KM3NeT

ICHEP 2024

42nd International Conference on High Energy Physics
Prague, Czech Republic

First measurement of light sterile neutrino mixing parameters with KM3NeT/ORCA

20/07/2024

Louis Bailly-Salins on behalf of the **KM3NeT Collaboration**

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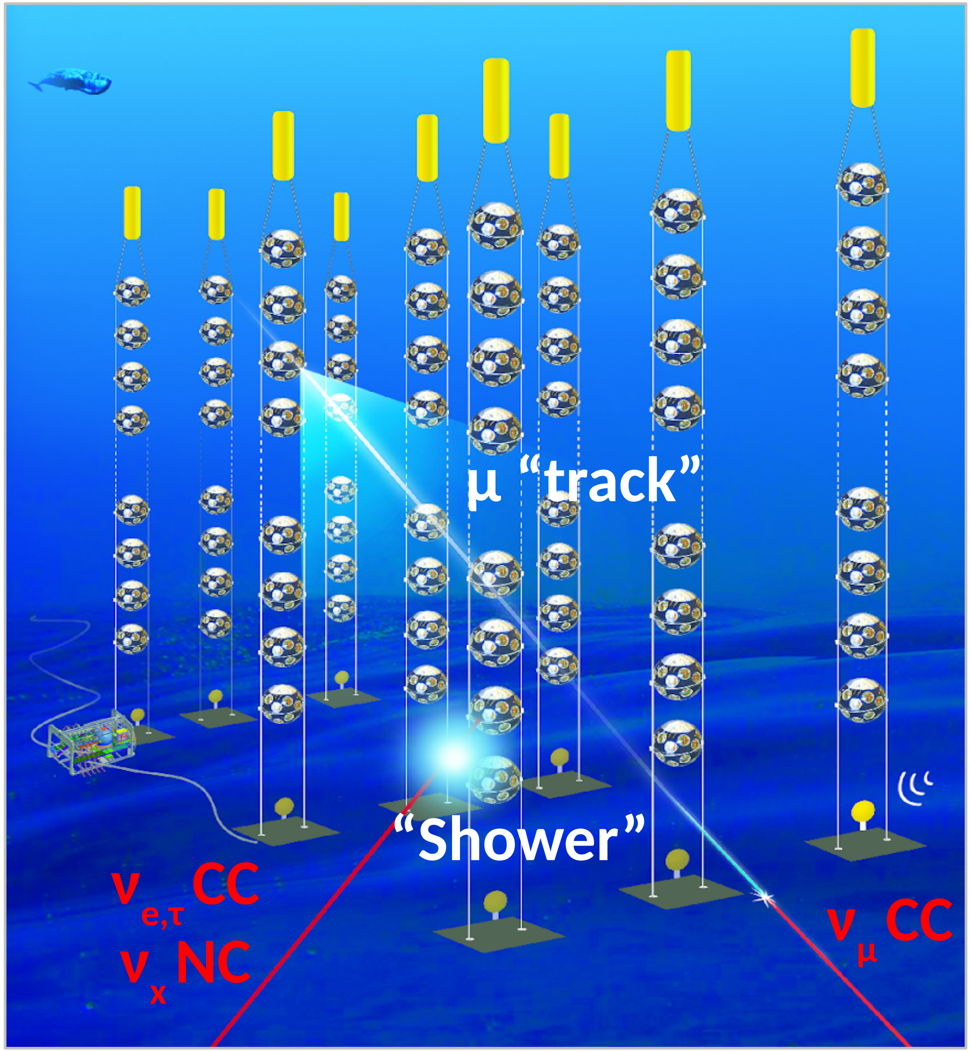
KM3NeT

Neutrino telescopes at the bottom of the Mediterranean sea

Oscillations — **ORCA**

Astronomy — *ARCA*

Sensitive to Cherenkov light induced by charged particles



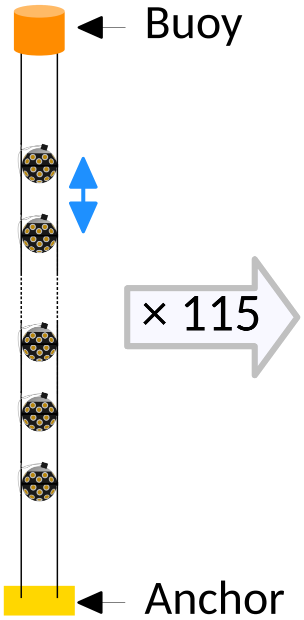
KM3NeT/ORCA

Digital Optical Module (DOM)

31 × 3” PMT, ⊘ =43 cm
2022 JINST 17 P07038

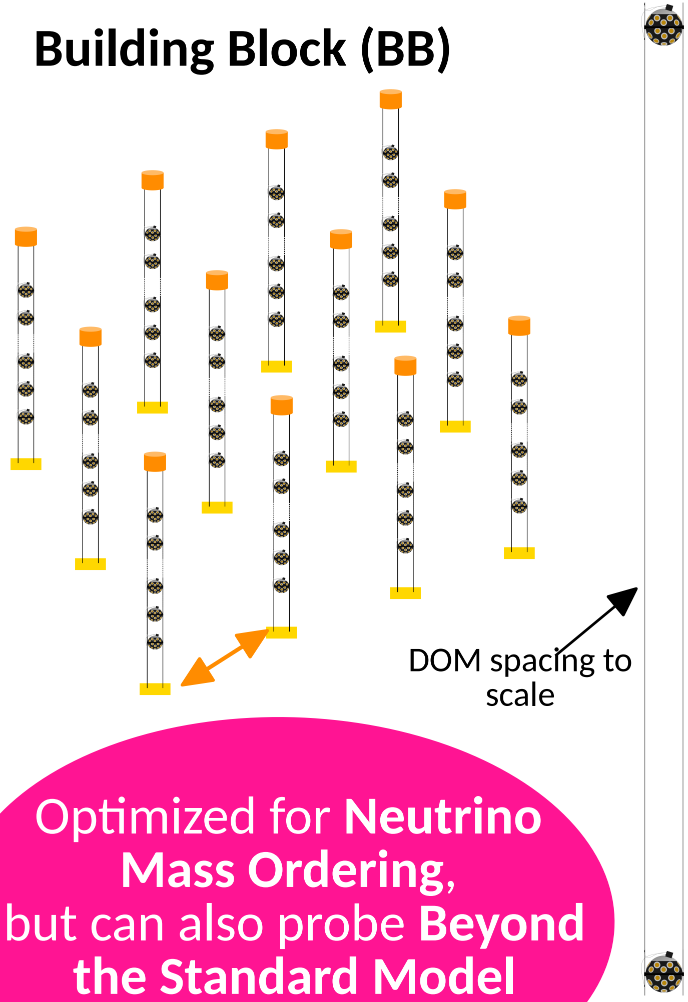
× 18

Detection Unit (DU)



× 115

Building Block (BB)



Full detector expected 2028
Currently **23** deployed DUs
(**20%** of total)

Energy: 2 – 100 GeV
Max. depth = 2450 m
7 Mt
H = 200 m
⊘ = 200 m
Vertical spacing: 9 m
Horizontal spacing: 20 m

