The experiment Neutrino-4 on the search for sterile neutrino at SM-3 reactor

1. The direct observation of sterile neutrino oscillation in Neutrino-4 experiment
2. Possibility of experimental confirmation of the 3 + 1 neutrino model with one sterile neutrino

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Neutrino-4 collaboration

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TWENTIETH LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS
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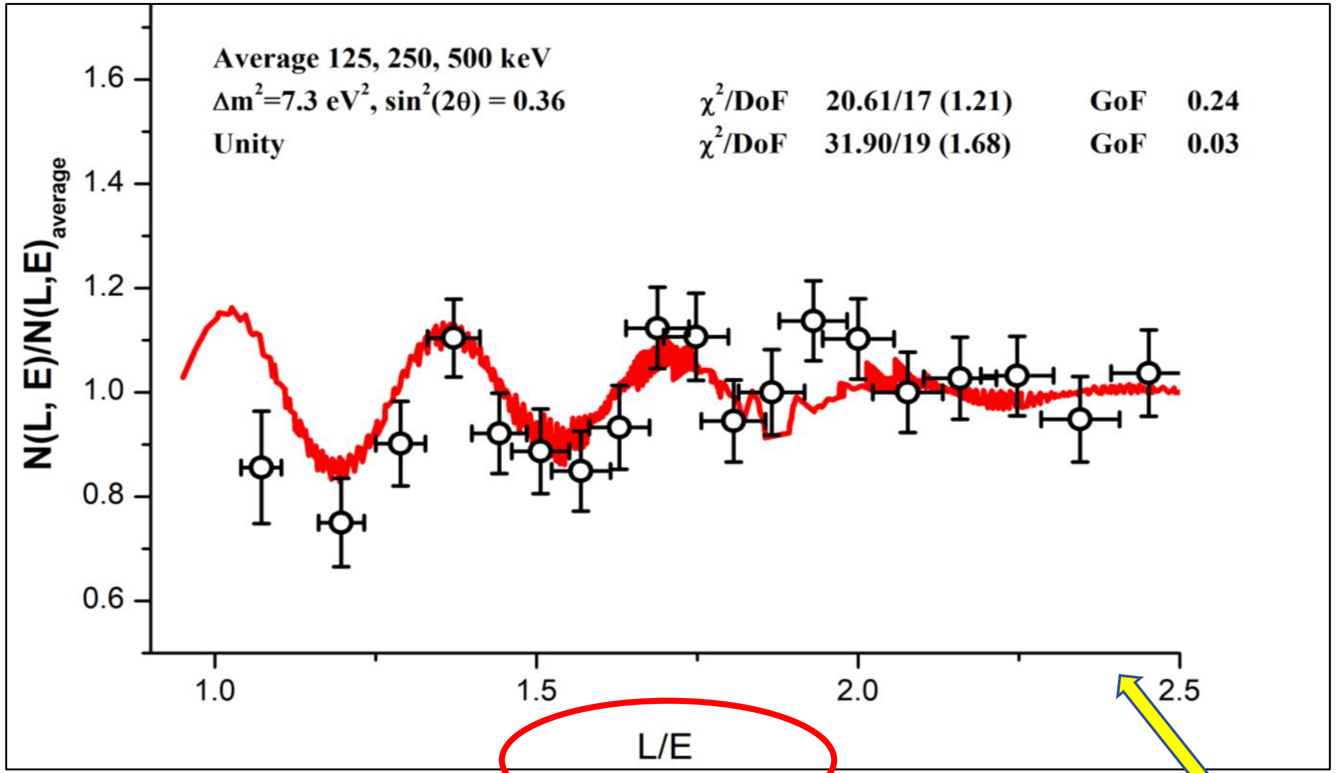
The direct observation of effect of oscillation in Neutrino-4 experiment on search for sterile neutrino

A.P. Serebrov, et al. PHYSICAL REVIEW D 104, 032003 (2021)



$$P(\tilde{\nu}_e \to \tilde{\nu}_e) = 1 - \sin^2 2\theta_{14} \; \sin^2\left(1.27 \frac{\Delta m^2_{14}[\mathrm{eV}^2] L[\mathrm{m}]}{E_{\tilde{\nu}}[\mathrm{MeV}]}\right)$$

The period of oscillation for neutrino energy 4 MeV is 1.4 m

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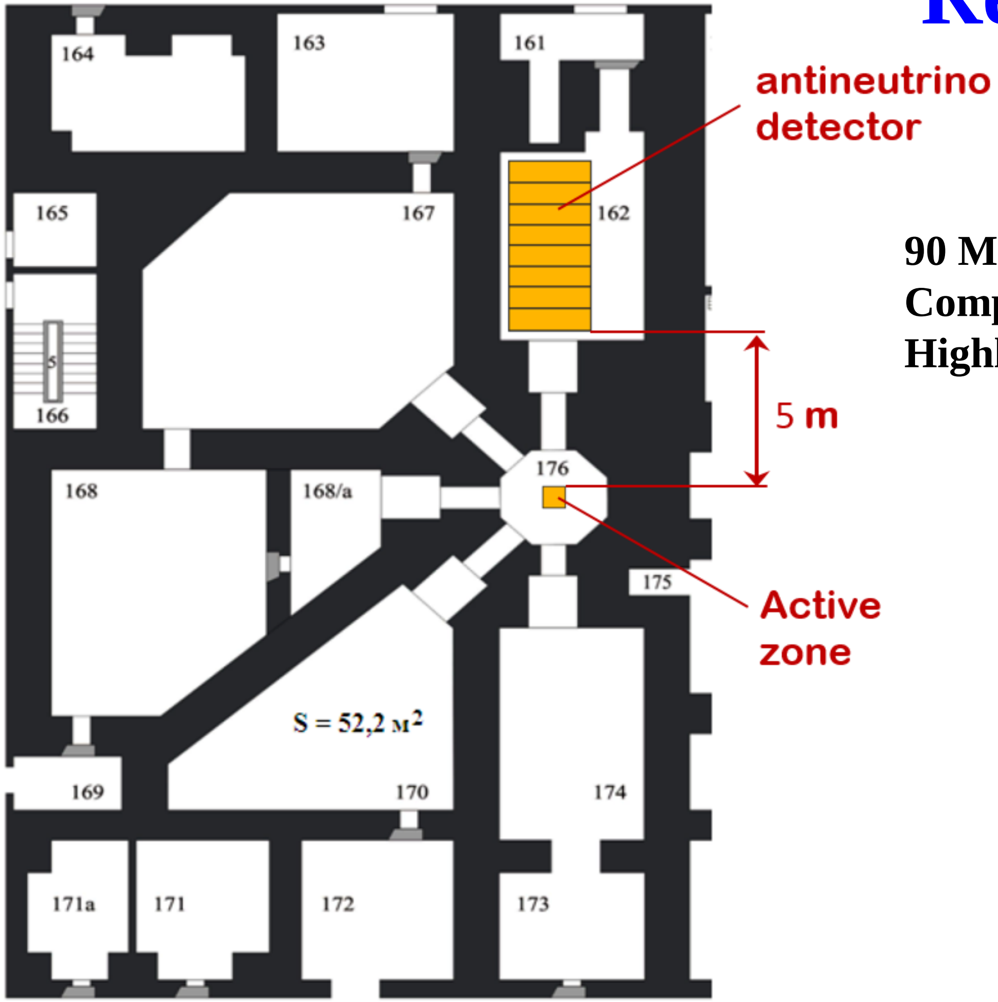
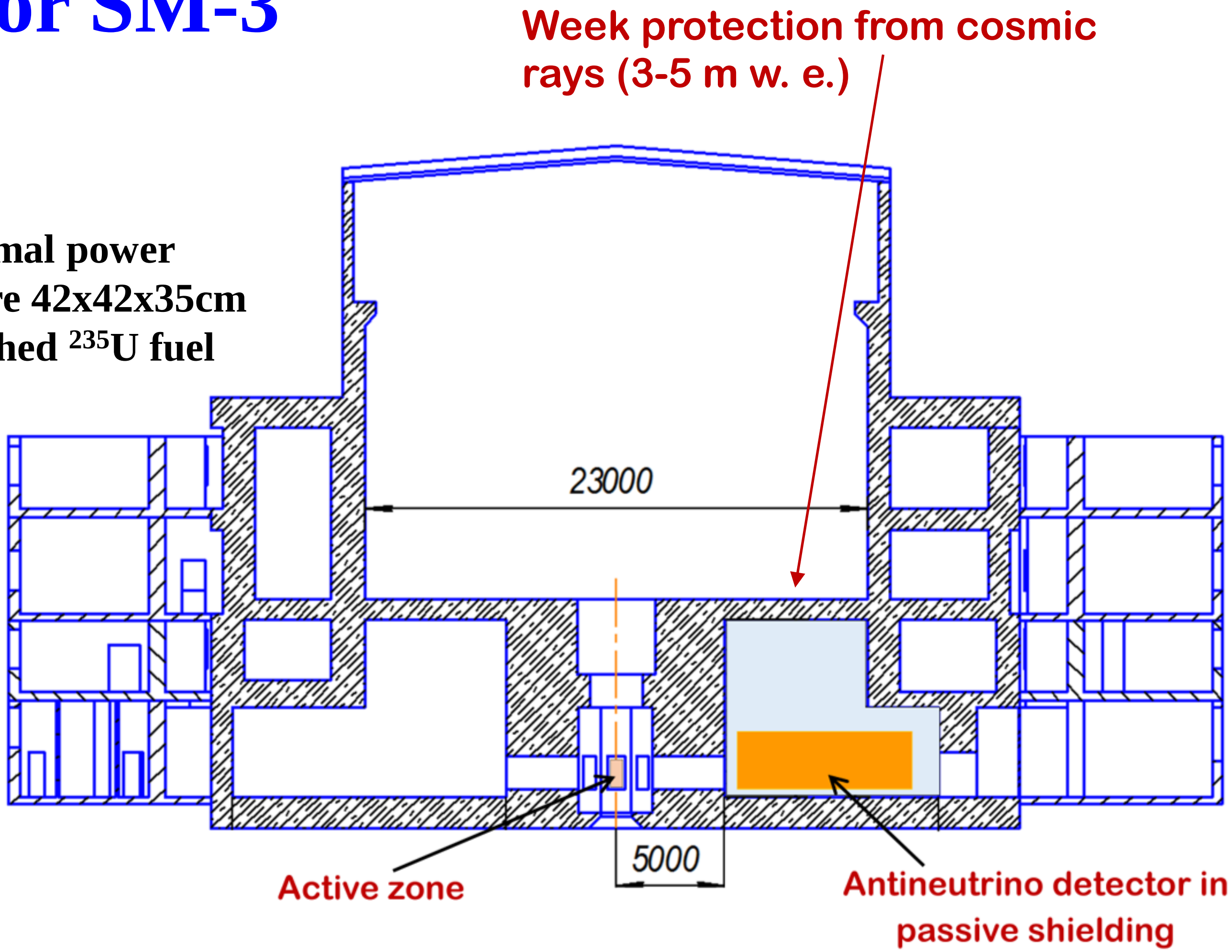
NEUTRINO 2020

