

Resent results from the **DANSS** experiment

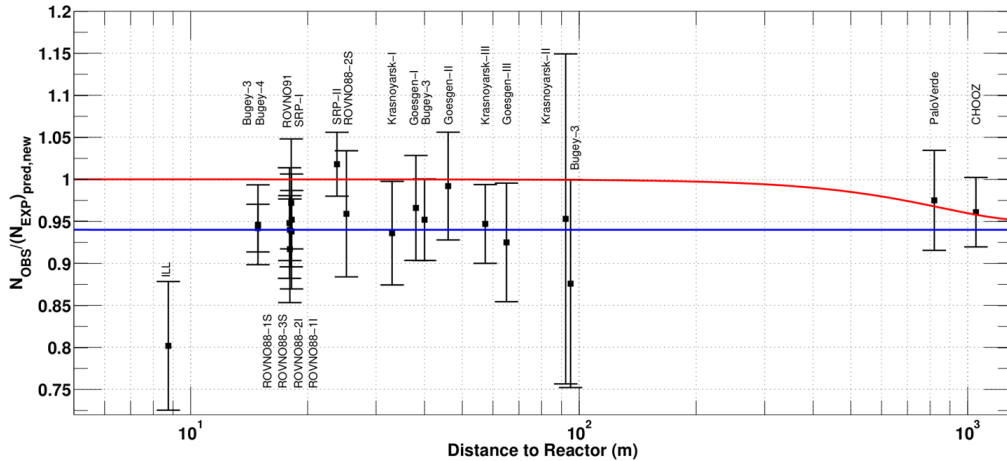
Igor Zhitnikov
on behalf of the DANSS collaboration

ICPPA 2022

Motivation

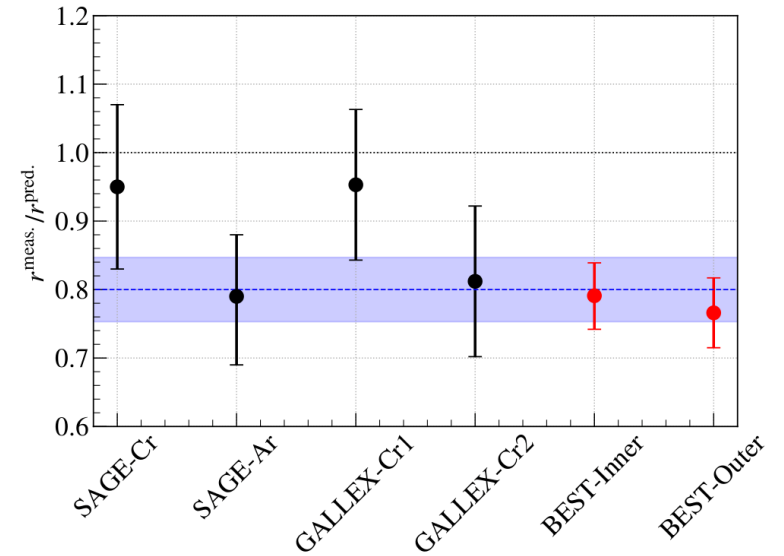
The Reactor Antineutrino Anomaly

[Phys.Rev.D83:073006 (2011)]



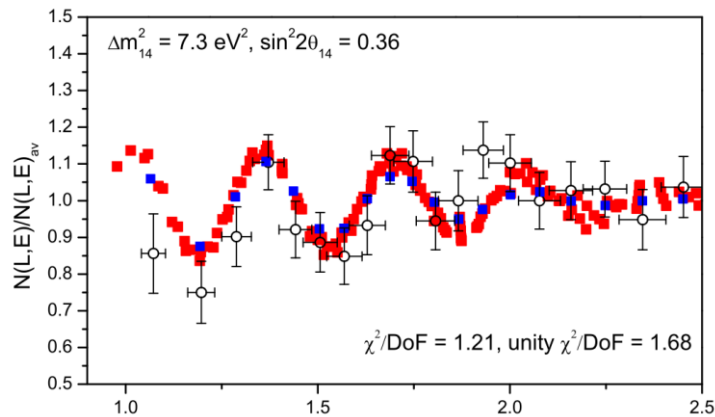
Gallium anomaly + new BEST results

[Phys. Rev. C 105, 065502 (2022)]



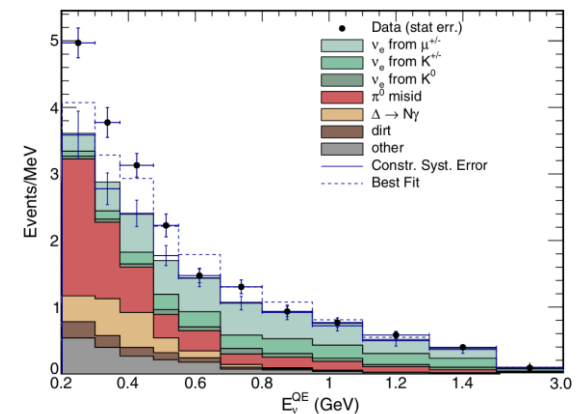
Neutrino-4 results

[Phys. Rev. D 104, 032003 (2021)]



Accelerator anomaly

[PRL 128, 221801 (2018)]

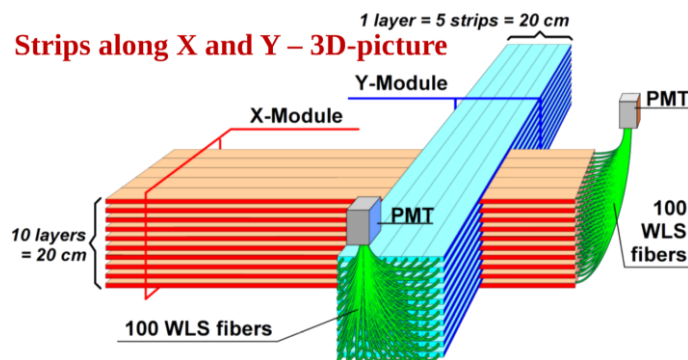
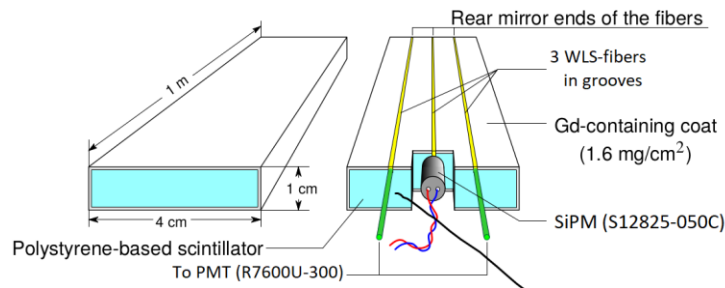
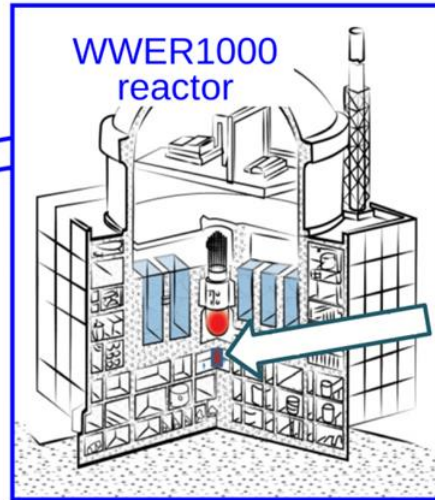


Anomalies can be described by 3+1v model at short baseline:

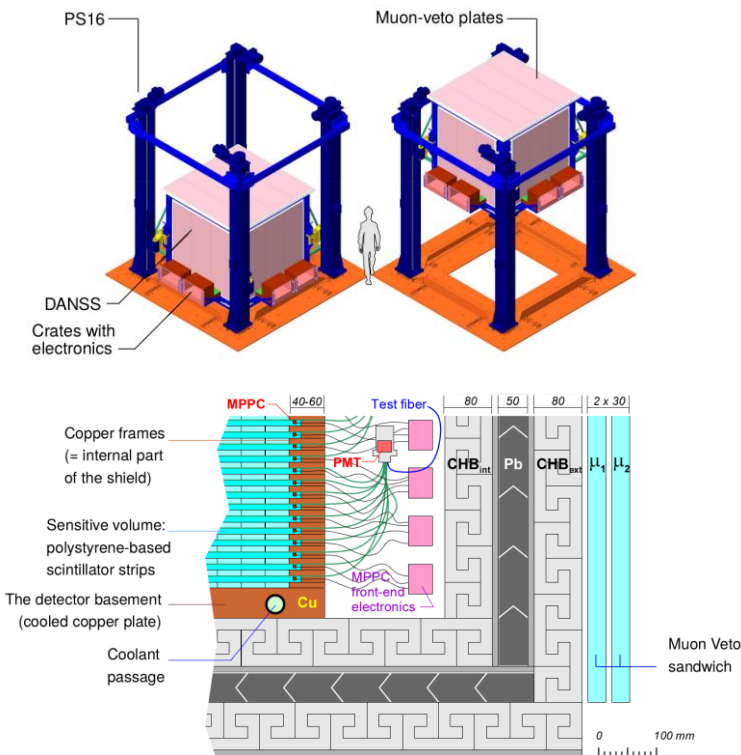
$$P_{ee} \approx 1 - \sin^2(2\theta_{41}) \sin^2\left(1.27 \frac{\Delta m_{41}^2 [\text{eV}^2] L [\text{m}]}{E_{\bar{\nu}_e} [\text{MeV}]}\right)$$

DANSS

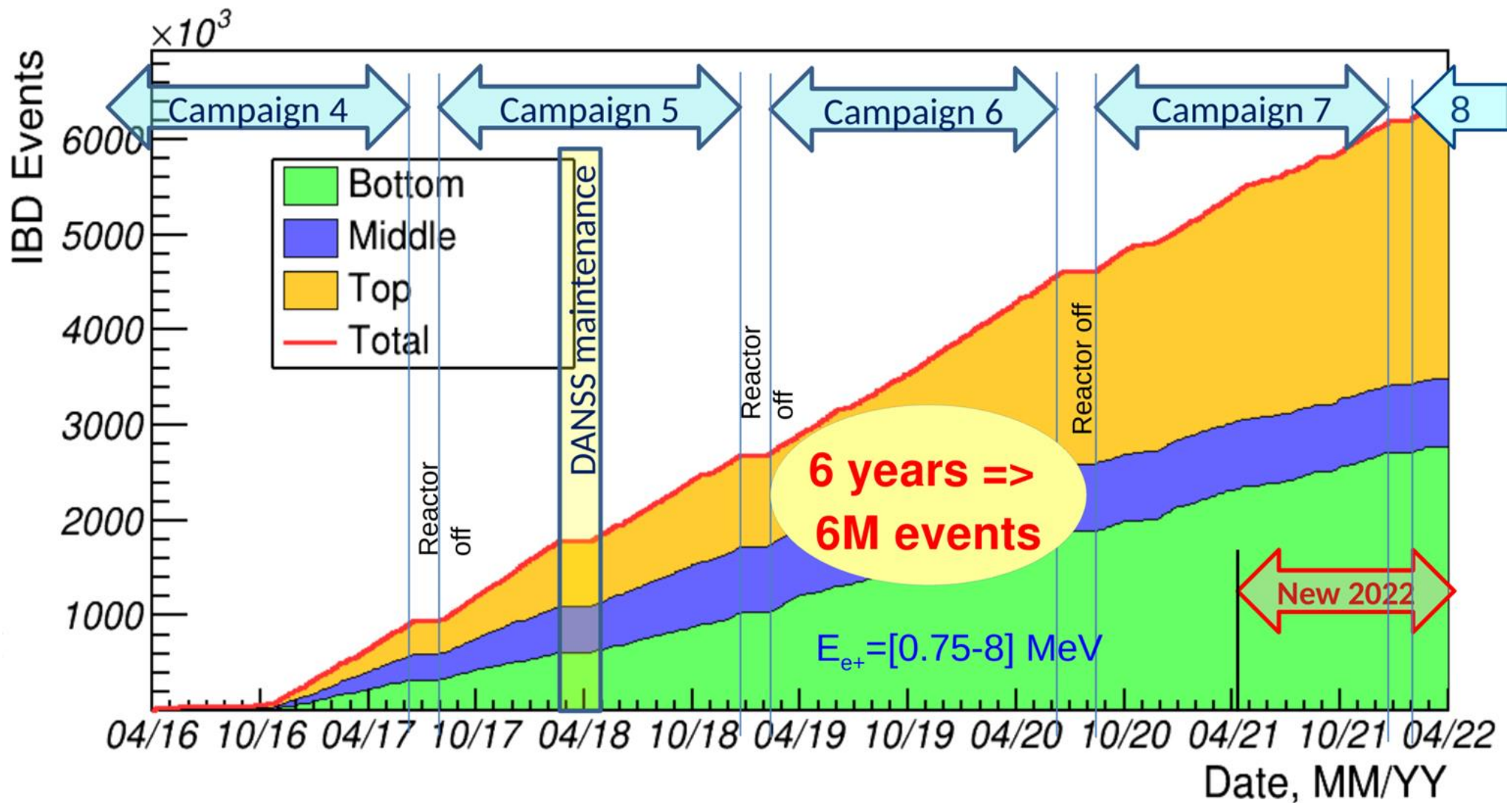
(Detector of the reactor AntiNeutrino based on Solid-state Scintillator)



