The Applied Antineutrino Physics workshops AAP 2023
18-21 September 2023
The Guildhall York, UK

DANSS reactor antineutrino spectrometer: results for 2023

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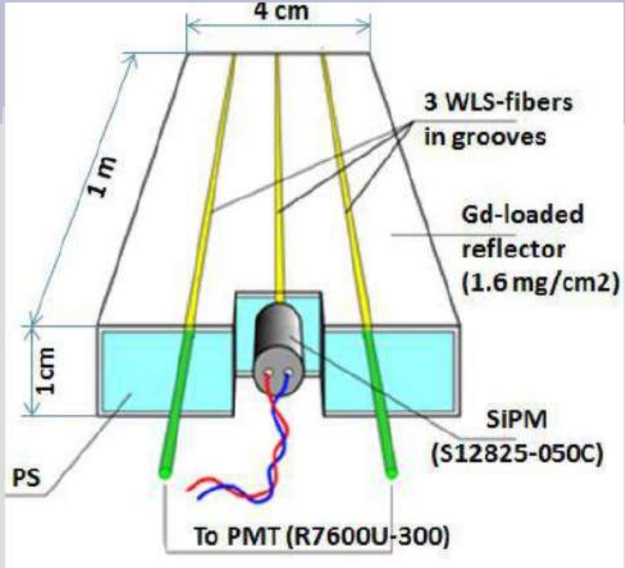
for the DANSS collaboration

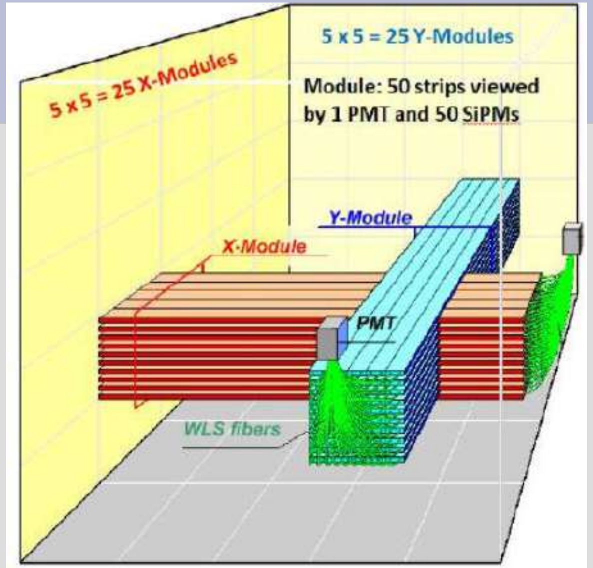
20/09/2023

The DANSS design

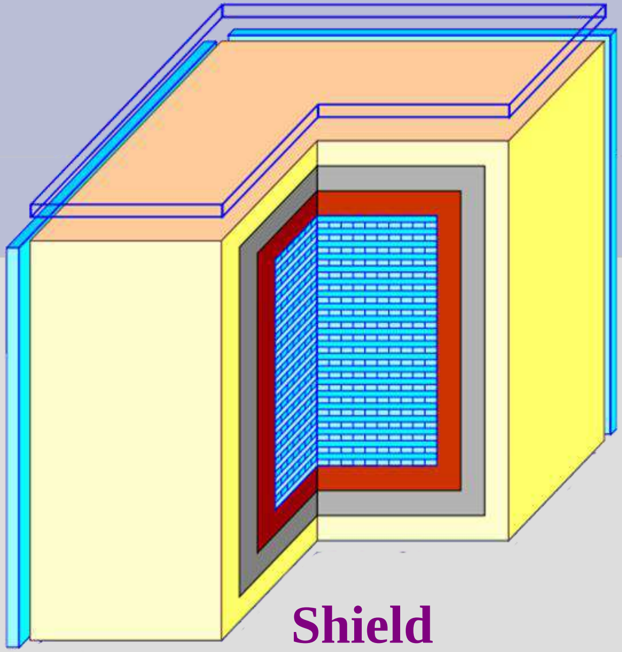
Strip



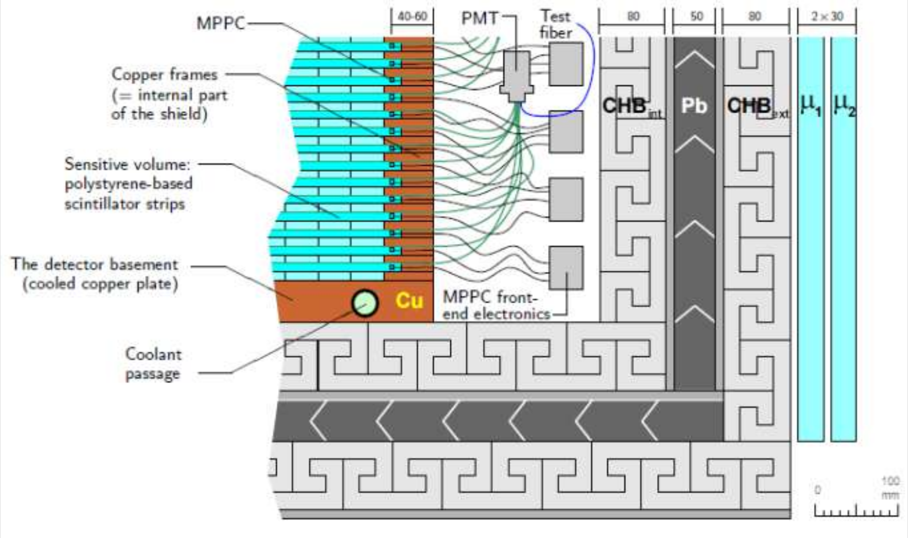
Module



Detector

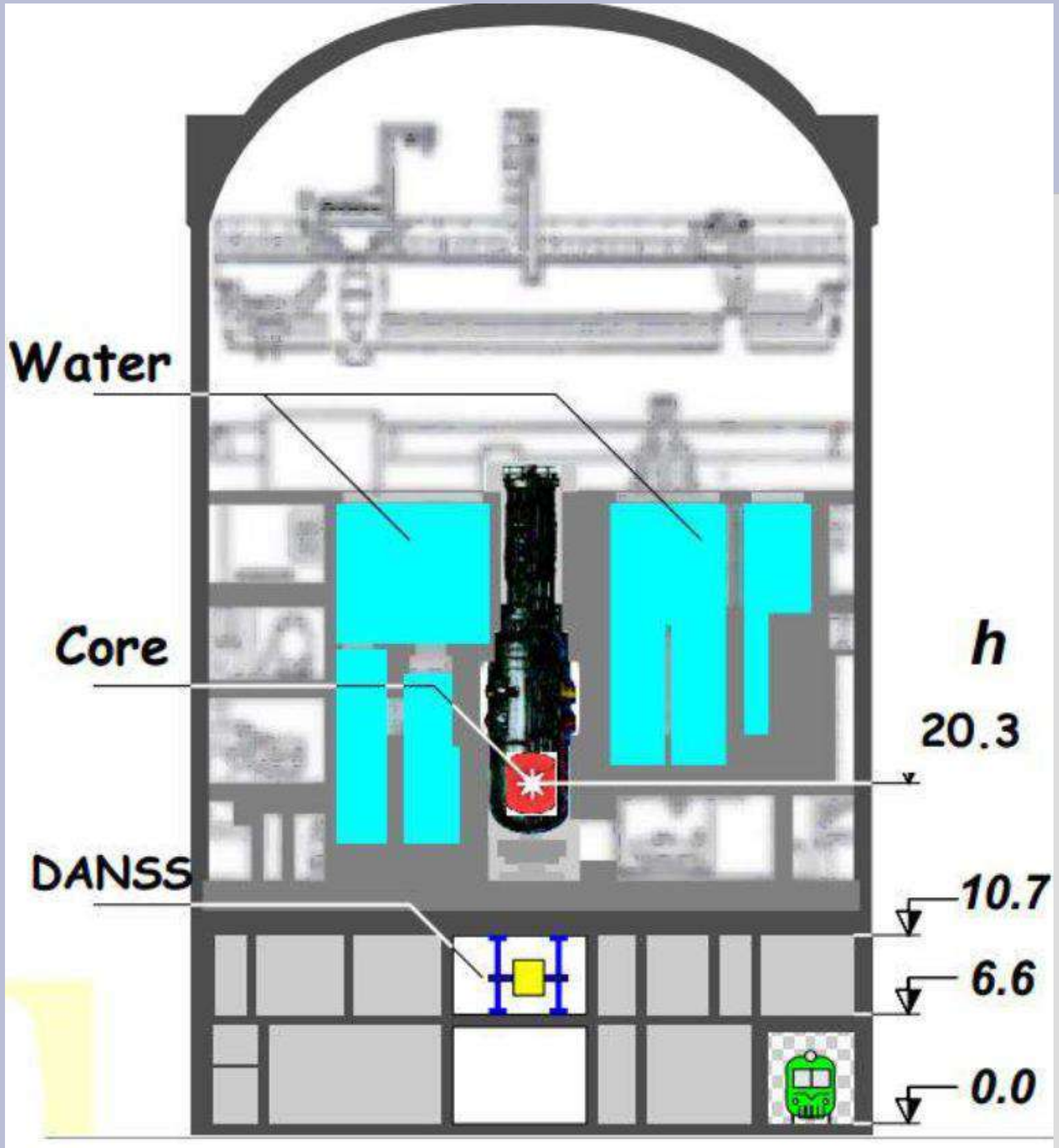


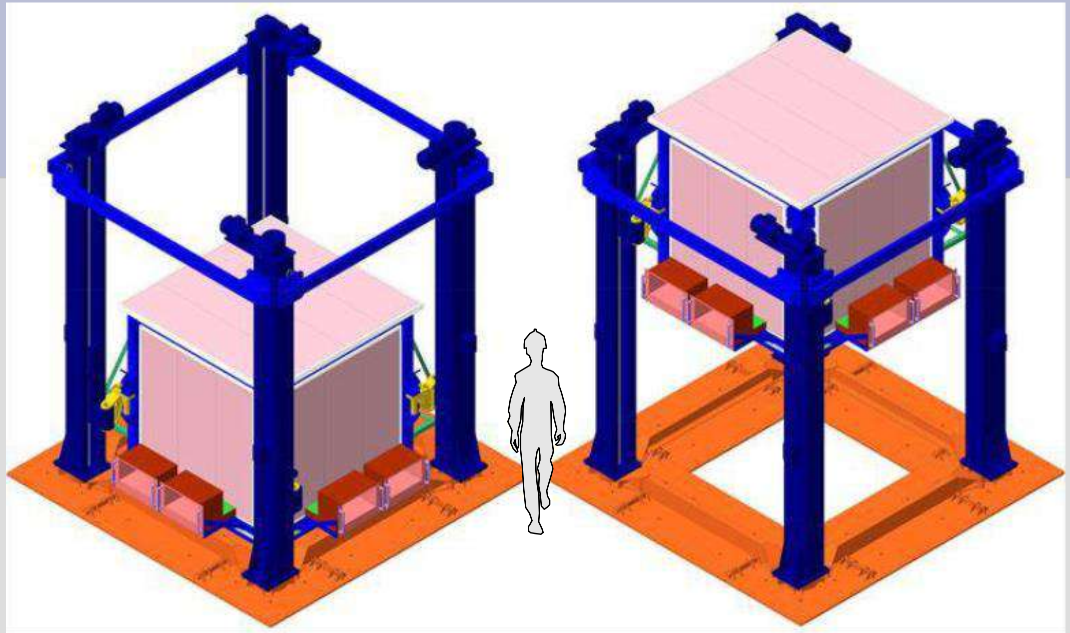
Shield



- Cubic meter highly segmented neutrino spectrometer made of 2500 PS strips viewed by 2500 SiPMs & 50 PMTs.
- Multilayer passive shielding: Cu/CHB/Pb/CHB=5/8/5/8 cm
- Active muon veto made of 2 x 3 cm PS plates from all sides except bottom.

