New results from the DANSS experiment

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for the DANSS collaboration

Motivation

There are several indications in favor of existence of the 4th neutrino type — "sterile" neutrino.

- 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) 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), 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 results could be explained by existence of sterile neutrino with $\Delta m^2_{14} = m^2_4 - m^2_1 \sim 1$ eV^2 which is much larger than the Δm^2 of the known neutrinos.

Sterile neutrinos would mean the New Physics beyond the Standard Model!

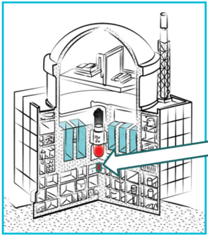
These are probably statistically strongest indications of physics BSM!

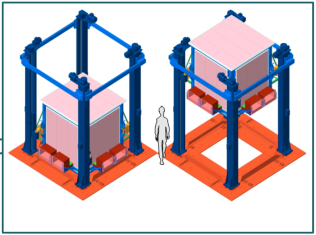
Detector DANSS

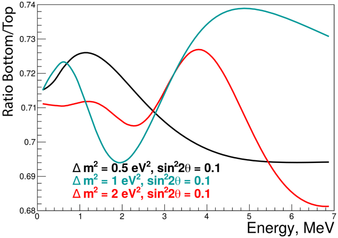
Survival probability of a reactor $\tilde{\nu_e}$ at short distances in the (3+1) mixing scenario:

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

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.



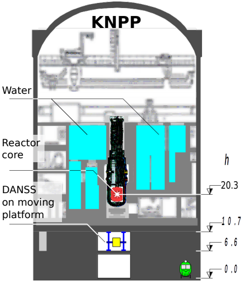


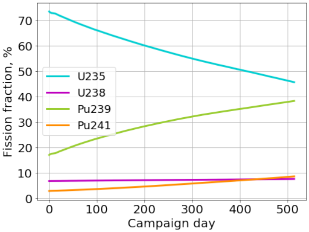


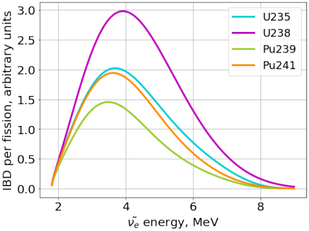
Detector site

Kalinin Nuclear Power Plant (KNPP):

- Commercial 3.1 GW_{th} reactor $\rightarrow$ high intensity flux ($5 \cdot 10^{13} \tilde{\nu}_e$ cm^{-2} 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 $\sim$50 m w.e. for cosmic background suppression

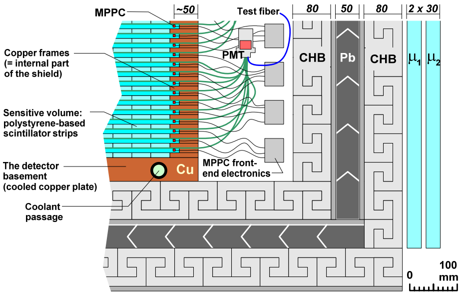


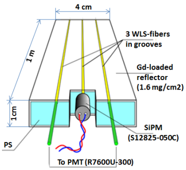


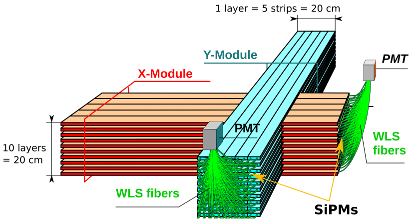


DANSS design [JINST 11 (2016) no.11, P11011]

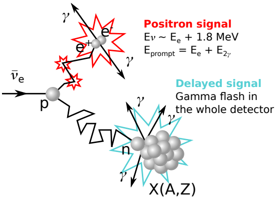
- Multilayer passive shielding: electrolytic copper frame 5 cm, borated polyethylene 8 cm, lead 5 cm, borated polyethylene 8 cm
- 2-layer active μ-veto on 5 sides
- 2500 scintillator strips with Gd containing coating for neutron capture
- Light collection with 3 WLS fibers
- Central fiber read out with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





