The 24th International Workshop on Neutrino from Accelerators, Seoul, Korea, 25.08.2023

Latest results of the DANSS experiment

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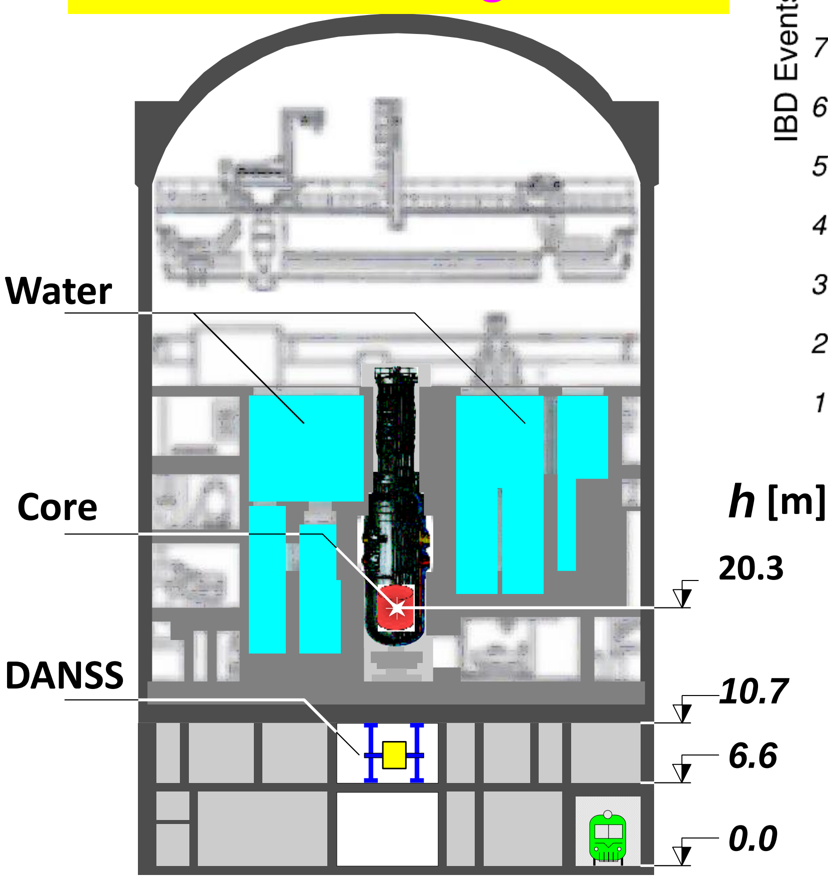
There are a few hints on sterile neutrinos with $\Delta m^2 \sim 1\ eV^2, sin^2 2\theta_{ee} \sim 0.1$

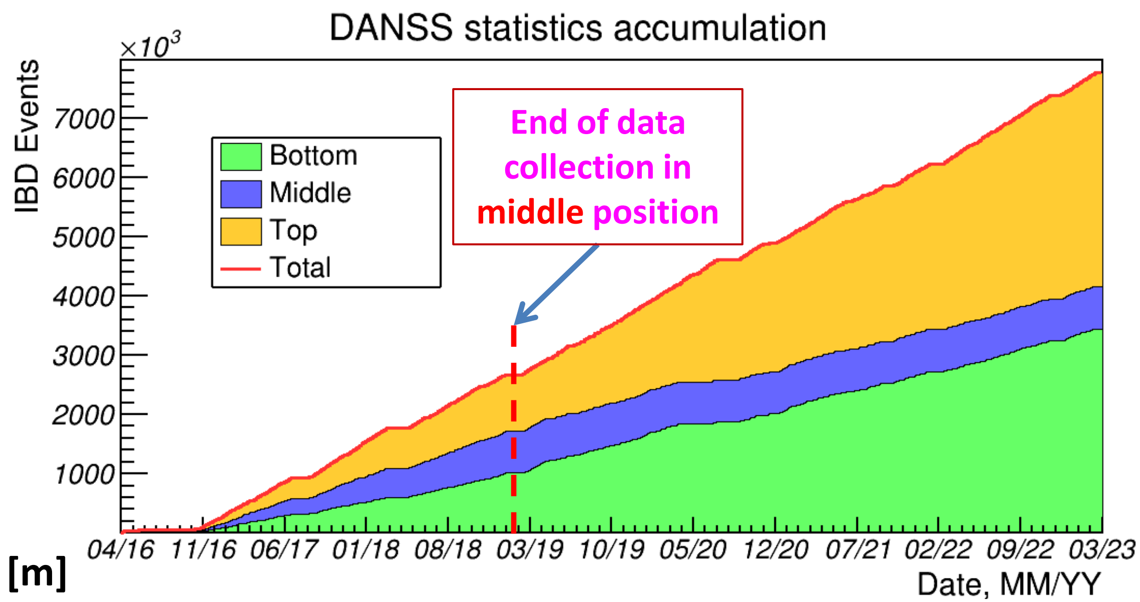
1. **LSND** and **MiniBoone** - $\nu_e(\overline{\nu_e})$ appearance in $\nu_\mu(\overline{\nu_\mu})$ beams: > 6σ
   Not confirmed, but not excluded by **MicroBoone**
   arXiv:2110.14054v2
2. **SAGE** and **GALEX** - ν_e deficit (GA) confirmed by **BEST**: > 5σ
   arXiv:2109.11482, arXiv:2201.07364, PRL 128.232501
3. Reactor $\overline{\nu_e}$ deficit (RAA): > 3σ
   Explained by **KI** (arXiv:2103.01684v1, **DayaBay** and **RENO** experiments ??
4. **Neutrino-4** claim of sterile neutrino observation with
   $\Delta m^2 = 7.3 \pm 1.17\ eV^2, sin^2 2\theta = 0.36 \pm 0.12$ 2.7σ
   Phys.Rev.D 104, 032003 (2021)

Here we work in **3+1ν** model where: $P_{\nu_\alpha \to \nu_\beta} \simeq sin^2 2\theta_{\alpha\beta} sin^2\left(\frac{\Delta m_{14}{}^2 L}{4E}\right)$

DANSS experiment

Detector arrangement:





Total statistics accumulated is 7.7 M IBD-events in 6.5 years and 4 reactor off periods

