Измерения абсолютных счетов антинейтрино от реактора и зависимости спектра антинейтрино от состава топлива

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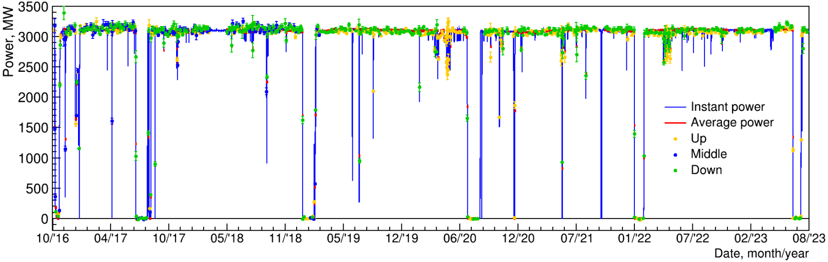
от коллаборации DANSS

Motivation

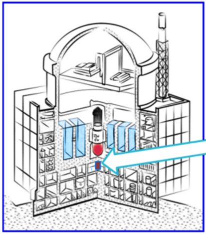
- Reactor Antineutrino Anomaly (Phys.Rev. D 83 073006): deficit in $\tilde{\nu}_e$ fluxes
- $\sigma_{235}/\sigma_{239}$ measured by DB (Phys. Rev. Lett. 120, 022503) is smaller than Huber+Mueller (Phys.Rev. C 84 024617, Phys.Rev. C 83 054615) predictions
- Resent KI measurements (Phys. Rev. D 104, L071301)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

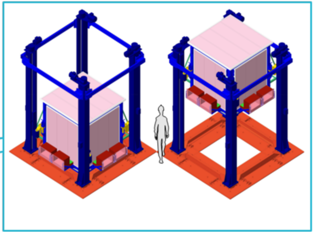
Stable performance of the DANSS detector allows us to perform analysis with absolute counting rates. Absolute counting rates address RAA directly.



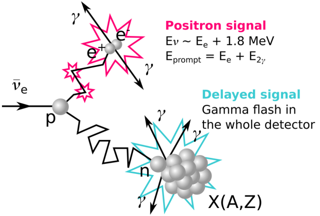
Reactor power measurements with $\tilde{\nu}_e$. Normalization from a short period at the beginning of data taking.

Introduction



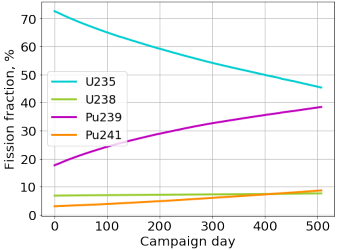


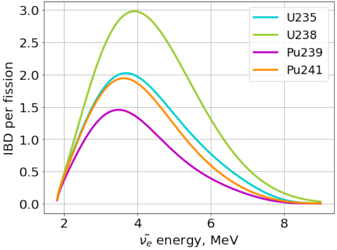
$\bar{\nu}_e$ registration: $\bar{\nu}_e + p \rightarrow e^+ + n$



Kalinin Nuclear Power Plant:

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



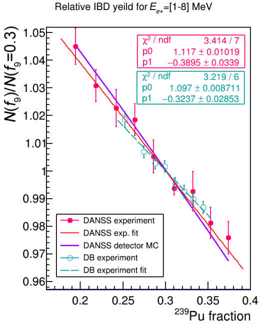


Measurements of σ_5/σ_9

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

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

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



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

(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: $\sigma_5/\sigma_9 = 1.459 \pm 0.052$.

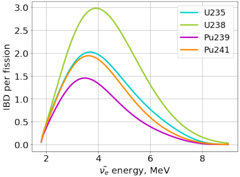
$\Rightarrow$ difference between DANSS and DB is due to slope

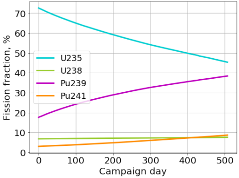
Maybe it's premature to say that RAA is solved by new σ_5/σ_9?

