Probing neutrino decay into axion-like particles: sensitivity of future neutrino experiments

Speaker: Maksim Danilchenko

Affiliation: Moscow State University, Faculty of Physics

Twenty-second Lomonosov conference on elementary particle physics,
Moscow(Russia), August 21-27, 2025

Plan

- Summary of article [1] (K. Stankevich, A. Studenikin, M. Vyalkov, **Generalized Lindblad master equation for neutrino evolution, Phys. rev. D 111, 036014 2025**), dedicated to obtaining equation of motion for neutrino density matrix in case of neutrino decay on massless particle

- Derivation of oscillation probability in case of decay on scalar particle

- Calculating upper limits for coupling constants of neutrino mass states with scalar particle for JUNO and DUNE

- Comparison with existing results

Oscillation decoherence due to decay on massles particle [1]

- Let's consider mass states neutrinos with different momentum, which interact with environment of some sort of particles. Then all system evolves unitary

$$\rho(t) = U(t)\rho_0 U^\dagger(t)$$

- Evolution of neutrino sub-system non-unitary described by Lindblad equation

$$\frac{\partial \rho_\nu(t)}{\partial t} = K(\rho_\nu(t)\,) \equiv [\,H(t), \rho_\nu(t)\,] + \sum_i \gamma_i \,(L_i \rho_\nu L_i^\dagger \; - \frac{1}{2}\{\,L_i^\dagger L_i, \rho_\nu\}\,) \qquad (1)$$

where ρ_ν - neutrino density matrix. H – Hamiltonian of free (or unitary) neutrino evolution, L_i, γ_i - Lindblad dissipative operators and parametrs, form of which should be determined for each specific case. (in our case – for neutrino decoherence due to decay)

Lindblad equation
Discussion of derivation

Lindblad equation can be derived using semi-group formalism [2]:

- Consider a member of a dynamical semi-group Φ_t
- Considering Φ_t as non-unitary evolution operator of quantum system requires that Φ_t be completely positive (CP) (i.e. Φ_t transform state into state)
- Require of CP determine the general form of semi-group generators:

If $\Phi_t = \exp(t \cdot K)$ is CP, than:

$$K(X) = \sum\left(V_j^{\dagger} X V_j - \left\{\tfrac{1}{2} V_j^{\dagger} V_j, X\right\}\right) + i[H, X] \quad (2)$$

Oscillation decoherence due to decay on massles particle [1]

- Most general form of Hamiltonian $H(t)$ of interaction between neutrino and medium of massless particles is:

$$H_{int}(t) = \int d^3x \sum_a j_a(x) A_a(x)$$

Where $A_a(x)$ – quantum field operator, $j_a(x) = \bar{\nu}(x)\Gamma_a \nu(x)$ – neutrino current

- Then evolution operator take form:

$$U(t_0, t) = Texp\left(-i \int_{t_0}^{t} H_{int}(t')dt'\right) \quad (3)$$

$$\rho(t) = U(t)\rho_0 U^\dagger(t)$$

Oscillation decoherence due to decay on massless particle [1]

- After expansion of evolution operator U(t) in terms of powers of coupling constants (holding only 2 first terms), taking the trace over environment states and making some approximation, the equation of motion for $\rho_\nu(t)$ is obtained ("generalized Lindblad equation" **which consider a transition between different neutrino states with change of momentum**)

$$\frac{\partial \rho_{\mathbf{p}}(t)}{\partial x} = \left[H(t), \rho_{\mathbf{p}}(t)\right] - \frac{1}{2}\sum_i \left(\Gamma_{i\boldsymbol{p}}^d + \Gamma_{i\boldsymbol{p}}^a\right)\left\{\Pi_{ii}, \rho_{\mathbf{p}}(t)\right\} +$$

$$+\sum_i \int \frac{d^3k}{2(2\pi)^3\omega}\left[\sum_{j:\{m_j>m_i\}} \int \frac{d^3q}{2(2\pi)^3 E_{\boldsymbol{q}j}} \Gamma_{j\boldsymbol{q}\to i\boldsymbol{p}}^d \Pi_{ij}\rho_{\mathbf{p}}(t)\Pi_{ji} + \sum_{j:\{m_j<m_i\}} \int \frac{d^3q}{2(2\pi)^3 E_{\boldsymbol{q}j}} \Gamma_{j\boldsymbol{q}\to i\boldsymbol{p}}^a \Pi_{ij}\rho_{\mathbf{p}}(t)\Pi_{ji}\right] \quad (4)$$

where $\Gamma_{i\boldsymbol{p}}^d$ – width of the decay of the neutrino stationary state $|i\boldsymbol{p}\rangle$ to all possible neutrino states with emission of massless particle, $(\Gamma_{i\boldsymbol{p}}^a)$ – width of inverse process;

