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New Results from the DANSS Experiment

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There are several indications sterile neutrino with $\Delta m^2 \sim 1\ eV^2$, $Sin^2 2\theta_{ee} \sim 0.1$

1. LSND, MiniBoone: ν_e ($\bar{\nu}_e$) appearance in ν_μ ($\bar{\nu}_\mu$) beams: > 6σ
   Not confirmed by MicroBoone arXiv:2110.14054v2 but not excluded

2. SAGE and GALEX ν_e deficit (GA) confirmed by BEST: > 5σ
   arXiv: 2109.11482, arXiv: 2201.07364 , PRL 128.232501

3 Reactor $\bar{\nu}_e$ deficit (RAA): > 3σ
   Explained by KI (arXiv:2103.01684v1), DayaBay, RENO experiments ??

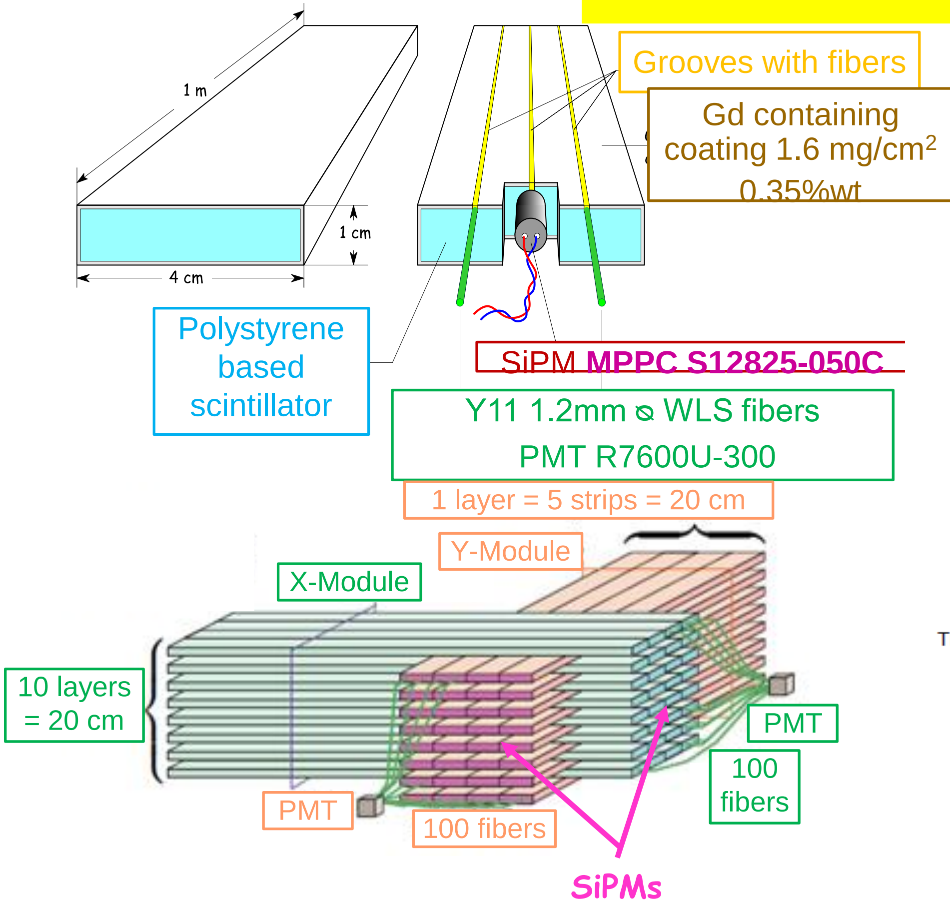
4. Neiutrino-4 claim of sterile neutrino observation
   $\Delta m^2 = 7.3 \pm 1.17 eV^2$ and $\sin^2 2\theta = 0.36 \pm 0.12$ 2.7σ Phys.Rev.D 104, 032003 (2021)

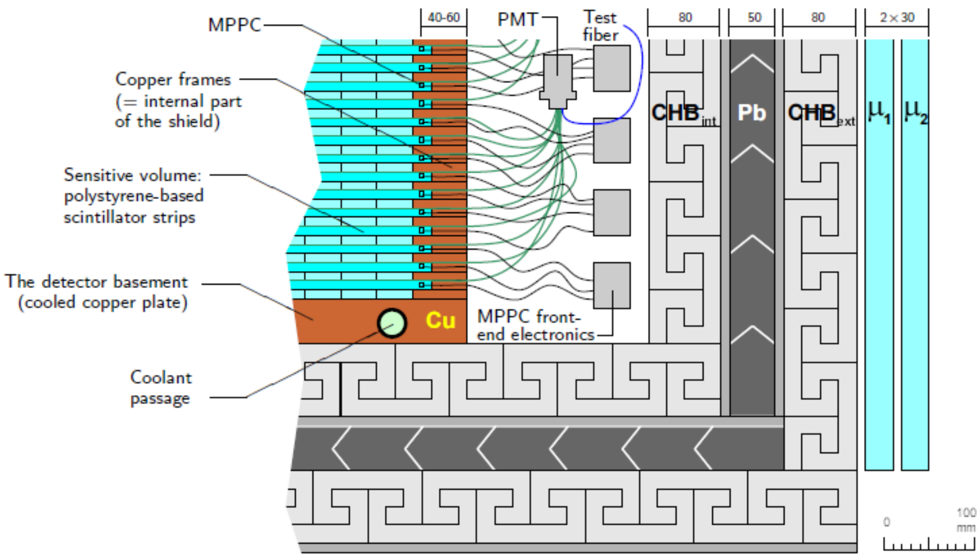
These are statistically strongest indications of physics BSM!

In 3+1ν model $P^{SBL}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$

DANSS Detector design

JINST 11(2016)no11,P11011

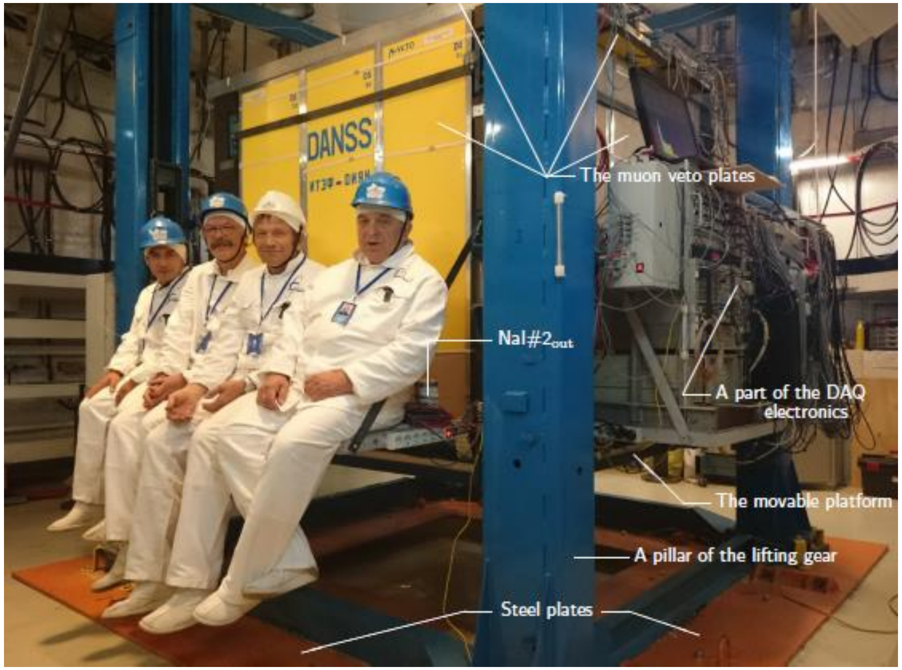


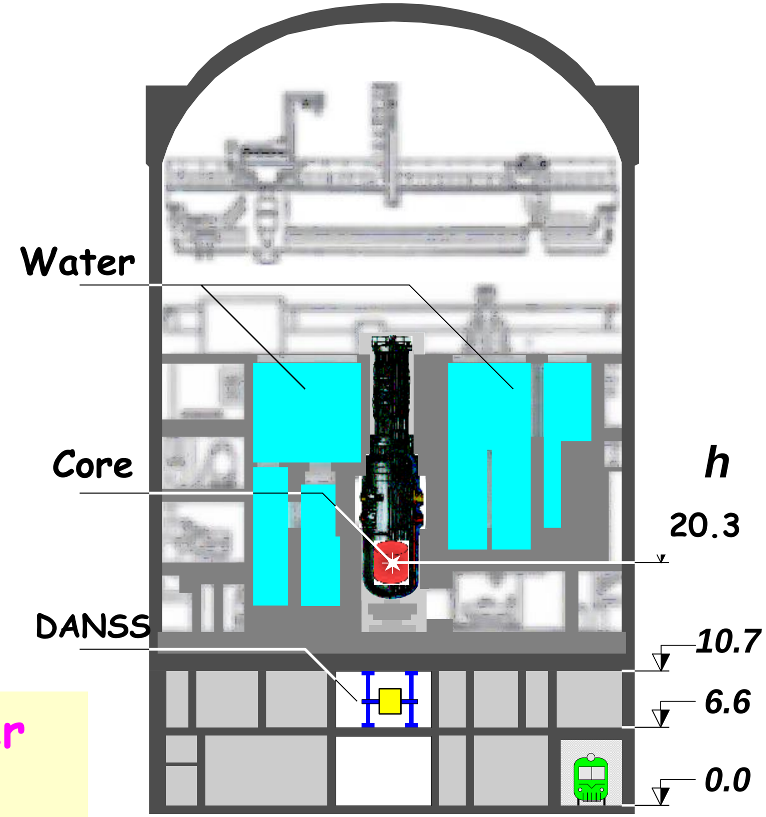


- 2500 scintillator strips with Gd containing coating for neutron capture
- Light collection with 3 WLS fibers
- Central fiber read out with individual SiPM
- Side fibers from 50 strips make a bunch of 100 on a PMT cathode = Module

- Two-coordinate detector with fine segmentation – spatial information
- 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

DANSS at Kalinin Nuclear Power Plant





DANSS is installed on a movable platform under 3.1 GW WWER-1000 reactor (Core:h=3.7m, ∅=3.1m) at Kalinin NPP.
~50 mwe shielding => μ flux reduction ~6!
No cosmic neutrons!

