Observation of tau neutrinos in KM3NeT/ORCA

Luc Cerisy

KM3NeT

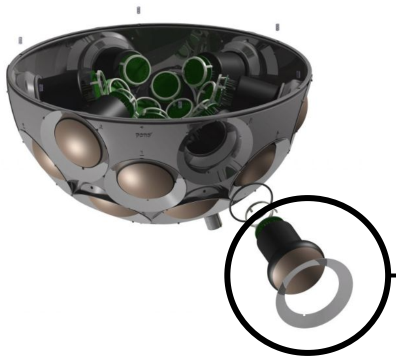


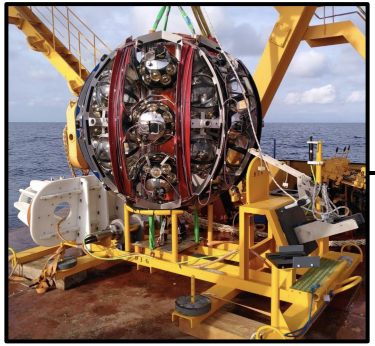
Photo-multiplier tubes (PMT)

detect cherenkov light from the charged products of neutrino interactions in sea-water

x31

Digital Optical Module (DOM)

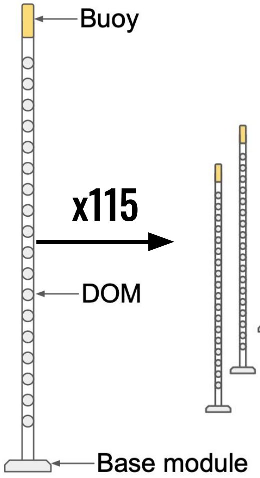
x18



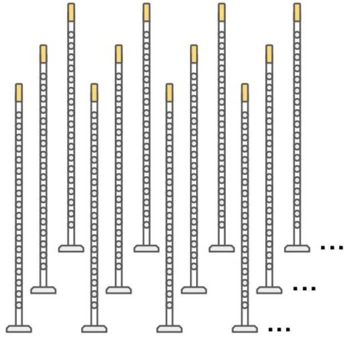
Launcher Optical Modules (LOM)

unfurl

Detection Unit (DU)



x115



Building Block (BB)

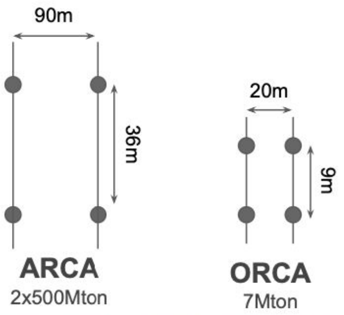
Dismantling ANTARES

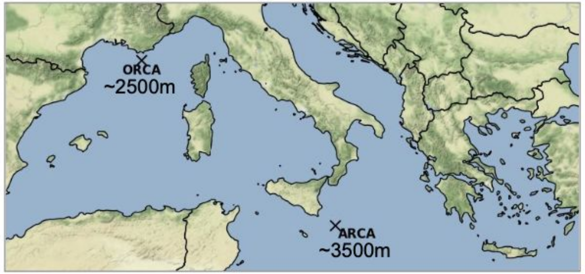
06/2022

Building KM3NeT

1st DU 2017 (picture 2023)

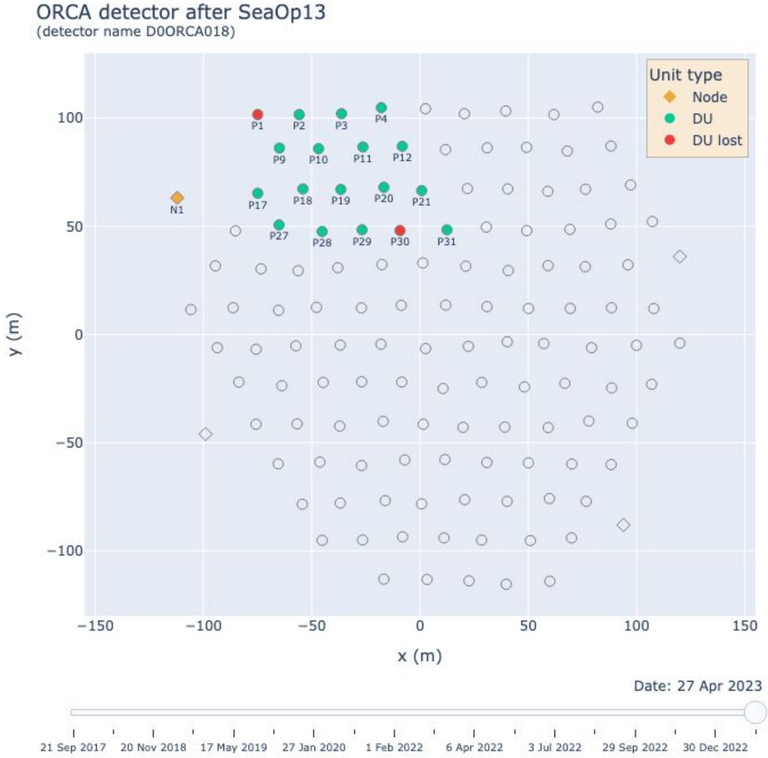
KM3NeT/ORCA
today





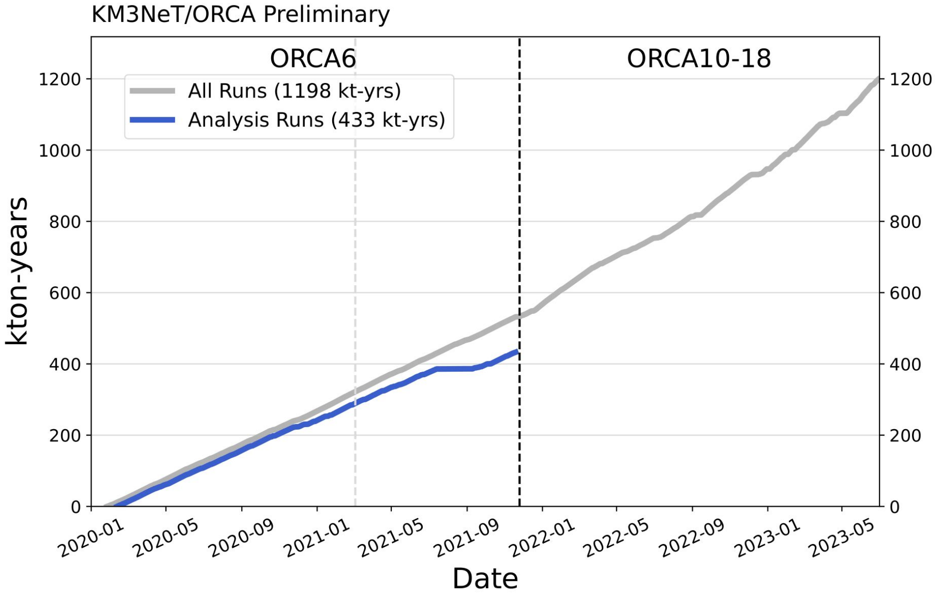
- Dense array (1BB) optimized for **1GeV→500GeV** neutrinos

