Наблюдение эффекта осцилляций в эксперименте Нейтрино-4 по поиску стерильного нейтрино – - продолжение

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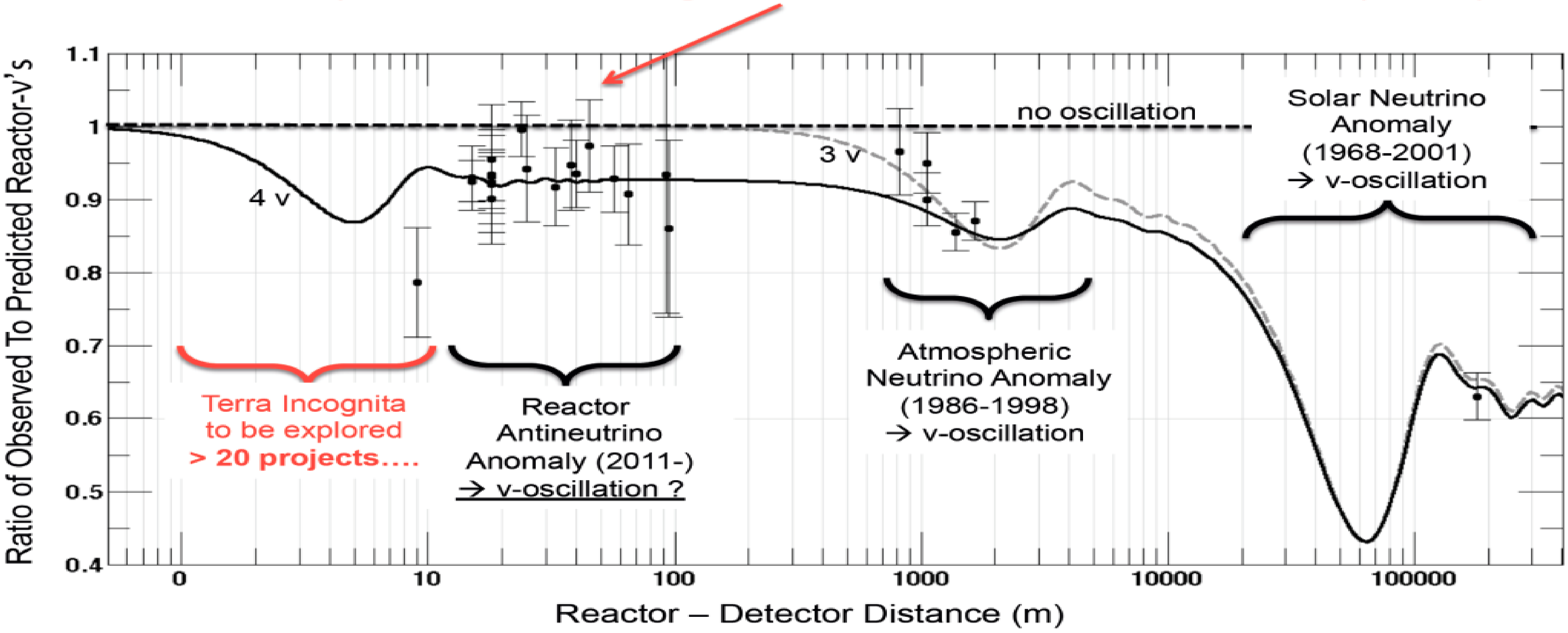
Reactor antineutrino anomaly

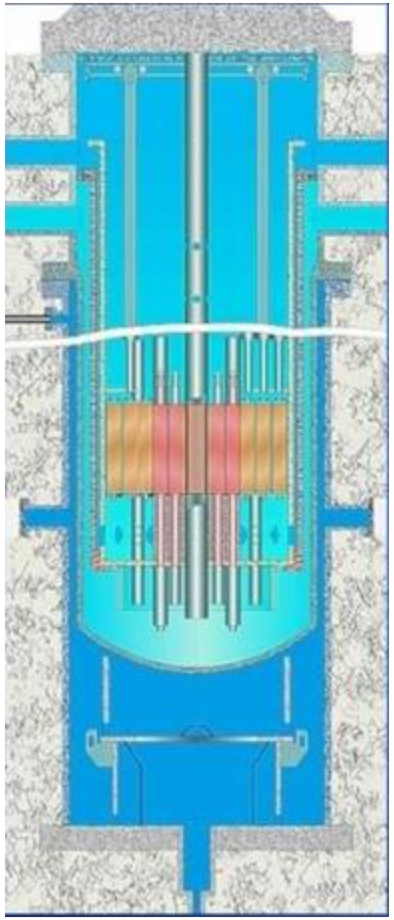
- Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)



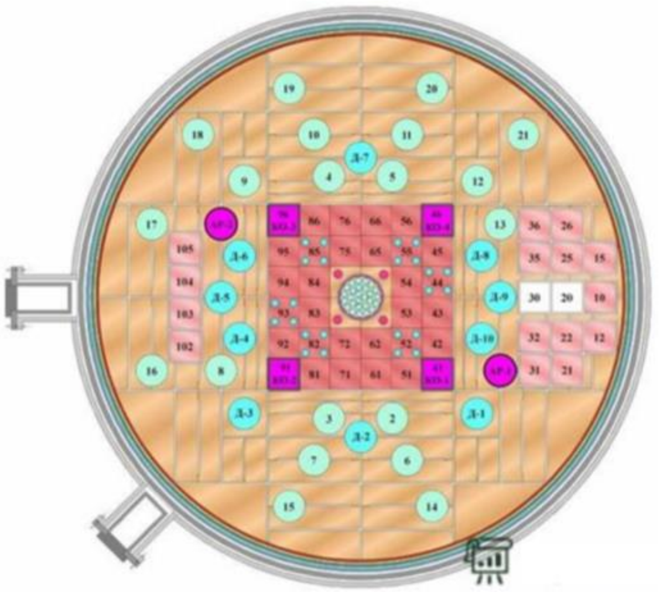
$$P(\tilde{\nu}_e \to \tilde{\nu}_e) = 1 - \sin^2 2\theta_{14} \ \sin^2 (1.27 \frac{\Delta m^2_{14}[eV^2]L[m]}{E_{\tilde{\nu}}[MeV]})$$

SM-3 research reactor

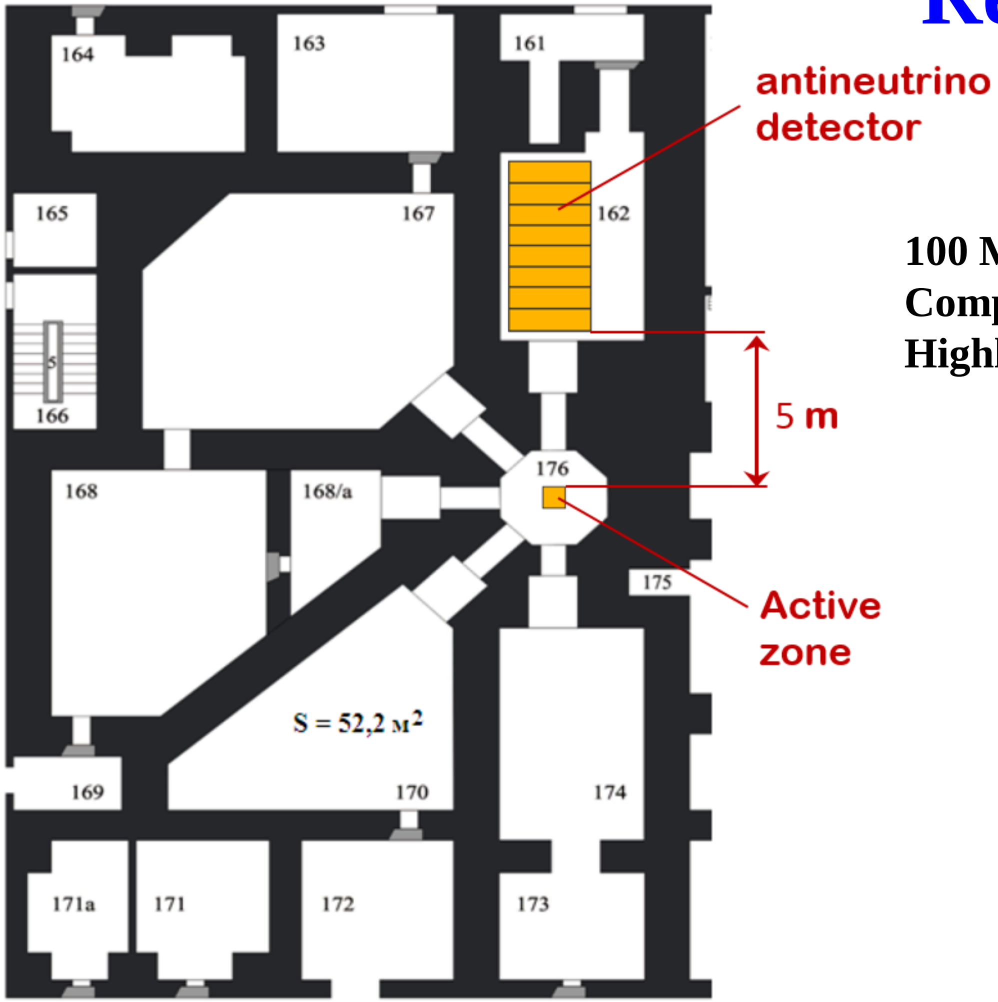
- 100 MW thermal power
- Compact core 42x42x35cm
- Highly enriched ^{235}U fuel
- Separated rooms for experimental setup
- The laboratory is poorly protected from cosmic rays



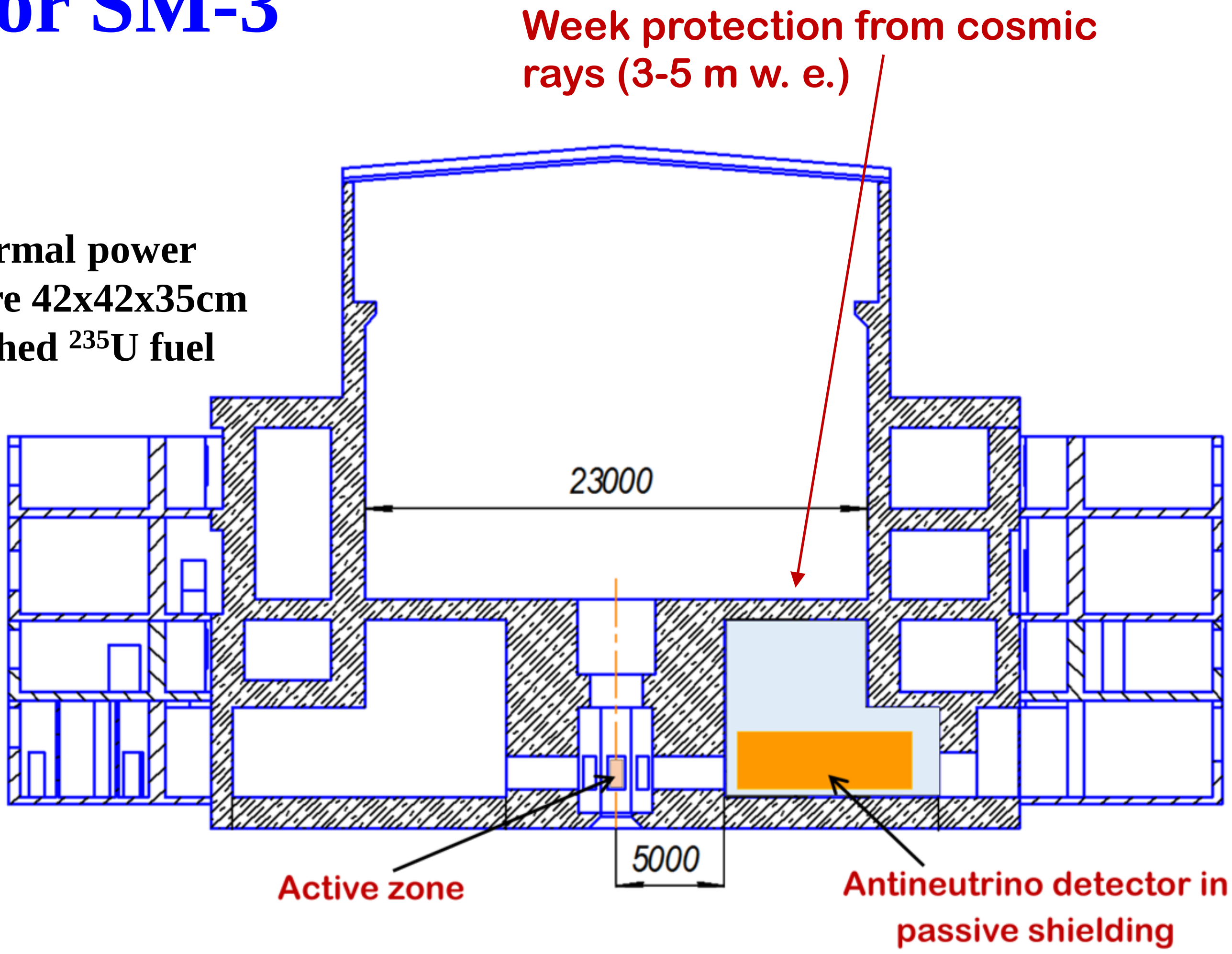
Vertical and horizontal sections of SM-3 reactor



Reactor SM-3

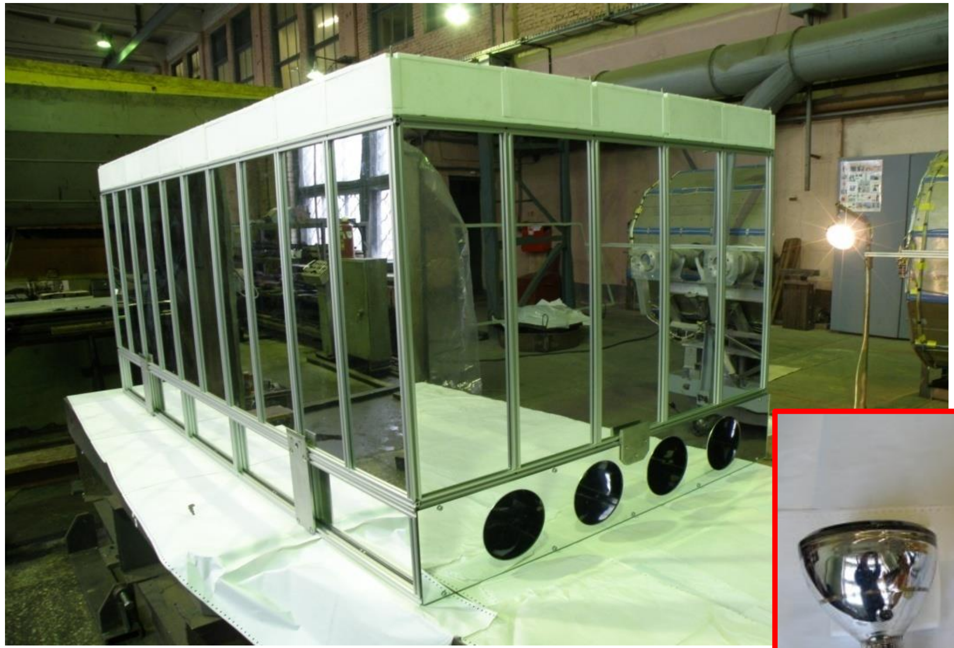


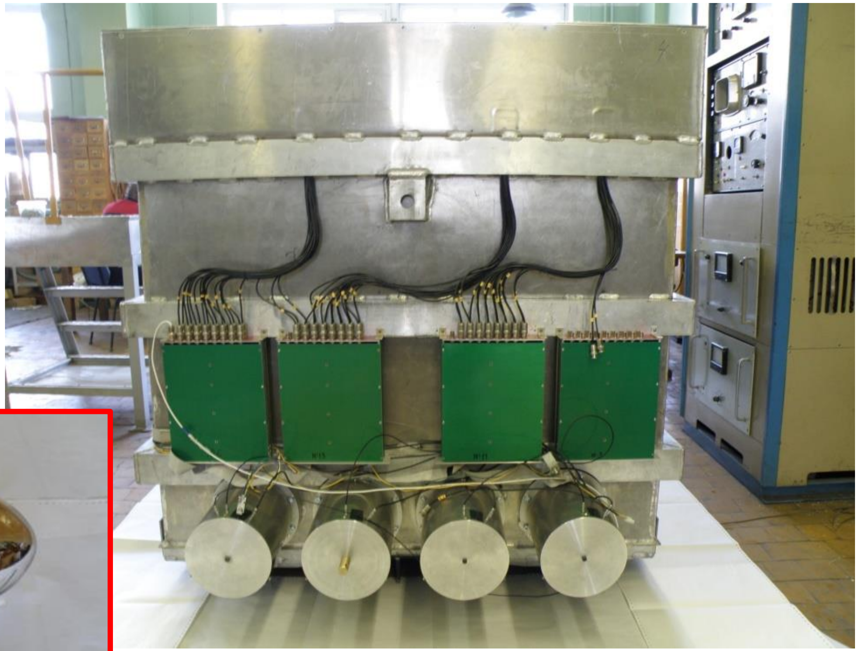
100 MW thermal power
Compact core 42x42x35cm
Highly enriched ^{235}U fuel



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.

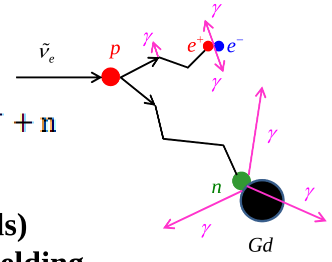
The full-scale detector with liquid scintillator volume of 3 m^3 (5x10 sections) have been prepared in NRC “KI” PNPI, Gatchina, Russia

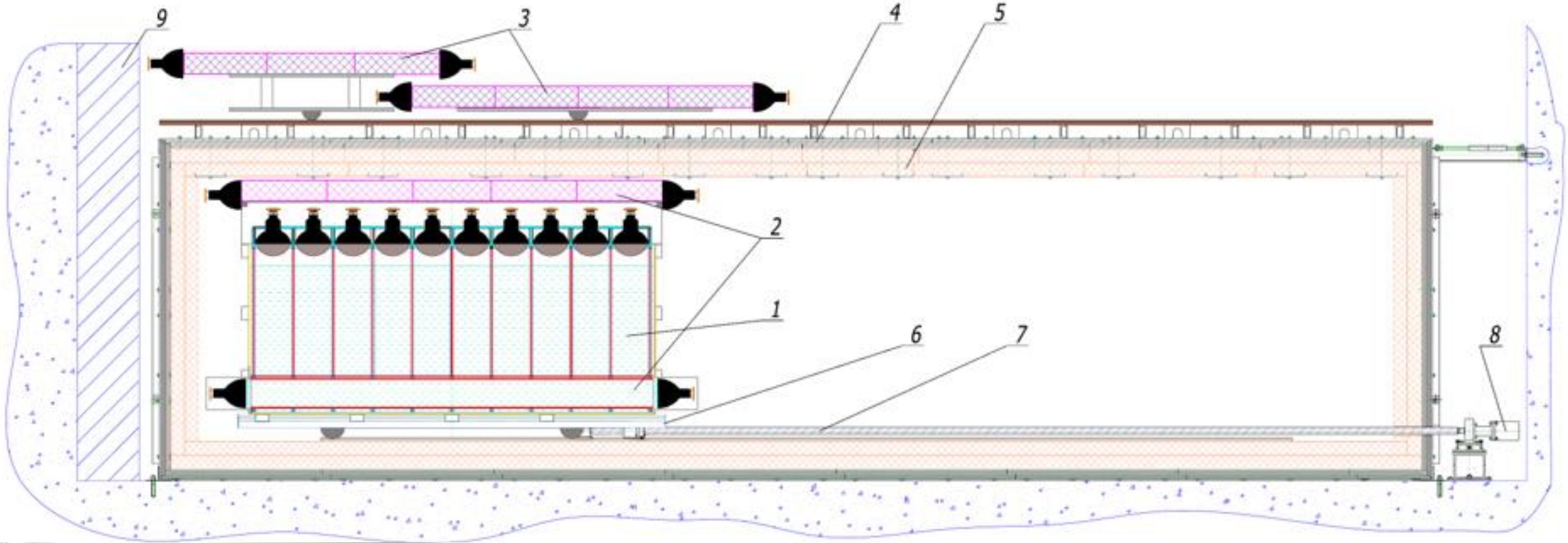




Movable and spectrum sensitive antineutrino detector at SM-3 reactor

$\bar{\nu}_e + p \rightarrow e^+ + n$





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

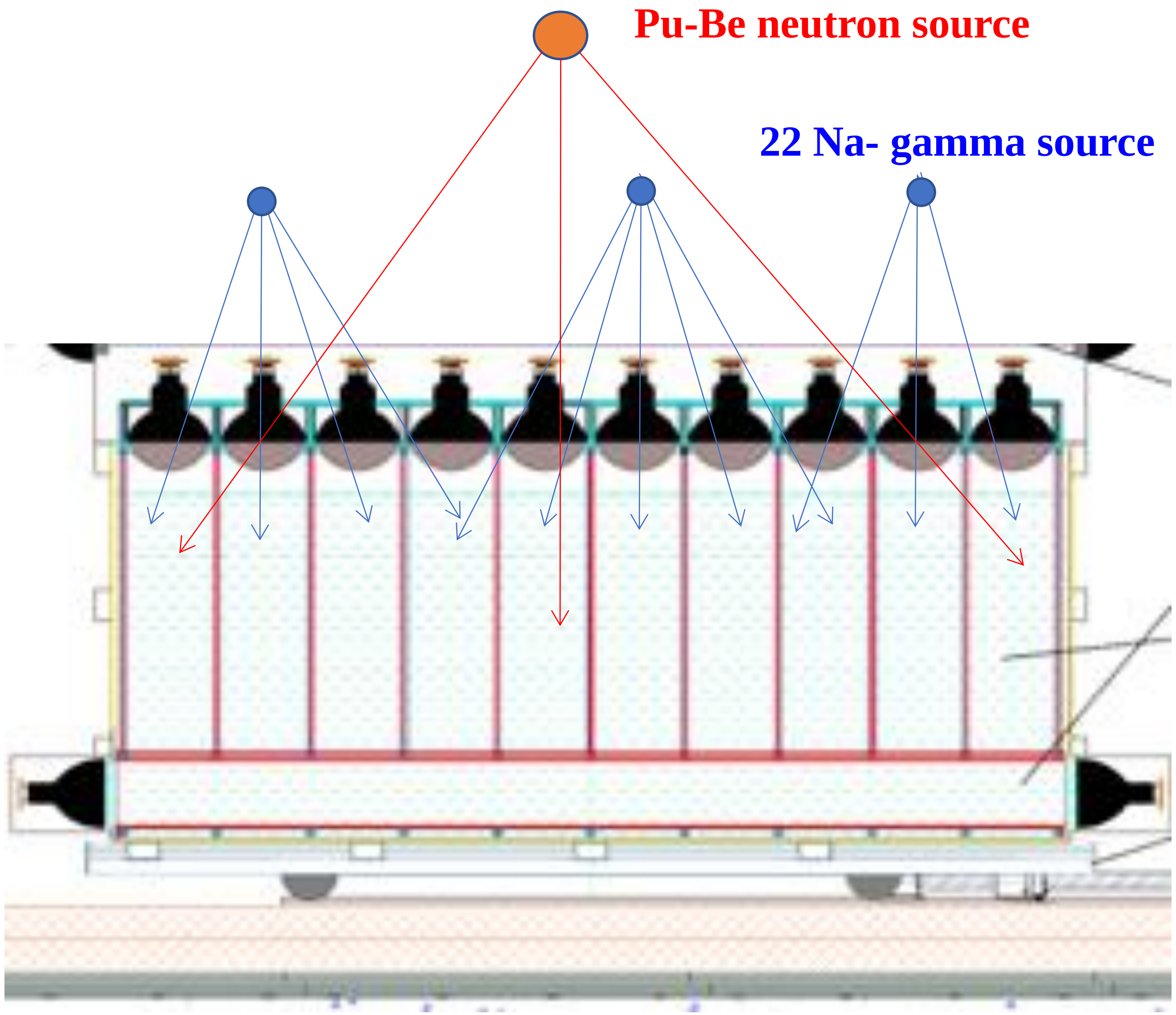
Detector prototype

Full-scale detector

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

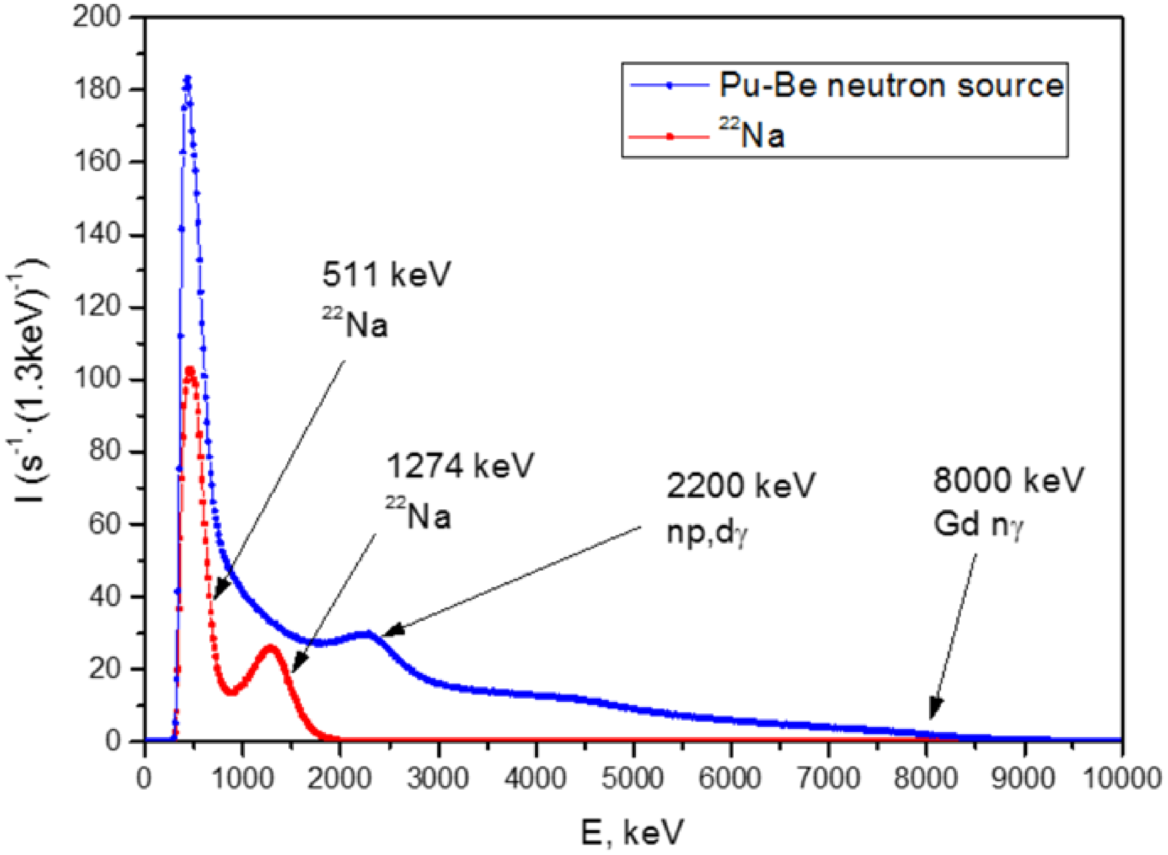
Energy calibration of the full-scale detector

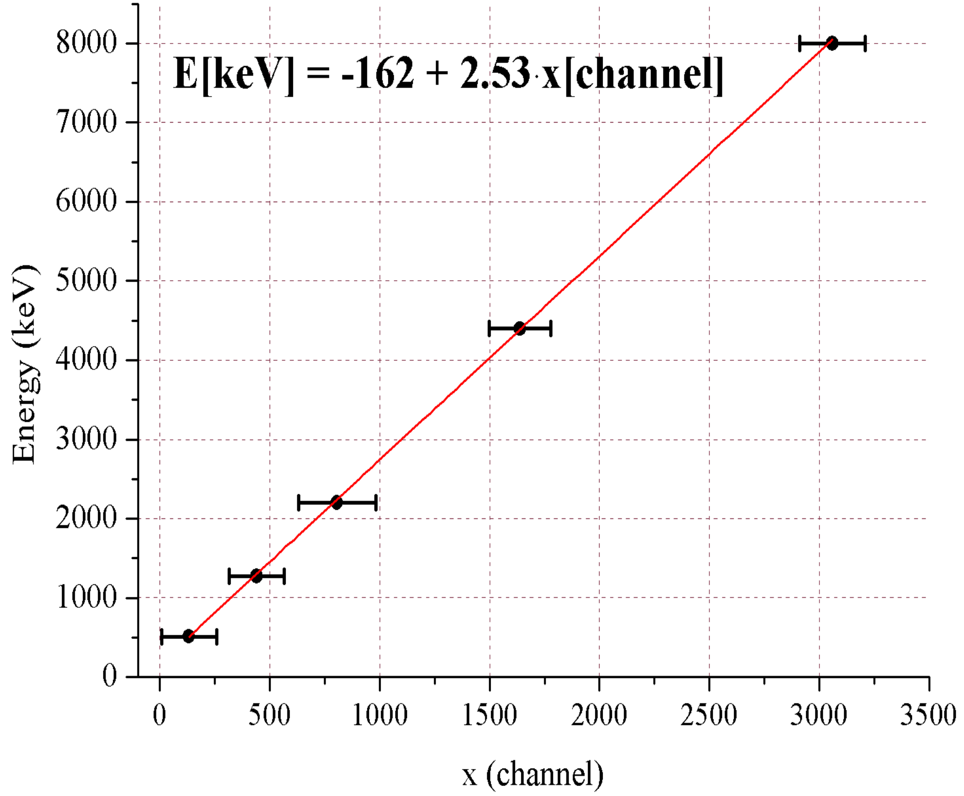
The source 22Na is installed above the detector at distance about 0.8 meters and irradiate about 16 sections at once. PMTs were normalized to one energy scale by selecting voltage on them. Simultaneous calibration of several sections is required. For all detector only 6 positions of the source were used.
Overlapping of the irradiated sections unifies the calibration.



The neutron Pu-Be source irradiated all sections at once. This method has advantage relatively to using of internal sources. The difficulty of calibration at energy 8MeV is that quanta from neutron capture by gadolinium can't be absorbed in the same row. Therefore the detector calibration should be conducted on a diffuse edge of spectrum.

Energy calibration of the full-scale detector





In the left - ranges of sources. In the right - the calibration of gamma quanta scale.

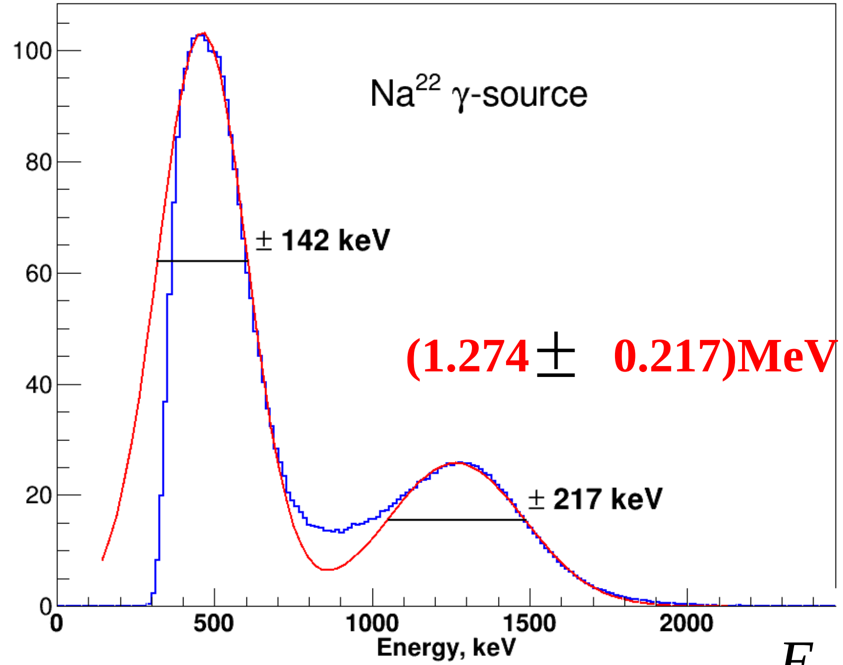
Registration of positrons includes inevitable loss of a part of energy of 511keV gamma-quanta. Because of the threshold of registration in the adjacent section we have to increase errors up to **±250 keV**.

It is the calibration which needs to be used at data processing.

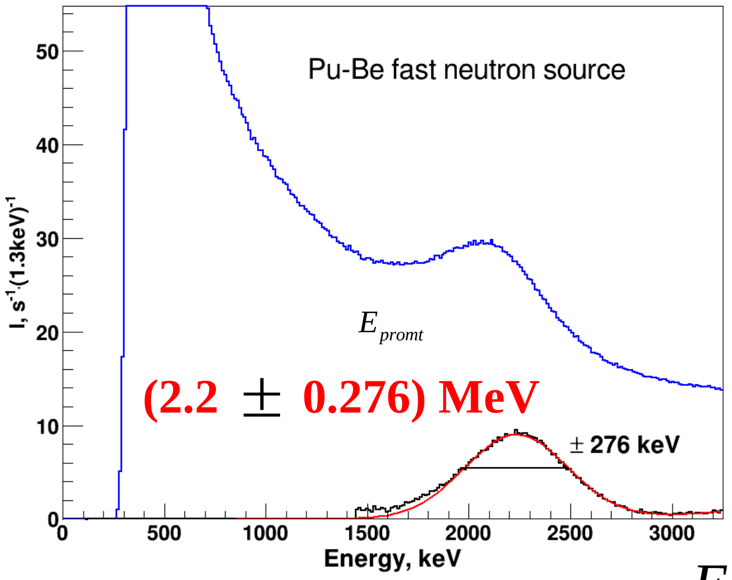
Energy calibration of the full-scale detector

$$E_\nu = E_{promt} + 0.8MeV$$

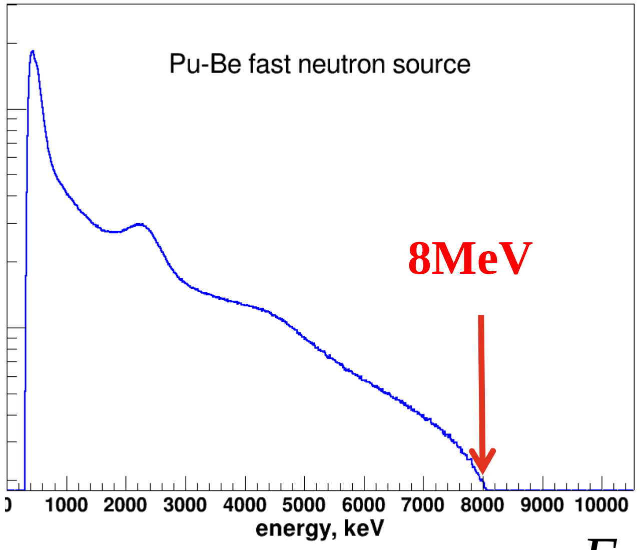
(0.511 ± 0.142) MeV



E_{promt}



E_{promt}



E_{promt}

$$\Delta E_\nu / E_\nu(2MeV) = 21\%$$

$$\Delta E_\nu(2MeV) = 440keV$$

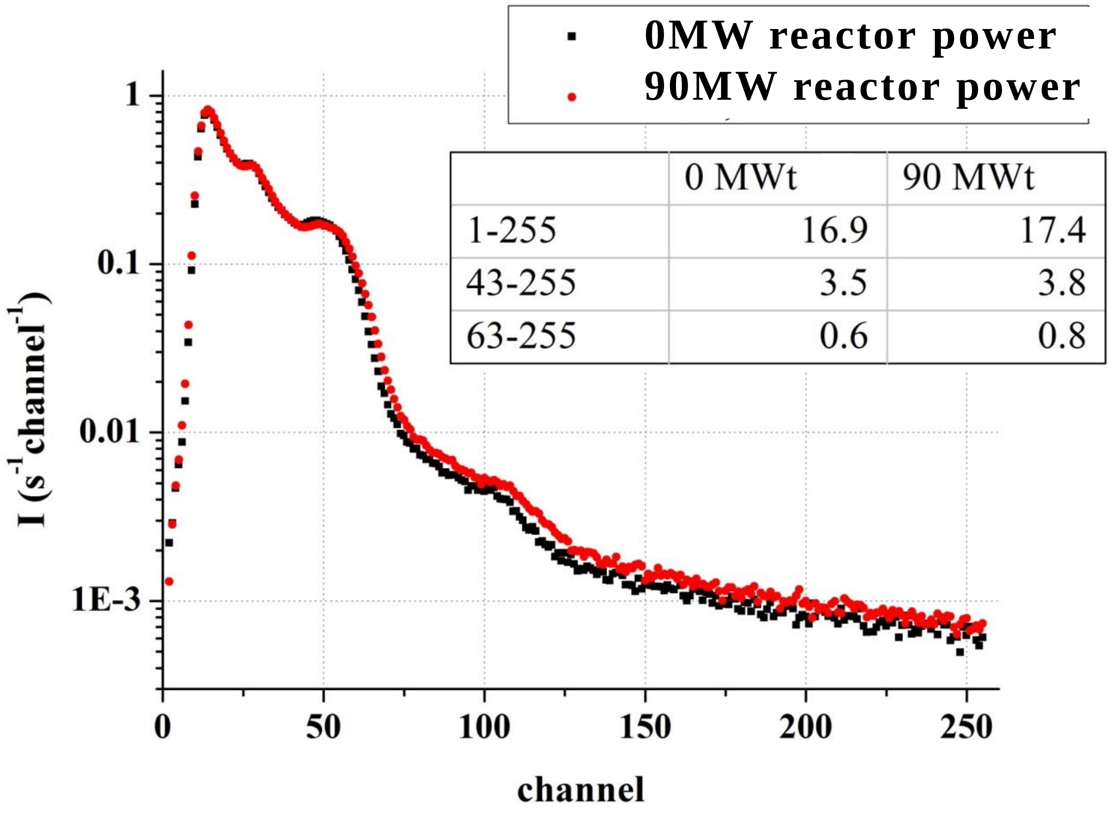
$$\Delta E_\nu / E_\nu(3MeV) = 18\%$$

$$\Delta E_\nu(3MeV) = 550keV$$

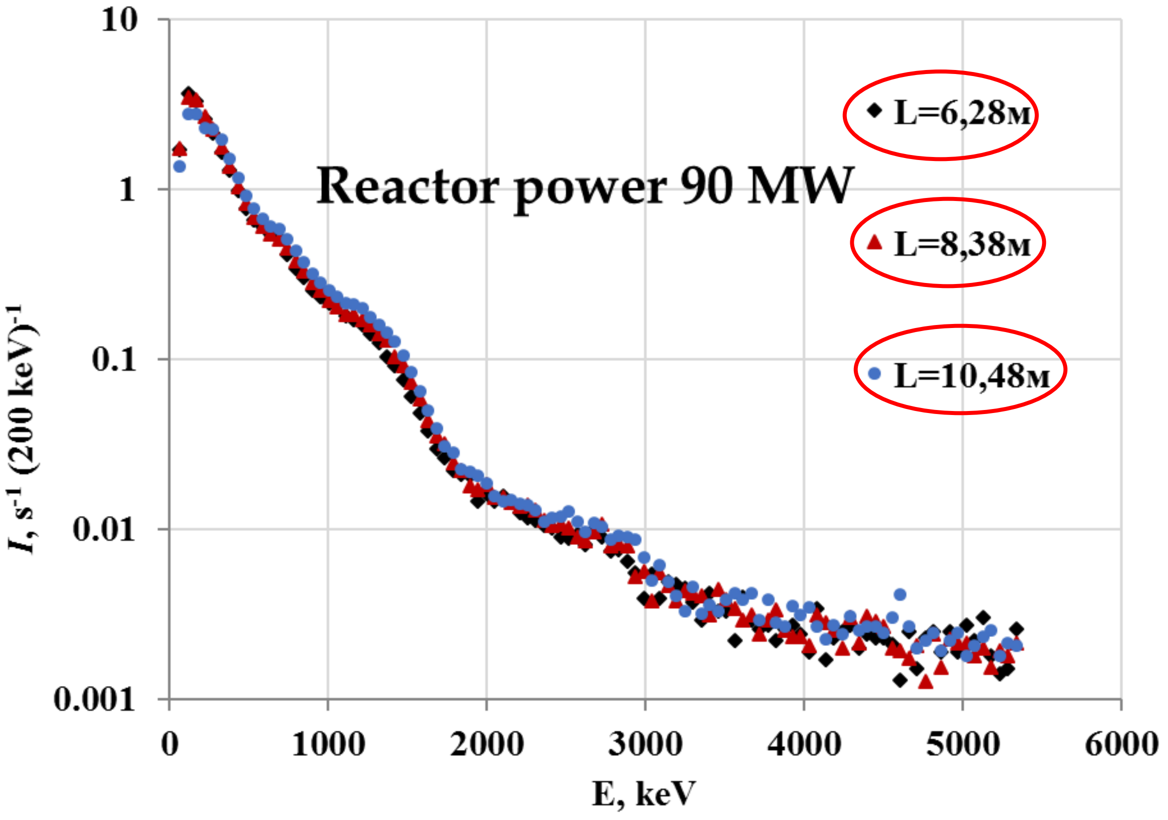
$$\Delta E_\nu / E_\nu(6MeV) = 14\%$$

$$\Delta E_\nu(6MeV) = 830keV$$

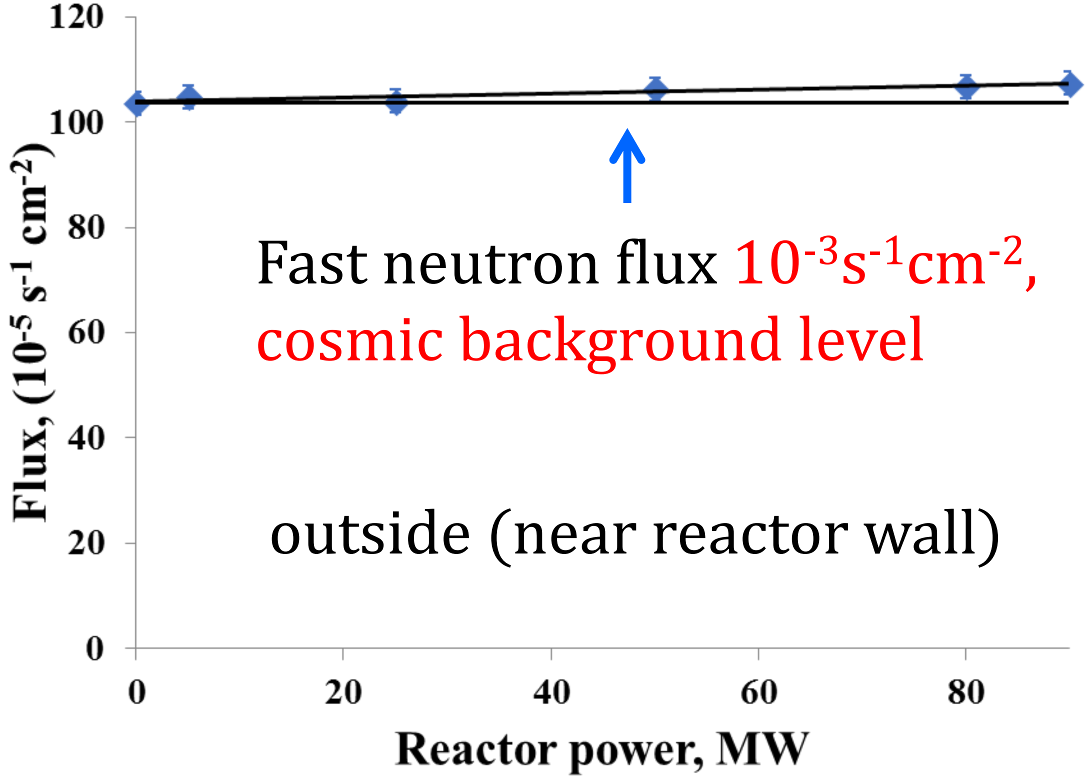
Gamma background in passive shielding does not depend neither on the power of the reactor nor on distance from the reactor

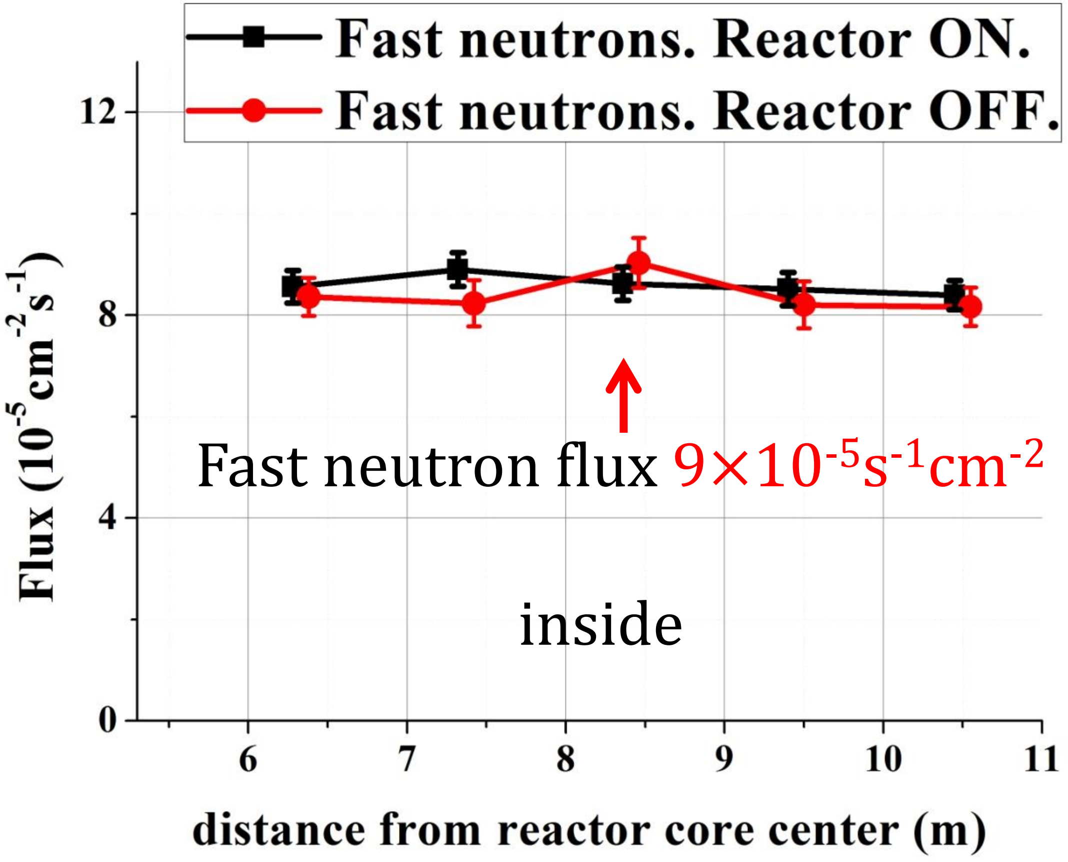


	0 MWt	90 MWt
1-255	16.9	17.4
43-255	3.5	3.8
63-255	0.6	0.8



The background of fast neutrons in passive shielding does not depend neither on the power of the reactor nor on distance from the reactor





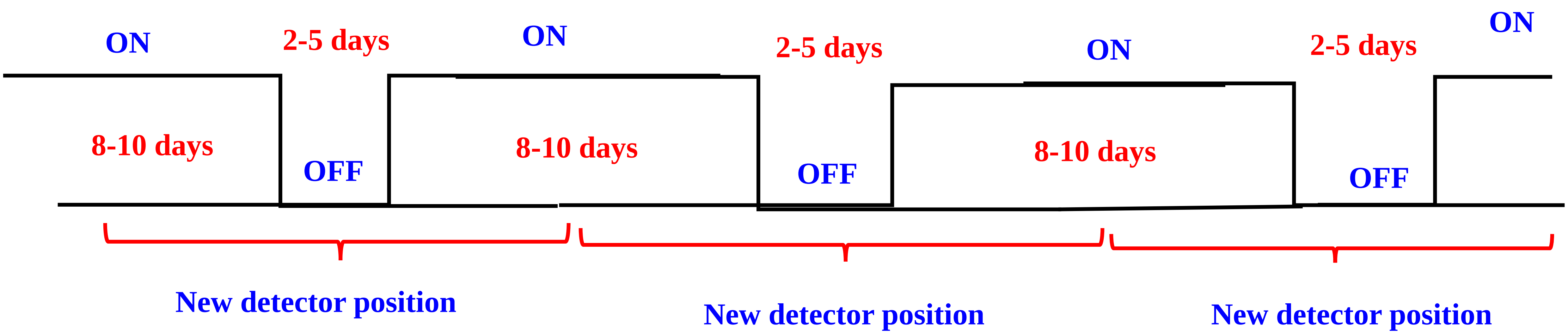
The background of fast neutrons in passive shielding is 10 times less than outside.
The background of fast neutrons outside of passive shielding is defined by cosmic rays and practically does not depend on reactor power.

