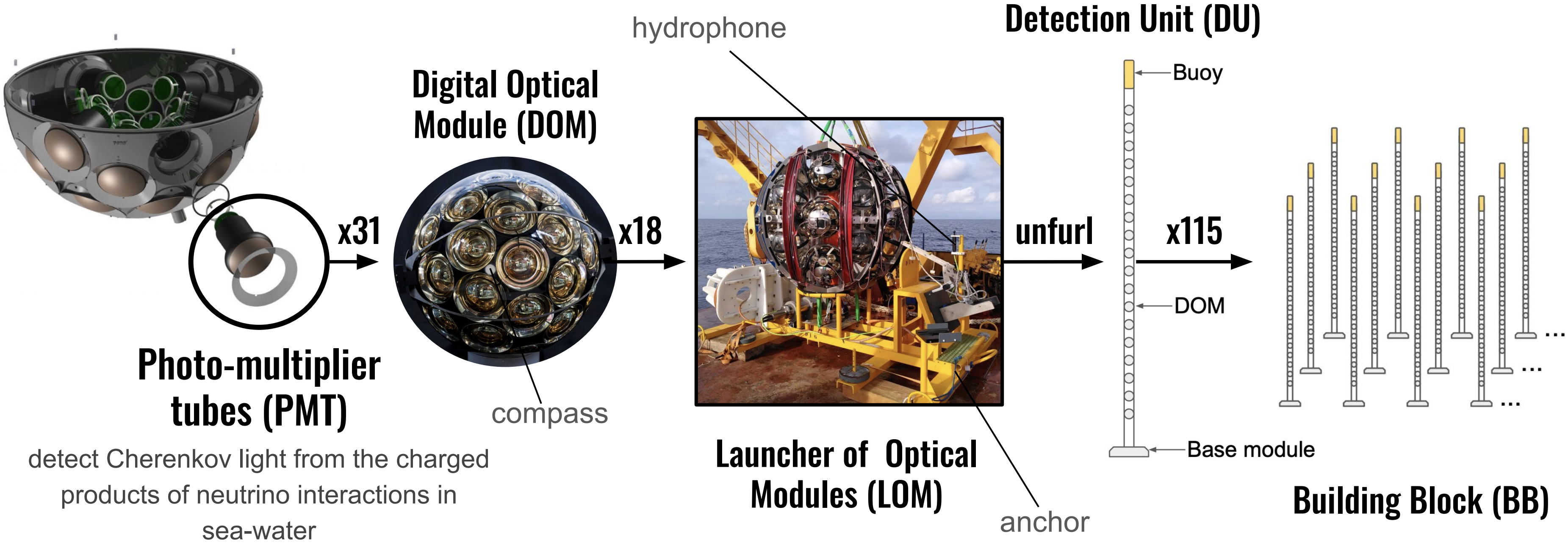
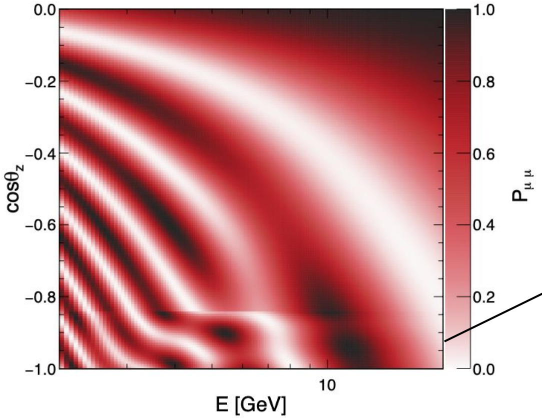
Undersea measurements of neutrino oscillations

Luc Cerisy,
on behalf of the KM3NeT collaboration

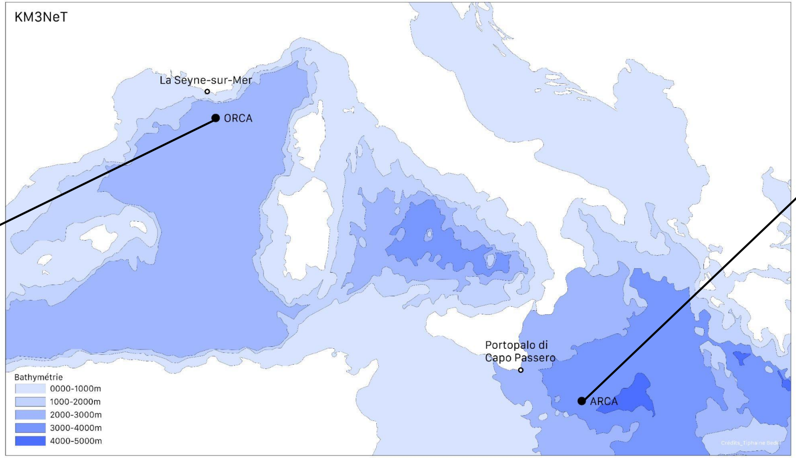
KM3NeT

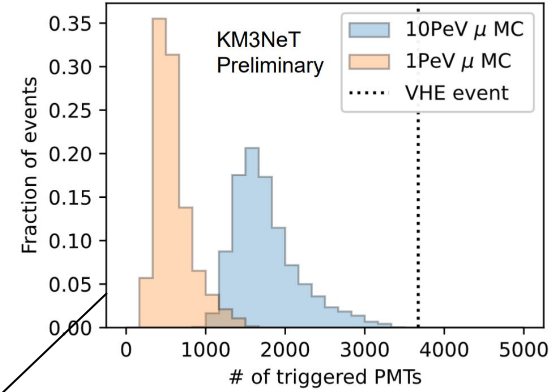

hydrophone
Detection Unit (DU)
Buoy
Digital Optical Module (DOM)
x31
x18
unfurl
x115
DOM
Photo-multiplier tubes (PMT)
compass
detect Cherenkov light from the charged products of neutrino interactions in sea-water
Launcher of Optical Modules (LOM)
anchor
Base module
Building Block (BB)

KM3NeT



probe GeV neutrinos
ORCA





probe TeV-EeV neutrinos
ARCA

	KM3NeT/ARCA	KM3NeT/ORCA
Building blocks	2	1
Number of DUs	230	115
DOM vertical spacing [m]	36	9
DU horizontal spacing [m]	95	20
Depth [m]	3450	2450
Instrumented volume [Mton]	1000	7

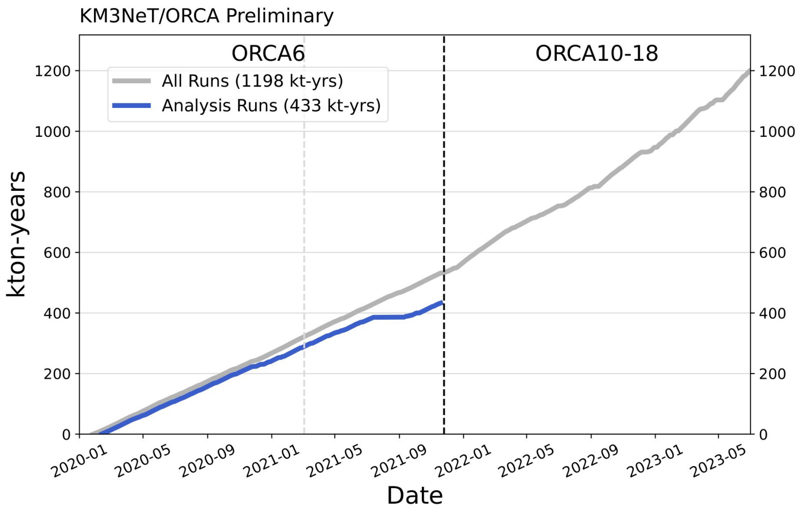
Dismantling ANTARES
06/2022

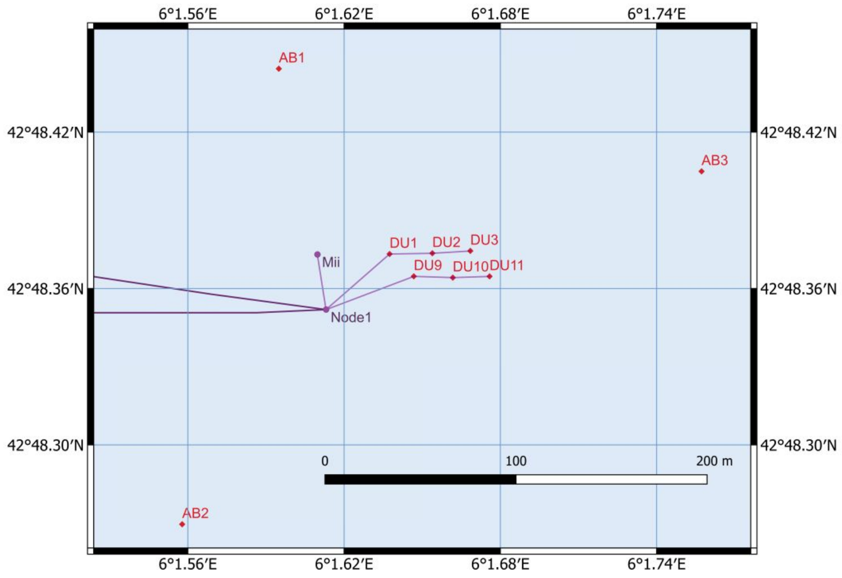
Building KM3NeT
1st DU 2017 (picture 2023)

