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On High Energy Physics
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New Results from the DANSS Experiment

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for the DANSS Collaboration

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

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

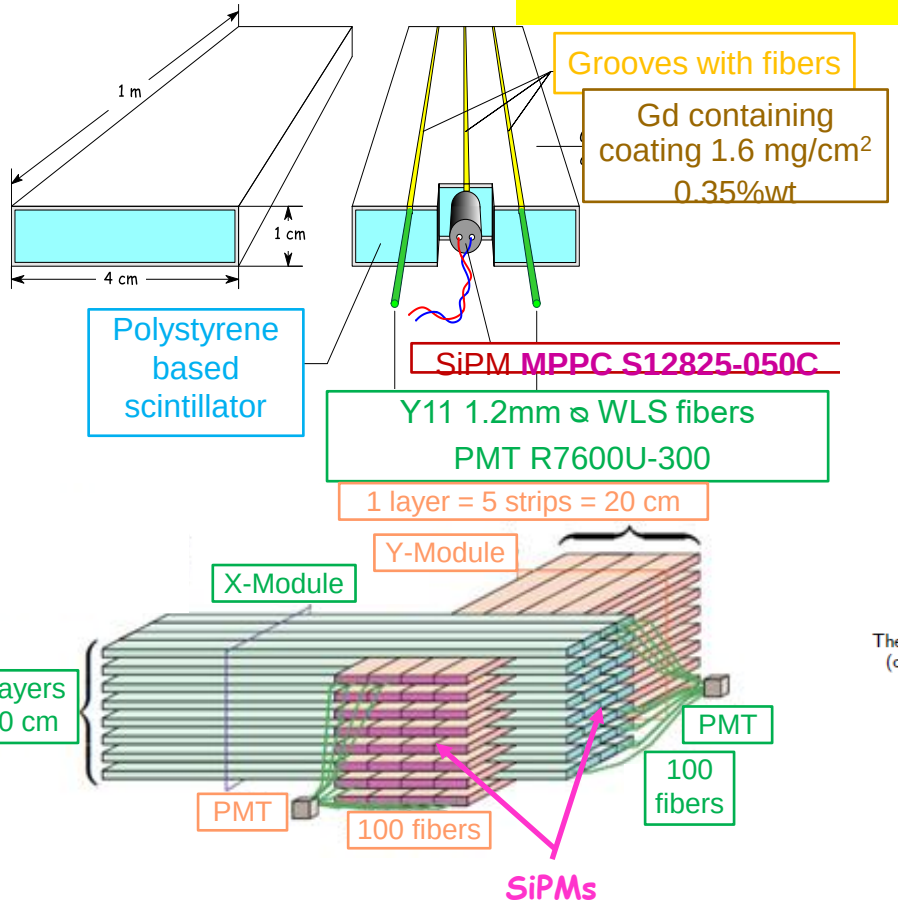
4. Neiutrino-4 claim of sterile neutrino observation
   $\Delta m^2 = 7.3 \pm 1.17 eV^2$ and $\sin^2 2\theta = 0.36 \pm 0.12$ 2.7σ Phys.Rev.D 104, 032003 (2021)

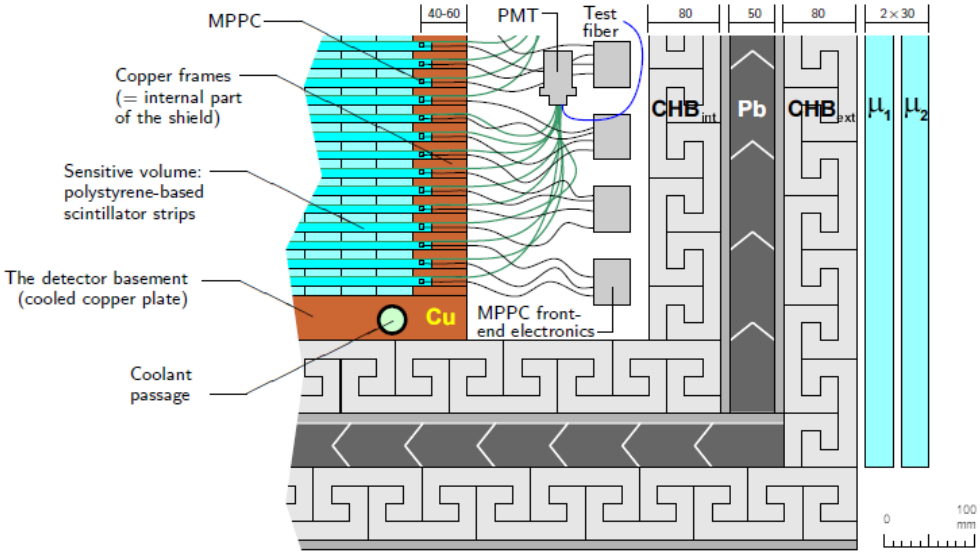
These are statistically strongest indications of physics BSM!

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

DANSS Detector design

JINST 11(2016)no11,P11011

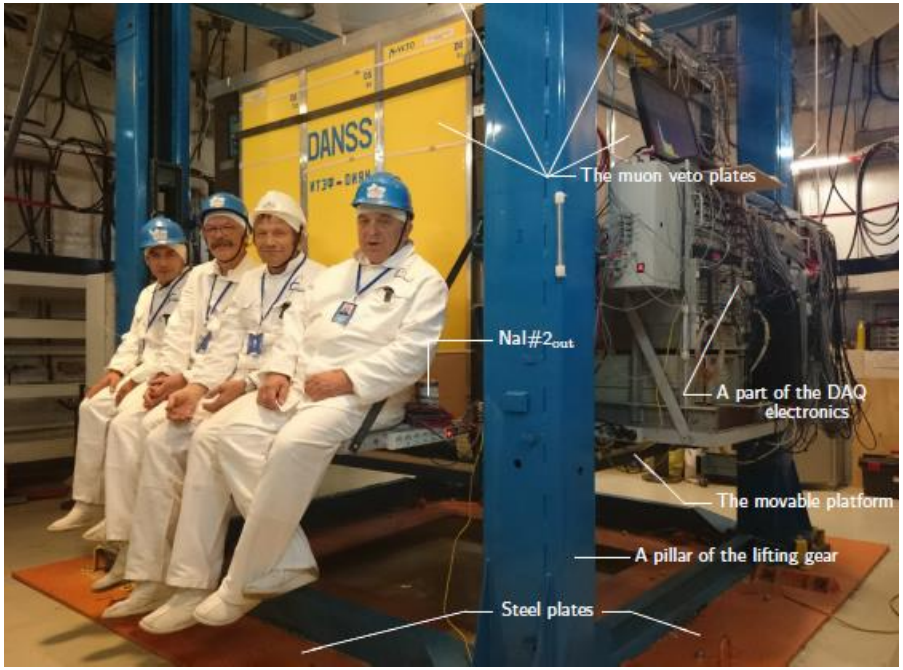


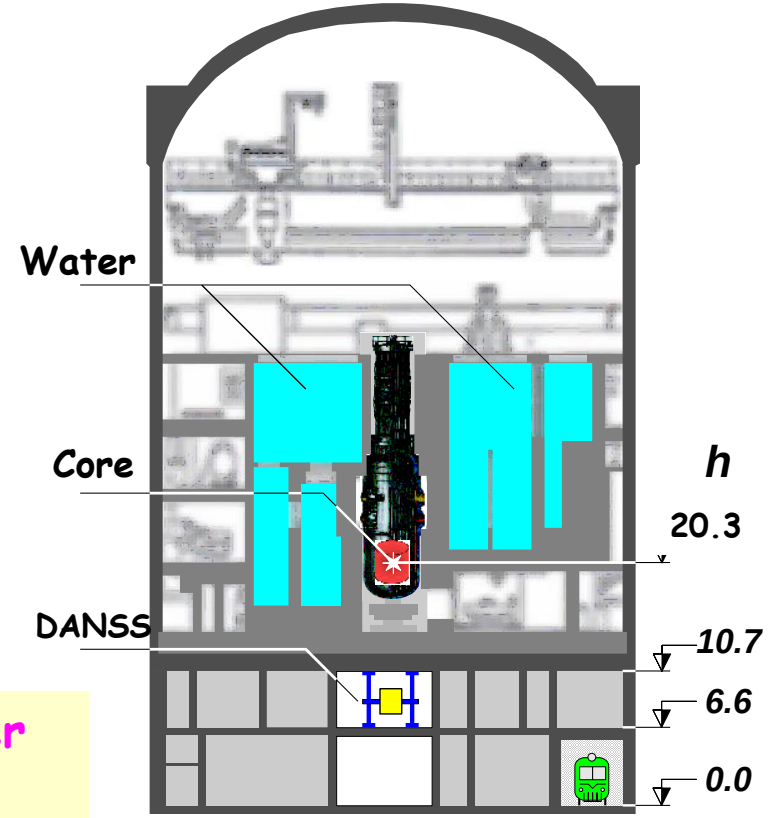


- **2500 scintillator strips with Gd containing coating for neutron capture**
- **Light collection with 3 WLS fibers**
- **Central fiber read out with individual SiPM**
- **Side fibers from 50 strips make a bunch of 100 on a PMT cathode = Module**

- **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 10.9-12.9m (center to center) is changed 2-3 times a week