Absence of noticeable dependence of the background on both distance and reactor power was observed. As a result, we consider that difference in reactor ON/OFF signals appears mostly due to antineutrino flux from operating reactor.

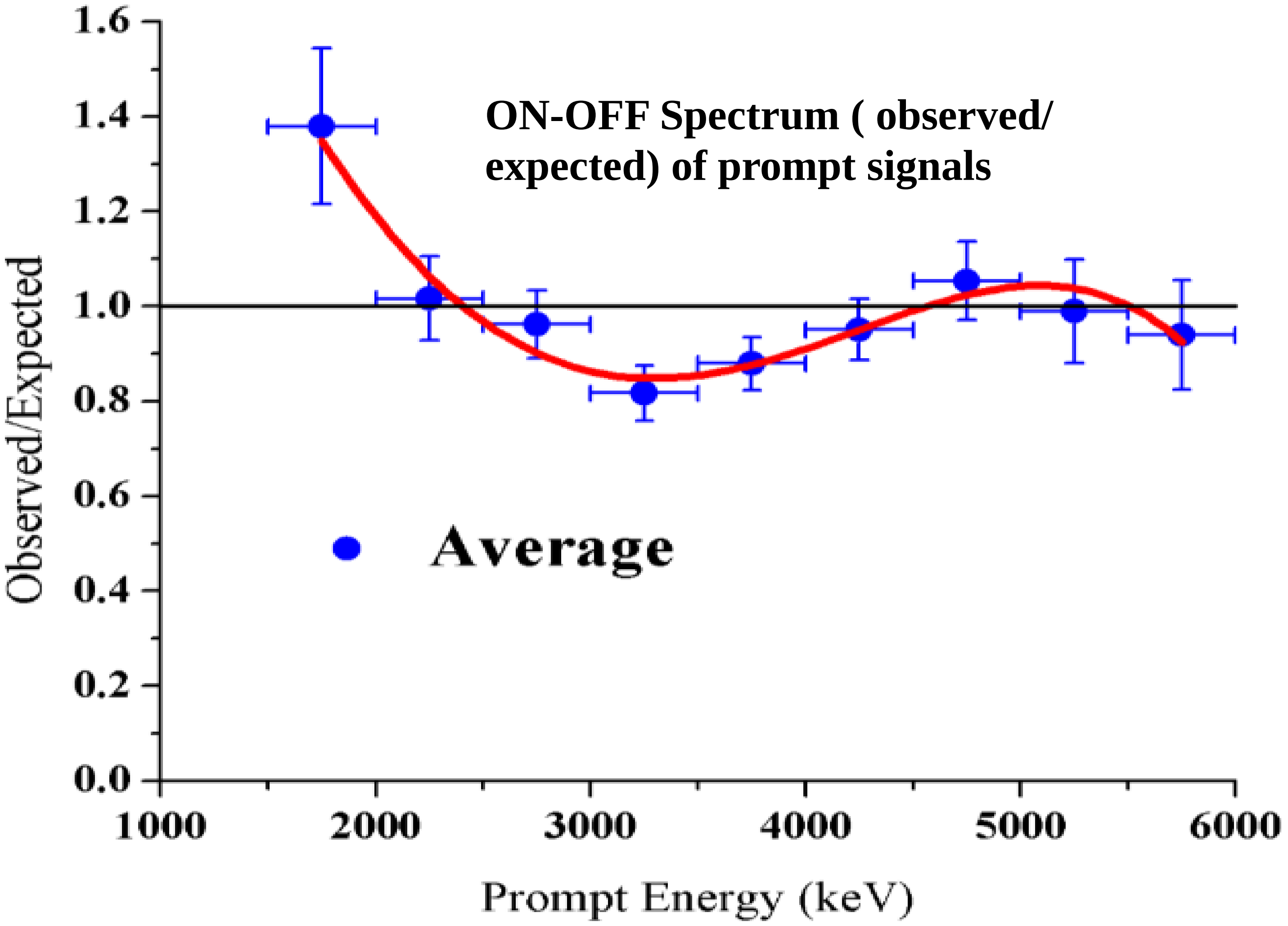
ON
90 MW

Measurements with the detector have started in June 2016. Measurements with the reactor ON were carried out for 480 days, and with the reactor OFF- for 278 days. In total, the reactor was switched on and off 58 times.

(ON – OFF)/ OFF = 50%



There is problems with energy spectrum therefore we proposed the spectrum independent method of the experimental data analysis



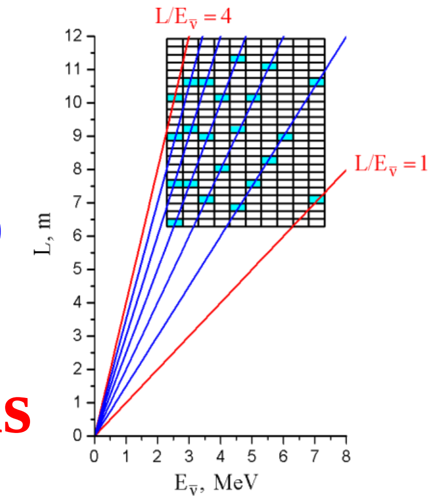
Spectrum (observed/ expected) of prompt signals in the detector for a total cycle of measurements summed over all distances (average distance — 8.6 meters).
Expected - Monte -Carlo simulation with neutrino spectrum of ^{235}U, as the SM-3 reactor works on highly enriched uranium.

Probability of antineutrino disappearance

$N(E_i, L_k)$

Number of antineutrino events

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



The spectrum independent method of experimental data analysis

$$R^{\exp}_{i,k} = \frac{N(E_i, L_k)L_k^2}{K^{-1}\sum\limits_{k}^{K} N(E_i, L_k)L_k^2} = \frac{[1-\sin^2 2\theta_{14}\sin^2(1.27\Delta m^2_{14}L_k / E_i)]}{K^{-1}\sum\limits_{k}^{K}[1-\sin^2 2\theta_{14}\sin^2(1.27\Delta m^2_{14}L_k / E_i)]} = R^{th}_{i,k} \quad (2)$$

The method of the analysis of experimental data should not rely on precise knowledge of spectrum. One can carry out model independent analysis using equation (2), where numerator is the rate of antineutrino events with correction to geometric factor $1/L^2$ and denominator is its value averaged over all distances.

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

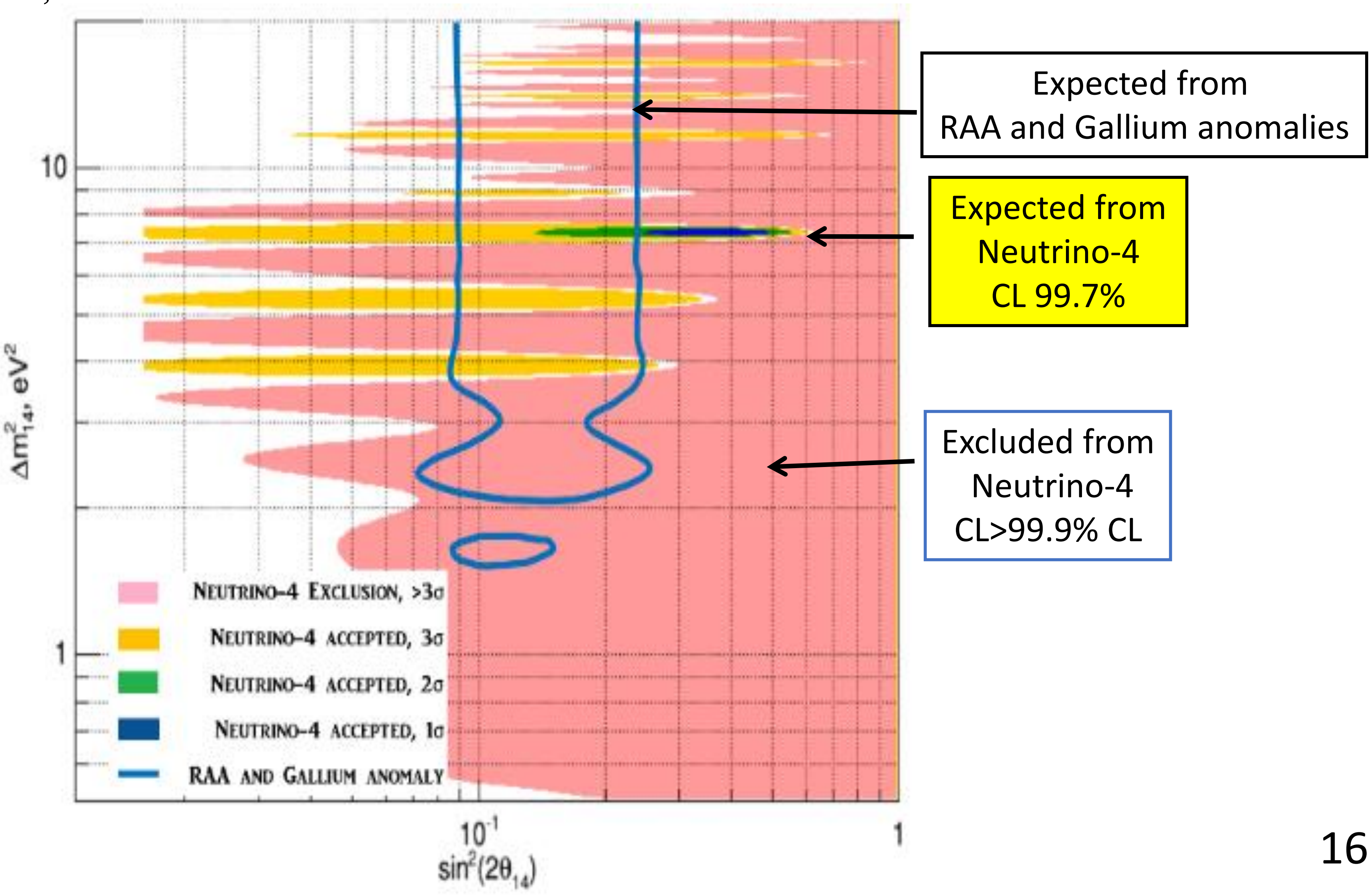
The results of the analysis of optimal parameters Δm^2_{14} and $\sin^2 2\theta_{14}$ using χ^2 method

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

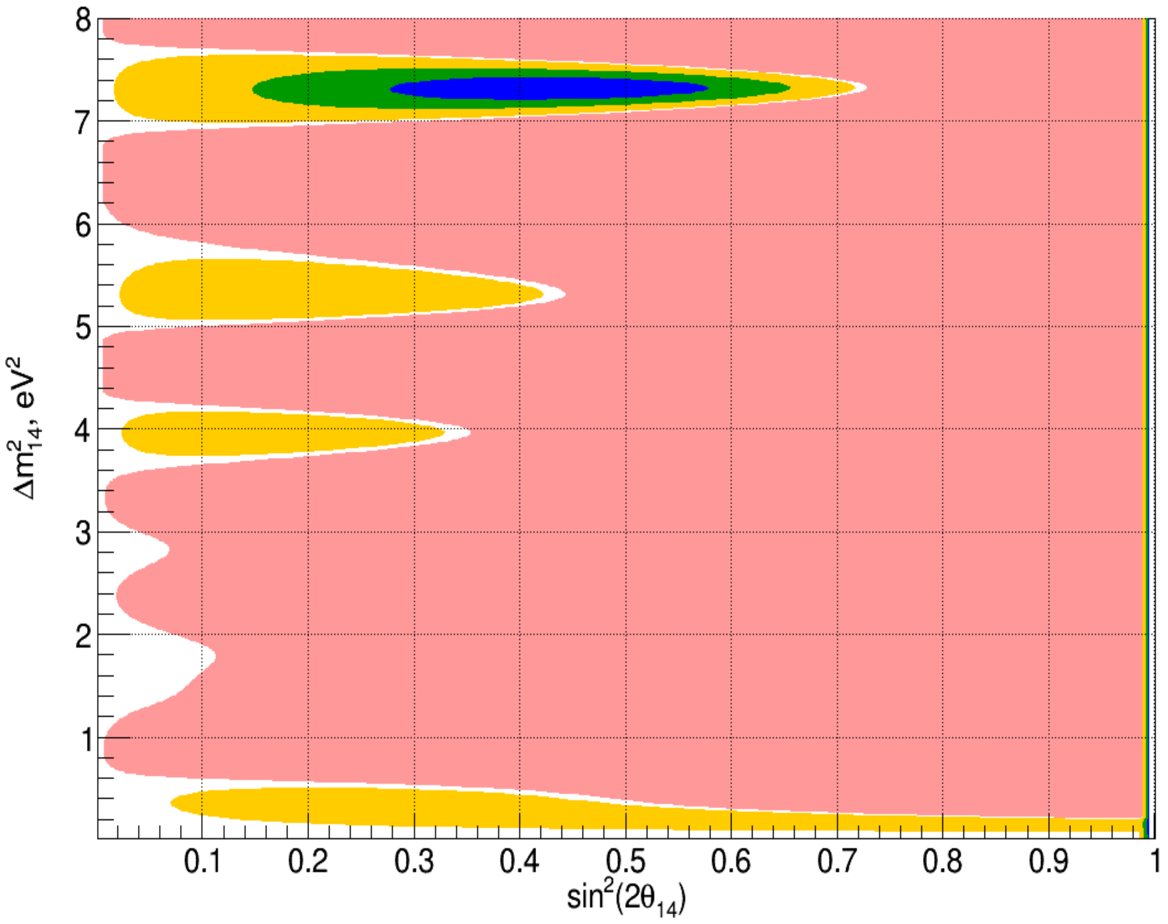
We observed the oscillation effect at C.L. 99.7% (3σ) in vicinity of :

$\Delta m^2_{14} \approx 7 eV^2$

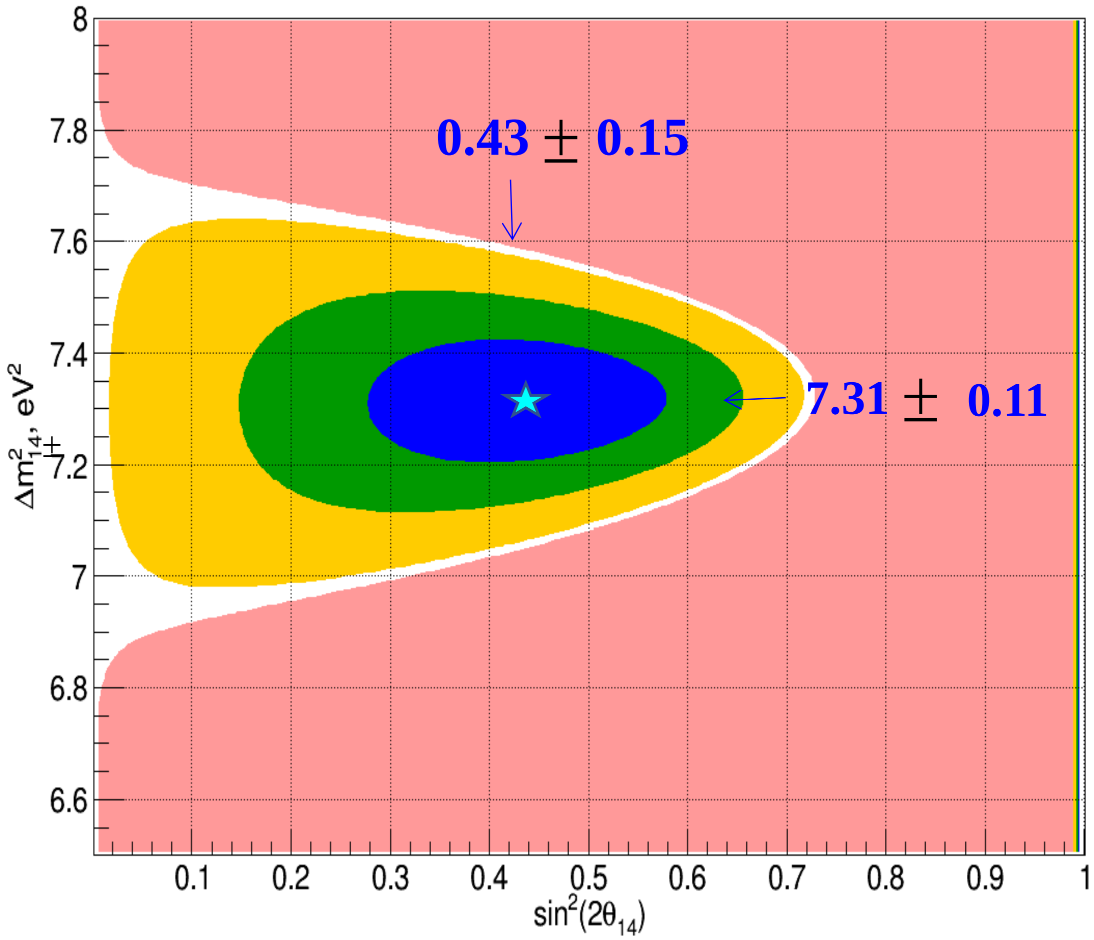
$\sin^2 2\theta_{14} \approx 0.4$



Результаты анализа на оптимальные параметры Δm^2_{14} и $\sin^2 2\theta_{14}$ методом χ^2

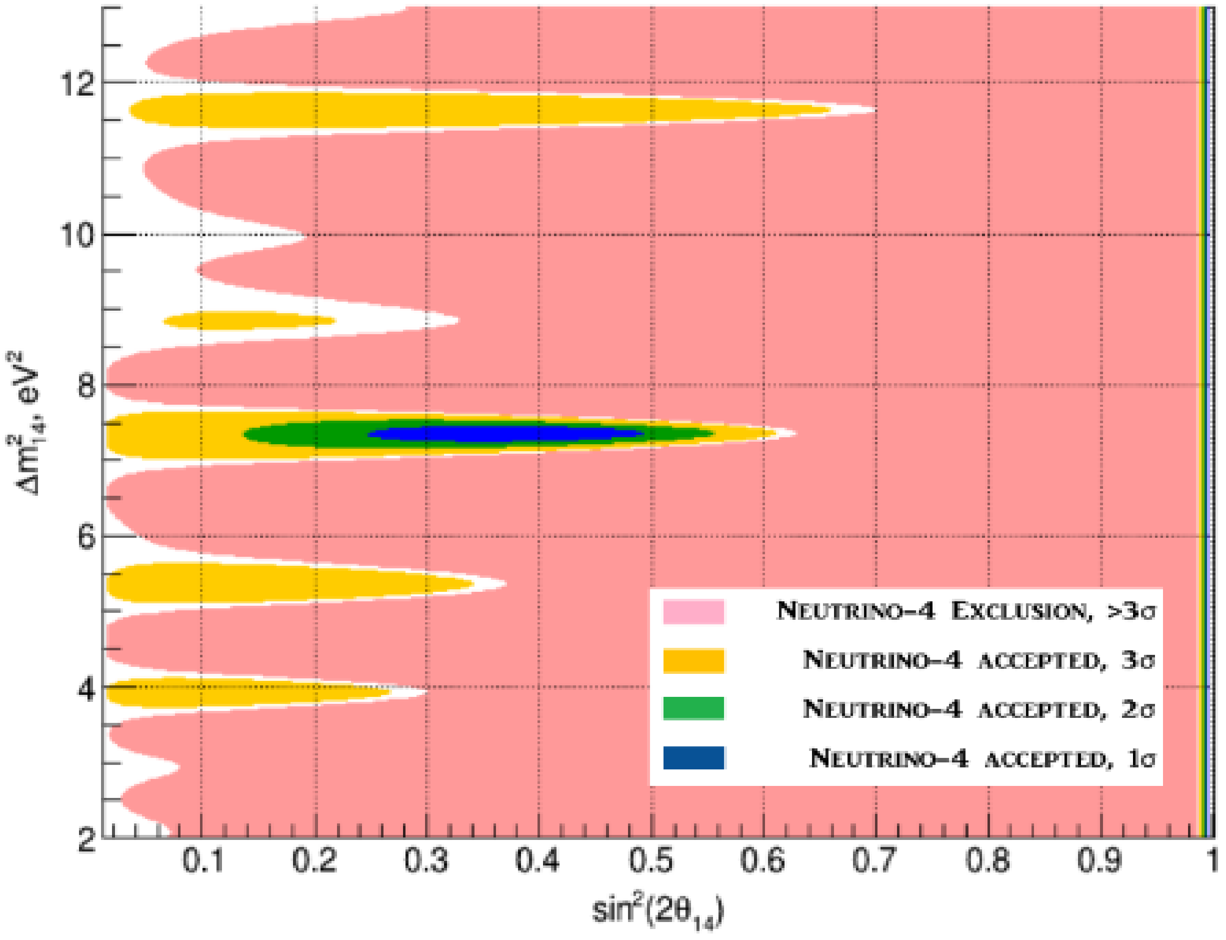


область вокруг центральных значений в линейном масштабе и с большим увеличением

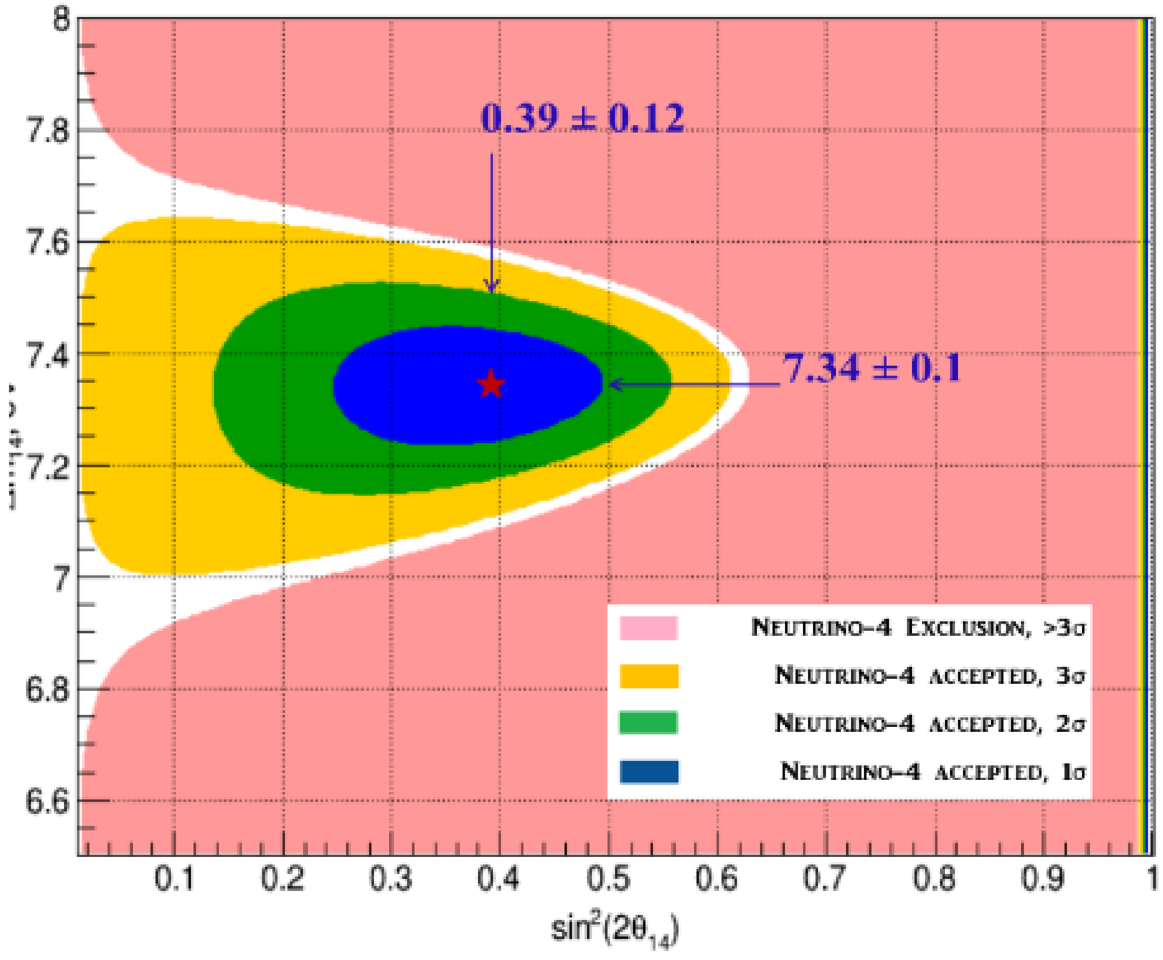


центральная область с ещё большим увеличением

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



Area around central values in linear scale and significantly magnified



Central part even further magnified

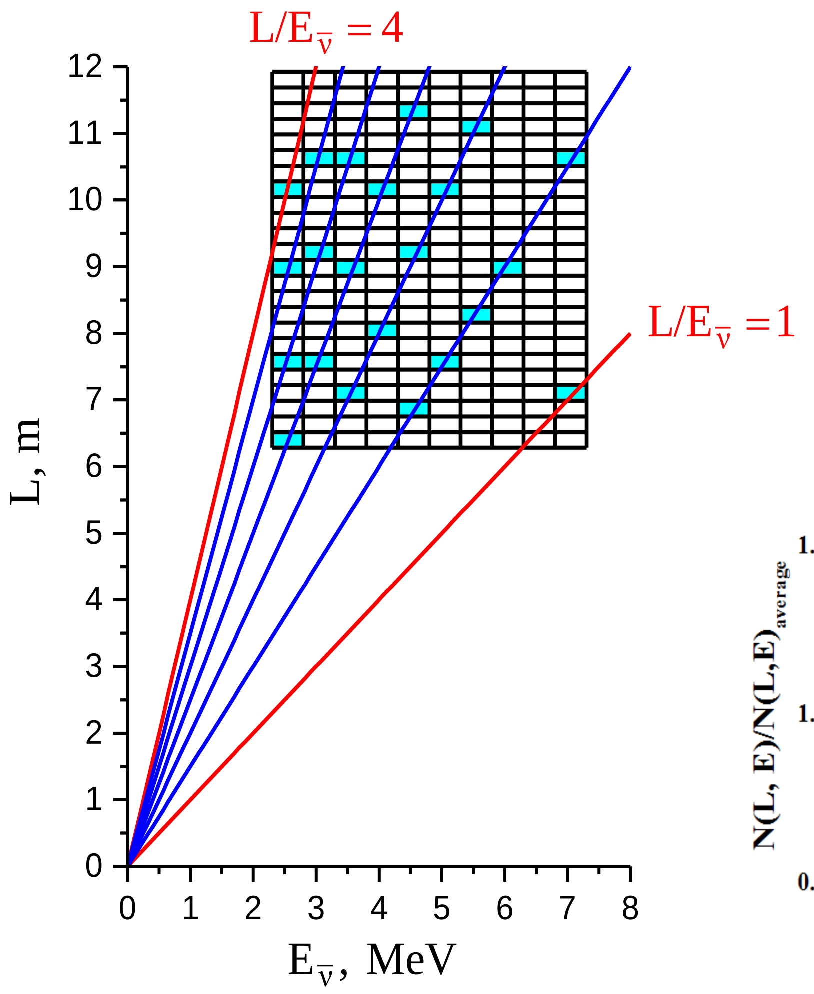
It seems that the effect predicted in gallium and reactor experiments is confirmed, but at sufficiently large values

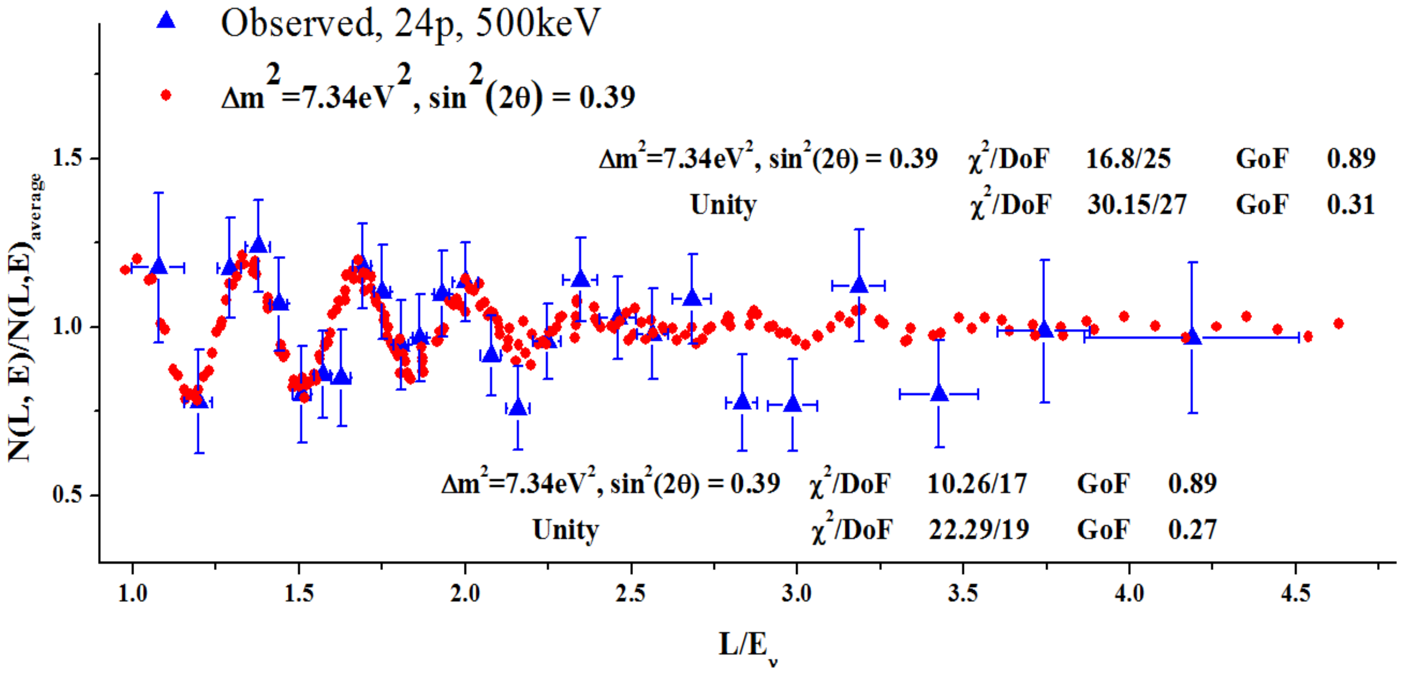
$$\Delta m_{14}^2 \approx 7.3 эВ^2 \qquad \sin^2 2\theta_{14} = 0.39 \pm 0.12$$

The mixing parameter appears to be large enough in comparison with existing limitations from the Daya Bay and Bugey-3 experiments, but the difference between the results is 0.19 ± 0.18, i.e. one standard deviation. Therefore, there is no clear contradiction.

The method of coherent addition of results of measurements allows us to directly observe the effect of oscillations

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



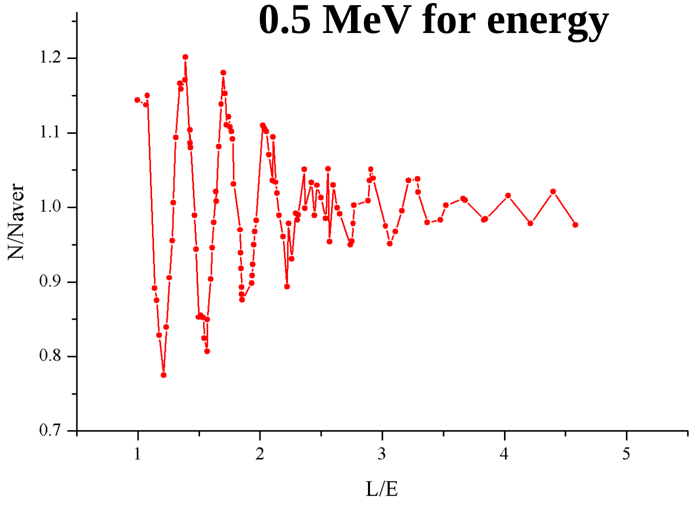


The expected effect at the different interval for distance and for energy (right part of equation 2)

$\Delta m^2_{14} \approx 7\,\text{эВ}^2$

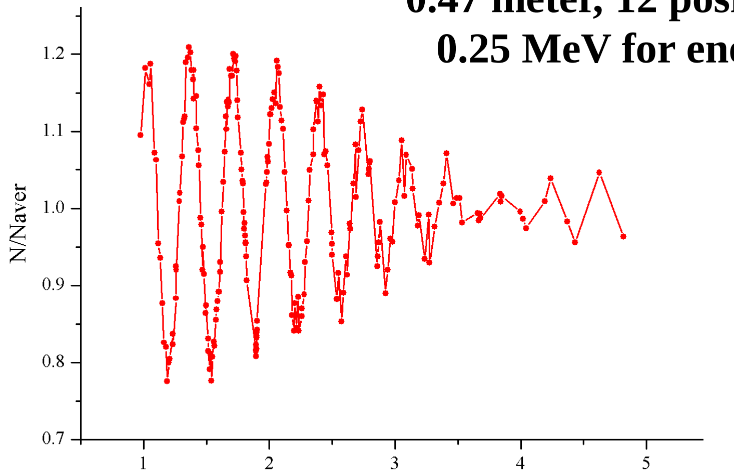
$\sin^2 2\theta_{14} \approx 0.4$

0.47 meter, 12 positions, 0.5 MeV for energy

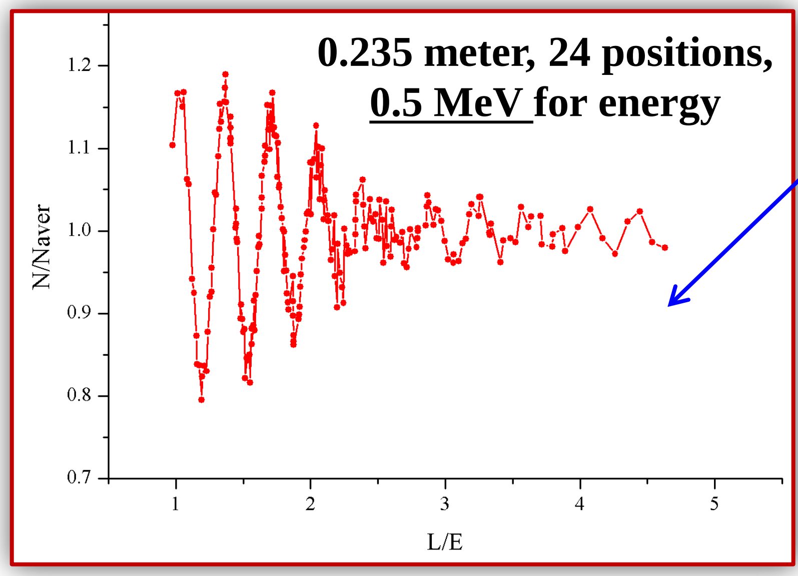


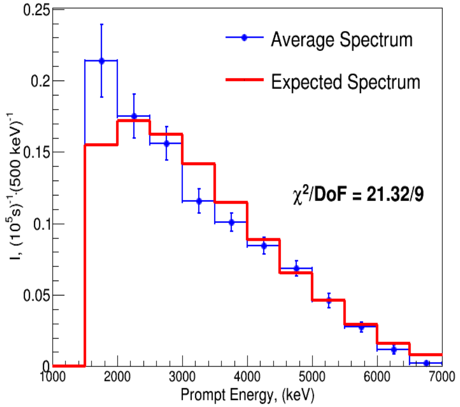
The attenuation of sinusoidal process for red curve in area L/E >2.5 is explained by taken energy interval 0.5MeV.
This energy interval corresponds to experimental energy resolution **±250keV**