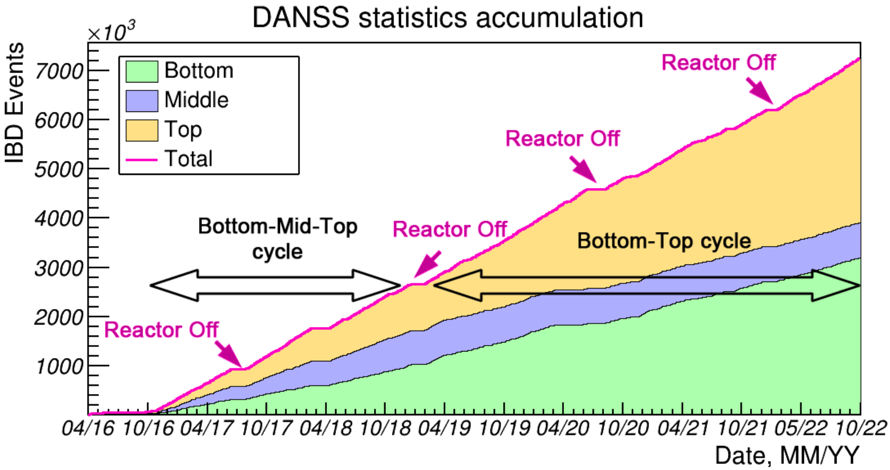


$\bar{\nu}_e$ registration: $\bar{\nu}_e + p \rightarrow e^+ + n$



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

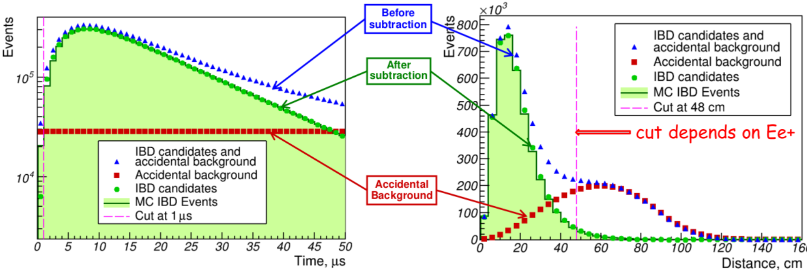
Statistics accumulation



More than 7 mln neutrino events collected.

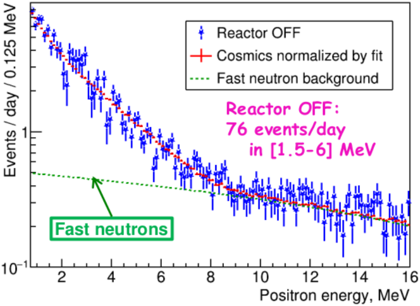
5 mln events are used in sterile neutrino oscillation fits.

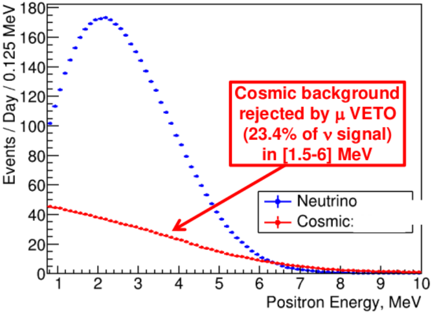
Accidental coincidence background



- Accidental coincidence of 2 uncorrelated signals (e^+-like and neutron-like) in a IBD window [1-50] μs $\rightarrow$ accidental coincidence background
- Background estimate from data: search for a positron candidate where it can not be present – [1-50] μs intervals far away from neutron candidate (5, 10, 15 etc millisec)
- 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

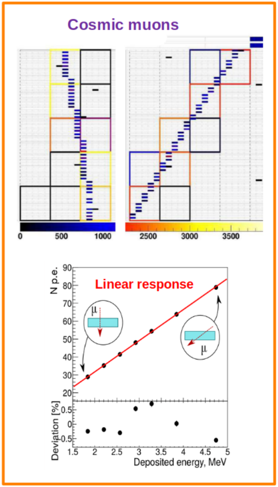


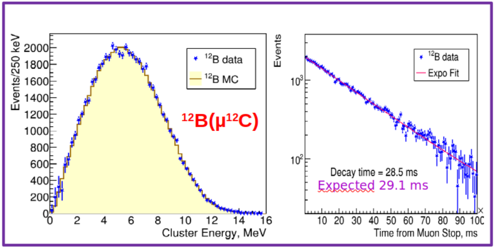


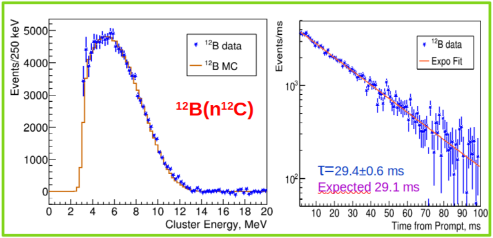
- 25 $\tilde{\nu}_e$ events/day from neighbor reactors were subtracted
- Fast neutrons: linearly extrapolate from high energy region and subtract separately from positron and visible cosmic spectra = 16 events/day (in 1.5-6 MeV range).
- Visible cosmic background has been directly rejected by VETO, it 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!