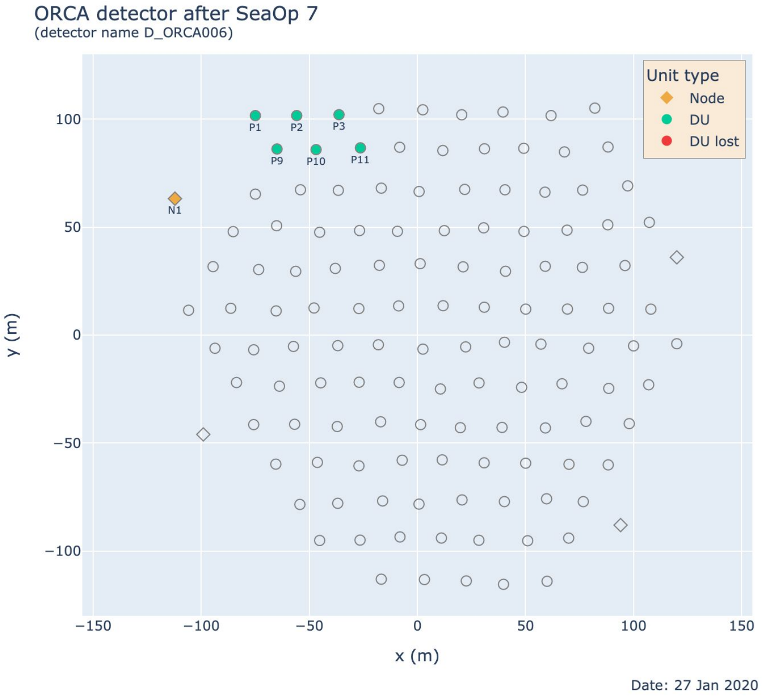
- Measure atmospheric neutrino oscillation
- GeV/MeV neutrino astronomy
- < 0.5° angular resolution



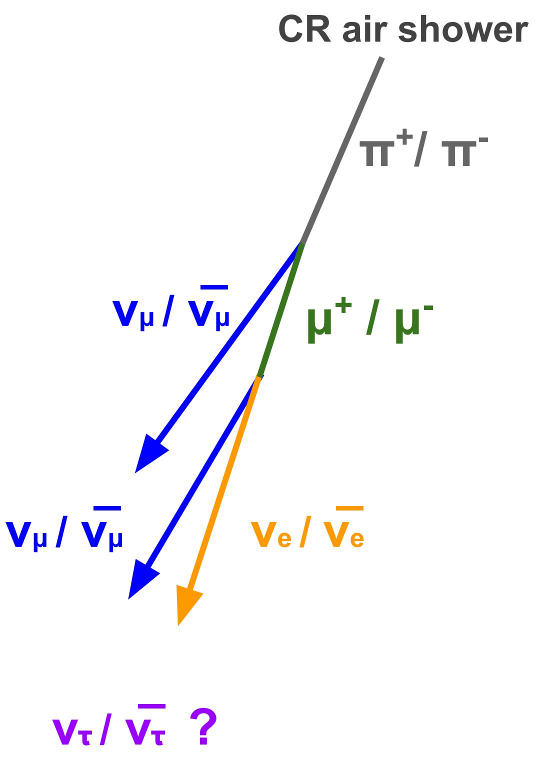
KM3NeT/ORCA6
end of 2021

- data used in the **latest** results in blue
- 6 Detection Units (DUs) configuration
- 5% of the total fiducial volume
- **510 days** mid-Feb. 2020 → mid-Nov. 2021
- stable data-taking conditions





atmospheric neutrinos

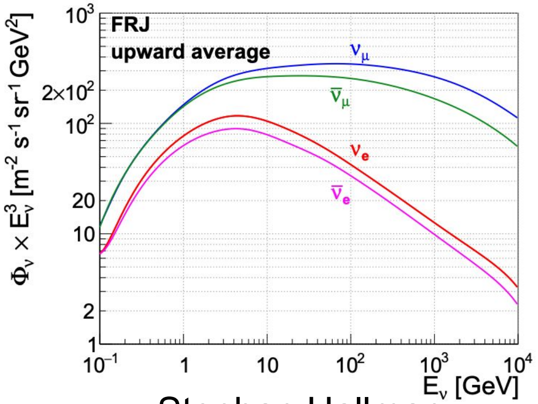


$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

→ 2 : 1 : 0 ratio

- cosmic ray air shower
- neutrinos mostly from pion decay
- no tau neutrinos produced in atm.
- more positive pions → slightly more neutrinos than anti-neutrinos



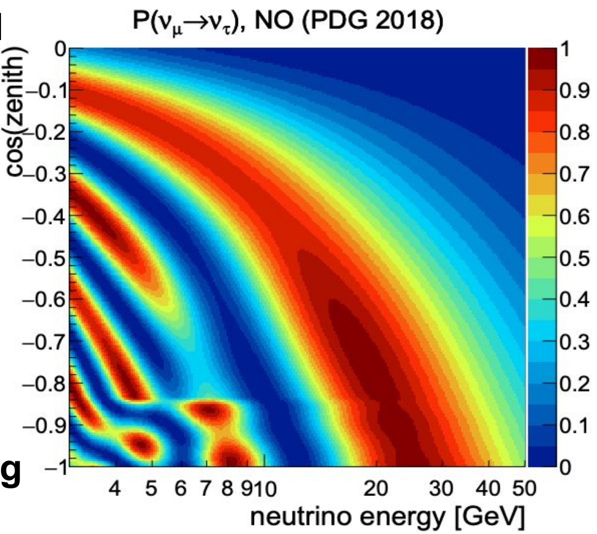
Stephan Hallman.

tau neutrino

- 25 GeV oscillation maximum → tau appearance
- GeV tau neutrinos appear only through oscillations
- effective mass drop below few GeVs

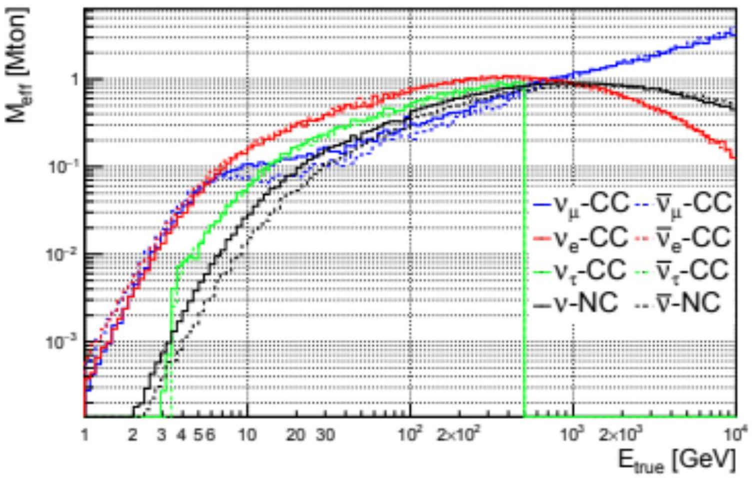
main channel for tau appearance

horizontal



up-going

shower class



track shower

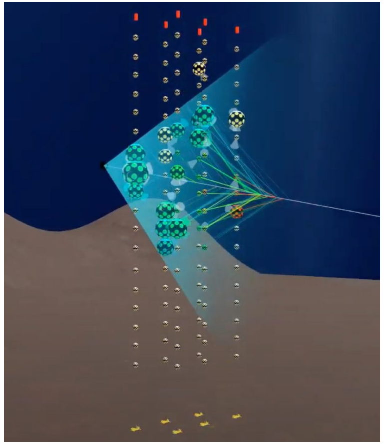
$\nu_{\mu CC}$ → tracks
ν_{eCC} → showers
$\nu_{\tau CC}$ → showers
ν_{xNC} → showers

