Searches for effects beyond the Standard Model with KM3NeT

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on behalf of the KM3NeT Collaboration

NOW 2024

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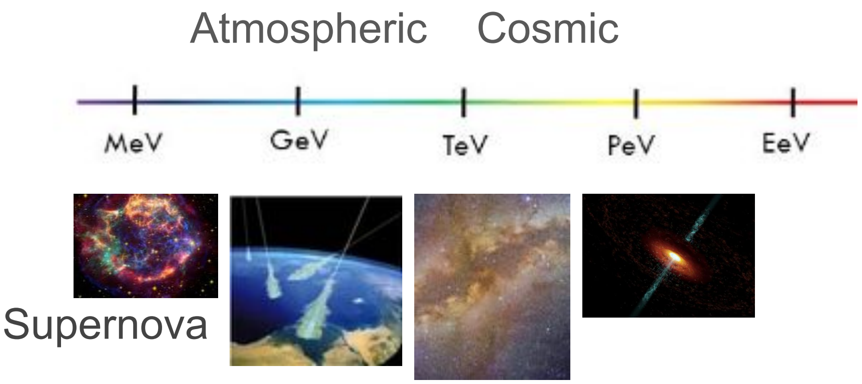
Possibilities for beyond Standard Model searches with ν

- Neutrinos can travel very **large distances** and are available at a **broad range of energies**.
  - → Beyond Standard Model (BSM) effects can accumulate along their path.
  - → BSM effects that scale with the energy are enhanced at high energies.

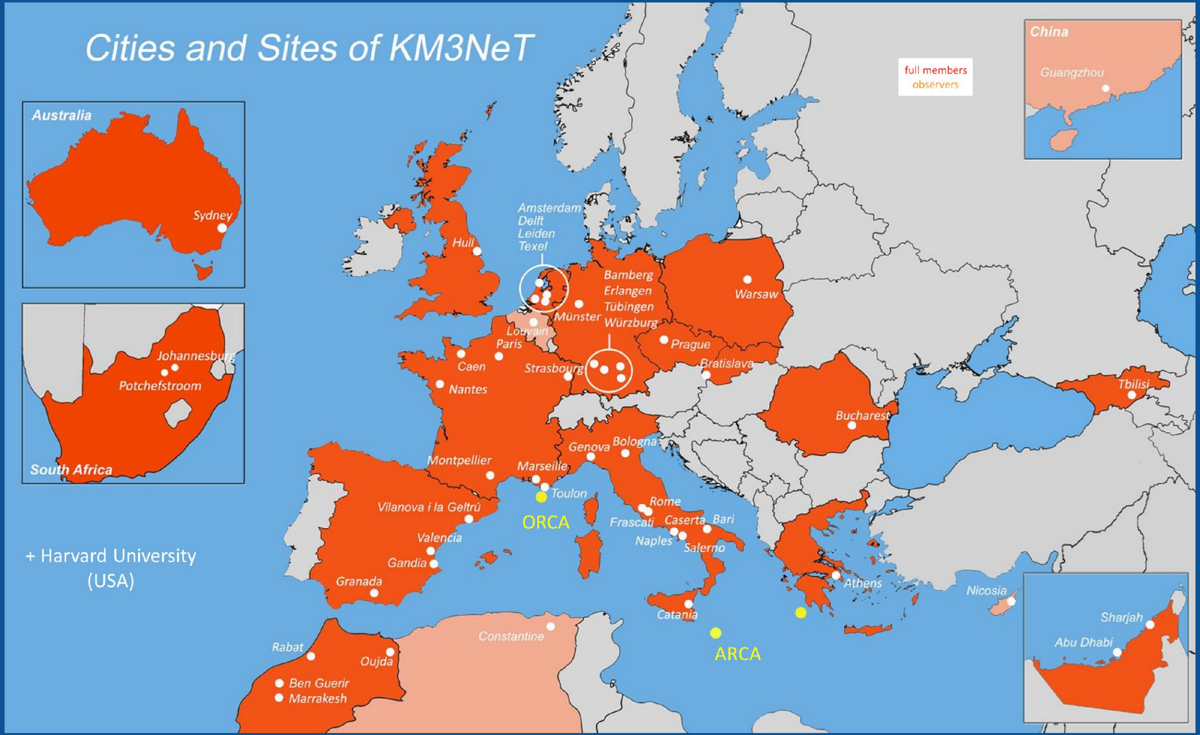
Neutrino telescopes as KM3NeT can observe **atmospheric and cosmic** neutrinos from **GeV to PeV** energies.

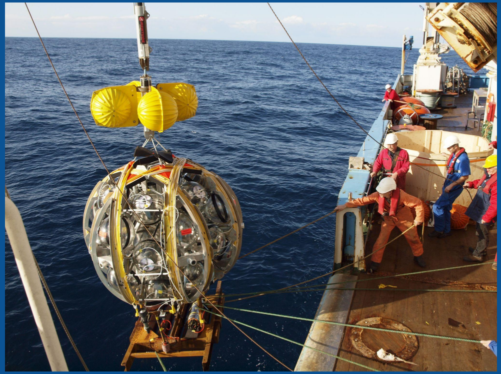
- Neutrinos **oscillate**.
  - → Study of oscillation patterns can reveal new physics!

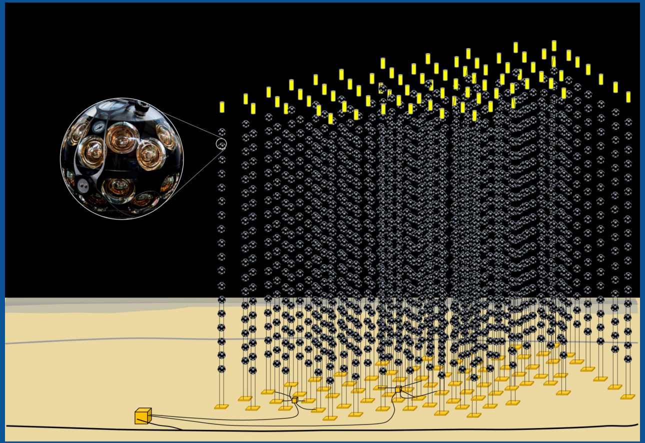
KM3NeT measures atmospheric **neutrino oscillations**.
See presentation by Luc Cerisy.