Calibration I

- 2500 SiPM gains and X-talks are calibrated every 30-40 min.
- All 2550 channels are calibrated every 2 days using cosmic muons
- Energy scale has been fixed using β-spectrum of ^{12}B, which is similar to positron signal

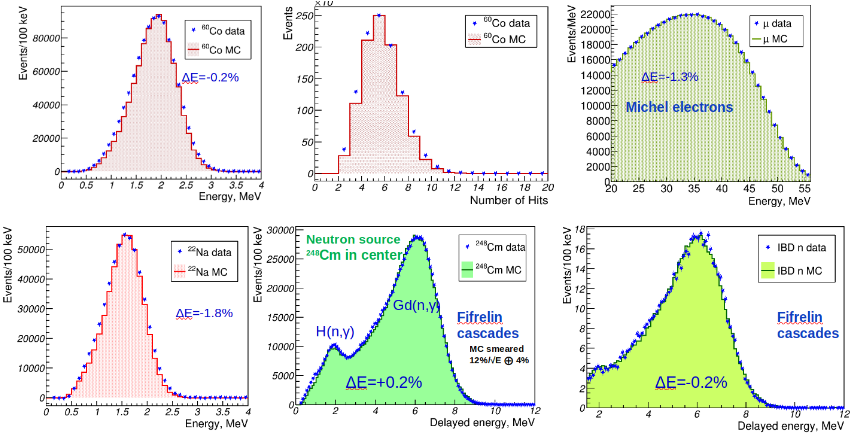




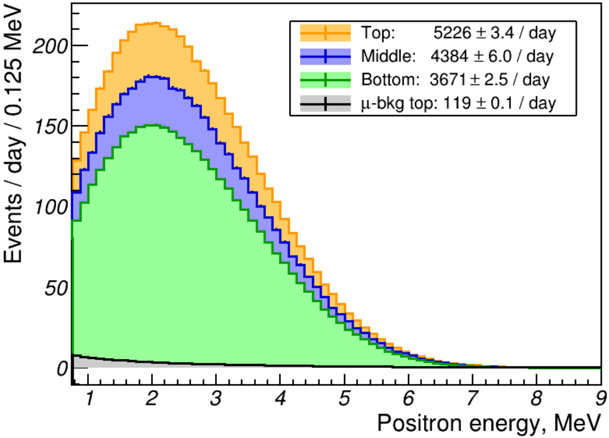


Calibration II

- Other sources agree within ± 0.2% with exception of ^{22}Na which is 1.8% below.
- Systematic error on E scale of ±2% was added due to ^{22}Na disagreement. Hope to reduce this error soon



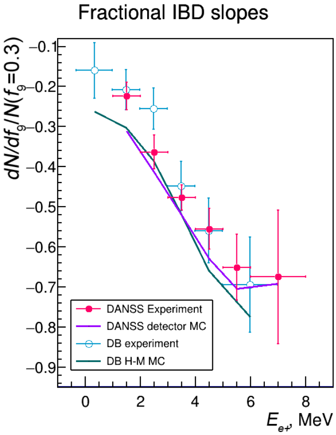
Positron spectrum

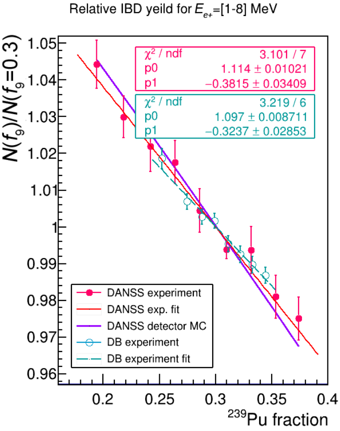


- 3 detector positions
- Pure positron kinetic energy (annihilation photons not included)
- ∼ 5000 neutrino events/day in detector fiducial volume of 78% ('Top' position closest to the reactor)
- μ - induced neutron background not rejected by VETO system is 1.8% only, S/B > 50! (for [1.5 – 6 MeV], Top position)

Spectrum dependence on fuel composition

- Positron spectrum is split into several energy intervals
- The whole dataset is split into several intervals depending on ^{239}Pu fission fraction
- Slope at F239=0.3 (as Daya Bay) is used for normalization





IBD rate dependence on 239Pu fission fraction (dN/dF239)/N(F239=0.3) for various E_{e+} agrees with Huber and Mueller (HM) model and a bit more steep than at Daya Bay.

Measurements of σ_5/σ_9

$$N = \alpha \cdot (\sigma_8 f_8 + \sigma_1 f_1 + \sigma_5 f_5 + \sigma_9 f_9)$$

$$\frac{dN}{df_9} = \alpha \cdot \left(\sigma_8 \frac{df_8}{df_9} + \sigma_1 \frac{df_1}{df_9} + \sigma_5 \frac{df_5}{df_9} + \sigma_9 \right)$$

$$Sl = \left(\frac{dN}{df_9} \right) / N = \frac{\frac{\sigma_8}{\sigma_9}\frac{df_8}{df_9} + \frac{\sigma_1}{\sigma_9}\frac{df_1}{df_9} + \frac{\sigma_5}{\sigma_9}\frac{df_5}{df_9} + 1}{\frac{\sigma_8}{\sigma_9} f_8 + \frac{\sigma_1}{\sigma_9} f_1 + \frac{\sigma_5}{\sigma_9} f_5 + f_9}$$

$$\frac{\sigma_5}{\sigma_9} = - \frac{\frac{\sigma_8}{\sigma_9}(Sl \cdot f_8 - \frac{df_8}{df_9}) + \frac{\sigma_1}{\sigma_9}(Sl \cdot f_1 - \frac{df_1}{df_9}) + (Sl \cdot f_9 - 1)}{Sl \cdot f_5 - \frac{df_5}{df_9}}$$

(σ_8/σ_9 and σ_1/σ_9 are taken from HM)

DANSS result $\sigma_5/\sigma_9 = 1.53 \pm 0.09$ is larger than Day Bay (1.445 ± 0.097) and agrees with HM (1.53 ± 0.05) .