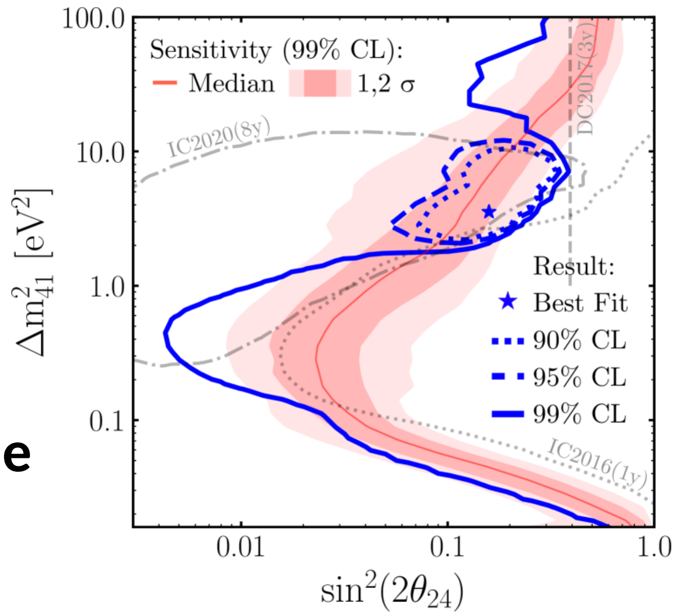
Optimized for **Neutrino Mass Ordering**,
but can also probe **Beyond the Standard Model** hypothesis

Light sterile neutrinos

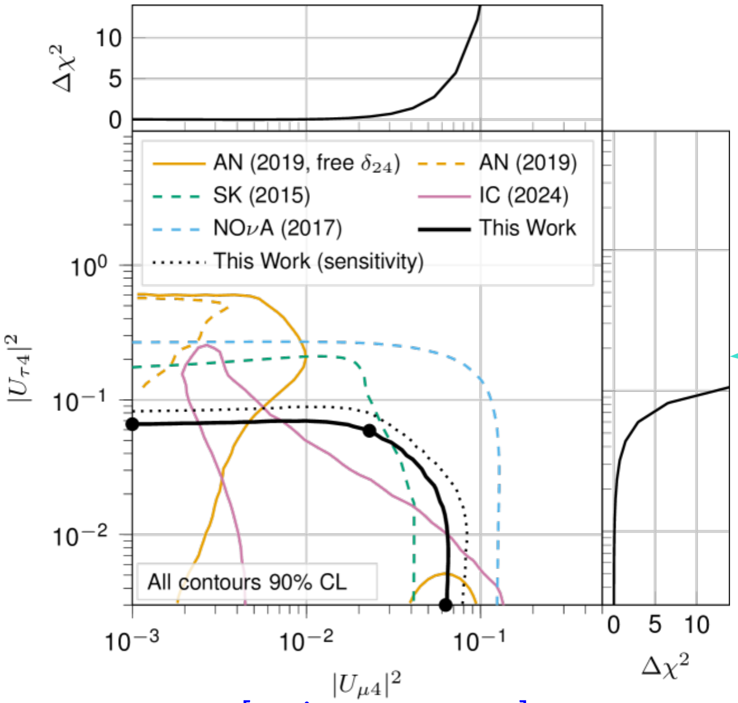
Simple extension of SM: 3+1 sterile

New parameters: Δm^2_{41}, θ_{14}, θ_{24}, θ_{34}, δ_{14}, δ_{24}

[arXiv:2405.08070]



Short baseline anomalies → **eV-scale sterile neutrino ?**



[arXiv:2407.01314]

But also studied on longer baselines with atmospheric neutrinos: e.g. IceCube

KM3NeT results at **fixed Δm^2_{41} = 1 eV^2** in this talk

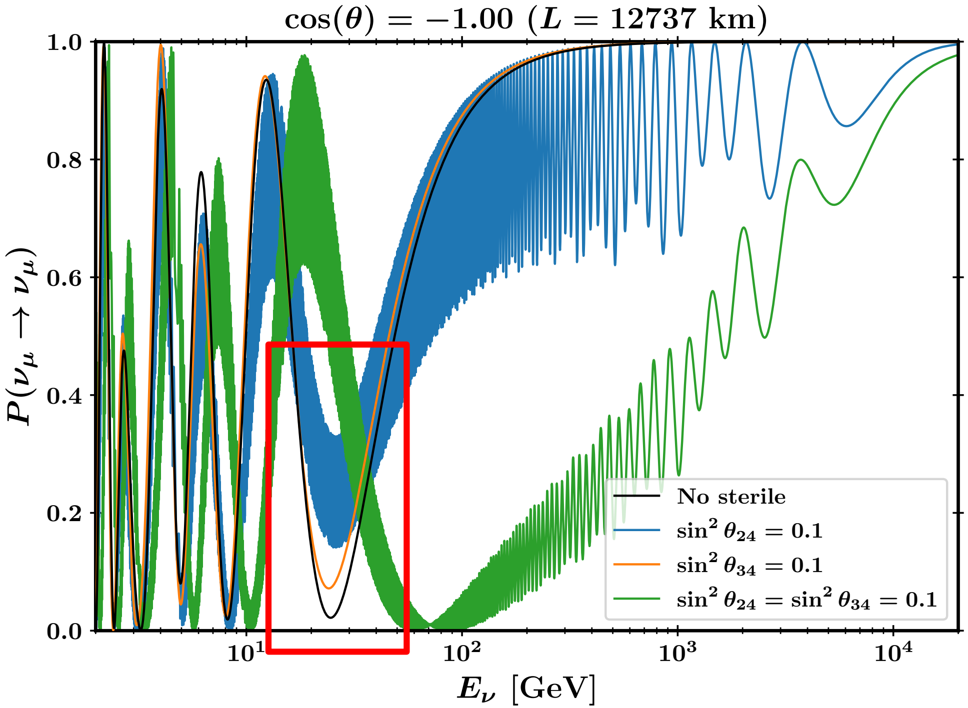
Simultaneous measurement of $|U_{\mu 4}|^2$ and $|U_{\tau 4}|^2$

$$(|U_{\mu 4}|^2 = \cos^2\theta_{14}\,\sin^2\theta_{24}\ ;\ |U_{\tau 4}|^2 = \cos^2\theta_{14}\cos^2\theta_{24}\,\sin^2\theta_{34})$$

Sterile neutrino with $\Delta m^2_{41} \sim 1\ eV^2$ in KM3NeT/ORCA

Sterile: additional matter effects due to **neutron density N_n**
→ MSW resonances on (anti)ν_μ disappearance >1 TeV hard to see with ORCA

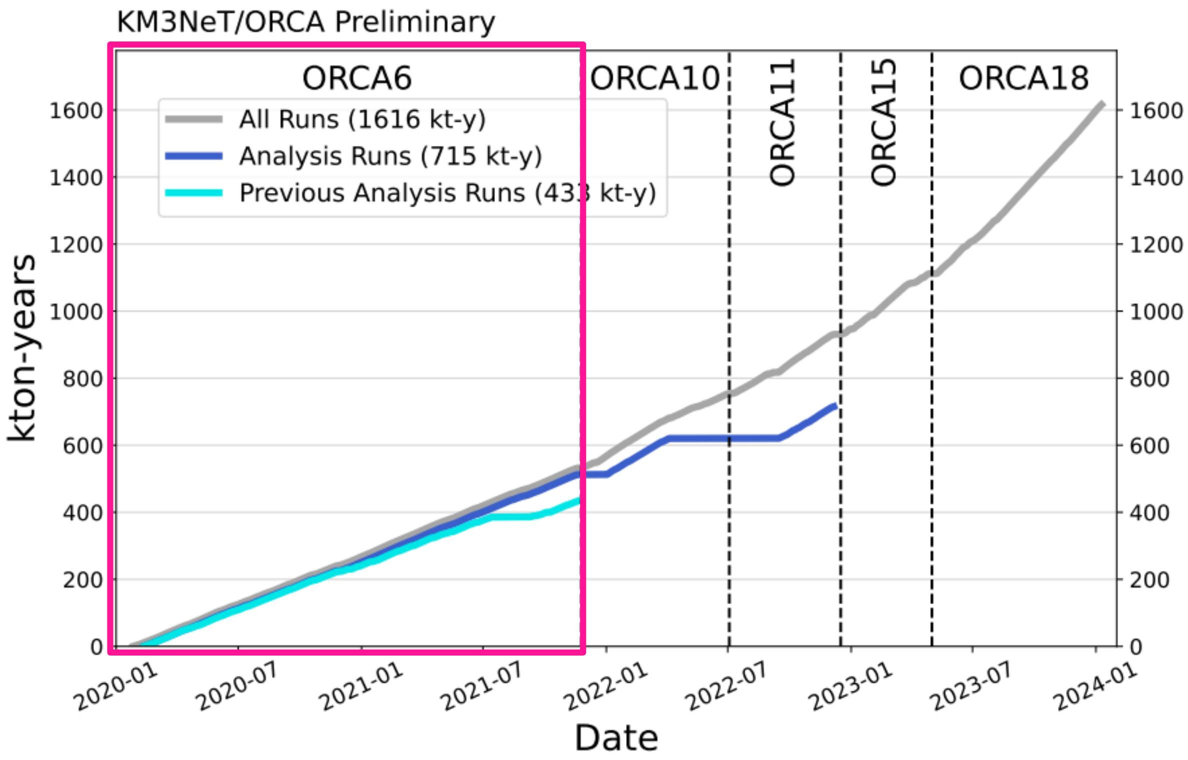
Signal expected to affect **1st ν_μ disappearance max** ~25 GeV:
- θ_{24}, θ_{34} : change amplitude
- when both ≠ 0: shift position depending on δ_{24} value