KM3NeT - neutrino telescopes in the Mediterranean Sea

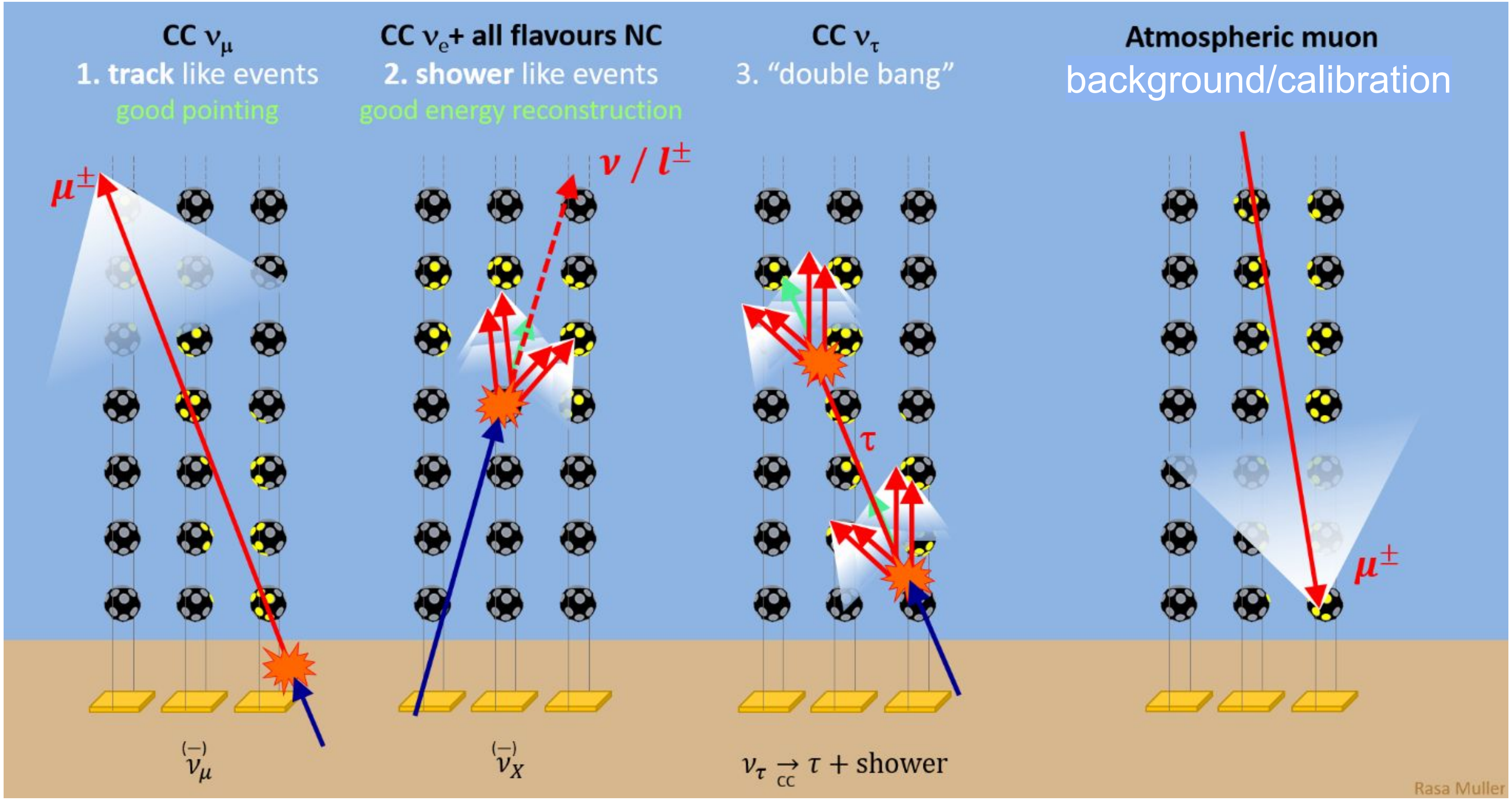






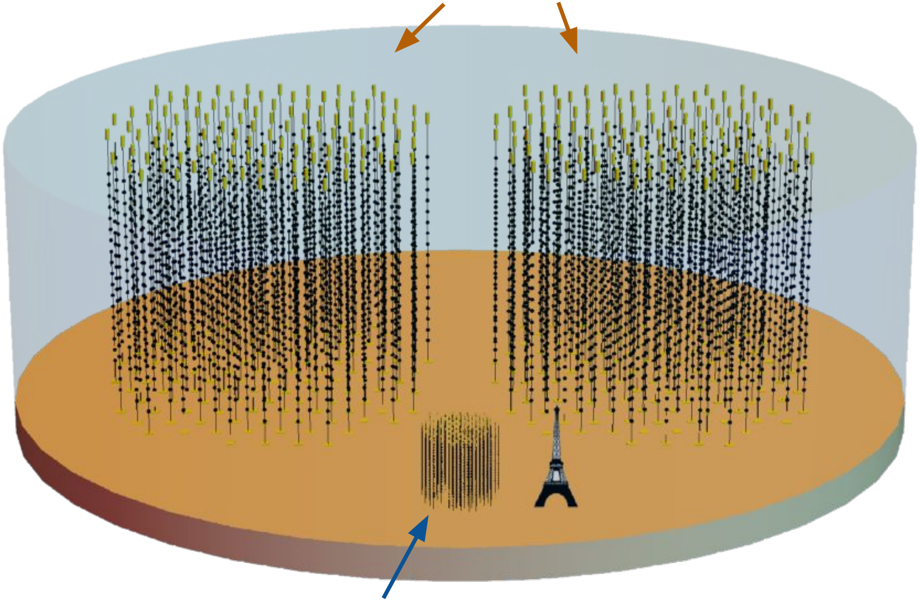
~250 members, 45 partner institutes, over 14 countries.

KM3NeT - detection principle



KM3NeT - ARCA and ORCA

ARCA
36m vert. x 90m horiz. spacing



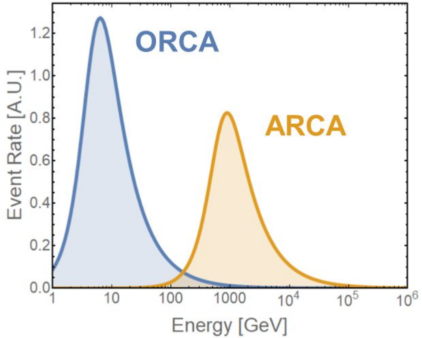
ORCA
9m vert. x 20m horiz. spacing

KM3NeT/ARCA (astrophysics):
Capo Passero, Sicily, Italy

- Search for astrophysical neutrinos.
- Very high energies (sub-TeV to few PeV).

KM3NeT/ORCA (oscillations):
La Seyne-sur-Mer, France

- Study of atmospheric ν oscillations, NMO.
- Lower energies (few GeV to ∼100 GeV).



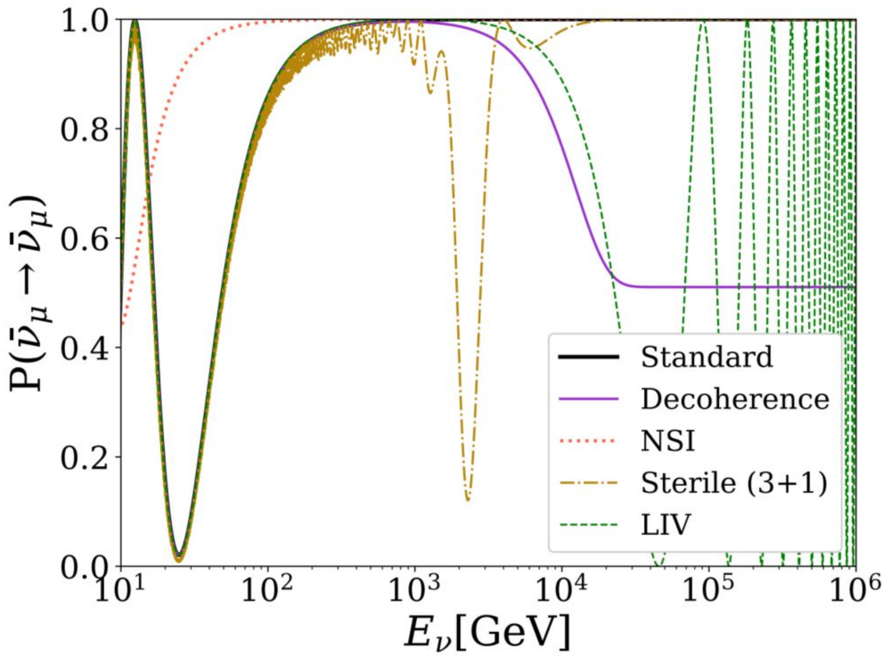
BSM searches with KM3NeT/ARCA

- ARCA can search for BSM effects at high energies (TeV to few PeV) where standard oscillations for atmospheric neutrinos are suppressed.

→ Anything different from $P = 1$ is a BSM effect!

- e.g. sterile neutrinos: eV-scale sterile ν produces matter-enhanced resonance at TeV energies.

- **Searches with ARCA**:
  - Neutrino Decoherence $\propto E, E^2$
  - Lorentz Invariance Violation $\propto E, E^2, \ldots$
  - Sterile neutrinos (3+1)



Plot generated with OscProb: upgoing neutrino, see parameter values in backup slides.

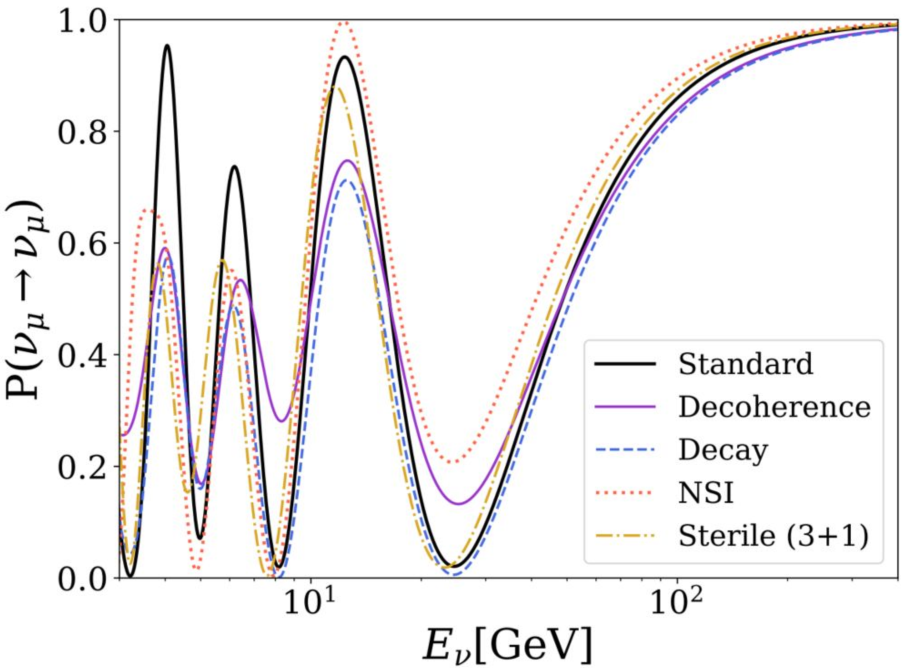
BSM searches with KM3NeT/ORCA

- ORCA is sensitive to atmospheric neutrino oscillations in the GeV range where BSM effects can modify the standard oscillation pattern.

→ Need a very good measurement of the standard oscillation parameters!

https://arxiv.org/abs/2408.07015

- **Data analyses for ORCA**:
  - Decoherence $\propto E^{-2}, E^{-1}$
  - Non-standard interactions (NSI)
  - Sterile neutrinos (3+1)
  - Neutrino decay
  - Lorentz Invariance Violation
  - Non-unitary mixing



Plot generated with OscProb: upgoing neutrino, see parameter values in backup slides.

