The DANSS Collaboration: recent results and perspectives

Igor Alekseev (KCTEP NRC «Kurchatovskiy Institut»)
For the DANSS Collaboration

Kalininskaya NPP, Udomlya
300 km from Moscow

7th International Conference on Particle Physics and Astrophysics

National Research Nuclear University "MEPhI"

22-25 October 2024

There are several indications in favor of existence of the 4th neutrino flavor - "sterile" neutrino seen in short distance oscillations

LSND + MiniBooNE – **accelartor anomaly**: appearance of ν_e ($\overline{\nu}_e$)
6.1σ combined result

MiniBooNE, PRL **121**, 221801 (2018)

MicroBooNE – doesn't confirm MiniBooNE, but doesn't exclude

MicroBooNE, PRL **128**, 241802 (2022)

GALEX (Gran Sasso) and SAGE (Baksan) – **gallium anomaly**: deficit of ν_e from neutrino source in gallium detectors calibration.

Phys. Rev. C **80**, 015807 (2009)

Recent results from BEST demonstrate event larger deficit of neutrinos.
The combined significance >5σ

Phys. Rev. D **105**, L051703 (2022)

Reactor anomaly – deficit of ν_e (5.7%) in combined analysis of reactor experiments.

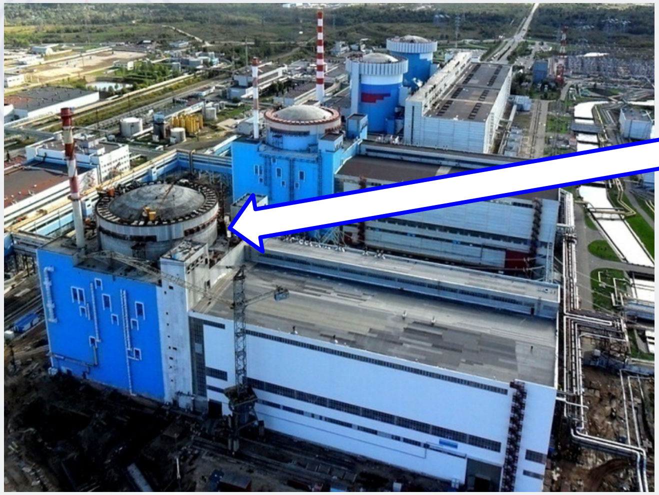
G. Mention et al. Phys. Rev. D **83**, 073006 (2011)

Much smaller (3.7%): M. Estienne et al. PRL **123**, 022502 (2019)
No anomaly (0.6%): V. Kopeikin et al. Phys. Rev. D **104**, L071301 (2021)
^{235}U rate measurements by Daya Bay and RENO

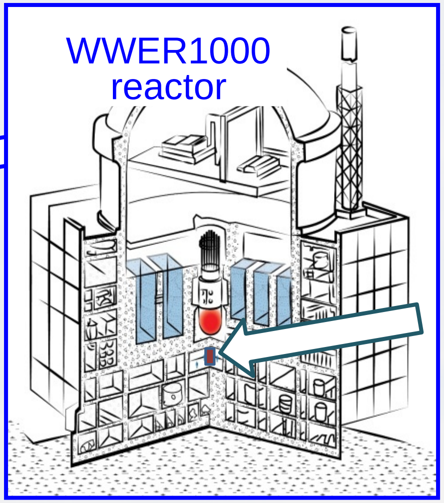
Neutrino-4: 2.7σ @ $\Delta m^2 \sim 7 eV^2$ $\sin^2 2\theta \sim 0.35$ Phys. Rev. D **104**, 032003 (2021)

Criticism of the Neutrino-4 analysis: M. Danilov et al. JETP Lett. **112** no. 7, 452 (2020)
C. Giunti et al. *Phys. Lett. B* 816, 136214 (2021)

These are one of the statistically strongest indications of the New Physics



Kalininskaya Nuclear Power Plant, Russia, ~300 km NW from Moscow



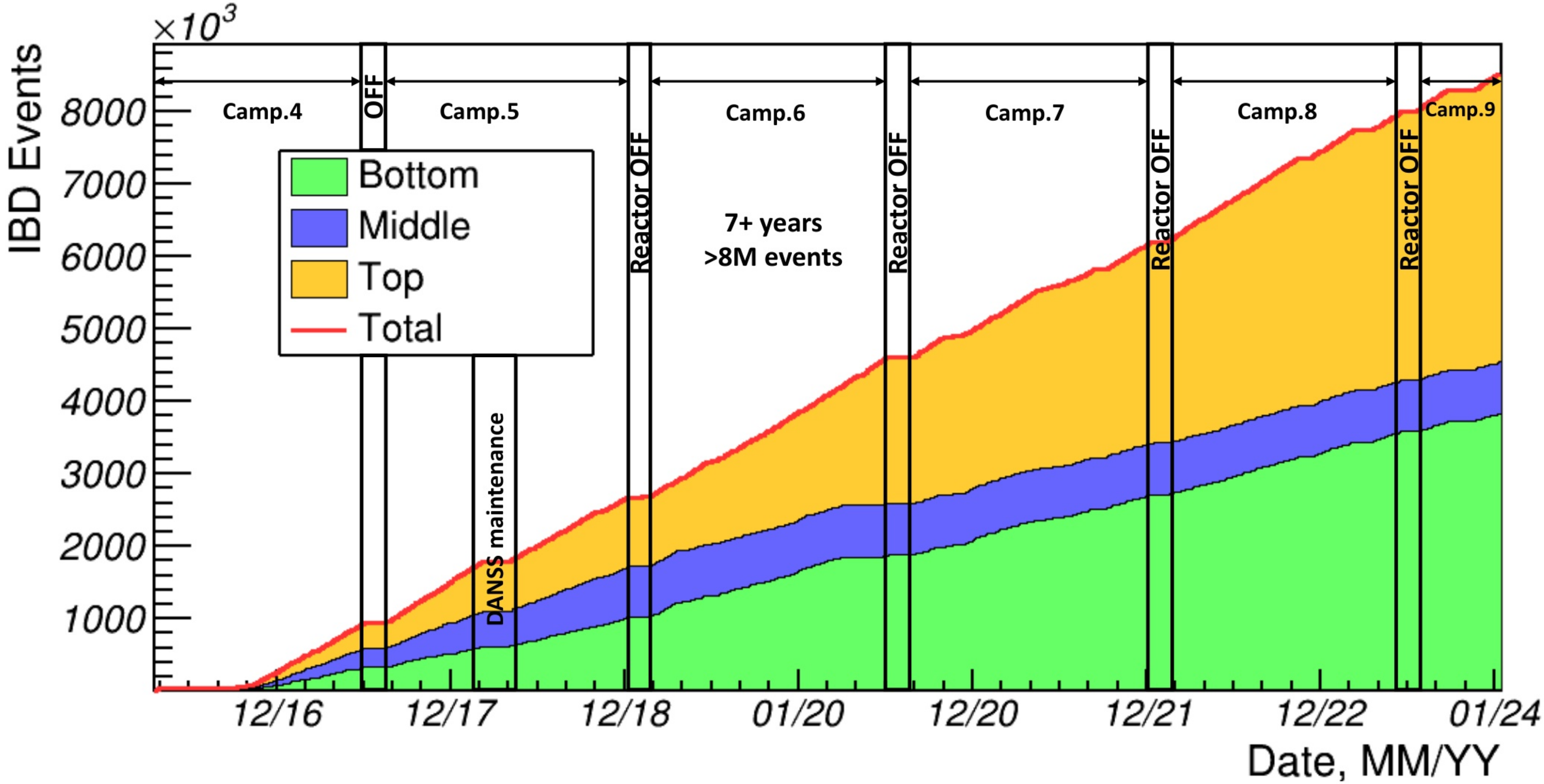
Below 3.1 GW_{th} commercial reactor

~$5 \cdot 10^{13}$ $\nu \cdot cm^{-2} c^{-1}$@11m

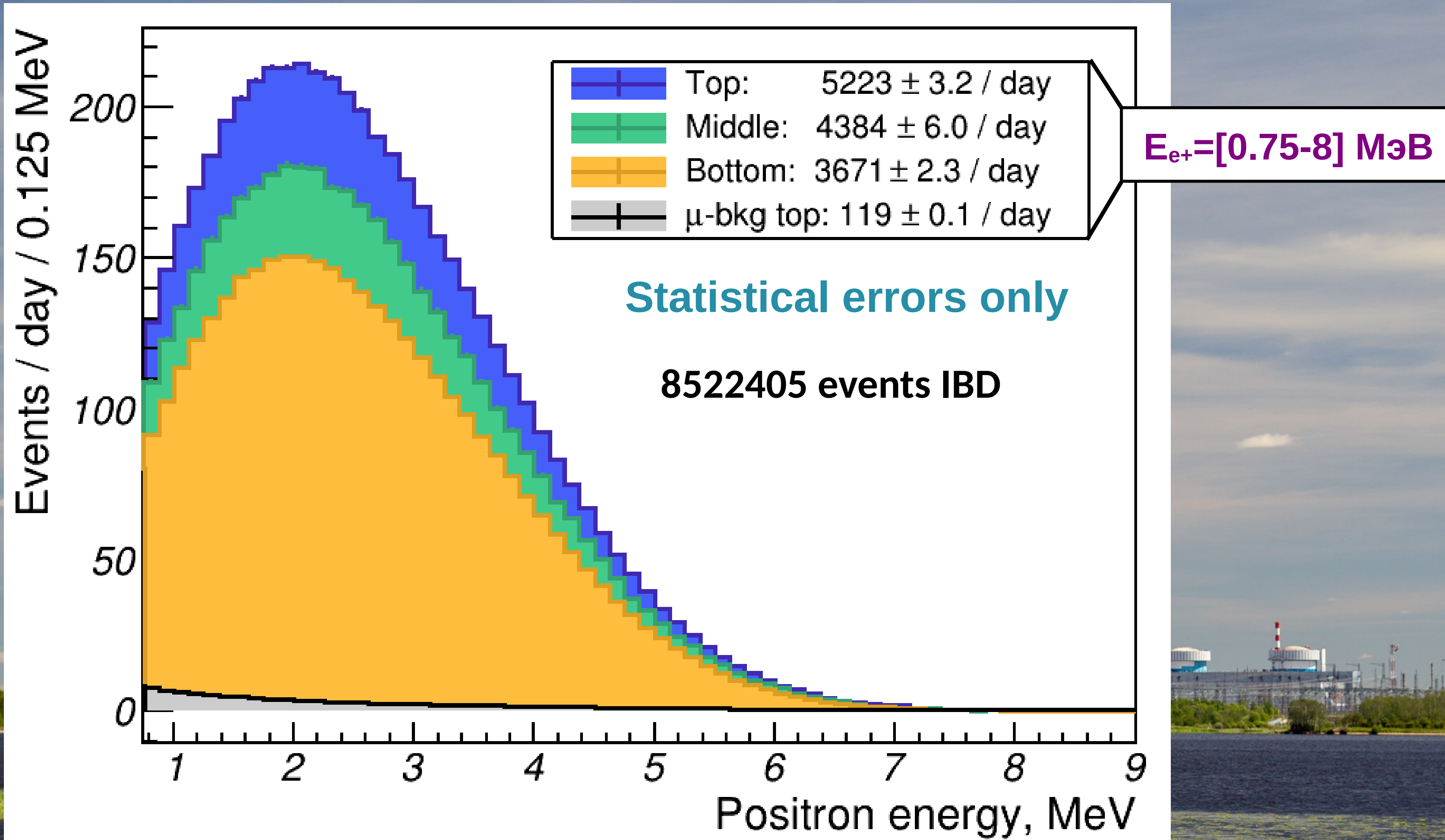
DANSS on a lifting platform
A week cycle of up/middle/down position