Detector distance from reactor core 10.9-12.9 (center to center) is changed 2-3 times a week

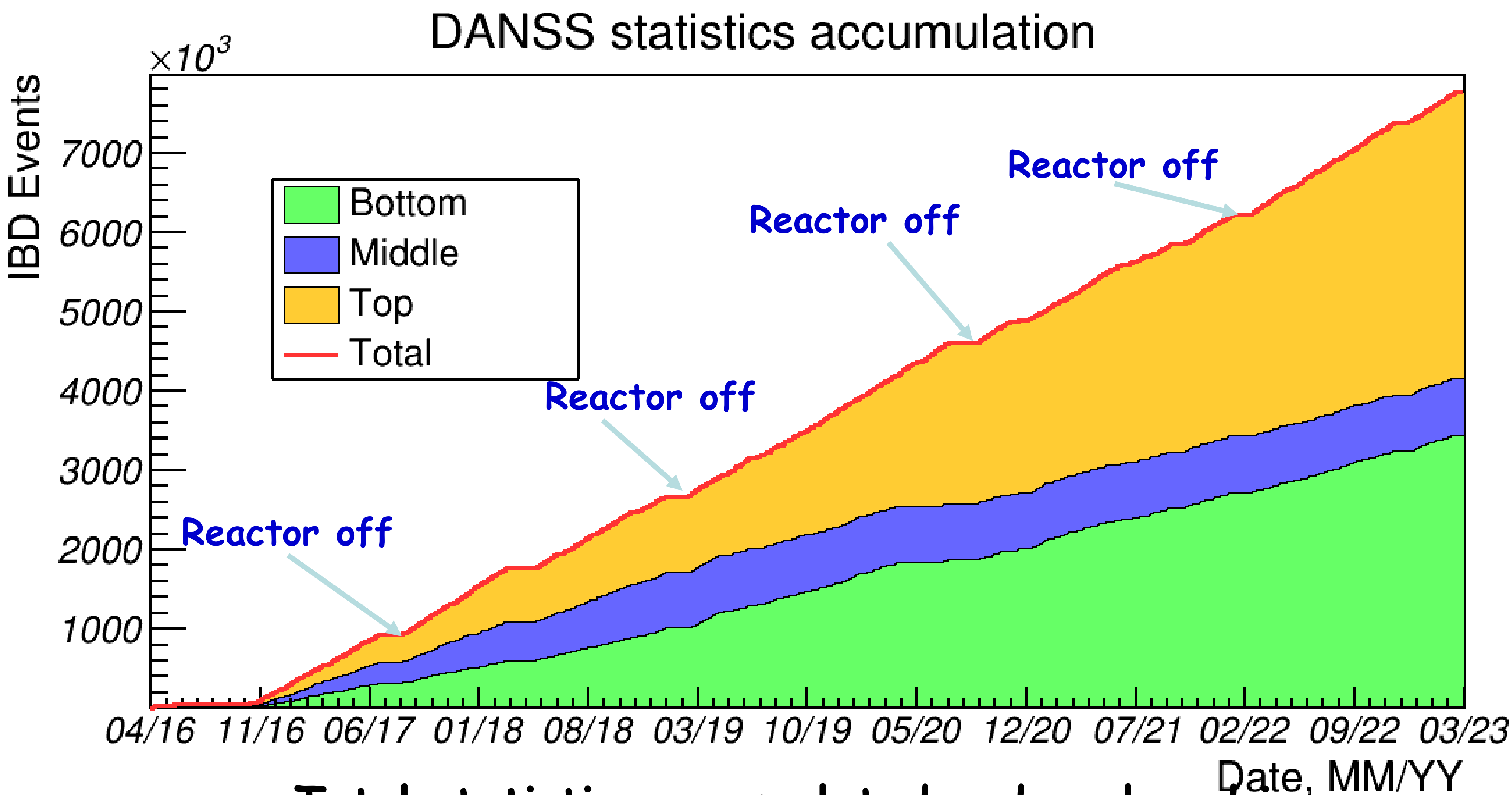
Trigger: ΣE(PMT)>0.5-0.7MeV=>Read 2600 wav forms (125MHz), look for correlated pairs offline.

Fuel fission fractions: average, start and end of campaign [%]

235U	54.1	63.7	44.7
239Pu	33.2	26.6	38.9
238U	7.3	6.8	7.5
241Pu	5.5	2.8	8.5

(for a typical campaign)

DANSS collected 7.7 M antineutrino events in 6.5 years



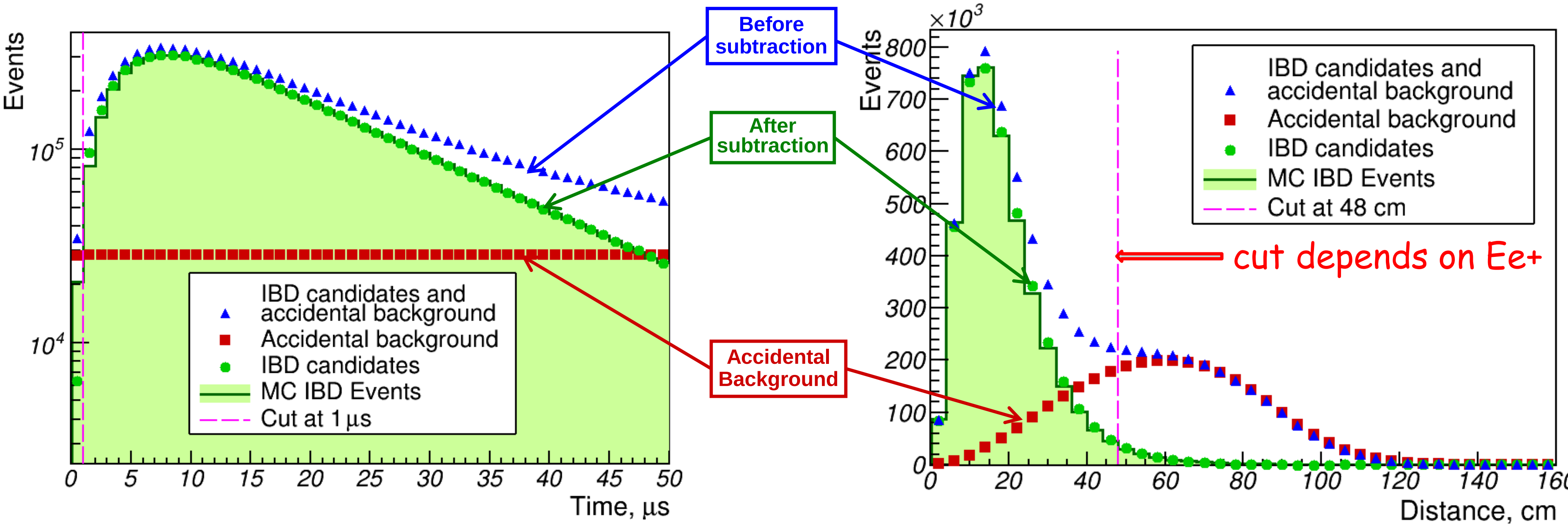
Total statistics accumulated and analyzed is

7.7M IBD-events in 6.5 years and 4 reactor off periods

1.5 M additional events since last Summer

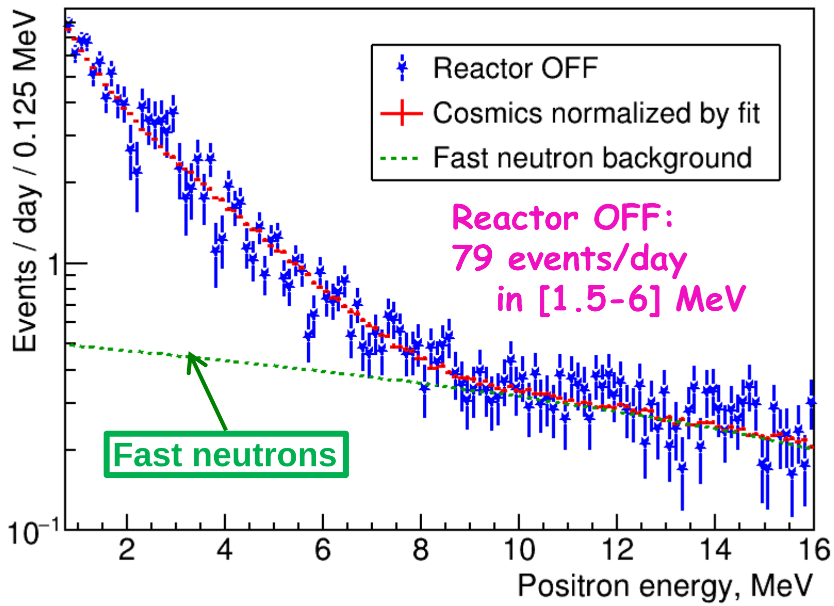
5.5 M events in oscillation analysis

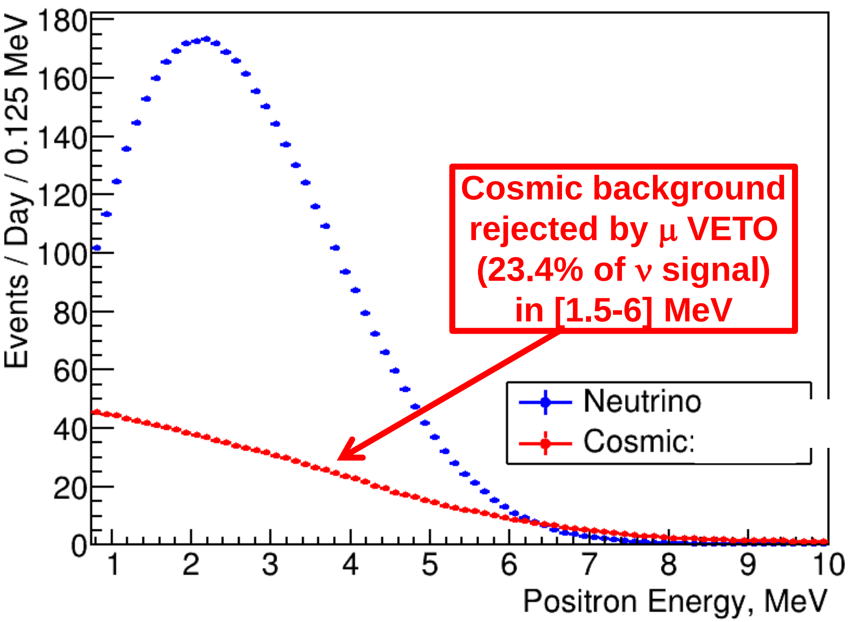
Accidental coincidence background



- Accidental coincidence of 2 uncorrelated signals (e+-like and neutron-like) in a IBD window [1-50] μs → accidental coincidence background (ACB)
- ACB spectrum is constructed directly from data applying the same physics cuts as for IBD signal except coincidence time taken outside IBD time window [1-50] μs in numerous non-overlapping intervals (large statistics is essential to decrease statistical errors of subtraction) → No systematic errors
- ACB rate is 15.0% of IBD rate (Top detector position in [1-50] μs, Ee+: 1.5-6 MeV).
- Selection of cuts (e.g. geometric) to reduce ACB ⇒ smaller statistical errors