Delayed signal

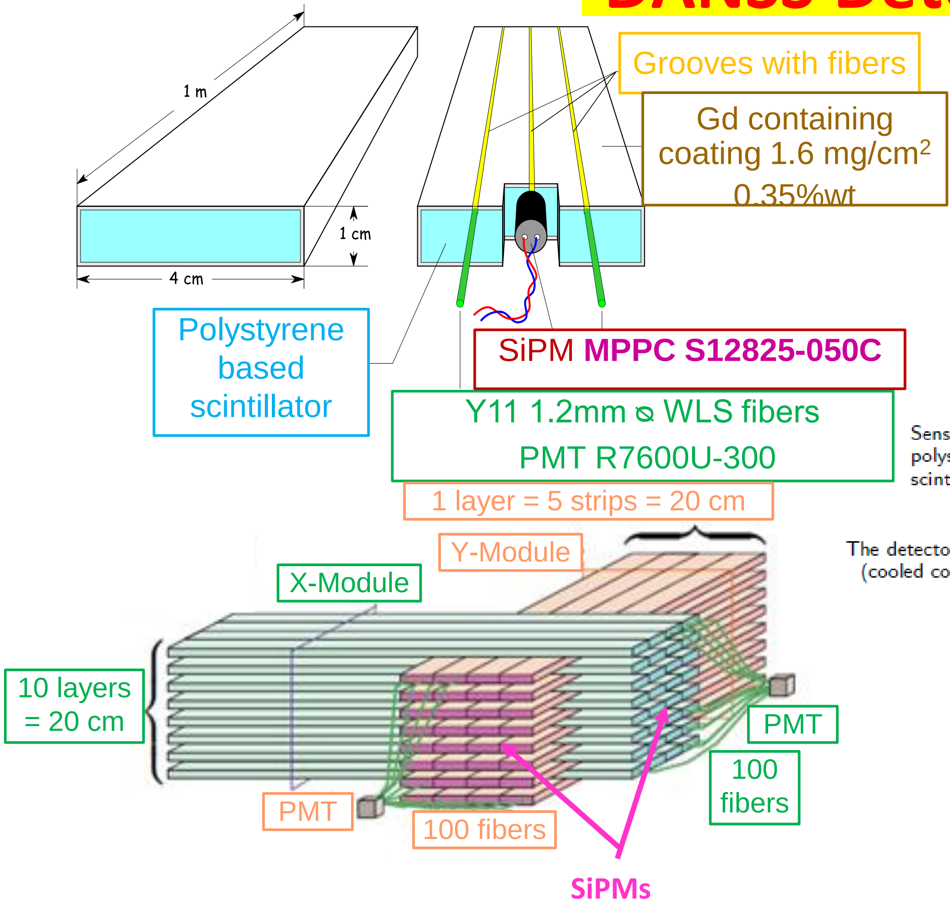
Fast signal

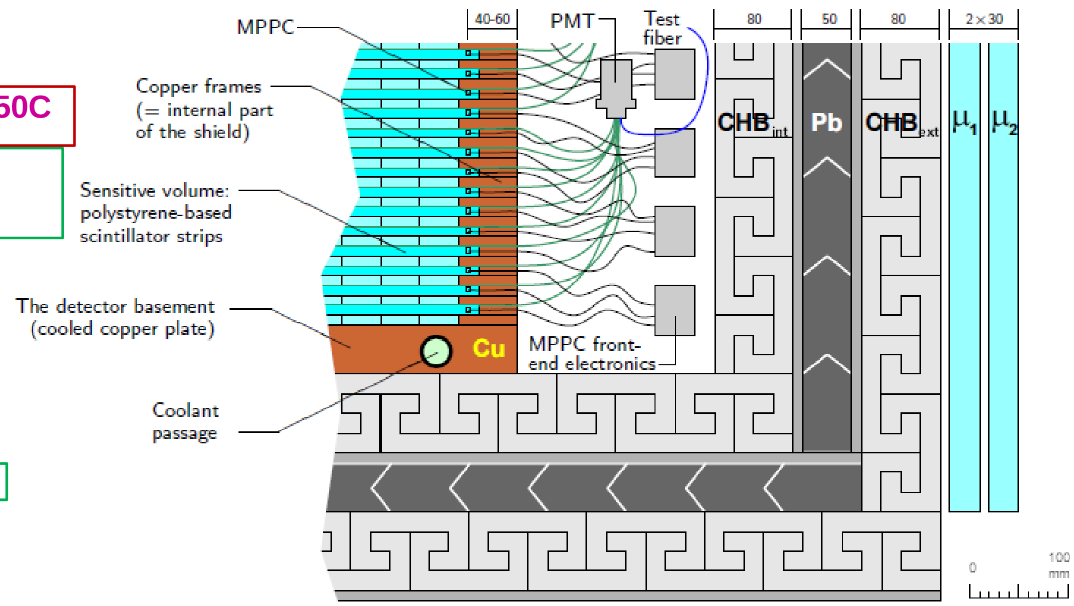
IBD reaction: $\tilde{\nu}_e + p \to n + e^+$

DANSS is installed on a movable platform under 3.1 GW WWER-1000 reactor (Core: h=3.7m, ∅=3.1m) at Kalinin NPP.
Detector distance from reactor core 10.9-12.9m (center to center) is changed 2-3 times a week

DANSS Detector design

JINST 11(2016)no11,P11011

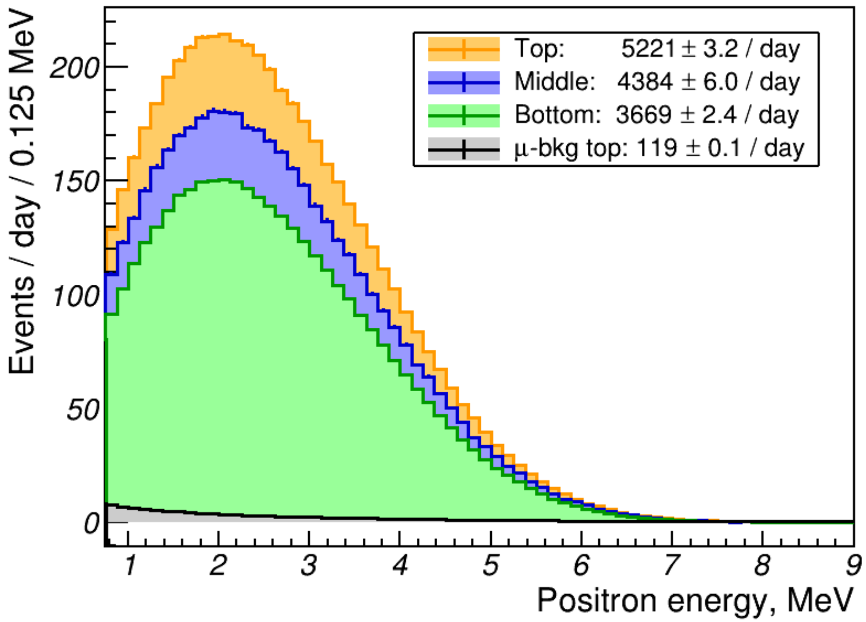




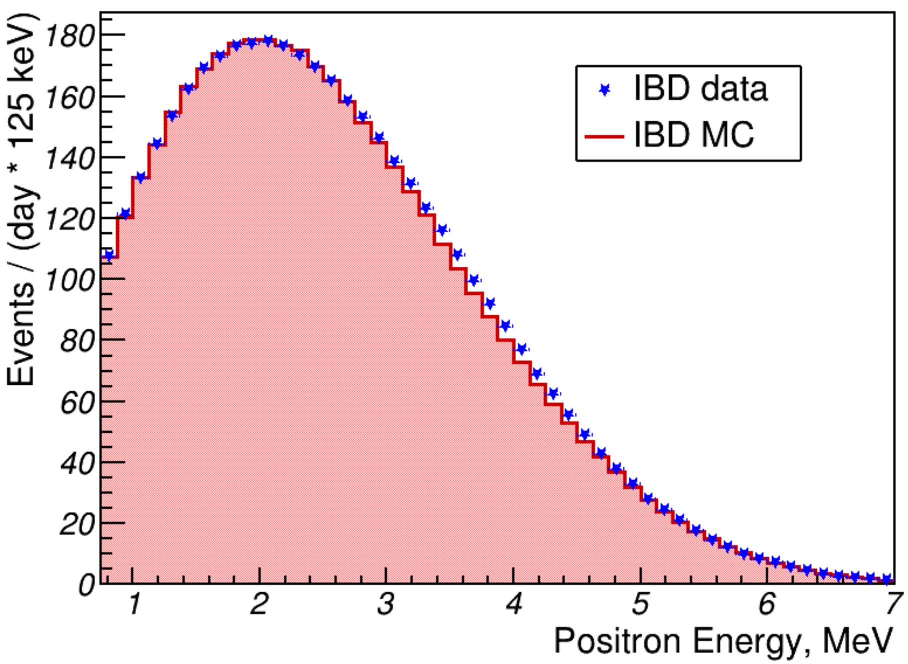
- 2500 scintillator strips with Gd containing coating for neutron capture
- Light collection with 3 WLS fibers
- Central fiber read out with individual SiPM
- Side fibers from 50 strips make a bunch of 100 on a PMT cathode = Module

