

Поиски Новой физики в эксперименте DANSS

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Сессия-конференция СЯФ ОФН РАН

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Motivation

There are several anomalies in neutrino sector:

- LSND and MiniBoone: appearance of $\tilde{\nu}_e$ in $\tilde{\nu}_\mu$ beam at short distances. Significance – 6σ for combined results. (*Phys.Rev.Lett.* 121, 221801 (2018)). Not confirmed by MicroBoone ([arXiv:2110.14054v2](https://arxiv.org/abs/2110.14054v2)) but not excluded.
- Neutrino4: disappearance of $\tilde{\nu}_e$ from reactor. Significance 2.7σ (*Jetp Lett.* 109, 213-221 (2019), *Phys. Rev. D* 104, 032003 (2021)).
- Reactor antineutrino anomaly (RAA): deficit in reactor $\tilde{\nu}_e$ fluxes 3σ (*Phys.Rev.C* 83 054615). Probably explained by Kurchatov Institute (KI) ([arXiv:2103.01684v1](https://arxiv.org/abs/2103.01684v1)), Daya Bay, RENO results.
- Galium anomaly (SAGE, GALEX): deficit of ν_e in calibration runs with radioactive sources (*Phys.Rev.C* 83 065504). Results from BEST (*PhysRevLett.*128.232501) confirm GA. Significance $> 5\sigma$

These are probably statistically strongest indications of physics BSM!

They should be carefully scrutinized!

Possible solutions

These results could be explained by existence of **sterile neutrino** with $\Delta m_{14}^2 = m_4^2 - m_1^2 \sim 1 \text{ eV}^2$ which is much larger than the Δm^2 of the known neutrinos.

Survival probability for ν_e ($\tilde{\nu}_e$) at very short distances in (3+1) model:

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

Another “exotic” explanation for GA and RAA is existence of **Large Extra Dimensions (LED)**. Usually considered a model with one extra dimension that is compactified on a circle with radius R_{ED} , which is much larger than the size of the other extra dimensions (if exist). Amplitude: $A_{ee} = \sum_{i=1,2,3} |U_{ei}|^2 A_i$, and

$$A_i = \left(1 - \frac{\pi^2}{6} m_i^2 R_{ED}^2 \right)^2 \exp \left(i \frac{m_i^2 L}{2E} \right) + 2m_i^2 \exp \left(i \frac{m_i^2 L}{E} \right) \sum_{n=1}^{\infty} \frac{\exp \left(i \frac{(m_n^{KK})^2 L}{2E} \right)}{(m_n^{KK})^2},$$

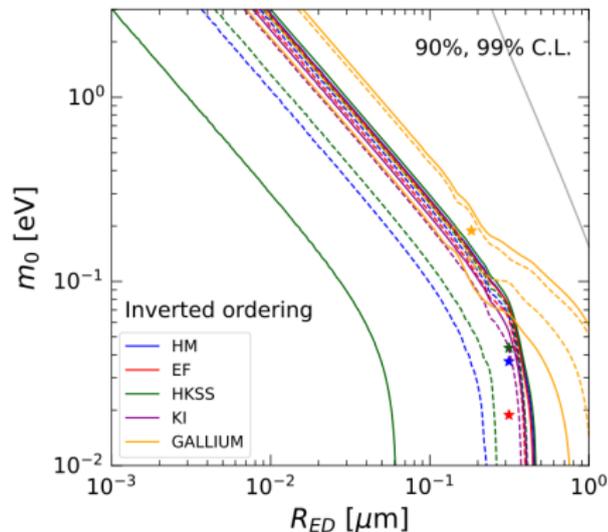
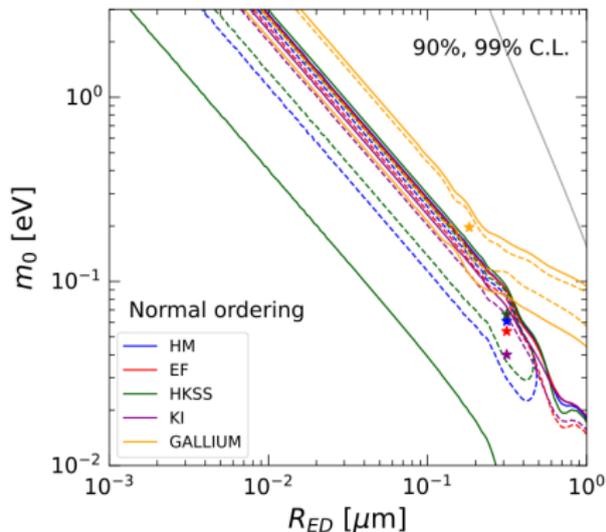
where m_i – mass of i-th neutrino state,

m_n^{KK} – mass of n-th Kaluza-Klein state ($m_n^{KK} = n/R_{ED}$),

R_{ED} – size of extra dimension

Large extra dimensions

LED can explain GA and RAA

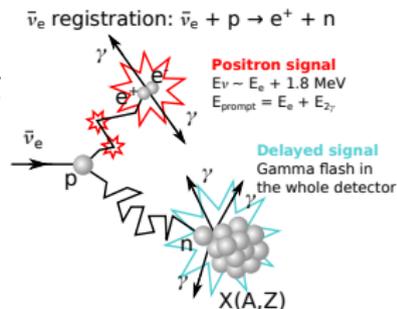
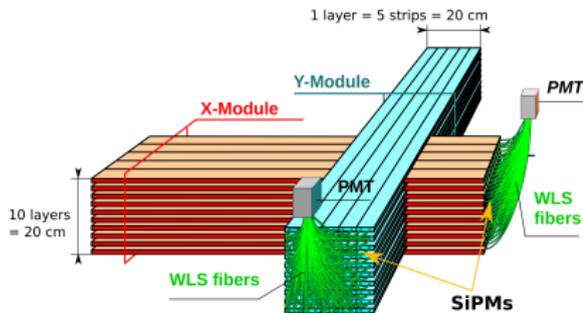
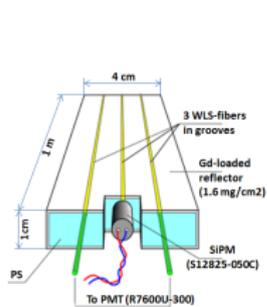
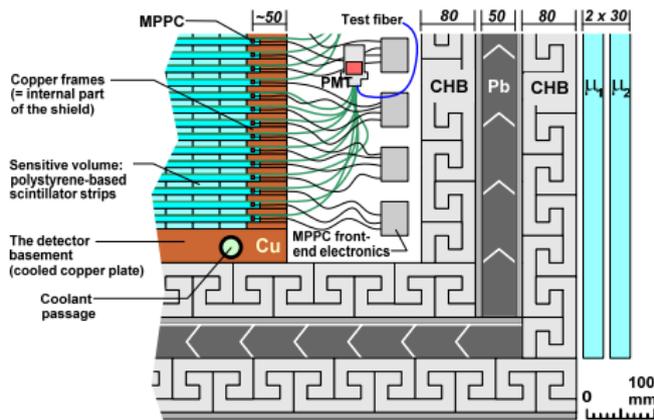