- Below 3.1 GW_{th} commercial reactor $\sim 5 \cdot 10^{13} \text{ v} \cdot \text{cm}^{-2} \cdot \text{c}^{-1} @ 11 \text{ m}$
- Reactor provide overburden $\sim 50 \text{ m w.e.}$ for cosmic background suppression
- Lifting system allows to change the distance between the centers of the detector and of the reactor core from 10.9 to 12.9 m on-line
- Double PMT (groups of 50) and SiPM (individual) readout
- SiPM: 18.9 p.e./MeV & 0.37 X-talk
- PMT: 15.3 p.e./MeV
- 2500 strips = 1 m³ of sensitive volume
- IBD ($\bar{\nu}_e + p \rightarrow e^+ + n$) reaction is used



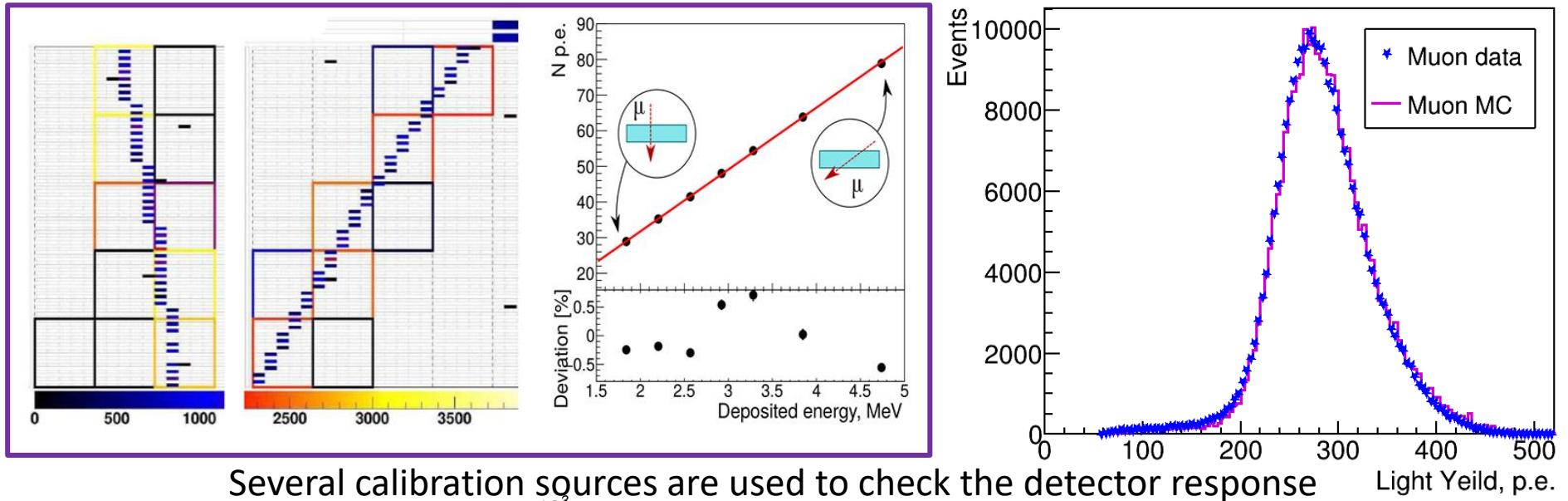
Data acquisition



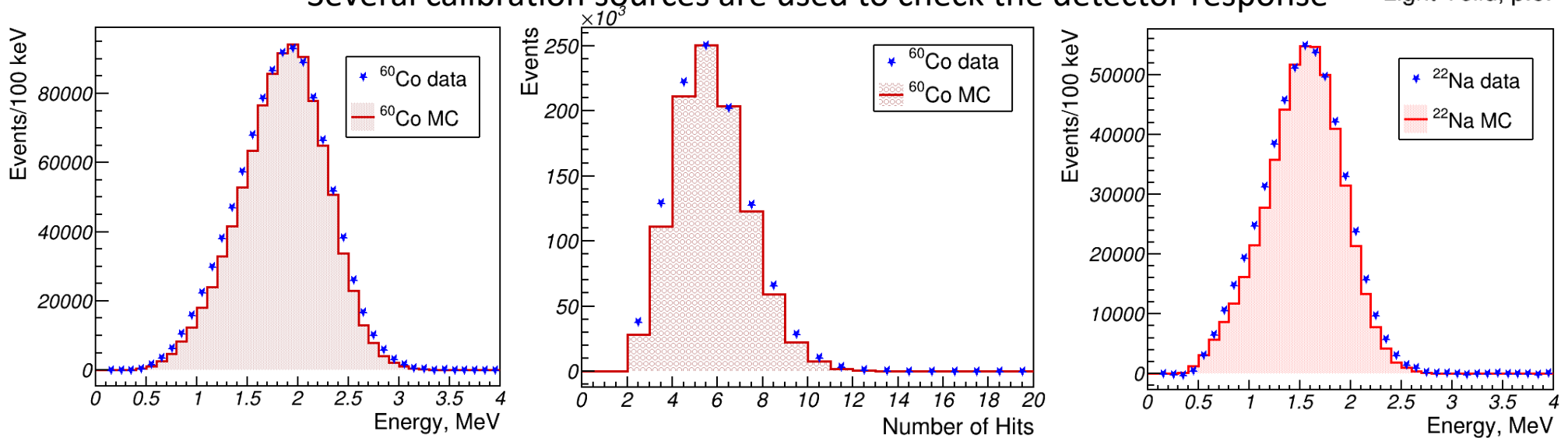
Calibration

2500 SiPM gains and X-talks are calibrated every 30-40 min.

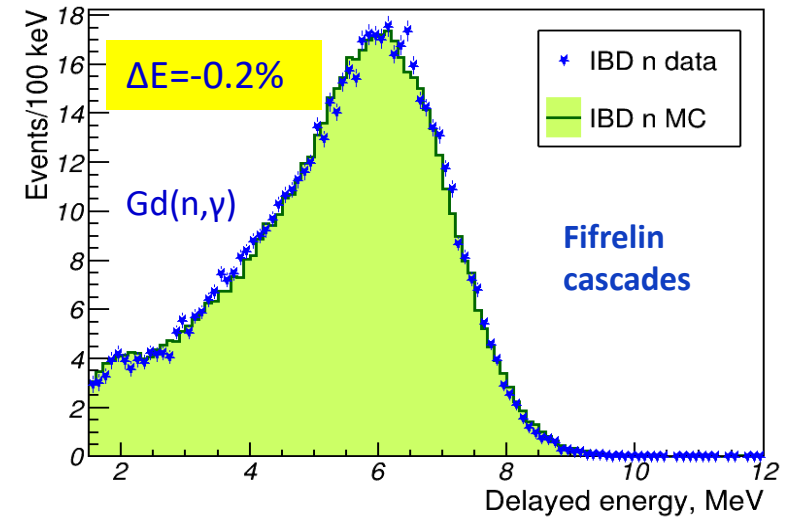
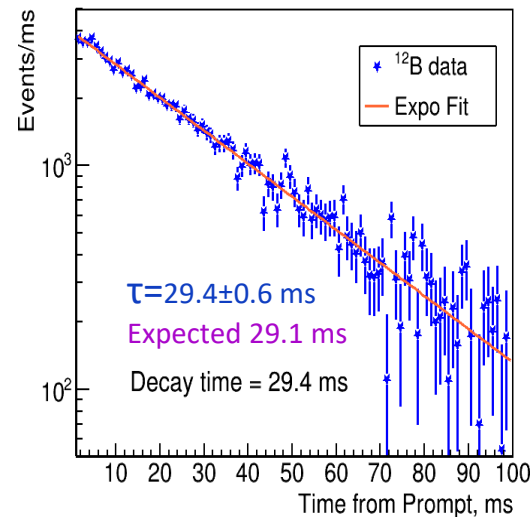
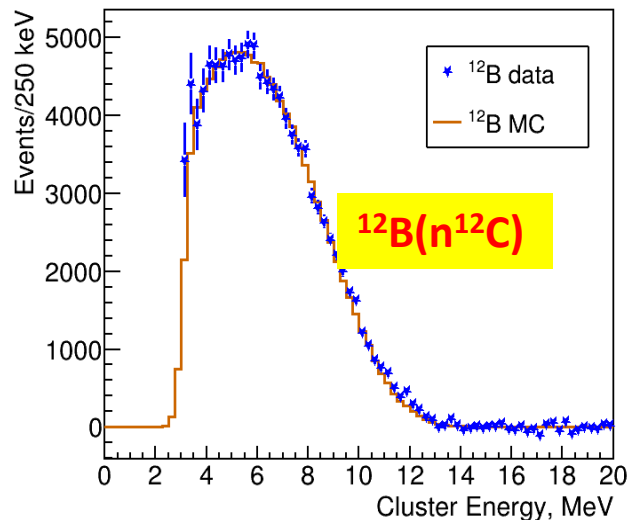
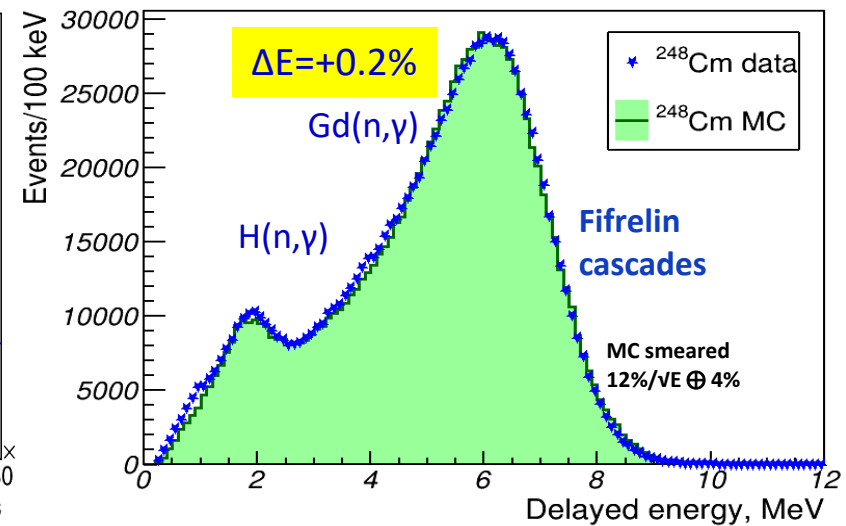
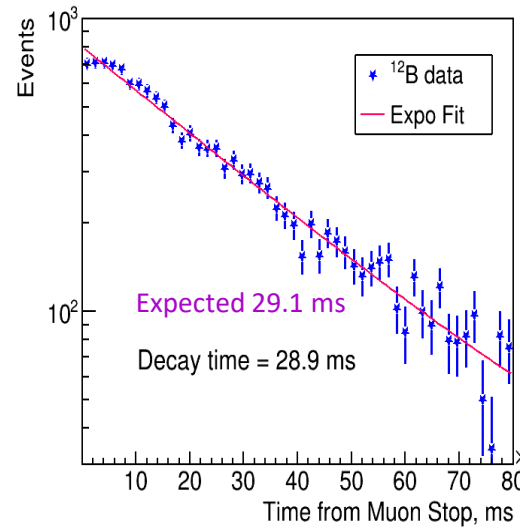
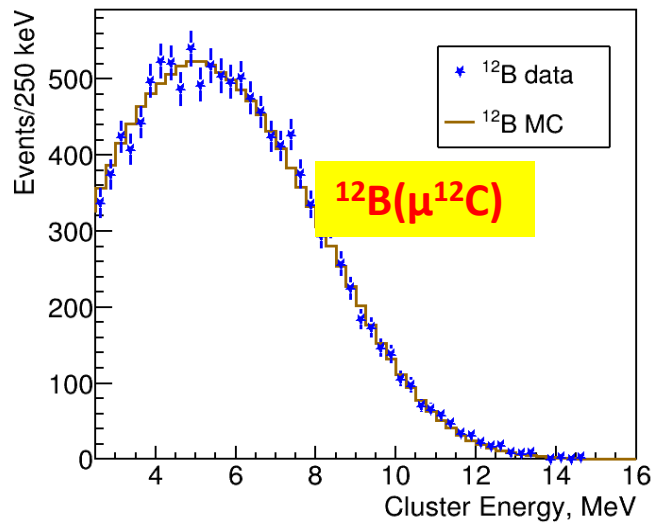
All 2550 channels are calibrated every 1-2 days using cosmic muons



