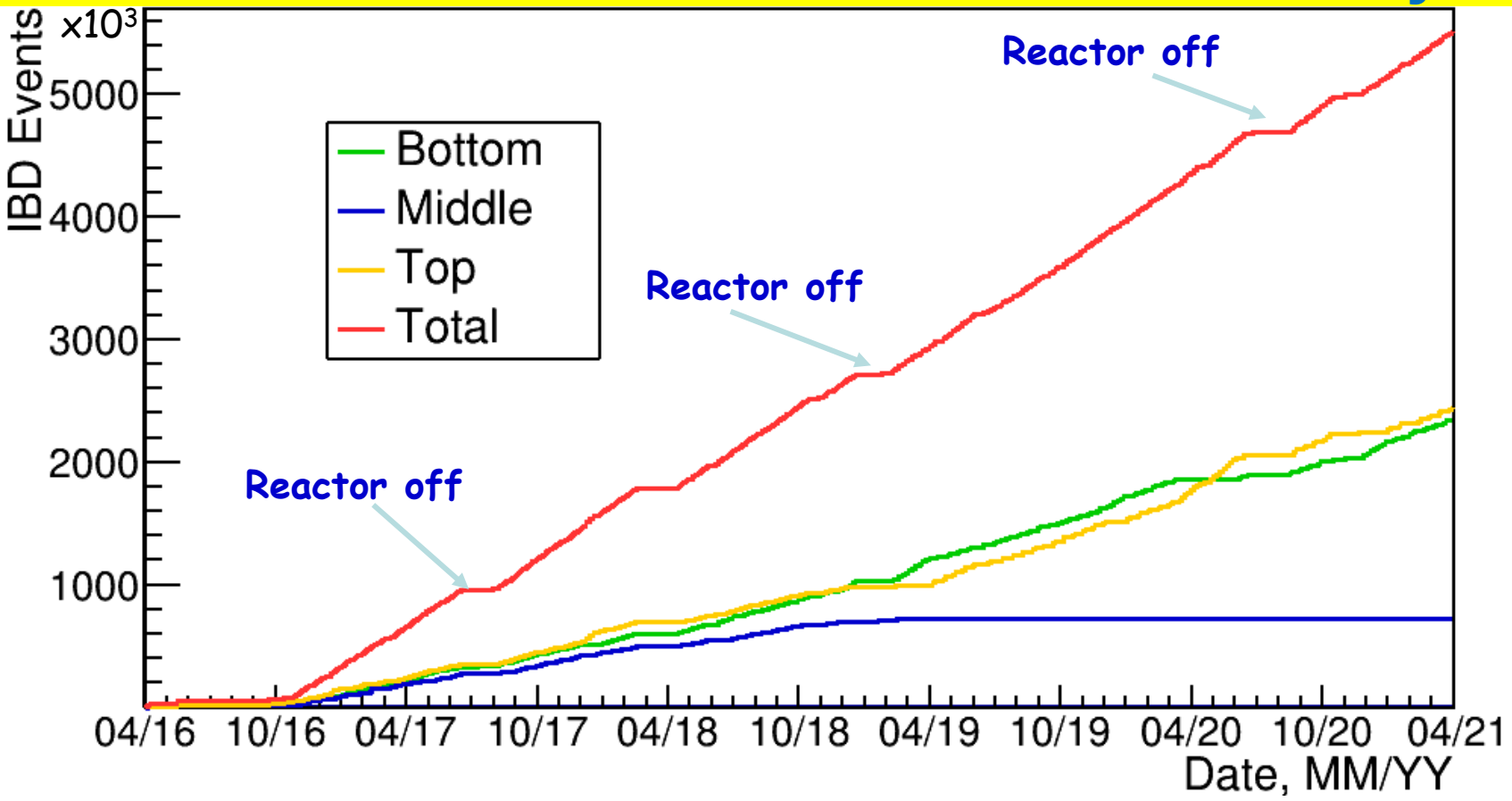
20th Lomonosov Conference on Elementary Particle Physics
Moscow State University
August 20, 2021

Five years of sterile neutrino searches with DANSS

Mikhail Danilov, LPI (Moscow)
for the DANSS Collaboration

DANSS collected 5.5M antineutrino events in 5 years



- Total statistics accumulated is **5.5M IBD-events in 5 years**

  Including 2.46M/2.32M events at Top/Bottom positions

  and 3 reactor off periods

  (5M events in oscillation analysis)

There are several indications of 4th neutrino

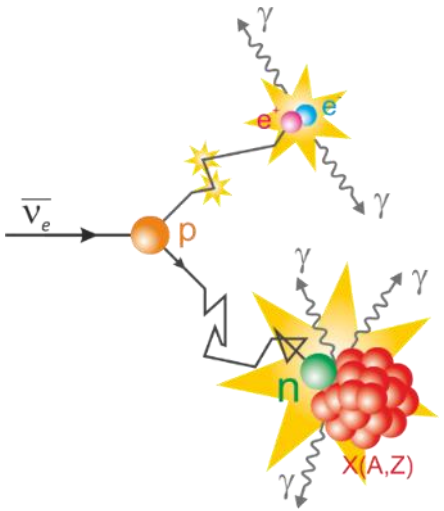
LSND, MiniBoone: $\bar{\nu}e$ appearance
SAGE and GALEX ν_e deficit (GA)
Reactor $\bar{\nu}_e$ deficit (RAA)

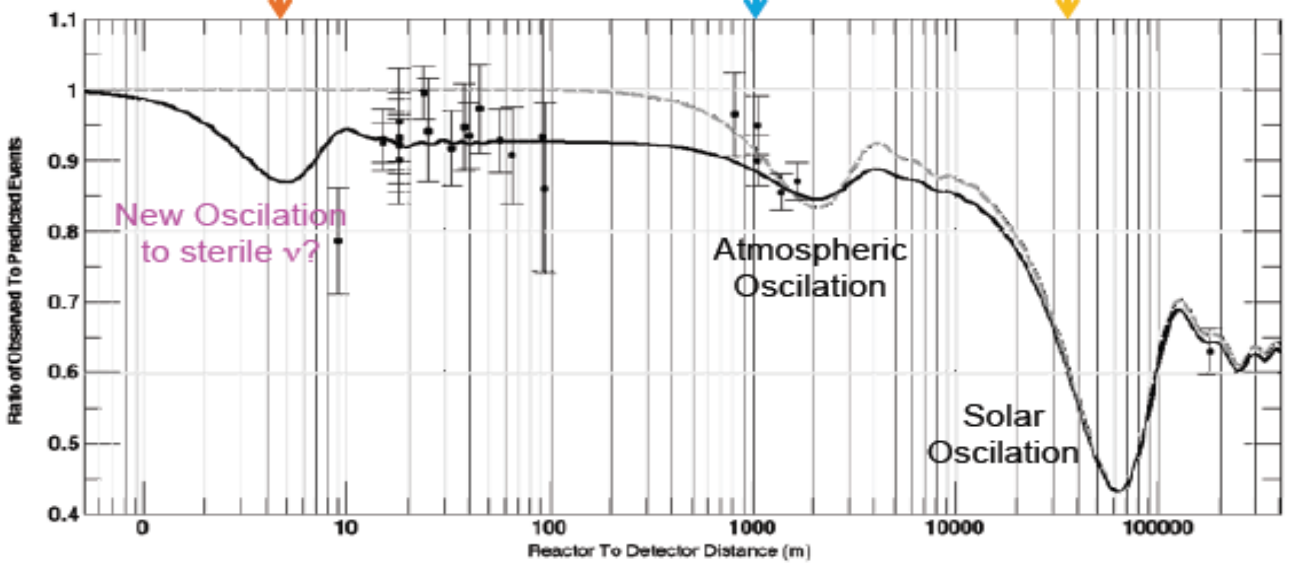
➡

Indication of a sterile neutrino
$\Delta m^2 \sim 1\ eV^2$
$Sin^2 2\Theta_{14} \sim 0.1$
=> Short range neutrino oscillations

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\Theta_{14} \sin^2(1.27\Delta m^2_{41} \frac{L}{E}) - c^4_{14} \sin^2 2\Theta_{13} \sin^2(1.27\Delta m^2_{31} \frac{L}{E}) - c^4_{14} c^4_{13} \sin^2 2\Theta_{12} \sin^2(1.27\Delta m^2_{21} \frac{L}{E})$$

Inverse Beta Decay (IBD) process



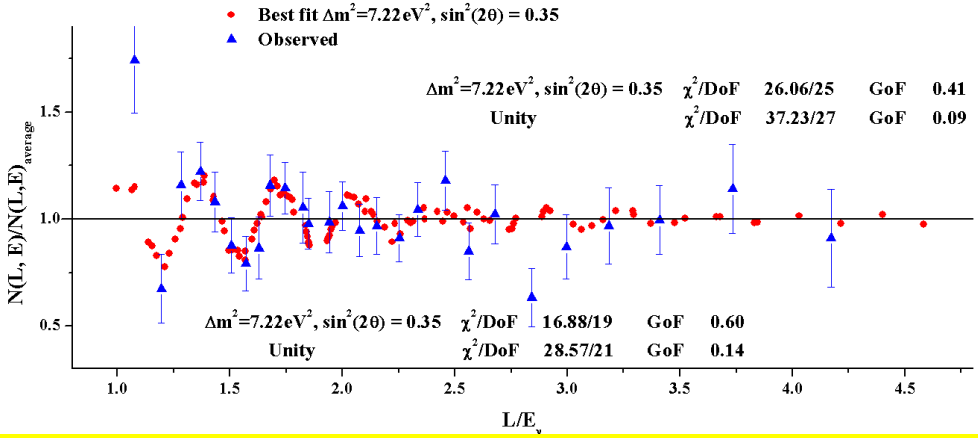


G. Mention et al. Phys Rev D 83 073006 (2011)

Reactor models are based on ILL measurements of 235U, 239Pu, 241Pu electron spectra.
Recently Kurchatov Inst. Group observed 5.4% smaller e- yields for 235U, 239Pu (arXiv:2103.01684v1). This can explain the RAA!

Recent (2018) indications of sterile neutrinos

NEUTRINO-4: $\Delta m^2 \sim 7 eV^2$ $\sin^2 2\theta \sim 0.35$! JETP Lett. 109 (2019) no.4, 213; Arxiv:2005.05301

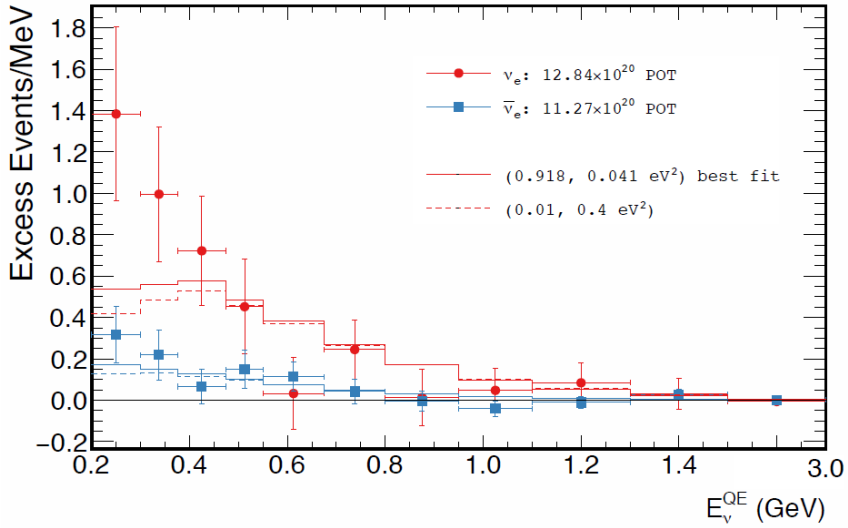


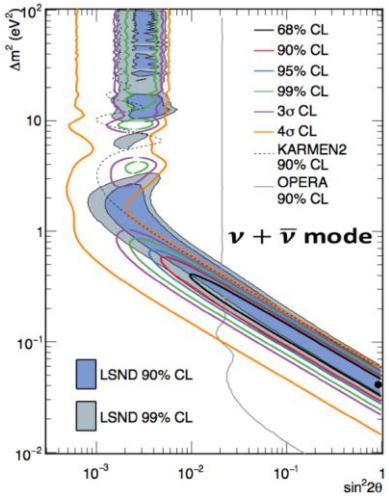
NEUTRINO-4 claimed observation of sterile neutrinos although significance is only 3σ and there are concerns about validity of the analysis:

M.D., N.Skrobova JETP Lett.112,199(2020)