Preferred regions from [PhysRevD.106.035027](https://arxiv.org/abs/1006.03502)

R_{ED} – size of extra dimension,

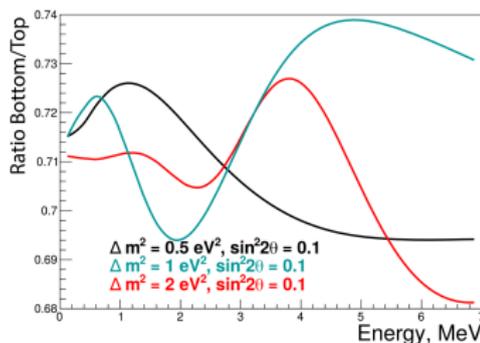
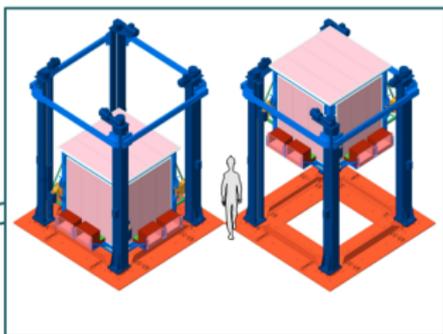
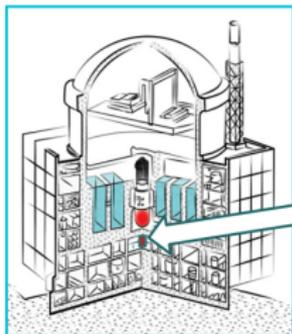
m_0 – mass of the lightest neutrino state

- Multilayer passive shielding: electrolytic copper frame 5 cm, borated polyethylene 8 cm, lead 5 cm, borated polyethylene 8 cm
- 2-layer active μ -veto on 5 sides
- 2500 scintillator strips with Gd containing coating for neutron capture
- Light collection with 3 WLS fibers
- Central fiber read out with individual SiPM
- Side fibers from 50 strips make a bunch of 100 on a PMT cathode = Module



Due to high granularity we can measure positron kinetic energy (without annihilation γ)

Detector site and data taking strategy

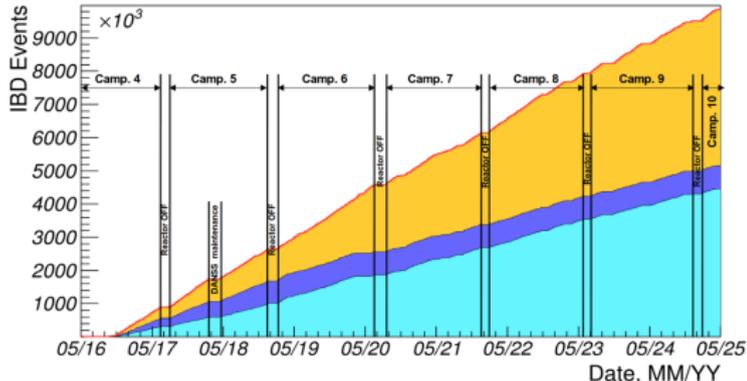
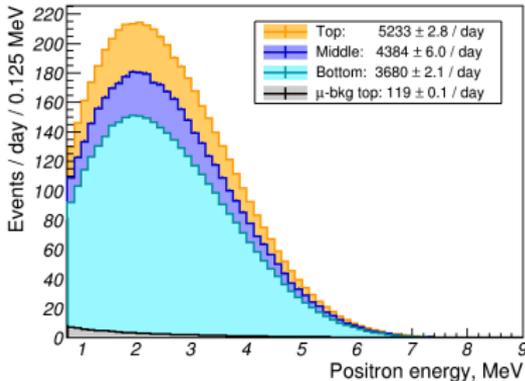


DANSS: Measure ratio of neutrino spectra at different distance from the reactor core — both spectra are measured in the same experiment with the same detector. No dependence on the theory, absolute detector efficiency or other experiments.

Survival probability of a reactor $\tilde{\nu}_e$ at short distances in the (3+1) mixing scenario:

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

Positron spectrum



- 3 detector positions
- Pure positron kinetic energy (annihilation photons not included)
- ~ 5000 neutrino events/day in detector fiducial volume of 78% ('Top' position closest to the reactor)
- μ - induced neutron background not rejected by VETO system is 1.8% only, S/B > 50!
- All backgrounds are subtracted
- About 10 mln neutrino events collected [0.75 – 8 MeV]

Oscillation analysis: test statistics (relative counting rates)

For different points in parameter space Θ predicted e^+ spectra are calculated for each (*Top*, *Middle*, *Bottom*) detector position.

$\Theta = \{\Delta m_{41}^2, \sin^2 2\theta_{ee}\}$ for sterile neutrino,

$\Theta = \{m_0, R_{ED}\}$ for LED

Observed (R^{obs}) and predicted (R^{pre}) e^+ **spectra ratios** (per day normalization) are compared using test statistics:

$$\chi_{rel}^2 = \min_{\eta} \sum_{bins} \frac{(R_{bt}^{obs} - R_{bt}^{pre}(\Theta, \eta))^2}{\sigma^2} + \sum_{bins} (R_{bt}^{obs} - R_{bt}^{pre}) (R_{mbt}^{obs} - R_{mbt}^{pre}) \cdot W^{-1} \cdot \begin{pmatrix} R_{bt}^{obs} - R_{bt}^{pre} \\ R_{mbt}^{obs} - R_{mbt}^{pre} \end{pmatrix} + \sum_{syst} \frac{(\eta - \eta^0)^2}{\sigma_{\eta}^2}$$

