Investigation of reactor neutrino in the DANSS experiment

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on behalf of the DANSS collaboration

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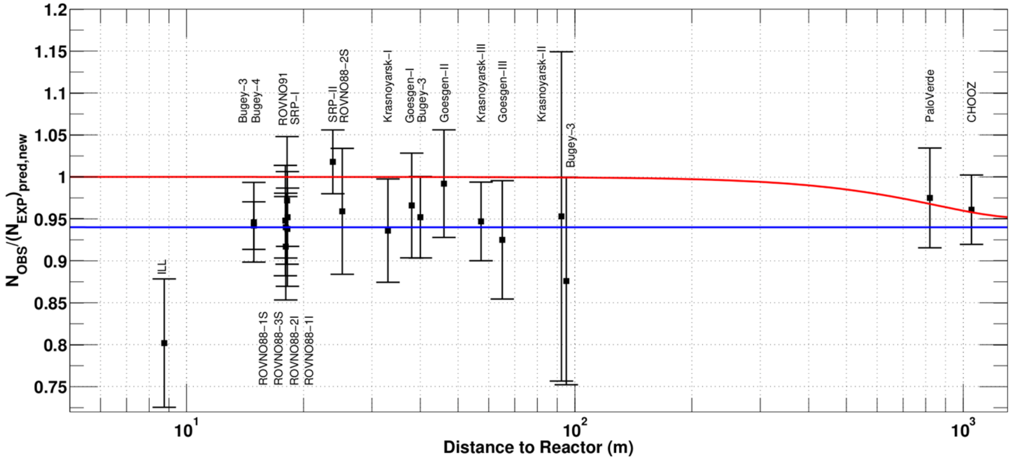
NUCLEUS-2024

Motivation.

Search for sterile neutrino oscillations.

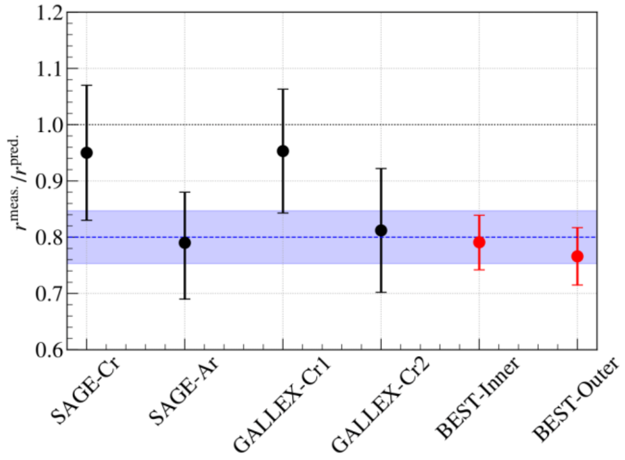
The Reactor Antineutrino Anomaly

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



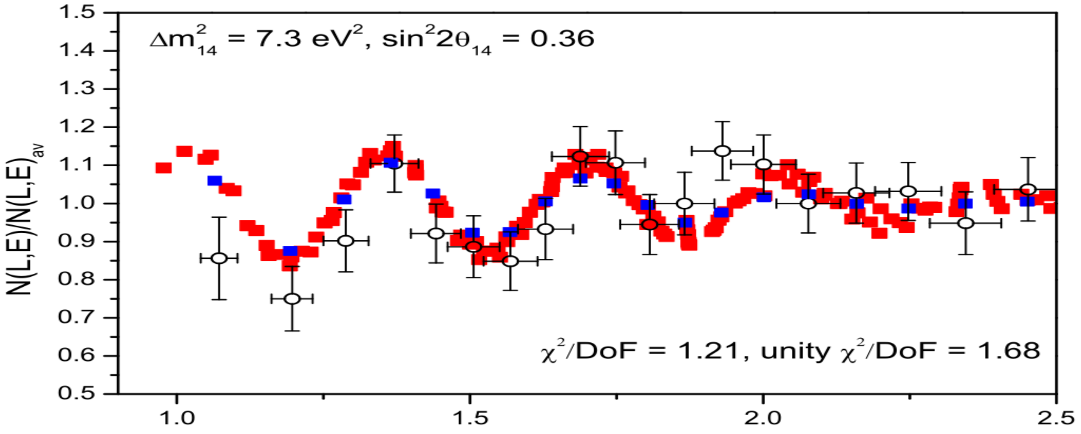
Gallium anomaly + new BEST results

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



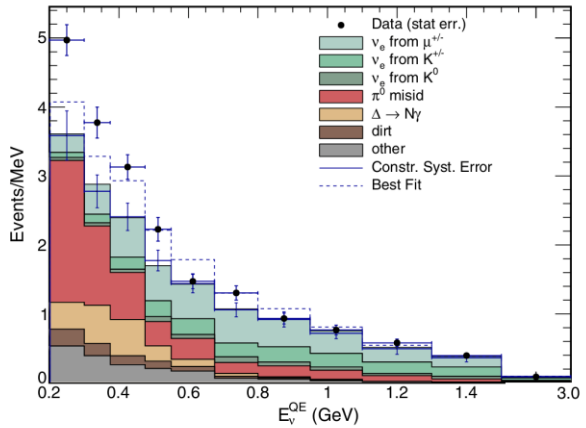
Neutrino-4 results

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



Accelerator anomaly

[PRL 128, 221801 (2018)]

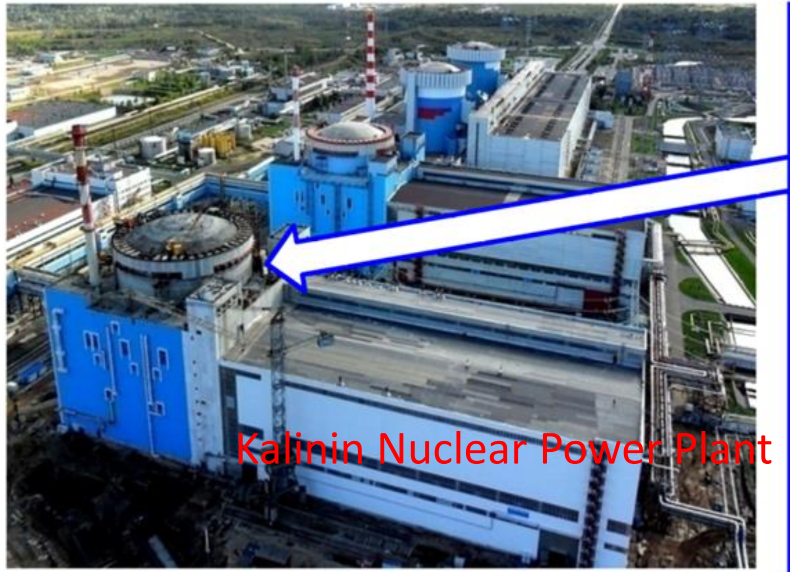


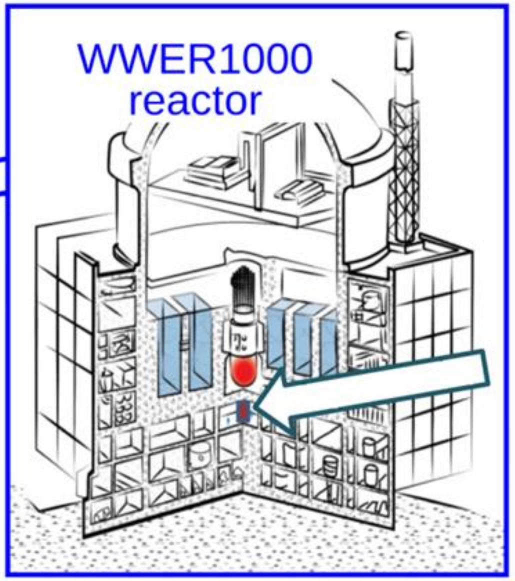
Anomalies can be described by 3+1ν model at short baseline:

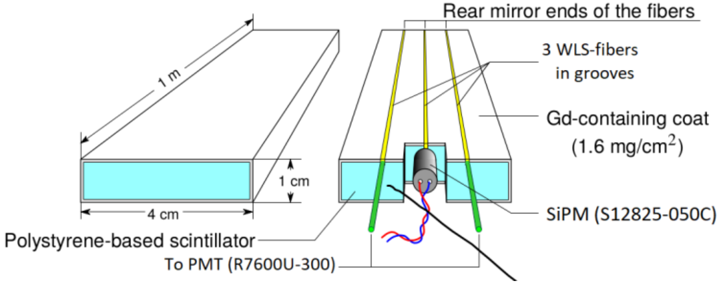
$$P_{ee} \approx 1 - sin^2(2\theta_{41}) sin^2(1.27 \frac{\Delta m^2_{41}[eV^2] L[m]}{E_{\bar{\nu}_e}[MeV]})$$

DANSS

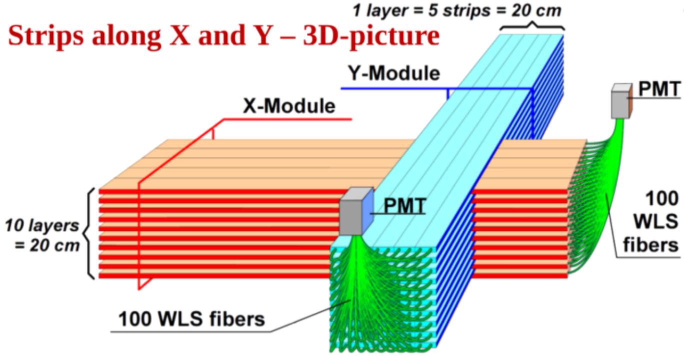
(Detector of the reactor AntiNeutrino based on Solid-state Scintillator)





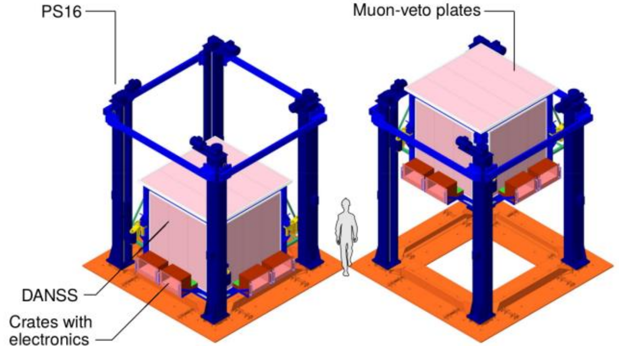


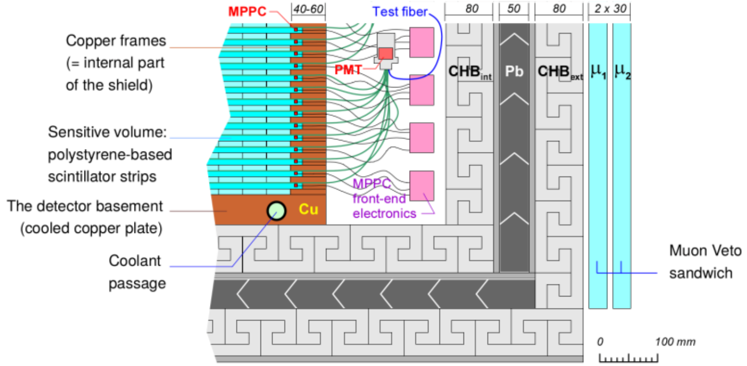
Strips along X and Y – 3D-picture



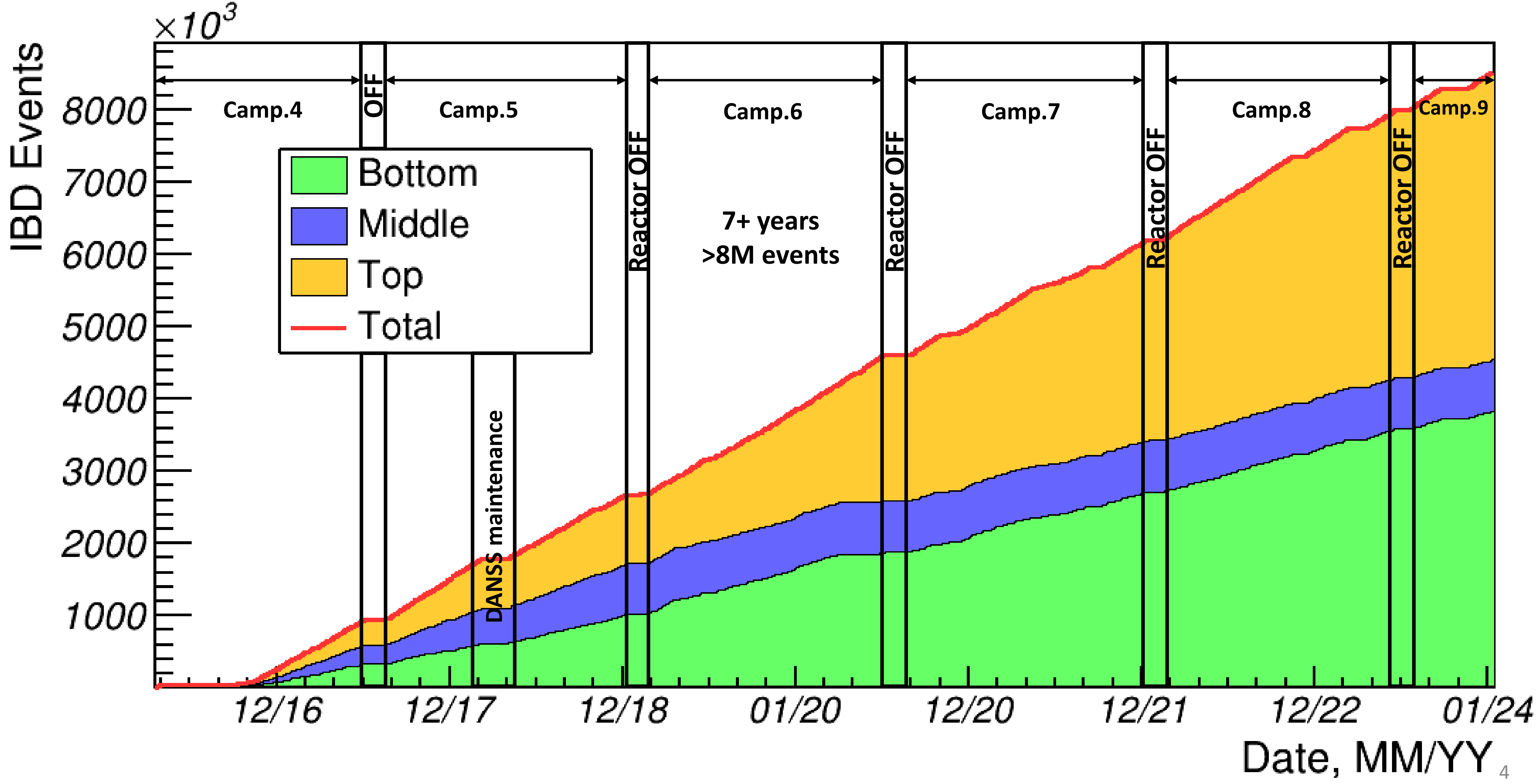
- Located below 3.1 GW_{th} commercial reactor **~$5\cdot10^{13}$ ν·cm^{-2}c^{-1}@11m**
- Reactor provide overburden **~50 m w.e.** for cosmic background suppression
- Lifting system allows to change the distance between the centers of the detector and the reactor core **from 10.9 to 12.9** m on-line
- 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 m^3** of sensitive volume
- IBD ($\bar{\nu}_e + p \rightarrow e^+ + n$) reaction is used

[JINST 11 (2016) no.11, P11011]