KM3NeT/ORCA6

433 kt-yr · 02/20 to 11/21

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

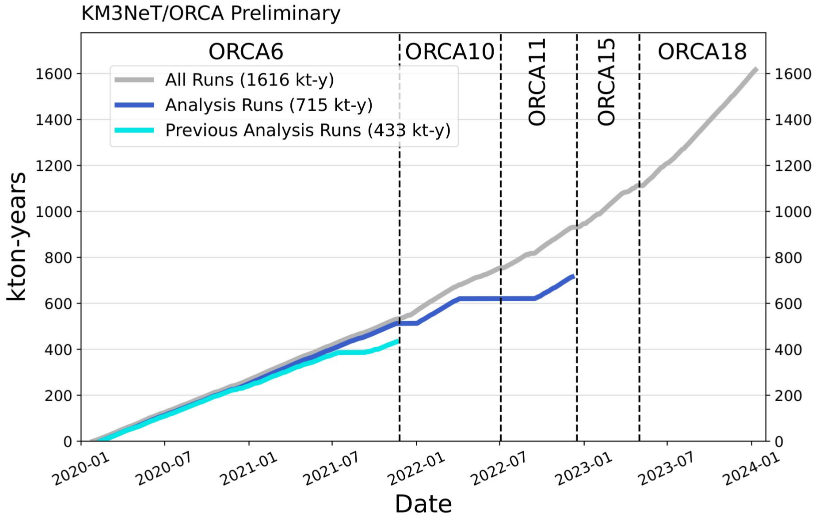


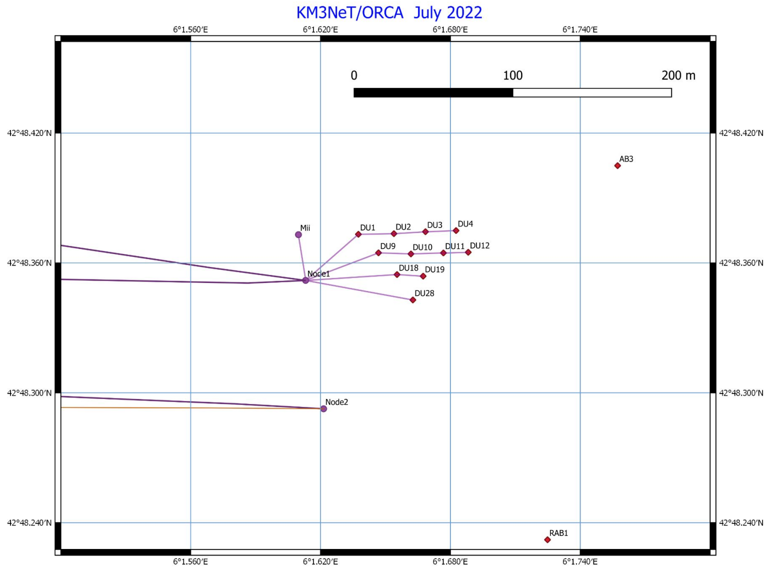


KM3NeT/ORCA6-10-11

715 kt-yr · 02/20 to 12/22

- data used in the **latest** results in **blue**
- 6-10-11 Detection Units (DUs) configuration
- Feb. 2020 → Dec. 2022
- 715 kt-years **+40%**
- stable data-taking conditions



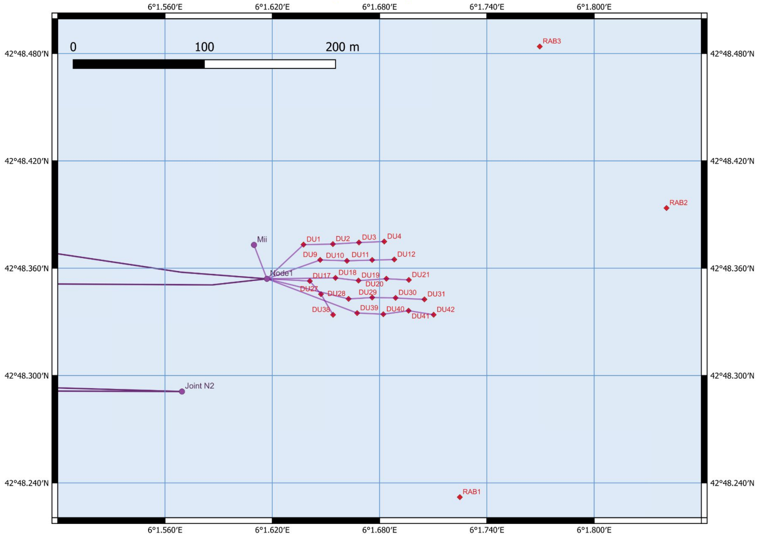


KM3NeT/ORCA23

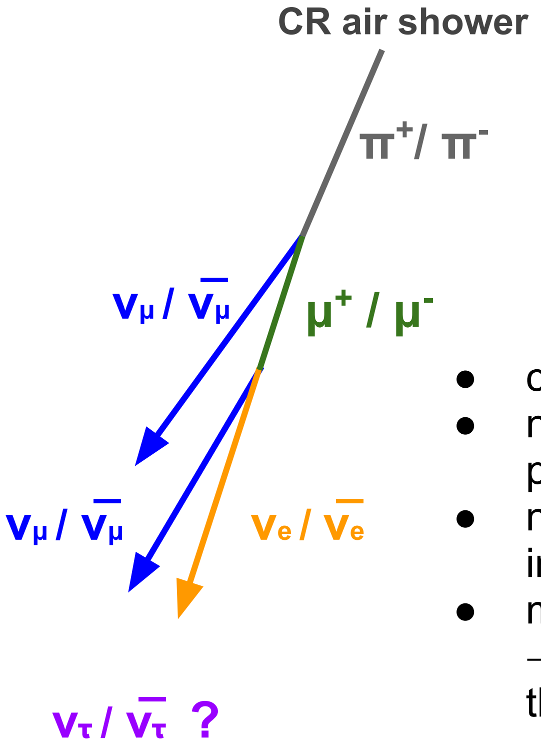
today (summer 2024)

current status

- 23 Detection Units (DUs) configuration
- after sea operation June 2024
- 20% of the total fiducial volume
- **1.6 Mt-year** of data on tape



atmospheric neutrinos

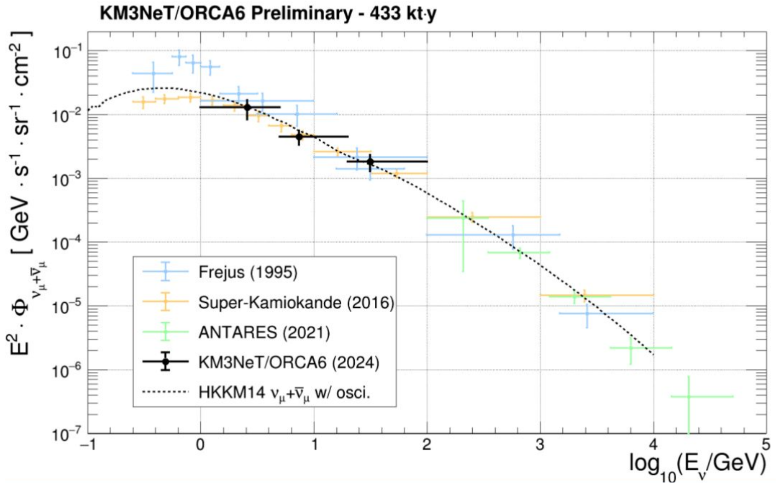


$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

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

$\rightarrow$ ~ 2 : 1 : 0 ratio

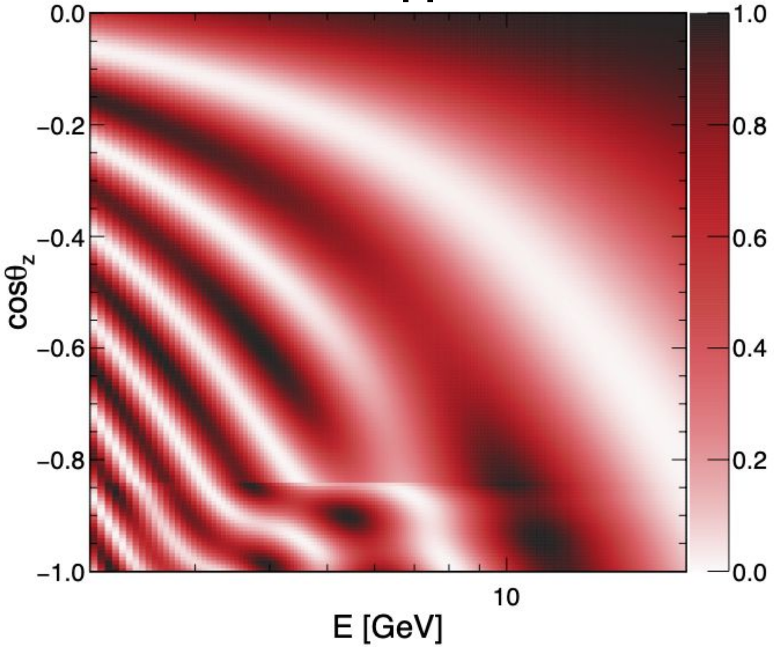
- cosmic ray air shower
- neutrinos mostly from pion decay
- no tau neutrinos produced in the atmosphere
- more positive pions
  $\rightarrow$ slightly more neutrinos than anti-neutrinos