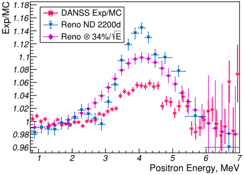
Fission fraction reconstruction

Inverse problem: reconstruct fission fractions by fitting positron spectra

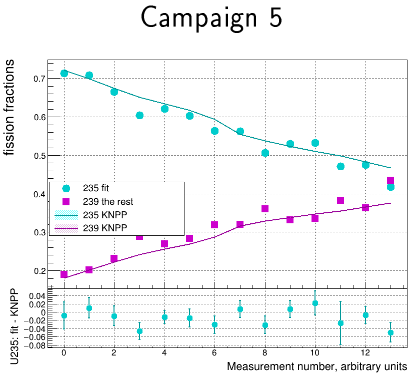
- We fit observed positron spectra using the sum of 4 isotops (HM model)
- U238 and Pu241 fission fractions are fixed (corresponding to KNNP data), U235 fission fraction is free parameter
- Each measurement corresponds to $\sim$ 6-10 days of data taking
- Correction for dead time, efficiency, neighbor reactors power (individually)
- Mean normalization for the whole campaign is used
- Reactor 4 power and fission points distribution profile are not taken into account
- Fit range: 1 – 3 and 5.5 – 7 MeV (excluding "bump")

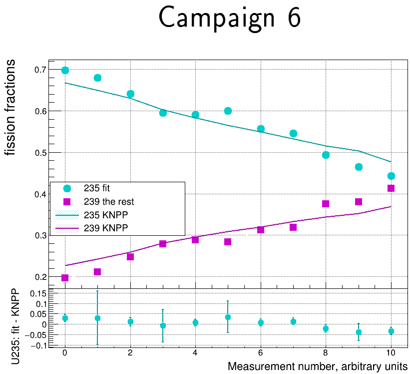






Fission fraction reconstruction: preliminary!





- Results for the top detector position
- Statistical errors only!
- All measurements are independent
- Fit is consistent with the KNPP data

Absolute IBD counting rates

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

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

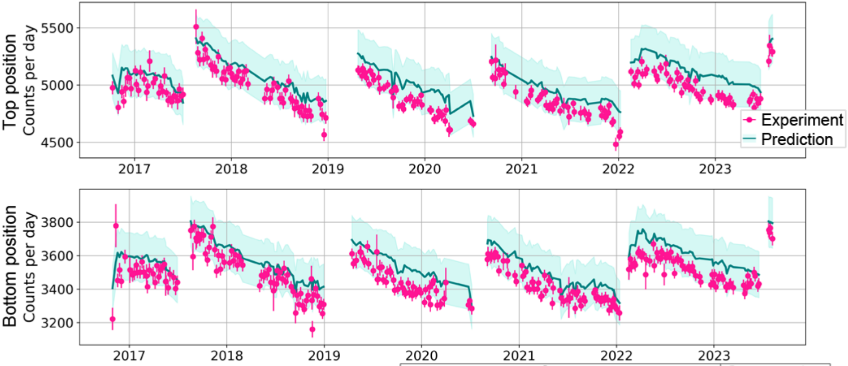
N_p – the number of target protons,
ε – detector efficiency,
L – the distance between the centers of the detector and the reactor core (distribution of fission points, reactor and detector sizes are taken into account)
$\sigma(E_\nu)$ – the IBD reaction cross section,
W_{th} – reactor thermal power (data 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

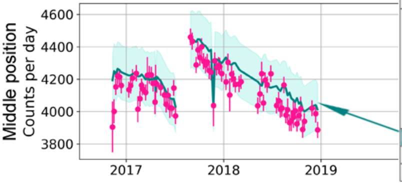
Systematic uncertainties

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.



