Non unitary neutrino mixing with KM3NeT/ORCA

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The NUNM model

New physics, beyond the Standard Model (SM), is required to explain the generation of the neutrino mass. The seesaw model [1] implies the existence of Neutral Heavy Leptons (NHLs) as seesaw messengers to explain the smallness of neutrino masses. The NUNM [2, 3] is useful to probe in a model-independent way the case of any number of NHLs, including the possibility of 3 heavy right-handed sterile neutrinos as partners of the SM left-handed neutrinos, that naturally arise in the type-1 seesaw model.

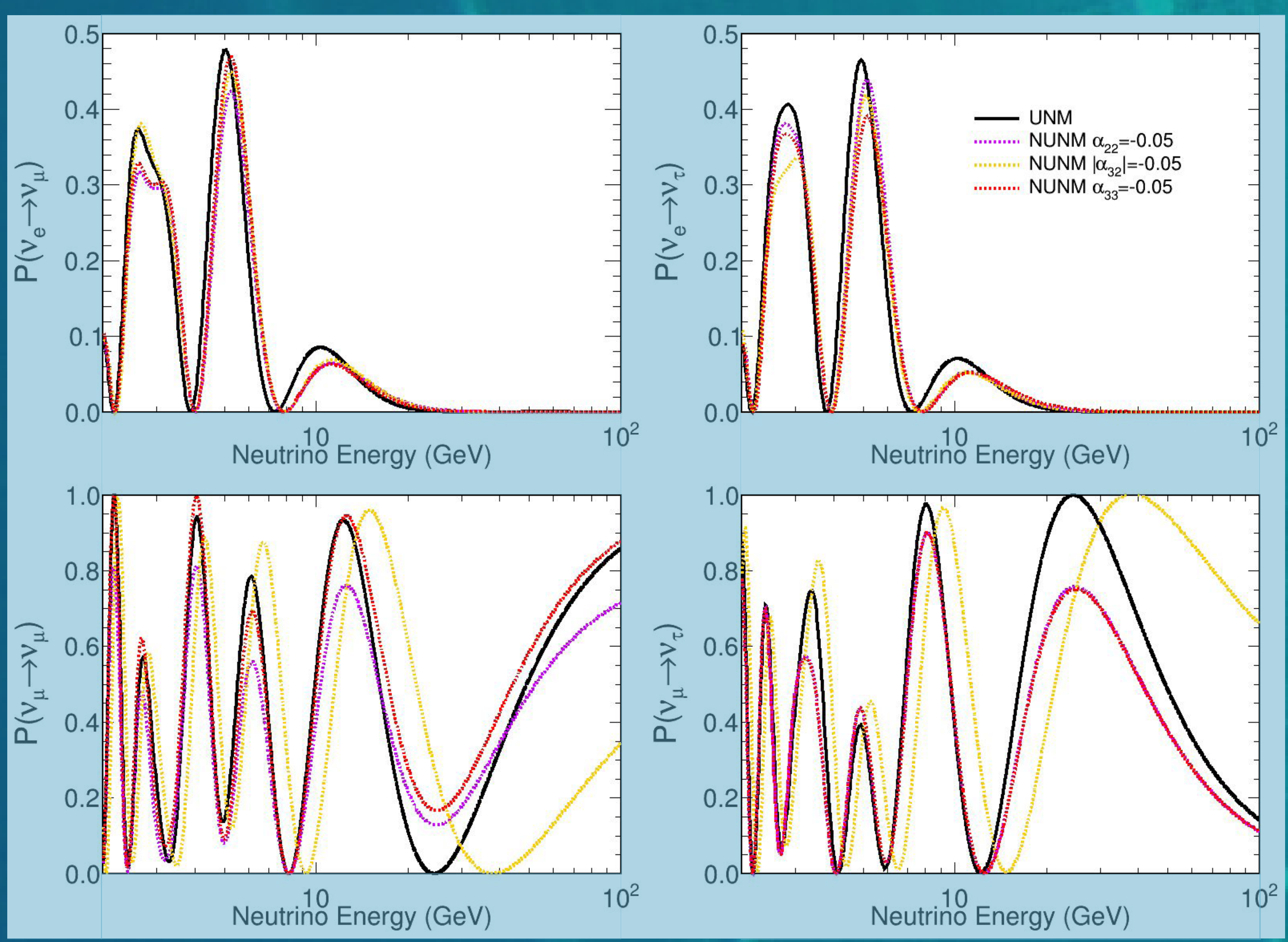
In the case of additional sterile states, the full (nxn) neutrino mixing matrix remains unitary. The non-unitary matrix N corresponds to the upper left 3x3 component of the larger unitary matrix.