C.Giunti et al. Phys.Lett.B 816(2021)136214

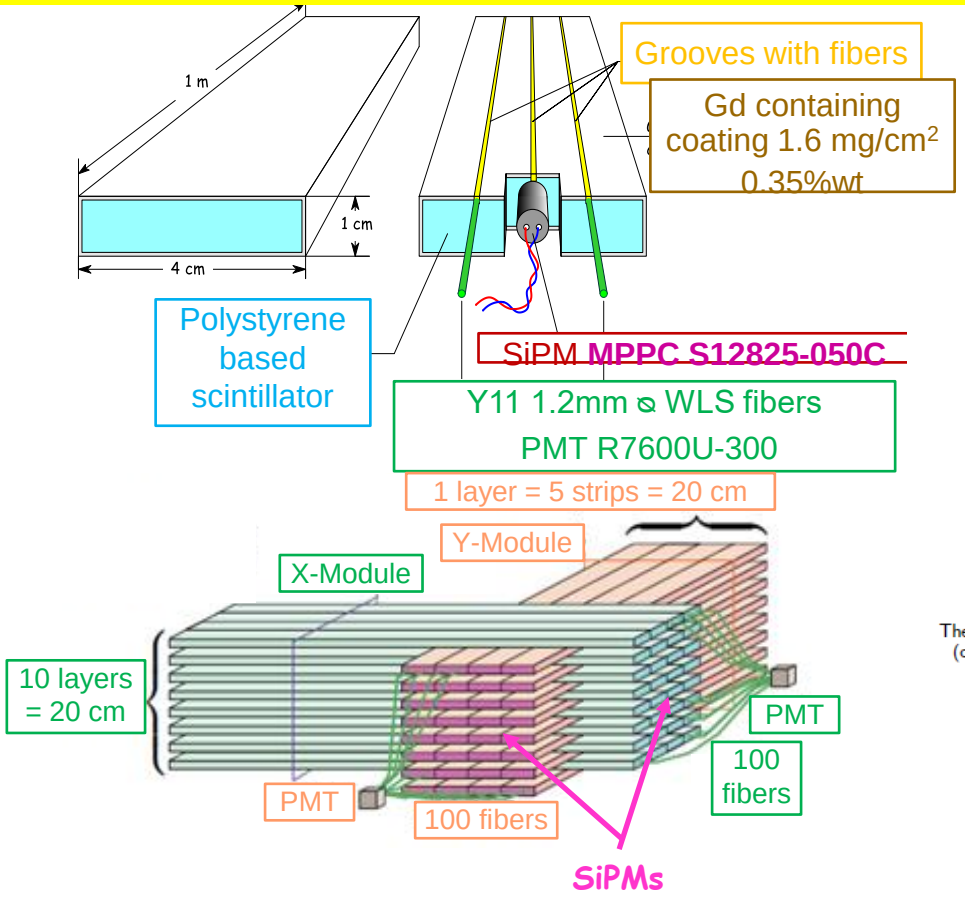
MiniBooNE ν_e excess of 4.8σ (6σ with LSND) Phys.Rev.Lett. 121 (2018) no.22, 221801



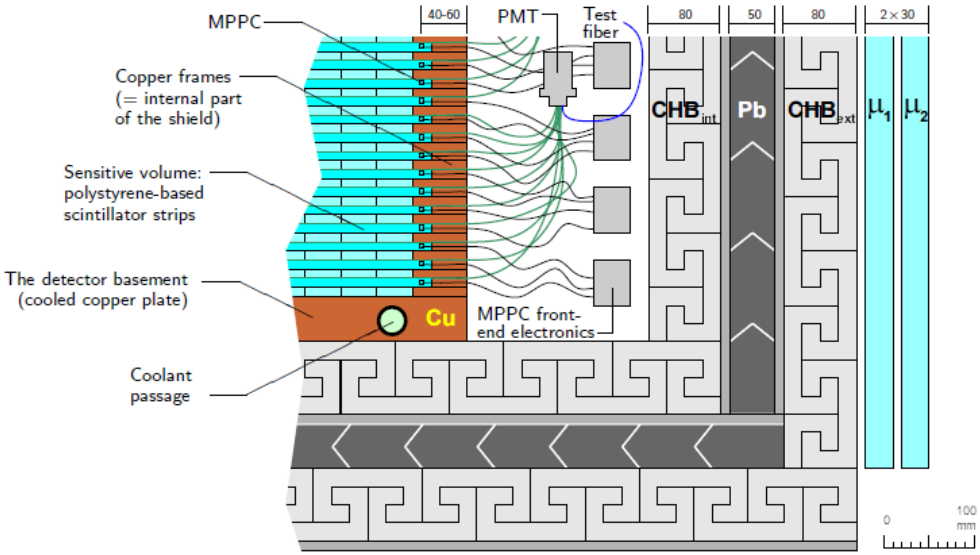


Searches for sterile neutrinos are very exciting

DANSS Detector design (ITEP-JINR Collaboration)



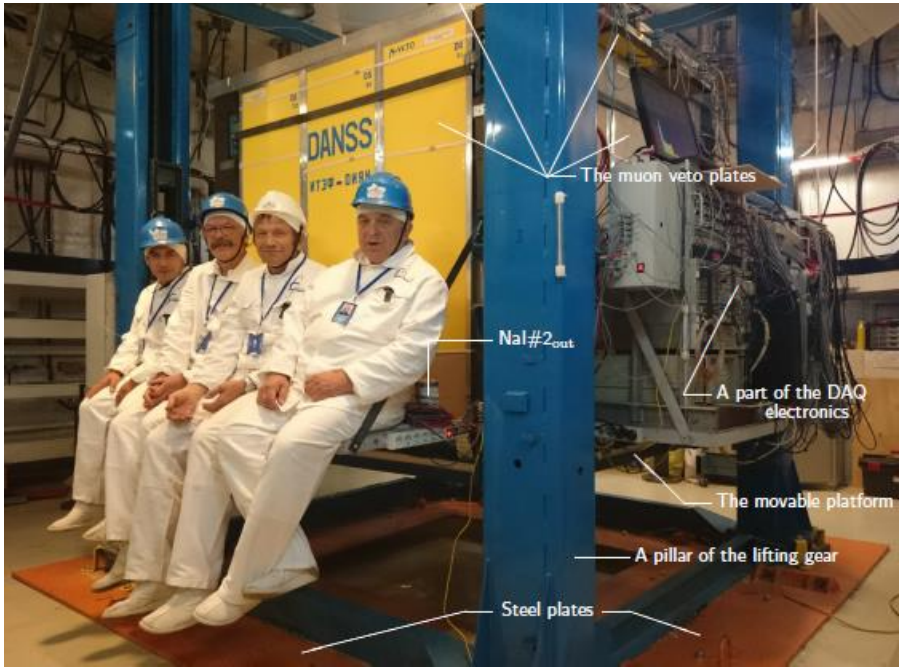
JINST 11(2016)no11,P11011

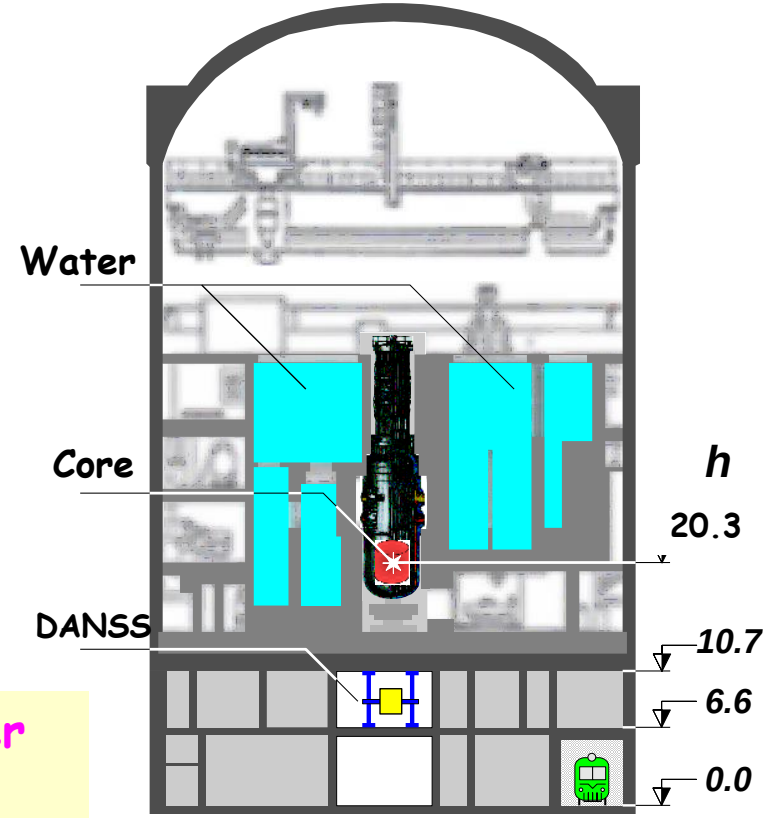


- **2500 scintillator strips with Gd containing coating for neutron capture**
- **Light collection with 3 WLS fibers**
- **Central fiber read out with individual SiPM**
- **Side fibers from 50 strips make a bunch of 100 on a PMT cathode = Module**

- **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)

Improvements since last year*

(in comparison with our presentations in 2020: M.D. arXiv:2012.10255)

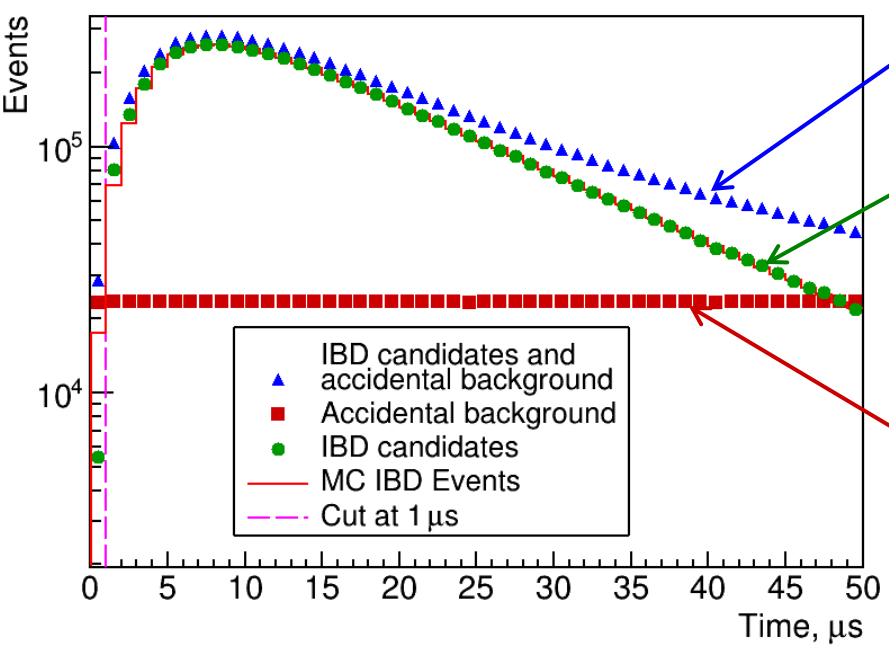
- Median of Landau distribution is used in muon calibration instead of most probable value → More stable calibration.
  SiPM - 18.9p.e./MeV; PMT – 15.3p.e/MeV

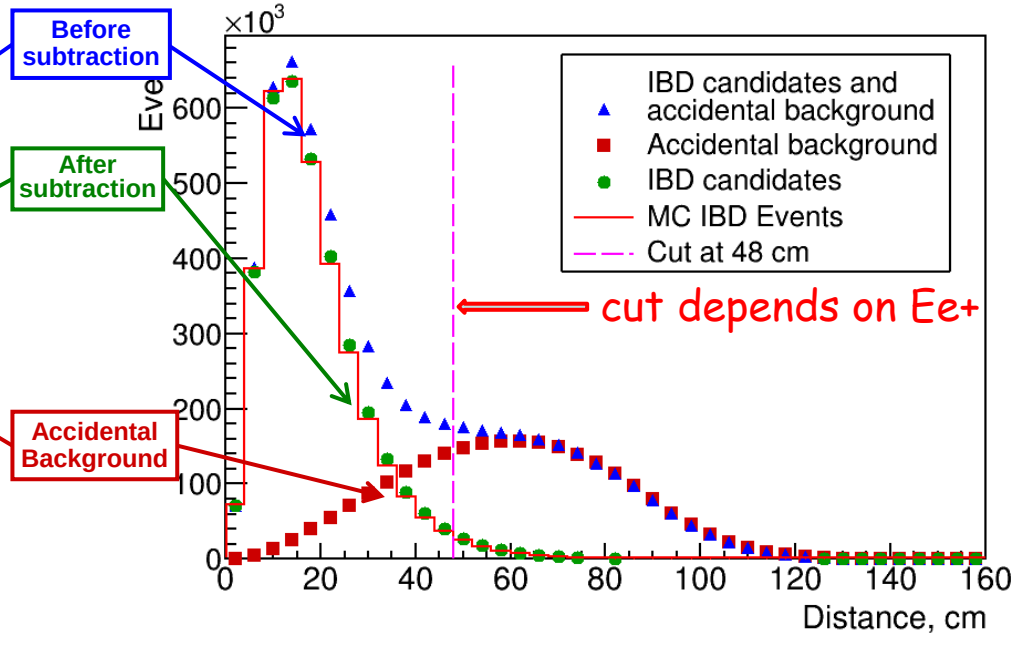
- Use of additional ^{12}B production mechanism: $\mu^- + {}^{12}C \rightarrow {}^{12}B + \nu_\mu$
  Consistent results in Energy scale calibration with $n + {}^{12}C \rightarrow {}^{12}B + p$