Reactor SM-3

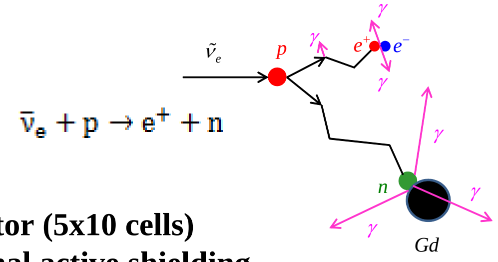


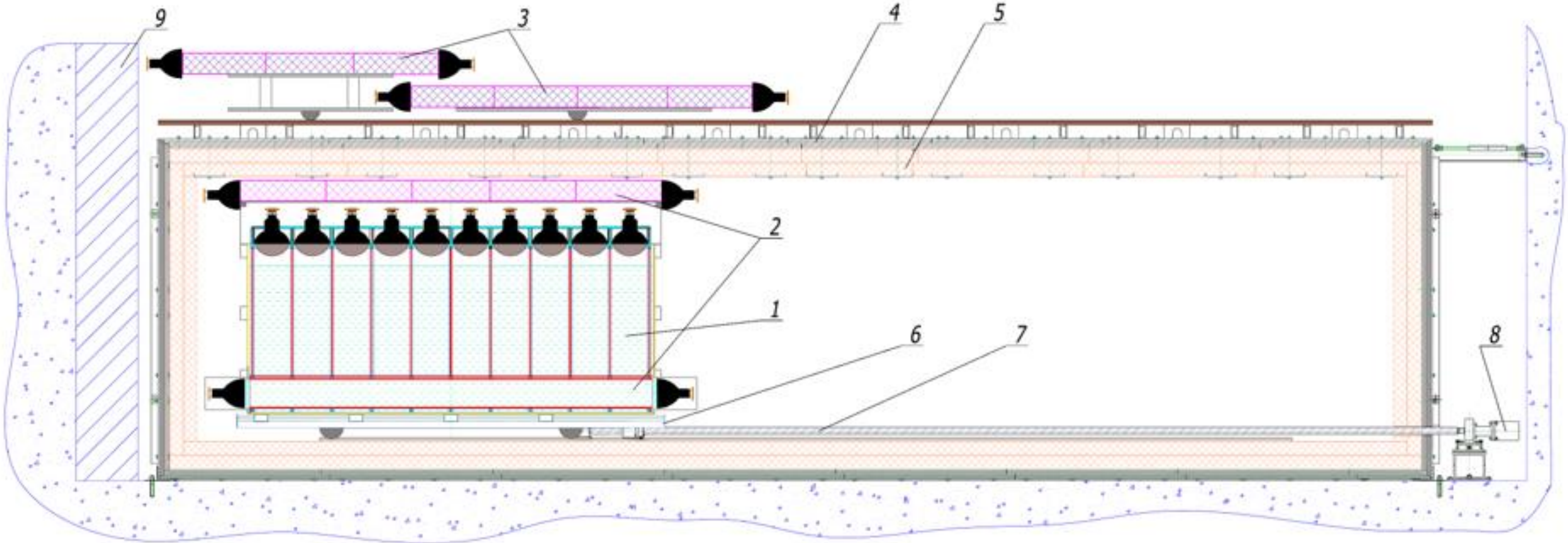
90 MW thermal power
Compact core 42x42x35cm
Highly enriched ^{235}U fuel



Due to some peculiar characteristics of its construction, reactor SM-3 provides the most favorable conditions to search for neutrino oscillations at short distances. However, SM-3 reactor, as well as other research reactors, is located on the Earth's surface, hence, cosmic background is the major difficulty in considered experiment.

Movable and spectrum sensitive antineutrino detector at SM-3 reactor





1. detector (5x10 cells)
2. internal active shielding
3. external active shielding
4. steel and lead
5. borated polyethylene
6. moveable platform
7. feed screw
8. step motor
9. shielding