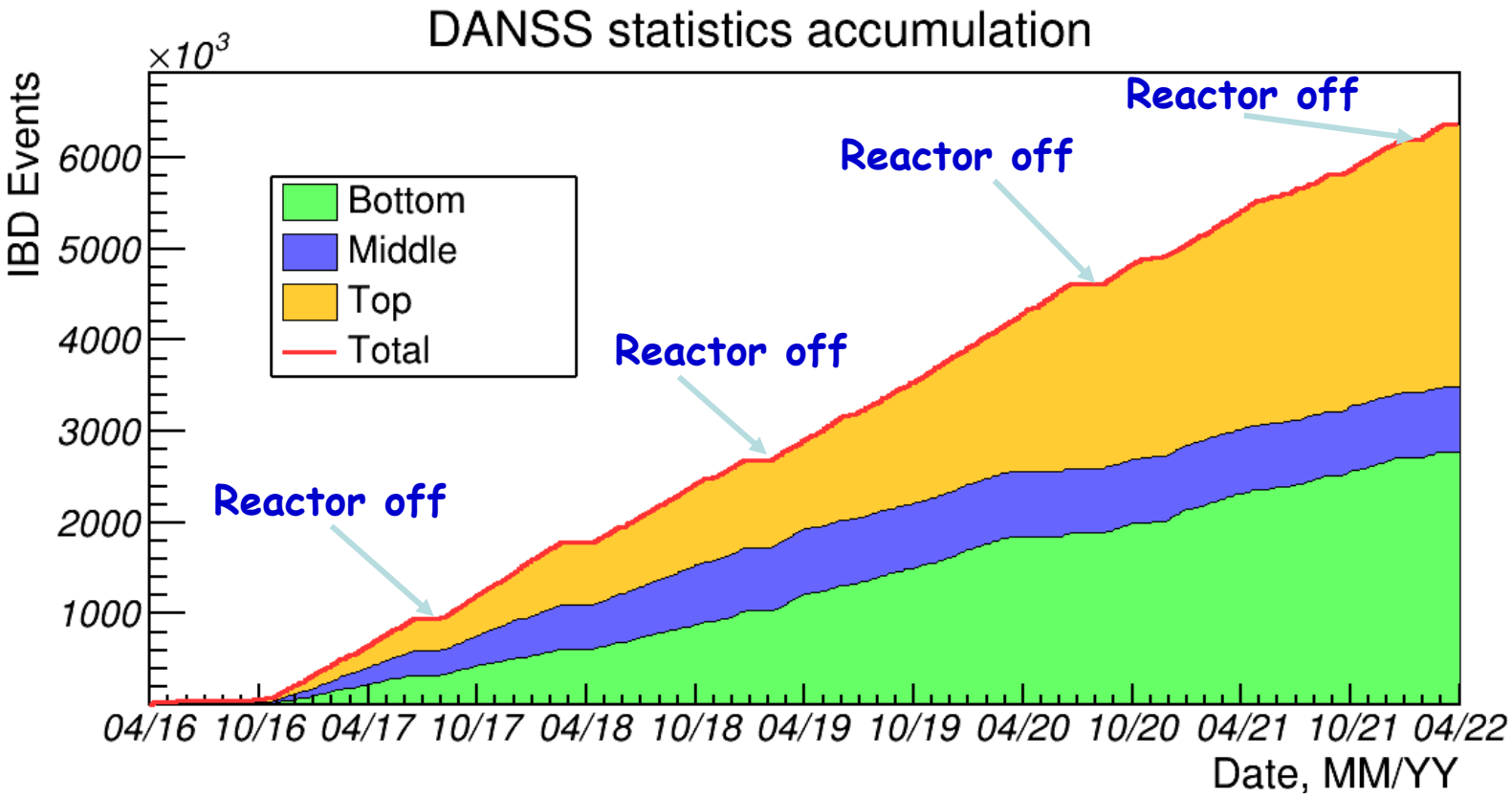
Trigger: ΣE(PMT)>0.5-0.7MeV=>Read 2600 wave forms (125MHz), look for correlated pairs offline.

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

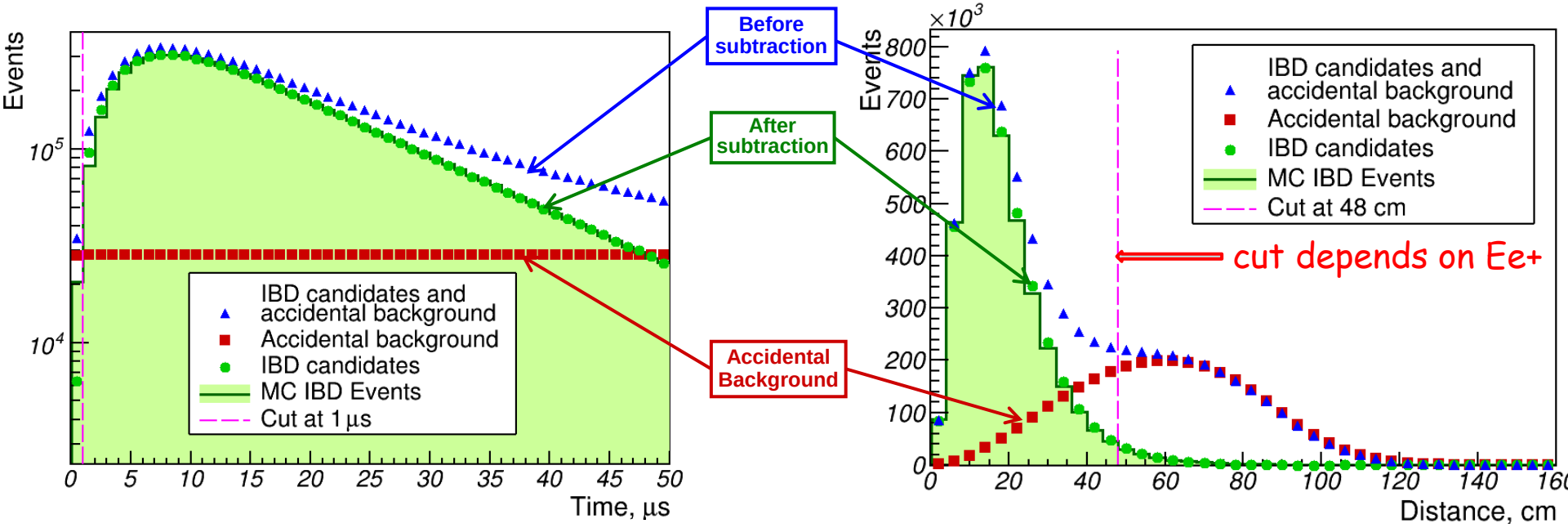
(for a typical campaign)

DANSS collected 6M antineutrino events in 6 years



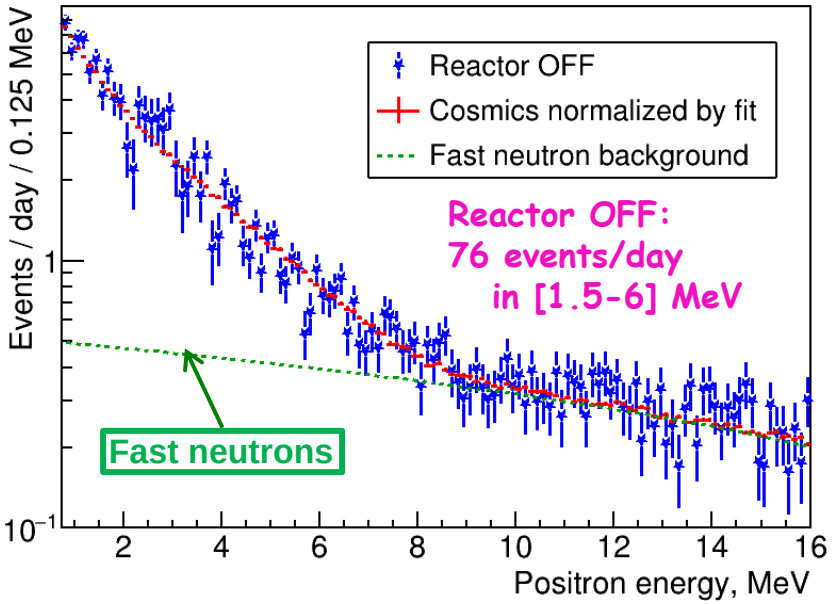
- Total statistics accumulated is **6M IBD-events in 6 years**
  and 4 reactor off periods
  (4.4M events in oscillation analysis)

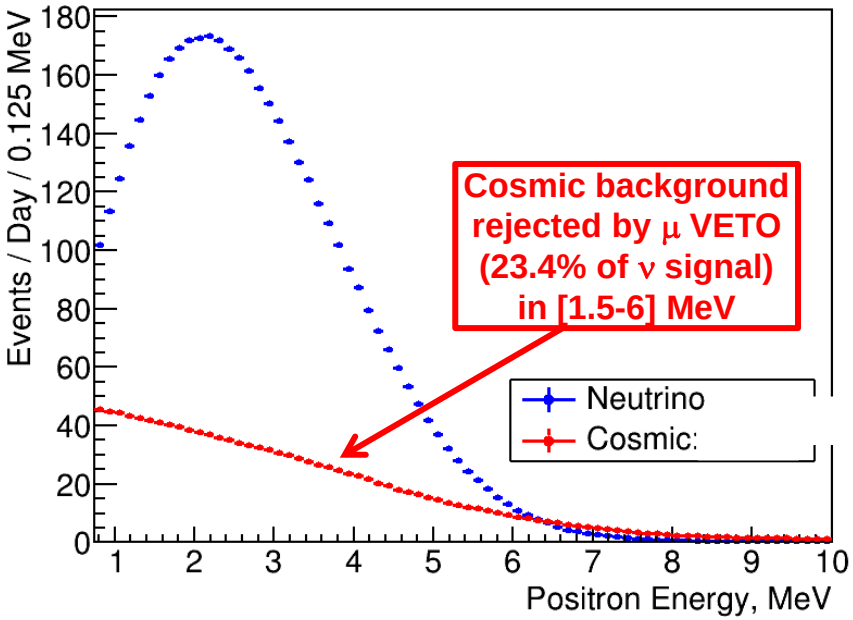
Accidental coincidence background



- **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 15.3% 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

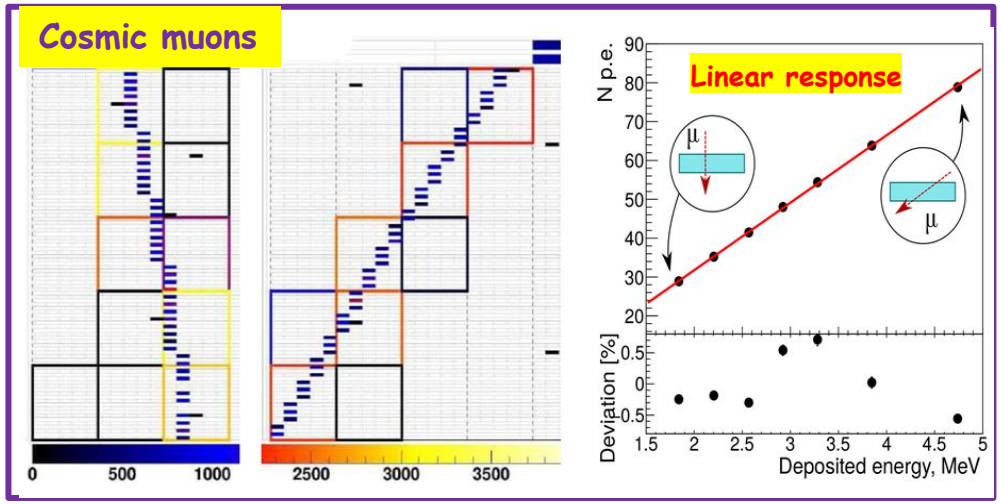


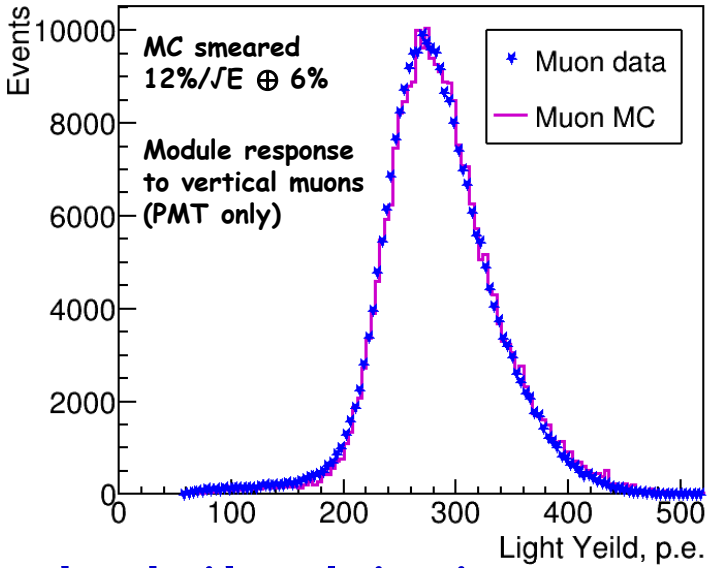


- 25 ν events/day from neighbor reactors were subtracted
- **Fast neutrons**: linearly extrapolate from high energy region and subtract separately from positron and visible cosmic spectra, CR (fast neutron) = 16 events/day (in 1.5-6 MeV range)
- **Visible cosmic background (CB)** has been **directly 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 (41 events/day).
- Additional 19 events/day at low energies observed in reactor off data were subtracted
- Total subtracted background is 1.76% for the top detector position. S/B>50!