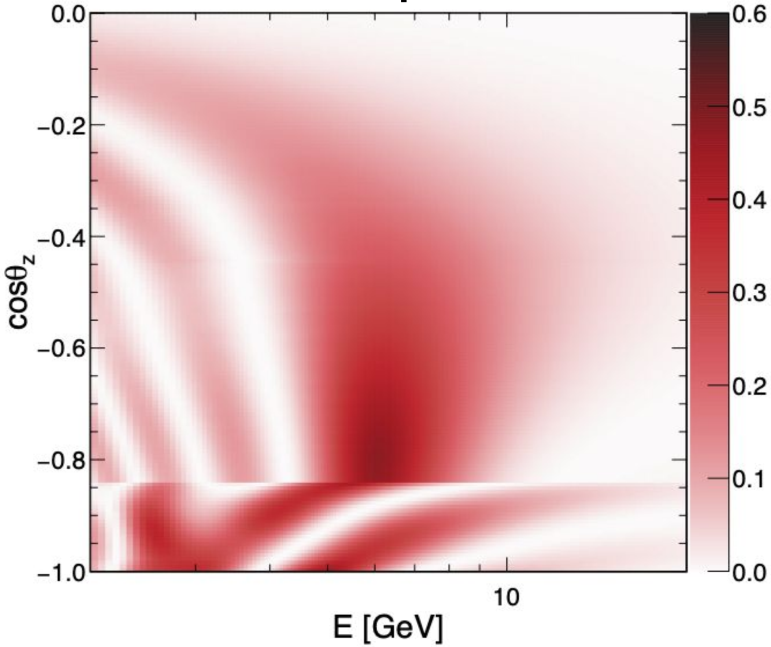
neutrinos oscillations

- muon neutrino disappearance [10-40 GeV] → Δm^2_{31} & $\sin^2\theta_{23}$
- ν/anti-ν asymmetry in matter resonance [4-10 GeV] → NMO

$P_{\mu\mu}$



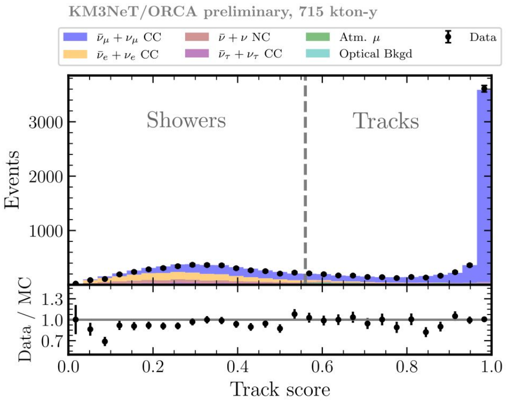
$P_{\mu e}$

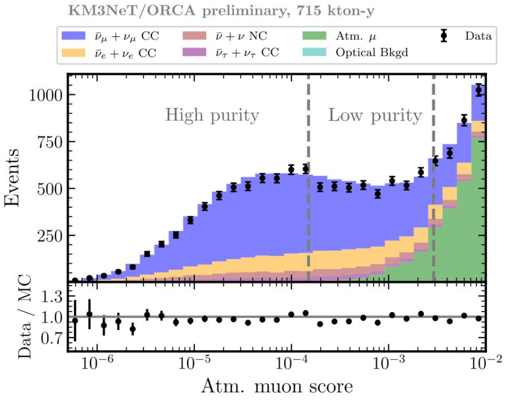


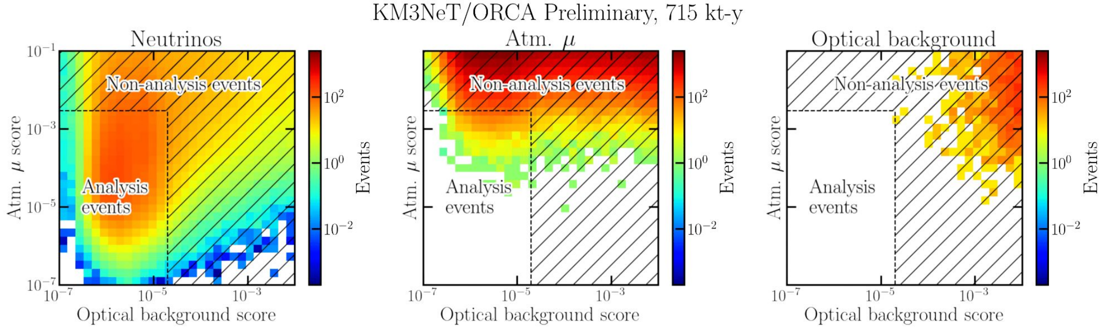
KM3NeT/ORCA

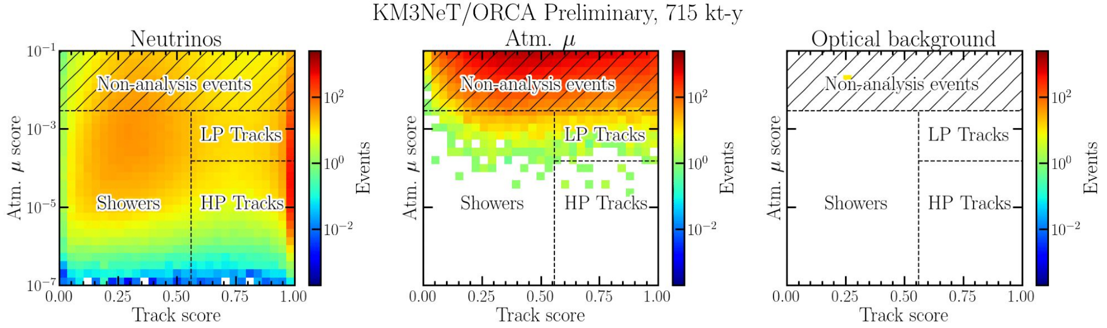
715 kt-yr

- 9751 neutrinos in 3 PID classes
- 97% muon neutrino purity in HP Tracks
- 91% of electron neutrino in the Showers









2D fit

- 3 PID classes: [17 bins HP-tracks, 17 LP Tracks and 19 Showers] x 10 cos(zenith) bins
  → 530 bins used in the fit
- 2D-profiled likelihood scans of Δm^2_{31} , $\sin^2\theta_{23}$ (and other parameters of interest)
- $-2\Delta \ln L$ between fixed $\Delta m^2_{31}/\sin^2\theta_{23}$ and free (Best Fit)
- 14 systematic uncertainties on flux, x-sec, background

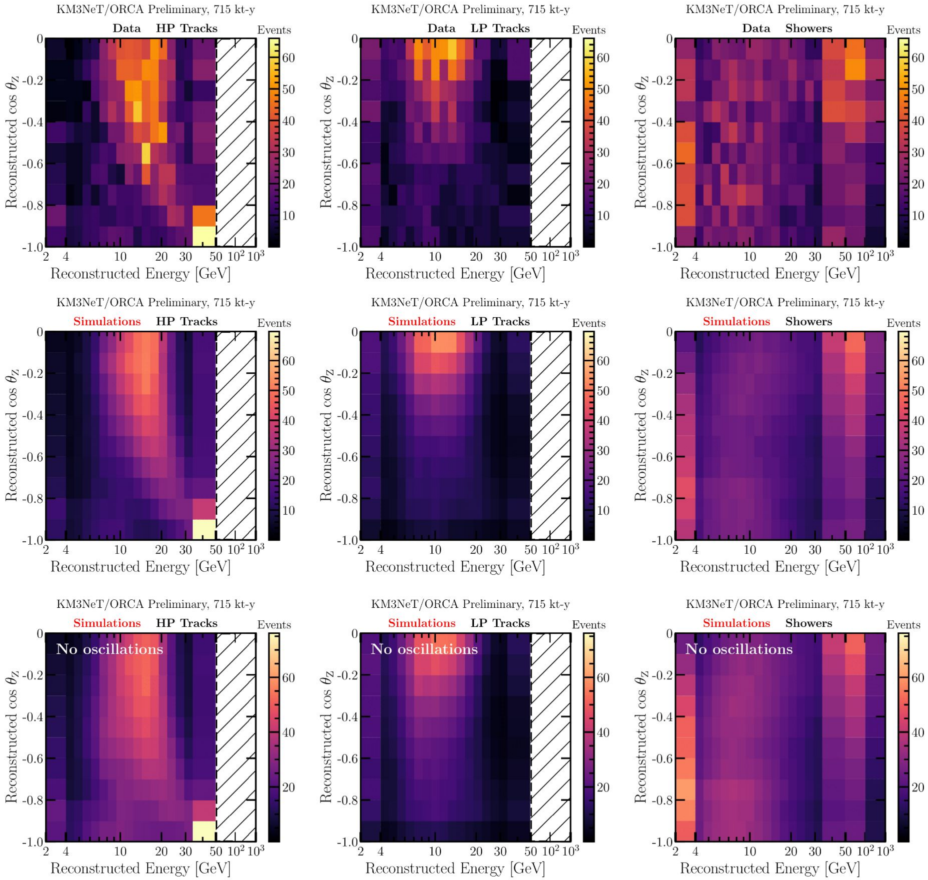
$$-2\log\mathcal{L} = -2\sum_{c}\sum_{ij}\left(n_{ij}^{\text{model}} - n_{ij}^{\text{data}} + n_{ij}^{\text{data}}\log\left(\frac{n_{ij}^{\text{data}}}{n_{ij}^{\text{model}}}\right)\right) + \sum_{\epsilon}\left(\frac{\epsilon_{\text{exp}} - \epsilon_{\text{obs}}}{\sigma_{\epsilon}}\right)^2$$