$$N = (1+\alpha)\, U_{PMNS}$$

The non-unitary part, alpha is composed of 9 new parameters including 3 phases. The following study will concentrate on the bottom right corner of α where KM3NeT/ORCA has the most sensitivity.

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

The figure below illustrates the effect of the single parameter α_{33}, α_{22} or α_{32} non-zero. The amplitude in the muon disappearance and the tau appearance channel is suppressed in the case of non-zero α_{22} or α_{33}, with a heavier effect of α_{22} in the muon disappearance channel where KM3NeT/ORCA has high statistics. The effect of non-zero α_{22} is a shift of the maximum of the oscillation probability in both channels.



Analysis

The analysis explores the data collected with 5% of the nominal instrumented volume and 433 kton-years of data taking. Events are separated in the selection process into the High Purity Tracks, the Low purity Tracks and the Showers defined to maximise the sensitivity to oscillation measurements, while keeping more than 2 events per bin. The NUNM is tested by fitting a model to the observed event distribution. The event distribution predicted by the model depends on the parameter of interest α_{ij}, as well as several nuisance parameters that account for systematic uncertainties. The events are distributed in a two-dimensional histogram where the direction is divided into 10 equally spaced bins between $-1<\cos(\theta_{zenith})<0$ The reconstructed energy is divided into 15 bins between 2 GeV and 1 TeV. The model introduced is fitted to the data through the minimisation of a negative log-likelihood function summed over every bin of the 3 classes.

KM3NeT

KM3NeT consists of two water Cherenkov neutrino telescopes at the bottom of the Mediterranean sea: ARCA (large array) to measure high energy (>1TeV) neutrinos and ORCA (denser array) to measure GeV neutrinos.

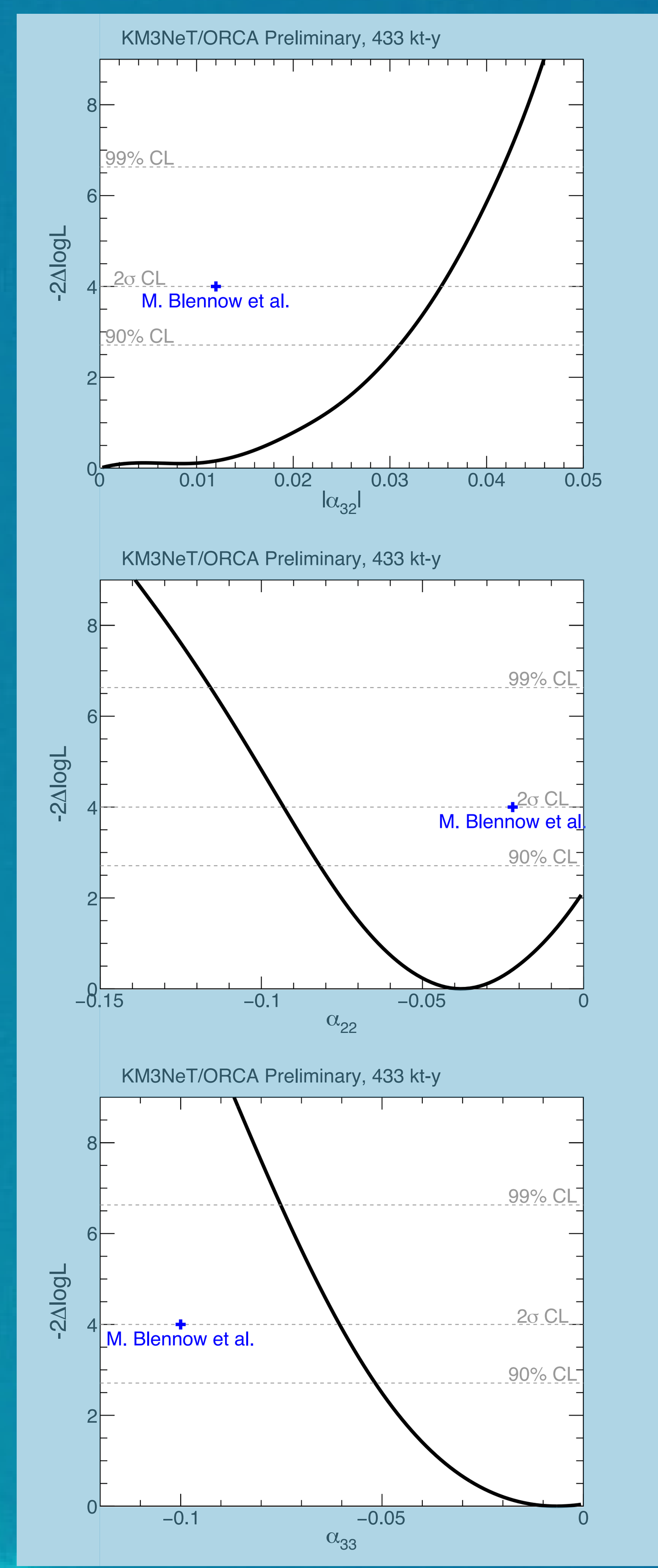
3D array of photomultiplier tubes:
1 Digital Optical Module = 31 PMTS
1 Detection Unit = 18 DOMs
1 Building Block = 115 DUs
ARCA: 2 BB 36 m - 90 m spacing
ORCA: 1 BB 9 m - 20 m spacing