- Detector of the reactor AntiNeutrino based on Solid-state Scintillator - no flammable or dangerous materials – can be put just after reactor shielding
- Inverse Beta-Decay (IBD) to measure antineutrinos: $\bar{\nu}_e + p \rightarrow e^+ + n$
- 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
- The setup details: JINST 11 (2016) no.11, P11011
- The first results: Phys.Lett. B787(2018)56 – one year of running

DANSS statistics accumulation

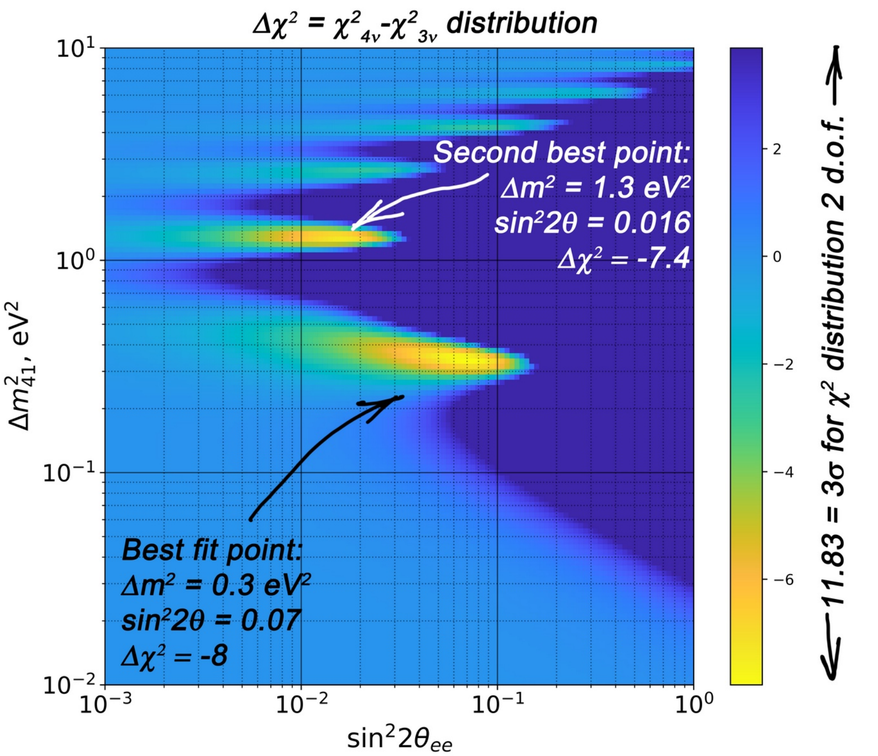


- ✓ **4 full reactor cycles !**
- ✓ **Data January-August 24 is under processing – to be released soon.**
- ✓ **Exciting results on reactor power and nuclei composition monitoring – see talk by Nataliya Skrobova and Eduard Samigullin**
- ✓ **Previous analysis (2023): I.G. Alekseev. Bull. Lebedev Phys. Inst. 51, 8 (2024)**

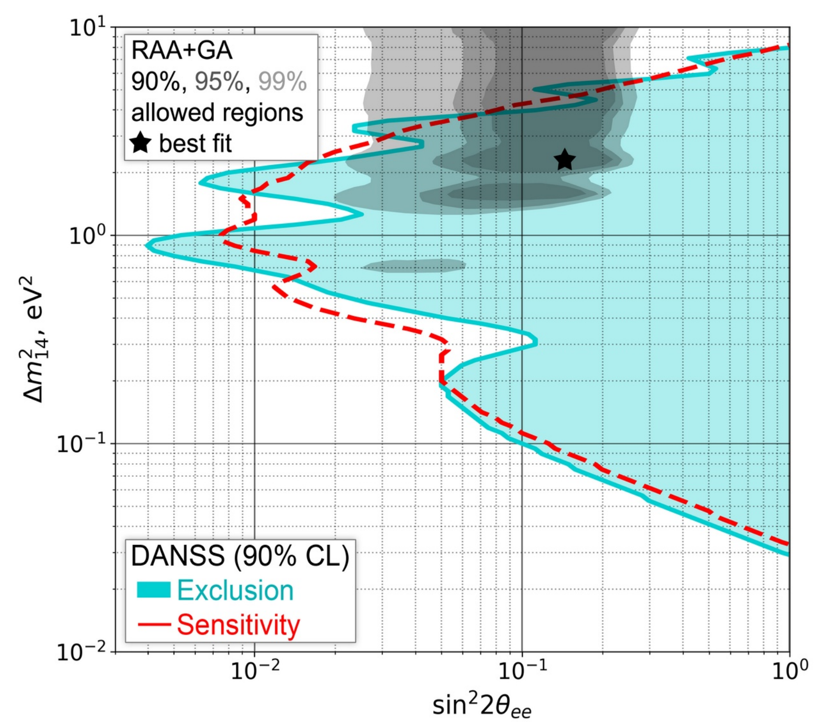


- ✓ **All backgrounds subtracted**
- ✓ **Neighbor reactors at 160 m, 334 m, and 478 m, 0.6% of neutrino signal at top position, subtracted**
- ✓ **For E_{e+}=[1.5-6] MeV background = 1.75% in top position: S/B > 50 !**

Sterile neutrino search



CLs method: **X. Qian et al. Nucl.Inst. Meth. A 827 (2016) 63**



- ✓ **6 M IBD events 1.5 MeV < E < 7 MeV (conservative approach)**
- ✓ **$\Delta\chi^2$=-8.0 (2.0σ) – No statistically significant hint of 4ν oscillations**
- ✓ **The RAA best point is deep inside the exclusion region (5σ level reached in 2018** [PLB **787** (2018) 56]**)**

Using absolute counting rates

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

χ^2_{rel} — χ^2 using counts ratios only, $N_{top/mid/botom}$ — total counts in the corresponding detector positions

σ_{abs} — systematic uncertainty taken as **7%** (very conservative)

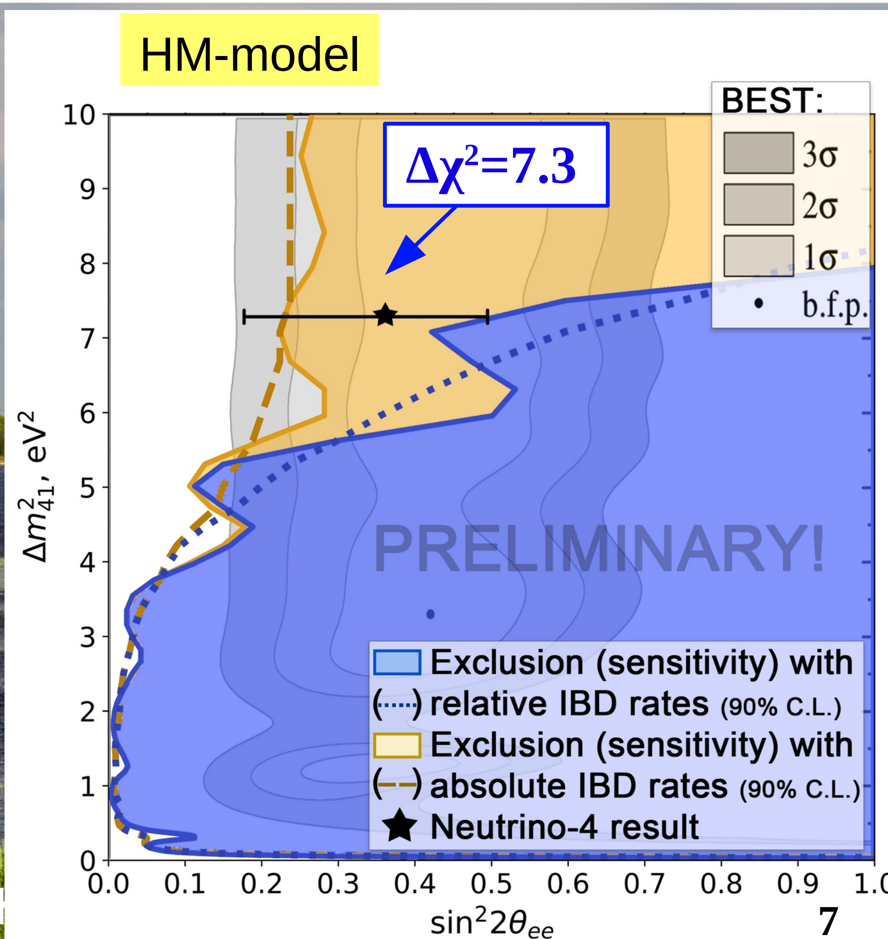
Exclusions for large Δm^2_{41} are consistent with previous results (Daya Bay, Bugey-3, …)

Our preliminary results exclude the dominant fraction of BEST expectations [Phys.Rev.Lett.128,232501] as well as best fit point of Neutrino-4 experiment [Phys. Rev. D 104, 032003].

