Measurements of the reactor antineutrino energy spectrum dependence on the fuel composition and absolute antineutrino counting rates

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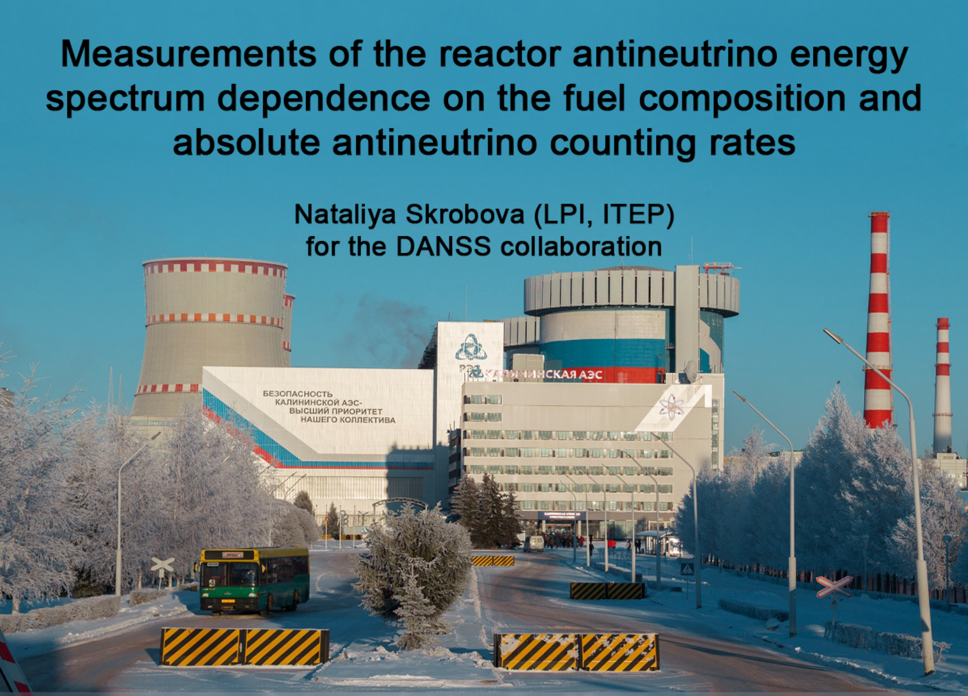
for the DANSS collaboration

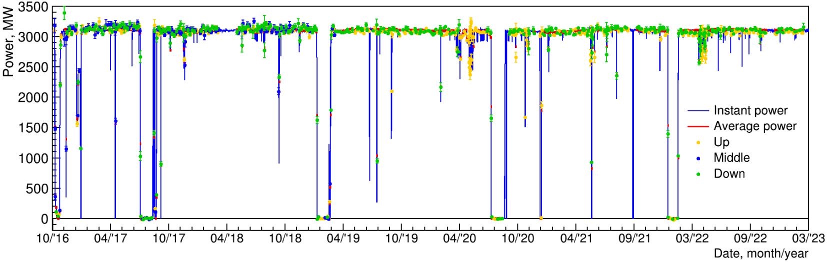


21st Lomonosov Conference on Elementary Particle Physics

Motivation

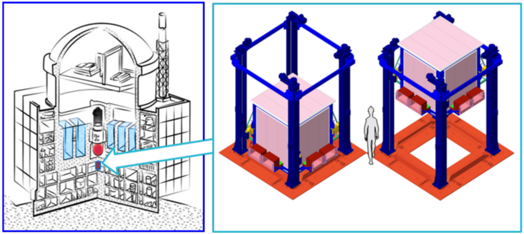
- Reactor Antineutrino Anomaly (Phys.Rev. D 83 073006): deficit in $\tilde{\nu}_e$ fluxes
- $\sigma_{235}/\sigma_{239}$ measured by DB (Phys. Rev. Lett. 120, 022503) is smaller than Huber+Mueller (Phys.Rev. C 84 024617, Phys.Rev. C 83 054615) predictions
- Resent KI measurements (Phys. Rev. D 104, L071301) don't agree with ILL measurements and hence with HM model
- Sterile neutrino searches for large Δm^2_{41} values

Stable performance of the DANSS detector allows us to perform analysis with absolute counting rates. Absolute counting rates address RAA directly.