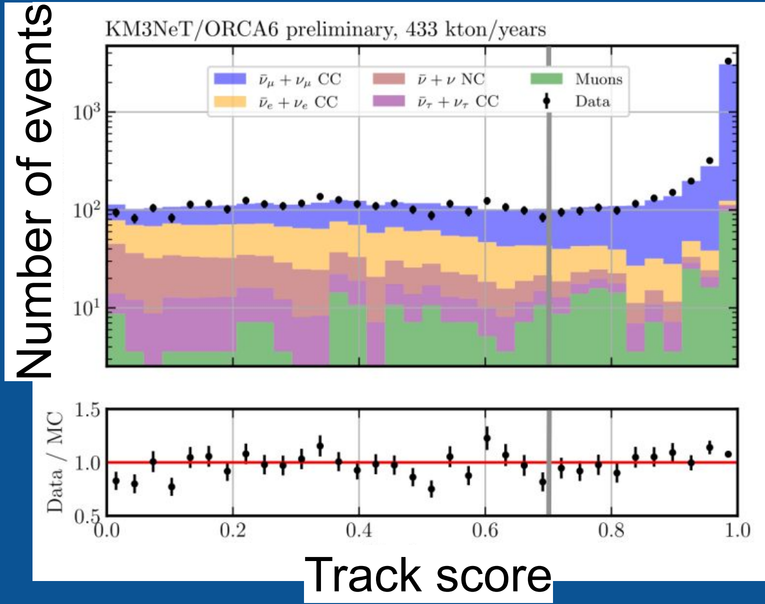
ORCA6 data analyses

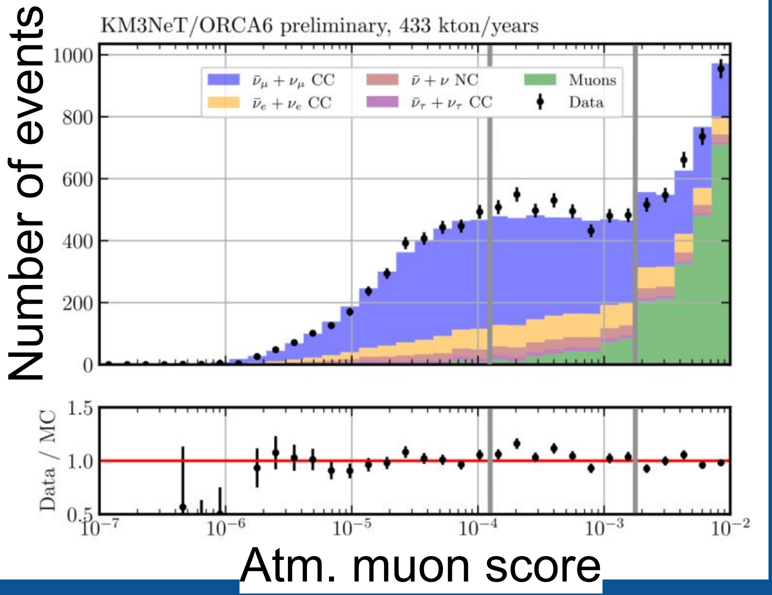
Data set:

- 510 days data-taking time
- 433 kton-years exposure
- 5828 observed events

Analysis:

- Event classification with Boosted Decision Trees (BDTs).
- Histograms of reconstructed energy and zenith angle.





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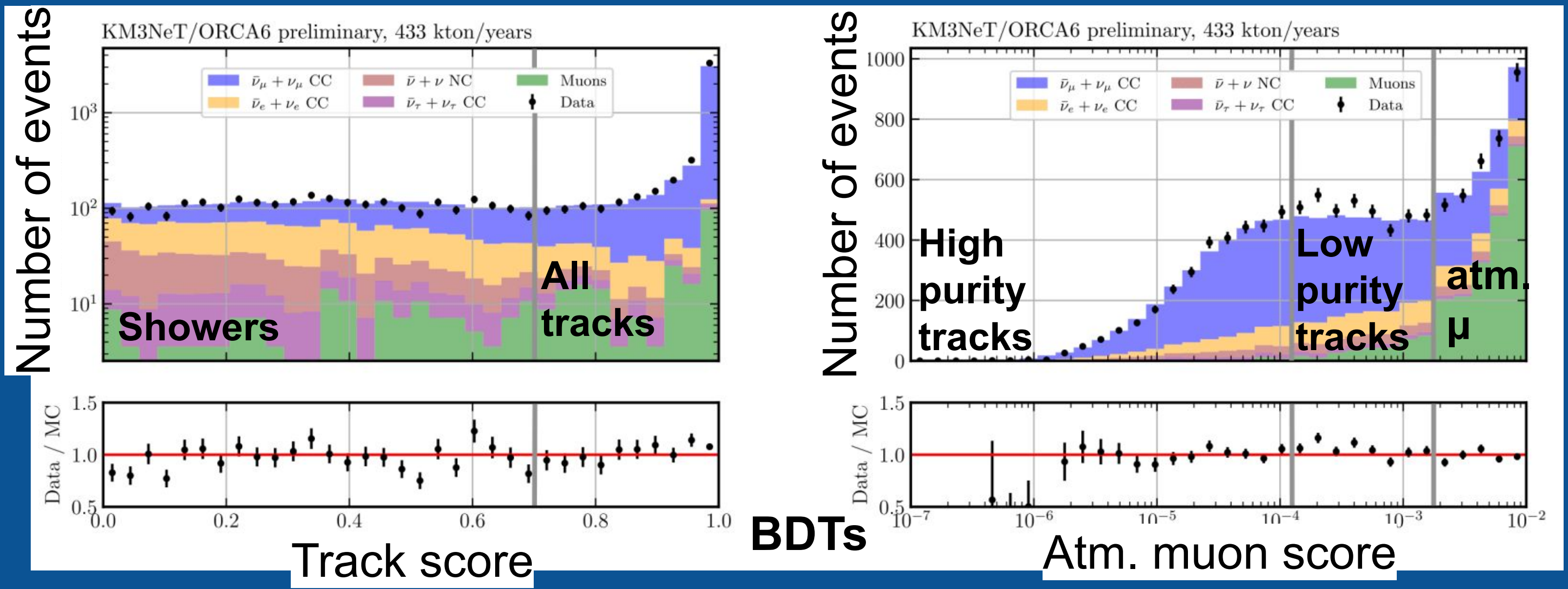
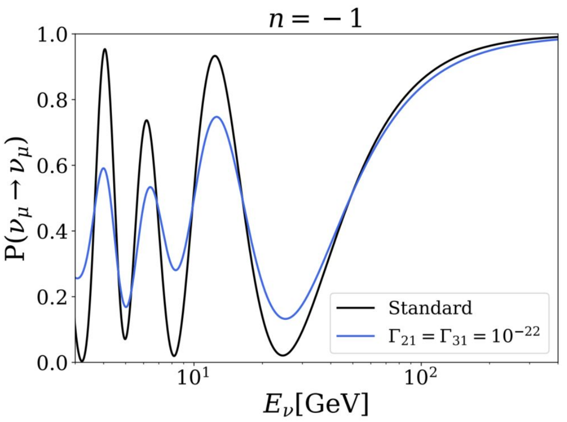


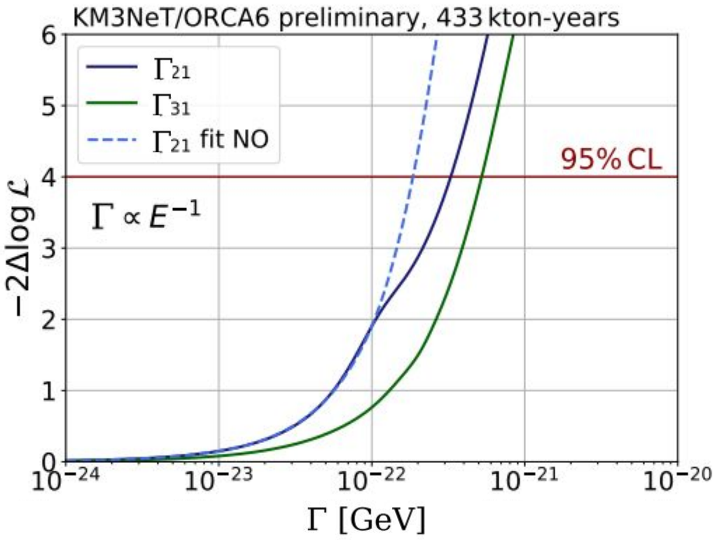
Neutrino Quantum Decoherence

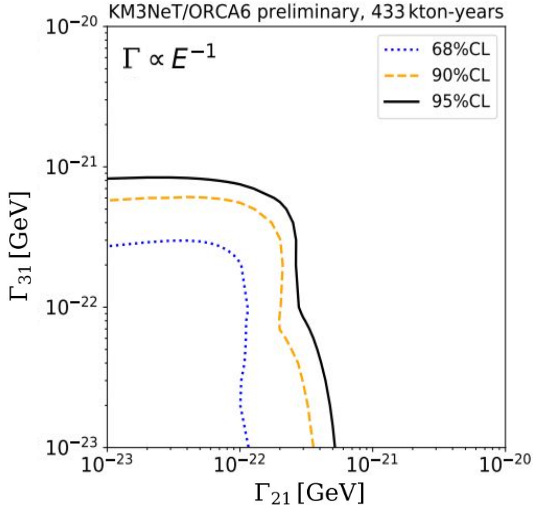
https://doi.org/10.22323/1.444.1025

- New physics effect predicted by theories of quantum gravity.
- Neutrino mass eigenstates lose their coherent superposition due to interactions with the environment ⟶ oscillation amplitude is suppressed: $P \propto e^{-\Gamma L}, \Gamma = \Gamma_0 (E/E_0)^n$
- Effect accumulates along the path: atmospheric ν in KM3NeT have long baselines.