Subtraction of residual backgrounds

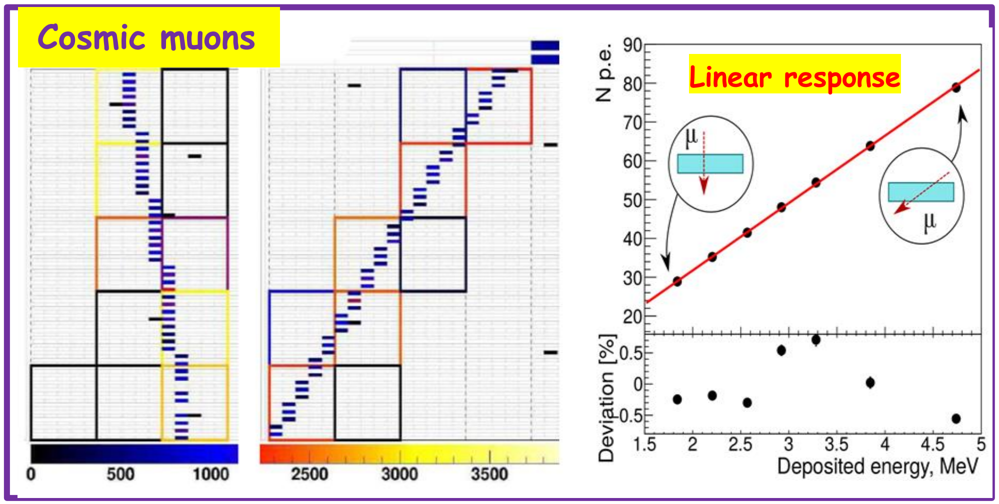


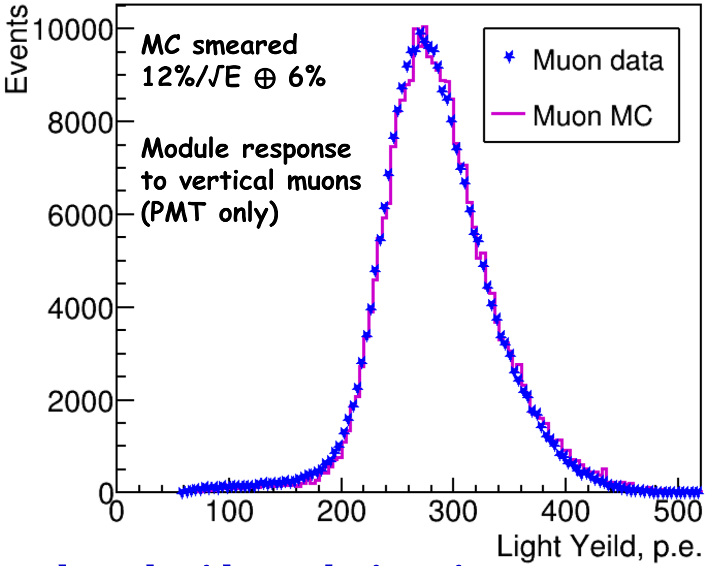


- 25 ν events/day from neighbor reactors were subtracted
- **Fast neutrons: linearly extrapolate from high energy region and subtract separately from positron and visible cosmic spectra, CR (fast neutron) = 16 events/day (in 1.5-6 MeV range)**
- **Visible cosmic background (CB) has been directly rejected by VETO,**
  it is 23.4% of neutrino signal (for top position in [1.5-6 MeV] range)
- **CB of ~1% at Top position due to VETO inefficiency, which was found to be ~4.5% from reactor OFF data, was subtracted (44 events/day).**
- **Additional 19 events/day at low energies observed in reactor off data were subtracted**
- **Total subtracted background is 1.75% for the top detector position. S/B>50!**

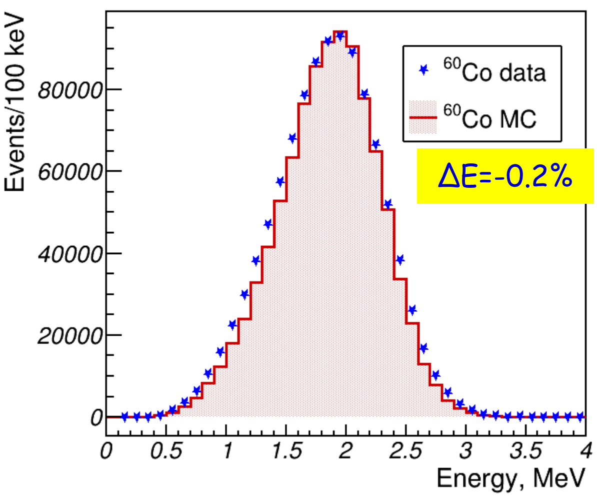
Calibration

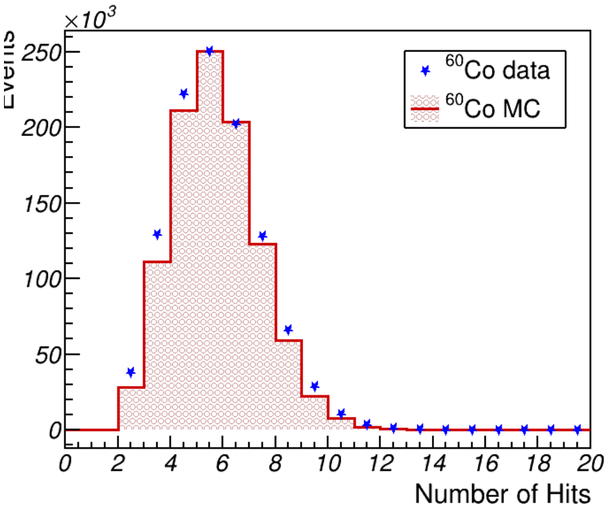
2500 SiPM gains and X-talks are calibrated every 30-40 min.
All 2550 channels are calibrated every 2 days using cosmic muons

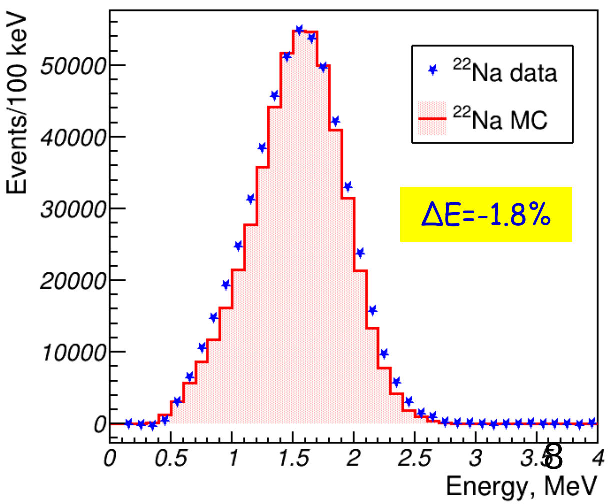




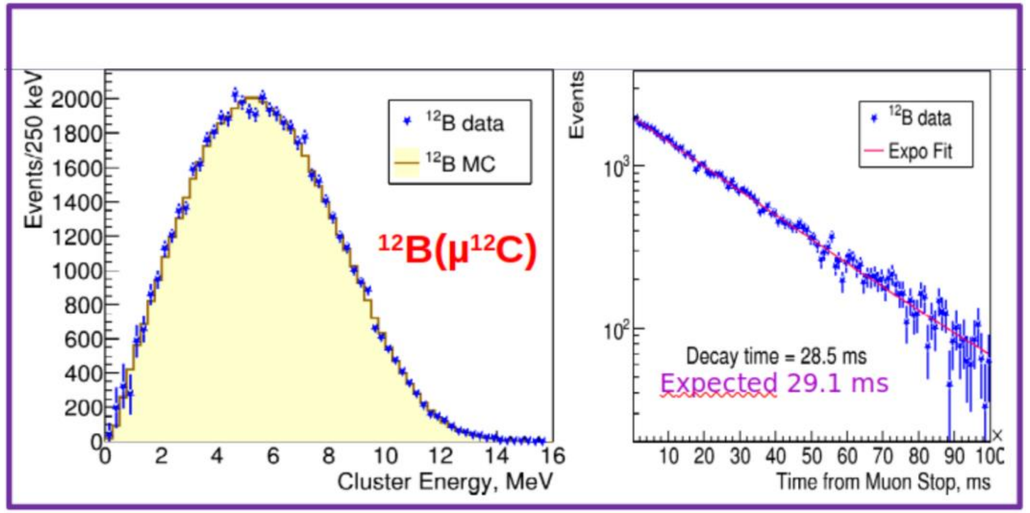
Several calibration sources are used to check the detector response

