
ICHEP 2020
Virtual Conference
Prague
July 29, 2020
New results from
the DANSS experiment
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for the DANSS Collaboration

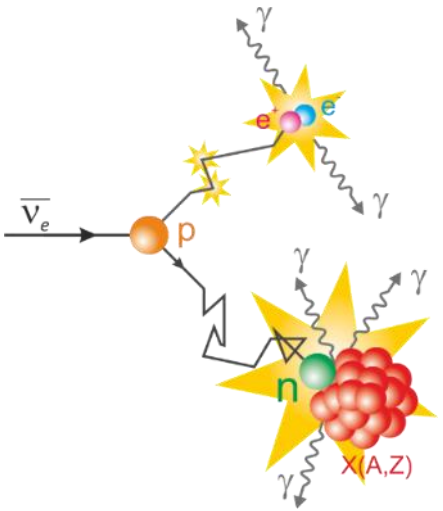
There are several indications of 4th neutrino

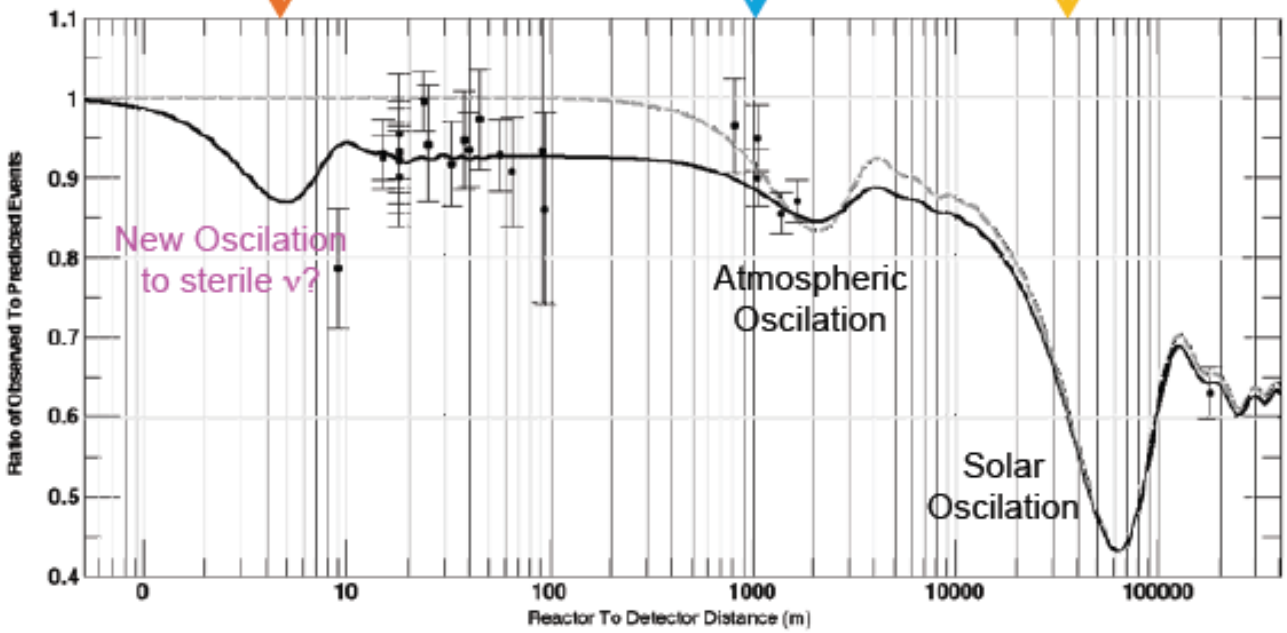
LSND, MiniBoone: $\bar{\nu}e$ appearance
SAGE and GALEX ν_e deficit
Reactor $\bar{\nu}_e$ deficit

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

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

Inverse Beta Decay (IBD) process



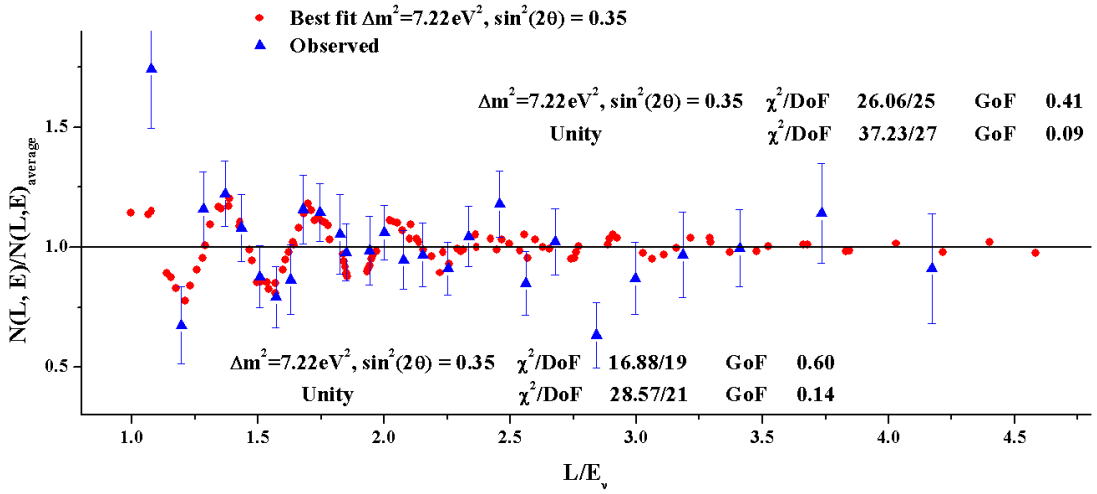


G. Mention et al. Phys Rev D 83 073006 (2011)

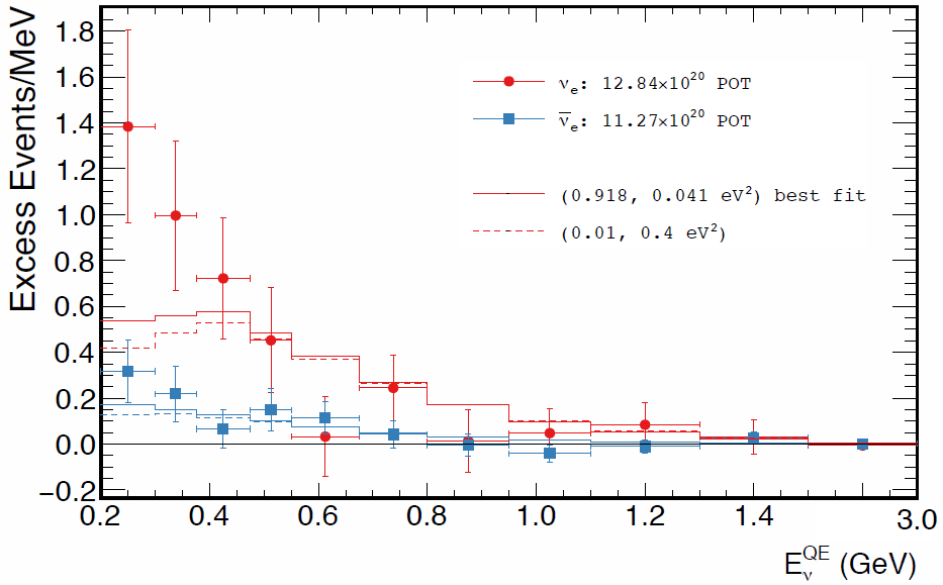
Reactor models do not describe well neutrino spectrum
Measurements at one distance are not sufficient!

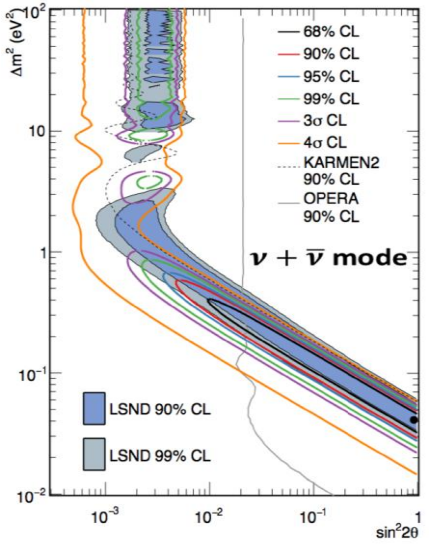
New (2018) indications of sterile neutrinos

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

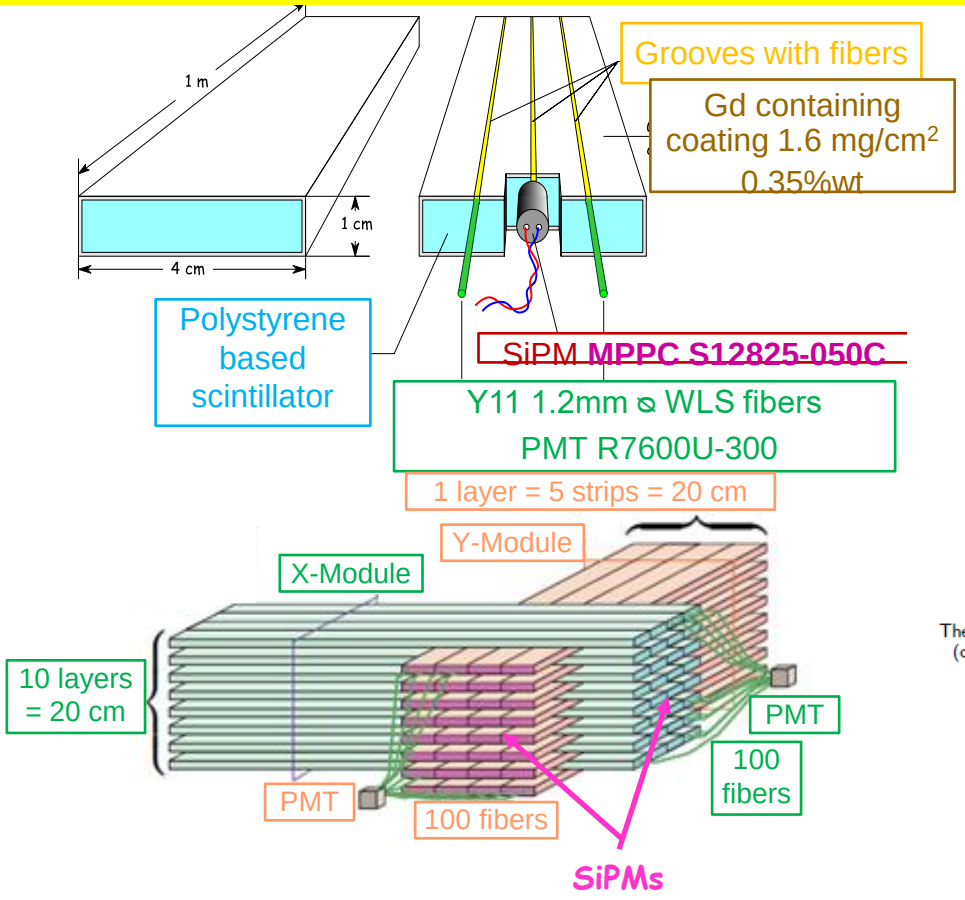


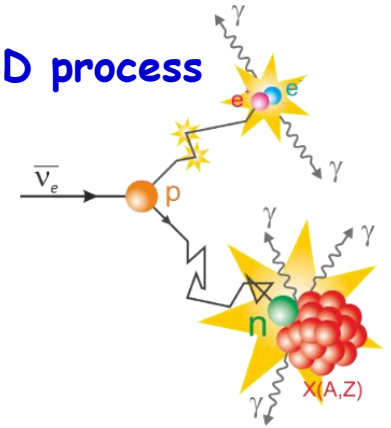
MiniBooNE ν_e excess of 4.8σ (6σ with LSND) Phys.Rev.Lett. 121 (2018) no.22, 221801