Results available for n = -2 and n = -1





Neutrino non-standard interactions

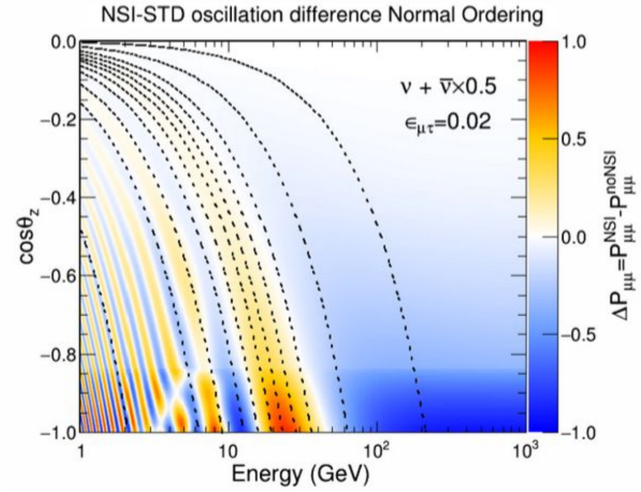
https://doi.org/10.22323/1.444.0998

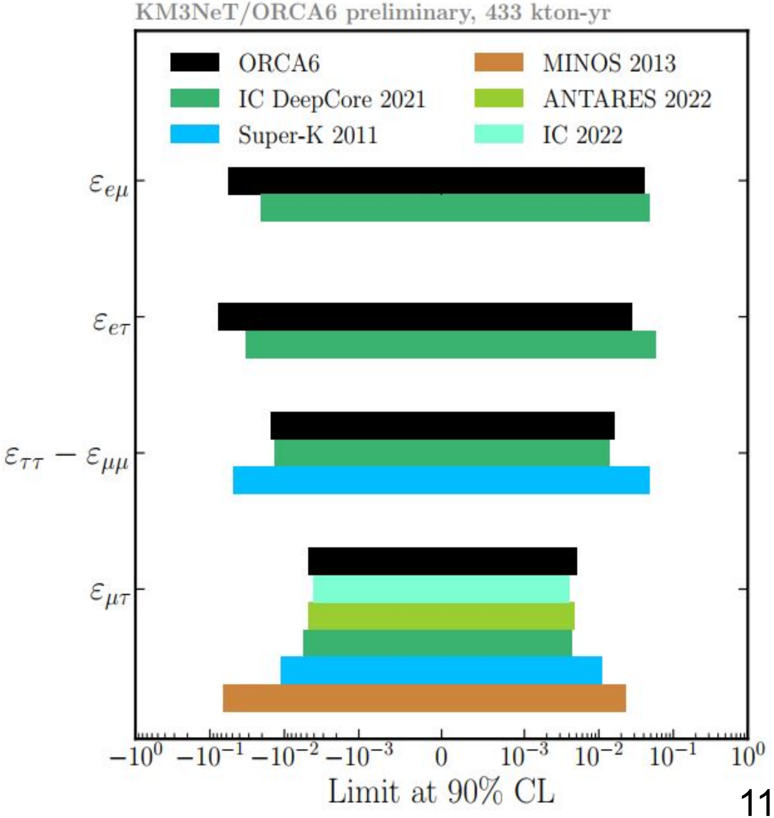
- Non-standard interactions (NSIs) arise when extending the Standard Model Lagrangian with new operators.

- NC forward scattering of ν inside the Earth is modified.

$$\mathcal{H}_{\rm nsi} = A(x)\begin{bmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{bmatrix}$$

- Flavour-dependent matter effects alter neutrino oscillations inside the Earth.

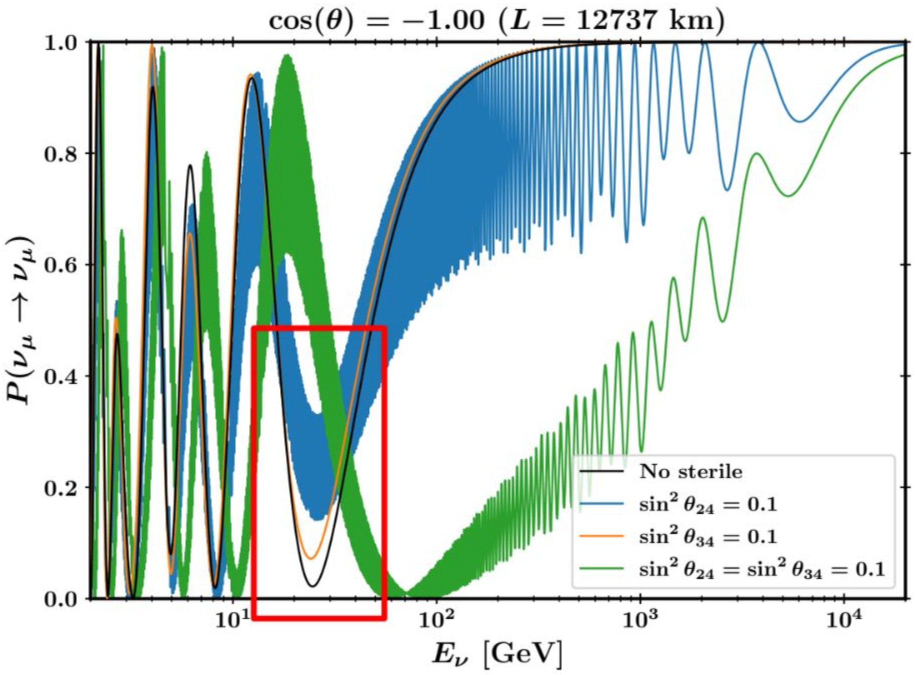


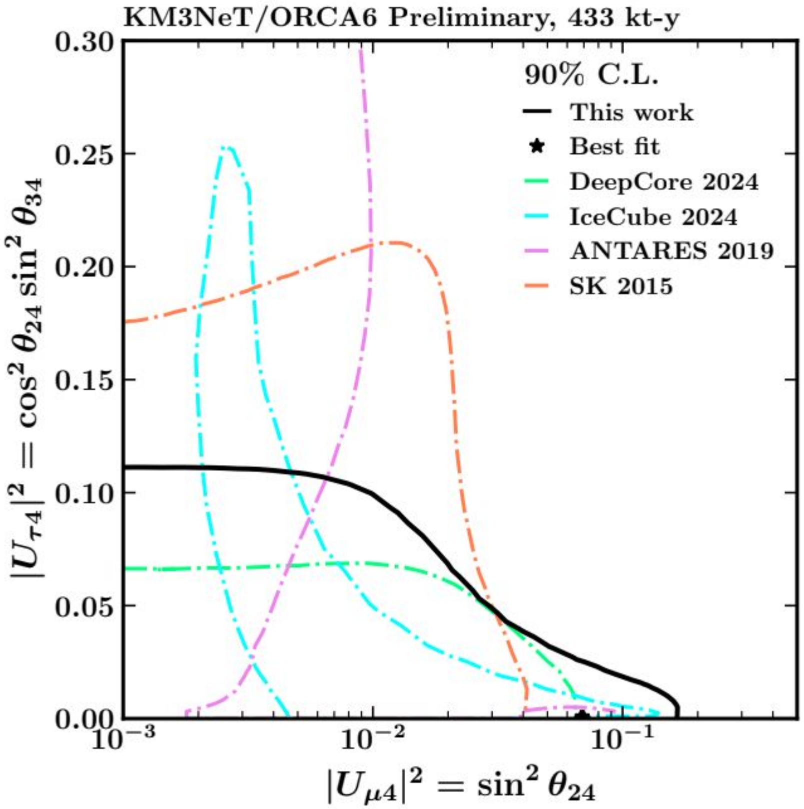


Sterile neutrinos (3 + 1)

ICHEP_presentation

- Short-baseline anomalies can be explained by sterile neutrino with $\Delta m^2_{41} \sim 1\,\mathrm{eV}^2$
- ORCA6 is sensitive to Θ_{24} and Θ_{34} .