$\Gamma_{j\boldsymbol{q}\to i\boldsymbol{p}}^d$ - width of decay $|j\boldsymbol{q}\rangle \to |i\boldsymbol{p}\rangle$,

$\Pi_{ij} = \langle j \mid i \rangle$ - is the projector on the neutrino stationary state

Oscillation decoherence due to decay on massless particle [1]

- For the case of scalar particle interaction is given by Lagrangian:

$$\Gamma_a \to (g^s \mathbb{1} + i g^p \gamma^5), \quad A_a \to \phi$$

$$L_{int} = i\phi \sum_{i \neq j} g_{ij} \overline{\nu}_i \nu_j + H.c.$$

where ϕ – scalar field, g_{ij} - coupling constants, ν_j - neutrino mass state

- Then equation on $\rho_\nu(t)$ take a form

$$\frac{\partial \rho(|\mathbf{p}|,t)}{\partial t} = -i[H(t), \rho(|\mathbf{p}|,t)] + \sum_{i,f:\{i>f\}} \left[-\frac{1}{2} \Gamma^S_{if} \{\Pi_{ii}, \rho(|\mathbf{p}|,t)\} + g^2_{if} \int_{|\mathbf{p}|}^{(\frac{m_i}{m_f})^2 |\mathbf{p}|} \frac{d|\mathbf{q}|}{16\pi^4} \left(\frac{m_f^2}{|\mathbf{p}|^2} + \frac{m_i^2}{|\mathbf{q}|^2} + 2\frac{m_i m_f}{|\mathbf{p}||\mathbf{q}|} \right) \Pi_{if} \rho(|\mathbf{q}|,t) \Pi_{fi} \right] \quad (5)$$

Oscillation decoherence due to decay on scalar particle [1]

In case of degenerate mass hierarchy ($m_i \approx m_j$) :

$$g_{ij}^2 \int_{|\mathbf{p}|}^{(\frac{m_i}{m_f})^2|\mathbf{p}|} \frac{d|\mathbf{q}|}{16\pi^4}\left(\frac{m_f^2}{|\mathbf{p}|^2}+\frac{m_i^2}{|\mathbf{q}|^2}+2\frac{m_i m_f}{|\mathbf{p}||\mathbf{q}|}\right) \approx \Gamma_{if}^S \qquad \Gamma_{if}^S = \frac{g_{if}^2}{\pi}\frac{(m_i^2-m_f^2)}{|\mathbf{p}|}$$

Then we get Lindblad equation with following L_i and γ_i :

$$L_1 = \Pi_{12} \;\; \& \;\; \gamma_1 = \Gamma_{21}^S,$$
$$L_2 = \Pi_{13} \;\; \& \;\; \gamma_2 = \Gamma_{31}^S,$$
$$L_3 = \Pi_{23} \;\; \& \;\; \gamma_3 = \Gamma_{32}^S.$$

Oscillation decoherence due to decay on scalar particle [1]

Solution can be obtained using expansion on SU(3) generators (8 Gell-Mann matricies) + unit matrix :

$$\frac{\partial P_k(t)}{\partial t} F_k = 2\epsilon_{ijk} H_i P_j(t) F_k + D_{kl} P_k(t) F_l \qquad (6)$$

where: $F_0 = \mathbb{1}$, $F_i = \frac{1}{2}\lambda_i$, λ_i - Gell-Mann matricies, D_{kl} - dissipative matrix:

$$D^{(3)}_{kl} = -\frac{1}{2}\begin{pmatrix} 0 & 0 & 0 & -\frac{1}{3}(2\Gamma^S_{21}+\Gamma^S_{31}-\Gamma^S_{32}) & 0 & 0 & 0 & 0 & -\frac{1}{\sqrt{3}}(\Gamma^S_{32}+\Gamma^S_{31}) \\ 0 & \Gamma^S_{21} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \Gamma^S_{21} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2\Gamma^S_{21} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \Gamma^S_{32}+\Gamma^S_{31} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \Gamma^S_{32}+\Gamma^S_{31} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \Gamma^S_{32}+\Gamma^S_{31}+\Gamma^S_{21} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \Gamma^S_{32}+\Gamma^S_{31}+\Gamma^S_{21} & 0 \\ 0 & 0 & 0 & -\frac{2}{\sqrt{3}}(\Gamma^S_{21}+\Gamma^S_{32}-\Gamma^S_{31}) & 0 & 0 & 0 & 0 & 2(\Gamma^S_{32}+\Gamma^S_{31}) \end{pmatrix}.$$

Oscillation decoherence due to decay on scalar particle

Oscillation probability

$$P_{\alpha\to\beta}(t) = Tr(\,\rho_\alpha(t)\rho_\beta(0)\,) = 3\rho_\alpha(t)_0\rho_\beta(0)_0 + \frac{1}{2}\sum_{i=1}^{i=8}\rho_\alpha(t)_i\rho_\beta(0)_i =$$

$$= \delta_{\alpha\beta} - 2\sum_{j<k}\Re(U^*_{\alpha k}\,U_{\alpha j}U_{\beta k}U^*_{\beta j})\left(1 - \cos\left(\frac{\Delta m^2_{jk}}{2E}\cdot t\right)e^{-\Gamma_{jk}t}\right)$$

$$+2\sum_{j<k}\Im(U^*_{\alpha k}\,U_{\alpha j}U_{\beta k}U^*_{\beta j})sin\left(\frac{\Delta m^2_{jk}}{2E}\cdot t\right)e^{-\Gamma_{jk}t} +$$

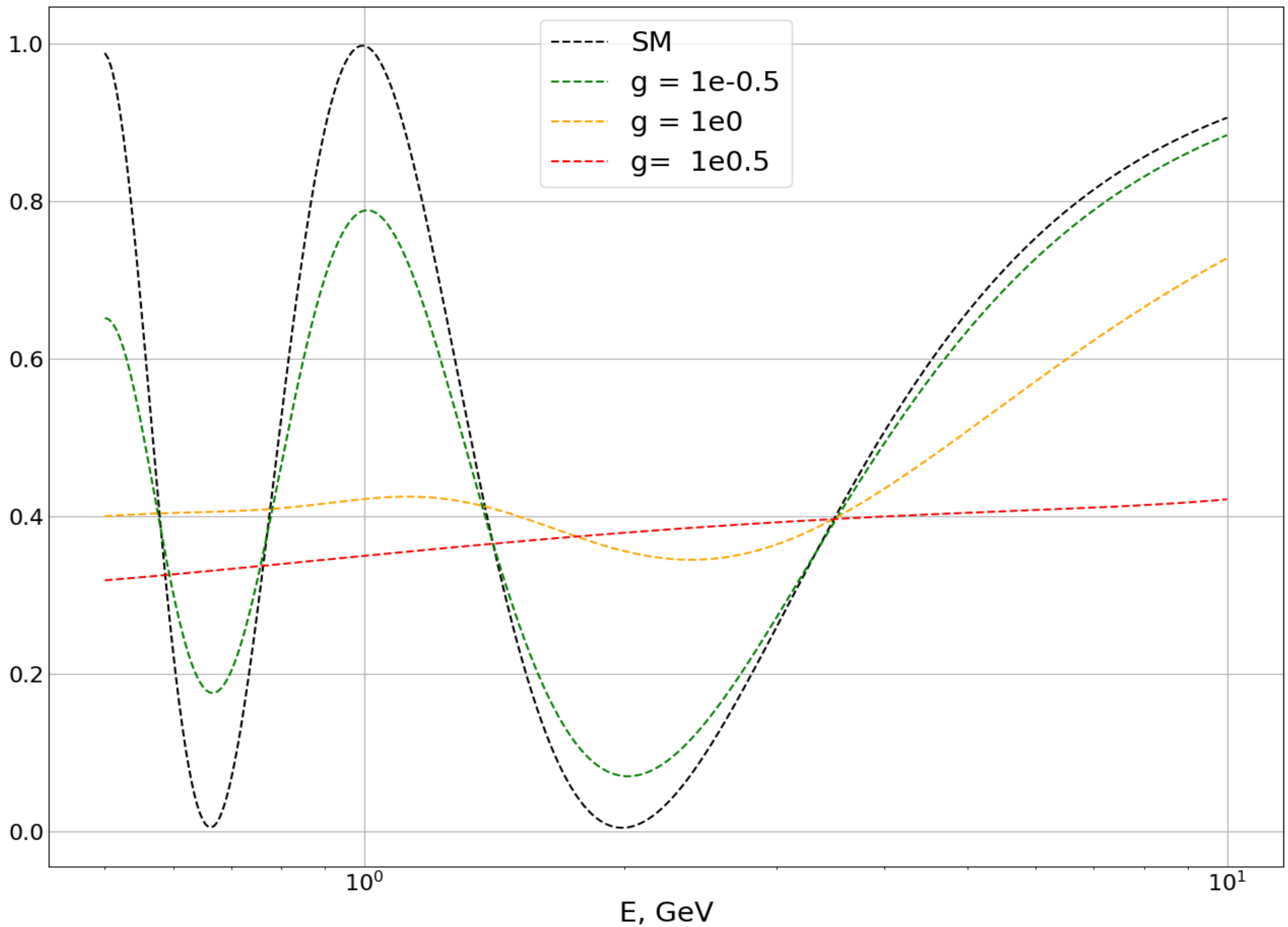
$$+\frac{1}{2}\left(\left|U_{\beta 1}\right|^2 - \left|U_{\beta 2}\right|^2\right)\left[\left(1 - e^{-\Gamma_{21}t}\right)\left(\frac{1}{6} - (|U_{\alpha 1}|^2 - |U_{\alpha 2}|^2)\right) + \frac{c}{3}\cdot\frac{e^{-\Gamma_{21}t} - e^{-bt}}{\Gamma_{21} - b}\left(\frac{1}{6} - (1 - 3|U_{\alpha 3}|^2)\right)\right] +$$