Several calibration sources are used to check the detector response

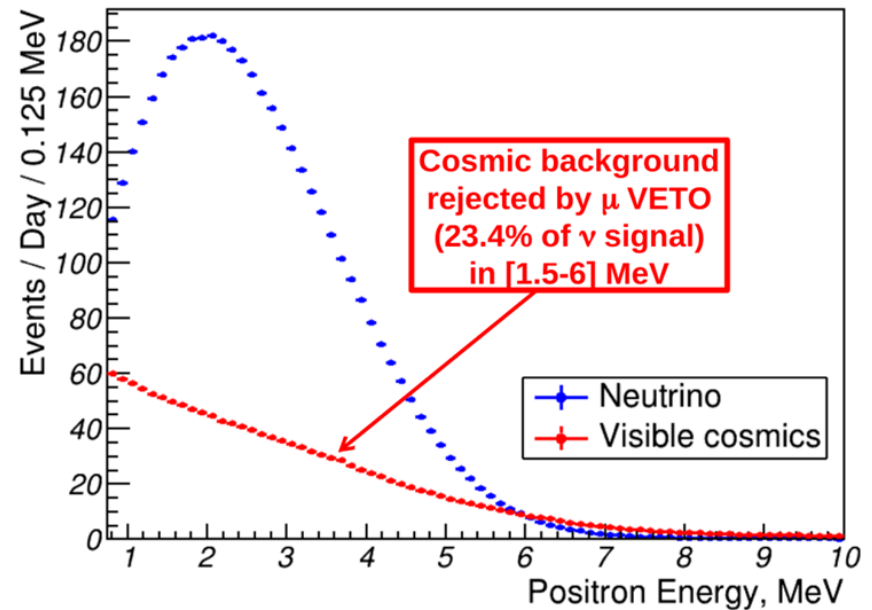
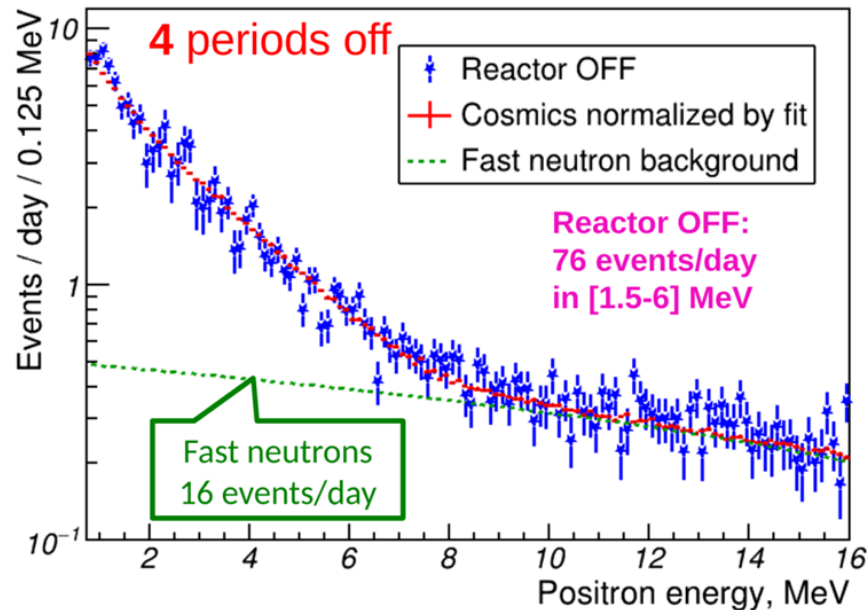
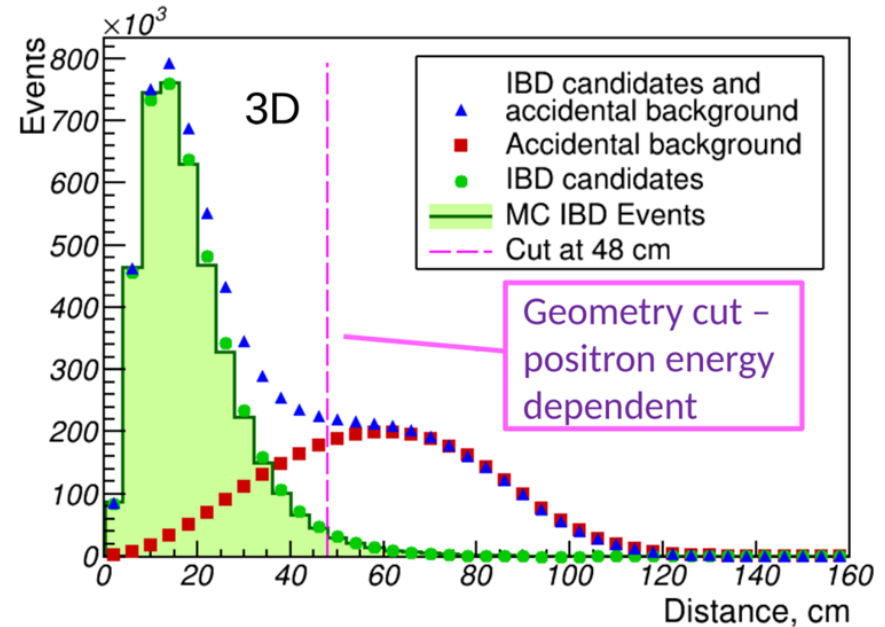
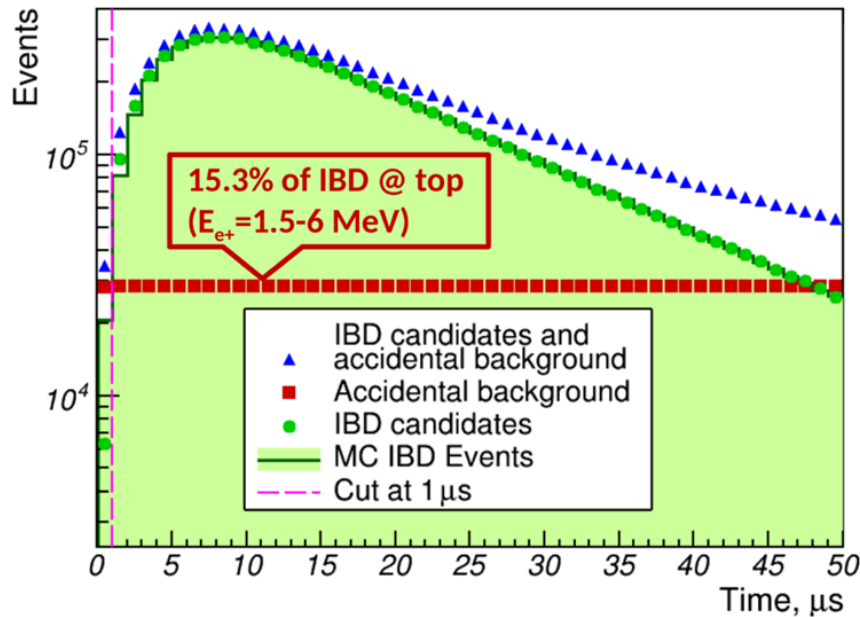