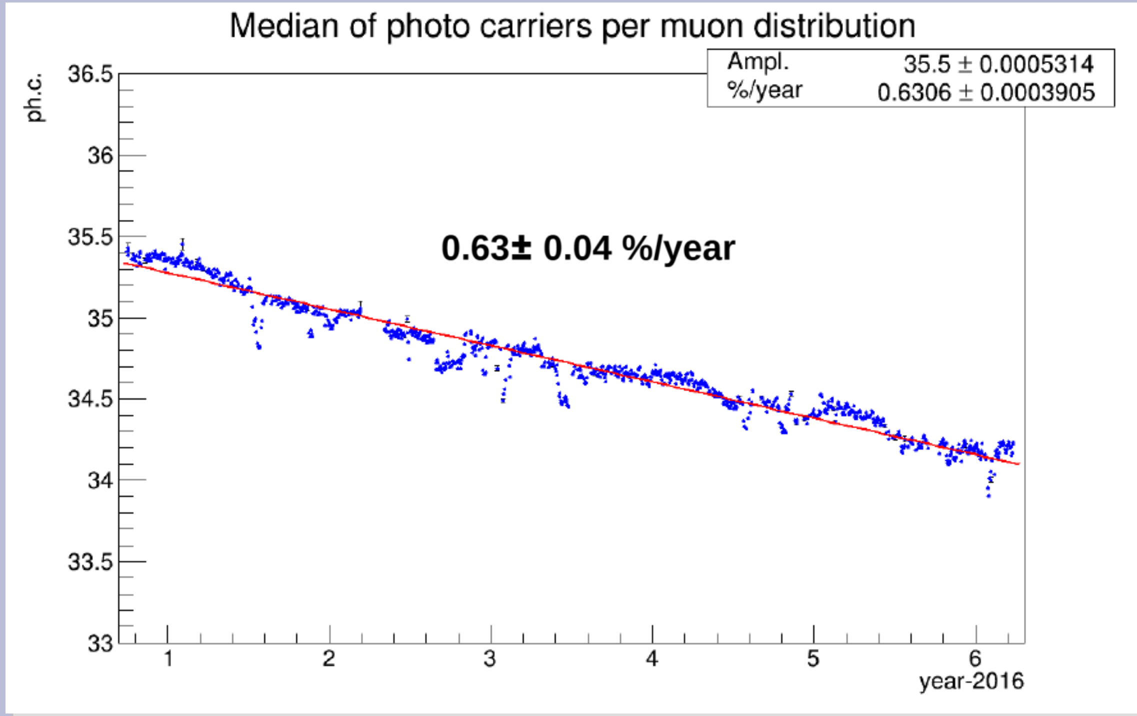
The location and movable platform

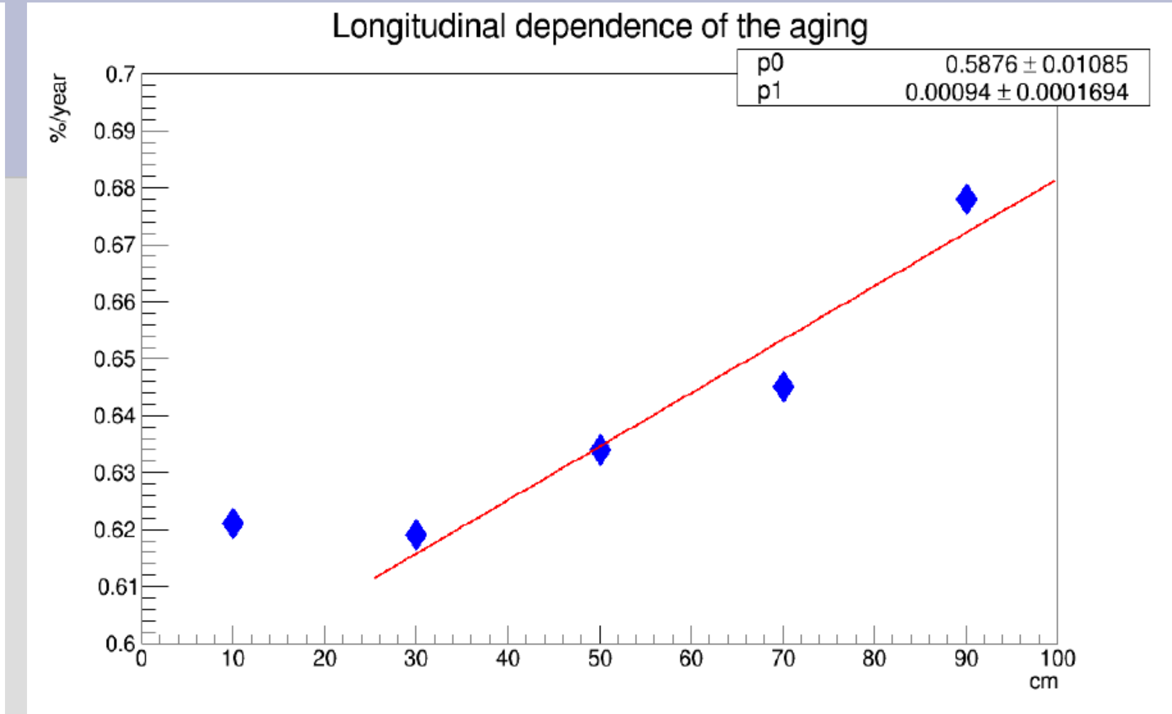




- The DANSS is located at Kalininskaya NPP (KNPP) under 3 GW WWER-1000 reactor (H=3.6 m, ∅ =3.1 m), which provides ~ 50 m.w.e. (6-fold μ reduction and no cosmic n).
- The detector is built on a movable platform.
  Data are taken at 3 distances 10.9 m (Up), 11.9 m (Middle), and 12.9 m (Down) from the reactor (center to center), changed sequentially 3 times per week.

Detector aging



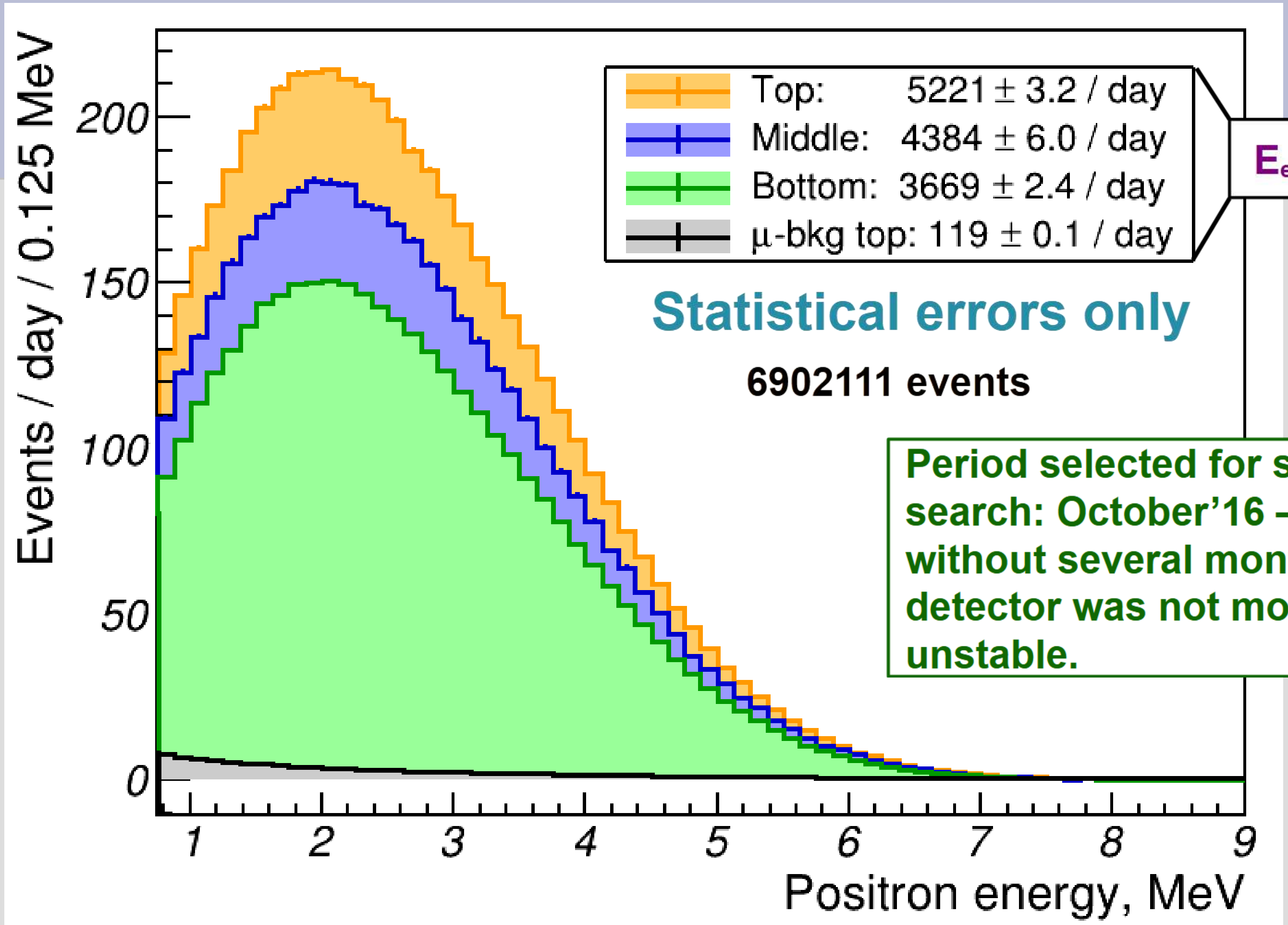


DANSS – 7 years of continuous operation.

- Light collection by central WLS fiber KURARAY Y-11(200)M read by SiPM HAMAMATSU S12825-050C. **WLS degradation is also visible with** $-dL_{att}/dt$ = **0.37 ± 0.07**(stat.) %/year
- Close to vertical muon tracks with tg$\theta < 0.2$ selected.
- Median of Landau distribution was taken.