Use of DB-Slope in our formula gives: $\sigma_5/\sigma_9 = 1.459 \pm 0.052.$

$\Rightarrow$ difference between DANSS and DB is due to slope

Maybe it's premature to say that RAA is solved by new σ_5/σ_9?

Comparison of reactor power and IBD rate

- DANSS points after all corrections (all backgrounds including adjacent reactor fluxes (0.6%), fuel composition using HM model, etc.) and free overall normalization agree with reactor power measured with several methods.
- Reactor power is measured by the DANSS with neutrino flux with 1.5% accuracy in 2 days during 6 years.
- The stable performance of the DANSS detector allows us to perform an analysis using absolute neutrino counting rates.

Absolute IBD counting rates

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

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

$$< E_{fis} > = \sum E_i \cdot f_i$$

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

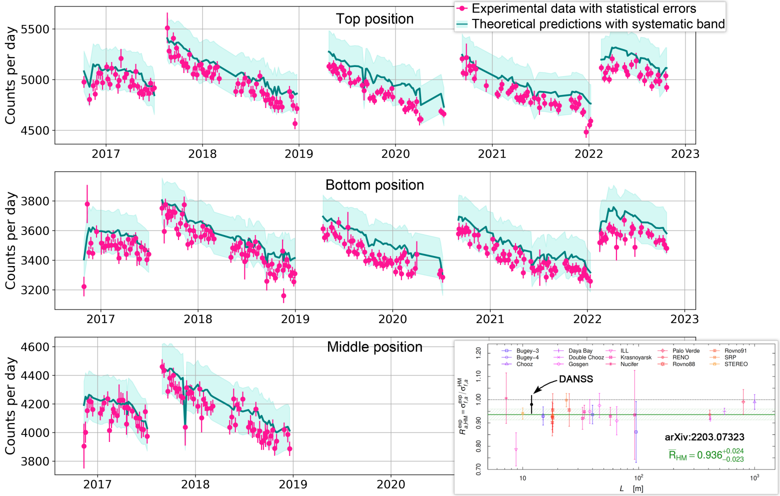
Systematic uncertainties in absolute $\tilde{\nu}_e$ counting rates

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 $\tilde{\nu}_e$ counting rate. We hope to reduce experimental uncertainties in future. However, flux prediction uncertainty dominates.

Comparison of the predicted and observed DANSS rates

Huber+Mueller predictions. Model uncertainties are not included!

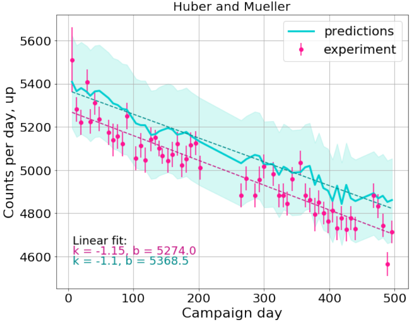


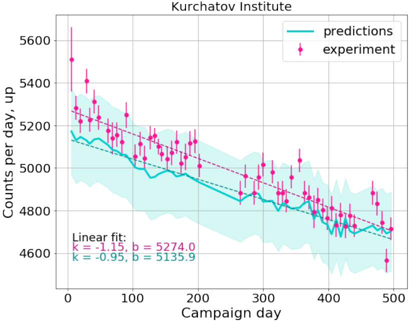
DANSS results are bellow HM predictions but within experimental uncertainties.

(average ratio: 0.98 ± 0.04)

Comparison with HM and KI models (example of campaign 5)

We estimate KI model predictions by reducing σ_5 and σ_8 by 5.4% in comparison with HM model





Model uncertainties are not included!

- Absolute counting rates are smaller than predictions in HM model but consistent within errors.
- Absolute counting rates are larger than predictions from KI model but consistent within errors.
- Uncertainties in flux predictions are large.

Oscillation analysis: test statistics

Test statistics is defined as follows:

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

phase I
Top, Middle, Bottom

phase II
Top, Bottom

penalty
terms

i – energy bin (36 total) in range 1.5–6 MeV,
$Z_j = R_j^{\mathrm{obs}} - k_j \times R_j^{\mathrm{pre}}(\Delta m^2,\ \sin^2 2\theta,\ \eta)$ for each energy bin, (obs for observed, pre for predicted),
$R_1 = Bottom/Top, R_2 = Middle/\sqrt{Bottom \cdot Top}$, 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.