Passive shielding - 60 tons

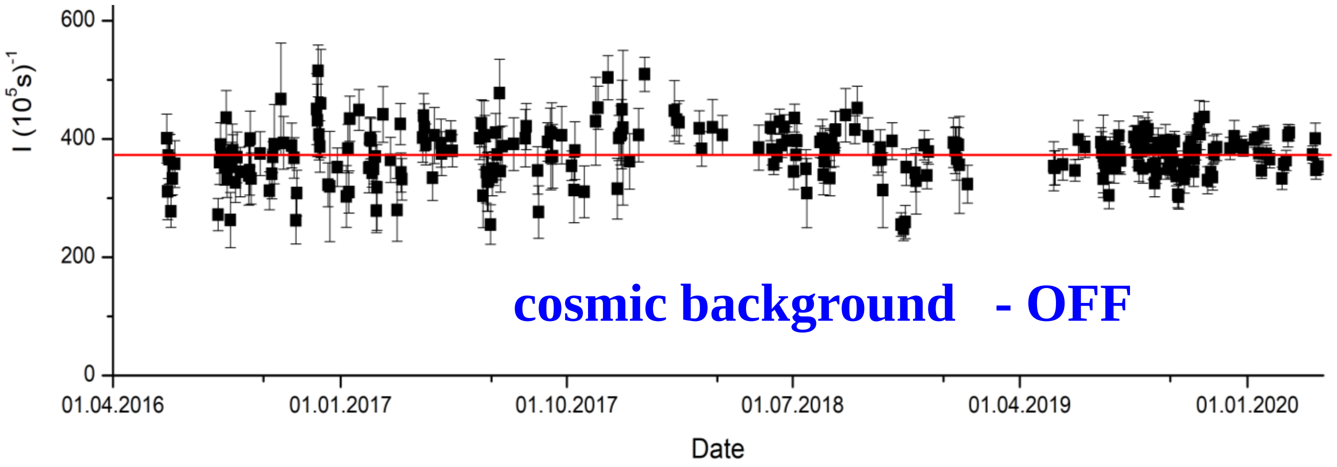
Neutrino channel outside and inside

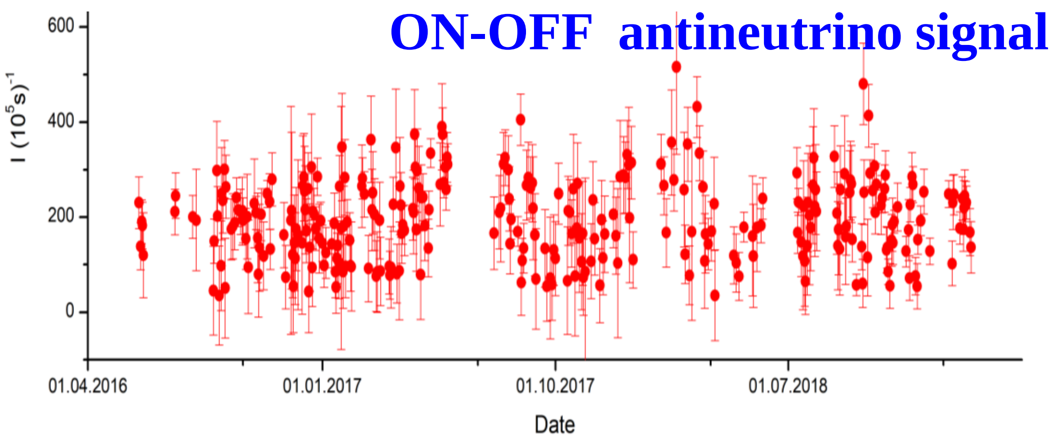
Range of measurements is 6 – 12 meters

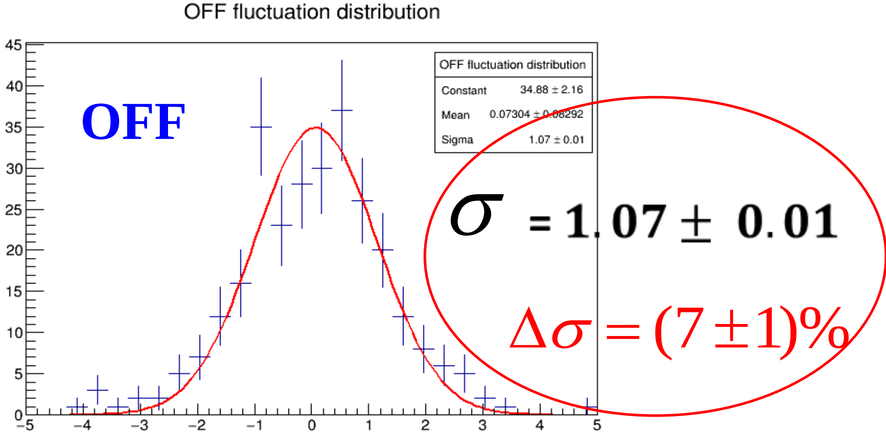
Detector prototype

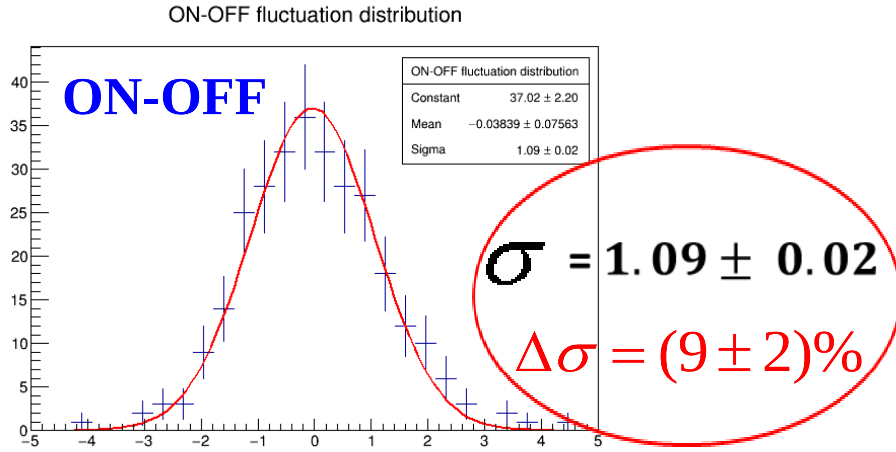
Full-scale detector

Liquid scintillator detector
50 sections 0.235x0.235x0.85м³





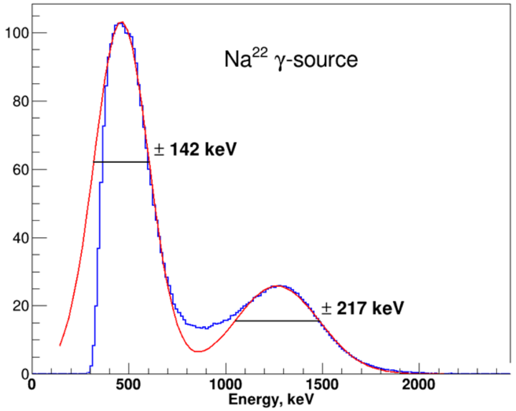


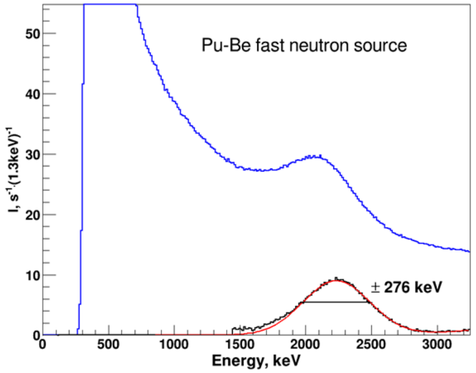


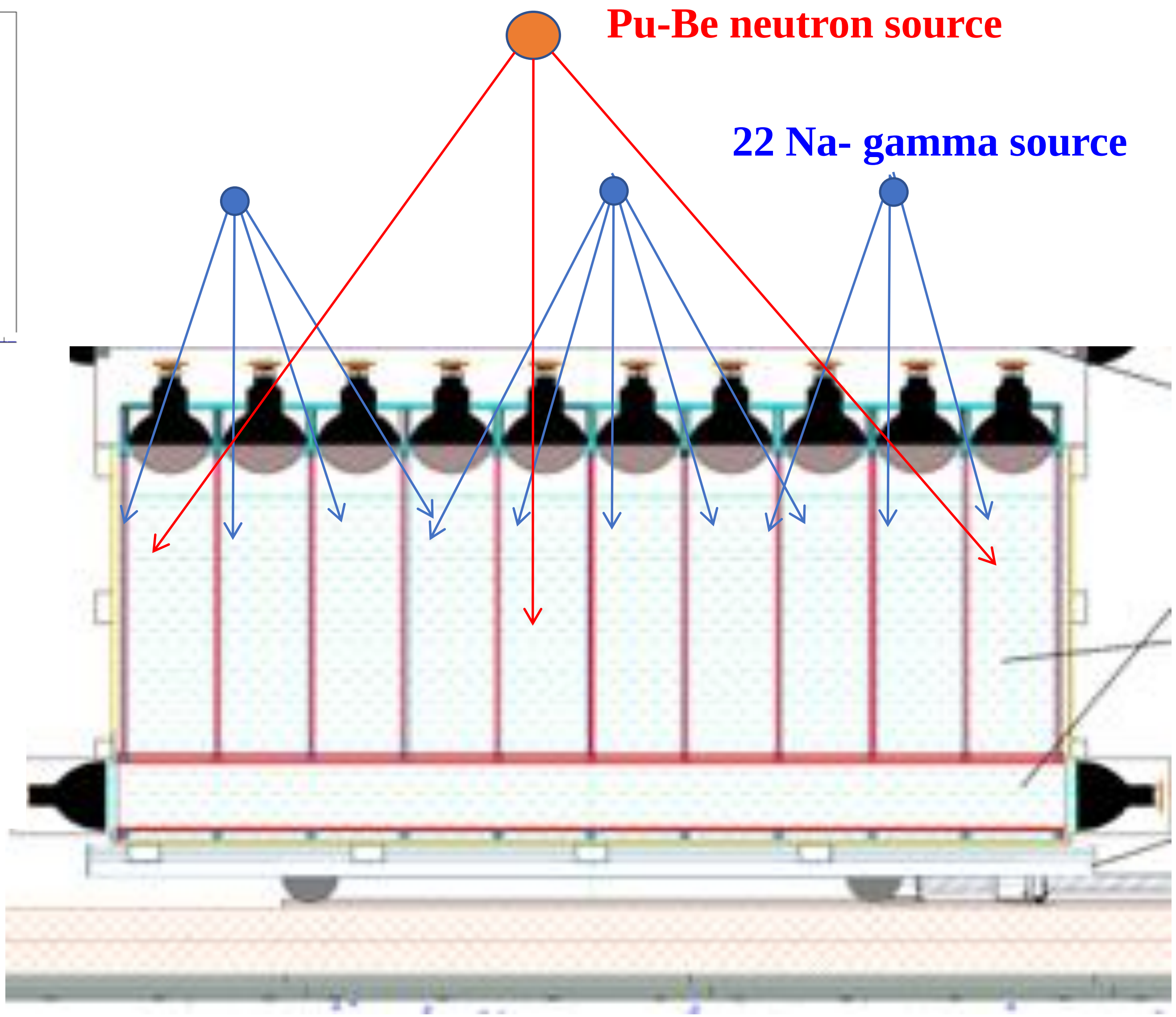
The correlated signal produced by the cosmic background measured over the whole time (up). The correlated ON-OFF signal over the whole time (down).

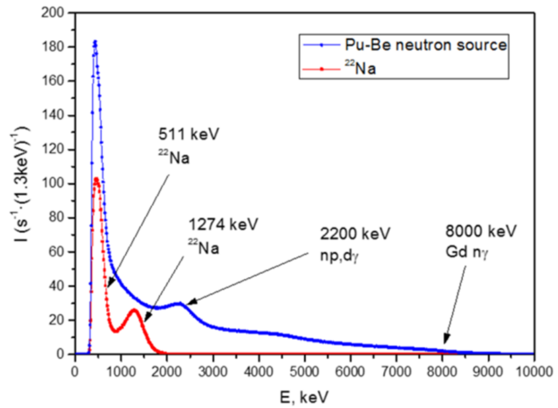
The distribution of deviations from average value of correlated events rates background (OFF) and differences (ON-OFF) normalized on their statistical uncertainties.

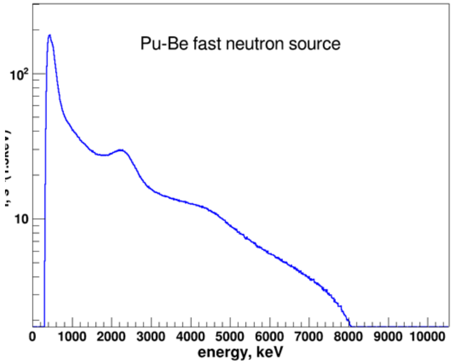
Energy calibration of the full-scale detector