T2K (several det-s) — **0.9-2.2 %/year**; **MINOS — 2 %/year**; **MINERvA — 7-10 %/year @80F(**27.6^{oC})

Positron spectrum of IBD-signal

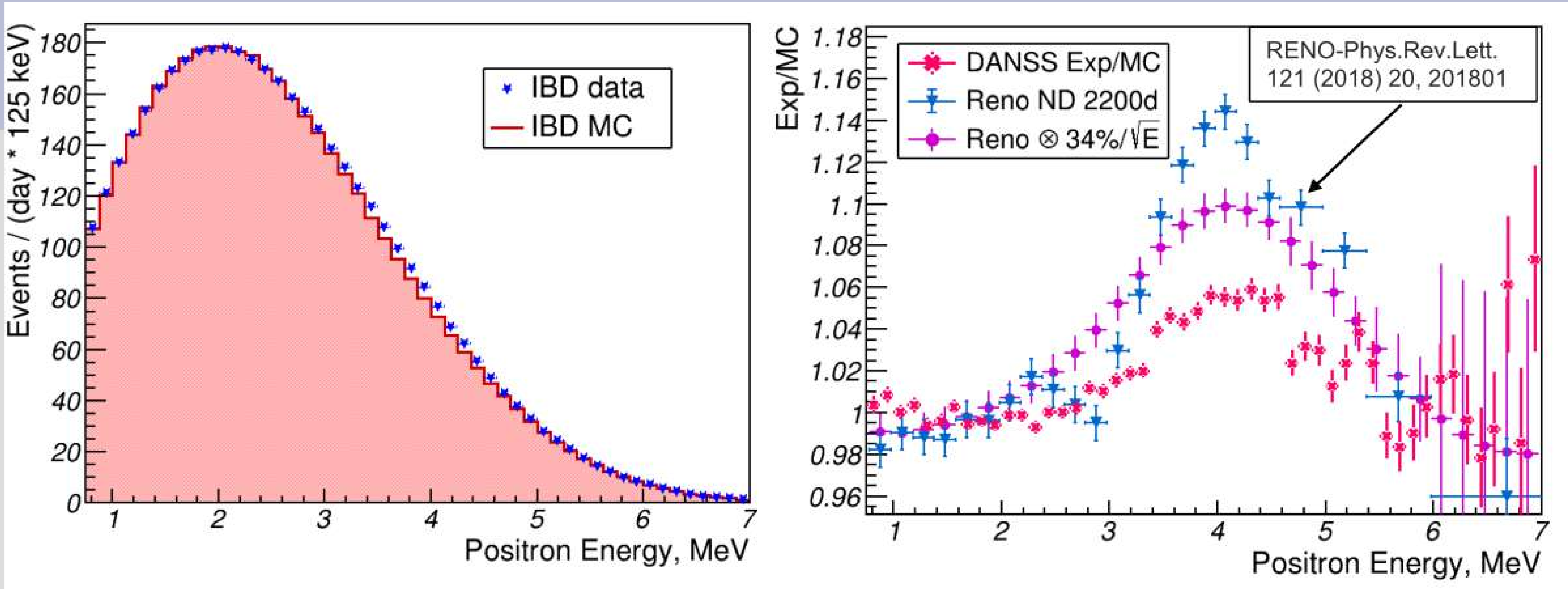


E_{e+}=[0.75-8] MeV

Period selected for sterile neutrino search: October'16 – March'23 without several months, when detector was not moved or was unstable.

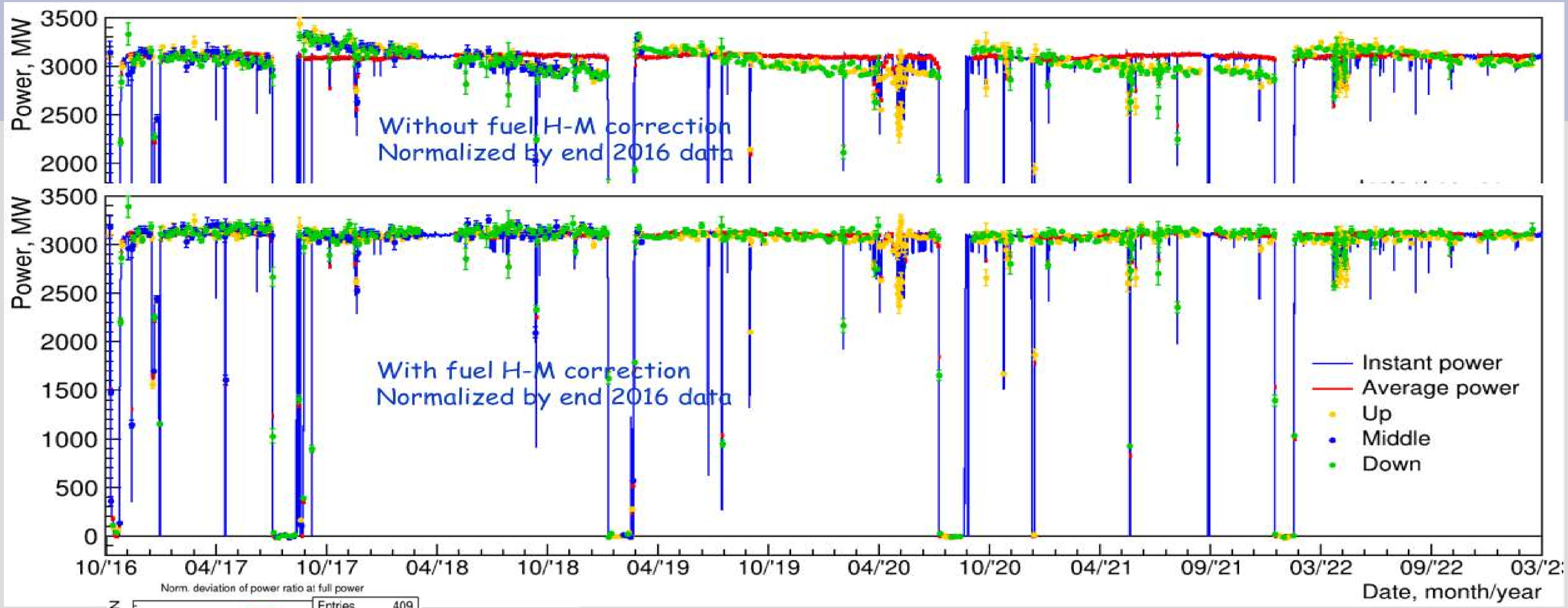
- All backgrounds were subtracted including signal from neighbor reactors (0.6% of S @ top position)
- **> 5000 events/day** in fiducial volume (78% of full) @ top position: **7.7M events in 6.5 y**.
- For positrons with E=[1.5-6] MeV background subtracted @ top position is 1.75% and **S/B > 50**.

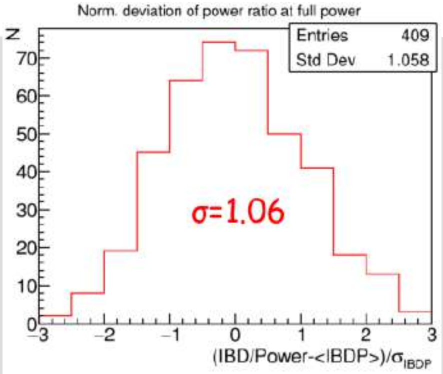
Positron spectrum: experiment vs. theory



- For best agreement with H-M model MC spectrum was shifted on +50 keV w.r.t. experimental data. The nature of this shift is still under investigation.
- We see like a bump in e+ spectrum similar to other experiments, but smaller than in RENO e.g.
- We are not claiming decisively existence of the bump because of high sensitivity of the shape on E scale and shift. Similar energy scale issues should also affect other experiments.

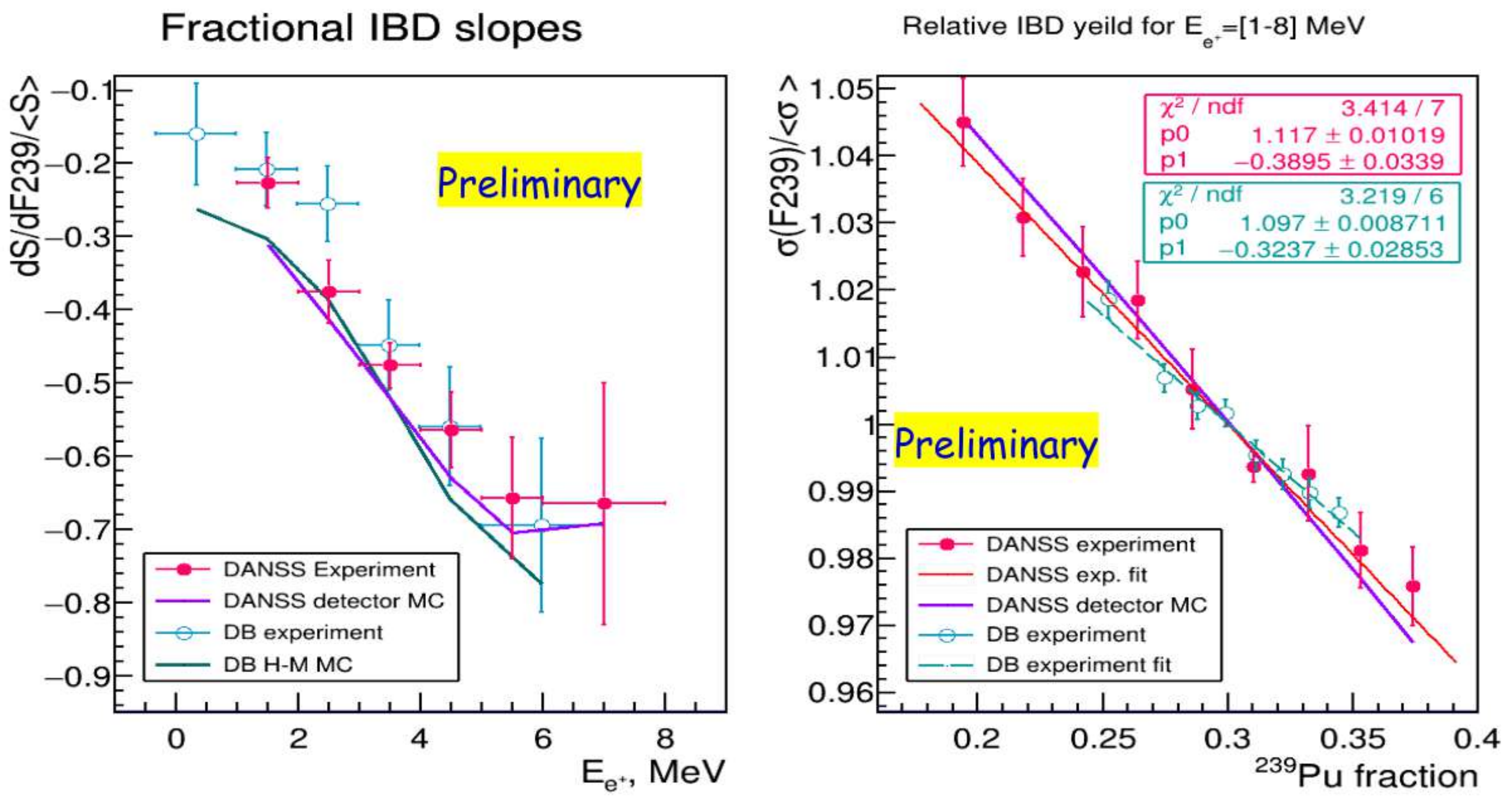
Reactor power monitoring





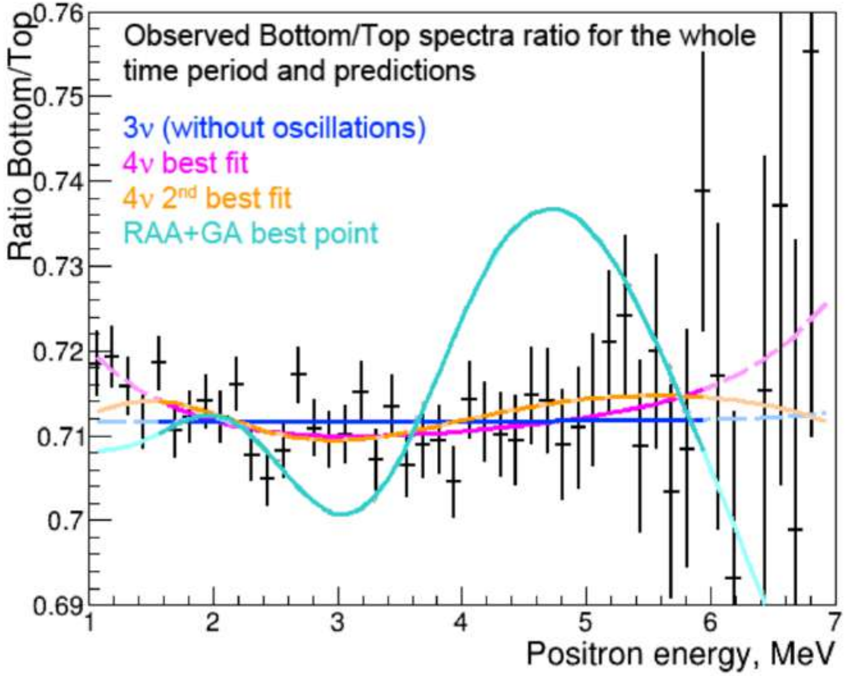
- 6.5 years of successful reactor monitoring with 1.5% accuracy in 2 days, no evidence for systematic effects has been observed.