Data taking in two positions

$R_{bt} = Bottom/Top$,

Data taking in three positions

$R_{mbt} = Middle/\sqrt{Bottom \cdot Top}$,

W - covariance matrix,

Penalty terms

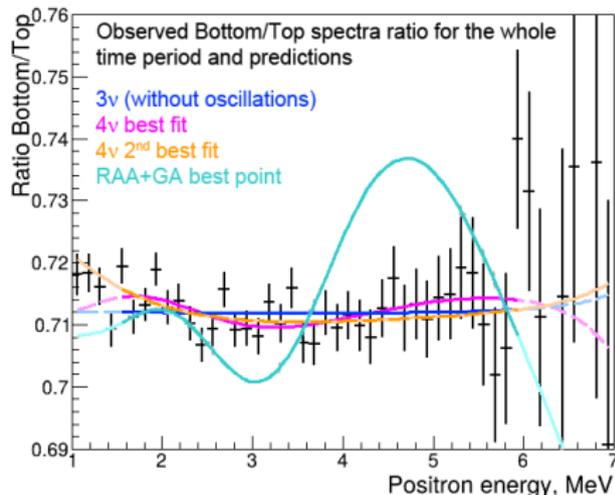
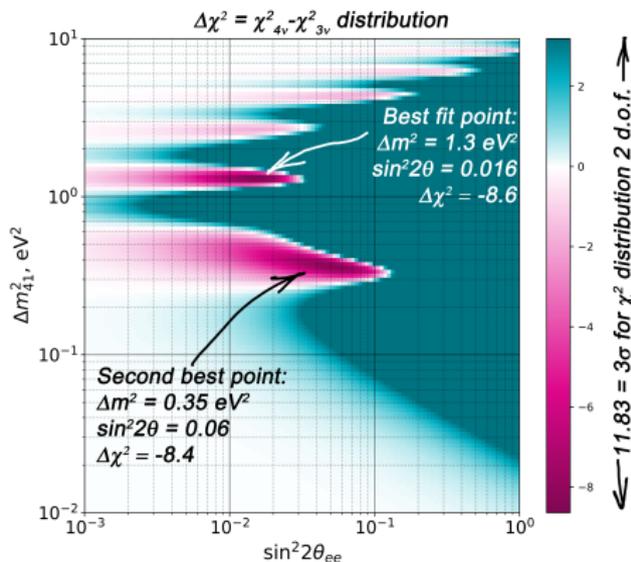
$\eta(\eta^0)$ - nuisance parameters (and their nominal values)

Systematic uncertainties are treated as nuisance parameters

During the fit each absolute (*Top*, *Middle*, *Bottom*) spectrum $S(E, \eta)$ was approximated using first-order Taylor expansion: $S(E, \eta) = S(E, \eta^0) + \sum_i \partial S / \partial \eta_i \cdot d\eta_i$

Sterile neutrino searches

Difference in χ^2 between 4ν and 3ν hypotheses.



Using current statistics 2016-2025 (~ 7.2 million IBD events) we see **no statistically significant evidence of 4ν signal**. Best points:

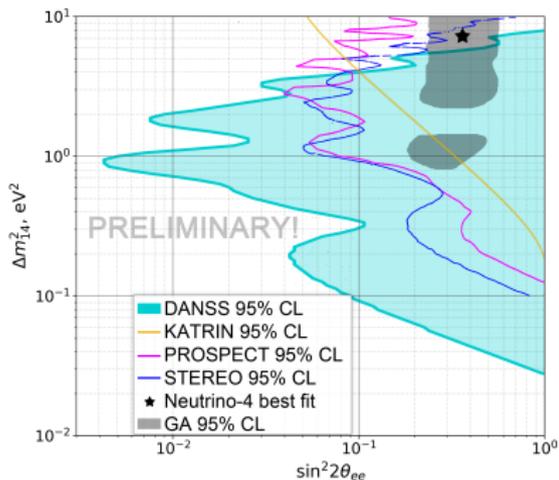
$$\Delta m_{41}^2 = 1.3 \text{ eV}^2, \sin^2 2\theta_{ee} = 0.016, \chi_{4\nu}^2 - \chi_{3\nu}^2 = -8.6 (\sim 2.5\sigma)$$

$$\Delta m_{41}^2 = 0.35 \text{ eV}^2, \sin^2 2\theta_{ee} = 0.06, \chi_{4\nu}^2 - \chi_{3\nu}^2 = -8.4$$

RAA and GA best point has been excluded with much more than 5σ .

Sterile neutrino searches

95% C.L. exclusion calculated using Gaussian CL_s method.



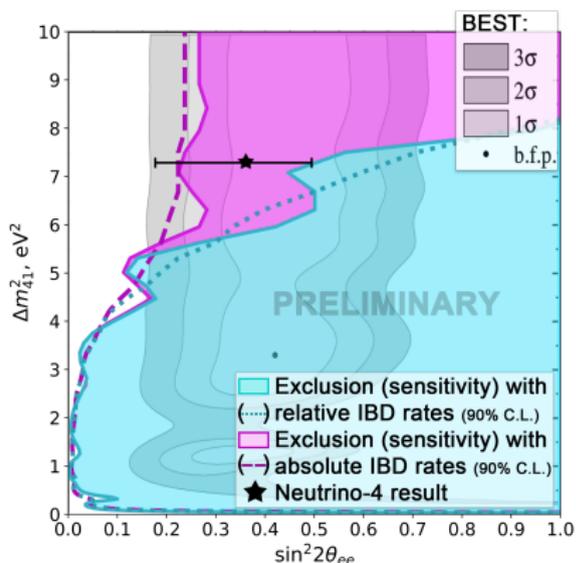
1σ values used in the penalty terms
(changes with respect to nominal values):

- relative detector efficiencies at different distances (0.4%)
- distance to the fuel burning profile center (5 cm)
- correlated backgrounds (35%)
- additional smearing in energy resolution ($6\%/\sqrt{E} \oplus 2\%$)
- energy scale (2%)
- energy shift (50 keV)

DANSS analysis without absolute counting rates **excludes a large and the most interesting fraction of sterile neutrino parameter space** using only ratio of e^+ spectra at 3 distances (7.2 mln IBD events in 1.5–7 MeV positron energy range).