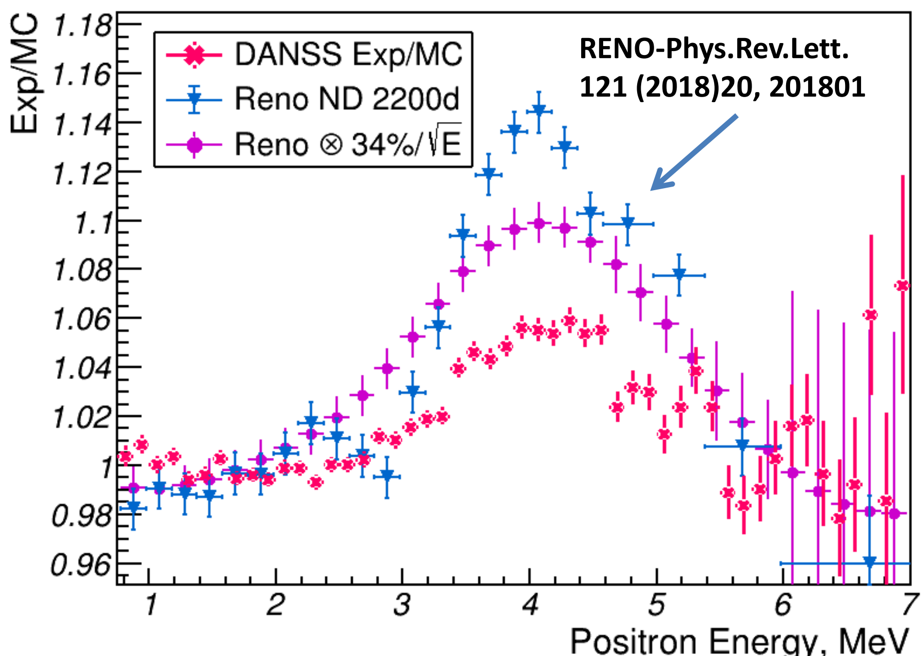
- Two-coordinate detector with fine segmentation – spatial information
- Multilayer closed passive shielding: electrolytic copper frame ~5 cm, borated polyethylene 8 cm, lead 5 cm, borated polyethylene 8 cm
- 2-layer active μ-veto on 5 sides