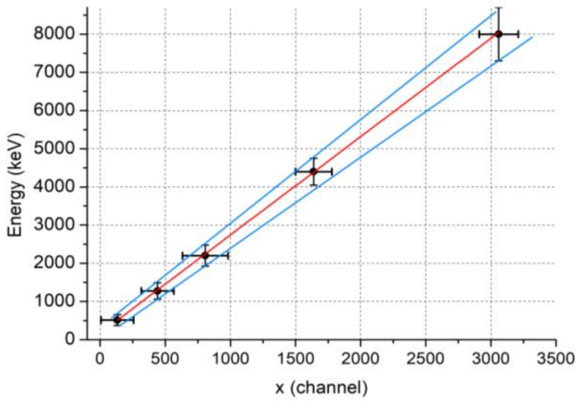




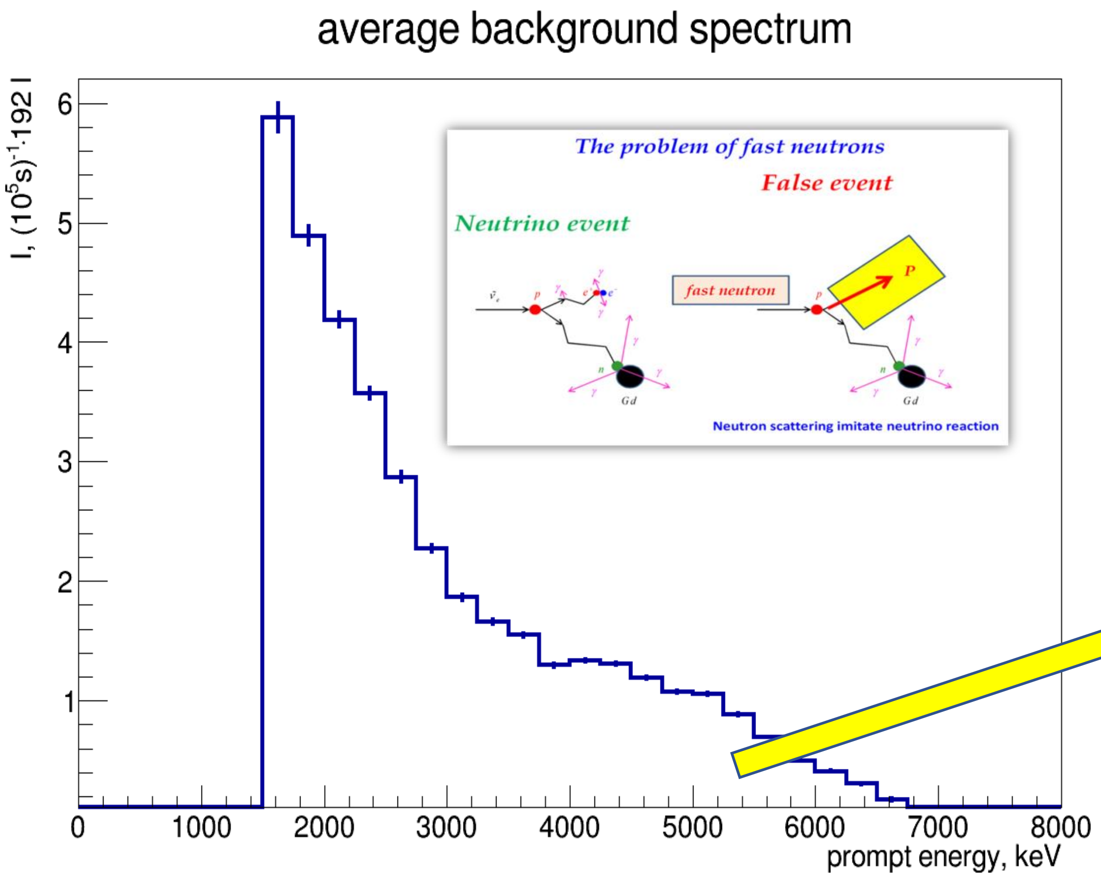


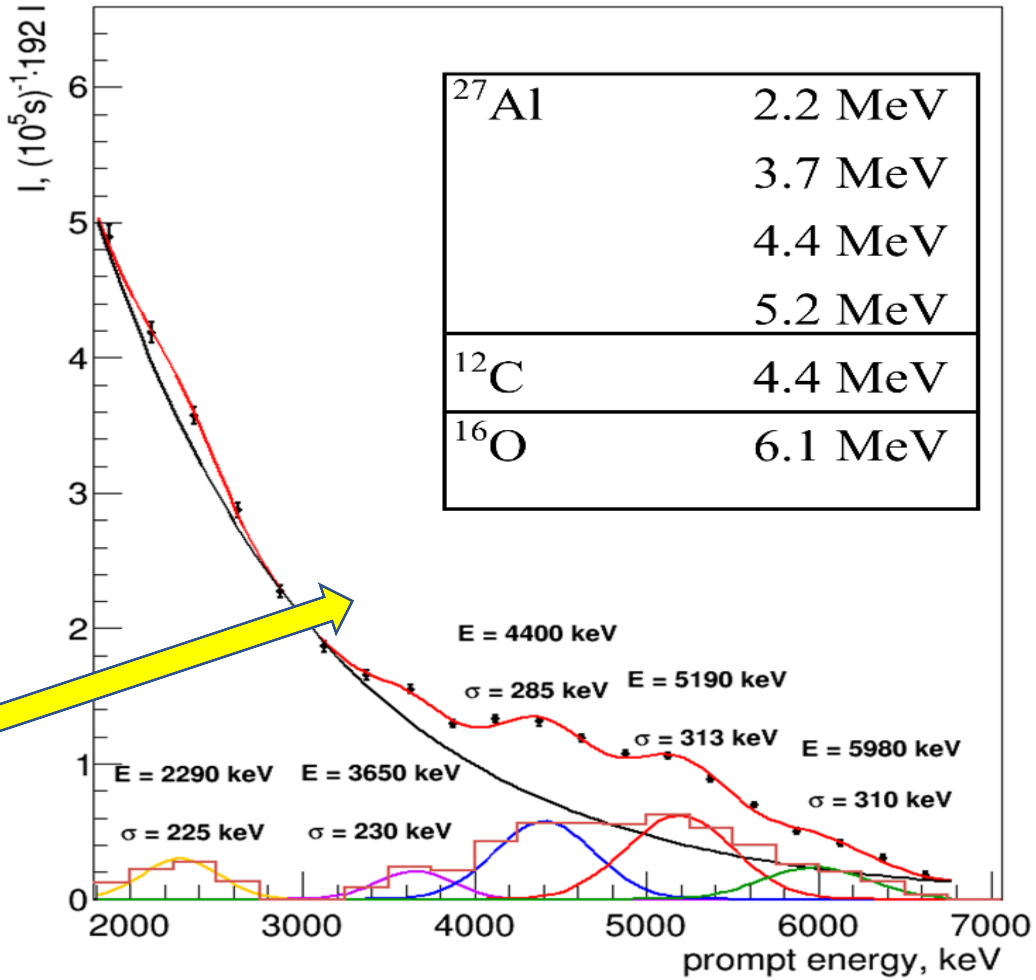






BACKGROUND SPECTRUM

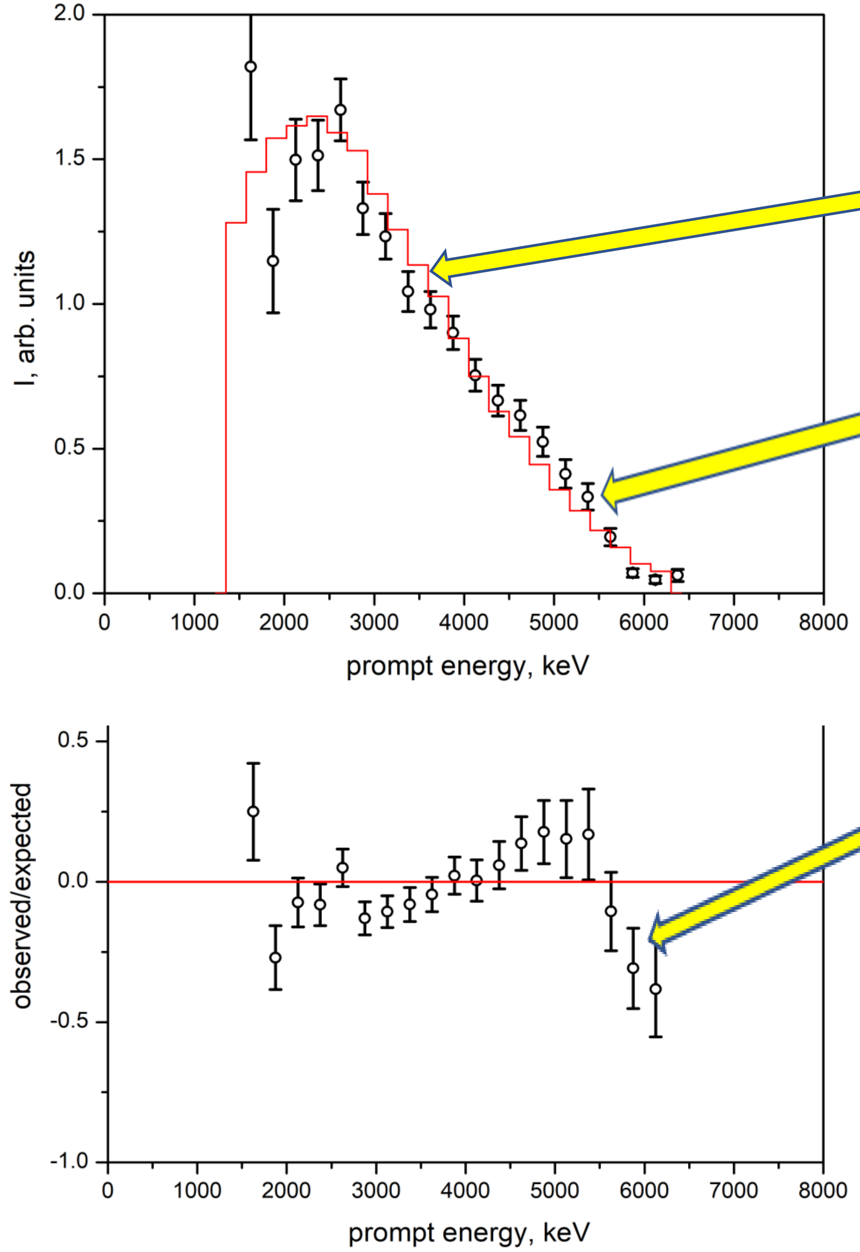




Presence of that structure in the energy spectrum indicates that energy calibration of the detector was the same in all measurements.

Energy resolution of the detector σ=250 keV which does not depend on the energy of a positron.

Comparison of MC spectrum of antineutrino for ^{235}U with the experimental ON-OFF spectrum



calculated MC spectrum of antineutrino for ^{235}U

experimental ON-OFF spectrum.

difference normalized to the calculated spectrum

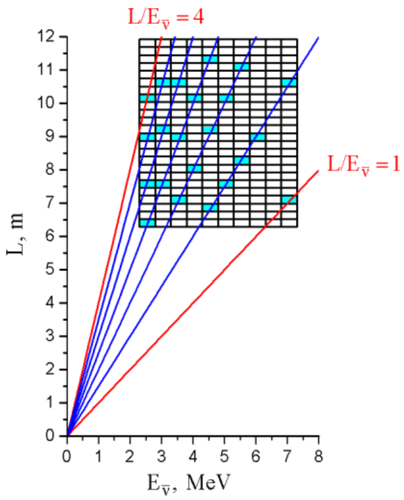
Spectrally independent method for analyzing experimental data is needed

$N(E_i, L_k)$

Number of antineutrino events

Probability of antineutrino disappearance

$$P(\tilde{\nu}_e \to \tilde{\nu}_e) = 1 - \sin^2 2\theta_{14} \; \sin^2\left(1.27 \frac{\Delta m_{14}^2 [eV^2] L[m]}{E_{\tilde{\nu}}[MeV]}\right) \qquad (1)$$



The spectrum independent method of experimental data analysis

$$R_{i,k}^{exp} = \frac{N(E_i, L_k) L_k^2}{K^{-1} \sum_k^K N(E_i, L_k) L_k^2} = \frac{S(\cancel{E}) \mathcal{E}(\cancel{E}) [1 - \sin^2 2\theta_{14} \sin^2(1.27 \Delta m_{14}^2 L_k / E_i)]}{S(\cancel{E}) \mathcal{E}(\cancel{E}) K^{-1} \sum_k^K [1 - \sin^2 2\theta_{14} \sin^2(1.27 \Delta m_{14}^2 L_k / E_i)]} = R_{i,k}^{th} \qquad (2)$$

The denominator is significantly simplified with a range of measurement distances significantly greater than the characteristic oscillation period:

$S(E)$ - Spectrum

$\mathcal{E}(E)$ - Detector efficiency

$$\boxed{R_{ik}^{th} \approx \frac{1 - \sin^2 2\theta_{14} \sin^2(1.27 \Delta m_{14}^2 L_k / E_i)}{1 - 1/2 \sin^2 2\theta_{14}} \xrightarrow[\theta_{14}=0]{} 1}$$

$$\sum_{i,k} [(R_{i,k}^{exp} - R_{i,k}^{th})^2 / (\Delta R_{i,k}^{exp})^2] = \Delta\chi^2 (\sin^2 2\theta_{14}, \Delta m_{14}^2)$$

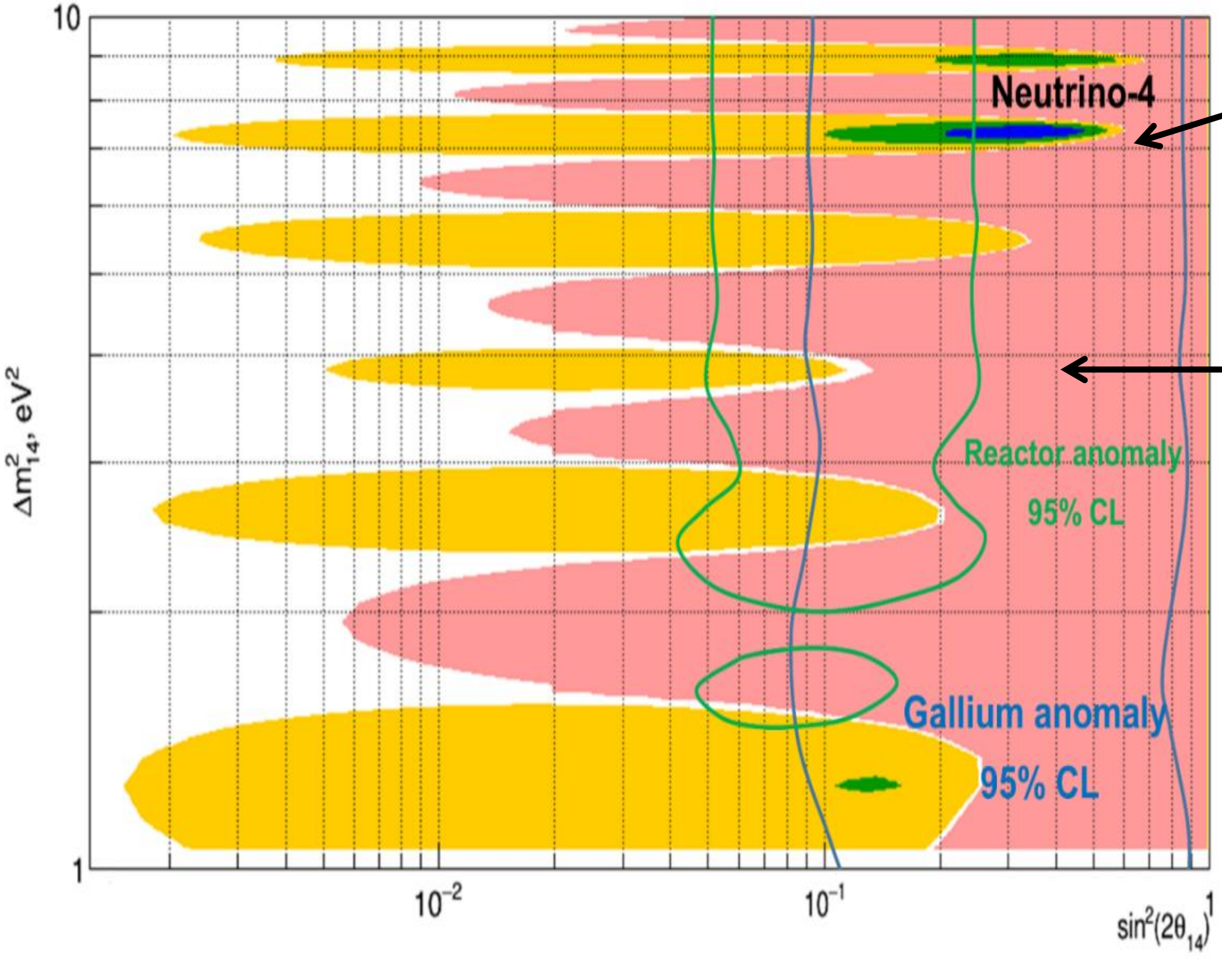
The results of the analysis of optimal parameters Δm^2_{14} and $\sin^2 2\theta_{14}$ using $\Delta\chi^2$ method

$$\sum_{i,k}[(R^{\exp}_{i,k} - R^{th}_{i,k})^2/(\Delta R^{\exp}_{i,k})^2] = \chi^2(\sin^2 2\theta_{14}, \Delta m^2_{14})$$

We observed the oscillation effect at C.L. 2.9 σ in vicinity of :