Search for sterile neutrinos using absolute counting rates

Test statistics with absolute counting rates: $\chi_{abs}^2 = \chi_{rel}^2 + ((N_{top} + N_{mid} + N_{bottom})^{obs} - (N_{top} + k_2 \cdot \sqrt{k_1} \cdot N_{mid} + k_1 \cdot N_{bottom})^{pre})^2 / \sigma_{abs}^2$
 σ_{abs} – total systematic uncertainty (7% in absolute rates). HM model used for predictions.



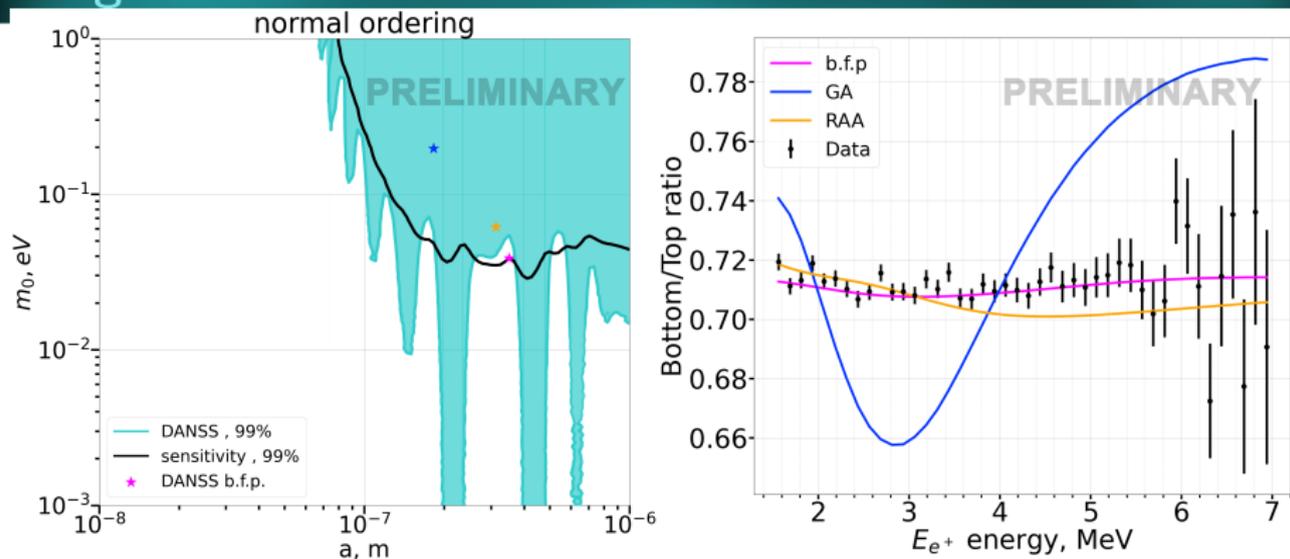
A large and the most interesting fraction of available parameter space for sterile neutrino was excluded with model-independent analysis.

Exclusions based on absolute counting rates for large Δm_{41}^2 support previous results (Daya Bay, Bugey-3, ...)

Our preliminary results exclude the dominant fraction of BEST expectations as well as best fit point of Neutrino-4 experiment. In KI model exclusions are even more strict.

These results depend on the predictions of the $\bar{\nu}_e$ flux from reactors, for which we assumed a conservative uncertainty of 5%.

Large Extra Dimensions searches

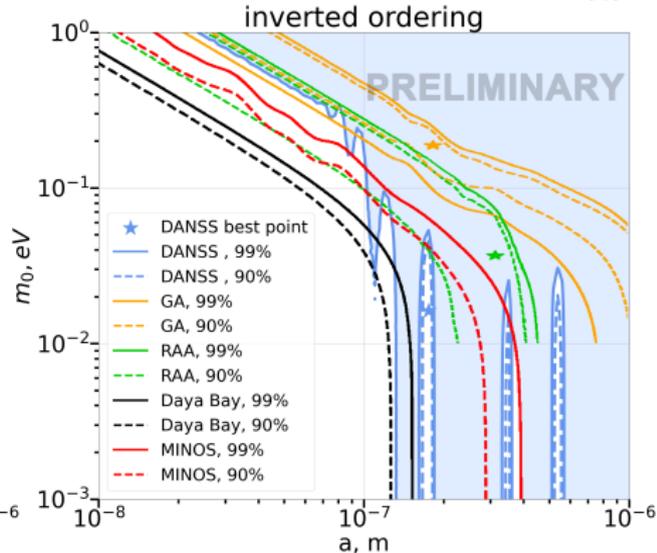
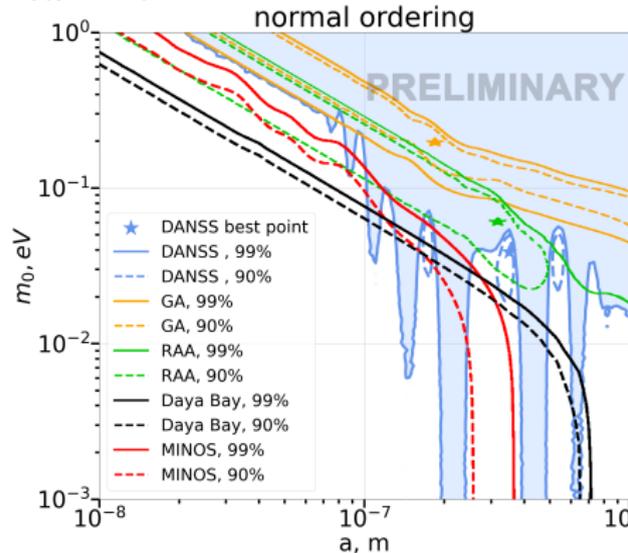


- Exclusion and sensitivity areas are calculated using test statistics $\Delta\chi^2 = \chi^2 - \chi_{min}^2$ (assuming Wilks' theorem), $\Delta\chi^2 = 4.61(9.21)$ corresponds to 90% (99%) C.L.
- Data collected at Top and Bottom detector positions are included into analysis (6.7 mln IBD events).
- Exclusions are based only on spectra ratio information

Large Extra Dimensions searches

Test statistics with absolute counting rates:

$$\chi_{abs}^2 = \chi_{rel}^2 + ((N_{top} + N_{mid} + N_{bottom})^{obs} - (N_{top} + k_2 \cdot \sqrt{k_1} \cdot N_{mid} + k_1 \cdot N_{bottom})^{pre})^2 / \sigma_{abs}^2$$