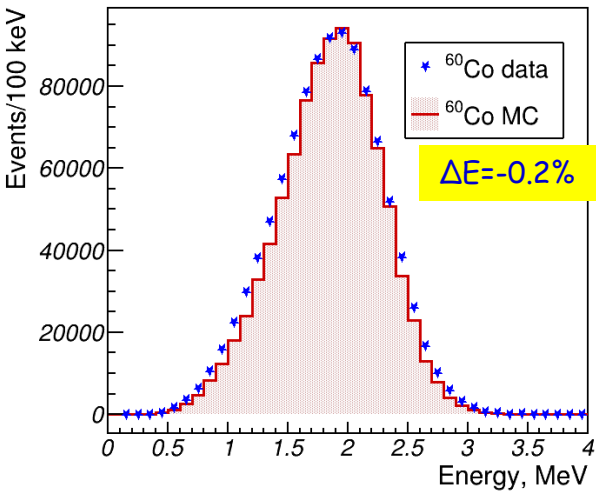
Calibration

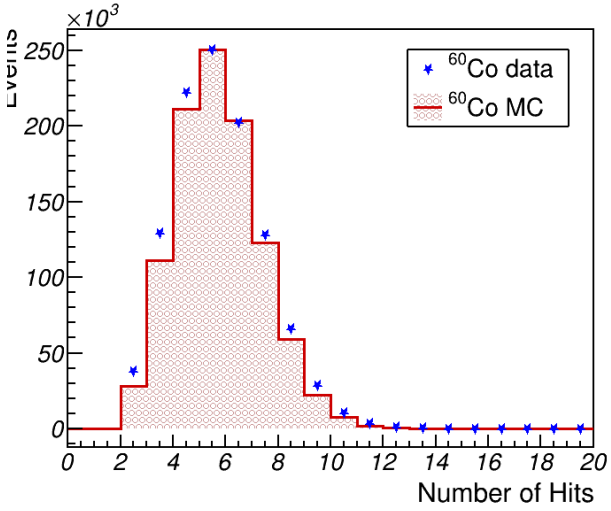
2500 SiPM gains and X-talks are calibrated every 30-40 min.
All 2550 channels are calibrated every 2 days using cosmic muons

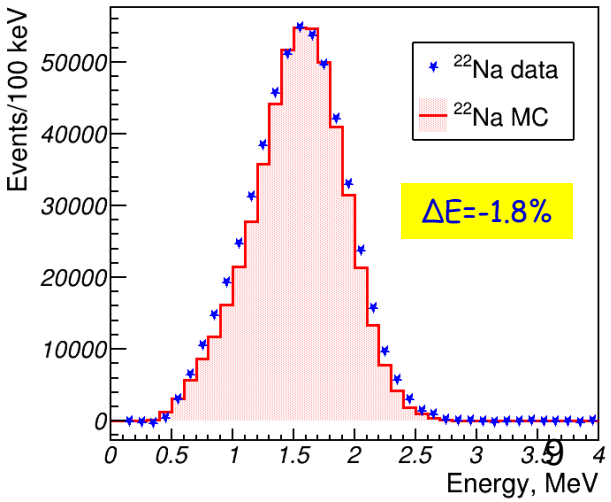




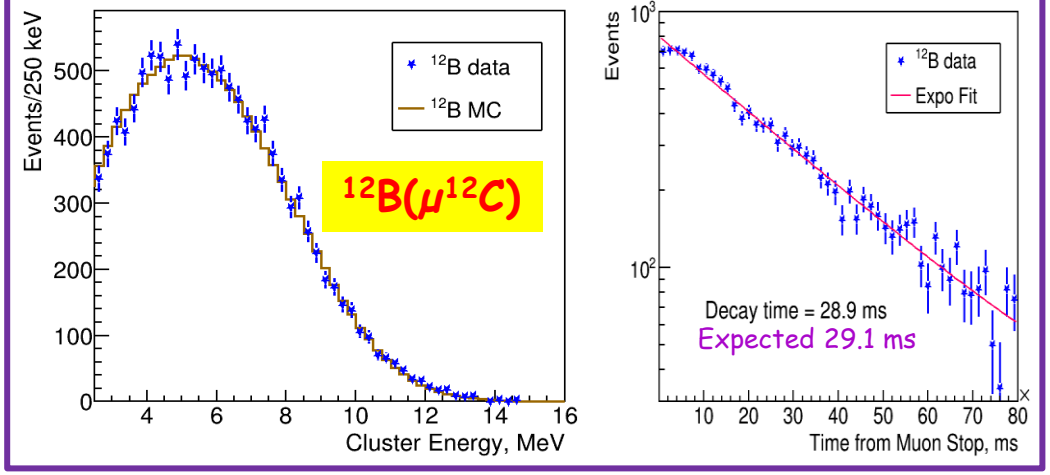
Several calibration sources are used to check the detector response