tau decay
τ = 2.9e-13 s
d = ~1mm
m_{tau} = 1.77 GeV

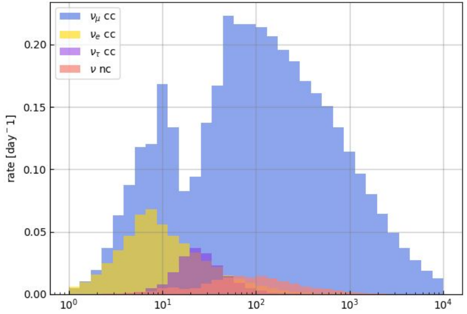
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$	(17.8%)	**leptonic (35.2%)**
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$	(17.4%)	
$\tau^- \to \pi^- \pi^0 \nu_\tau$	(25.5%)	**hadronic (64.8%)**
$\tau^- \to \pi^- \nu_\tau$	(10.8%)	
$\tau^- \to \pi^- \pi^0 \pi^0 \nu_\tau$	(9.3%)	
$\tau^- \to \pi^- \pi^- \pi^+ \nu_\tau$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

- difficult to achieve a pure shower selection
- not possible yet to distinguish em. vs had. showers

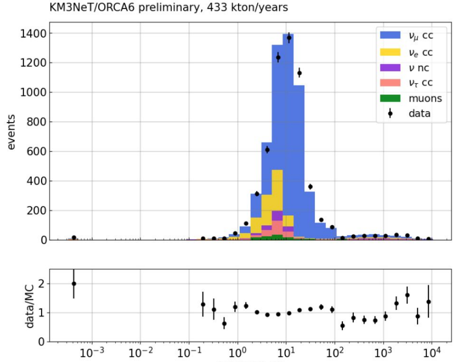
ORCA6 event



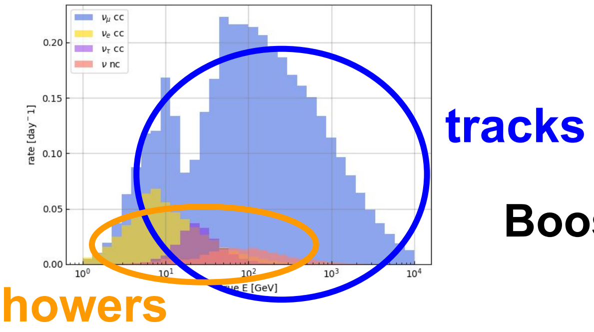
true energy



reco. energy



PID



Random Grid Search (RGS)

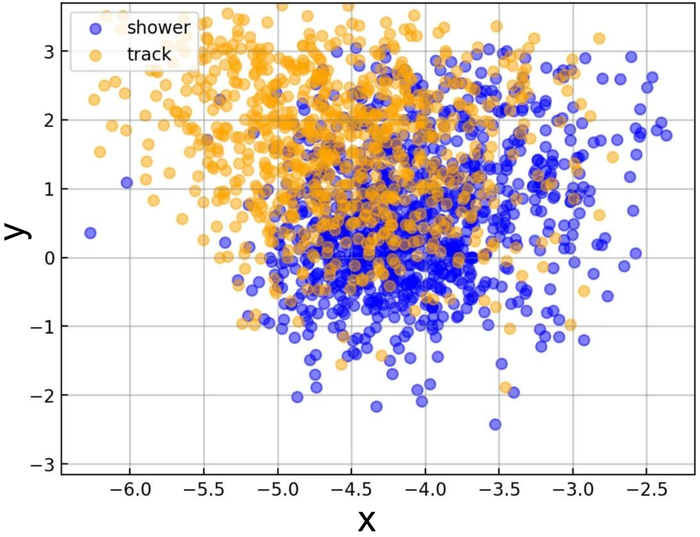
- quick search for the best combination of cuts in nD to separate two population of events
- uses few features

Boosted Decision Trees (BDT)

- n features used for training
- a decision tree makes a prediction
- boost = the wrongly classified events are given a higher weight for the next iteration
- boost = most performing tree have higher weight → have more influence on the final model
- evaluation of the classifier → score