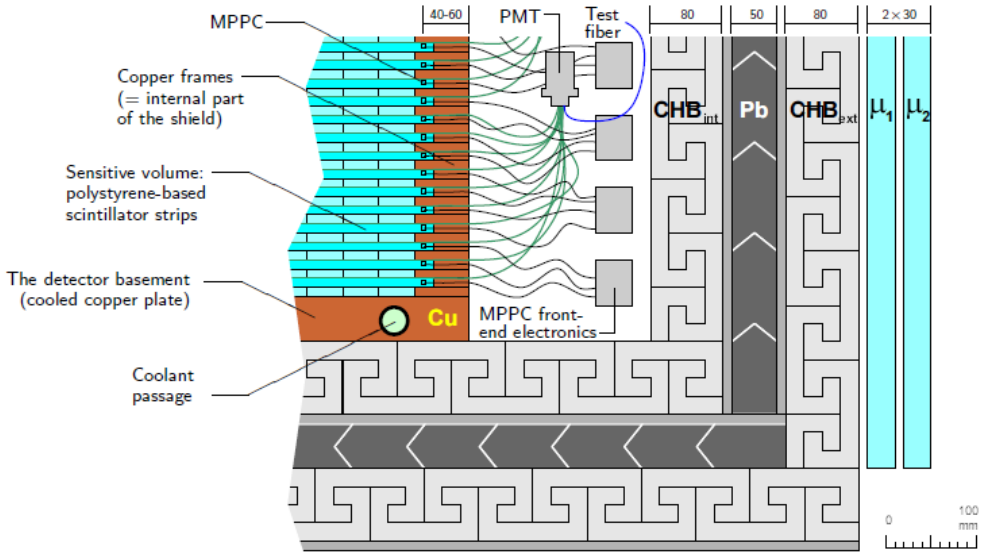




DANSS Detector design (ITEP-JINR Collaboration)



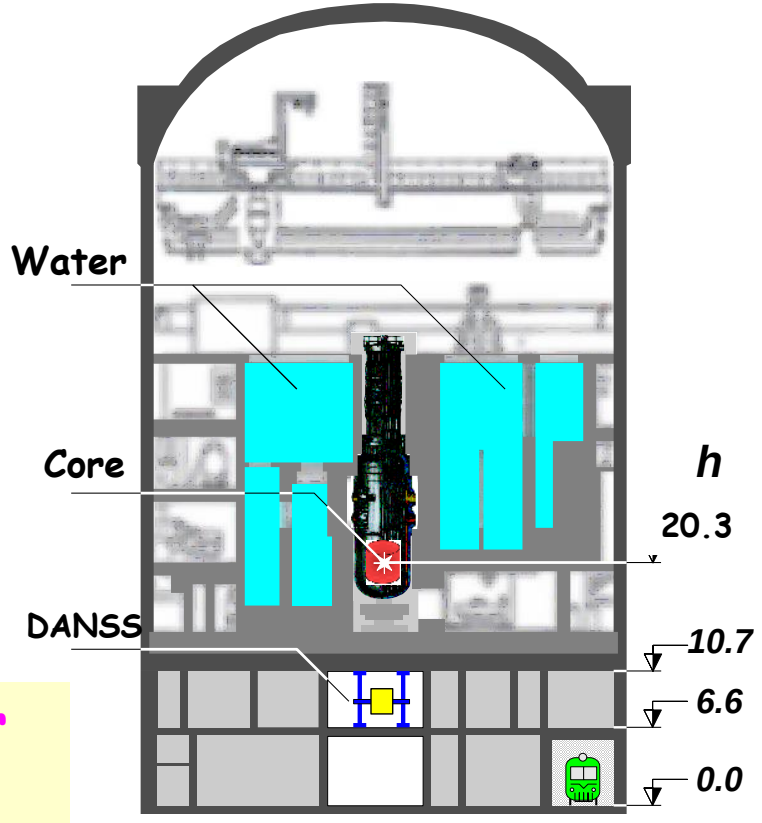




- **2500 scintillator strips with Gd containing coating for neutron capture**
- **Light collection with 3 WLS fibers**
- **Central fiber read out with individual SiPM**
- **Side fibers from 50 strips make a bunch of 100 on a PMT cathode = Module**

- **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) 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 [%]

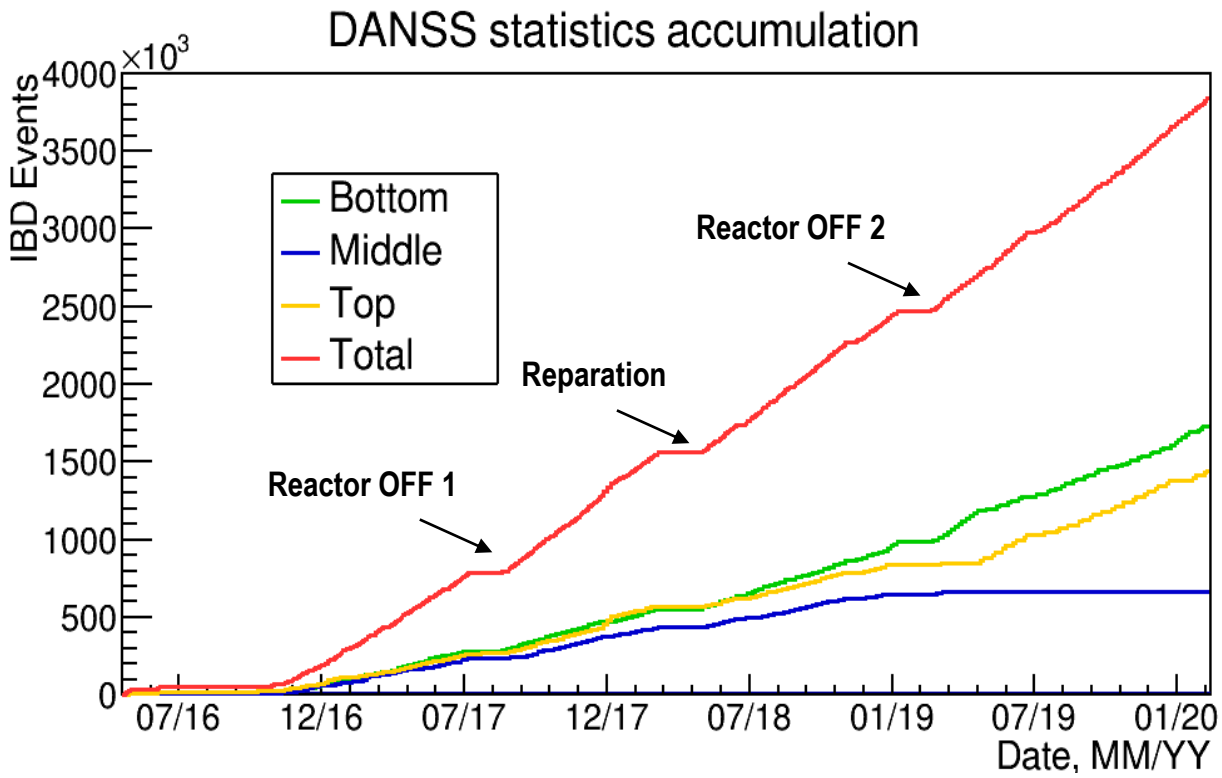
235U	54.1	63.7	44.7
239Pu	33.2	26.6	38.9
238U	7.3	6.8	7.5
241Pu	5.5	2.8	8.5

Improvements in analysis*

- Using STEREO datasets made on base of FIFRELIN library (arXiv: 1905.11967) to simulate neutron capture in Gd: essential improvement of neutron signal.
- Positron energy dependent distance and neutron energy cuts. This allowed to increase the total number of reconstructed IBD-events, especially in the high-energy part of spectra, more sensitive to the effect searched.
- Improved strip surface description corrected on real measurements.
- Corrected (on real data) signal models of SiPM (17.7 p.e./MeV and 0.37 X-talks) & PMT (15.9 p.e./MeV)
- More detailed study of systematics.
- Improvement of ^{12}B energy calibration (reconstruction with higher statistics) used as main calibration for the DANSS spectrometer.
- Reconstruction of Michel electrons from decay of muons stopped at DANSS
- Relative Rate + Shape analysis was implemented.
- 3 detector positions in fit. Small gain in sensitivity but check for consistency