0.47 meter, 12 positions, 0.25 MeV for energy

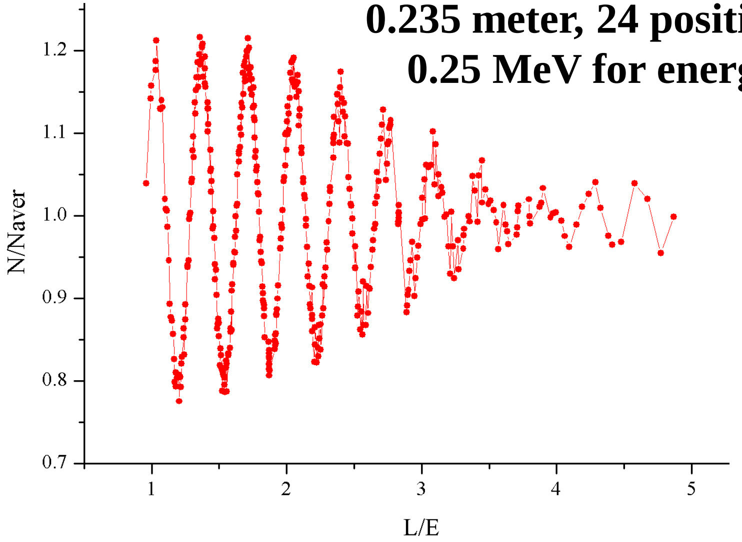


0.235 meter, 24 positions, 0.5 MeV for energy

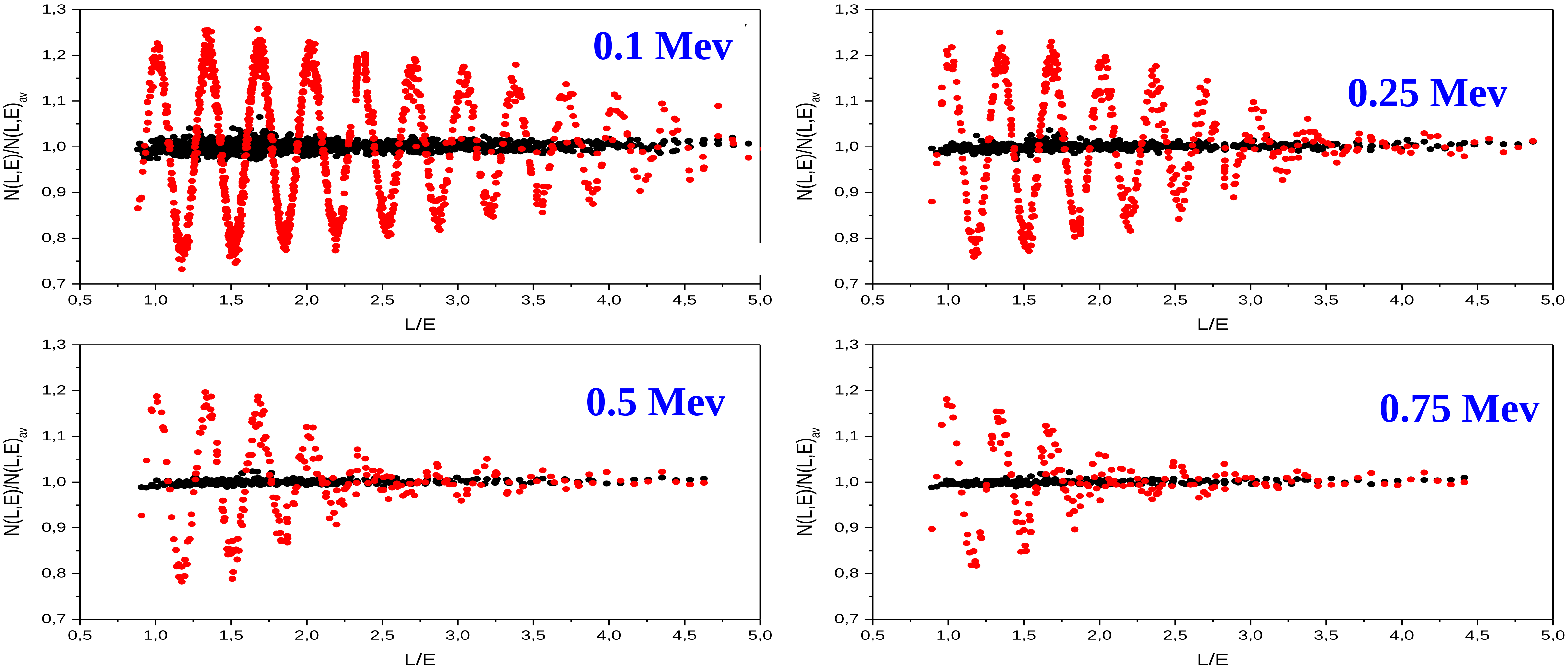




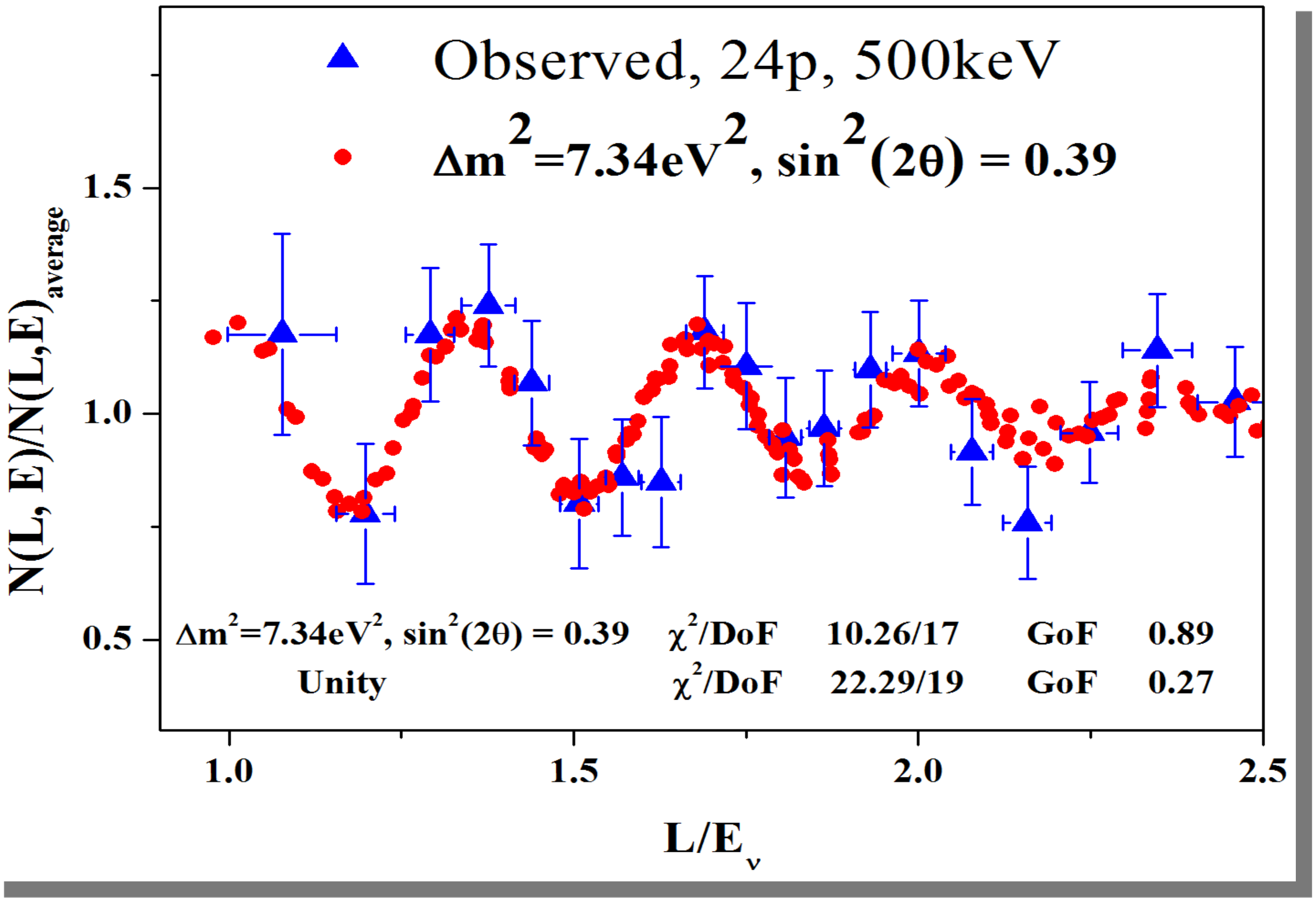
0.235 meter, 24 positions, 0.25 MeV for energy



The expected effect for the different energy resolution



The first observation of oscillation of reactor antineutrino in sterile neutrino



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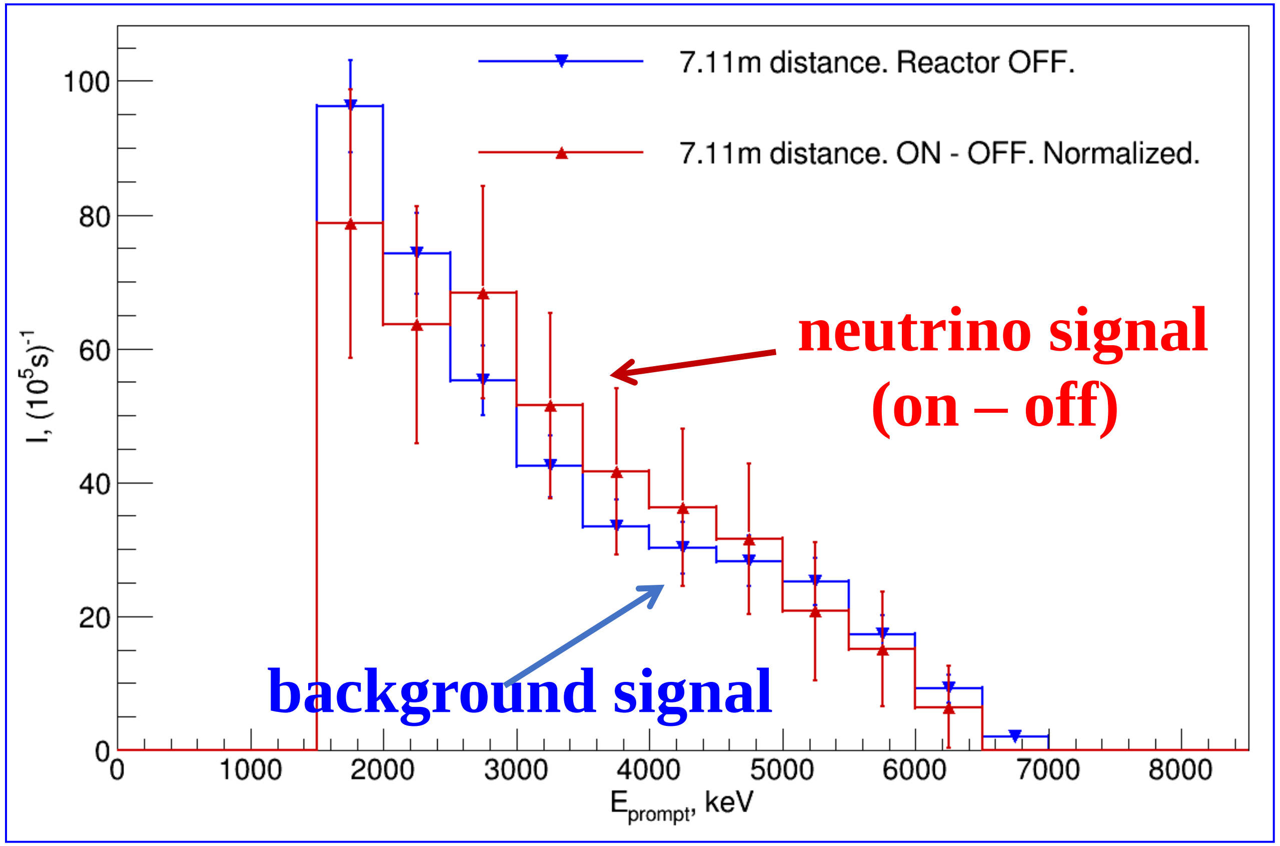
https://doi.org/10.1134/S0021364019040040,
arxiv:1809.10561

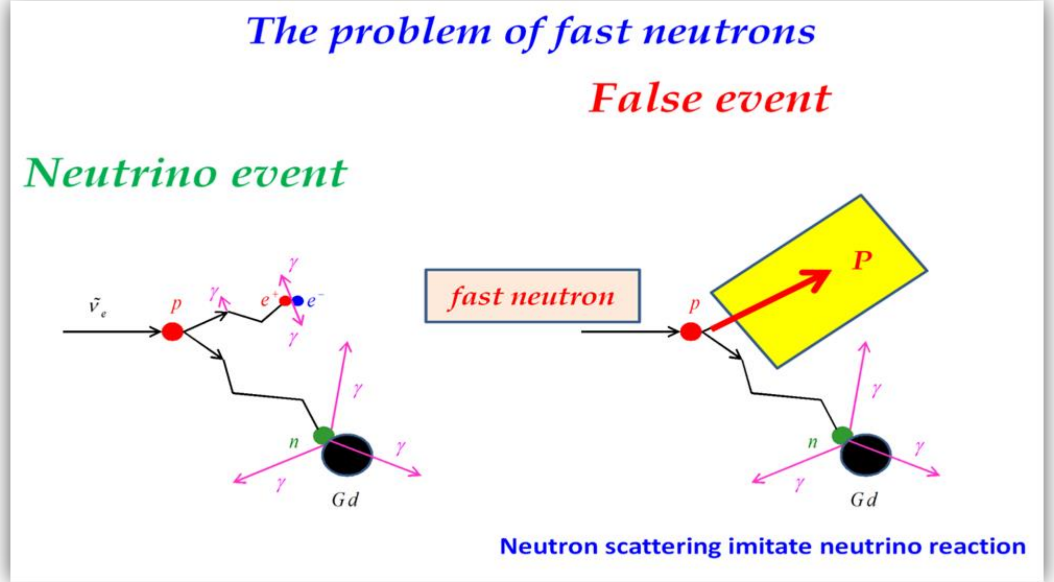
The period
of oscillation
for neutrino energy
4 MeV is 1.4 m

Analysis of possible systematic effects

To carry out analysis of possible systematic effects one should turn off antineutrino flux (reactor) and perform the same analysis of background data

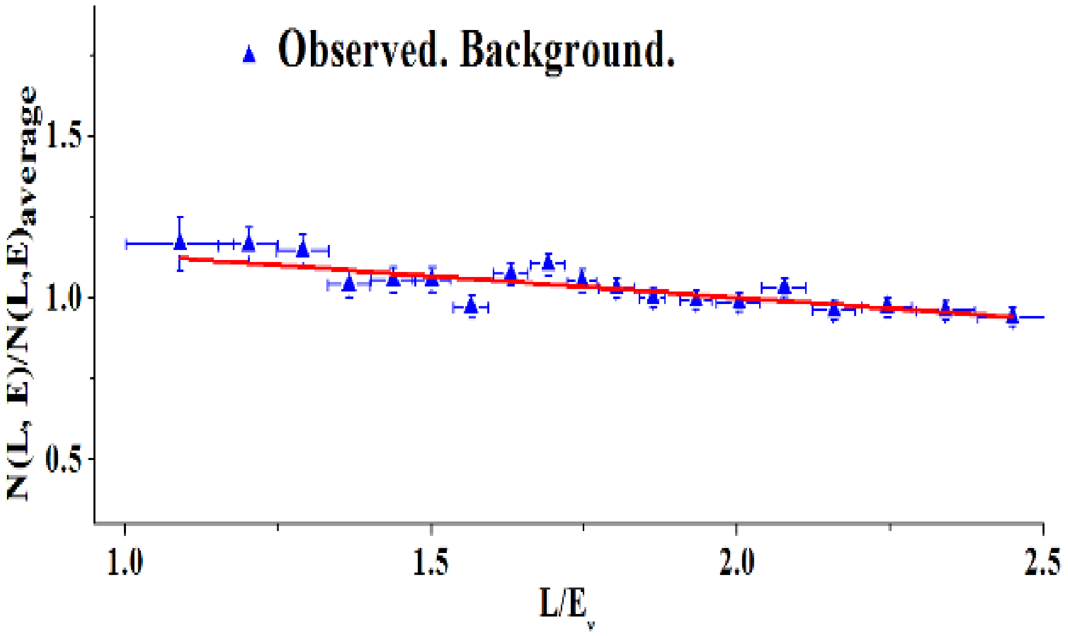


The spectrum for neutrino signal and background signal are similar therefore test for systematic effect have to be adequate .

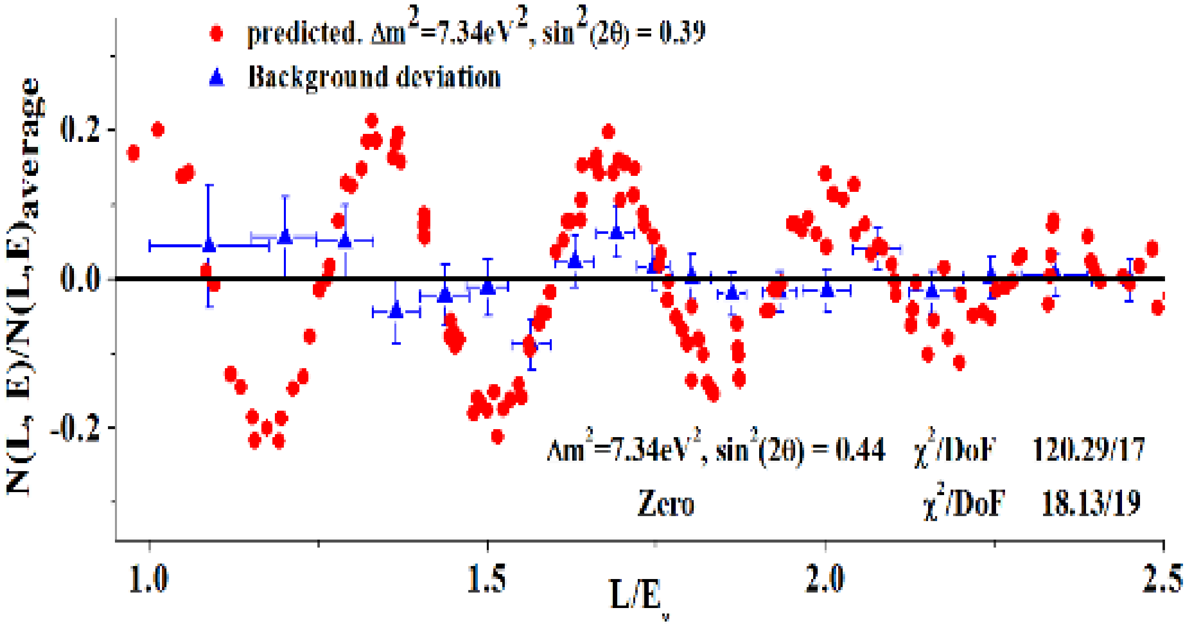


Test of systematic effects

To carry out analysis of possible systematic effects one should turn off antineutrino flux (reactor) and perform the same analysis of obtained data



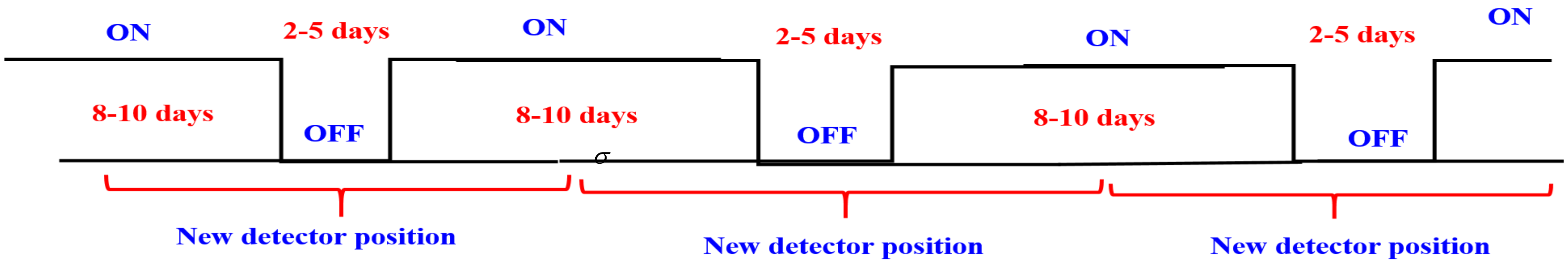
data analysis using coherent summation method

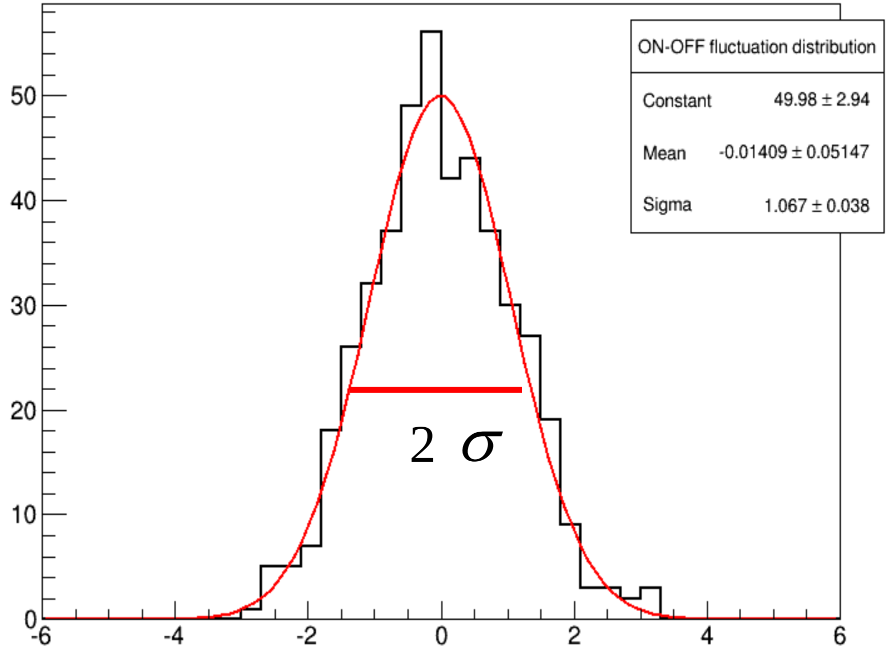


analysis of the results on oscillation parameters plane

Thus no instrumental systematic errors were observed.

Additional dispersion of measurement result which appears due to fluctuations of cosmic background





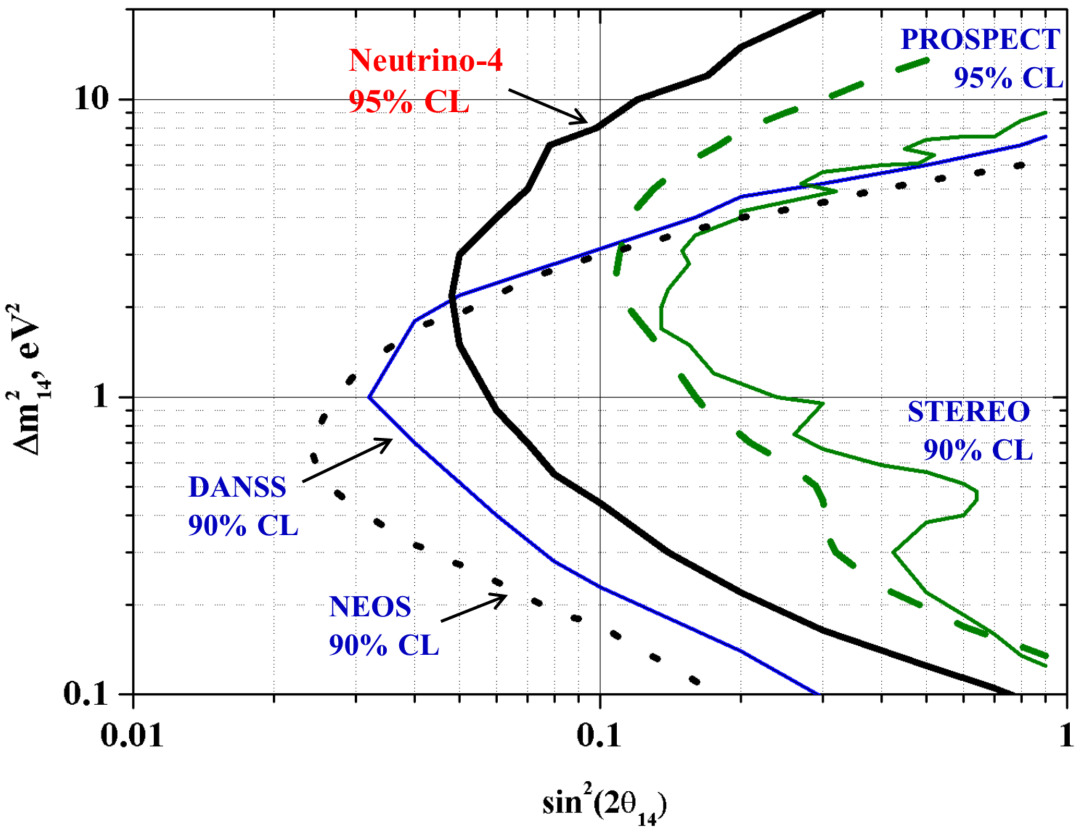
That distribution has the form of normal distribution, but its width exceeds unit by ~ **7%.**

$$\sigma = 1.067 \pm 0.038$$

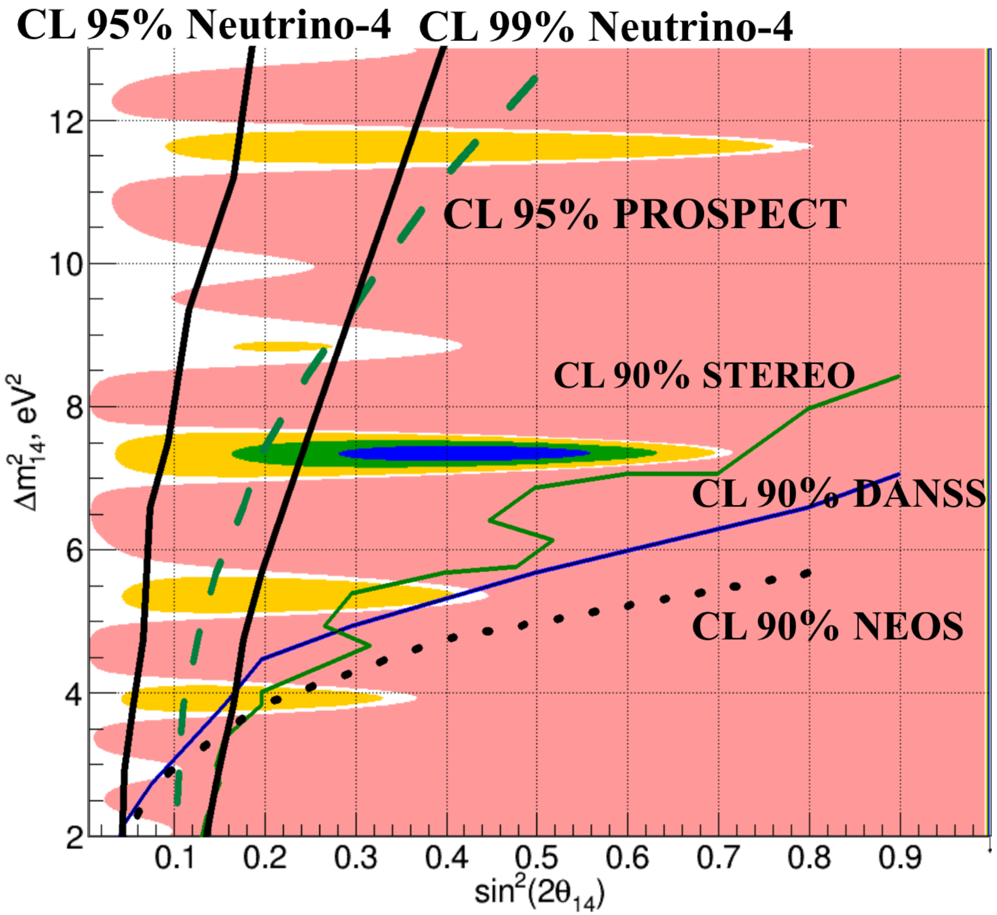
Since the measurements of the background carried out during the annual scheduled reactor repair works, then total additional dispersion is increased up to ~ **9%**.

That is considered as systematic correction of uncertainties of results of measurements and it results in decreasing of confidence level of the results to 2.8σ.

Sensitivity of other experiments NEOS , DANSS , STEREO and PROSPECT together with Neutrino-4



sensitivity regions of various experiments (logarithmic scale)



region of oscillation effect in linear scale.

Experiment Neutrino-4 has some advantages in sensitivity to big values of Δm^2_{14} owing to a compact reactor core, close minimal detector distance from the reactor and wide range of detector movements. Next highest sensitivity to large values of Δm^2_{14} belongs to PROSPECT experiment. Currently its sensitivity is two times lower than Neutrino-4 sensitivity, but it recently has started data collection so it possibly can confirm or refute our result.

Some advantages of experiment Neutrino-4

Experiment Neutrino-4 has some advantages in sensitivity to big values of Δm_{14}^2 owing to a compact reactor core, close minimal detector distance from the reactor and wide range of detector movements. In total, the reactor was switched on and off 58 times.

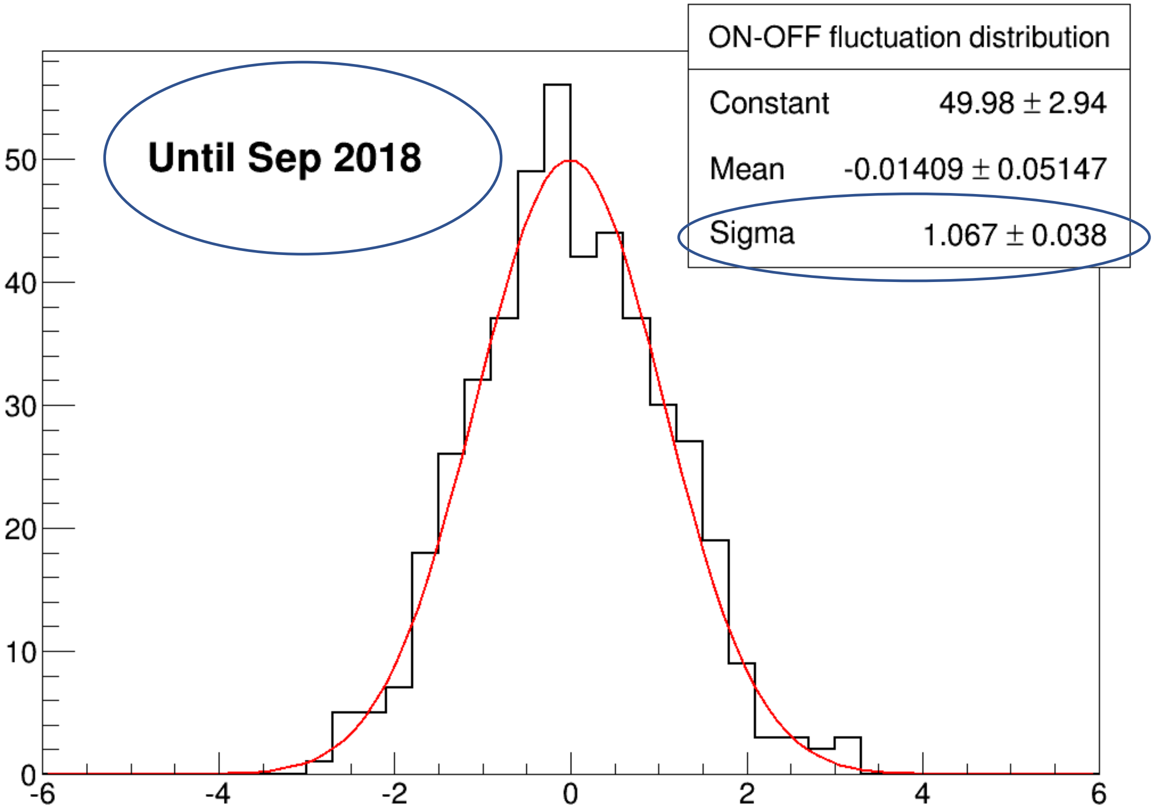
New measurements

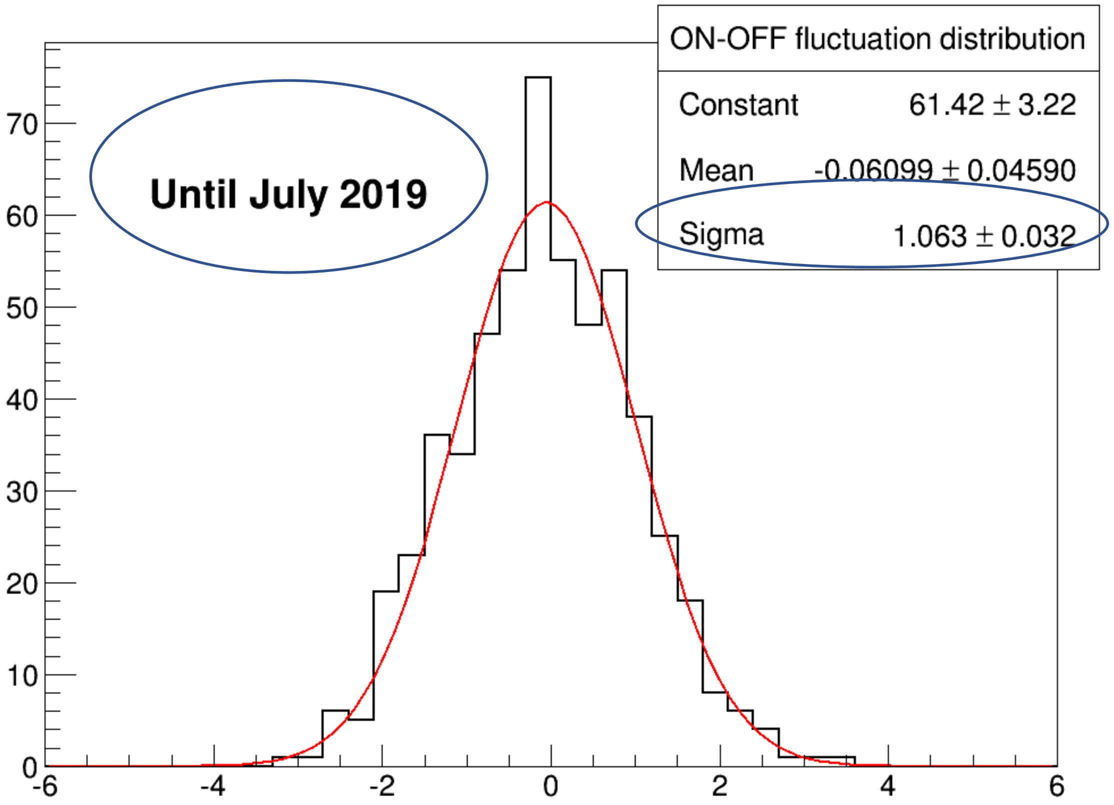
New measurements

Deviation from statistic distribution 6.7 +_ 3.8 %

ON – OFF fluctuation distribution

Deviation from statistic distribution 6.3+_ 3.2 %



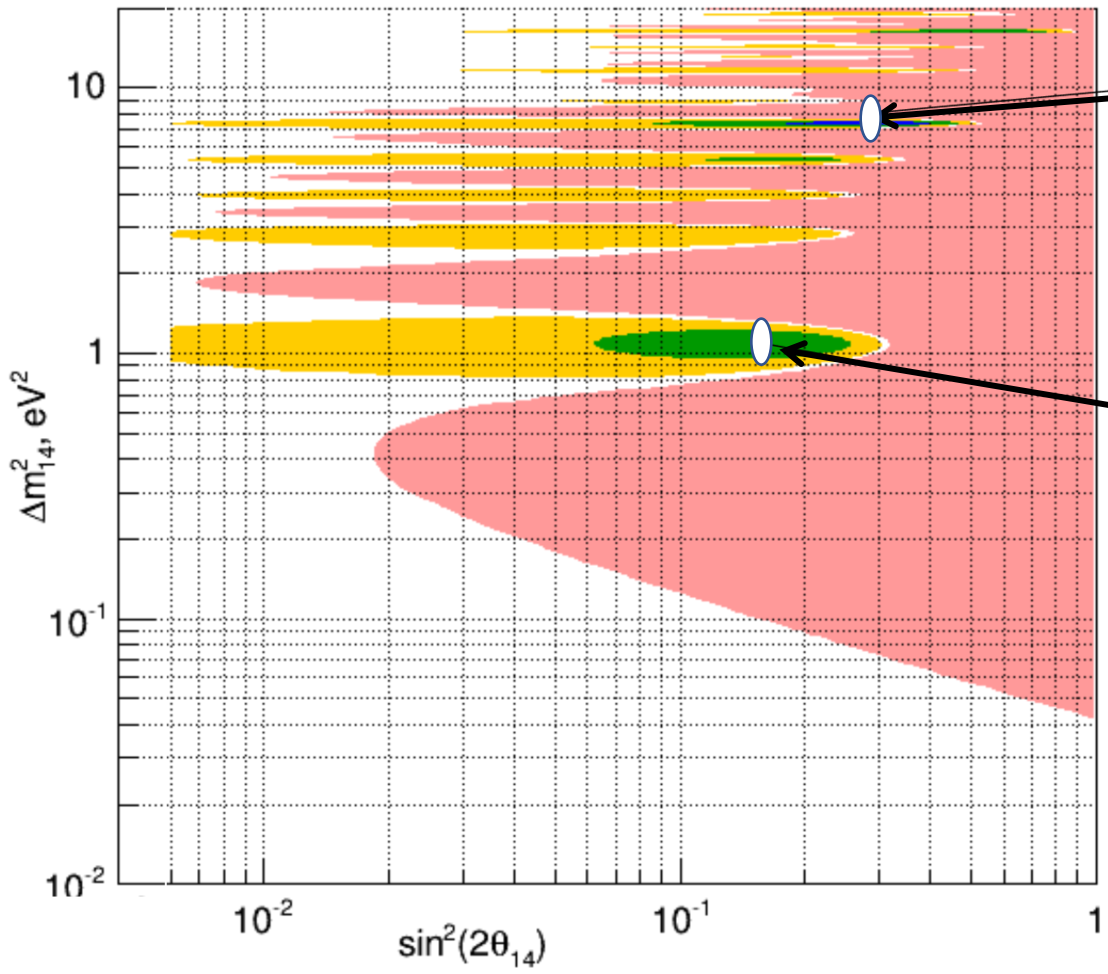


Here is twice statistic because new measurements have been carried out at short distance where signal background ratio is much better

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

June 2016 – Julv 2019

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

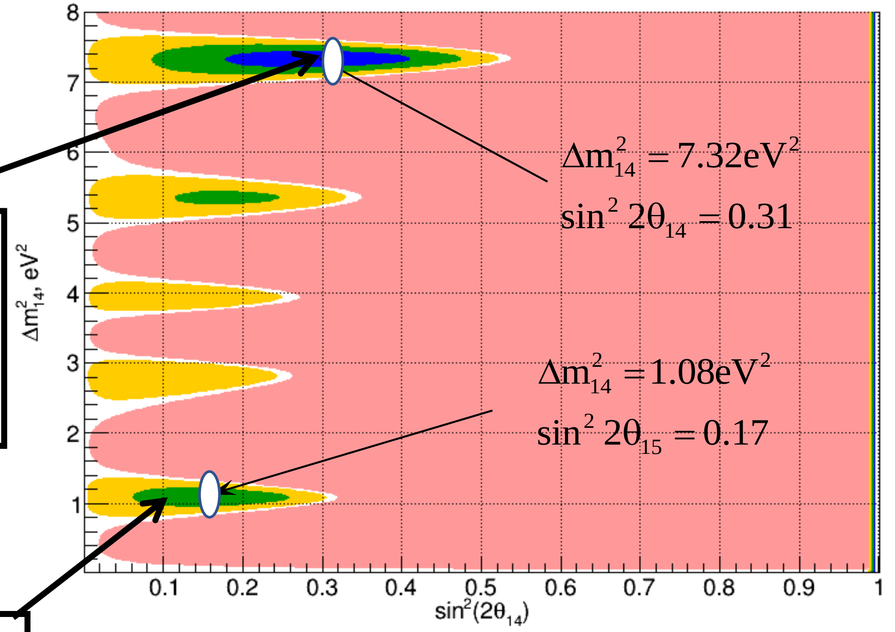


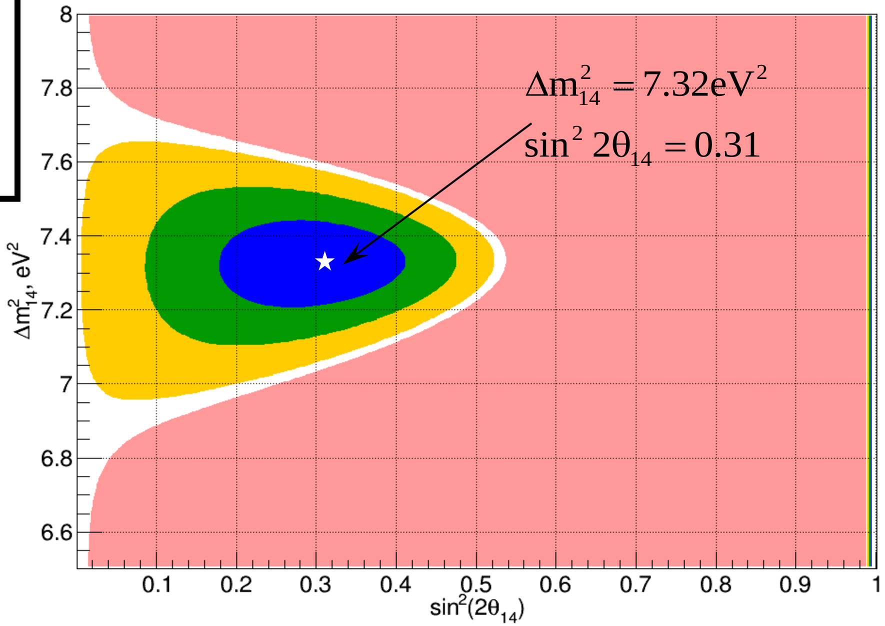
$\Delta m^2_{14} = 7.32 eV^2$

$\sin^2 2\theta_{14} = 0.31$

$\Delta m^2_{14} = 1.08 eV^2$

$\sin^2 2\theta_{15} = 0.17$





Here is twice statistic. Effect of neutrino oscillation still live.