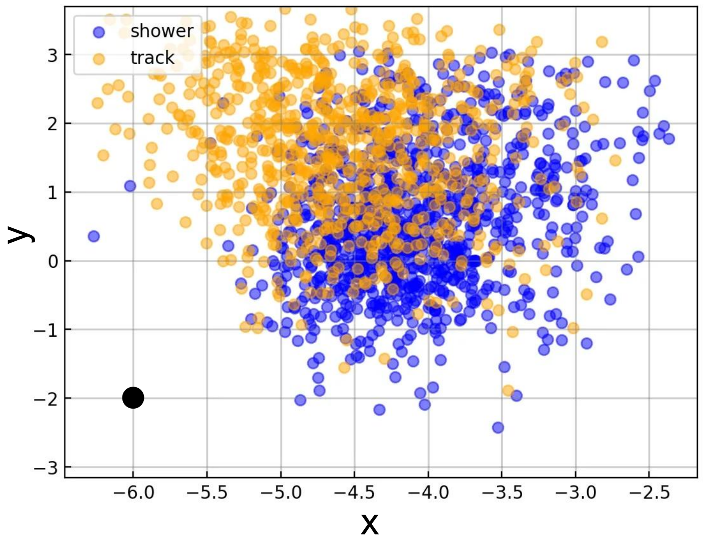
Random Grid Search principle

separate two populations using a set of features x, y, z …

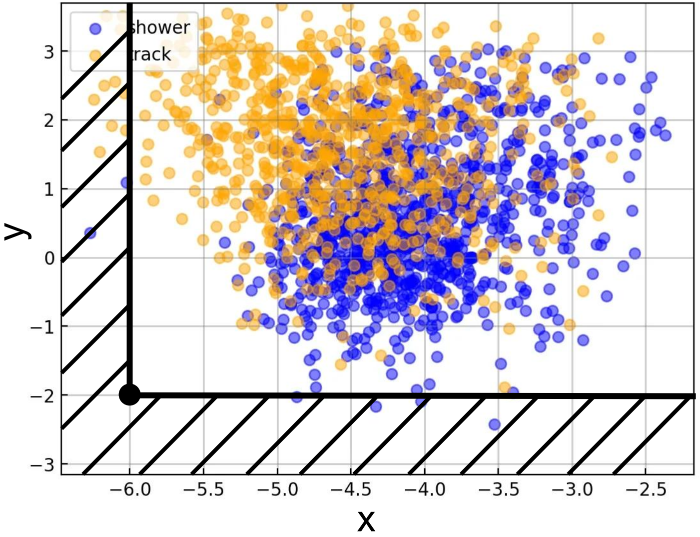


first approach

→ grid scan



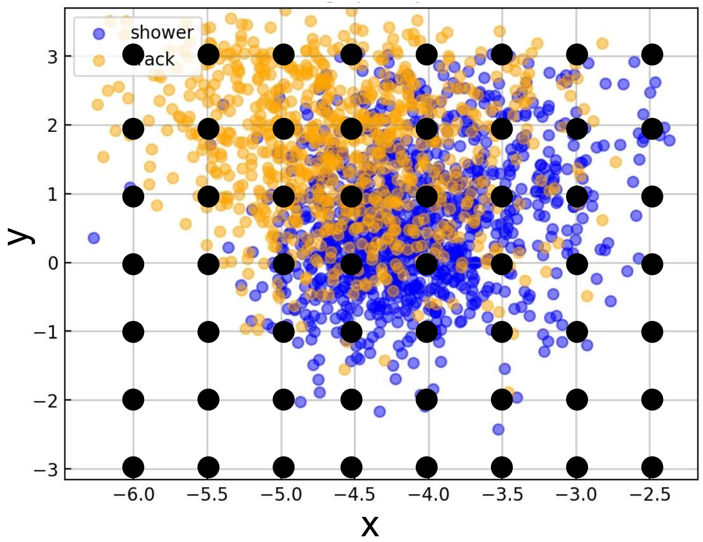
use this selected point
on the grid to cut on