Results

Likelihood profile

The table below shows the present bounds at 2 σ on the single α parameters, derived from no-observation of zero distance oscillations in [4]. The limits are also reported on the likelihood profiles shown in the figures below. The previous limit on α_{33} has been replaced by the KM3NeT/ORCA limit, in the case of the model with a single parameter.

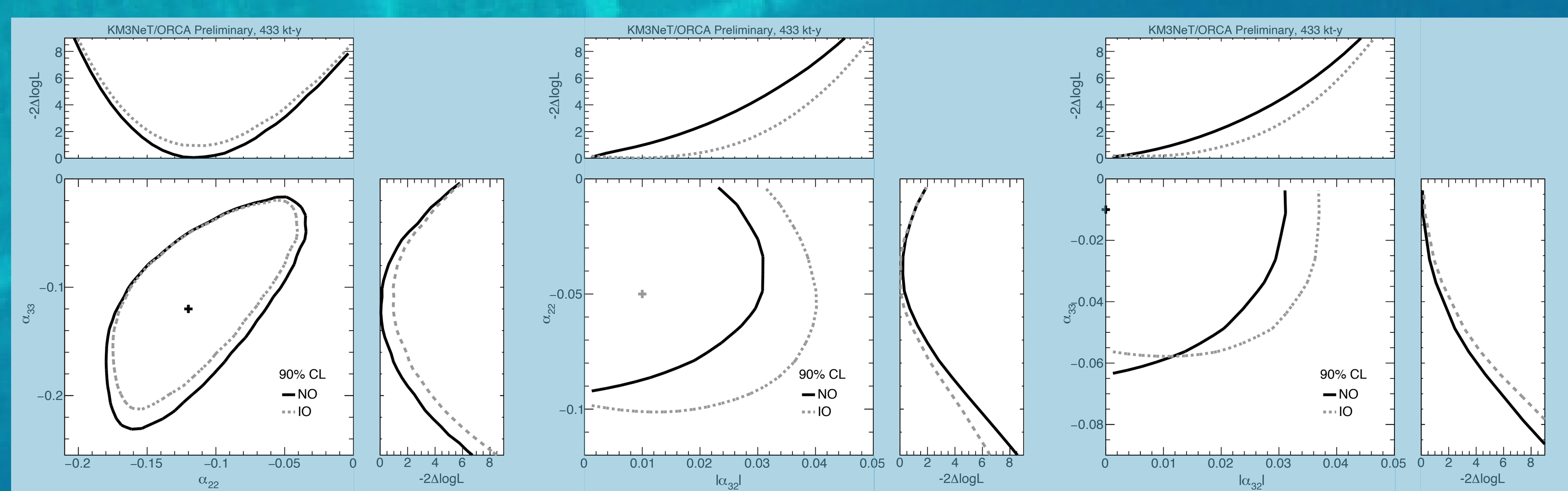
NUNM single parameter	Present Bounds 2σ	KM3NeT/ORCA data 2σ
$\alpha_{33} >$	-0.10	-0.06
$\alpha_{22} >$	-0.022	-0.09
$\|\alpha_{32}\| <$	0.012	0.03