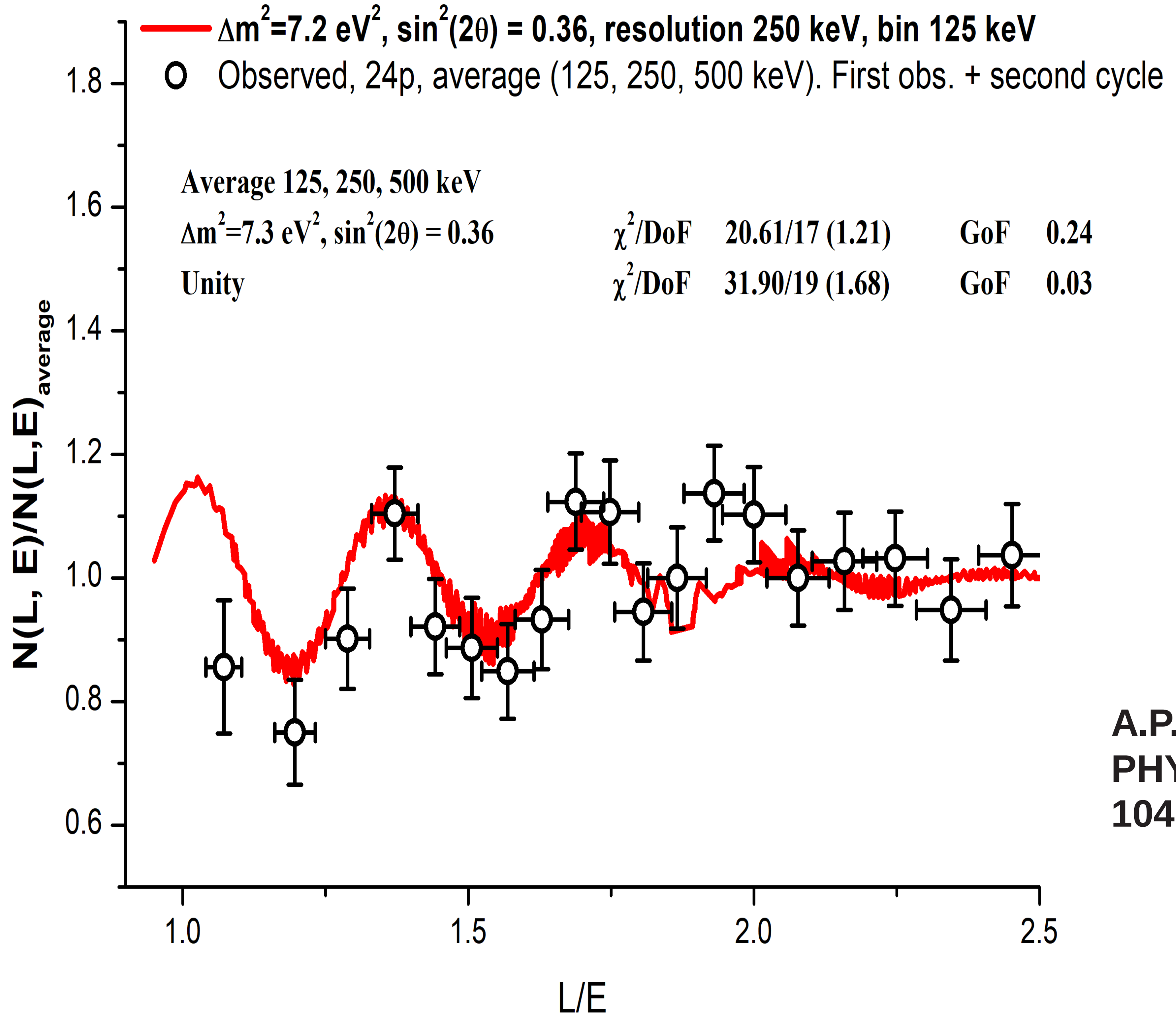
$$\Delta m^2_{14} \approx 7.25 \mathrm{eV}^2$$

$$\sin^2 2\theta_{14} \approx 0.36$$



Expected from Neutrino-4 CL 99.7%

Excluded from Neutrino-4 CL>99.9% CL



$$\Delta m^2_{14} = 7.30 \pm 0.13_{st} \pm 1.16_{syst}$$

$$sin^2 2\theta_{14} = 0.36 \pm 0.12$$

The period of oscillation for neutrino energy 4 MeV is 1.4 m

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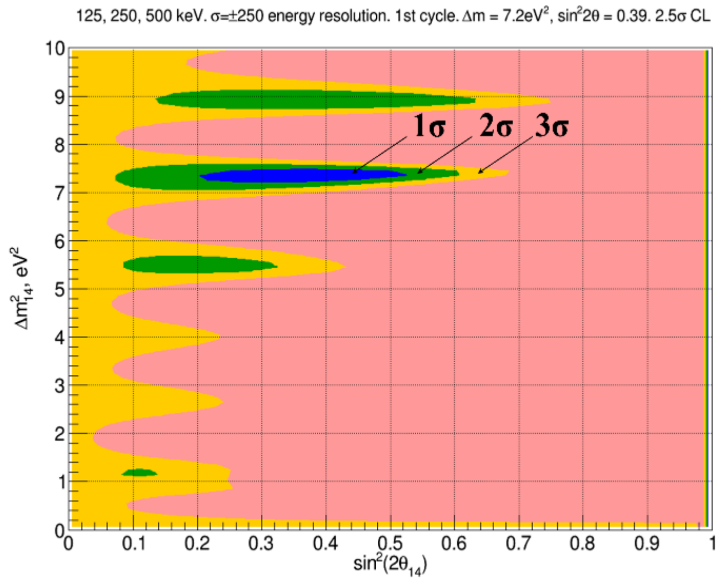

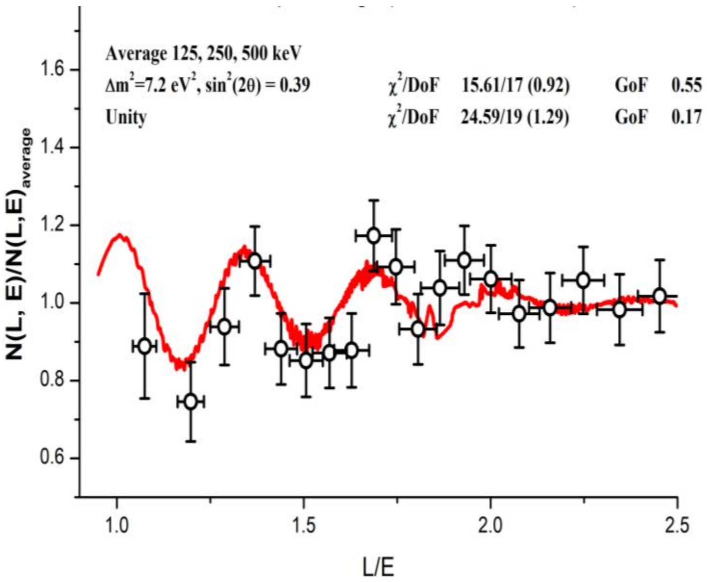

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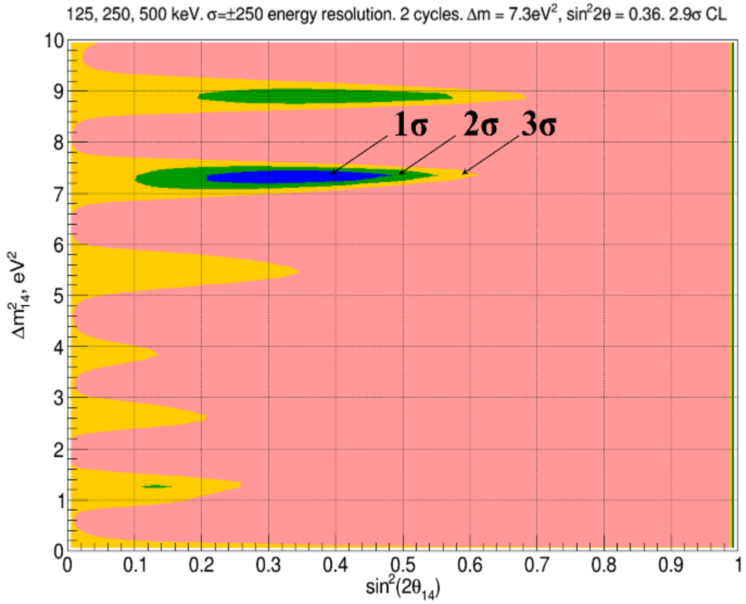
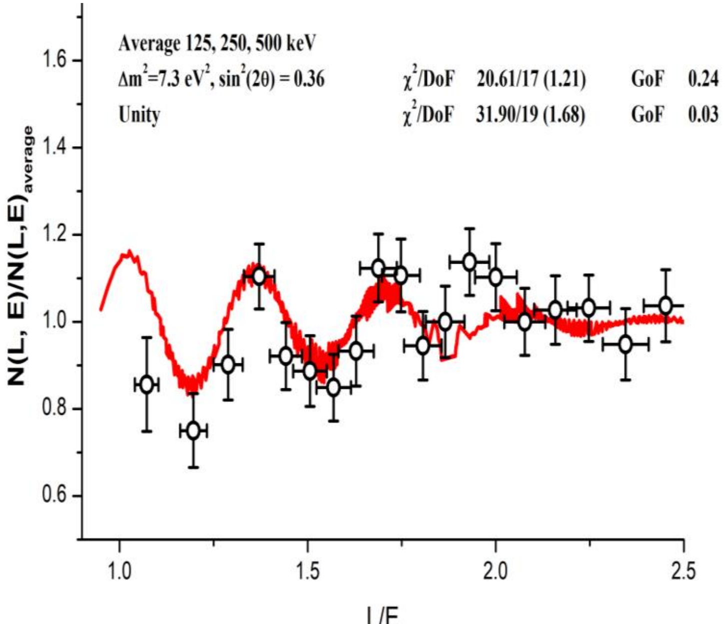




Best fit oscillation parameters Δm^2_{14}, $\sin^2 2\theta_{14}$	χ^2/d.o.f. (Reduced χ^2) fit w/ and w/o oscillation	Goodness of fit w/ and w/o oscillation
7.2 eV^2, 0.39(2.5σ)	**15.61/17(0.92)** 24.59/19 (1.29)	0.55 0.17
7.3 eV^2, 0.36(2.9σ)	**20.61/17(1.21)** 31.90/19 (1.68)	0.24 0.03