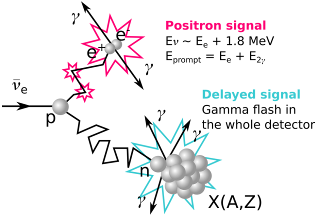


Reactor power measurements with $\tilde{\nu}_e$. Normalization from a short period at the beginning of data taking.

Introduction



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



Positron signal

$E_\nu \sim E_e + 1.8$ MeV

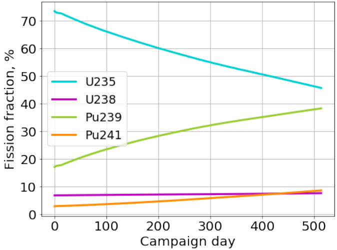
$E_{prompt} = E_e + E_{2\gamma}$

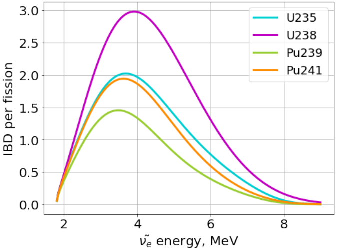
Delayed signal

Gamma flash in the whole detector

Kalinin Nuclear Power Plant:

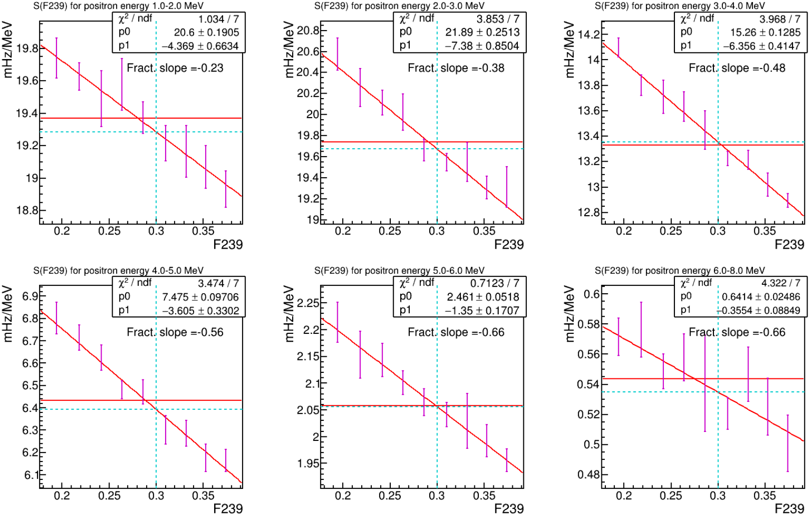
- High $\tilde{\nu}_e$ flux ($5 \cdot 10^{13} \tilde{\nu}_e$ cm^{-2} s^{-1})
- Large core: h = 3.7 m, d = 3.2 m
- Fuel: ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu (other components $< 0.3\%$)