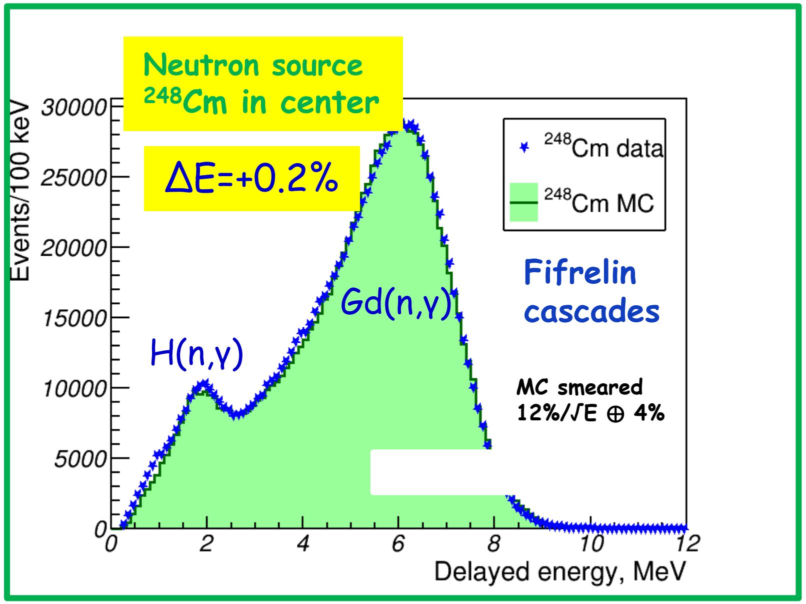


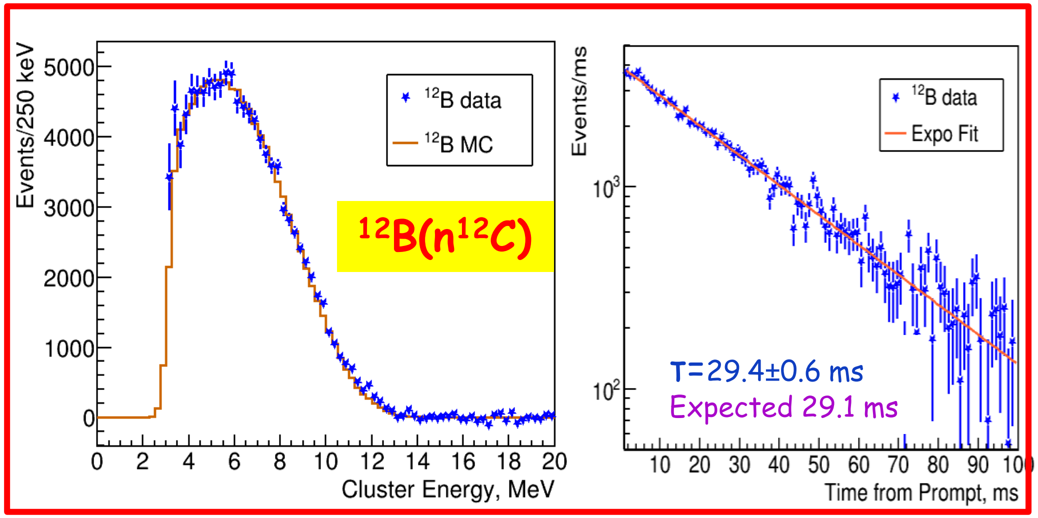


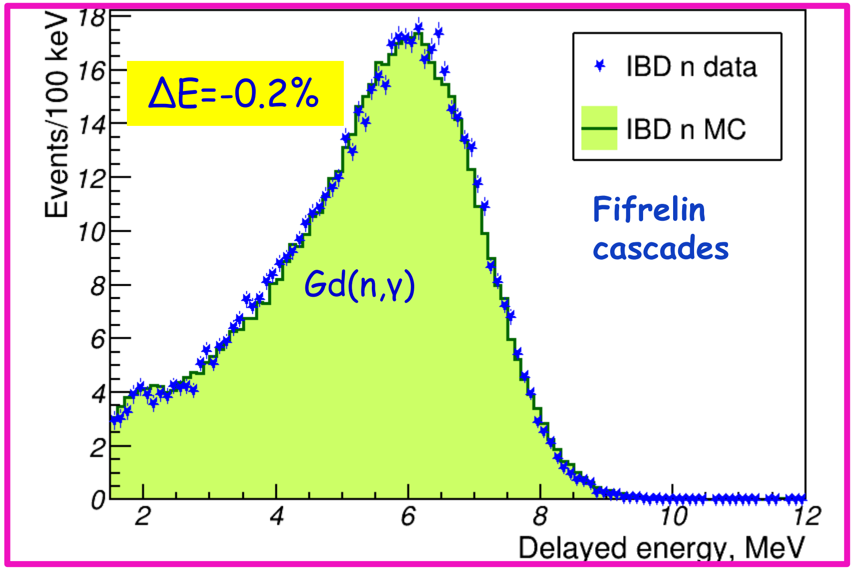


Calibrations



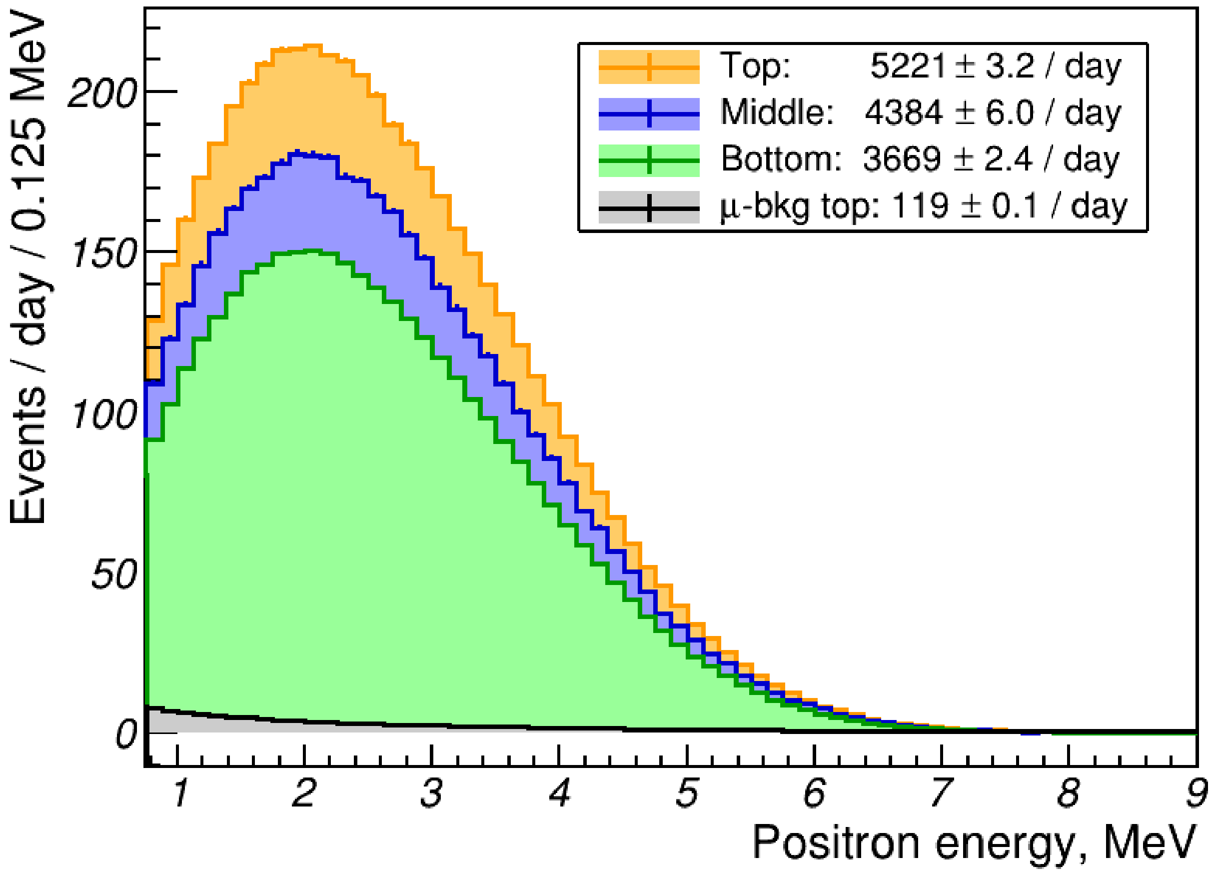






- **Energy scale has been fixed using β-spectrum of ^{12}B, which is similar to positron signal**
- **Other sources agree within +/- 0.2% with exception of ^{22}Na which is 1.8% below.**
- **Systematic error on E scale of +/-2% was added due to ^{22}Na disagreement**
  Hope to reduce this error soon

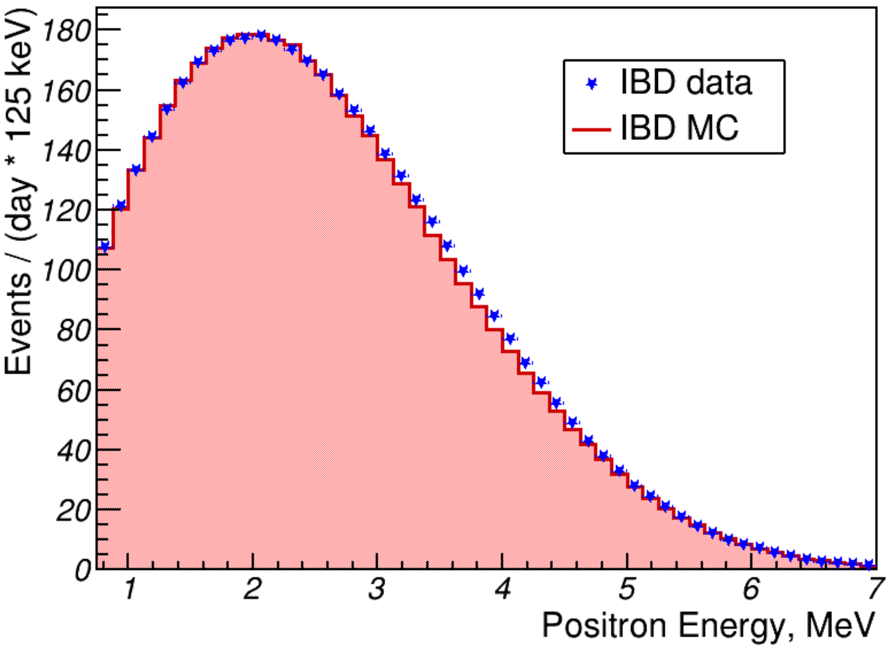
Positron spectrum of IBD-signal

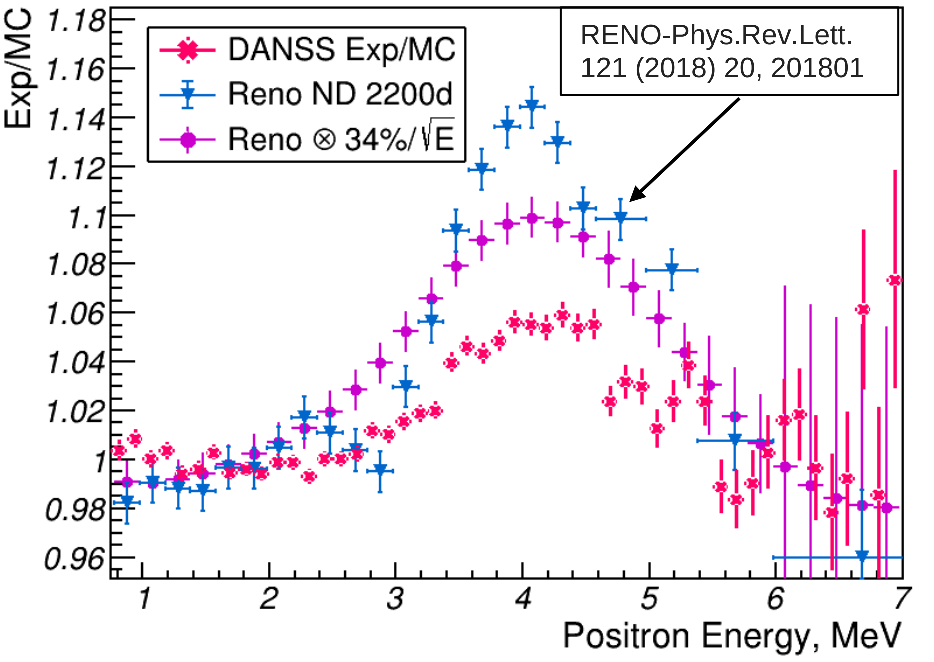


- **Positron kinetic energy spectra (no annihilation photons) at 3 detector positions**
- **> 5000 events/day in detector fiducial volume (78% of full volume)**

  at 'Top' position (closest to the reactor).
- **Background (subtracted) ~1.8% (Top position, E: 1.5-6MeV).**
- **Signal/Background >50!**

Positron spectrum: experiment vs. H-M Model





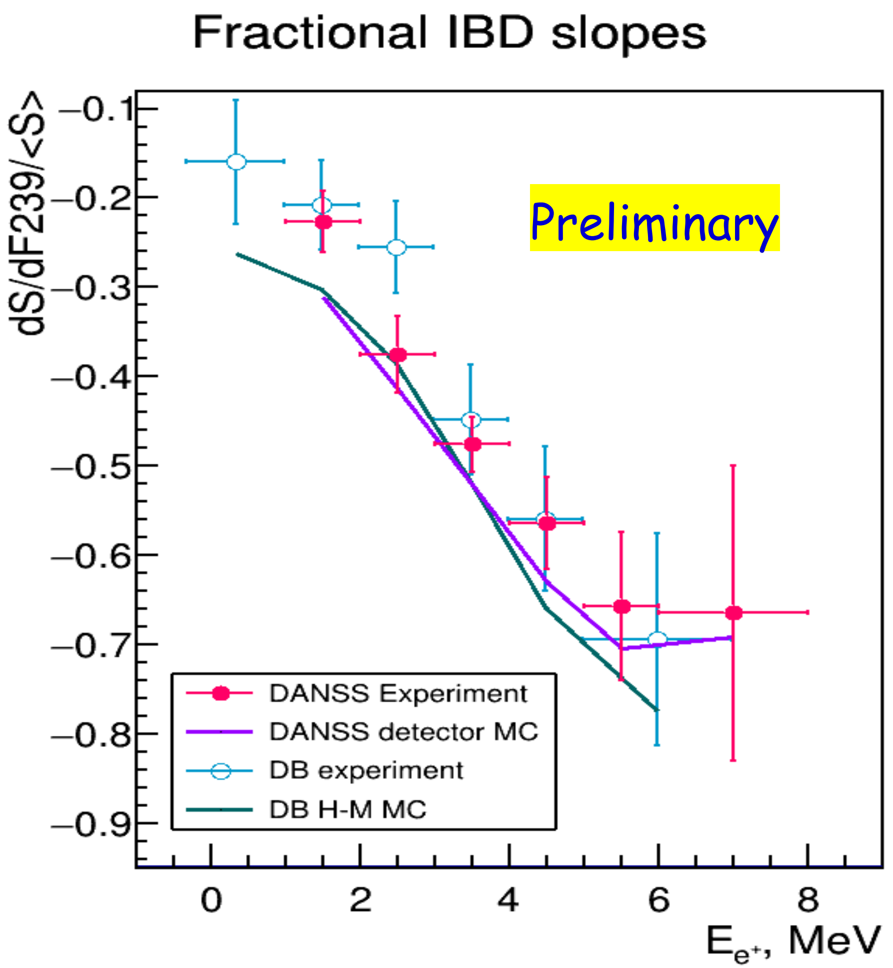
- We see a bump in e+ spectrum at similar position to other experiments ($E_{prompt}=E_{e+}+1MeV$) if E is shifted by -50 keV
- Bump height is smaller than in RENO
- However, we can not claim bump existence yet