- DANSS best-fit point significance is 2.5 (2.4) σ only for NO (IO)
- DANSS data exclude RAA and GA at at $> 5\sigma$ CL.
- For NO DANSS exclusions are the most stringent for some R_{ED} values
- For IO DANSS exclusions are consistent with other experiments

Summary

- DANSS records about 5 thousand antineutrino events per day with cosmic background $\sim 1.8\%$, $S/B > 50$; ~ 10 million IBD events were collected in 9 years.
- We see **no significant evidence** in favor of exotic physics
- Preliminary DANSS analysis without absolute counting rates **excludes a large and the most interesting fraction of available parameter space for sterile neutrino** using only ratio of e^+ spectra at 3 distances (**with no dependence on $\tilde{\nu}_e$ spectrum and detector absolute efficiency!**)
- A significant fraction of LED parameter space preferred by GA and RAA is excluded by DANSS using Bottom/Top ratio of e^+ spectra **DANSS exclusions are the most stringent for some R_{ED}** . RAA and GA best fit points are excluded $> 5\sigma$ and C.L.
- Oscillation analysis with absolute counting rates (HM model) allows to improve sensitivity significantly and **excludes practically all sterile parameter space preferred by GA**. These results depend on the predictions of the $\tilde{\nu}_e$ flux from reactors, for which we assumed a conservative uncertainty of 5%.
- DANSS upgrade plans will be presented by **D. Svirida 10 March 2026**

Thank you!

Absolute IBD counting rates

$$\frac{dN(t)}{dt} = N_p \cdot \int_{E_{min}}^{E_{max}} \varepsilon \frac{1}{4\pi L^2} \sigma(E_\nu) \frac{d^2\phi(E_\nu, t)}{dEdt} \cdot P(L, E_\nu) dE$$

$$\frac{d^2\phi(E, t)}{dEdt} = \frac{W_{th}}{\langle E_{fis} \rangle} \sum f_i \cdot s_i(E)$$

$$\langle E_{fis} \rangle = \sum E_i \cdot f_i$$

N_p – the number of target protons,

ε – detector efficiency,

L – the distance between the centers of the detector and the reactor core
(distribution of fission points, reactor and detector sizes are taken into account)

$\sigma(E_\nu)$ – the IBD reaction cross section,

W_{th} – reactor thermal power (data from KNPP),

E_{fis} – energy released per fission (Phys. Rev. C 88, 014605),

f_i – fission fraction

s_i – $\tilde{\nu}_e$ energy spectrum per fission (Huber + Mueller and Kurchatov Institute models are considered),

$P(L, E_\nu)$ is the survival probability due to neutrino oscillations

Systematic uncertainties in absolute $\bar{\nu}_e$ counting rates

Source	Rate uncertainty
Number of protons	2%
Selection criteria	2%
Geometry (distance + fission points distribution)	1%
Fission fractions (from KNPP)	2%
Average energy per fission (Phys. Rev. C 88, 014605)	0.3%
Reactor power (from KNPP)	1.5%
Backgrounds	0.5%
Total	4%
Flux predictions	2-5%
Total with fluxes	5-7%

The values of uncertainties are our estimates of the 1σ deviations and are given in percent according to their contributions to the absolute $\bar{\nu}_e$ counting rate. We hope to reduce experimental uncertainties in future. However, flux prediction uncertainty dominates.

Oscillation analysis: test statistics with absolute IBD rates

Test statistics is defined as follows:

$$\chi_{rel}^2 = \min_{\eta, k} \sum_{i=1}^{N_{bins}} (Z_{1i} \quad Z_{2i}) \cdot W^{-1} \cdot \begin{pmatrix} Z_{1i} \\ Z_{2i} \end{pmatrix} + \sum_{i=1}^{N_{bins}} \frac{Z_{1i}^2}{\sigma_{1i}^2} + \sum_{j=1,2} \frac{(k_j - k_j^0)^2}{\sigma_{k_j}^2} + \sum_l \frac{(\eta_l - \eta_l^0)^2}{\sigma_{\eta_l}^2}$$

phase I

Top, Middle, Bottom

phase II

Top, Bottom

penalty

terms

i – energy bin (36 total) in range 1.5–6 MeV,

$Z_j = R_j^{\text{obs}} - k_j \times R_j^{\text{pre}}(\Delta m^2, \sin^2 2\theta, \eta)$ for each energy bin, (obs for observed, pre for predicted),

$R_1 = \text{Bottom}/\text{Top}$, $R_2 = \text{Middle}/\sqrt{\text{Bottom} \cdot \text{Top}}$, where

Top , Middle , Bottom – absolute count rates per day for each detector position,

k – relative efficiency (nominal values $k_1^0 = k_2^0 = 1$),

$\eta(\eta^0)$ – other nuisance parameters (and their nominal values),

W – covariance matrix to take into account correlations in spectra ratios at different positions

(Z_1 and Z_2),

N – total absolute rates.

With absolute counting rates:

$$\chi_{abs}^2 = \chi_{rel}^2 + ((N_{top} + N_{mid} + N_{bottom})^{\text{obs}} - (N_{top} + k_2 \cdot \sqrt{k_1} \cdot N_{mid} + k_1 \cdot N_{bottom})^{\text{pre}})^2 / \sigma_{abs}^2$$

σ_{abs} – systematic uncertainty (7% in absolute rates)

Large extra dimensions

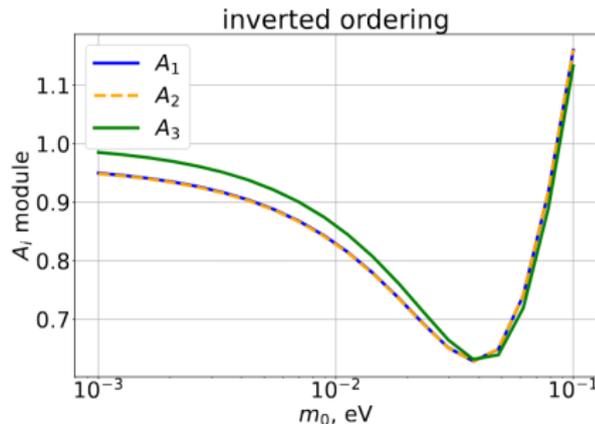
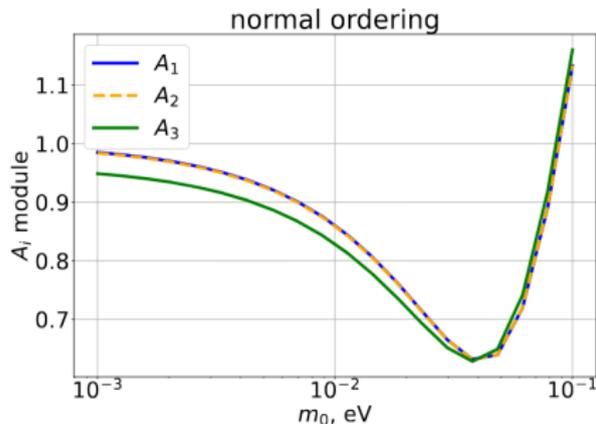
$$M_{Pl} \sim 10^{18} \text{ GeV}, M_W \sim 80 \text{ GeV}$$