- One more Reactor Off period

- Additional 1.5 million of IBD events

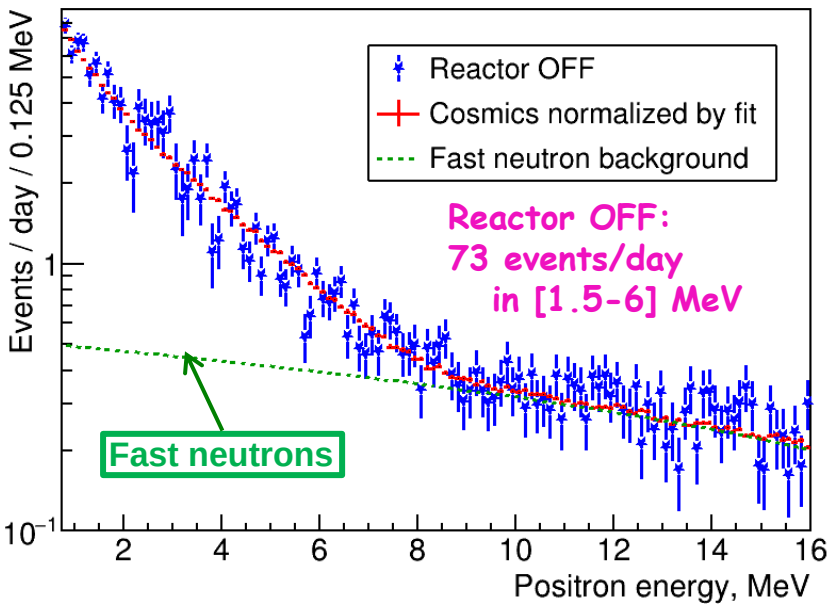
Accidental coincidence background

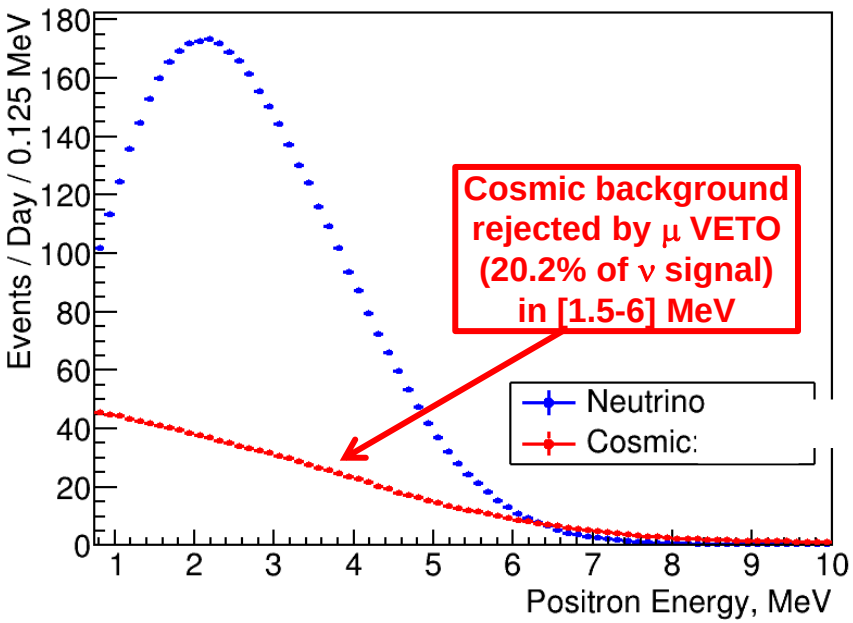




- **Accidental coincidence of 2 uncorrelated signals (e+-like and neutron-like) in a IBD window [1-50] μs → accidental coincidence background (ACB)**
- **ACB spectrum is constructed directly from data applying the same physics cuts as for IBD signal except coincidence time taken outside IBD time window [1-50] μs in numerous non-overlapping intervals (large statistics is essential to decrease statistical errors of subtraction) ➔ No systematic errors**
- **ACB rate is 15.4% 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

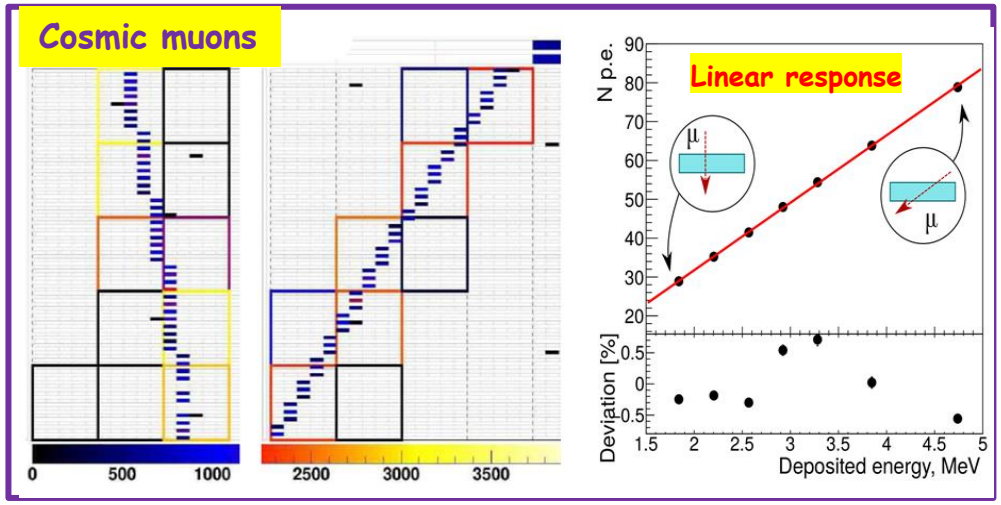


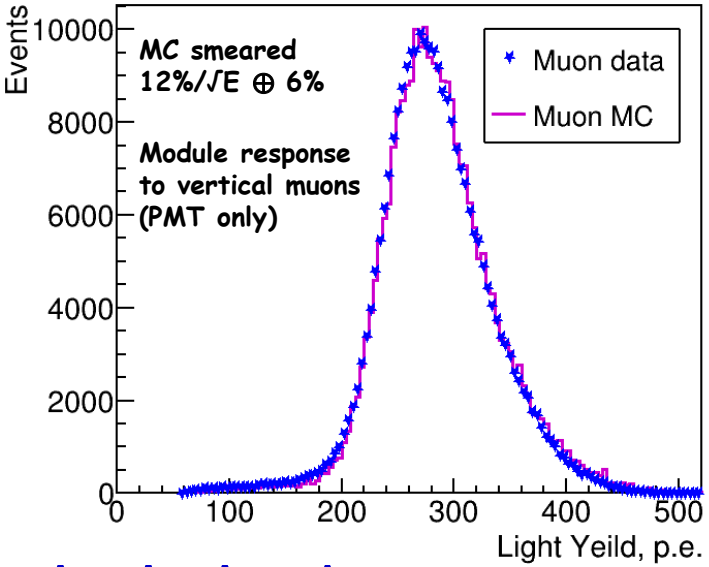


- 25 ν events/day from neighbor reactors were subtracted
- **Fast neutrons**: linearly extrapolate from high energy region and subtract separately from positron and visible cosmic spectra, CR (fast neutron) = 16 events/day (in 1.5-6 MeV range)
- **Visible cosmic background (CB)** has been **directly rejected** by VETO, it is 20.2% 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 ~5% from reactor OFF data, was subtracted (41 events/day).
- Additional 16 events/day at low energies observed in reactor off data were subtracted
- Total background subtracted background is 1.7% for the top detector position. S/B>50!

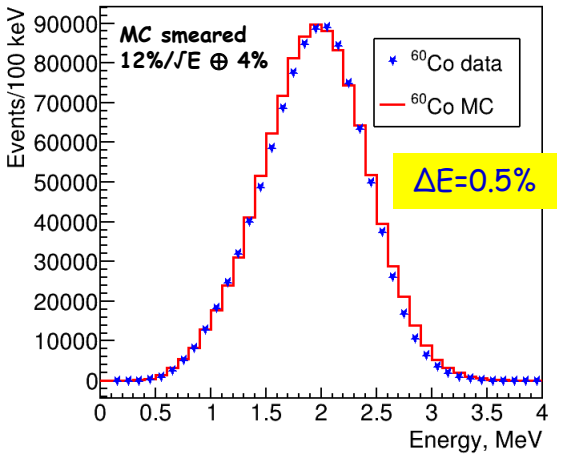
Calibration

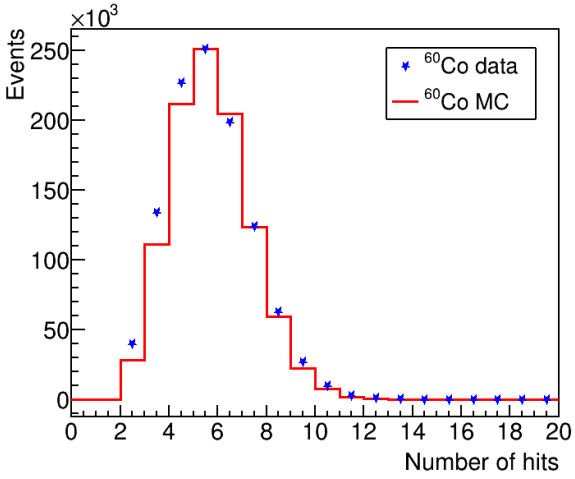
2500 SiPM gains and X-talks are calibrated every 30-40 min.
All 2550 channels are calibrated every 2 days using cosmic muons

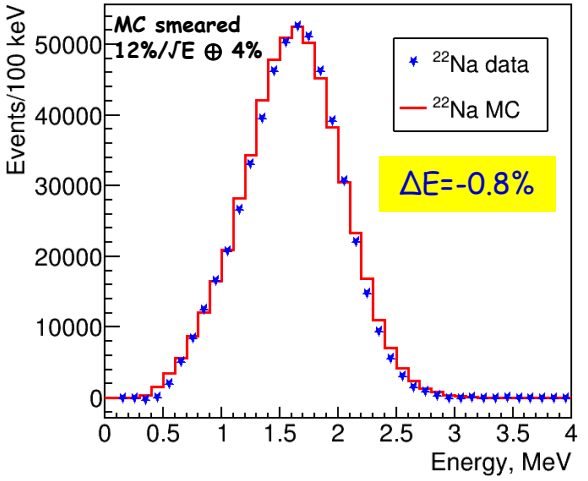




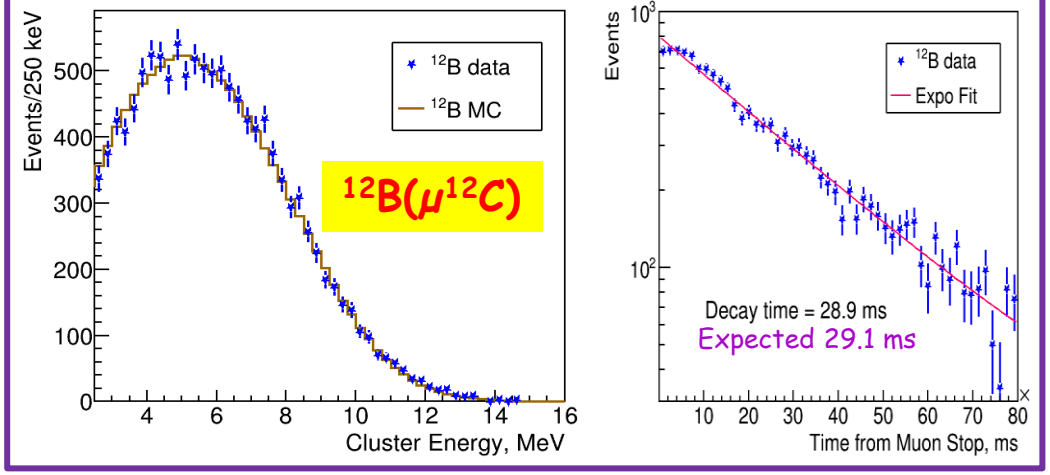
Several calibration sources are used to check the detector response