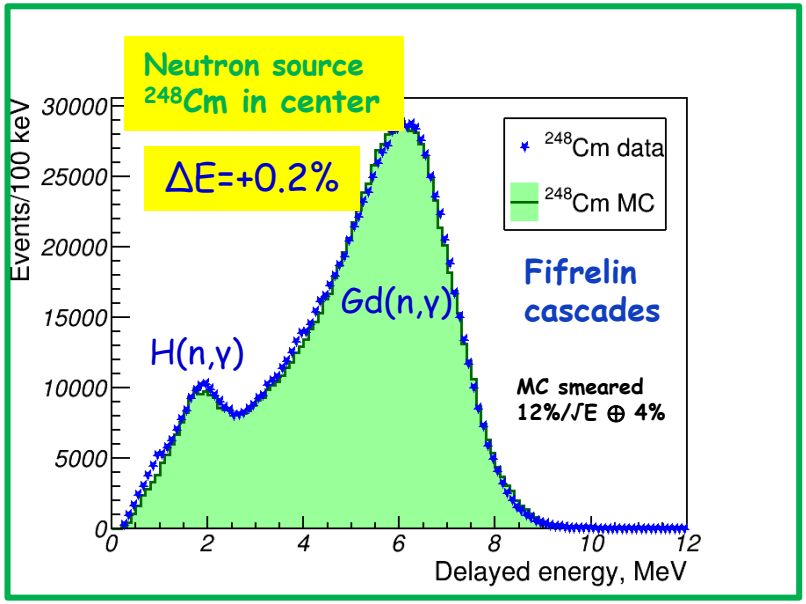


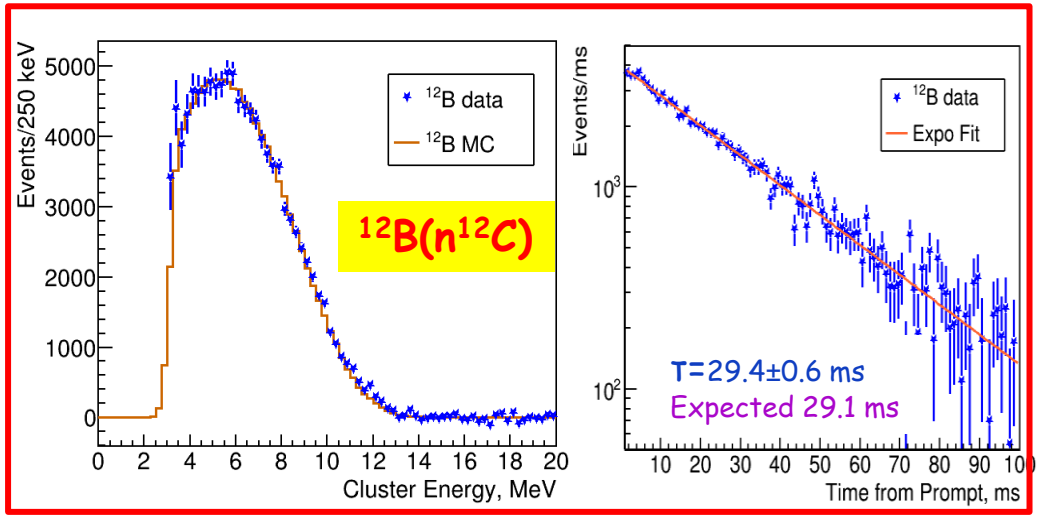


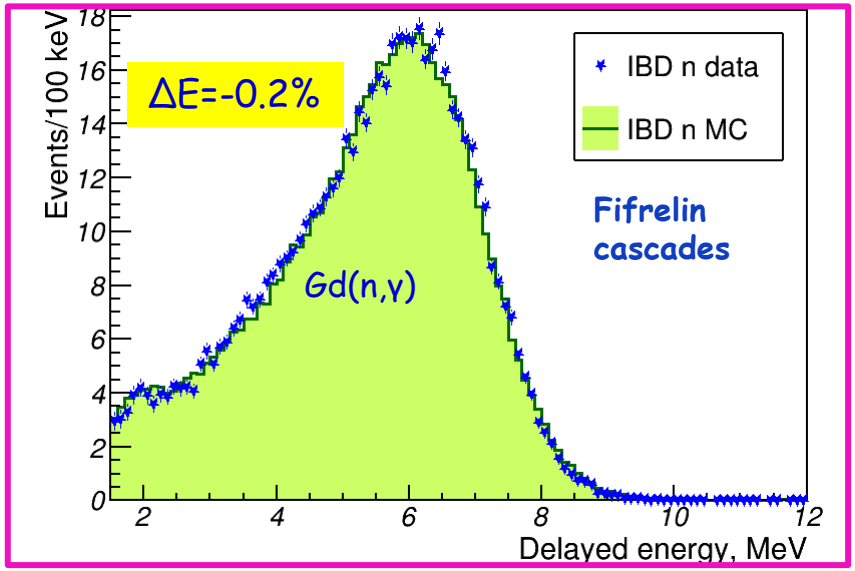


Calibrations



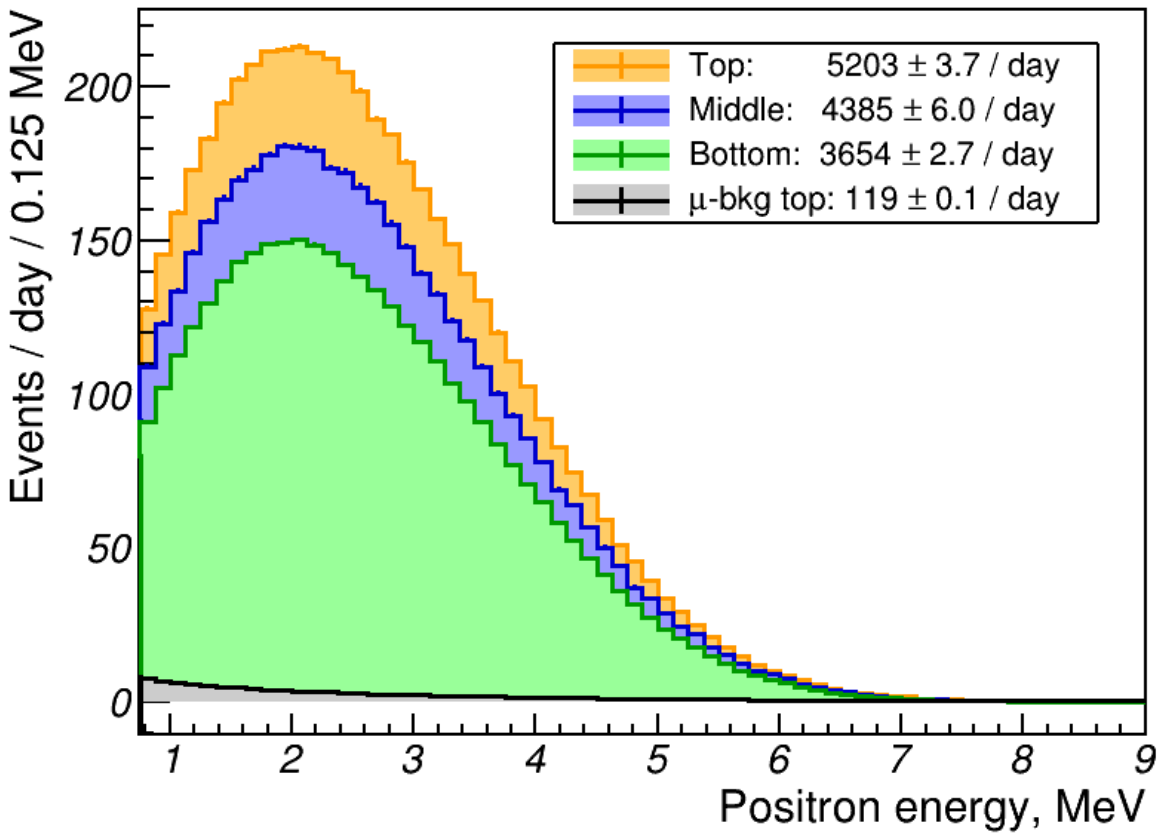






- Energy scale has been fixed using β-spectrum of ^{12}B, which is similar to positron signal
- Other sources agree within +/- 0.2% with exception of ^{22}Na which is 1.8% below.
- Systematic error on E scale of +/-2% was added due to ^{22}Na disagreement
  Hope to reduce this error soon

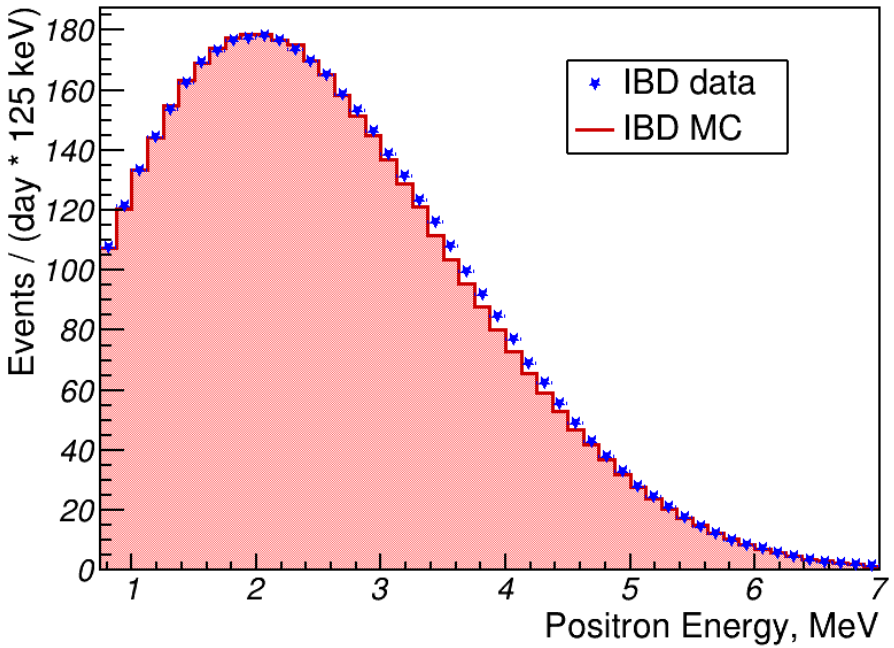
Positron spectrum of IBD-signal

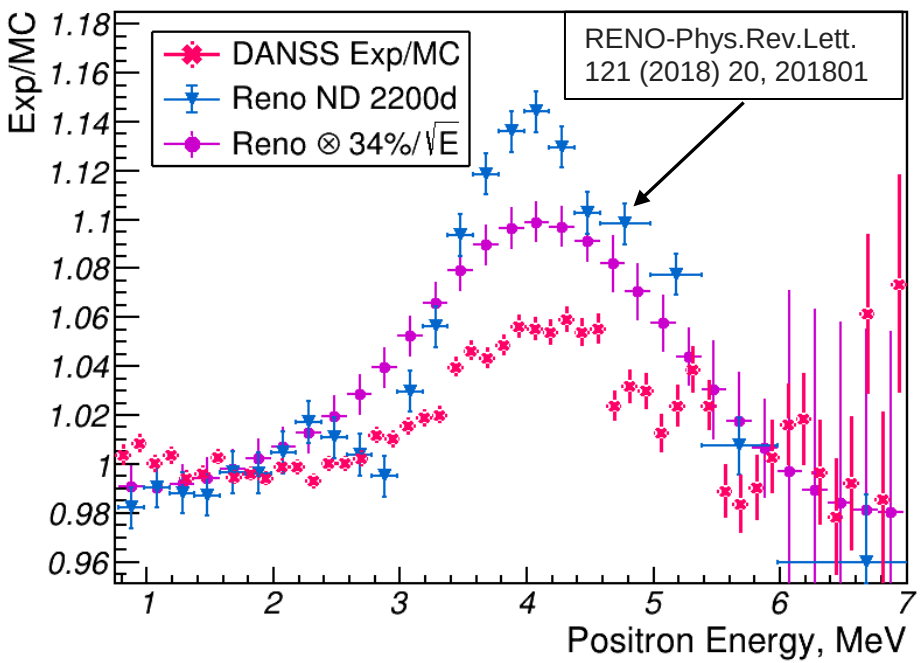


- Positron kinetic energy spectra (no annihilation photons) at 3 detector positions
- ~5000 events/day in detector fiducial volume (78% of full volume)

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

Positron spectrum: experiment vs. H-M Model





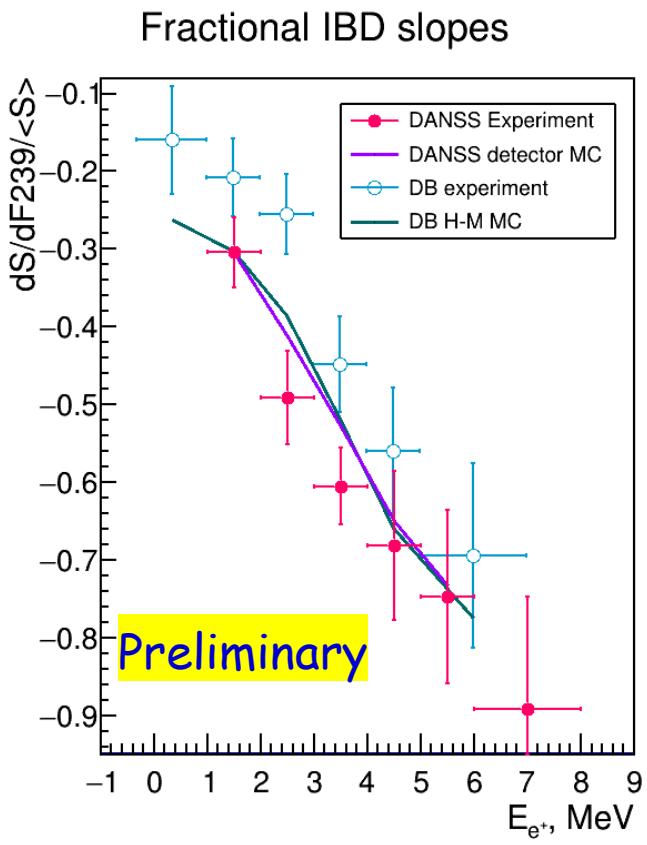
- We see a bump in e+ spectrum at similar position to other experiments ($E_{prompt}=E_{e+}+1MeV$) if E is shifted by -50 keV
- Bump height is smaller than in RENO
- However, we can not claim bump existence yet

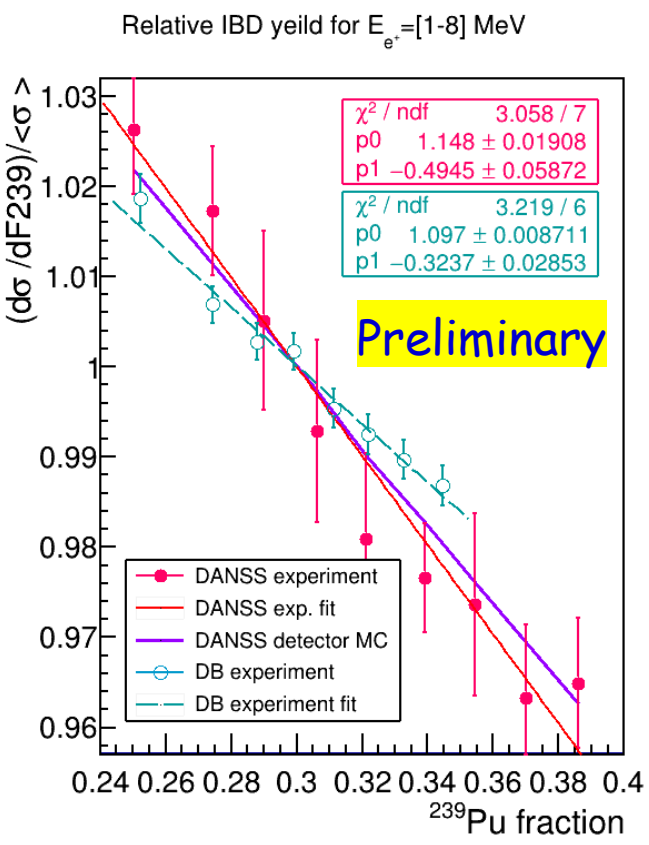
  because of high sensitivity of the shape to energy scale and shift.