KM3NeT/ORCA

715 kt-yr

- events [energy-cosθ_z] distribution
- **top** : data
- **middle** : simulations at best fit
- **bottom** : no-oscillation simulated

effect of oscillation visible in the track channel event distribution

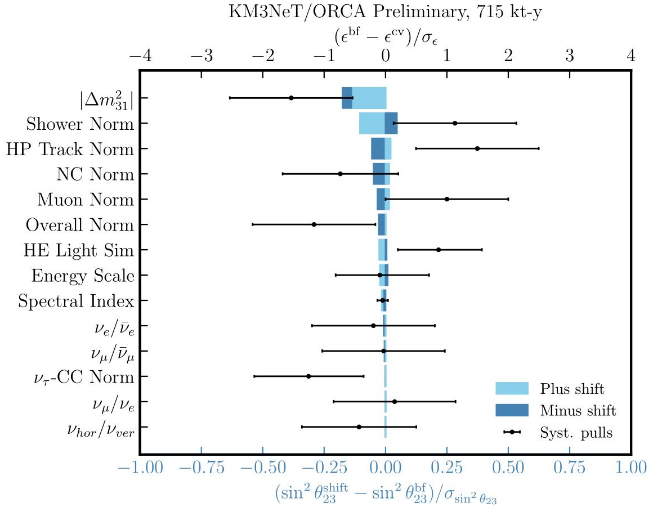


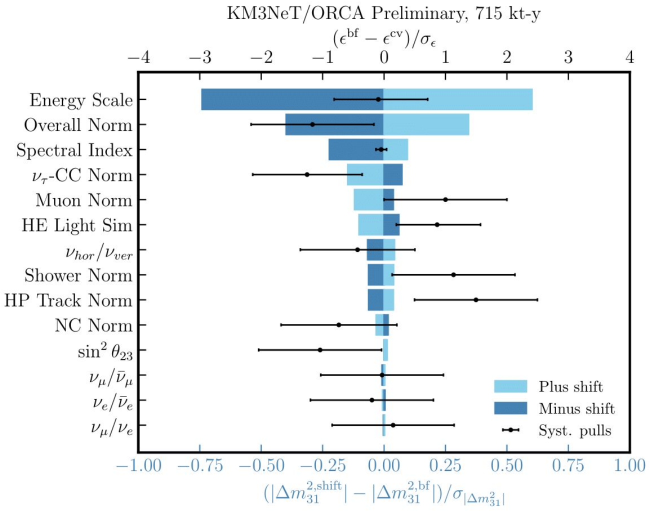
standard oscillation

KM3NeT/ORCA

715 kt-yr

- systematic pulls wrt. nominal divided by the 1σ post fit uncertainty → < 2σ
- impact of 1σ shift of the systematics on the measurement

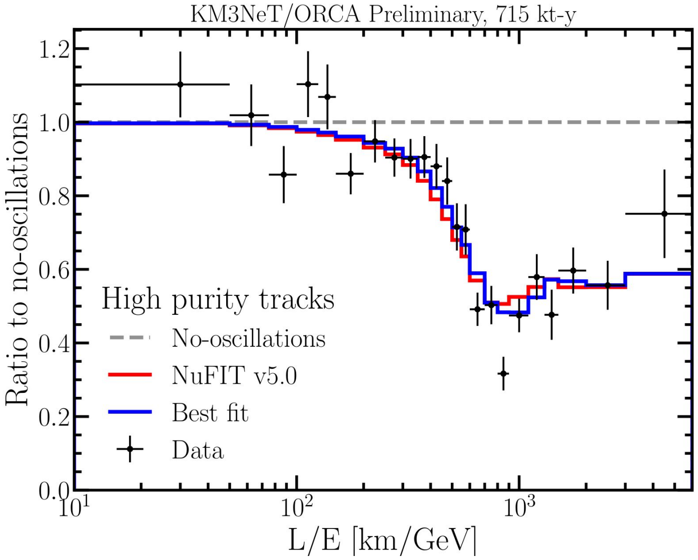


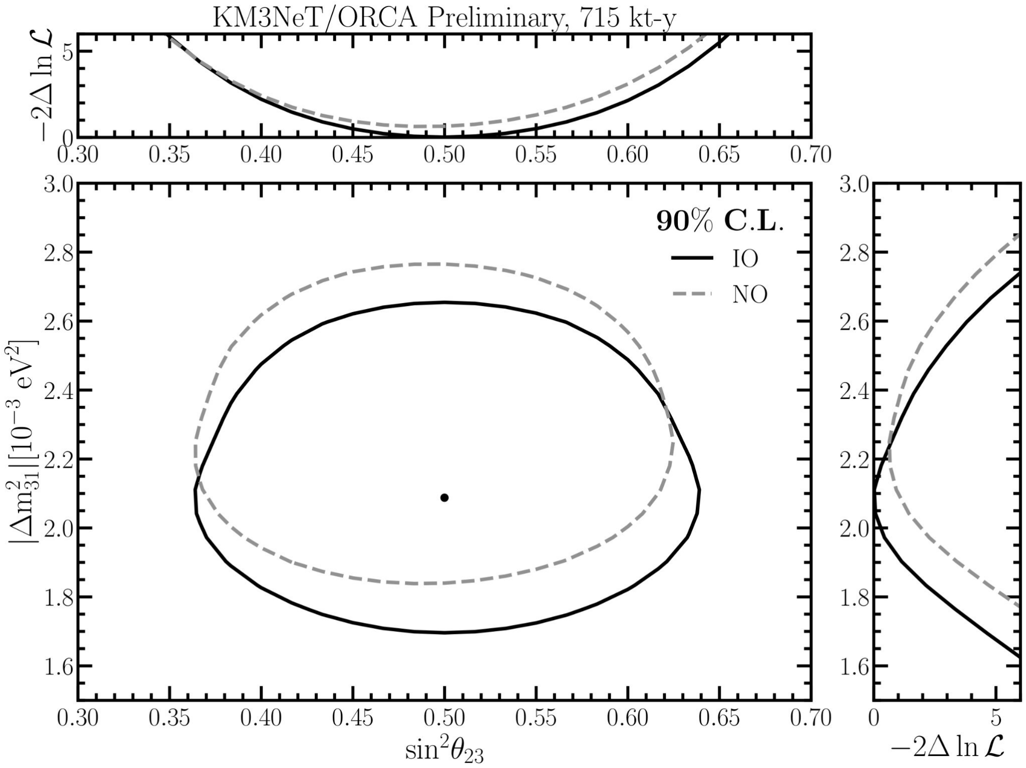


KM3NeT/ORCA

715 kt-yr

- clear oscillation gap in L/E
- small preference for IO
- maximum mixing preferred





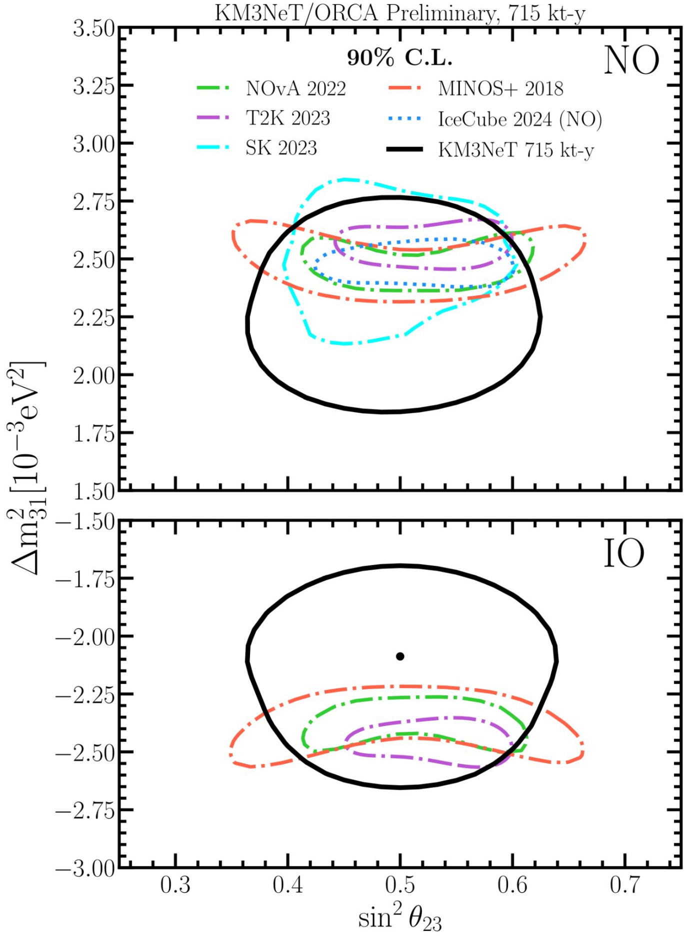
KM3NeT/ORCA

715 kt-yr

- small preference for IO
- maximum mixing preferred
- competitive in $\sin^2\theta_{23}$

$$\Delta m^2_{31} = \begin{cases} -2.09^{+0.17}_{-0.21} \times 10^{-3}\text{eV}^2, & \text{IO} \\ [2.10, 2.37] \times 10^{-3}\text{eV}^2, & \text{NO} \end{cases}$$

$$\sin^2\theta_{23} = 0.50 \pm 0.07$$



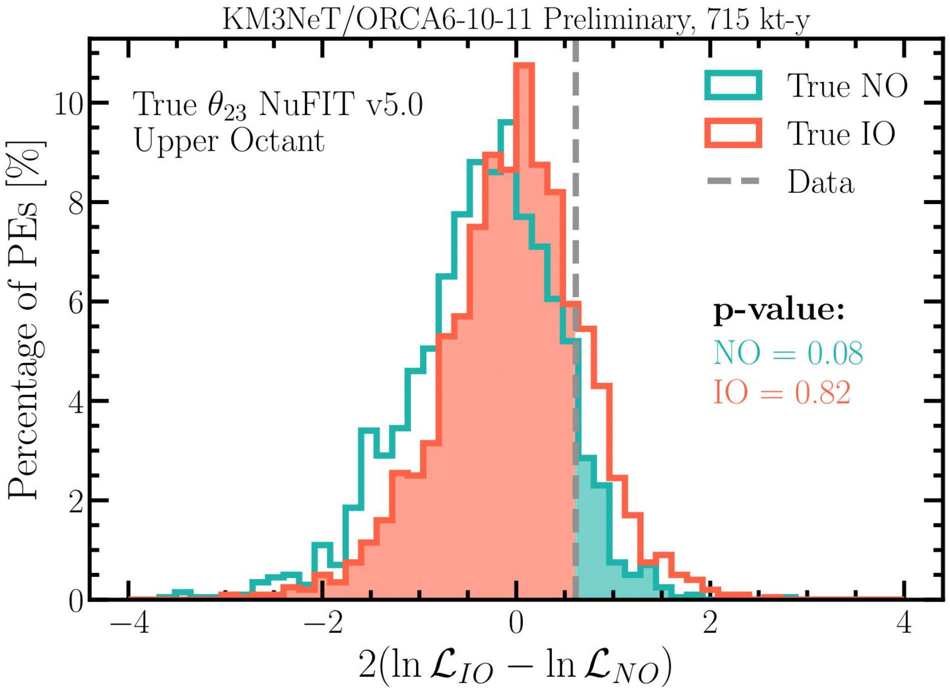
KM3NeT/ORCA

715 kt-yr

- small preference for IO

→ non-significant rejection

$$2\log(\mathcal{L}_{IO}/\mathcal{L}_{NO}) = 0.61$$



tau-appearance

motivation ?