$$V(r) \sim \frac{m_1 m_2}{M_{Pl(4+n)}^{n+2}} \frac{1}{r^{n+1}}, r \ll a.$$

$$V(r) \sim \frac{m_1 m_2}{M_{Pl(4+n)}^{n+2}} \frac{1}{a^n r}, r \gg a.$$

$$\text{Renorm. of Planck Mass: } M_{Pl}^2 \sim M_{Pl(4+n)}^{2+n} a^n$$

Large extra dimensions



$$P(\alpha\alpha; L, E) = |A_{\alpha\alpha}(L, E)|^2, \quad A_{ee} = \sum_{i=1,2,3} |U_{ei}|^2 A_i,$$

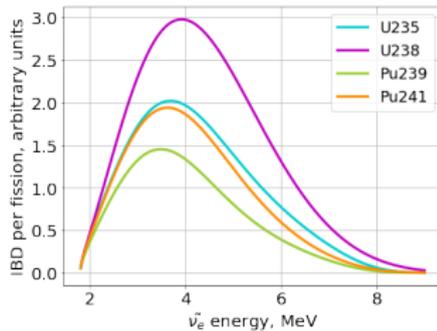
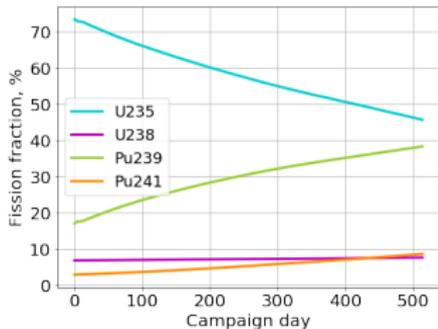
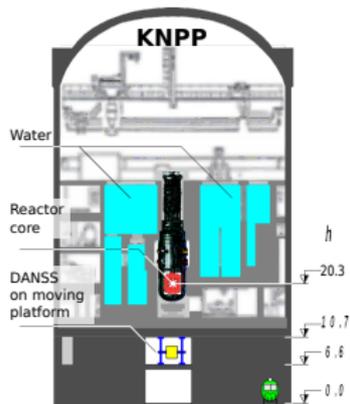
$$A_i = \left(1 - \frac{\pi^2}{6} m_i^2 a^2\right)^2 \exp\left(i \frac{m_i^2 L}{2E}\right) + 2m_i^2 \exp\left(i \frac{m_i^2 L}{E}\right) \sum_{n=1}^{\infty} \frac{\exp\left(i \frac{(m_n^{KK})^2 L}{2E}\right)}{(m_n^{KK})^2}$$

$$|U_{e1}| \sim 0.8, |U_{e2}| \sim 0.5, |U_{e3}| \sim 0.1$$

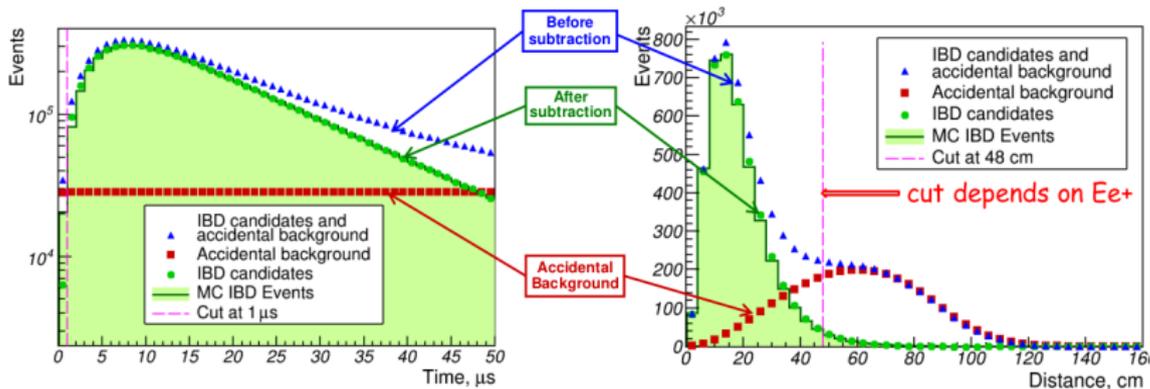
Detector site

Kalinin Nuclear Power Plant (KNPP):

- Commercial 3.1 GW_{th} reactor → high intensity flux ($5 \cdot 10^{13} \tilde{\nu}_e \text{ cm}^{-2} \text{ s}^{-1}$) at detector site
- Fuel: ^{235}U , ^{238}U , ^{239}Pu , ^{241}Pu (other components < 0.1%). Fission fractions change during campaign
- Lifting system allows to change the distance between the centers of the detector and of the reactor core from 10.9 to 12.9 m on-line
- Reactor fuel and body with cooling pond and other reservoirs provide overburden ~ 50 m w.e. for cosmic background suppression