*) in comparison with our previous presentations in 2019

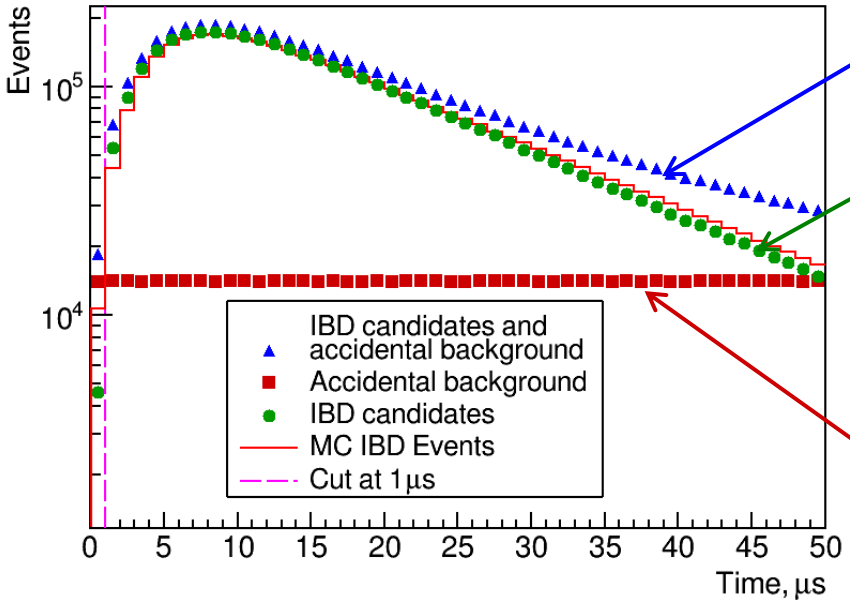
Statistics accumulated

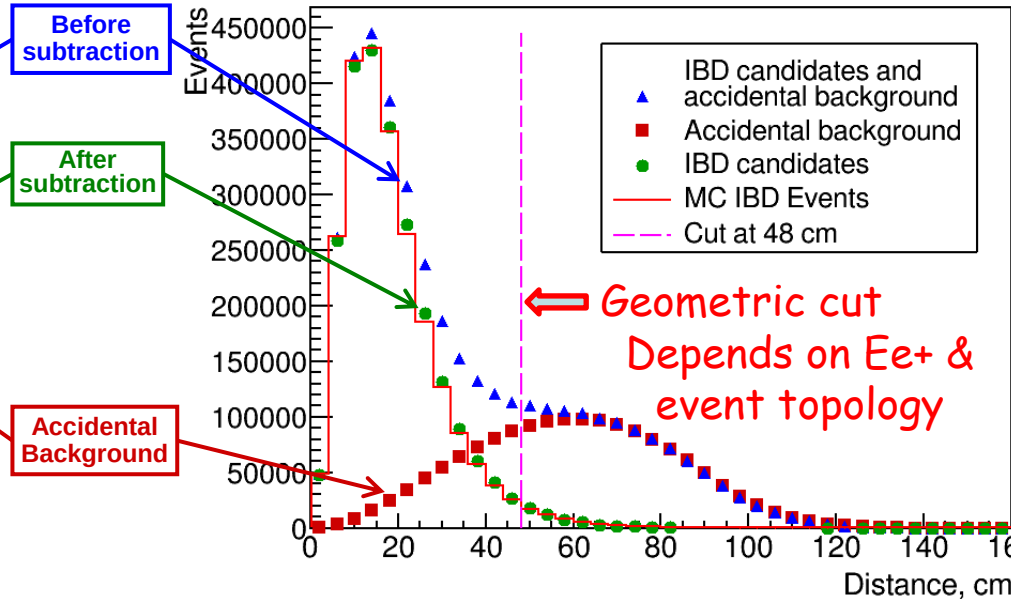


❖ **Total statistics accumulated is close to 4M IBD-events, including 1.4M/1.5M events in Top/Bottom position**

❖ **Sensitivity of experiment was improved by a factor ~2 in 1 eV² region**

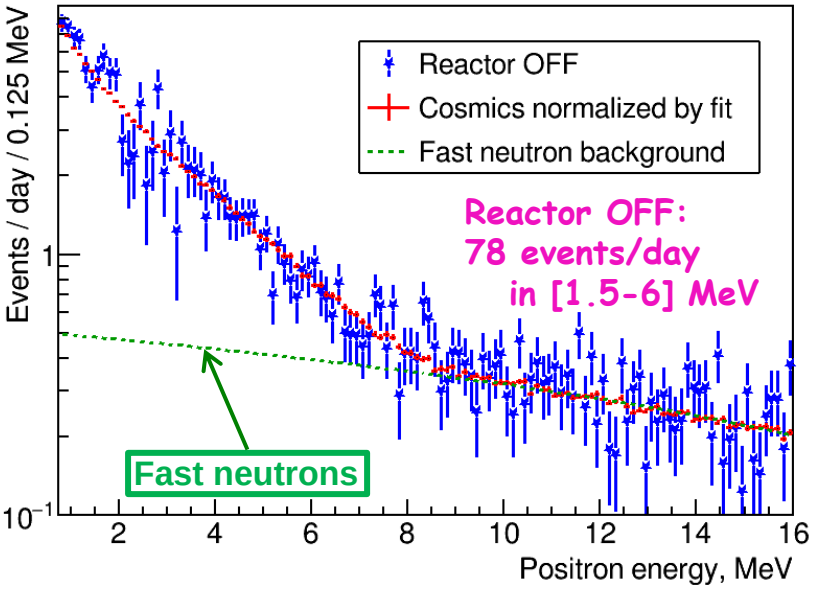
Accidental coincidence background

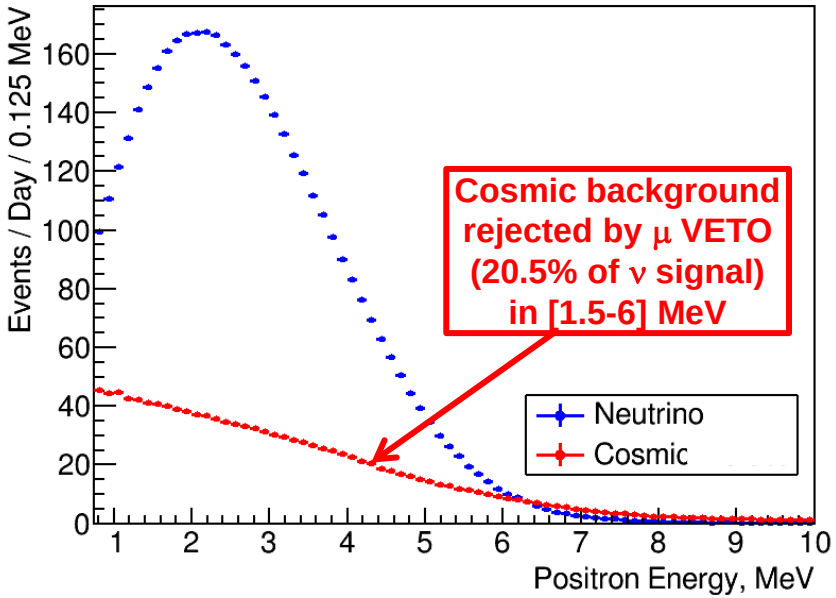




- Accidental coincidence of 2 uncorrelated signals (e+-like and neutron-like) in a IBD window [1-50] μs → accidental coincidence background (ACB)
- ACB spectrum is constructed directly from data applying the same physics cuts as for IBD signal except coincidence time taken outside IBD time window [1-50] μs in numerous non-overlapping intervals (large statistics is essential to decrease statistical errors of subtraction) ➔ No systematic errors
- ACB rate is 13.8% 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