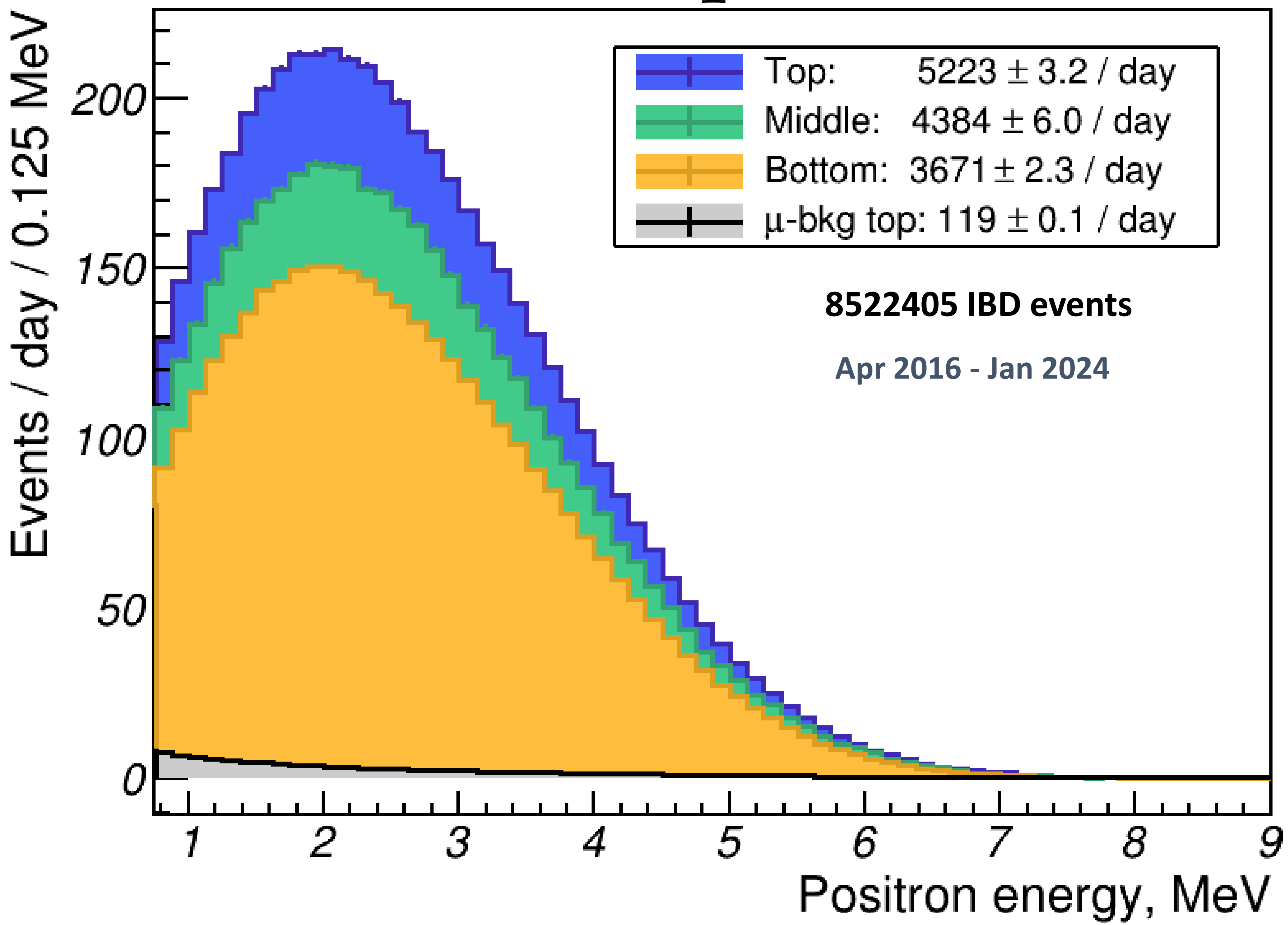




DANSS statistics accumulation

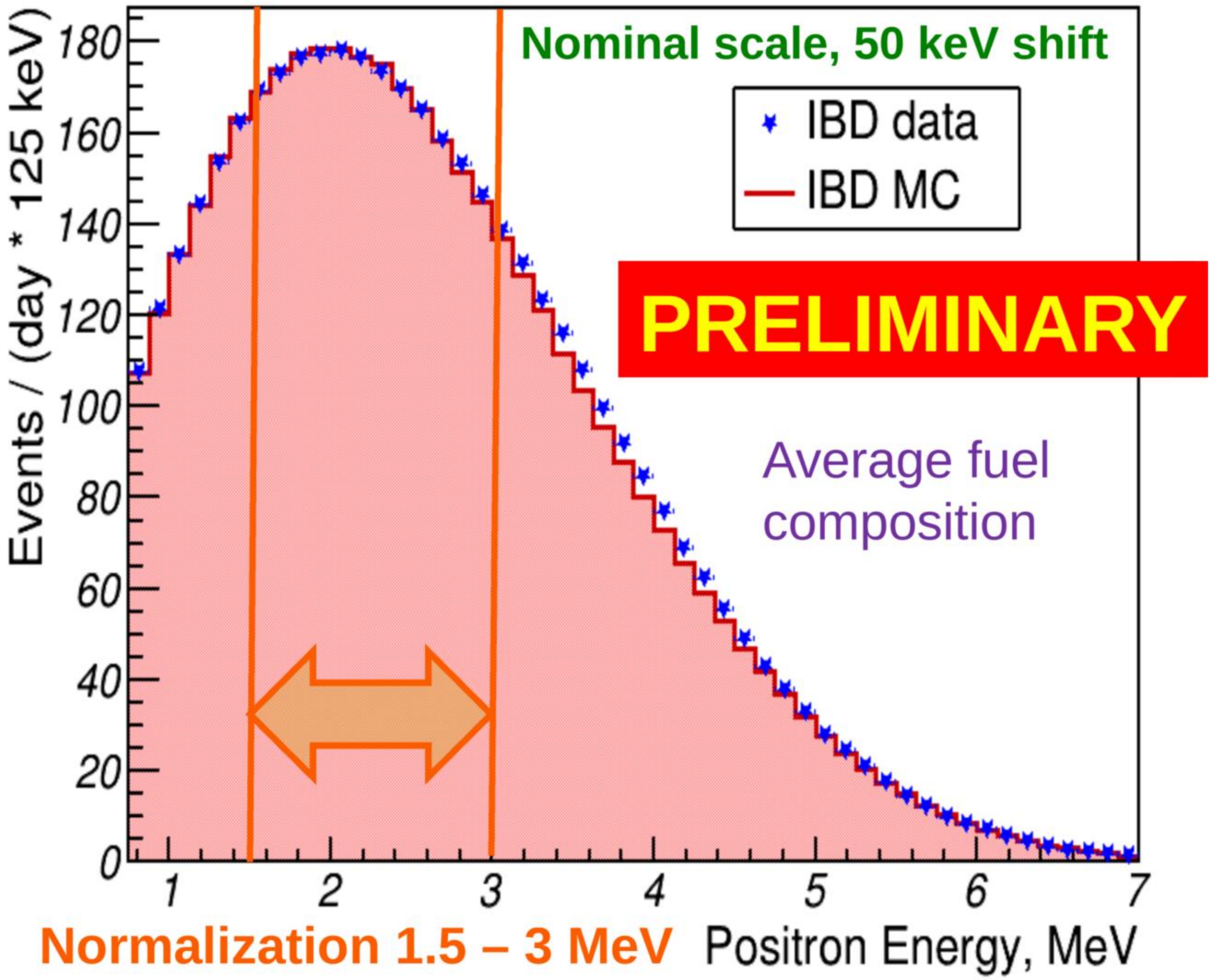


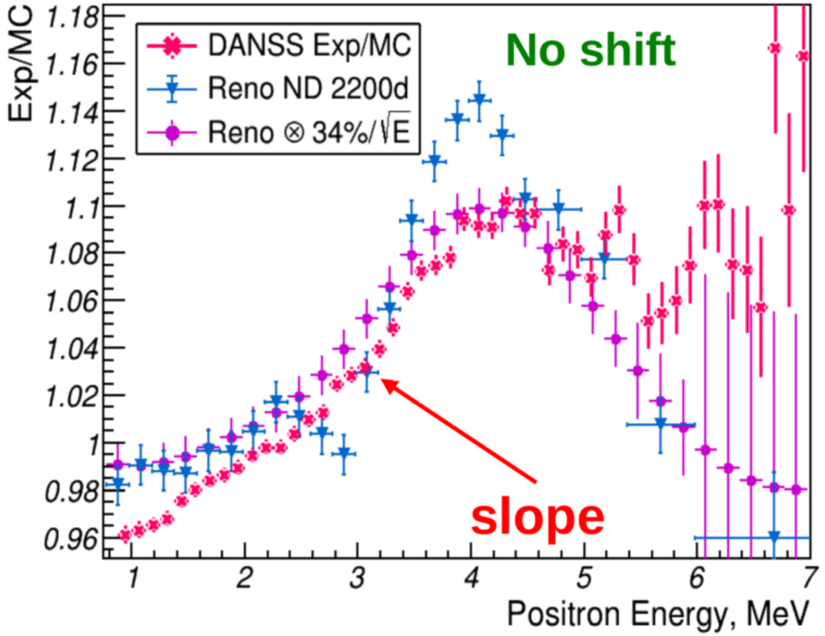
Positron spectrum of IBD-signal

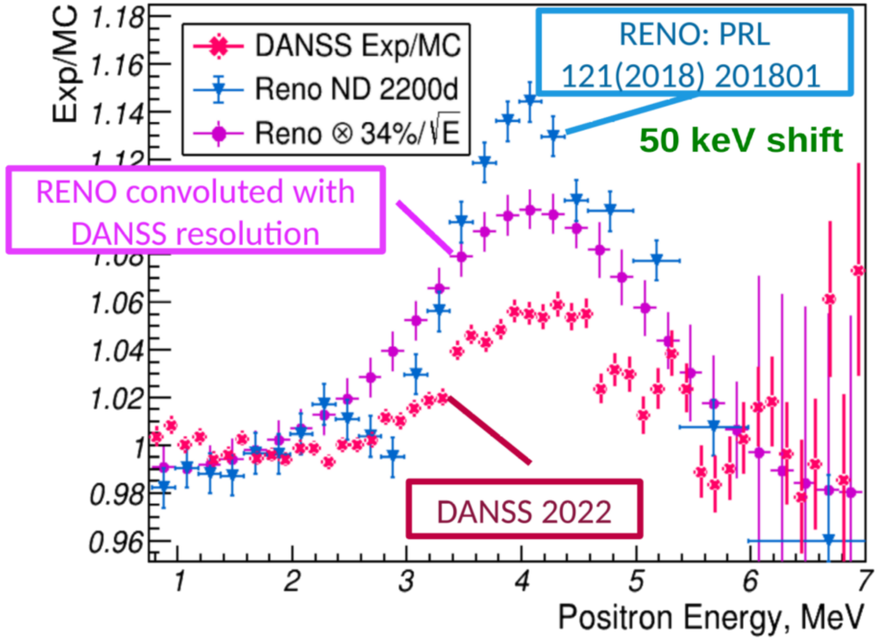


- All backgrounds subtracted
- Neighbor reactors background at 160m, 334m and 478 m subtracted(0.6% of neutrino signal at top position)
- For E_{e+}=[1.5-6] MeV background = 1.75% in top position: **S/B > 50**.

Positron spectrum vs model

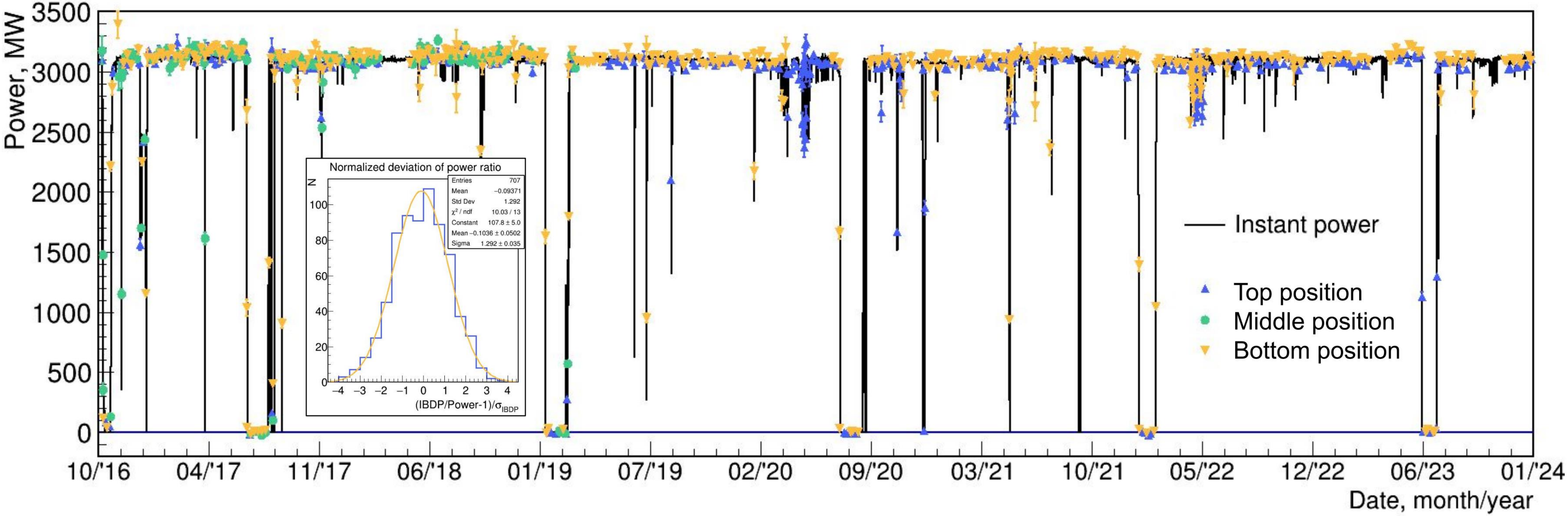






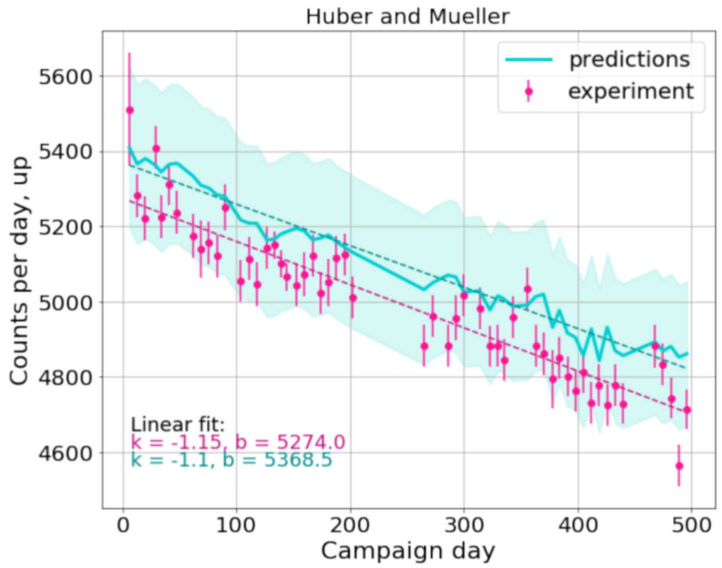
- Strong dependence on energy shift and scale
- Effect (if does exist) looks twice smaller than expected from other experiments

Power monitoring

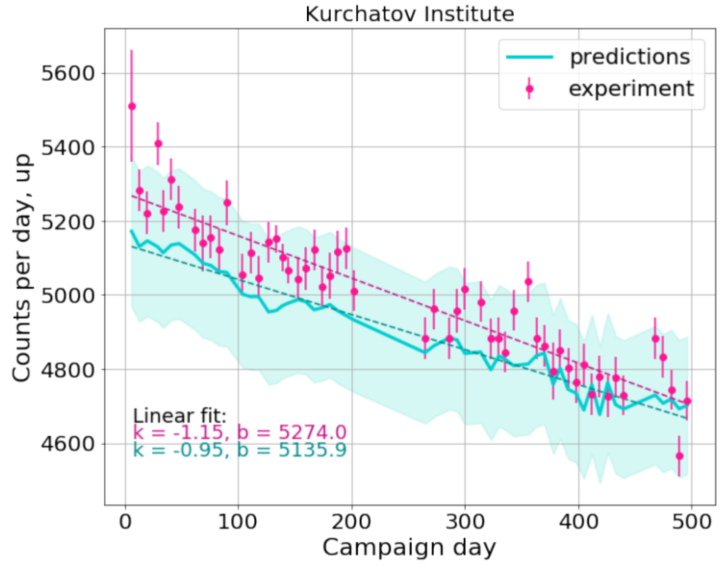


- Reactor power is measured by neutrino flux with **1.3% statistical accuracy in 3 days** for **7+ years**.
- **Relative efficiency** is even more stable **(<0.4%)** because of frequent changes of detector positions