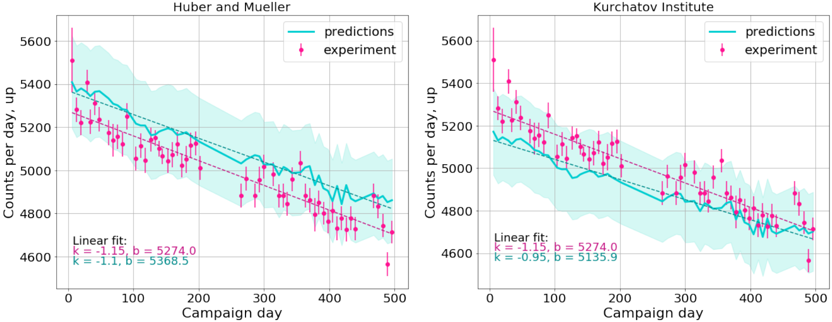


Source	Rate uncertainty
Number of protons	2%
Selection criteria	2%
Geometry (distance + fission points distribution)	1%
Fission fractions (from KNPP)	2%
Average energy per fission (Phys. Rev. C 88, 014605)	0.3%
Reactor power (from KNPP)	1.5%
Backgrounds	0.5%
Total	4%
Flux predictions	2-5%
Total with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

DANSS results are bellow Huber and Mueller 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

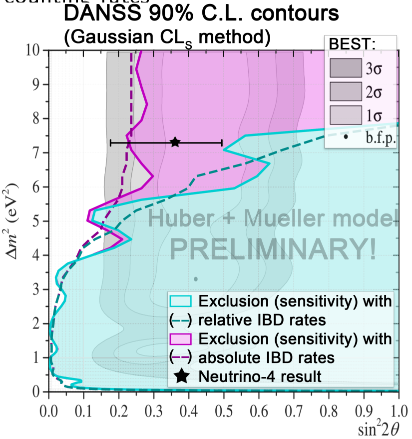
$$+((N_{top} + N_{mid} + N_{bottom})^{\mathrm{obs}} - (N_{top} + k_2 \cdot \sqrt{k_1} \cdot N_{mid} + k_1 \cdot N_{bottom})^{\mathrm{pre}})^2 / \sigma_{abs}^2$$

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

- 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.
- Reconstructed fission fractions are consistent with the KNPP data.
- Absolute $\tilde{\nu}_e$ counting rates are smaller than predictions in HM model but consistent within errors (Ratio $= 0.98 \pm 0.04$).
- Absolute $\tilde{\nu}_e$ counting rates are larger than predictions from KI model but consistent within errors (Ratio $= 1.015 \pm 0.04$).
- 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!

See DANSS talks by I. Alekseev, E. Samigullin, D. Svirida, and poster by N. Mashin

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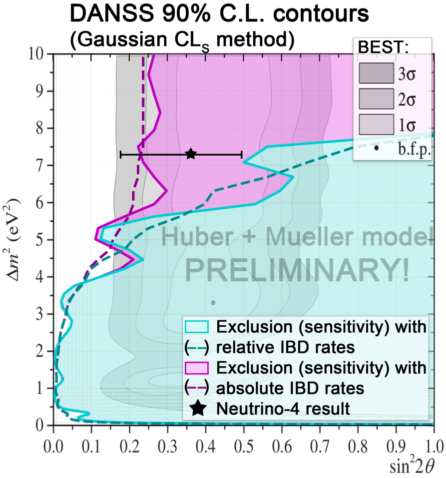
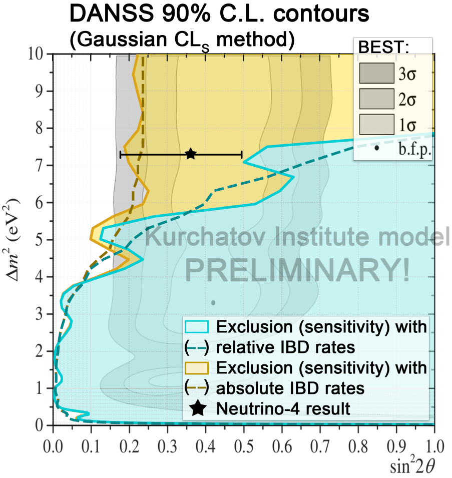
Exclusions