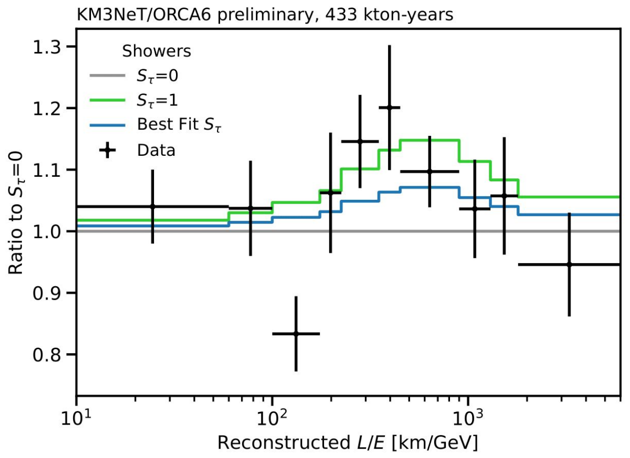
- rare observation → only ~2100 detected so far
- full KM3NeT/ORCA will measure **3000/year**
- help to constrain tau neutrino cross section

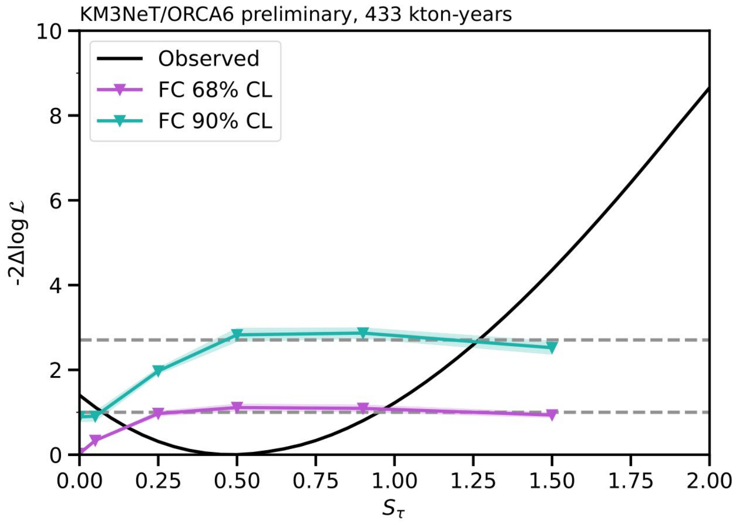
KM3NeT/ORCA6

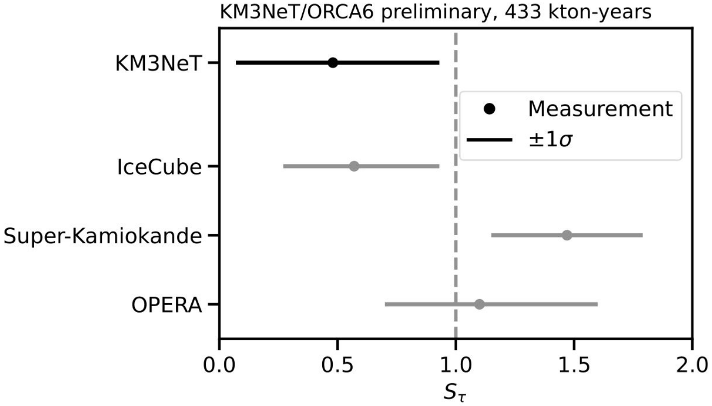
433 kt-yr

$$S_\tau = (0.48^{+0.45}_{-0.41})$$

- half the expected number of CC tau neutrinos
- FC corrections incorporated → effect of limit
- large errors compatible with nominal
- already competitive with other experiments







KM3NeT/ORCA6

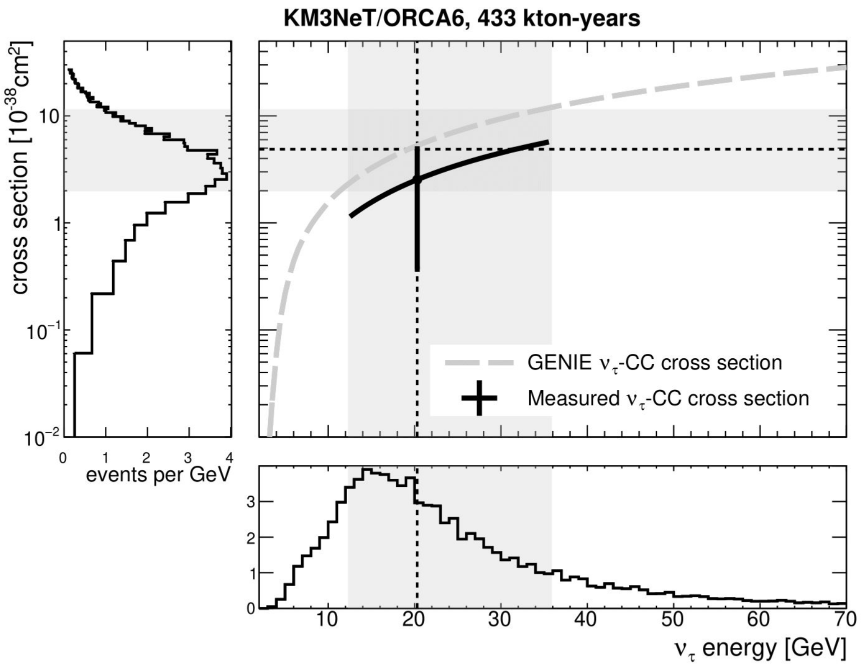
433 kt-yr

- median CC nu tau energy **20.3 GeV** [12.3 - 35.9] GeV at 68% CL
- probe CC tau neutrino x-sec structure function
- GENIE software used to simulate interaction

$$\sigma_\tau^{\mathrm{meas}}(E_\nu) = S_\tau \times \sigma_\tau^{\mathrm{th}}(E_\nu)$$

$$\sigma_\tau^{\mathrm{th}}(E_{\nu_\tau}) = 5.29 \times 10^{-38}\mathrm{cm}^2$$

$$\sigma_\tau^{\mathrm{meas}}(E_{\nu_\tau}) = (2.54^{+2.38}_{-2.17}) \times 10^{-38}\mathrm{cm}^2$$

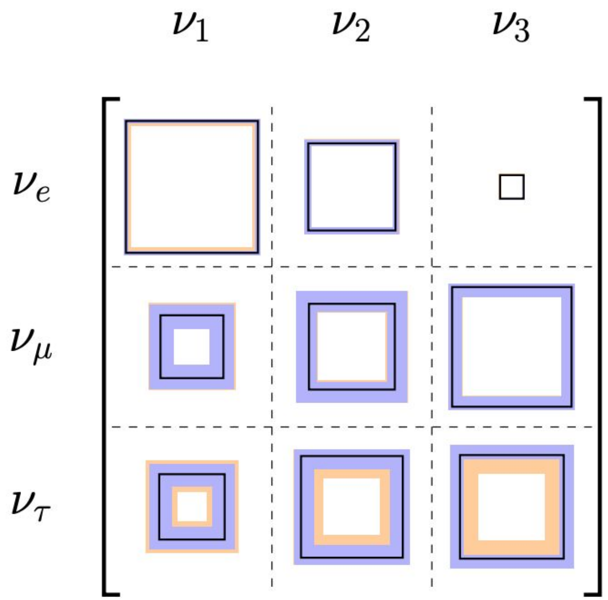


beyond 3-ν oscillation ?

lies non-unitarity of the neutrino mixing

- uncertainty on the neutrino mixing matrix elements
- w. unitarity constraints
- wo. unitarity constraints

→ low constraints on the tau row of the PMNS



theoretical framework

- new **non unitary** motivated by the **seesaw** mass generation model
- assume **nxn unitary** matrix U
- parametrise non unitarity with α
- new neutrino mixing matrix **non unitary N**
- **V_{NC} term relevant** in contrast to untarity case
- new states kinematically accessible → low scale

$$U = \begin{pmatrix} N & S \\ W & T \end{pmatrix} = \begin{pmatrix} N^{3\times 3} & S^{3\times(n-3)} \\ W^{(n-3)\times 3} & T^{(n-3)\times(n-3)} \end{pmatrix}$$