  Similar problems should exist in other experiments

Positron spectrum dependence on fuel composition is clearly seen

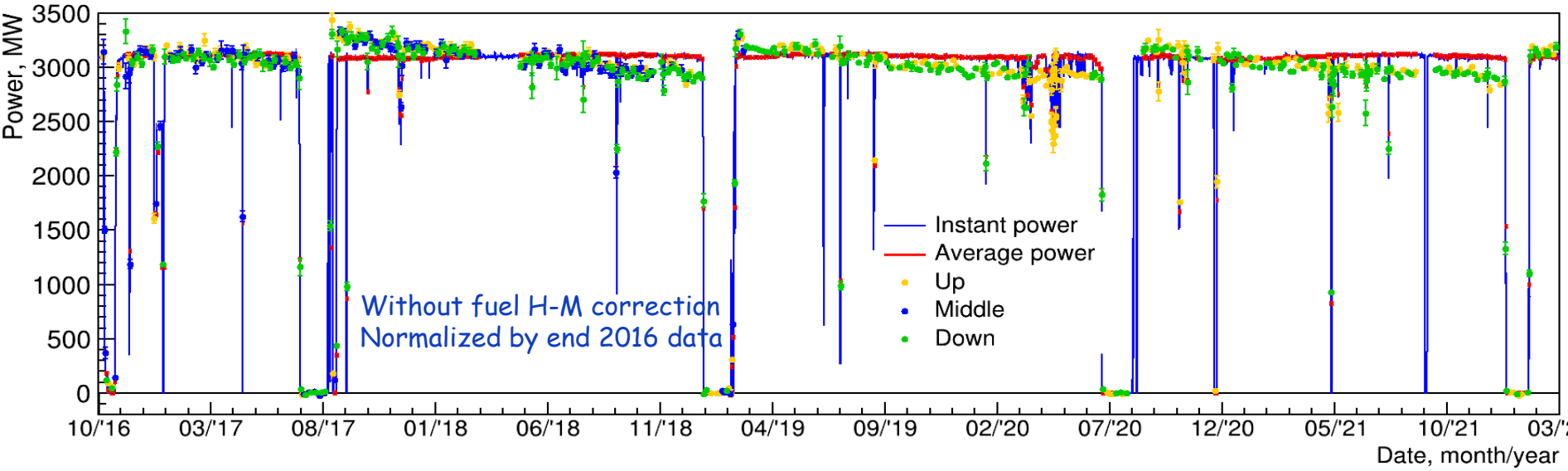
IBD rate dependence on 239Pu fission fraction (dσ/dF239)/σ(F239=0.3) for various Ee+
It agrees with H-M model and somewhat larger than at DayaBay

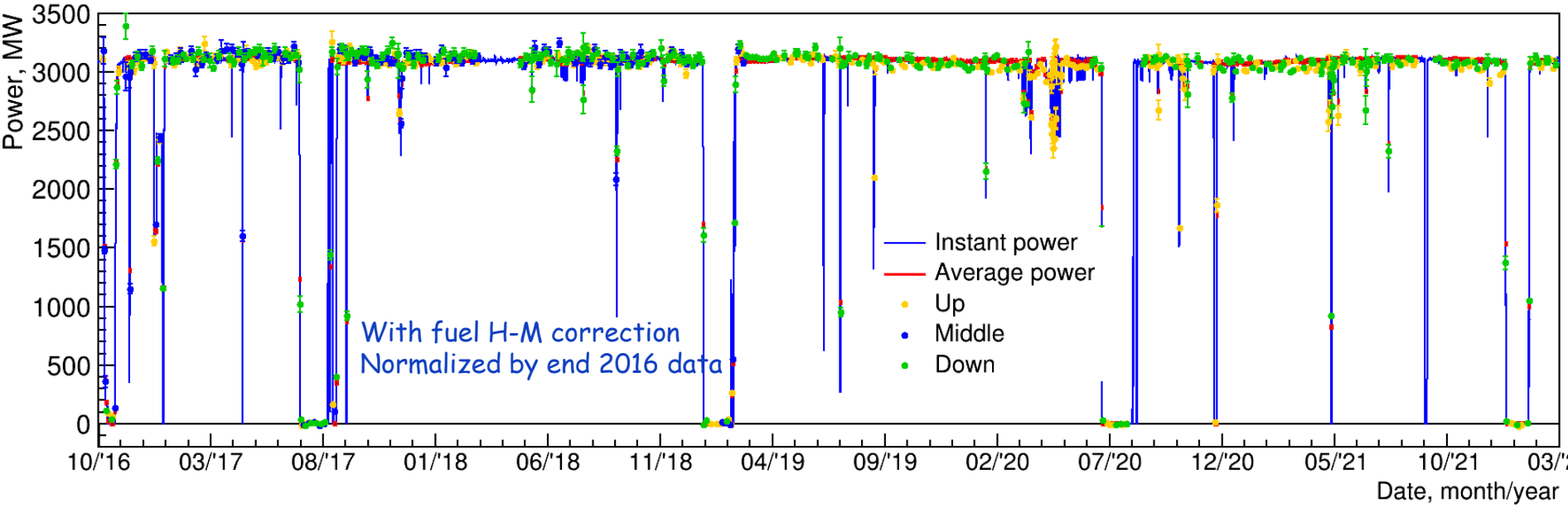




Errors are dominated by systematics estimated from the spread between campaigns
Probably errors are overestimated

Neutrino reactor power monitoring with 1.5% accuracy in 2 days during 6 years





Test statistics

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

3 position data — 2 position data — Nuisance parameters (systematics and efficiency)

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

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

η – nuisance parameters;

W – covariance matrix;

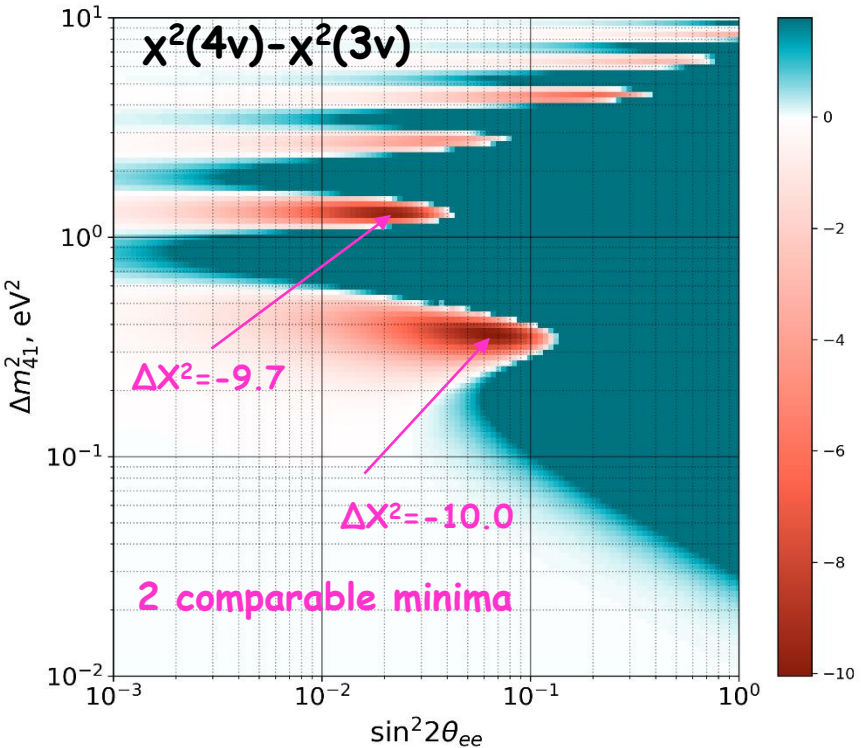
Difference in χ^2 between 4v and 3v hypotheses

Red - $\chi^2(4v)<\chi^2(3v)$,

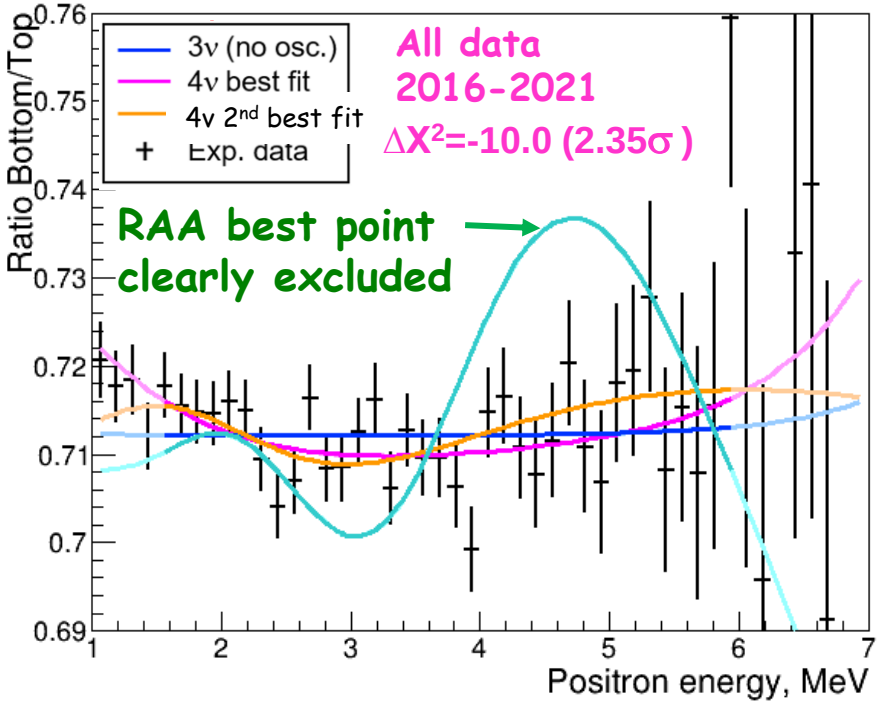
Blue – $\chi^2(4v)>\chi^2(3v)$,

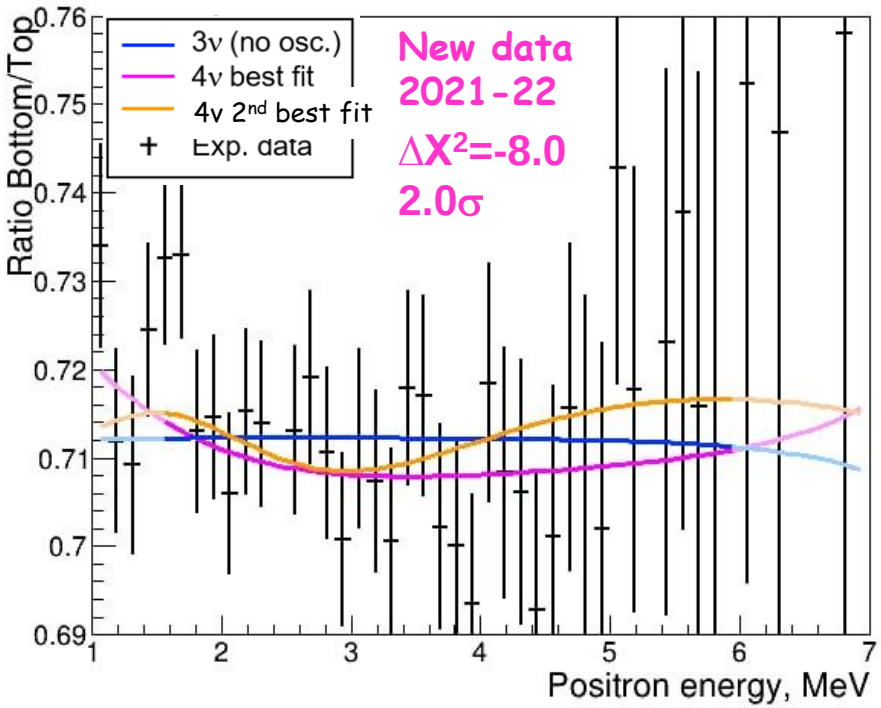
Dark blue region is excluded at 3σ CL in case of χ^2 distribution with 2 DoF $(\chi^2(4v)-\chi^2_{min})=11.8$