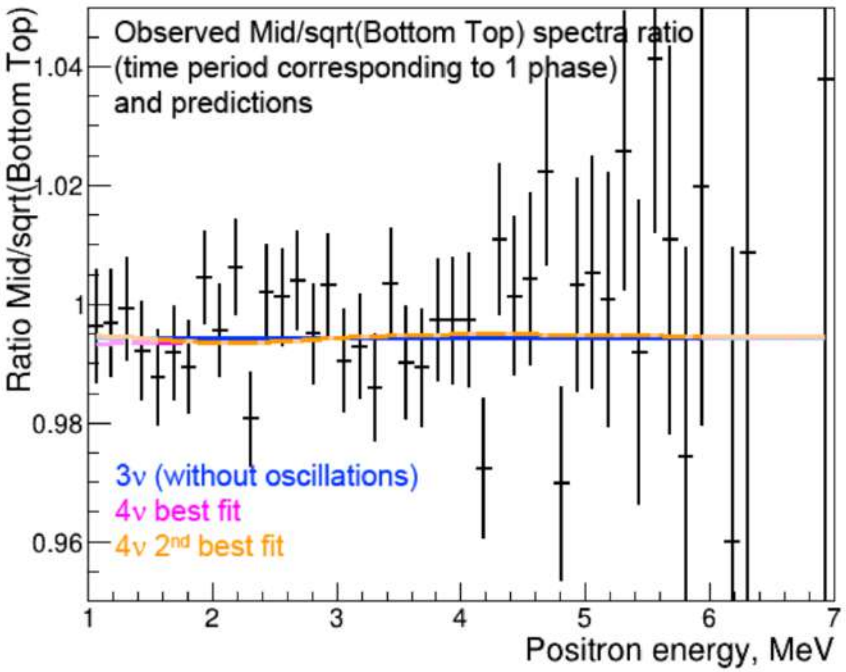
Fuel composition sensitivity



- Positron spectrum dependence on fuel composition is clearly seen
- IBD rate dependence on ^{239}Pu fission fraction ($d\sigma/dF239)/\sigma(F239=0.3)$ 1.53 ± 0.06 for various positron energies is closer to H-M model (1.53 ± 0.05) than DayaBay result (1.445 ± 0.097).
- Errors (probably overestimated) are dominated by systematics from the spread between the reactor campaigns.

Ratio of positron spectra





- **Fit is 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 do not see a statistically significant signal 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

RAA+GA best point was excluded long time ago.

Test statistics

1. Relative method (w/o theory info):

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

3-position movement
Oct.2016-Dec.2018

2-position movement
Mar.2019-Mar.2023

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

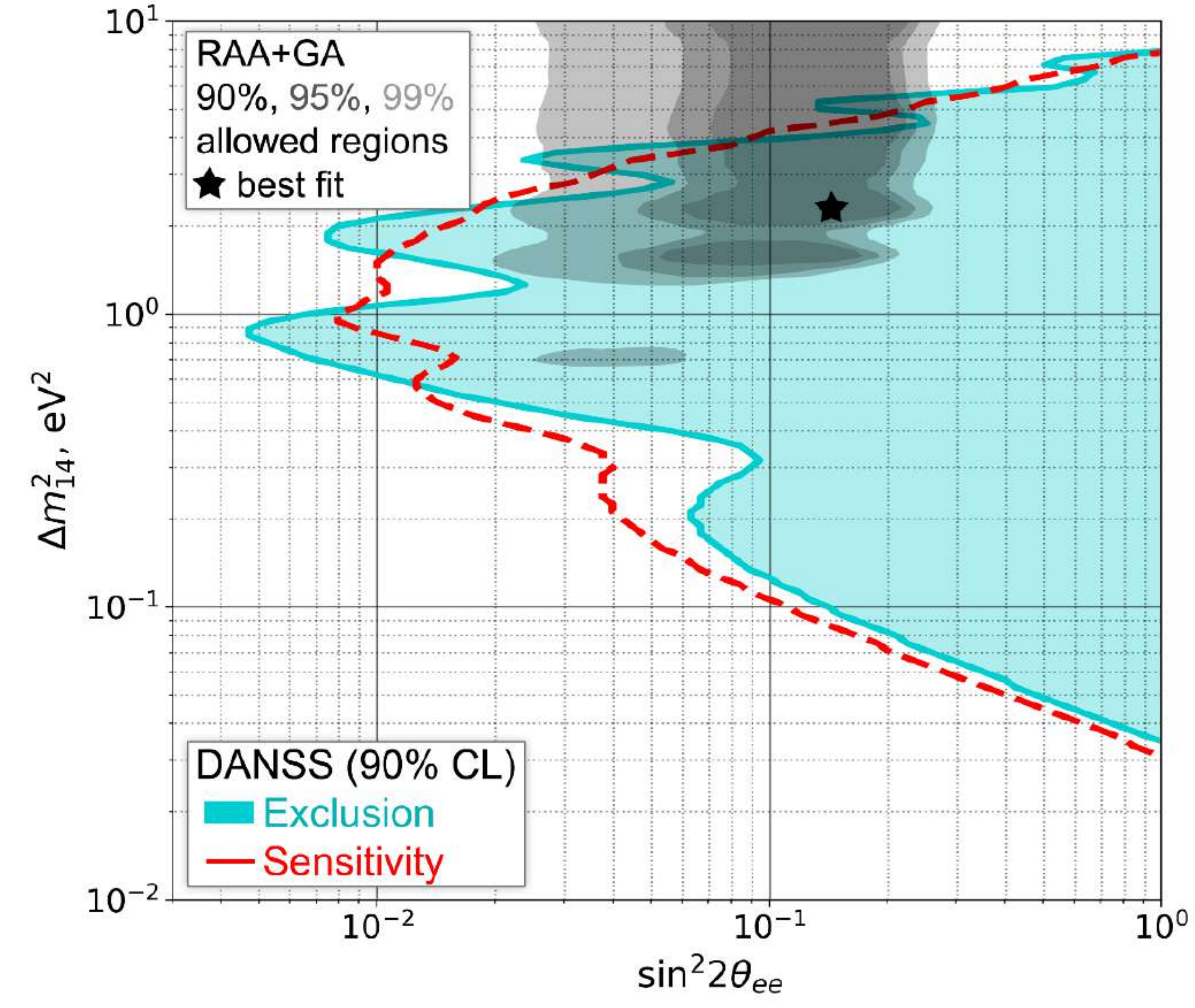
2. Absolute method (with theory info – absolute CRs):

$$\chi^2_{abs} = \chi^2_{rel} + ((N_{top} + N_{mid} + N_{bottom})^{\rm obs} - (N_{top} + k_2 \cdot \sqrt{k_1} \cdot N_{mid} + k_1 \cdot N_{bottom})^{\rm pre})^2 / \sigma^2_{abs}$$

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

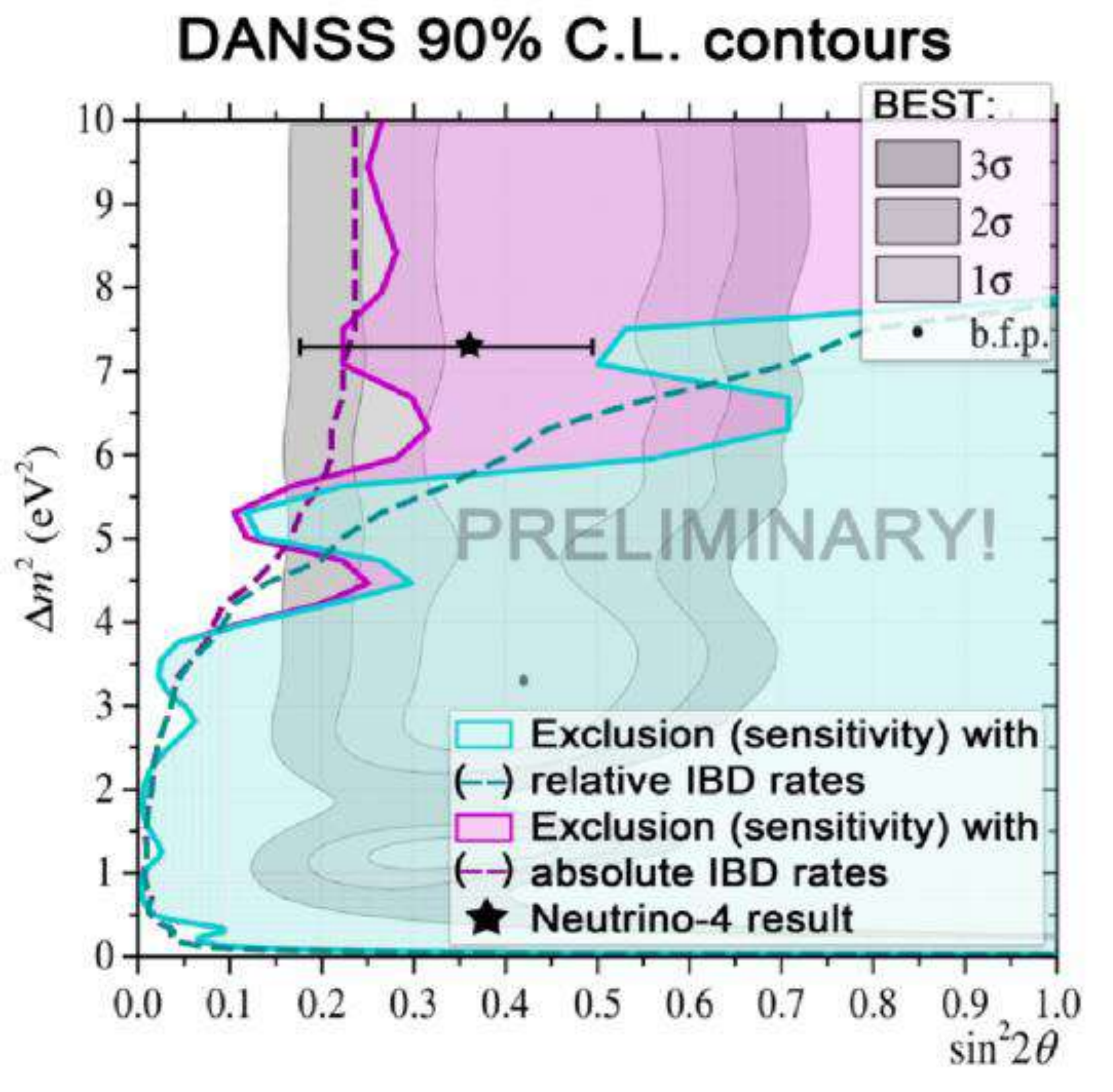
The DANSS limits: related method

- This is the model independent result (relative method) obtained w/o information about the reactor antineutrino spectrum
- 5.5M IBD events with positrons in energy range E=[1.5-6] MeV were used in the χ2 fit (very conservative).
- Gaussian CLs method – the most stringent limit reaches $\sin^2(2\Theta) < 5 \cdot 10^{-3}$ level
- The most interesting region of 4ν parameters space has been excluded
- The best point (2.1σ) is not significant enough to claim the signal
- RAA+GA best point is deep in the exclusion region. 5σ exclusion already in 2018 [PLB 787 (2018) 56]



The DANSS limits: absolute method

- Model dependent result (absolute method) use HM model and Gaussian CL_S
- All known systematics is here including dominant flux uncertainty 5% (total err.sys. – 7%).
- Almost the entire interesting region of phase space is excluded
- The most interesting region of 4ν parameters space has been excluded
- Most of the BEST and the best NEUTRINO-4 fit are also excluded



The DANSS upgrade

Main goal: to reach resolution **12%/√E** w.r.t. current 33%/√E.