KM3NeT/ORCA6 dataset

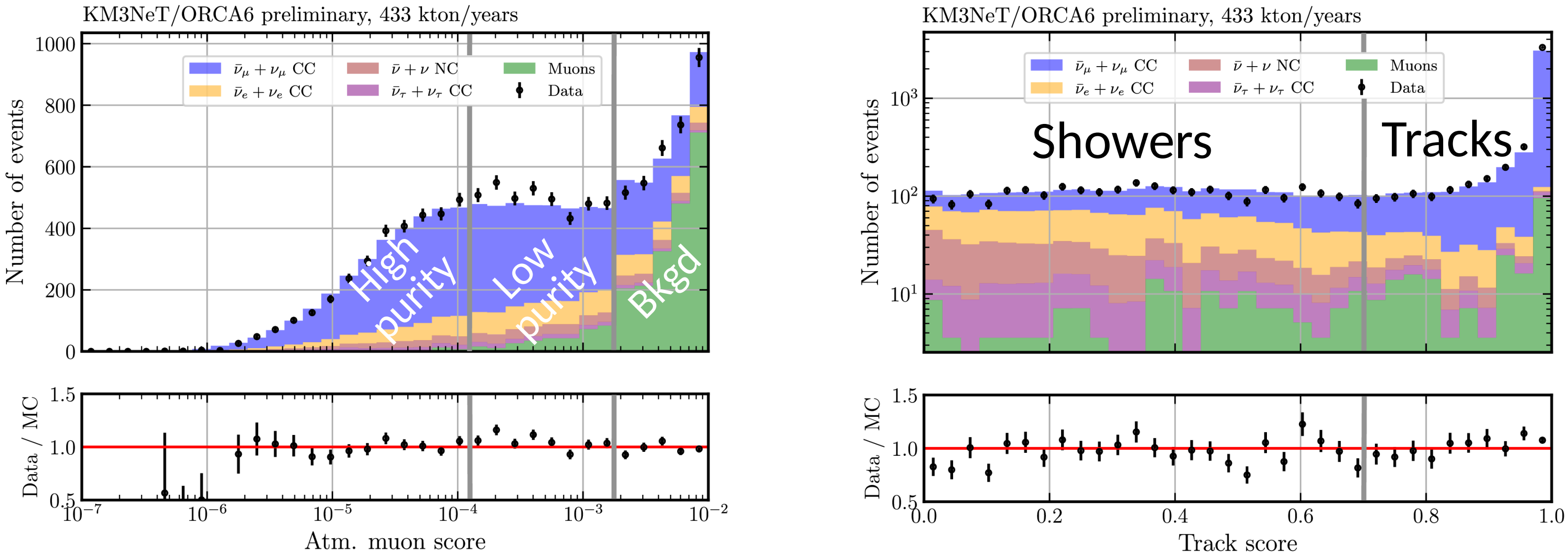
Analysis performed with data from 6-DU configuration (ORCA6)

Exposure = instrumented volume of working PMTs × livetime => **433 kton-yr**



KM3NeT/ORCA6 event selection

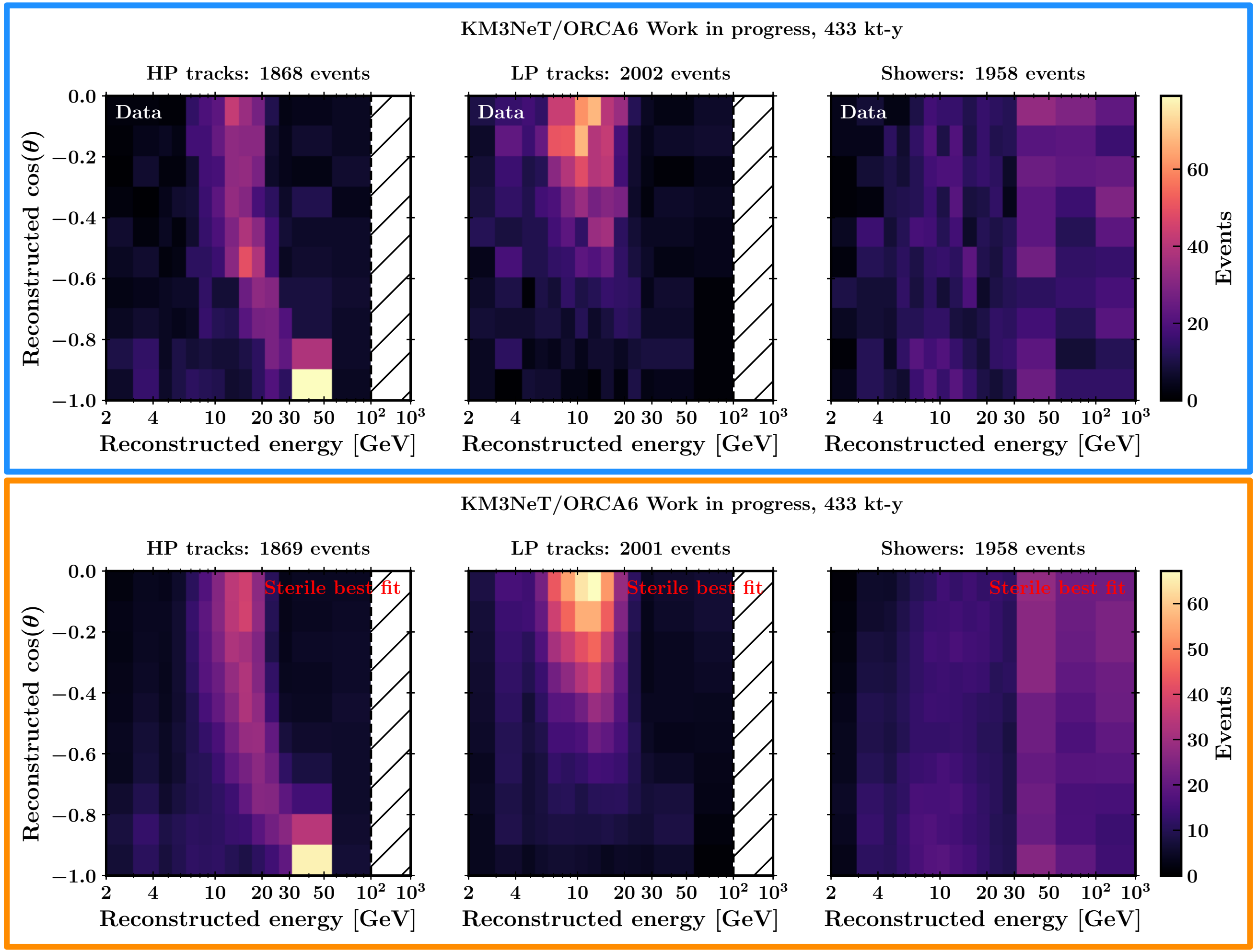
Use BDTs to summarize reconstructed quantities into **atmospheric muon score** (for background rejection) and **track score** (to distinguish track/shower)