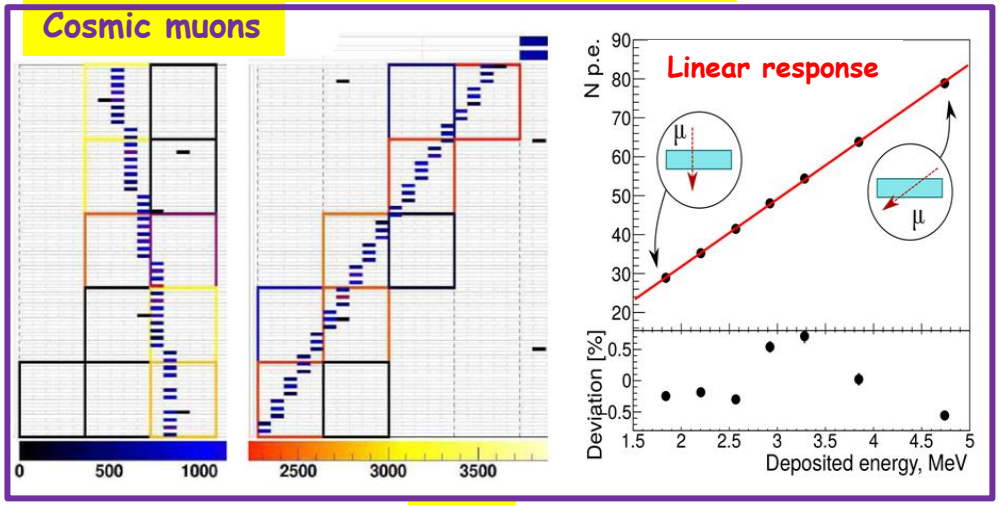
Subtraction of residual backgrounds

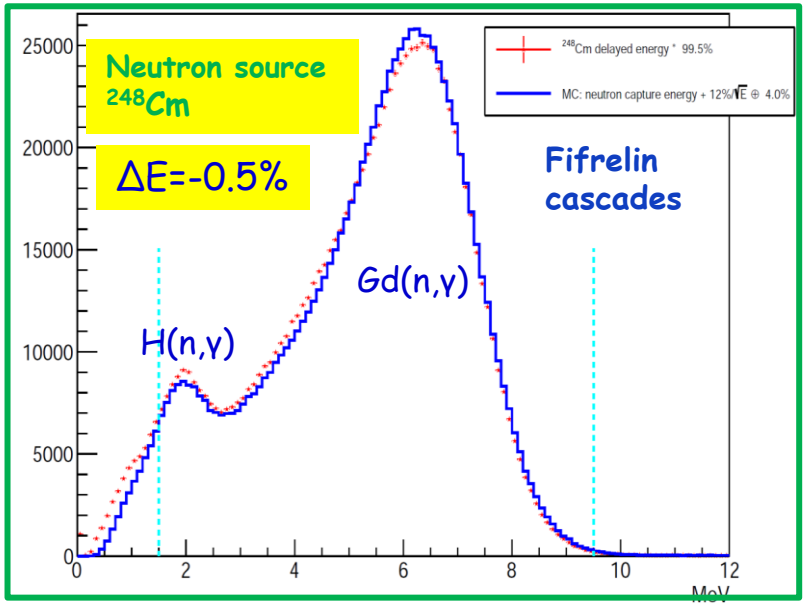


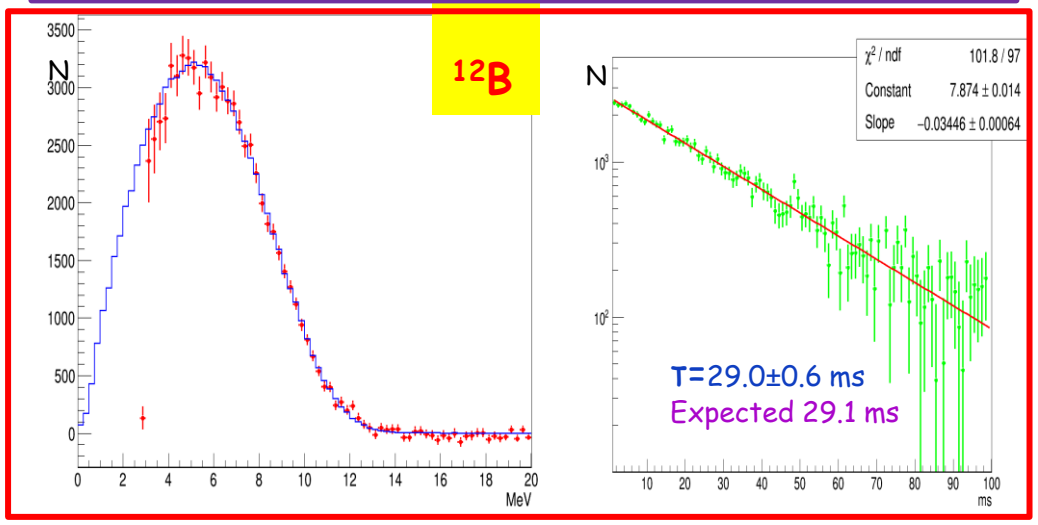


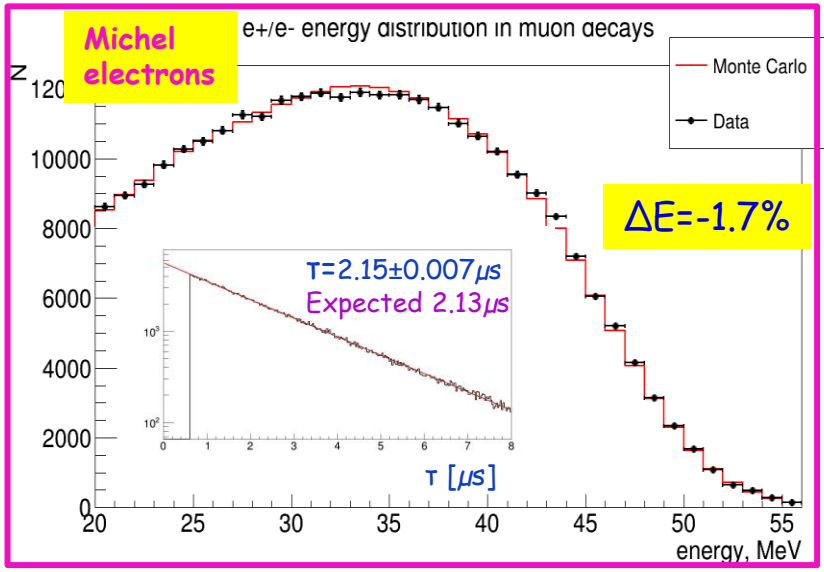
- 25 ν events/day from neighbor reactors were subtracted
- **Fast neutrons**: linearly extrapolate from high energy region and subtract separately from positron and visible cosmic spectra, CR (fast neutron) = 16 events/day (in 1.5-6 MeV range)
- **Visible cosmic background (CB)** has been **directly rejected** by VETO, it is 20.5% 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 19 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.

Calibrations



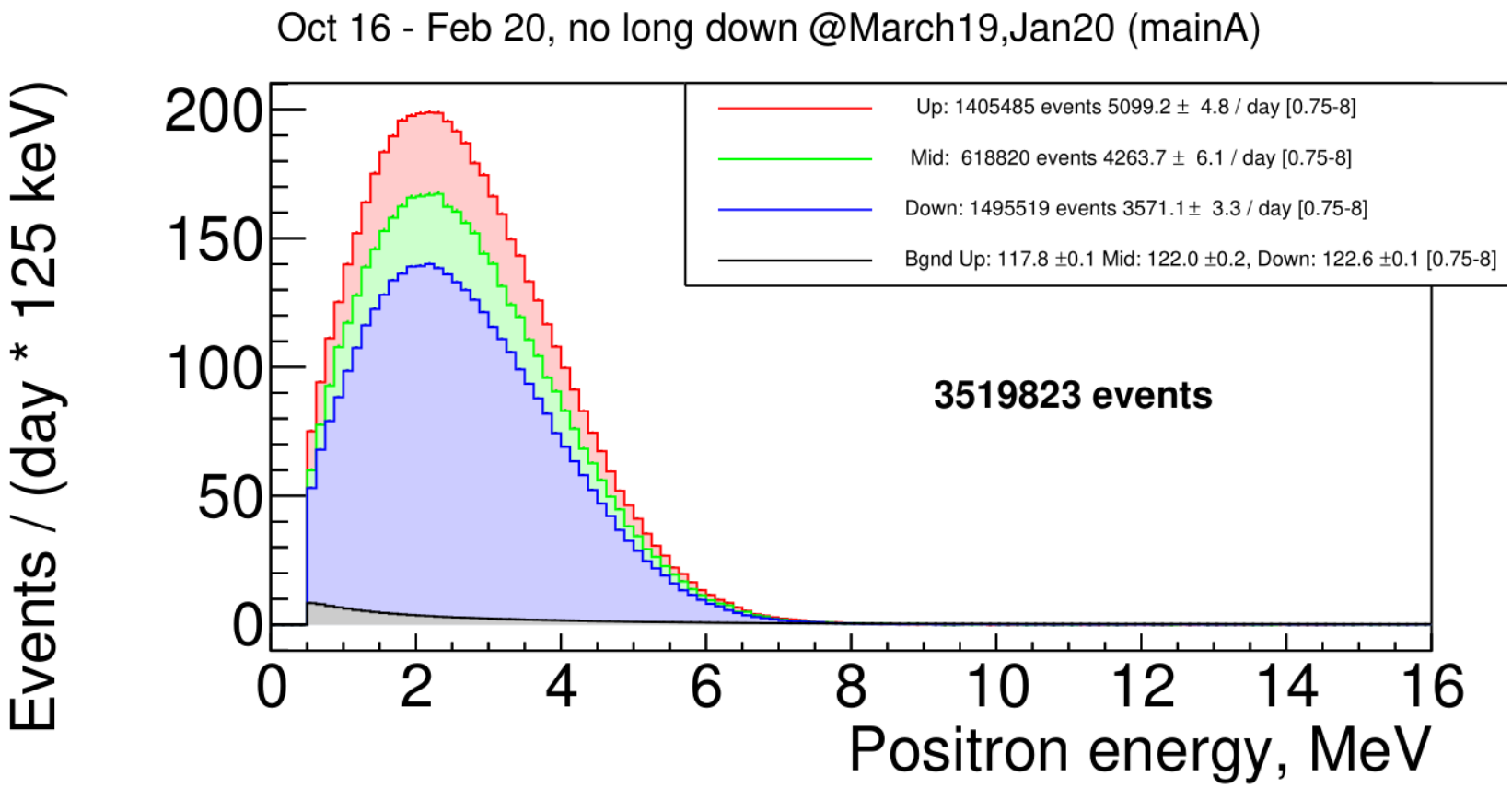






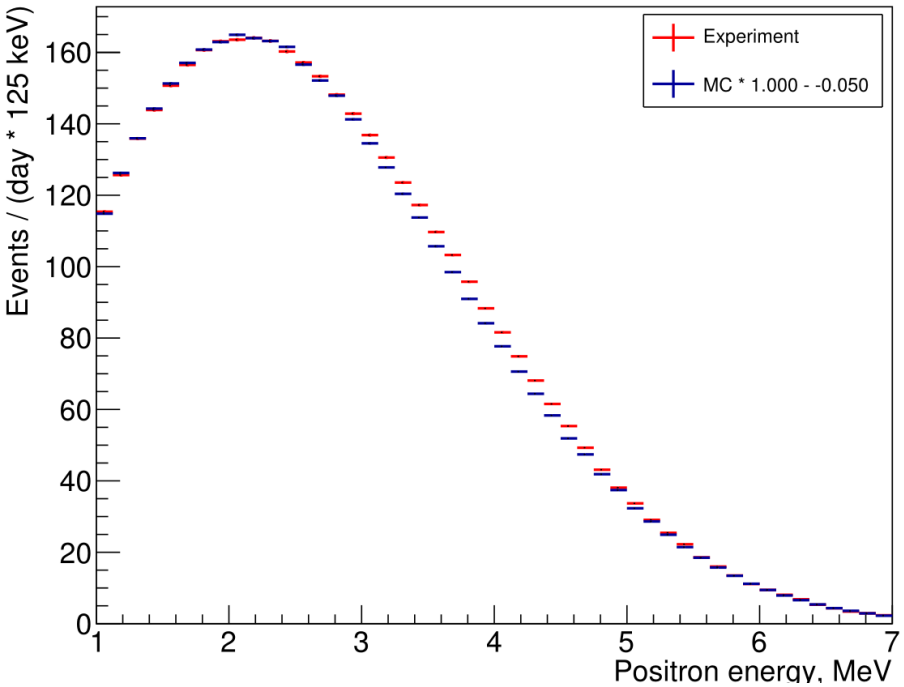
- **Energy scale has been fixed using β-spectrum of ^{12}B, which is similar to positron signal**
- **Systematic error on E scale of +/-2% was added due to source response uncertainties**
- **Energy resolution for calibration sources is still worse than in MC and additional smearing of 12%/√E ⊕ 4% has been added to MC**