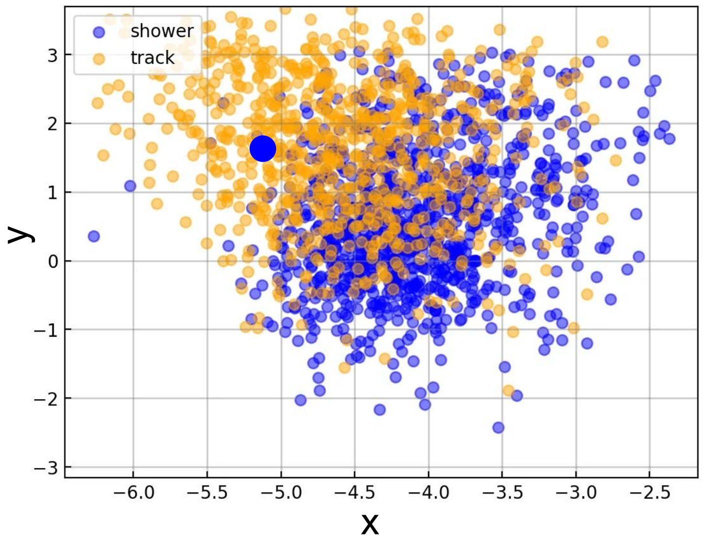
do it for every nodes of the grid

→ inefficient search

→ some cuts are unworthy to try

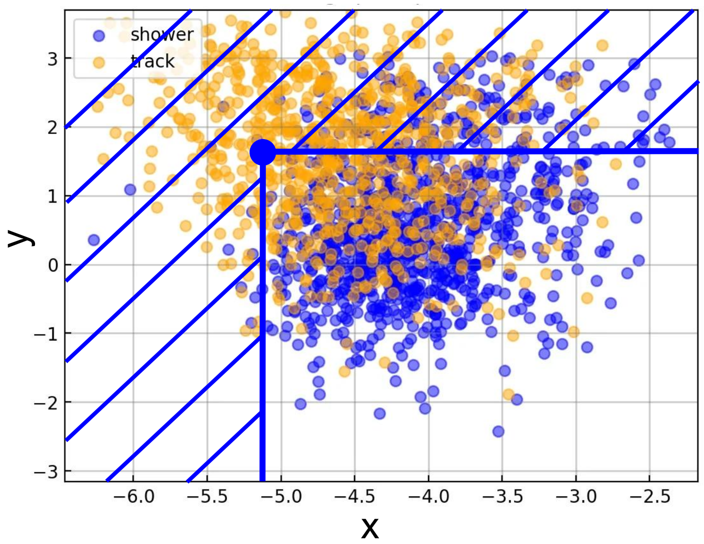


RGS algorithm uses the events coordinates to cut on



then counts the number of blues & orange points before & after the cut

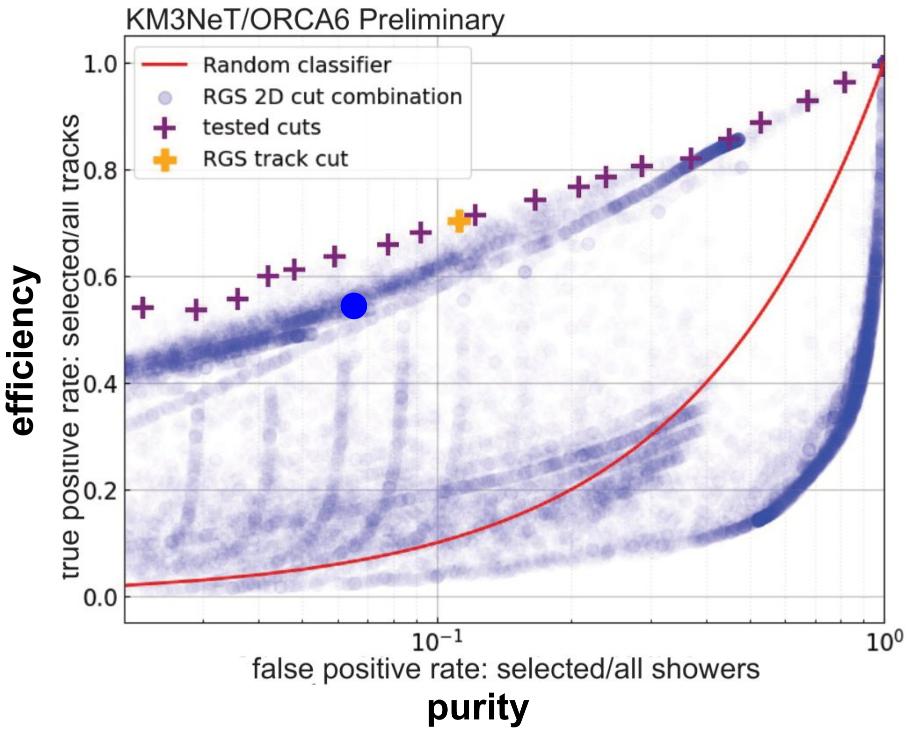
→repeat it for every event



RGS performance

- each point is a set of cuts applied consecutively

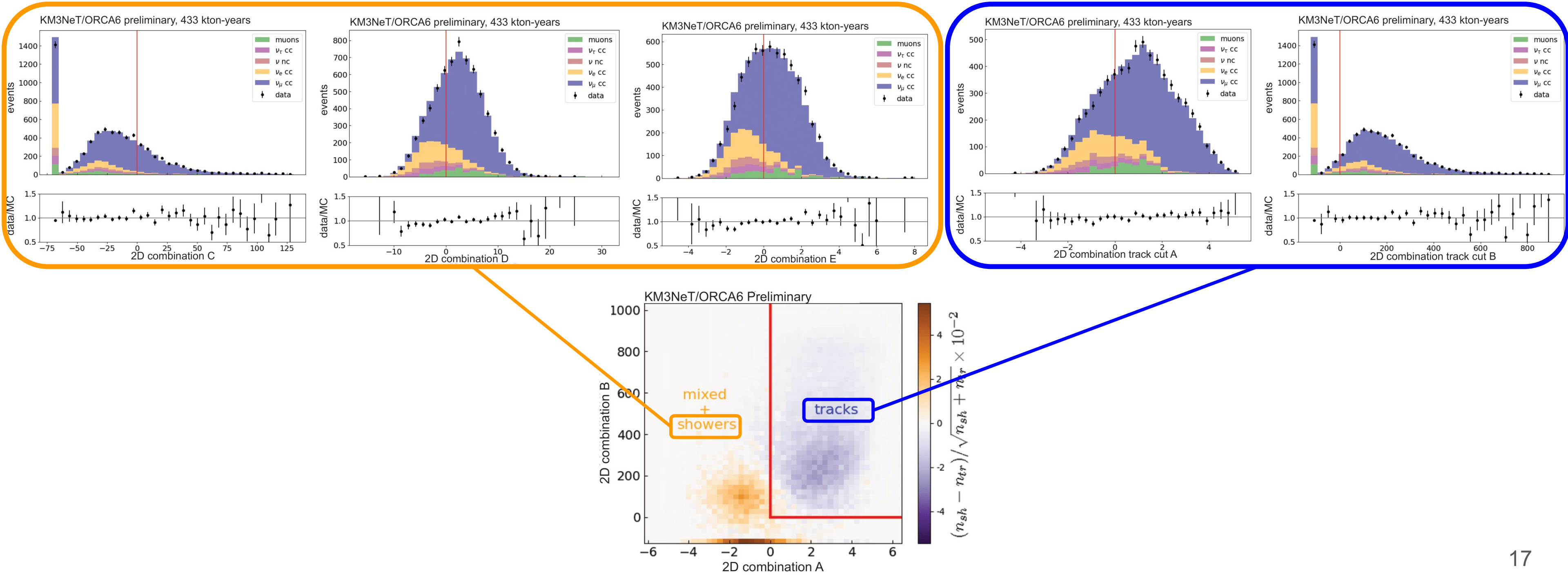
- the best points are used to test the sensitivity to the measurement



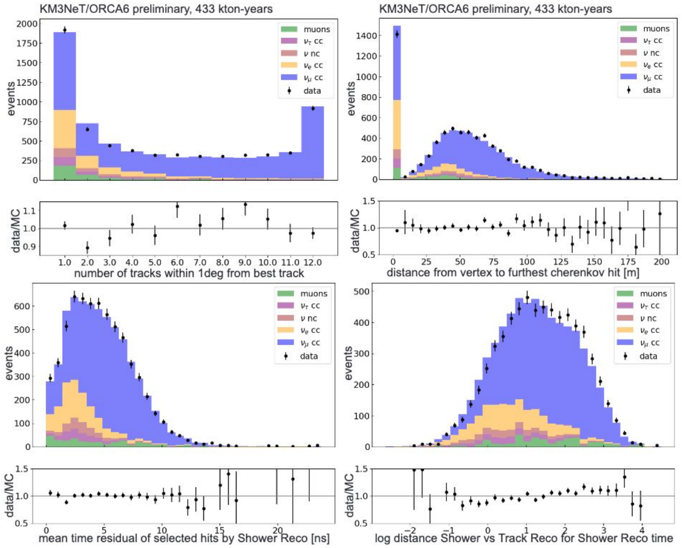
RGS applied

RGS uses 5 features instead of 45 for the BDT to define 3 classes

tracks **mixed** **showers**



why RGS ?



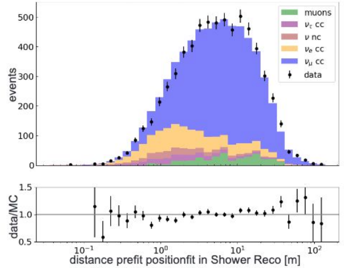


Figure 4: The distribution of all MC events is shown in colors with atmospheric muons in green, $\nu_\tau + \bar{\nu}_\tau$ CC in purple, $\nu + \bar{\nu}$ NC in brown, $\nu_e + \bar{\nu}_e$ CC in orange and $\nu_\mu + \bar{\nu}_\mu$ CC in blue. The number of data events is represented with black dots and errors bars. The data/MC ratio is shown for each feature on the bottom part of the figure.

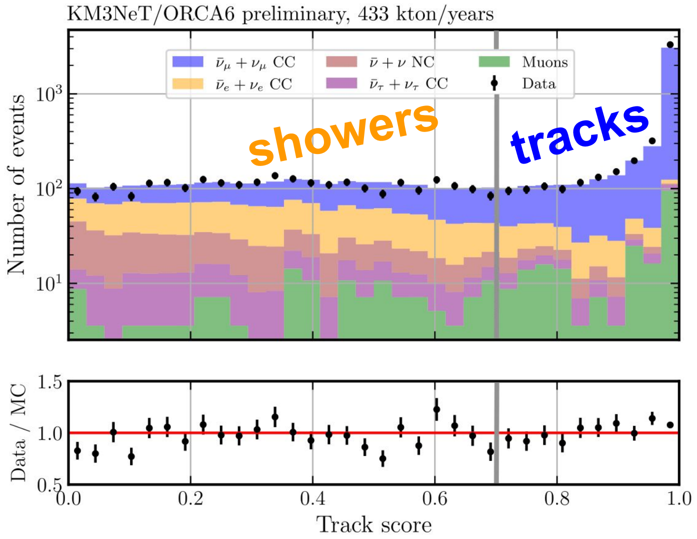
- robust to changes in the data

small variation in the data induce small change in performance

- use few variables to defines the classes
- understand the variables and verify the data/MC agreement
- no training of the classifier

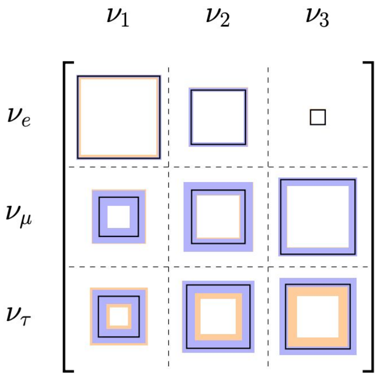
BDT separation

- 43 features summarized into one score
- score to describe how muon neutrino like is the event
- track-shower separation at **0.7**
- overall good data/MC agreement
- risk of overtraining the classifier on given MC