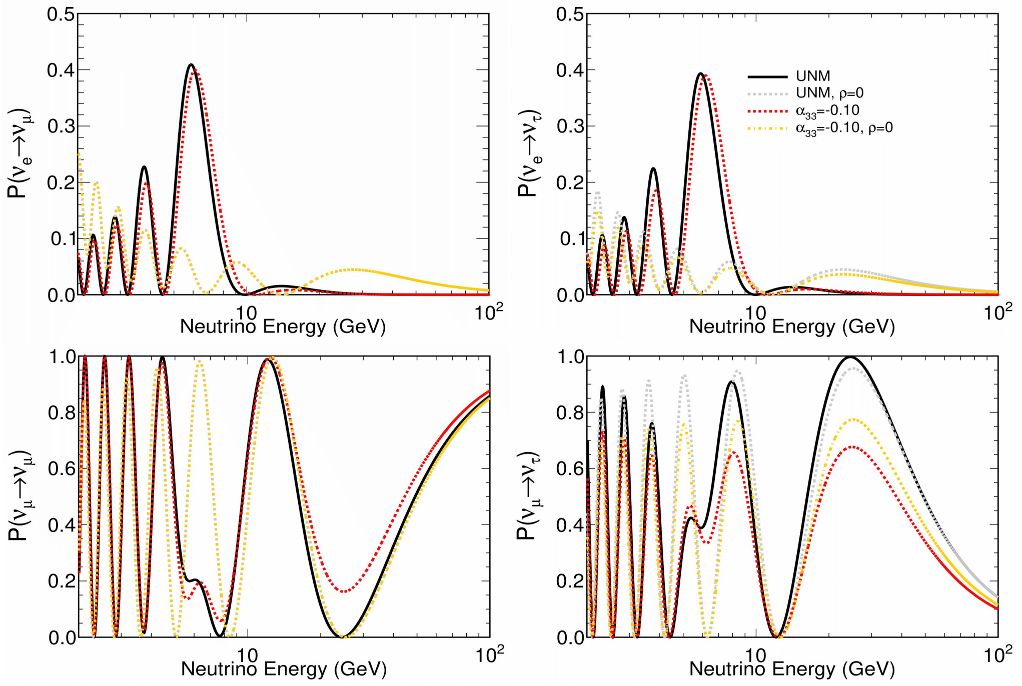
$$\alpha = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ |\alpha_{21}|e^{i\phi_{21}} & \alpha_{22} & 0 \\ |\alpha_{31}|e^{i\phi_{31}} & |\alpha_{32}|e^{i\phi_{32}} & \alpha_{33} \end{pmatrix}$$

$$\boxed{N = (I + \alpha)\, U_{PMNS}}$$

$$H_m^{3\times 3} = \Delta + N^\dagger V N$$

effect

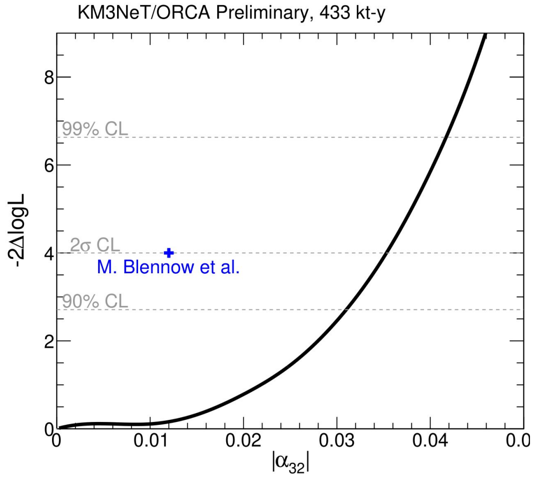
- UNM vs α_{33} = -0.1 w/wo matter effects
- 12750 km of average earth density
- earth matter density enhance the effects of non-unitarity
- particularly in the muon disappearance channel

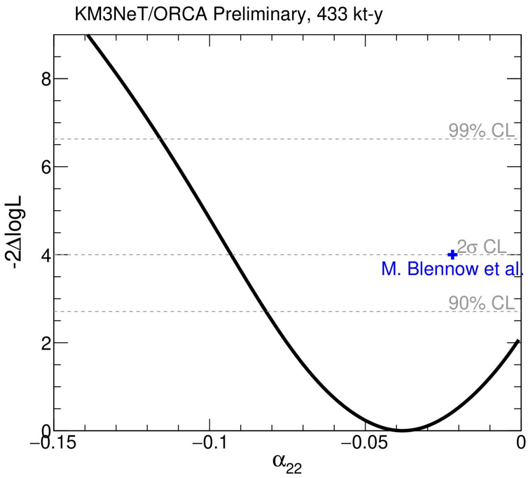


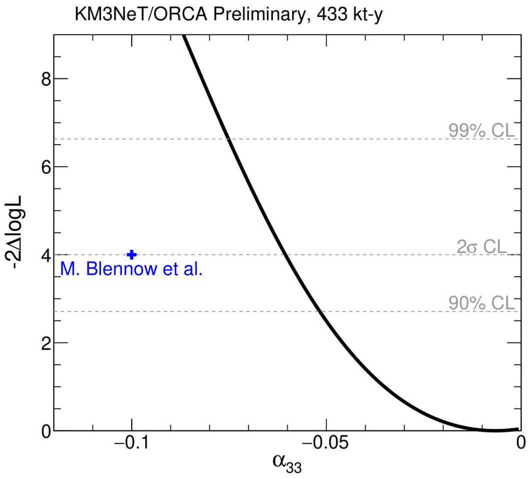
KM3NeT/ORCA6

433 kt-yr

- improve current limit on α_{33}
- thanks to the earth matter effects
- present bounds from non-observation of zero(very short)-distance oscillations







NUNM single parameter	Present Bounds 2σ	KM3NeT/ORCA data 2σ
$\alpha_{33} >$	-0.10	-0.06
$\alpha_{22} >$	-0.022	-0.09
$\lvert\alpha_{32}\rvert <$	0.012	0.03

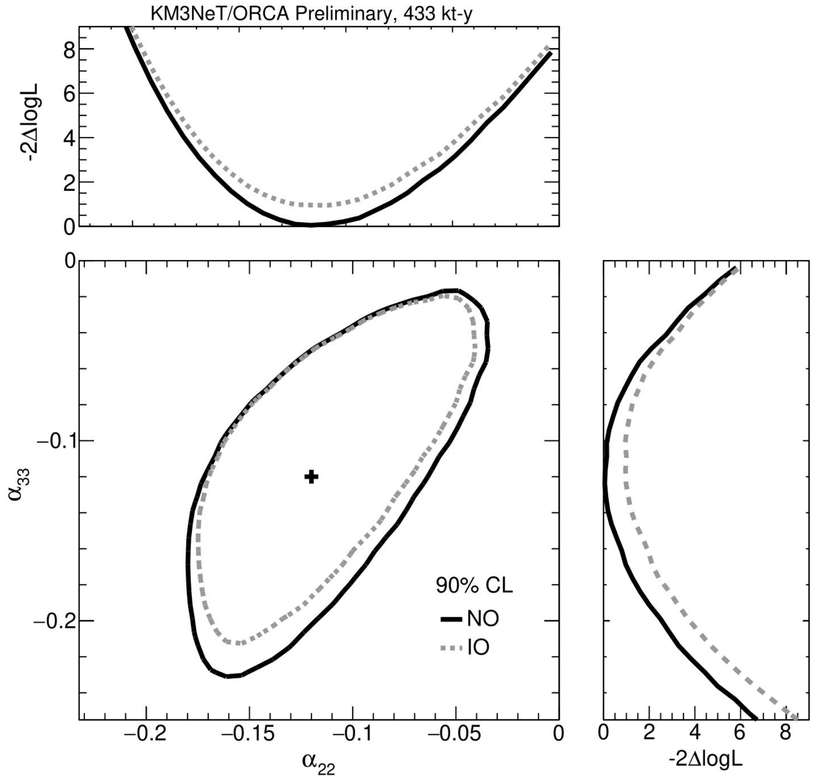
KM3NeT/ORCA6
433 kt-yr

- first simultaneous fit of α_{22} and α_{33}
- 8.3 units of -2ΔlnL away from nominal case [0,0]

→ p-value = 0.9% (Feldman-Cousins)

- deviation most visible in $\alpha_{22} + \alpha_{33}$

Measured NUNM parameters	Best fit $\pm 1\sigma$
α_{22}	$-0.114^{+0.033}_{-0.033}$
α_{33}	$-0.118^{+0.048}_{-0.055}$



other beyond 3-ν oscillation studies ?

Searches for effects beyond the Standard Model with KM3NeT

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on behalf of the KM3NeT Collaboration