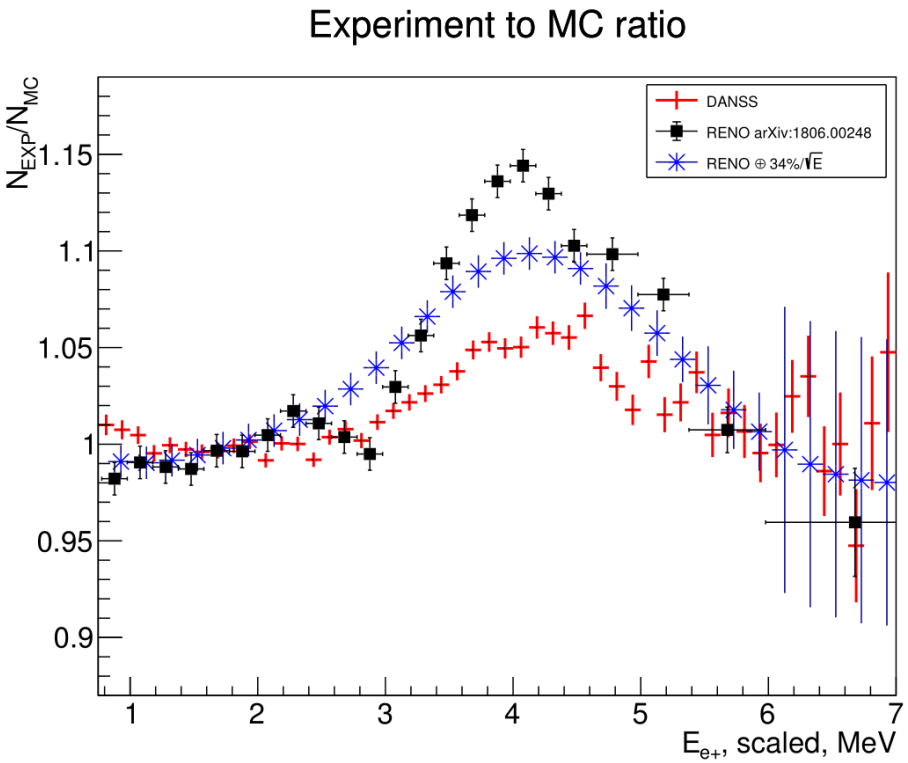
Positron spectrum of IBD-signal



- **Positron kinetic energy spectra (no annihilation photons) at 3 detector positions**
- **~5000 events/day (~4000 ev/d in previous analysis) in detector fiducial volume (78% of full volume) at 'Top' position (closest to the reactor).**
- **Cosmic background ~1.7% (Top position, E: 1.5-6MeV). Signal/Background >50!**

Positron spectrum: experiment vs. H-M Model

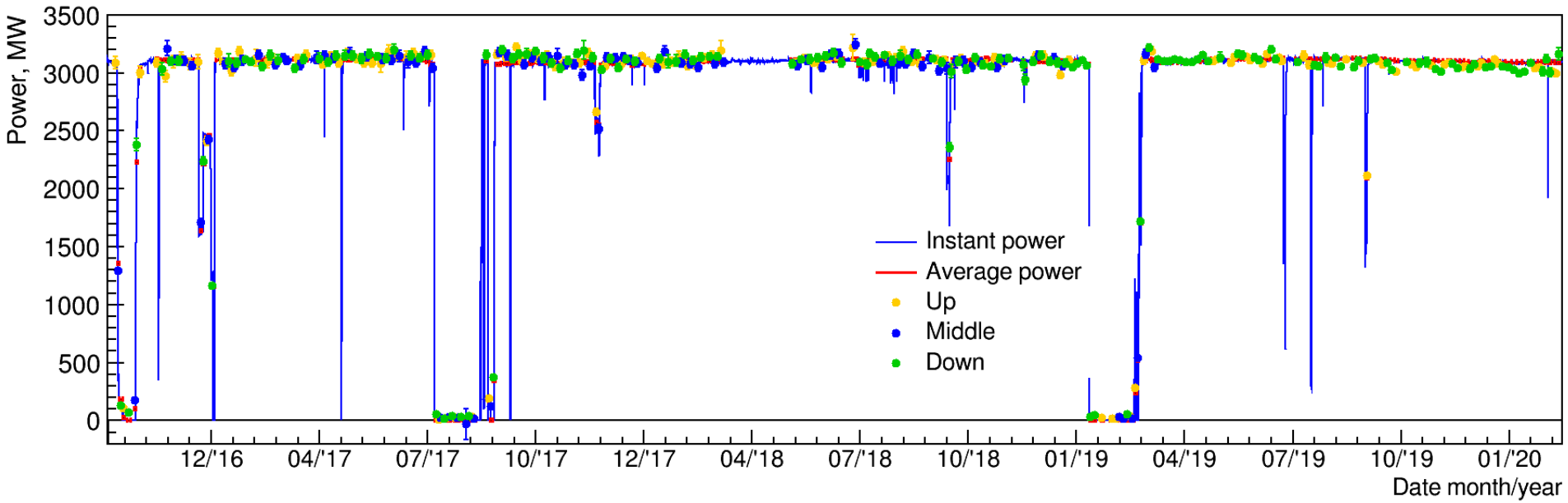




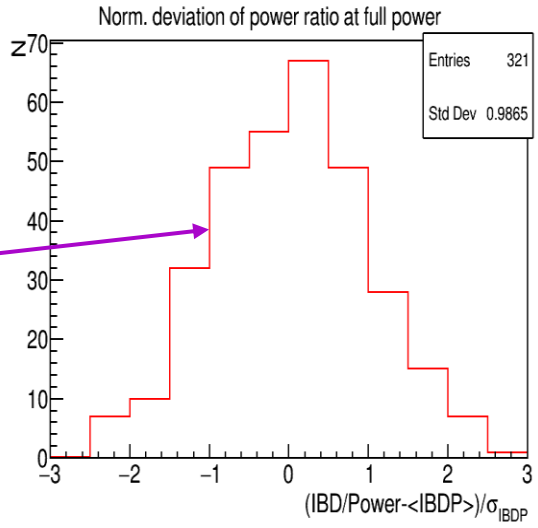
- **In order to reach best agreement with H-M model in 1-3 MeV region our MC spectrum was shifted on +50 keV w.r.t. experimental data.**

  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.**

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 3+ years,
- Consistent with statistical fluctuations.
- ➡ Changes in absolute detector efficiency are known with accuracy better than ~ 1% during 3.5 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;

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

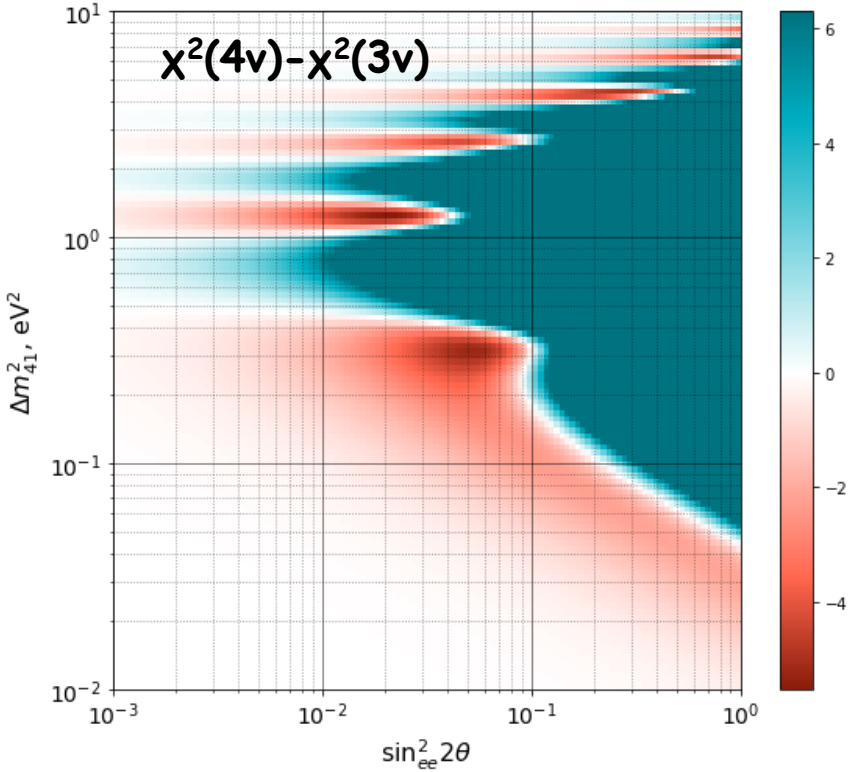
Difference in χ^2 between 4v and 3v hypotheses

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

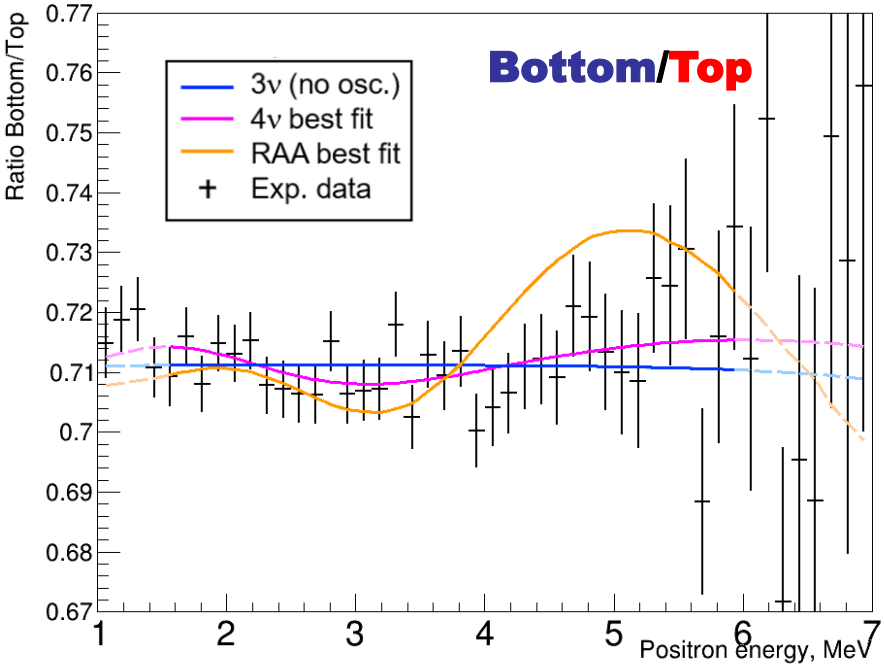
Blue - $\chi^2(4v)>\chi^2(3v)$,

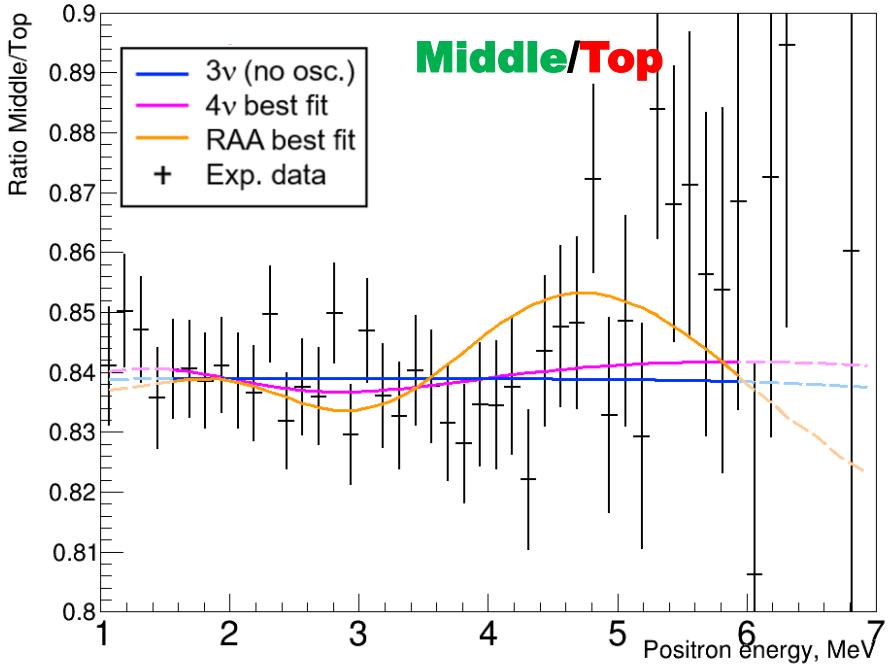
Dark blue region is excluded at 3σ CL in case of χ^2 distribution with 2 DoF $(\chi^2(4v)-\chi^2min)=11.83$