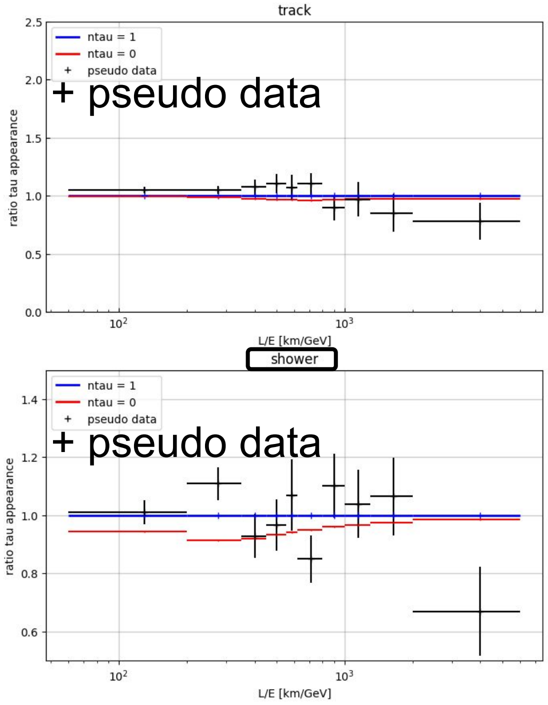


why studying tau neutrino ?

- rare observation → only ~2100 detected so far
  full KM3NeT/ORCA will measure **3000/year**
- test unitarity of the PMNS flavor mixing matrix
- test sterile hypothesis (through theta34)
- constrain tau neutrino cross section

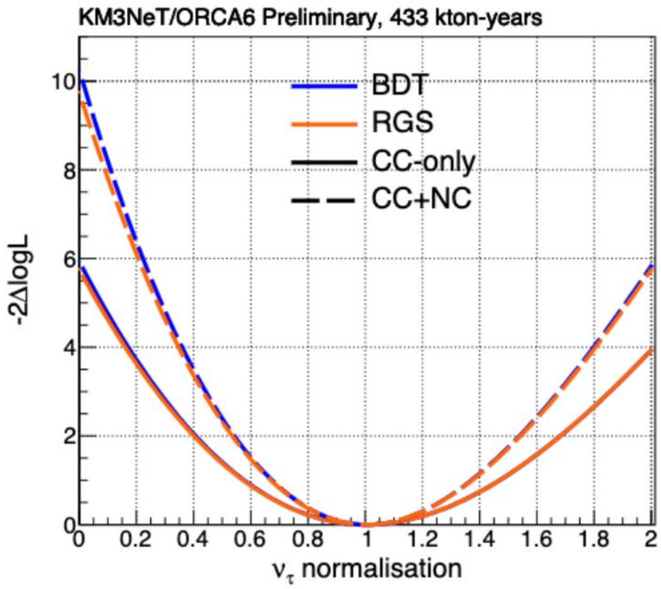


tau norm sensitivity



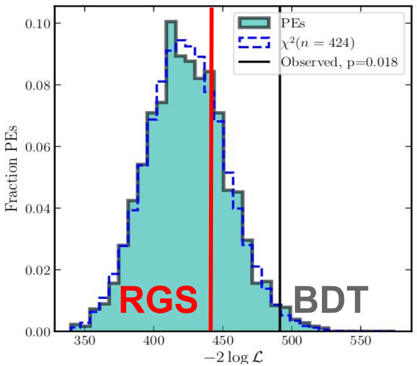
- 2D binned log-likelihood fit of reco E & cos(zenith) distributions for the 3 classes
- **tau norm = measured/expected** number of tau neutrinos
- tau neutrinos are most visible in the **shower** class
- same sensitivity between the two approaches
- escale and shower norm largest systematic that impact tau norm

Systematics	***Priors***
Spectral Index	± 0.3
ν_{hor}/ν_{ver}	± 2%
$\nu_\mu/\bar{\nu}_\mu$	± 5%
$\nu_e/\bar{\nu}_e$	± 7%
ν_μ/ν_e	± 2%
NC Normalisation	± 20%
Energy scale	± 9%
High-energy Light Simulation	± 50%
Overall Normalisation	free
Track Normalisation	free
Shower Normalisation	free
Muon Normalisation	free



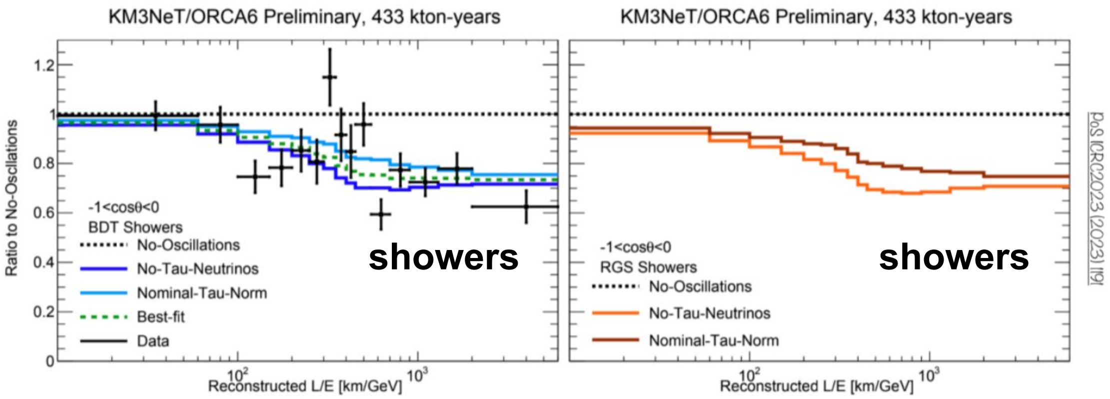
tau norm measurement

- RGS/BDT data → better chi2 from the fit
- the best-fit lies in the middle between nominal tau norm and no nu tau
- same sensitivity as expected