NOW 2024

Otranto, Italy

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06/09/2024

16:40

KM3NeT

VEGA

GENERALITAT VALENCIANA

Conselleria d'Innovació, Universitats, Ciència i Societat Digital

CSIC

VNIVERSITAT DE VALÈNCIA

IFIC

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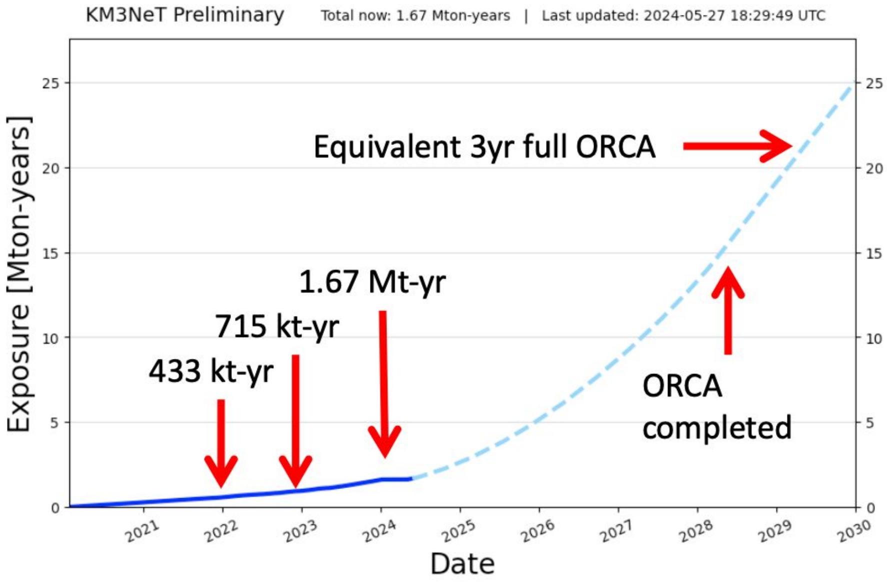
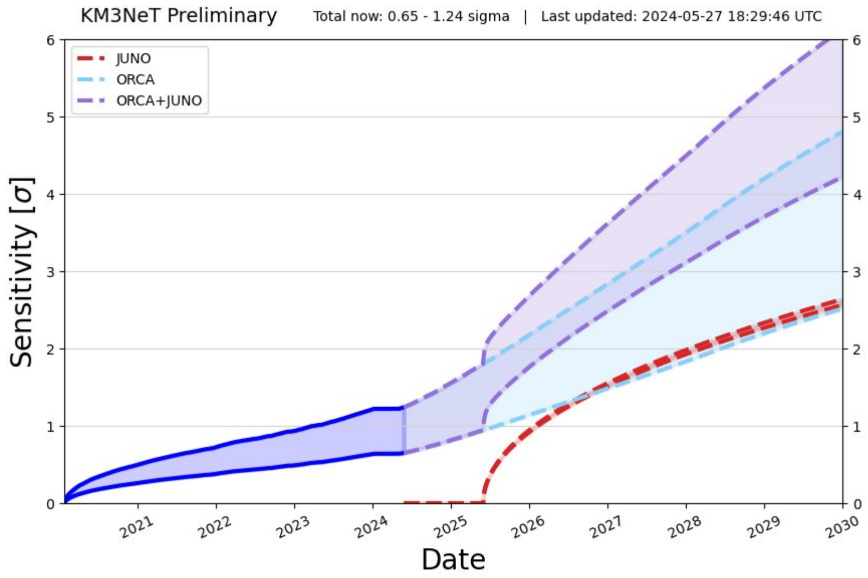
KM3NeT/ORCA115
future

- 1.7 Mt-yr of data on tape
- from 2028 completion ~3000 tau neutrinos per year
- NMO known by 2030





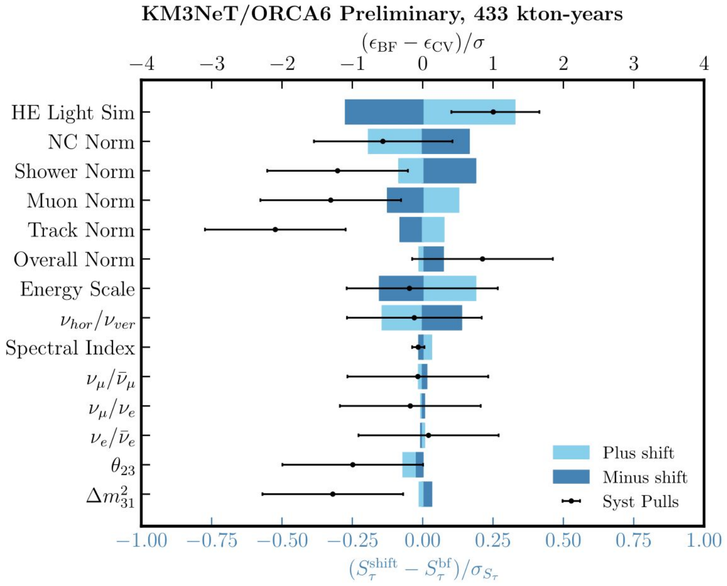
THANKS

BACKUP

KM3NeT/ORCA6

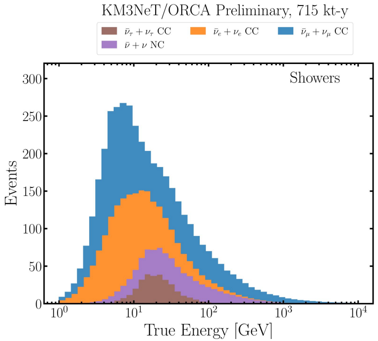
433 kt-yr

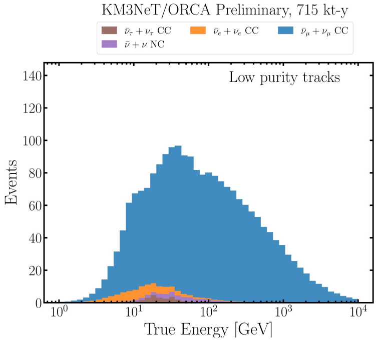
- systematic pulls wrt. nominal divided by the 1σ post fit uncertainty → < ~2σ
- impact of 1σ shift of the systematics on the measurement

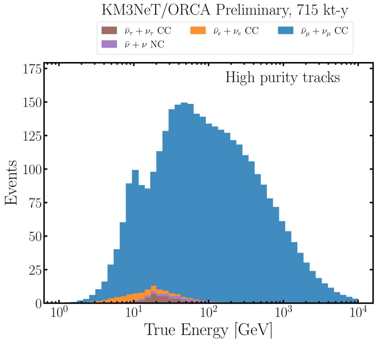


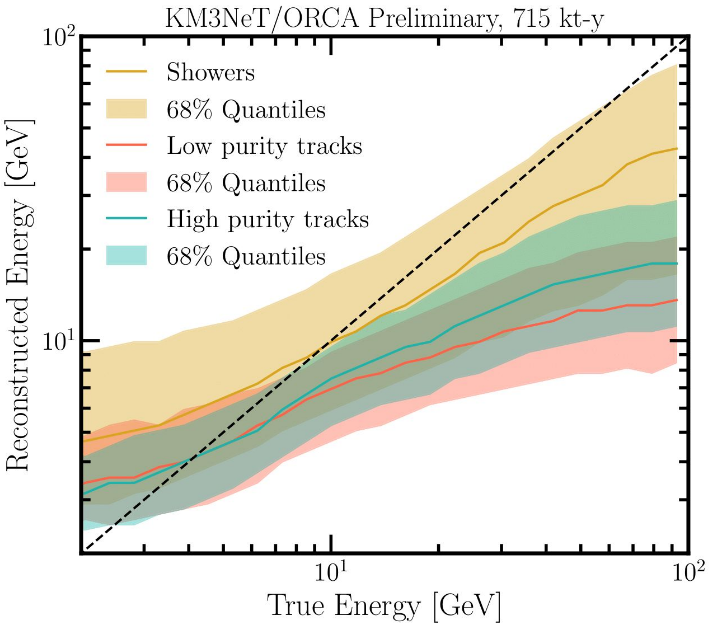
KM3NeT/ORCA

715 kt-yr



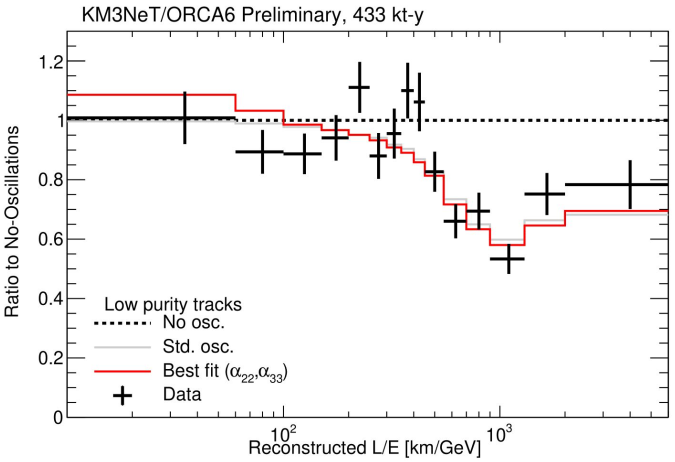


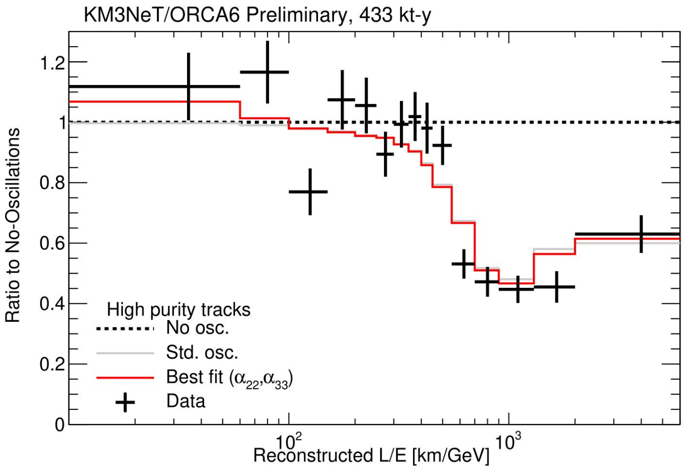


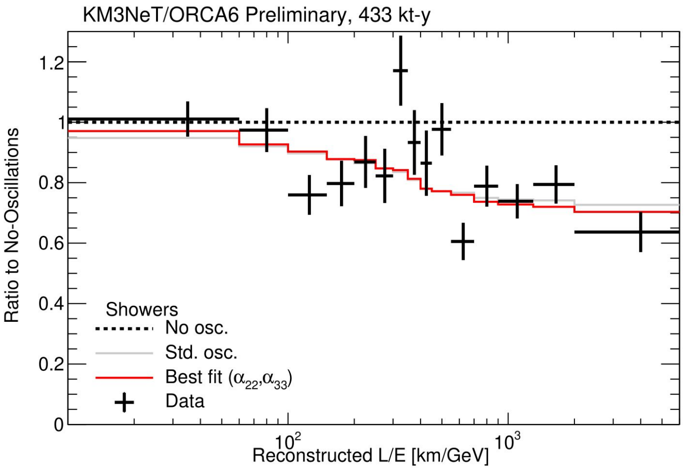


L/E ratio

- L/E ratio showing BF
  - α_{33} vs α_{22}
- High NuID → High purity
- looks like fluctuations