Positron spectra

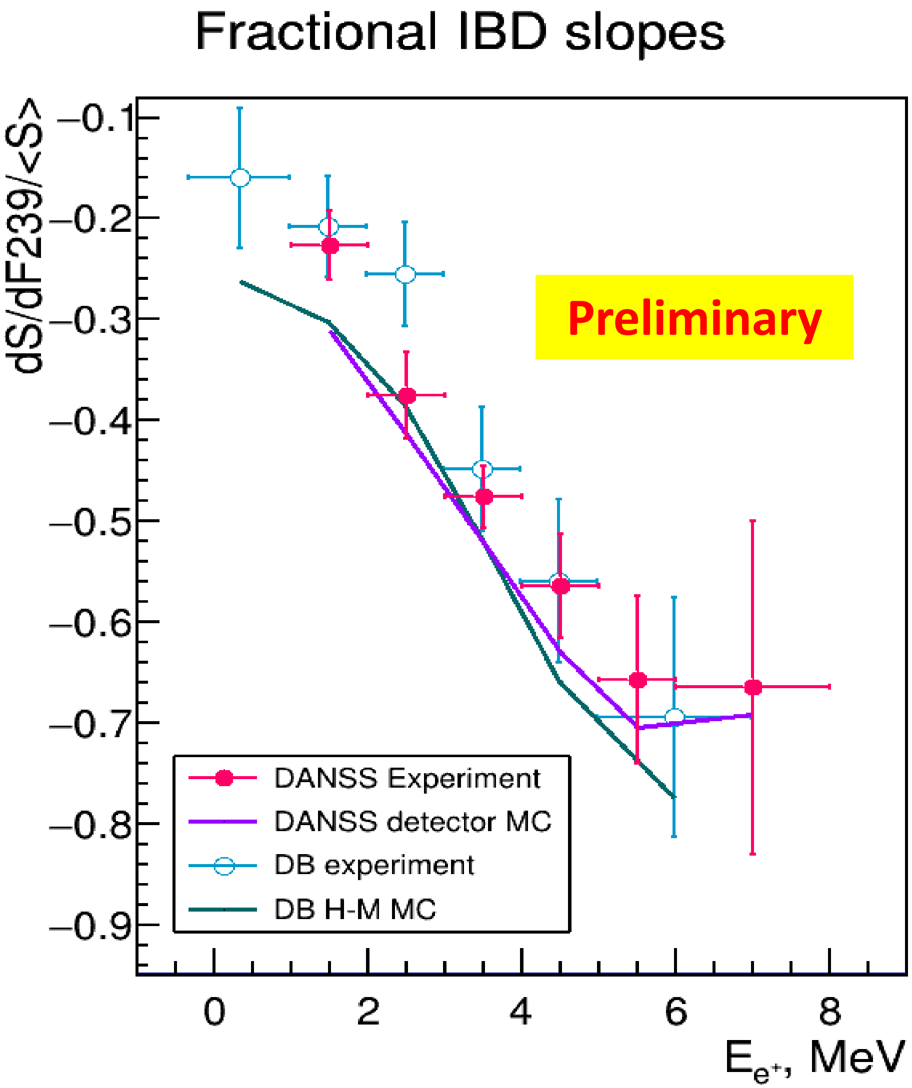


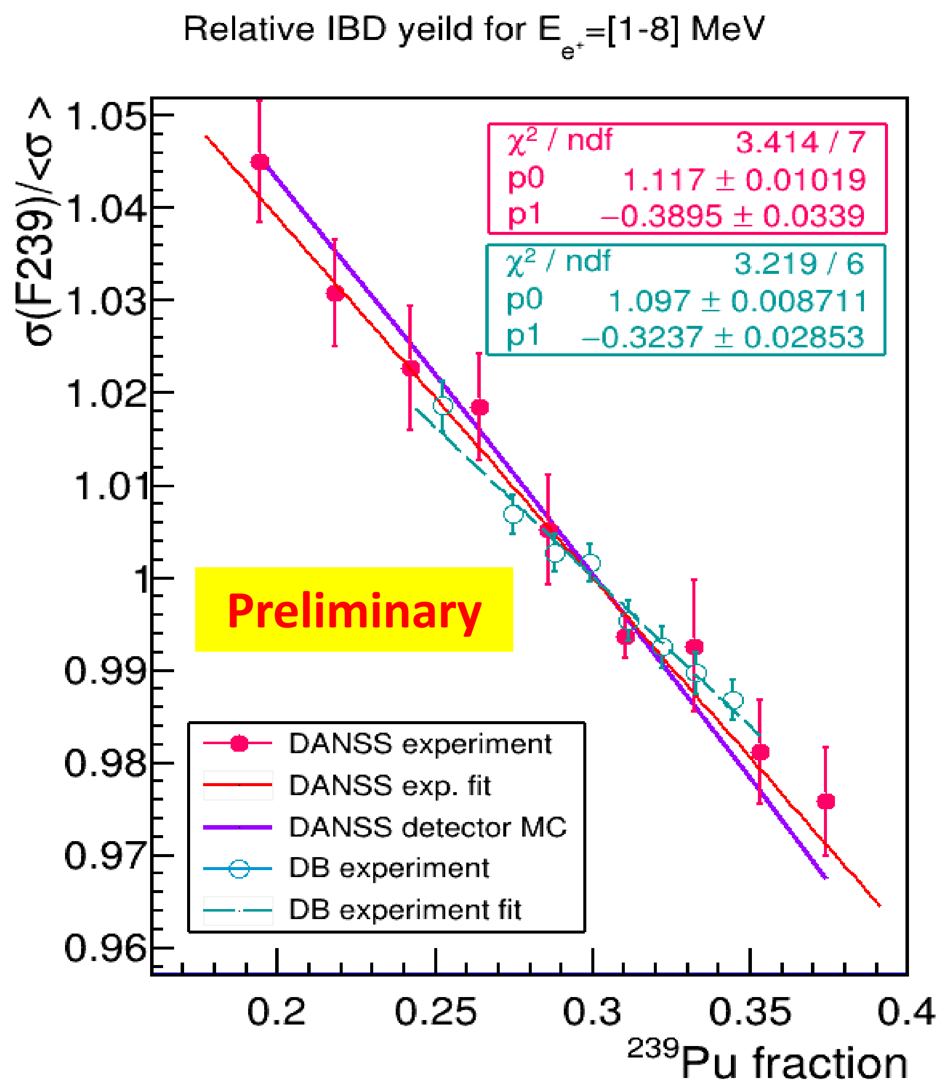
- Bump in e^+ spectrum at similar position to other experiments ($E_{prompt} = E_{e^+} + 1$ MeV) if E is shifted by -50 keV;
- Bump height is smaller than in RENO;
- However, we can not claim the bump existence because of high sensitivity of the shape to energy scale and shift;





Positron spectrum dependence on fuel composition





- **Fractional IBD slopes are closer to H-M model than DayaBay results;**
- **Errors are dominated by systematics estimated from the spread between campaigns and could be overestimated;**

Calculation of σ_5/σ_9 using the slope

$$N = \alpha \cdot (\sigma_8 f_8 + \sigma_1 f_1 + \sigma_5 f_5 + \sigma_9 f_9)$$

$$\frac{dN}{df_9} = \alpha \cdot \left(\sigma_8 \frac{df_8}{df_9} + \sigma_1 \frac{df_1}{df_9} + \sigma_5 \frac{df_5}{df_9} + \sigma_9 \right)$$

$$Sl = \left(\frac{dN}{df_9} \right) / N = \frac{\frac{\sigma_8}{\sigma_9}\frac{df_8}{df_9} + \frac{\sigma_1}{\sigma_9}\frac{df_1}{df_9} + \frac{\sigma_5}{\sigma_9}\frac{df_5}{df_9} + 1}{\frac{\sigma_8}{\sigma_9} f_8 + \frac{\sigma_1}{\sigma_9} f_1 + \frac{\sigma_5}{\sigma_9} f_5 + f_9}$$

$$\frac{\sigma_5}{\sigma_9} = -\frac{\frac{\sigma_8}{\sigma_9}(Sl \cdot f_8 - \frac{df_8}{df_9}) + \frac{\sigma_1}{\sigma_9}(Sl \cdot f_1 - \frac{df_1}{df_9}) + (Sl \cdot f_9 - 1)}{Sl \cdot f_5 - \frac{df_5}{df_9}}$$

Fuel fission fractions [%]

	Average	Start	End
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

(σ_8/σ_9 and σ_1/σ_9 are taken from HM)

DANSS result $\sigma_5/\sigma_9 = 1.53 \pm 0.09$ 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: $\sigma_5/\sigma_9 = 1.459 \pm 0.052.$

$\Rightarrow$ difference between DANSS and DB is due to slope

Maybe it's premature to say that RAA is solved by new σ_5/σ_9?

Test statistics

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

3 position data **2 position data** **Nuisance parameters (systematics and efficiency)**

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

$Z_j = R_j^{obs} - k_j \times R_j^{pre}(\Delta m^2,\ \sin^2 2\theta,\ \eta)$ 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, $k^0=1$ $\eta^0=0$

η – nuisance parameters;

W – covariance matrix;

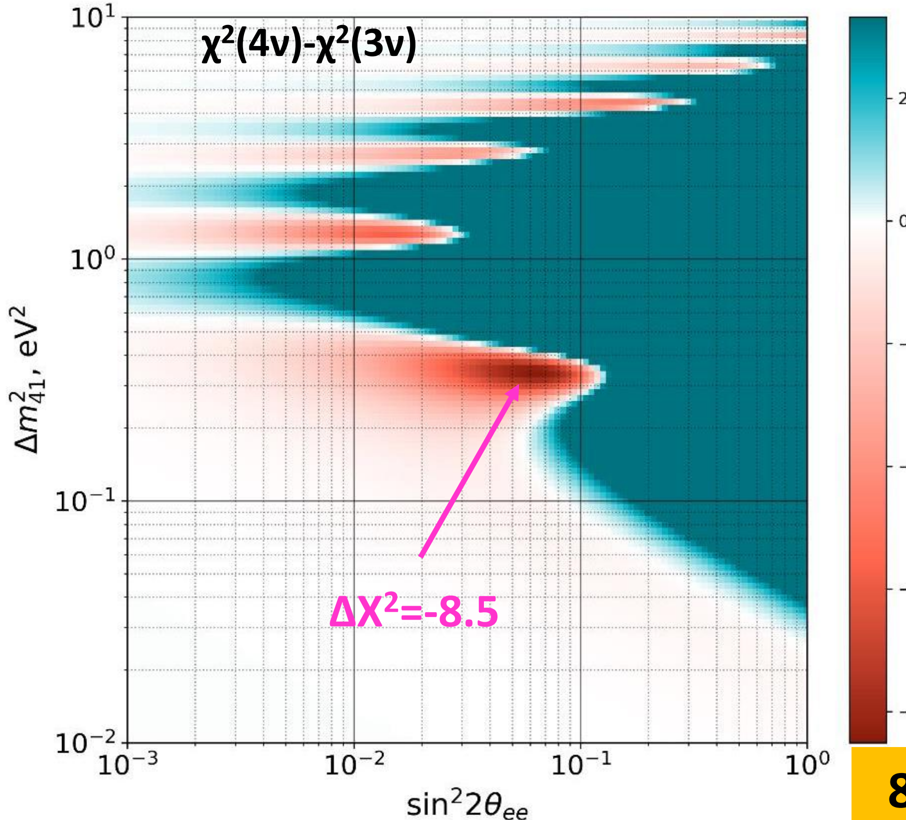
Difference in χ^2 between 4ν and 3ν hypotheses