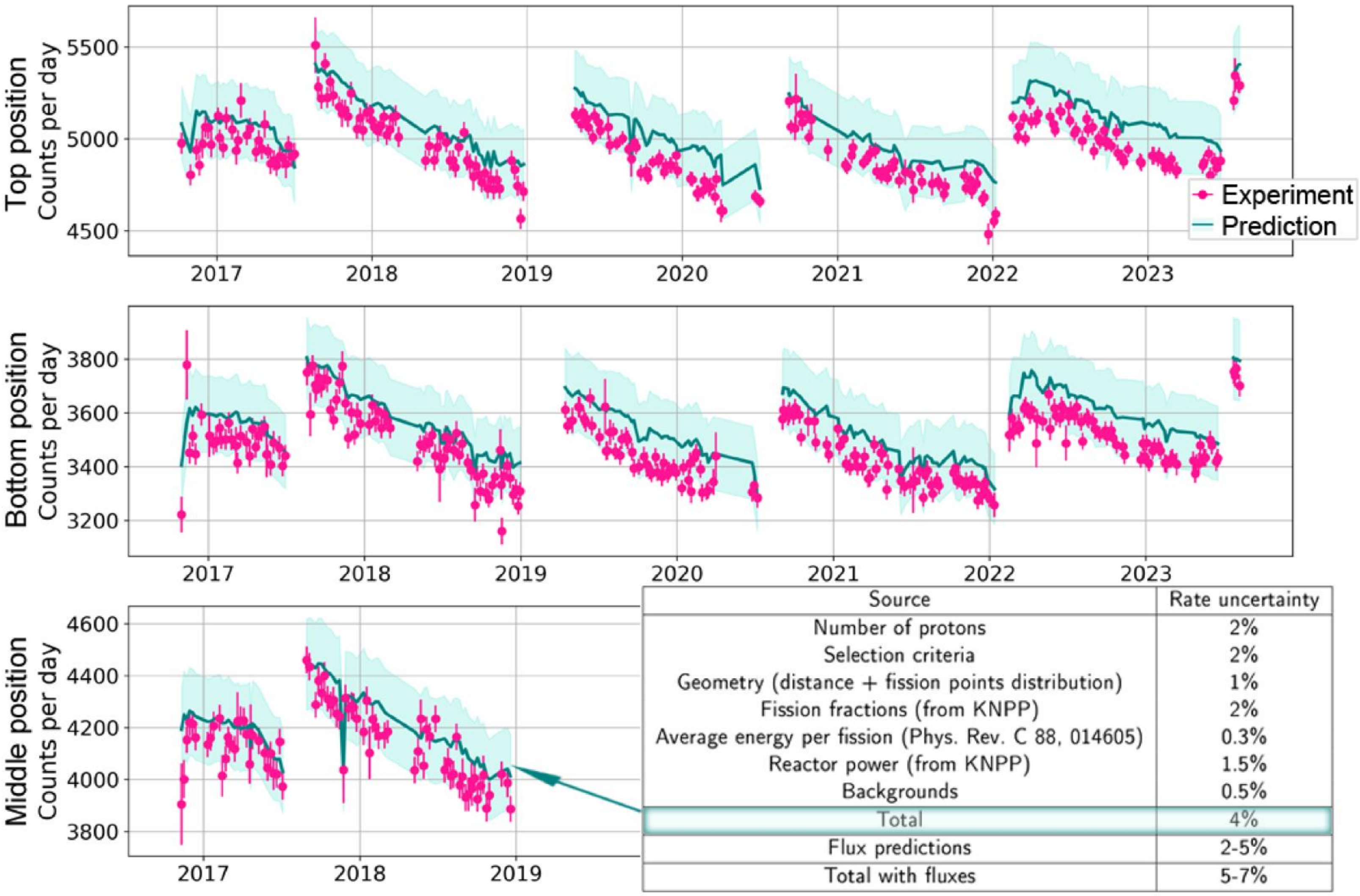
Absolute counting IBD rates



Observed to predicted ratio:
0.98±0.04 (HM model)
1.02±0.04 (KI model)



DANSS data

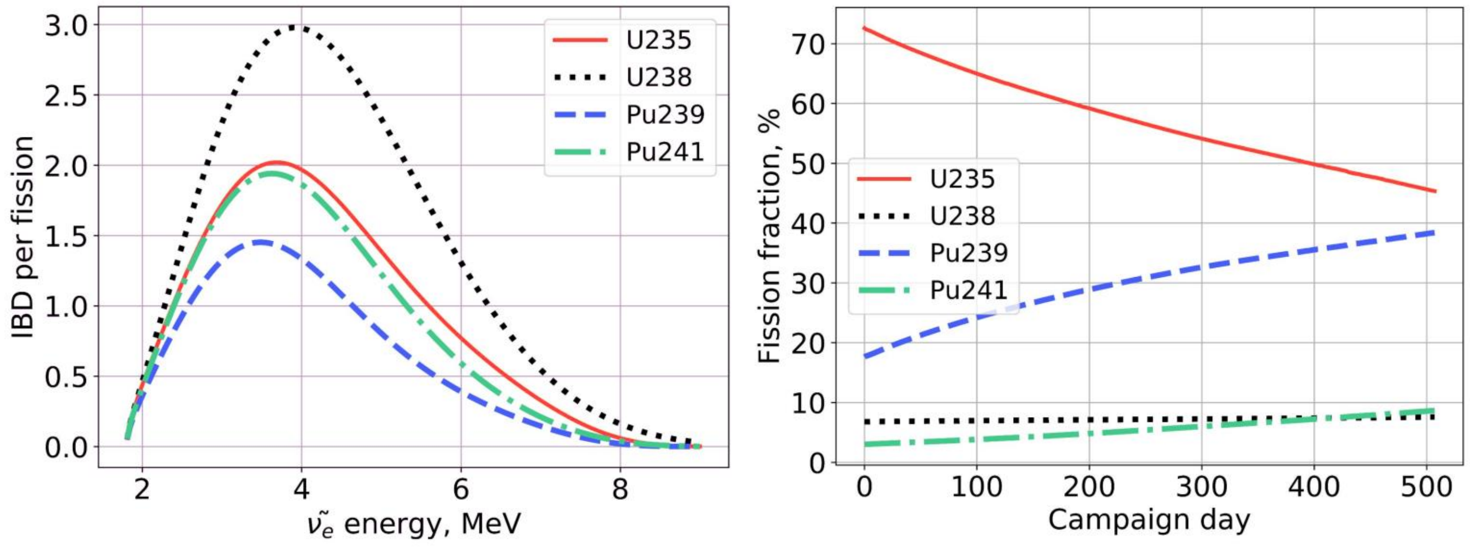


Source	Rate uncertainty
Number of protons	2%
Selection criteria	2%
Geometry (distance + fission points distribution)	1%
Fission fractions (from KNPP)	2%
Average energy per fission (Phys. Rev. C 88, 014605)	0.3%
Reactor power (from KNPP)	1.5%
Backgrounds	0.5%
Total	4%
Flux predictions	2-5%
Total with fluxes	5-7%

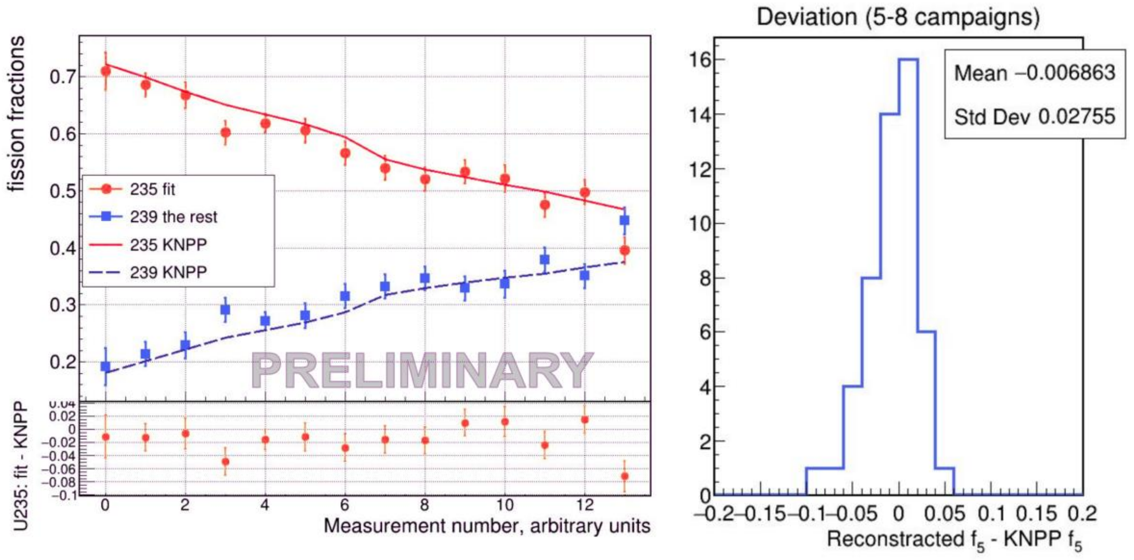
Huber and Mueller (HM) model was used

Fission fraction reconstruction

Model



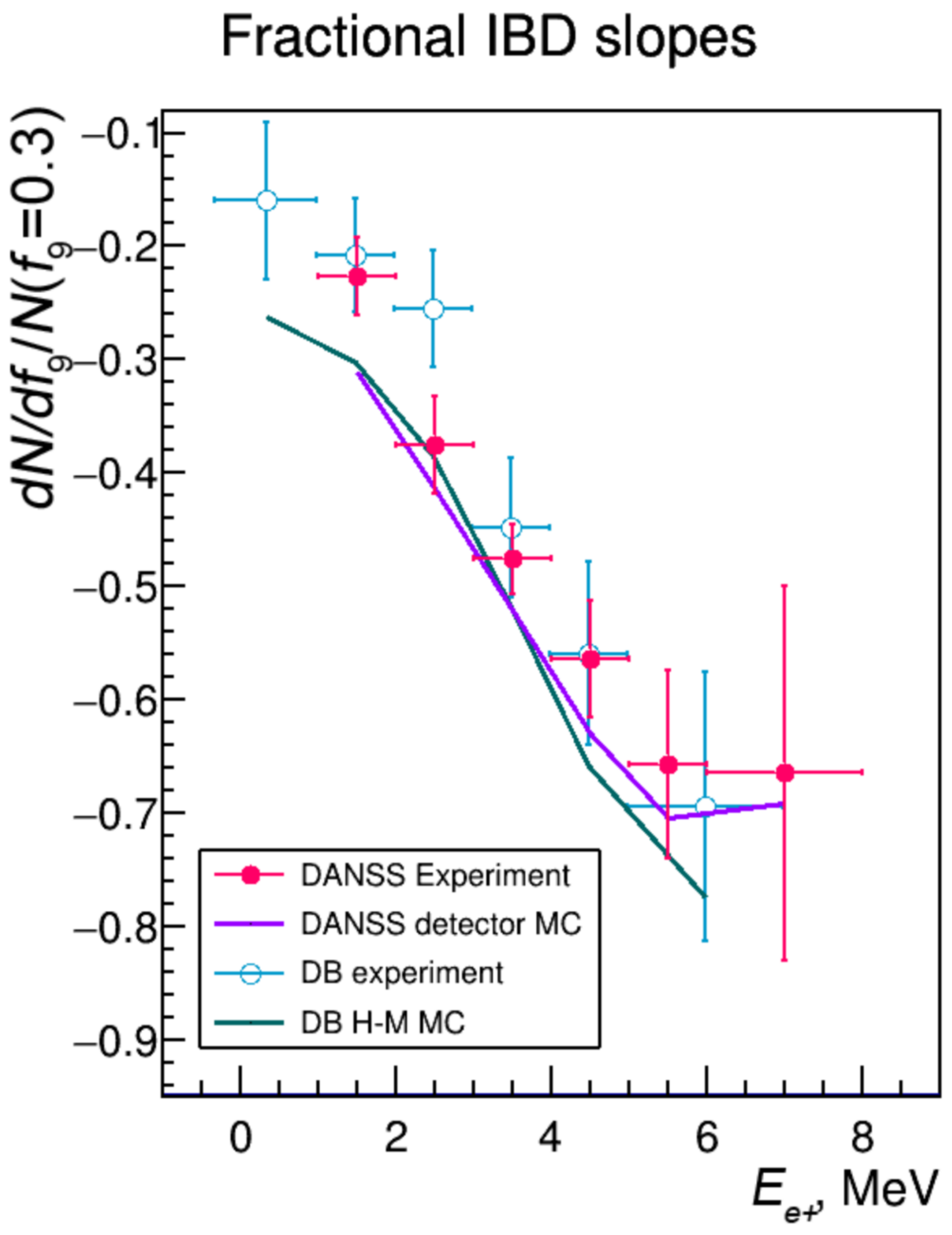
DANSS data

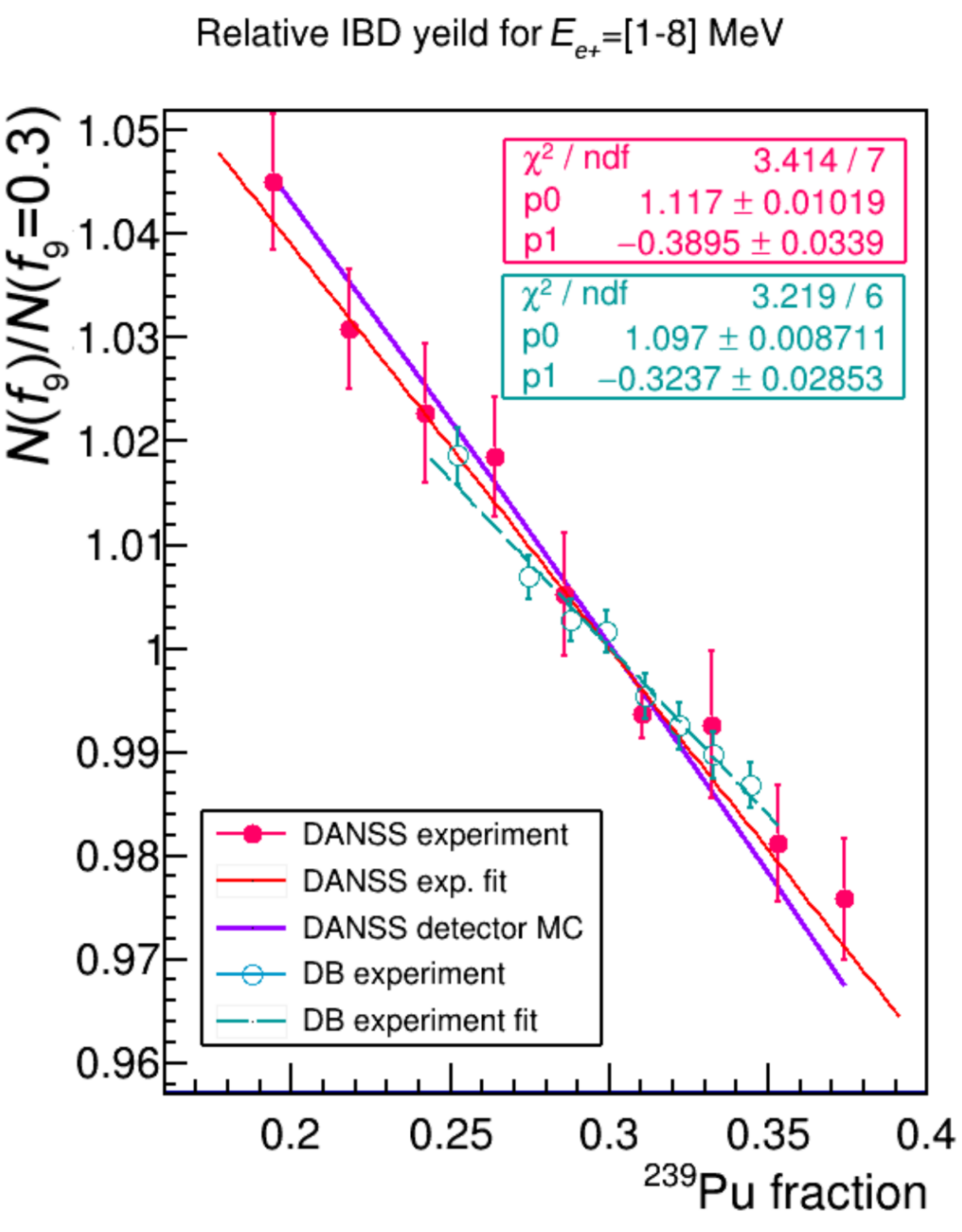


- We fit observed positron spectra using the sum of 4 isotopes (HM model)
- ^{238}U and ^{241}Pu fission fractions are fixed (from KNPP data).
- ^{235}U fission fraction is free parameter
- Each measurement corresponds to ~ 6-10 days of data taking
- (~1% stat accuracy)
- Fit range: 1-3 and 5.5 -7 MeV (excluding bump)
- Mean normalization for the whole campaign is used
- Top detector position