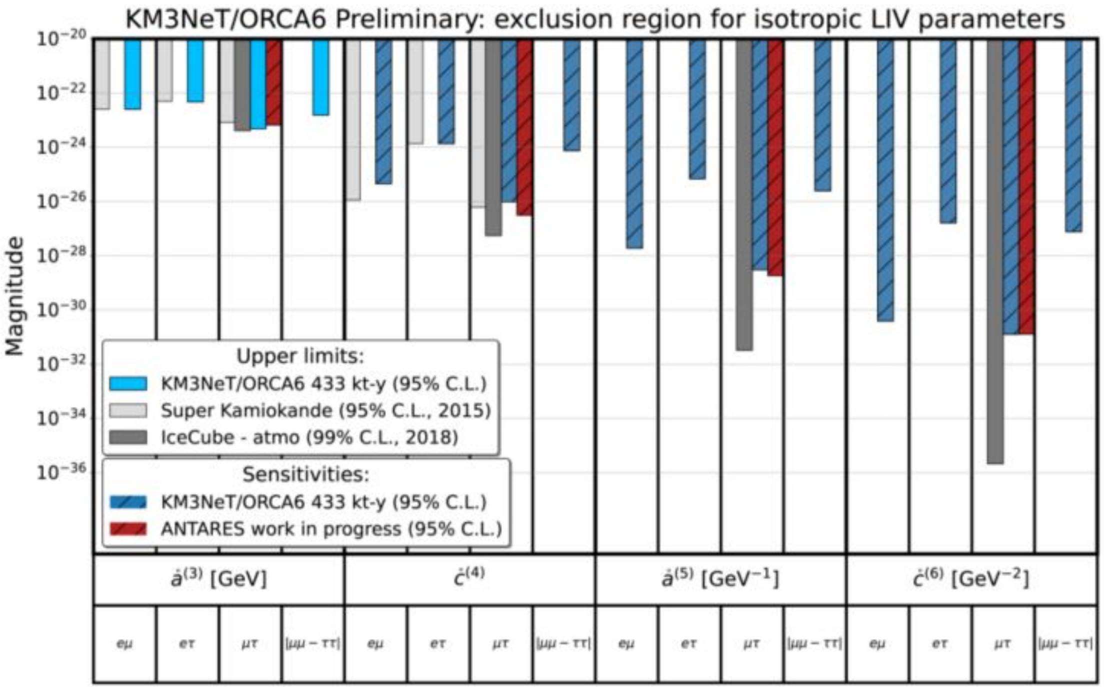




Further results:

Lorentz Invariance Violation (LIV):

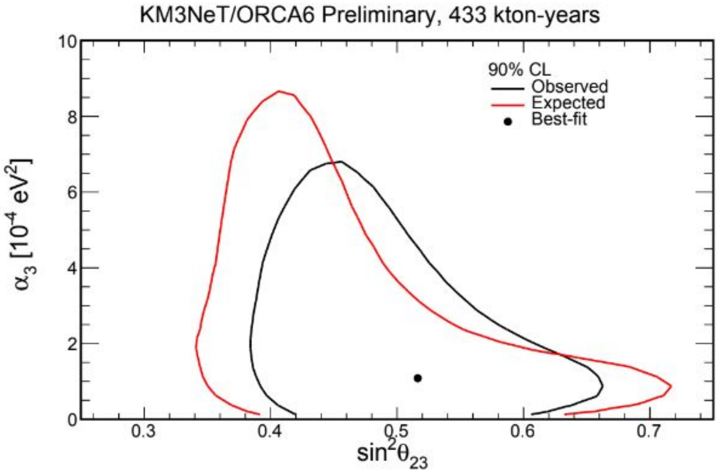
https://agenda.infn.it/event/37867/contributions/228296/



Neutrino decay:

$$\alpha_3 = \frac{m_3}{\tau_3}$$

https://pos.sissa.it/444/997/



Non-unitary mixing:

See presentation about ORCA6 standard oscillations by Luc.

Conclusions

- With KM3NeT we are already able to constrain many BSM effects indirectly.
- So what if we find **new physics** at some point?

Conclusions

KM3NeT

- With KM3NeT we are already able to constrain many BSM effects indirectly.
- So what if we find **new physics** at some point?

1)  2) We want to know more…

To study BSM physics in the future we will need:

- high statistics (ORCA115 detector) and a good understanding of systematics.
- input from other experiments that are sensitive to neutrino oscillations.
- new models as input from theorists.

Thank you very much for your attention!

Backup: parameters for BSM oscillations plot, normal ordering

- Software: OscProb (https://github.com/joaoabcoelho/OscProb)
- Neutrino traversing the Earth with $\cos(\Theta_Z) = -1$
- Decoherence:

$$\Gamma_{21} = \Gamma_{31} = 1e - 22\,\mathrm{GeV},\ \Gamma \propto (E_\nu / 1\,\mathrm{GeV})^{-1}, \Theta_{\mathrm{Deco}} = 0$$

- Decay:

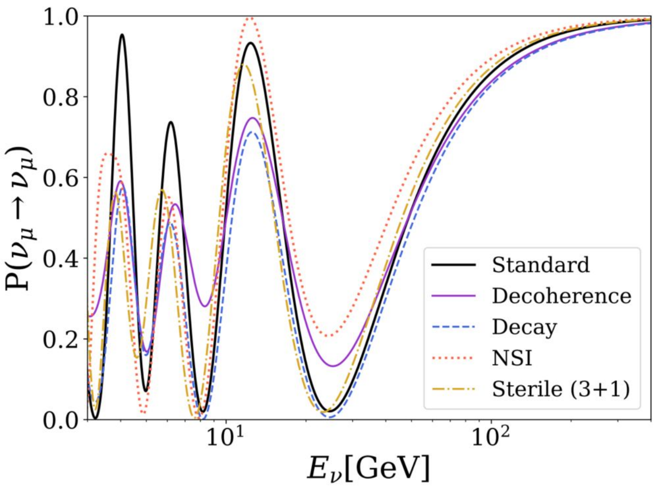
$$\alpha_3 = 1e - 4\,\mathrm{eV}^2$$

- NSI:

$$\epsilon_{\tau\tau} = 0.05, \epsilon_{\mu\mu} = 0.025$$

- Sterile:

$$\Delta m^2_{41} = 1e - 3\,\mathrm{eV}^2, \sin^2(\Theta_{24}) = 0.1$$



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- Software: OscProb (https://github.com/joaoabcoelho/OscProb)
- Neutrino traversing the Earth with $\cos(\Theta_Z) = -1$
- Decoherence:

$$\Gamma_{31} = 1e-31 \text{ GeV} \quad , \Gamma \propto (E_\nu/1\,\mathrm{GeV})^2, \Theta_{\mathrm{Deco}} = 0$$

- NSI:

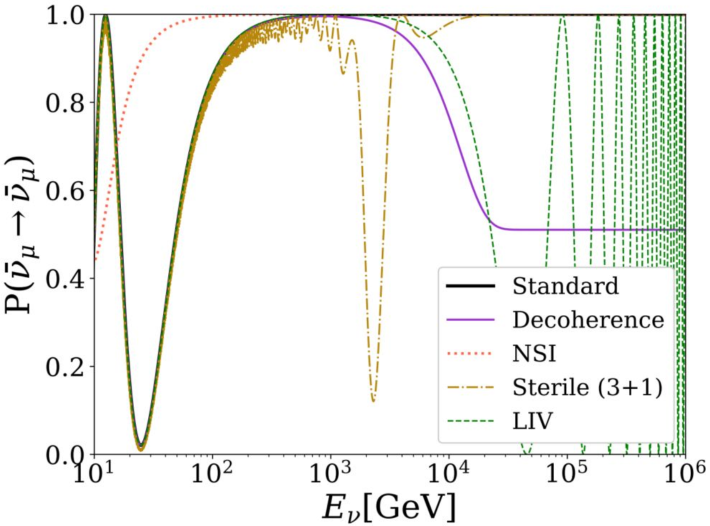
$$\epsilon_{\mu\mu} = -0.3$$

- Sterile:

$$\Delta m^2_{41} = 1\,\mathrm{eV}^2, \sin^2(2\Theta_{24}) = 0.04$$

- LIV:

$$c_{\mu\tau} = 4e-28$$



Backup: oscillation/systematic parameters for ORCA6

Parameter	Value NO	Value IO	Treatment
Δm^2_{31} [eV^2]	$2.517 \cdot 10^{-3}$	$-2.424 \cdot 10^{-3}$	free
Δm^2_{21} [eV^2]	$7.42 \cdot 10^{-5}$	$7.42 \cdot 10^{-5}$	fixed
θ_{12} [°]	33.44	33.45	fixed
θ_{13} [°]	8.57	8.60	fixed
θ_{23} [°]	49.2	49.3	free
δ_{CP} [°]	197	282	fixed

Likelihood to minimize:

$$-2\log(\mathcal{L}) = 2\sum_{i,j}\left[(N^{\text{mod}}_{ij} - N^{\text{dat}}_{ij}) + N^{\text{dat}}_{ij}\log\left(\frac{N^{\text{dat}}_{ij}}{N^{\text{mod}}_{ij}}\right)\right] + \sum_k\left(\frac{\eta_k - \langle\eta_k\rangle}{\sigma_k}\right)^2$$