New geometry:

Strips: 2x5x120 cm with **2-side** SiPM readout

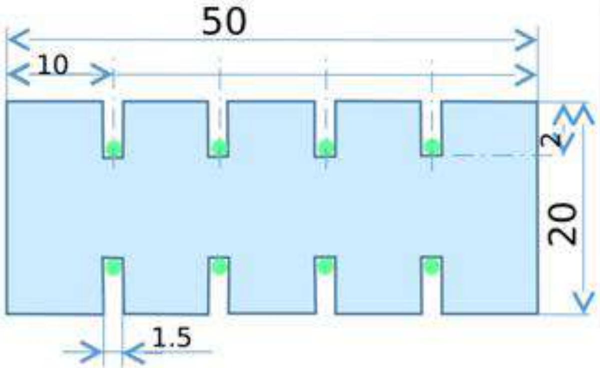
Structure: 60 layers x 24 strips: **1.7 m^3** setup

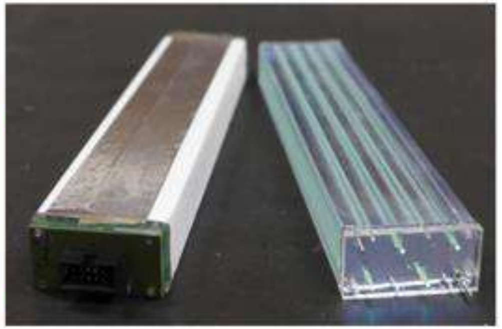
used **the same shield and moving platform**.

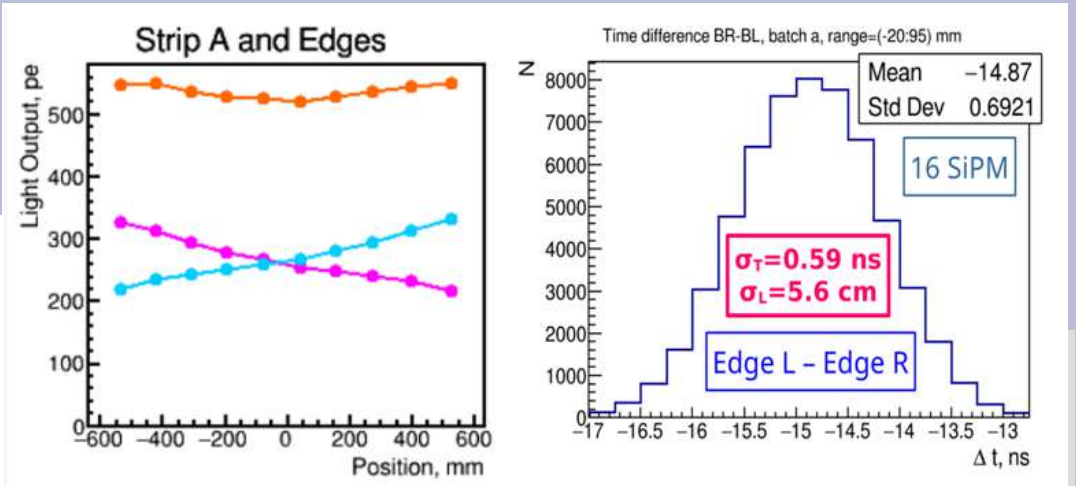
Gd is in foils between layers.

New faster YS-2 fibers.

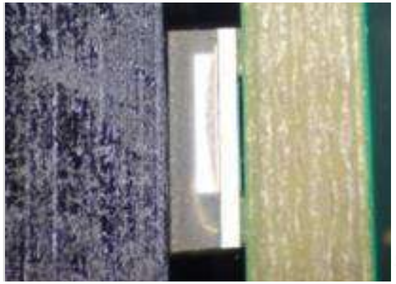
Upgraded strip:

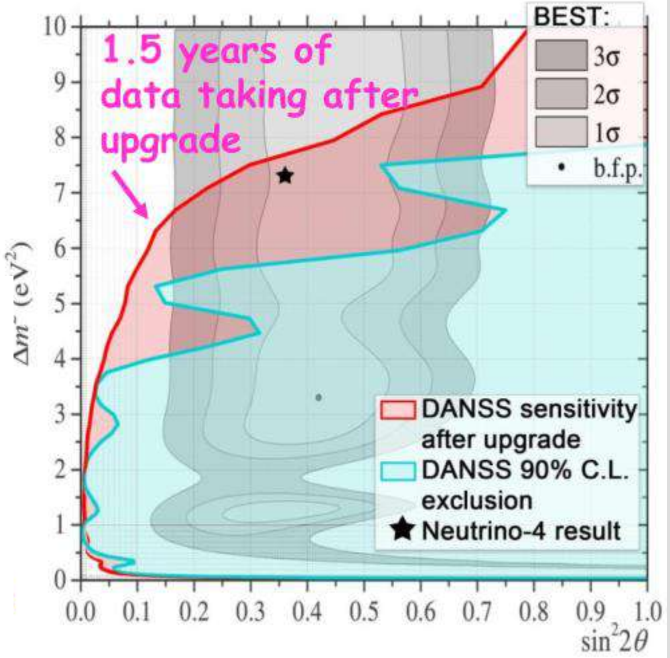






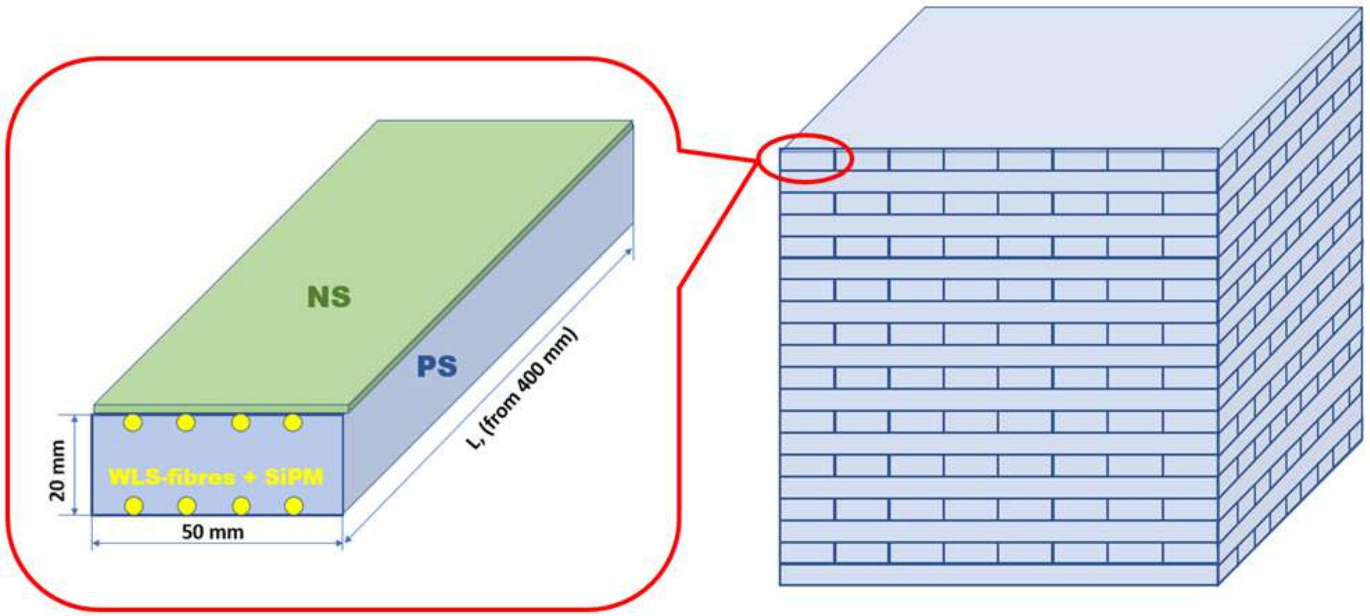
μ-beam tests of new strips: LO > 500 p.e. @ ~ 4MeV, σ_τ = 0.6 ns (5.6 cm vertex resolution)



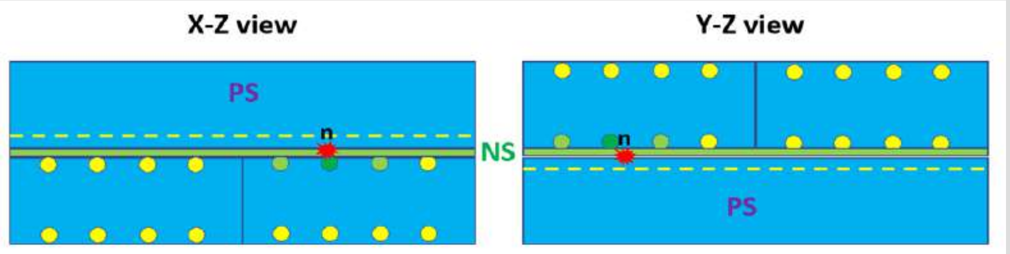


The ENIGMA project (Slovakia-Czechia)

Exploration of Neutrinos: Instrument for Global Monitoring and Analysis (given by ChatGPT-4)

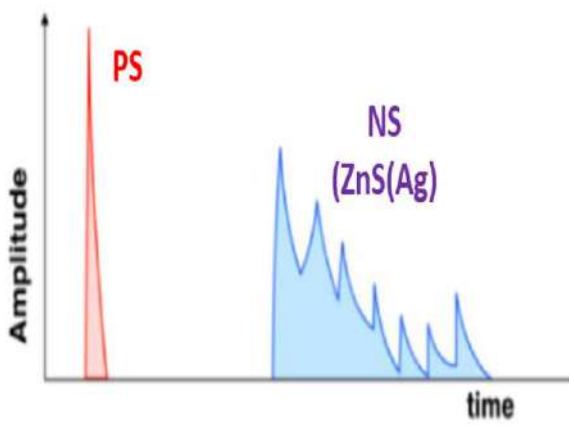


Goal: combine DANSS&SOLID technologies taking the best from them.
Idea: use all optimal geometry found for DANSS-2, **but replace Gd with $^{6}Li/^{10}B$ in neutron scintillator based on ZnS(Ag).**