- Statistical errors only
- Each point is independent measurement
- Fit is consistent with the KNPP data
- Reactor 4 power and fission points distribution profile are not taken into account
- Correction for dead time, efficiency, neighbor reactors power (individually)
- **Difference in ^{235}U fraction between KNPP and DANSS is ~3%**

Spectrum dependence on fuel composition





IBD rate dependence on ^{239}Pu fission fraction $(dN/df_9)/N(f_9=0.3)$ for various E_{e+} agrees with HM model and a bit more steep than at Daya Bay

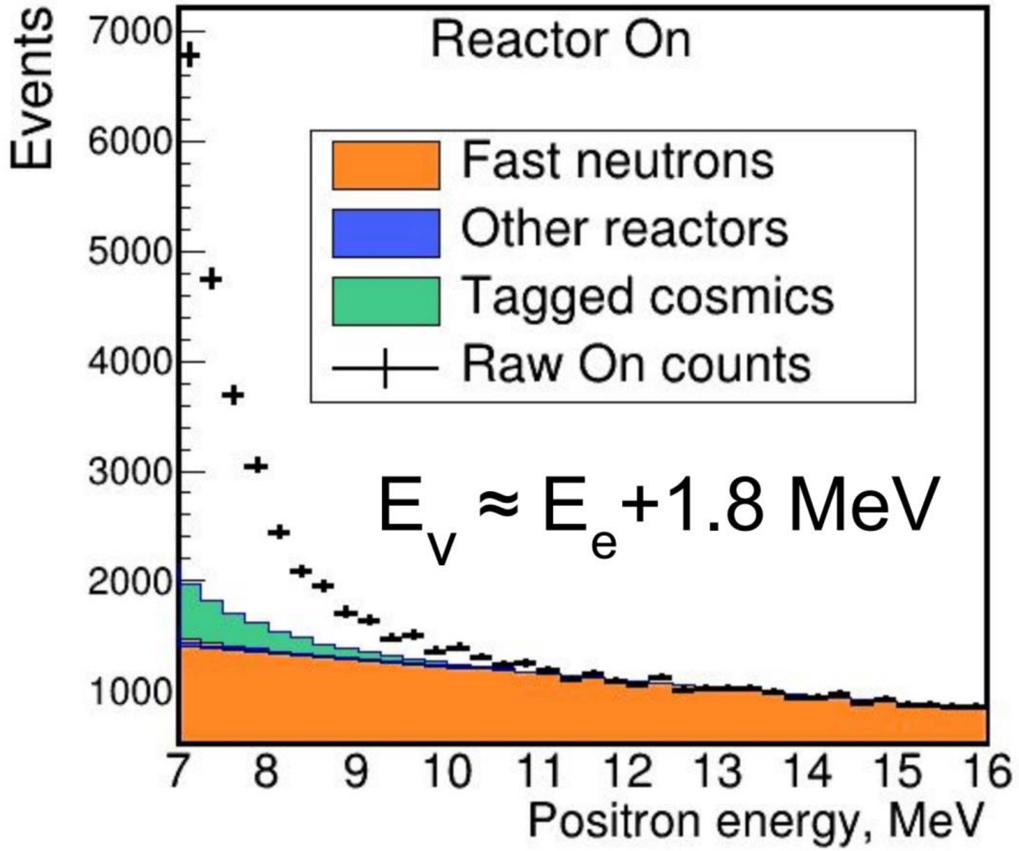
DANSS result $\sigma_5/\sigma_9 = 1.54 \pm 0.06$ is larger than Day Bay (1.445 ± 0.097) and agrees with HM (1.53 ± 0.05).

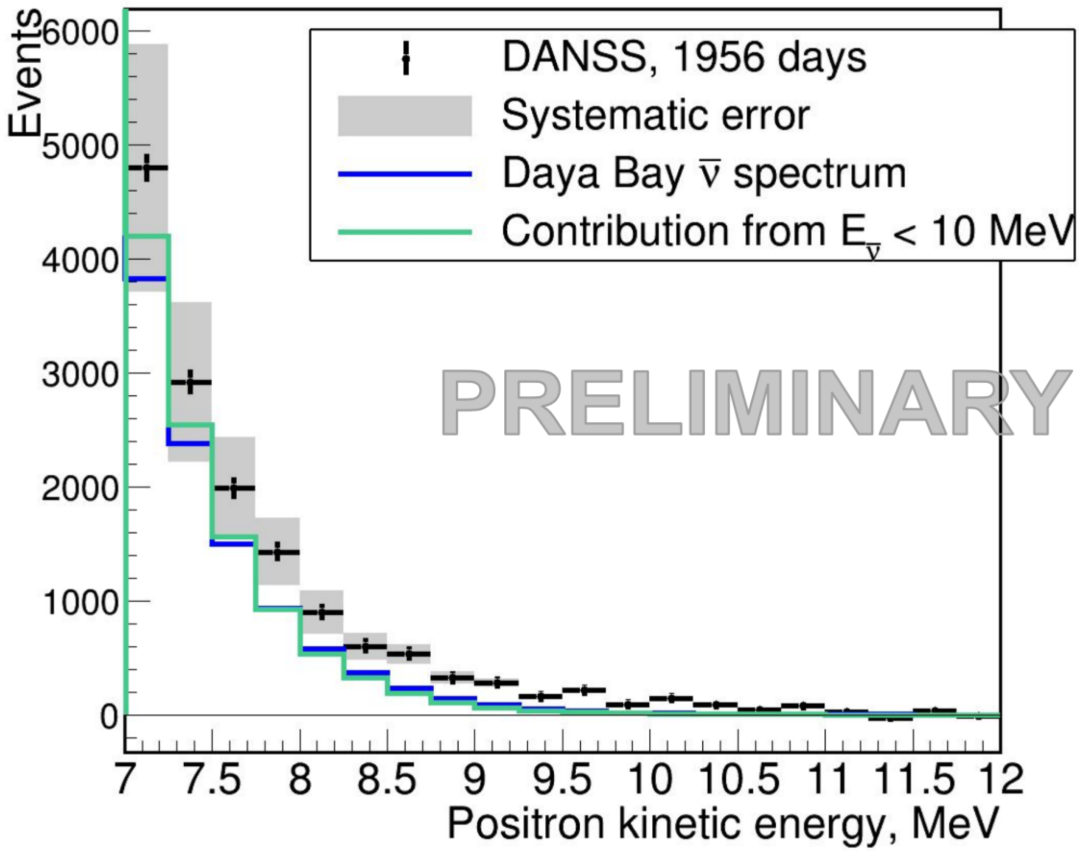
Use of DB-Slope in our formula gives: $\sigma_5/\sigma_9 = 1.459 \pm 0.052$

Difference between DANSS and DB is due to slope

High-energy reactor antineutrinos

Motivation: CEvNS experiments needs a information about high-energy part of antineutrino spectra.

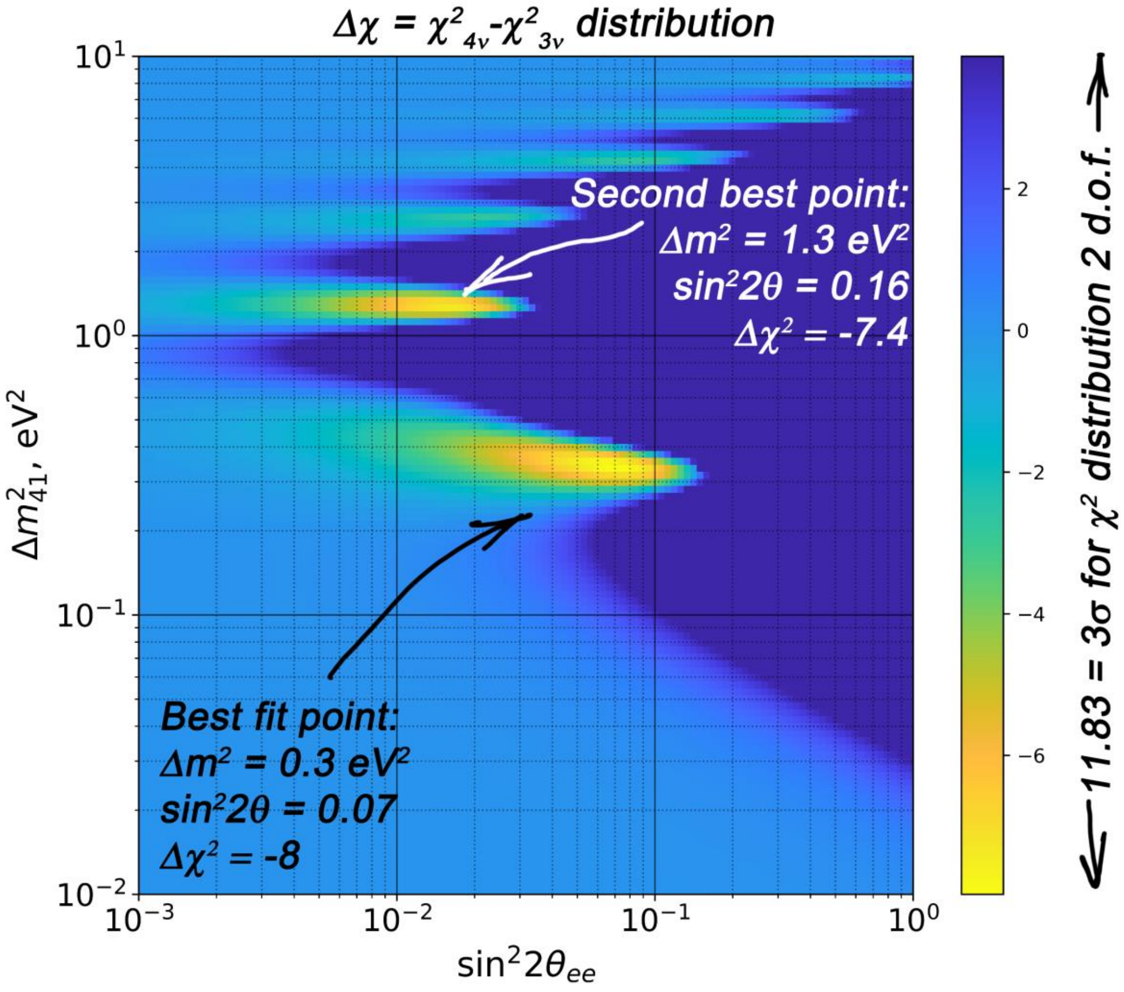


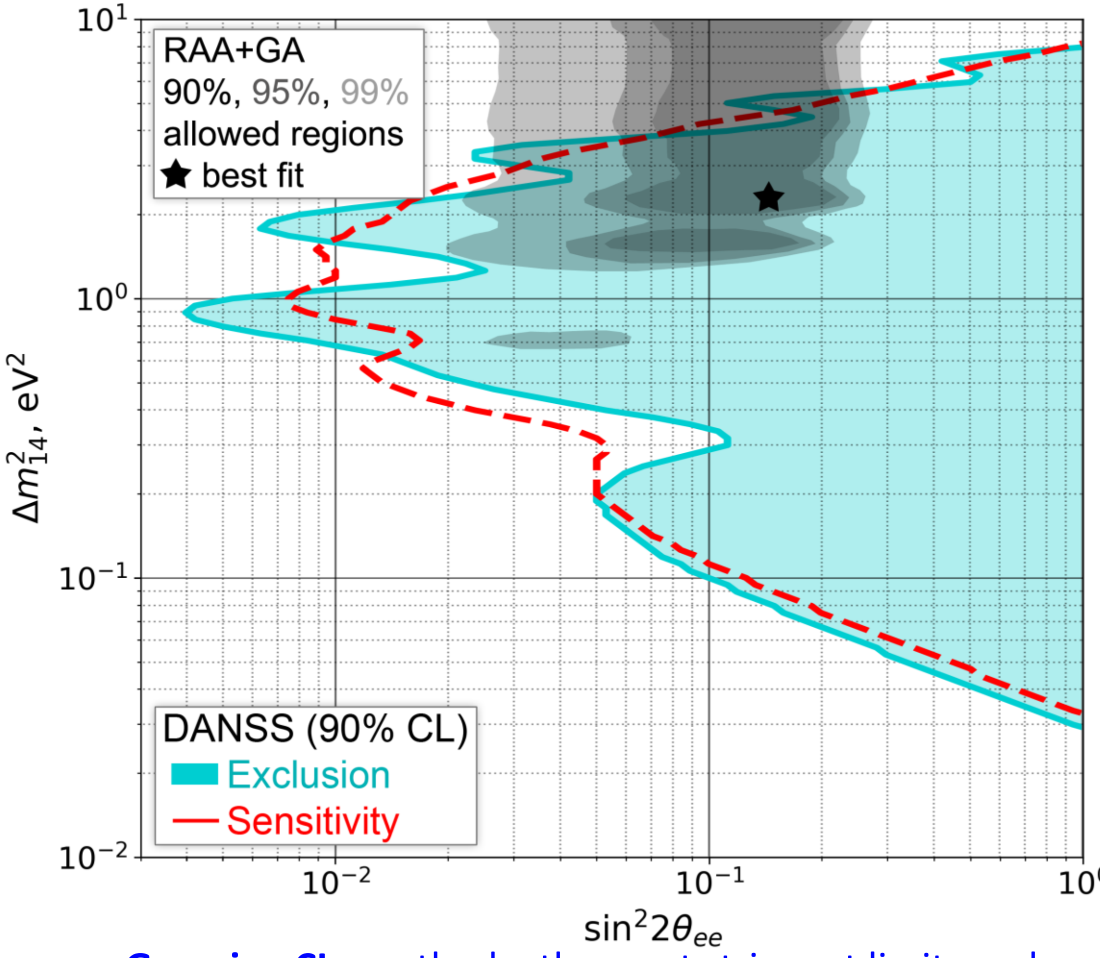


- Background subtraction is based on 5 "reactor off" periods
- DANSS observes $\bar{\nu}_e$ events with energy > 10 MeV: **1561 ± 157$_{stat}$ ± 168$_{sys}$ ev. (6.8σ)**
- Fraction of high energy $\bar{\nu}_e$ events is somewhat larger than at Daya Bay **[PhysRevLett.129.04180]**

DANSS limits on sterile neutrino parameters

obtained in model independent way (without $\overline{\nu}_e$ spectrum information)



