Statistical data analysis in the DANSS experiment

Nataliya Skrobova (LPI, ITEP)
for the DANSS collaboration

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Motivation

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

- LSND and MiniBoone: appearance of $\tilde{\nu_e}$ in $\tilde{\nu_\mu}$ beam: $\tilde{\nu_\mu} \rightarrow$ sterile $\tilde{\nu} \rightarrow \tilde{\nu_e}$. Significance – 6σ for combined results (Phys.Rev.Lett. 121, 221801 (2018))
- Neutrino4: disappearance of $\tilde{\nu_e}$ from reactor. Significance more than 3σ (arXiv:2003.03199)
- Reactor antineutrino anomaly (RAA): deficit in reactor $\tilde{\nu_e}$ fluxes (Phys.Rev.C 83 054615)
- Galium anomaly (SAGE, GALEX): deficit of ν_e in calibration runs with radioactive sources (Phys.Rev.C 83 065504)

All this 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.

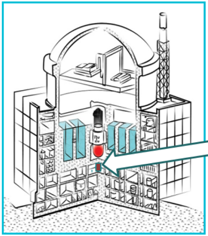
Sterile neutrinos would mean the New Physics beyond the Standard Model!

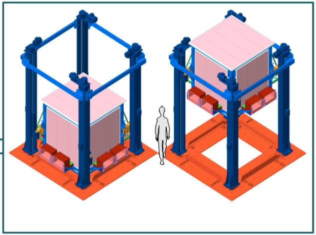
Detector DANSS

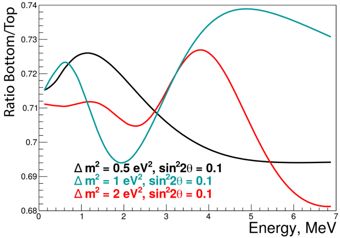
Survival probability of a reactor $\tilde{\nu}_e$ at short distances in the (3+1) mixing scenario:

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

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.

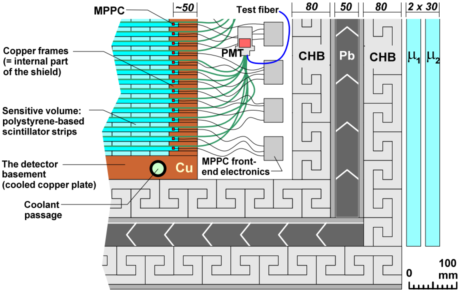


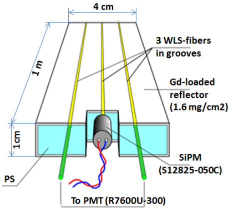


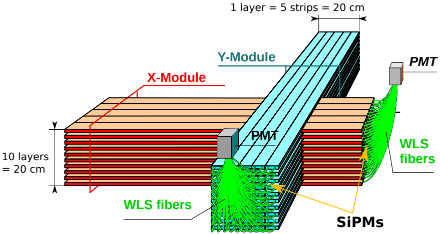


DANSS design [JINST 11 (2016) no.11, P11011]

- Multilayer closed passive shielding: electrolytic copper frame, borated polyethylene, lead, borated polyethylene
- 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
- 3D structure $\rightarrow$ reconstruction of positron cluster without γ



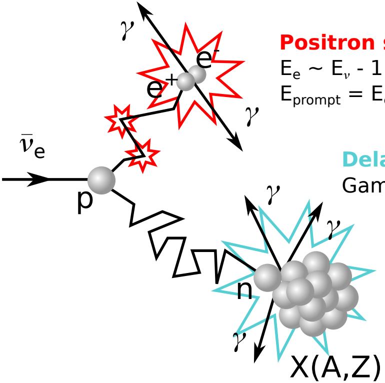




Antineutrino registration

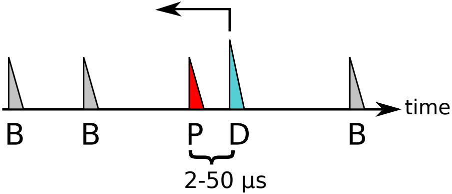
Inverse Beta-Decay (IBD) reaction:

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



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



Positron spectra calculation

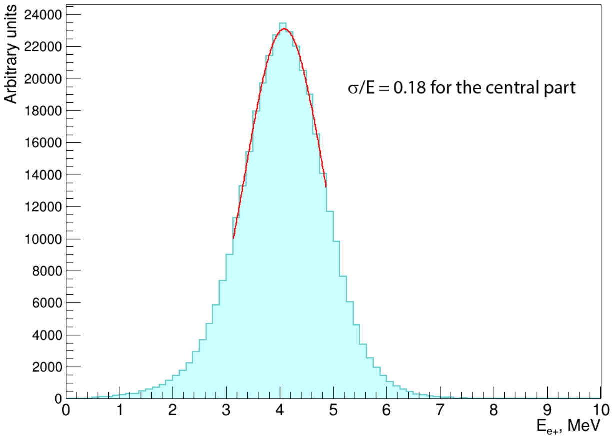
For every Δm^2_{41} and $\sin^2 2\theta_{ee}$ positron spectra were calculated for Top, Bottom and Middle detector positions taking into account:

- Reactor and detector size
- Distance between reactor and detector
- Average reactor burning profile
- Expected e^+ spectrum (from Huber and Mueller)
  Results don't depend on this choice!
- IBD crossection
- Oscillation probability
- Detector energy resolution. Observed energy resolution for radioactive sources was worse than in MC (33% instead of predicted 31% at 1 MeV)$\rightarrow$ additional smearing of $12\%/\sqrt{E} \oplus 4\%$ has been added to MC

Predicted spectra were calculated separately for different types of systematic uncertainties for small deviations from nominal values

Energy resolution

Detector energy response for 4.0625 MeV positron. The same processing algorithm as for data. Additional smearing has been added.



Updates in analysis

Calculated spectra ratios compared with observed. Previous definition of test statistics:

$$\chi^2 = \sum_{i=1}^{N_{bins}} (R_i^{\mathrm{obs}} - k \times R_i^{\mathrm{pre}}(\eta))^2 / \sigma_i^2,$$

R_i^{obs} (R_i^{pre}) – the observed (predicted) ratio of $\tilde{\nu}_e$ counting rates at the two detector positions *Bottom*/*Top*, σ_i – statistical standard deviation of R_i^{obs}, η – nuisance parameter (systematic uncertainties), k – relative efficiency.

Updates in analysis:

- **Inclusion of information about IBD relative counting rate** $\rightarrow$ penalty term for relative efficiency k. Uncertainty in the relative efficiency – 0.2%. **This allows to expend sensitivity region**
- **Inclusion of the third (middle) position** $\rightarrow$ taking into account correlations. Correlations are small if we choose $R_2 = Middle/\sqrt{Bottom \cdot Top}$ as second ratio. **Small improvements in sensitivity, but results are more stable to systematic uncertainties**
- **Splitting of data into two phases** corresponding to different data taking strategies
  First phase: Top-Middle-Bottom cycle,
  Second phase: Top-Botton cycle.
  Within each phase average fuel composition differs negligibly for different positions

Test statistics

As a result χ^2 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

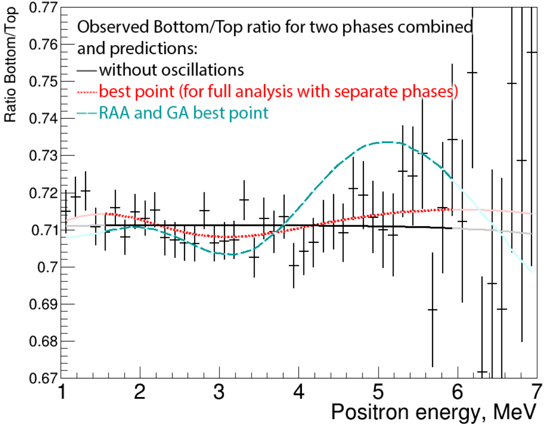
i – energy bin (36 total) in range 1.5–6 MeV;
$Z_j = R_j^{\mathrm{obs}} - k_j \times R_j^{\mathrm{pre}}(\Delta m^2,\ \sin^2 2\theta,\ \eta)$ for each energy bin,
$R_1 = Bottom/Top$, $R_2 = Middle/\sqrt{Bottom \cdot Top}$, where
Top, *Middle*, *Bottom* – absolute count rates per day for each detector 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:

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

Bottom/Top ratio

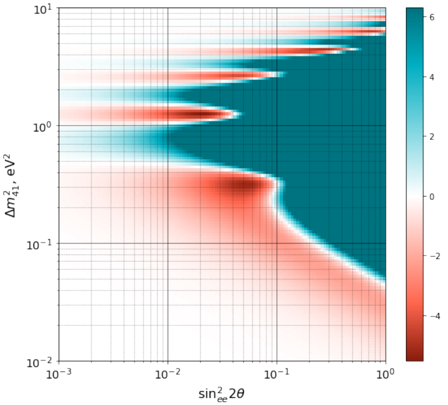


Using current statistics 2016-2020 ($\sim$3.5 million IBD events) we see no statistically significant indication of 4ν signal: $\chi^2_{4\nu} - \chi^2_{3\nu} = -5.5$ ($\sim 1.5\sigma$) for 4ν hypothesis best point $\Delta m^2_{41} = 1.3\text{eV}^2$, $\sin^2 2\theta_{ee} = 0.02$.