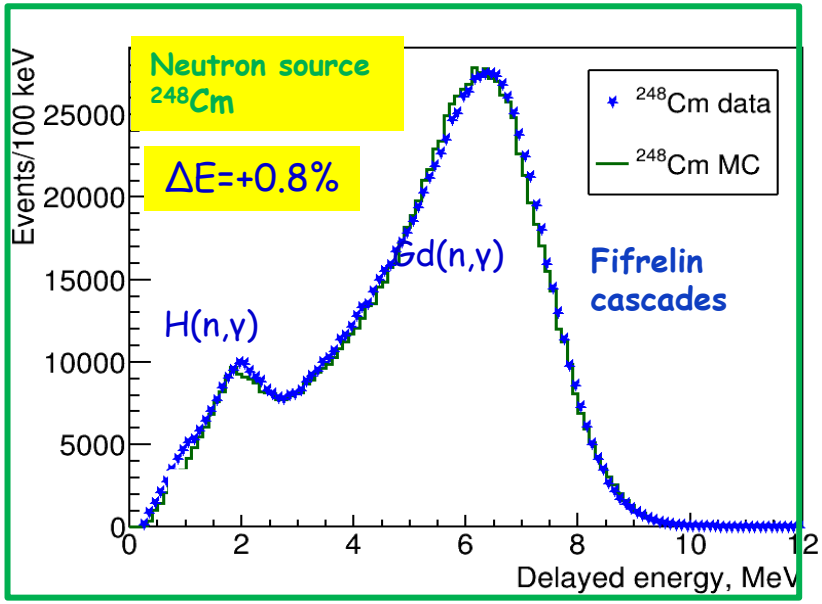


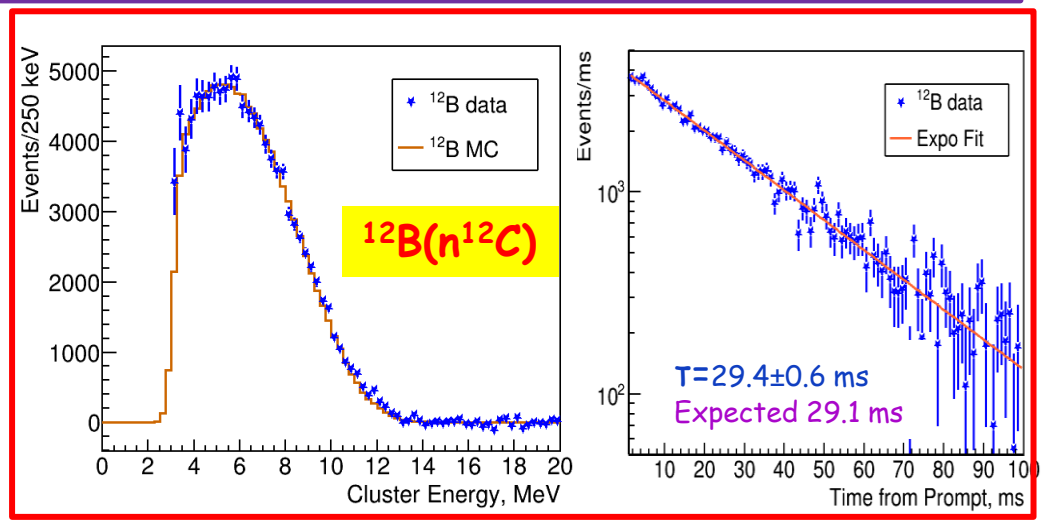


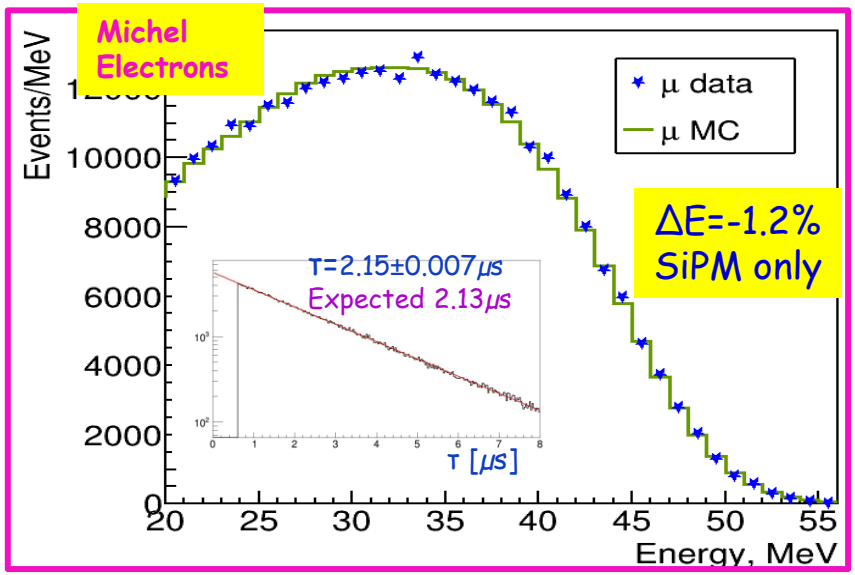


Calibrations



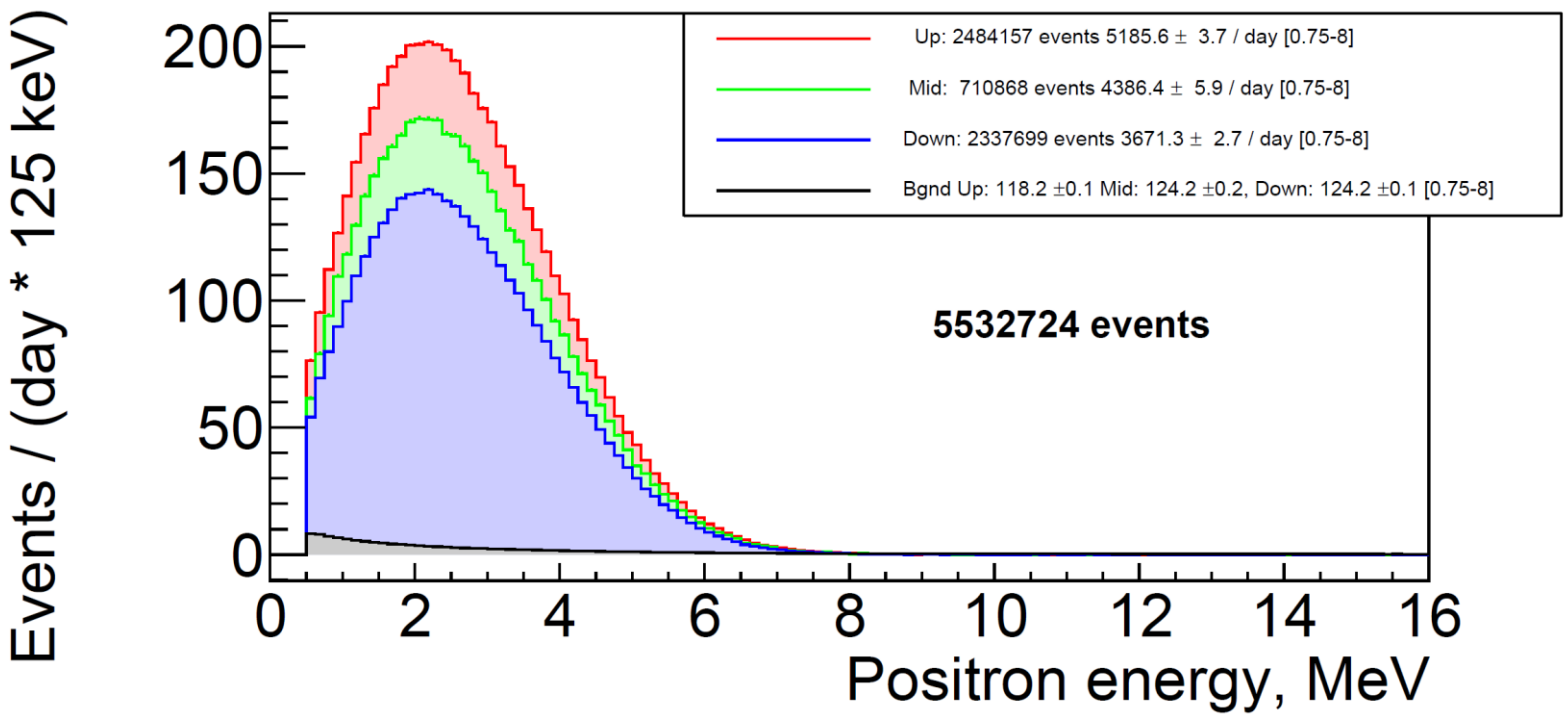






- Energy scale has been fixed using β-spectrum of ^{12}B, which is similar to positron signal
- Systematic error on E scale of +/-2% was added due to spread in source responses (<1%)
  Hope to reduce this error soon
- Energy resolution for calibration sources is still worse than in MC and additional smearing of $12\%/\sqrt{E} \oplus 4\%$ has been added to MC

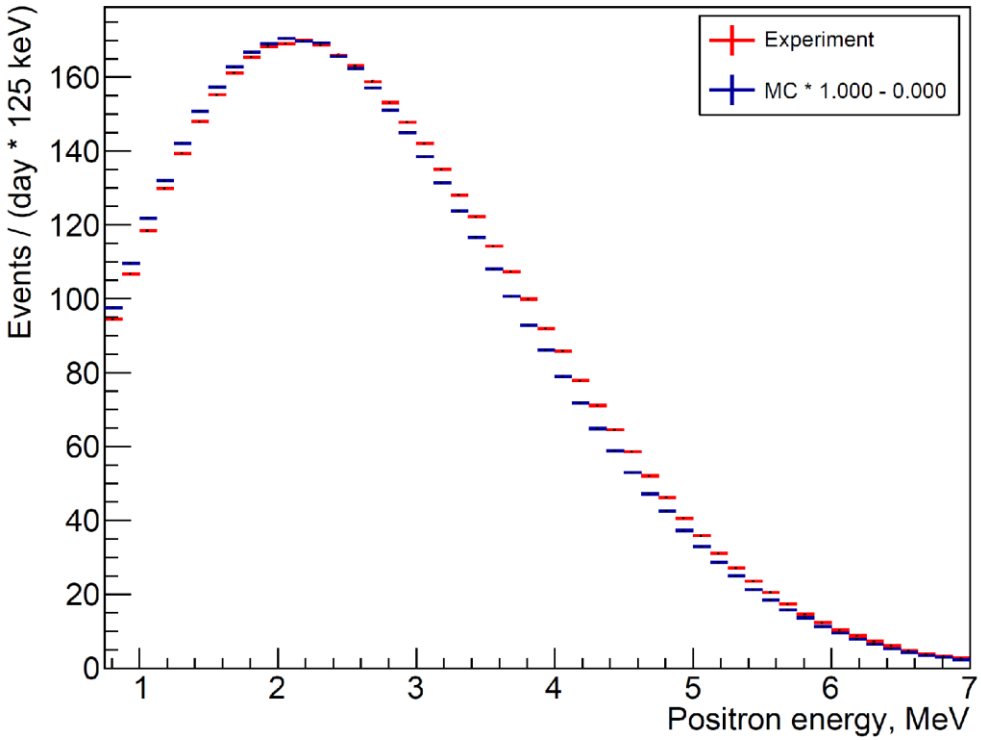
Positron spectrum of IBD-signal

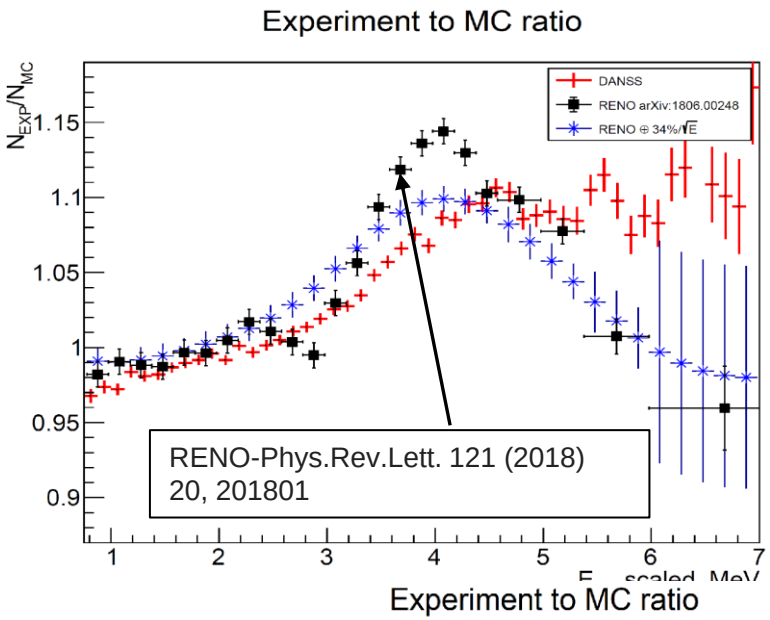


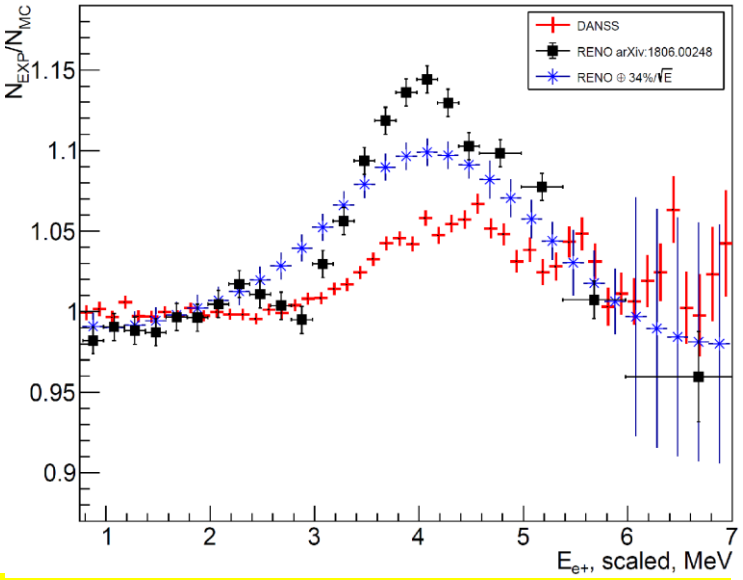
- **Positron kinetic energy spectra (no annihilation photons) at 3 detector positions**
- **~5000 events/day in detector fiducial volume (78% of full volume)**

  at 'Top' position (closest to the reactor).
- **Background ~1.7% (Top position, E: 1.5-6MeV). Signal/Background >50!**