Excellent data/MC agreement

Define three classes: High-purity tracks, Low-purity tracks, Showers

Oscillation analysis in KM3NeT/ORCA

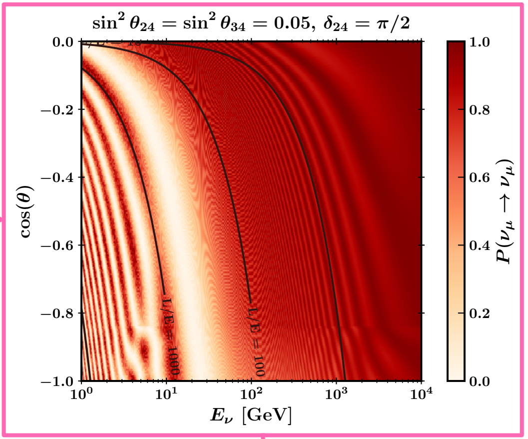


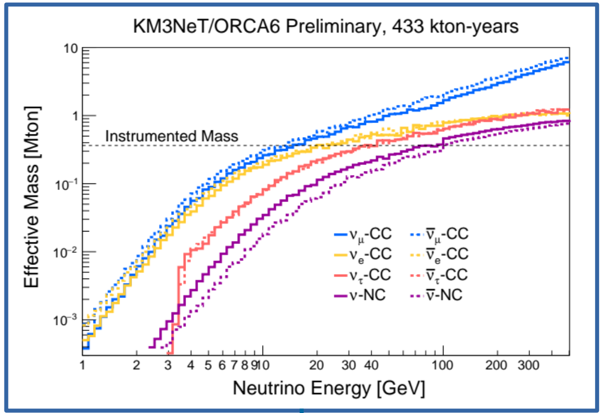
5828 events in total

Compare measured $n_{i,j}$ and predicted $\mu_{i,j}$ 2D reconstructed (E, cos θ) event distribution for each class i

Predicted event distribution

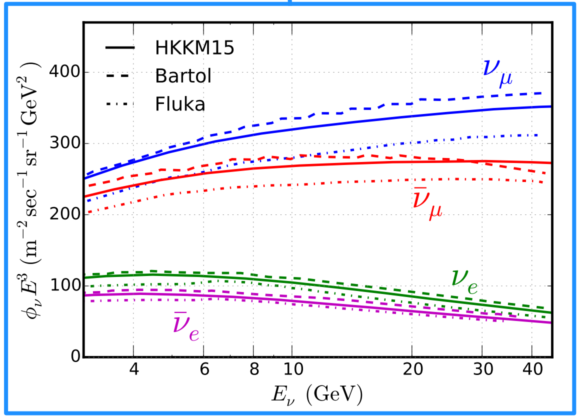
Δm_{ij}
θ_{ij}
δ_{ij}



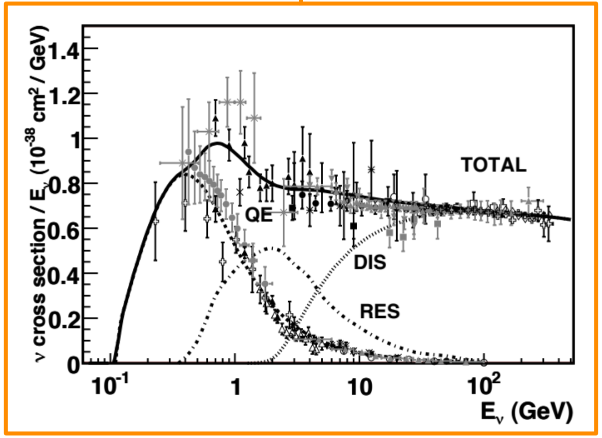


+ 15 nuisance parameters to model uncertainties on flux, oscillation parameters, cross sections and detector effects

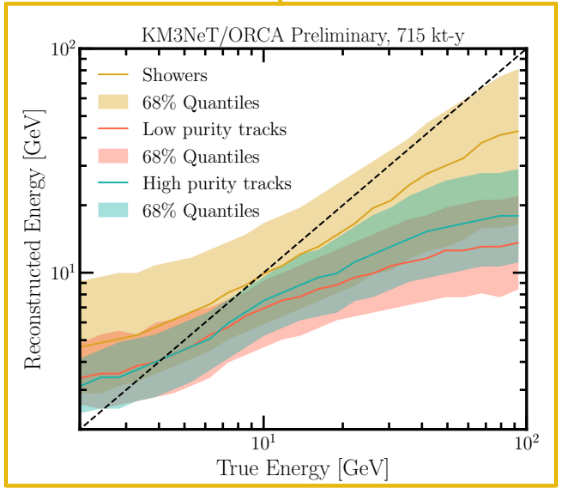
$$\phi_{atm}^{\nu_y}(E_t, \theta_t) \times P_{\nu_y \to \nu_x}(E_t, \theta_t) \times \sigma_{\nu_x}(E_t) \times M_{eff}^{\nu_x}(E_t) \times R_i(E_t, \theta_t, \nu_x, E_r, \theta_r) \Rightarrow \mu_i(E_r, \theta_r)$$



J. Phys. G: Nucl. Part. Phys. 43 084001



Rev. Mod. Phys. 84, 1307



Results: $U_{\mu4}$ and $U_{\tau4}$ fit

Frequentist analysis : scan ($|U_{\mu4}|^2$, $|U_{\tau4}|^2$)

Δm^2_{41} = 1 eV^2 ; $\theta_{14} = \delta_{14} = 0$; **$\delta_{24}$ free**

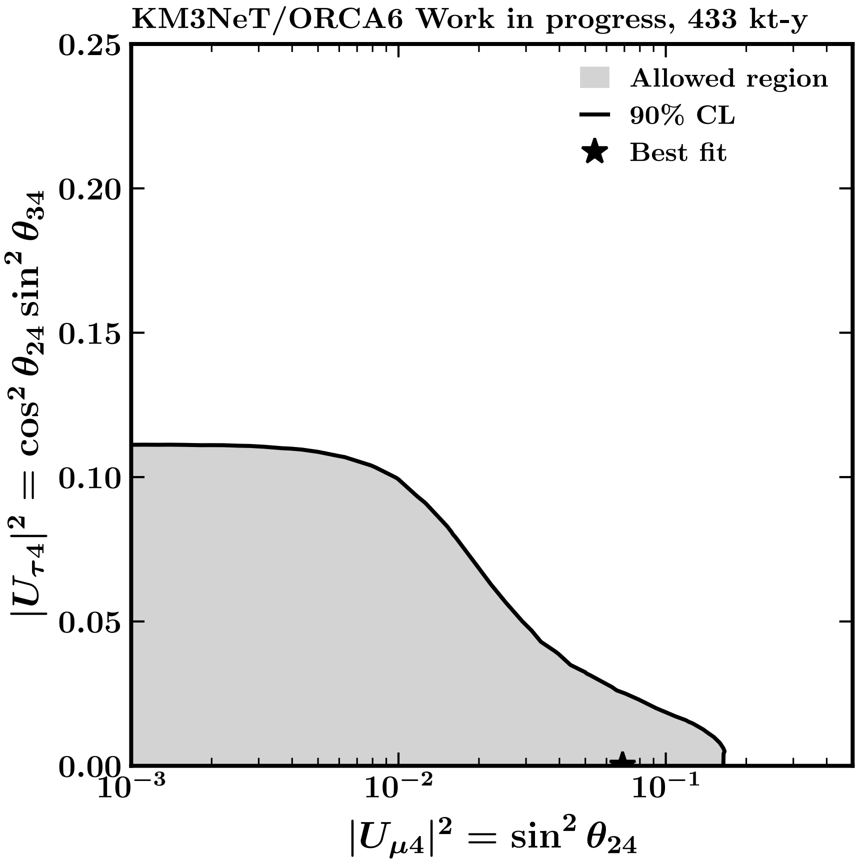
Assume $\Delta \ln \mathcal{L} \sim \chi^2$ distribution with 2 d.o.f