Calibration

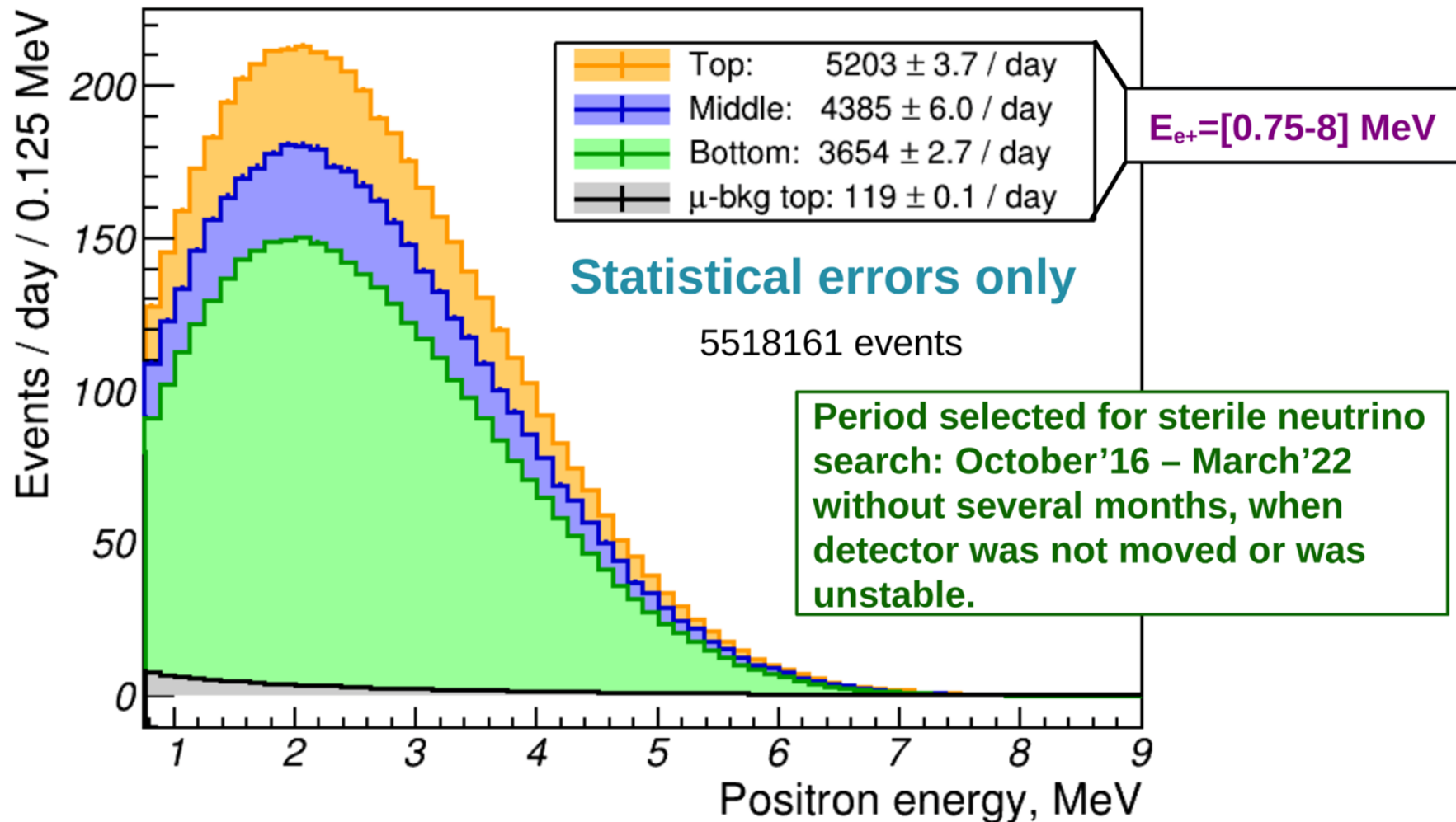


- Energy scale has been fixed using β -spectrum of ^{12}B , which is similar to positron signal
 - Other sources agree within $\pm 0.2\%$ with exception of ^{22}Na which is 1.8% below.
 - Systematic error on E scale of $\pm 2\%$ was added due to ^{22}Na disagreement
- Hope to reduce this error soon

Background

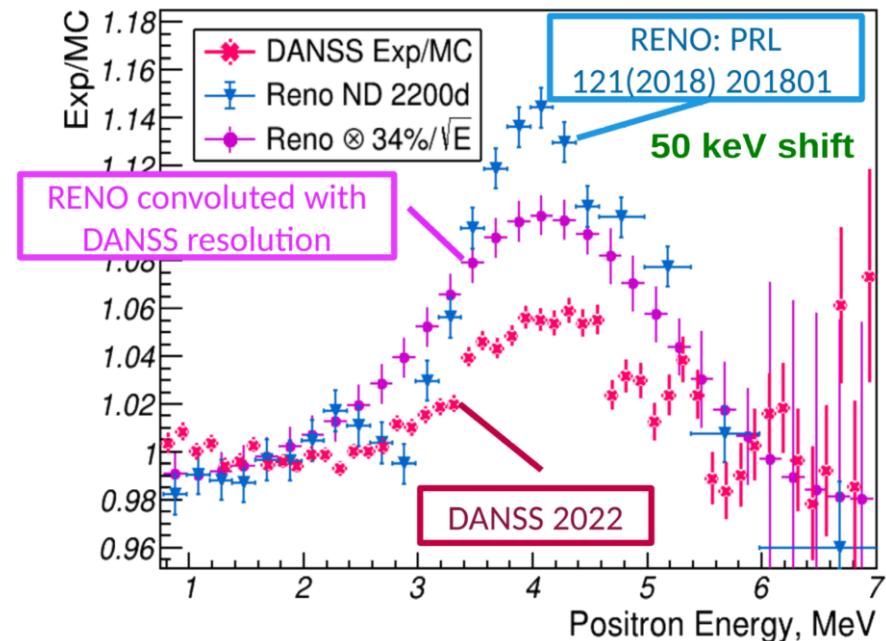
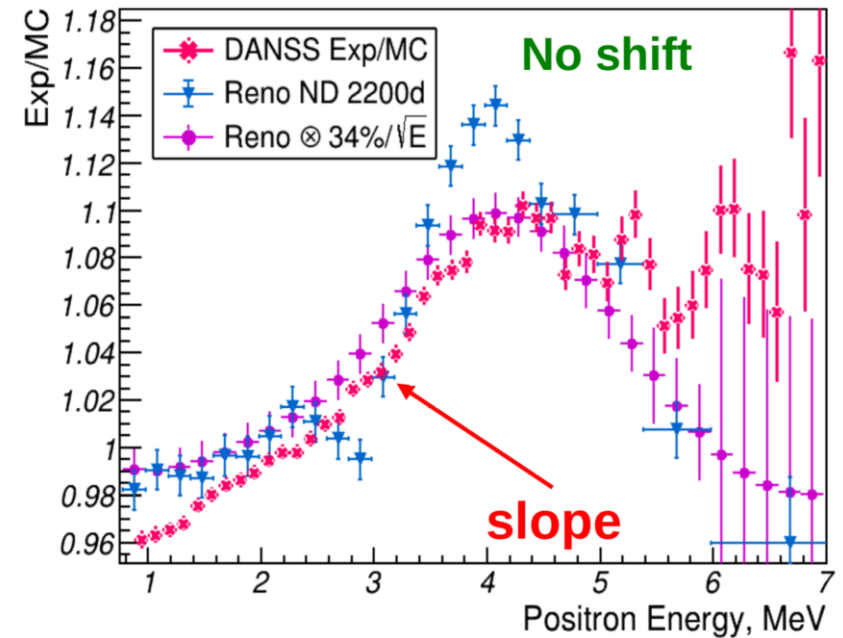
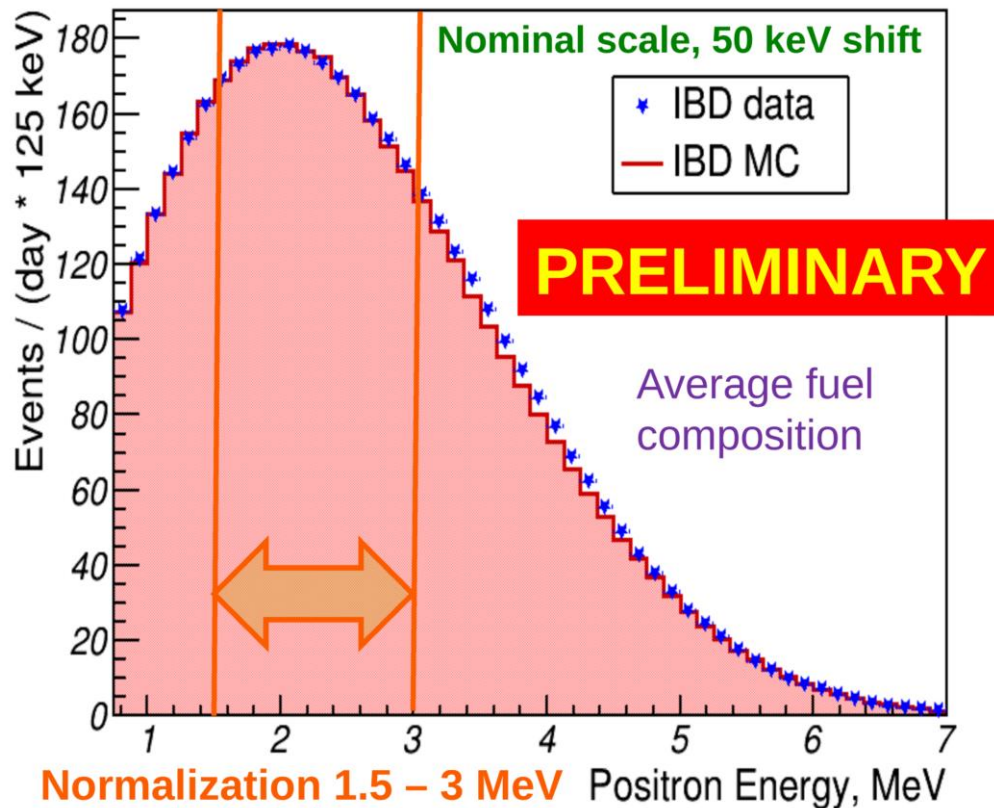


Positron spectrum of IBD-signal



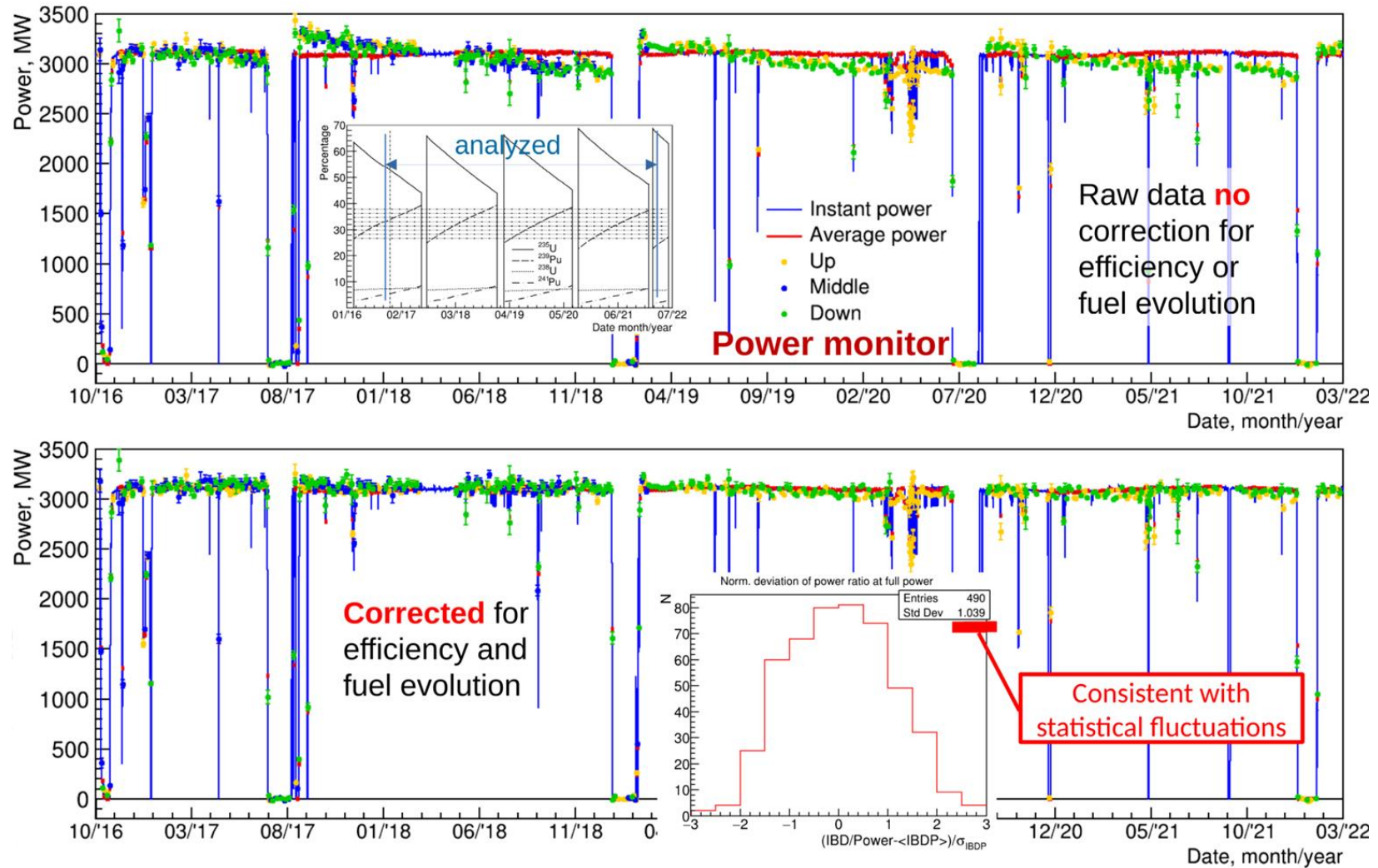
- All backgrounds subtracted
- Neighbor reactors background at 160m, 334m and 478 m subtracted(0.6% of neutrino signal at top position)
- For $E_{e^+}=[1.5-6]$ MeV background = 1.76% in top position: $S/B > 50$.