Contours

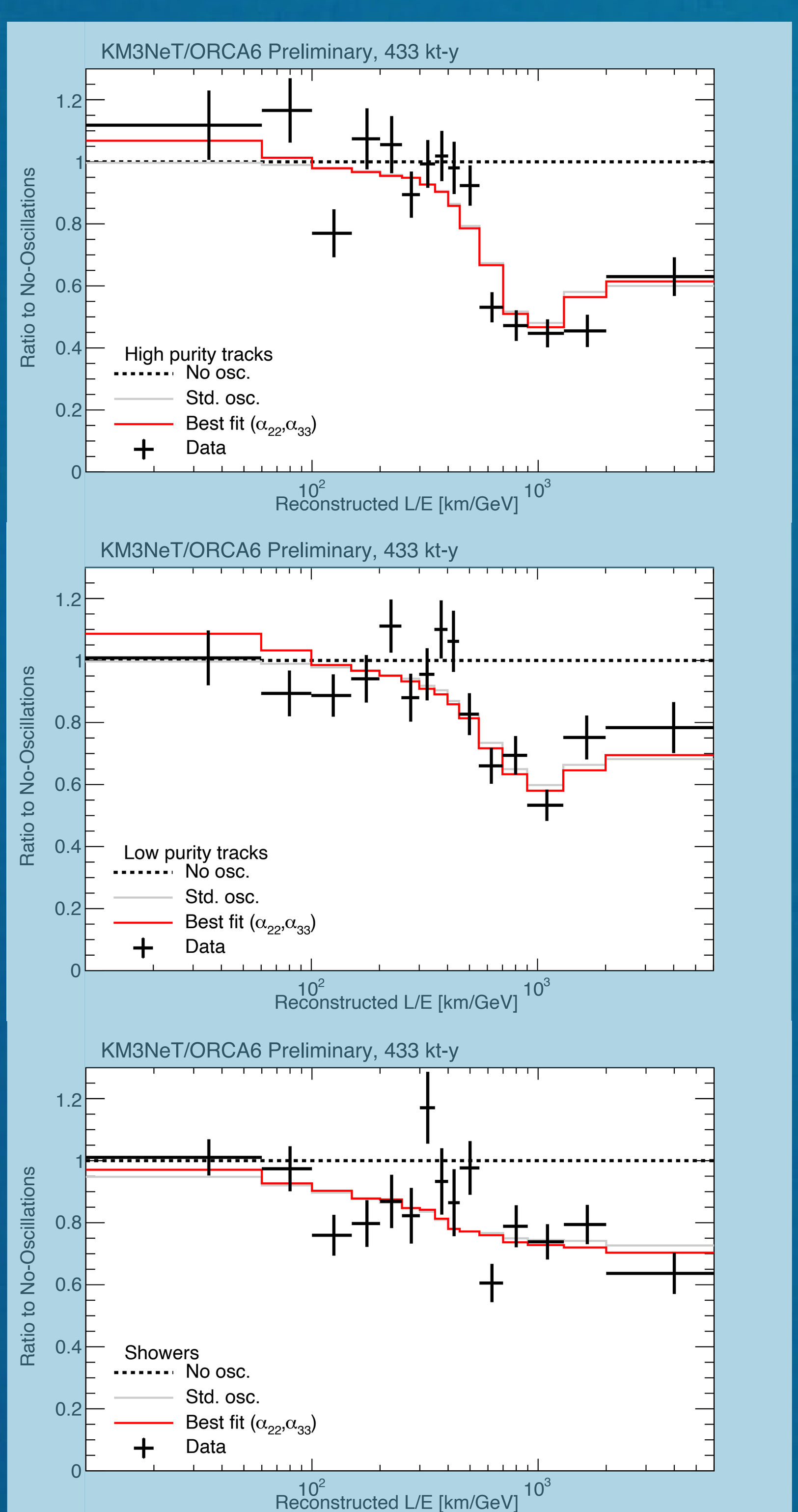
The 90% CL contours are shown in the figures below for all the 2D combination of α_{22}, α_{33} and α_{32}, testing both normal and inverted ordering. The contours involving α_{32} are consistent with the unitarity hypothesis, while the unitarity is not contained in the 90% CL contours of α_{22} and α_{33}.