(Wilk's theorem)

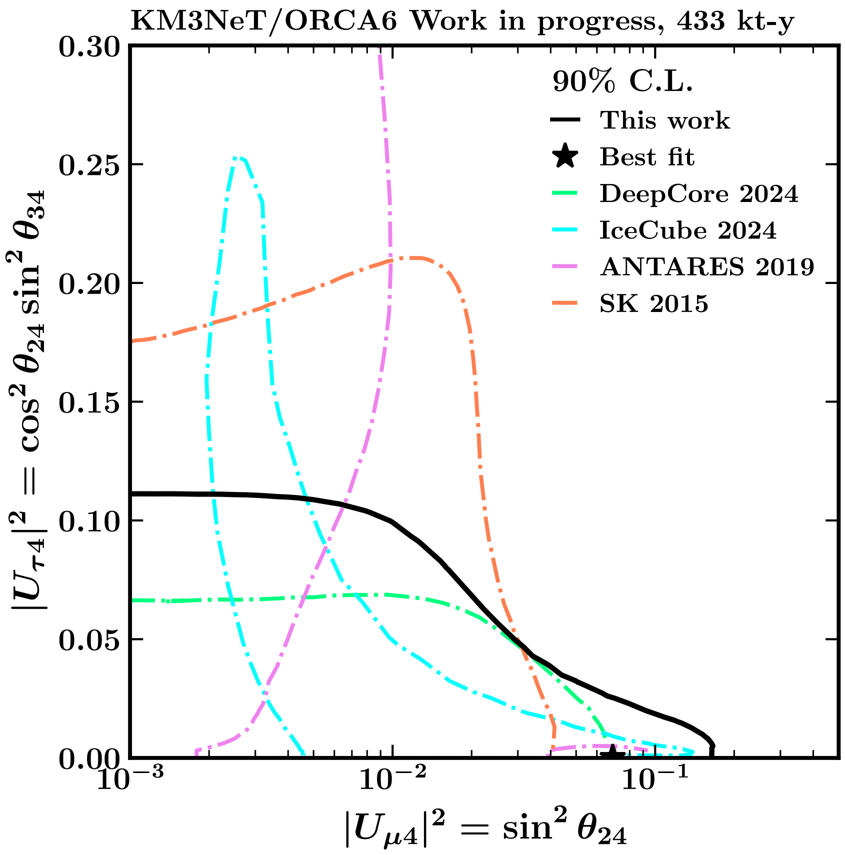
Best fit:

$|U_{\mu4}|^2 = 6.89 \times 10^{-2}$

$|U_{\tau4}|^2 = 2.35 \times 10^{-4}$



Results: $U_{\mu 4}$ and $U_{\tau 4}$ fit vs the world



Already competitive limits with only 6 DUs and 1.4 yrs livetime (equivalent to 1 month of ORCA115)!

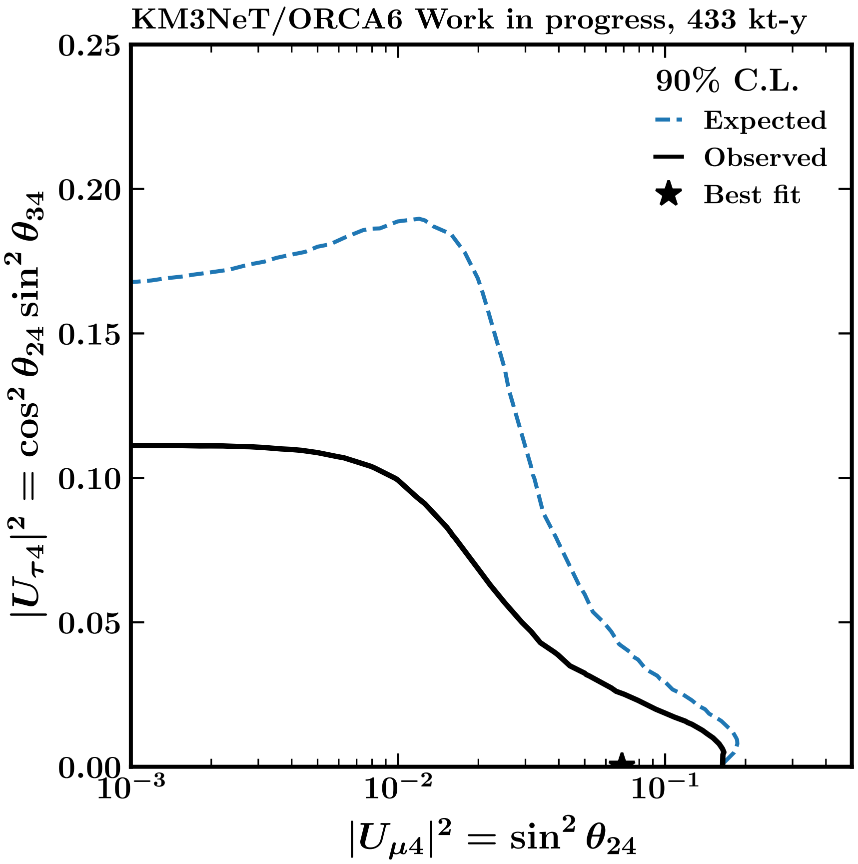
(SK: 12.2 yrs; ANTARES: 7.8 yrs;

IceCube: 10.7 yrs; DeepCore 7.5 yrs)

DeepCore: [arXiv:2407.01314]
IceCube: [arXiv:2406.00905]
ANTARES: J. HEP 2019, 113
SK: Phys. Rev. D 91, 052019

Results: $U_{\mu4}$ and $U_{\tau4}$ fit vs expected (sensitivity)

Much lower limits than expected from sensitivity, especially on $U_{\tau4}$

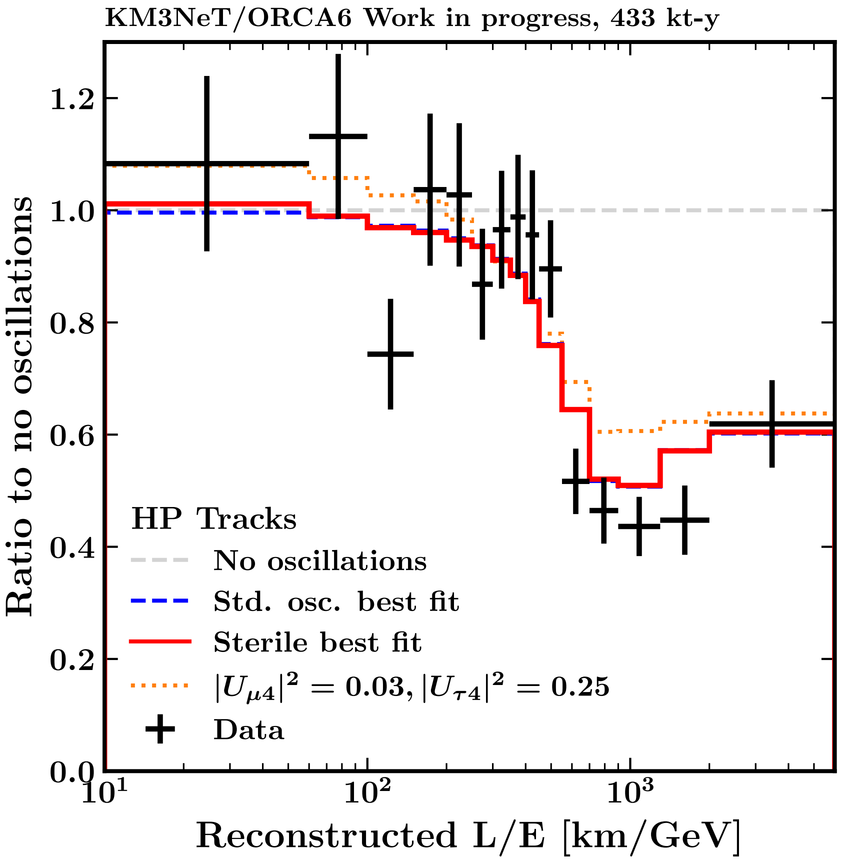


Results: $U_{\mu4}$ and $U_{\tau4}$ fit vs expected

Much lower limits than expected from sensitivity, especially on $U_{\tau4}$

→ Track classes data at first ν_μ disappearance lower than model can get: excludes high $U_{\mu4}$ and $U_{\tau4}$ values