Systematic uncertainties are treated as nuisance parameters

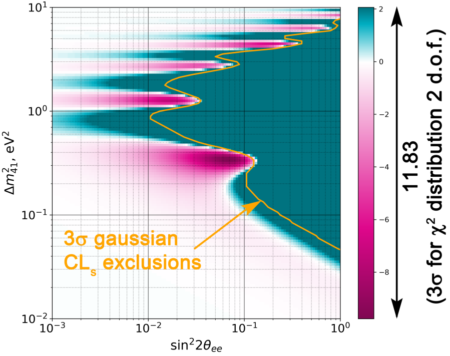
During the fit each absolute (*Top*, *Middle*, *Bottom*) spectrum $S(E,\eta)$ was approximated using first-order Taylor expansion:

$$S(E,\eta) = S(E,\eta^0) + \sum_l \frac{\partial S}{\partial \eta_l} d\eta_l$$

$\Delta\chi^2$ distribution

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

Magenta: $\chi^2_{4\nu} < \chi^2_{3\nu}$, cyan: $\chi^2_{4\nu} > \chi^2_{3\nu}$.

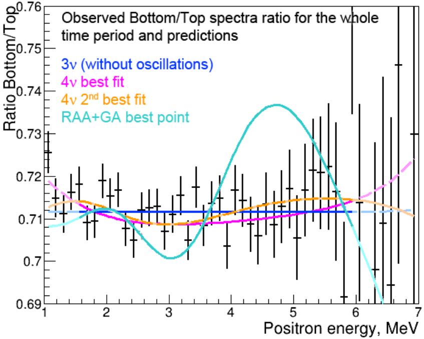


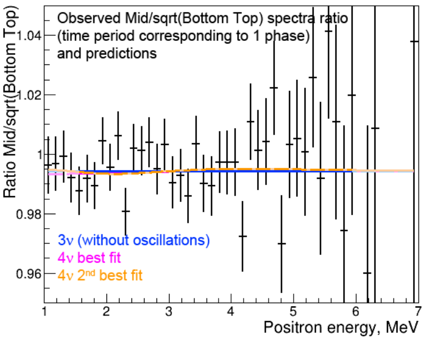
1σ values used in the penalty terms (changes with respect to nominal values):

- relative detector efficiencies at different distances (0.2%)
- distance to the fuel burning profile center (5 cm)
- cosmic background (25%)
- fast neutron background (30%)
- additional smearing in energy resolution (25%)
- energy scale (2%)
- energy shift (50 keV)

Dark cyan region is excluded at 3σ C.L. in case of χ^2 distribution with 2 d.o.f ($\chi^2_{4\nu} - \chi^2_{\text{min}} = 11.83$). This assumption is not valid $\rightarrow$ we use Gaussian CL_s method to get limits

$Bottom/Top$ and $Mid/\sqrt{Bottom \cdot Top}$ ratios





Using current statistics 2016-2022 (∼5 million IBD events) we see no statistically significant evidence of 4ν signal.

Best points:

$\Delta m^2_{41} = 0.34\text{eV}^2$, $\sin^2 2\theta_{ee} = 0.07$, $\chi^2_{4\nu} - \chi^2_{3\nu} = -9.8$ ($\sim 2.3\sigma$)

$\Delta m^2_{41} = 1.3\text{eV}^2$, $\sin^2 2\theta_{ee} = 0.018$, $\chi^2_{4\nu} - \chi^2_{3\nu} = -7.5$

RAA and GA best point has been excluded with $\Delta\chi^2 = \chi^2_{RAA+GA} - \chi^2_{\text{min}} = 155$ (much more than 5σ).

Oscillation analysis: test statistics with absolute IBD rates

Test statistics is defined as follows:

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

phase I	phase II	penalty
Top, Middle, Bottom	Top, Bottom	terms

i – energy bin (36 total) in range 1.5–6 MeV,
$Z_j = R_j^{\mathrm{obs}} - k_j \times R_j^{\mathrm{pre}}(\Delta m^2,\ \sin^2 2\theta,\ \eta)$ for each energy bin, (obs for observed, pre for predicted),
$R_1 = Bottom/Top, R_2 = Middle/\sqrt{Bottom \cdot Top}$, 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.

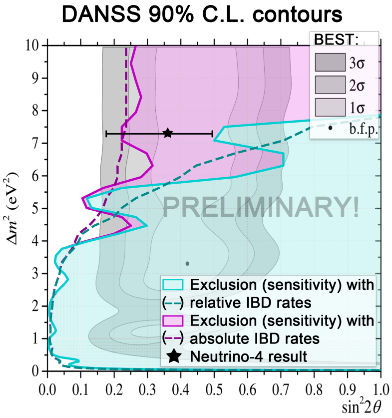
With absolute counting rates:

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

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

Oscillation analysis: preliminary results

DANSS 90% C.L. exclusion and sensitivity areas calculated with with Gaussian CL_s method (Nucl.Inst.Meth. A 827 63) and HM model using information about absolute $\tilde{\nu}_e$ counting rates



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

Absolute counting rates: all systematic uncertainties discussed earlier are included
flux uncertainty is 5%, total: 7%

Exclusions for large Δm^2_{41} are consistent with 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 more strict.