$$+\frac{1}{6}\left(1 - 3\left|U_{\beta 3}\right|^2\right)\left(1 - e^{-bt}\right)\left(\frac{1}{6} - (1 - 3|U_{\alpha 3}|^2)\right) \qquad (7)$$

where

$$b = \Gamma_{32} + \Gamma_{31}, \qquad c = \Gamma_{21} + \Gamma_{32} - \Gamma_{31}$$

$P_{\nu_\mu \to \nu_\mu}(E)$ at $L = 1000\ km$



Above derivation can be easily generalized to the presence of matter:

one should replace vacuum mixing angle and masses on effective ones – because eigenstates in matter are no longer mass states, decay will occur between these matter eigenstates

$$\theta \to \tilde{\theta}, \qquad \mathrm{m}_i \to \widetilde{m_i}$$

Constraints on coupling constants

Software and statistical methods

- For all experiments simulations we use the GLoBES software [3], [4]
- For setting upper limits we use Feldman – Cousin method [5]:
  - We consider statistic:

$$\Delta\chi^2 \overset{\text{def}}{=} -2\log\left(\frac{P(N|\theta)}{P(N|\theta_{best})}\right) = \chi^2(\theta) - \chi^2_{min} \quad (8)$$

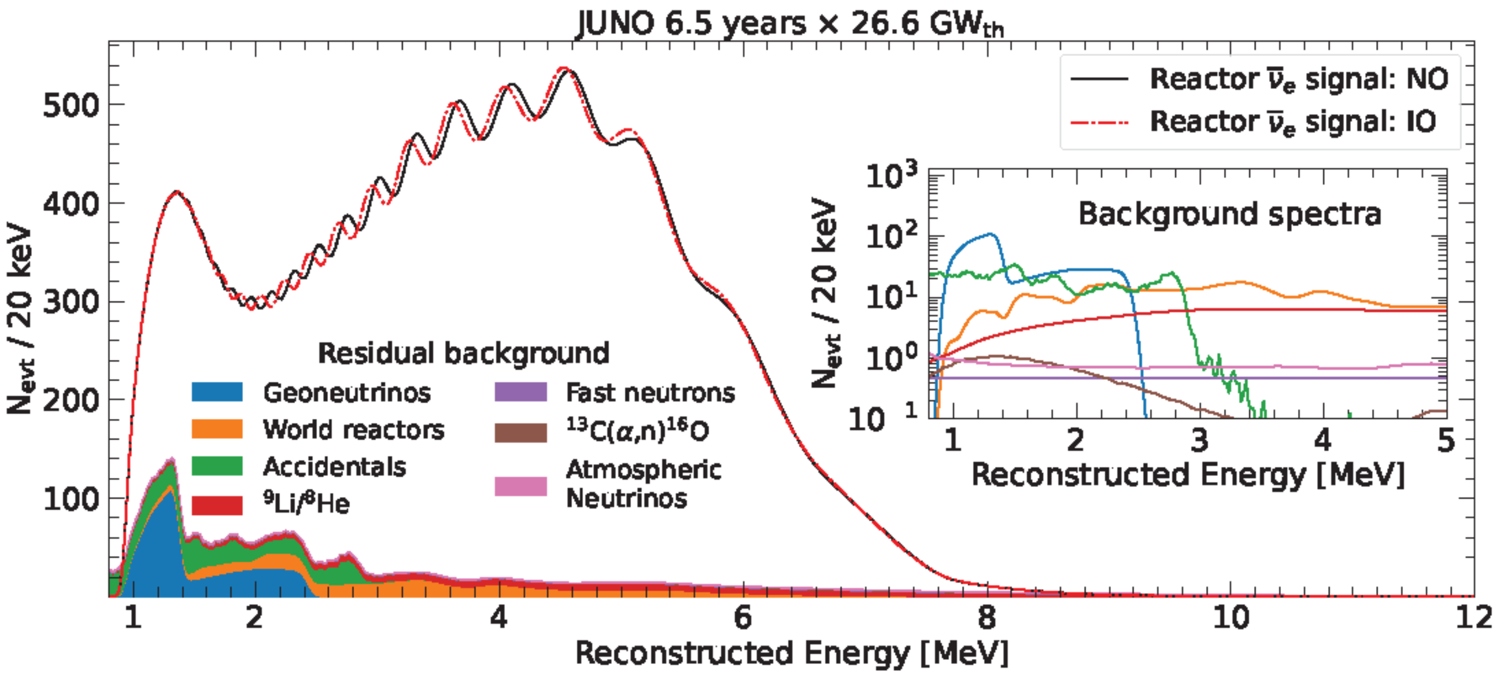
  - For sensitivity test number of observed events in experiment replaced by number of events, calculated in no-decay model

Constraints on coupling constants

Sensitivity test: JUNO

JUNO is a reactor experiment using a 20 kton liquid scintillator (LS) detector located approximately 52.5 km from the Taishan and Yangjiang nuclear power plants (NPPs) in Jiangmen City, Guangdong Province,China.