RAA and GA best point has been excluded with $\Delta\chi^2 = \chi^2_{RAA+GA} - \chi^2_{\min} = 68$.

$\Delta\chi^2$ distribution

Difference in χ^2 between 4ν and 3ν hypotheses.
Red: $\chi^2_{4\nu} < \chi^2_{3\nu}$, cyan: $\chi^2_{4\nu} > \chi^2_{3\nu}$.



Systematics and 1σ values used in the penalty terms (changes in nominal values):

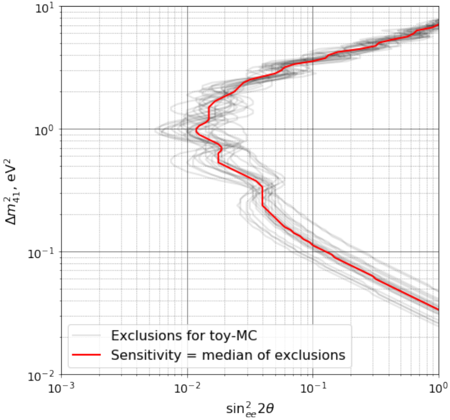
- relative detector efficiencies (0.2%)
- distance to the fuel burning profile center (5 cm)
- cosmic background (25%)
- fast neutron background (30%)
- additional smearing in energy resolution (25%)
- energy scale (2%)
- energy shift (50 keV)

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

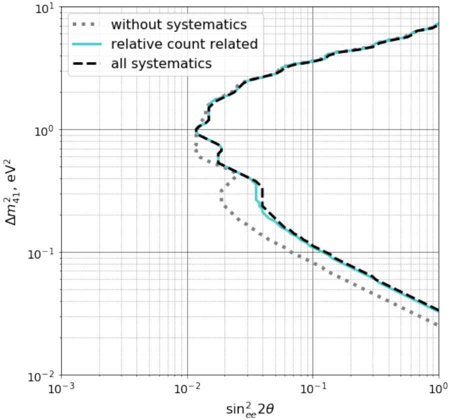
Sensitivity

90% C.L. sensitivity contours calculated with Gaussian CL_s method

Many toy-MC experiments assuming 3ν $\rightarrow$ distribution of boundaries for each Δm^2_{41}. Sensitivity boundary – median value of this distribution



Impact on sensitivity for different types of systematics. The largest effect: systematic uncertainties related to relative counting rate



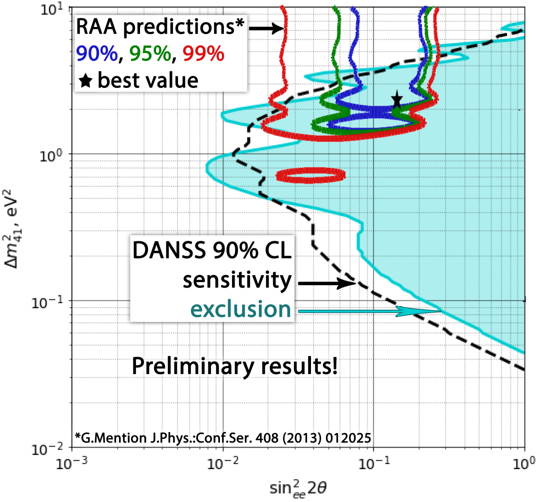
Preliminary results

DANSS 90% C.L. exclusion and sensitivity areas calculated with Gaussian CL_s method (Nucl.Inst.Meth. A 827 63).

Colored lines – RAA predictions.

A large and the most interesting fraction of available parameter space for sterile neutrino was excluded.

Obtained exclusions don't depend on theoretical predictions for $\tilde{\nu}_e$ spectrum and absolute detector efficiency.



Feldman-Cousins approach

To evaluate the significance of the best point Feldman-Cousins approach was used. Here the test statistics was defined as follows:

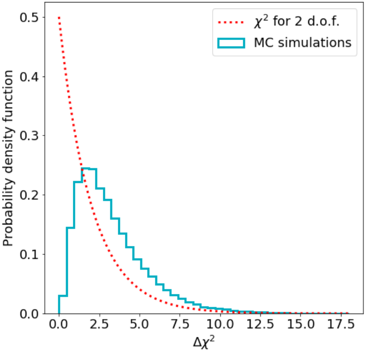
$$\Delta\chi^2 = \chi^2_{point} - \chi^2_{\min}$$

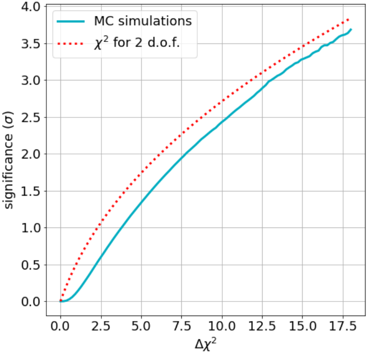
then for each point the C.I. can be calculated with the following algorithm.