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

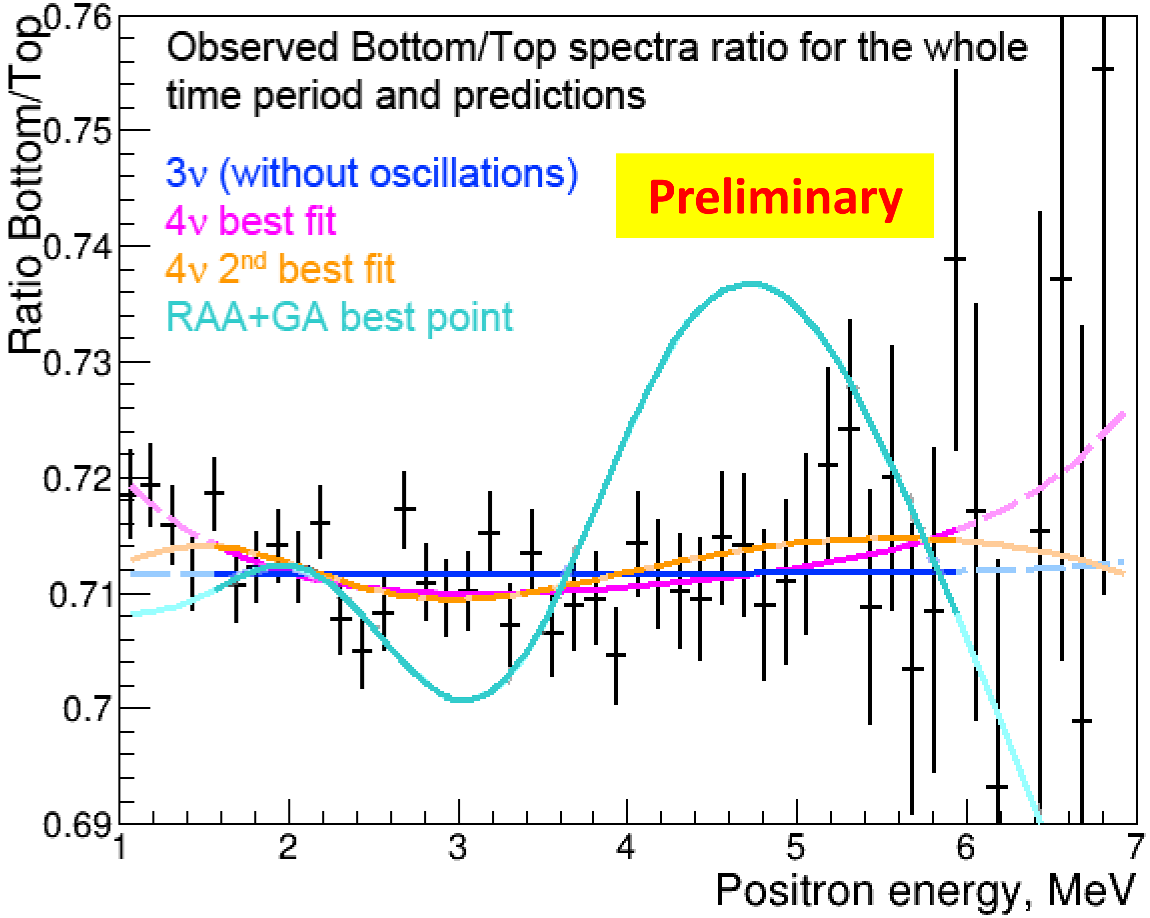
Blue – $\chi^2(4\nu)>\chi^2(3\nu)$,

Dark blue region is excluded at 3σ CL in case of χ^2 distribution with 2 DoF ($\chi^2(4\nu)-\chi^2_{min}$)=11.8

This assumption is not valid ➔ we use Gaussian CLs method to get limits



Bottom/top ratio of positron spectra



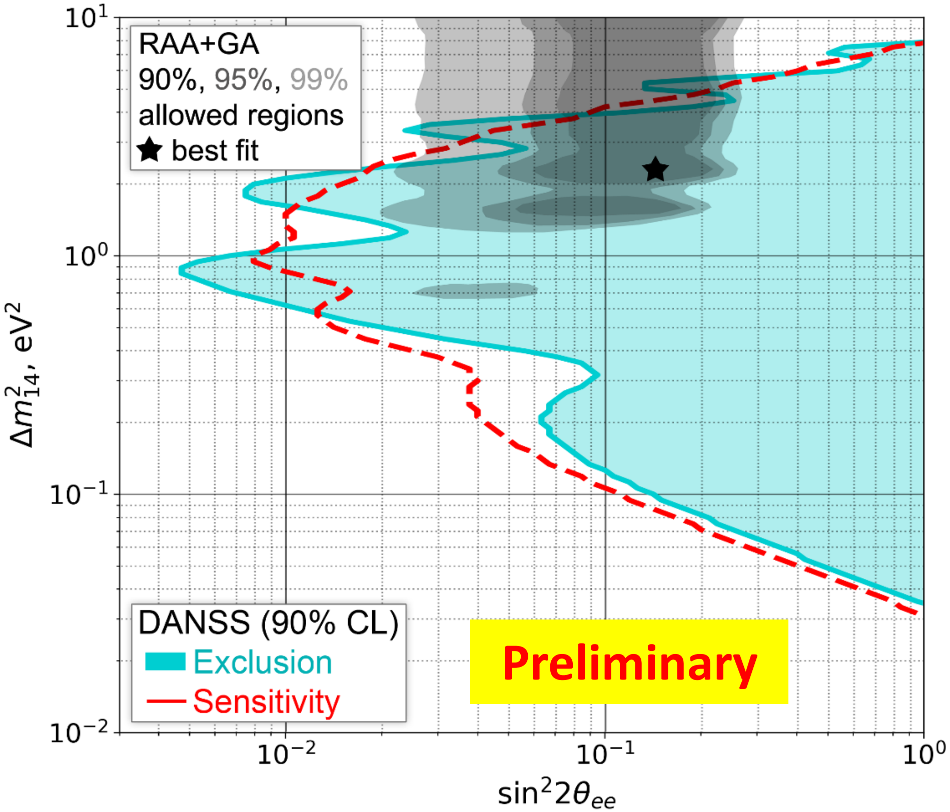
- **Fitting in 1.5 – 6 MeV range:** to cut influence of spent fuel in area $E_{e^+} < 1.5$ MeV that may case unreliable e^+ reconstruction **and** big statistical uncertainties at high energy region;
- **There is no statistically significant evidence in favor of 4ν signal:**

  $\Delta\chi^2$=-8.5 (2.1σ) for 4ν hypothesis best fit point $\Delta m^2 = 0.35\ eV^2$, $\sin^2 2\theta = 0.06$

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

RAA best point has been excluded with $\Delta\chi^2$= 155, but it was already excluded by DANSS with more than 5σ in 2018 (arXive:1804.04046v1)

DANSS limits on sterile neutrino parameters obtained in model independent way (without $\overline{\nu_e}$ spectrum information)



Systematic uncertainties:

- **Relative detector efficiencies at different positions (0.2%);**
- **Distance to the fuel burning profile center (5 cm);**
- **Cosmic background (25%);**
- **Fast neutrons background (30%);**
- **Additional smearing in energy resolution $(6\%/\sqrt{E} \oplus 2\%)$;**
- **Energy scale (2%);**
- **Energy shift (50 keV);**

Exclusion area was calculated using Gaussian CLs method using E_{e^+} in 1.5 – 6 MeV range;

The most stringent limit reaches at $\sin^2 2\theta < 5 \times 10^{-3}$ level;

A very interesting part of the 4 ν parameters was excluded;