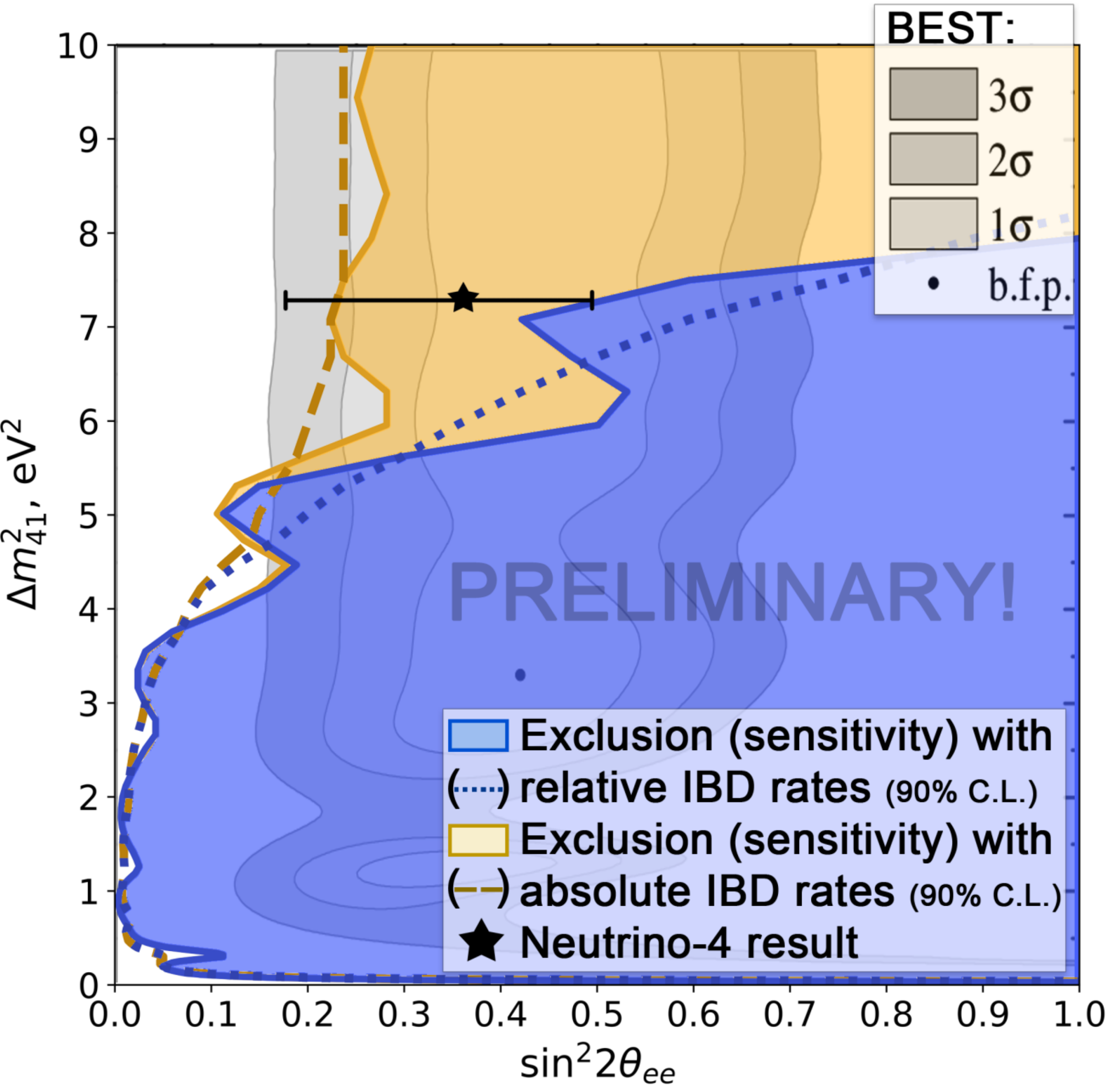


- **6M** IBD events in the E_{e+} range 1.5-7 MeV
- The **best fit point** is **not significant** enough to claim indication of 4ν: **$\Delta\chi^2$=-8.0 (2.0σ)** for 4ν hypothesis **best point Δm^2=0.3 eV², $\sin^2 2\theta$=0.07**
  Second best fit point: Δm^2=1.3 eV², $\sin^2 2\Theta$=0.016, $\Delta\chi^2$= -7.4

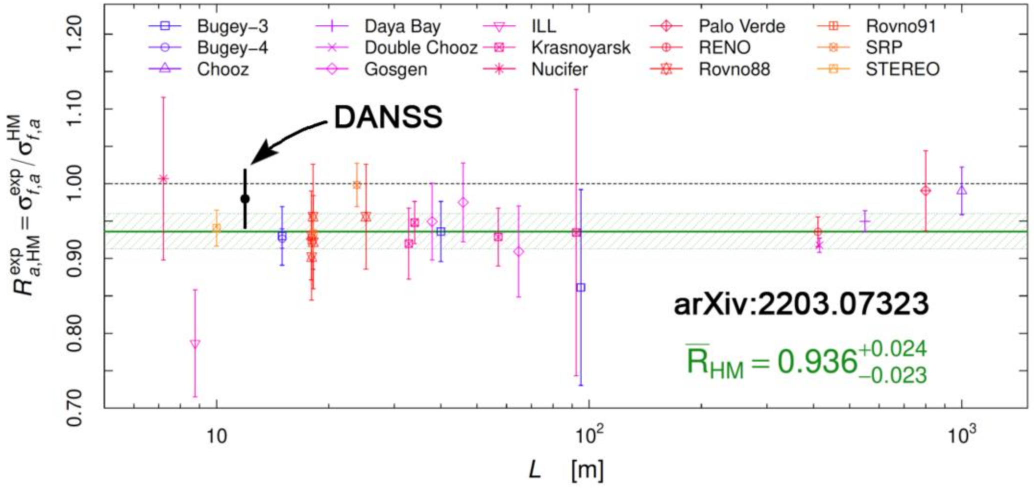
- **Gaussian CLs** method – the most stringent limit reaches $\sin^2 2\Theta < 5 \cdot 10^{-3}$ level
- A very interesting region of 4ν parameters space excluded
- RRA+GA best point is deep in the exclusion region. 5σ exclusion already in 2018 [PLB 787 (2018) 56]

DANSS limits on sterile neutrino parameters

(absolute IBD rates analysis)



- 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 $\bar{\nu}_e$ counting rates
- 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 [Phys.Rev.Lett.128,232501] as well as best fit point of Neutrino-4 experiment [Phys. Rev. D 104, 032003]. In KI model exclusions are even more strict.
- **These results depend on the predictions of the $\bar{\nu}_e$ flux from reactors, for which we assumed a conservative uncertainty of 7%**

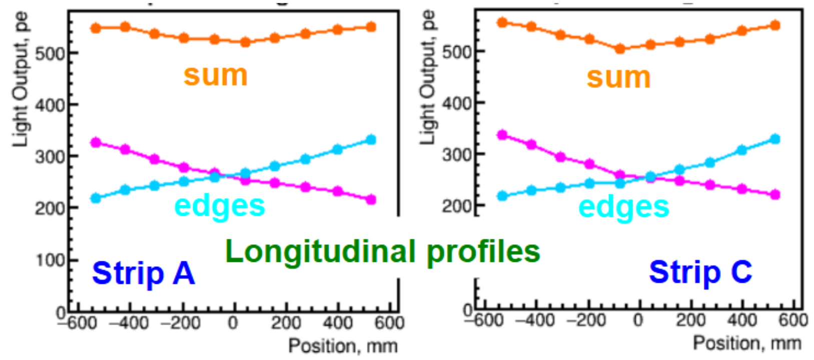


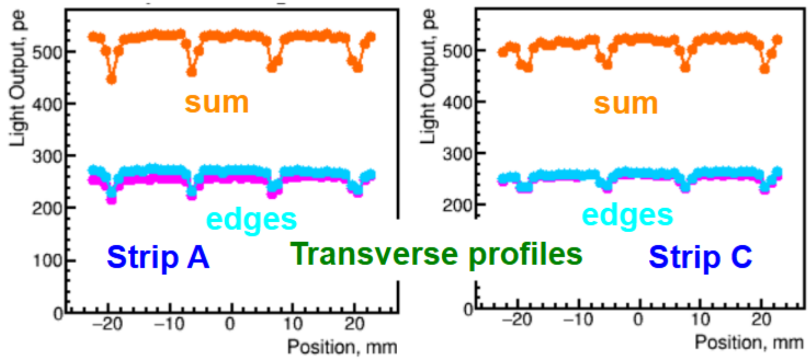
DANSS upgrade

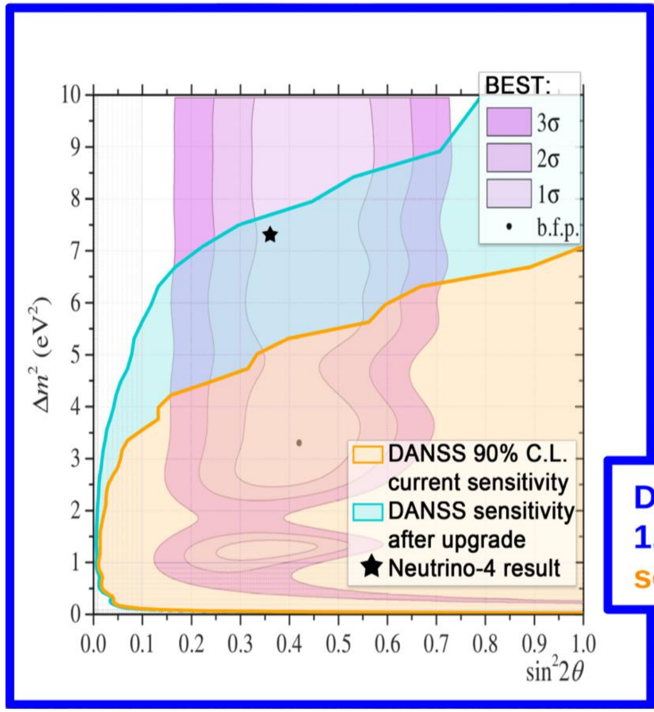
- Main goal of the upgrade sis to **improve energy resolution**:

$$34\%/\sqrt{E} \rightarrow 12\%/\sqrt{E}$$

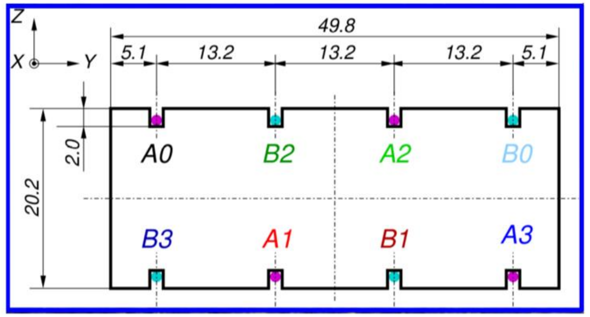
- **New scintillation strips**: 20x50x1200mm^3
- 60 layers x 24 strips – **1.7 times larger fiducial volume**
- No PMT – SiPM readout from both sides
- 8 grooves with WLS, 8(16 – in development) SiPM per strip get high light yield and uniformity
- TOF to get longitudinal coordinate in each strip. Faster (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.







Strip cross section



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 **8M 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 1.3% precision in three days** during **7+ years** of operation.
- Obtained **accuracy** in **^{235}U fission fraction reconstruction** is **~3%**
- DANSS observes $\overline{\nu}_e$ **events with $\overline{\nu}_e$ energy > 10 MeV (6.8σ)**
- **6M IBD events are included in χ^2 calculation for the model independent sterile neutrino search (E_{e+}=1.5-7 MeV)**. Only ratio of positron spectra at different distances used. No dependence on ν spectra and the detector absolute efficiency.
- Resent 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**]
- The full data set has two close best points:

  Δm^2=0.3 eV^2, $\sin^2 2\Theta$=0.07: $\Delta\chi^2$= -8.0 (2.0σ)

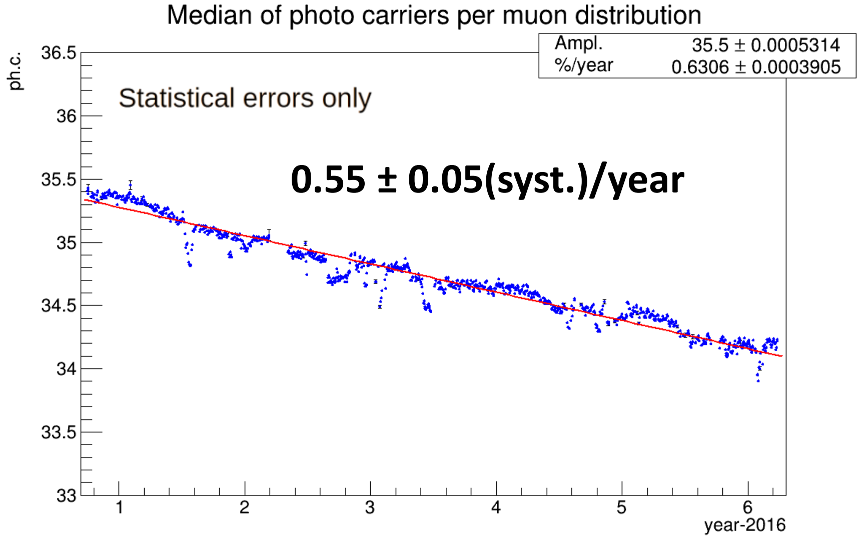
  Δm^2=1.3 eV^2, $\sin^2 2\Theta$=0.016: $\Delta\chi^2$= -7.4

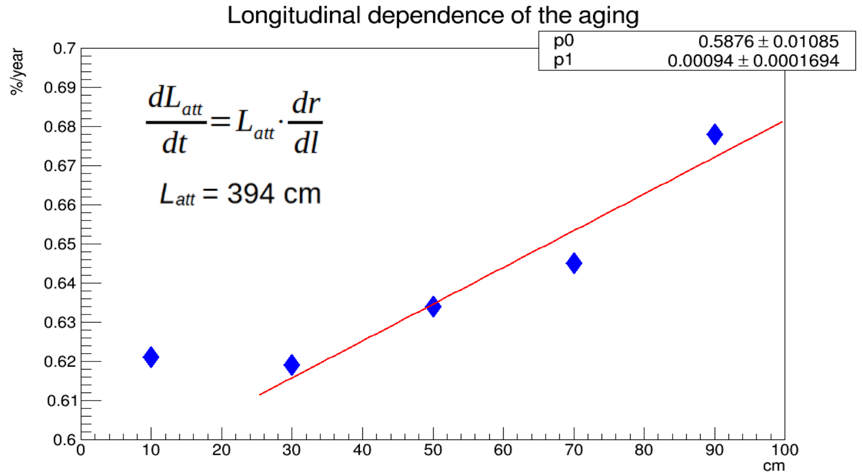
  This hint is **not statistically significant** (2.0 σ) to claim even the indication of sterile neutrino
- **Oscillation analysis with absolute counting rates** (HM model) excludes practically all sterile parameter space preferred by BEST and the best fit point of Neutrino-4 experiment at 90% CL. These results depend on the predictions of the $\overline{\nu}_e$ flux from reactors, for which we assumed a conservative uncertainty of 5%.
- DANSS upgrade is planned in 2025 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

Aging of DANSS scintillator

- **T2K** (several detectors) — **0.9-2.2 %/year**; **MINOS — 2 %/year**; **MINERvA — 7-10 %/year @ 80F(**27.6^{oC})
- DANSS – 7 years of continuous operation.
- The experimental hall is air conditioned and very dry.
- A chilled water cooling system is used for electronics inside the passive shielding, providing a stable temperature for the central part of the detector.
- Scintillator strips extruded from polystyrene by Institute of Scintillating Materials, Kharkiv, Ukraine.
- The surface is covered by ~0.2 mm co-extruded layer with admixture of TiO_2 and Gd_2O_3 which serves as a diffuse reflector. Gadolinium is used to capture neutrons from the inverse beta-decay after their moderation.
- Light collection by 3 wave length shifting fibers **KURARAY Y-11(200)M**
- Central fiber is read by **SiPM HAMAMATSU S12825-050C**. Two side fibers are read by PMT. The other ends of the fibers are polished and covered by reflective paint.
- Only SiPM data is used in the analysis. SiPM bias voltages were set once at the very beginning and never changed.
- Close to vertical muon tracks with tgϑ < 0.2 selected.
- Median value of Landau distribution.