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



Ratio of positron spectra



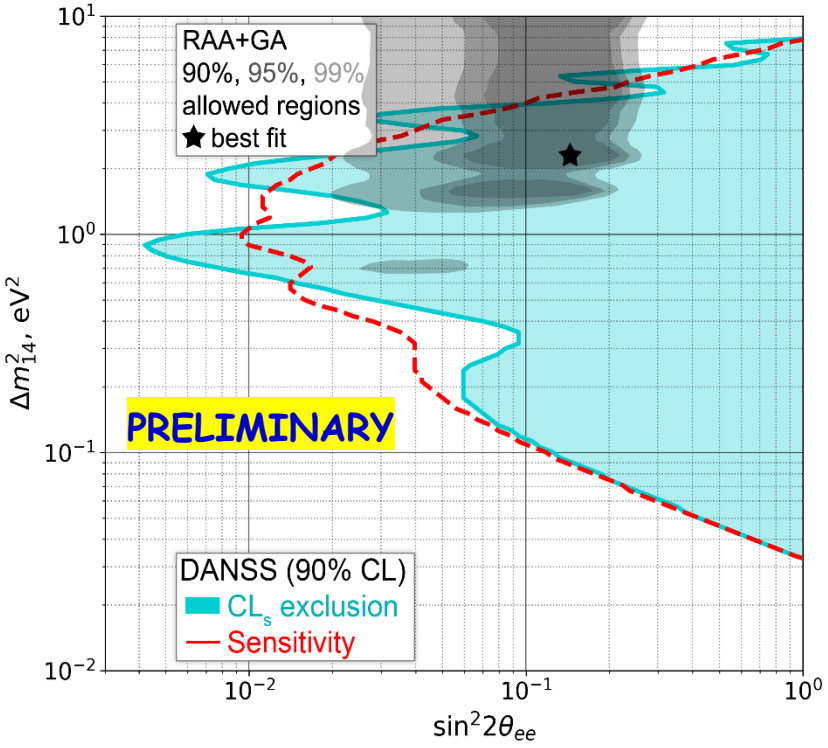


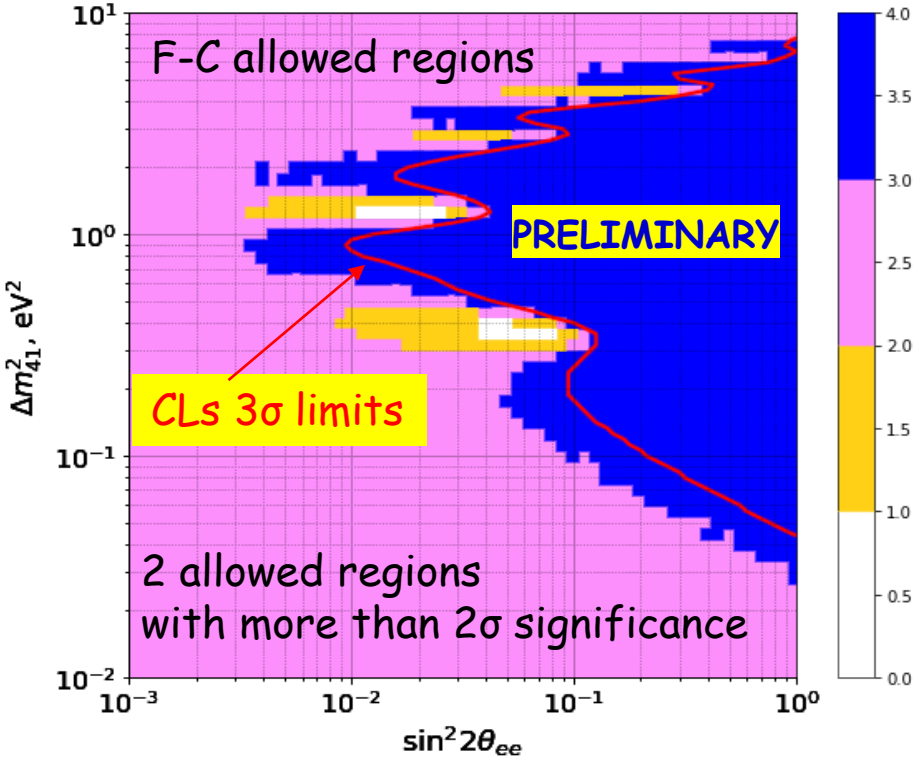
- Fit in 1.5-6 MeV range (to be conservative).
- 2016-2020 data – no statistically significant indication of 4ν(ΔX^2=-5.6, 1.5σ)
- 2021-2022 data - weak, statistically not significant hint in favor of 4ν (ΔX^2=-8.0, 2.0σ)
- Using current statistics 2016-2022 (~4.4 million IBD events with 1.5 MeV<E<6MeV) we see statistically not significant hint in favor of 4ν signal:

  ΔX^2=-10 (2.35σ) for 4ν hypothesis best point Δm^2=0.35 eV², $\sin^2 2\theta$=0.07

  ΔX^2=-9.7 for 4ν hypothesis second best point Δm^2=1.3 eV², $\sin^2 2\theta$=0.02
- RAA has been excluded with ΔX^2= 155.
- RAA was excluded by DANSS with more than 5σ already in 2018 (arXive:1804.04046v1)

The DANSS results





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

The most stringent limit reaches $\sin^2 2\theta < 4\times10^{-3}$ 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

There are two F-C allowed 1σ regions

However even the best one (2.35σ from 3ν hypothesis) is not significant enough to claim indication of 4ν

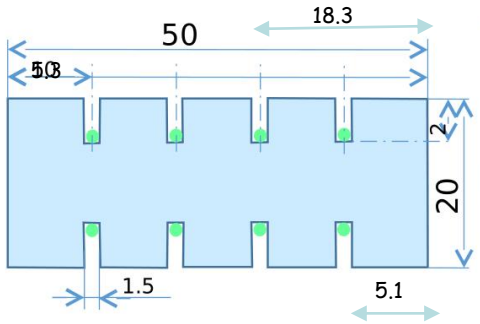
The DANSS upgrade(see poster by N.Skrobova)

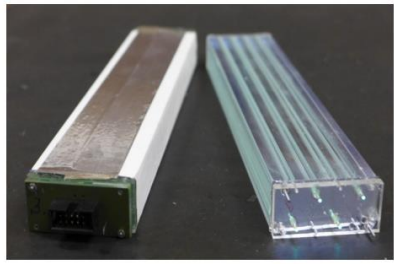
Main goal: to reach resolution **13%/√E**
w.r.t. current very modest 33%/√E.

New geometry:

Strips: 2x5x120 cm, 2-side 8SiPM readout
Structure: 60 layers x 24 strips: 1.7 m^3
Setup uses **the same shielding and moving platform.**
Gd is in foils between layers.
Upgrade will be finished in 2023

New scintillator strips

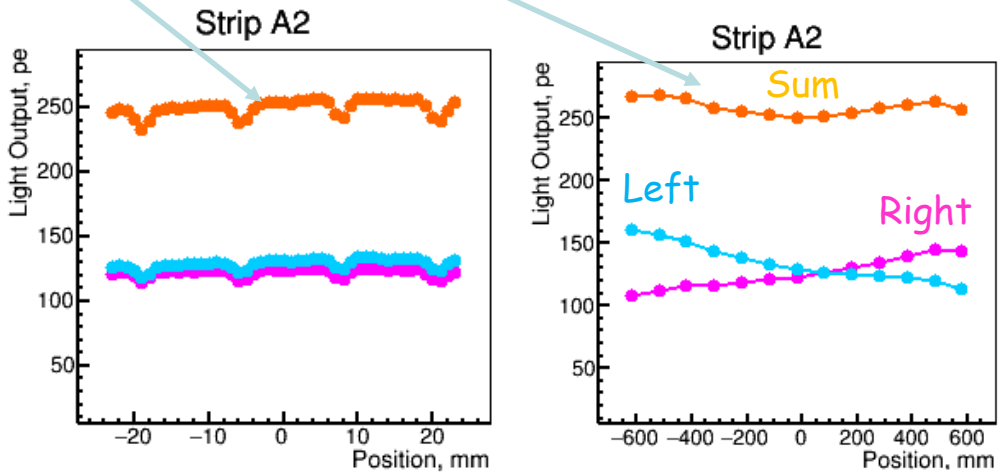




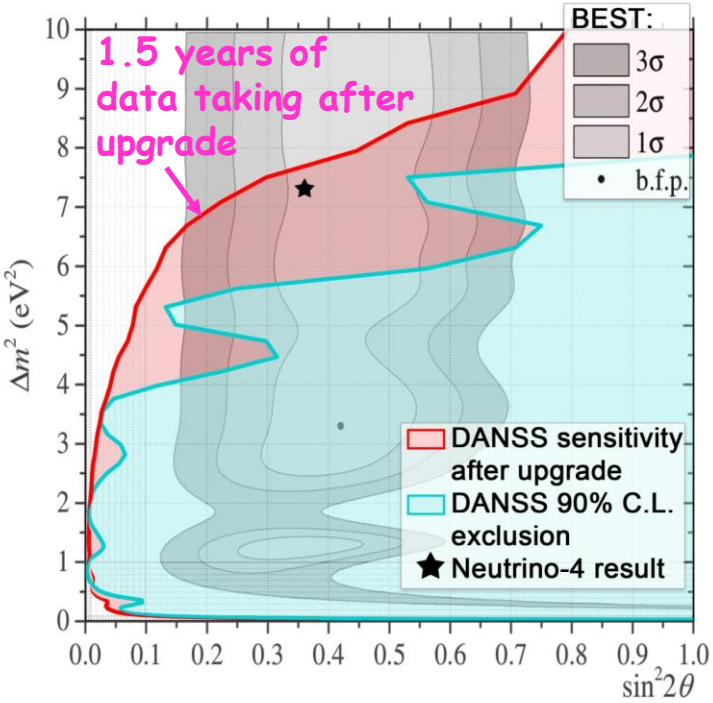
WLS fiber positions were optimized for better uniformity of response
New fast (4ns decay time) YS2 fiber will be used
JINST 17 (2022) P01031