There is a maximum at zero, from here the process of oscillations begins

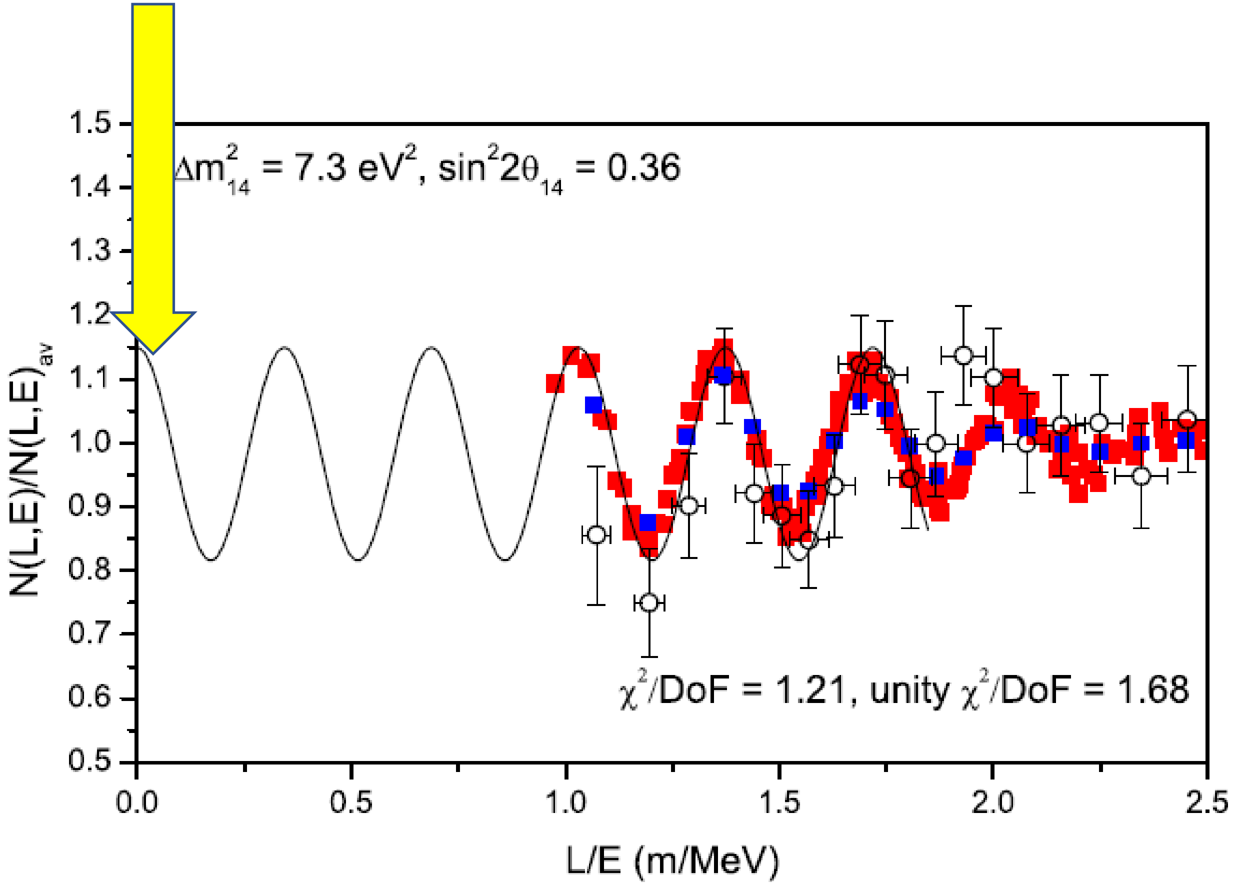
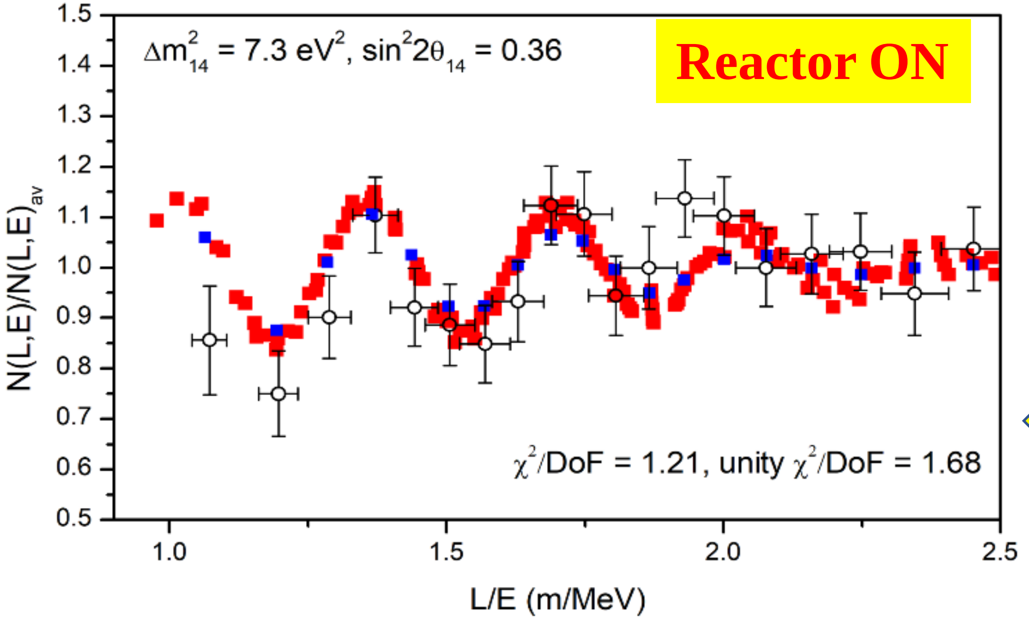
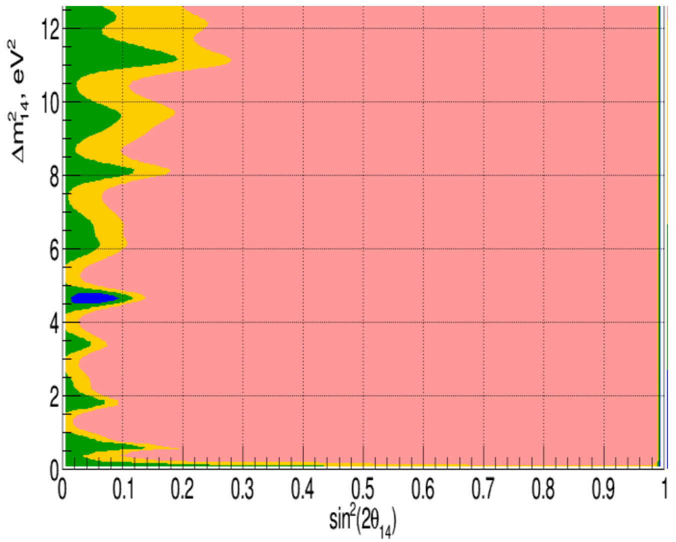


FIG. 47. Complete curve of the oscillation process starting from the reactor core center.

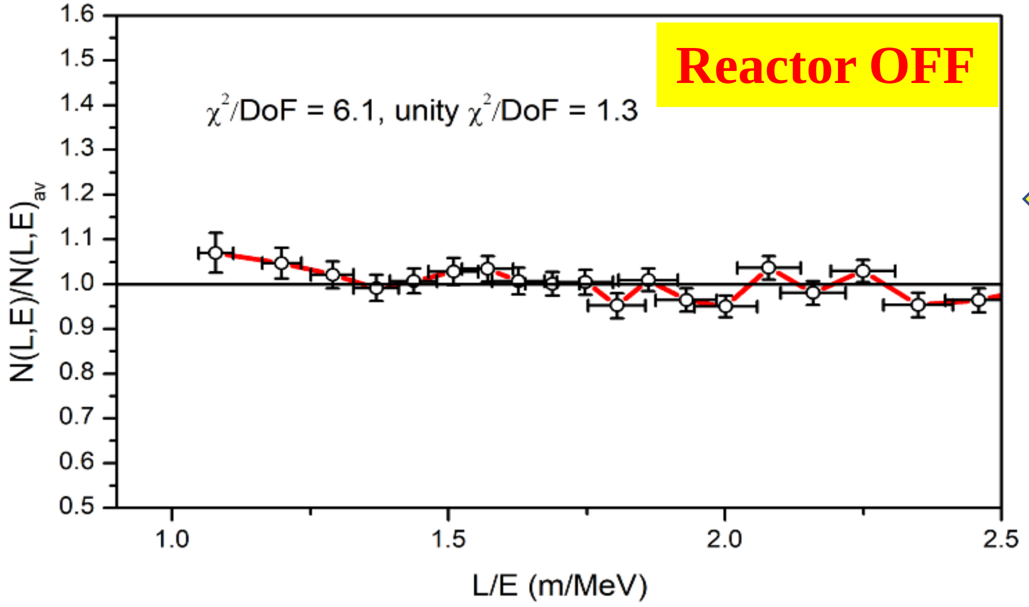
It should be noted that the experimental points should be fitted with such a sinusoidal dependence, which has a maximum at the origin, since the process of oscillations starts from the source. This significantly reduces the set of sinusoids available for fitting. FIG. shows the complete curve of the oscillation process starting from the reactor.

ANALYSIS OF POSSIBLE SYSTEMATIC EFFECTS





Comparison of the R-ratio versus L/E for the neutrino signal (top)



and the R-ratio versus L/E for the background (bottom).

RESULT OF THE EXPERIMENT NEUTRINO-4

$$\Delta m_{14}^2 = 7.30 \pm 0.13_{st} \pm 1.16_{syst} = 7.30 \pm 1.17$$

$$sin^2 2\theta_{14} = 0.36 \pm 0.12 (2.9\sigma)$$

Monte Carlo based statistical analysis gave an estimation of the confidence level at 2.7σ.

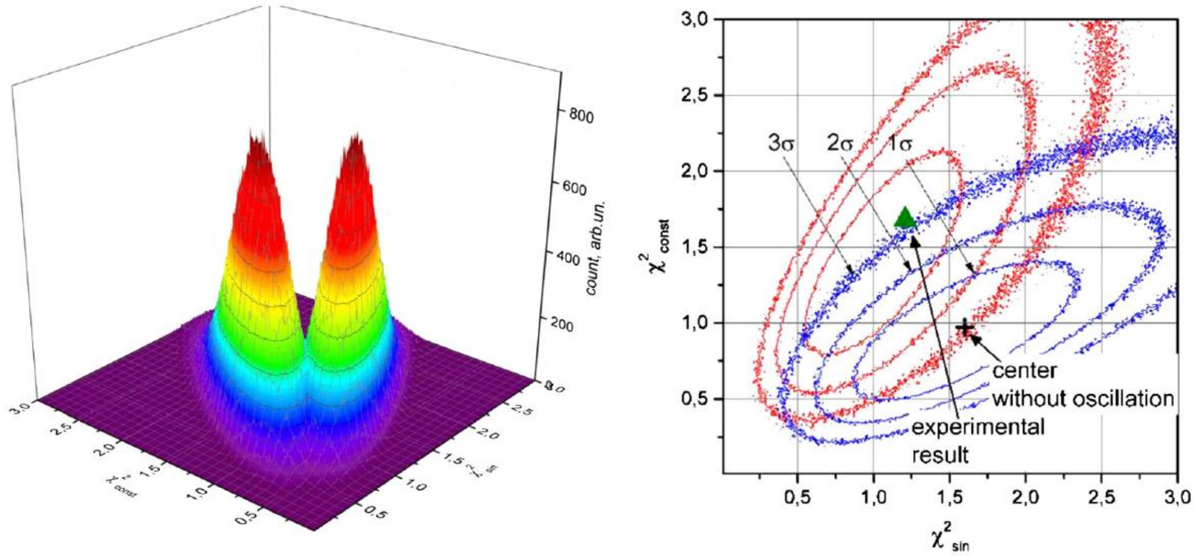


FIG. 53. On the left, the distribution of the reduced χ^2 on the plane $(\chi^2_{\mathrm{const}}, \chi^2_{\sin})$ is shown for modeling with accuracy according to the experimental statistics and with a background level corresponding to the experimental background. Two cases were simulated with the hypothesis of oscillations and with the hypothesis without oscillations. For each case, an analysis was carried out with the hypothesis of oscillations and with the hypothesis without oscillations. On the right is the same picture, where the center of the distribution without oscillations (black cross), and the deviation from this center of the experimental result (green triangle—first and second cycle) are indicated. The result of the analysis of the experimental data when processed with the hypothesis with and without oscillations gives $\chi^2_{\sin} = 1.21$ or 20.6 for 17 degrees of freedom and $\chi^2_{\mathrm{const}} = 1.68$, or 31.9 for 19 degrees of freedom, respectively, and $\Delta\chi^2 = 11.3$. Distribution contours with 1σ, 2σ, and 3σ are marked. The deviation of the experimental result from the center of the distribution without oscillations is approximately 3σ.