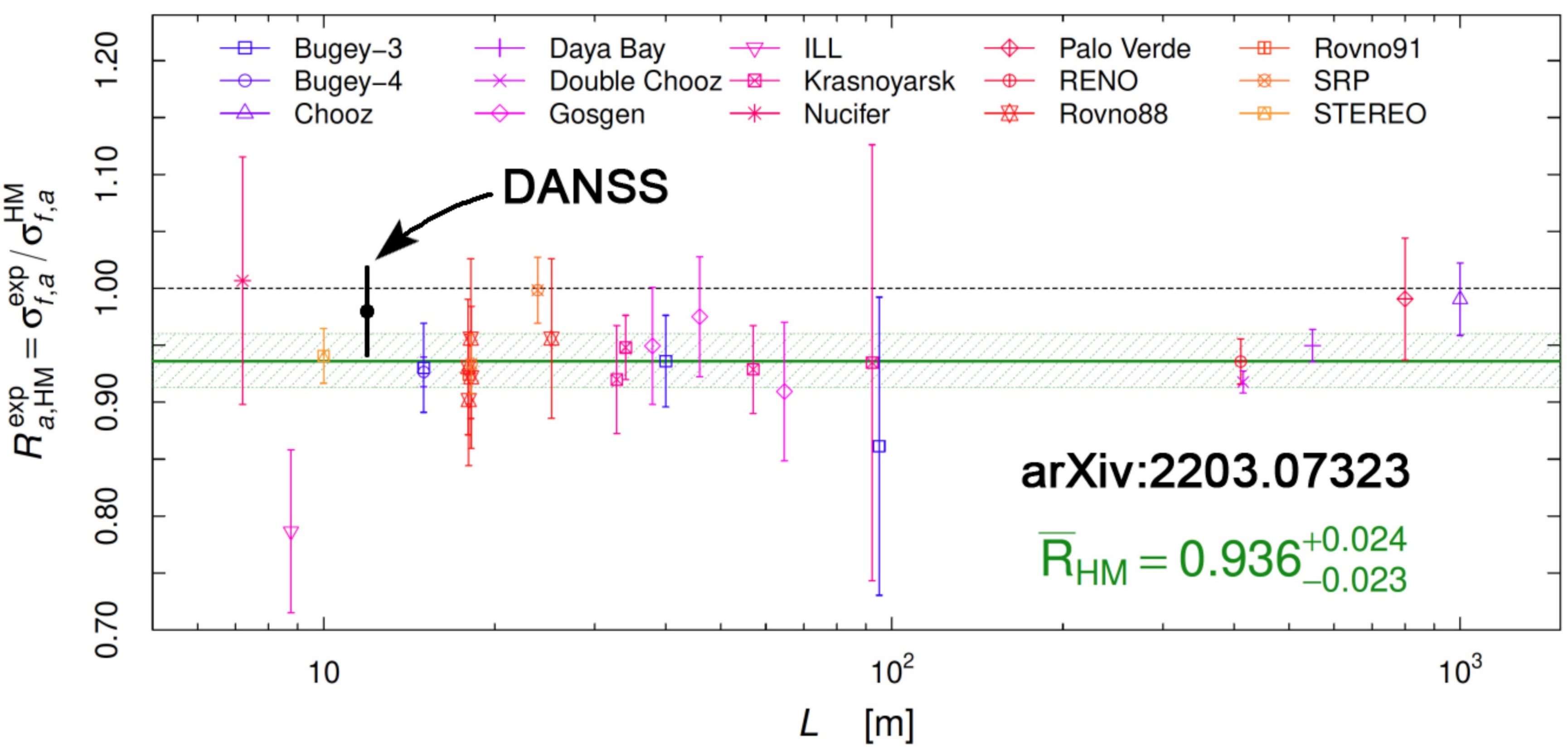
Systematic uncertainties

Source	Uncertainty
Number of protons	2%
Selection criteria	2%
Geometry (distance and 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 without flux predictions	**4%**
Flux predictions	2-**5%**
Total	5-**7%**

KI model exclusions are slightly stronger

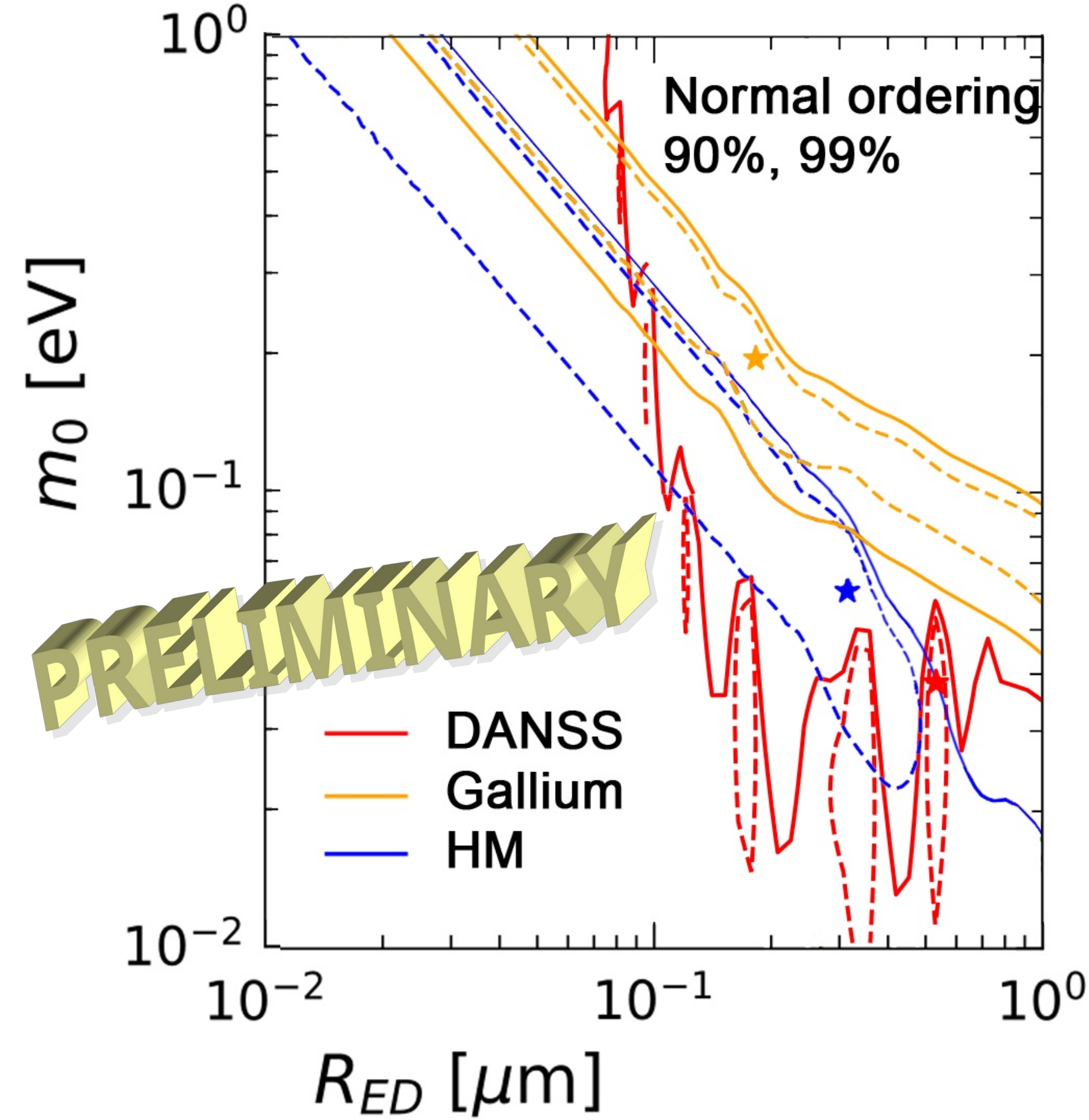


Direct comparison with RAA



Observed to predicted ratio with absolute ν_e counting rates is 0.98±0.04 for HM model, and is 1.02±0.04 for KI model