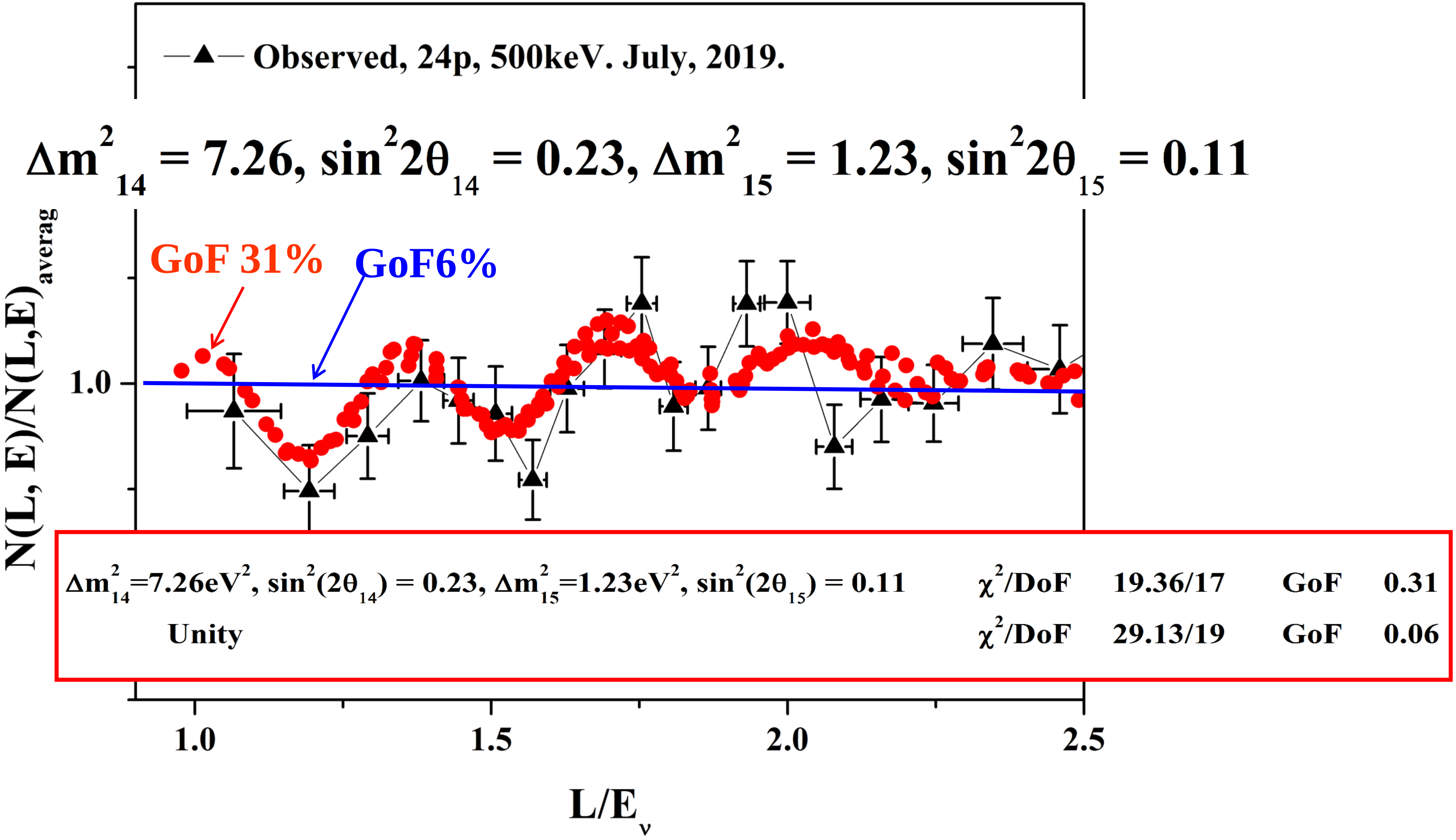
Analysis of experimental data with two sterile neutrino

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{14} \sin^2 \frac{1.27\Delta m^2_{14}[eV^2]L[m]}{E_{\bar{\nu}_e}[MeV]}$$

$$-\sin^2 2\theta_{15} \sin^2 \frac{1.27\Delta m^2_{15}[eV^2]L[m]}{E_{\bar{\nu}_e}[MeV]}$$

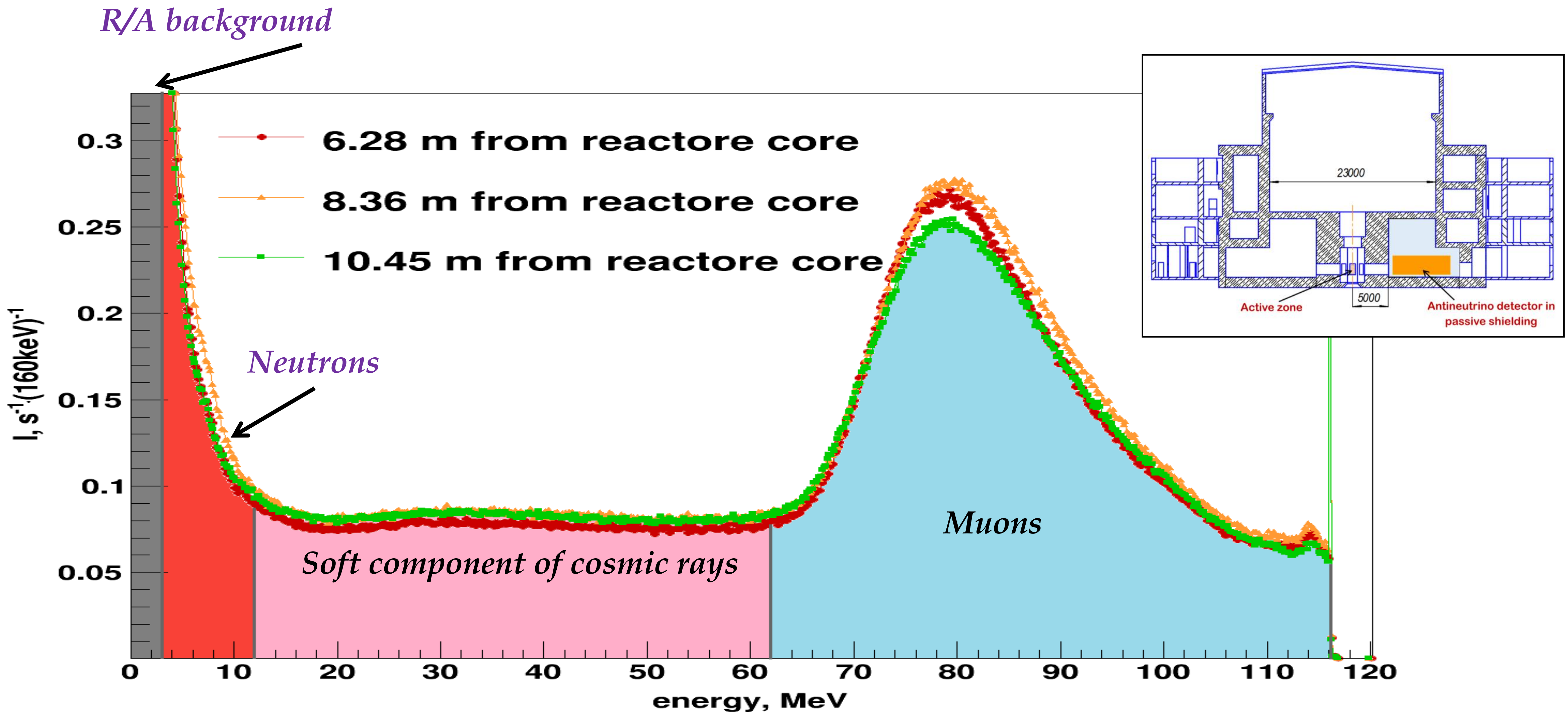
$\Delta m^2_{14} = 7.26$, $\sin^2 2\theta_{14} = 0.23$, $\Delta m^2_{15} = 1.23$, $\sin^2 2\theta_{15} = 0.11$

Analysis of experimental data with two sterile neutrino

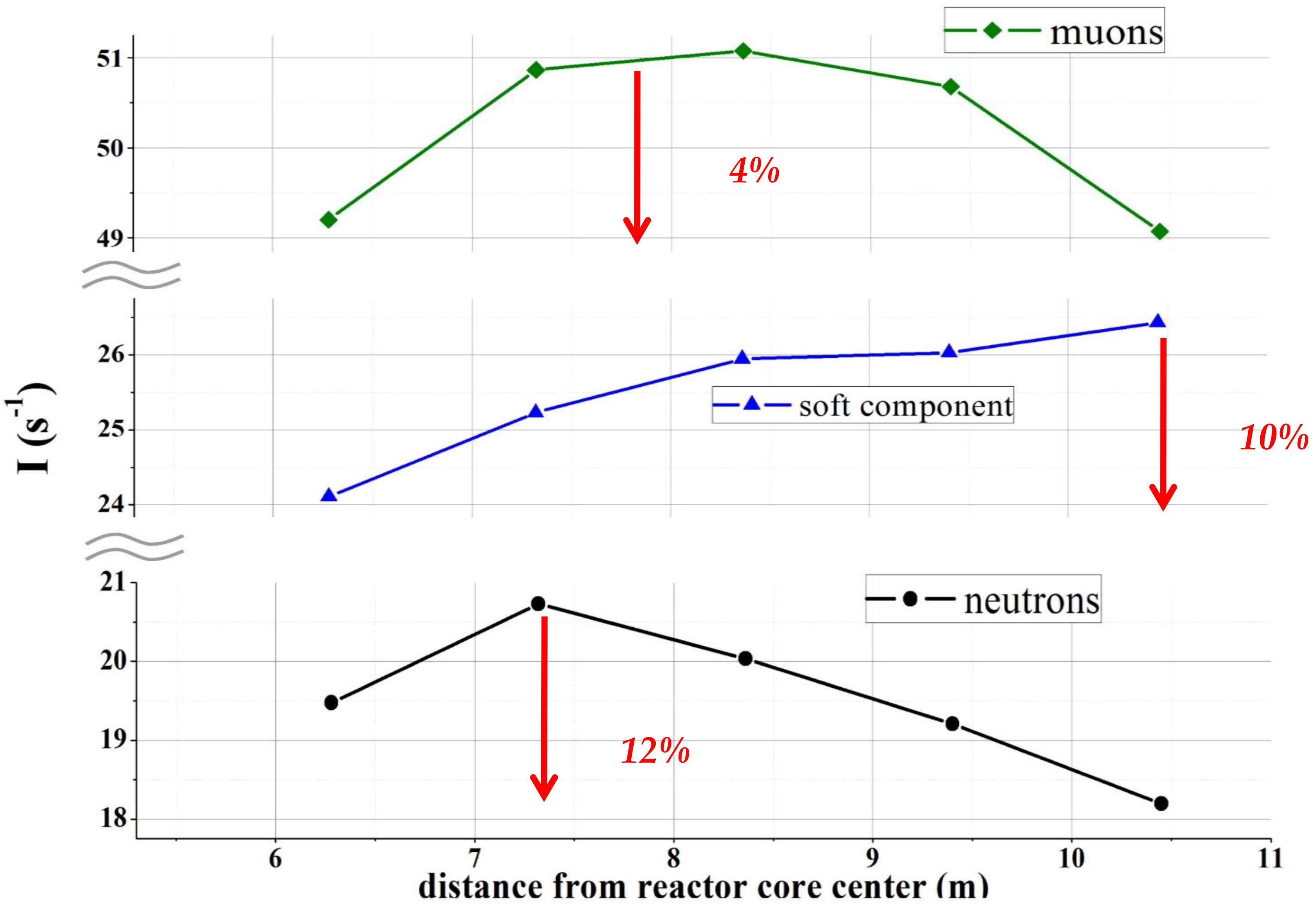


Background -
- Space and time distribution

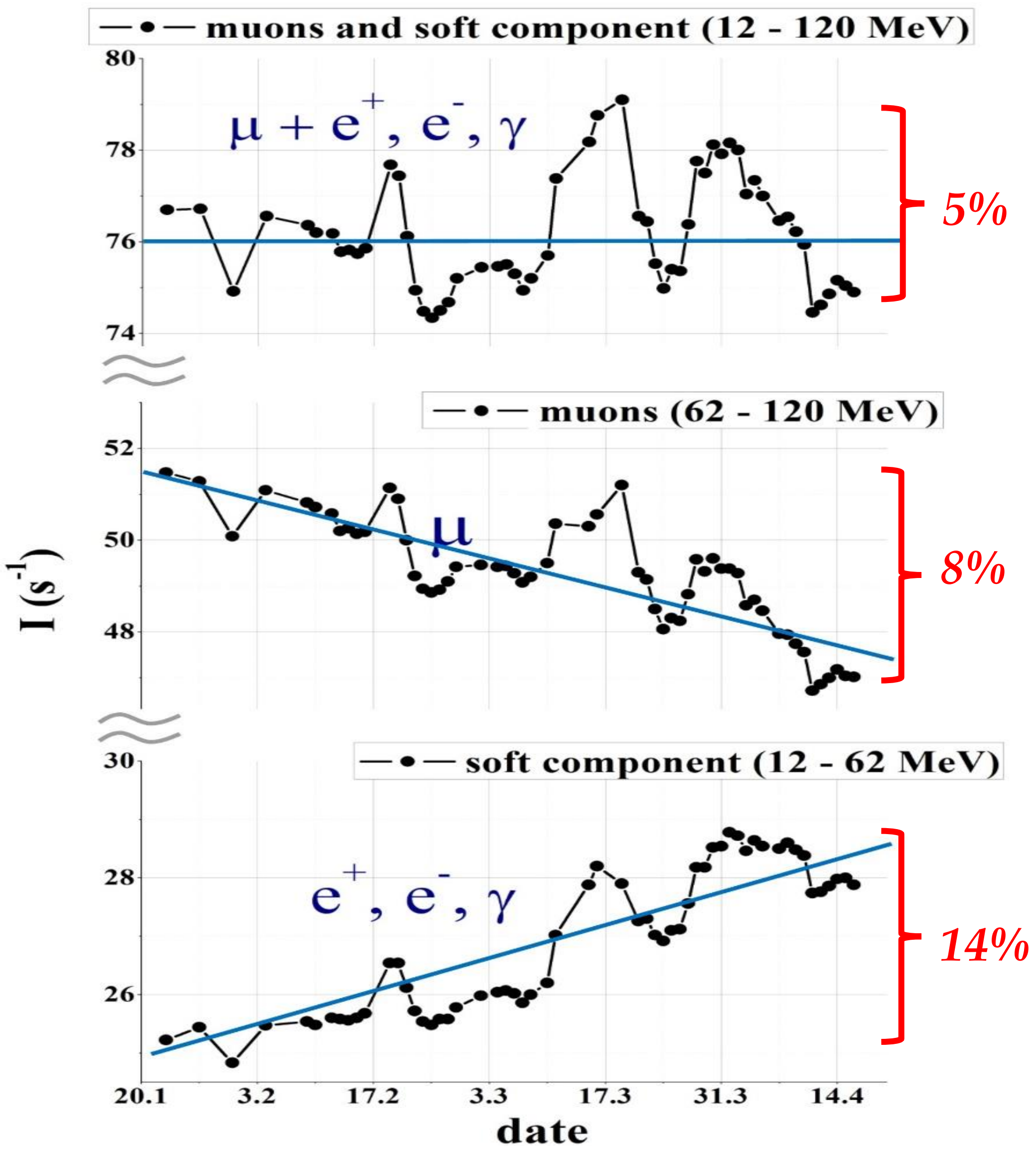
Different part of spectrum at the different distance

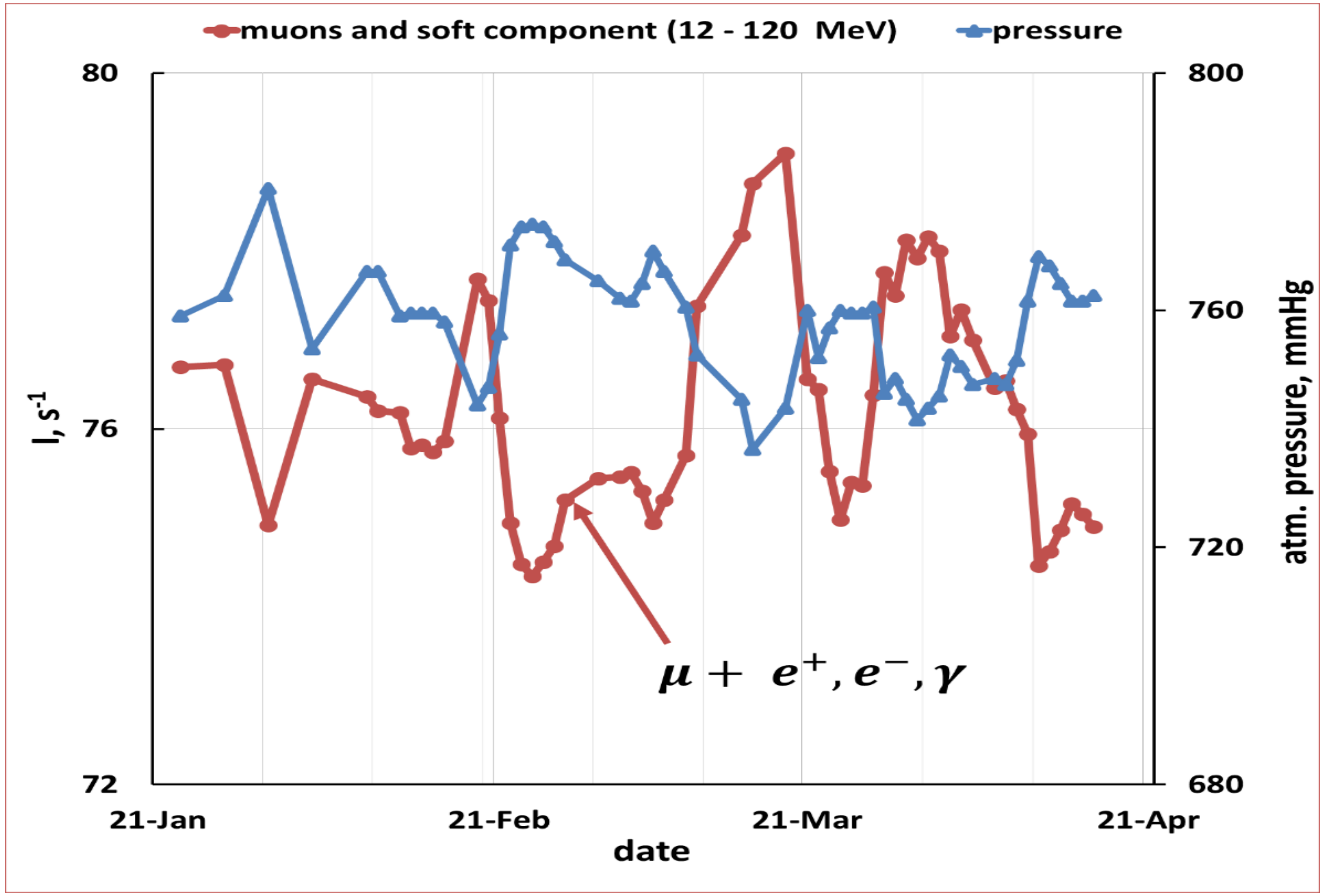


Distance dependence of intensity in different parts of neutrino prototype detector spectrum (larger scale)

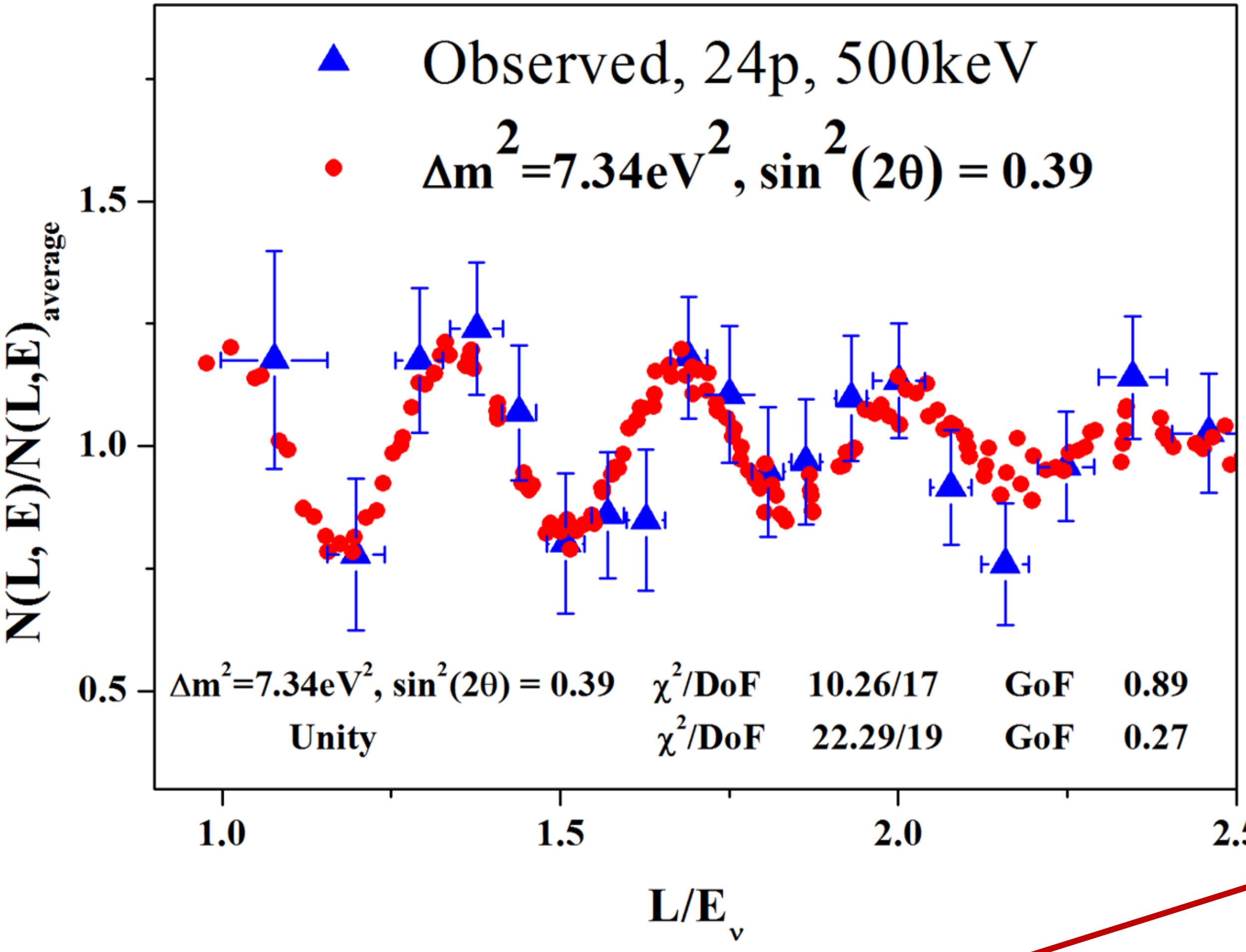


The effects of atmospheric temperature and pressure on cosmic rays

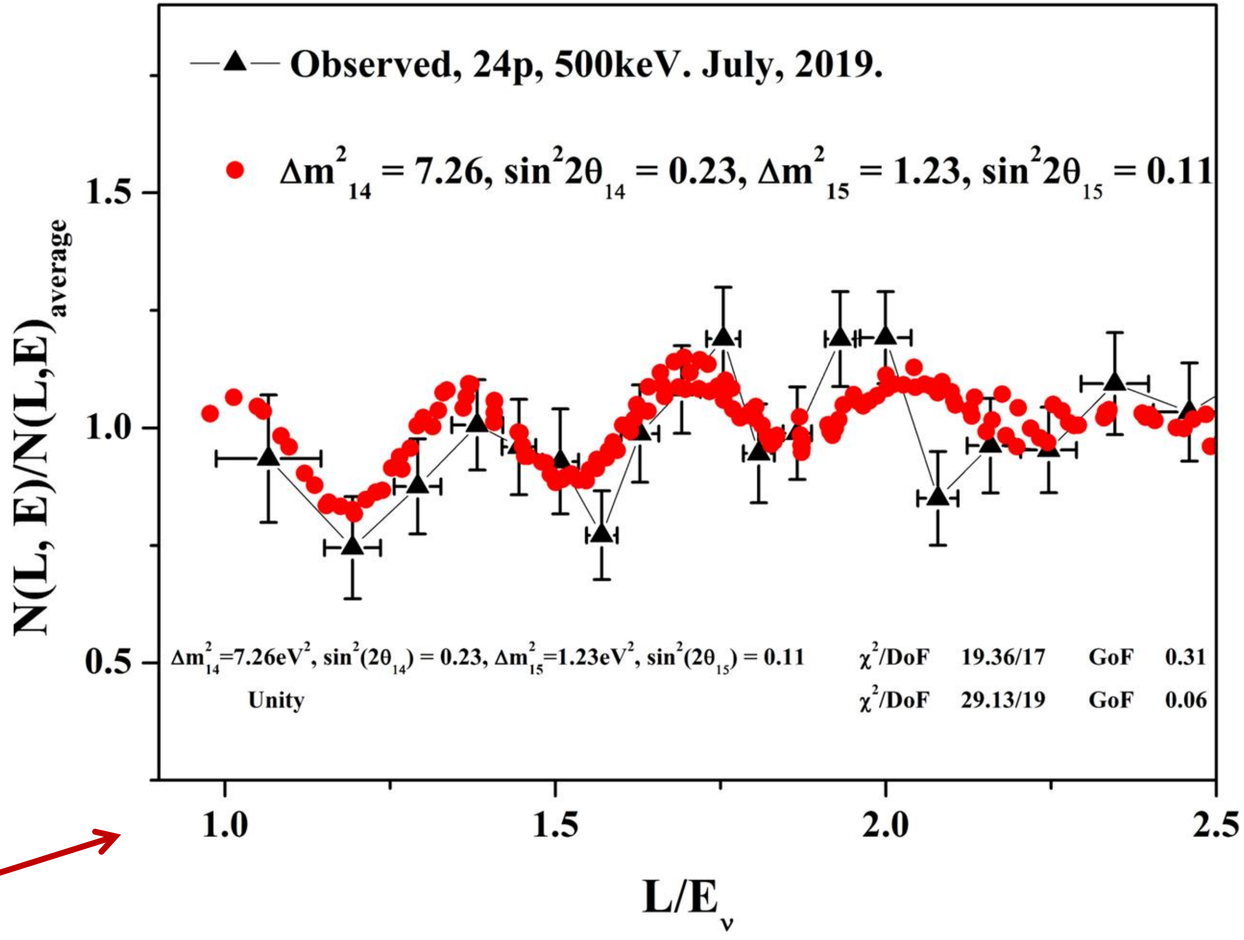




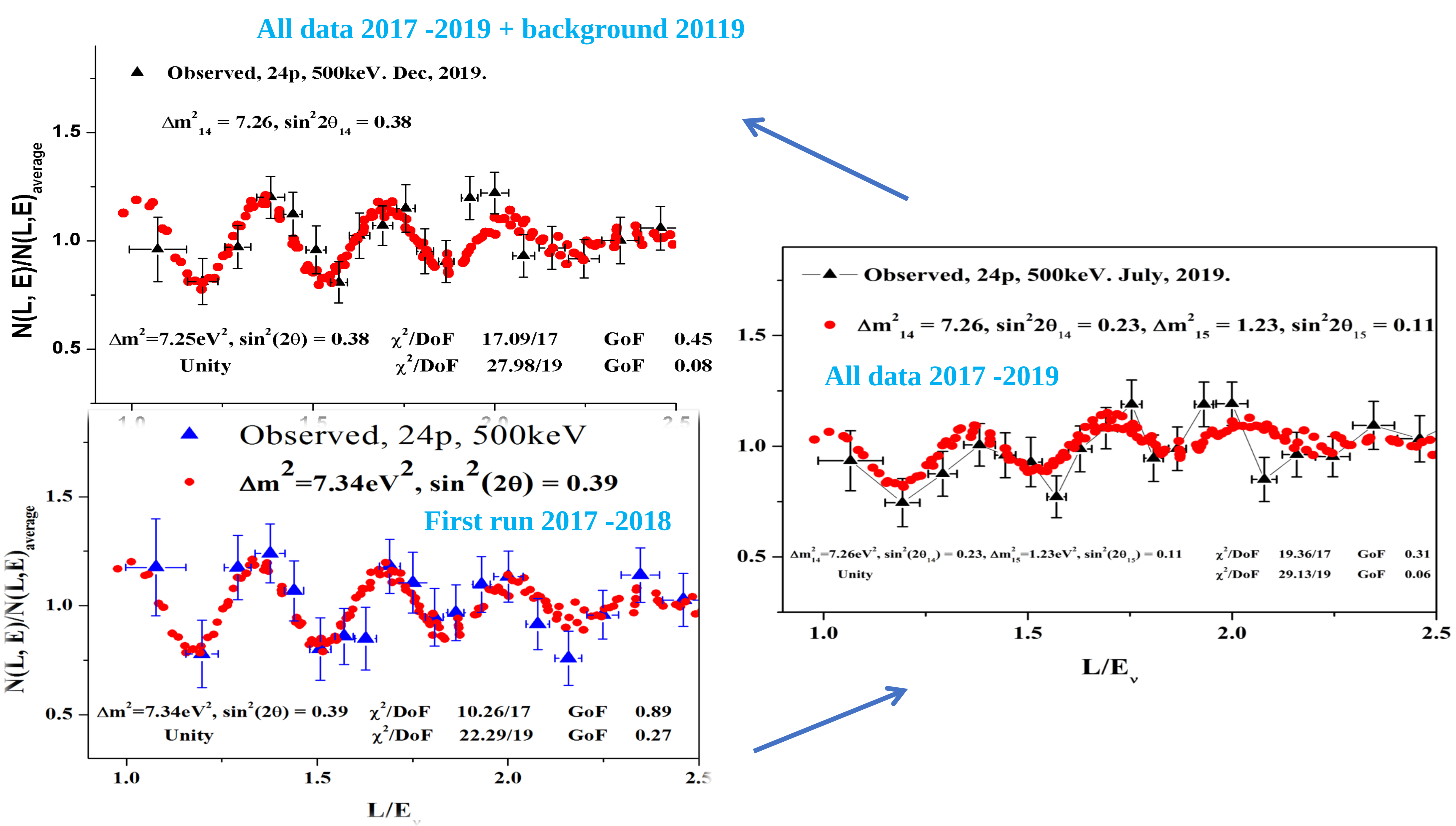
First run 2017 -2018



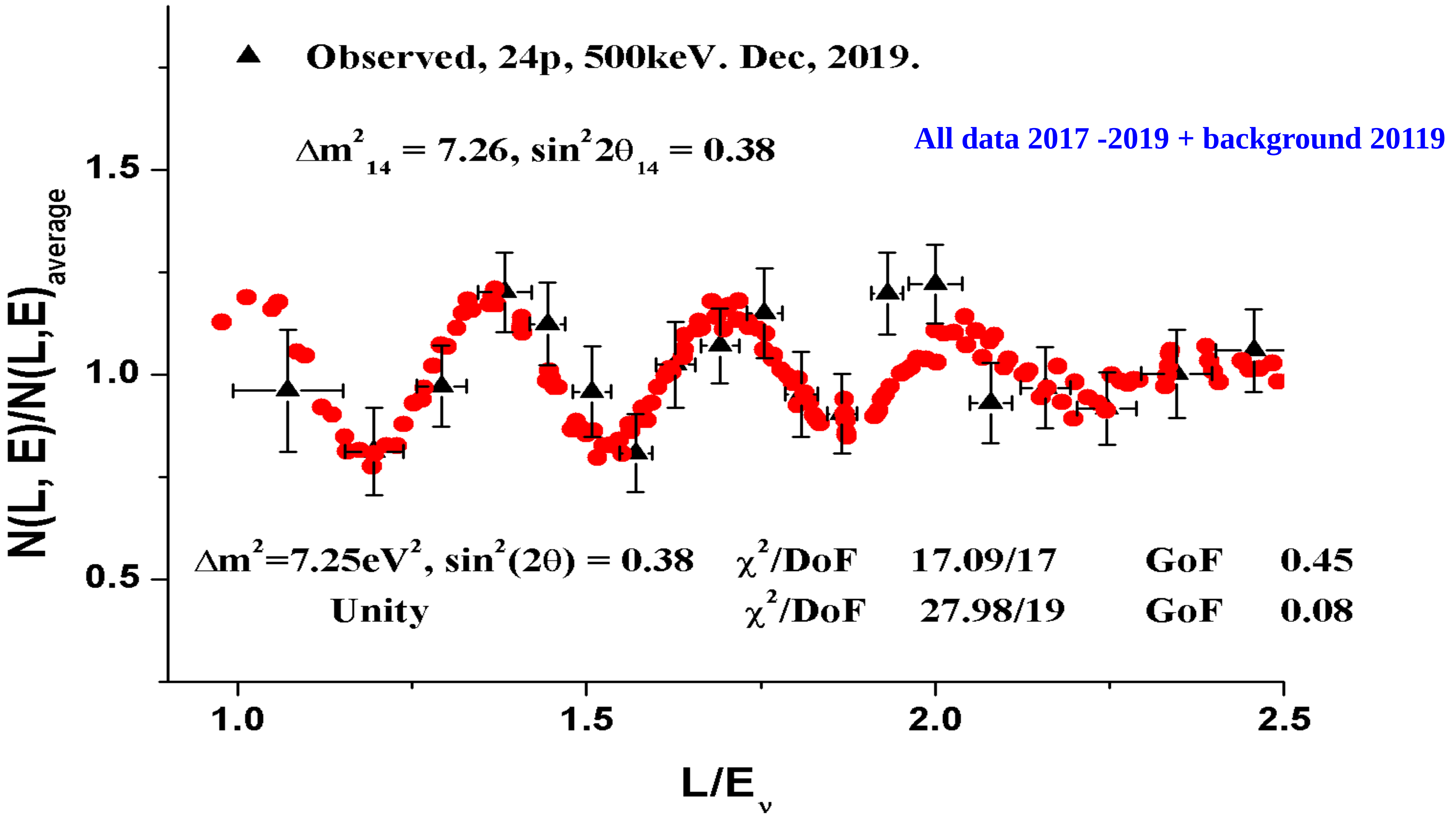
All data 2017 -2019

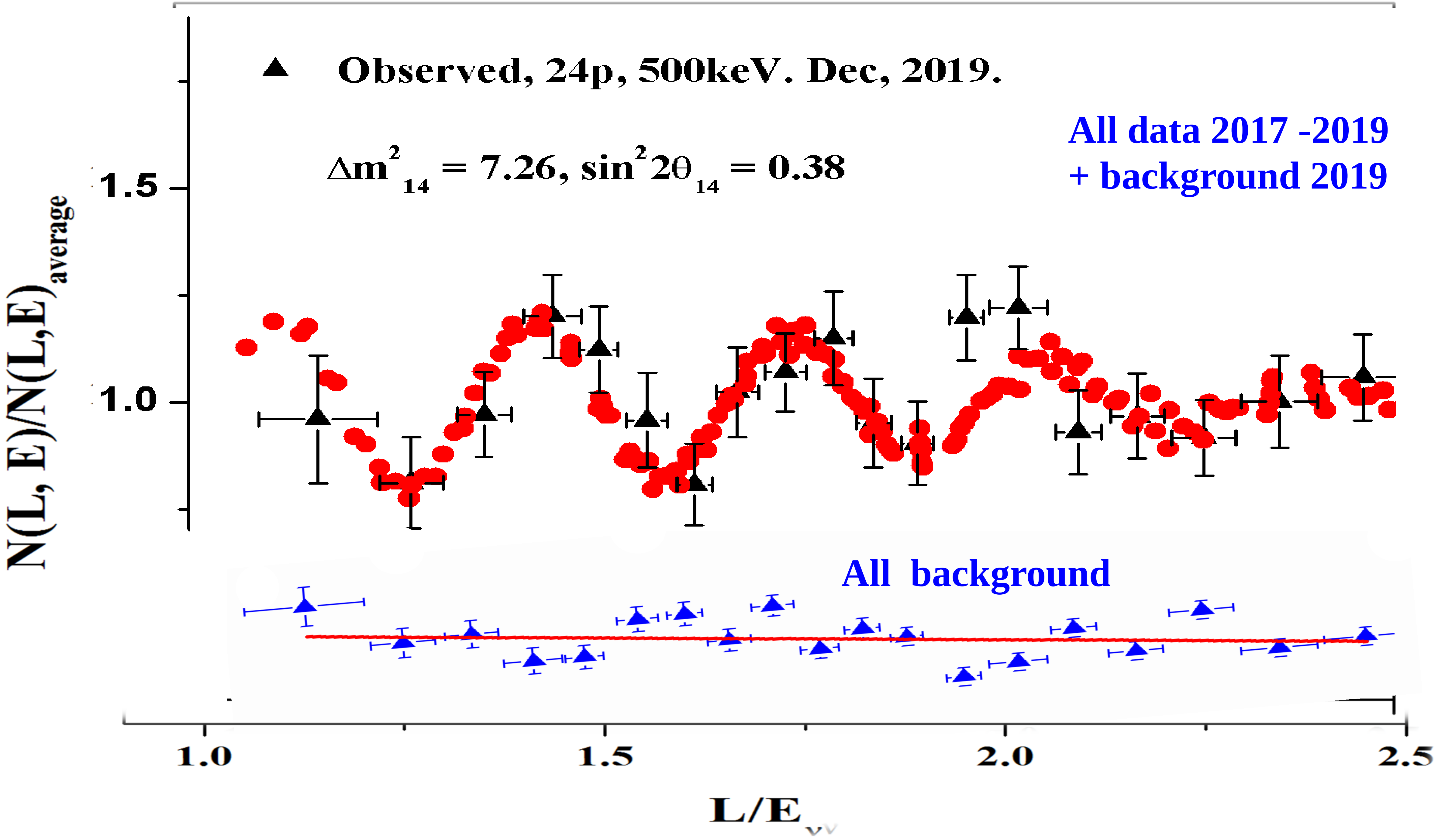


Here is twice statistic. Effect of neutrino oscillation still live.

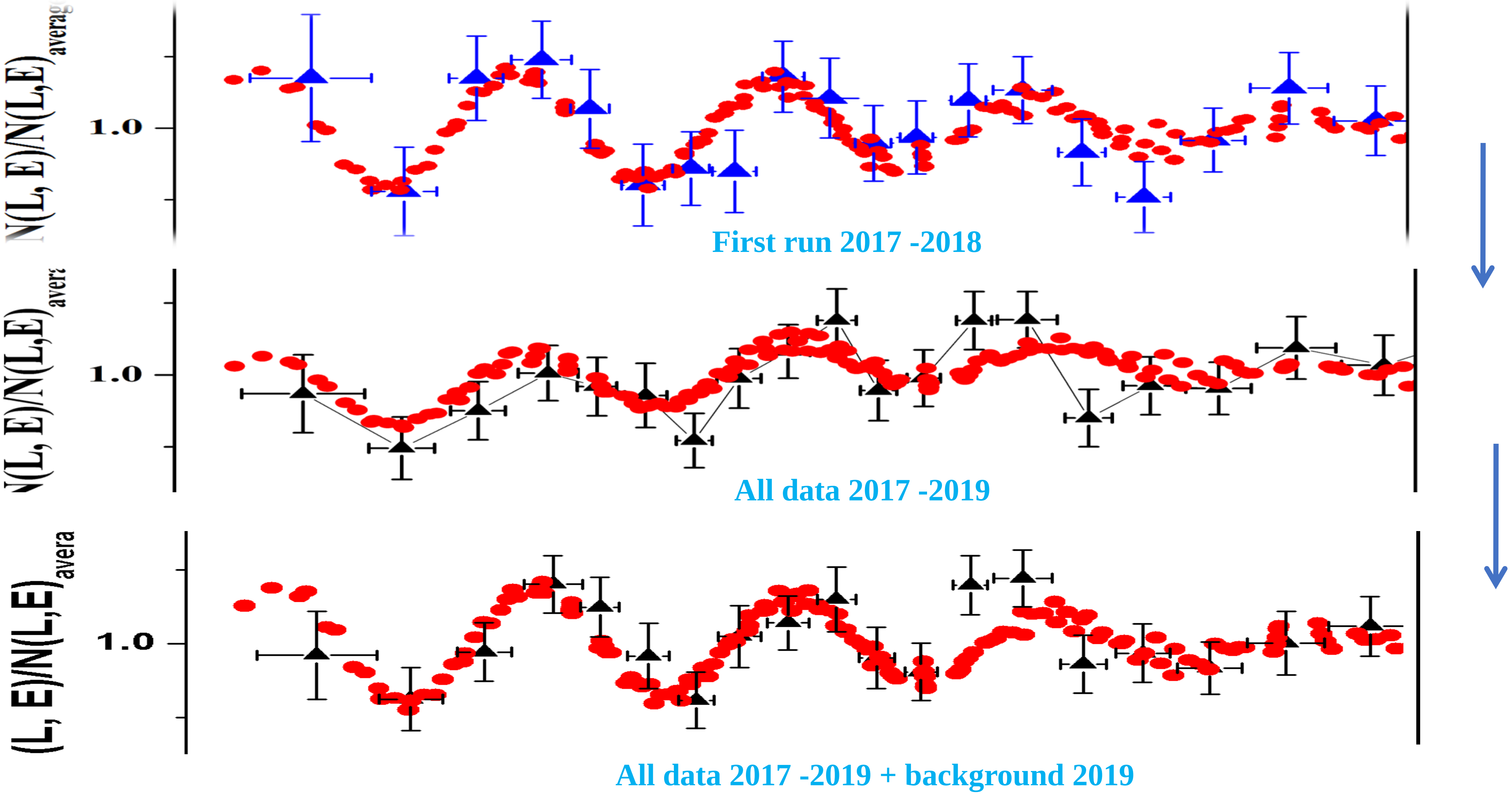


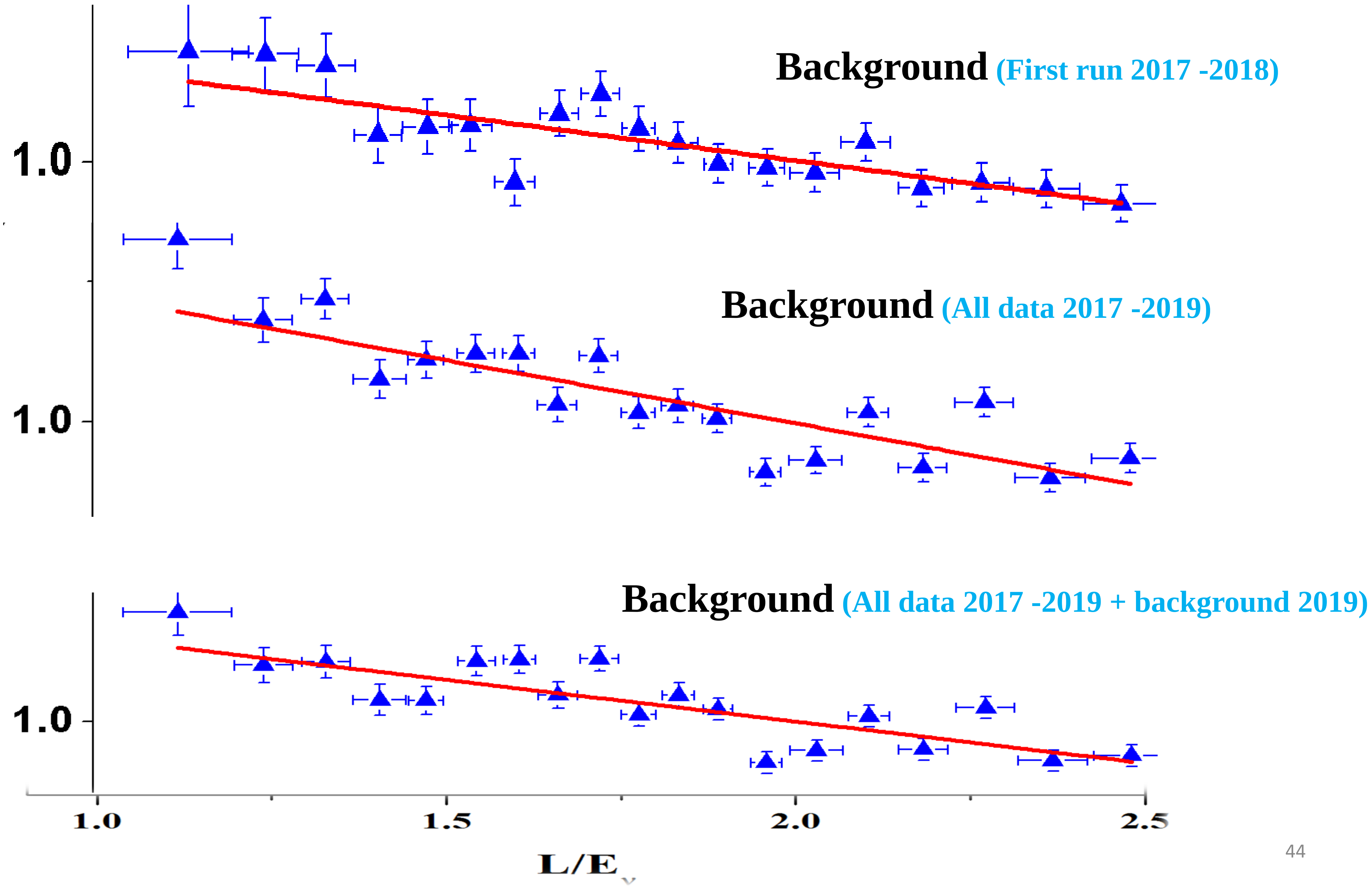
All data 2017 -2019 + background 20119
Observed, 24p, 500keV. Dec, 2019.
Δm²₁₄ = 7.26, sin²2θ₁₄ = 0.38
Δm²=7.25eV², sin²(2θ) = 0.38   χ²/DoF   17.09/17   GoF   0.45
Unity   χ²/DoF   27.98/19   GoF   0.08
N(L, E)/N(L,E)average
Observed, 24p, 500keV
Δm²=7.34eV², sin²(2θ) = 0.39
First run 2017 -2018
Δm²=7.34eV², sin²(2θ) = 0.39   χ²/DoF   10.26/17   GoF   0.89
Unity   χ²/DoF   22.29/19   GoF   0.27
N(L, E)/N(L,E)average
L/Eν
Observed, 24p, 500keV. July, 2019.
Δm²₁₄ = 7.26, sin²2θ₁₄ = 0.23, Δm²₁₅ = 1.23, sin²2θ₁₅ = 0.11
All data 2017 -2019
Δm²₁₄=7.26eV², sin²(2θ₁₄) = 0.23, Δm²₁₅=1.23eV², sin²(2θ₁₅) = 0.11   χ²/DoF   19.36/17   GoF   0.31
Unity   χ²/DoF   29.13/19   GoF   0.06
L/Eν


Observed, 24p, 500keV. Dec, 2019.
Δm²₁₄ = 7.26, sin²2θ₁₄ = 0.38
All data 2017 -2019 + background 20119
Δm²=7.25eV², sin²(2θ) = 0.38 χ²/DoF 17.09/17 GoF 0.45
Unity χ²/DoF 27.98/19 GoF 0.08
N(L, E)/N(L,E)average
L/Eν
1.5
1.0
0.5
2.0
2.5



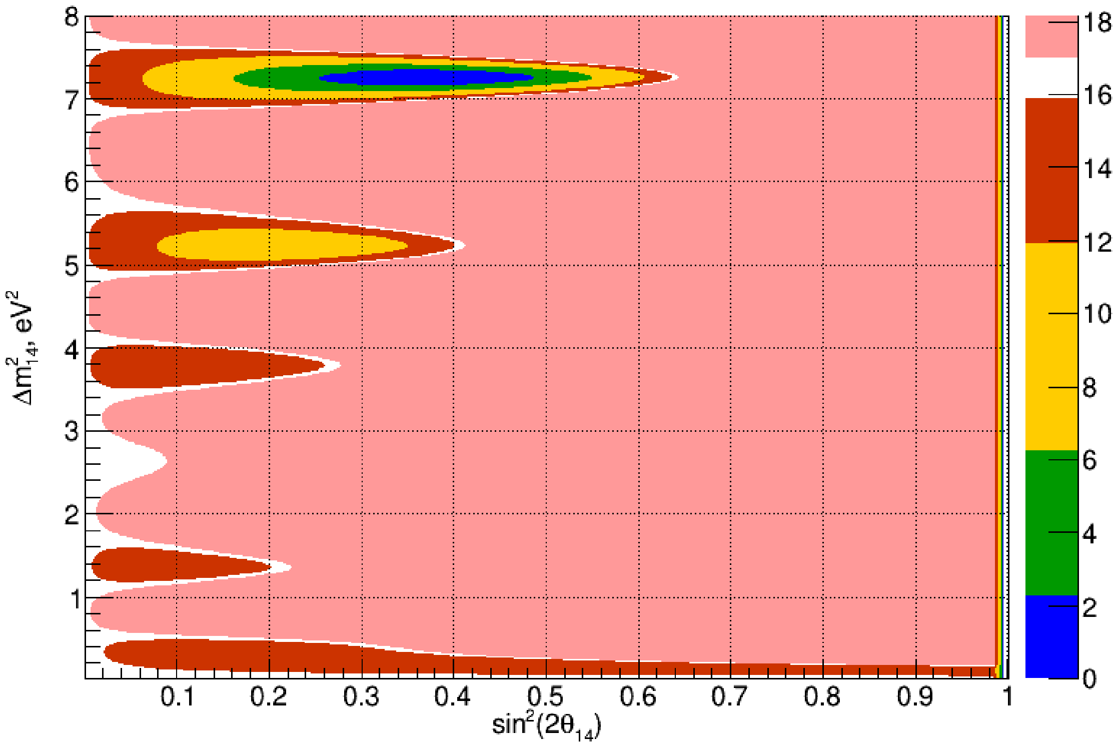
Observed, 24p, 500keV. Dec, 2019.
Δm²14 = 7.26, sin²2θ14 = 0.38
All data 2017 -2019
+ background 2019
All background
N(L, E)/N(L,E)average
1.5
1.0
1.0
1.5
2.0
2.5
L/Eν