HM

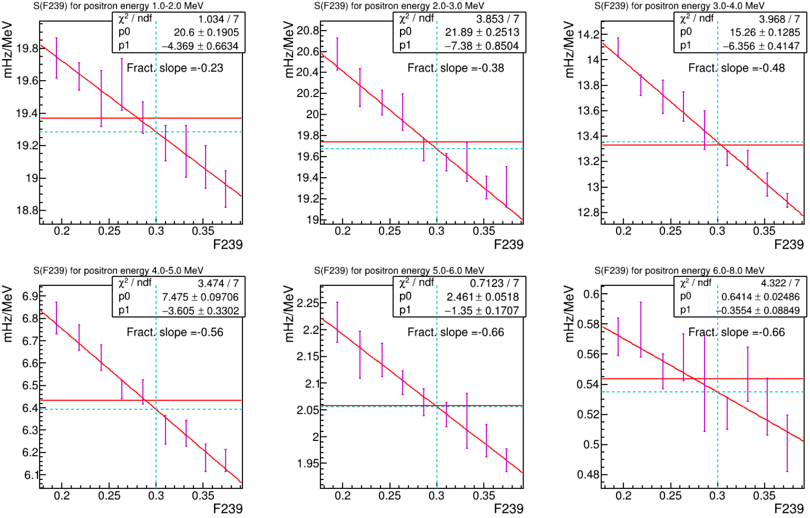


KI

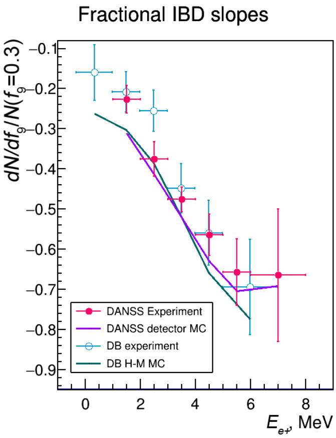


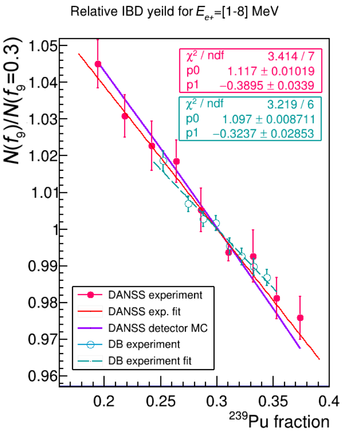
Relative slopes: $(dN/df_9)/N(f_9{=}0.3)$

- 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



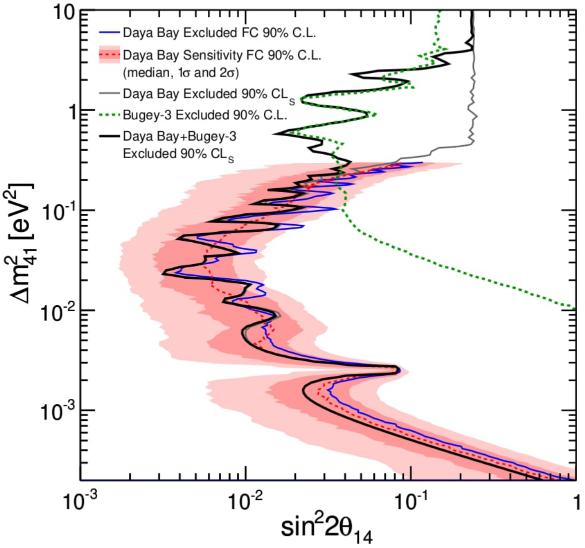
Spectrum dependence on fuel composition



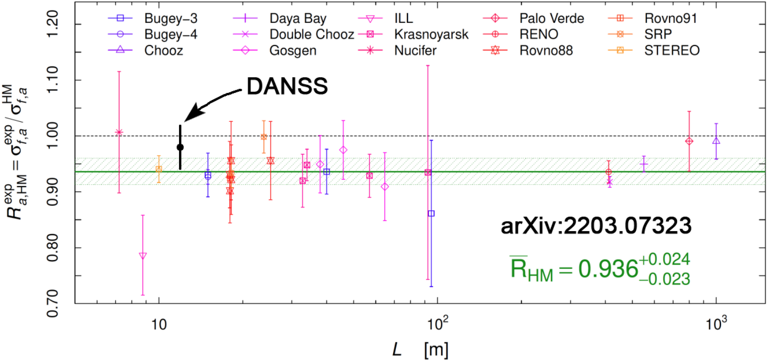


IBD rate dependence on 239Pu fission fraction $(\mathrm{d}N/\mathrm{d}f_9)/N(f_9{=}0.3)$ for various E_{e^+} agrees with H-M model and a bit more steep than at Daya Bay.