Measured NUNM parameters	Best fit $\pm1\sigma$
α_{22}	$-0.114^{+0.033}_{-0.033}$
α_{33}	$-0.118^{+0.048}_{-0.055}$



Best fit

The figures at the bottom are shown for the best fit with both α_{22} and α_{33} free. The unitarity scenario is 8.3 units in -2ΔlogL away from the best fit.

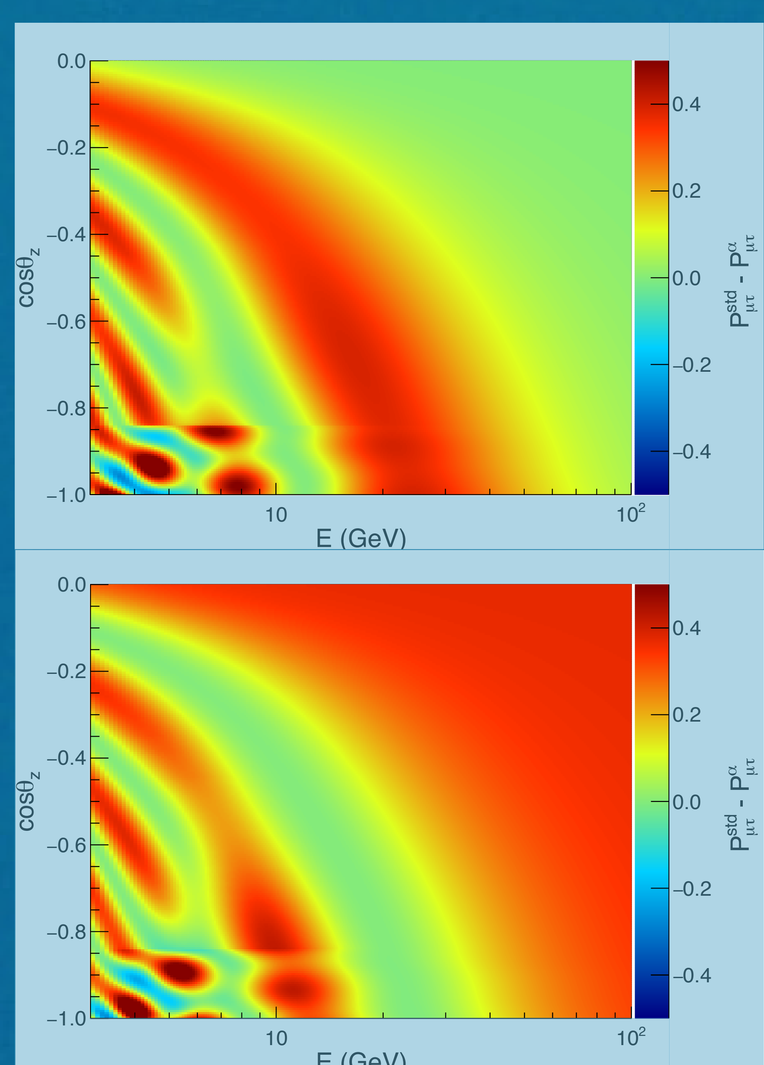


L/E

The figure on the left illustrates the comparison between the model in the unitarity case and the case with α_{22} and α_{33} free. Both models and the data are divided by the no-oscillation model, to show the clear oscillation dip that KM3NeT/ORCA is sensitive to. The effects of non-zero α_{22} and α_{33} appears to be consistent with statistical fluctuations.