Positron spectrum vs model



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

Power monitoring



- Reactor power is measured by neutrino flux with **1.5% statistical accuracy in 2 days** for 5.5+ years.
- Changes in absolute detector efficiency are known with accuracy better than 1% during 5.5+ years.
- Relative efficiency is even more stable (<0.2%) because of frequent changes of detector positions

Analysis method

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

3-position movement
Oct.2016-Dec.2018
2-position movement
Mar.2019-Mar.2022
Penalty terms for nuisance
parameters: relative efficiencies and systematics

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

$Z_i = R_j^{obs} - k_i \times R_j^{pre}(\Delta m^2, \sin^2 2\theta, \eta)$ for each energy bin

$R_1 = \frac{Bottom}{Top}, R_2 = \frac{Middle}{\sqrt{Bottom \cdot Top}}$, where

$Top, Middle, Bottom$ – absolute count rates per day for each detector position

k – relative efficiency,

η – nuisance parameters,

W – covariance matrix

Nuisance parameters and their errors ($\sigma_{k,\eta}$):

Relative detector efficiencies – 0.2%

Energy scale – 2%

Additional smearing in energy resolution 3%

Energy shift 50 keV

Distance to fuel burning profile center – 5 cm

Cosmic background – 25%

Fast neutron background – 30%

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

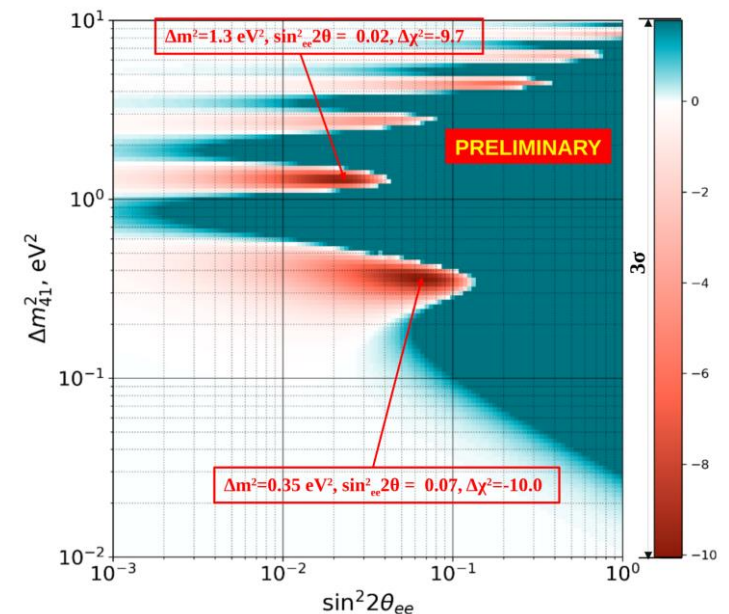
Red: $\chi^2(4\nu) < \chi^2(3\nu)$,

Blue: $\chi^2(4\nu) > \chi^2(3\nu)$,

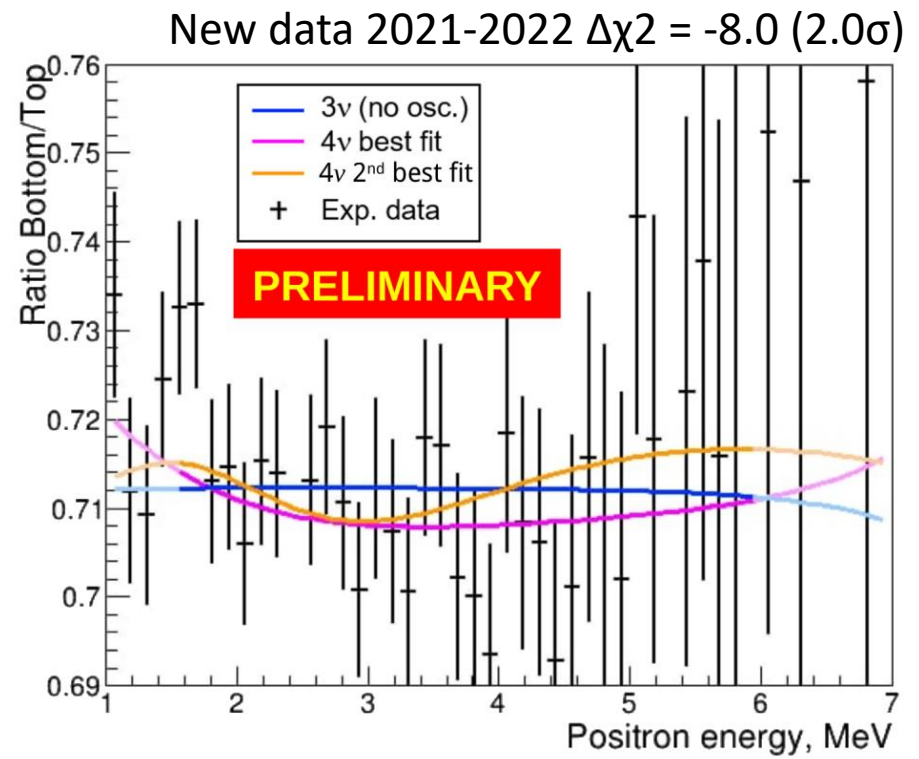
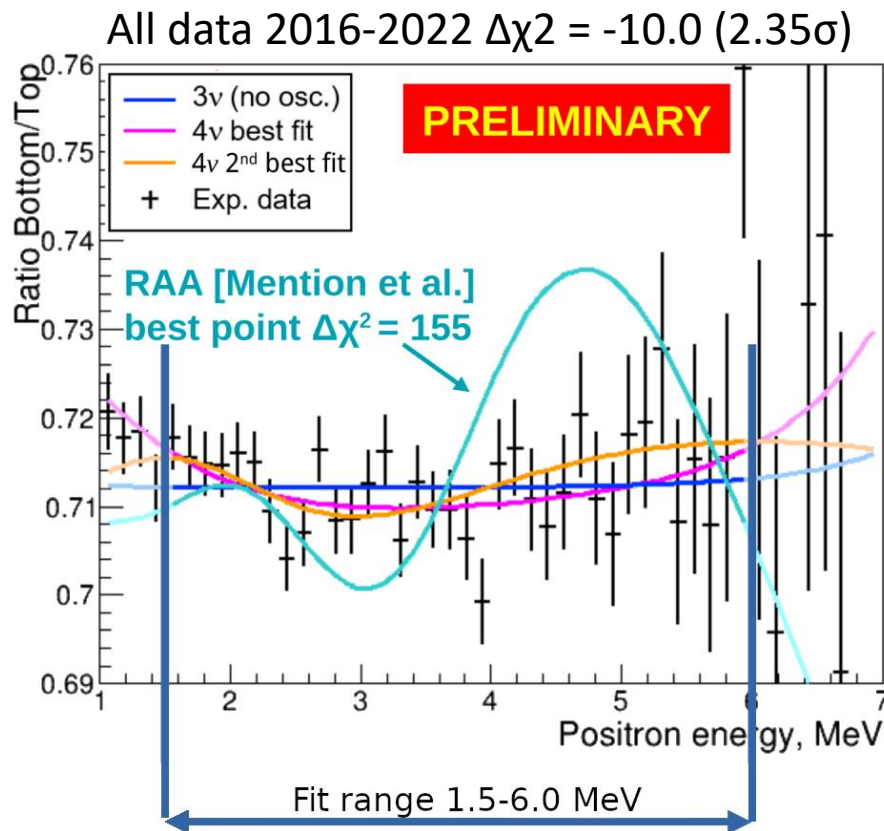
Dark blue: $(\chi^2(4\nu) - \chi^2_{min}) > 11.8$

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).
- **2016-2020** data – no statistically significant indication of 4v ($\Delta\chi^2 = -5.6$, 1.5σ)
- **2021-2022** data – weak, statistically **not significant hint** in favor of 4v ($\Delta\chi^2 = -8.0$, 2.0σ)
- Using current statistics 2016-2022 (~4.4 million IBD events with $1.5 \text{ MeV} < E < 6 \text{ MeV}$) we see statistically not significant hint in favor of 4v signal:

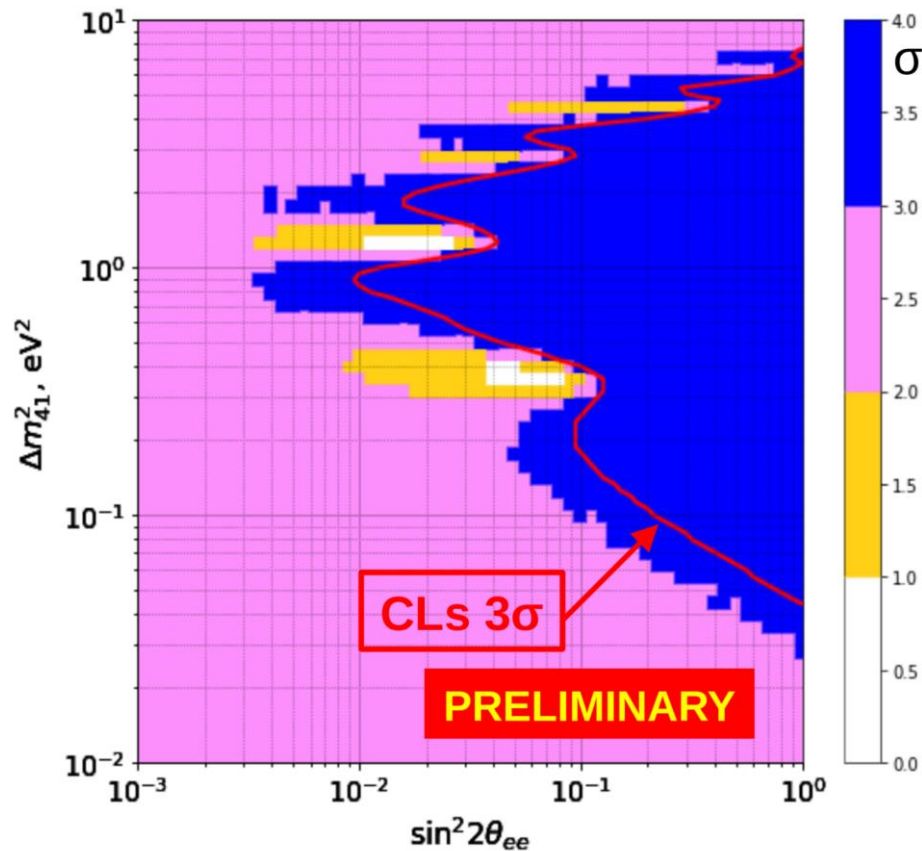
$\Delta\chi^2 = -10$ (2.35σ) for 4v hypothesis best point $\Delta m^2 = 0.35 \text{ eV}^2$, $\sin^2 2\theta = 0.07$