Positron spectrum: experiment vs. H-M Model



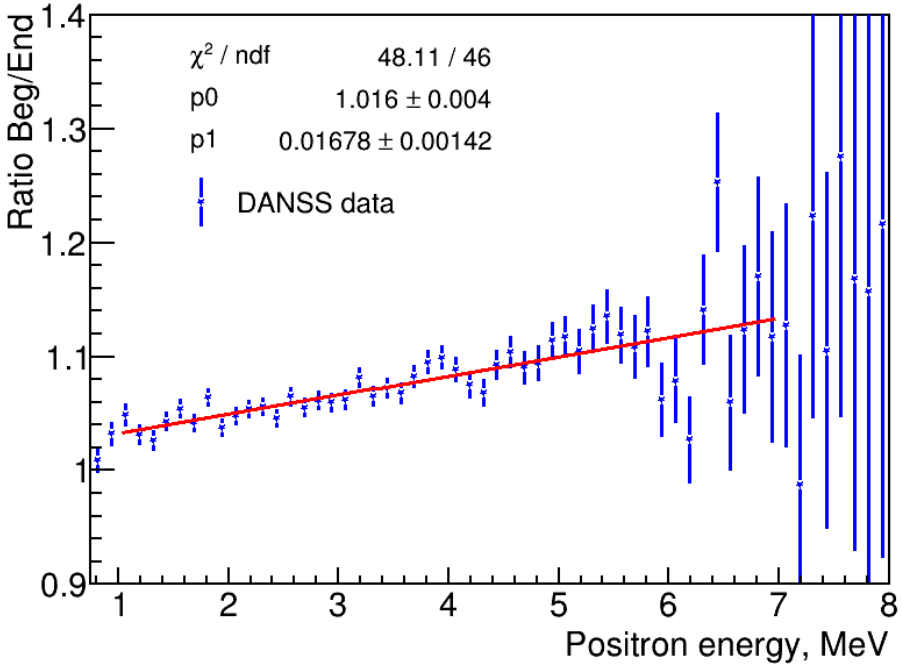




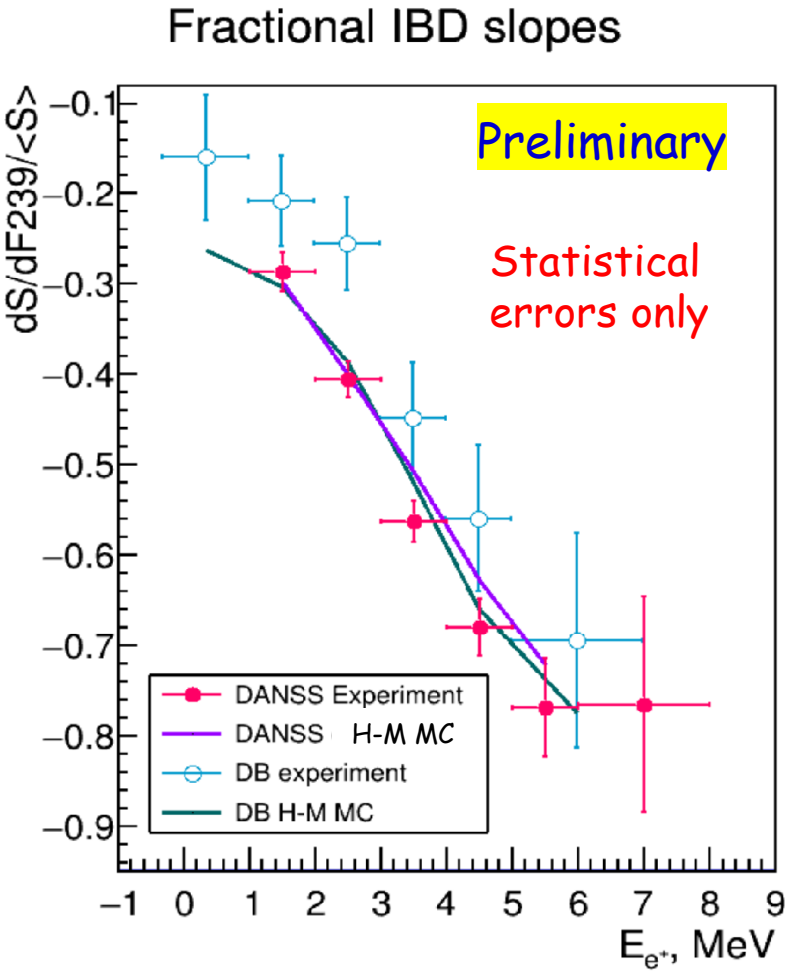
- In order to reach best agreement with H-M model in 1-3 MeV region e+ spectrum was scaled by 0.995 and shifted on -25 keV.
  The nature of this shift (if it exists!) is still under investigation.
- With such a shift we see a bump in e+ spectrum
- similar to other experiments.
- However, we can not claim its existence yet because of high sensitivity of the shape to energy scale and shift.

Positron spectrum dependence on fuel composition is clearly seen

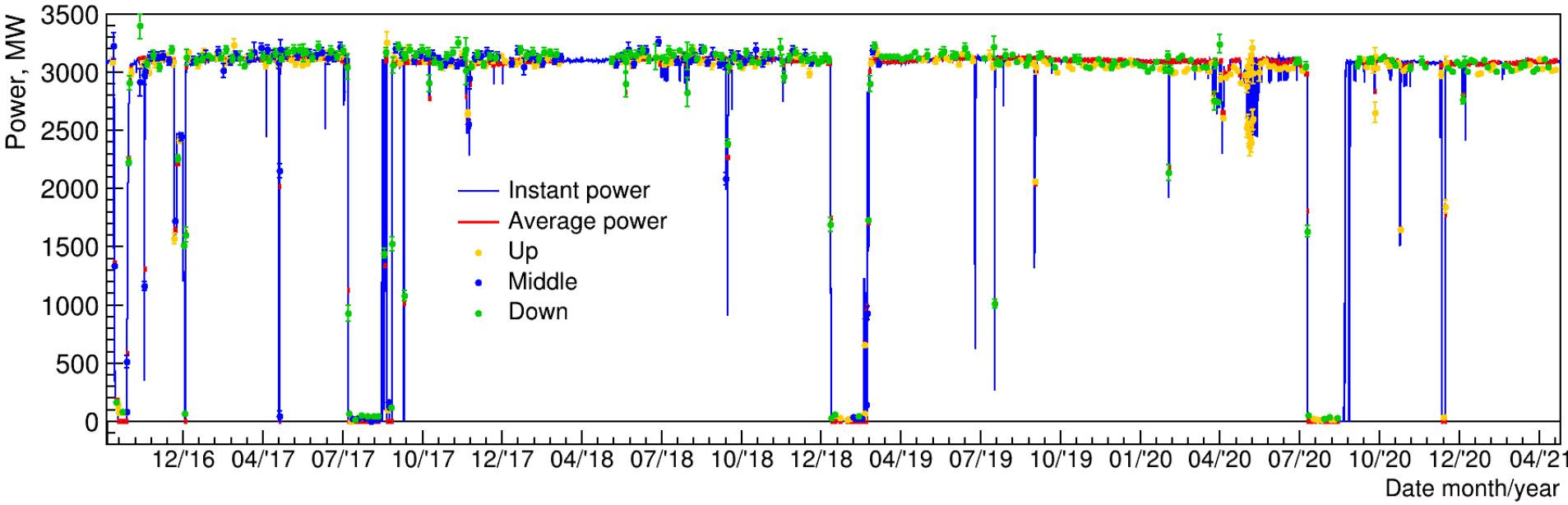
Ratio of e+ spectra 1-4 months after reactor shutdown and 3 months before shutdown



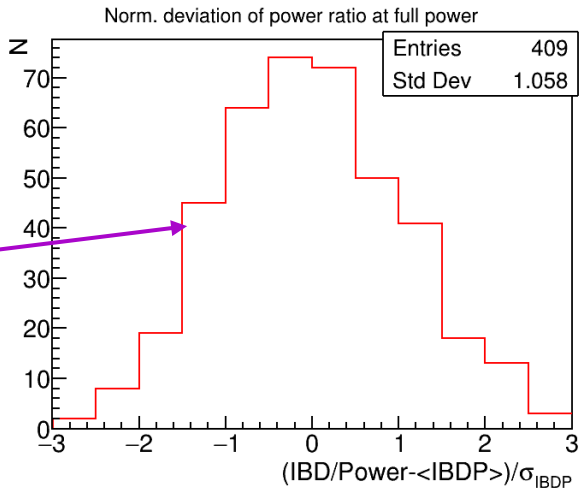
IBD rate dependence on 239Pu fission fraction
(dσ/dF239)/σ(F239=0.3) for various Ee+
It agrees with H-M model
and somewhat larger than at DayaBay



Reactor power monitoring



- **DANSS points after all corrections (all backgrounds including adjacent reactor fluxes (0.6%), fuel composition using H-M model, etc.) and free overall normalization agree with reactor power measured with several methods**
- **Reactor power is measured by the DANSS with neutrino flux with 1.5% accuracy in 2 days during 4.5 years,**
- **Consistent with statistical fluctuations.**
- **➡ Changes in absolute detector efficiency are known with accuracy better than ~ 1% during 4.5 years!**
- **Relative efficiency is even more stable (<0.2%) because of frequent changes of detector positions**



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;

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

η – nuisance parameters;

W – covariance matrix;

$k^0=1$ $\eta^0=0$

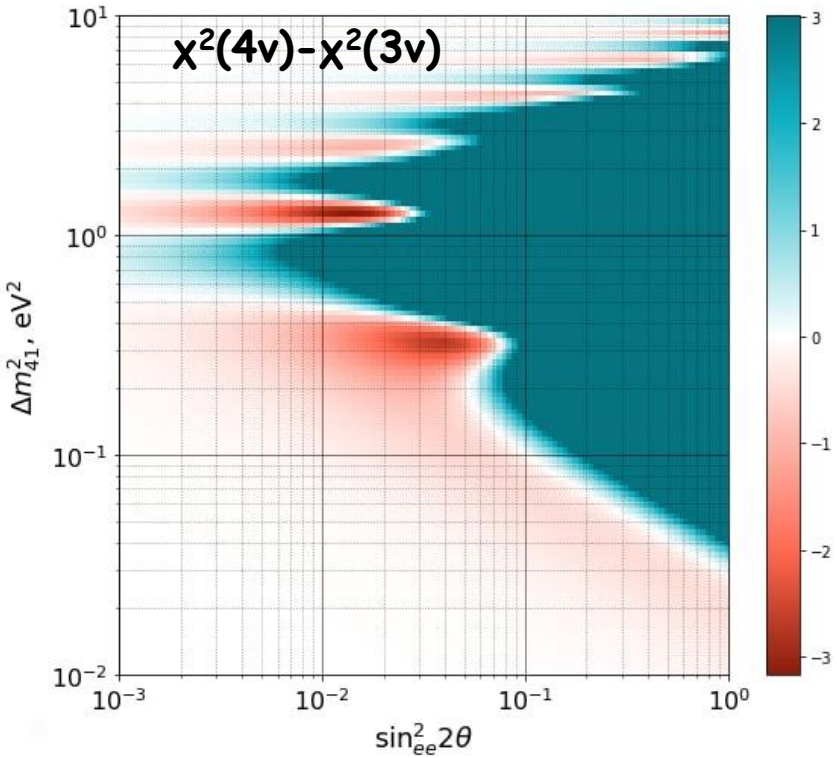
Difference in χ^2 between 4v and 3v hypotheses

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

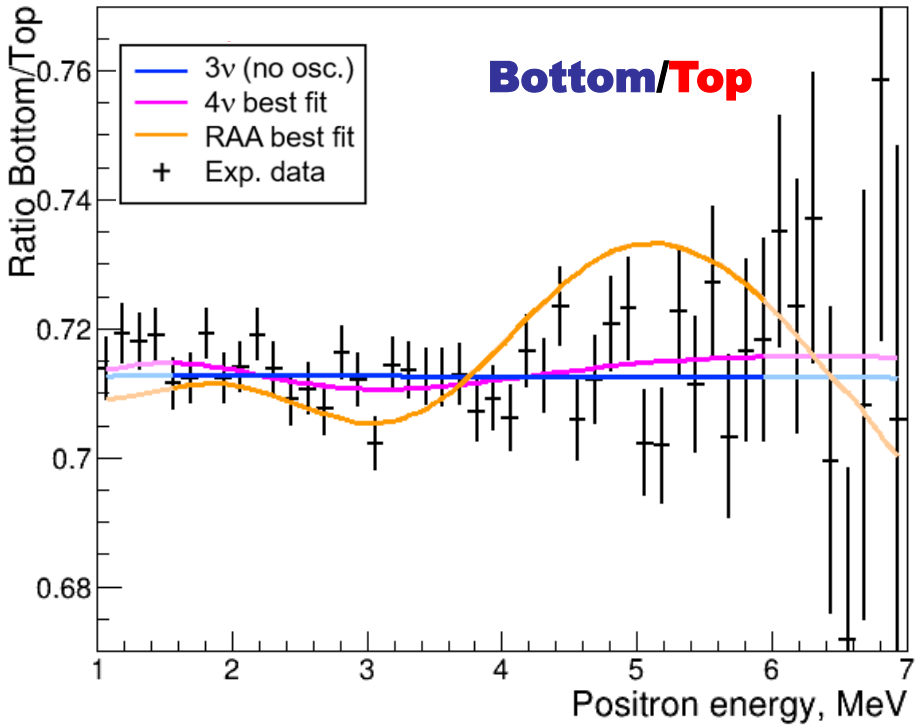
Blue – $\chi^2(4v)>\chi^2(3v)$,

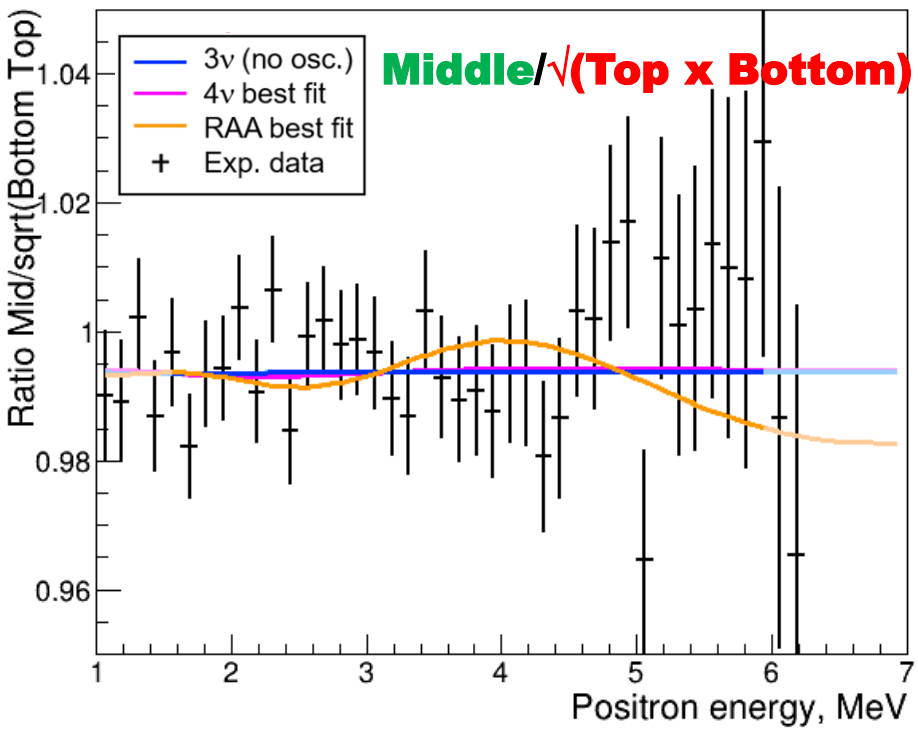
Dark blue region is excluded at 2σ CL in case of χ^2 distribution with 2 DoF $(\chi^2(4v)-\chi^2min)=6.18$