→ Consistent with standard oscillation analysis (narrower θ_{23} profile than expected)



Summary

Oscillation analysis with eV-scale sterile neutrino

Only 5% of the final detector

Already competitive limits on $|U_{\mu 4}|^2$ and $|U_{\tau 4}|^2$

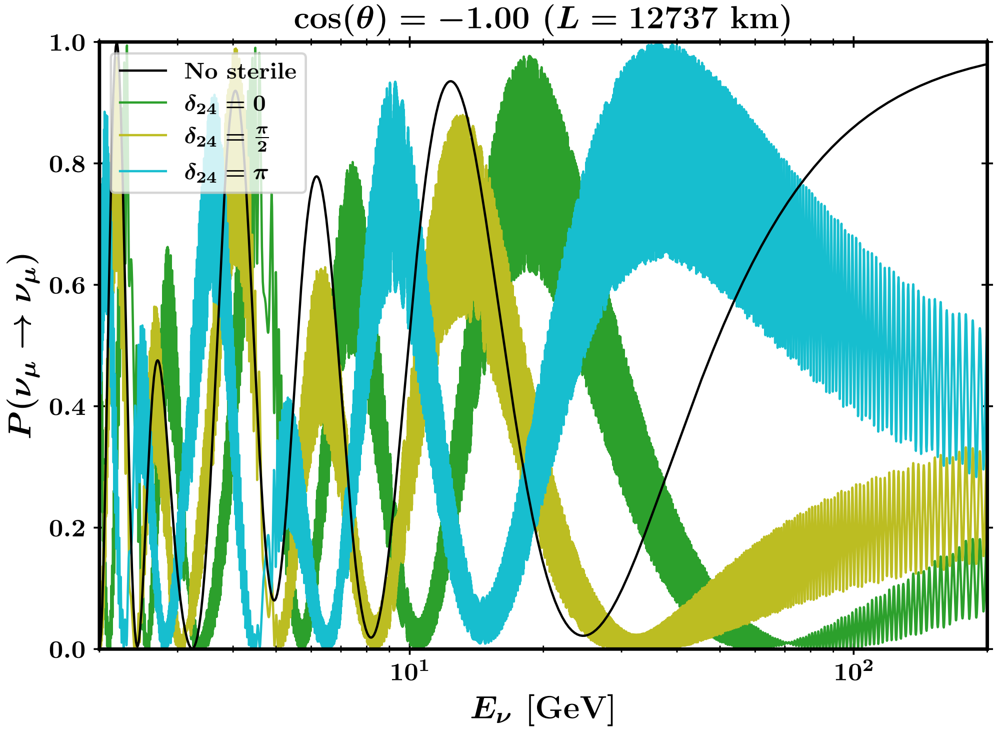
Several improvements in the near future:

- Δm^2_{41} dependent measurements of θ_{24} and θ_{34}
- Bigger detector, exposure ×4
- Bayesian parameter estimations

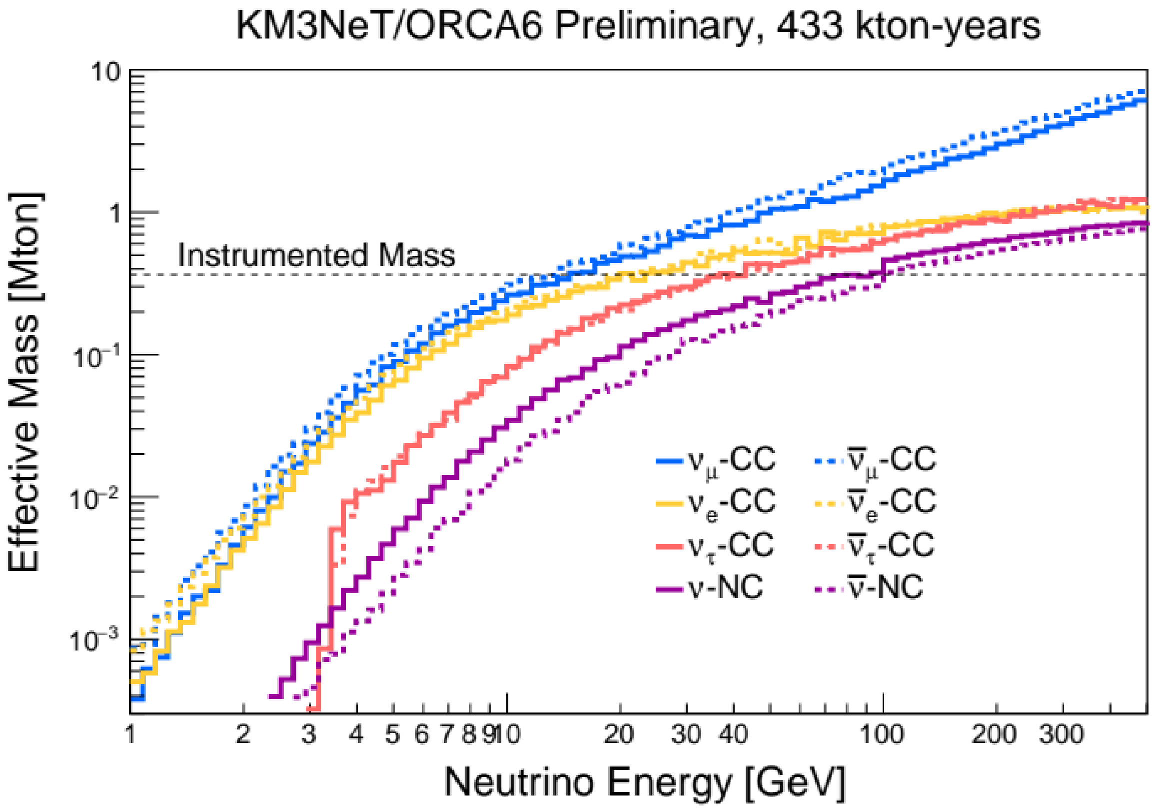
Backup

Sterile neutrino with Δm^2_{41} ~ 1 eV² in KM3NeT/ORCA

When both θ_{24}, $\theta_{34} \neq 0$, **1st ν_μ disappearance max** ~25 GeV shift position depending on δ_{24} value



KM3NeT/ORCA6 effective mass



Instrumented mass:
367 kton

Oscillation analysis in KM3NeT/ORCA

Compare this measured $n_{i,j}$ with predicted $\mu_{i,j}(\boldsymbol{x},\boldsymbol{\eta})$ 2D reconstructed (E, $\cos\theta$) event distribution for each class i

Determine parameters of interest $\boldsymbol{x}$ through Maximum Likelihood Estimator (binned Poisson + Gaussian penalty for constrained nuisance parameters $\boldsymbol{\eta}$')

$$l(\boldsymbol{x},\boldsymbol{\eta})=2\sum_{i=1}^{N_{classes}}\sum_{j=1}^{N_{bins}}\left[\mu_{i,j}(\boldsymbol{x},\boldsymbol{\eta})-n_{i,j}+n_{i,j}\ln\left(\frac{n_{i,j}}{\mu_{i,j}(\boldsymbol{x},\boldsymbol{\eta})}\right)\right]+\sum_{k=1}^{N_{priors}}\left(\frac{\eta_k'-\langle\eta_k'\rangle}{\sigma_k}\right)^2$$