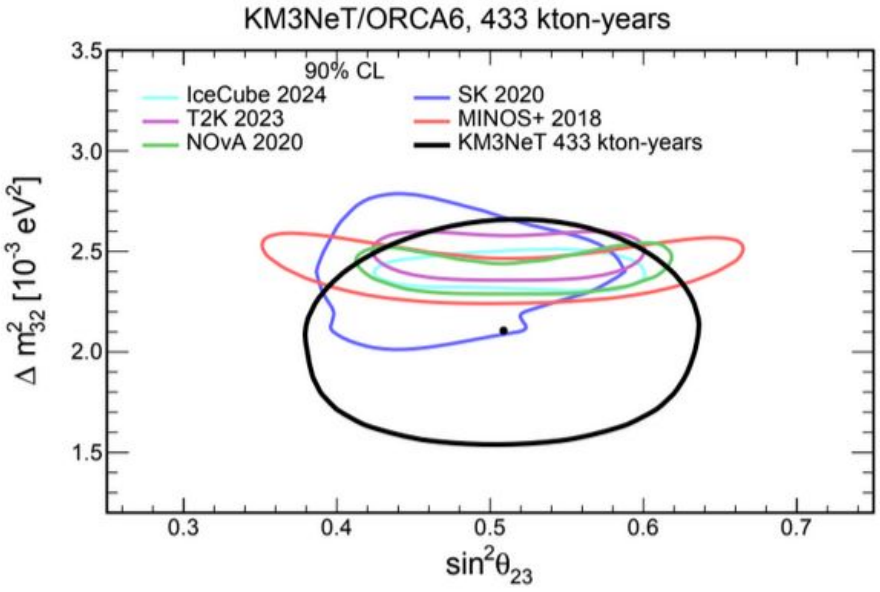
Standard oscillation results:

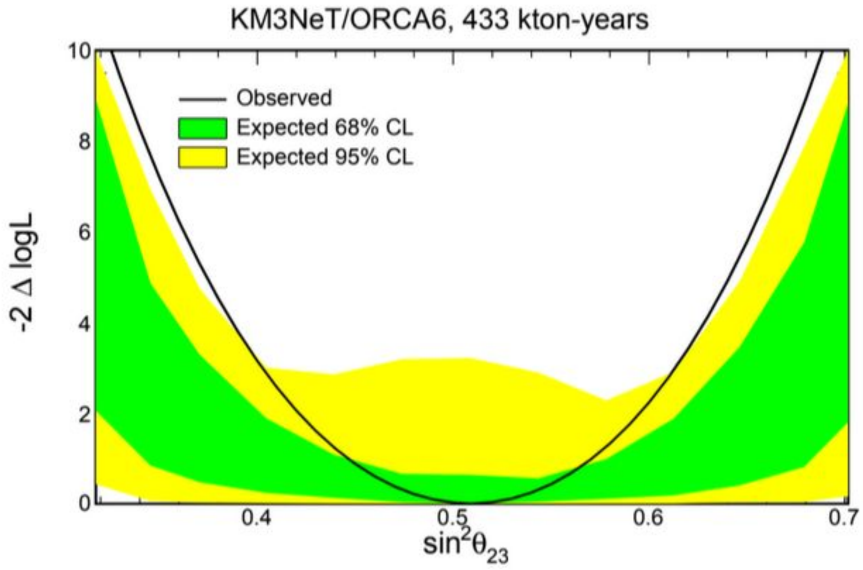
$$\sin^2\theta_{23} = 0.51^{+0.04}_{-0.05}$$

$$\Delta m^2_{31} = \begin{cases} 2.14^{+0.25}_{-0.35} \times 10^{-3}\ \text{eV}^2, & \text{for NO.} \\ [-2.25, -1.76] \times 10^{-3}\ \text{eV}^2, & \text{for IO} \end{cases}$$

Parameter	Prior
$(\nu_\mu+\bar{\nu}_\mu)/(\nu_e+\bar{\nu}_e)$ ratio	±2 %
$\nu_e/\bar{\nu}_e$ ratio	±7 %
$\nu_\mu/\bar{\nu}_\mu$ ratio	±5 %
$\nu_{\text{hor}}/\nu_{\text{ver}}$ ratio	±2 %
Spectral index	±10 %
n^{NC}	±20 %
n^{CC}_τ	±20 %
Energy scale	±9 %
Light simulation for high energy events	±50 %
n_μ	no prior
n_{Tracks}	no prior
n_{Showers}	no prior
$n_{\text{Abs.}}$	no prior

Backup: standard oscillations result for ORCA6





Backup: decoherence theory

Time evolution:

$$\frac{d\rho(t)}{dt} = -i[H, \rho(t)] + \mathcal{D}[\rho(t)]$$

$$\mathcal{D}[\rho] = \frac{1}{2}\sum_{k=1}^{N^2-1}\left(\left[V_k, \rho(t)V_k^\dagger\right] + \left[V_k\rho(t), V_k^\dagger\right]\right)$$

Expansion in SU(3):

$$\mathcal{D}[\rho(t)] = (D_{\mu\nu}\rho^\nu)\lambda^\mu$$

Conditions:

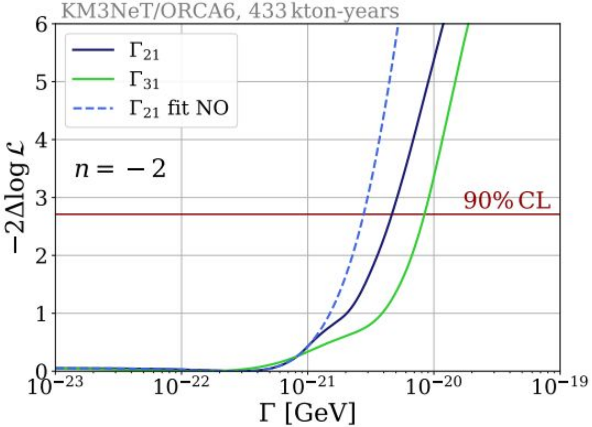
- Energy conservation
- Probability conservation
- Complete positivity

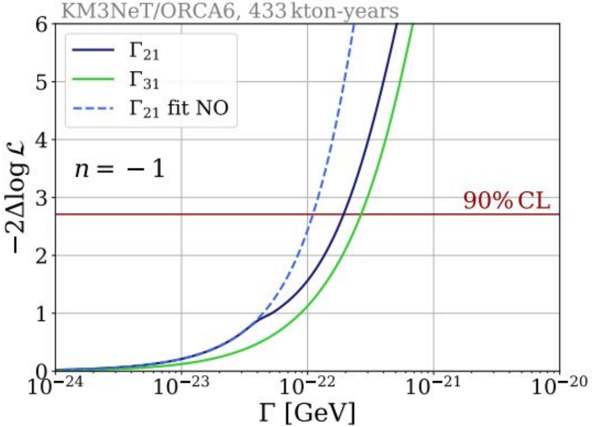
$$D = -\mathrm{diag}(0, \Gamma_{21}, \Gamma_{21}, 0, \Gamma_{31}, \Gamma_{31}, \Gamma_{32}, \Gamma_{32}, 0)$$

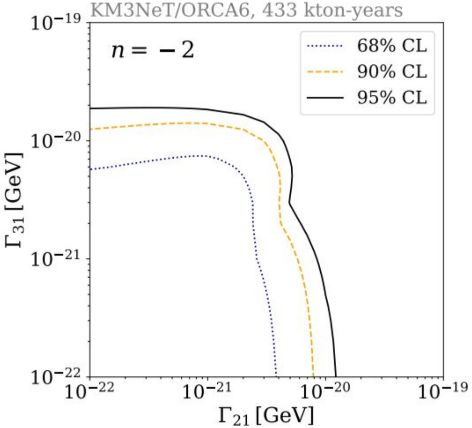
→ Parameter relation:

$$\Gamma_{32} = \Gamma_{31} + \Gamma_{21} - 2\sqrt{\Gamma_{31}\Gamma_{21}}$$

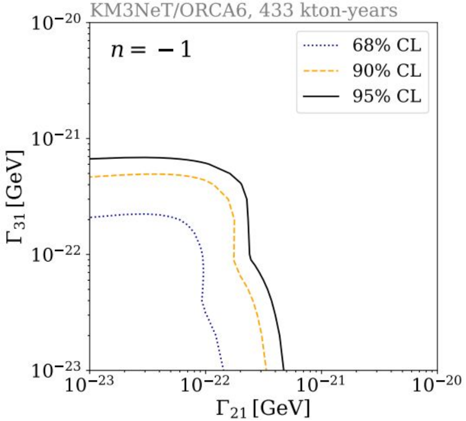
Backup: decoherence results with ORCA6



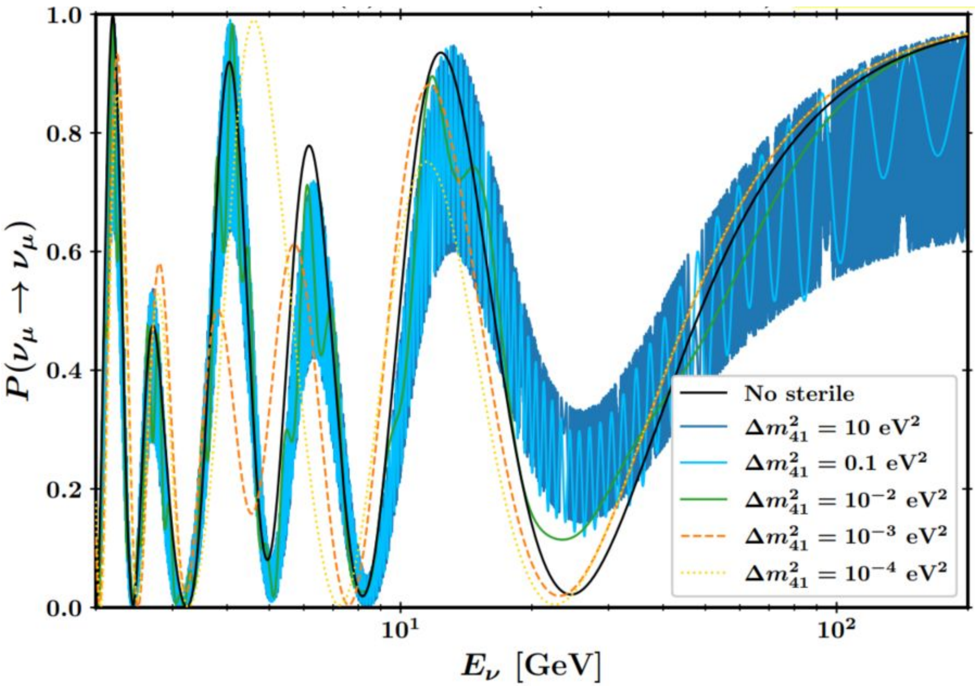




Upper limits [GeV]	$n = -2$		$n = -1$	
ORCA6, 90 %CL	NO	IO	NO	IO
Γ_{21}	$2.8 \cdot 10^{-21}$	$\mathbf{4.6 \cdot 10^{-21}}$	$1.1 \cdot 10^{-22}$	$\mathbf{1.9 \cdot 10^{-22}}$
Γ_{31}	$\mathbf{8.4 \cdot 10^{-21}}$	$2.2 \cdot 10^{-21}$	$\mathbf{2.7 \cdot 10^{-22}}$	$0.8 \cdot 10^{-22}$
$\Gamma_{21} = \Gamma_{31}$	$\mathbf{4.1 \cdot 10^{-21}}$	$2.9 \cdot 10^{-21}$	$\mathbf{1.8 \cdot 10^{-22}}$	$1.1 \cdot 10^{-22}$
ORCA6, 95 %CL	NO	IO	NO	IO
Γ_{21}	$3.7 \cdot 10^{-21}$	$\mathbf{6.9 \cdot 10^{-21}}$	$1.6 \cdot 10^{-22}$	$\mathbf{3.0 \cdot 10^{-22}}$
Γ_{31}	$\mathbf{11.7 \cdot 10^{-21}}$	$3.2 \cdot 10^{-21}$	$\mathbf{4.2 \cdot 10^{-22}}$	$1.3 \cdot 10^{-22}$
$\Gamma_{21} = \Gamma_{31}$	$\mathbf{5.2 \cdot 10^{-21}}$	$3.6 \cdot 10^{-21}$	$\mathbf{2.3 \cdot 10^{-22}}$	$1.4 \cdot 10^{-22}$