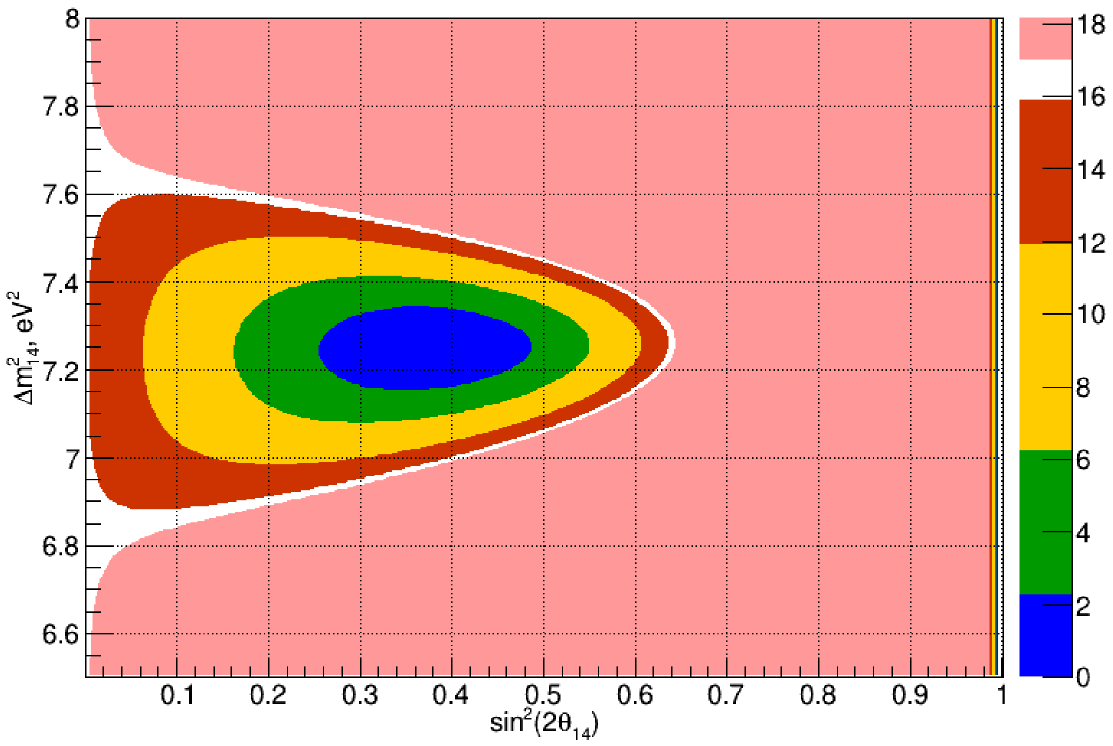

1.0
First run 2017 -2018
1.0
All data 2017 -2019
1.0
All data 2017 -2019 + background 2019



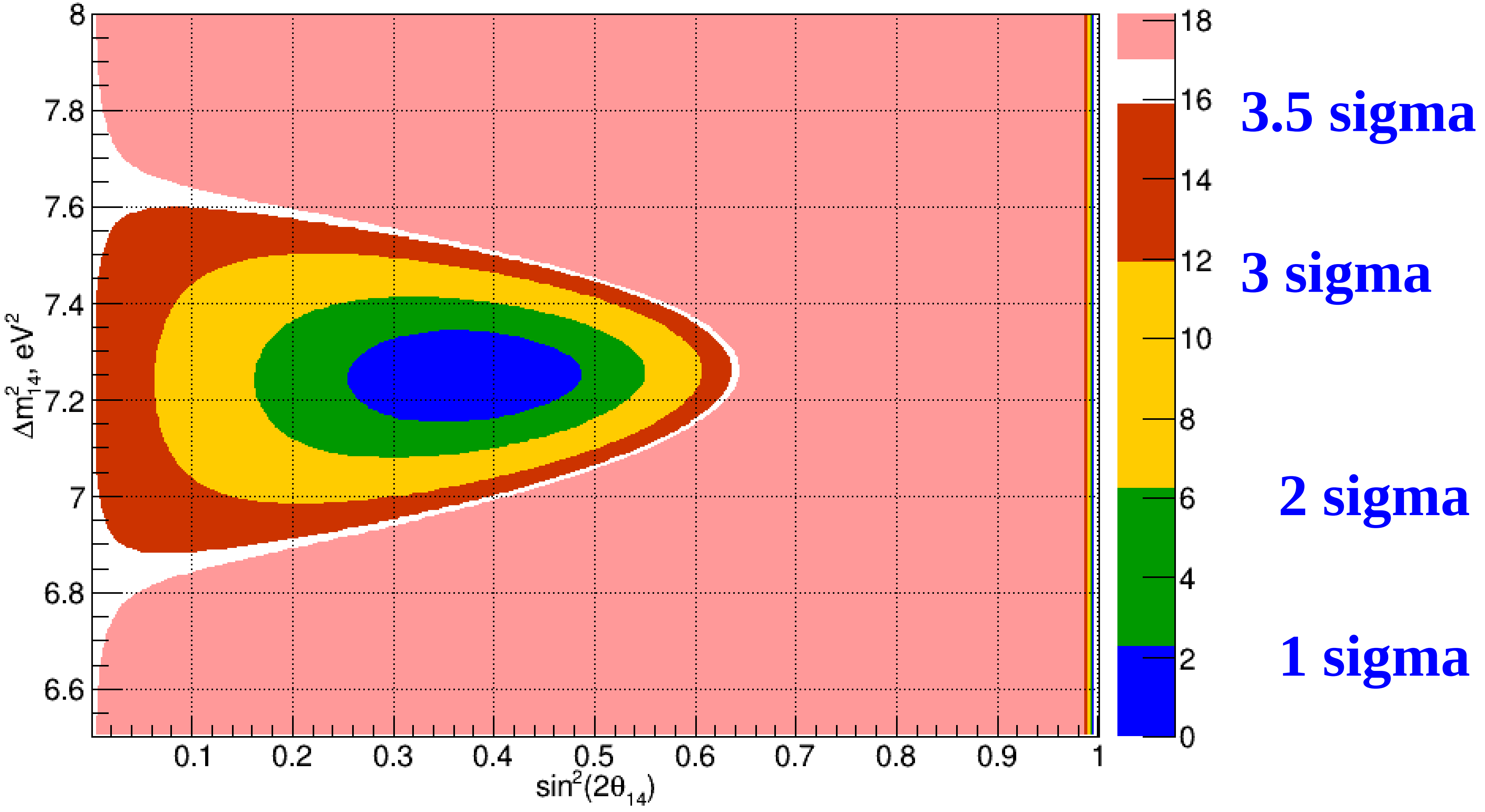
Background (First run 2017 -2018)
Background (All data 2017 -2019)
Background (All data 2017 -2019 + background 2019)
1.0
1.0
1.0
1.0
1.5
2.0
2.5
L/E

All data 2017 -2019 + background 2019





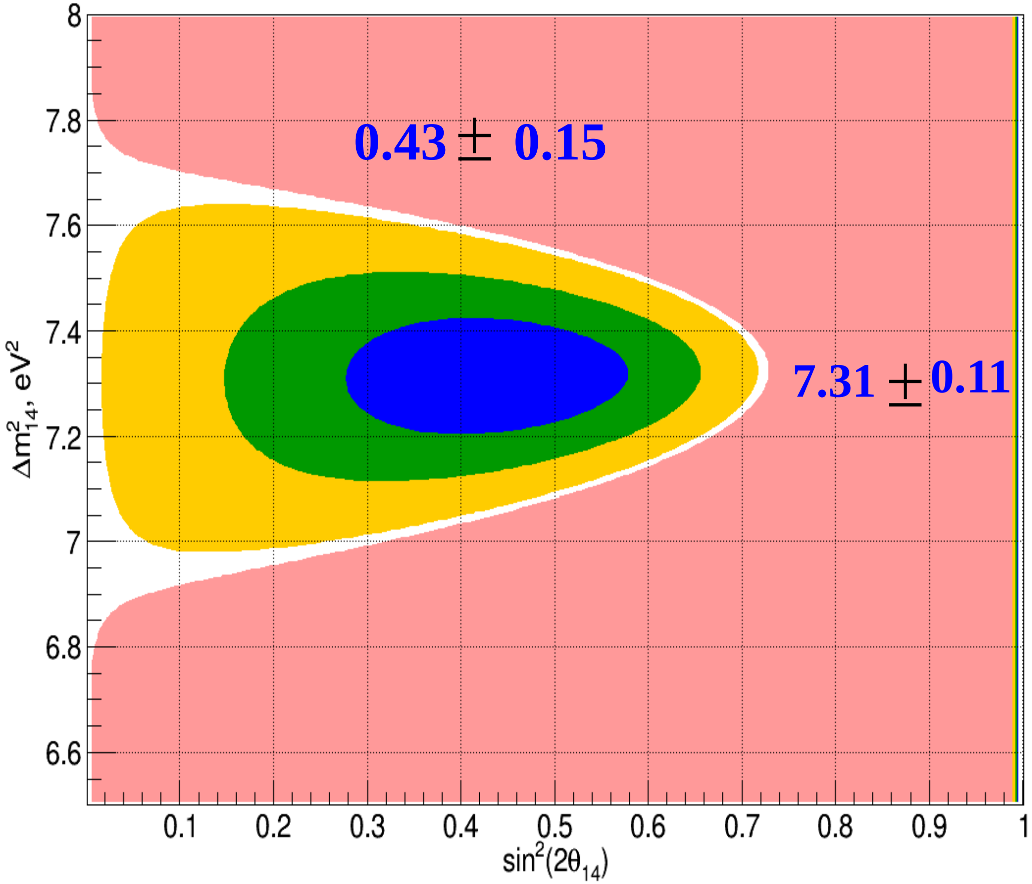
3.5 sigma



8
7.8
7.6
7.4
7.2
7
6.8
6.6
Δm^2_{14}, eV^2
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
$\sin^2(2\theta_{14})$
18
16
14
12
10
8
6
4
2
0
3.5 sigma
3 sigma
2 sigma
1 sigma