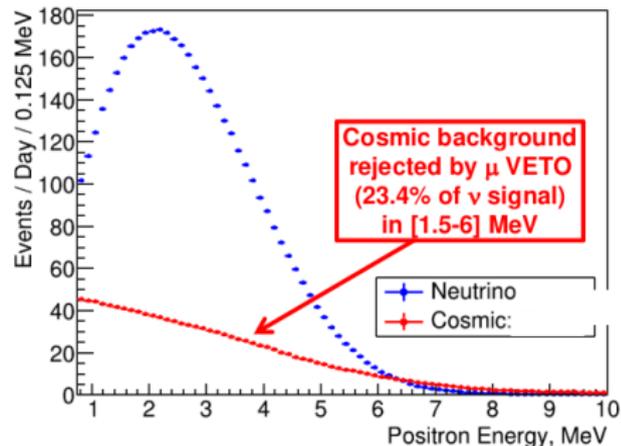
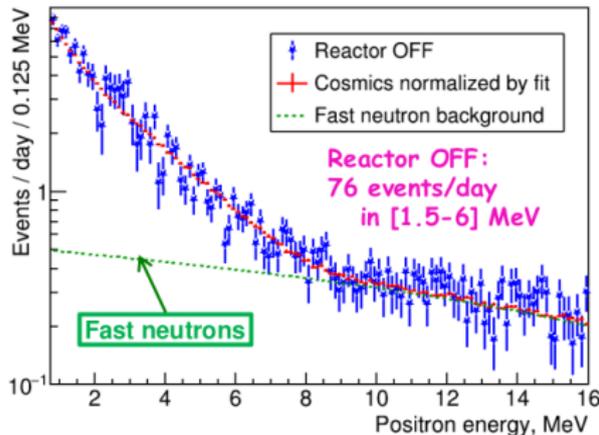


Accidental coincidence background



- Accidental coincidence of 2 uncorrelated signals (e^+ -like and neutron-like) in a IBD window $[1-50] \mu\text{s} \rightarrow$ accidental coincidence background
- Background estimate from data: search for a positron candidate where it can not be present – $[1-50] \mu\text{s}$ intervals far away from neutron candidate (5, 10, 15 etc millisecc)
- Enlarge statistics for accidentals by searches in numerous non-overlapping intervals
- Accidental background is subtracted without systematic errors, but it increases statistical errors
- Apply cuts to reduce accidental background contribution \Rightarrow smaller statistical errors
- Cuts for the accidental coincidence exactly the same as for physics events
- Accidental rate is 15.3% of IBD rate (up detector position)

Correlated background from “Reactor Off” data



- 25 $\bar{\nu}_e$ events/day from neighbor reactors were subtracted
- Fast neutrons: linearly extrapolate from high energy region and subtract separately from positron and visible cosmic spectra = 16 events/day (in 1.5-6 MeV range).
- Visible cosmic background has been directly rejected by VETO, it is 23.4% of neutrino signal (for top position in [1.5-6 MeV] range)
- VETO inefficiency – 5% from “Reactor Off” spectra.
- Not vetoed cosmic background fraction is $\sim 1\%$ of neutrino signal (41 events/day).
- Additional 19 events/day at low energies observed in reactor off data were subtracted.
- Total background subtracted background is 1.8% for the top detector position. $S/B > 50!$

Analysis for 3 detector positions

Most of the data were accumulated at 3 detector positions. We can include middle position into analysis, **taking into account correlations in spectra ratios**.

Let us denote T, B, M as absolute counts (predicted or observed) for each detector position ("Top, Bottom, Middle"). Consider vector \mathbf{r} : $\mathbf{r} = (Z_1 \ Z_2)^T$, where $Z_i = Z_i^{obs} - Z_i^{pre}$, and $Z_1 = B/T, Z_2 = M/\sqrt{B \cdot T}$.

For every energy bin

$$\chi^2 = \mathbf{r} \cdot \mathbf{W}^{-1} \cdot \mathbf{r}^T$$

\mathbf{W} – covariance matrix, and Σ – error matrix: $\mathbf{W} = \mathbf{A} \cdot \Sigma \cdot \mathbf{A}^T$, where

$$\mathbf{A} = \begin{pmatrix} \frac{\partial Z_1}{\partial T} & \frac{\partial Z_1}{\partial M} & \frac{\partial Z_1}{\partial B} \\ \frac{\partial Z_2}{\partial T} & \frac{\partial Z_2}{\partial M} & \frac{\partial Z_2}{\partial B} \end{pmatrix}, \Sigma = \begin{pmatrix} \sigma_T^2 & 0 & 0 \\ 0 & \sigma_M^2 & 0 \\ 0 & 0 & \sigma_B^2 \end{pmatrix}, \text{ then}$$

$$\mathbf{W} = \begin{pmatrix} \frac{B^2}{T^2} \left(\left(\frac{\sigma_T}{T} \right)^2 + \left(\frac{\sigma_B}{B} \right)^2 \right) & \frac{M \cdot B}{2T\sqrt{T \cdot B}} \left(\left(\frac{\sigma_T}{T} \right)^2 - \left(\frac{\sigma_B}{B} \right)^2 \right) \\ \frac{M \cdot B}{2T\sqrt{T \cdot B}} \left(\left(\frac{\sigma_T}{T} \right)^2 - \left(\frac{\sigma_B}{B} \right)^2 \right) & \frac{M^2}{T \cdot B} \left(\left(\frac{\sigma_T}{2T} \right)^2 + \left(\frac{\sigma_M}{M} \right)^2 + \left(\frac{\sigma_B}{2B} \right)^2 \right) \end{pmatrix}$$

DB exclusions

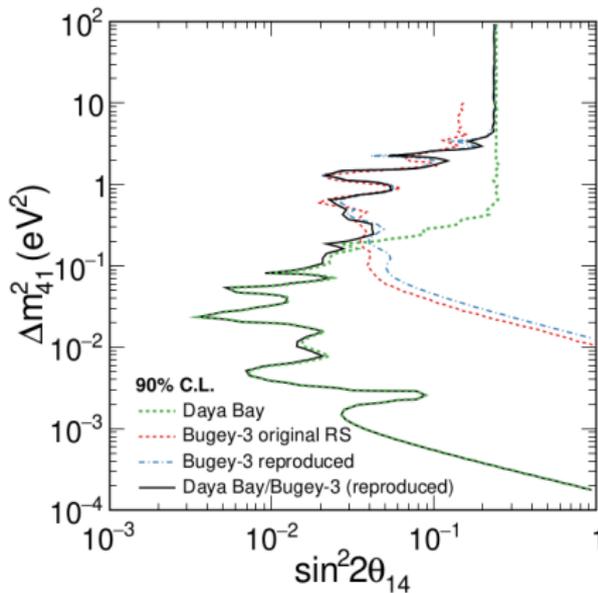


FIG. 2. Excluded regions for the original Bugey-3 raster scan (RS) result [14], for the reproduced Bugey-3 with adjusted fluxes, for the Daya Bay result [12], and for the combined Daya Bay and reproduced Bugey-3 results. The region to the right of the curve is excluded at the 90% C.L.

