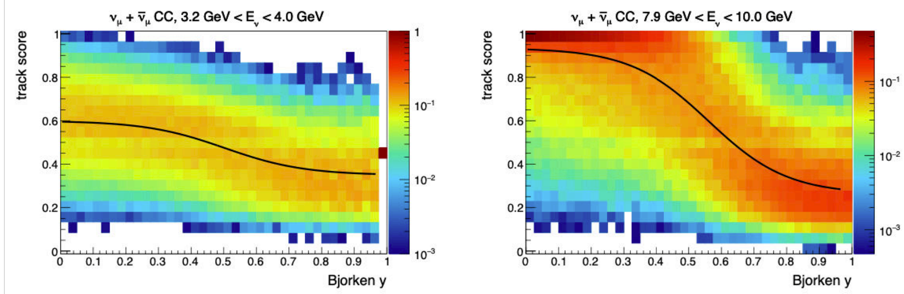
note different scale



[Hallmann, PhD thesis]

Event identification, track

- How long does the muon track need to be to see it?



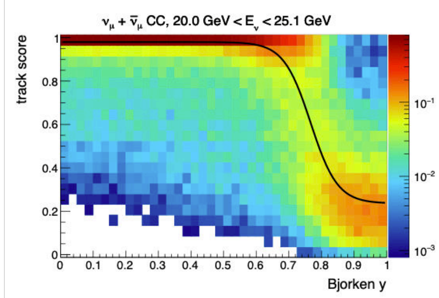


Figure 11.5: The `track score` for $\overset{\leftrightarrow}{\nu}_\mu^{CC}$ events as a function of Bjorken y for three different energies. Distributions are for training without hit-based features. Histograms are normalised along each slice of Bjorken y. Lines represent a hyperbolic tangent fit to the median values of each slice.

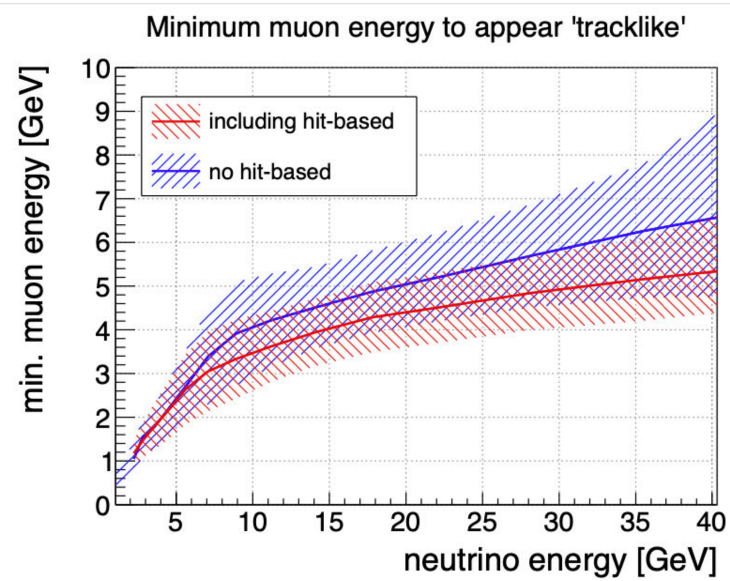
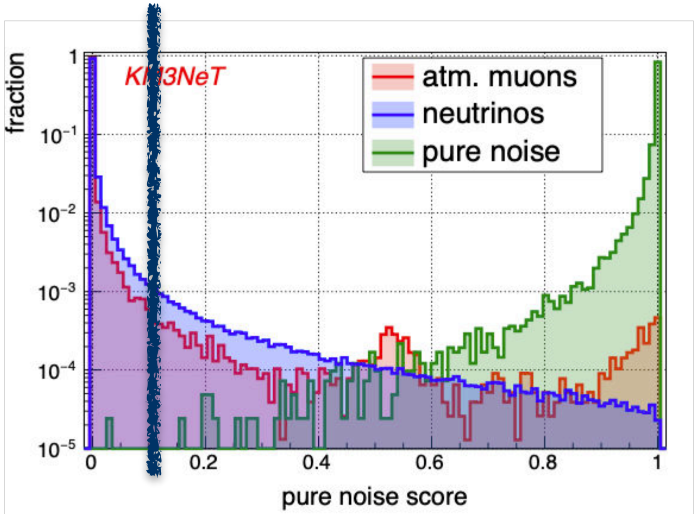


Figure 11.7: Minimum muon energy needed for clear identification as track as a function of neutrino energy. The transition region between the track- and shower-like regime is indicated by the shaded bands.