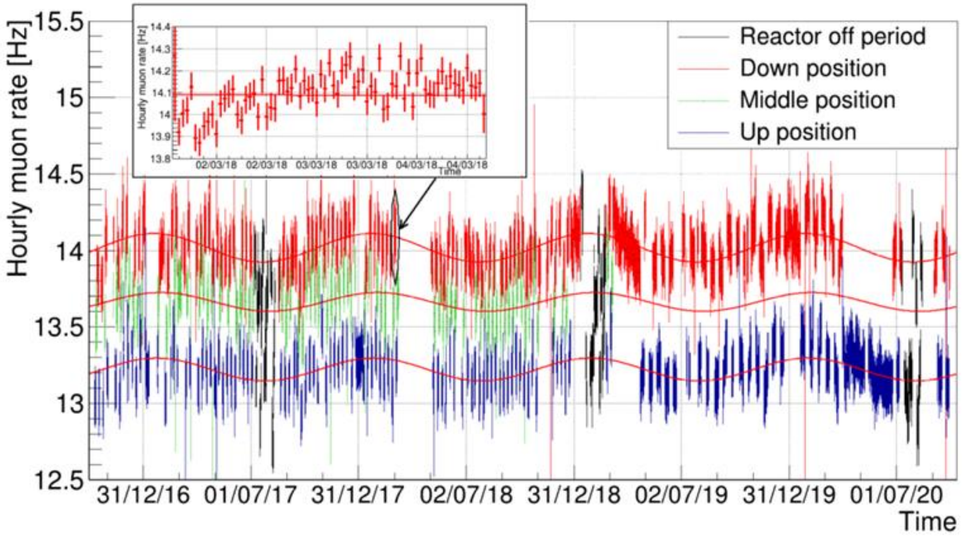


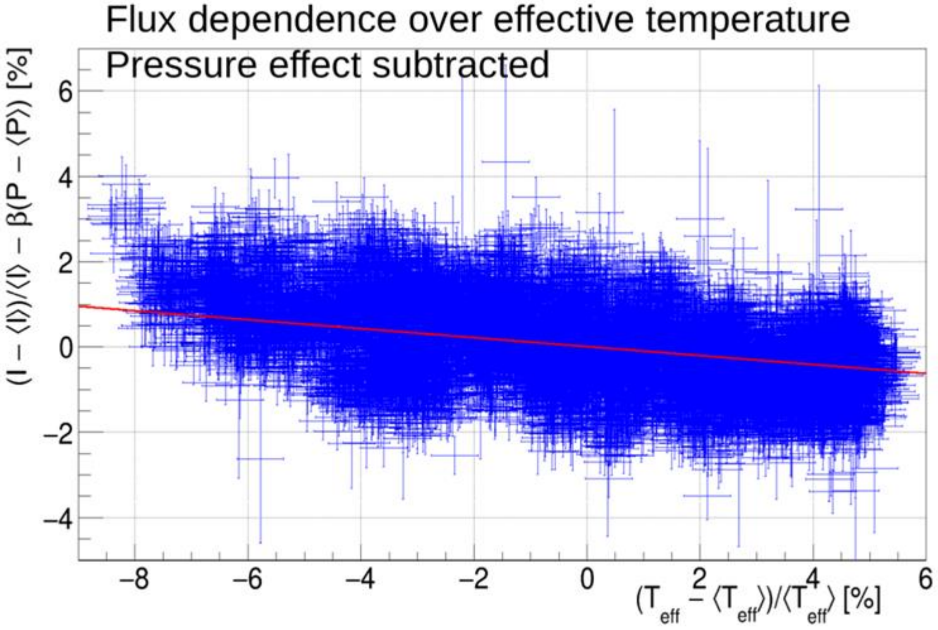


We can not separate aging of the scintillator and of the conversion efficiency of the WLS fiber. But we observe a hint of some decrease in its attenuation length. The increase of aging effect with the distance from SiPM gives an estimation of WLS attenuation length shortening $-dL_{att}/dt$ = **0.26 ± 0.04**(stat.) %/year

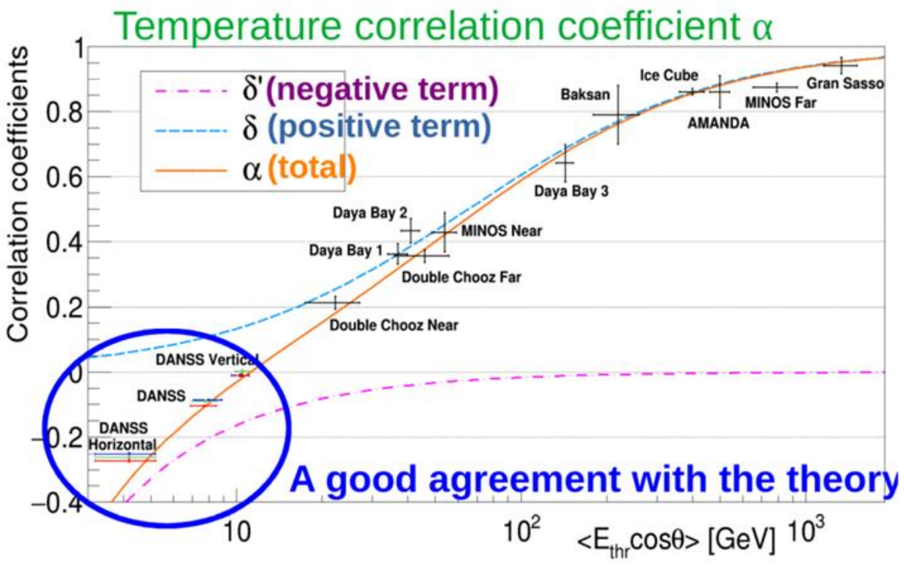
Meteorological effects on cosmic muon flux

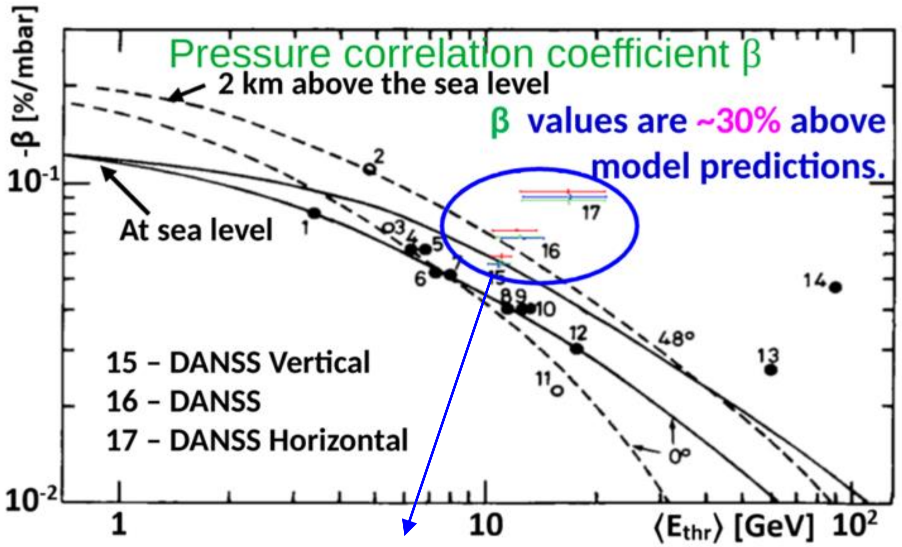
[European Physical Journal C, 2022, 82(6), 515]





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



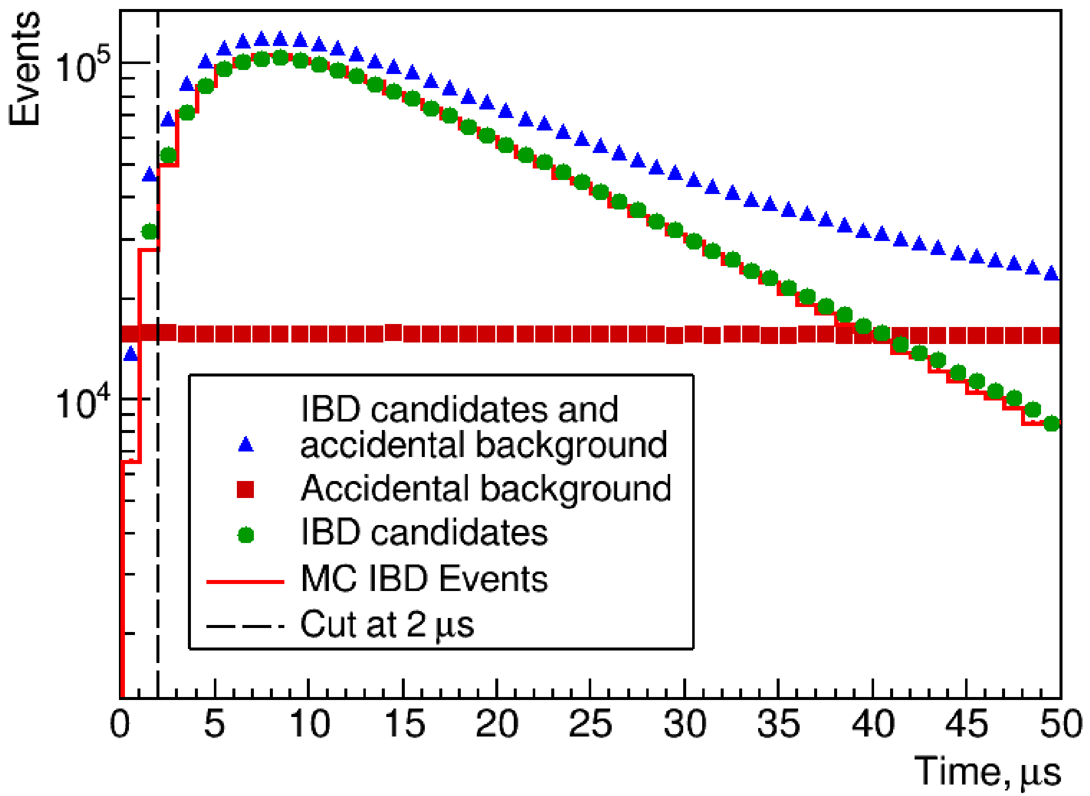


Possible explanation:

J. Dutt and T. Thambyahpillai [Journal of Atmospheric and Terrestrial Physics, vol. 27, no. 3, pp. 349–358 (1965)]

Trigger and events

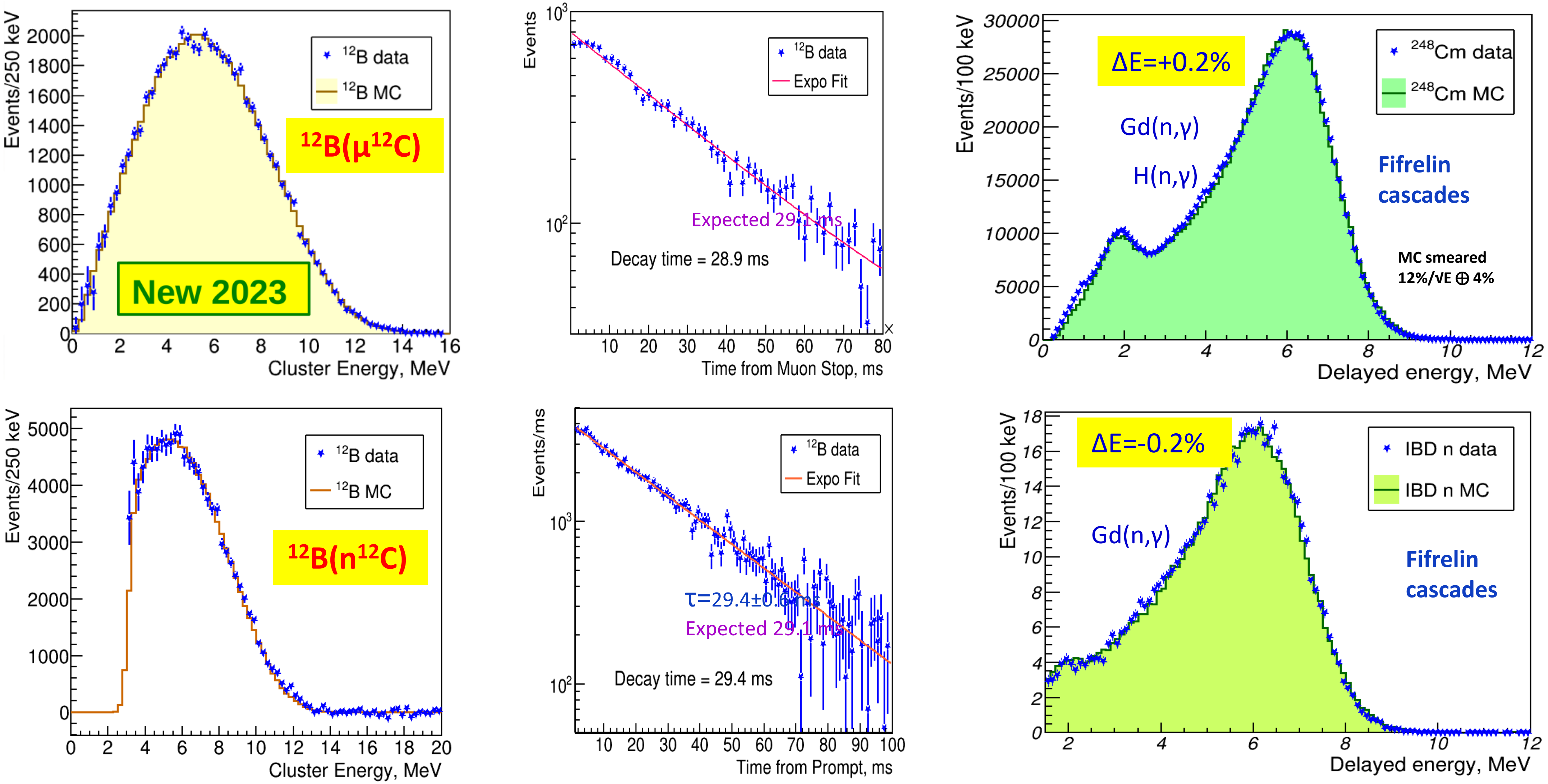
- **Trigger** = digital sum of **PMT > 0.5 MeV** or VETO
  - Total trigger rate ≈ **1 kHz**
  - Veto rate ≈ **400 Hz**
  - True muon rate ≈ **180 Hz**
  - Positron candidate rate ≈ **170 Hz**
  - Neutron candidate rate ≈ **30 Hz**
  - IBD rate ~ **0.1 Hz**
- **IBD event** = two time separated triggers:
  - 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 µs backwards** from **neutron**

Significant background by uncorrelated triggers. Subtract accidental background events: search for a positron candidate where it can not be present **– 50 µs 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

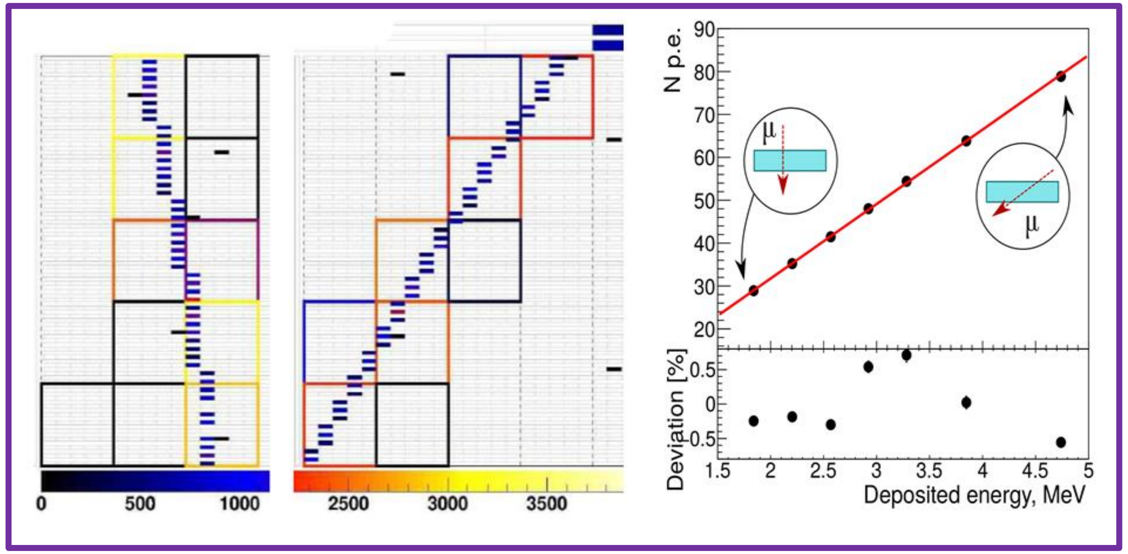
Calibration

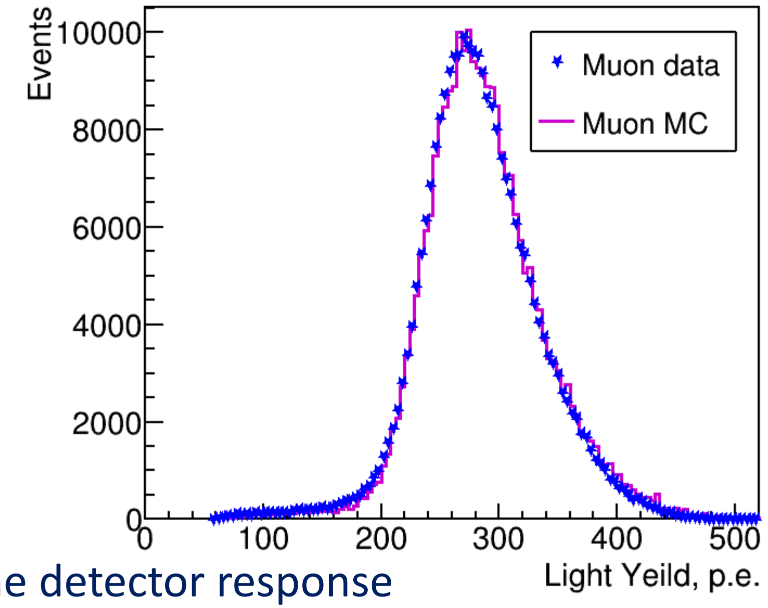


- Energy scale has been fixed **using β-spectrum of ^{12}B**, which is similar to positron signal
- Other sources agree within +/- 0.2% with exception of ^{22}Na which is 1.8% below.
- Systematic error on E scale of +/-2% was added due to ^{22}Na disagreement
  Hope to reduce this error soon