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 (~3.5 million IBD events)

  we see no statistically significant indication of 4v signal:

  ΔX^2=-5.5 (~ 1.5 σ) for 4v hypothesis best point Δm^2=1.3 eV^2 , $\sin^2 2\theta$=0.02
- RAA has been excluded with ΔX^2= 67.9.
- 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), which is also more conservative than usual CI method.**
- **σ's for nuisance parameters**

relative detector efficiencies - 0.2%

additional smearing in energy resolution - 25%

energy scale - 2%

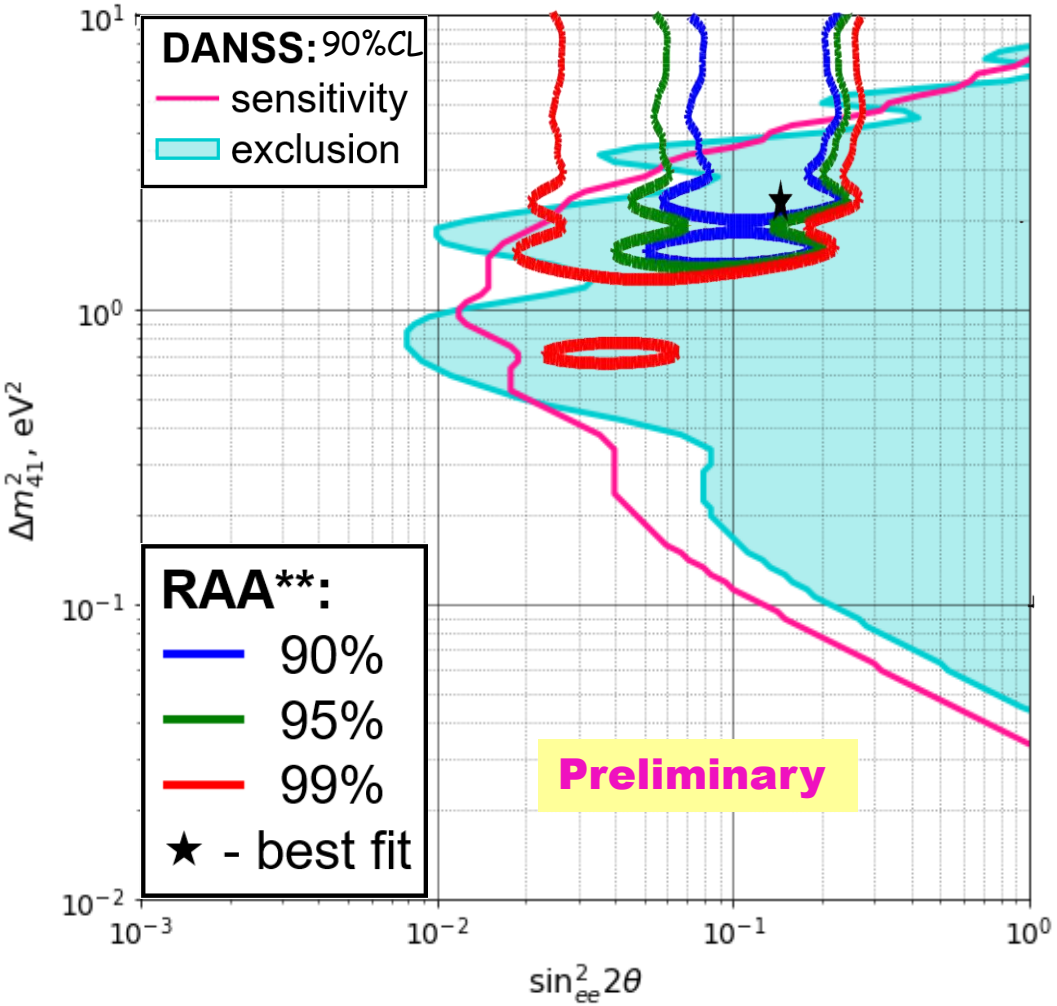
energy shift - 50 keV

distance to fuel burning profile center - 5 cm

cosmic background - 25%

fast neutron background - 30%

- **New data allowed to extend excluded area of 4ν phase space in comparison with previous results shown in 2018 and 2019.**
- **The most stringent limit reaches $\sin^2 2\theta < 8\times10^{-3}$ level.**
- **The most probable point of RAA+GA is excluded at 5σ confidence level**



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

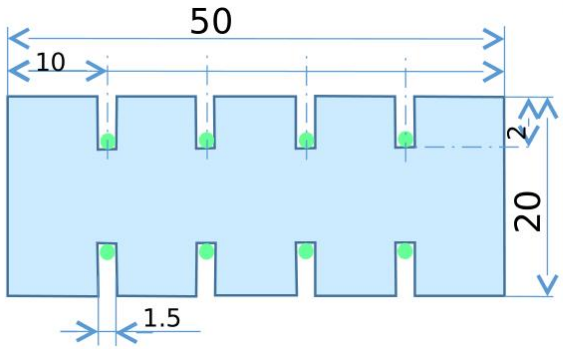
The DANSS upgrade

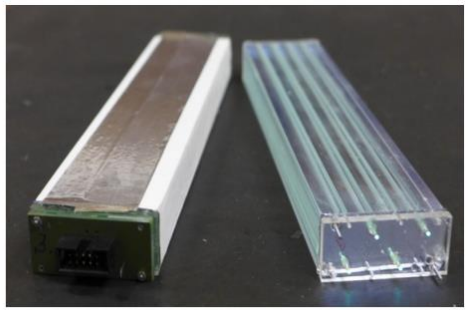
Main goal: to reach resolution **13%/√E**
w.r.t. current 34%/√E.

New geometry:

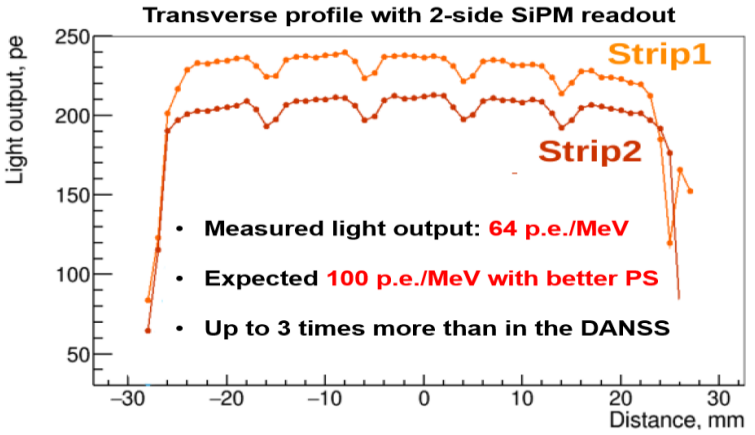
Strips: **2x5x120 cm, 2-side 4SiPM readout**
Structure: **60 layers x 24 strips: 1.7 m³**
Setup uses **the same shielding and moving platform.**
Gd is in foils between layers.
Upgrade timescale: ~2 years

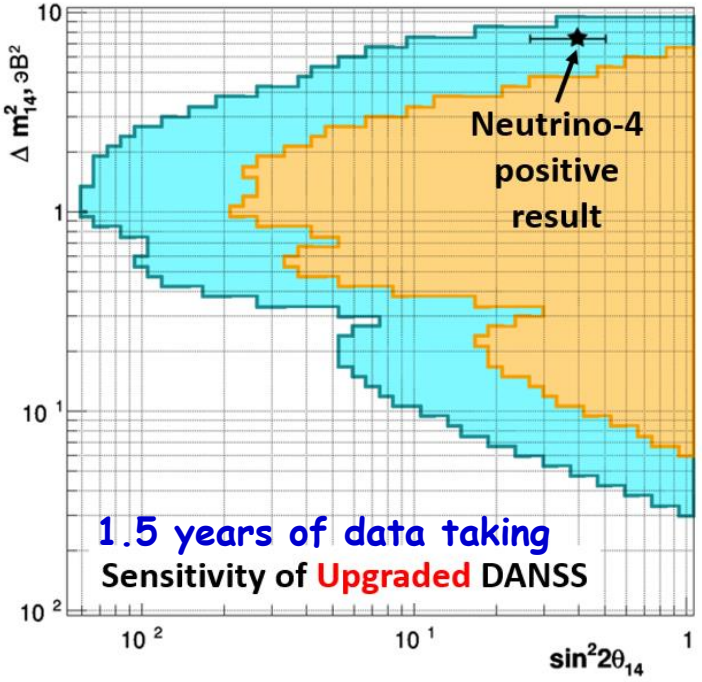
Upgraded strip:





Strip prototypes tests on π-beam





Summary

- With improved analysis DANSS records about 5 thousand antineutrino events per day with cosmic background ~1.7%, S/B>50
- Reactor power was measured using anti-ν rate with statistical error of ~1.5% in two days during 3.5 years of operation, dependence on fuel composition is clearly observed.
- Indication of 5MeV bump, but not conclusive
- Preliminary DANSS analysis based on 3.5 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)

We plan:

To upgrade detector

To improve MC for perfect description of detector response

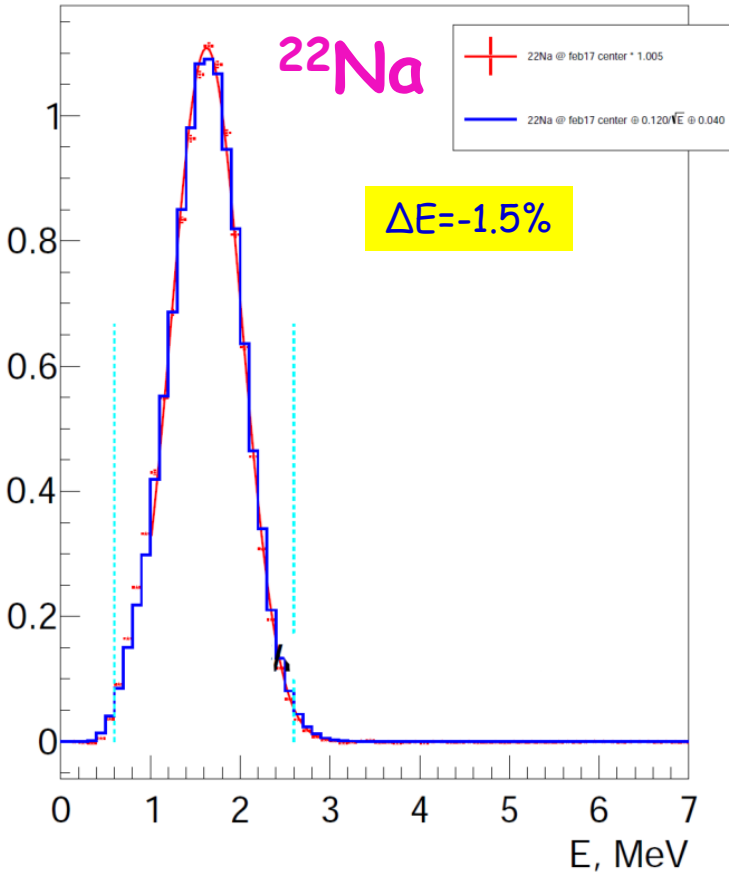
To refine detector calibration and energy scale determination

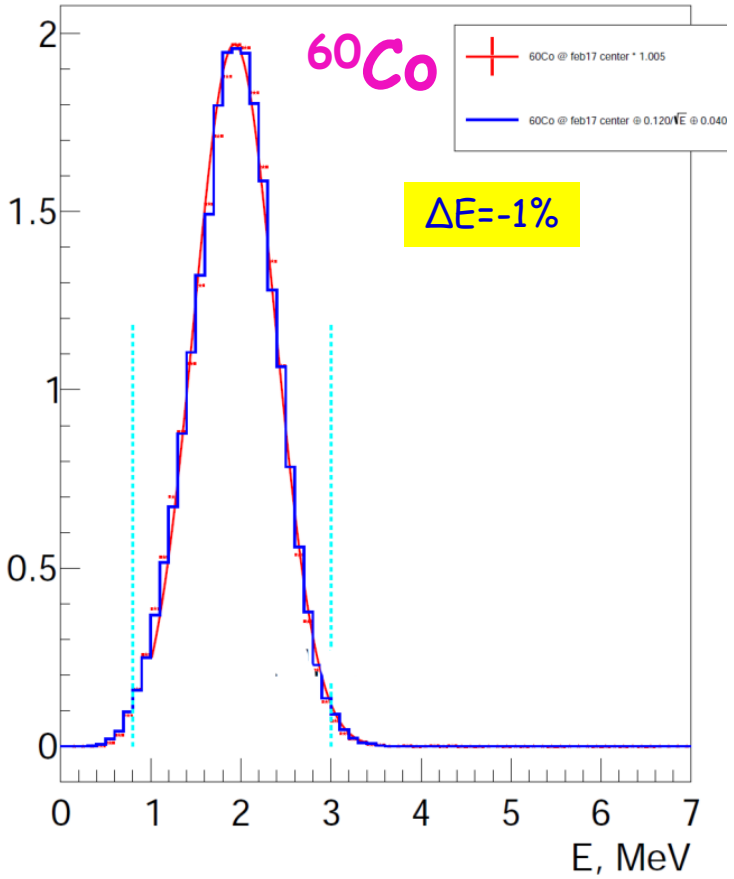
To compare e+ spectrum with Daya Bay

Thank you !

Backup slides

Calibrations: radioactive sources

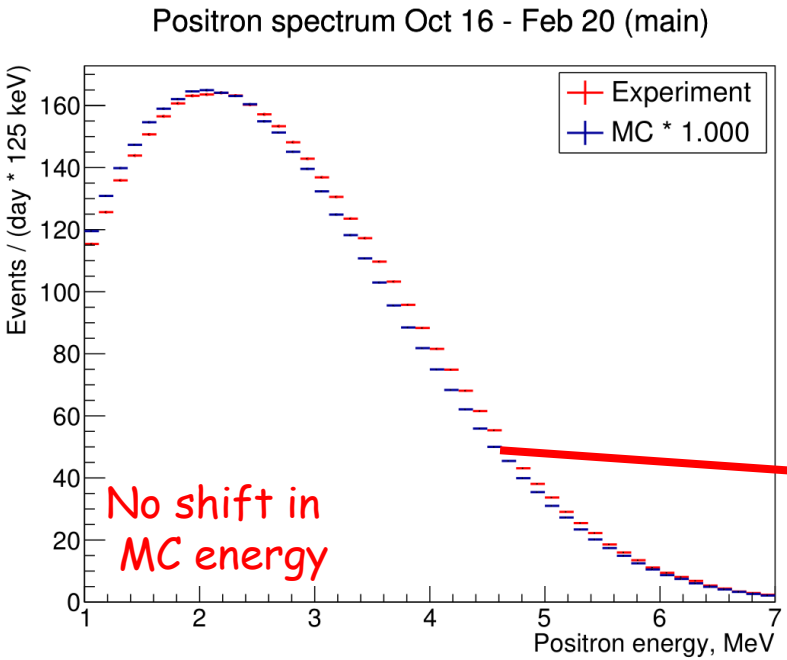


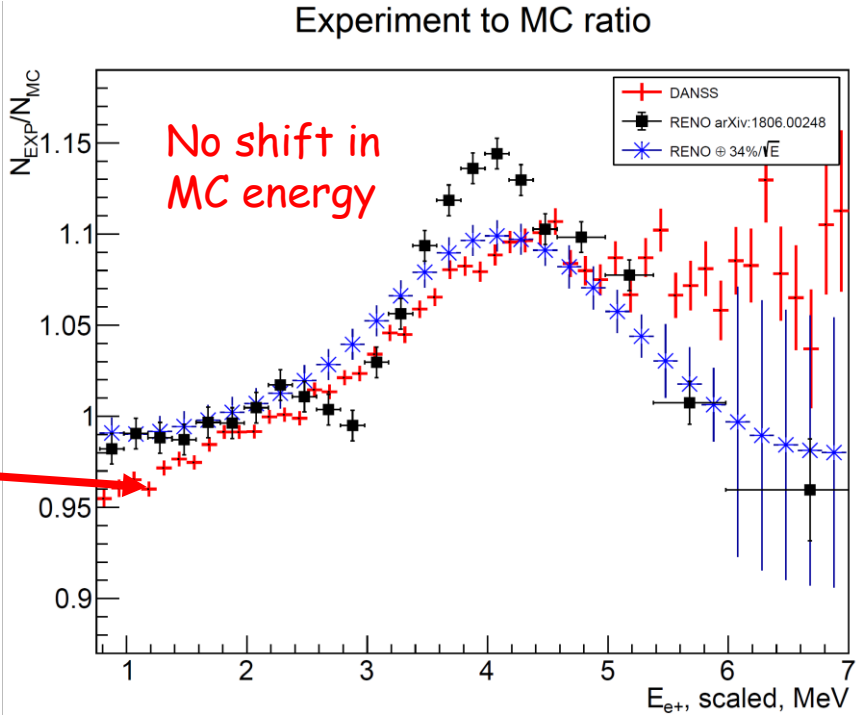


Most probably shifts in E are due to nonperfect description of Birks effect for many soft electrons from radioactive sources. ^{22}Na has more soft electrons.
We DO NOT fit data to obtain better description

Effect is not important for IBD positrons since we don't use annihilation γ's
No correction for energy scale is required