Sterile neutrinos



RAA



Bugey−3
Bugey−4
Chooz
Daya Bay
Double Chooz
Gosgen
ILL
Krasnoyarsk
Nucifer
Palo Verde
RENO
Rovno88
Rovno91
SRP
STEREO
DANSS
arXiv:2203.07323
$\overline{R}_{HM} = 0.936^{+0.024}_{-0.023}$
$R^{exp}_{a,HM} = \sigma^{exp}_{f,a} / \sigma^{HM}_{f,a}$
L [m]

Cross-sections

Table 1. Cross section for the reaction $\bar{\nu}_e + p \to n + e^+$ in the $\bar{\nu}_e$ spectra of fissile isotopes, σ_f^i ($i = 5, 9, 8$, and 1 stand for, respectively, ^{235}U, ^{239}Pu, ^{238}U, and ^{241}Pu), and in the reactor-antineutrino spectrum, σ_Σ, as well as the cross-section ratio σ_f^5/σ_f^9 obtained from experimental data and from the calculated and conversion spectra of $\bar{\nu}_e$ (the cross sections are given in 10^{-43} cm^2 fiss^{-1} units)

	$\sigma_\Sigma^{(1)}$	σ_f^5	σ_f^9	σ_f^8	σ_f^1	σ_f^5/σ_f^9
1. Experiment:						$1.44^{(2)}$
Daya Bay [24]	5.94 ± 0.09	6.10 ± 0.15	4.32 ± 0.25	–	–	1.412
RENO [23]	–	6.15 ± 0.19	4.18 ± 0.26	–	–	1.471
2. Calculation:						$1.44^{(2)}$
[10]	6.00	6.28	4.42	10.1	6.23	1.421
[28]	6.16	6.49	4.49	10.2	6.4	1.445
[15]$^{(3)}$	6.09	6.50	4.50	9.07	6.48	1.444
3. Conversion:						$1.52^{(2)}$
Huber–Mueller	6.22	6.69	4.40	10.1	6.10	1.520
Mueller	6.16	6.61	4.34	10.1	6.04	1.523
ILL–Vogel	5.93	6.44	4.22	9.07	5.81	1.526
4. Conversion with correction:						$1.44^{(2)}$
Huber–Mueller	6.02	6.33	4.40	10.1	6.10	1.439
Mueller	5.96	6.26	4.34	10.1	6.04	1.442
ILL–Vogel	5.73	6.09	4.22	9.07	5.81	1.443

$^{(1)}$ For the ^{235}U, ^{239}Pu, ^{238}U, and ^{241}Pu fuel composition in the following fractions of fission events (Daya Bay): $\alpha 5 = 0.564$, $\alpha 9 = 0.304$, $\alpha 8 = 0.076$, and $\alpha 1 = 0.056$.

$^{(2)}$ Average value.

$^{(3)}$ The data on the cross section for the reaction in (1) were normalized to the free-neutron lifetime of 880.2 s.

KI spectra

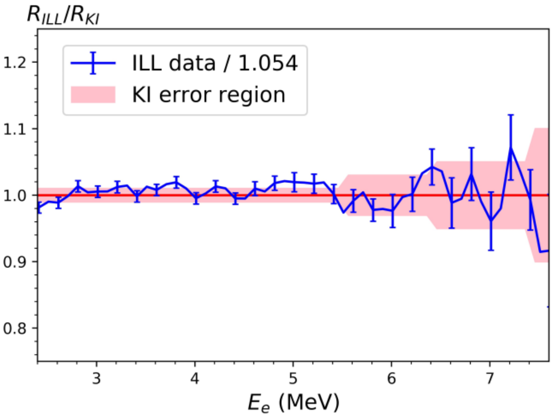


FIG. 2. Ratios R between cumulative β spectra from ^{235}U and ^{239}Pu, normalized to the KI data. Plotted ILL quantities were divided by 1.054, as explained in the text. The colored region shows KI uncertainties.

Fission points distribution