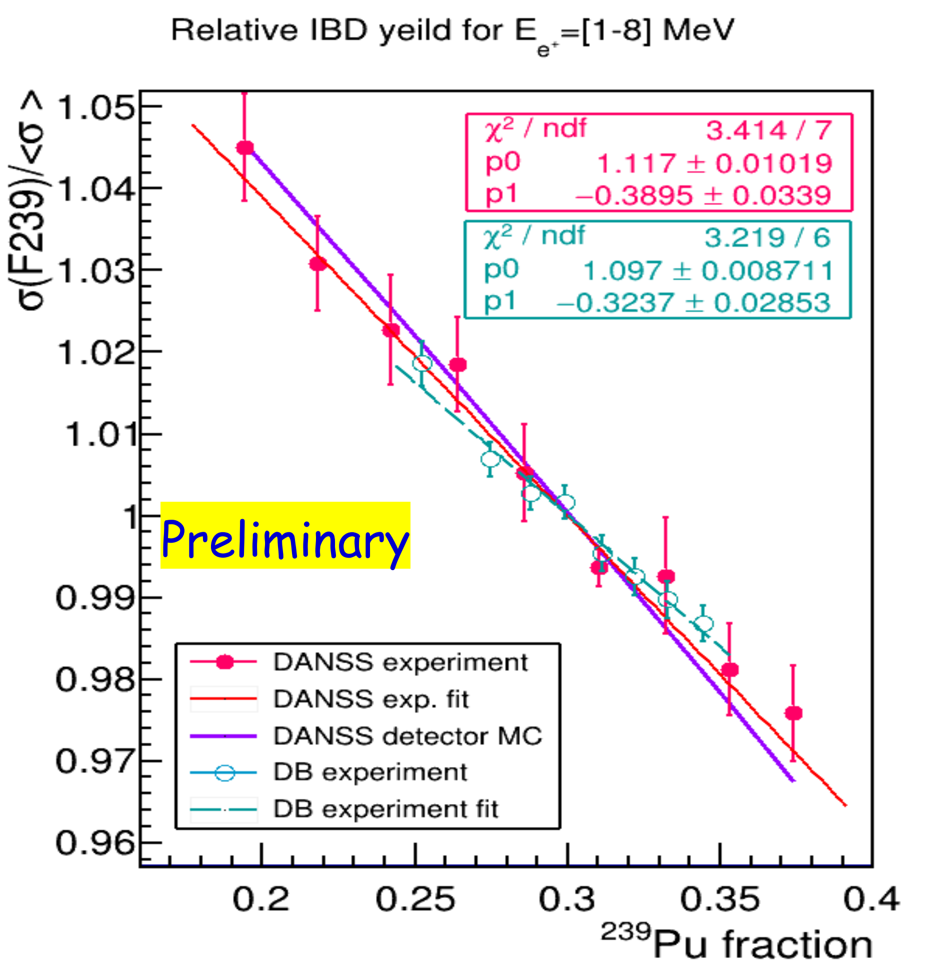
  because of high sensitivity of the shape to energy scale and shift.

  Similar problems should exist in other experiments

Positron spectrum dependence on fuel composition is clearly seen

IBD rate dependence on 239Pu fission fraction (dσ/dF239)/σ(F239=0.3) for various Ee+
It is closer to H-M model than DayaBay results





Errors are dominated by systematics estimated from the spread between campaigns
Probably errors are overestimated

Determination of 235U / 239Pu contributions from the slope

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

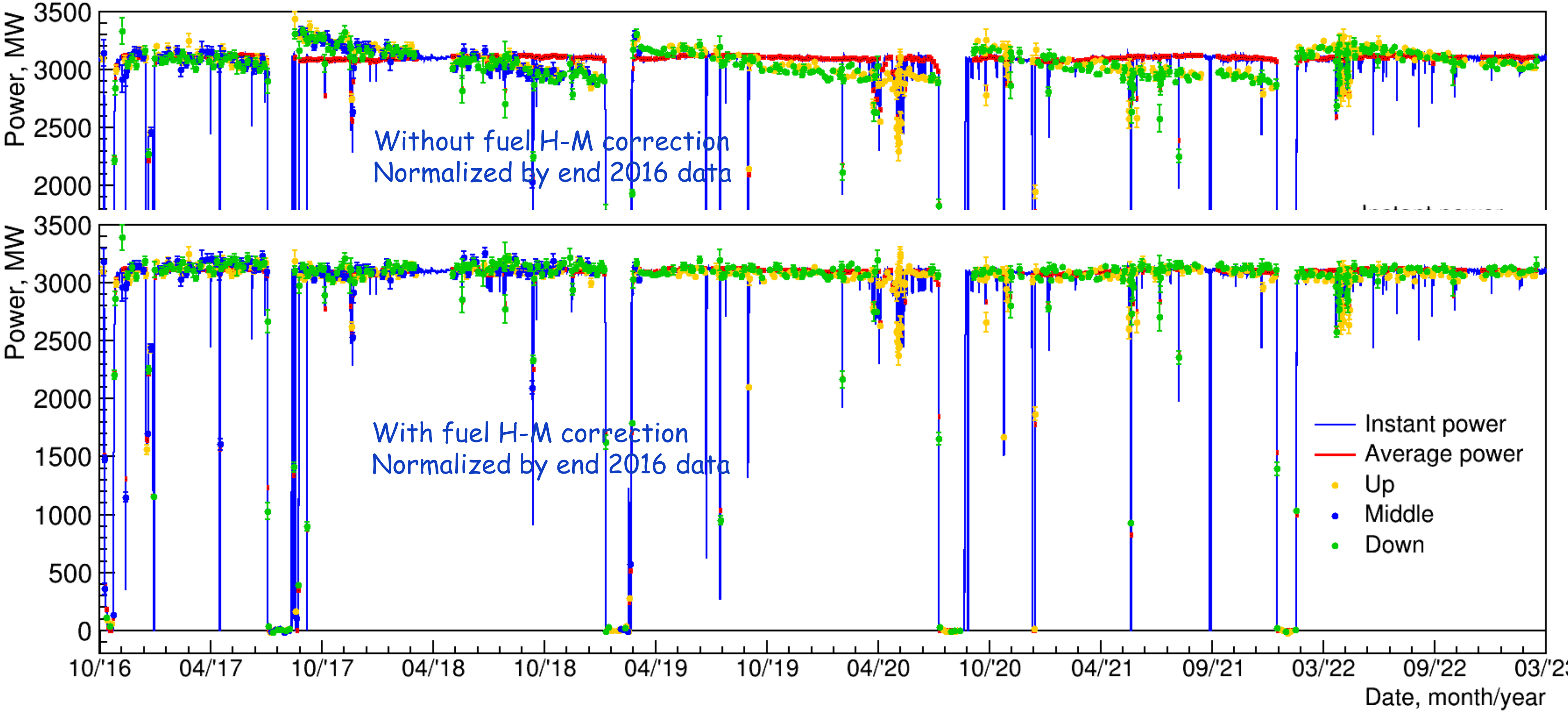
$$\frac{dN}{df_9} = \alpha \cdot \left(\sigma_8 \frac{df_8}{df_9} + \sigma_1 \frac{df_1}{df_9} + \sigma_5 \frac{df_5}{df_9} + \sigma_9\right)$$

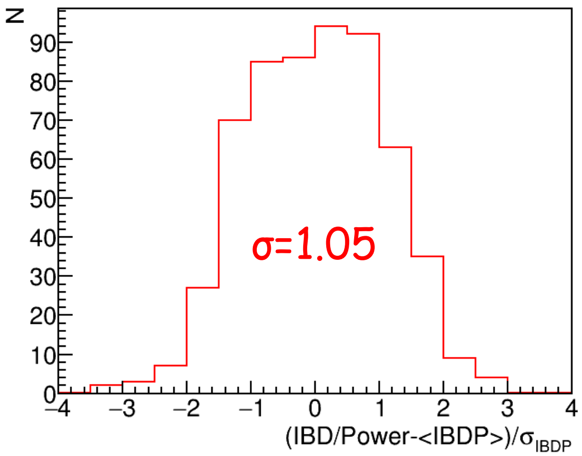
$$SI = \left(\frac{dN}{df_9}\right) / N = \frac{\frac{\sigma_8}{\sigma_9} \frac{df_8}{df_9} + \frac{\sigma_1}{\sigma_9} \frac{df_1}{df_9} + \frac{\sigma_5}{\sigma_9} \frac{df_5}{df_9} + 1}{\frac{\sigma_8}{\sigma_9} f_8 + \frac{\sigma_1}{\sigma_9} f_1 + \frac{\sigma_5}{\sigma_9} f_5 + f_9}$$

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

(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?

Neutrino reactor power monitoring with 1.5% accuracy in 2 days during 6.5 years





Deviations of IBD rate from reactor power are consistent with statistical fluctuations of 1.5% in 2 days

Test statistics

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

3 position data

2 position data

Nuisance parameters (systematics and efficiency)

i – energy bin (36 total) in range 1.5–6 MeV;

$Z_j = R_j^{obs} - k_j \times R_j^{pre}(\Delta m^2,\ \sin^2 2\theta,\ \eta)$ 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, $k^0=1$ $\eta^0=0$

η – nuisance parameters;

W – covariance matrix;

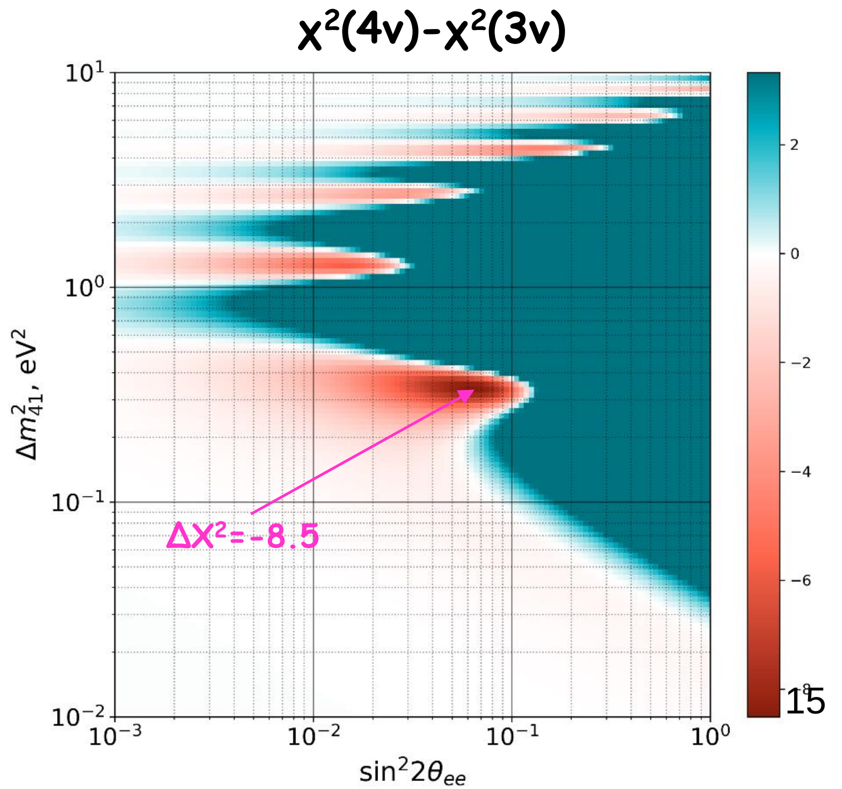
Difference in χ^2 between 4ν and 3ν hypotheses