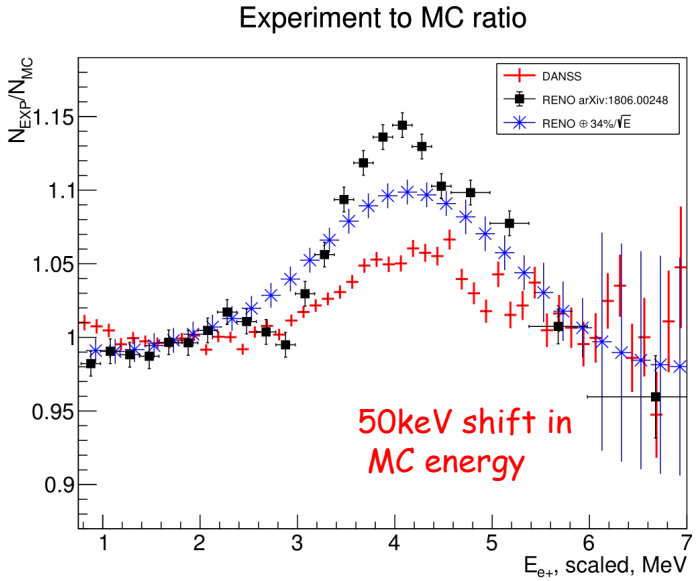
Positron spectrum vs H-M Model



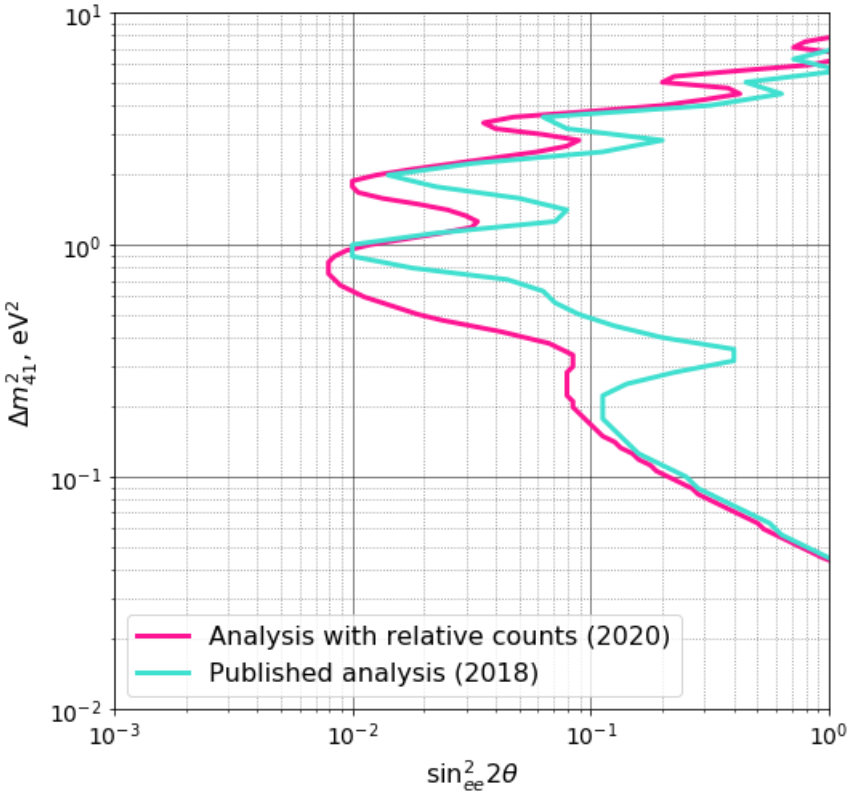


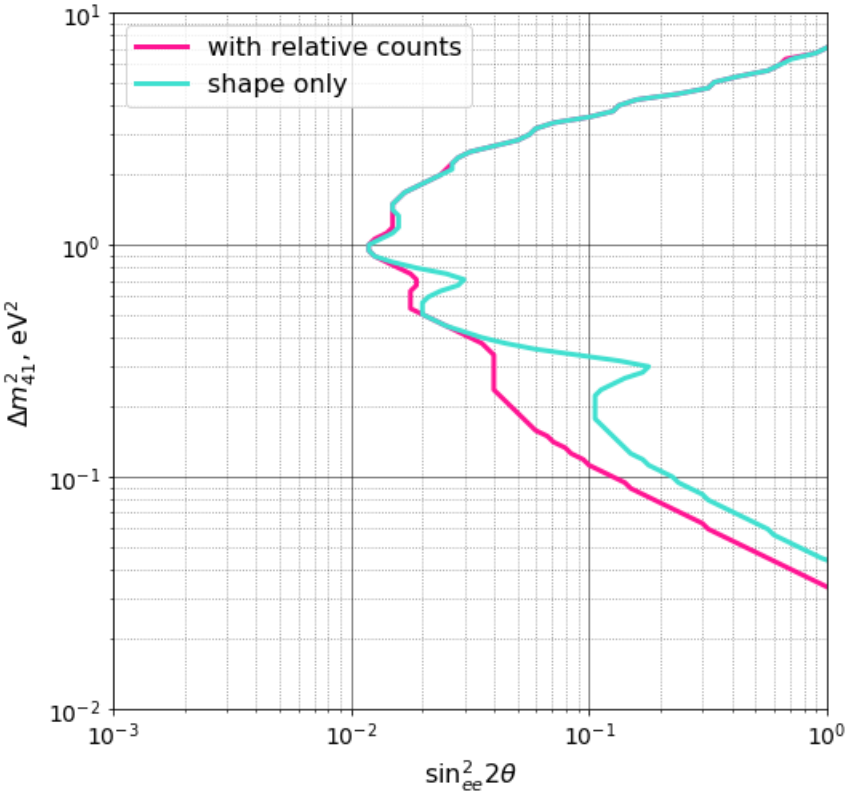
- **High sensitivity to energy scale and shift ➔**

  Can not claim bump existence



Comparison of results



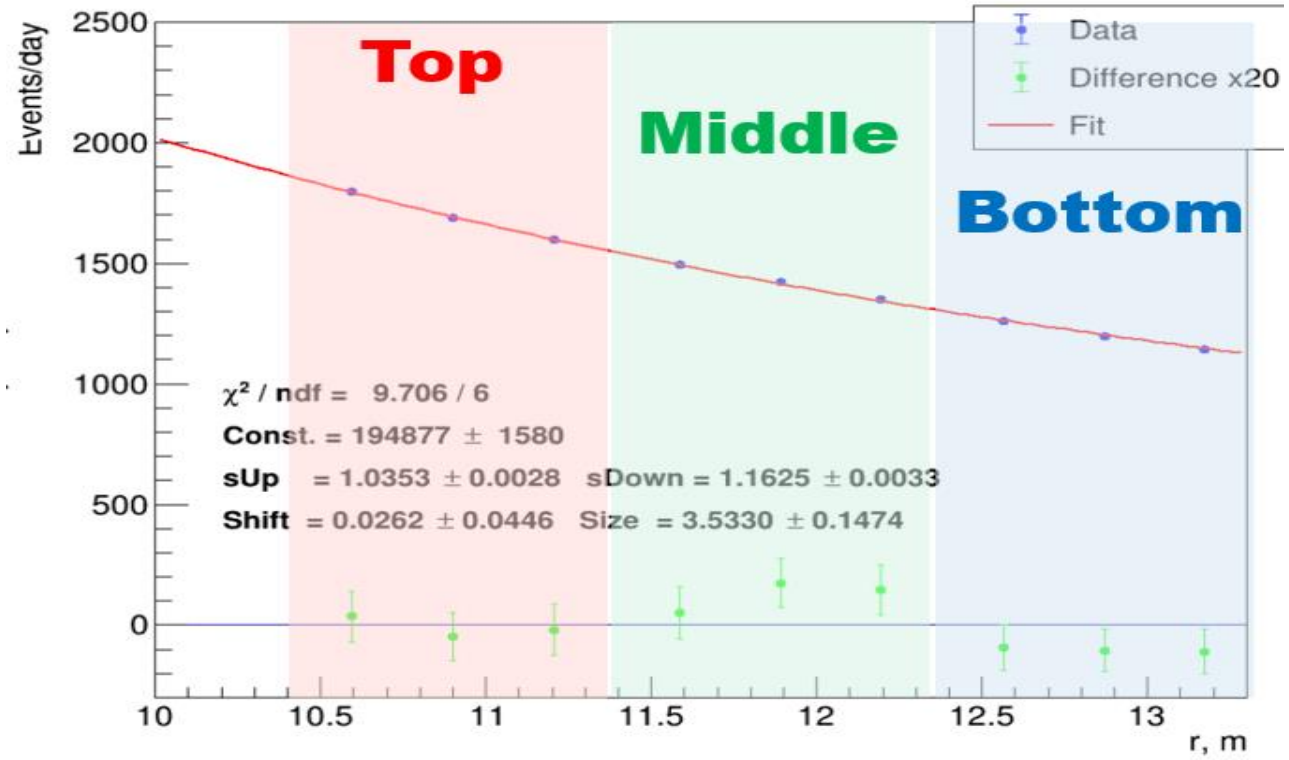


- Large progress in 90% CL exclusion area since published results

  (Phys.Lett. B787 (2018) 56)

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

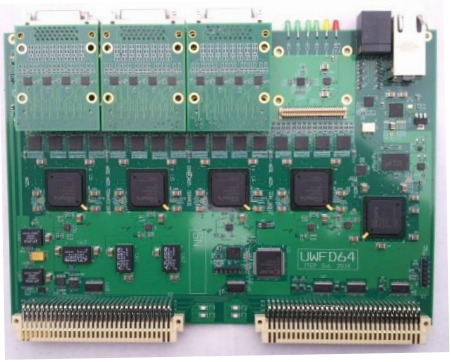
IBD total rate vs. effective distance

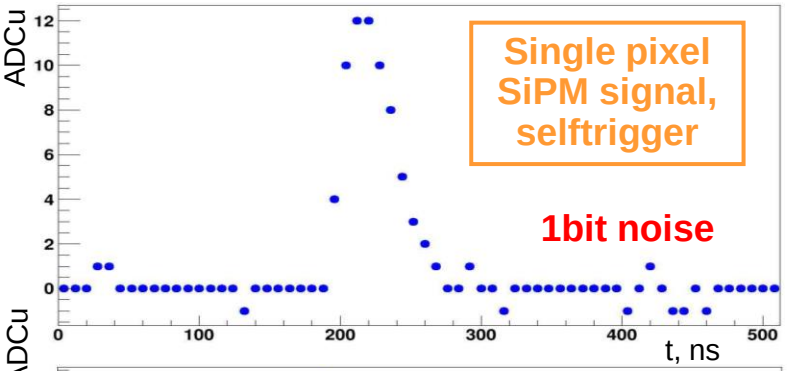


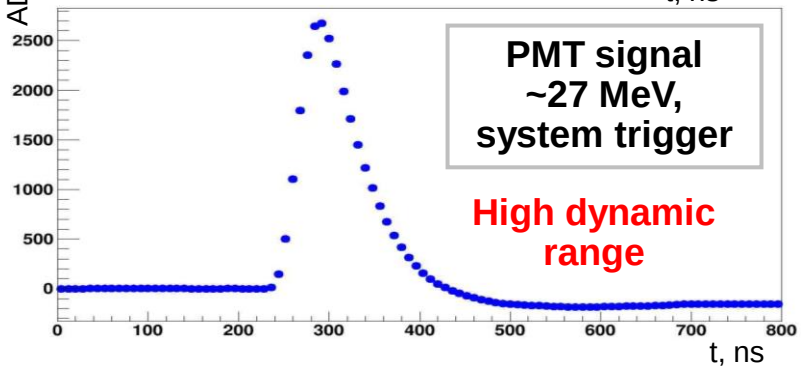
- **IBD intensity follows reasonably the $1 / L^2$ dependence.**
- **Detector was divided on 3 parts in each position.**

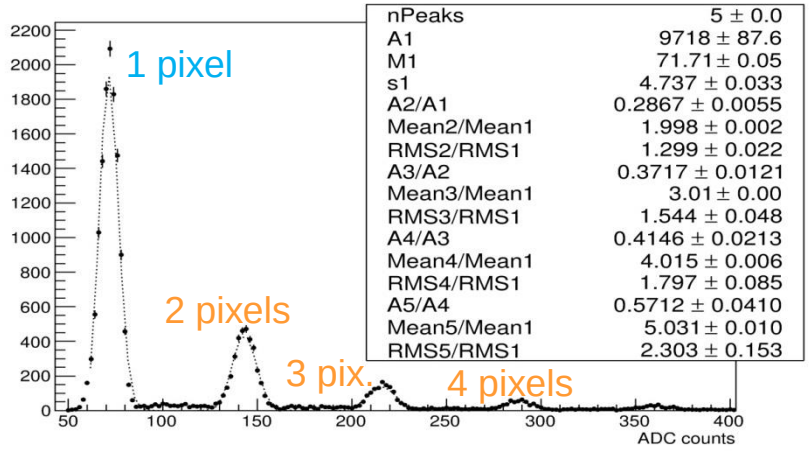
Data acquisition system

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 fuel evolution correction