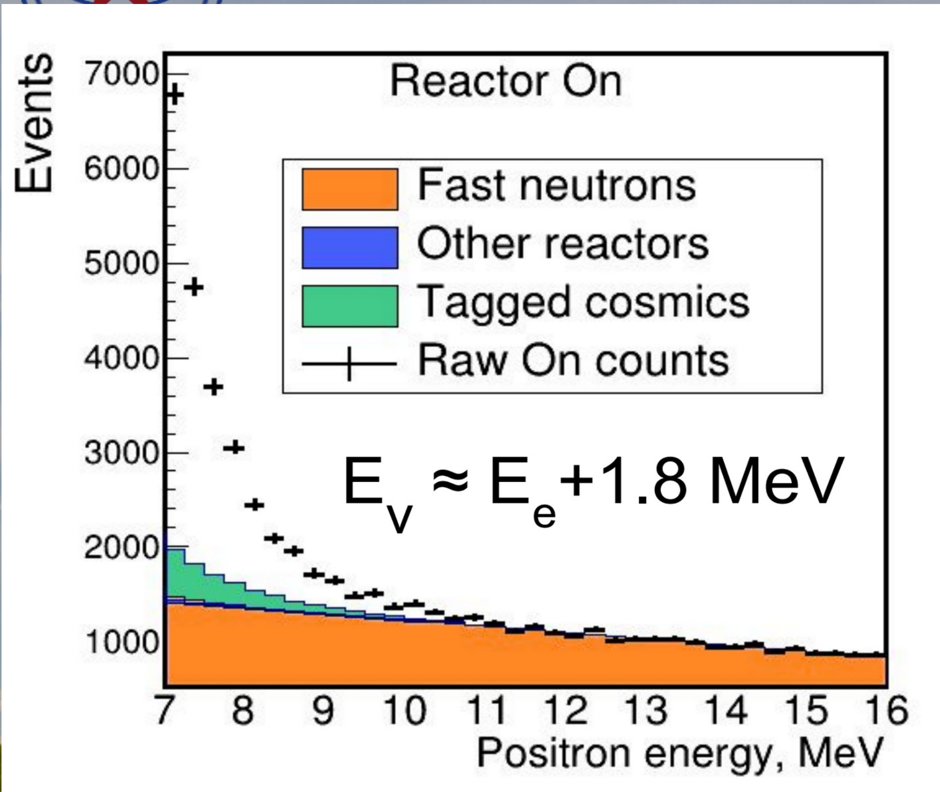
Large extra dimensions

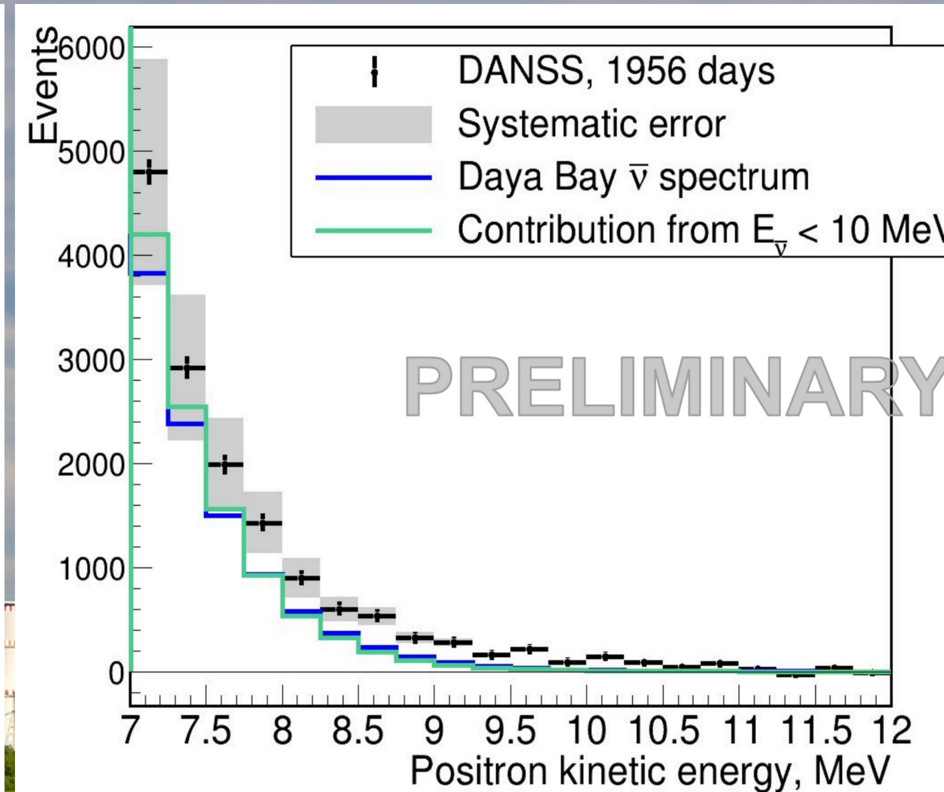


- Another way to solve reactor and gallium anomalies — oscillation to large extra dimensions.
- The analysis is similar to sterile neutrino search, but different L/E pattern.
- Only normal neutrino mass ordering studied so far.
- No statistically significant evidence for LED. The best point significance is 2σ only.
- We exclude large and interesting region preferred by GA and RAA.
- GA best point is excluded at > 3σ level.

See poster by Petr Gorovtsov and Nataliya Skrobova for more details.

High energy antineutrinos





Background subtraction is based on 5 “reactor off” periods

DANSS observes antineutrino with energy > 10 MeV: **$1561 \pm 157_{stat} \pm 168_{sys}$ ev. (6.8σ)**

Scale uncertainty makes the largest contribution to the systematic error

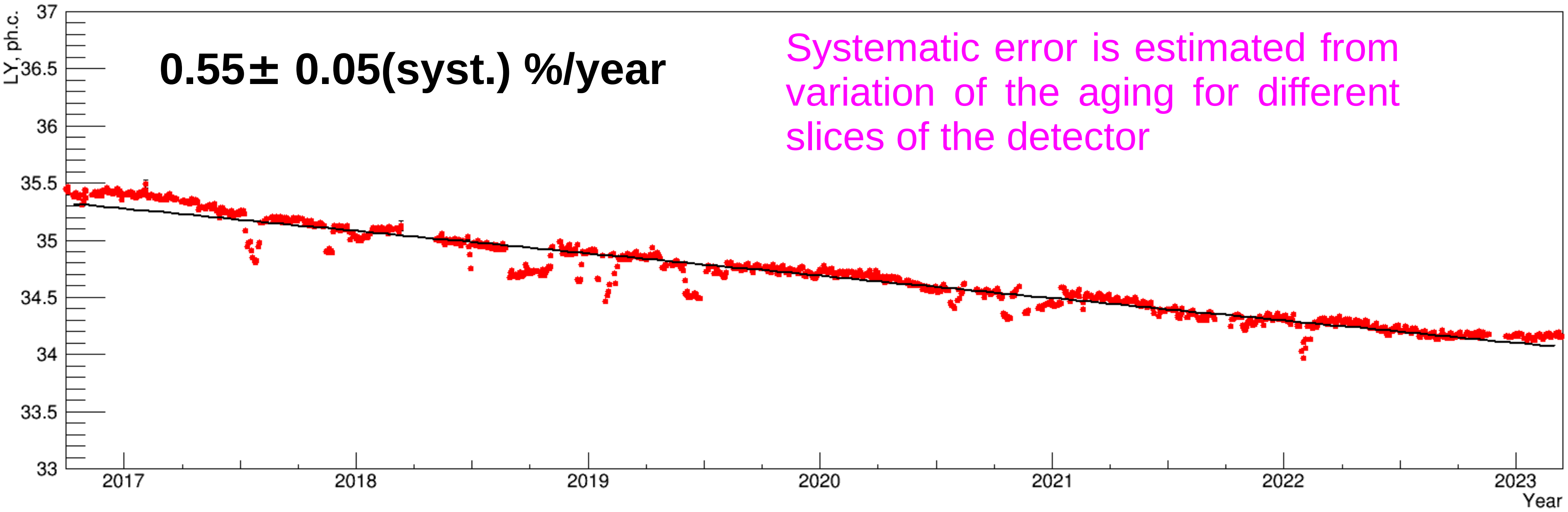
Fraction of high energy events is somewhat larger than at Daya Bay **[PhysRevLett.129.04180]**

Aging of DANSS scintillator

- T2K (several detectors) — 0.9-2.2 %/year; MINOS — 2 %/year; MINERvA — 7-10 %/year @ 80F(27.6^{o}C)
- DANSS – 7 years of continuous operation.
- The experimental hall is air conditioned and very dry.
- A chilled water cooling system is used for electronics inside the passive shielding, providing a stable temperature for the central part of the detector.
- Scintillator strips extruded from polystyrene by Institute of Scintillating Materials, Kharkiv, Ukraine.
- The surface is covered by ~0.2 mm co-extruded layer with admixture of TiO_2 and Gd_2O_3 which serves as a diffuse reflector. Gadolinium is used to capture neutrons from the inverse beta-decay after their moderation.
- Light collection by 3 wave length shifting fibers KURARAY Y-11(200)M Multi
- Central fiber is read by SiPM HAMAMATSU S12825-050C. Two side fibers are read by PMT. The other ends of the fibers are polished and covered by reflective paint.
- Only SiPM data is used in the analysis. SiPM bias voltages were set once at the very beginning and never changed.
- Close to vertical muon tracks with tgθ<0.2 selected.
- Median value of Landau distribution.

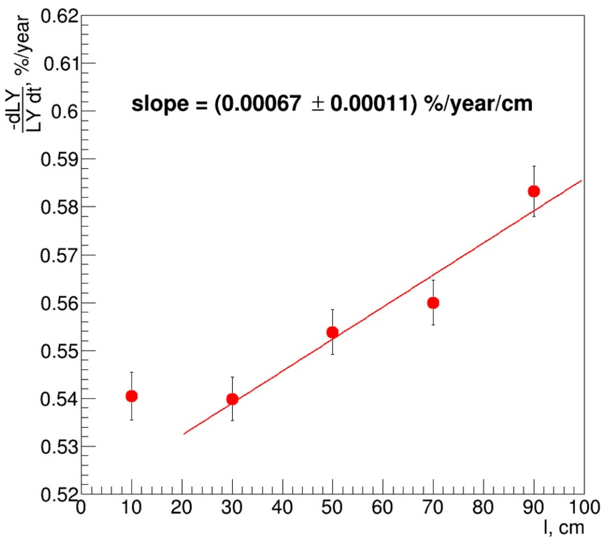
Aging of DANSS scintillator

JINST 19 (2024) P04031



$$\frac{1}{L_{\mathrm{att}}}\frac{\partial L_{\mathrm{att}}}{\partial t} = L_{\mathrm{att}}\frac{\partial}{\partial l}\left(\frac{1}{LY}\frac{\partial LY}{\partial t}\right)$$

L_{att} = 394 cm



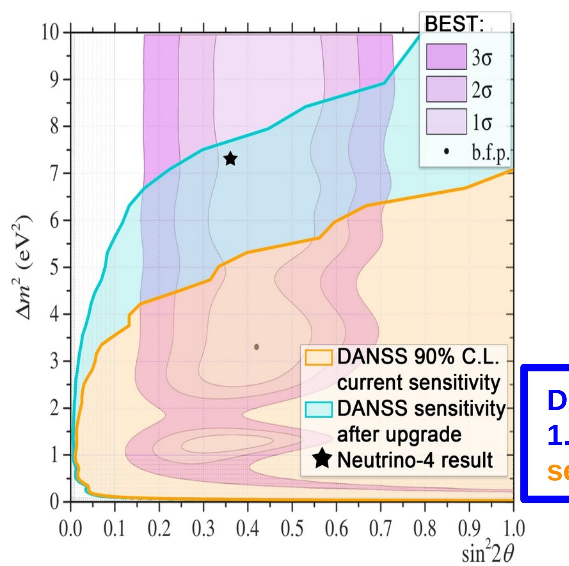
We can not separate aging of the scintillator and of the conversion efficiency of the WLS fiber. But we observe a hint of some decrease in its attenuation length. The increase of aging effect with the distance from SiPM gives an estimation of WLS attenuation length shortening $-dL_{att}/dt$ = **0.26 ± 0.07**(stat.) %/year

The DANSS upgrade

Main goal of the upgrade is to improve energy resolution:

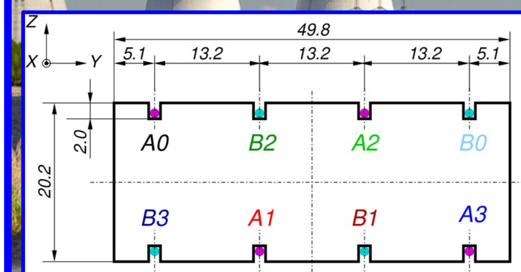
34%/√E --> 12%/√E

- ✓ New scintillation strips: 20x50x1200 mm³; **JINST 17 (2022) P04009**
- ✓ 60 layers x 24 strips — cube (120 cm)³ → 1.7 times larger fiducial volume;
- ✓ **No PMT** – SiPM readout from both sides of each WLS;
- ✓ 8 grooves with WLS, **16 SiPM** per strip to get high light yield and uniformity;
- ✓ TOF to get longitudinal coordinate in each strip. Faster (4.0 ns decay time) WLS fiber KURARAY **YS-2**; **JINST 17 (2022) P01031**
- ✓ Chemical whitening of strips – no large dead layer with titanium and gadolinium;
- ✓ Gadolinium in polyethylene film between layers;
- ✓ New front end electronics – low power inside passive shielding. Cool SiPMs to 10°C.
- ✓ Keep platform, passive shielding and digitization.