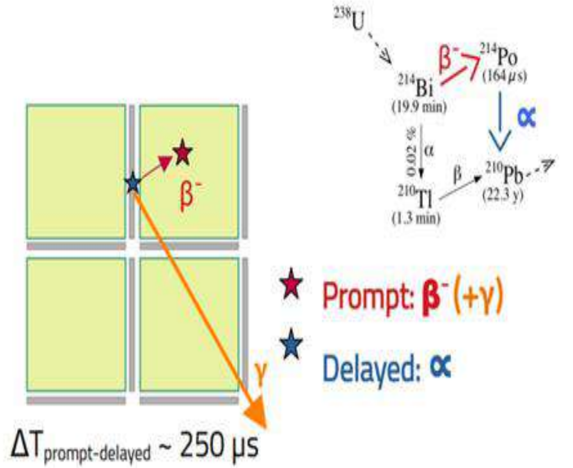
Advantages:

- Neutron localization
- PSD identification
- No edge effect
- Directionality
- Scalability



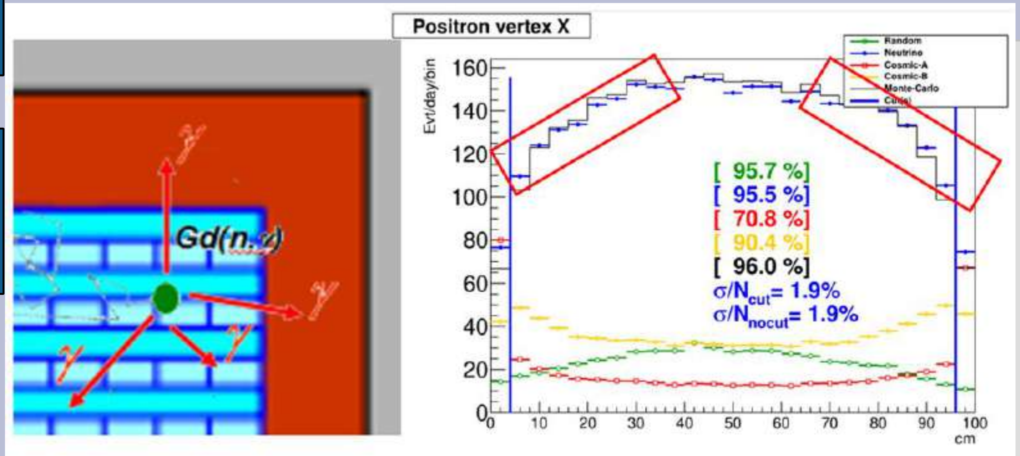
Critical point:

- NS radiopurity
- NS production must be under control
- Solved in LBE

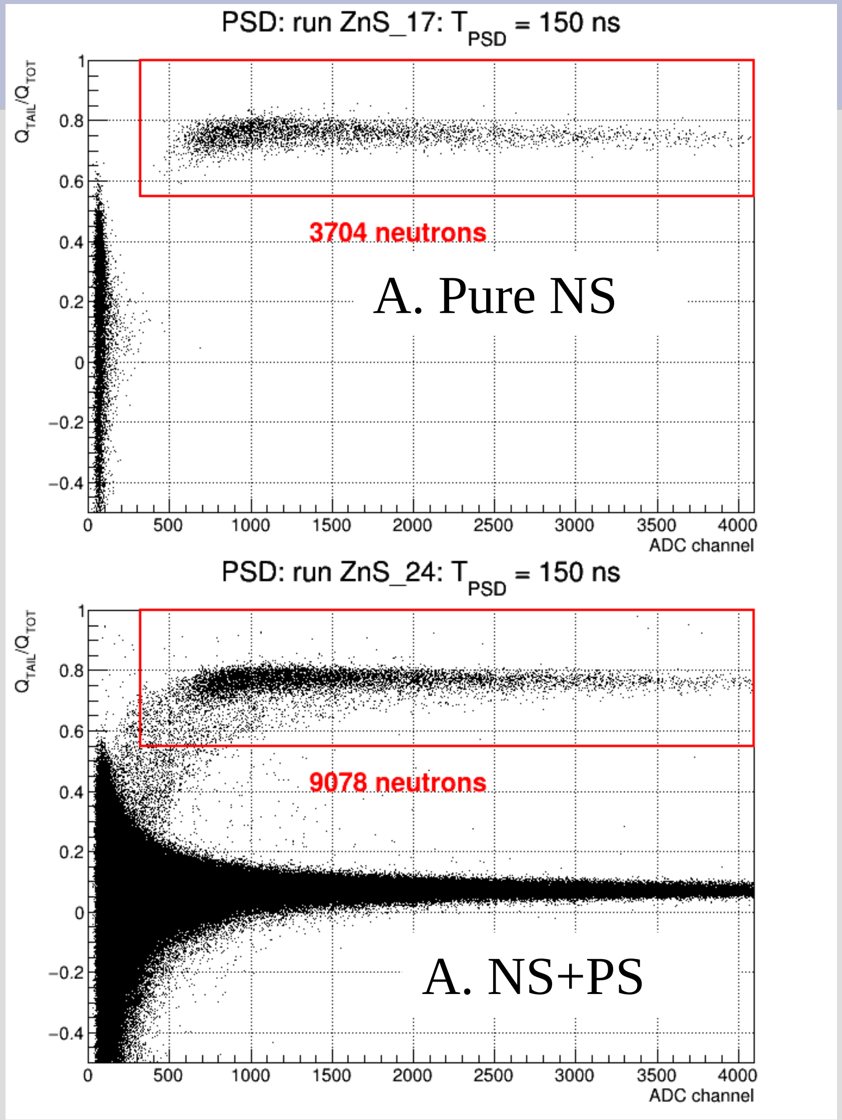


The ENIGMA II

Edge effects in DANSS



Powder mixture of nano-B with ZnS(Ag): measurements with AmBe source



$$n + {}^{10}B(20\%)$$
$$\rightarrow {}^{7}Li(1.0\ MeV) + {}^{4}He(1.8\ MeV) \quad BR\ 7\%$$
$$\rightarrow {}^{7}Li(0.83\ MeV) + {}^{4}He(1.47\ MeV)$$
$$+ \gamma(0.48\ MeV) \quad BR\ 93\% \quad \sigma = 2100\ barn.$$

^{10}B instead ^{6}Li?

Pro:

- Available on market @ relatively low price.
- No limitation to use
- 5x times bigger n-capture
- γ adds to n pattern!

Contra:

- Weaker signal & shorter paths of n-capture products

Summary

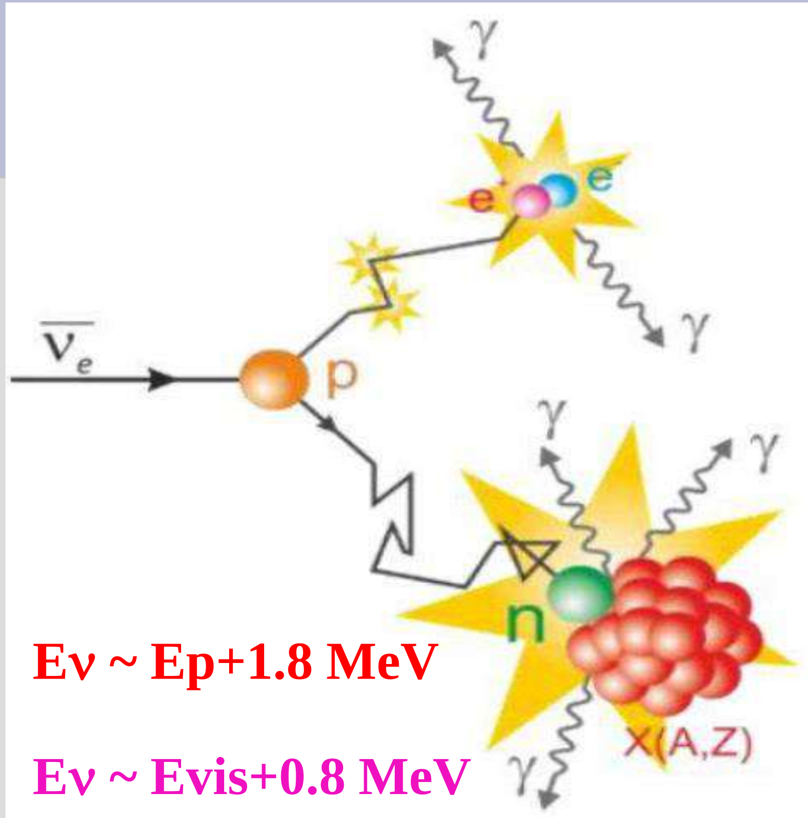
- DANSS is in operation since April 2016 with regular (physics) data taking since October 2016 at a rate of ~5000 events per day with cosmic background ~ 1.7%, S/B > 50.
- Reactor power was measured using anti-ν rate with statistical error of ~1.5% in two days during 6.5 years of operation. Sensitivity to fuel composition was clearly demonstrated in 5 reactor campaigns.
- With current data set 2016-2023 (almost 8M events) we have no significant sign of sterile ν oscillations.
- σ235/σ239 was measured and is in perfect agreement with HM model unlike DB result.
- Indication of 5MeV bump but not decisive.
- Preliminary model independent (relative) DANSS analysis (using 5.5M events) excludes a large and most interesting part of parameter phase space for sterile neutrino oscillation including large area of the BEST result. Model-depend (absolute one using CR) analysis excludes practically all BEST region and best N-4 point.
- Future plans: further improvements of MC & calibrations & energy scale determination in order to reduce systematics. Modernized DANSS detector will scrutinize further N-4 & BEST results with model-independent analysis.

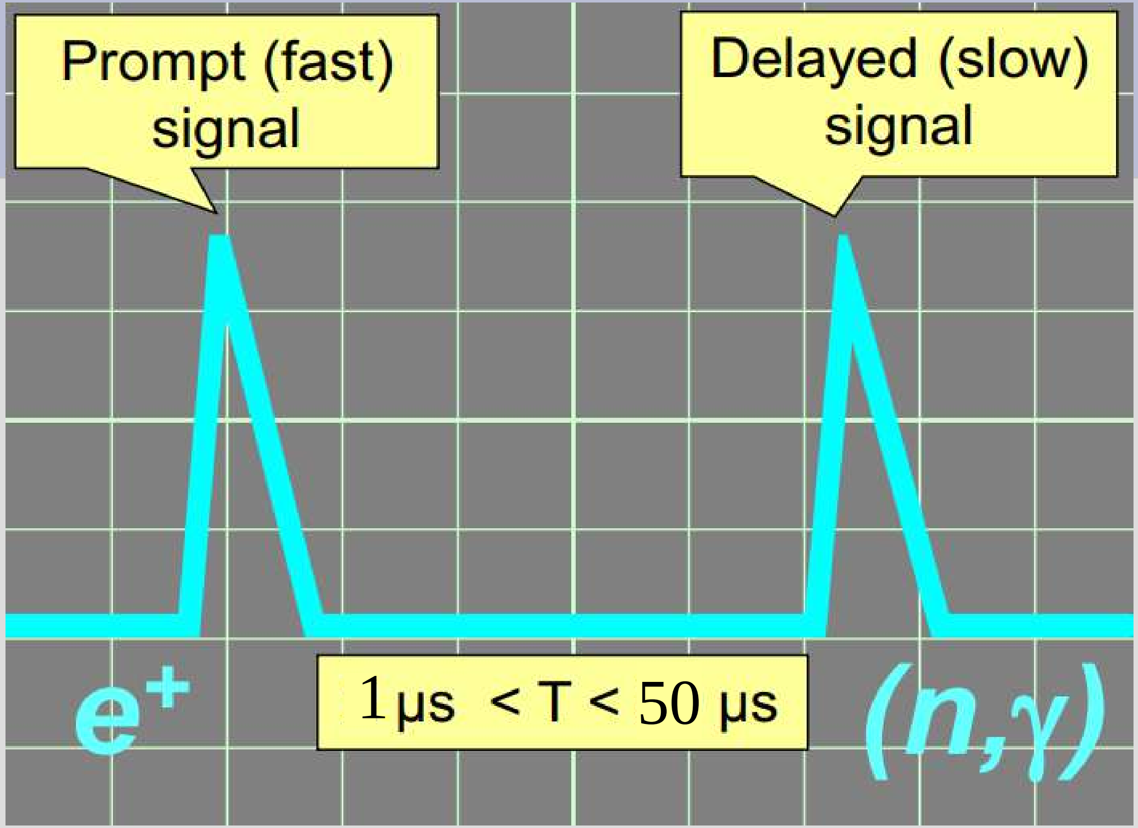
Meanwhile, somewhere in the future...