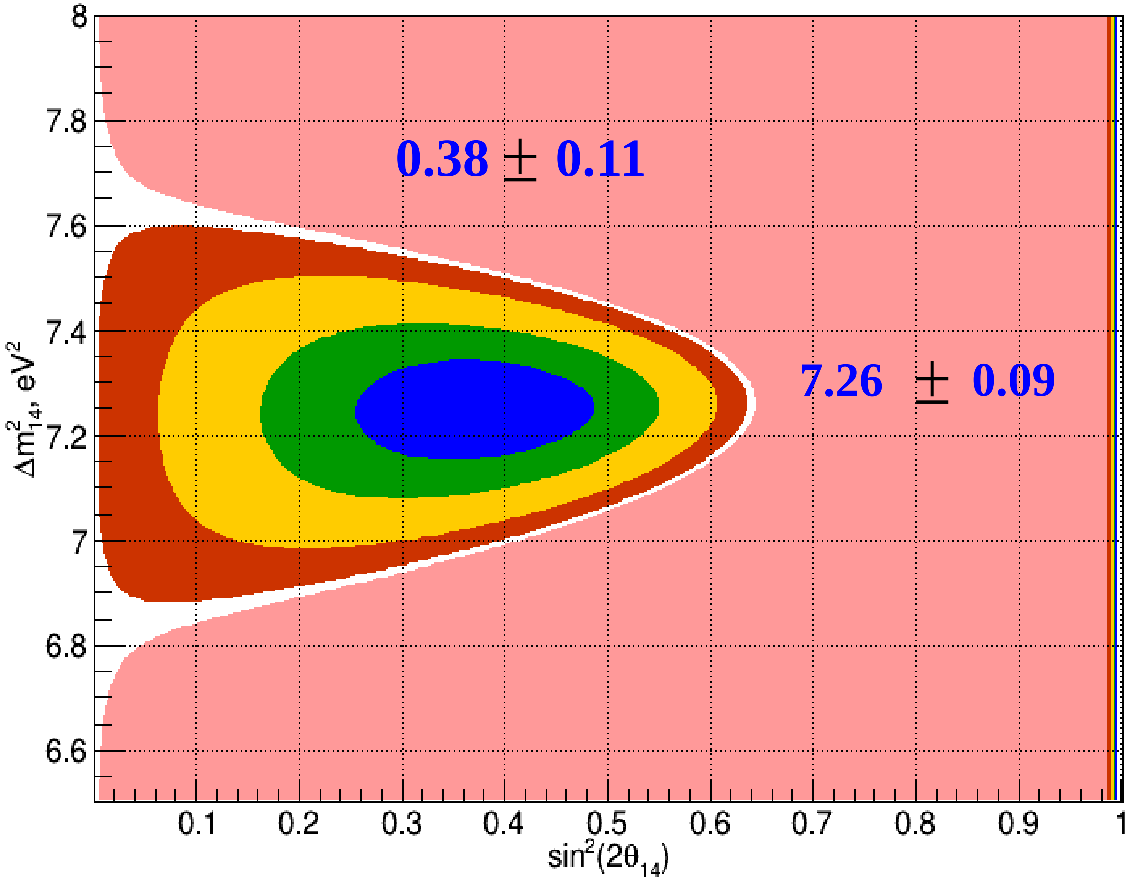
First run 2017 -2018

2.9 sigma



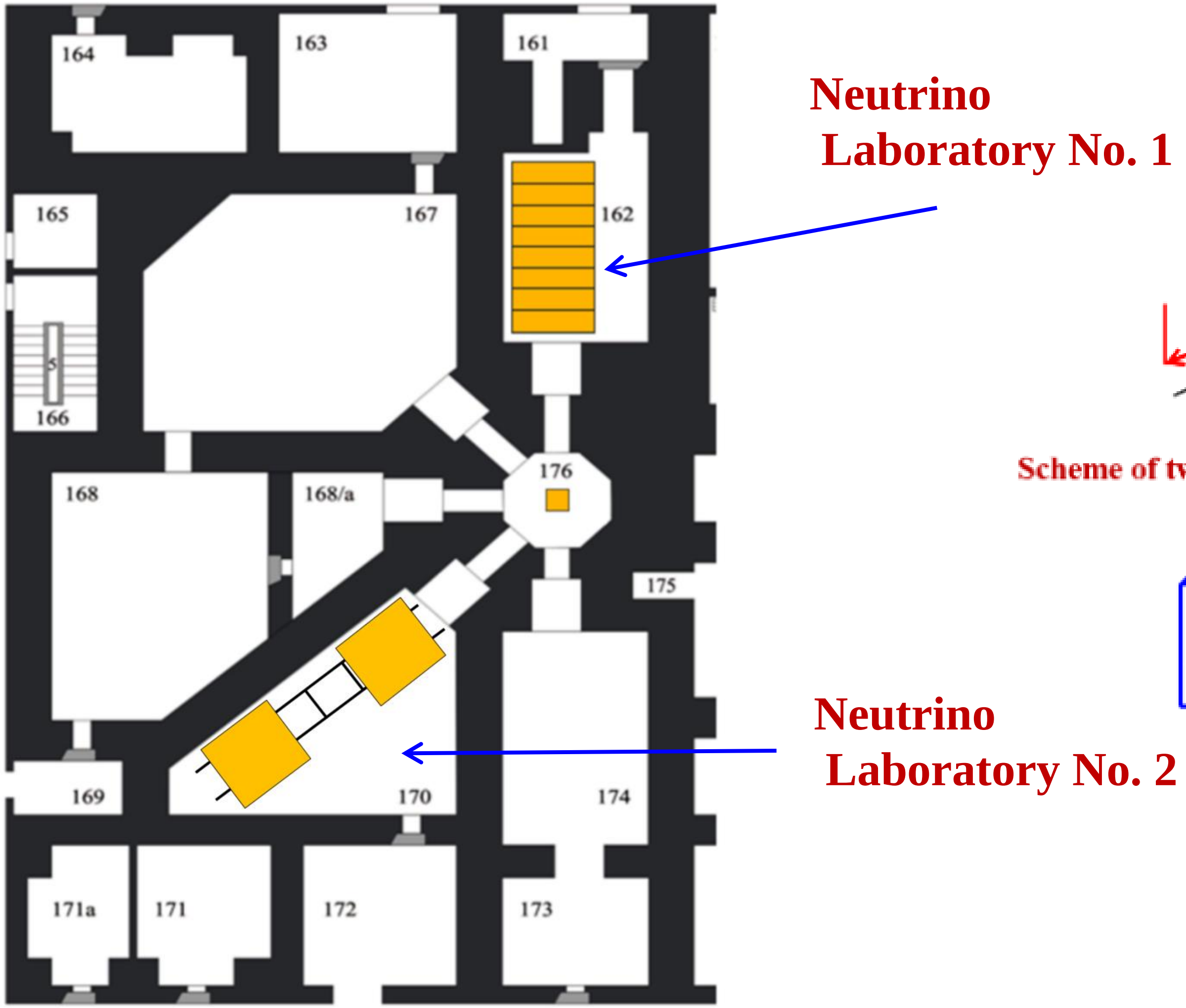
All data 2017 -2019 + background 2019

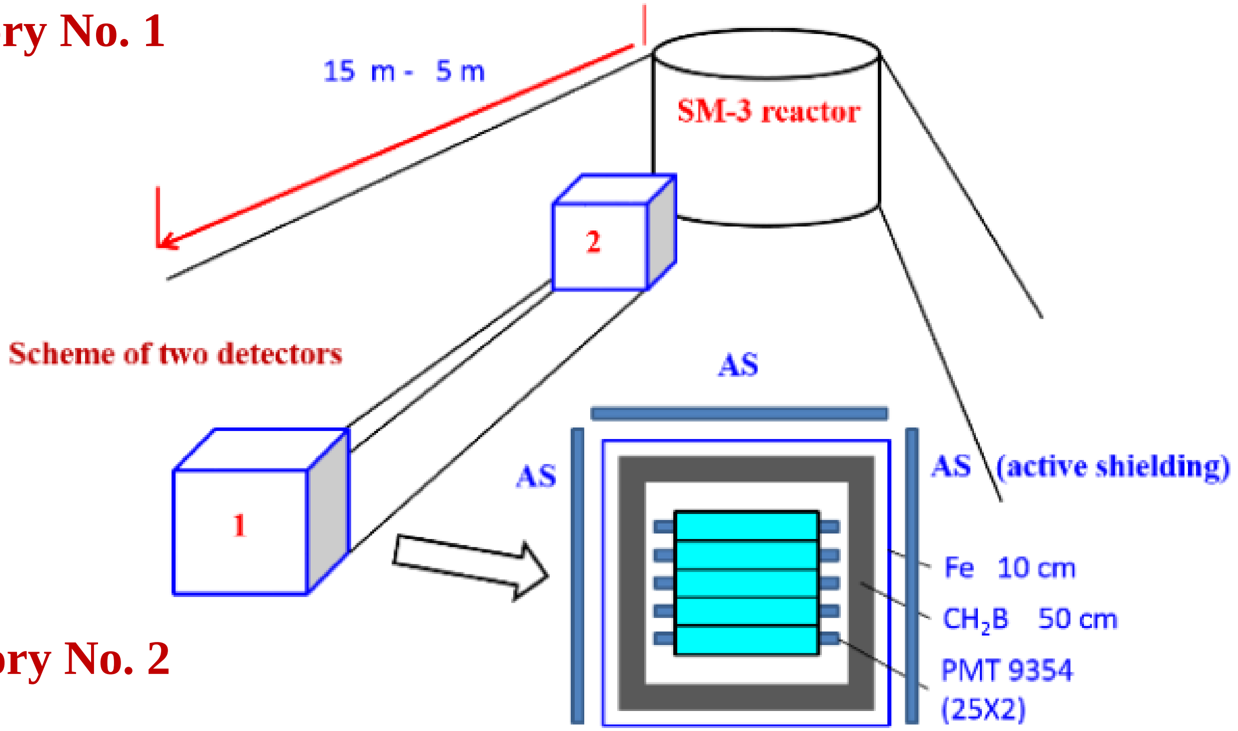
3.5 sigma



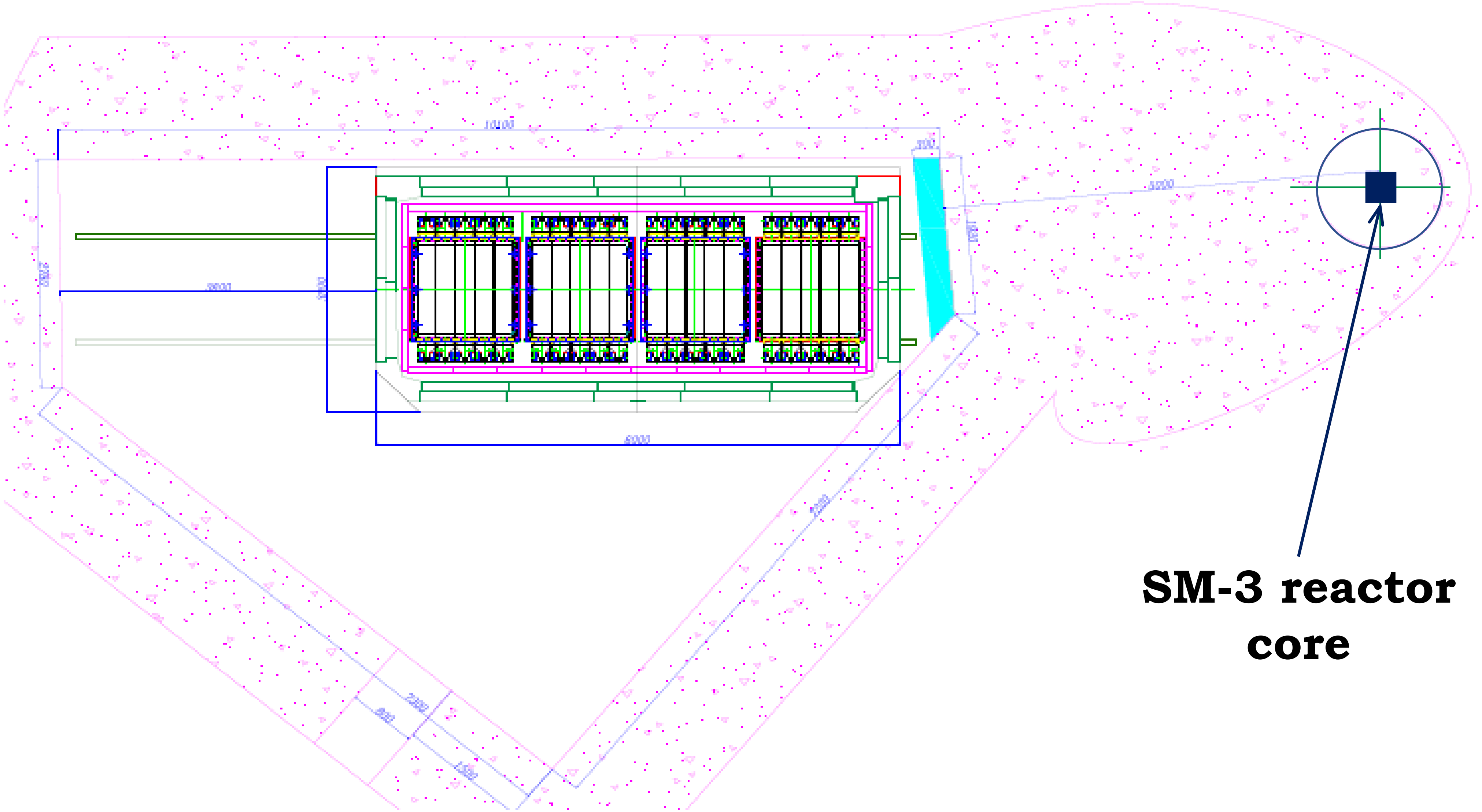
Future: Neutrino-6 experiment

Future: Neutrino-6 experiment

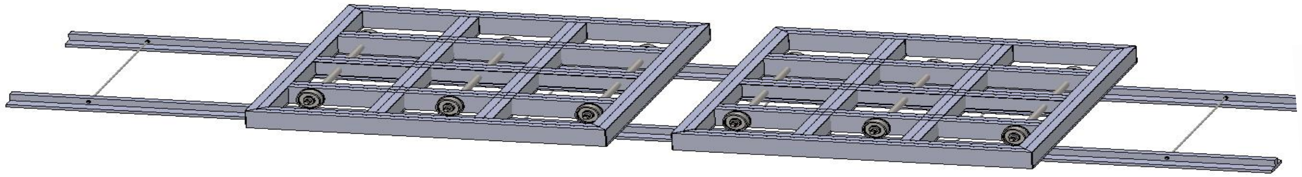




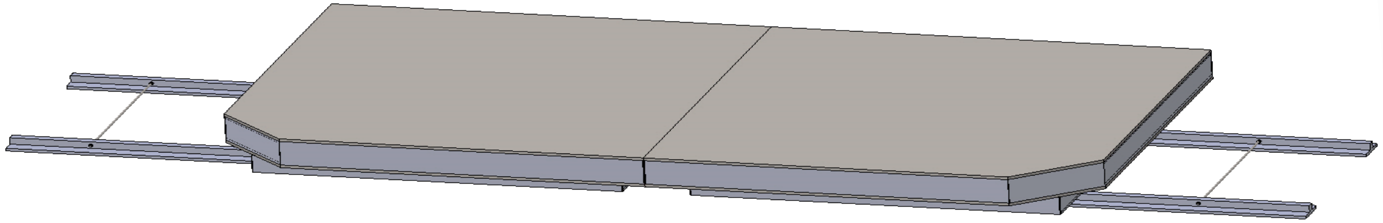
Neutrino-6 experiment location

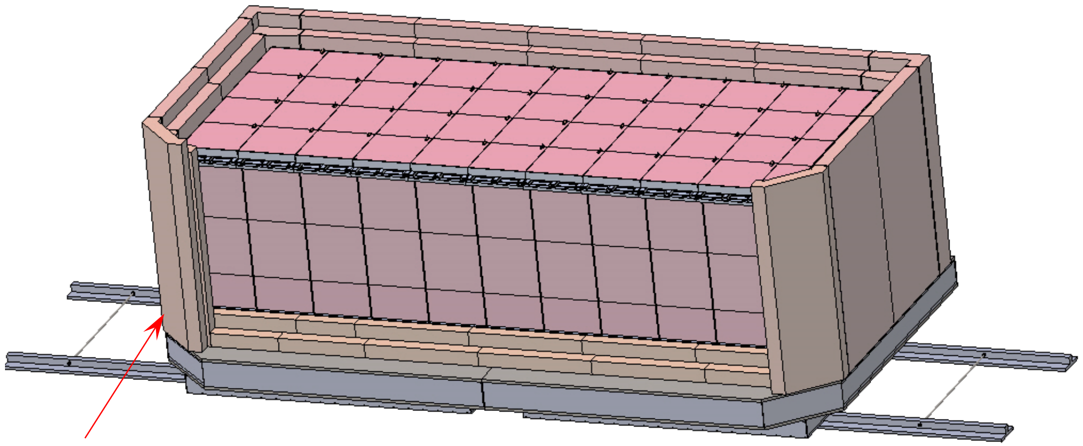


Detector’s design.
Transport system

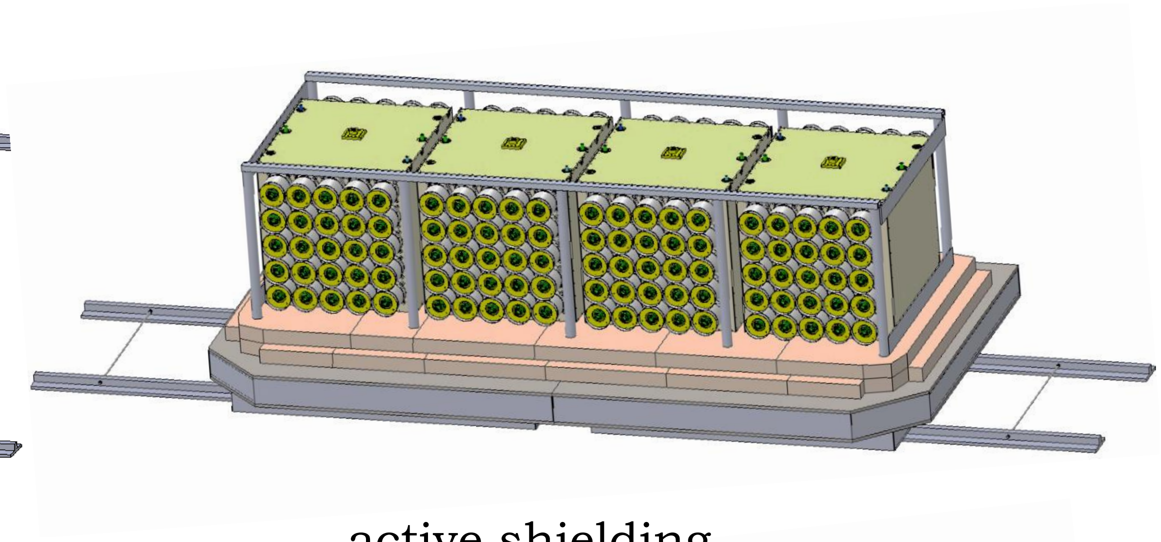


Rails, carts and platforms

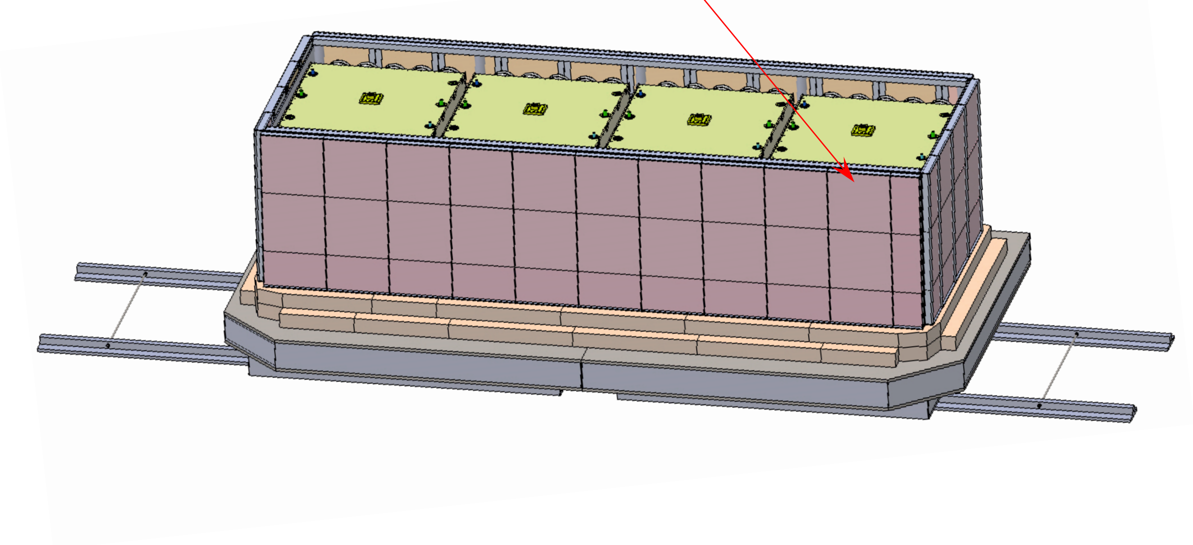




borated polyethylene

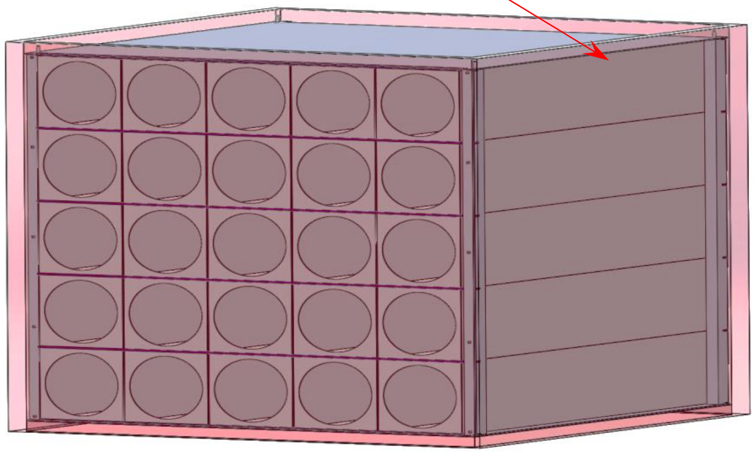


active shielding

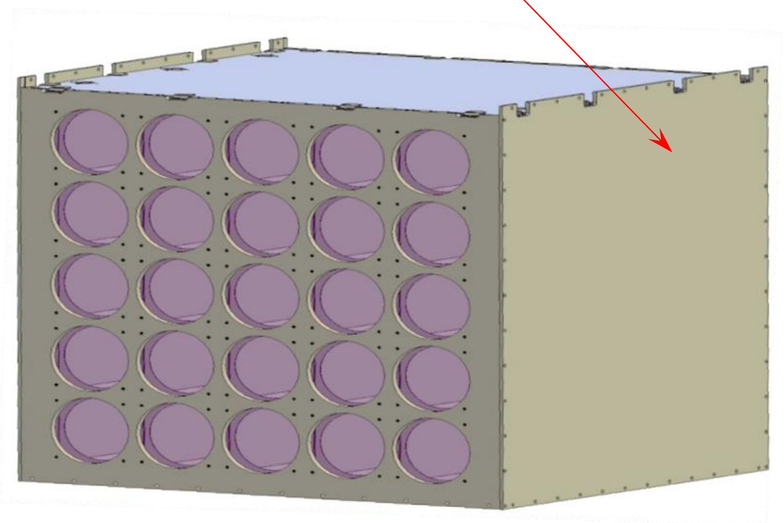


Detector's design. Models

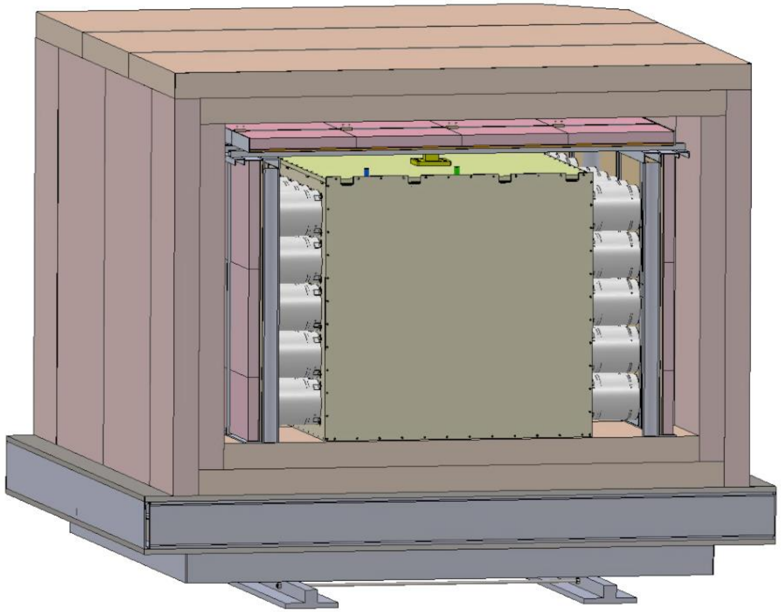
Transparent plex tank



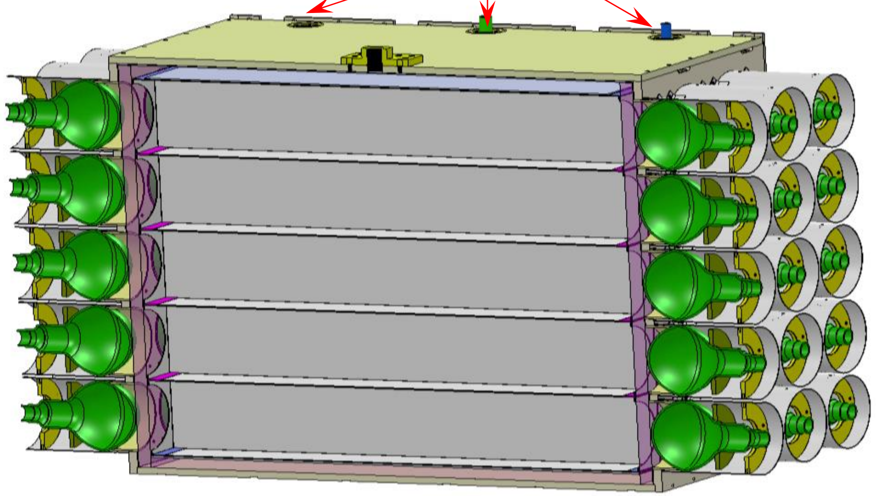
Detector's case



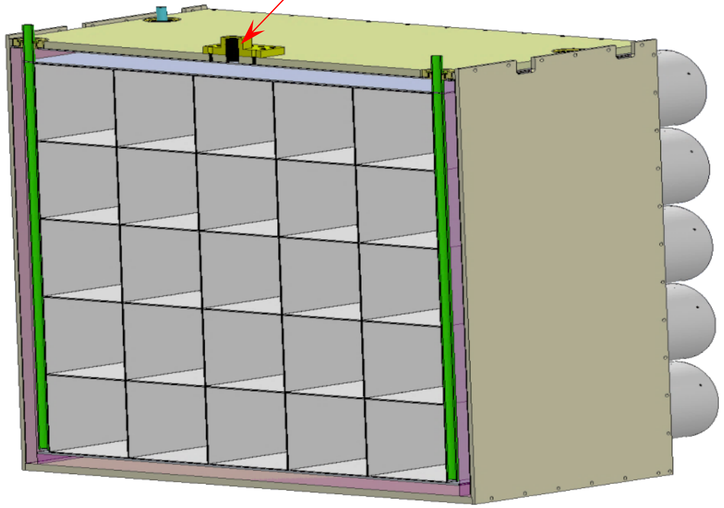
Detector fully assembled



Calibration holes



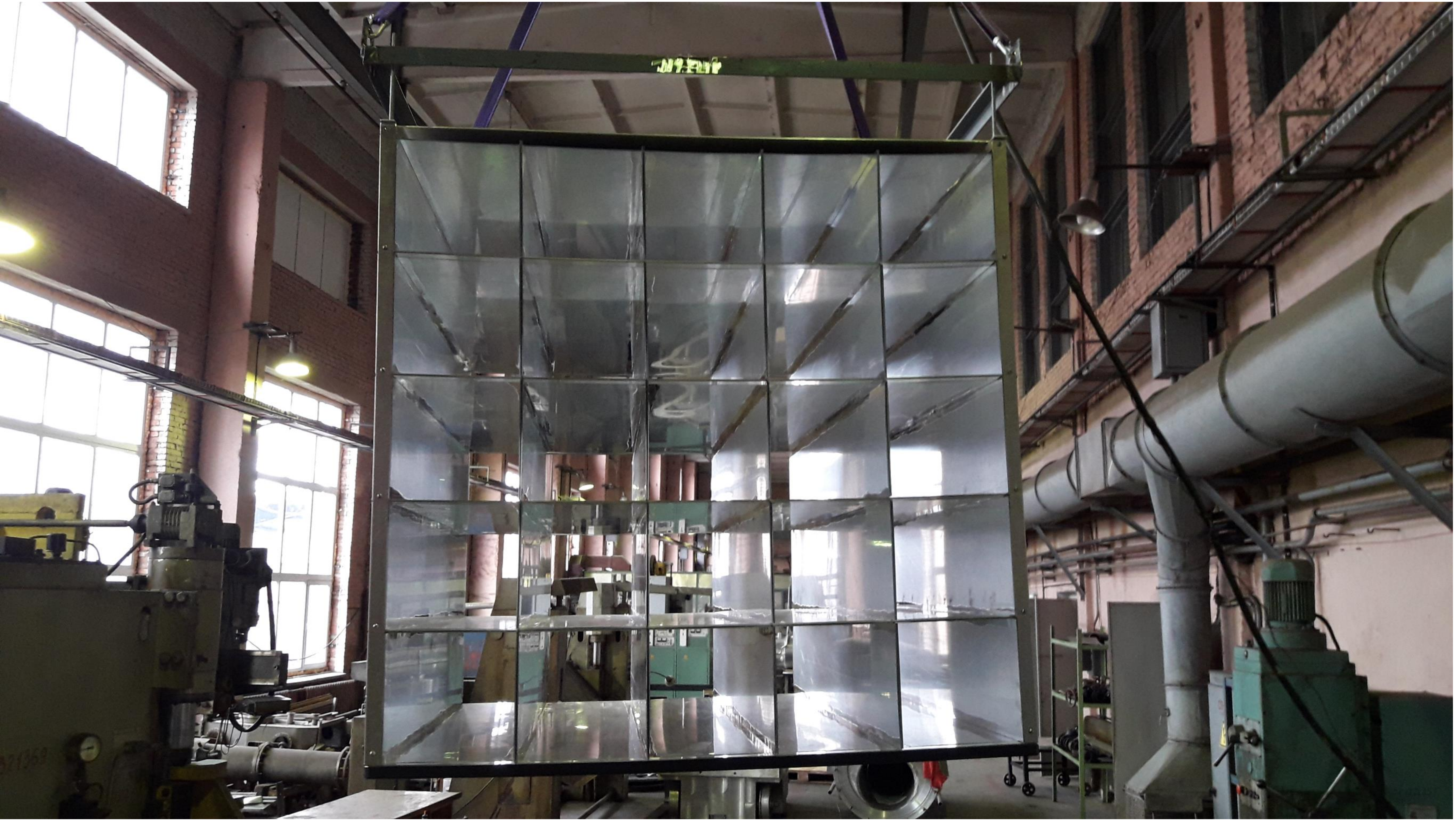
Scintillator filling hole



Detector's design.
Transport system

Platforms

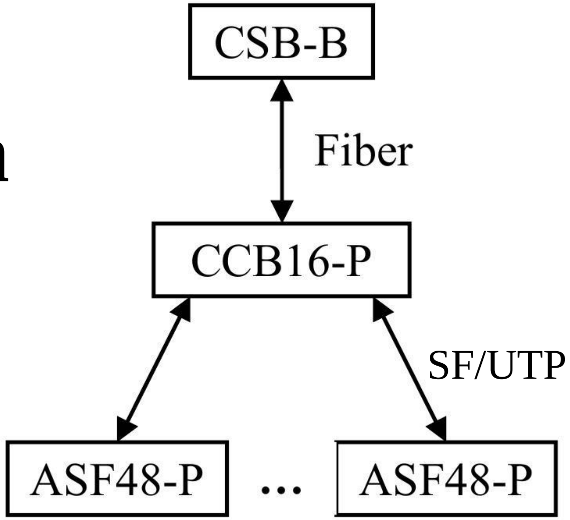
Inner cavities

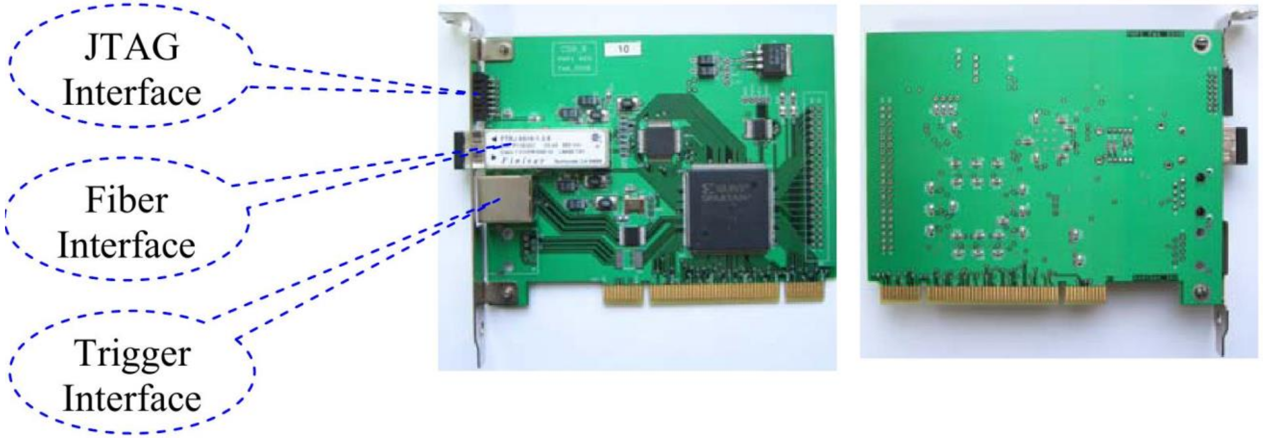


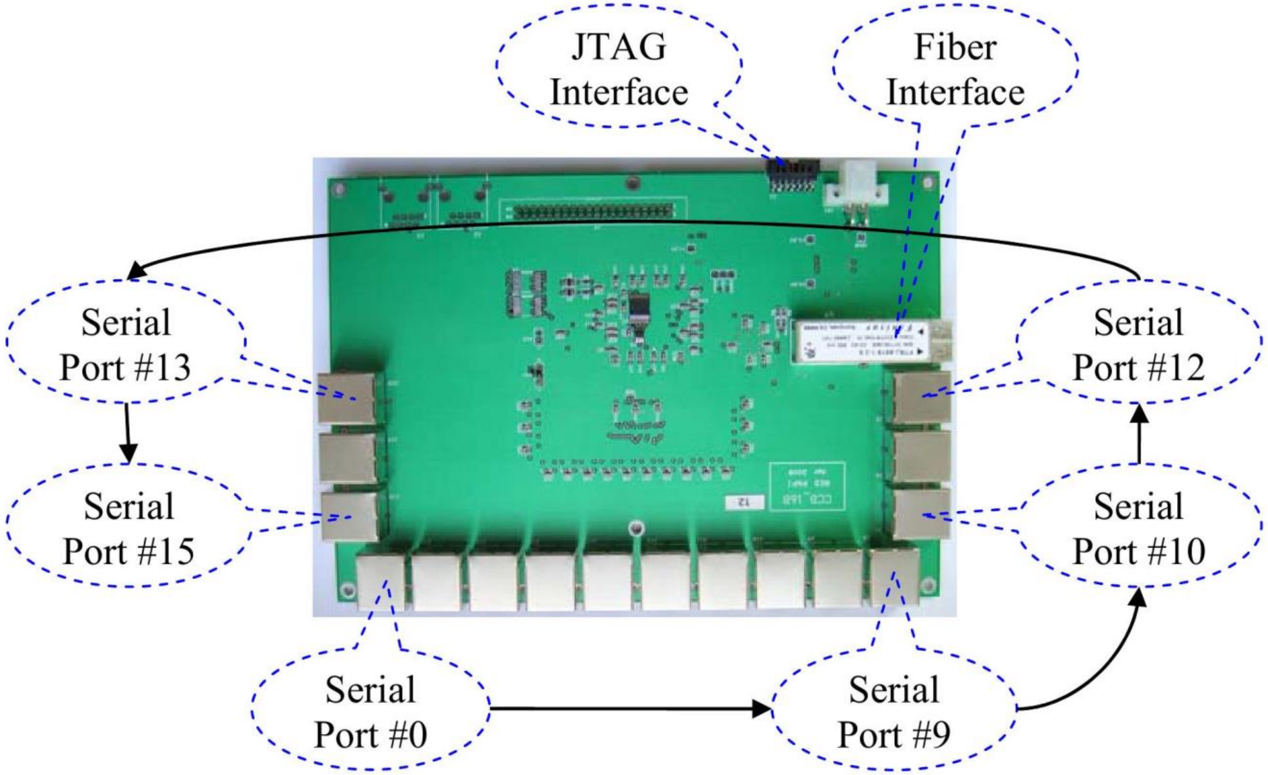
Detector's design.
Transparent tank

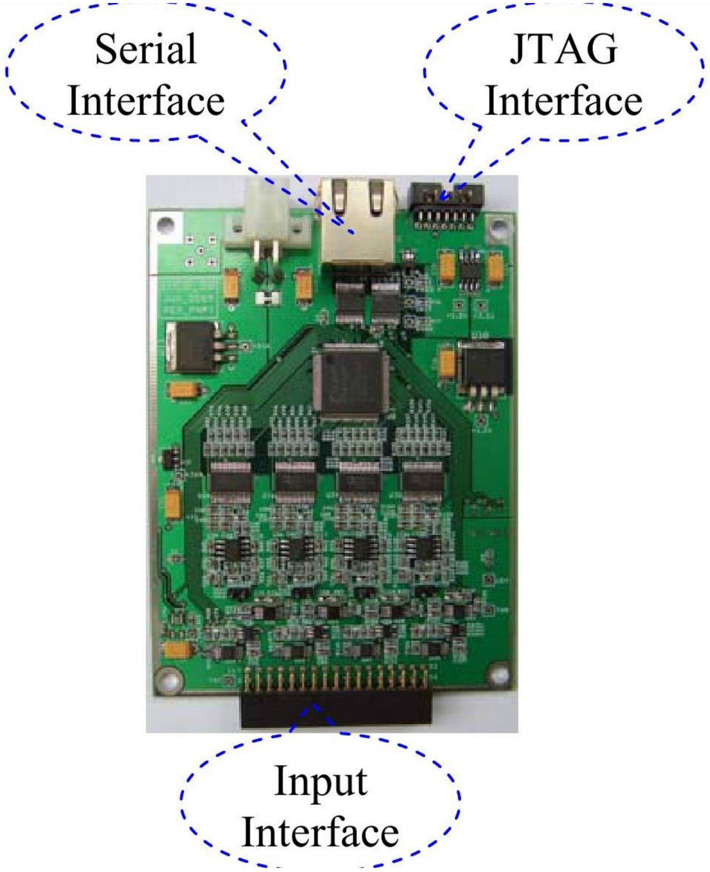
Detector's design.
Case

Data acquisition system CROS3

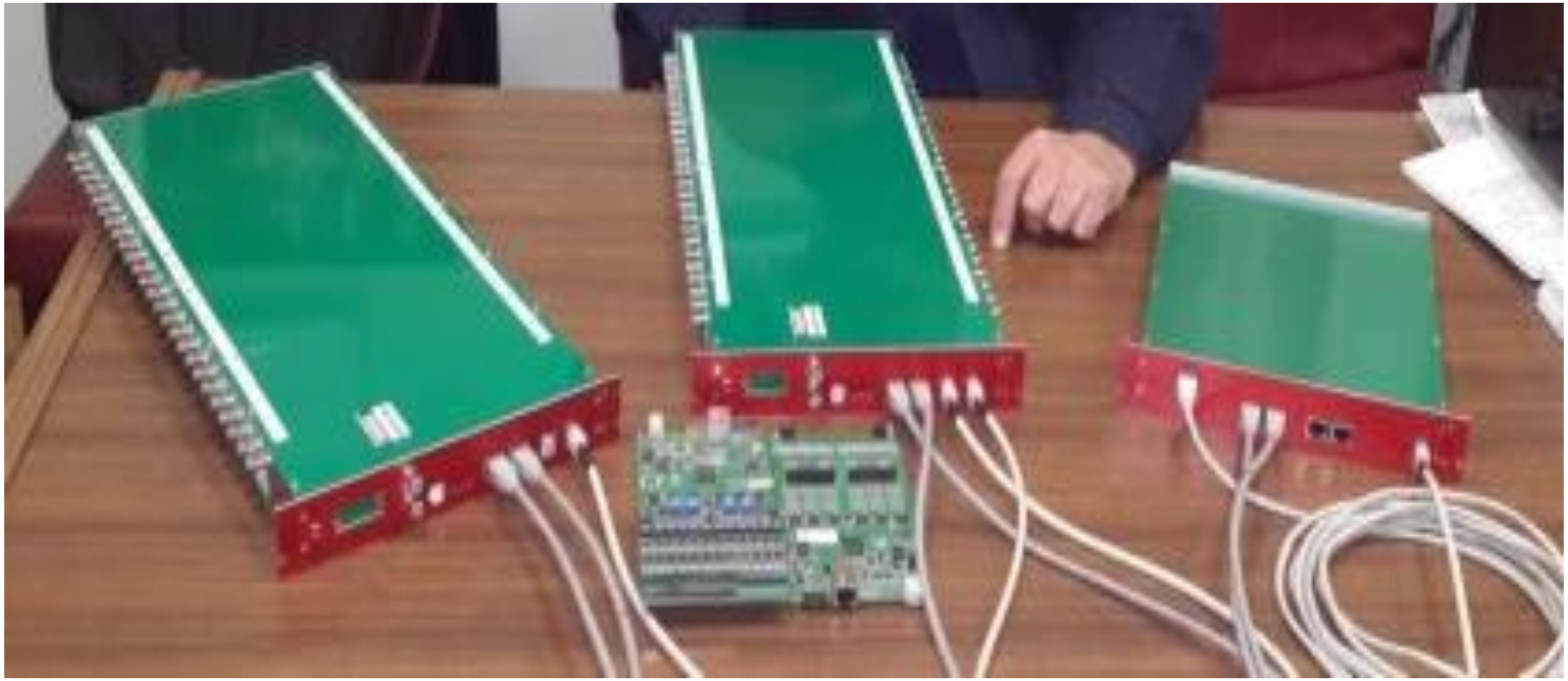


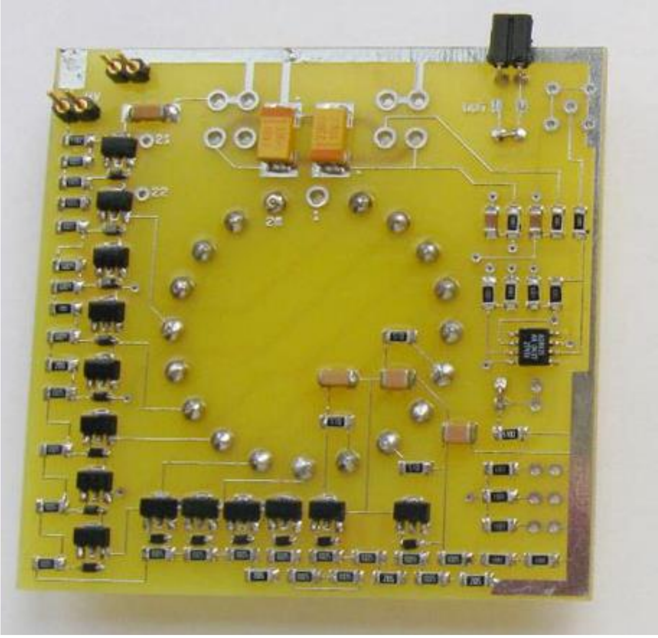




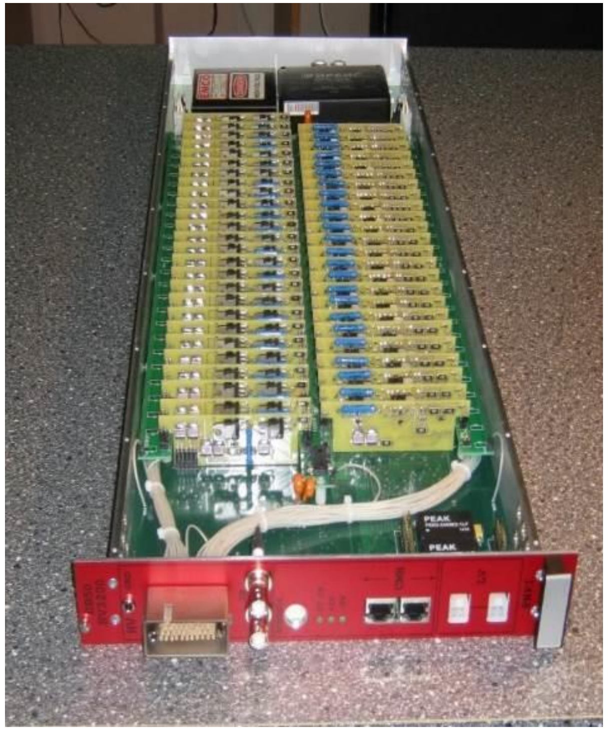


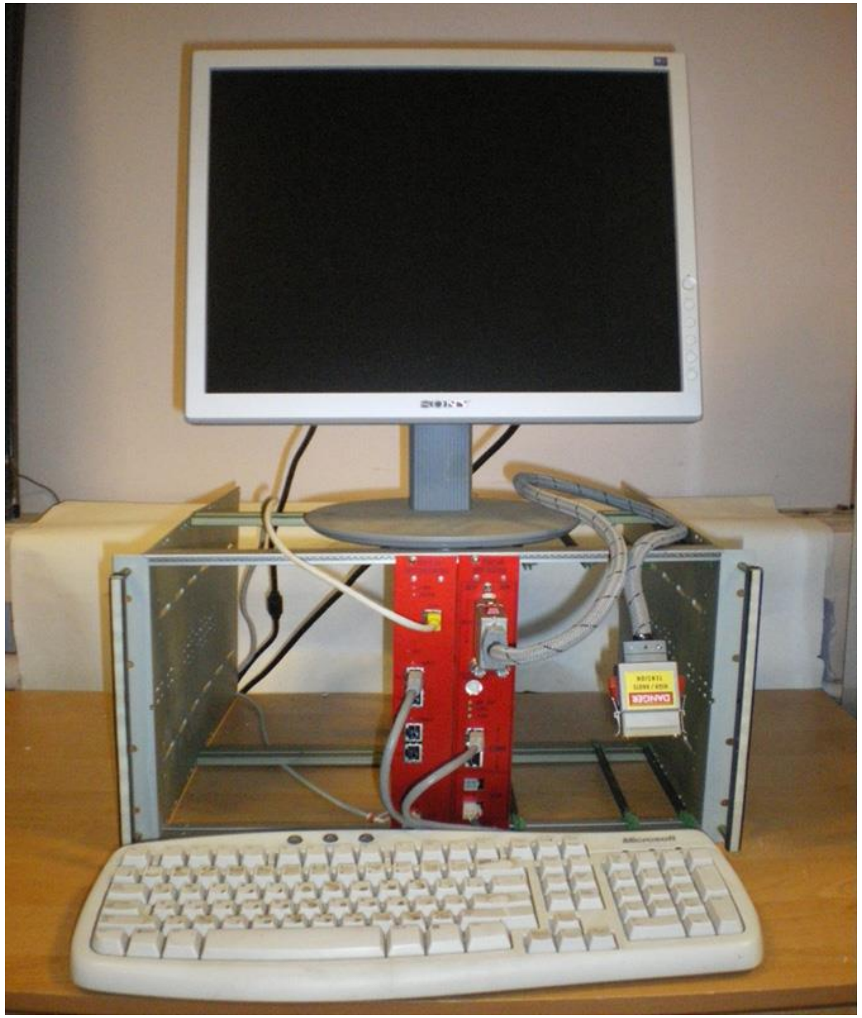
High Voltage Distribution System HVDS3200 and active voltage-dividers





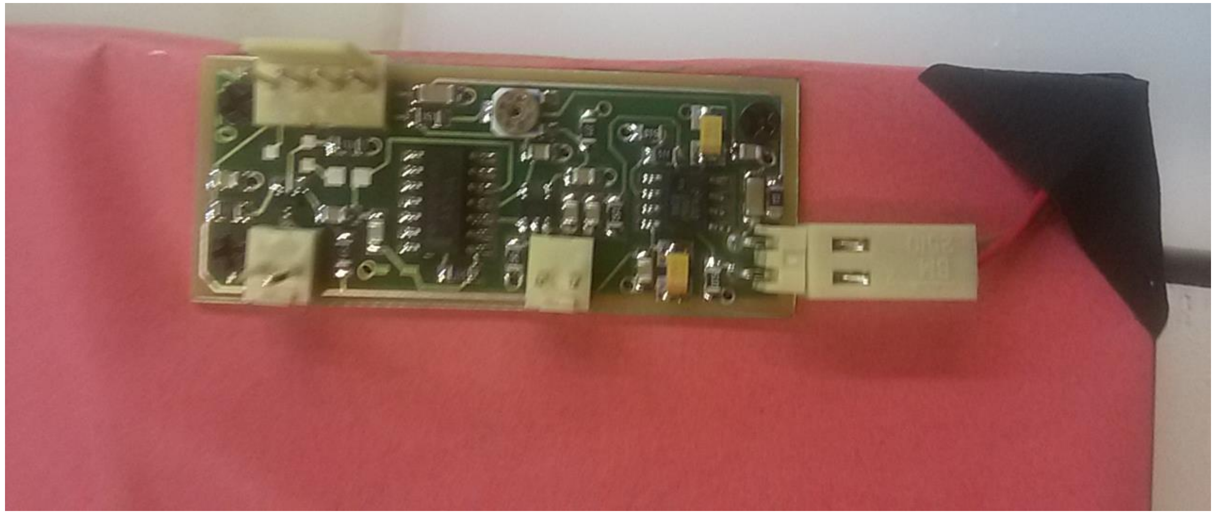
High Voltage Distribution System HVDS3200





- Voltage adjustment 0...1500 V; 0.1%
- Maximum current 0.5 mA
- Current monitoring 0.1%
- Voltage monitoring 0.1%
- Stability (during 1 day) 0.1%

Active shielding



- Polysterene based scintillator
- Optical fibers with SiPM are used
- “Spectral” or “logical” operating modes

Expecting improvements of statistical accuracy for Neutrino-6

Method	Consequence	Increasing accuracy factor
4 detectors	3x larger volume	**1.6**
Gd concentration	4x less accidental background	**1.5**
PSD	4x less correlated background	**1.3**
Total		**3.1**

Проблемы финансирования

Закупка ФЭУ 220 шт - 250 тыс. долларов

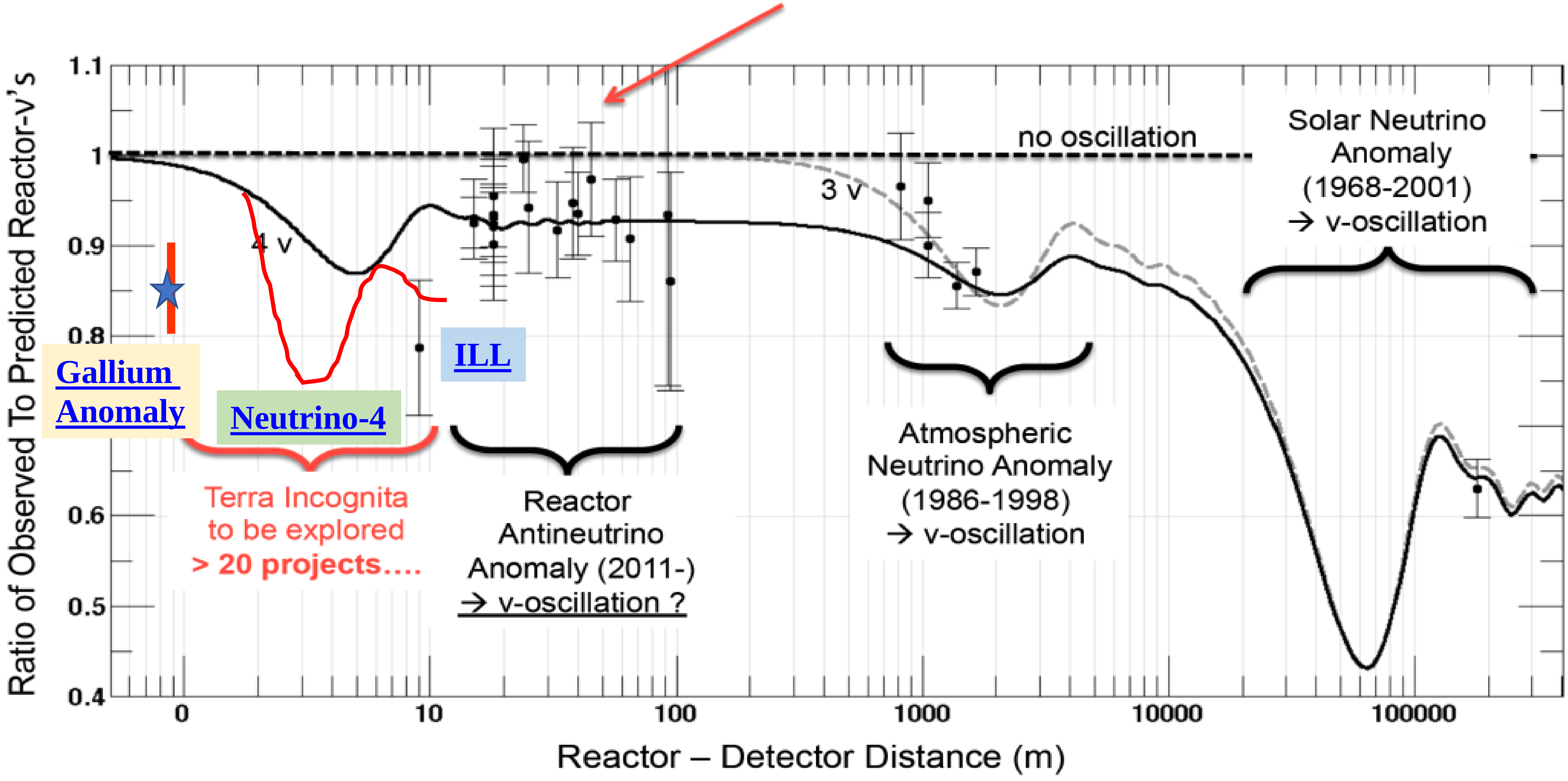
Закупка сцинтилятора 10 тонн – 650 тыс. долларов

<u>Possible conformation of our results</u>

First of all there is no large contradiction with Reactor Antineutrino Anomaly and Gallium Anomaly

There is no large contradiction with Reactor Antineutrino Anomaly

- Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)



Where our result can be confirmed or refuted ?

1. PROSPECT, STEREO, SoLiD - can be …… because small size of reactor core.
2. DANSS –it is difficult because big size (3.7m) of reactor core.
3. NEOS – it is very difficult because big size of reactor core and distance 24 m.
4. BEST - new measurements is going right now.
5. KATRIN, Troisk

The period of oscillation for $\Delta m_{14}^2 \approx 7.3эВ^2$ and neutrino energy 4 MeV is **1.4 m**

V.Egorov DLNP JINR, Dubna
(on behalf of the DANSS collaboration)

JINR Dubna

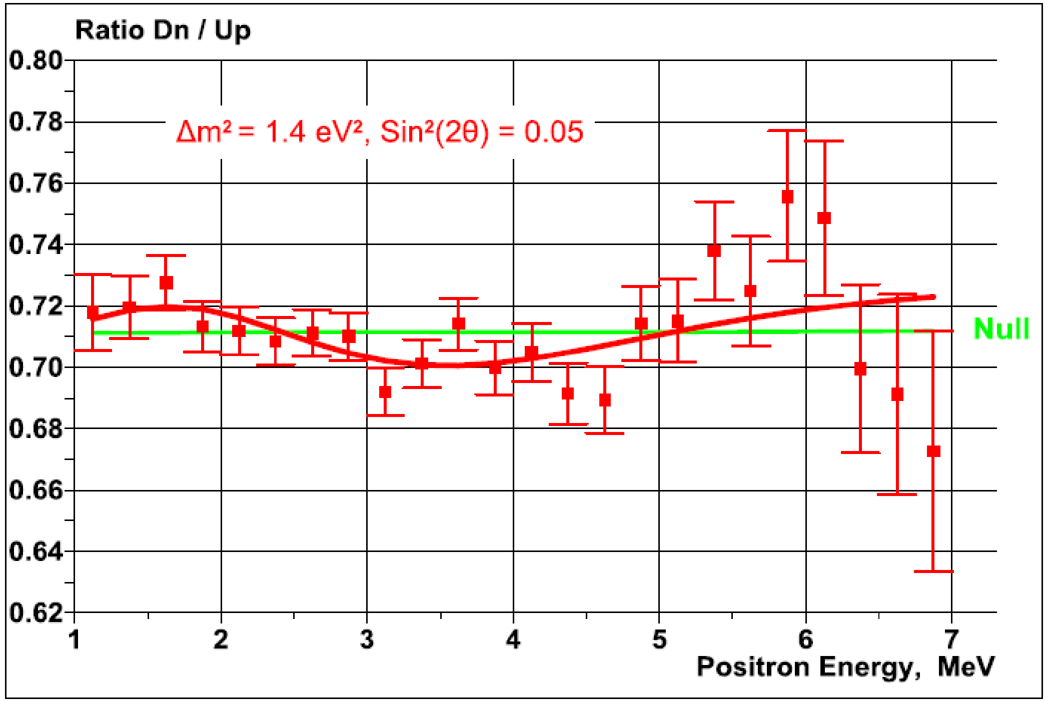
ITEP Moscow

DANSS

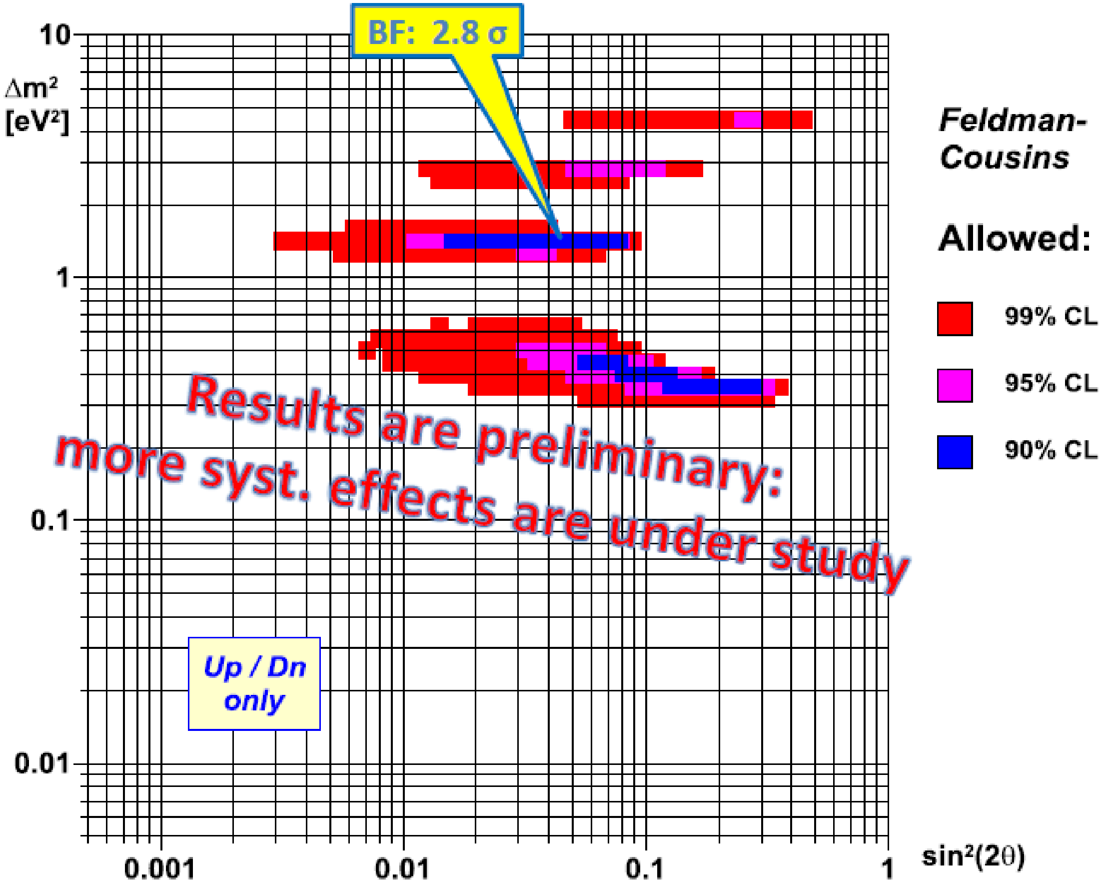
Detector of the reactor AntiNeutrino based on Solid-state Scintillator

Best Fit:

$\Delta m^2 = 1.4\ eV^2,\ Sin^2(2\theta) = 0.05$



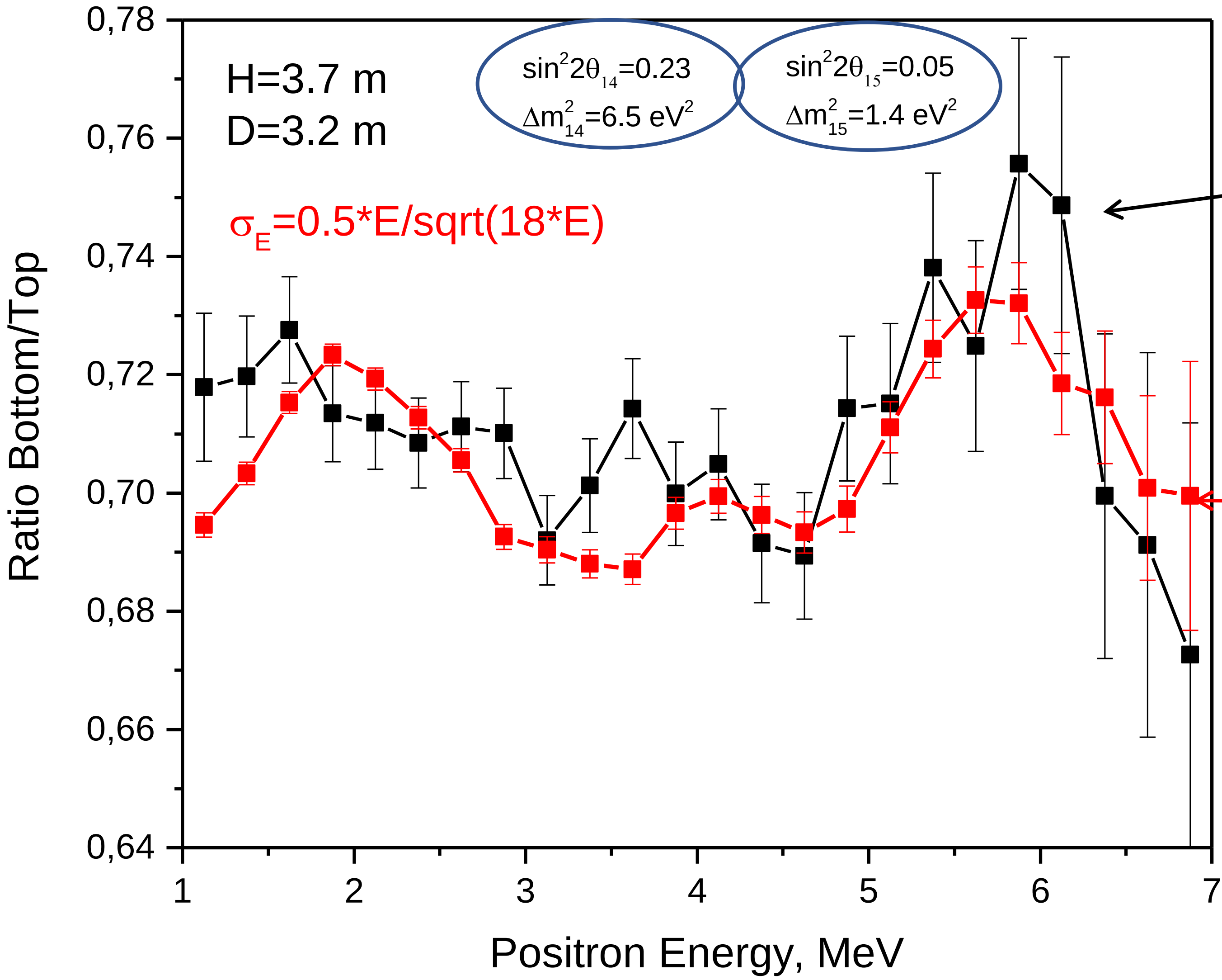
Significance of the best regions



MC simulation of experiment DANSS
and analysis of experimental data DANSS with two sterile neutrino

Possible confirmation of effect of anti-neutrino oscillations with

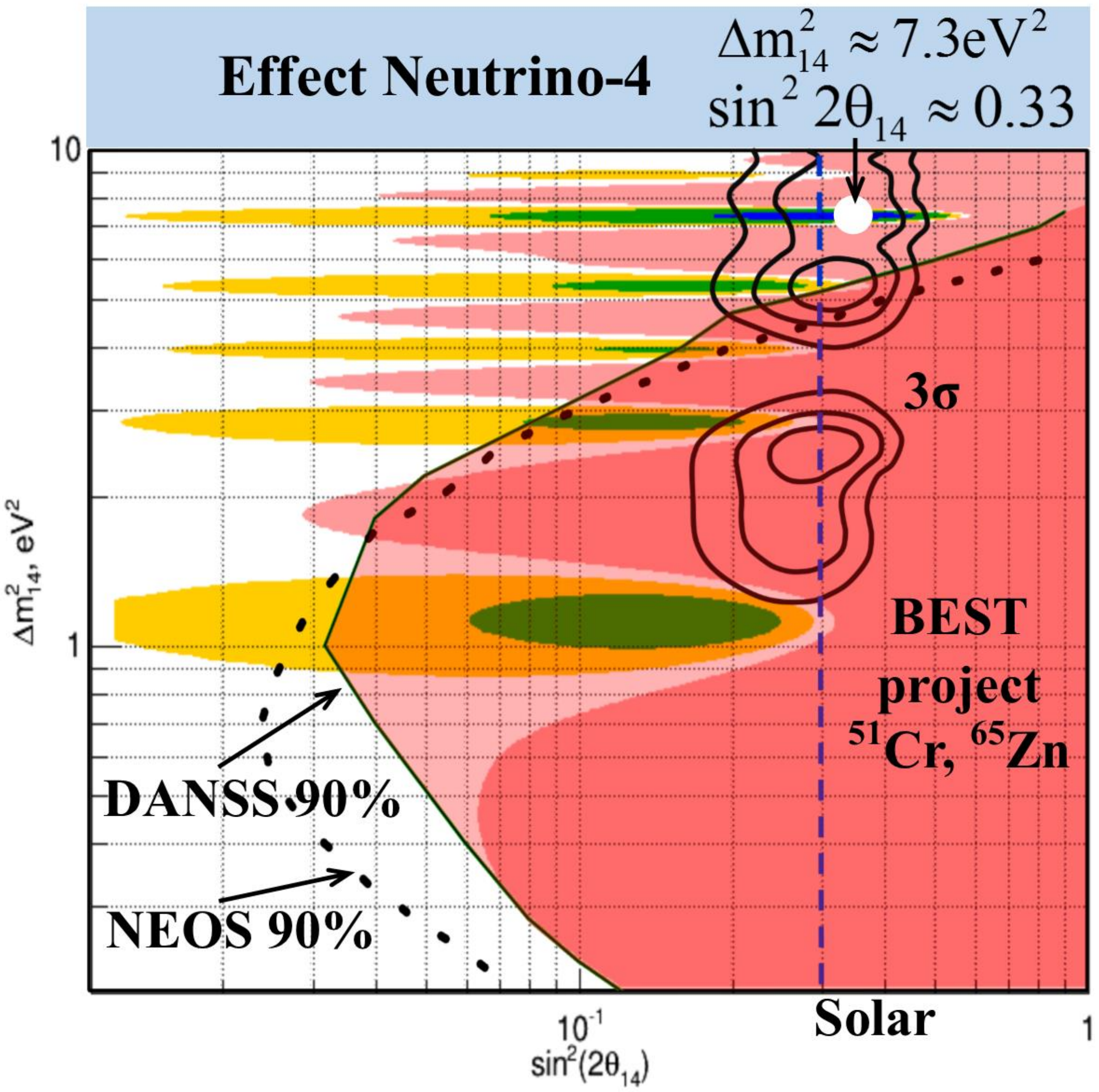
$\Delta m^2_{14} \approx 7.3 эВ^2$



experimental data DANSS

MC simulation of experimental data DANSS with two sterile neutrino

BEST experiment - Sensitivity Area



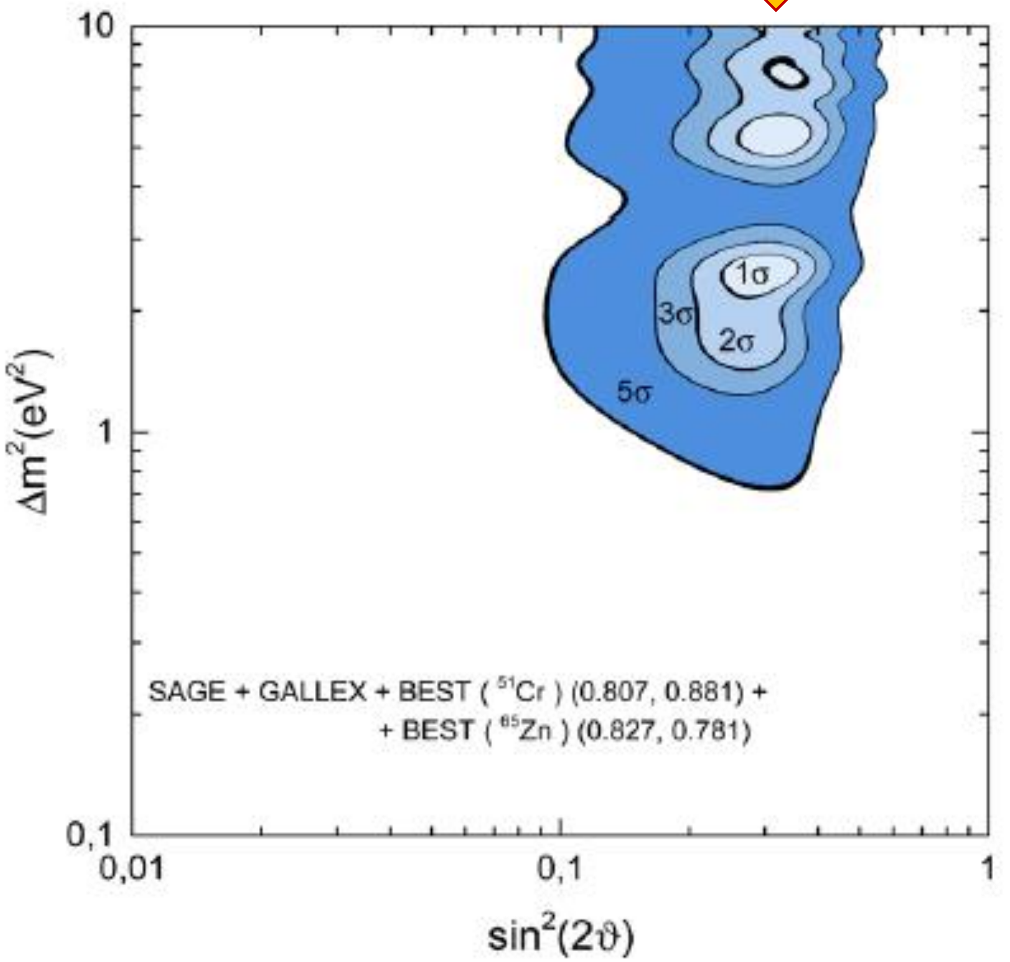


FIG. 7. Allowed regions of oscillation parameters, built on the basis of new data, in the case of combining the results of SAGE + GALLEX with the result of BEST for two sources (^{51}Cr and ^{65}Zn), which corresponds to the best fit point.