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

Summary

- DANSS records about 5 thousand antineutrino events per day with cosmic background $\sim$ 1.8%, S/B>50; 7 million IBD events were collected in 6 years.
- Absolute $\tilde{\nu}_e$ counting rates are smaller than predictions in HM model but consistent within errors (Ratio = 0.98±0.04).
- Absolute $\tilde{\nu}_e$ counting rates are larger than predictions from KI model but consistent within errors (Ratio = 1.015±0.04).
- The relative IBD σ dependence on the ^{239}Pu fission fraction is consistent with the HM model and it is slightly steeper than the Daya Bay results.
- The estimated ratio of $\sigma_5/\sigma_9 = 1.53 \pm 0.09$ is consistent with the HM model (1.53 ± 0.05) and it is slightly larger than the KI (1.45 ± 0.03) and Daya Bay (1.445 ± 0.097) results.
- Preliminary DANSS analysis without absolute counting rates based on 5 million IBD events 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!)
- Oscillation analysis with absolute counting rates (HM model) excludes practically all sterile parameter space preferred by BEST and the best fit point of Neutrino-4 experiment. These results depend on the predictions of the $\tilde{\nu}_e$ flux from reactors, for which we assumed a conservative unsertainty of 5%.

Thank you!

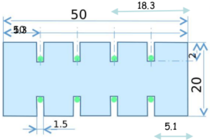
DANSS upgrade

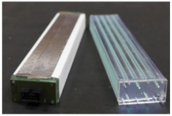
Main goal: to reach resolution **13%/√E**
w.r.t. current very modest 33%/√E.

New geometry:

Strips: 2x5x120 cm, 2-side 8SiPM readout
Structure: 60 layers x 24 strips: 1.7 m³
Setup uses **the same shielding and moving platform.**
Gd is in foils between layers.
Upgrade will be finished in 2023

New scintillator strips

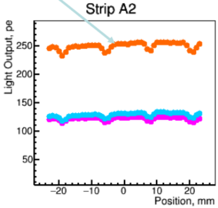


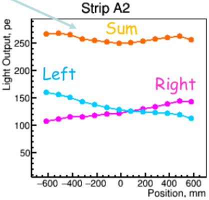


WLS fiber positions were optimized for better uniformity of response
New fast (4ns decay time) YS2 fiber will be used
JINST 17 (2022) P01031

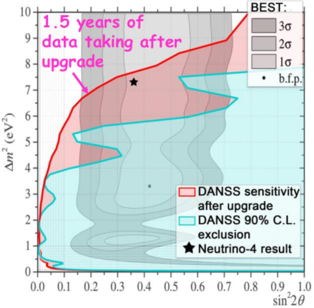
Strip tests at π-beam

Transverse and longitudinal responses are very uniform





Longitudinal nonuniformity can be further corrected
More work on SiPM-WLS fiber connection is needed



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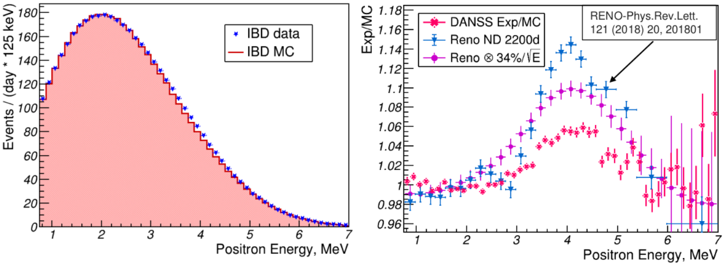


- In order to reach best agreement with HM model in 1-3 MeV region e+ spectrum was shifted on -50 keV. The nature of this shift (if it exists!) is still under investigation.
- With such a shift we see a bump in e+ spectrum similar to other experiments ($E_{prompt} = E_{positron} + 1$ MeV).
- Bump amplitude is smaller than in RENO
- However, we can not claim its existence yet because of high sensitivity of the shape to energy scale and shift.