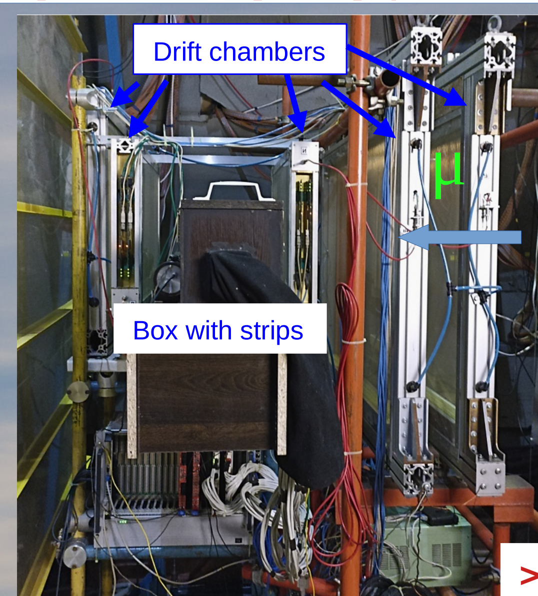


DANSS sensitivity after upgrade – 1.5 years of running and current setup – 4.5 years of running

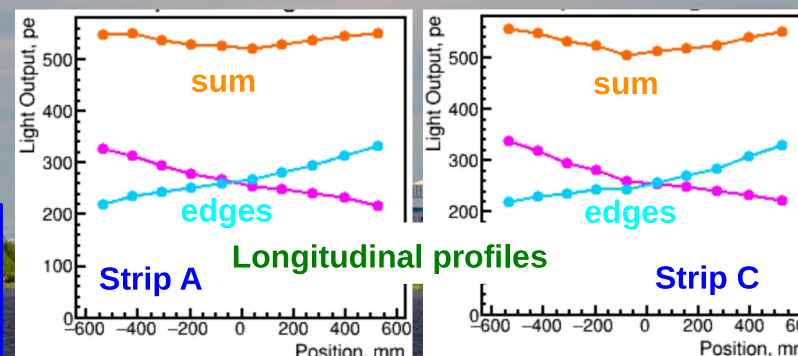
Strip cross section

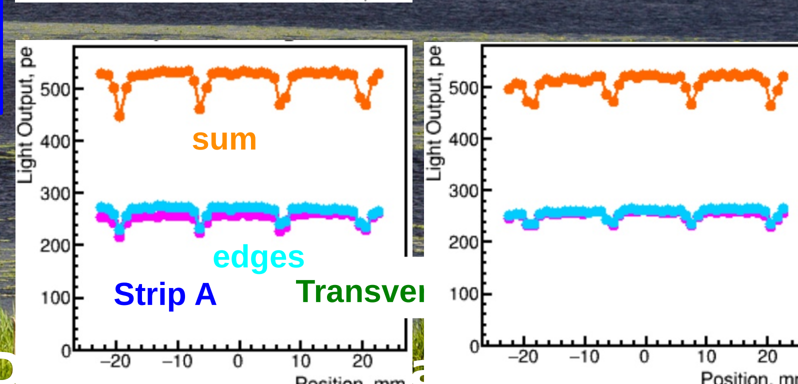


New strip test (16 SiPM per strip) μ-beam at U-70 (Protvino)



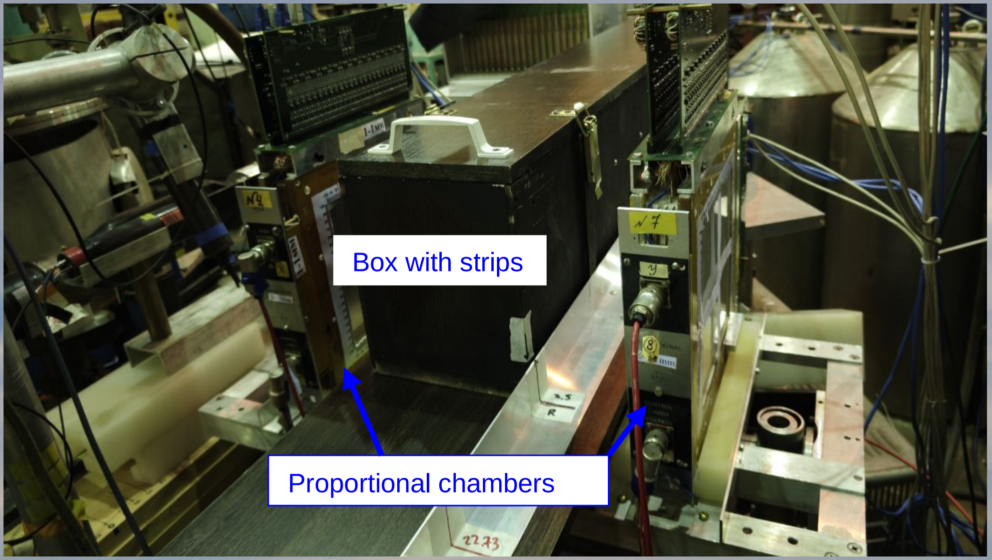
> 140 p.e./MeV





2024 new strip test in Gatchina

- Pion beam of synchrocyclotron SC-1000 at PNPI, 730 MeV/c;
- Individual fiber readout;
- Trigger from external scintillation counters
- 1 mm pitch proportional chambers for track reconstruction
- 12 strips, but only 4 sets of SiPM boards => moving the boards between strips



2 types of scintillator machined from a block of a bulk polystyrene:

✔ **IPTP (Dubna, Russia)**, air-based polymerization chamber **100%**

✔ ASPECT (Dubna, Russia), liquid-based polymerization chamber **85%**

5 types of WLS fibers:

✔ Kuraray Y11 multi-cladding non-strained 1.2 mm

✔ Kuraray Y11 multi-cladding non-strained 1.0 mm

✔ Kuraray Y11 multi-cladding strained 1.0 mm

✔ Kuraray Y11 single cladding non-strained 1.0 mm

✔ Saint Gobain BFC-91A multi-cladding 1.2 mm

Single cladding / multi-cladding	**72%**	1.0 mm / 1.2 mm	**96%**
Strained / non-strained	**91%**	BFC-91A / Y11	**62%**

- DANSS recorded the first data in April 2016 and is running now. More than 8.5 million IBD events collected. The experiment is still running.
- We record more than 5 thousand antineutrino events per day in the closest position. Signal to background ratio is > 50.
- A search for sterile neutrinos done using relative counts only (model-independent approach). Two best points observed:

$$\Delta m^2=0.3\ eV^2,\ \sin^2_{ee}2\theta=0.07:\ \Delta\chi^2=-8.0\ (2.0\sigma)$$

$$\Delta m^2=1.3\ eV^2,\ \sin^2_{ee}2\theta=0.016:\ \Delta\chi^2=-7.4$$

This is not statistically significant (2.0σ) to claim an indication of sterile neutrino.

- We use relative counts at top and bottom positions to search for large extra dimensions (LED). A large exclusion region set covering a very interesting part of LED parameters space, preferred by gallium and reactor anomalies. The significance of DANSS best point a = 0.536 μm, m_0 = 0.038 eV is 2σ only => no evidence of LED effect. GA best point is excluded with significance more than 3σ.
- Analysis using absolute rates allows further (though model dependent) advance into larger Δm^2. It practically excludes all sterile neutrino parameter space preferred by BEST. Observed to predicted ratio with absolute νe counting rates is 0.98±0.04 for HM model, and is 1.02±0.04 for KI model.
- DANSS observes antineutrino with energy > 10 MeV: $1561 \pm 157_{stat} \pm 168_{sys}$ (6.8σ).
- Aging of DANSS scintillator detectors was studied during 6.5 years of operation. We observe average aging 0.55±0.05 %/year and a hint of WLS attenuation length shortening at the level of 0.26±0.07 %/year.
- The work on the DANSS upgrade with installation of new strips with SiPM only readout from both ends is under way. The upgraded setup will provide much better energy resolution and higher counting rate. It will allow to scrutinize Neutrino-4 and BEST results. New strip design with 16 SiPM per strip was successfully tested at muon beam. New strips have high light yield more than 140 ph.c./MeV.

RSF grant https://rscf.ru/en/project/23-12-00085/

Thank you !

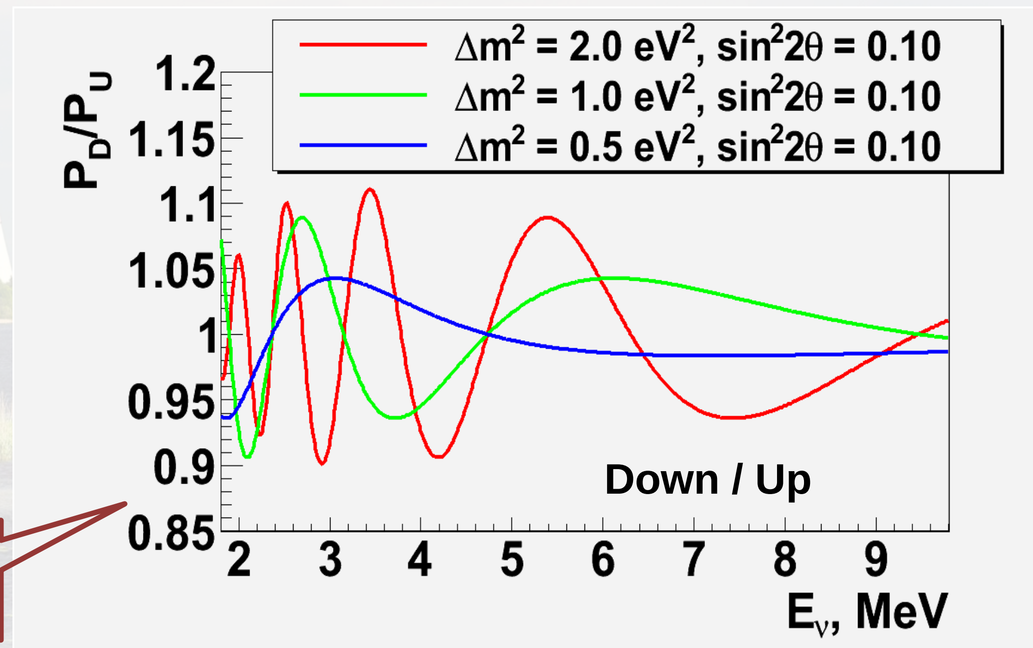
RSF grant https://rscf.ru/en/project/23-12-00085/

In a simple model with the 4th neutrino survival probability of electron antineutrino from the reactor is given by the formula:

$$P_{ee}^{2\nu}(L) = 1 - \sin^2(2\theta_i)\sin^2\left(1.27\frac{\Delta m_i^2[\mathrm{eV}^2]L[\mathrm{m}]}{E_{\bar{\nu}_e}[\mathrm{MeV}]}\right)$$

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.