Nuisance parameters

All nuisance parameters are fitted

Some are constrained (Gaussian prior), others are *unconstrained*

$$\phi^{\nu_y}_{atm}(E_t,\theta_t) \times P_{\nu_y \to \nu_x}(E_t,\theta_t) \times \sigma_{\nu_x}(E_t) \times M^{\nu_x}_{eff}(E_t) \times R_i(E_t,\theta_t,\nu_x,E_r,\theta_r) \Rightarrow \mu_i(E_r,\theta_r)$$

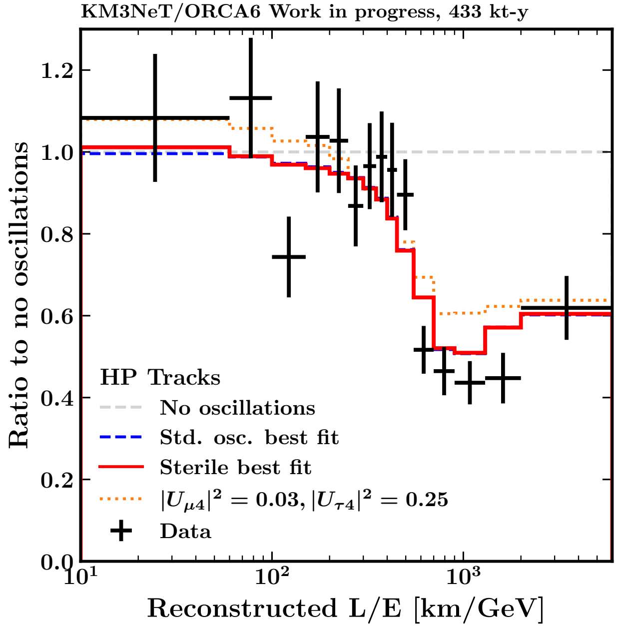
- ν_{hor}/ν_{ver} skew
- $\nu_e/\bar{\nu}_e$ skew
- $\nu_\mu/\bar{\nu}_\mu$ skew
- ν_μ/ν_e skew
- Spectral index
- *Overall norm.*

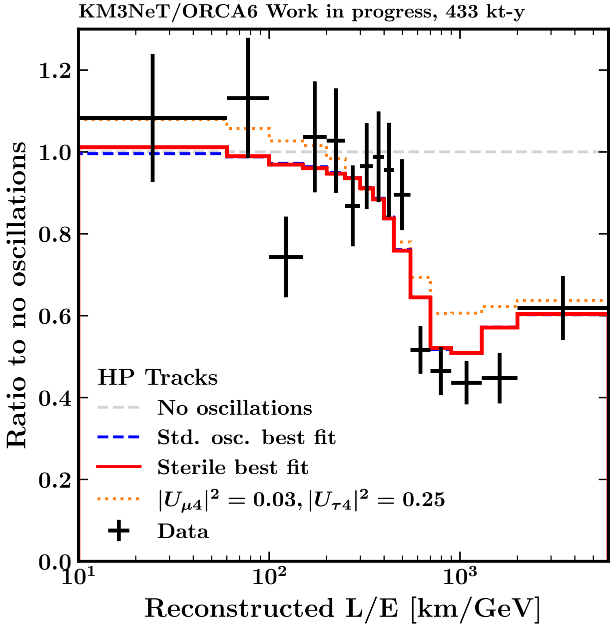
- Δm^2_{31}
- *θ_{23}*

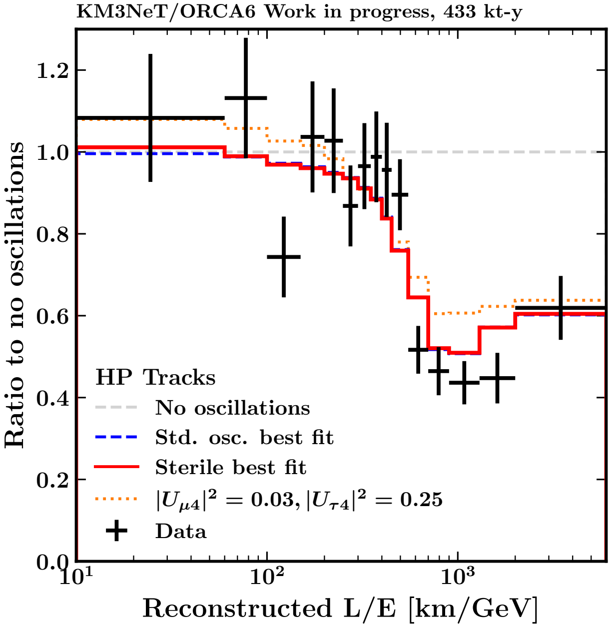
- ν_τ-CC norm.
- NC norm.

- Energy scale
- HE light simulation
- *HP track norm.*
- *Shower norm.*
- *Muon norm.*