Ad here

Backup slides

IBD signal pattern & basic cuts





Main cuts:

- Prompt signal (E > 0.5 MeV)
- Delayed signal (E>2-4.5 MeV)
- Time between signals is in [1, 50] μs
- No muons before prompt signal in 90 μs

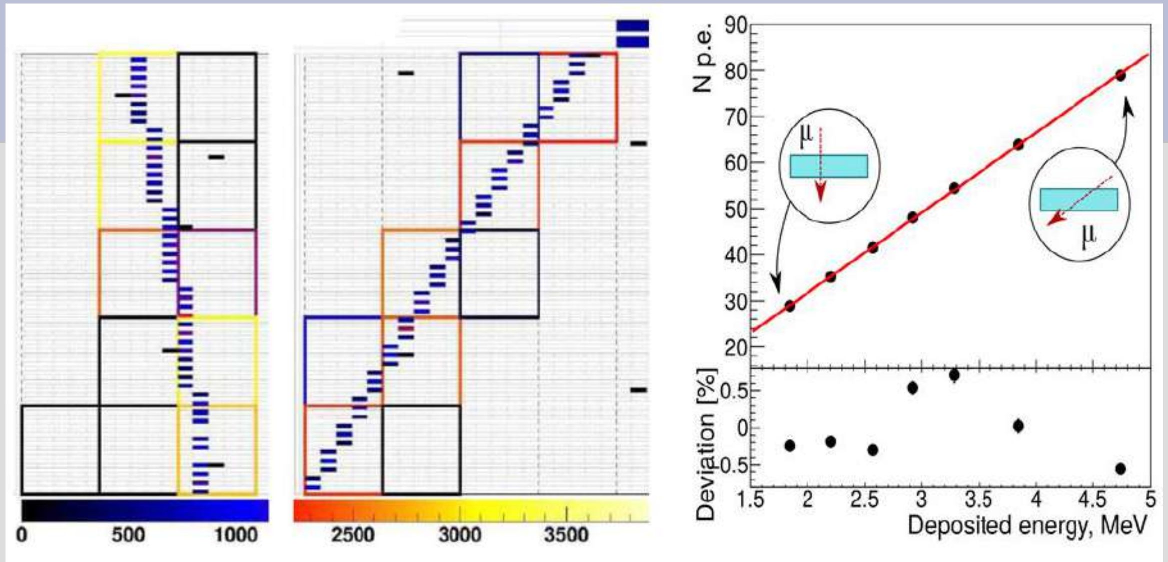
Additional cuts:

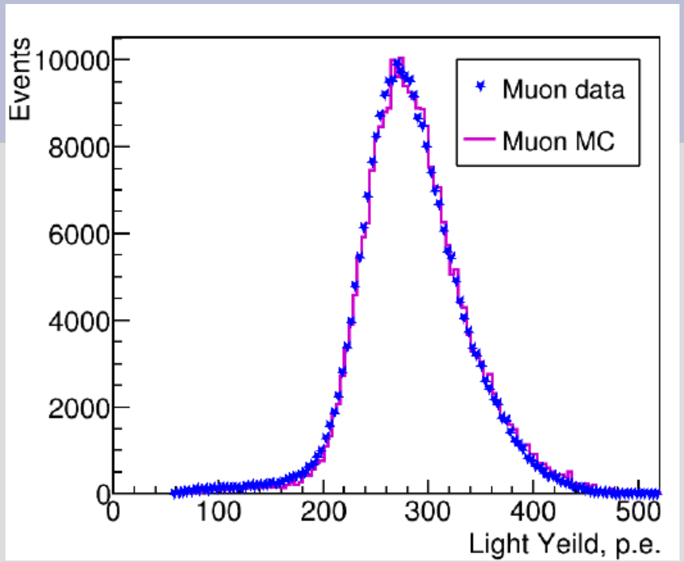
- Spatial cut on distance between fast and slow signal vertices
- Hit multiplicities for both signals
- Positron clustering pattern cuts
-

Detector Assembly

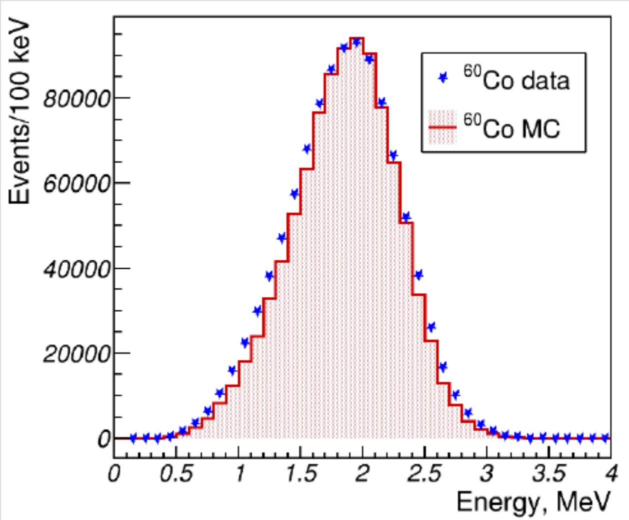
Calibration 1

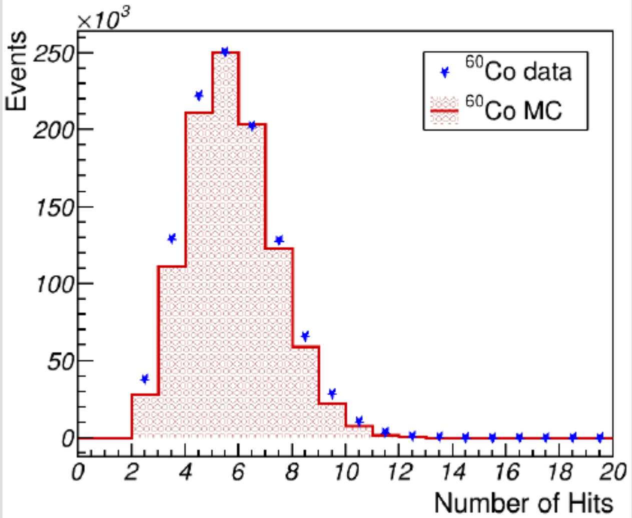
2500 SiPM gains and X-talks are calibrated **every 30-40 min**. All **2550 channel**s are calibrated **every 1-2 days** using cosmic muons

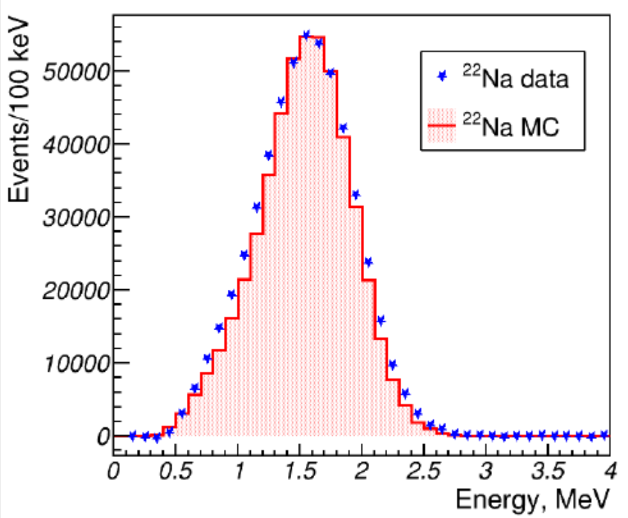




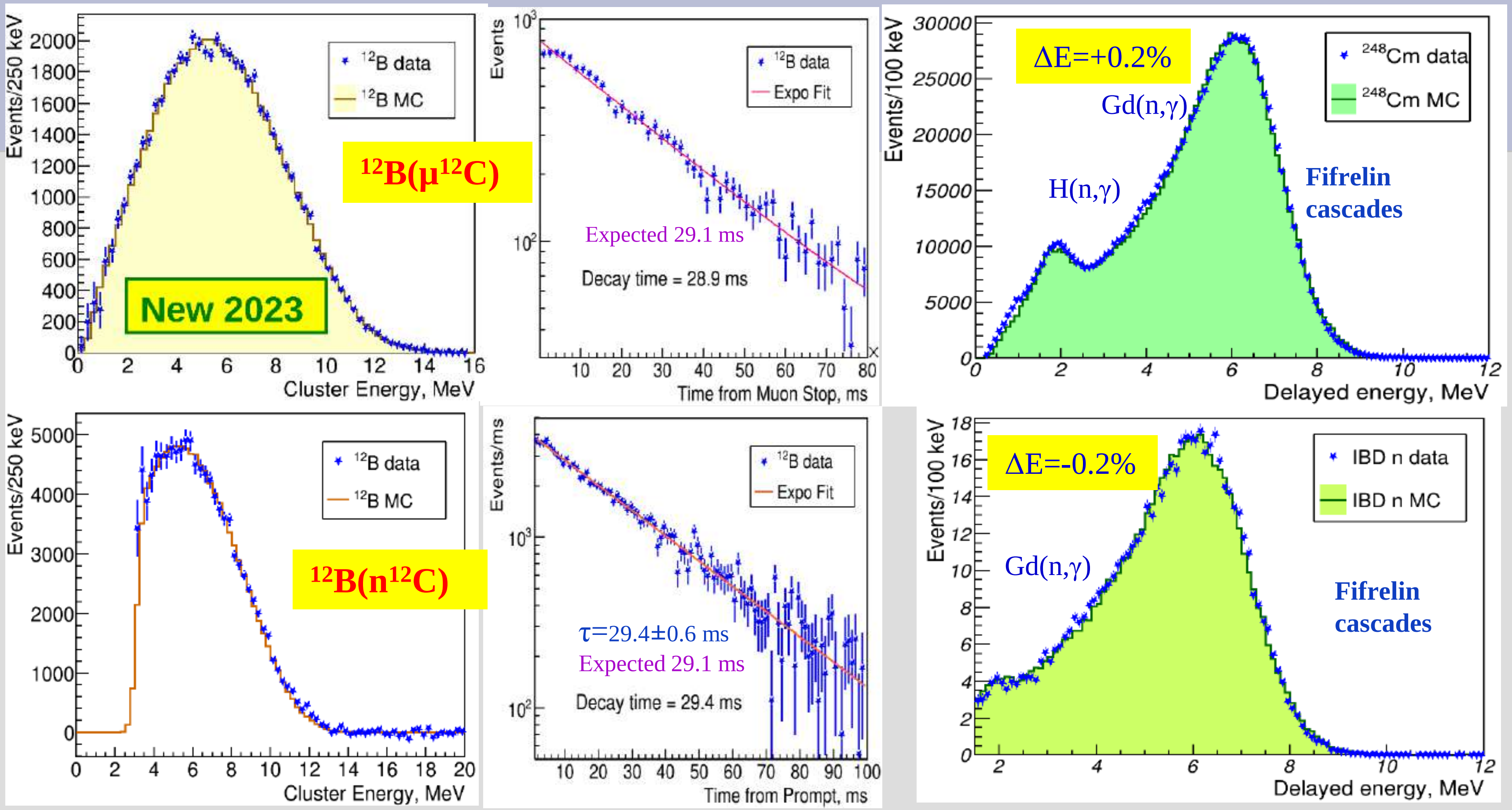
Several calibration sources are used to check the detector response