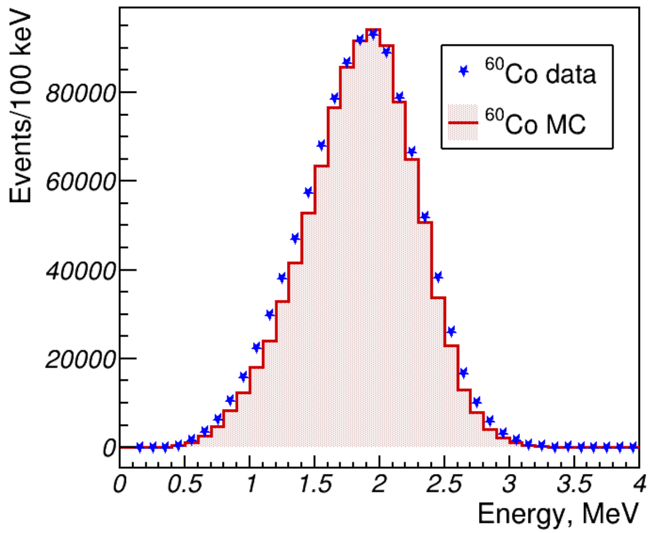
Calibration

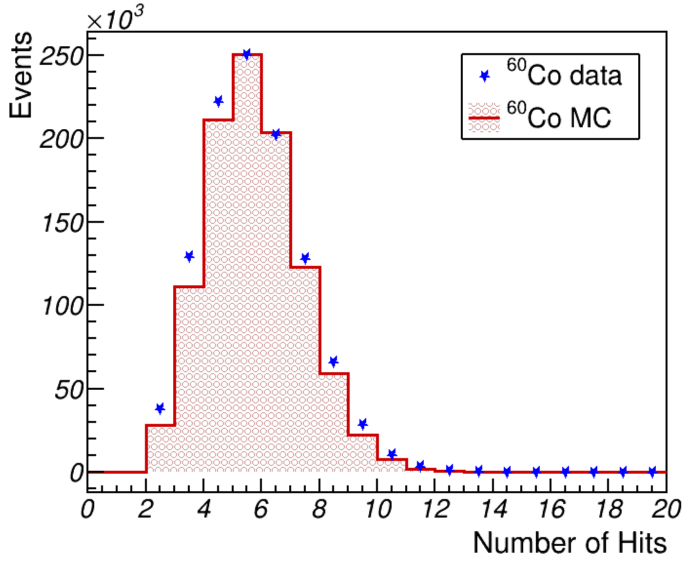
2500 SiPM gains and X-talks are calibrated **every 30-40 min**.
All **2550 channel**s are calibrated **every 1-2 days** using cosmic muons

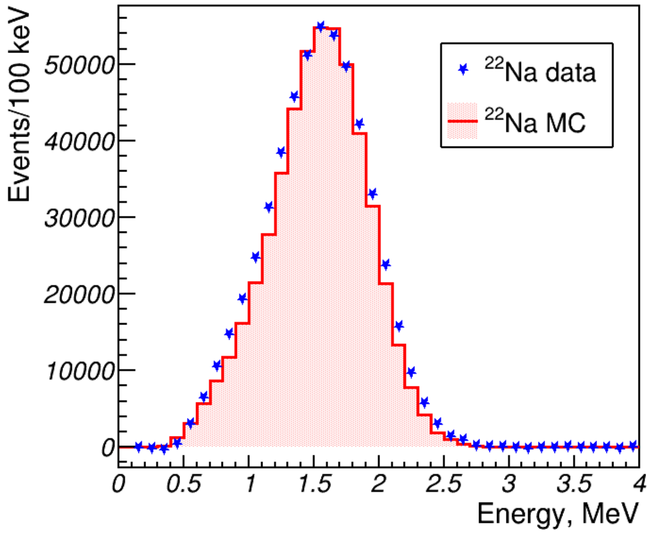




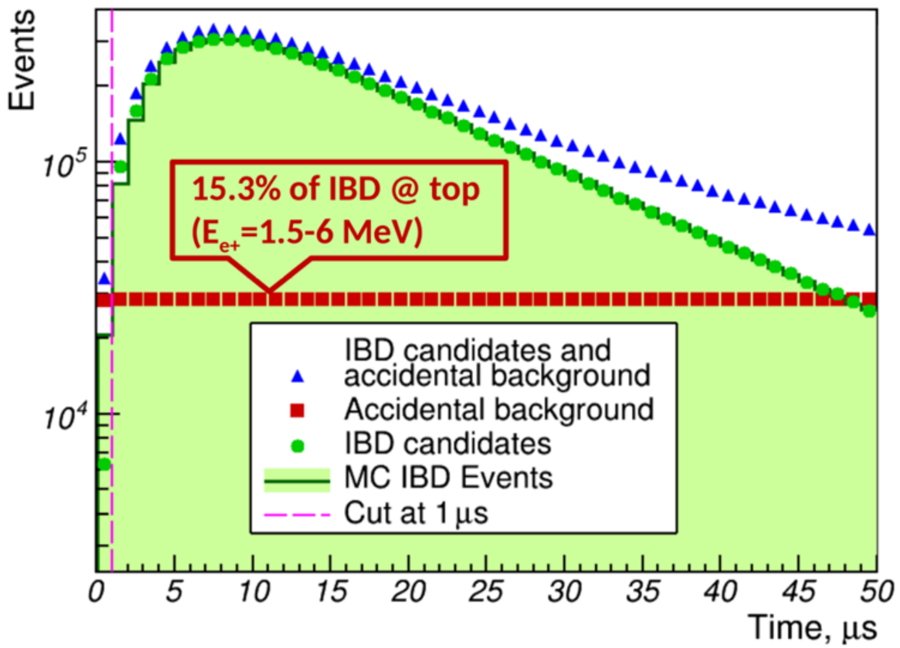
Several calibration sources are used to check the detector response



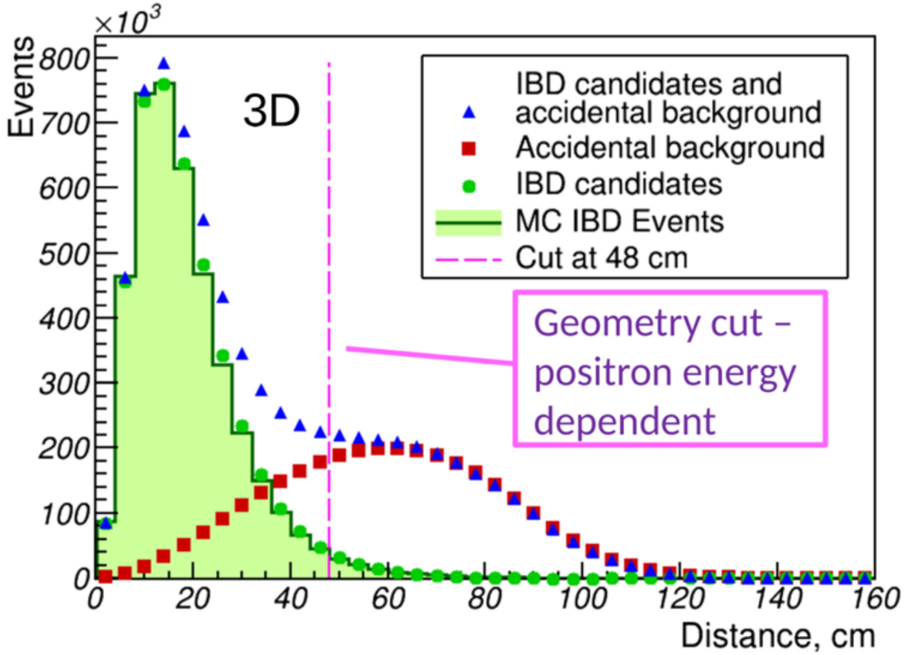




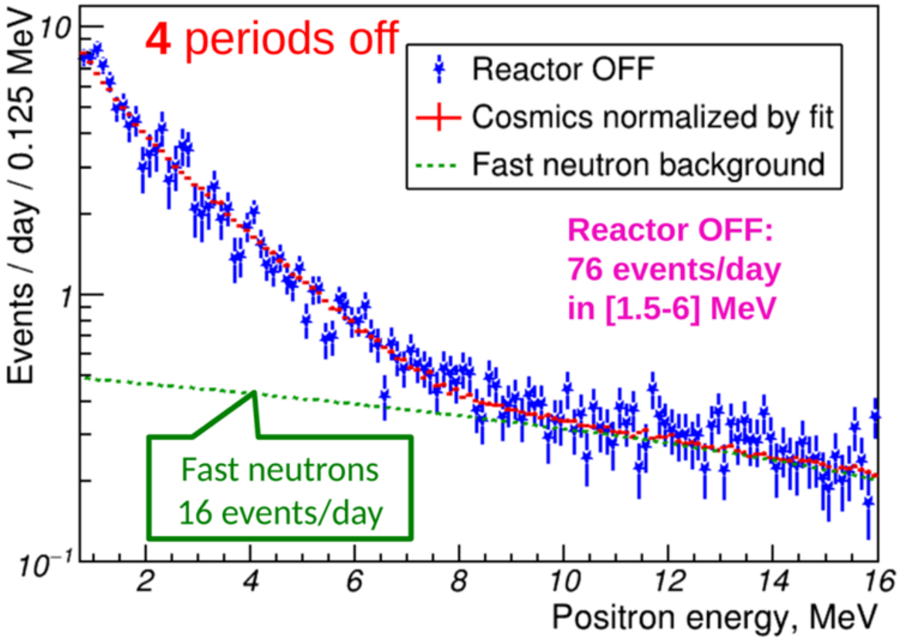
Background



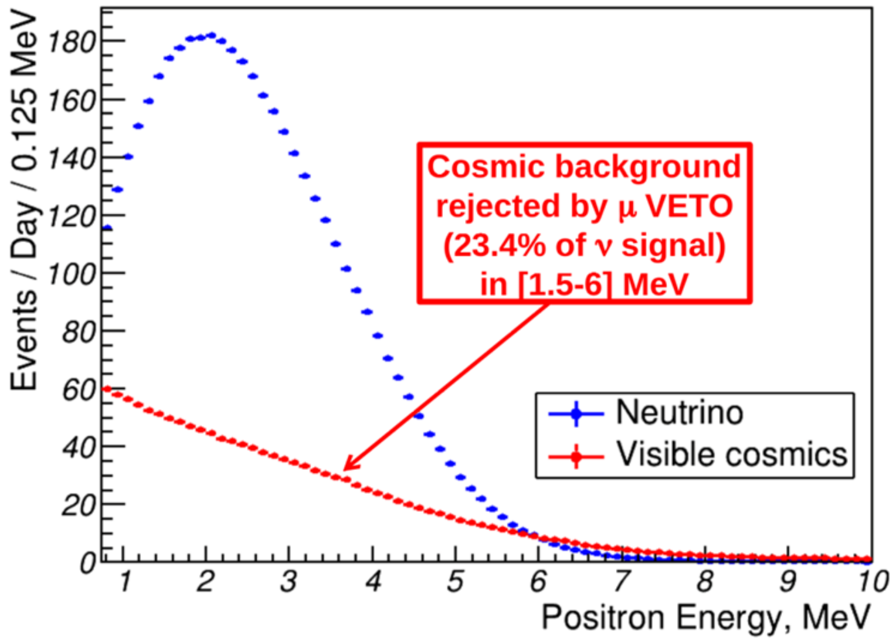
Events
Time, μs
15.3% of IBD @ top
(E_{e+}=1.5-6 MeV)
IBD candidates and accidental background
Accidental background
IBD candidates
MC IBD Events
Cut at 1 μs



Events
×10^3
3D
Distance, cm
IBD candidates and accidental background
Accidental background
IBD candidates
MC IBD Events
Cut at 48 cm
Geometry cut – positron energy dependent



Events / day / 0.125 MeV
4 periods off
Reactor OFF
Cosmics normalized by fit
Fast neutron background
Reactor OFF:
76 events/day
in [1.5-6] MeV
Fast neutrons
16 events/day
Positron energy, MeV



Events / Day / 0.125 MeV
Cosmic background
rejected by μ VETO
(23.4% of ν signal)
in [1.5-6] MeV
Neutrino
Visible cosmics
Positron Energy, MeV

Muon cuts

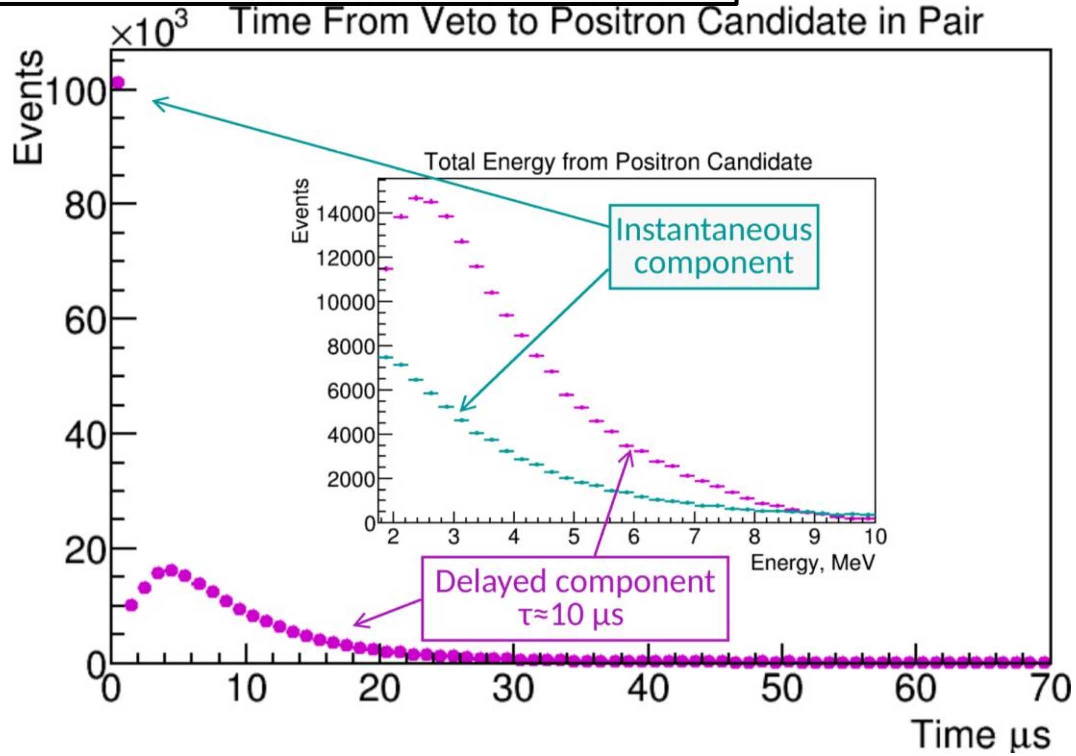
VETO 'OR':

- 2 hits in veto counters
- 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:

$$L_{2D}[cm] < 40 - 17 \cdot e^{-0.13 \cdot E_e^2}$$

$$L_{3D}[cm] < 48 - 17 \cdot e^{-0.13 \cdot E_e^2}$$

$$E_N[MeV] > 1.5 + 2.6 \cdot e^{-0.15 \cdot E_e^2}$$

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

Test statistics

(in model independent way)

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

3-position movement
Oct.2016-Dec.2018

2-position movement
Mar.2019-Jan.2024

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 – **0.4%**
- Energy scale – **2%**
- Energy shift **50 keV**
- Distance to fuel burning profile center – **5 cm**
- Correlated backgrounds – **35%**
- Additional smearing energy resolution: **($6\%/\sqrt{E} \oplus 2\%$)**