Naïve ratio without smearing by reactor and detector sizes and the resolution

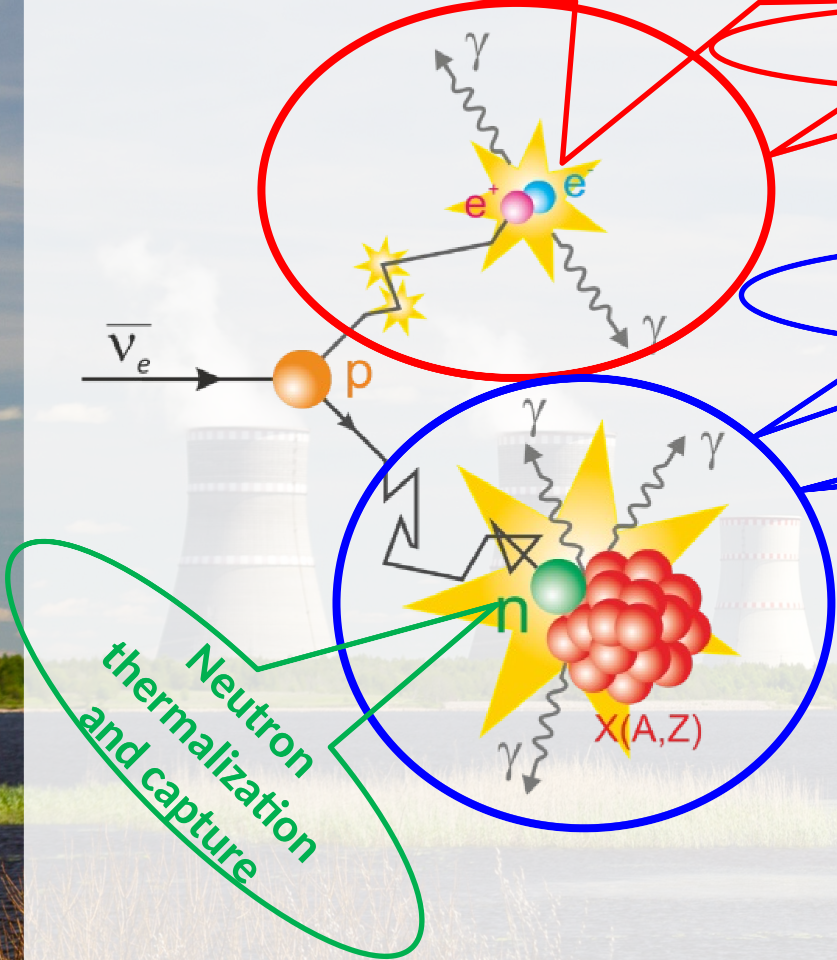


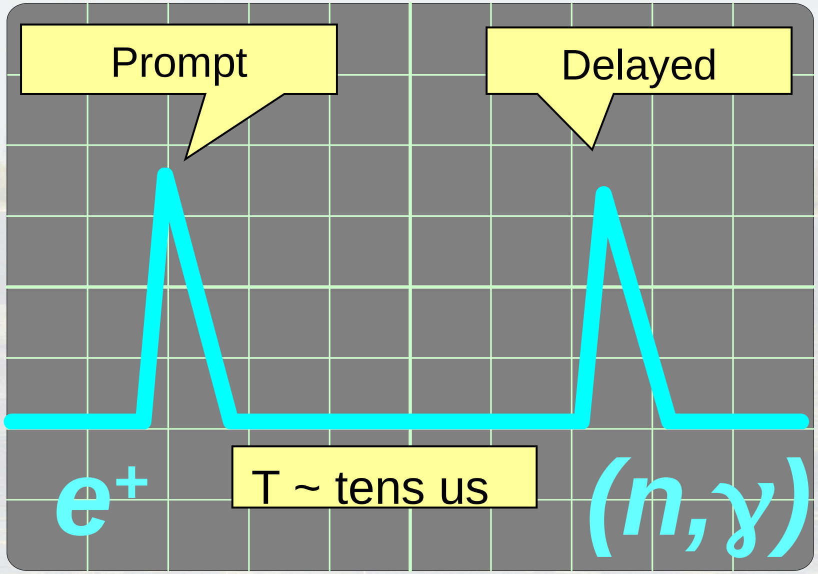
Inverse Beta-Decay (IBD)

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

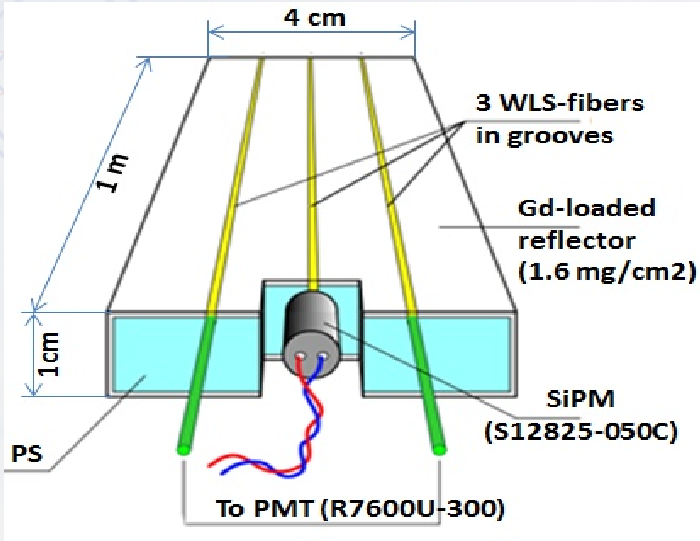
H. Bethe and R. Peierls 1934.
F. Reines and C. L. Cowan 1953-56

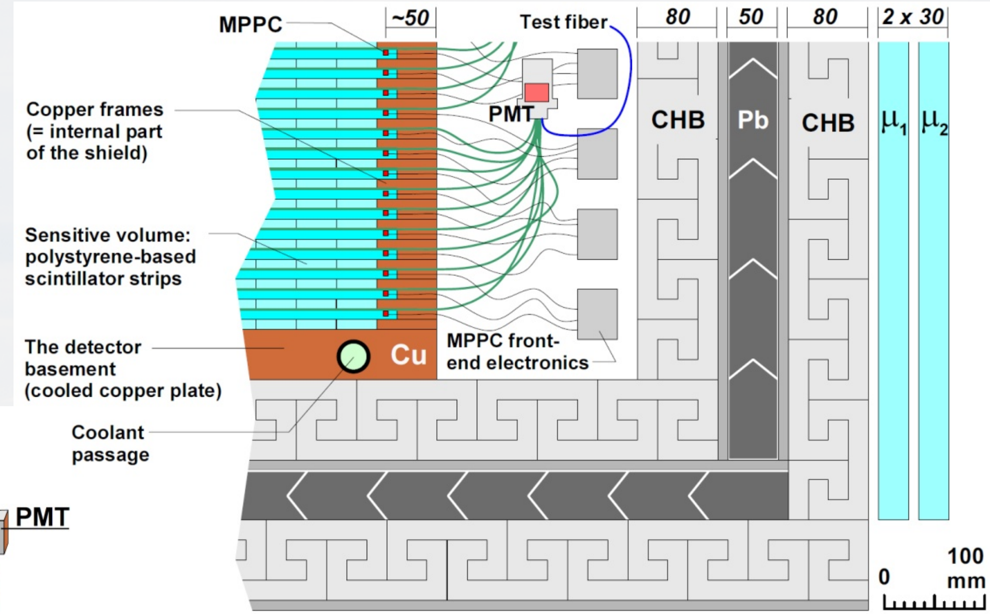
$E_e \approx E_\nu$ – 1806 MeV



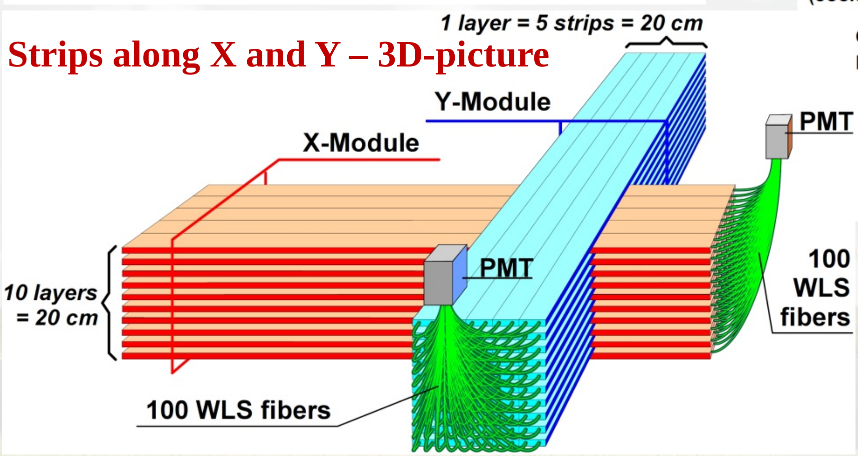


Detector of the reactor AntiNeutrino based on Solid-state Scintillator (ITEP and JINR Collaboration)