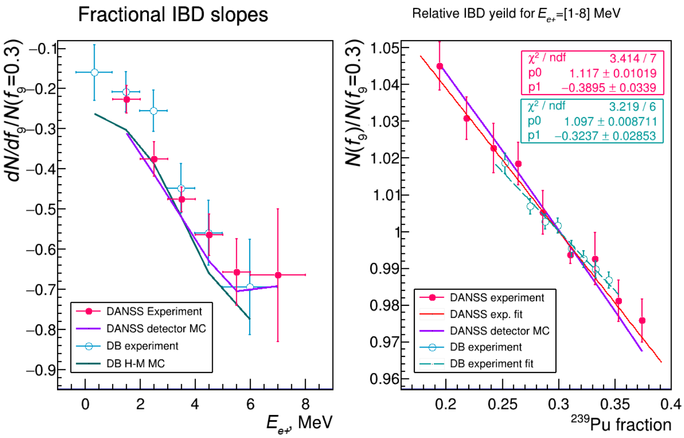


Relative slopes: $(\mathrm{d}N/\mathrm{d}f_9)/N(f_9\!=\!0.3)$

- 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



Spectrum dependence on fuel composition



IBD rate dependence on 239Pu fission fraction $(\mathrm{d}N/\mathrm{d}f_9)/N(f_9{=}0.3)$ for various E_{e^+} agrees with H-M 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 $\sigma_5/\sigma_9 = 1.53 \pm 0.06$ 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?

Absolute DANSS counting rates

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

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

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

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),

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

Systematic uncertainties

Source	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%

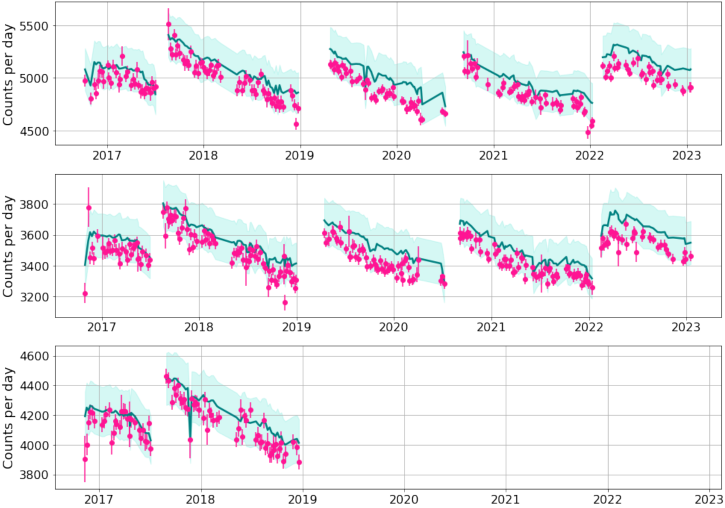
The values of uncertainties are given in percent according to their contributions to the absolute IBD counting rate.

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!

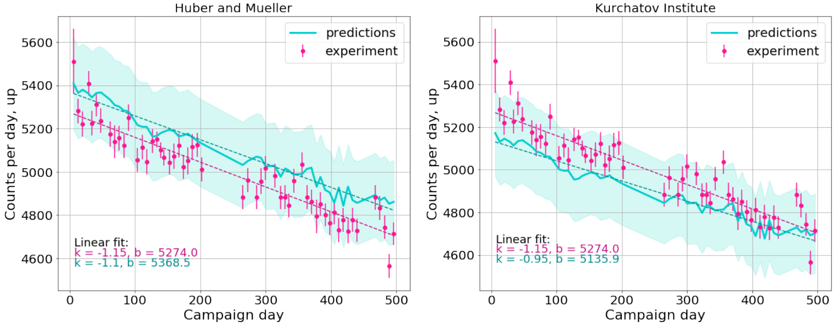


DANSS results are bellow HM predictions but within experimental uncertainties.

(average ratio: 0.98 ± 0.04)

Comparison with HM and KI models (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:

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

phase I
Top, Middle, Bottom

phase II
Top, Bottom

penalty
terms

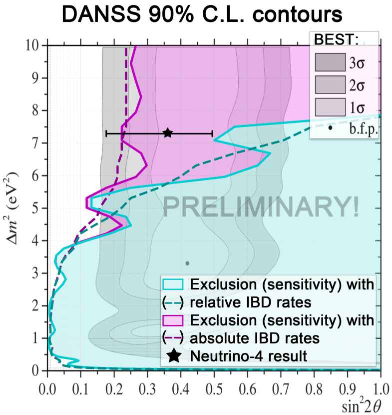
$$+((N_{top} + N_{mid} + N_{bottom})^{\mathrm{obs}} - (N_{top} + k_2 \cdot \sqrt{k_1} \cdot N_{mid} + k_1 \cdot N_{bottom})^{\mathrm{pre}})^2 / \sigma_{abs}^2$$

term for absolute rates

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),
N – total absolute rates,
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 unsertainty of 5%.