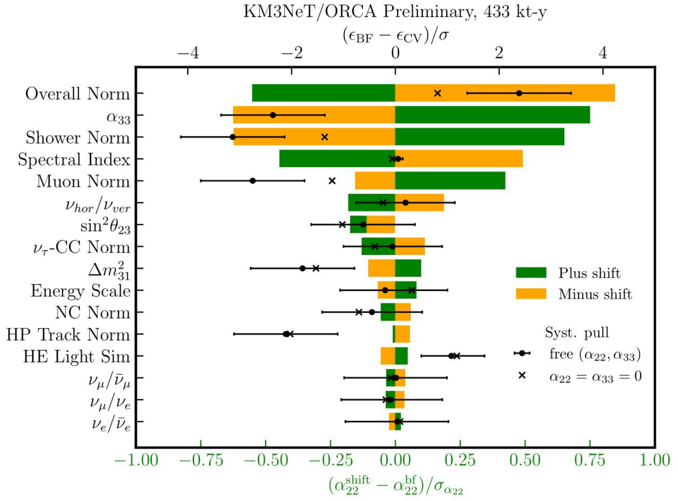


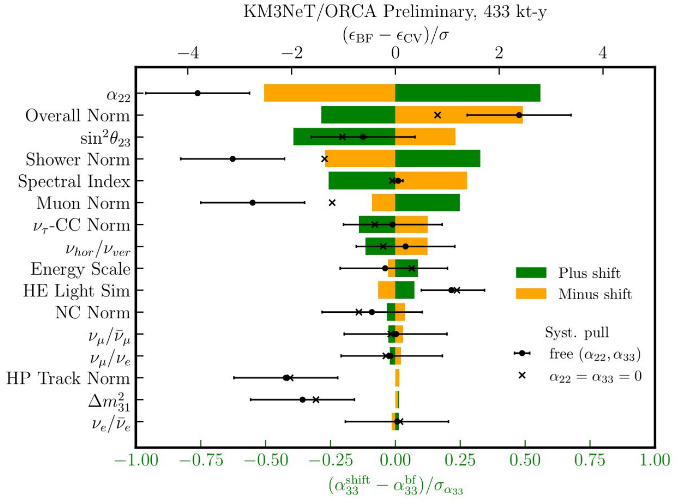
systematics BF

- **top axis** → pull of the systematics at BF compared to CV
- **bottom axis** → shift of a_{ij} compared to BF value when moving each syst. by 1σ post-fit error

- main impact from overall norm

- pulls below 3σ from CV



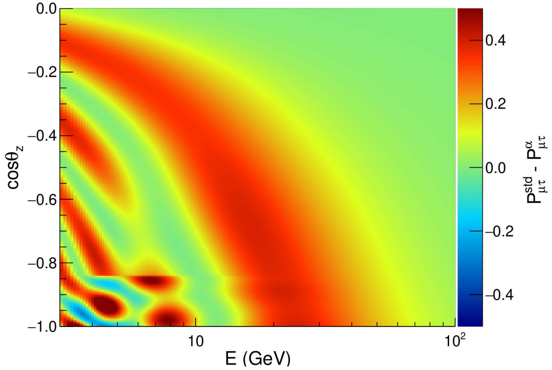


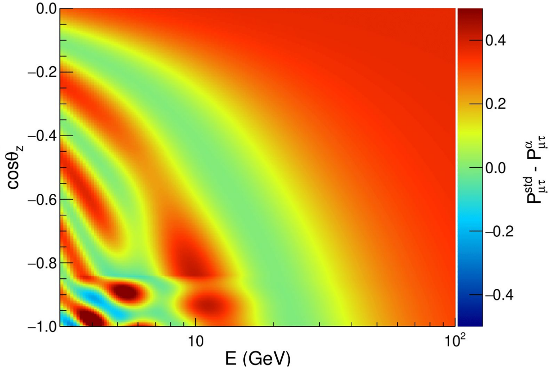
Best Fit

- best fit with α_{33} & α_{22} free
- nuisance parameters table
- physics parameters table
- probabilities at best fit

Systematic uncertainty	BF $\pm 1\sigma$
θ_{23}	$46.2^{+4.85}_{-5.06}$
Δm^2_{31} [10^{-3} GeV^2]	$2.06^{+0.25}_{-0.25}$
Spectral Index	$0.01^{+0.03}_{-0.03}$
$\nu_{\text{hor}}/\nu_{\text{ver}}$	$0.004^{+0.02}_{-0.02}$
$\nu_\mu/\bar{\nu}_\mu$	$0.0007^{+0.05}_{-0.05}$
$\nu_e/\bar{\nu}_e$	$0.002^{+0.07}_{-0.07}$
ν_μ/ν_e	$-0.002^{+0.02}_{-0.02}$
High-energy Light Sim.	$1.54^{+0.32}_{-0.29}$
Energy Scale	$0.98^{+0.11}_{-0.08}$
Overall Norm.	$1.47^{+0.23}_{-0.20}$
Track Norm.	$0.91^{+0.04}_{-0.04}$
Shower Norm.	$0.80^{+0.06}_{-0.06}$
Muon Norm.	$0.14^{+0.31}_{-0.14}$
S_{NC}	$0.91^{+0.19}_{-0.19}$
S_τ	$0.99^{+0.19}_{-0.19}$

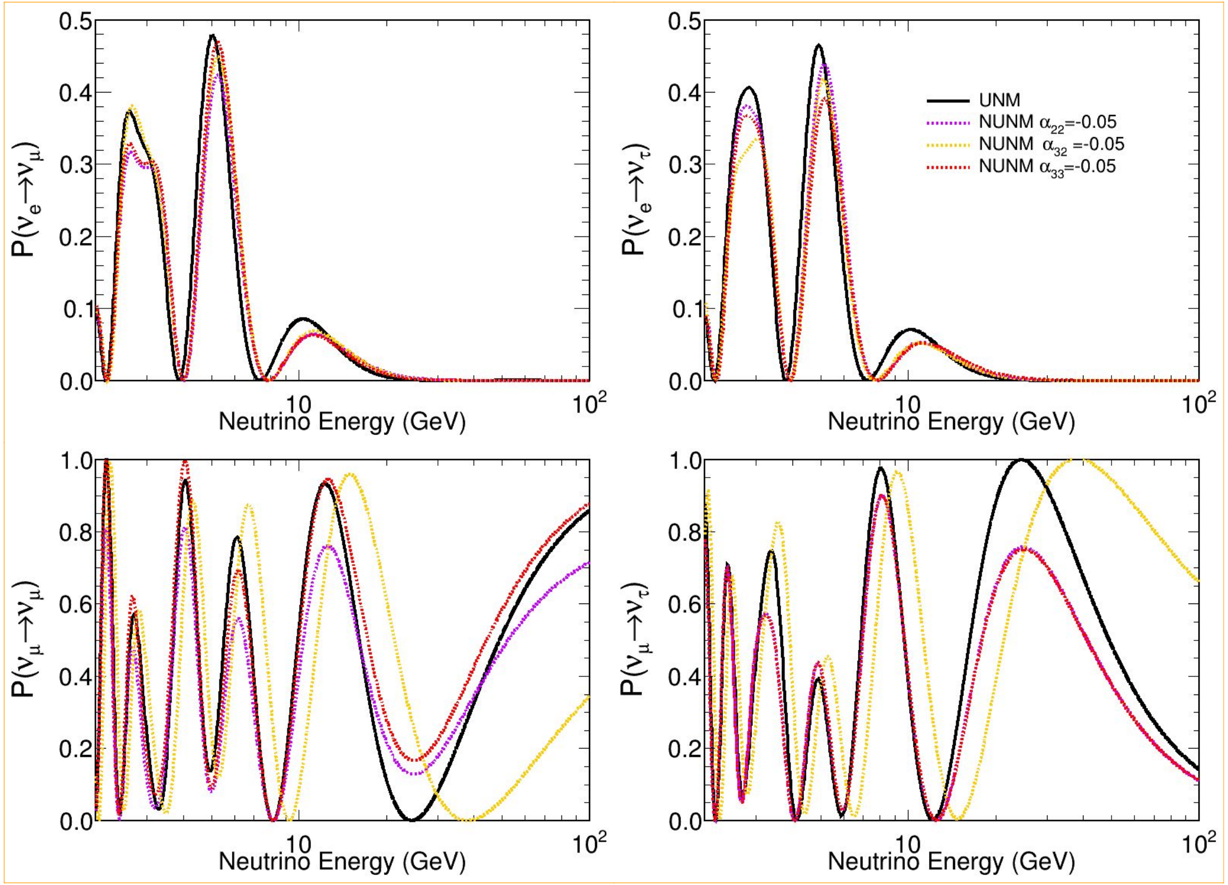
Table 1: All systematic uncertainties for data and their best fit values along with their post-fit 1σ uncertainties given by the profiles.





probability

- UNM vs NUNM (low scale) with α_{22} / α_{32} / α_{33} non zero (-5%)
- sizable effect on tau neutrino appearance and muon neutrino channels
- α_{33} also affects muon disappearance channel because of the matter potential effects in the presence of NUNM
- source of the measured sensitivity in the present analysis



probability

- UNM vs NUNM (low scale) with α_{33} non zero (-5%)

- Vnc = 0
- Vnc > 0