Test statistics including neutrino absolute counting rates

Test statistics is defined as follows:

$$\chi^2_{rel} = \min_{\eta,k} \sum_{i=1}^{N_{bins}} \left(Z_{1i} \quad Z_{2i}\right) \cdot W^{-1} \cdot \begin{pmatrix} Z_{1i} \\ Z_{2i} \end{pmatrix} + \sum_{i=1}^{N_{bins}} \frac{Z_{1i}^2}{\sigma_{1i}^2} + \sum_{j=1,2} \frac{(k_j - k_j^0)^2}{\sigma_{kj}^2} + \sum_{l} \frac{(\eta_l - \eta_l^0)^2}{\sigma_{\eta l}^2}$$

phase I
Top, Middle, Bottom

phase II
Top, Bottom

penalty
terms

i – energy bin (36 total) in range 1.5–6 MeV,
$Z_j = R_j^{\mathrm{obs}} - k_j \times R_j^{\mathrm{pre}}(\Delta m^2,\ \sin^2 2\theta,\ \eta)$ for each energy bin, (obs for observed, pre for predicted),
$R_1 = Bottom/Top$, $R_2 = Middle/\sqrt{Bottom \cdot Top}$, where
Top, $Middle$, $Bottom$ – absolute count rates per day for each detector position,
k – relative efficiency (nominal values $k_1^0 = k_2^0 = 1$),
$\eta(\eta^0)$ – other nuisance parameters (and their nominal values),
W – covariance matrix to take into account correlations in spectra ratios at different positions (Z_1 and Z_2),
N – total absolute rates.

With absolute counting rates:

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

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

Calculation of predicted neutrino counting rates

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

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

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

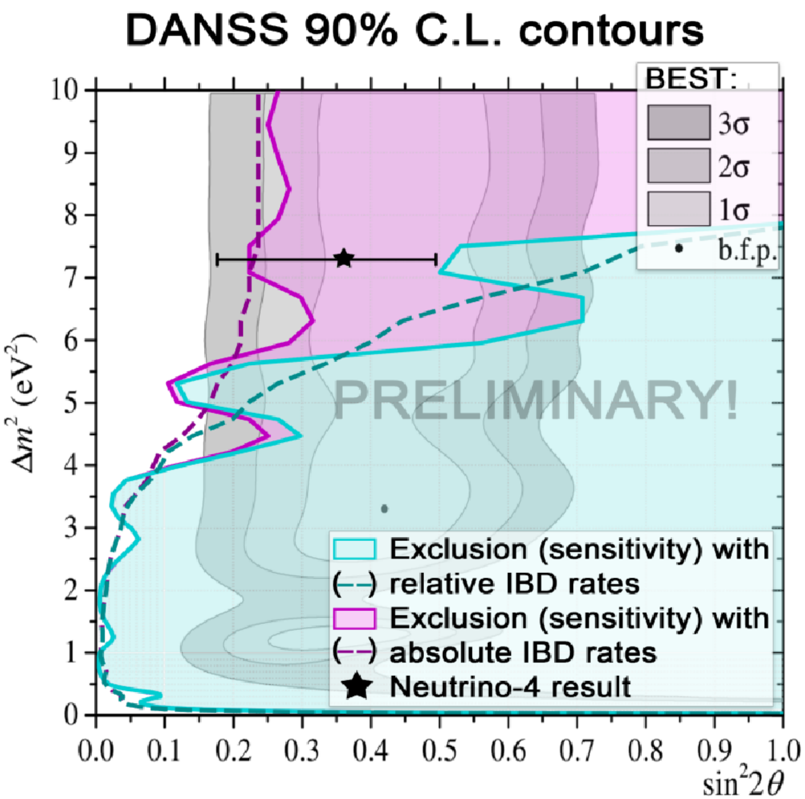
N_p – the number of target protons,
ε – detector efficiency,
L – the distance between the centers of the detector and the reactor core (distribution of fission points, reactor and detector sizes are taken into account)
$\sigma(E_\nu)$ – the IBD reaction cross section,
W_{th} – reactor thermal power (data 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 neutrino counting rates

Source	Uncertainty
Number of the 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%
Background	0.5%
Total	4%
Flux predictions	2-5%
Total with fluxes	5-7%

Results with neutrino absolute counting rates

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 $\tilde{\nu}_e$ counting rates



A large and the most interesting fraction of available parameter space for sterile neutrino was excluded with model-independent analysis.

Absolute counting rates: all systematic uncertainties discussed earlier are included

flux uncertainty is 5%, total: 7%

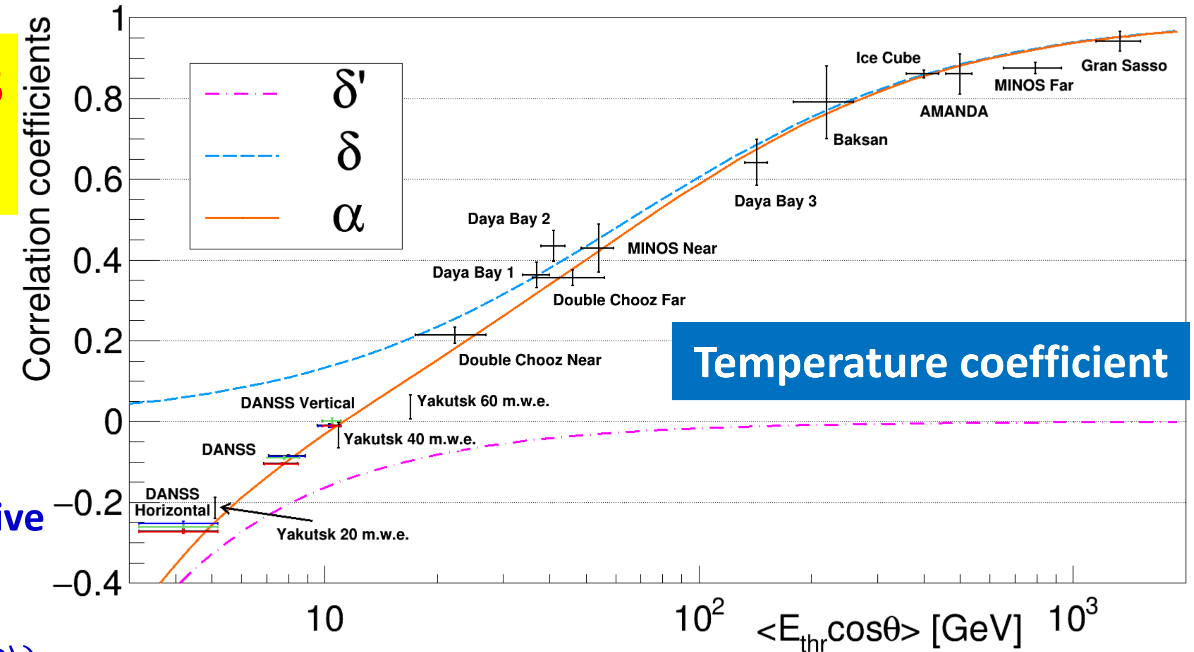
Exclusions for large Δm^2_{41} are consistent with previous results (Daya Bay, Bugey-3, ...)

Our preliminary results exclude the dominant fraction of BEST expectations as well as best fit point of Neutrino-4 experiment. In KI model exclusions are even more more strict.

These results depend on the predictions of the $\tilde{\nu}_e$ flux from reactors, for which we assumed a conservative unsertainty of 5%.