Summary

- 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 $\sigma_5/\sigma_9 = 1.53 \pm 0.06$ 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.
- 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%.

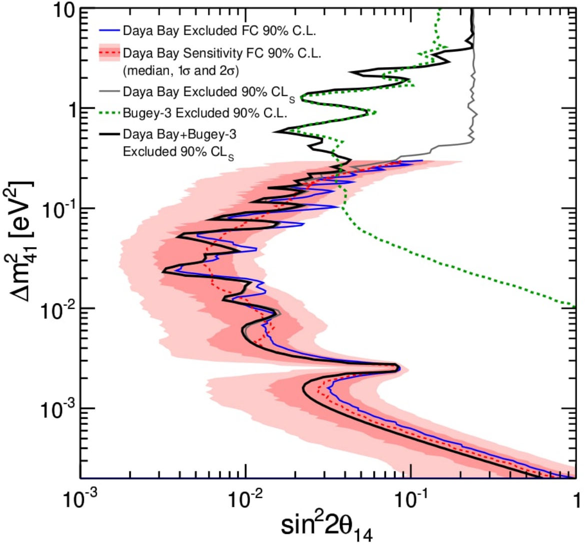
Thank you!

Large Δm^2_{41} limit

Raster Scan method

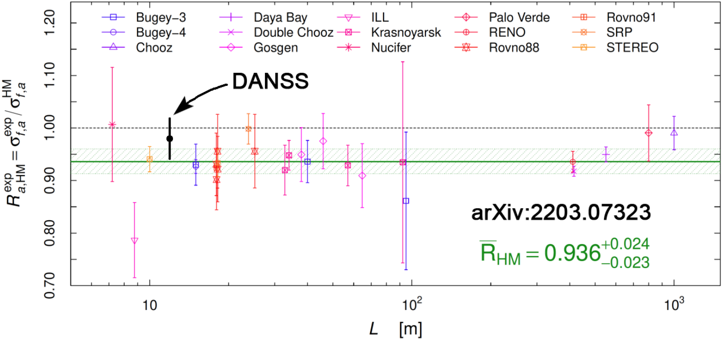
For each fixed Δm^2 text statistics is defined:
$\Delta\chi^2 = \chi^2_{\Delta m^2, \sin^2 2\theta_{ee}} - \chi^2_{min(\sin^2 2\theta_{ee})}$
90% C.L: $\Delta\chi^2 > 2.71$
Sensitivity: $\chi^2_{min} = 0, \sin^2 2\theta_{ee} = 0 \Rightarrow$ 90% C.L at $\chi^2_{\Delta m^2, \sin^2 2\theta_{ee}} = 2.71$
Large Δm^2_{41} limit: $N^{pre} \sim 1 - \frac{1}{2}\sin^2 2\theta_{ee}$
$\chi^2_{\Delta m^2, sin^2 2\theta} = \sum \frac{(N^{obs} - N^{pre})^2}{\sigma^2} = \sum \frac{N(1-(1-1/2\sin^2 2\theta_{ee}))^2}{\sigma^2}$
Sensitivity border (90% C.L.): $\sin^2 2\theta_{ee} \approx 2 \cdot \sigma_{rel} \cdot \sqrt{2.71} \approx 0.24$

Sterile neutrinos



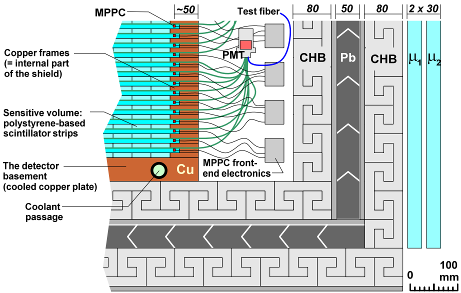
Comparison of the predicted and observed DANSS rates