$\Delta\chi^2 = -9.7$ for 4v hypothesis second best point $\Delta m^2 = 1.3 \text{ eV}^2$, $\sin^2 2\theta = 0.02$

Results

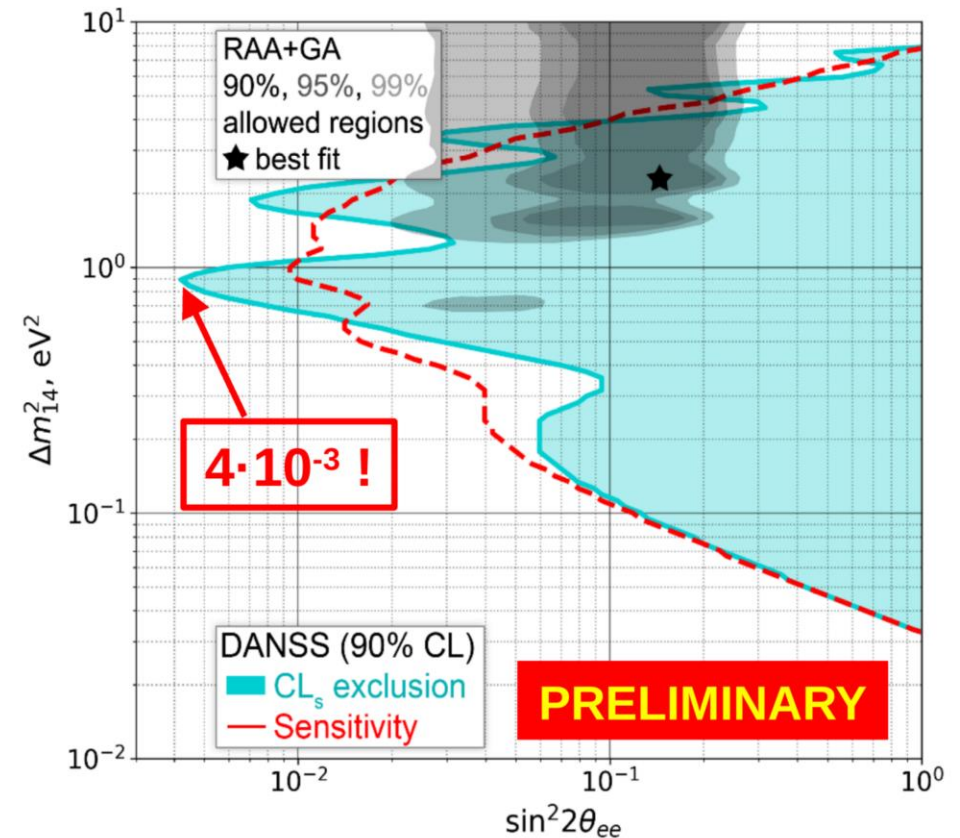
Feldman and Cousins

[Phys.Rev.D57:3873-3889,1998]



Gaussian CLs

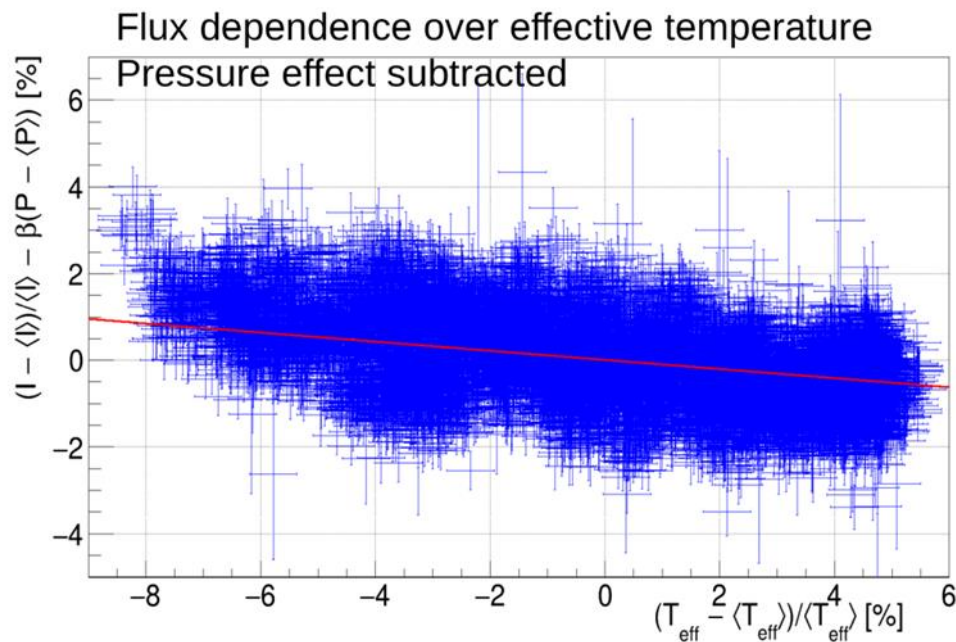
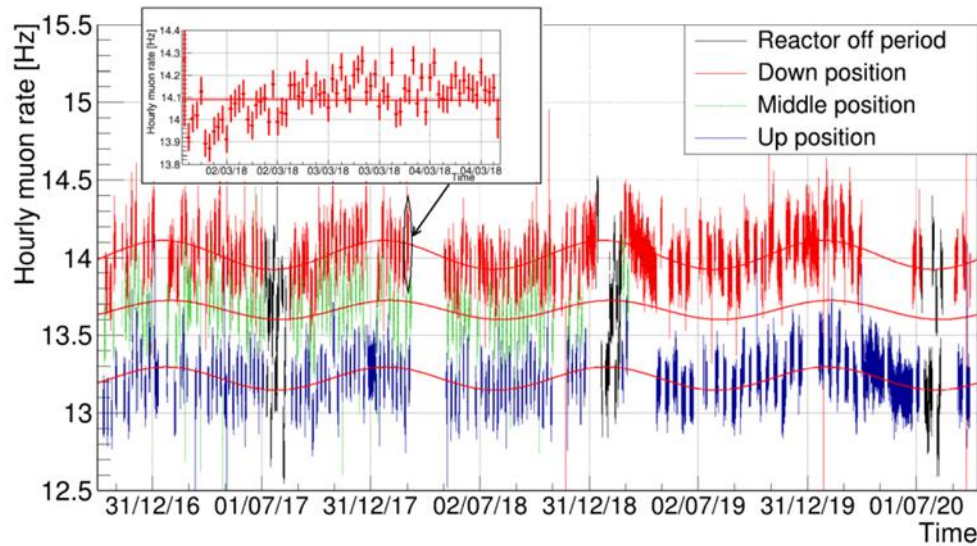
[X. Qian et al. Nucl.Inst. Meth. A 827 (2016) 63]



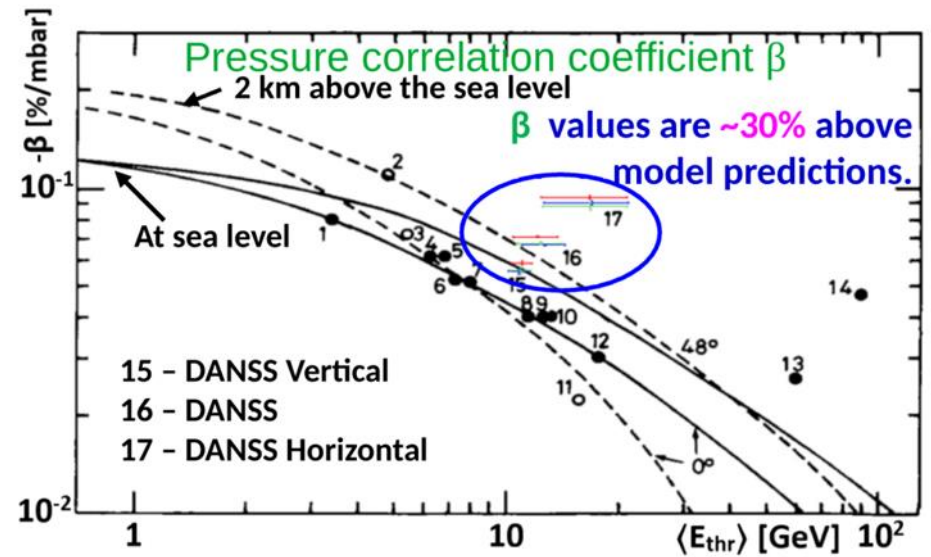
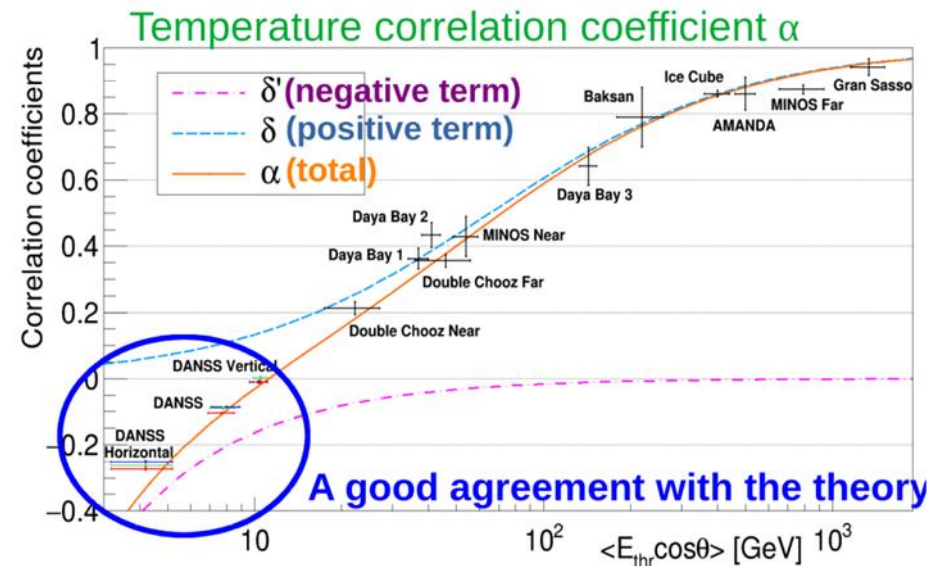
- 4.4M IBD events in the E_{e^+} range 1.5-6 MeV included in the χ^2 (very conservative)
- Gaussian CLs method – the most stringent limit reaches $\sin^2 2\theta < 4 \cdot 10^{-3}$ level
- A very interesting region of 4ν parameters space excluded
- Two F-C allowed regions with close significance more than 2σ
- The best point (2.35σ) is not significant enough to claim indication of 4ν
- RRA+GA best point is deep in the exclusion region. 5σ exclusion already in 2018 [PLB 787 (2018) 56]

Muon flux

[European Physical Journal C, 2022, 82(6), 515]



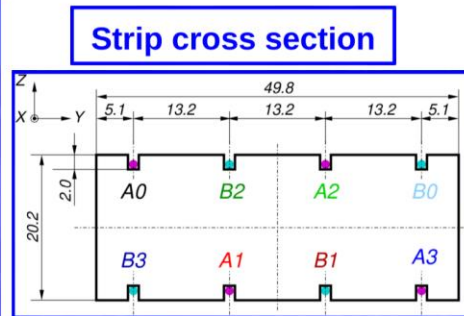
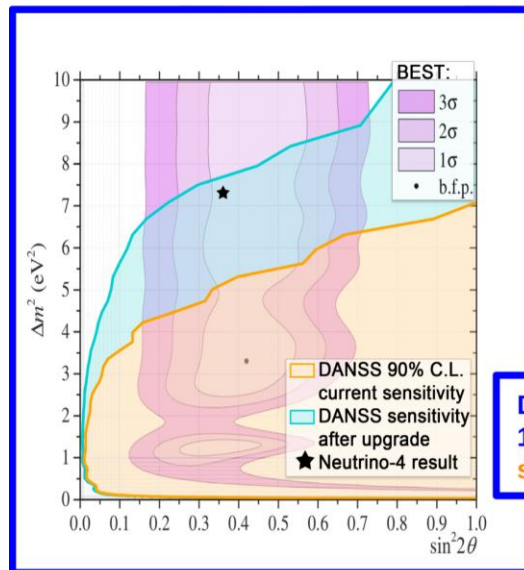
Weather data obtained from **ERA5** database of European Center for Medium-Range Weather Forecasts (ECMWF).