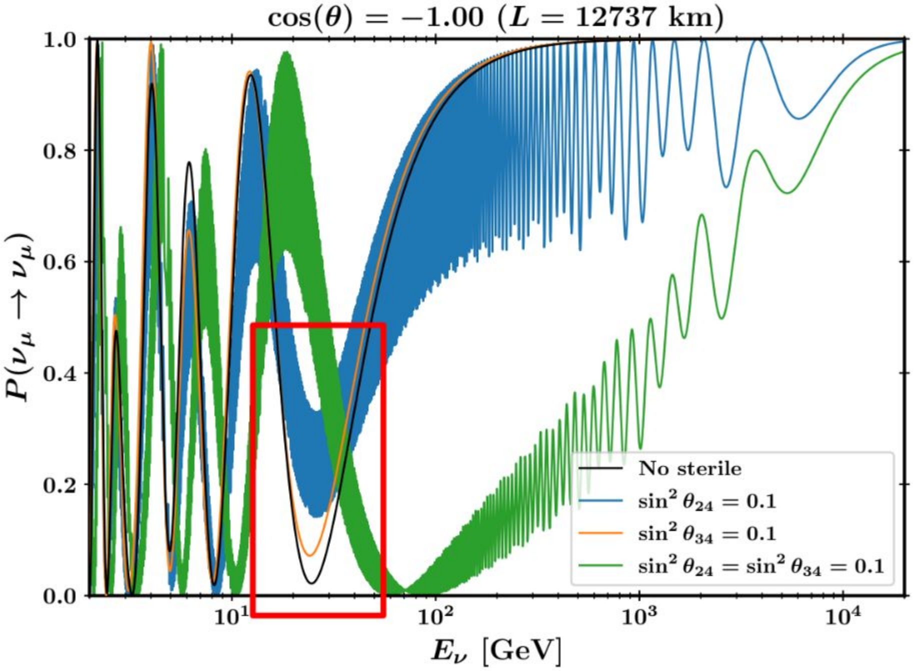


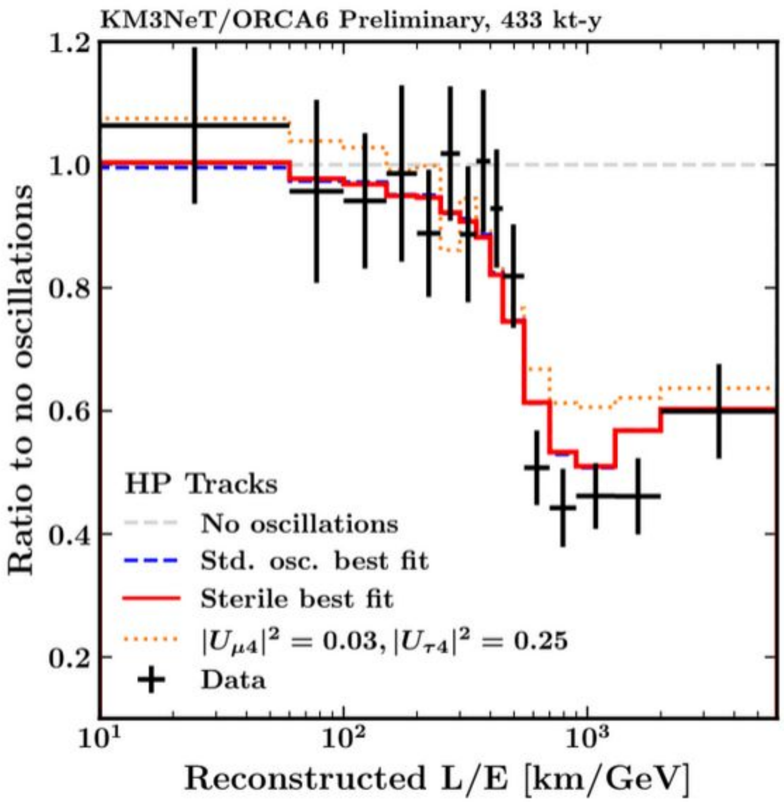
Backup: sterile neutrino theory



$$\cos(\Theta_Z) = -1, \sin^2(\Theta_{24}) = 0.1$$

Backup: sterile neutrino results with ORCA6





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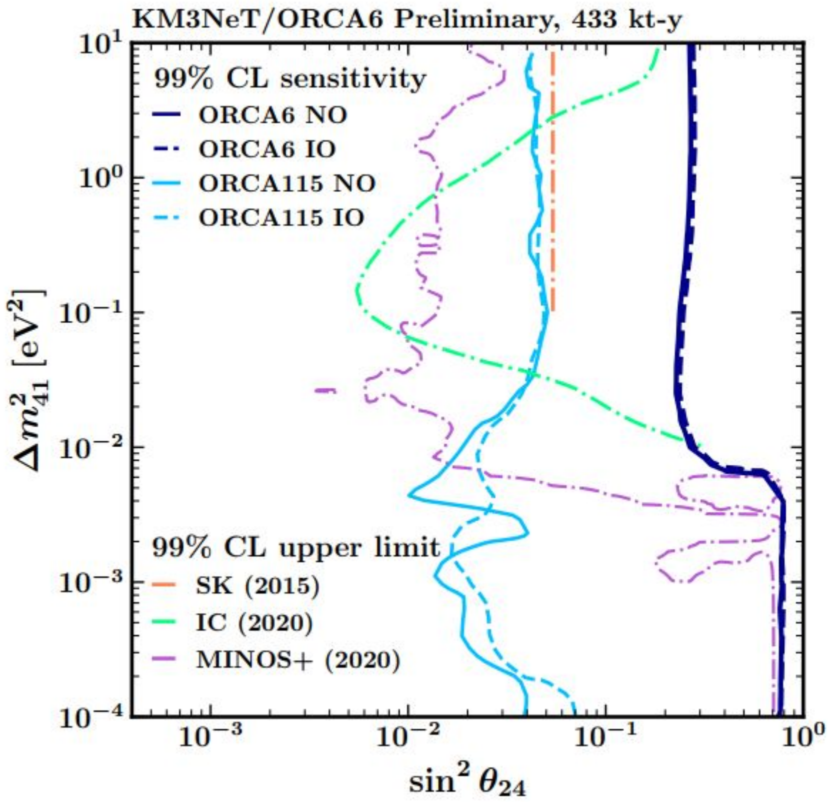
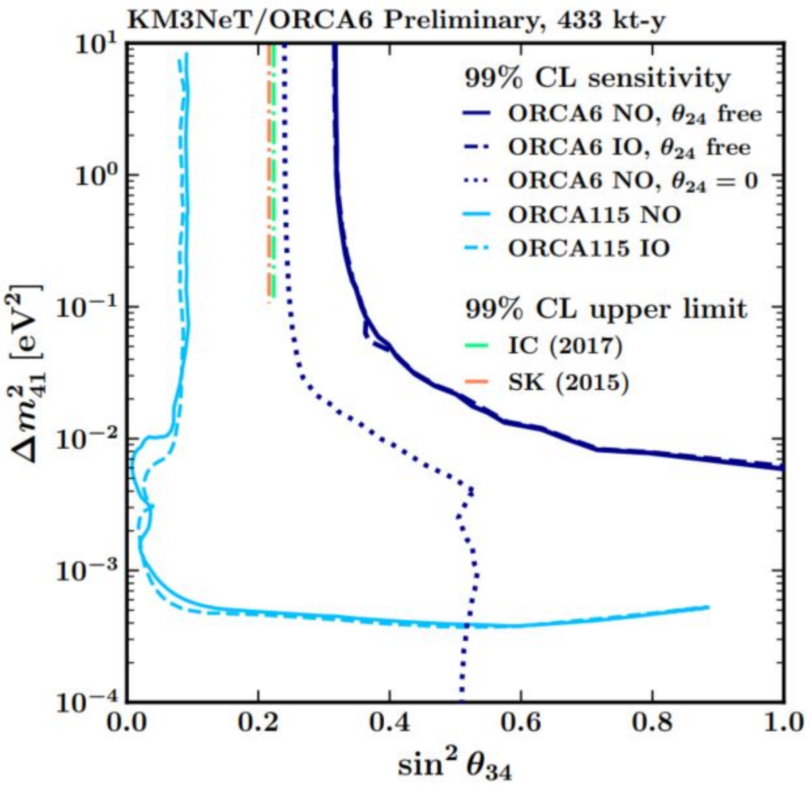


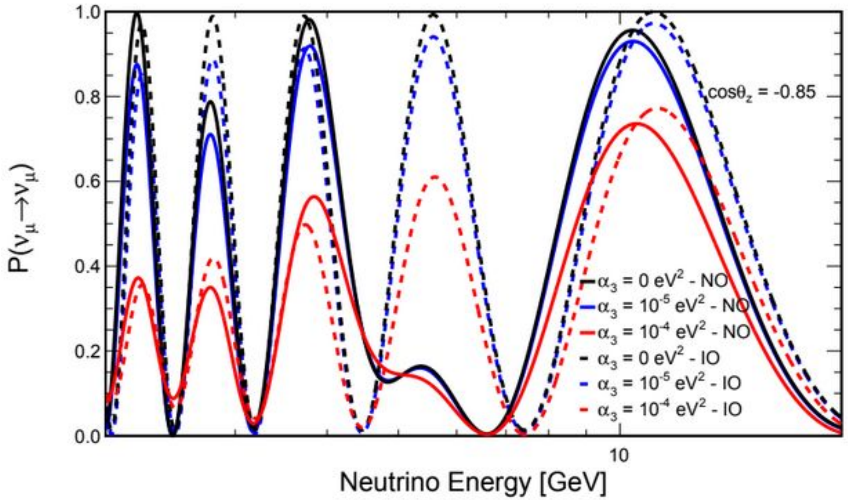


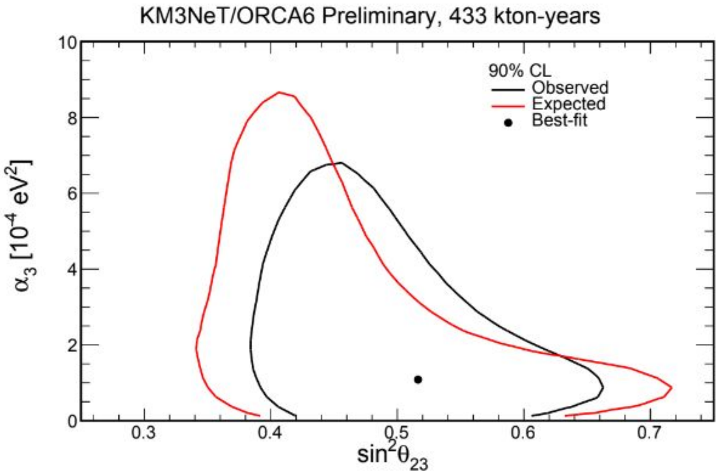
Backup: neutrino decay theory

- Neutrino mass eigenstates may decay into a particle that is not detected (sterile ν).
- Measurement of the neutrino lifetime via modifications in the oscillation pattern:

$$H = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + U \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -i\alpha_3 \end{pmatrix} U^\dagger + \begin{pmatrix} V & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\alpha_3 = \frac{m_3}{\tau_3}$$

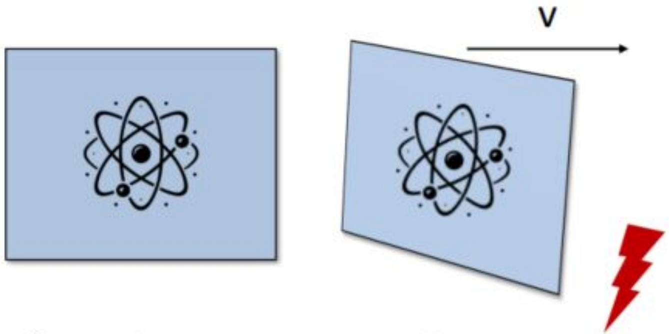




Backup: Lorentz Invariance Violation theory

- **Lorentz invariance** states that
  the outcome of an experiment is…
  1) the same for two inertial observers.
  2) independent of the inertial laboratory.

- LIV preserves observer independence
  but violates the second condition!



$(i\gamma^\mu \frac{\partial}{\partial x^\mu} - m)\,\psi(x) = 0$ $\quad$ $(i\gamma^\mu \frac{\partial}{\partial x^\mu} - m)\,\psi'(x) = 0$

- Isotropic LIV model (rotational invariance preserved)

$$H_{LIV} = \begin{pmatrix} \mathring{a}^{(3)}_{ee} & \mathring{a}^{(3)}_{e\mu} & \mathring{a}^{(3)}_{e\tau} \\ \mathring{a}^{(3)*}_{e\mu} & \mathring{a}^{(3)}_{\mu\mu} & \mathring{a}^{(3)}_{\mu\tau} \\ \mathring{a}^{(3)*}_{e\tau} & \mathring{a}^{(3)*}_{\mu\tau} & \mathring{a}^{(3)}_{\tau\tau} \end{pmatrix} - \frac{4}{3}E \begin{pmatrix} \mathring{c}^{(4)}_{ee} & \mathring{c}^{(4)}_{e\mu} & \mathring{c}^{(4)}_{e\tau} \\ \mathring{c}^{(4)*}_{e\mu} & \mathring{c}^{(4)}_{\mu\mu} & \mathring{c}^{(4)}_{\mu\tau} \\ \mathring{c}^{(4)*}_{e\tau} & \mathring{c}^{(4)*}_{\mu\tau} & \mathring{c}^{(4)}_{\tau\tau} \end{pmatrix} +$$

$$E^2\mathring{a}^{(5)} - E^3\mathring{c}^{(6)} + E^4\mathring{a}^{(7)} - E^5\mathring{c}^{(8)} + \ldots$$

Coefficient	Unit	CPT	Oscillation effect
$\mathring{a}^{(3)}$	GeV	odd	$\propto L$
$\mathring{c}^{(4)}$	-	even	$\propto LE$
$\mathring{a}^{(5)}$	GeV^{-1}	odd	$\propto LE^2$
$\mathring{c}^{(6)}$	GeV^{-2}	even	$\propto LE^3$
$\mathring{a}^{(7)}$	GeV^{-3}	odd	$\propto LE^4$
$\mathring{c}^{(8)}$	GeV^{-4}	even	$\propto LE^5$