[Hallmann, PhD thesis]

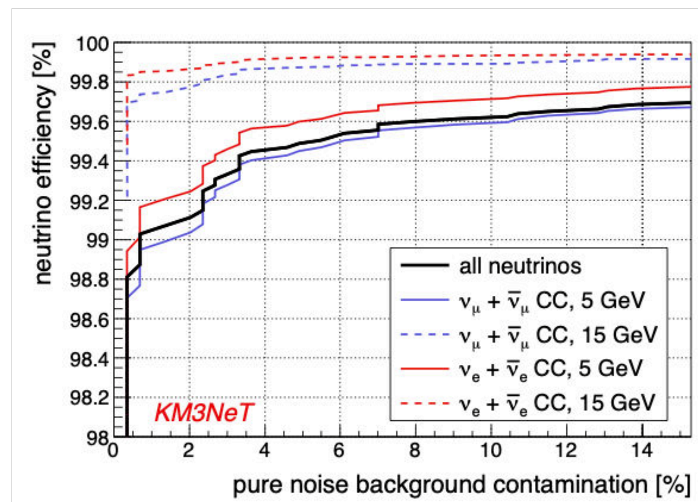
Noise background suppression [arXiv:2103.09885]

▷ few-% contamination can be achieved
→ neglect in sensitivity studies



(a) Pure noise score distribution

$$\frac{N(\nu \text{ after cut})}{N(\text{all preselected } \nu)}$$

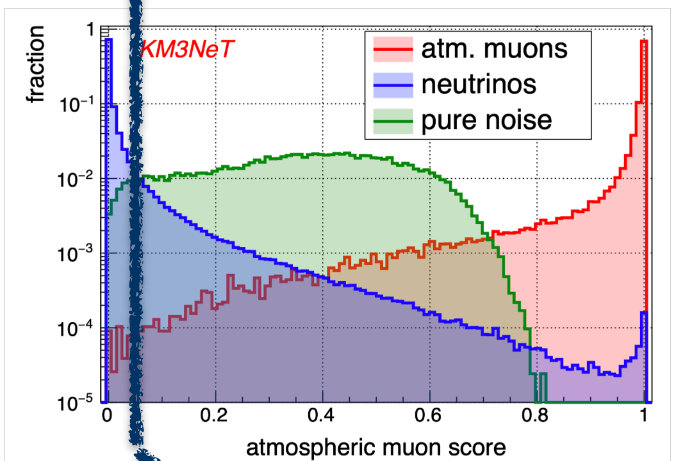


(b) Pure noise suppression performance

$$\frac{N(\text{atm. } \mu \text{ after cut})}{N(\nu + \mu \text{ after cut})}$$

Atmospheric muon background suppression

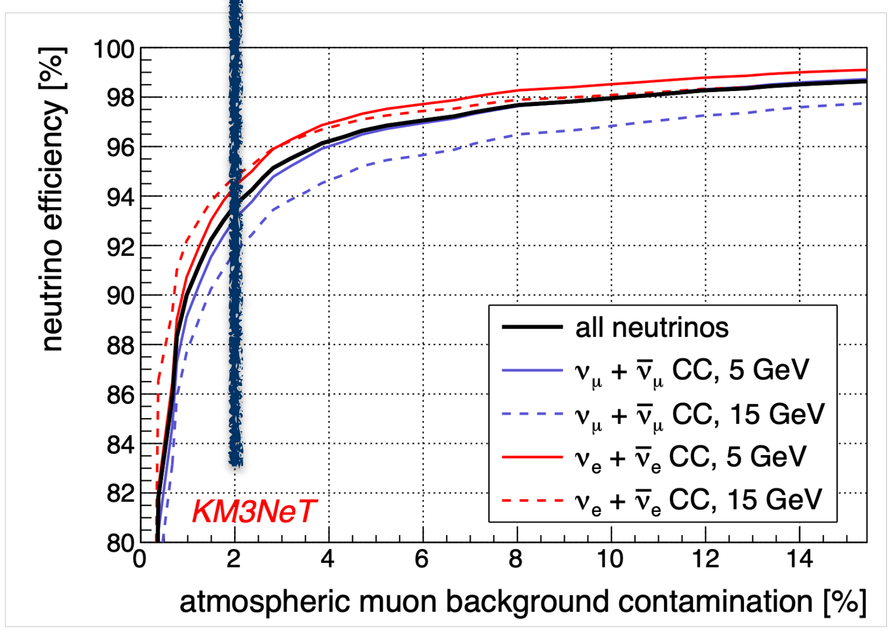
[arXiv:2103.09885]



- few-% contamination can be achieved
- same (and better) for pure noise

→ neglect in sensitivity studies

$$\frac{N(\nu\ \text{after cut})}{N(\text{all preselected}\ \nu)}$$



$$\frac{N(\text{atm.}\ \mu\ \text{after cut})}{N(\nu + \mu\ \text{after cut})}$$