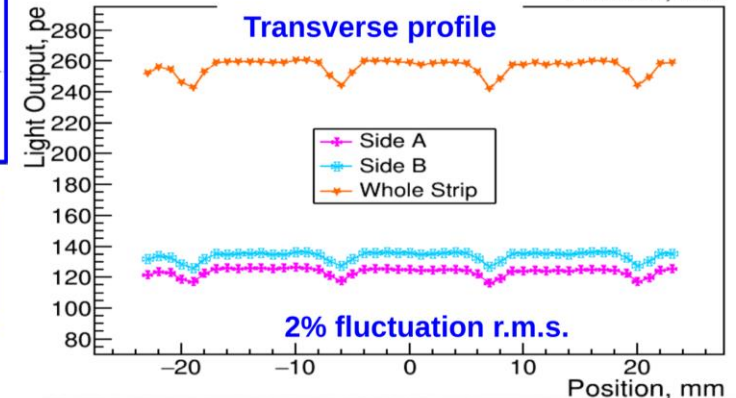
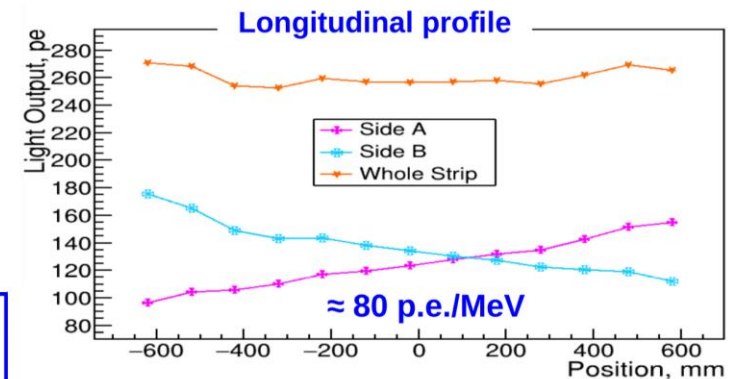
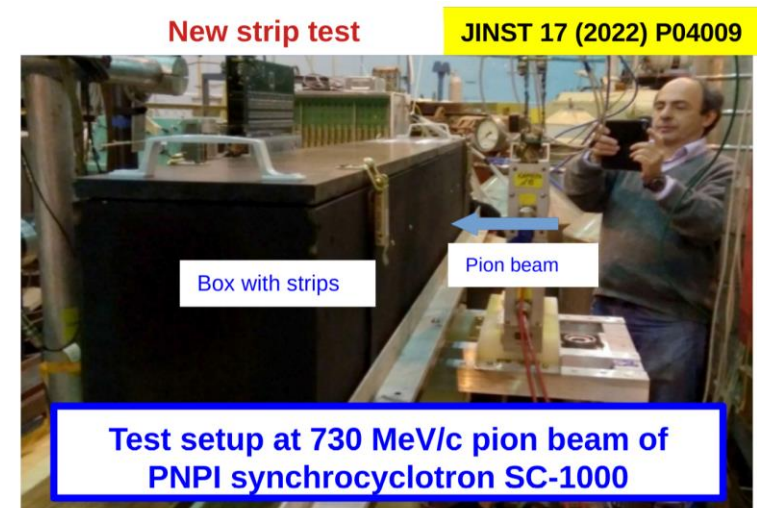
DANSS upgrade

- Main goal of the upgrade is to **improve energy resolution**:
 $34\%/\sqrt{E} \rightarrow 12\%/\sqrt{E}$
- **New scintillation strips**: 20x50x1200mm³
- 60 layers x 24 strips – **1.7 times larger fiducial volume**
- No PMT – SiPM readout from both sides
- 8 grooves with WLS, 8(16 – in development) SiPM per strip get high light yield and uniformity
- TOF to get longitudinal coordinate in each strip. Faster (4.0 ns decay time) WLS fiber KURARAY YS-2 [JINST 17 (2022) P01031]
- Chemical whitening of strips – no large dead layer with titanium and gadolinium
- Gadolinium in polyethylene film between layers
- New front-end electronics – low power inside passive shielding. Cool SiPM to 10°C
- Keep platform, passive shielding and digitization.

We plan to upgrade in 2023



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



Summary

- DANSS recorded the first data in April 2016 and is still running. More than **6M IBD events** collected.
- DANSS records more than **5k antineutrino events per day** in the closest position to reactor core. **Signal to background ratio is > 50**.
- We clearly observe antineutrino spectrum and counting rate dependence on fuel composition.
- We measure **reactor power with 1.5% precision in two days** during more than 5.5 years of operation.
- Muon flux dependence on atmospheric temperature and pressure was measured. The temperature correlation coefficient is in a good agreement with the theoretical expectation though pressure correlation coefficient is ~30% above theoretical expectations.
- **4.4M IBD events are included in χ^2 calculation for the sterile neutrino search ($E_{e^+}=1.5-6$ MeV).** Only ratio of positron spectra at different distances used. No dependence on ν spectra and the detector absolute efficiency.
- Recent analysis of the data excludes a large portion of the oscillation parameter space. The new result provides even stronger exclusion of the parameters from RAA best fit [5σ exclusion was reached already with one-year statistics: [Phys.Lett. B787(2018)56]
- New data (2021-2022) reveals some weak hint of sterile neutrino ($\Delta\chi^2=-8.0, 2\sigma$). The full data set has two close best points:
$$\Delta m^2=0.35 \text{ eV}^2, \sin^2 2\theta=0.07: \Delta\chi^2=-10.0 (2.35\sigma)$$
$$\Delta m^2=1.3 \text{ eV}^2, \sin^2 2\theta=0.02: \Delta\chi^2=-9.7 (2.35\sigma)$$

This hint is **not statistically significant** (2.35σ) to claim even the indication of sterile neutrino
- Our analysis plans include finalize the energy calibration and include larger E_{e^+} range in the analysis.
- DANSS upgrade is planned in 2023 with installation of new strips with SiPM only readout from both ends. This will provide much better energy resolution and higher counting rate and allow scrutinize Neutrino-4 and BEST results.

BACKUP SLIDES

Trigger and events

- Trigger = digital sum of PMT > 0.7 MeV or VETO

- Total trigger rate ≈ 1 kHz
- Veto rate ≈ 400 Hz
- True muon rate ≈ 180 Hz
- Positron candidate rate ≈ 170 Hz
- Neutron candidate rate ≈ 30 Hz
- IBD rate ~ 0.1 Hz

- IBD event = two time separated triggers:

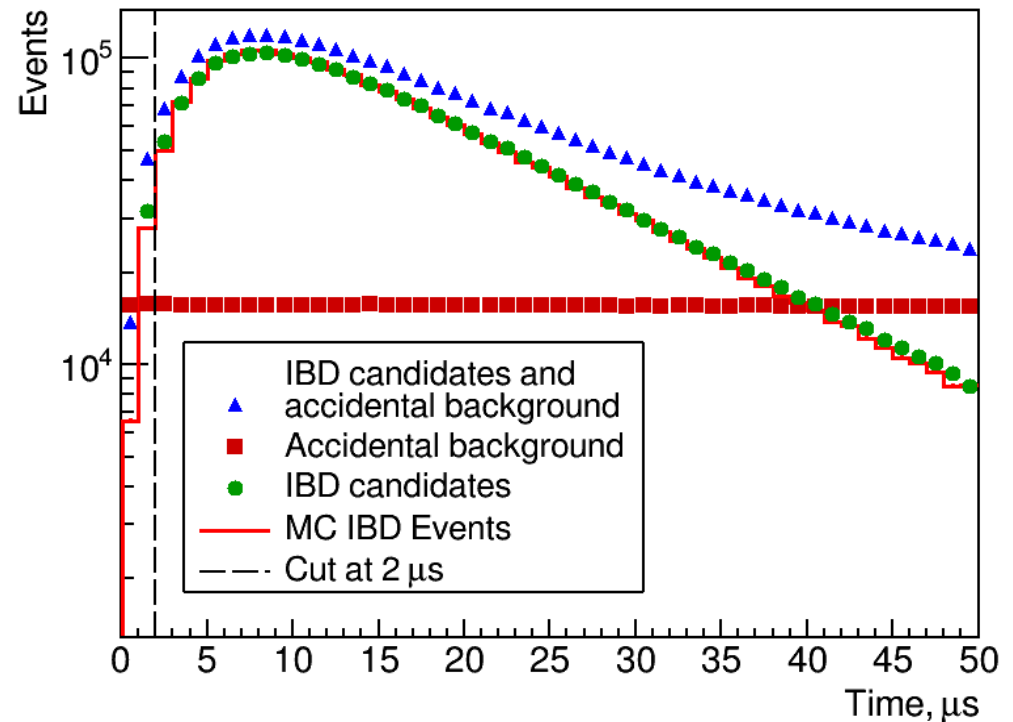
- Positron track and annihilation
- Neutron capture by gadolinium

- SiPM noise cut:

- Time window ± 10 ns
- SiPM hits require PMT confirmation

- Building Pairs

- Positron candidate: > 1 MeV in continuous ionization cluster (PMT+SiPM)
- Neutron candidate: > 3.5 MeV total energy (PMT+SiPM), SiPM multiplicity >3
- Search positron 50 μ s backwards from neutron



Significant background by uncorrelated triggers. Subtract accidental background events: search for a positron candidate where it can not be present – 50 μ s intervals 5, 10, 15 ms etc. away from neutron candidate. Use 16 non-overlapping intervals to reduce statistical error. All physics distributions = events - accidental events/16