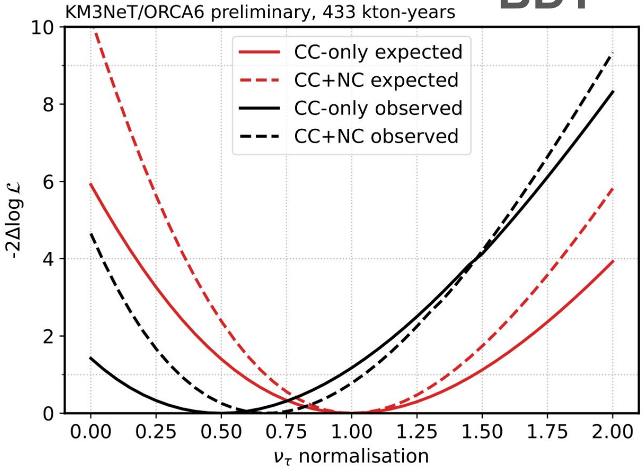


BDT

RGS



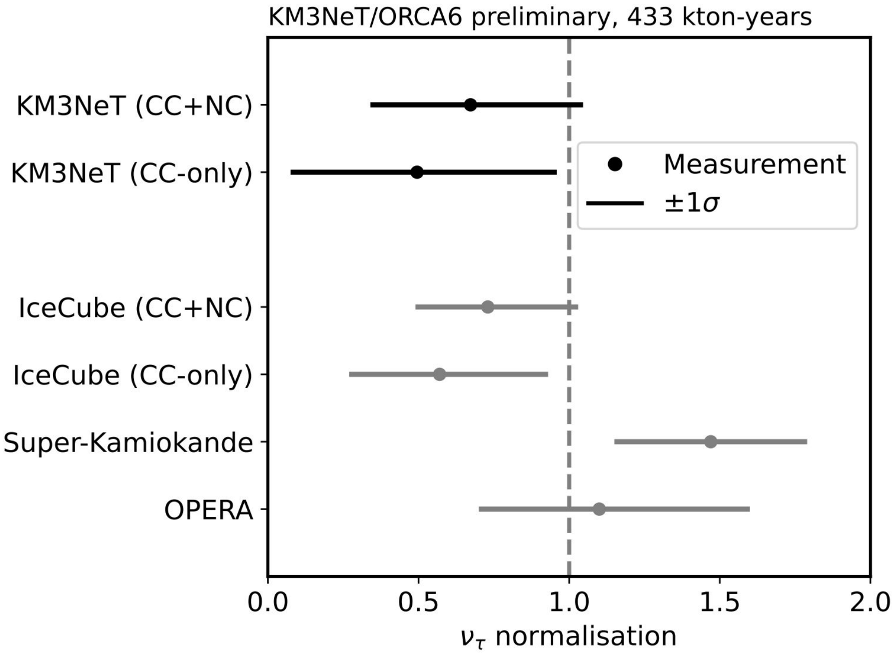
BDT



tau norm world measurement

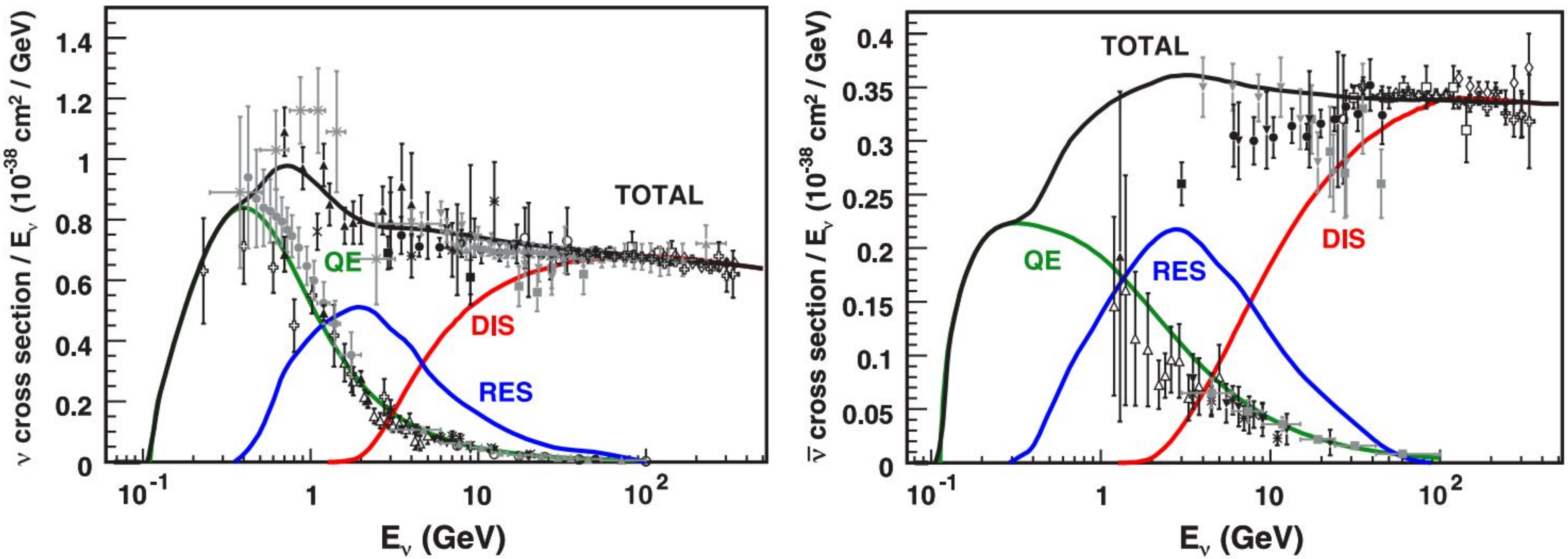
	measured value	1σ error
tau norm CC	**0.50**	[+0.46 -0.42]
tau norm CC+NC	**0.67**	[+0.37 -0.33]

- **neither 0 nor 1 exluded**
- competitive with world best measurement
- similar to IC results
- 6 lines 5% of fiducial volume
- 510 days
- investigation on the origin of that deficit

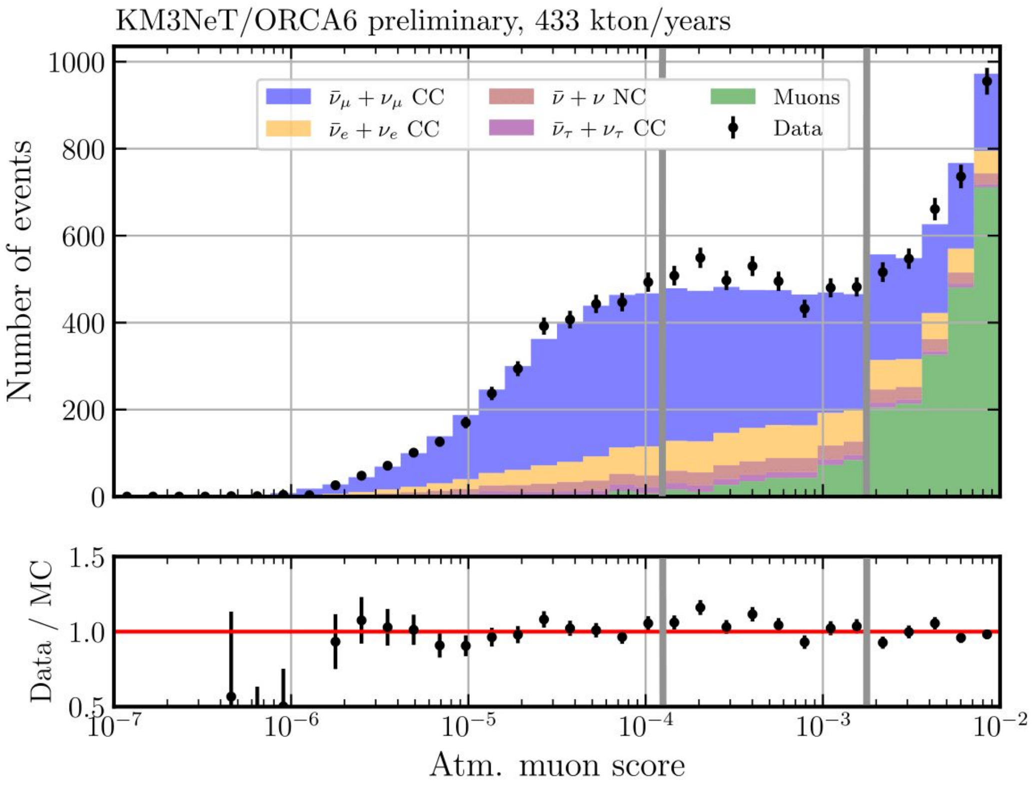


Thanks for listening !