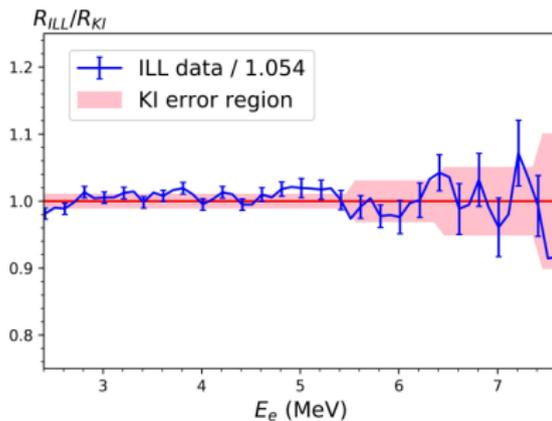
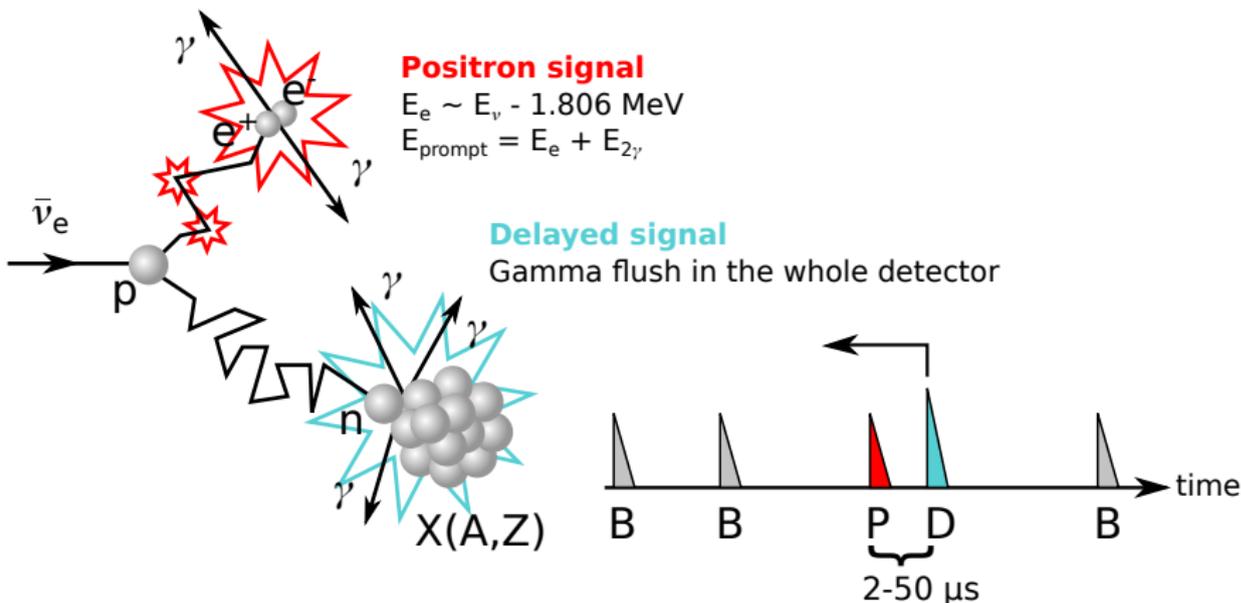
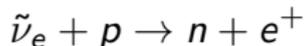


FIG. 2. Ratios R between cumulative β spectra from ^{235}U and ^{239}Pu , normalized to the KI data. Plotted ILL quantities were divided by 1.054, as explained in the text. The colored region shows KI uncertainties.

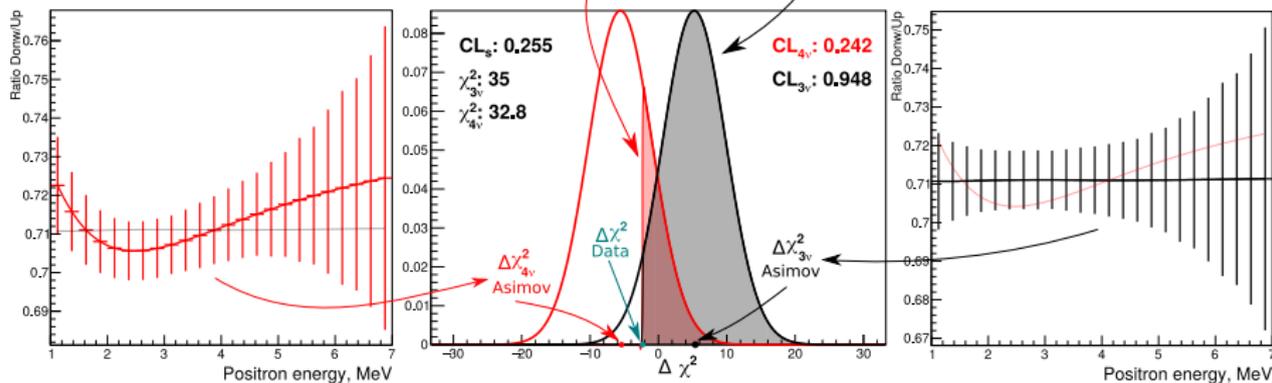
Antineutrino registration

Inverse Beta-Decay (IBD) reaction:



Due to high granularity we can measure positron kinetic energy (without γ)

- $\Delta\chi^2 = \chi_{4\nu}^2 - \chi_{3\nu}^2$ has Gaussian(μ, σ) distribution
- Parameters (μ, σ) determined from Asimov data set:
 $\mu = \Delta\chi^2 = \chi_{4\nu}^2 - \chi_{3\nu}^2$, $\sigma = 2\sqrt{|\Delta\chi^2|}$;
 Asimovo data set ($3\nu/4\nu$) $\rightarrow \mu_{3\nu/4\nu}, \sigma_{3\nu/4\nu}$
- Calculate $\Delta\chi_{data}^2$
- $CL_s = \frac{CL_{4\nu}}{CL_{3\nu}}$, where $CL_{4\nu} = \int_{\Delta\chi_{data}^2}^{\infty} G_{4\nu}$, and $CL_{3\nu} = \int_{\Delta\chi_{data}^2}^{\infty} G_{3\nu}$



4ν excluded at 90(95)% confidence level $CL_s < 0.1(0.05)$