Meteorological effects on cosmic muon flux

Eur. Phys. J. C (2022) 82: 515



Total effect on cosmic muons in effective temperature approach:

$$\frac{I-\langle I\rangle}{\langle I\rangle} = \alpha\frac{T_{eff}-\langle T_{eff}\rangle}{\langle T_{eff}\rangle} + \beta(P-\langle P\rangle),$$

where:

I – muon counting rate;

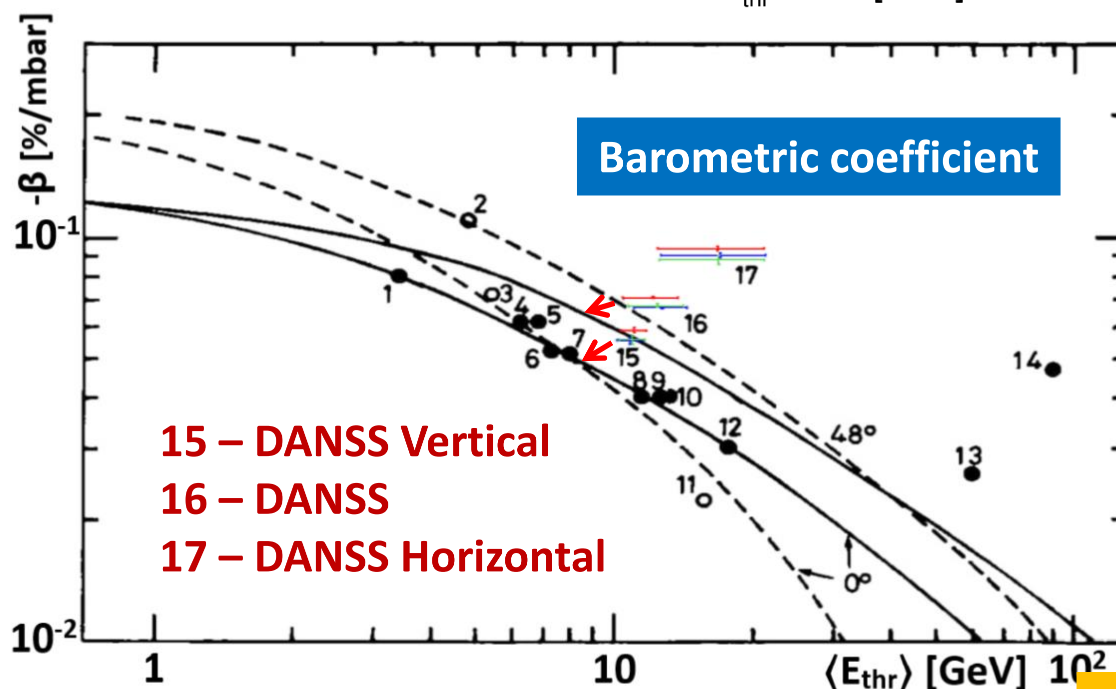
T_{eff} - effective temperature of the atmosphere;

P – atmospheric pressure in ground level;

α – temperature coefficient;

β – barometric coefficient;

- All values of α are in perfect agreement with theory curve;
- β values are ~ 30% above model predictions!



Temperature and barometric effects on cosmic muons in effective level of generation approach

Sum of both effects:

$$\frac{I-\langle I\rangle}{\langle I\rangle} = \beta(P-\langle P\rangle) + \mu'(H_{100}-\langle H_{100}\rangle) + \\ + \mu''(T_{100}-\langle T_{100}\rangle),$$

where:

I – muon counting rate

T_{100} - temperature of the 100 mb level;

H_{100} - height of the 100 mb level;

P – atmospheric pressure on ground level;

$\beta(<E_{thr}>)$ – barometric correlation coefficient;

$\mu'(<E_{thr}>)$ – height correlation coefficient;

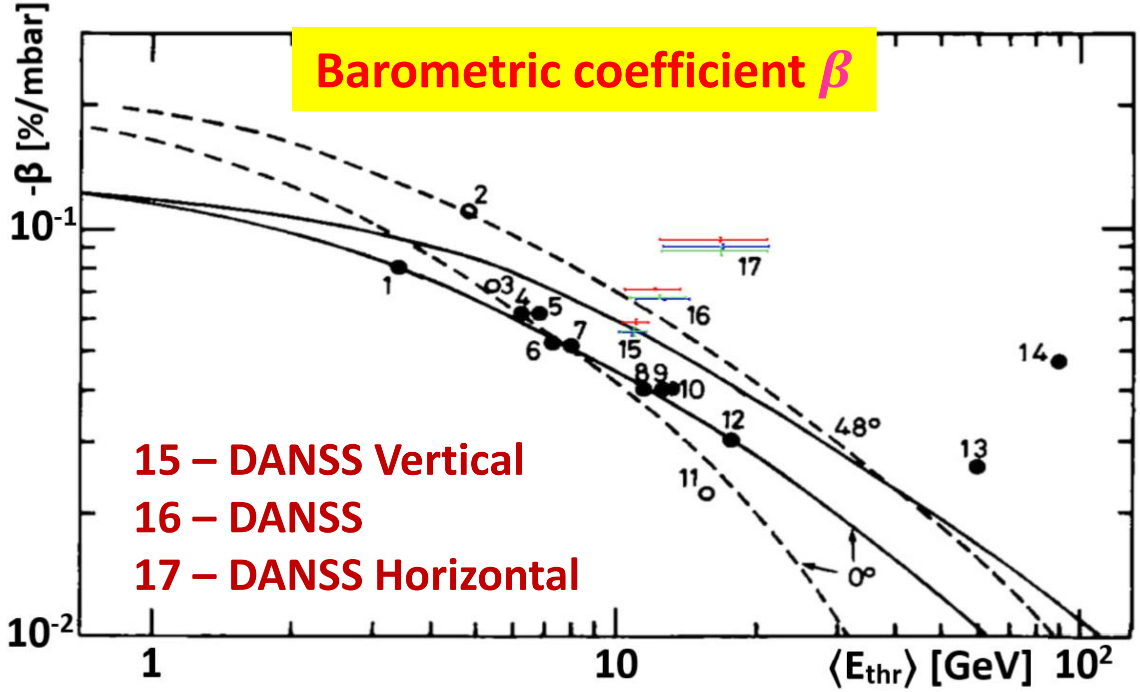
$\mu''(<E_{thr}>)$ – temperature correlation coefficient;

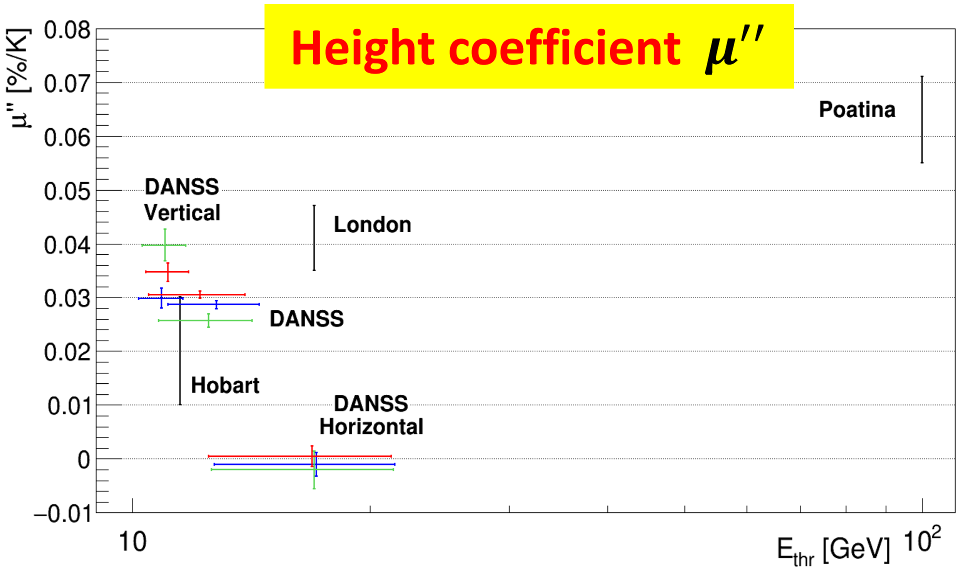
E_{thr} – muon threshold energy;