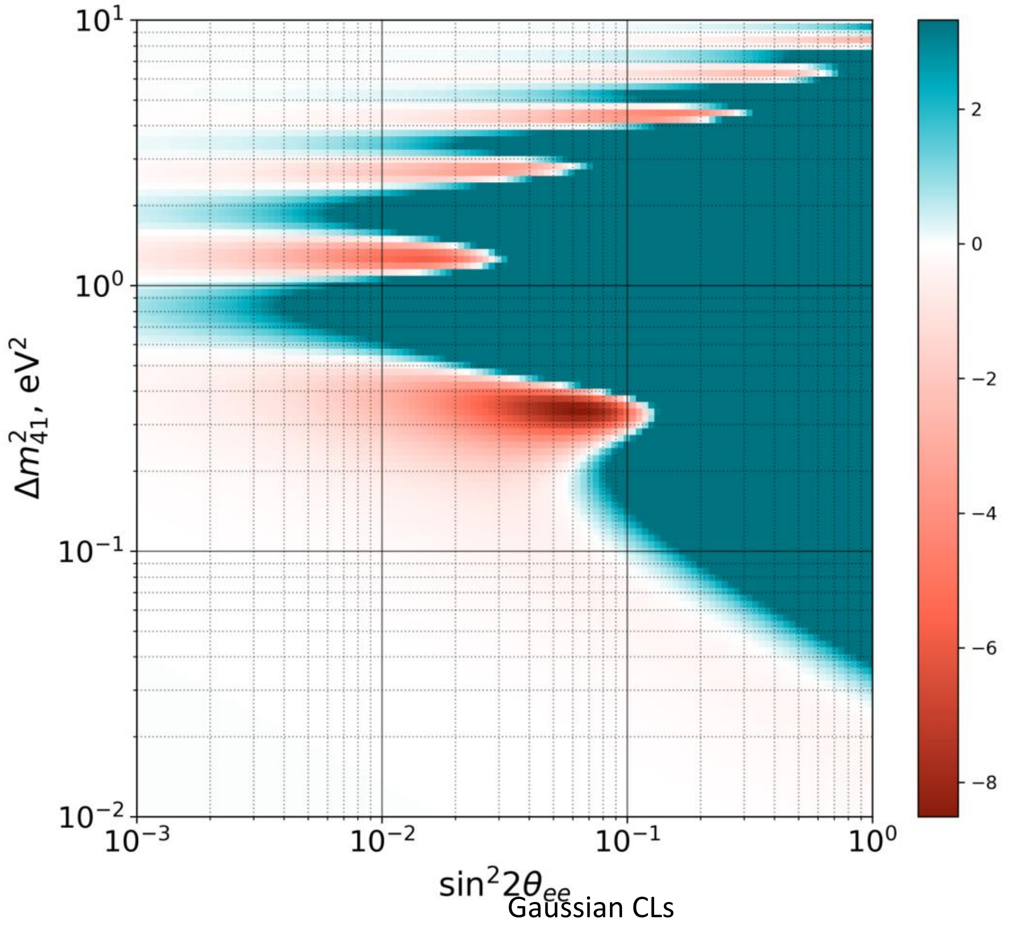
Difference in χ^2 between 4ν and 3ν hypotheses

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

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

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

We use Gaussian CL_s method to get limits



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

Test statistics

(absolute IBD rates analysis)

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

3-position movement Oct.2016-Dec.2018

2-position movement Mar.2019-Jan.2024

Penalty terms for nuisance parameters: relative efficiencies and systematics

$$+\left(\left(\mathrm{N}_{top} + \mathrm{N}_{mid} + \mathrm{N}_{bottom}\right)^{obs} - \left(\mathrm{N}_{top} + k_2 \cdot \sqrt{k_1} \cdot \mathrm{N}_{mid} + k_1 \cdot \mathrm{N}_{bottom}\right)^{pre}\right)^2 / \sigma_{abs}^2$$

Term for absolute rates

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(η⁰) – nuisance parameters (and their nominal values)

W – covariance matrix to take into account correlations in spectra ratios at different postions (Z_1 and Z_2)

N – total absolute rates

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

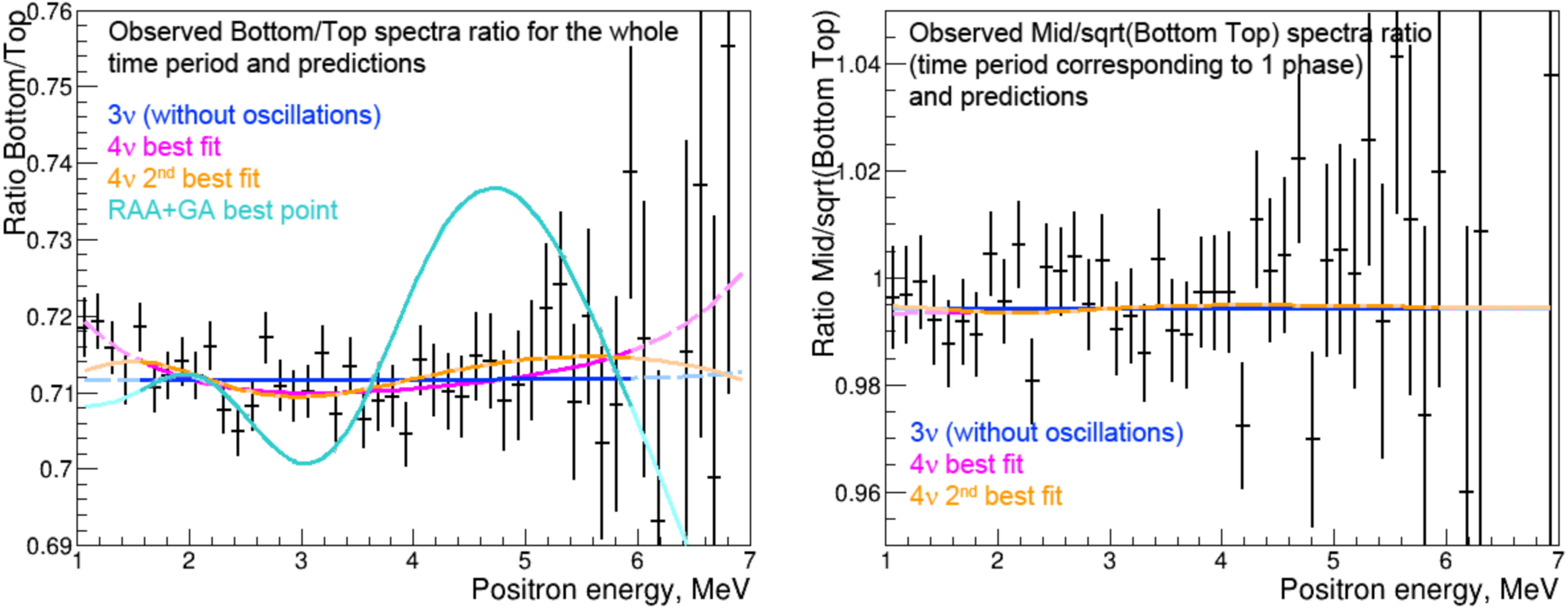
Nuisance parameters and their errors ($\sigma_{k,\eta}$):

- Relative detector efficiencies – **0.4%**
- Energy scale – **2%**
- Energy shift **50 keV**
- Distance to fuel burning profile center – **5 cm**
- Cosmic background – **25%**
- Fast neutron background – **30%**
- Additional smearing energy resolution: **($6\%/\sqrt{E} \oplus 2\%$)**

Gaussian CLs

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

Ratio of positron spectra

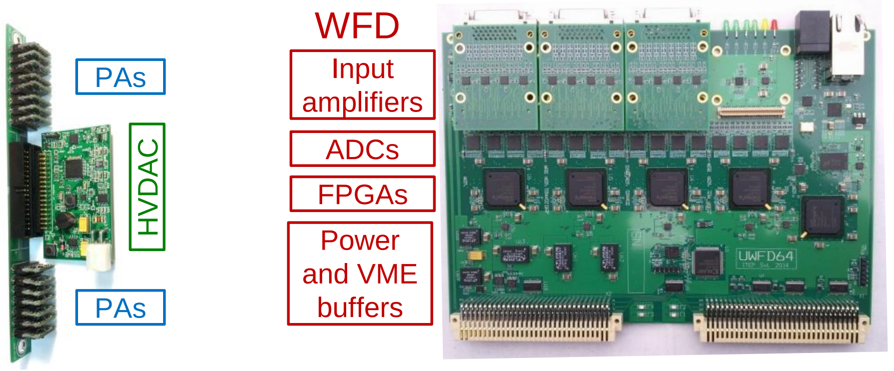


- Fit in **1.5-6 MeV** range (to be conservative).
- Using current statistics 2016-2023 (~5.5 million IBD events with 1.5 MeV < E < 6MeV)
- We see statistically **not significant hint** in favor of 4ν signal:

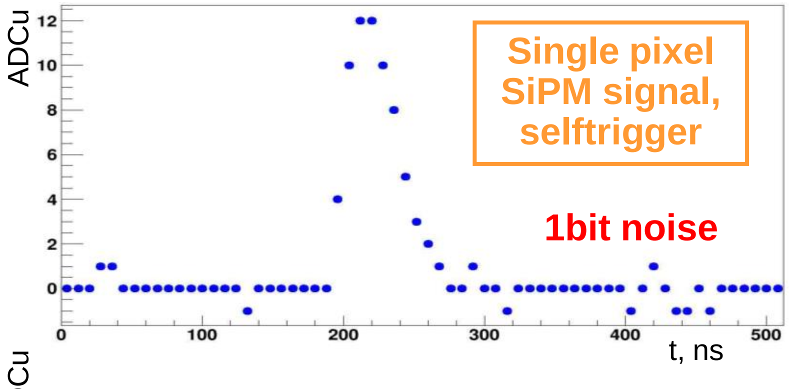
  $\Delta\chi^2$=-8.5 (2.1σ) for 4ν hypothesis best point **Δm^2=0.34 eV^2 , $\sin^2 2\theta$=0.06**

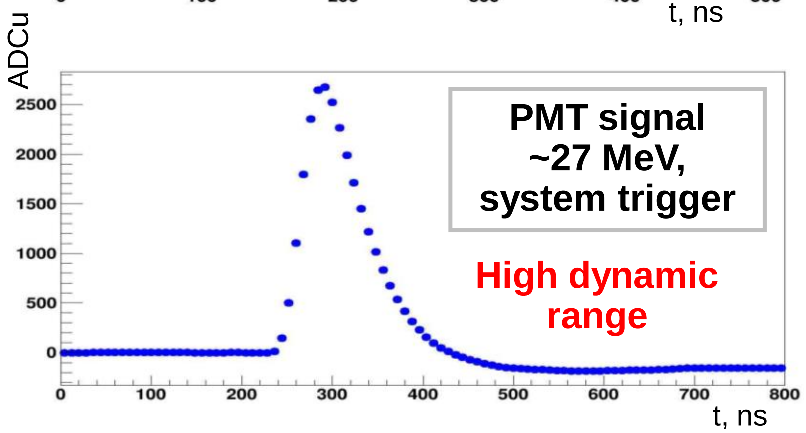
  $\Delta\chi^2$=-5.7 for 4ν hypothesis second best point **Δm^2=1.3 eV^2 , $\sin^2 2\theta$=0.015**

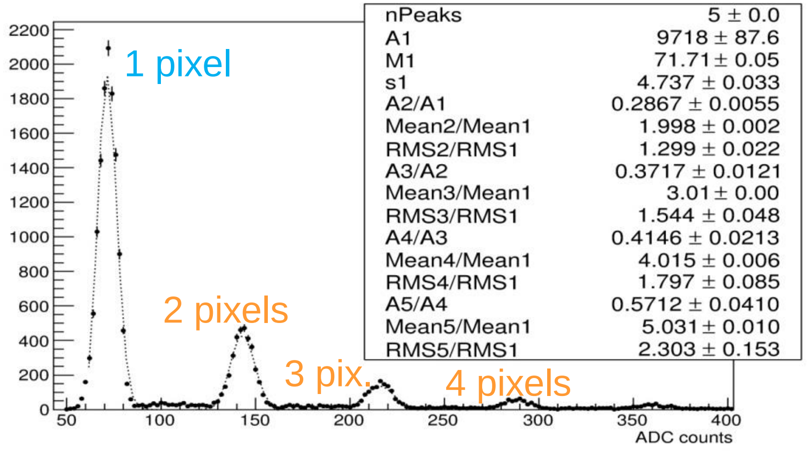
Readout electronics



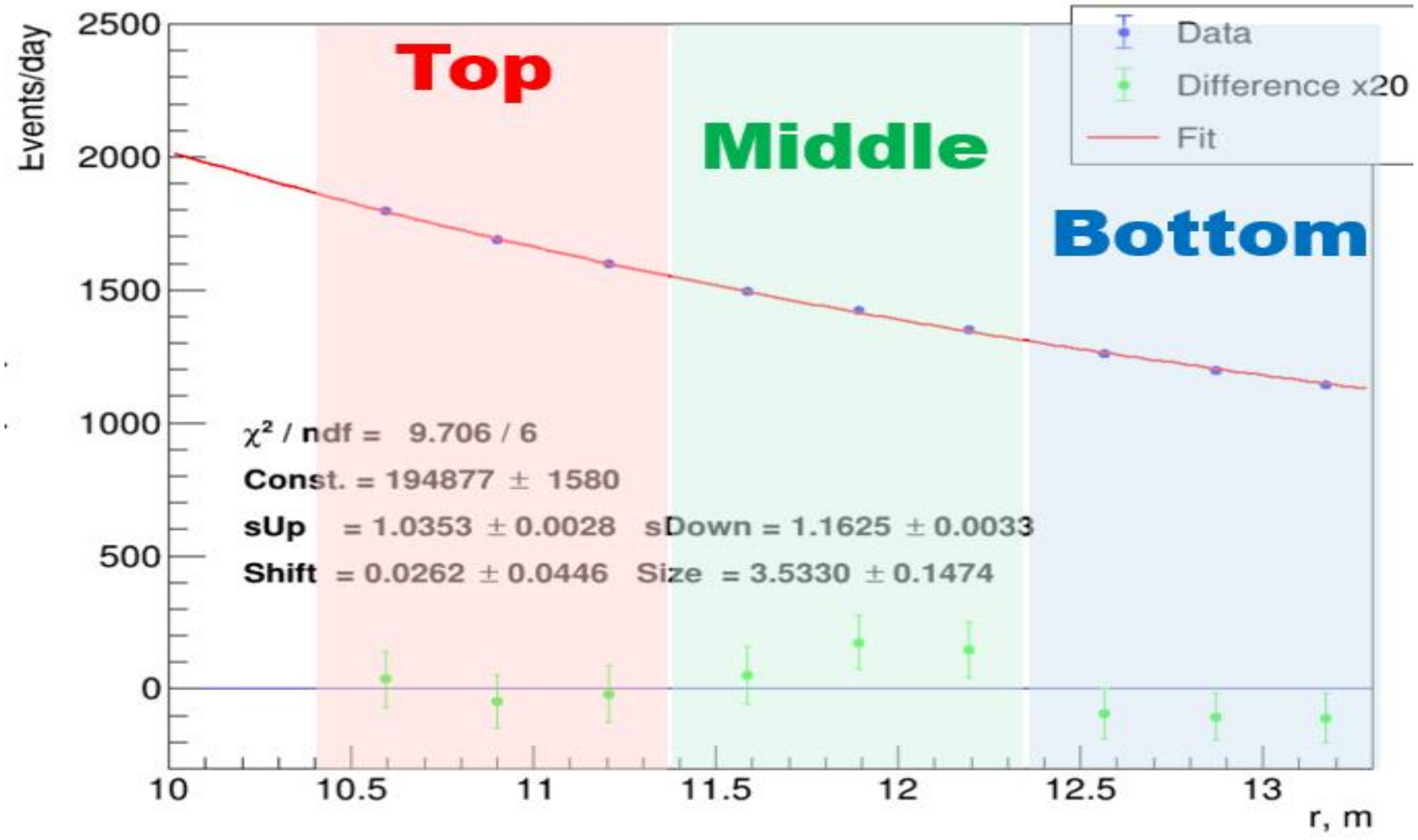
- Preamplifiers PA in groups of 15 and SiPM power supplies HVDAC for each group inside shielding, current and temperature sensing
- Total 46 Waveform Digitisers WFD in 4 VME crates on the platform
- WFD: 64 channels, 125 MHz, 12 bit dynamic range, signal sum and trigger generation and distribution (no 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 ~1/12 p.e.







Counting rate dependence on the distance from reactor core



- IBD intensity **follows reasonably the 1 / L² dependence**.
- Detector was divided on 3 parts in each position.

^{9}Li and ^{8}He background

~ 4 events per day