Strips along X and Y – 3D-picture

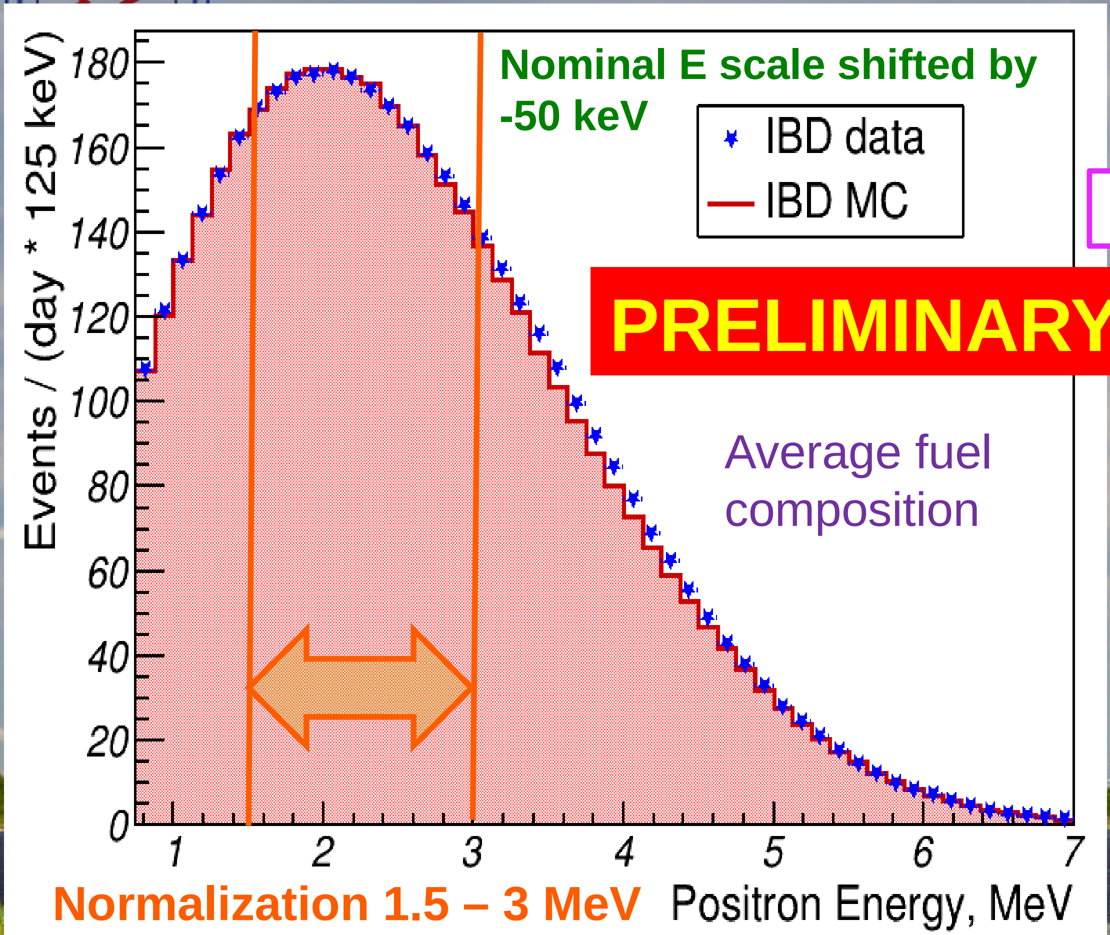


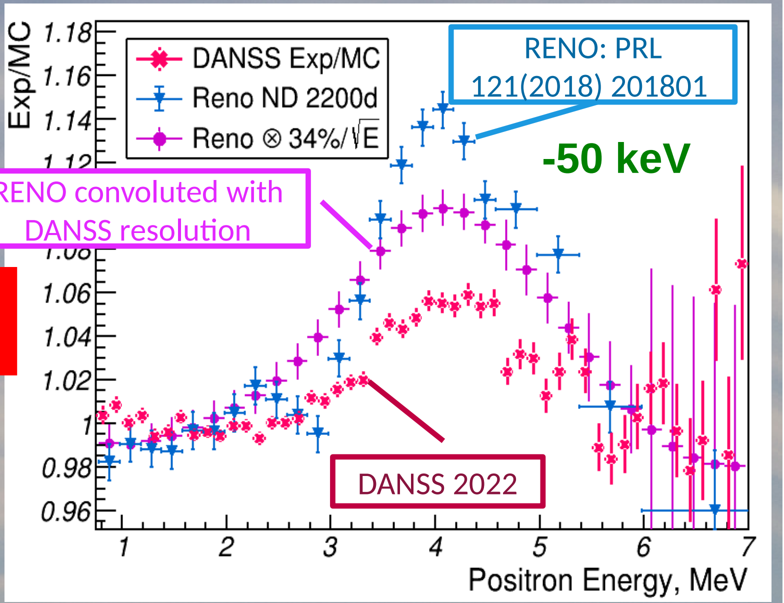
- Scintillation strips 10x40x100 mm³ with Gd-dopped coating (0.35%wt)
- Double PMT (groups of 50) and SiPM (individual) readout
- SiPM: 18.9 p.e./MeV & 0.37 X-talk
- PMT: 15.3 p.e./MeV
- 2500 strips = 1 m³ of sensitive volume

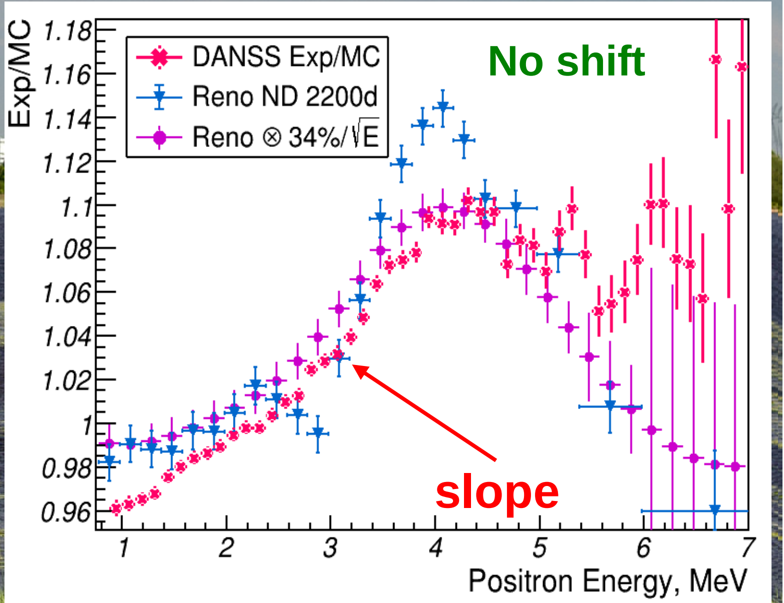
- Multilayer closed passive shielding: electrolytic copper frame ~5 cm, borated polyethylene 8 cm, lead 5 cm, borated polyethylene 8 cm
- 2-layer active μ-veto on 5 sides
- Dedicated WFD-based DAQ system
- Total 46 64-channel 125 MHz 12 bit Waveform Digitisers (WFD)
- System trigger on certain energy deposit in the whole detector (PMT based) or μ-veto signal
- Individual channel selftrigger on SiPM noise (with decimation)

JINST 11 (2016) no.11, P11011

Positron spectrum comparison to H-M model

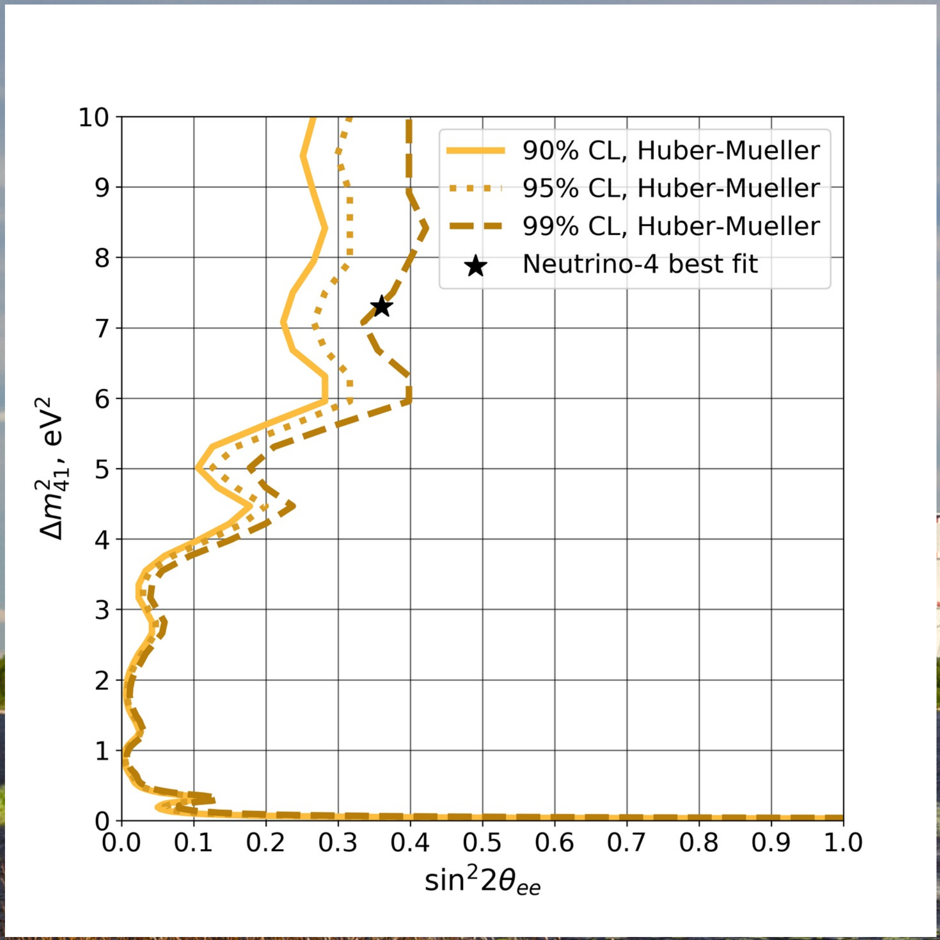


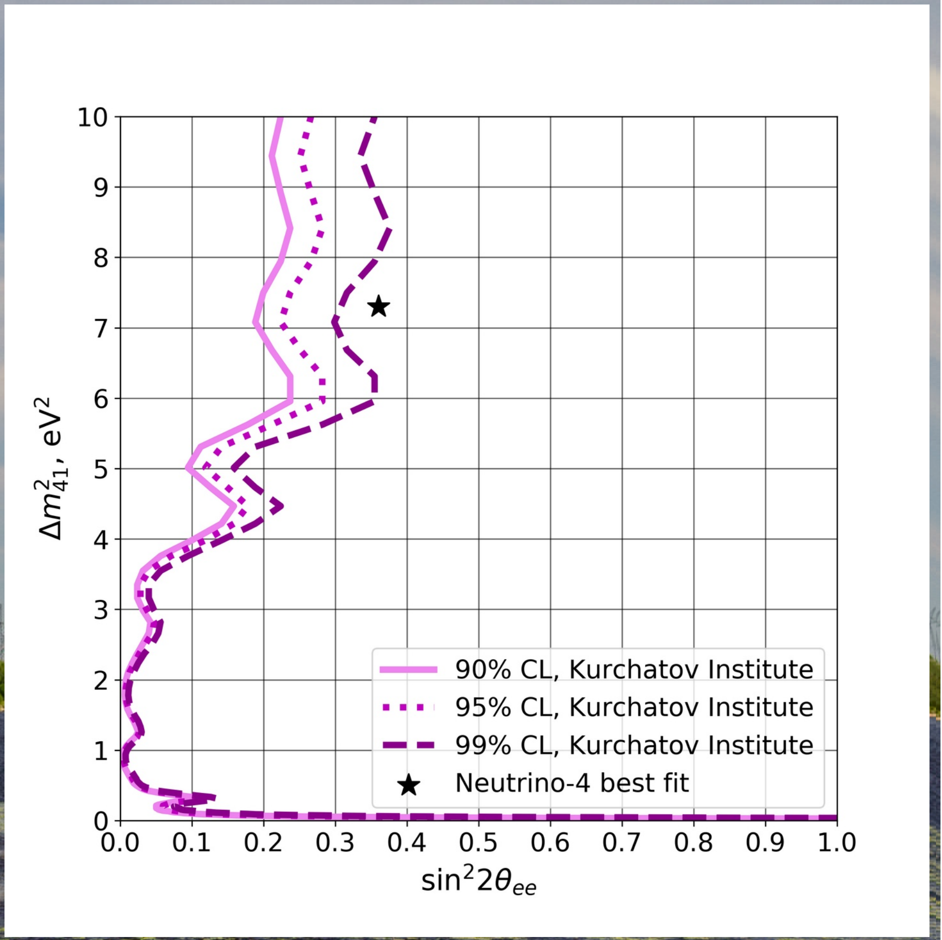




- New energy calibration
- Strong dependence on energy shift and scale
- Effect (if does exist) looks twice smaller than expected from other measurements