Experiment KATRIN and sterile neutrino from Neutrino-4

$$\Delta m_{14}^2 = 7.26 eV^2, \qquad Sin^2 2\vartheta_{14} = 0.38$$

$$m_\beta = \sqrt{\Sigma_i m_i^2 / U_{ei} /^2}$$

$$\Delta m_{14}^2 \approx m_4^2,$$

$$Sin^2 2\vartheta_{14} = 4 / U_{14} /^2 (1 - /U_{14} /^2)$$

$$/U_{14} /^2 \ll 1$$

$$/U_{14} /^2 \approx \frac{1}{4} Sin^2 2\vartheta_{14}$$

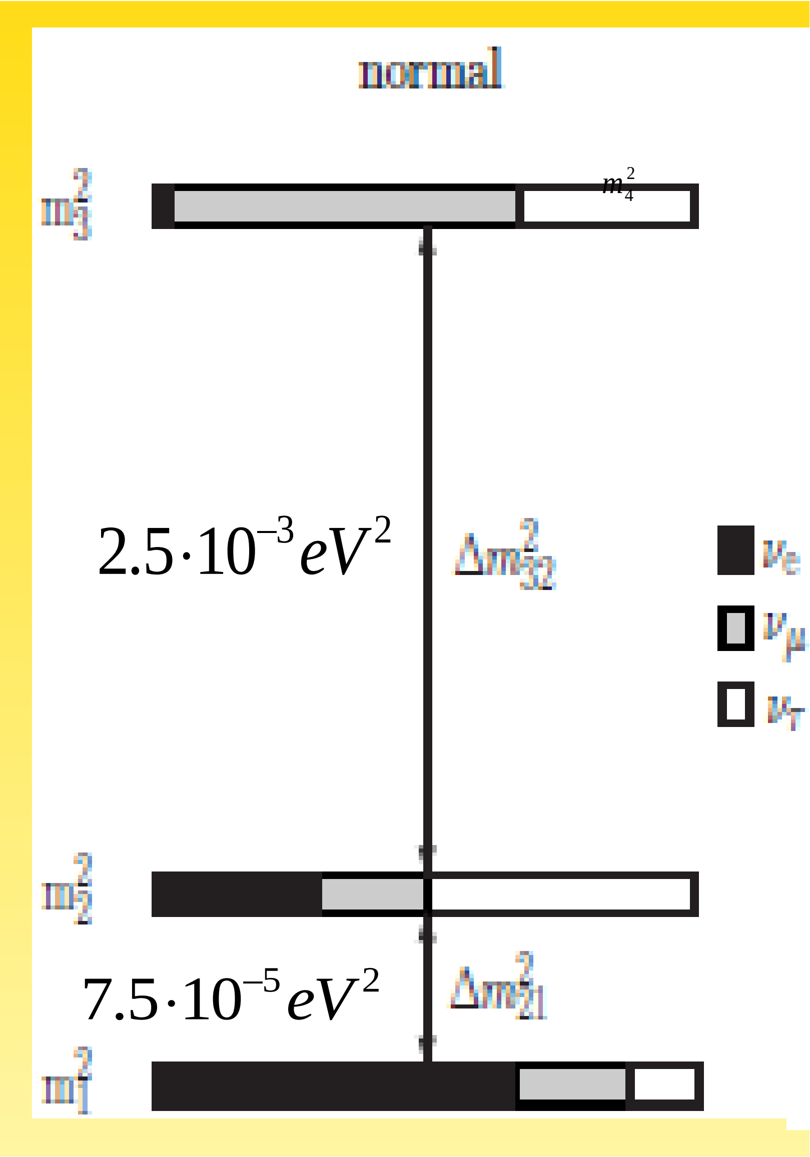
$$m_\beta \approx \frac{1}{2}\sqrt{7.3 \cdot 0.38} \approx 0.87 eV$$

1. There is no contradiction with restriction from experiment KATRIN - $m_\beta \leq 1 eV$

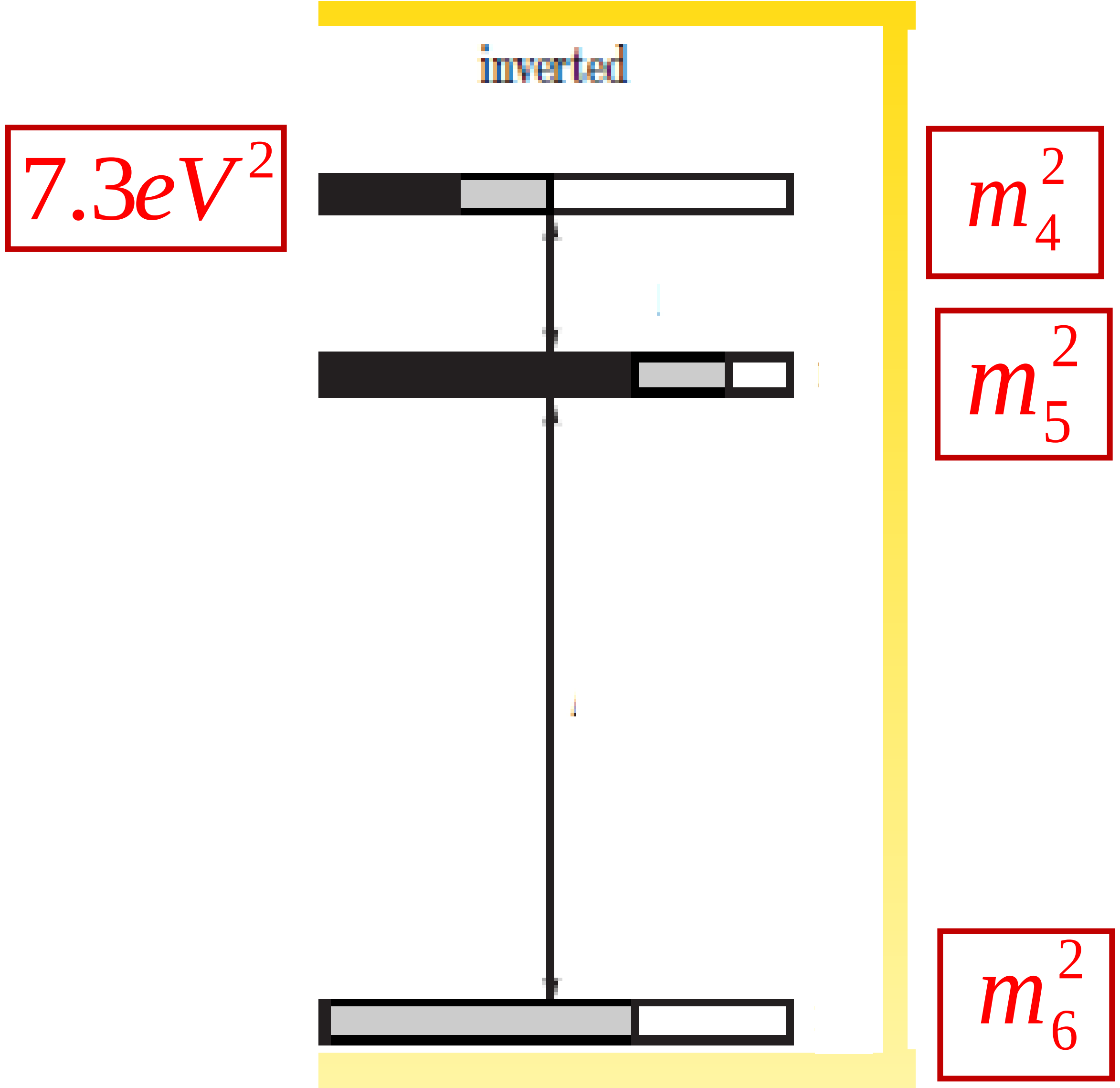
2. If effect of Neutrino-4 is correct then prediction for neutrino mass is $m_\beta \approx 0.87 eV$

Brave Ideas

Standard neutrino



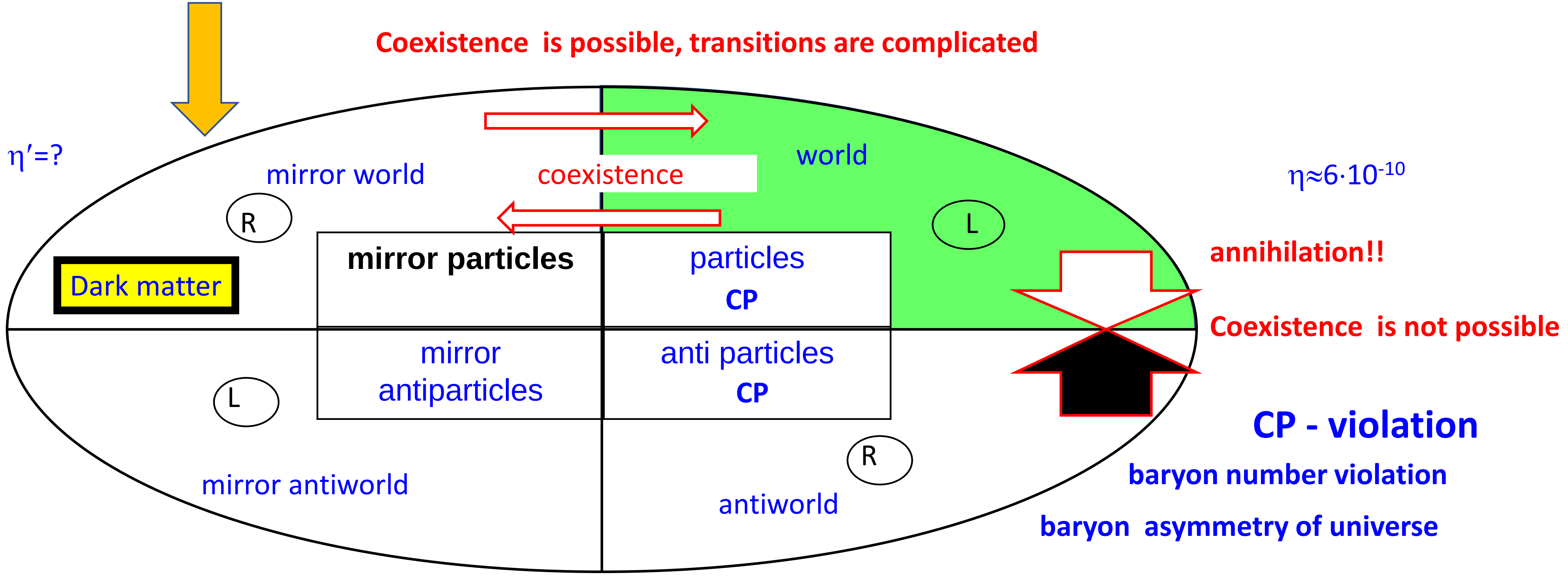
Sterile neutrino



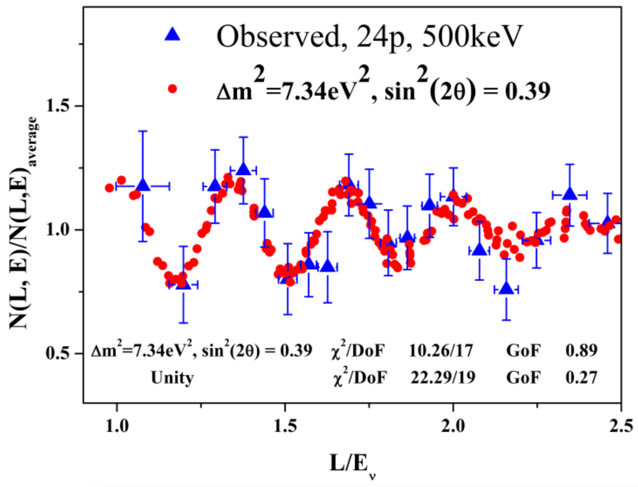
Two problems of fundamental interaction – baryon asymmetry of the universe and dark matter

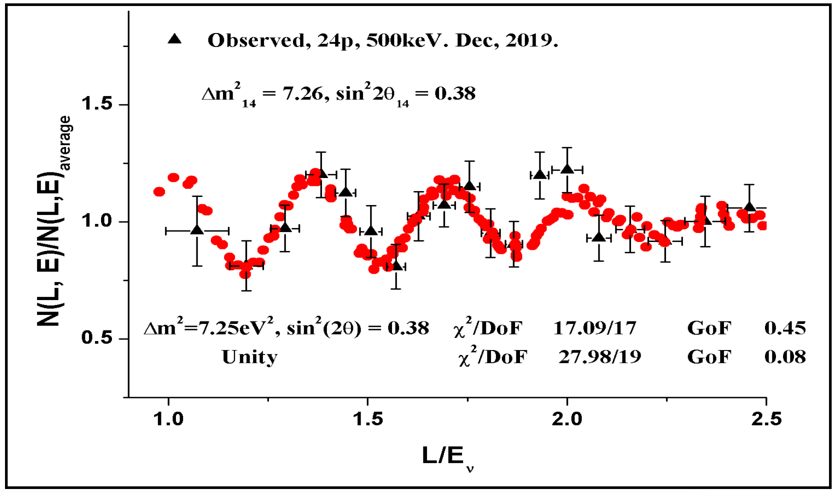
(left-right asymmetry in nature)

Sterile neutrino it is mirror neutrino – candidate for dark matter particle



Thank you for attention



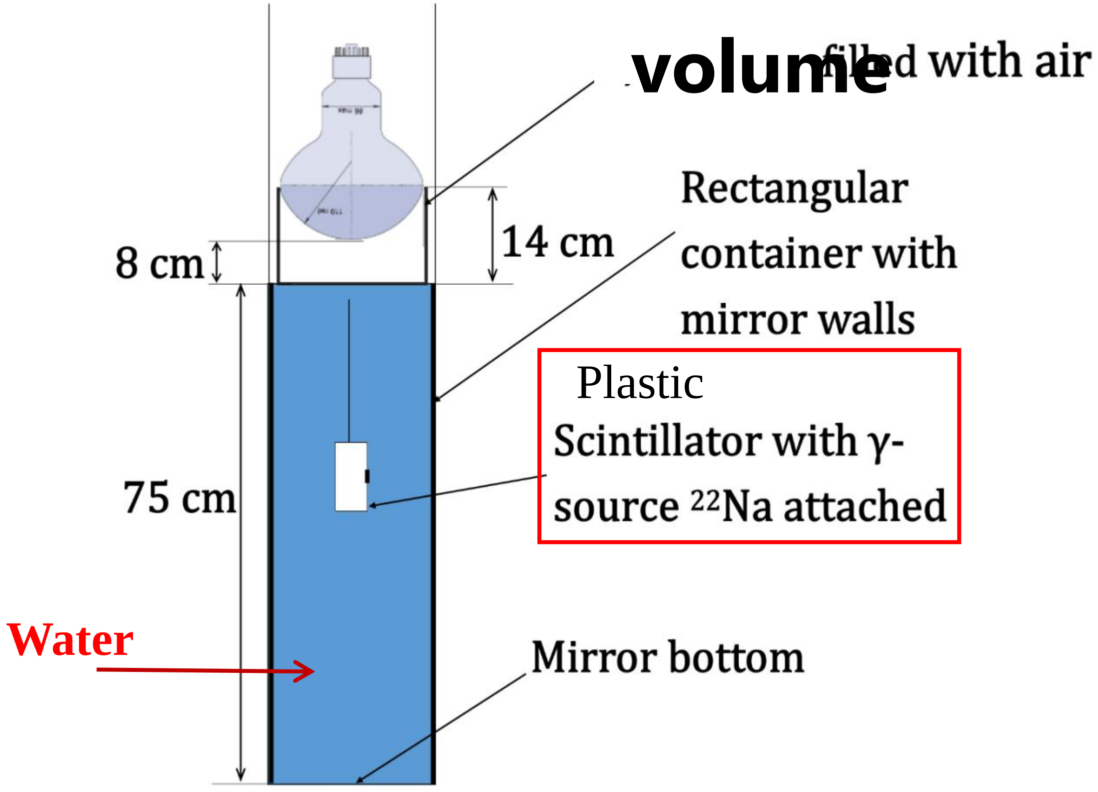


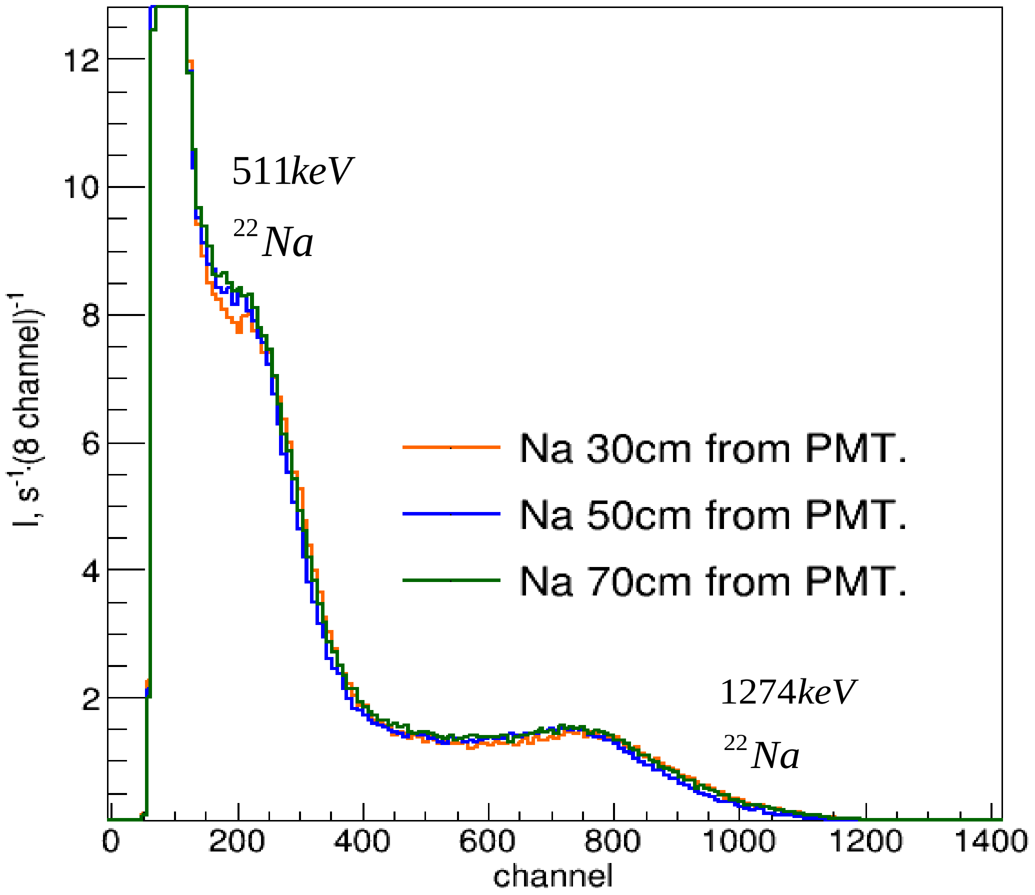
Best regards from Gatchina

Best regards from Dimitrovgrad

Энергетическая калибровка на модели одной секции

Мы используем эффект полного внутреннего отражения света на границе сцинтиллятор - воздух при малых углах падения, чтобы улучшить сбор света с разных расстояний. Поэтому калибровка может быть сделана, используя источники, расположенные снаружи – над детектором.

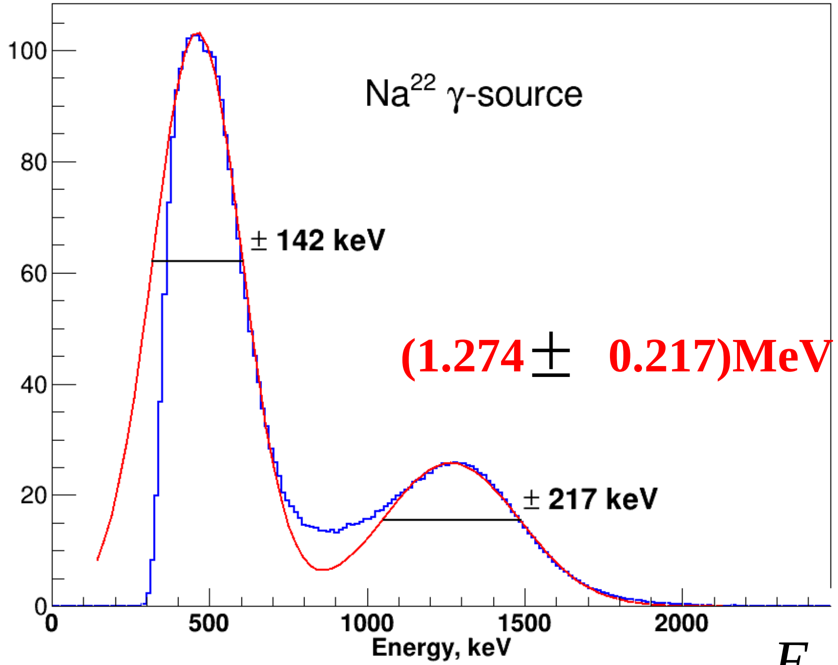




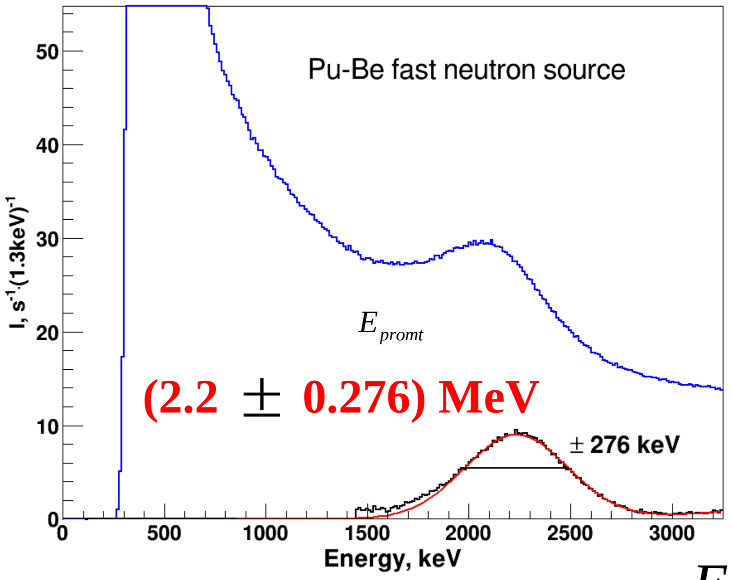
Energy calibration of the full-scale detector

(0.511 ± 0.142) MeV

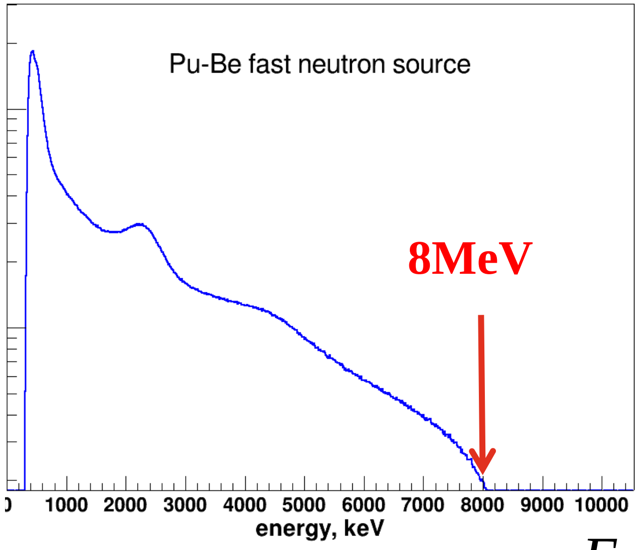
$$E_\nu = E_{promt} + 0.8 MeV$$



E_{promt}



E_{promt}



E_{promt}

$$\Delta E_\nu / E_\nu (2MeV) = 21\%$$

$$\Delta E_\nu (2MeV) = 440 keV$$

$$\Delta E_\nu / E_\nu (3MeV) = 18\%$$

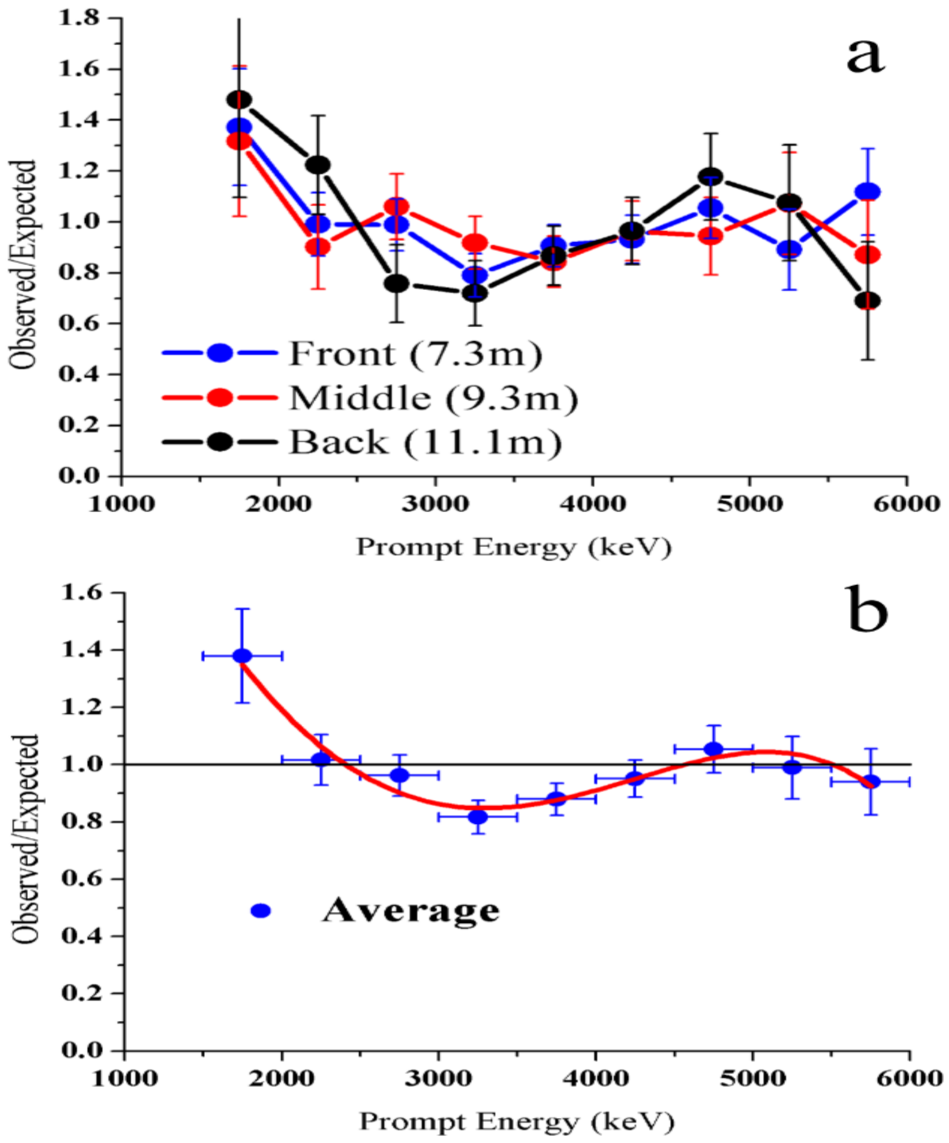
$$\Delta E_\nu (3MeV) = 550 keV$$

$$\Delta E_\nu / E_\nu (6MeV) = 14\%$$

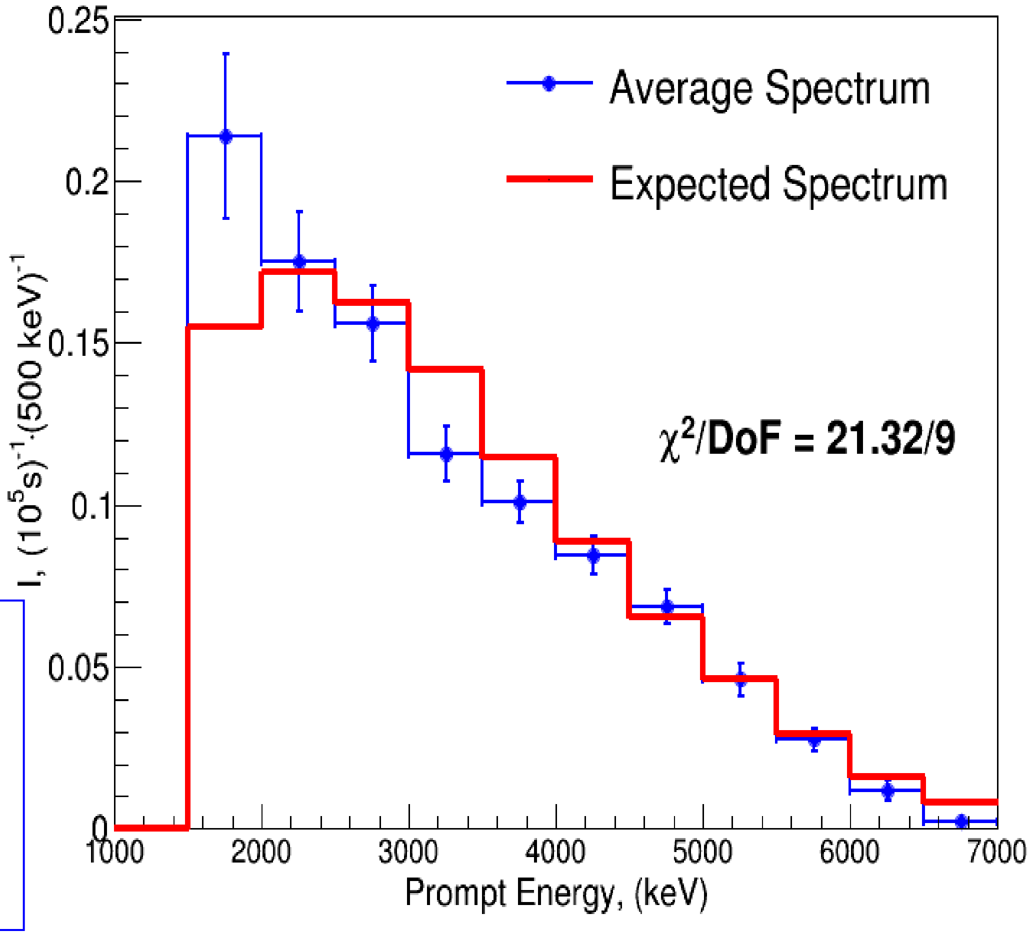
$$\Delta E_\nu (6MeV) = 830 keV$$

a) The ratio of an experimental spectrum of prompt signals to the spectrum, expected from MC calculations for 3 ranges (~2m) with centers 7.3m, 9.3m and 11.1m

b) polynomial fit of results averaged by distance (red curve)

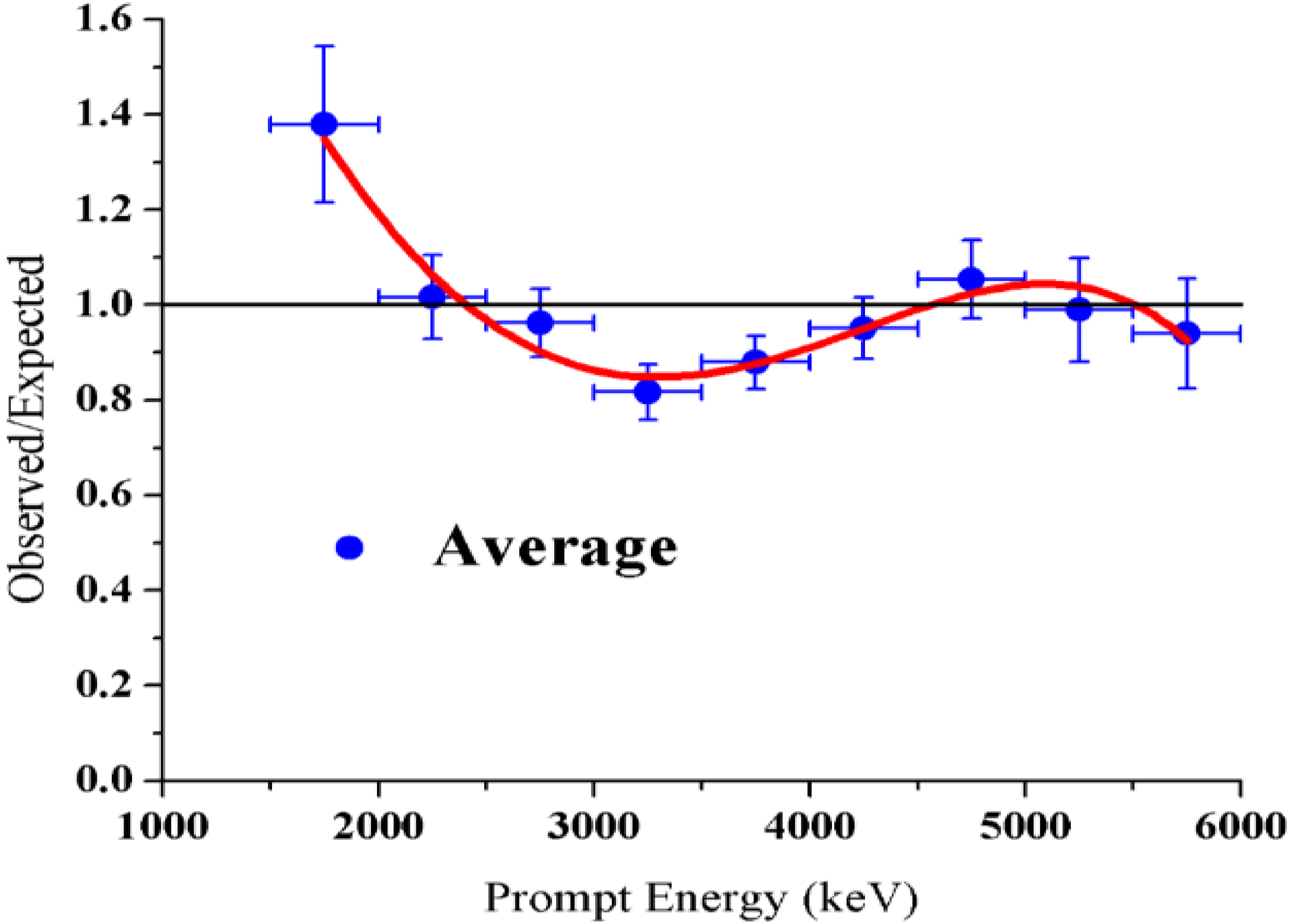


Problems with energy spectrum



Spectrum of prompt signals in the detector for a total cycle of measurements summed over all distances (average distance — 8.6 meters). The red line shows Monte -Carlo simulation with neutrino spectrum of ^{235}U, as the SM-3 reactor works on highly enriched uranium.

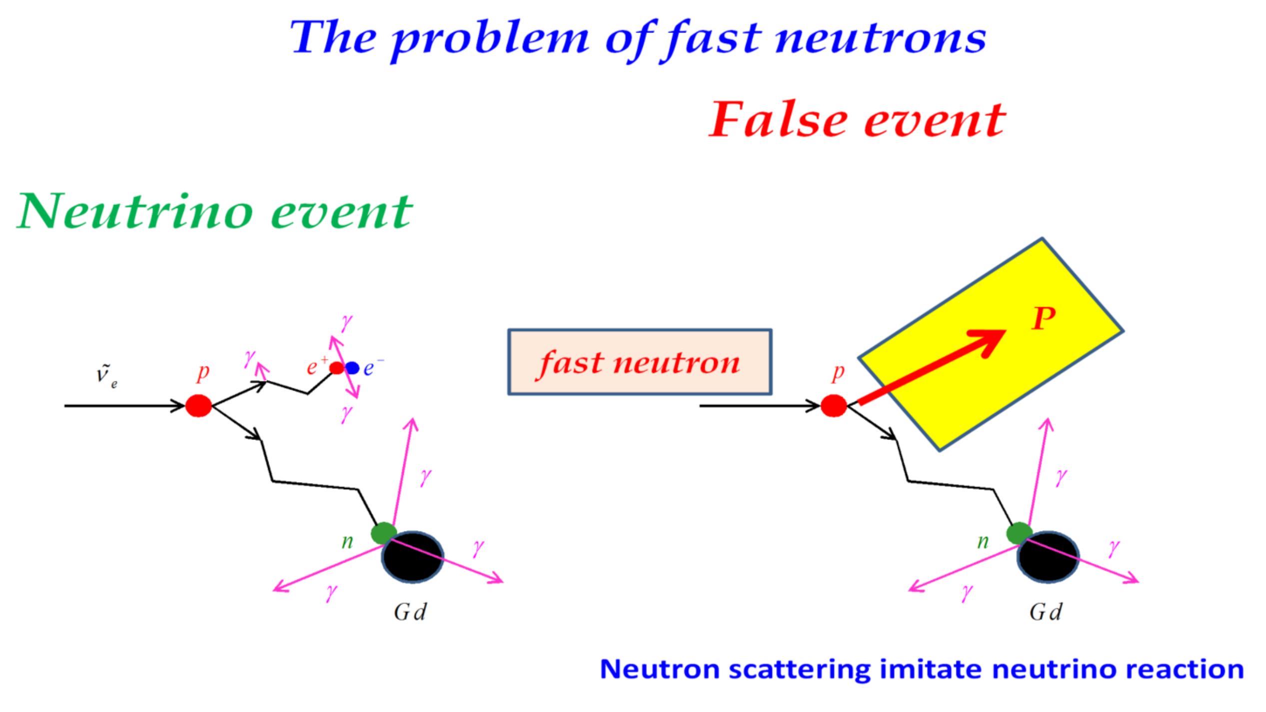
Spectrum (observed/ expected) of prompt signals



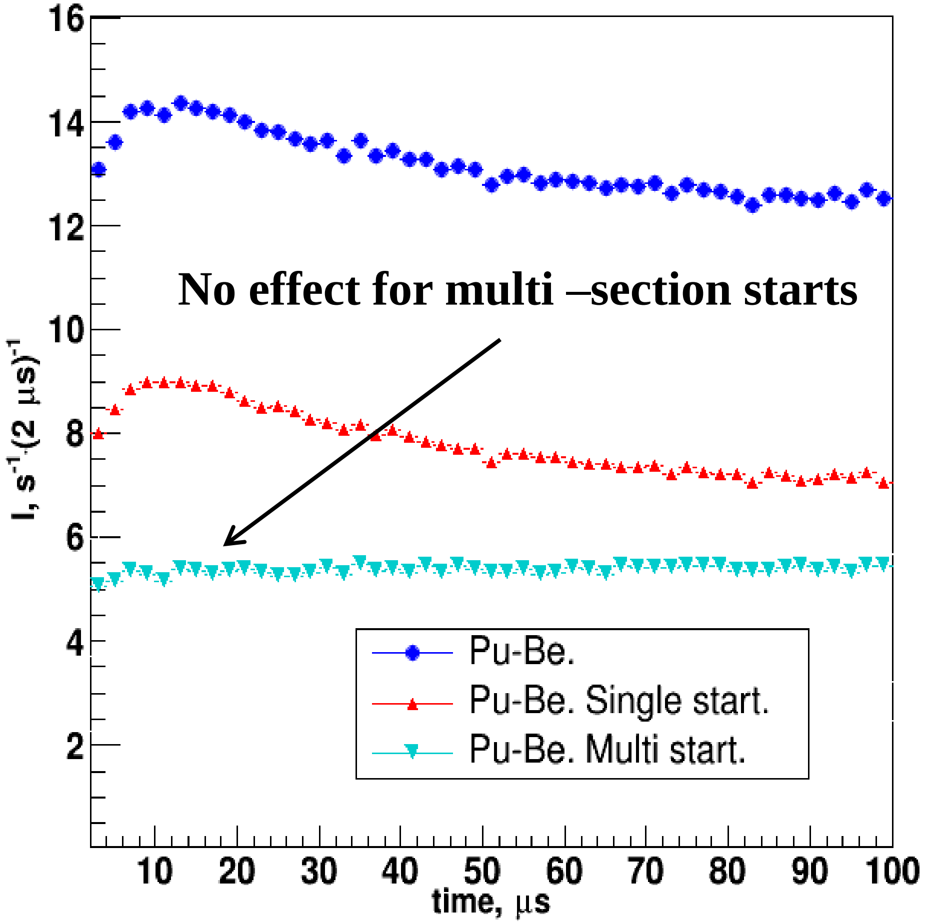
Problems with energy spectrum

Spectrum (observed/ expected) of prompt signals in the detector for a total cycle of measurements summed over all distances (average distance — 8.6 meters). Monte -Carlo simulation with neutrino spectrum of ^{235}U, as the SM-3 reactor works on highly enriched uranium.

- **Sectioning of the detector**
- **Problem of fast neutrons**
- **Allocation of a neutrino signal**



The test with a source of fast neutrons



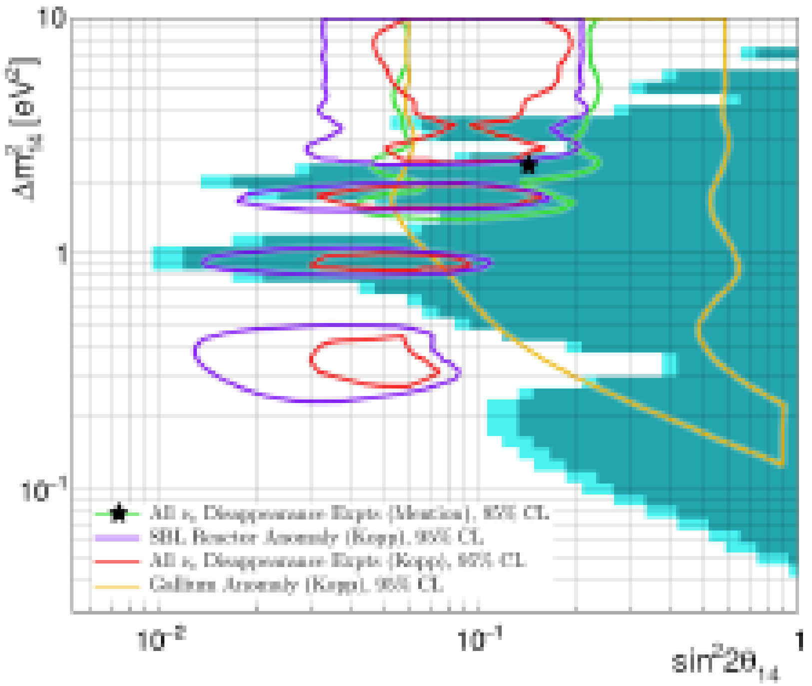
24 central and 16 side cells for full-scale detector

central cell	side cell	angular cell	in all cells
42%	29%	19%	37%

Calculated percentage of multi-start events

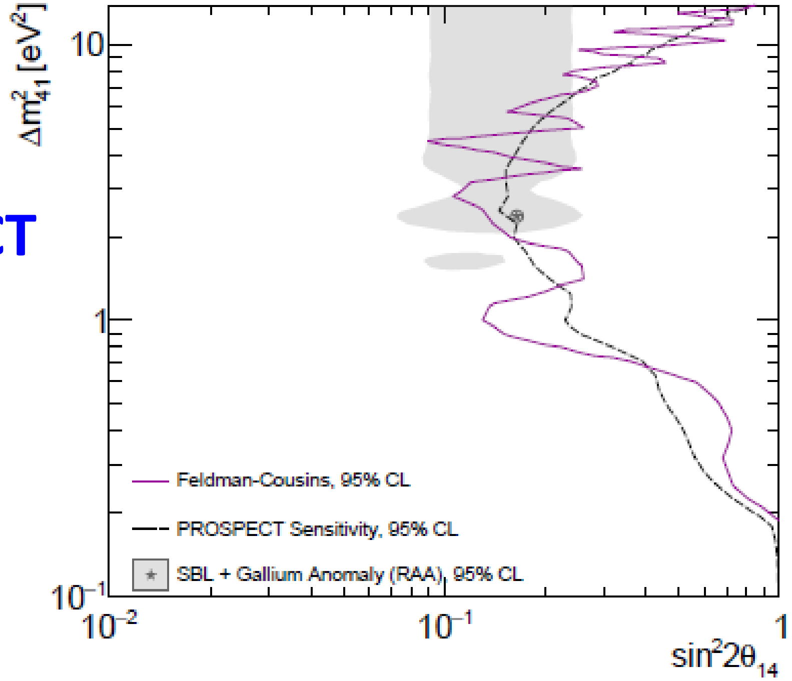
Experimental average percentage of multi-start events for full-scale detector

(37 ± 4)%

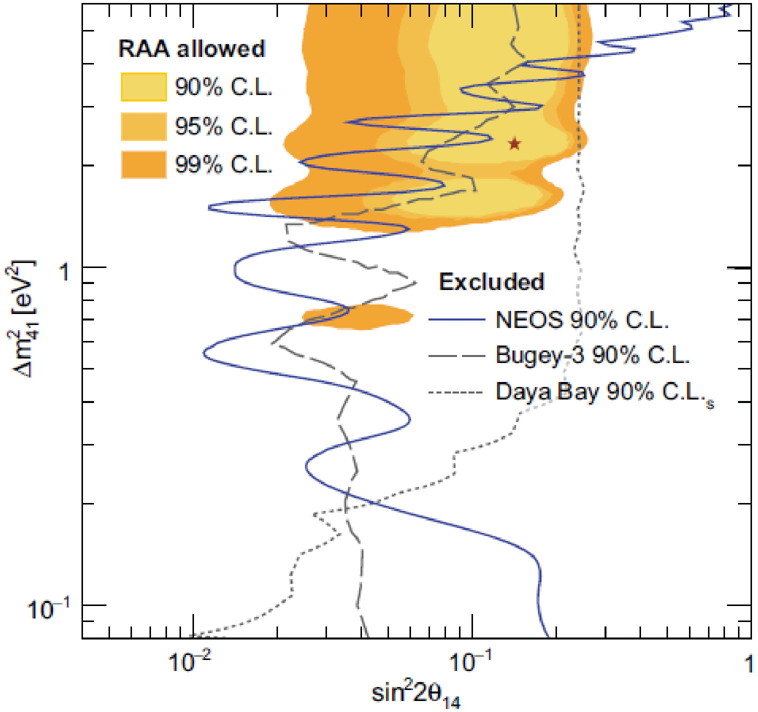


DANSS
90%

PROSPECT
95%

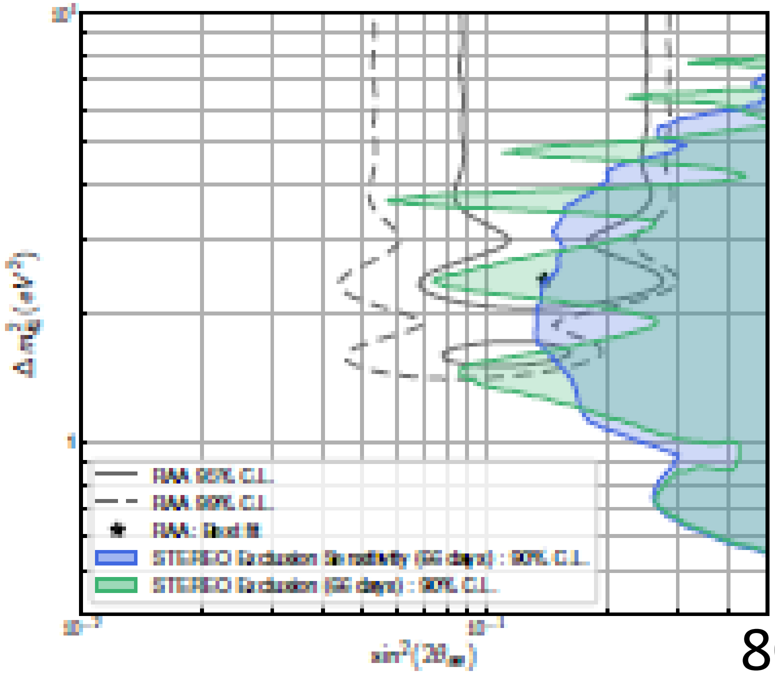


The slide illustrates sensitivity of other experiments: NEOS , DANSS , STEREO and PROSPECT