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)
- Using current statistics 2016-2020 (~5 million IBD events)
  we see no statistically significant indication of 4ν signal:
  ΔX^2=-3.2 (< 1.3σ) for 4ν hypothesis best point Δm^2=1.3 eV^2 , $\sin^2 2\theta$=0.014
- RAA has been excluded with ΔX^2= 107.
- 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^+ in 1.5-6 MeV to be conservative),**
- **σ's for nuisance parameters**

relative detector efficiencies - 0.2%

additional smearing in energy resolution - 25%

energy scale - 2%

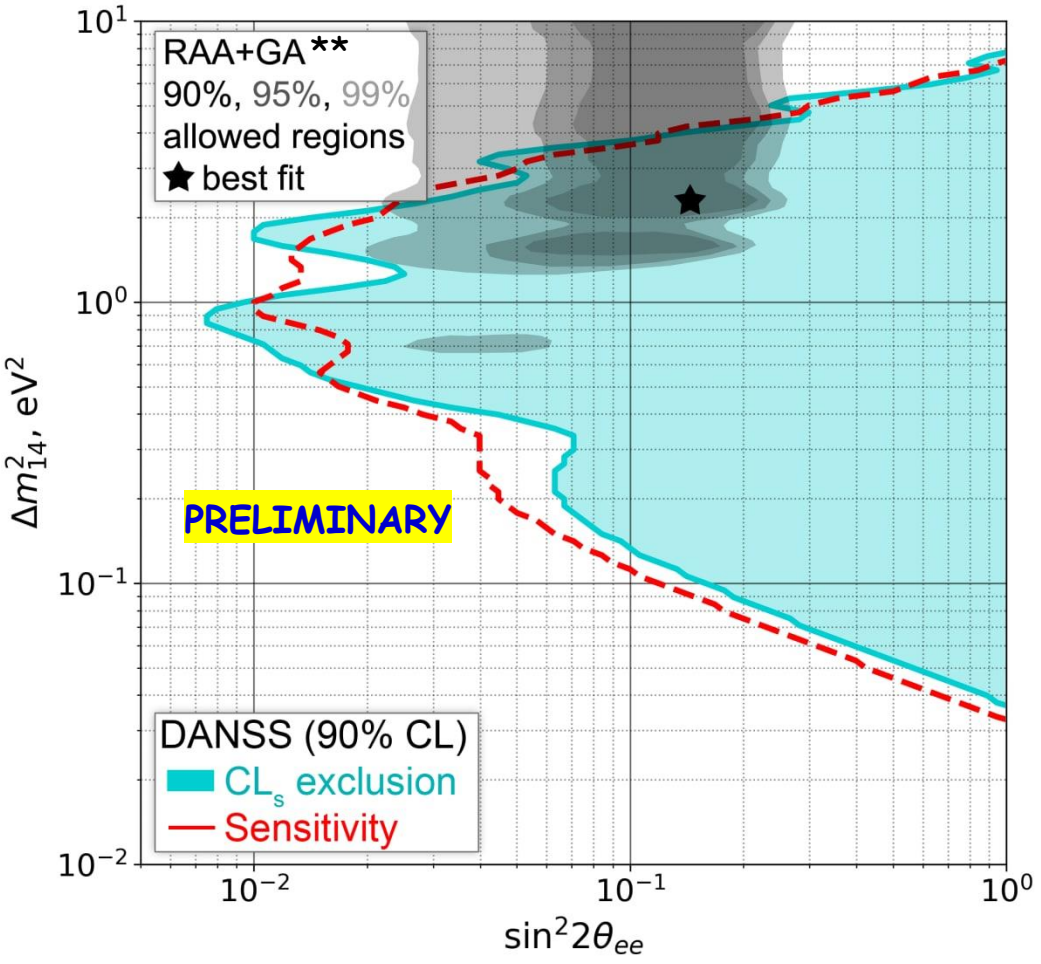
energy shift - 50 keV

distance to fuel burning profile center - 5 cm

cosmic background - 25%

fast neutron background - 30%

- **New data make limits more smooth in reasonable agreement with sensitivity**
- **The most stringent limit reaches $\sin^2 2\theta < 8\times10^{-3}$ level.**
- **A very interesting part of 4ν parameters is excluded.**
- **The most probable point of RAA+GA is excluded at 5σ confidence level**



** - G.Mention J.Phys.:Conf.Ser. 408 (2013) 012025

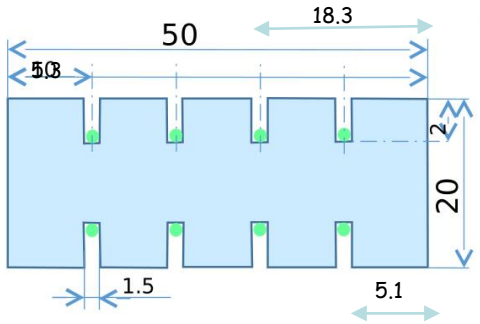
The DANSS upgrade

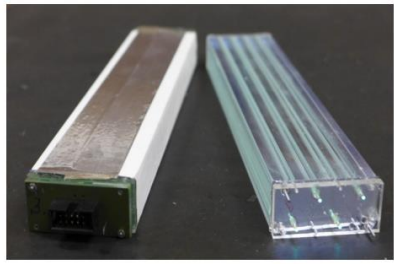
Main goal: to reach resolution **13%/√E**
w.r.t. current very modest 34%/√E.

New geometry:

Strips: 2x5x120 cm, 2-side 4SiPM readout
Structure: 60 layers x 24 strips: 1.7 m³
Setup uses **the same shielding and moving platform.**
Gd is in foils between layers.
Upgrade will be finished in 2022

New scintillator strips

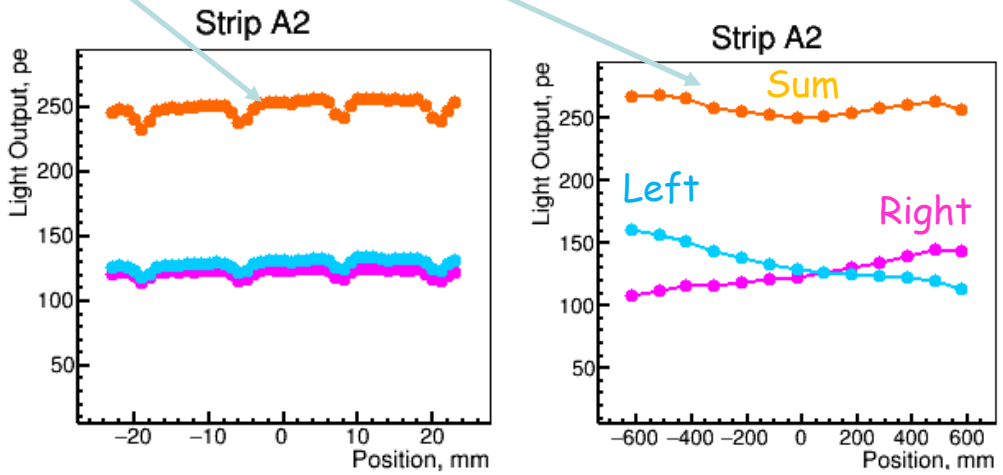




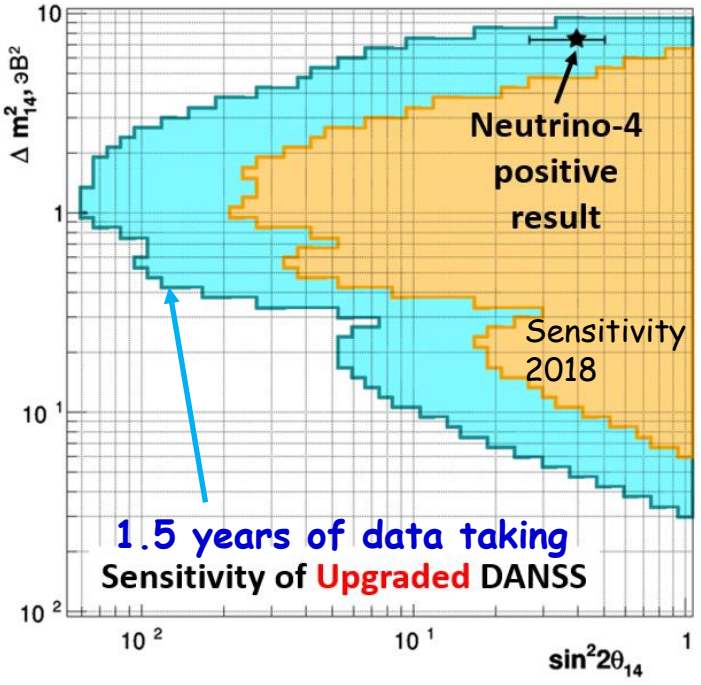
WLS fiber positions were optimized for better uniformity of response

Strip tests at π-beam

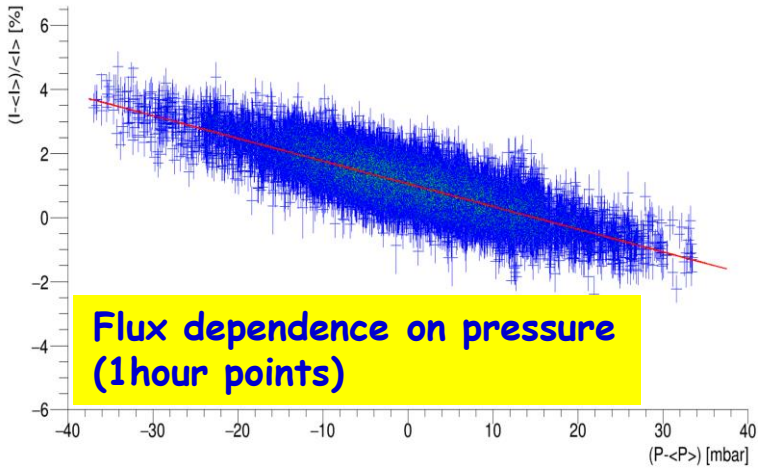
Transverse and longitudinal responses are very uniform



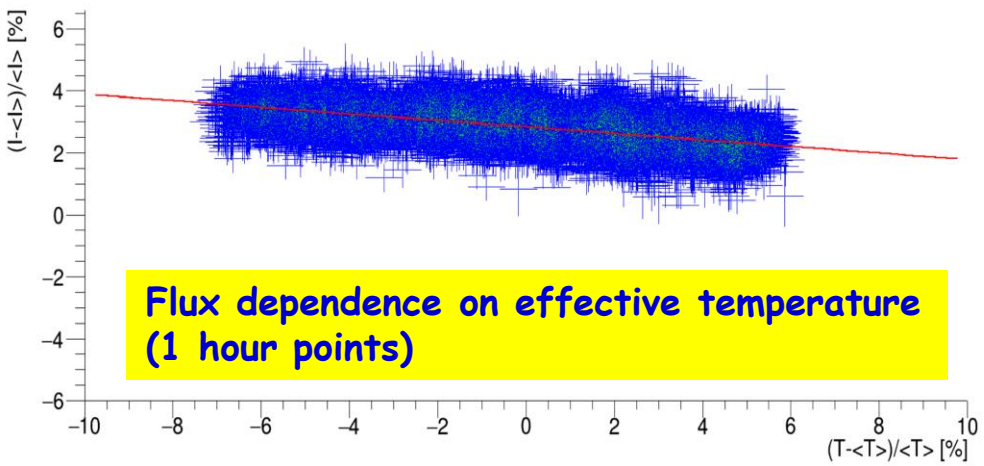
Longitudinal nonuniformity can be further corrected
More work on SiPM-WLS fiber connection is needed