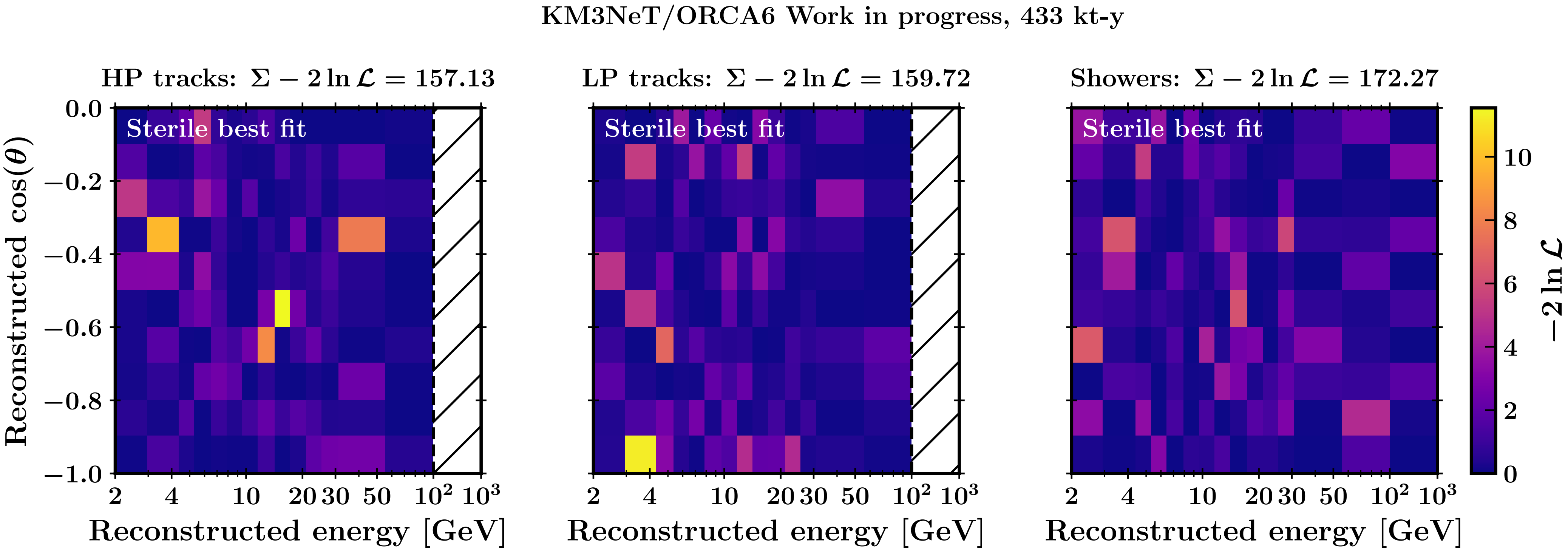
L/E neutrino distribution @ best fit



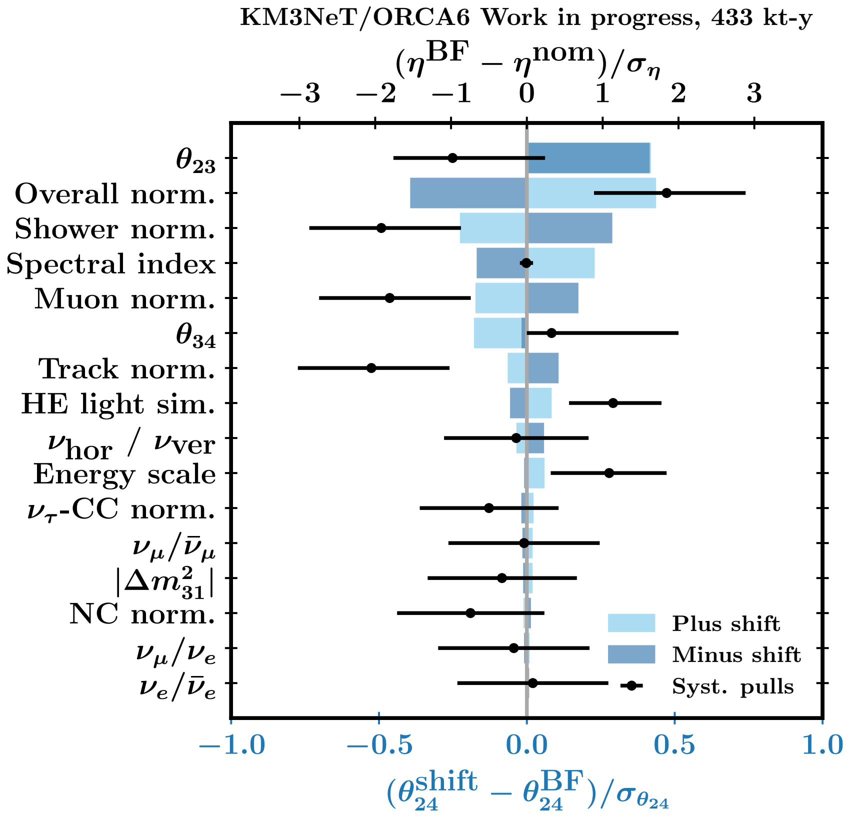


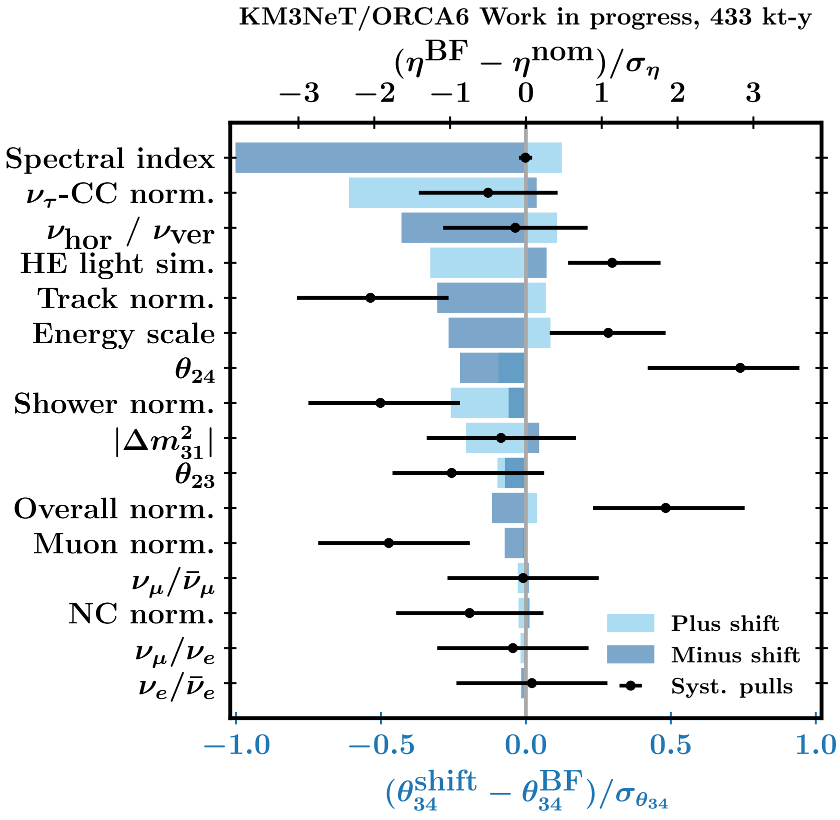


Log-likelihood ratio map @ best fit



Effect of systematics @ best fit



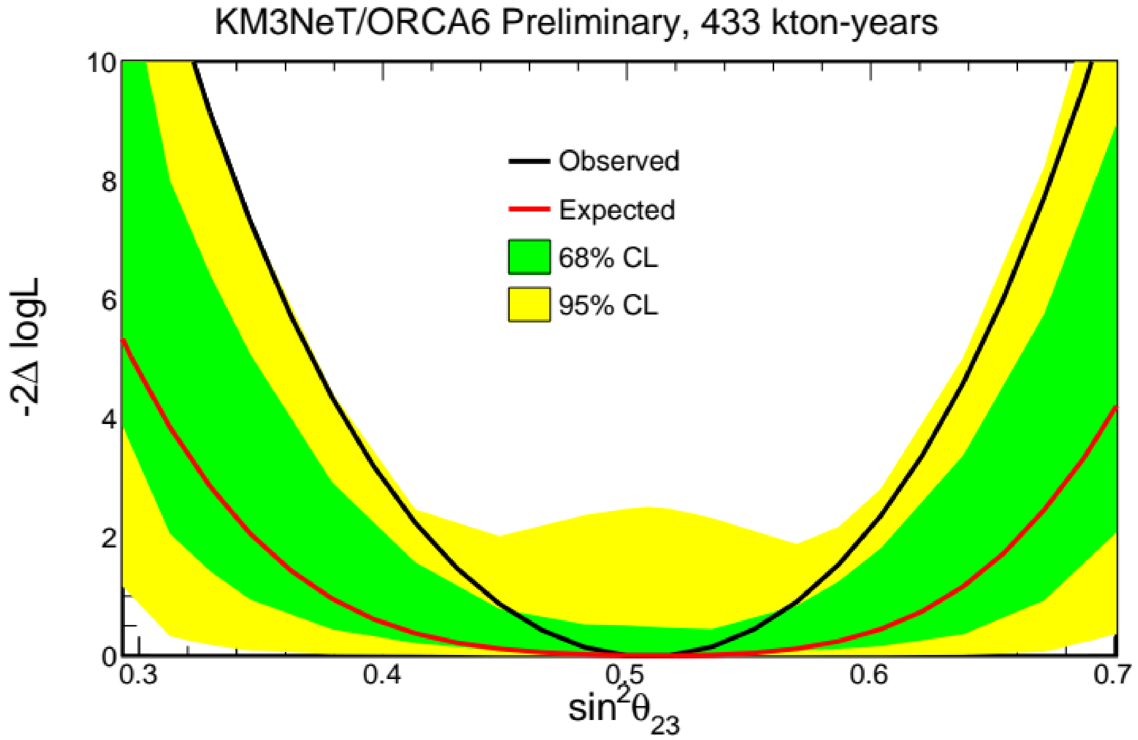


Black points: parameter value at BF normalized by std. dev. (from prior if constrained, from fit otherwise)

Blue bars: shifts in parameters of interest from fixing the nuisance parameters to their best fit value ±1 σ

Standard oscillations: θ_{23} profile

Observed θ_{23} profile lies on expected ~95% C.L. limit on most of the phase space



Δm^2_{41}-dependent sensitivities to θ_{24} & θ_{34}