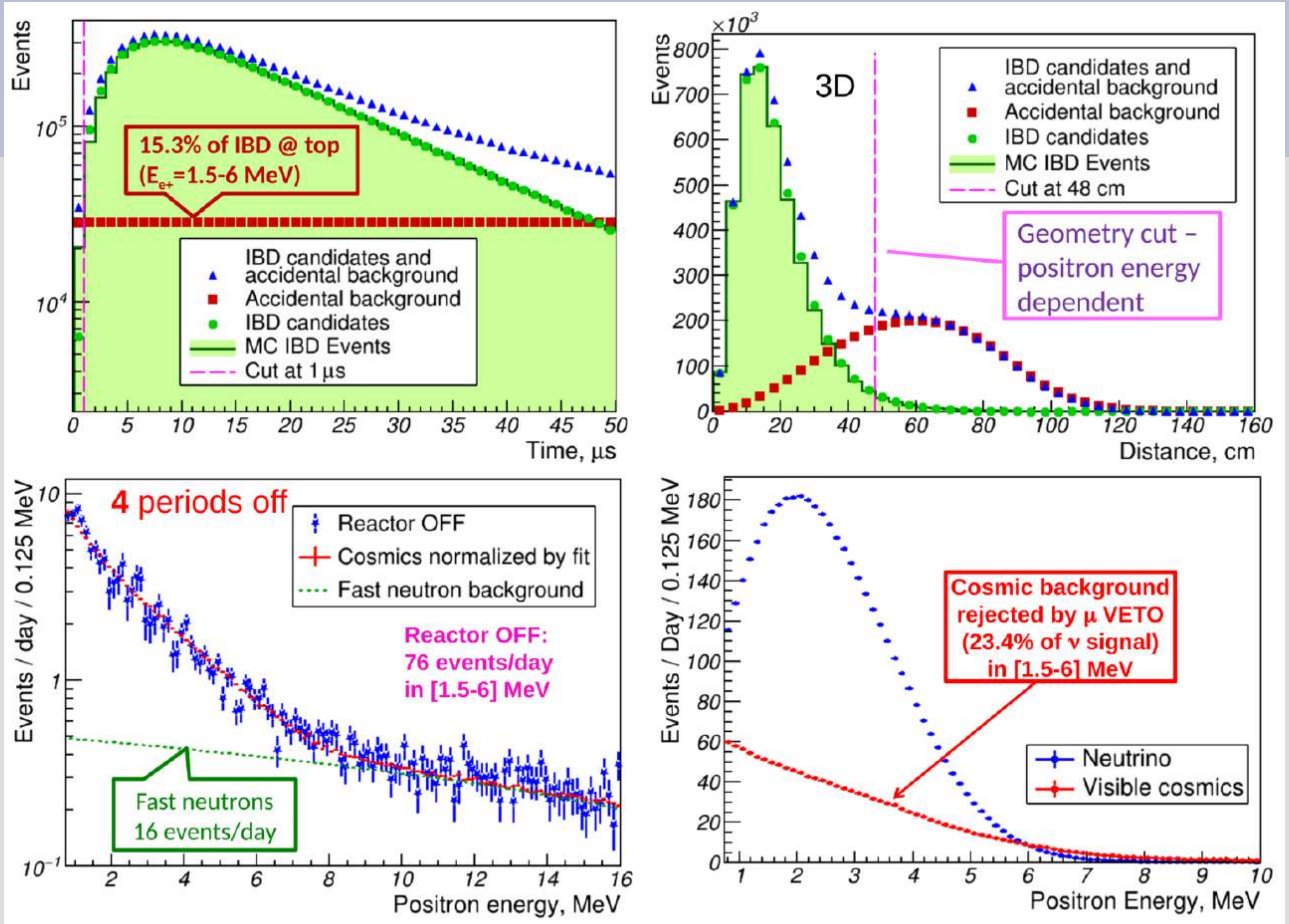


Calibration 2



- 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

Background


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

Analysis with absolute CR

$$\frac{dN(t)}{dt} = N_p \cdot \int_{E_{th}}^{E_{max}} \varepsilon \frac{1}{4\pi L^2} \sigma(E_\nu) \frac{d^2\phi(E_\nu, t)}{dEdt} \cdot P(L, E_\nu) dE$$

$$\frac{d^2\phi(E, t)}{dEdt} = \frac{W_{th}}{< E_{fis} >} \sum f_i \cdot s_i(E)$$

$$< E_{fis} > = \sum E_i \cdot f_i$$

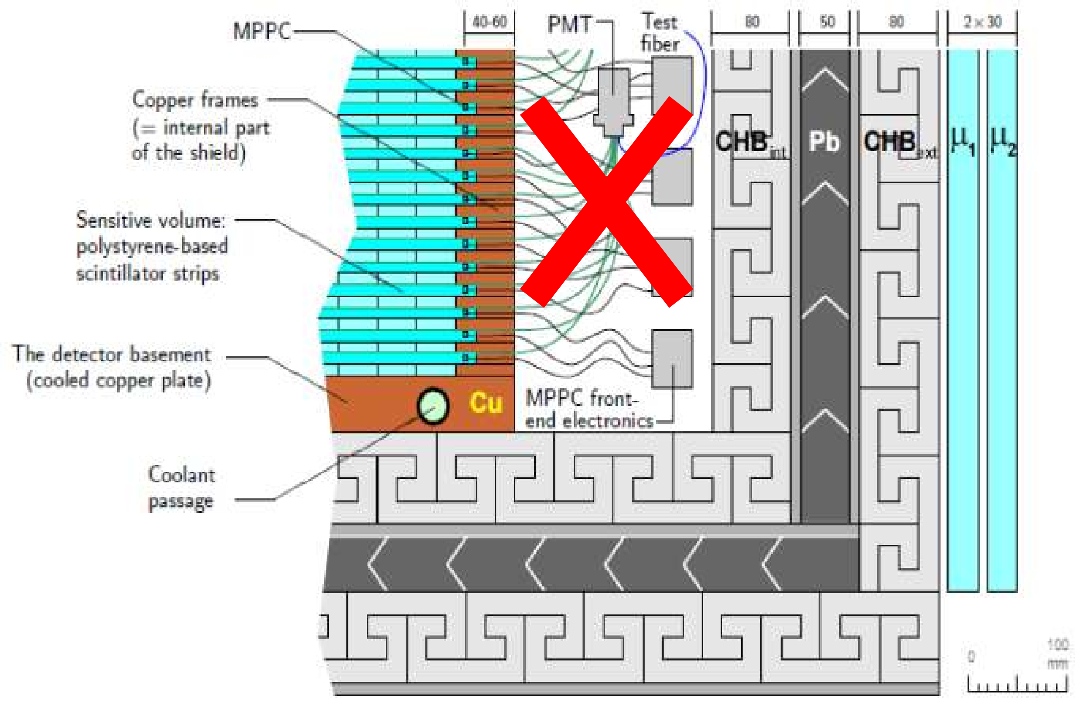
N_p – the number of target protons,
ε – detector efficiency,
L – the distance between the centers of the detector and the reactor core (distribution of fission points, reactor and detector sizes are taken into account)
$\sigma(E_\nu)$ – the IBD reaction cross section,
W_{th} – reactor thermal power (data from KNPP),
E_{fis} – energy released per fission (Phys. Rev. C 88, 014605),
f_i – fission fraction
s_i – $\tilde{\nu}_e$ energy spectrum per fission (Huber + Mueller and Kurchatov Institute models are considered),
P(E, L) is the survival probability due to neutrino oscillations

Systematic uncertainties in absolute CR

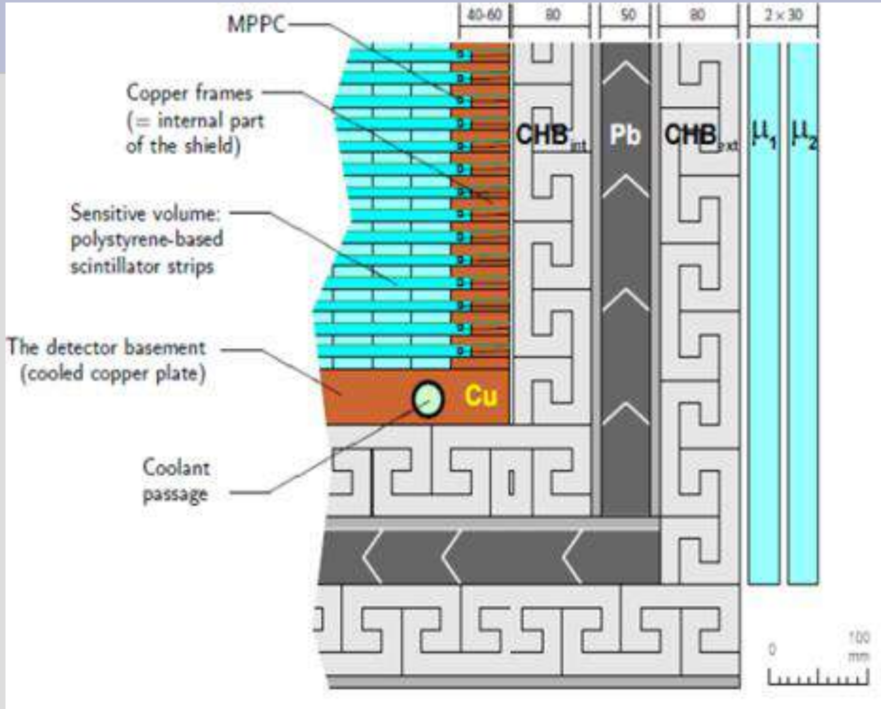
Source	Uncertainty
Number of protons	2%
Selection criteria	2%
Geometry (distance + fission points distribution)	1%
Fission fractions (from KNPP)	2%
Average energy per fission (Phys. Rev. C 88, 014605)	0.3%
Reactor power (from KNPP)	1.5%
Backgrounds	0.5%
Total	4%
Flux predictions	2-5%
Total with fluxes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

S3: no PMT for compactness

Current DANSS geometry



Future DANSS-2 & S3 geometries



- PMT must be removed as collecting fibers take too much space!
- To compact detector & shielding size one should use the SiPMs only!