DANSS has measured Pressure and Temperature dependence of muon flux

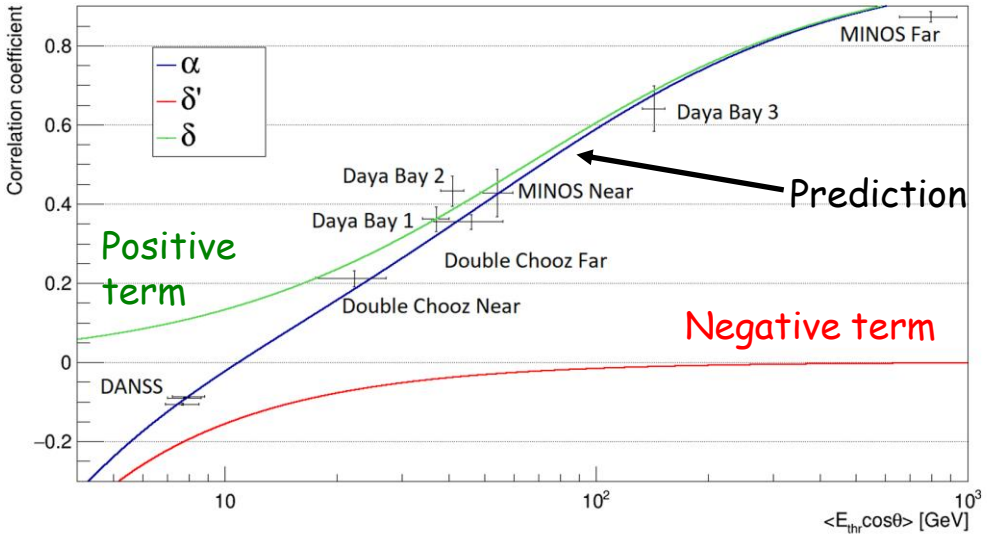


Flux dependence on pressure (1hour points)



Flux dependence on effective temperature (1 hour points)

Temperature correlation coefficient agrees well with expectations



Summary

- DANSS records about 5 thousand antineutrino events per day with cosmic background ~1.7%, S/B>50

5.5 million IBD events were collected in 5 years

- Reactor power was measured using anti-ν rate with statistical error of ~1.5% in two days during 4.5 years of operation.

- Relative IBD σ dependence on 239Pu fraction was measured. It agrees with H-M model

- Indication of 5MeV bump, but not conclusive

- Preliminary DANSS analysis based on 5 million IBD events excludes a large and the most interesting fraction of available parameter space for sterile neutrino using only ratio of e+ spectra at 3 distances (with no dependence on ν spectrum and detector absolute efficiency!)

- RAA was excluded by DANSS with more than 5s already in 2018 (arXive:1804.04046v1)

- Muon flux dependence on pressure and temperature was measured

We plan:

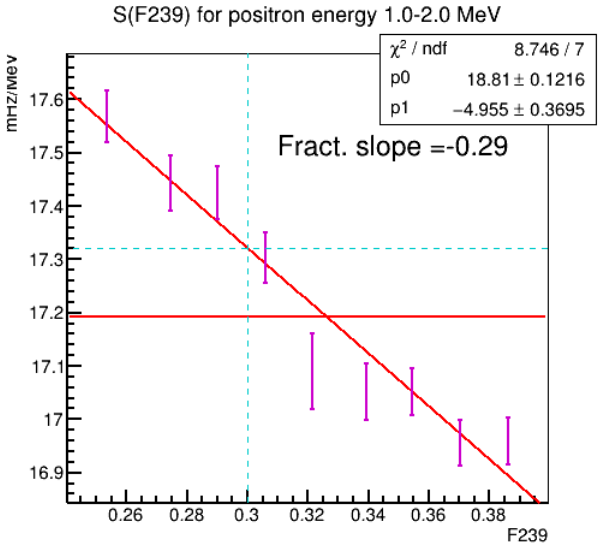
To take data for one more reactor off period

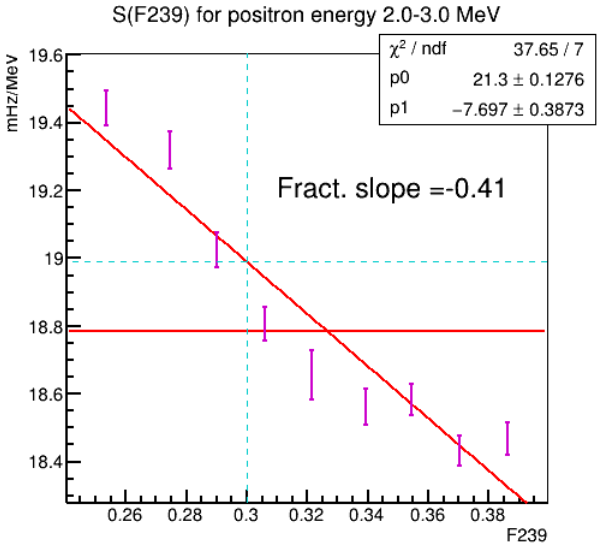
To refine detector calibration and energy scale determination in order to reduce systematic errors

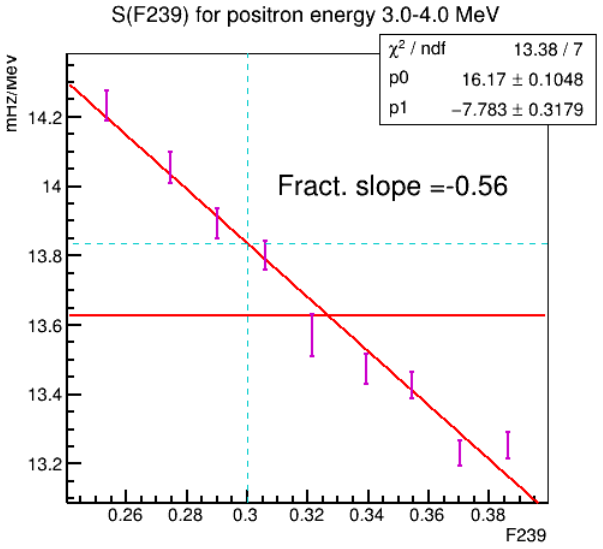
To upgrade detector in 2022

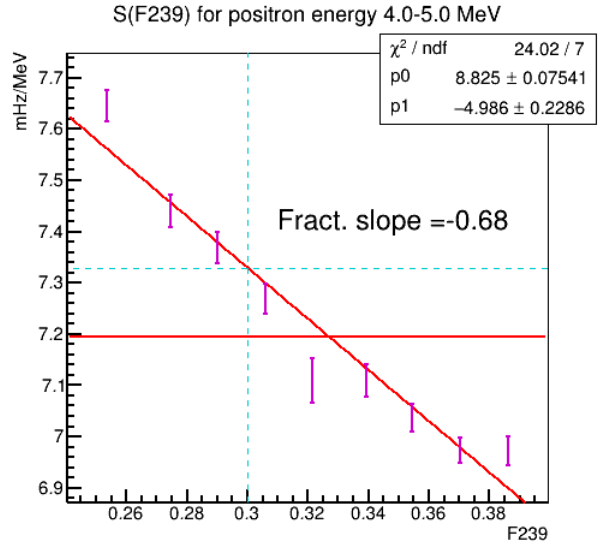
Thank you !