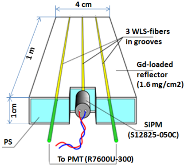
DANSS rates to Huber+Mueller: 0.98 ± 0.04

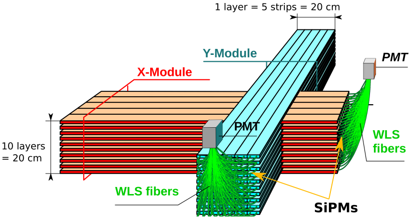


DANSS design [JINST 11 (2016) no.11, P11011]

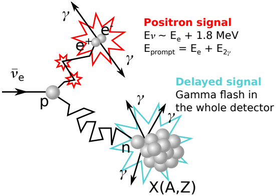
- Multilayer passive shielding: electrolytic copper frame 5 cm, borated polyethylene 8 cm, lead 5 cm, borated polyethylene 8 cm
- 2-layer active μ-veto on 5 sides
- 2500 scintillator strips with Gd containing coating for neutron capture
- Light collection with 3 WLS fibers
- Central fiber read out with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







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



Positron signal
$E\nu \sim E_e + 1.8$ MeV
$E_{prompt} = E_e + E_{2\gamma}$

Delayed signal
Gamma flash in
the whole detector

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

Test statistics

Test statistics is defined as follows:

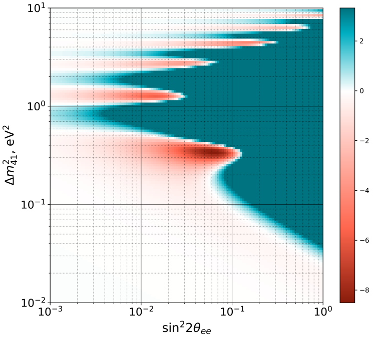
$$\chi^2 = \min_{\eta,k} \sum_{i=1}^{N_{bins}} \left(Z_{1i} \quad Z_{2i}\right) \cdot W^{-1} \cdot \begin{pmatrix} Z_{1i} \\ Z_{2i} \end{pmatrix} + \sum_{i=1}^{N_{bins}} \frac{Z_{1i}^2}{\sigma_{1i}^2} + \sum_{j=1,2} \frac{(k_j - k_j^0)^2}{\sigma_{kj}^2} + \sum_{l} \frac{(\eta_l - \eta_l^0)^2}{\sigma_{\eta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

phase I
Top, Middle, Bottom

phase II
Top, Bottom

penalty
terms

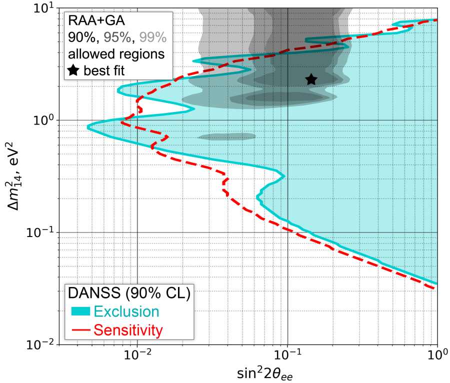
i – energy bin (36 total) in range 1.5–6 MeV; $Z_j = R_j^{\rm obs} - k_j \times R_j^{\rm pre}(\Delta m^2,\ \sin^2 2\theta,\ \eta)$ for each energy bin, $R_1 = Bottom/Top, R_2 = Middle/\sqrt{Bottom \cdot Top}$, where $Top,\ Middle,\ Bottom$ – absolute count rates per day for each detector position, k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



$\Delta\chi^2 = \chi^2_{4\nu} - \chi^2_{3\nu}$ distribution (5.5 mln events in oscillation analysis)

Preliminary results

DANSS 90% C.L. exclusion and sensitivity areas calculated with Gaussian CL_s method (Nucl.Inst.Meth. A 827 63). It is more conservative than Feldman-Cousins approach.



Systematic uncertainties (1σ 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 ($6\%/\sqrt{E} \oplus 2\%$)
- energy scale (2%)
- energy shift (50 keV)

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!