Red – $\chi^2(4\nu)<\chi^2(3\nu)$,

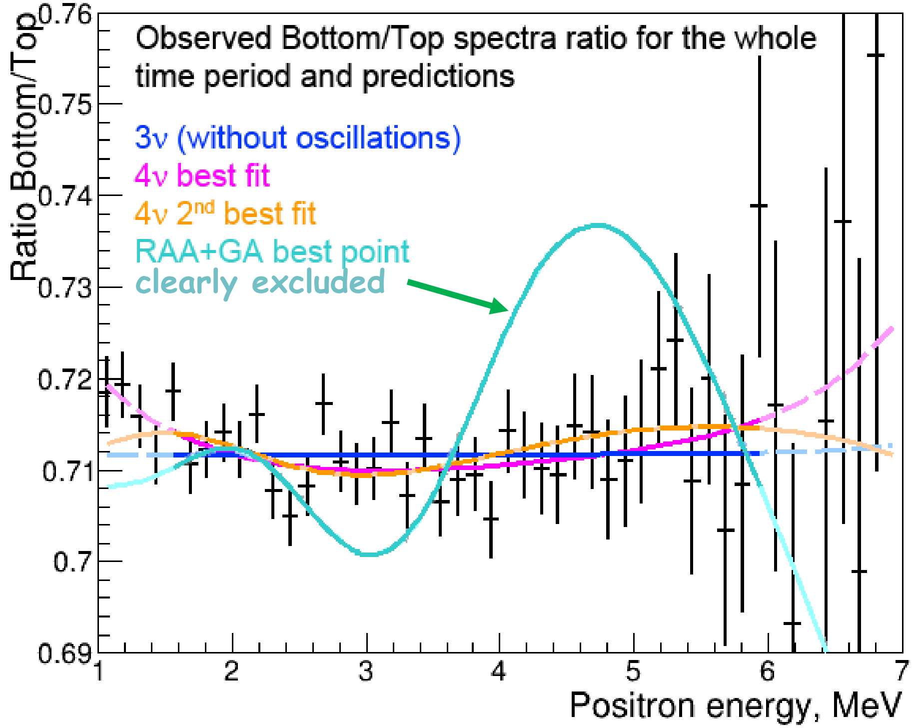
Blue – $\chi^2(4\nu)>\chi^2(3\nu)$,

Dark blue region is excluded at 3σ CL in case of χ^2 distribution with 2 DoF ($\chi^2(4\nu)-\chi^2_{min}$)=11.8

This assumption is not valid ➔ we use Gaussian CLs method to get limits



Ratio of positron spectra



Fit in 1.5-6 MeV range (to be conservative)

(5.5 million IBD events with 1.5 MeV<E<6MeV)

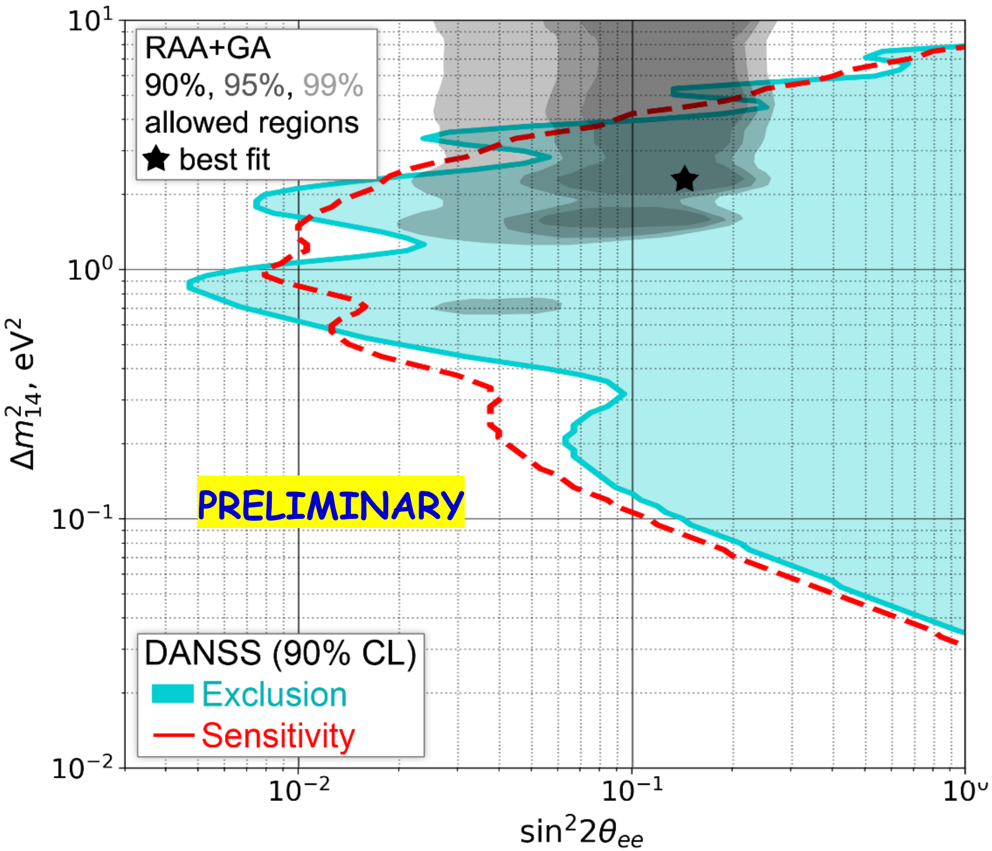
There is no statistically significant evidence in favor of 4ν signal:

ΔX^2=-8.5 (2.1σ) for 4ν hypothesis best fit point Δm^2=0.35 eV^2 , $\sin^2 2\theta$=0.06

ΔX^2=-5.7 for 4ν hypothesis second best fit point Δm^2=1.3 eV^2 , $\sin^2 2\theta$=0.015

- **RAA has been excluded with ΔX^2= 194**
- **RAA was excluded by DANSS with more than 5σ already in 2018 (arXive:1804.04046v1)**

DANSS limits on sterile neutrino parameters
(without neutrino spectrum information)



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)

Exclusion region was calculated using Gaussian CLs method using E_{e+} in 1.5-6 MeV region

The most stringent limit reaches $\sin^2 2\theta < 5\times10^{-3}$ level.

A very interesting part of 4ν parameters is excluded.

The most probable point of RAA is excluded at >5σ confidence level already in 2018

Analysis with absolute neutrino counting rates

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

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

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

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(E, L) is the survival probability due to neutrino oscillations

Systematic uncertainties in absolute neutrino counting rates

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%

Test statistics with neutrino absolute counting rates

Test statistics is defined as follows:

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

phase I
Top, Middle, Bottom

phase II
Top, Bottom

penalty
terms

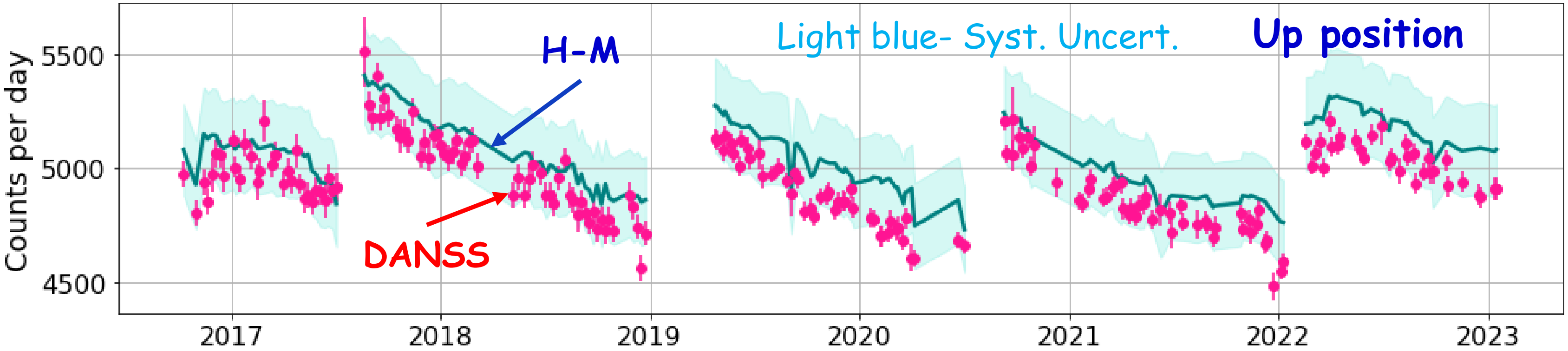
i – energy bin (36 total) in range 1.5–6 MeV,
$Z_j = R_j^{\mathrm{obs}} - k_j \times R_j^{\mathrm{pre}}(\Delta m^2, \ \sin^2 2\theta, \ \eta)$ for each energy bin, (obs for observed, pre for predicted),
$R_1 = Bottom/Top$, $R_2 = Middle/\sqrt{Bottom \cdot Top}$, where
Top, $Middle$, $Bottom$ – absolute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

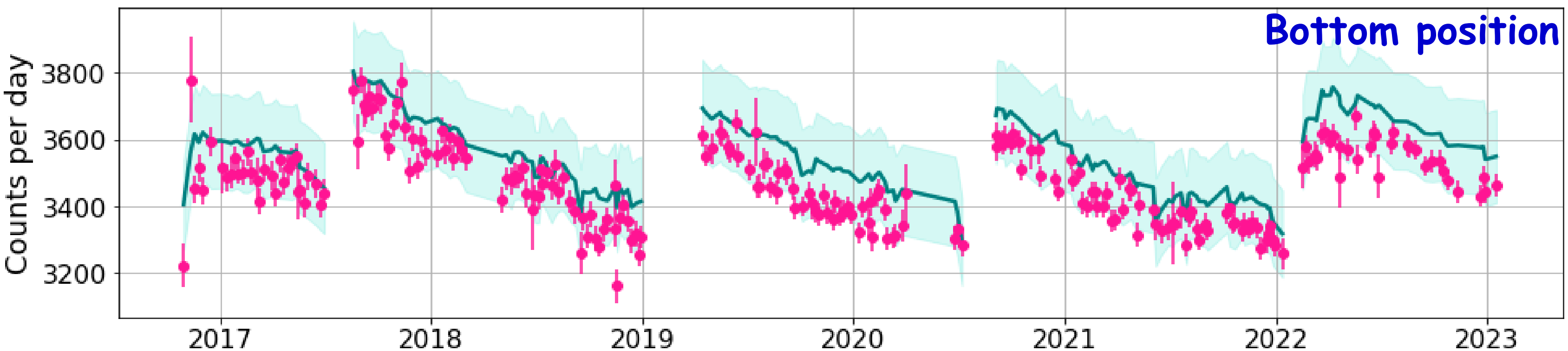
With absolute counting rates:

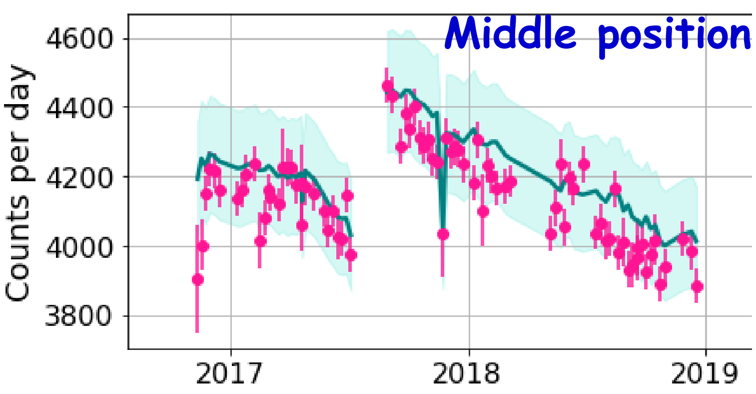
$$\chi^2_{abs} = \chi^2_{rel} + ((N_{top} + N_{mid} + N_{bottom})^{\mathrm{obs}} - (N_{top} + k_2 \cdot \sqrt{k_1} \cdot N_{mid} + k_1 \cdot N_{bottom})^{\mathrm{pre}})^2/\sigma^2_{abs}$$

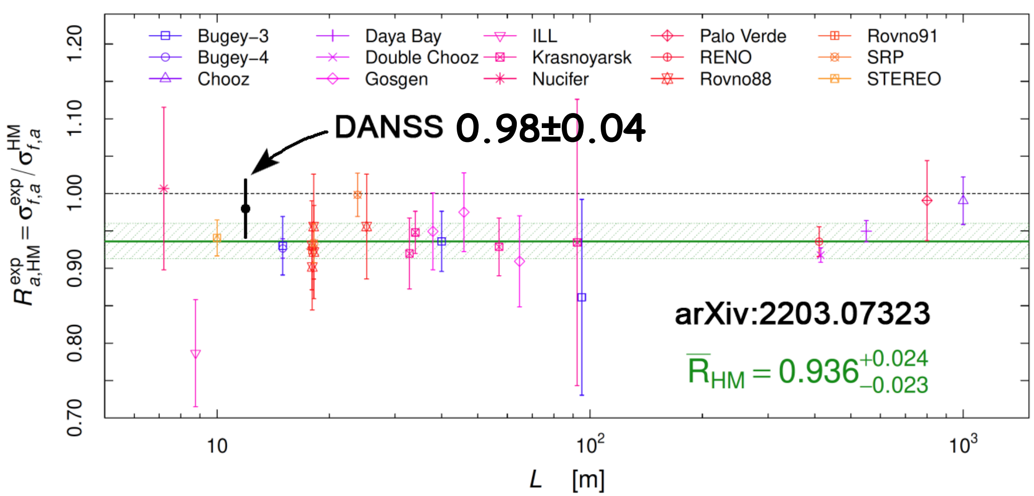
σ_{abs} – systematic uncertainty (7% in absolute rates)

Comparison of IBD rate with H-M model



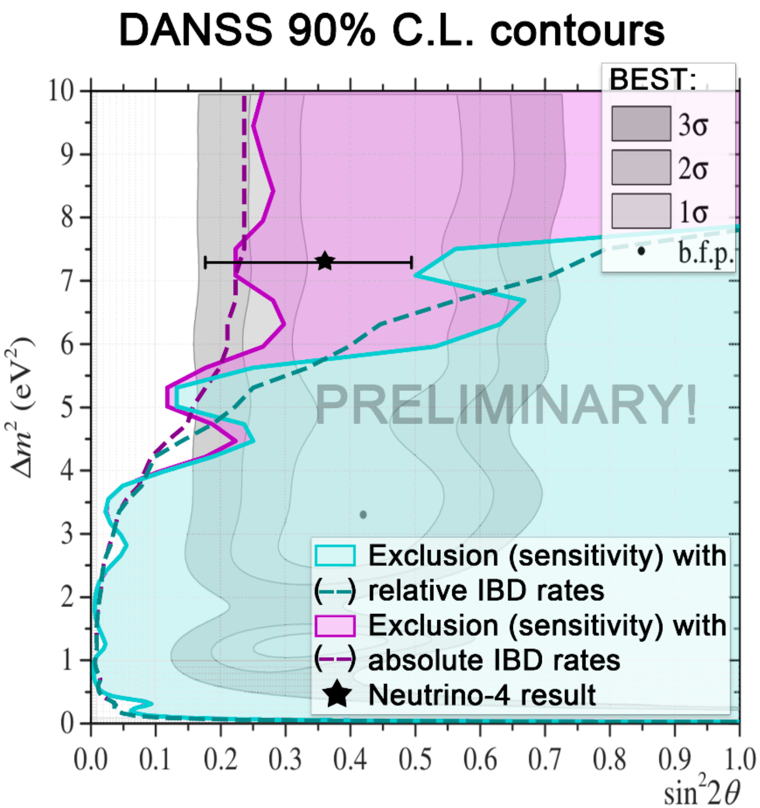






Results with neutrino absolute counting rates

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%.

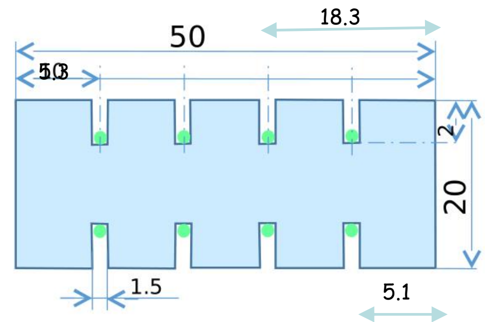
The DANSS upgrade

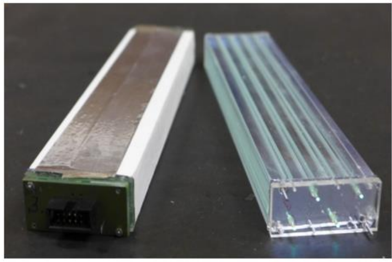
Main goal: to reach resolution 12%/√E
w.r.t. current very modest 33%/√E.

New geometry:

Strips: 2x5x120 cm, 2-side 16SiPM readout
Structure: 60 layers x 24 strips: 1.7 m^3
Gd is in foils between layers.
The same shielding and moving platform.

New scintillator strips



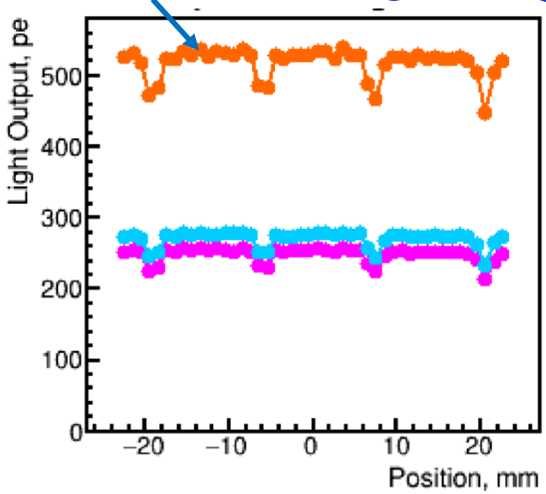


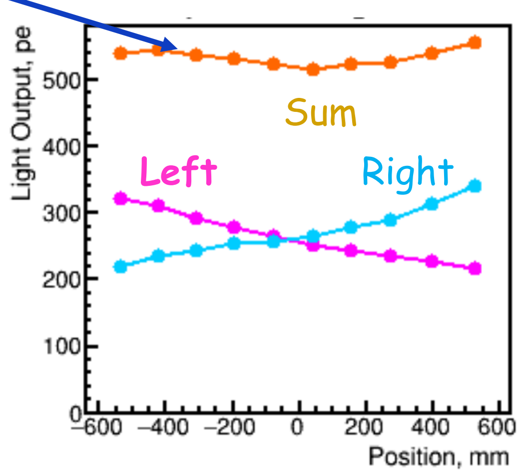
WLS fiber positions were optimized for better uniformity of response
New fast (4ns decay time) YS2 fiber is used
JINST 17 (2022) P01031

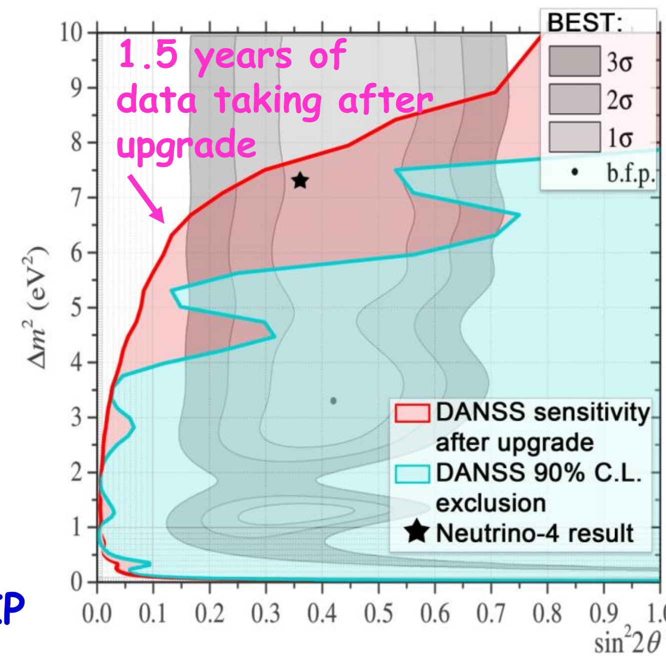
Upgrade is delayed due to external situation
But test results are very promissing

Strip tests at μ–beam

Transverse and longitudinal responses are very uniform







Longitudinal nonuniformity can be further corrected
LY>500p.e./MIP, Coordinate resolution 5.6cm for MIP

Summary

- DANSS records ~5 thousand antineutrino events per day with cosmic background ~1.8%, S/B>50
- 7.7 million IBD events were collected in 6.5 years
- Reactor power was measured using anti-ν rate with statistical error of ~1.5% in two days during 6.5 years of operation.
- Relative IBD σ dependence on 239Pu fission fraction was measured. It agrees with H-M model
- σ235/σ239 was measured. It's consistent with H-M model and larger than DB result .
- Indication of 5MeV bump, but not conclusive
- DANSS analysis based on 5.5 million IBD events excludes a large and the most interesting fraction of available parameter space for sterile neutrino including large fraction of the BEST preferred region and its best fit point.
- Analysis using absolute ν event rate excludes practically all sterile neutrino parameter space preferred by BEST

We plan:

To take data till the start of upgrade

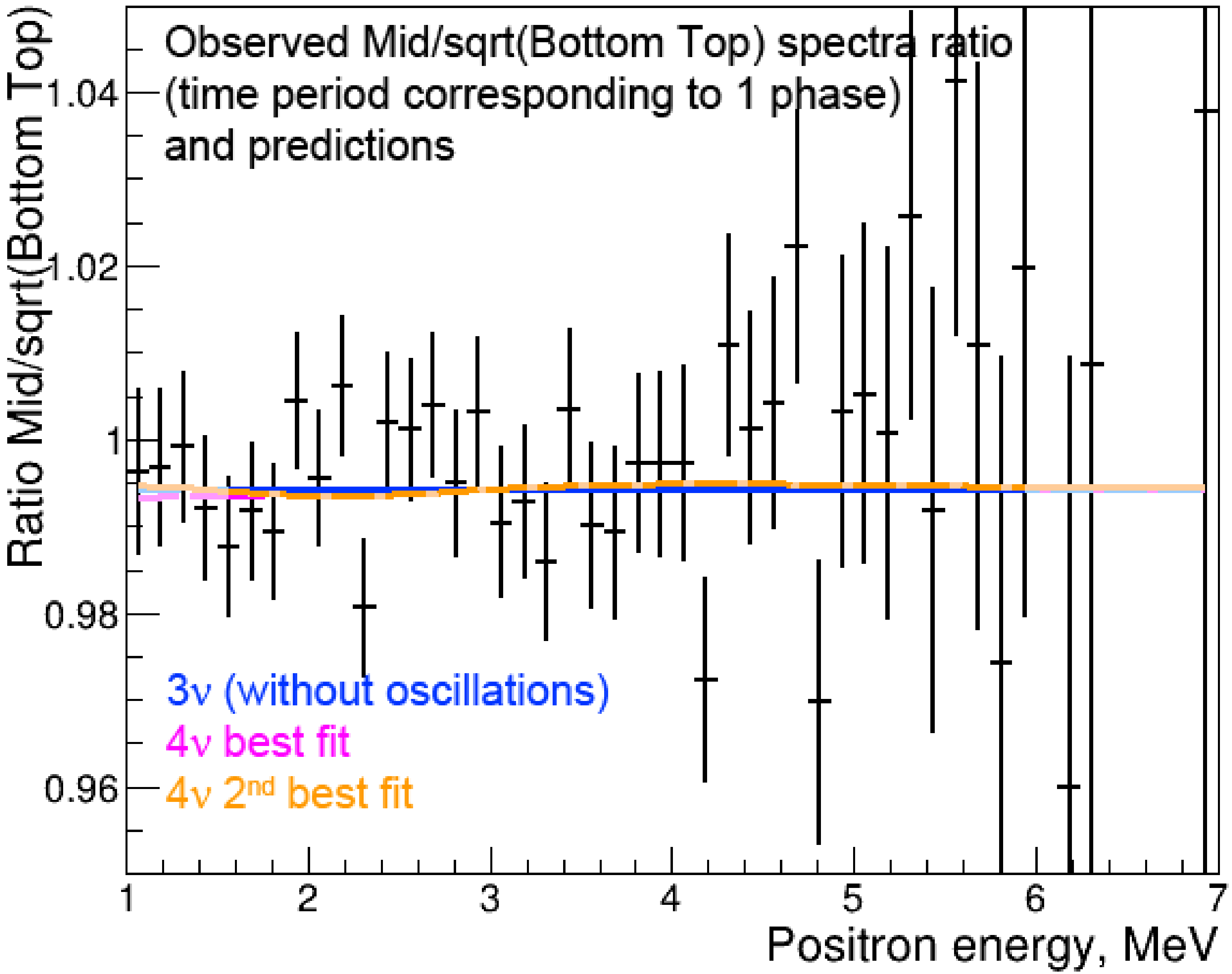
To refine detector calibration and energy scale determination in order to reduce systematic errors

To measure reactor characteristics using ν

To upgrade detector

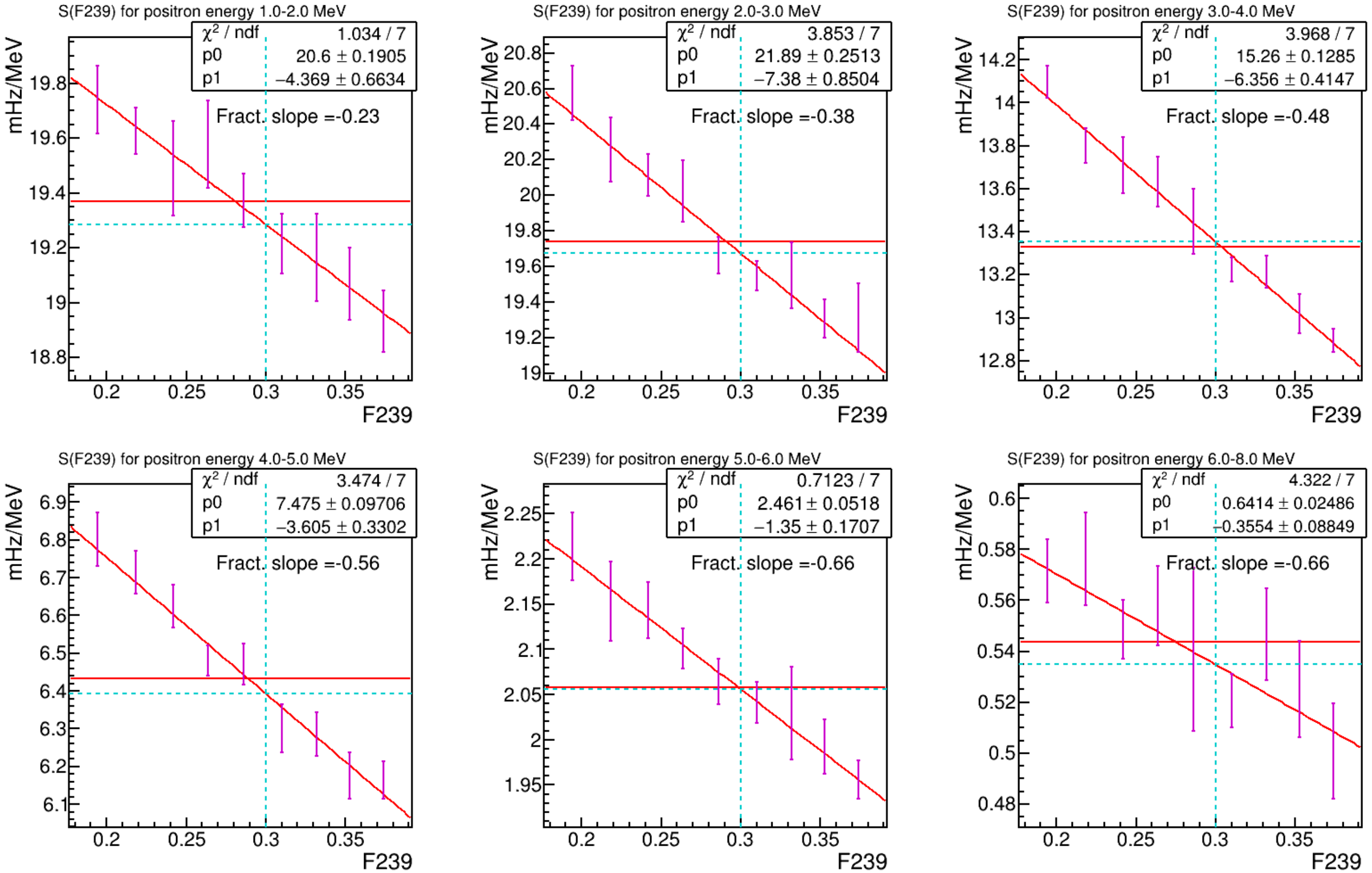
To scrutinize Neutrino-4 and BEST results

Backup slides



Observed Mid/sqrt(Bottom Top) spectra ratio
(time period corresponding to 1 phase)
and predictions
Ratio Mid/sqrt(Bottom Top)
1.04
1.02
1
0.98
0.96
3ν (without oscillations)
4ν best fit
4ν 2nd best fit
1
2
3
4
5
6
7
Positron energy, MeV

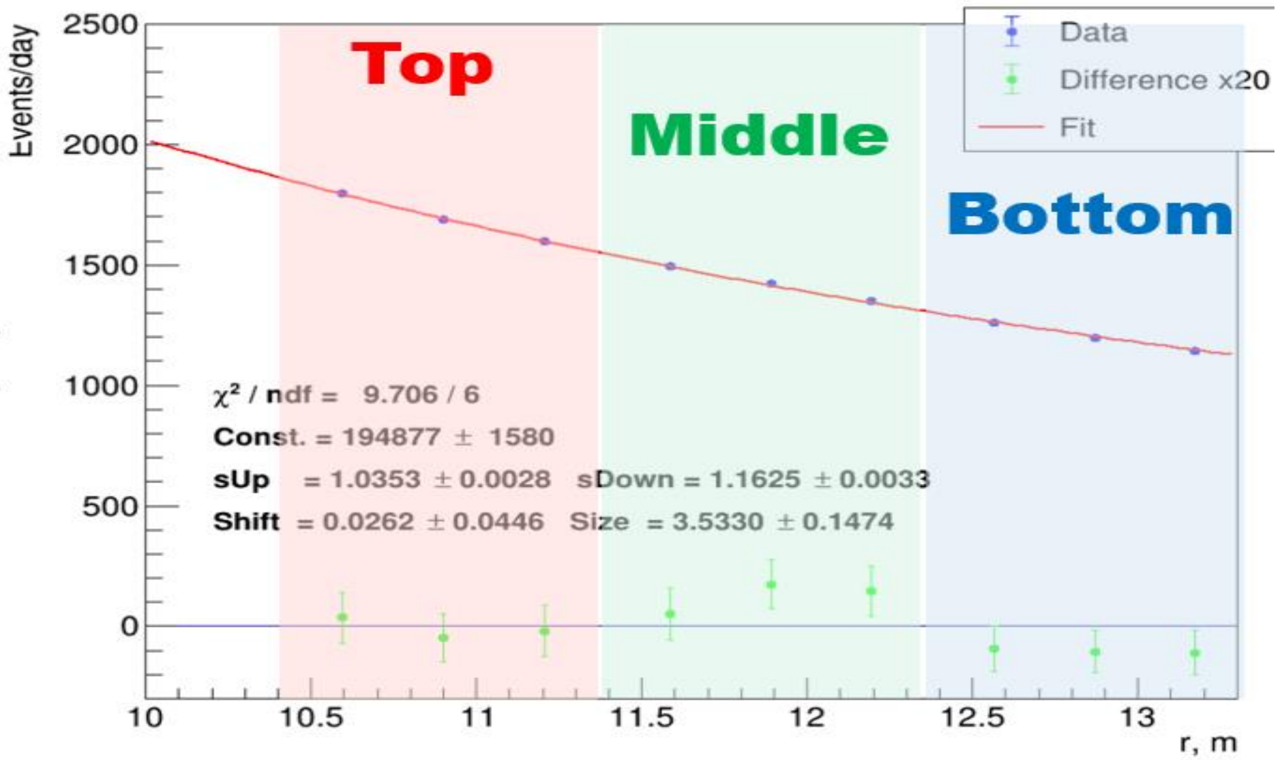
Partial slopes



Systematic errors dominate.
Estimated from the spread between reactor campaigns
Probably overestimated by a factor of ~2

DANSS has twice larger F239Pu range than DB

IBD total rate vs. effective distance



- **IBD intensity follows reasonably the 1 / L^2 dependence.**
- **Detector was divided on 3 parts in each position.**

Data acquisition system

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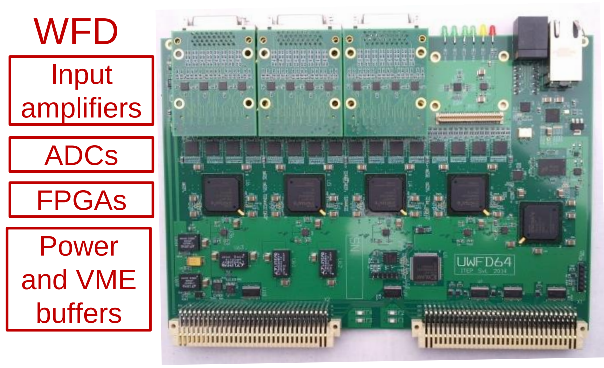

- Preamplifiers PA in groups of 15 and SiPM power supplies HVDAC for each group inside shielding, current and temperature sensing
- Total 46 Waveform Digitisers WFD in 4 VME crates on the platform
- WFD: 64 channels, 125 MHz, 12 bit dynamic range, signal sum and trigger generation and distribution (no additional hardware)
- 2 dedicated WFDs for PMTs and μ-veto for trigger production
- Each channel low threshold selftrigger on SiPM noise for gain calibration
- Exceptionally low analog noise ~1/12 p.e.