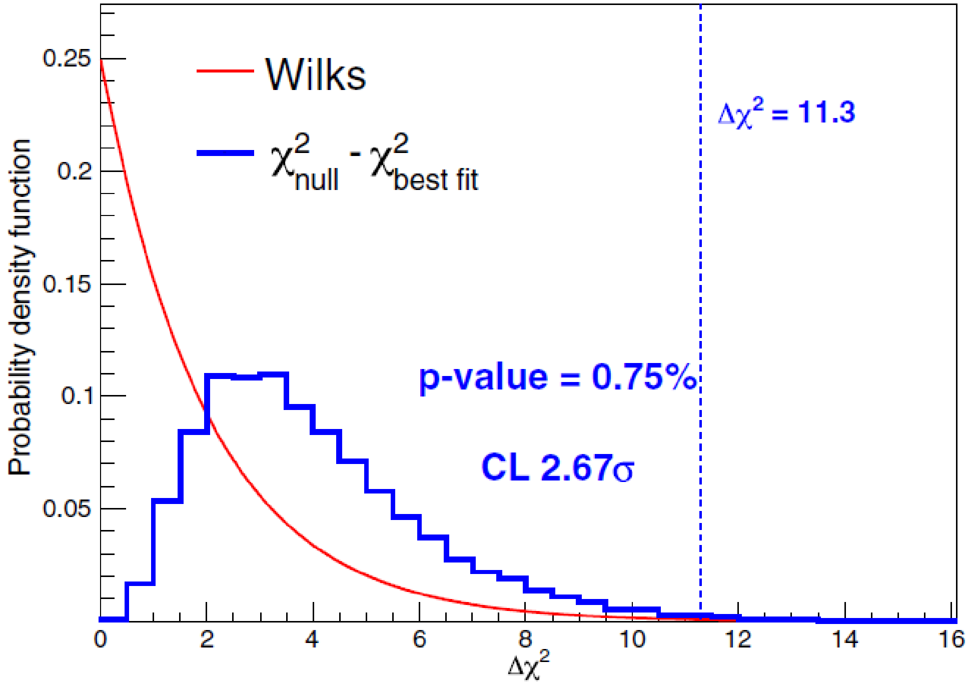


FIG. 54. T distribution for MC based approach to the statistical analysis (blue line) and χ^2 with 2 degrees of freedom function, which is claimed by Wilks's theorem.

Possibility of experimental confirmation of the 3 + 1 neutrino model with one sterile neutrino

THE STRUCTURE OF 3+1 NEUTRINO MODEL AND REPRESENTATION OF PROBABILITIES OF VARIOUS OSCILLATIONS

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$

$$|U_{e4}|^2 = \sin^2(\theta_{14})$$

$$|U_{\mu 4}|^2 = \sin^2(\theta_{24}) \cdot \cos^2(\theta_{14})$$

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

$$P_{\nu_e \nu_e} = 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2)\, sin^2\left(\frac{\Delta m_{14}^2 L}{4E_{\nu_e}}\right) = 1 - sin^2 2\theta_{ee}\, sin^2\left(\frac{\Delta m_{14}^2 L}{4E_{\nu_e}}\right)$$

$$P_{\nu_\mu \nu_\mu} = 1 - 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)\, sin^2\left(\frac{\Delta m_{14}^2 L}{4E_{\nu_\mu}}\right) = 1 - sin^2 2\theta_{\mu\mu}\, sin^2\left(\frac{\Delta m_{14}^2 L}{4E_{\nu_\mu}}\right)$$

$$P_{\nu_\mu \nu_e} = 4|U_{e4}|^2|U_{\mu 4}|^2\, sin^2\left(\frac{\Delta m_{14}^2 L}{4E_{\nu_e}}\right) = sin^2 2\theta_{\mu e}\, sin^2\left(\frac{\Delta m_{14}^2 L}{4E_{\nu_e}}\right)$$

The relations of oscillations parameters required for comparative analysis of experimental results are:

$$\sin^2 2\theta_{ee} \equiv \sin^2 2\theta_{14}$$

$$\sin^2 2\theta_{\mu\mu} = 4\sin^2\theta_{24}\cos^2\theta_{14}(1-\sin^2\theta_{24}\cos^2\theta_{14}) \approx \sin^2 2\theta_{24}$$

$$\sin^2 2\theta_{\mu e} = 4\sin^2\theta_{14}\sin^2\theta_{24}\cos^2\theta_{14} \approx \frac{1}{4}\sin^2 2\theta_{14}\sin^2 2\theta_{24}$$

The first important conclusion of the 3 + 1 model is that the oscillation frequency in all processes should be the same, i.e. it is determined by the value

$$\boldsymbol{\Delta m^2_{14}}$$

The second important relation for experimental verification of the 3 + 1 model.

$$sin^2 2\theta_{\mu\nu} \approx \frac{1}{4} sin^2 2\theta_{14} sin^2 2\theta_{24}$$

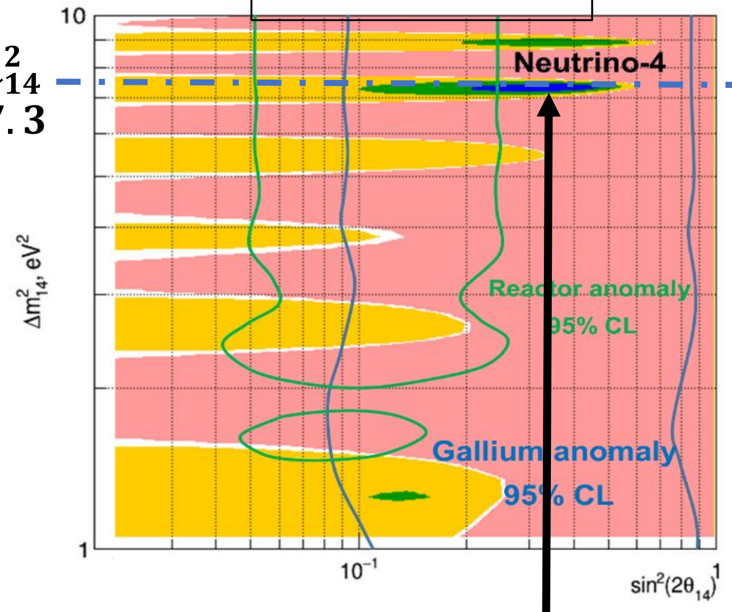
This relationship can be interpreted in a fairly simple way. The appearance of electron neutrinos in a muon neutrino beam: this is a second-order process, i.e. transition of a muon neutrino to a sterile neutrino, and then the transition of a sterile neutrino into an electron neutrino.

COMPARISON OF NEUTRINO-4 WITH ICECUBE, MINIBOONE AND LSND

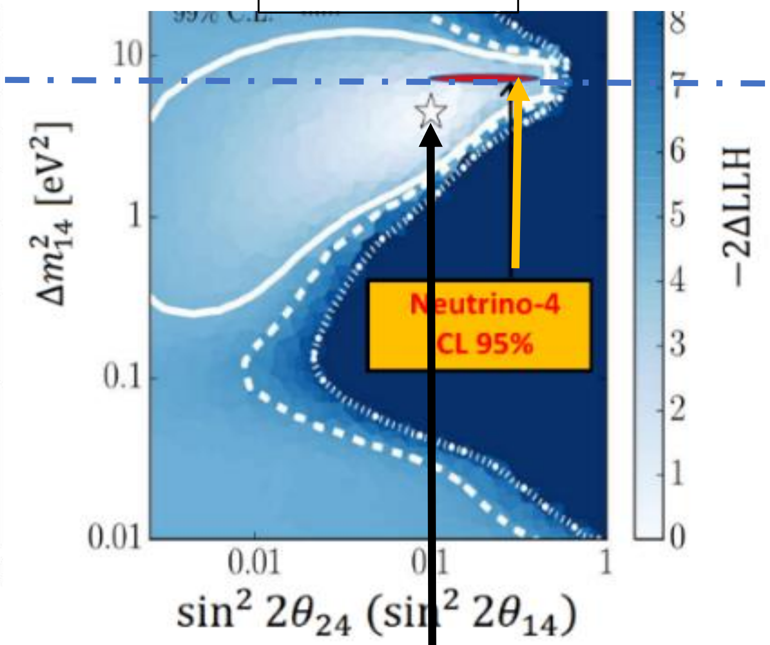
A.P. Serebrov *, R.M. Samoilov JETP Letters, Volume 112, 2020 Issue 4, pp 211–225 arxiv:2003.03199

$\Delta m^2_{14} = 7.3$

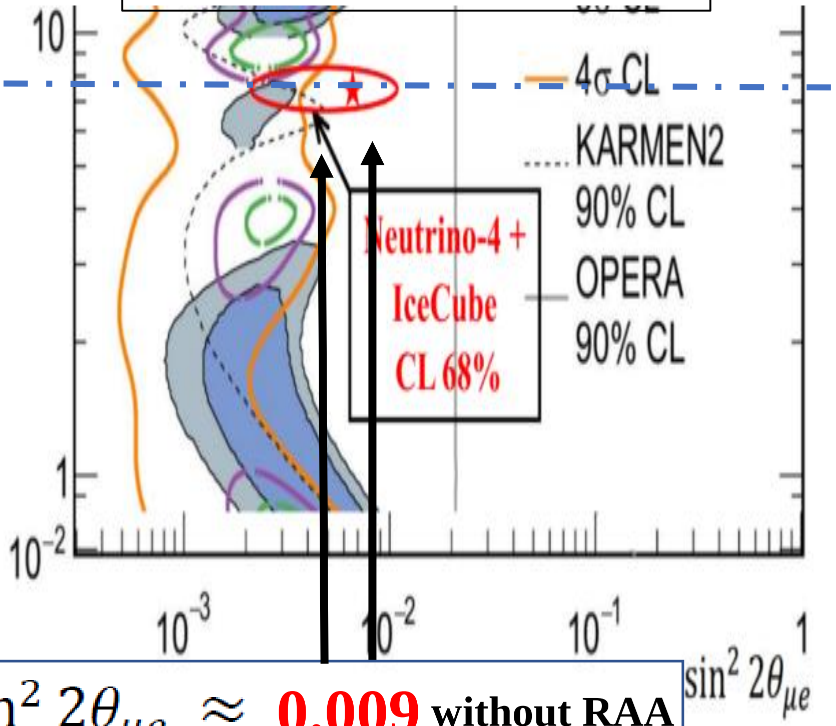
NEUTRINO-4



ICECUBE



MINIBOONE AND LSND



$\Delta m^2_{14} = 7.3$

$\sin^2 2\theta_{14} \approx$ **0.36** $\quad \sin^2 2\theta_{24} \approx$ **0.1** $\quad \sin^2 2\theta_{\mu e} \approx$ **0.009** without RAA

$$\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{14} \sin^2 2\theta_{24}$$