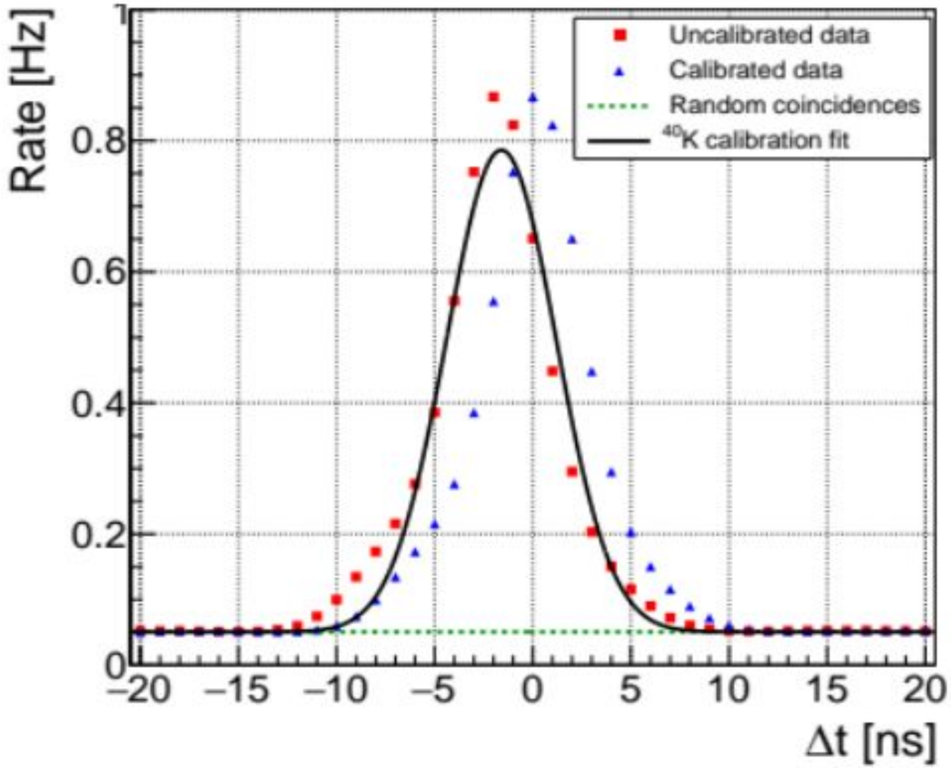
cross section



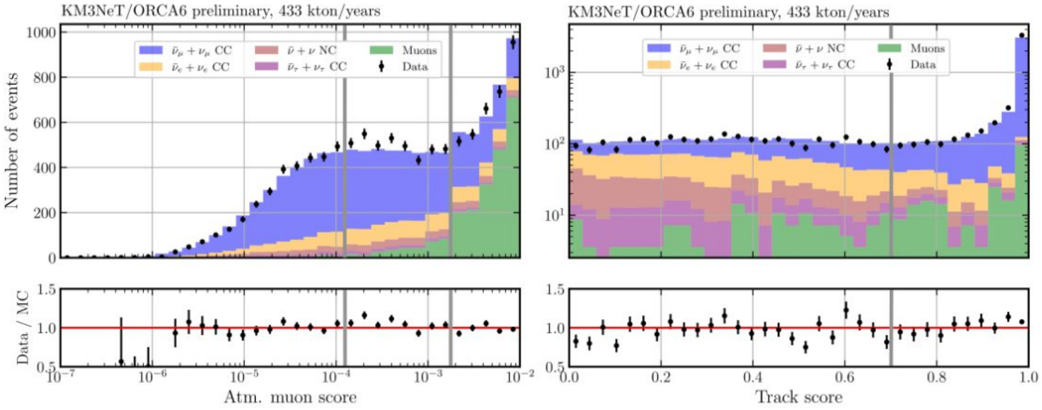
atm. muon background



PMT calibration

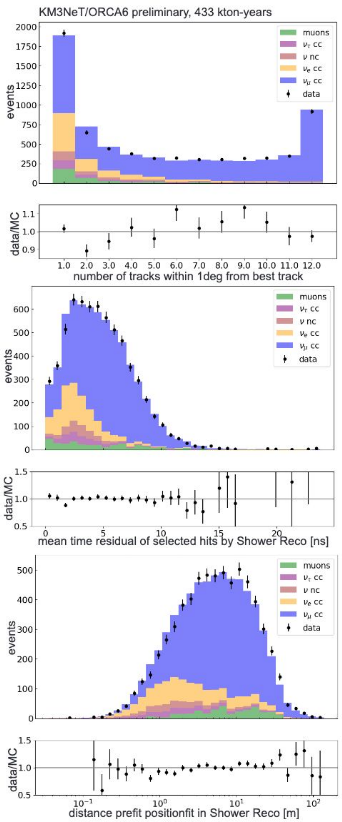


events



Selection	All events	Atm. muons	$\nu_\mu/\bar{\nu}_\mu$ CC	$\nu_\tau/\bar{\nu}_\tau$ CC
High Purity Tracks	1870	7	1779	20
Low Purity Tracks	2001	83	1792	18
Showers	1959	21	908	130
433 kton-years	5830	111	4480	169
296 kton-years	1250	38	900	65

RGS table



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2D combination $Z = y - (ax + b)$					
RGS track class definition: $A\&B$					
pars.	feature x	feature y	coeff a	coeff b	cut dir.
comb. A	n. tracks within 1°	log pre/pos fit dist. Shower Reco	-0.2356	+ 1.9124	$Z > 0$
comb. B	furthest Cherenkov hit	mean time residual of sel. hits	-5.0702	+125.6146	$Z > 0$
RGS shower class definition:$(\bar{A} or \bar{B})$ & $(C\&D\&F)$					
comb. C	log pre/pos fit dist. Shower Reco	furthest Cherenkov hit	-0.0101	+71.1553	$Z < 0$
comb. D	log pre/pos fit dist. Shower Reco	mean time residual of sel. hits	-3.0422	+7.4538	$Z < 0$
comb. E	mean time residual of sel. hits	log dist. Shower vs Track reco	-0.3291	+2.503	$Z < 0$

Table 2: Coefficients of RGS cut combination for Tracks and Showers classes definition.

futur prospects