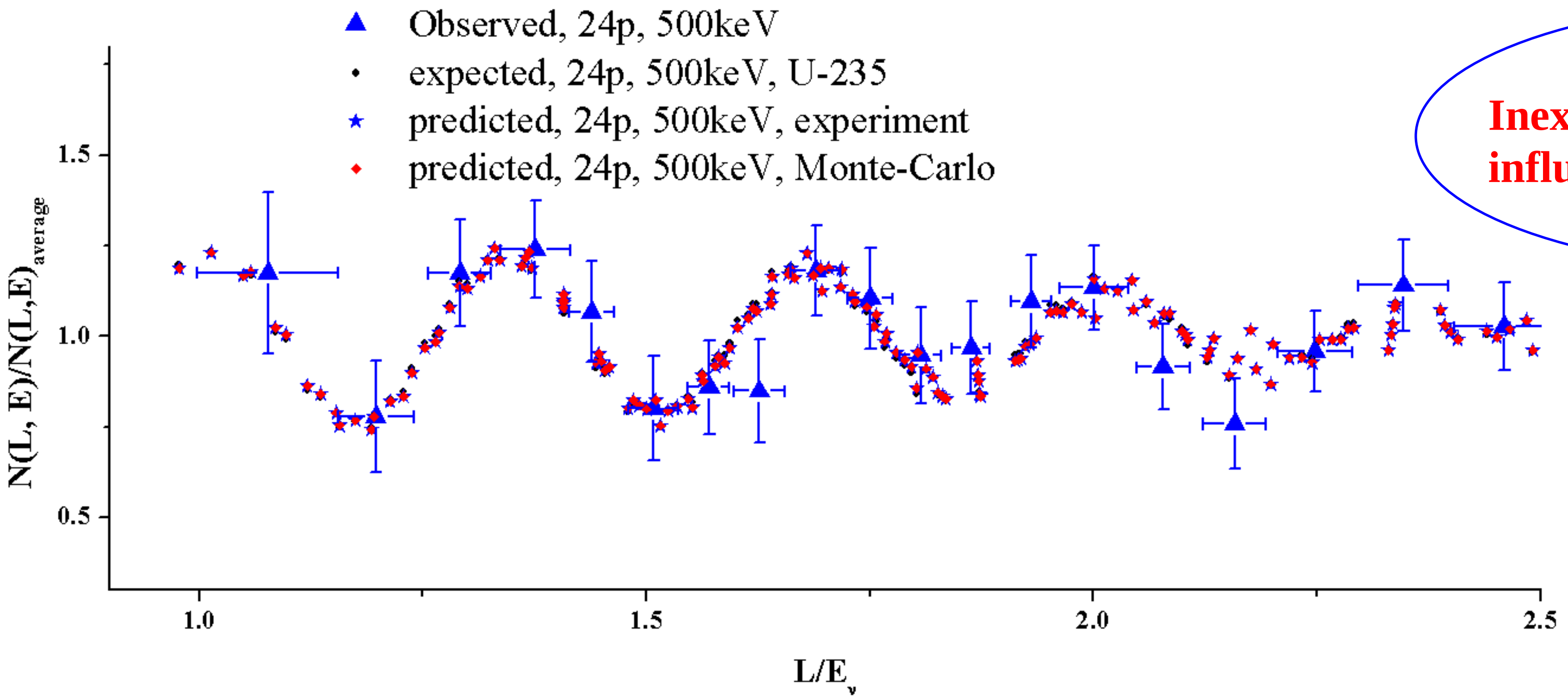
NEOS
90%

STEREO
90%



Independence of identification of effect of oscillations of a form of a neutrino spectrum

3 different ranges were chosen : 1) U-235, 2) Expetiment, 3) Monte-Carlo

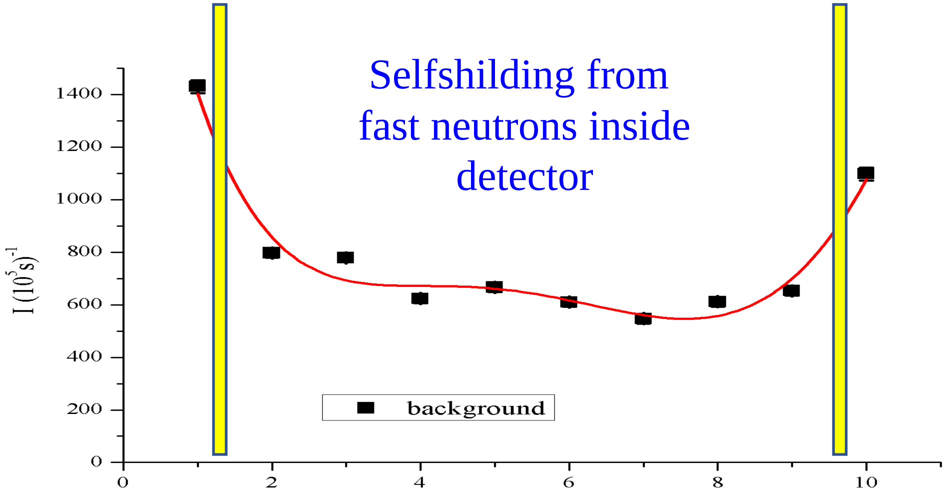


Inexact measurement of energy influences to definition of: Δm^2_{14}

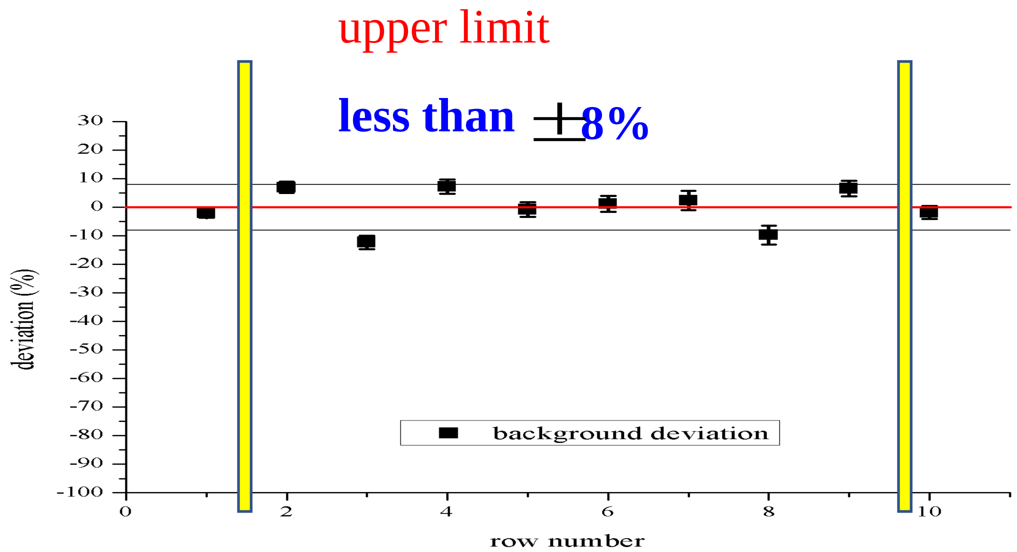
Apparently there is no difference. It also should not be because spectra are strictly canceled in formula (2)

$$R^{exp}_{i,k} = \frac{N(E_i, L_k) L_k^2}{K^{-1} \sum_k^K N(E_i, L_k) L_k^2} = \frac{[1 - \sin^2 2\theta_{14} \sin^2(1.27 \Delta m^2_{14} L_k / E_i)]}{K^{-1} \sum_k^K [1 - \sin^2 2\theta_{14} \sin^2(1.27 \Delta m^2_{14} L_k / E_i)]} = R^{th}_{i,k} \qquad (2)$$

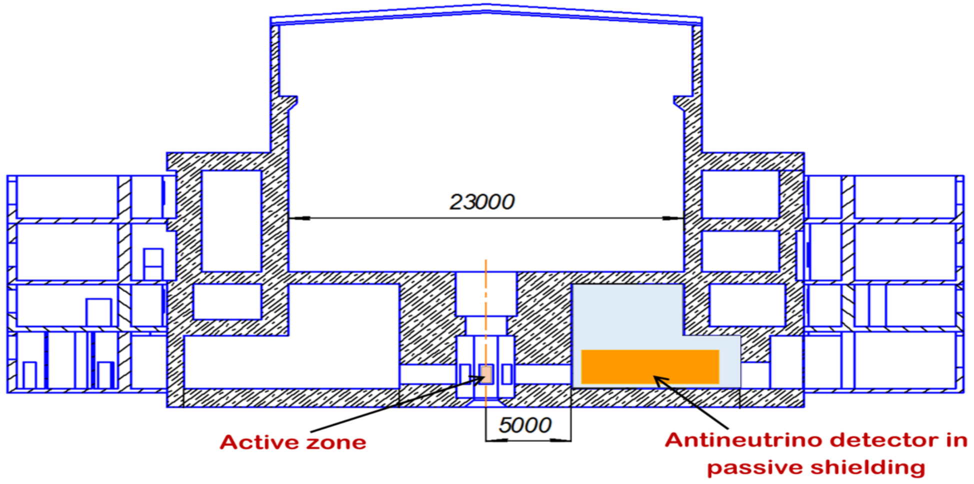
Analysis of possible difference in efficiency of rows of the detector, using the background of fast neutrons which is given rise into the building from cosmic muons.

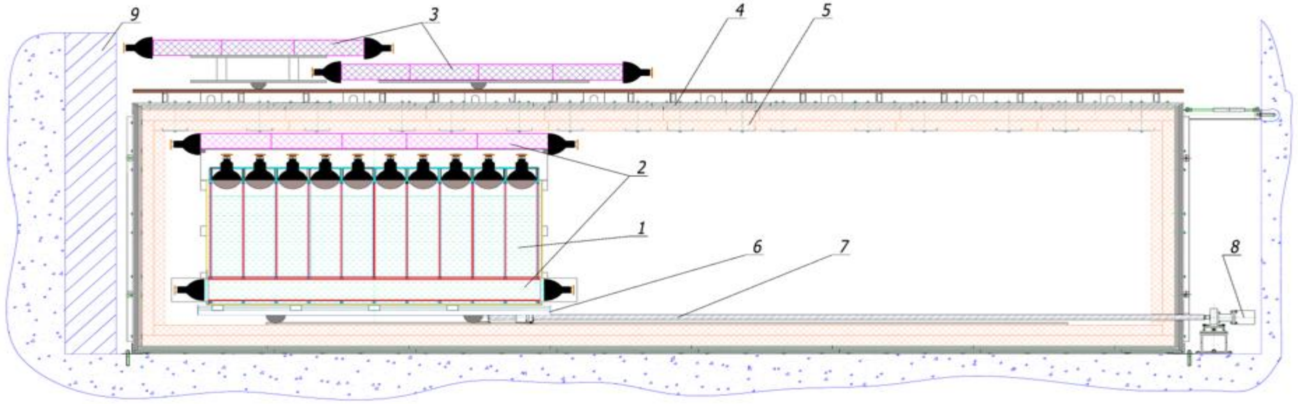


The background of fast neutrons is asymmetric because of structure of the building.



The dispersion on a background when moving the detector is within the same 8%.



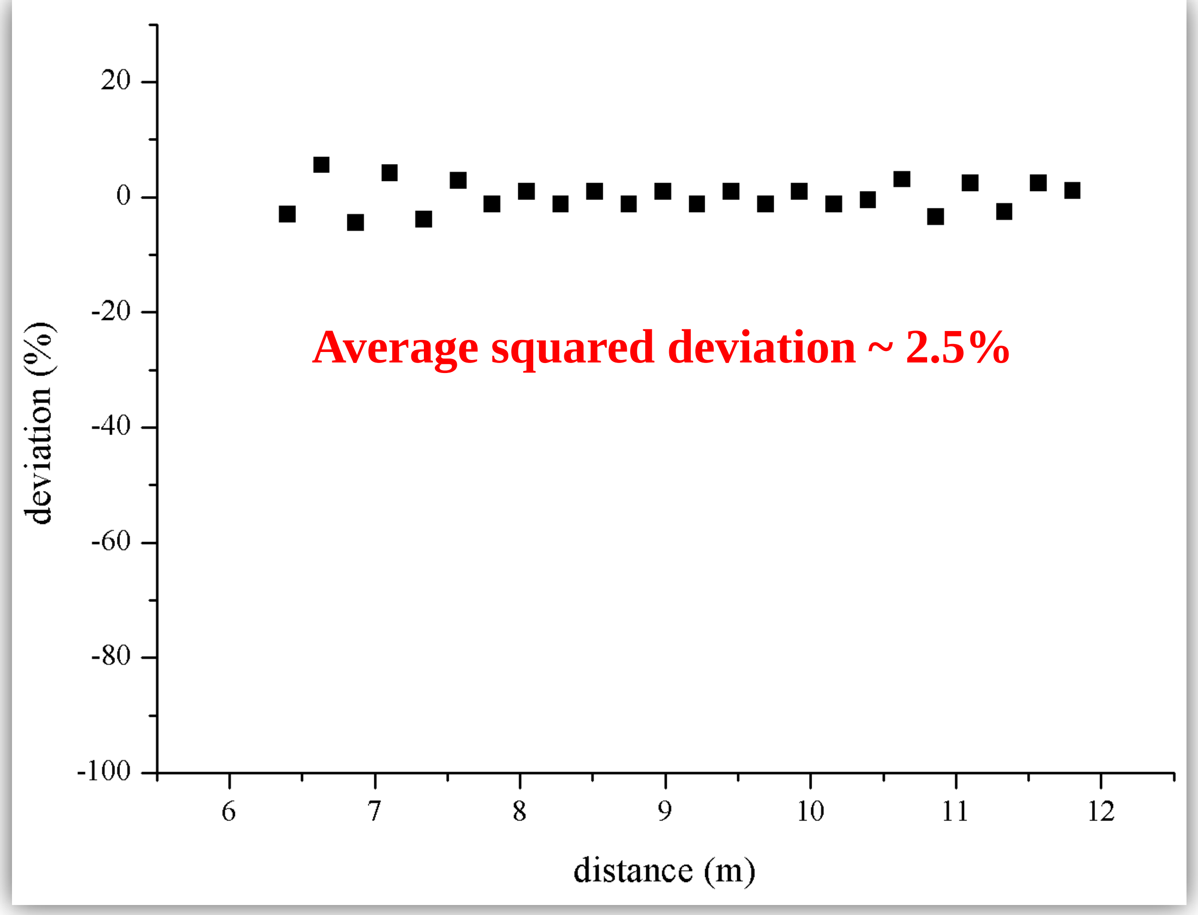


We use only 8 internal rows,
the first and tenth are protective.

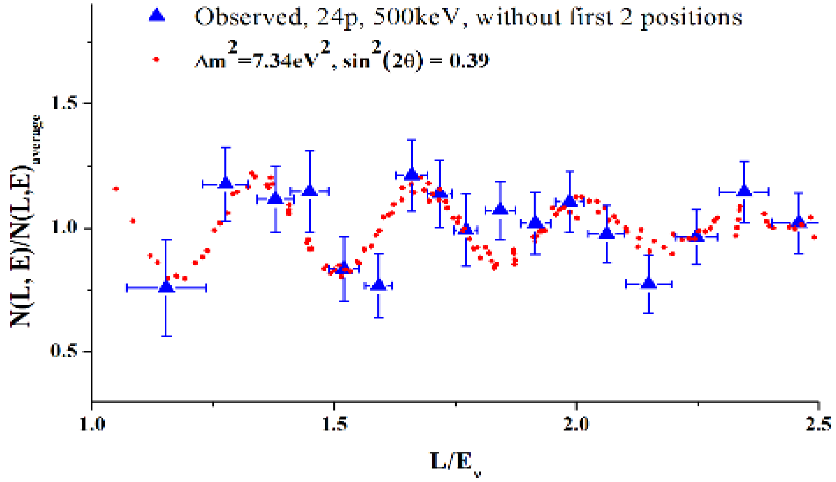
Averaging of detector rows efficiencies due to movements (above estimation)

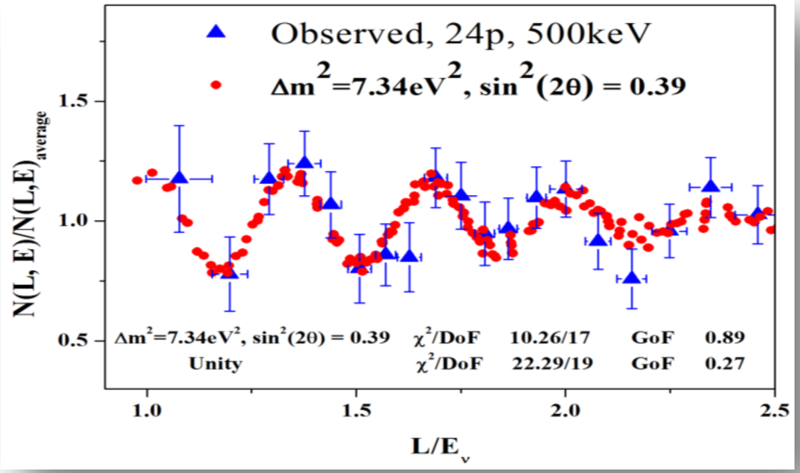
L(m)	Numbers of detector row				
6.4025	2				
6.6375	3				
6.8725	4	2			
7.1075	5	3			
7.3425	6	2	4		
7.5775	7	3	5		
7.8125	8	4	6	2	
8.0475	9	5	7	3	
8.2825	6	2	8	4	
8.5175	7	3	9	5	
8.7525	8	4	6	2	
8.9875	9	5	7	3	
9.2225	6	2	8	4	
9.4575	7	3	9	5	
9.6925	8	4	6	2	
9.9275	9	5	7	3	
10.1625	6	2	8	4	
10.3975	7	3	9	5	2
10.6325	8	4	6	3	
10.8675	9	5	7	4	
11.1025	6	8	5		
11.3375	7	9	6		
11.5725	8	7			
11.8075	9	8			

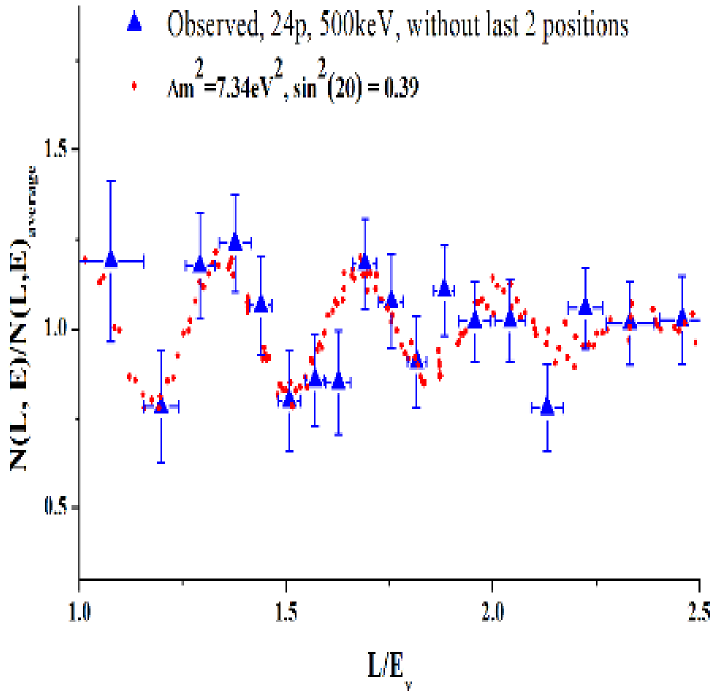
Average efficiency at various distances

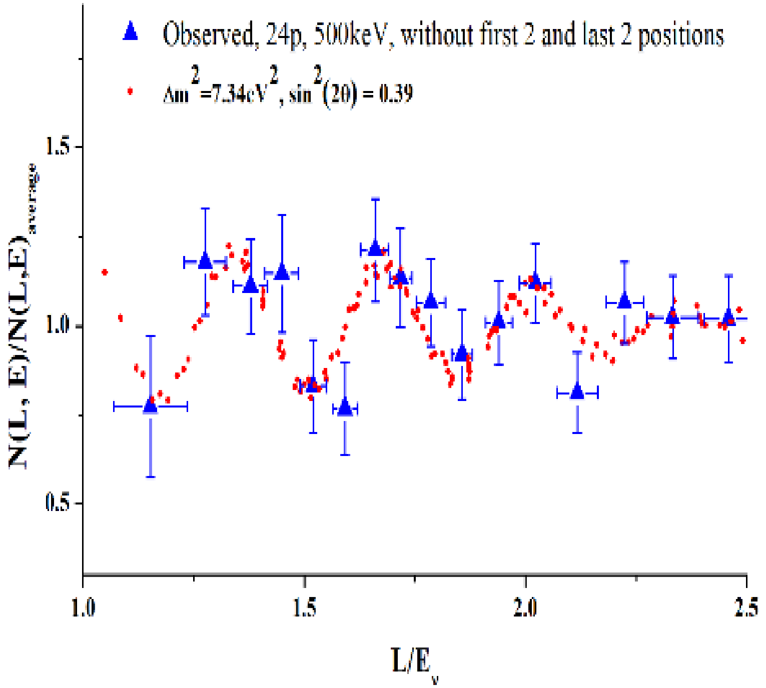


Test of stability of the effect by means of removal of extreme positions





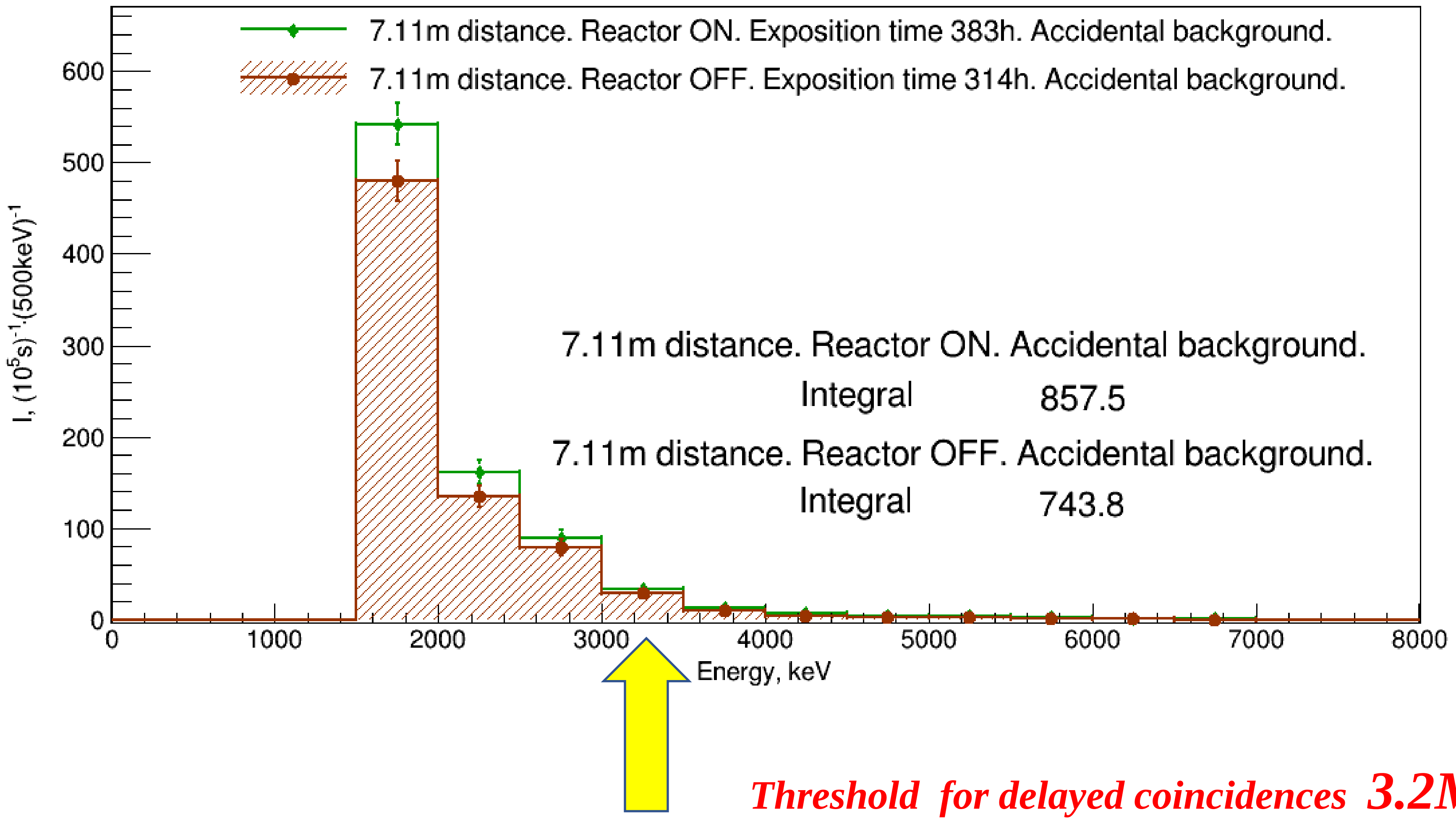




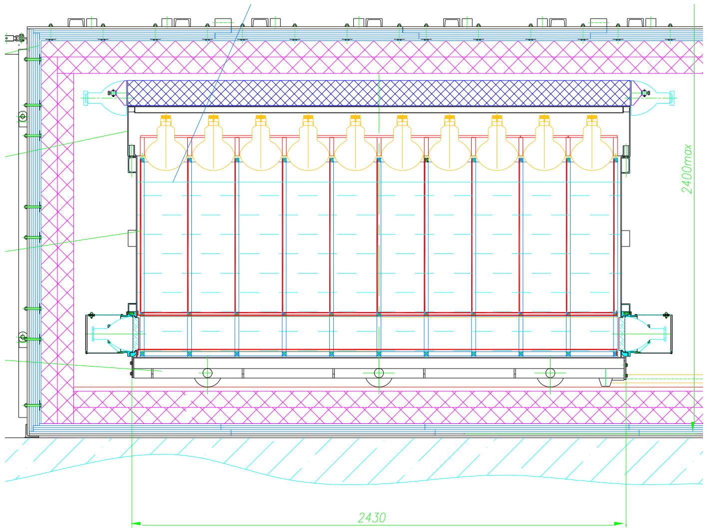
Conclusion

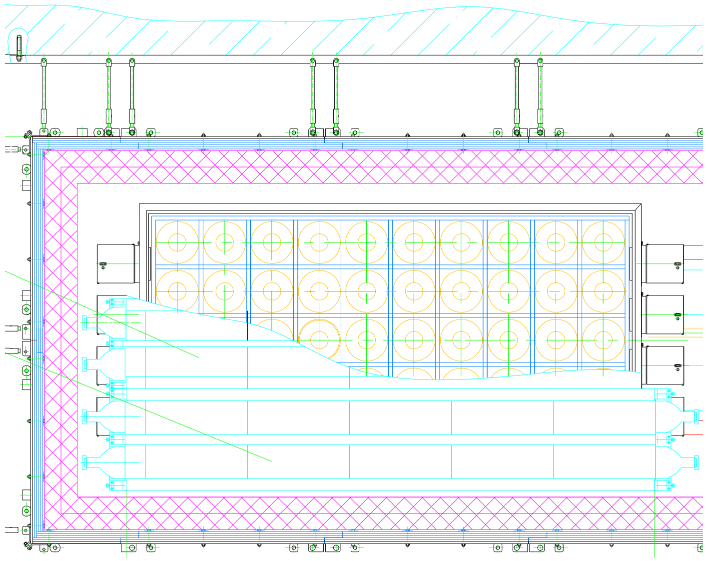
There is no reason to consider that the effect can be caused by structure of the detector. The possibility of averaging of efficiency of various sections by placing them at the same distance is the advantage of our experiment.

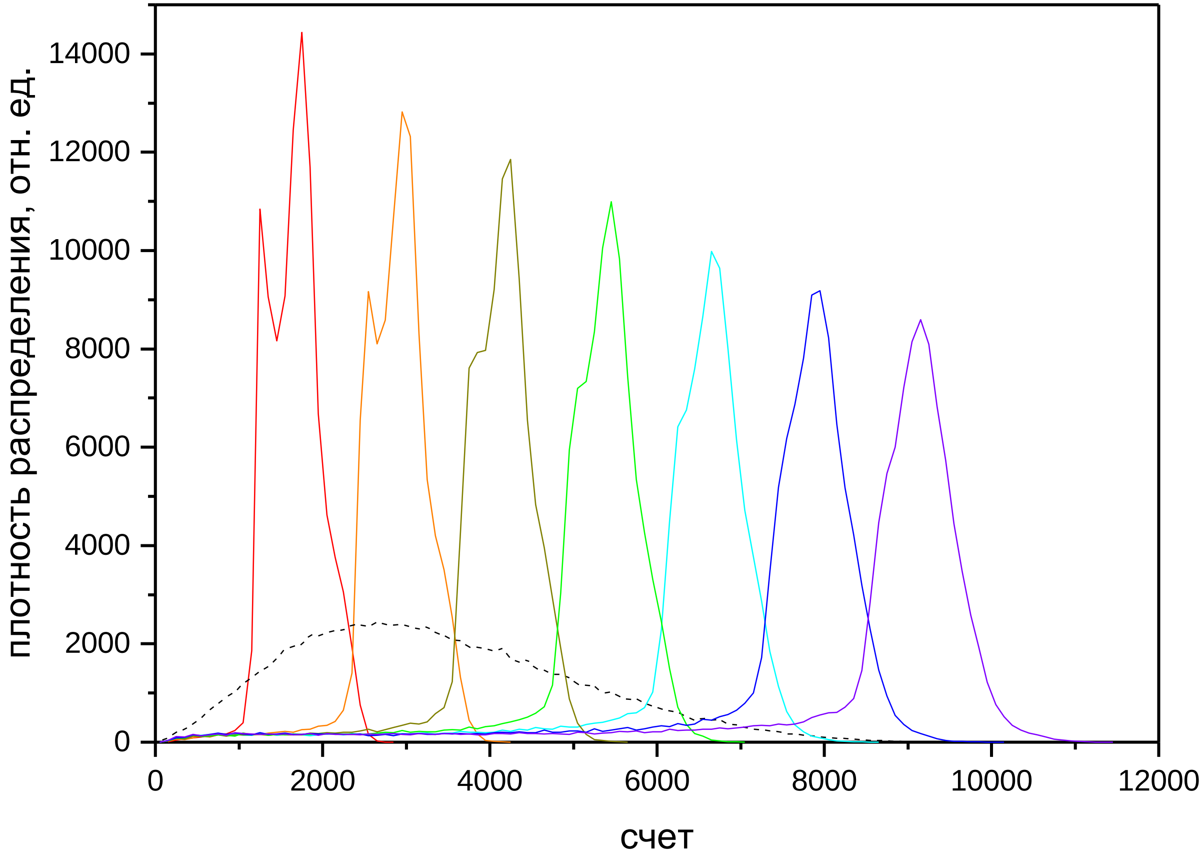
Accidental background practically does not depend on reactor, but it is rather big at low energies.



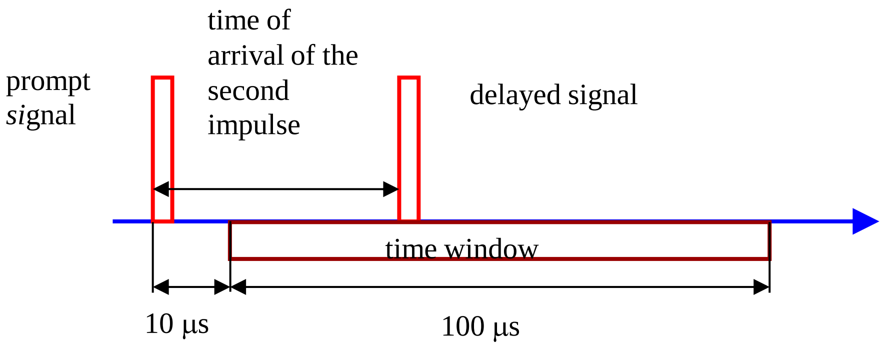
Threshold for delayed coincidences ***3.2MeV***


2400max
2430

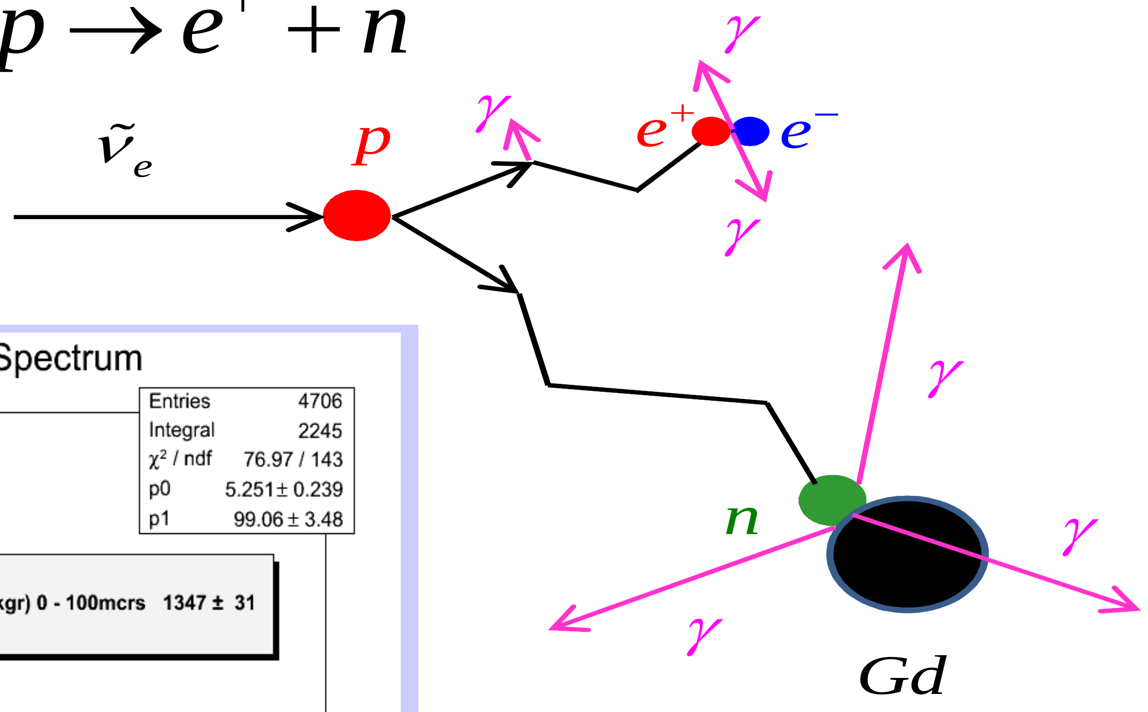


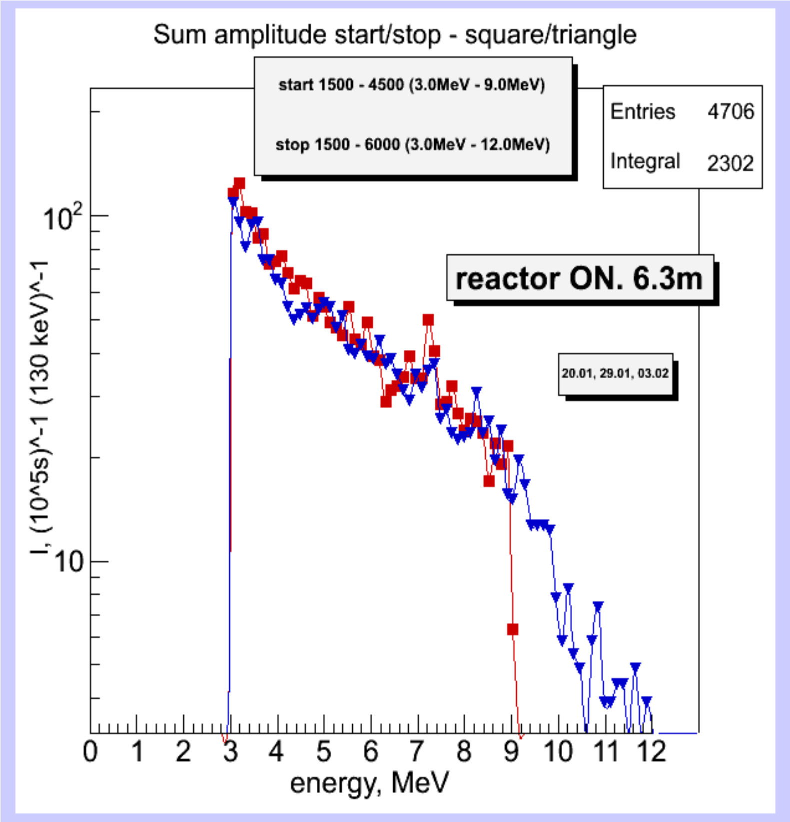

плотность распределения, отн. ед.
0
2000
4000
6000
8000
10000
12000
14000
0
2000
4000
6000
8000
10000
12000
счет

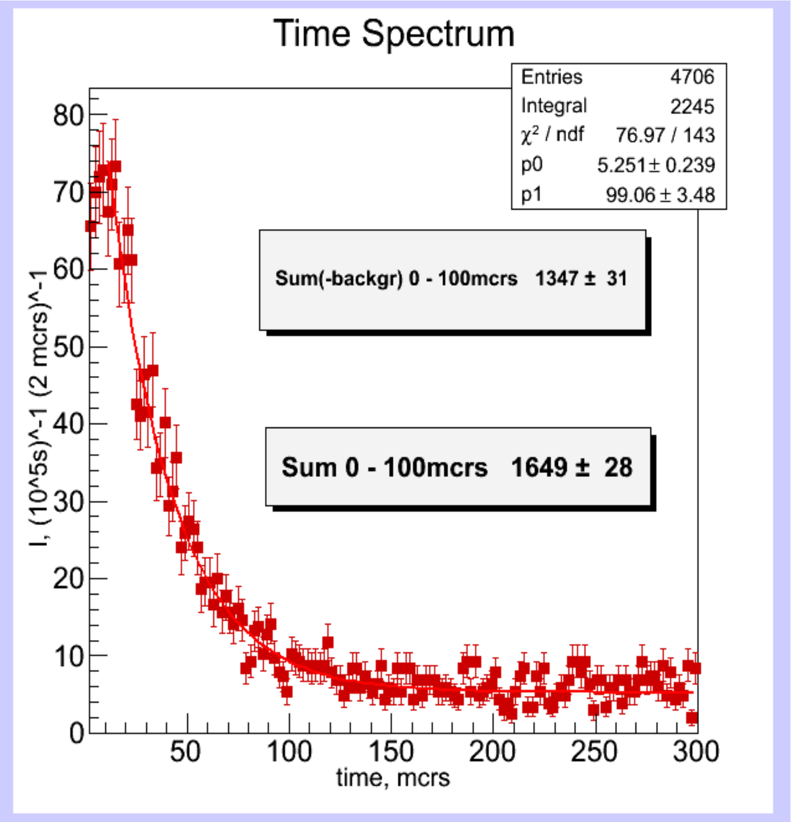
Signal of correlated events



$$\tilde{\nu}_e + p \rightarrow e^+ + n$$







Theory of Neutrino Masses

Max-Planck-Institut für Kernphysik

Werner Rodejohann

Pontecorvo School

29/08/15

MANITOP
Massive Neutrinos: Investigating their Theoretical Origin and Phenomenology

Heisenberg-Programm
DFG

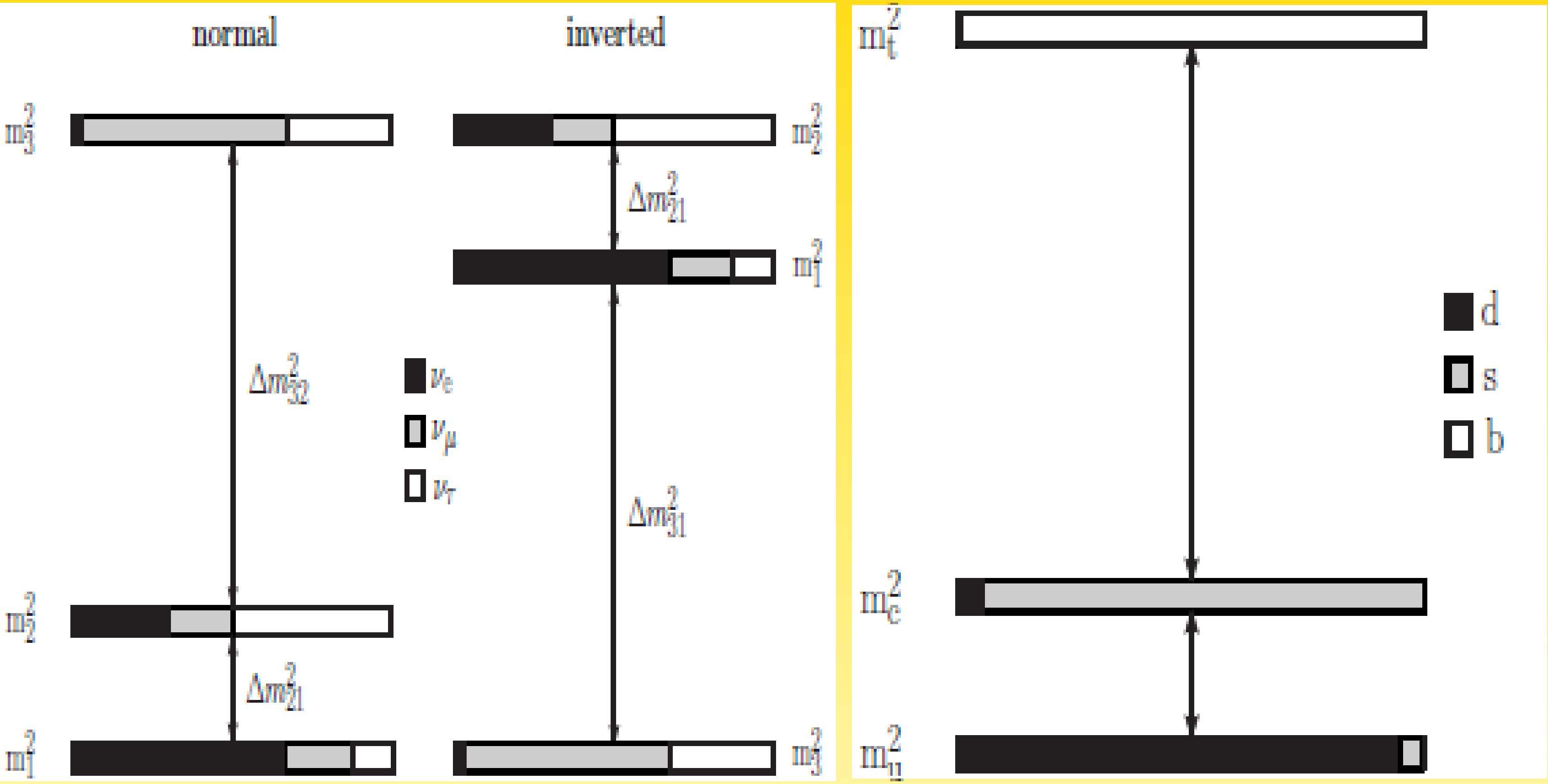
Neutrino mass

3 **complementary** methods to measure:

Method	Observable	curr. [eV]	near/far [eV]	pro	con
Kurie	$\sqrt{\sum \lvert U_{ei}\rvert^2 m_i^2}$	2.3	$0.2/0.1$	model-indep.; theo. clean	final?; weakest
Cosmo.	$\sum m_i$	0.7	$0.3/0.05$	best; NH/IH	systemat.; model-dep.
$0\nu\beta\beta$	$\lvert \sum U_{ei}^2 m_i \rvert$	0.3	$0.1/0.05$	fundament.; NH/IH	model-dep.; theo. dirty

$\begin{pmatrix} u \\ d \end{pmatrix}$ with $m_u \simeq m_d$ versus $\begin{pmatrix} \nu_e \\ e \end{pmatrix}$ with $m_\nu \simeq 10^{-6}\, m_e$

why so tiny?



Why so different? ↔ Flavor symmetries!