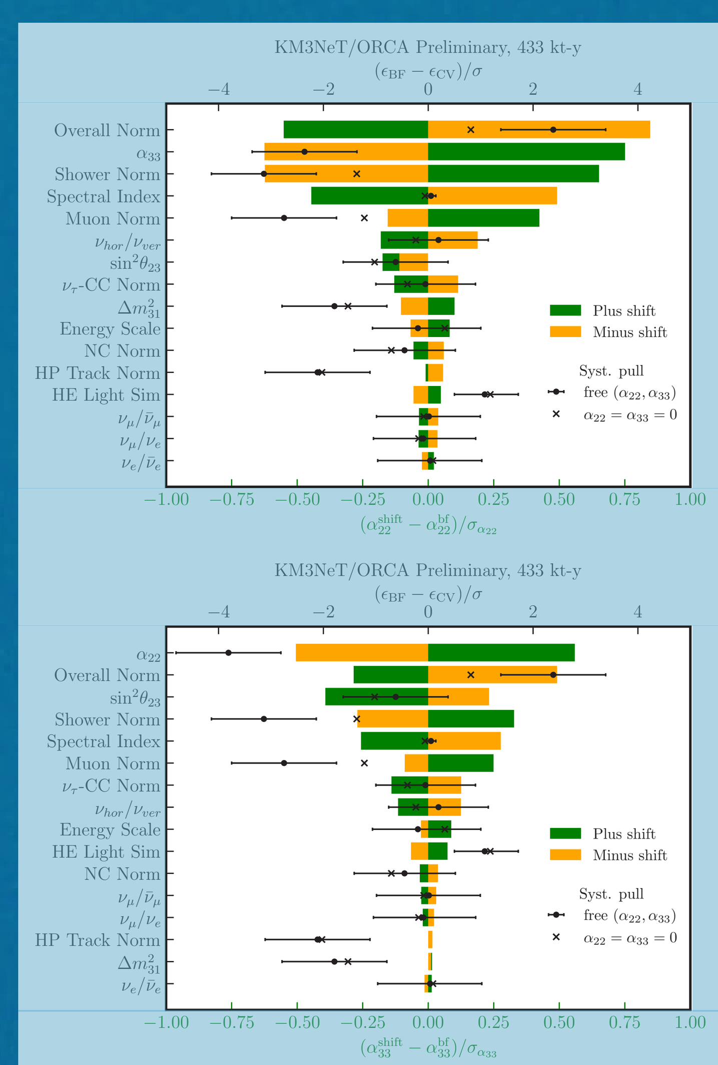
Probability

The figure below shows the effect of α_{22} and α_{32} at the best fit values on the oscillation probabilities, compared to the probabilities in case of unitarity for the muon disappearance and the tau appearance channel.



Systematics

The impact of the systematics on the measurement is illustrated below. The bars indicate the effect of moving a systematic by 1 σ on α_{ij}. The black dots and crosses indicate the pulls of the nuisance parameters with regards to their central value, for the NUNM case and the unitarity case respectively. Errors are given by the ratio between the post-fit and pre-fit uncertainties.



References

[1] Ahdida et al. The SHiP experiment at the proposed CERN SPS Beam Dump Facility. Eur. Phys. J. C 82, 486 (2022).

[2] C.S. Fong, Non-unitary evolution of neutrinos in matter and the leptonic unitarity test, J.High Energ. Phys. (2019).

[3] Miranda, L.S. et al. Searching for non-unitary neutrino oscillations in the present T2K and NOνA data. Eur. Phys. J. C 81, 444 (2021).

[4] Blennow, M., Coloma, P., Fernandez-Martinez, E. et al. Non-unitarity, sterile neutrinos, and non-standard neutrino interactions. J. High Energ. Phys. 2017, 153 (2017)