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

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

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

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

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

Test statistics

Test statistics is defined as follows:

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

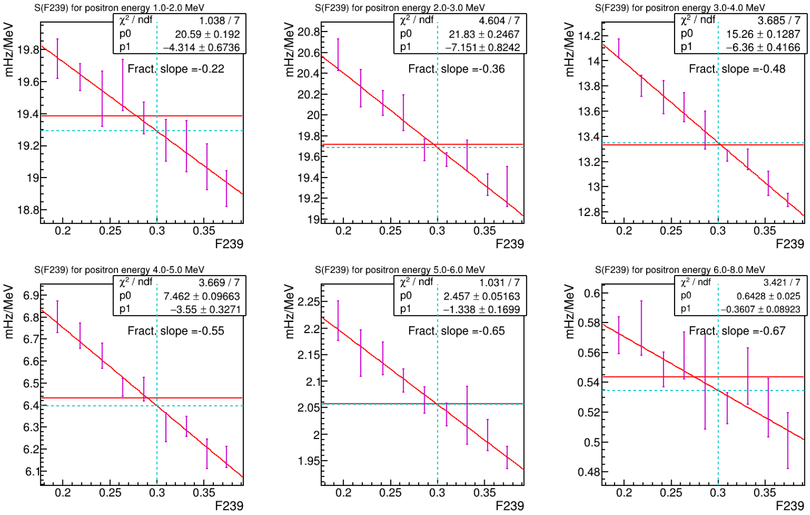
phase I — Top, Middle, Bottom; phase II — Top, Bottom; penalty terms

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,
$R_1 = Bottom/Top$, $R_2 = Middle/\sqrt{Bottom \cdot Top}$, 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).

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:

$$S(E,\eta) = S(E,\eta^0) + \sum_{l} \frac{\partial S}{\partial \eta_l} d\eta_l$$


S(F239) for positron energy 1.0-2.0 MeV
χ2 / ndf 1.038 / 7
p0 20.59 ± 0.192
p1 −4.314 ± 0.6736
Fract. slope =-0.22
S(F239) for positron energy 2.0-3.0 MeV
χ2 / ndf 4.604 / 7
p0 21.83 ± 0.2467
p1 −7.151 ± 0.8242
Fract. slope =-0.36
S(F239) for positron energy 3.0-4.0 MeV
χ2 / ndf 3.685 / 7
p0 15.26 ± 0.1287
p1 −6.36 ± 0.4166
Fract. slope =-0.48
S(F239) for positron energy 4.0-5.0 MeV
χ2 / ndf 3.669 / 7
p0 7.462 ± 0.09663
p1 −3.55 ± 0.3271
Fract. slope =-0.55
S(F239) for positron energy 5.0-6.0 MeV
χ2 / ndf 1.031 / 7
p0 2.457 ± 0.05163
p1 −1.338 ± 0.1699
Fract. slope =-0.65
S(F239) for positron energy 6.0-8.0 MeV
χ2 / ndf 3.421 / 7
p0 0.6428 ± 0.025
p1 −0.3607 ± 0.08923
Fract. slope =-0.67
mHz/MeV
F239

DB exclusions

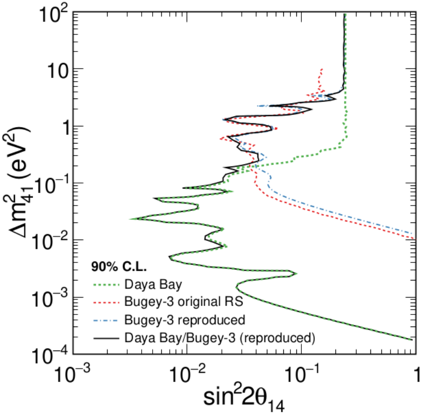


FIG. 2. Excluded regions for the original Bugey-3 raster scan (RS) result [14], for the reproduced Bugey-3 with adjusted fluxes, for the Daya Bay result [12], and for the combined Daya Bay and reproduced Bugey-3 results. The region to the right of the curve is excluded at the 90% C.L.

KI spectra

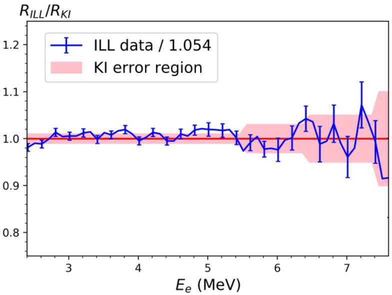


FIG. 2. Ratios R between cumulative β spectra from ^{235}U and ^{239}Pu, normalized to the KI data. Plotted ILL quantities were divided by 1.054, as explained in the text. The colored region shows KI uncertainties.

Event building

IBD event = two time separated triggers:
- Positron track and annihilation
- Neutron capture by gadolinium

- Neutron candidate: $> 1{,}5$ MeV total energy (PMT+SiPM), multiplicity > 3
- Search positron 50 μs backwards from neutron
- Positron candidate: > 0.5 MeV in continuous ionization cluster
- No other signals in the vicinity of IBD signal