Muon cuts

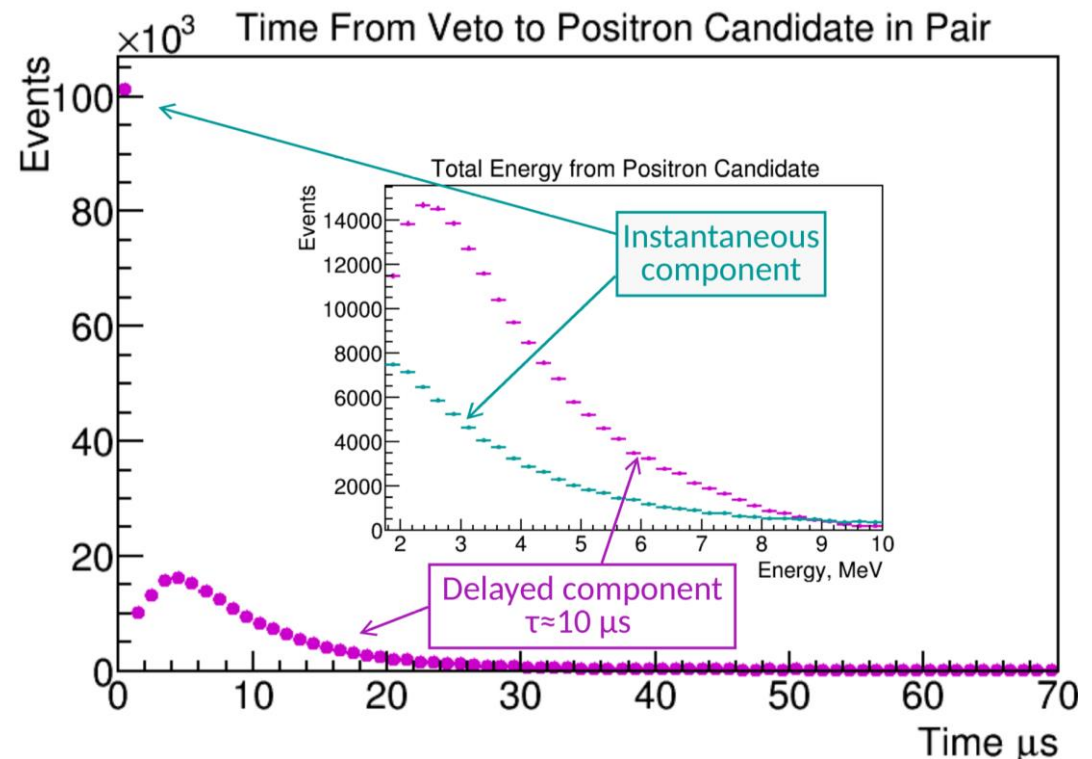
VETO 'OR':

- 2 hits in veto counters or veto energy > 4 MeV
- energy in strips > 20 MeV
- energy in two bottom strip layers > 3 MeV

Two distinct components of muon induced paired events with different spectra:

- 'Instantaneous' – fast neutron
- 'Delayed' – two neutrons from excited nucleus

- **Muon cut** : NO VETO 90 μs before positron
- **Isolation cut** : NO any triggers 50 μs before and 80 μs after positron (except neutron)
- **Showering cut** : NO VETO with energy in strips > 300 MeV for 120 μs before positron



Analysis cuts

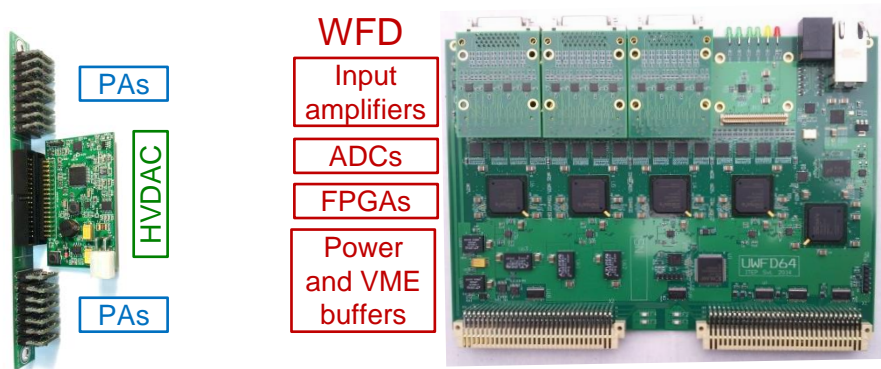
Cuts – suppress accidental and muon induced backgrounds:

- Fiducial volume - positron cluster position: 4 cm from all edges
- Positron cluster has < 8 strips
- Energy in the prompt event beyond the cluster < 1.2 MeV and there are < 12 hits out of the cluster
- Delayed event energy is < 9.5 MeV and number of hits is < 20
- Positron (cluster) energy E_e dependent cuts on prompt to delayed cluster distance and delayed event energy:

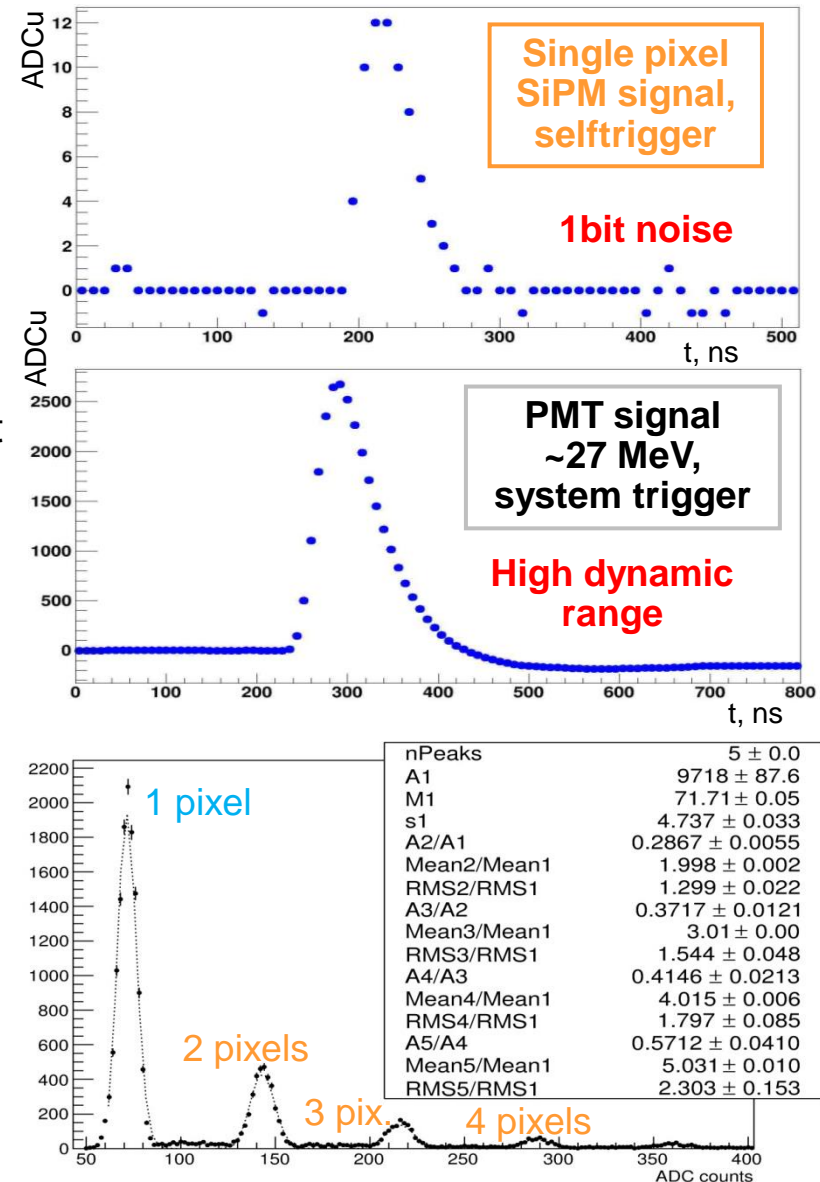
$$\begin{aligned}L_{2D}[cm] &< 40 - 17 \cdot e^{-0.13 \cdot E_e^2} \\L_{3D}[cm] &< 48 - 17 \cdot e^{-0.13 \cdot E_e^2} \\E_N[MeV] &> 1.5 + 2.6 \cdot e^{-0.15 \cdot E_e^2}\end{aligned}$$

For events with single hit positron cluster additional requirement of at least a hit out of the cluster and the energy beyond the cluster > 0.1 Me

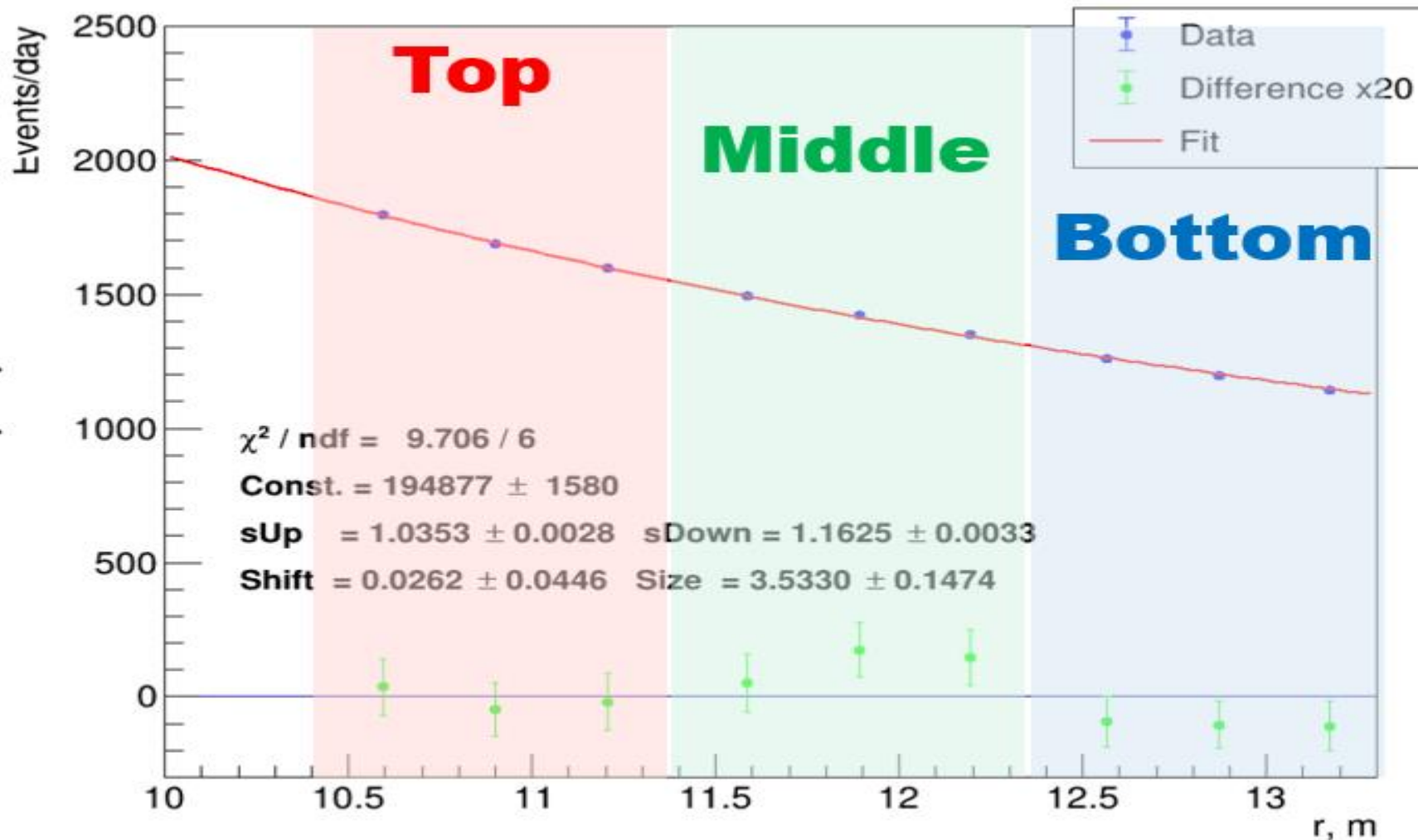
Readout electronics



- 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 self trigger on SiPM noise for gain calibration
- Exceptionally low analog noise $\sim 1/12$ p.e.



Counting rate dependence on the distance from reactor core



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

^9Li and ^8He background

~ 4 events per day