Strip tests at π-beam

Transverse and longitudinal responses are very uniform



Longitudinal nonuniformity can be further corrected
More work on SiPM-WLS fiber connection is needed



Summary

- DANSS records about 5 thousand antineutrino events per day with cosmic background ~1.8%, S/B>50
- 6 million IBD events were collected in 6 years
- Reactor power was measured using anti-ν rate with statistical error of ~1.5% in two days during 6 years of operation.
- Relative IBD σ dependence on 239Pu fission fraction was measured. It agrees with H-M model
- Indication of 5MeV bump, but not conclusive
- Preliminary DANSS analysis based on 4.4 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.
- New data (2021-22) give a weak hint of sterile ν (2σ)
- All data have two close best points

ΔX^2=-10 for Δm^2=0.35 eV^2 , $\sin^2 2\theta$=0.07

ΔX^2=-9.7 for Δm^2=1.3 eV^2 , $\sin^2 2\theta$=0.02

This hint is not statistically significant (2.35σ)

to claim even the indication of sterile neutrino

We plan:

To take data for few more months

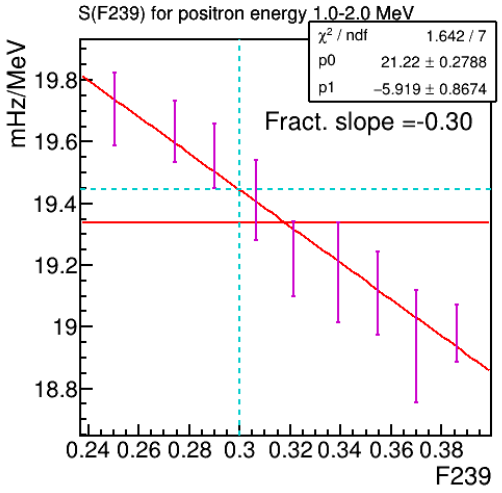
To refine detector calibration and energy scale determination in order to reduce systematic errors

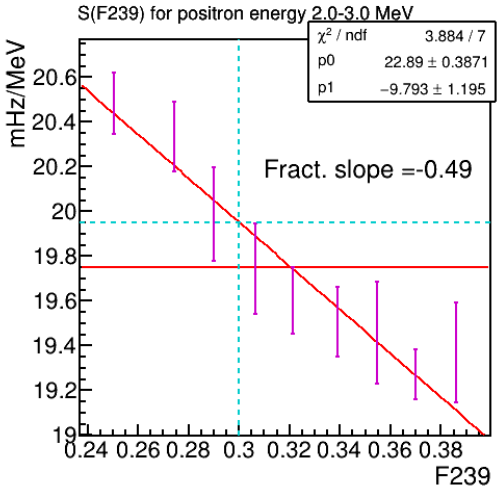
To upgrade detector in 2023

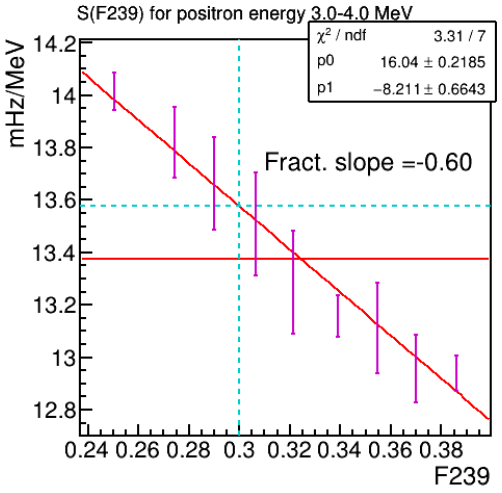
To scrutinize Neutrino-4 and BEST results