Additional cuts

- Fiducial volume - positron cluster position: 4 cm from all edges
- Positron cluster has < 8 strips
- Energy in the prompt event beyond the cluster < 1.2 MeV and there are < 12 hits out of the cluster
- Delayed event energy is < 9.5 MeV and number of hits is < 20
- Positron (cluster) energy E e dependent cuts on prompt to delayed cluster distance and delayed event energy:

$$E_n[MeV] > 1.5 + 3 \cdot \exp\left(-0.13 \cdot E_{e^+}^2\right)$$

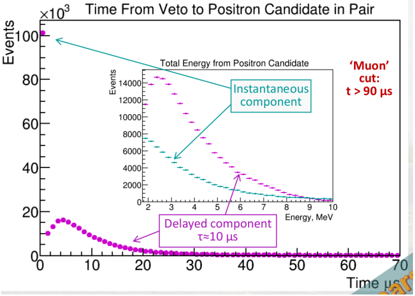
$$L_{2D}[cm] < 40 - 17 \cdot \exp\left(-0.13 \cdot E_{e^+}^2\right)$$

$$L_{3D}[cm] < 48 - 17 \cdot \exp\left(-0.13 \cdot E_{e^+}^2\right)$$

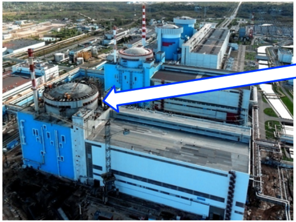
- For events with single hit positron cluster additional requirement of at least a hit out of the cluster and the energy beyond the cluster > 0.1 MeV

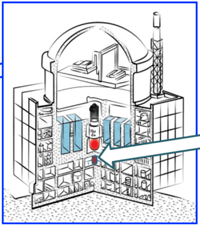
Muon cuts

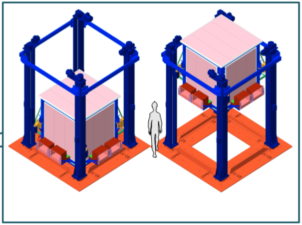
- VETO 'OR':
  - 2 hits in veto counters
  - veto energy > 4MeV
  - energy in strips > 20 MeV
  - energy in 2 bottom layers > 3 Mev
- Two distinct components of muon induced paired events with different spectra:
  - 'Instantaneous' – fast neutron
  - 'Delayed' – two neutrons from excited nucleus
- 'Muon' cut : NO VETO 90 μs before positron
- 'Isolation' cut : NO any triggers 50 μs before and 80 μs after positron (except neutron)
- 'Showering' cut : NO VETO with energy in strips > 300 MeV 120 μs before positron



Detector site





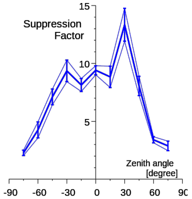


KNPP - Kalinin Nuclear Power Plant, Russia, ~350 km NW from Moscow

Below 3.1 GW commercial reactor ~ $5 \cdot 10^{13}$ $\nu \cdot cm^{-2} c^{-1}$ at detector position

DANSS on a lifting platform
A week cycle of up/middle/down position

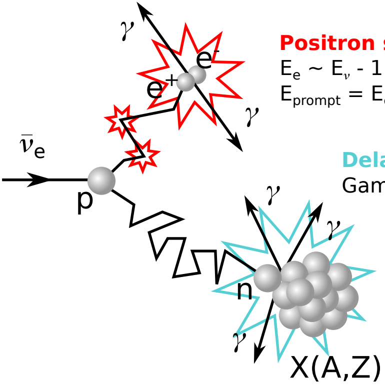
- No flammable or dangerous materials – can be put just after reactor shielding
- Reactor fuel and body with cooling pond and other reservoirs provide overburden ∼50 m w.e. for cosmic background suppression
- Lifting system allows to change the distance between the centers of the detector and of the reactor core from 10.9 to 12.9 m on-line



Cosmic muon suppression measured

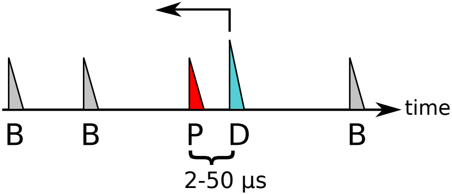
Inverse Beta-Decay (IBD) reaction:

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



Positron signal
$E_e \sim E_\nu$ - 1.806 MeV
$E_{prompt} = E_e + E_{2\gamma}$

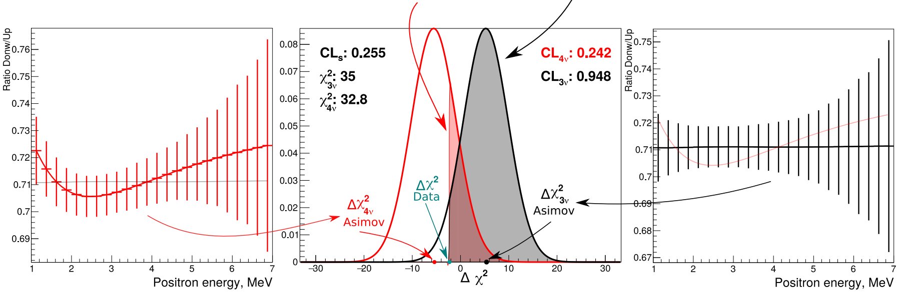
Delayed signal
Gamma flush in the whole detector



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

Gaussian CL_s [arXiv:1407.5052v4]

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



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