JUNO designed primarily for determining neutrino mass ordering (hierarchy) (figure taken from [6])



Constraints on coupling constants

Sensitivity test: JUNO. Experiment configuration

- Energy resolution [7]:

$$R(E,E') = \frac{1}{\sigma(E)\sqrt{2\pi}} e^{-\frac{(E-E')^2}{2\sigma^2(E)}}, \quad \sigma(E) = 2.95\% \sqrt{\frac{E-(m_n-m_p-m_e)}{1MeV}} \qquad (9), (10)$$

$$\sigma(E) = E\sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}$$

(11) – more accurate, but we assume simplified form as in (10)

- Density $\rho = 2.45\ g/cm^3$ as in [6]

- Exposure equal to 6.5 years

Constraints on coupling constants

Sensitivity test: JUNO. Systematic uncertainties

Systematic uncertainties are taken from [7] and [12]. They are include:

- IBD selection efficiency: parameterize efficiency coefficient – $(0.822 + \alpha_{eff}) \cdot N$
- Uncorrelated flux shape uncertainty: parameterize fluxes in each bin – $\left(1 + \alpha_{shape_i}\right) \cdot N_i$ (200 nuisance parameters)
- Uncorrelated reactor flux uncertainty: parameterize fluxes from each reactor - $\left(1 + \alpha_{reactor_j}\right) \cdot N_j$ (11 nuisance parameters)
- Correlated reactor flux normalization: parameterize total flux – $(1 + \alpha_{norm}) \cdot N$
- Calibration error due to non-linear detector energy response [12] - for neutrino decay sensitivity test calibration error gives change of $\Delta\chi^2 \approx 0.01$ and it's negligible small. That's why we don't account for this effect in final calculations