$\sin^2 2\theta_{\mu e} \approx$ **0.005** with RAA

$\approx$ **0.009** $\quad \approx$ **0.36** $\quad \approx$ **0.1**

without RAA

$\approx$ **0.005** $\quad \approx$ **0.19** $\quad \approx$ **0.1**

with RAA

Test of neutrino model 3+1

$\Delta m^2_{14} = 4.47^{+3.53}_{-2.08} \quad \sin^2(2\theta_{24}) = 0.10^{+0.102}_{-0.07}$ ICECUBE

A.P. Serebrov , Lomonosov Conference. 17-40. 20.08.2021

COMPARISON OF NEUTRINO-4 MASS PREDICTION WITH MEASUREMENT OF NEUTRINO MASS

A.P. Serebrov *, R.M. Samoilov JETP Letters, Volume 112, 2020
Issue 4, pp 211–225 arxiv:2003.03199

$$m_{\nu_e}^{eff} = \sqrt{\sum m_i^2 |U_{ei}|^2}$$

$$\Delta m_{14}^2 \approx m_4^2, \ldots |U_{14}^2| \ll 1$$

$$\boxed{m_4 = (2.70 \pm 0.22)\text{eV}}$$

$$\boxed{m_{\nu_e}^{eff} = (0.59 \pm 0.11)\text{eV}}$$

$$m(0\nu\beta\beta) = \sum |U_{ei}|^2 m_i$$

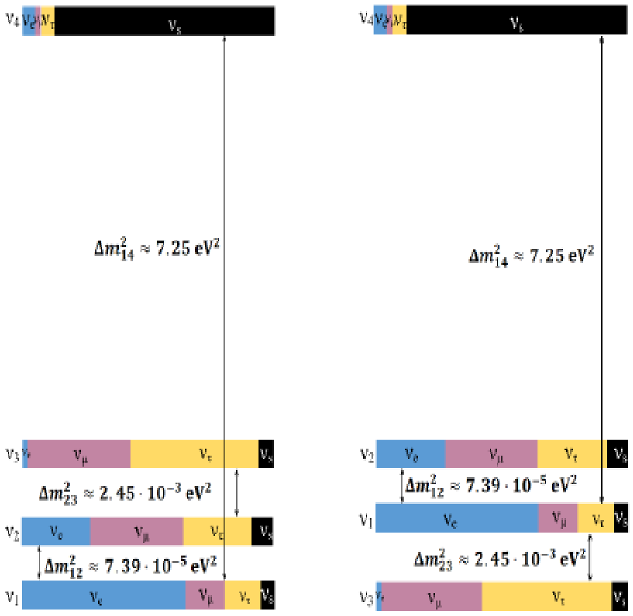
	Neutrino-4	KATRIN	GERDA $m(0\nu\beta\beta)$
Effective mass and masss quared ($m_{\nu_e}^{eff}, m_\nu^2$)	$m_\nu = 0.59 \pm 0.11$ $m_\nu^2 = 0.35 \pm 0.13$	$m_\nu < 0.8 @ (90\%)$ $m_\nu^2 = 0.26 \pm 0.34$	
Maiorana mass ($m(0\nu\beta\beta)$)	$m(0\nu\beta\beta) =$ (0.13 ± 0.04)eV.		$m_{\beta\beta}$ $< [0.80 - 0.182]$eV

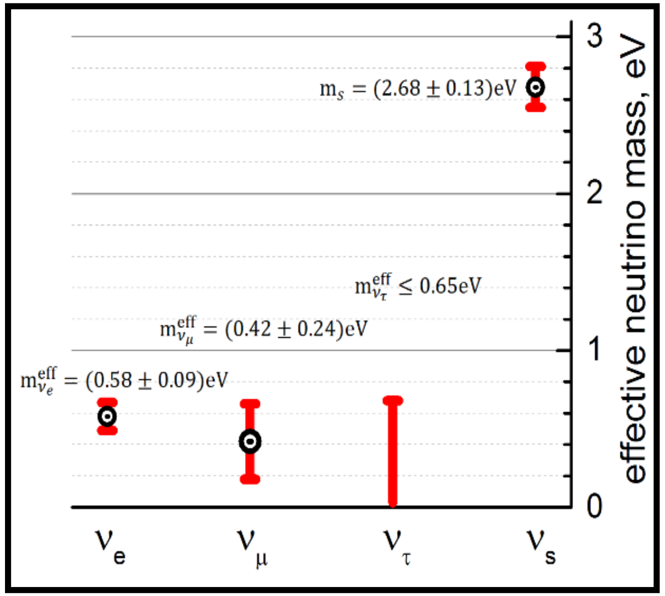
Neutrino flavors mixing scheme including sterile neutrino and effective mass hierarchy

A.P. Serebrov *, R.M. Samoilov JETP Letters, Volume 112, 2020 Issue 4, pp 211–225 arxiv:2003.03199

PMNS matrix for 3 + 1 model

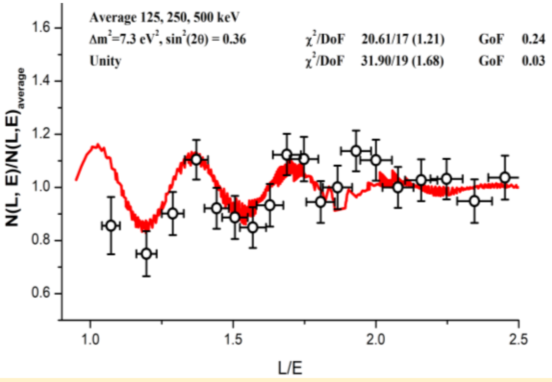
$$U_{PMNS}^{(3+1)} = \begin{pmatrix} 0.824^{+0.007}_{-0.008} & 0.547^{+0.011}_{-0.011} & 0.147^{+0.003}_{-0.003} & 0.224^{+0.025}_{-0.025} \\ 0.409^{+0.036}_{-0.060} & 0.634^{+0.022}_{-0.065} & 0.657^{+0.044}_{-0.014} & 0.160^{+0.08}_{-0.05} \\ 0.392^{+0.025}_{-0.048} & 0.547^{+0.056}_{-0.028} & 0.740^{+0.012}_{-0.048} & < 0.229 \\ < 0.24 & < 0.30 & < 0.26 & > 0.93 \end{pmatrix}$$





Conclusion

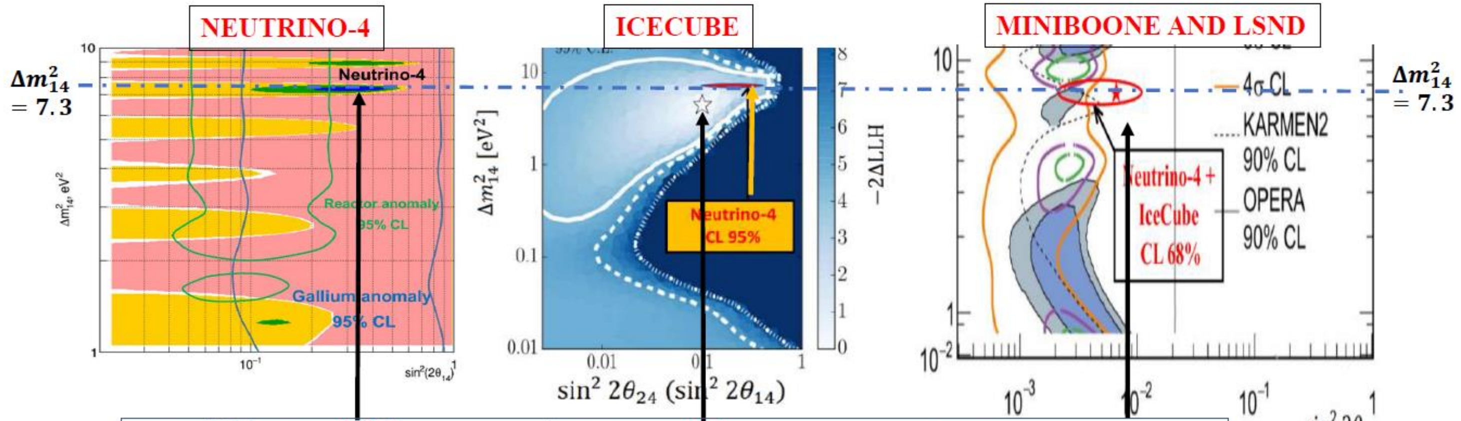
1. The direct observation of sterile neutrino oscillation in Neutrino-4 experiment



$$\Delta m^2_{14} = 7.30 \pm 0.13_{st} \pm 1.16_{syst}$$

$$\sin^2 2\theta = 0.36 \pm 0.12_{stat} (2.9\sigma)$$

2. Possibility of experimental confirmation of the 3 + 1 neutrino model with one sterile neutrino



$\sin^2 2\theta_{14} \approx$ **0.36** $\quad \sin^2 2\theta_{24} \approx$ **0.1** $\quad \sin^2 2\theta_{\mu e} \approx$ **0.009**

$$\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{14} \sin^2 2\theta_{24}$$

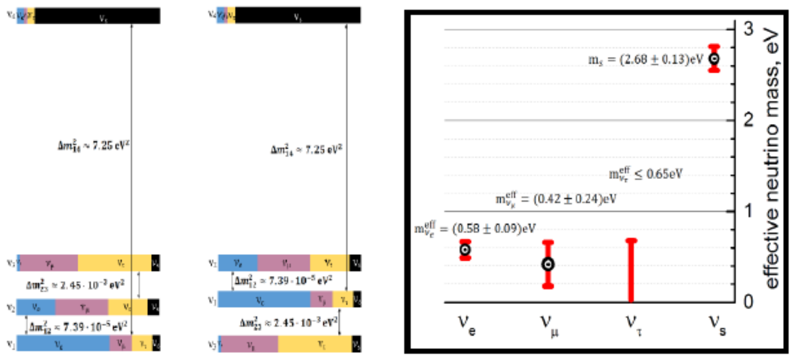
0.009 **0.36** **0.1**

Test of neutrino model 3+1

3. COMPARISON OF NEUTRINO-4 MASS PREDICTION WITH MEASUREMENT OF NEUTRINO MASS

	Neutrino-4	KATRIN	GERDA $m(0\nu\beta\beta)$
Effective mass and masss quared	$m_\nu = 0.59 \pm 0.11$ $m_\nu^2 = 0.35 \pm 0.13$	$m_\nu < 0.8 @ (90\%)$ $m_\nu^2 = 0.26 \pm 0.34$	
Maiorana mass ($m(0\nu\beta\beta)$)	$m(0\nu\beta\beta) =$ (0.13 ± 0.04)eV.		$m_{\beta\beta}$ $< [0.80 - 0.182]$eV

4. Neutrino flavors mixing scheme including sterile neutrino and effective mass hierarchy



5. PMNS matrix for 3 + 1 model

$$U^{(3+1)}_{PMNS} = \begin{pmatrix} 0.824^{+0.007}_{-0.008} & 0.547^{+0.011}_{-0.011} & 0.147^{+0.003}_{-0.003} & 0.224^{+0.025}_{-0.025} \\ 0.409^{+0.036}_{-0.060} & 0.634^{+0.022}_{-0.065} & 0.657^{+0.044}_{-0.014} & 0.160^{+0.08}_{-0.05} \\ 0.392^{+0.025}_{-0.048} & 0.547^{+0.056}_{-0.028} & 0.740^{+0.012}_{-0.048} & < 0.229 \\ < 0.24 & < 0.30 & < 0.26 & > 0.93 \end{pmatrix}$$

Thus, the analysis performed provides quite interesting generalizations and an indication of the possibility of the validity of the 3 + 1 neutrino model with one sterile neutrino.