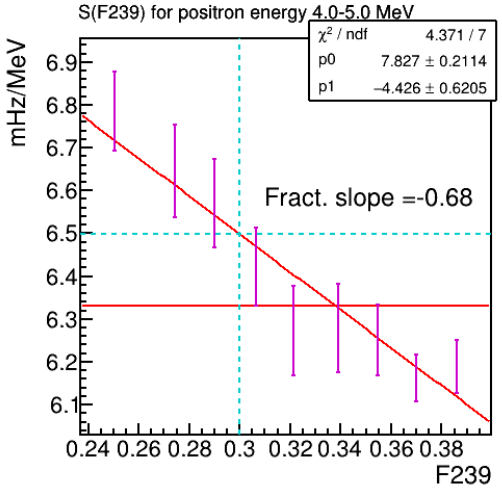
Backup slides

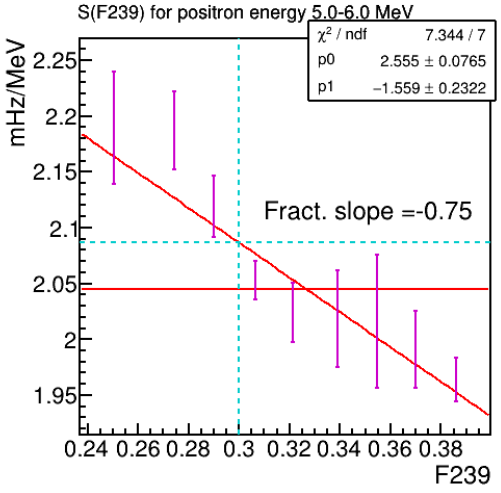
Partial slopes

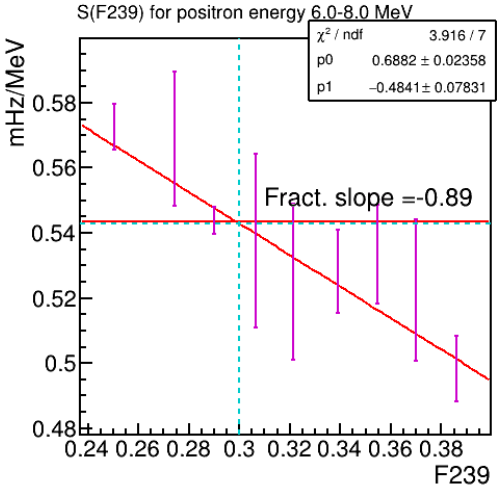










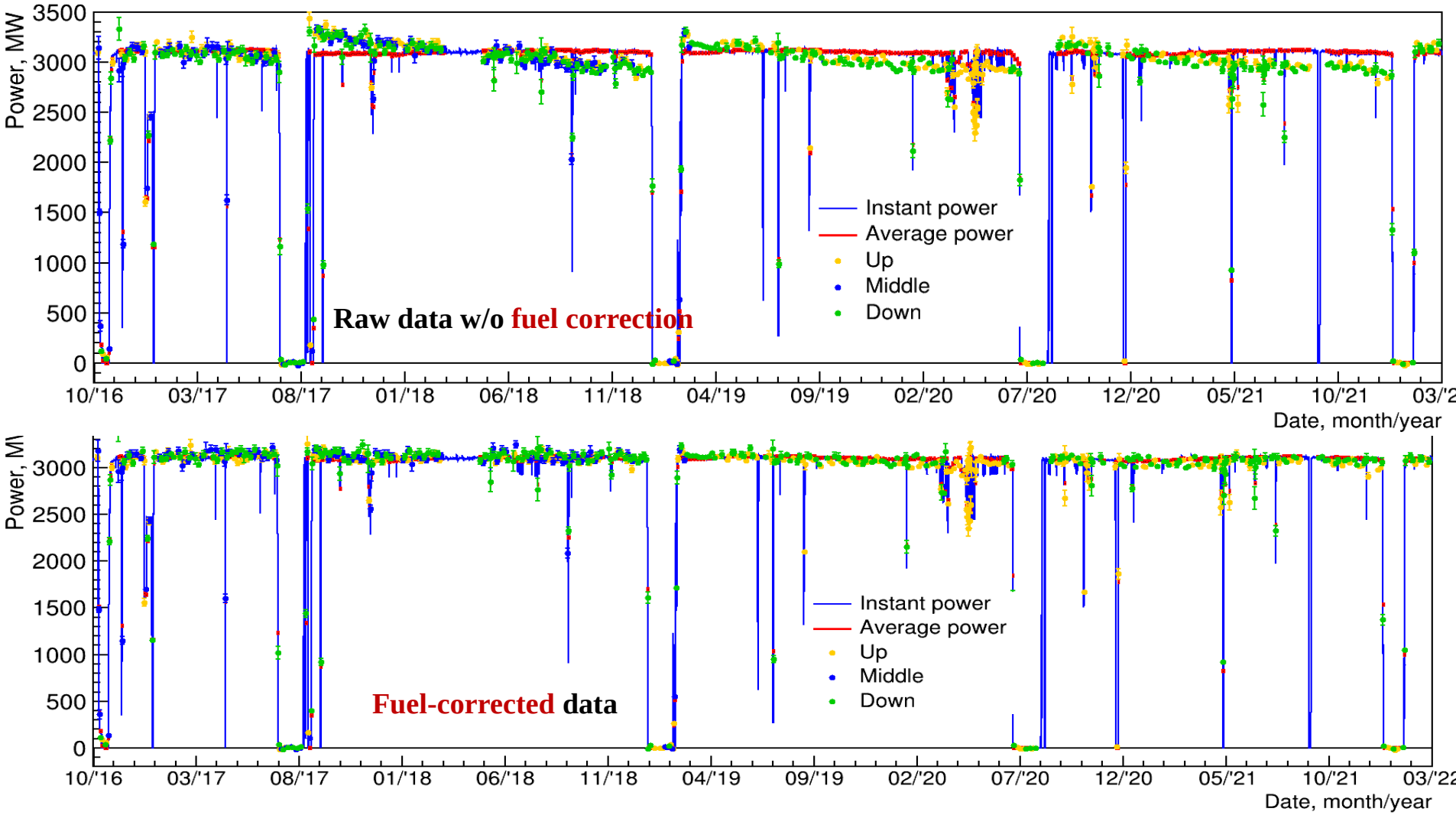


Systematic errors dominate. Estimated from the spread between reactor campaigns

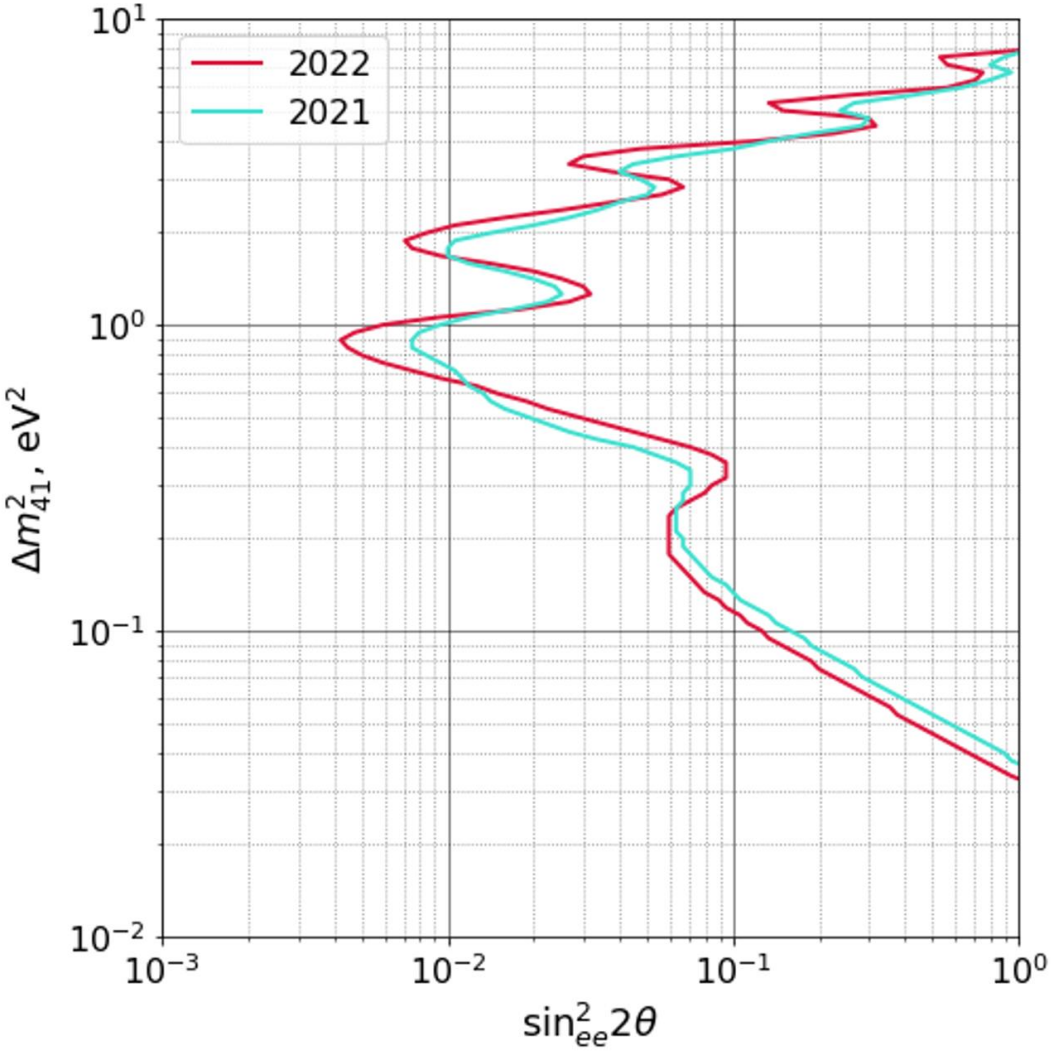
DANSS has 40% larger F239Pu range: DANSS 0.25-0.39 DB 0.25-0.35

Reactor power measurements with neutrino

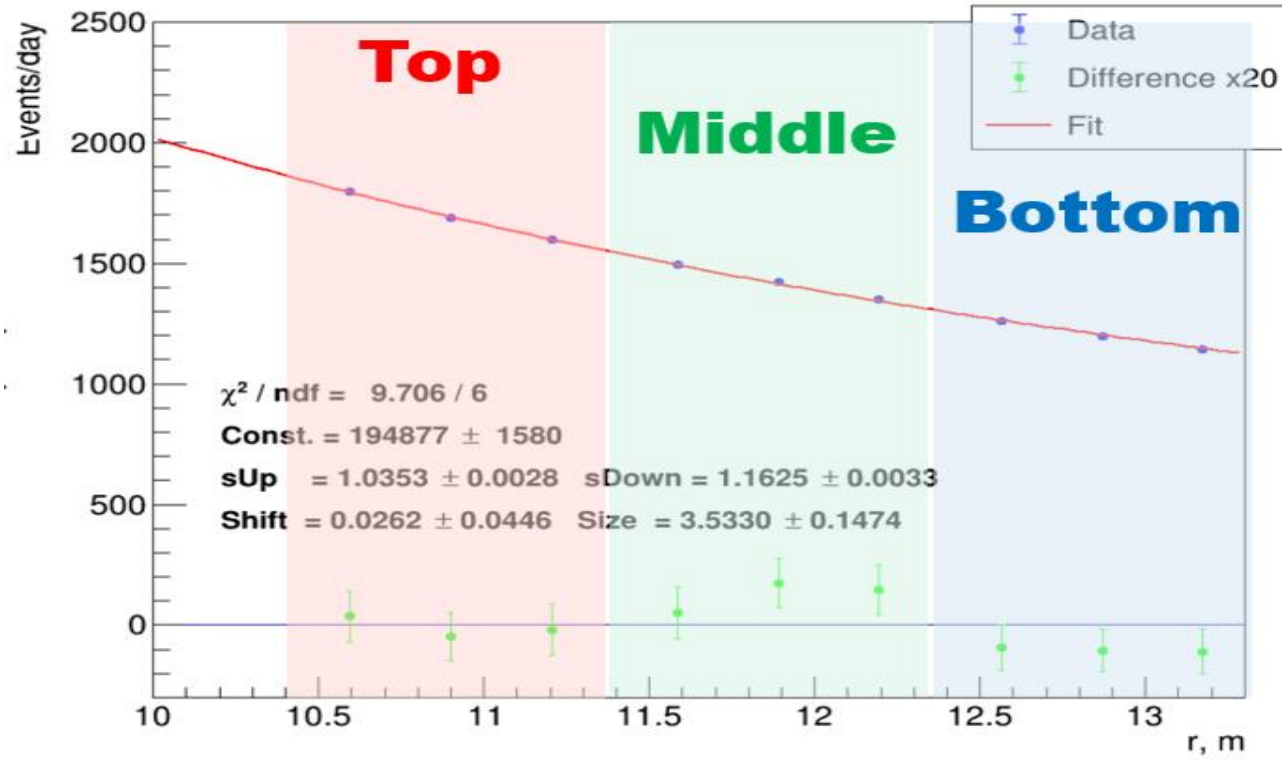
Top – Middle – Bottom data



Comparison of exclusions in 2022 and 2021



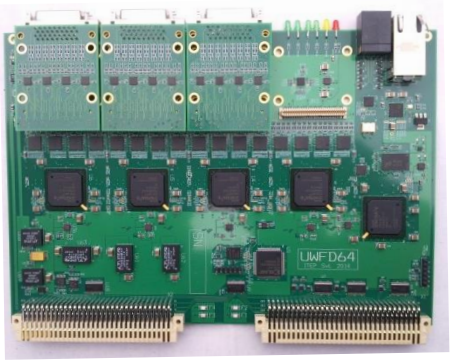
IBD total rate vs. effective distance

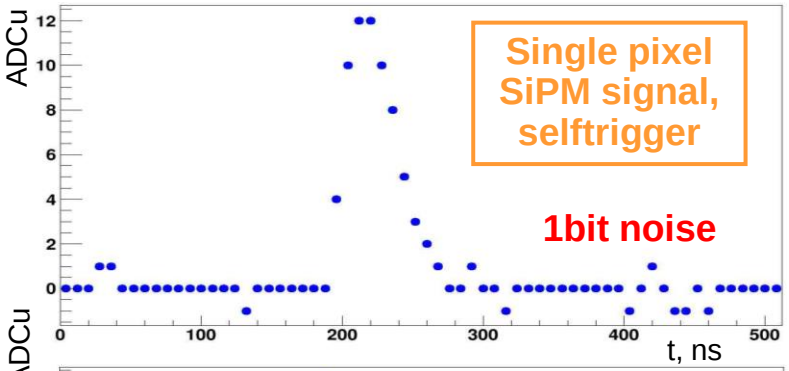


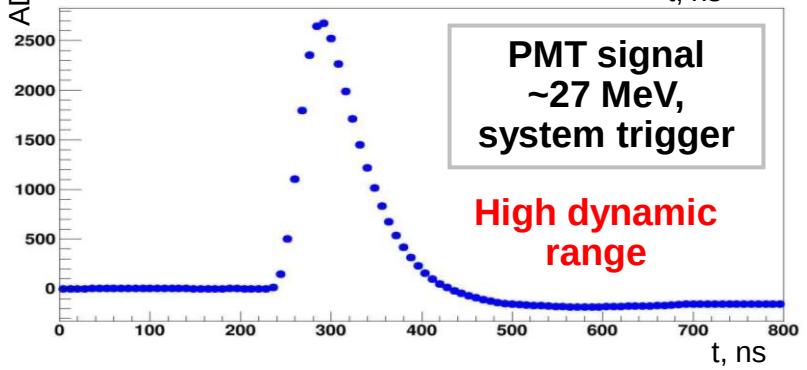
- **IBD intensity follows reasonably the $1 / L^2$ dependence.**
- **Detector was divided on 3 parts in each position.**

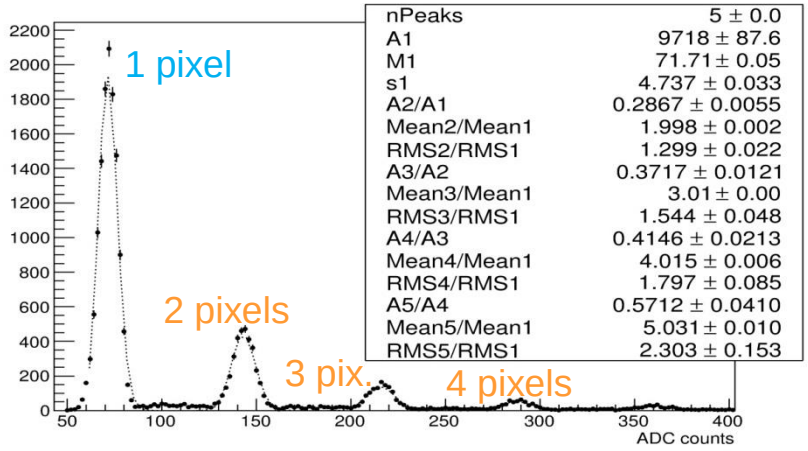
Data acquisition system

WFD
- Input amplifiers
- ADCs
- FPGAs
- Power and VME buffers









- 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.

❖ **σ's for nuisance parameters**

relative detector efficiencies - 0.2%

additional smearing in energy resolution - 3%

energy scale - 2%

energy shift - 50 keV

distance to fuel burning profile center - 5 cm

cosmic background - 25%

fast neutron background - 30%