Constraints on coupling constants

Sensitivity test: JUNO. Upper limits

- For sensitivity test we assume, that all coupling constants are equal ($g_{12} = g_{13} = g_{23}$)
- For check aplying Wilks theorem we simulate 20000 experiments and determine $\Delta\chi^2(g)_c$ for C.L. = 90%.
- Experiments are simulated assuming, that number of events in each bin n_i distributed normally with $\mu = n_i(\theta)$ and $\sigma = \sqrt{n_i(\theta)}$

Constraints on coupling constants

Sensitivity test: JUNO. Upper limits

- We've got result:

$$\Delta\chi^2 = 2.472\ for\ 90.14\%\ C.L.$$

- This gives next upper limits:

$$\boldsymbol{g < 0.0134215}$$

- In terms decay widths (for $E_\nu = 1GeV$)

$$\boldsymbol{\Gamma_{31} < 1.44 \cdot 10^{-25} GeV,\ \Gamma_{21} < 4.3 \cdot 10^{-27} GeV,\ \Gamma_{32} < 1.41 \cdot 10^{-25} GeV}$$

- In terms of value $\alpha = E \cdot \Gamma$:

$$\alpha_{31} < 1.44 \cdot 10^{-7} eV^2,\ \alpha_{21} < 4.3 \cdot 10^{-9} eV^2,\ \alpha_{32} < 1.41 \cdot 10^{-7} eV^2$$

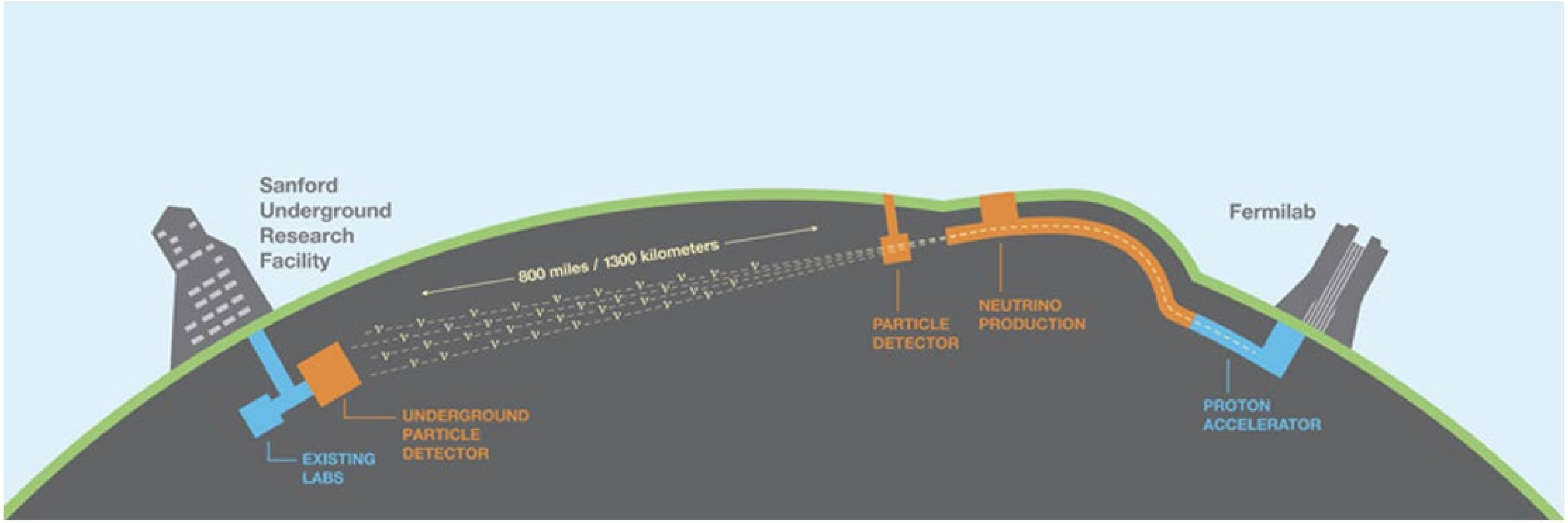
Constraints on coupling constants

Sensitivity test: DUNE. [13], [14]

DUNE – is a neutrino beam experiment, comprises three central components:
(1) high-intensity neutrino source generated from a megawatt-class proton accelerator at Fermilab

(2) a massive far detector (FD) situated 1.5km underground at the San ford Underground Research Facility (SURF) in South Dakota

(3) a composite near detector (ND) installed just downstream of the neutrino source [14]



Constraints on coupling constants

Sensitivity test: DUNE. Experiment configuration [13],[14].