Using absolute counting rates





Large extra dimensions

- Neutrino oscillations (case of n=1, other are much smaller if exist)
  - Right neutrinos ν_R (and $\bar{\nu}_L$) being $SU(2)$ singlets can oscillate to LED.
  - An amplitude for survival probability for $\bar{\nu}_{ee}$ is given by

$$A_i \approx \left(1 - \frac{\pi^2}{6} m_i^2 a^2\right) \exp\left(i\frac{m_i^2 L}{2E}\right) + 2m_i^2 a^2 \exp\left(i\frac{m_i^2 L}{E}\right) \sum_{n=0}^{\infty} \frac{\exp\left(i\frac{n^2 L}{2ea^2}\right)}{n^2}, am_i \ll 1$$

where m_i is a mass of i-th neutrino state and $\frac{n}{a} = m_n^{KK}$ - mass of n-th Kaluza-Klein state [1]

$$\bar{\boldsymbol{S}}_{MC} = \sum_{L\,(r_d, r_r)} \left(\left|Amplitude\left(\frac{\boldsymbol{E}_{\bar{\nu}}}{L}, a, m_0\right)\right|^2 \cdot profile(r_r) \cdot spectra(\boldsymbol{E}_{\bar{\nu}}) \cdot \frac{1}{L^2}\right) @M_{response}$$

Oscillations to LED

Distribution of fission points

$\bar{\nu}$ energy spectrum

Geometric flux attenuation

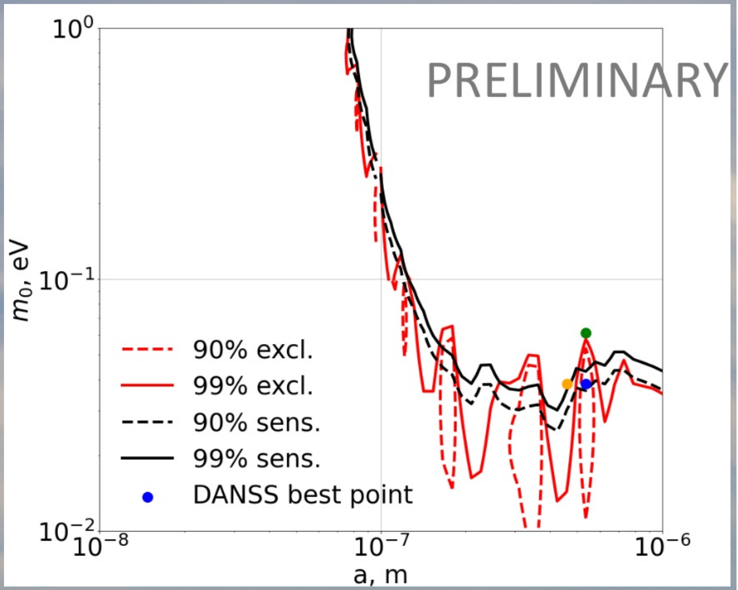
Modelled matrix of detector's response

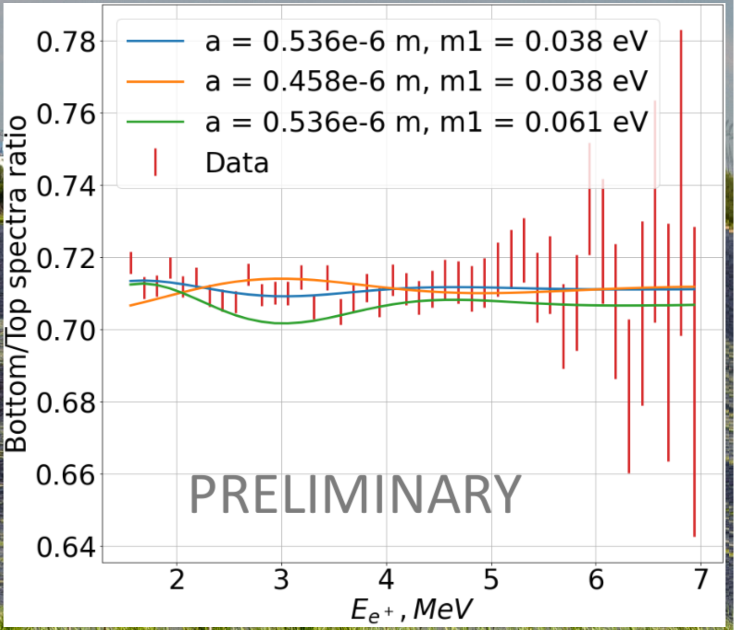
Test statistics

$$\chi^2 = \sum_{bins} \frac{(R_i^{MC}(\eta) - R_i^{Data})^2}{\sigma_i^2} + \sum_{syst} \frac{(\eta - \eta_0)^2}{\sigma_\eta^2}$$

- R – ratio of spectra in Bottom and Top position
- σ – experimental error
- η – systematic parameter:
  - Relative efficiency k: $k_0 = 1, \sigma_k = 0.3\%$
  - Background b: $b_0 = 0, \sigma_b = 35\%$ of subtracted correlated background [3]

See poster by Petr Gorovtsov and Nataliya Skrobova.





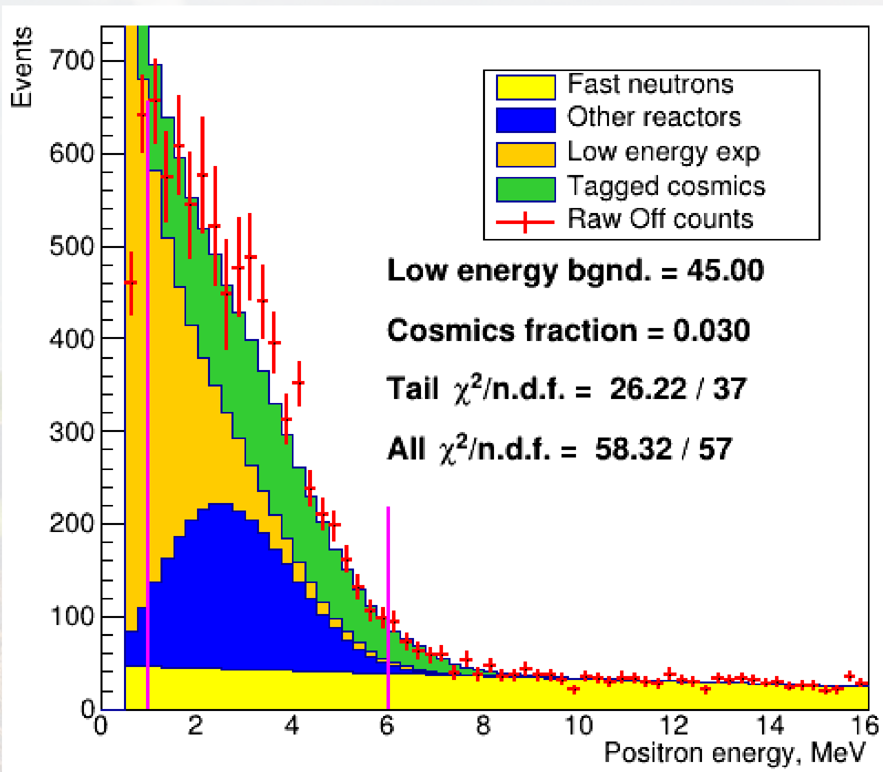
Reactor off background subtraction

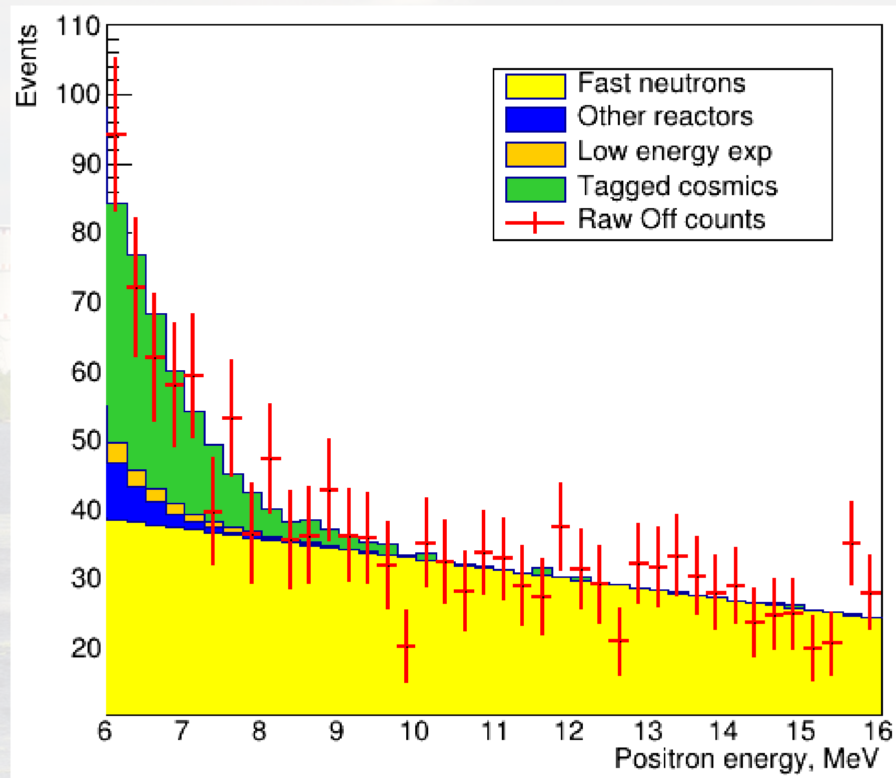
Fast neutron background is a line extrapolation from 11-16 MeV.

Neutrinos from the adjacent reactors — 0.6 % of the top position counts at reactor on.

Background from VETO inefficiency (missed muons) is from and approximation of reactor off spectrum above 6 MeV by scaling spectrum from tagged muon background events.

The residual background at low energies is appriximized by the function $e^{-(E/1.0\ \text{MэB})}$. The contribution is optimized using reactor off data. It is small at high energies.





Reactor on positron spectrum