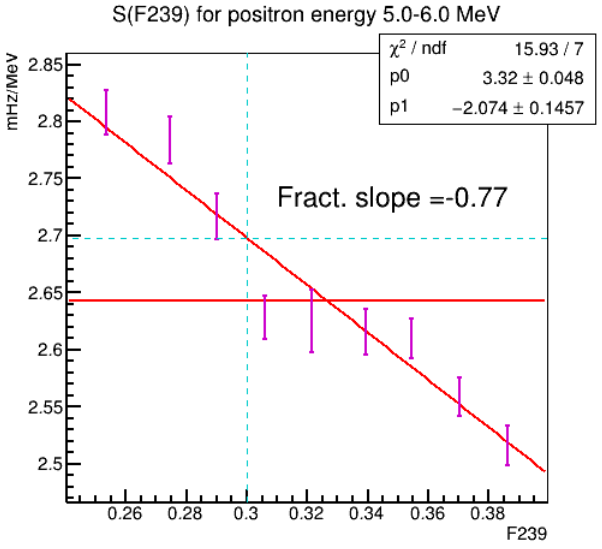
Backup slides

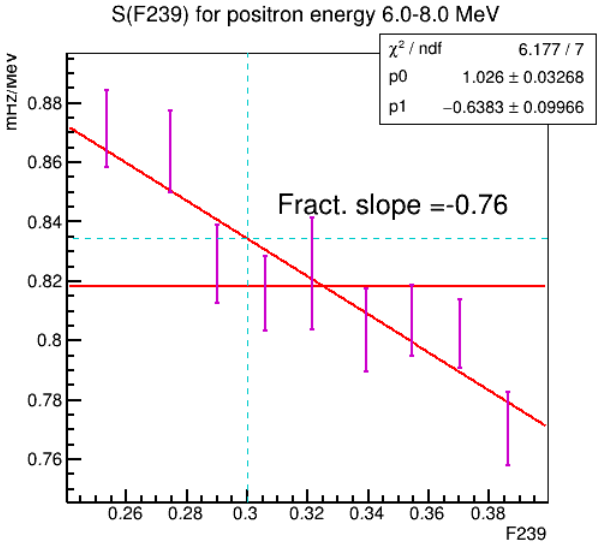






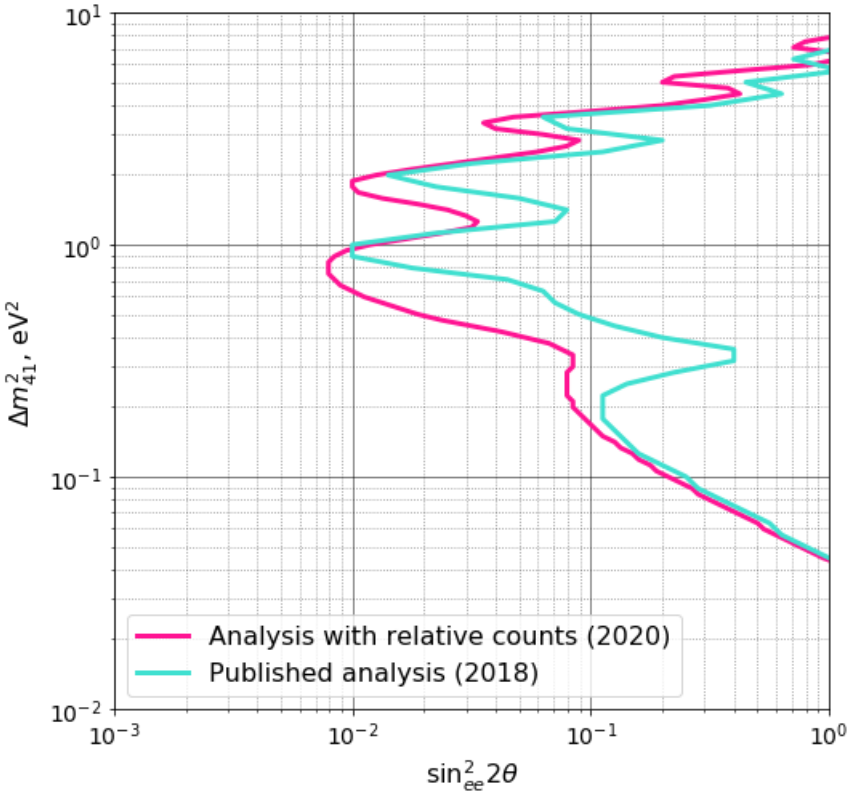


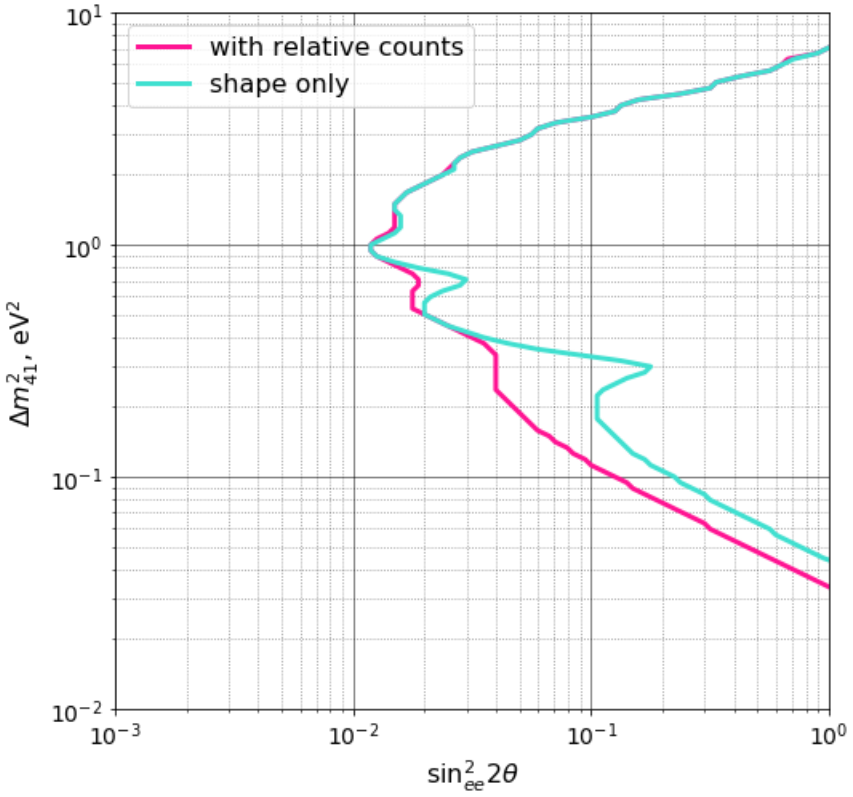




DANSS has 40% larger F239Pu range: DANSS 0.25-0.39 DB 0.25-0.35

Comparison of results



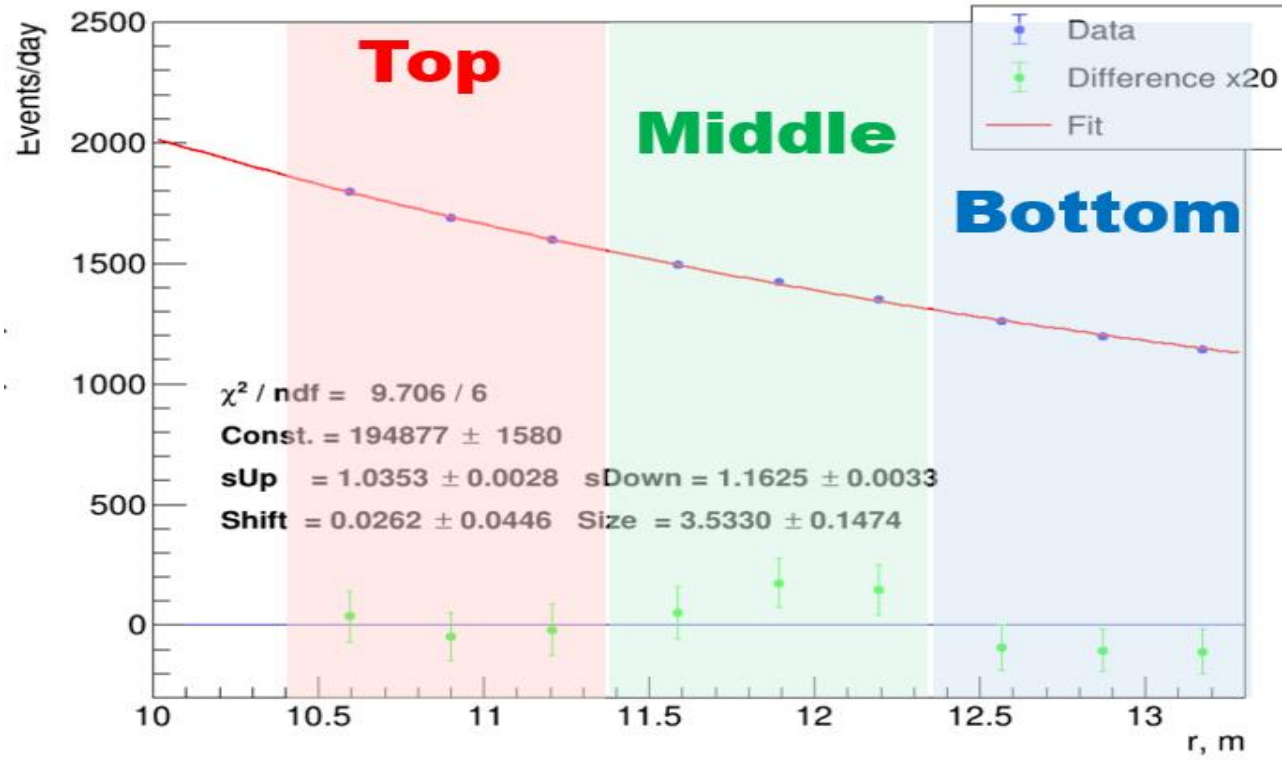


- **Large progress in 90% CL exclusion area since 2018**

  (Phys.Lett. B787 (2018) 56)

- **Sensitivity plots: relative rate analysis contributes mostly at low mass region**

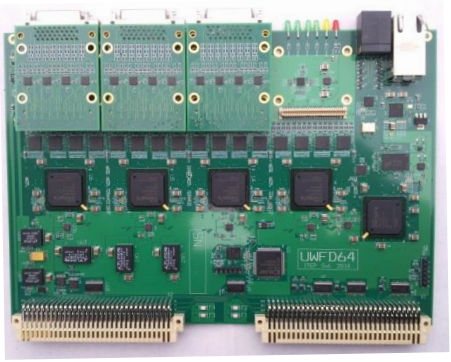
IBD total rate vs. effective distance

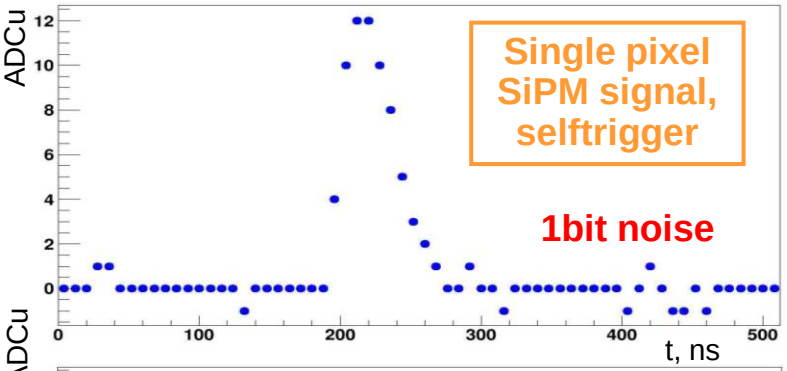


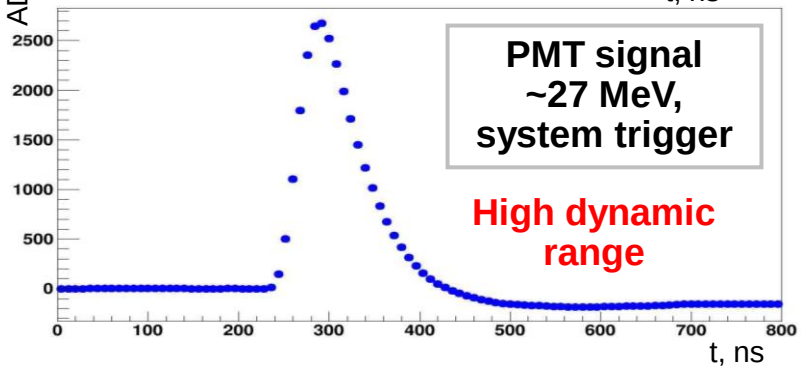
- **IBD intensity follows reasonably the $1 / L^2$ dependence.**
- **Detector was divided on 3 parts in each position.**

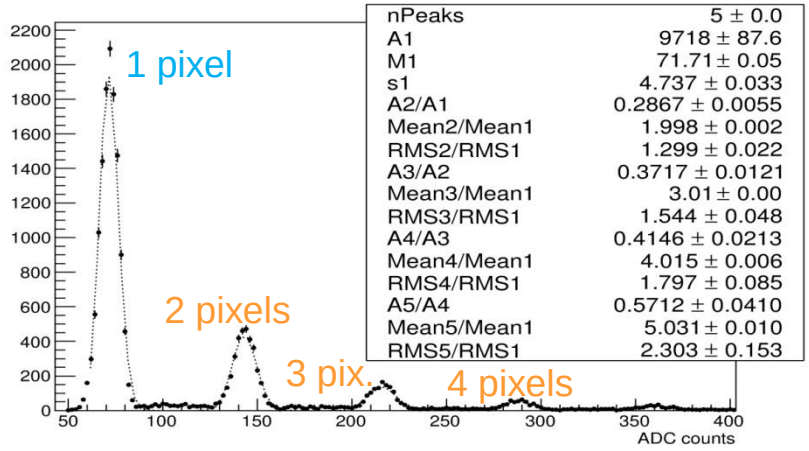
Data acquisition system

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







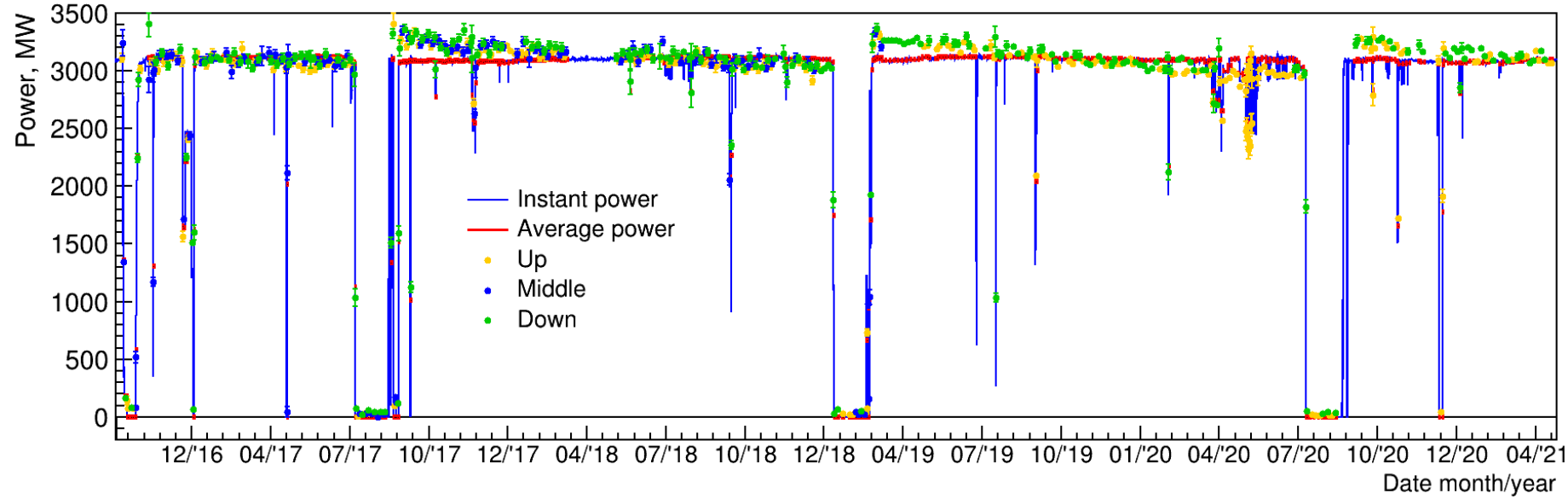


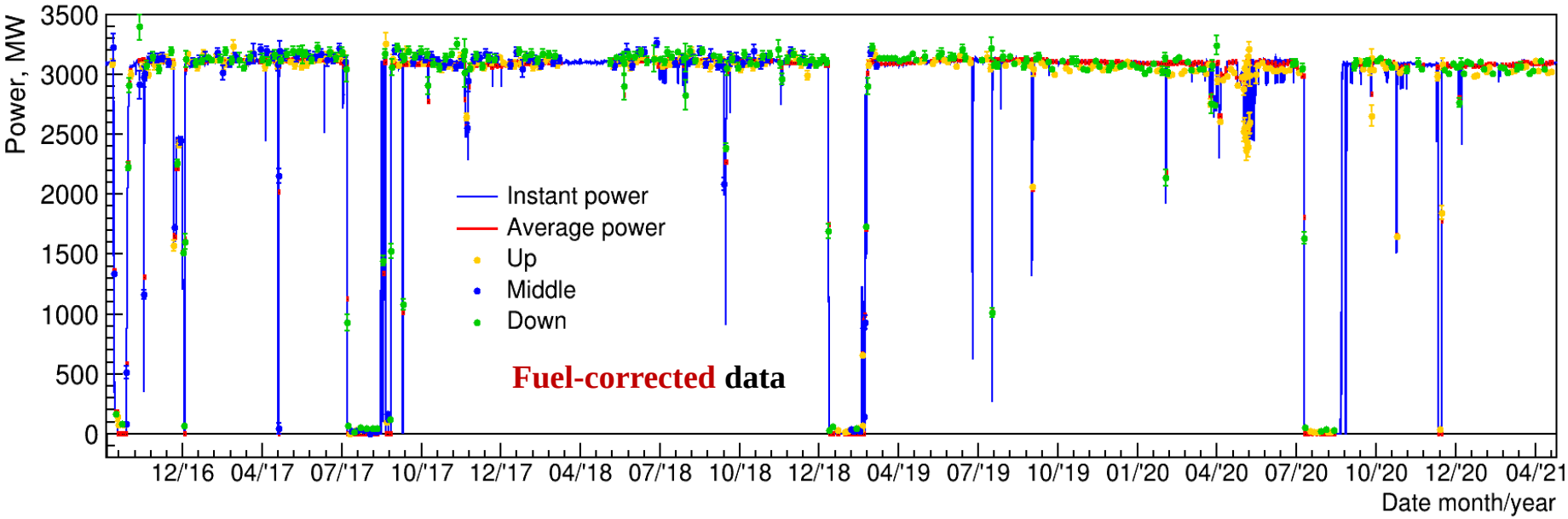
- Preamplifiers PA in groups of 15 and SiPM power supplies HVDAC for each group inside shielding, current and temperature sensing
- Total 46 Waveform Digitisers WFD in 4 VME crates on the platform
- WFD: 64 channels, 125 MHz, 12 bit dynamic range, signal sum and trigger generation and distribution (no 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.

Sensitivity to fuel evolution

Top – Middle – Bottom data

with and without efficiency and fuel evolution correction





Comparison of exclusions in 2021 and 2020