For DUNE simulation we use GLoBES configuration, provided by DUNE collaboration [13], [14] (but ν_τ cross sections are set to zero)

Name Includes	Process	Description
Appearance Mode:		
app_osc_nue	$\nu_\mu \to \nu_e$ (CC)	Electron Neutrino Appearance Signal
app_osc_nuebar	$\overline{\nu}_\mu \to \overline{\nu}_e$ (CC)	Electron Antineutrino Appearance Signal
app_bkg_nue	$\nu_e \to \nu_e$ (CC)	Intrinsic Beam Electron Neutrino Background
app_bkg_nuebar	$\overline{\nu}_e \to \overline{\nu}_e$ (CC)	Intrinsic Beam Electron Antineutrino Background
app_bkg_numu	$\nu_\mu \to \nu_\mu$ (CC)	Muon Neutrino Charged-Current Background
app_bkg_numubar	$\overline{\nu}_\mu \to \overline{\nu}_\mu$ (CC)	Muon Antineutrino Charged-Current Background
app_bkg_nutau	$\nu_\mu \to \nu_\tau$ (CC)	Tau Neutrino Appearance Background
app_bkg_nutaubar	$\overline{\nu}_\mu \to \overline{\nu}_\tau$ (CC)	Tau Antineutrino Appearance Background
app_bkg_nuNC	$\nu_\mu/\nu_e \to$ X (NC)	Neutrino Neutral Current Background
app_bkg_nubarNC	$\overline{\nu}_\mu/\overline{\nu}_e \to$ X (NC)	Antineutrino Neutral Current Background
Disappearance Mode:		
dis_bkg_numu	$\nu_\mu \to \nu_\mu$ (CC)	Muon Neutrino Charged-Current Signal
dis_bkg_numubar	$\overline{\nu}_\mu \to \overline{\nu}_\mu$ (CC)	Muon Antineutrino Charged-Current Signal
dis_bkg_nutau	$\nu_\mu \to \nu_\tau$ (CC)	Tau Neutrino Appearance Background
dis_bkg_nutaubar	$\overline{\nu}_\mu \to \overline{\nu}_\tau$ (CC)	Tau Antineutrino Appearance Background
dis_bkg_nuNC	$\nu_\mu/\nu_e \to$ X (NC)	Neutrino Neutral Current Background
dis_bkg_nubarNC	$\overline{\nu}_\mu/\overline{\nu}_e \to$ X (NC)	Antineutrino Neutral Current Background

Constraints on coupling constants

Sensitivity test: DUNE. Upper limits

- We again assume all coupling constants to be equal

- We assume that Wilk's theorem is holding. In this case, $\chi^2_{min} = 0$ and $\Delta\chi^2 \equiv \chi^2(\theta)$ follows χ^2 distribution with 1 d.o.f. Then 90% C.L. is reached at $\Delta\chi^2 \approx 2.7$

Constraints on coupling constants

Sensitivity test: DUNE. Upper limits

- In above assumptions we've got result:

$$\boldsymbol{g < 0.0537032 \;\; with\; 90.2\,\%\; C.L.}$$

- In terms decay widths (for $E_\nu = 1GeV$)

$$\boldsymbol{\Gamma_{31} < 2.32 \cdot 10^{-24} GeV,\;\; \Gamma_{21} < 6.89 \cdot 10^{-27} GeV,\;\; \Gamma_{32} < 2.25 \cdot 10^{-24} GeV}$$

- In terms of value $\alpha = E \cdot \Gamma$:

$$\alpha_{31} < 2.32 \cdot 10^{-6} eV^2,\;\; \alpha_{21} < 6.89 \cdot 10^{-9} eV^2,\;\; \alpha_{32} < 2.25 \cdot 10^{-6} eV^2$$