- Calculate test statistics $\Delta\chi^2$ for observed data
- Many toy-MC experiments according to the model $\rightarrow$ empirical distribution of $\Delta\chi^2$
- Calculate the percentage of MC samples such that $\Delta\chi^2_{MC} < \Delta\chi^2_{obs}$. Than the point is included in the 1σ C.I. if the percentage is smaller than 68%

Significance test: perform calculations for 3ν and obtain the corresponding C.I. ("how far" is null hypothesis from the best point?)

Best point significance





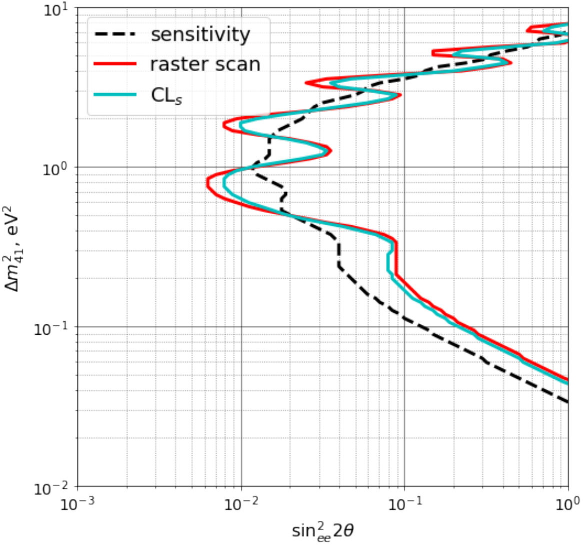
- $\Delta\chi^2 = \chi^2_{3\nu} - \chi^2_{\text{min}} = 5.5$
- 14% of toy-MC give $\Delta\chi^2$ larger than observed $\rightarrow$ 3ν hypothesis lies inside a 1.5σ interval
- We don't have statistically significant evidence for $\tilde{\nu}_e$oscillations to sterile neutrinos

Summary

- The stability of the detector absolute efficiency inferred from the coincidence between the IBD counting rate and the reactor power during almost 3 years allows us to include relative IBD counting rates into analysis. The corresponding uncertainties were taken into account by penalty terms.
- The middle detector position was included into the test statistics.
- DANSS analysis based on 3.5 million IBD events excludes a large and the most interesting fraction of available parameter space for sterile neutrino. For some values of Δm^2_{41} obtained exclusions are the most stringent in the world (up to $\sin^2 2\theta_{ee} < 0.008$ in the most sensitive region).
- Obtained exclusions don't depend on theoretical predictions for $\tilde{\nu}_e$ spectrum and absolute detector efficiency.
- We don't have statistically significant evidence for $\tilde{\nu}_e$ oscillations to sterile neutrinos. The significance of the best point is 1.5σ only.

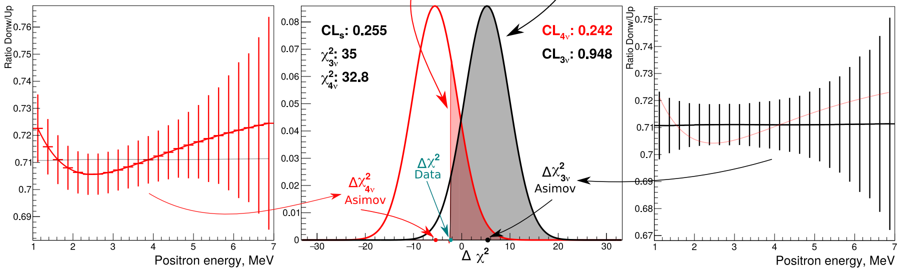
Thank you!

CL_s vs raster scan



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 $CL_s < 0.1(0.05)$

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 r: $\mathrm{r} = (Z_1\ Z_2)^T$, 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

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

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

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

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

Fuel

	begin 4	end 4	begin 5
^{235}U	63.7%	44.7%	66.1%
^{238}U	6.8%	6.5%	6.7%
^{239}Pu	26.6%	38.9%	24.9%
^{241}Pu	2.8%	8.5%	2.3%

core: $h = 3.7$ m, $d = 3.2$ m