Constraints on coupling constants

Sensitivity test: DUNE. Upper limits

Upper limits for DUNE are worse than for JUNO, because of DUNE works on the GeV scale and JUNO on MeV, and decoherence effect is bigger for smaller energies due to inverse energy dependence of decay width

$$\Gamma_{if}^{S} = \frac{g_{if}^2}{\pi} \frac{(m_i^2 - m_f^2)}{|\mathbf{p}|}$$

Constraints on coupling constants

Comparison with existing results

- In work [15] was considered case of neutrino decay to Majoron (massles scalar particle) in assumption, that there is only $\nu_3 \to \nu_1$ decay without change of momentum. This result based on T2K + MINOS data analysis

$$\alpha \lesssim 7.8 \cdot 10^{-5}\, eV^2$$

- In work [16] was considered model independent approach, when dissipative matrix is diagonal. From this article we compare with their case, when all Γ_{ij} are equal and $\Gamma_{ij} \sim \frac{1}{E_\nu}$. Then for JUNO there was obtained upper limit:

$$\alpha \lesssim 4.52 \cdot 10^{-7}\, eV^2$$

Summary

- Oscillation probability of neutrino in model of decay to massless scalar partical in case of degenerate mass hierarchy, based on work [1], was calculated

- Sensitivity of two future experiments – JUNO and DUNE – to neutrino decay was estimated:

JUNO : $\boldsymbol{\Gamma_{31} < 1.44 \cdot 10^{-25} GeV}$, $\boldsymbol{\Gamma_{21} < 4.3 \cdot 10^{-27} GeV}$, $\boldsymbol{\Gamma_{32} < 1.41 \cdot 10^{-25} GeV}$

DUNE: $\boldsymbol{\Gamma_{31} < 2.32 \cdot 10^{-24} GeV}$, $\boldsymbol{\Gamma_{21} < 6.89 \cdot 10^{-27} GeV}$, $\boldsymbol{\Gamma_{32} < 2.25 \cdot 10^{-24} GeV}$

Bibliography

- [1] – K. Stankevich, A. Studenikin, M. Vyalkov, **Generalized Lindblad master equation for neutrino evolution, Phys. rev. D 111, 036014 (2025)**
- [2] - G. Lindblad, **On the Generators of Quantum Dynamical Semigroups 1976**
- [3] - P. Huber, M. Lindner, and W. Winter, **Simulation of long-baseline neutrino os cillation experiments with GLoBES**
- [4] - P. Huber, J. Kopp, M. Lindner, M. Rolinec, and W. Winter, **New features in the simu lation of neutrino oscillation experiments with GLoBES 3.0**
- [5] - Gary J. Feldman, Robert D. Cousins, **A Unified Approach to the Classical Statistical Analysis of Small Signals**
- [6] - **Potential to identify neutrino mass ordering with reactor antineutrinos at JUNO 2025-02-13**
- [7] - IceCube-Gen2 Collaboration, JUNO Collaboration Members, **Combined sensitivity to the neutrino mass ordering with JUNO, the IceCube Upgrade, and PINGU**
- [8] – Patrick Huber, **On the determination of anti-neutrino spectra from nuclear reactors**
- [9] - Th. A. Mueller et al., **Improved Predictions of Reactor Antineutrino Spectra**
- [10] – Liang Zhan et al., **Determination of the Neutrino Mass Hierarchy at an Intermediate Baseline**
- [11] - X. B. Ma et al., **Improved Calculation of the Energy Release in Neutron Induced Fission**
- [12] – David V. Forero, Stephen J. Parke, Christoph A. Ternes, and Renata Zukanovich Funchal, **JUNO's prospects for determining the neutrino mass ordering**
- [13] - B. Abi et al., **DUNE 2020**
- [14] - B. Abi et al., **Experiment Simulation Configurations Approximating DUNE TDR**
- [15] Lena Funcke, Georg Raffelt, and Edoardo Vitagliano, **Distinguishing Dirac and Majorana neutrinos by their decays via Nambu-Goldstone bosons in the gravitational-anomaly model of neutrino masses**
- [16] – Valentina De Romeri, Carlo Giunti, Thomas Stuttard, and Christoph A. Ternes, **Neutrino oscillation bounds on quantum decoherence**