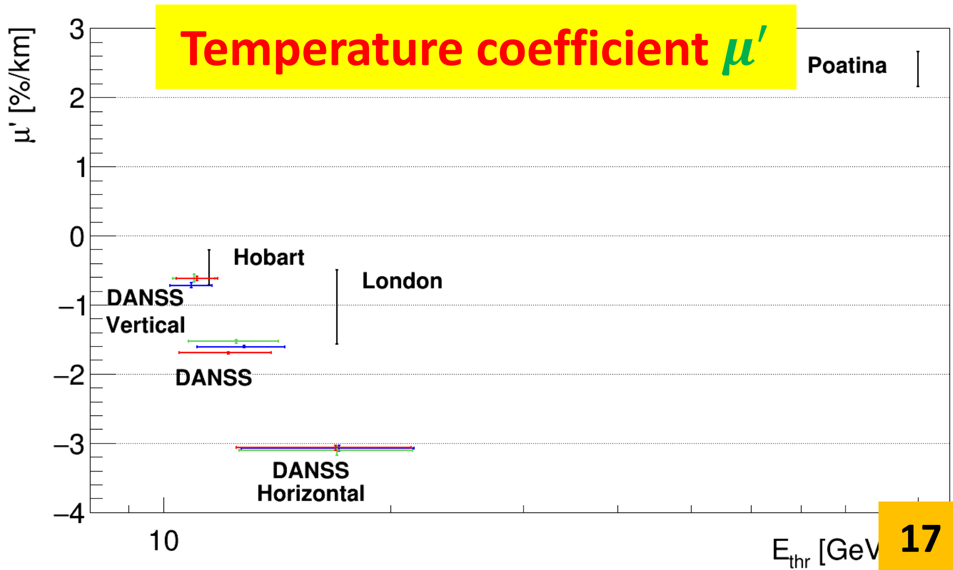
Comparison with theory and other experiments

- μ'' and μ' are in good agreement with other experiments;
- β values are still $\sim 30\%$ above model predictions;

(arXive:2307.04899v1)

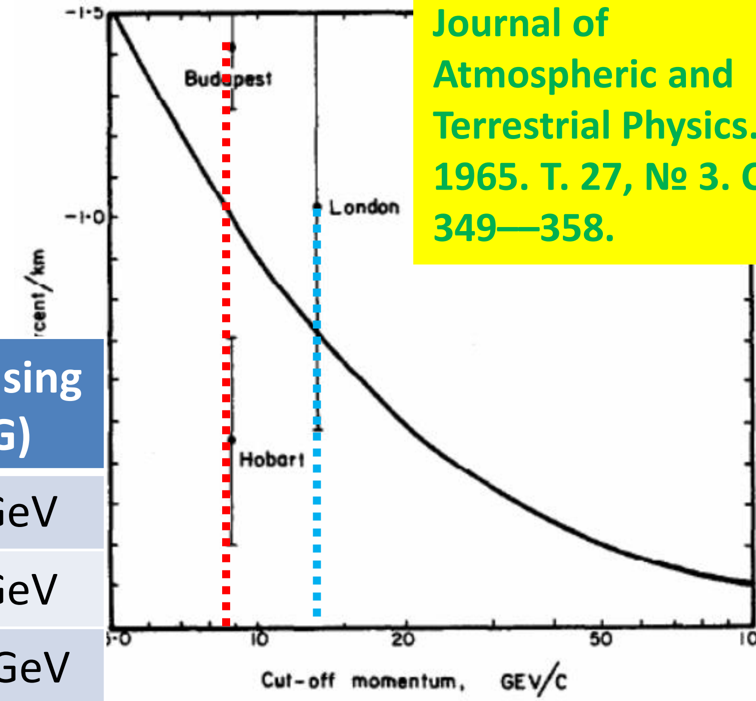






Possible explanation: not equal converting from m.w.e. to GeV

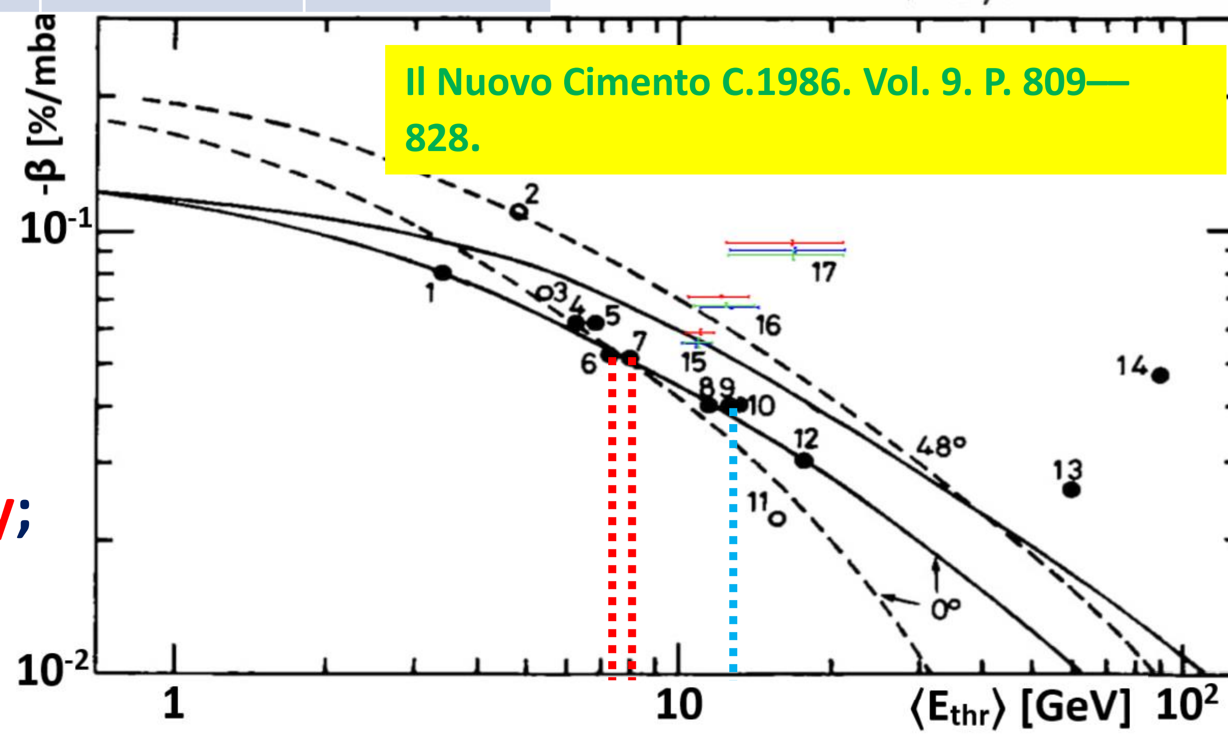
	E_{thr} (m.w.e)	E_{thr} (London)	E_{thr} (Sagisaka)	E_{thr}(using PDG)
Budapest	40	~9 GeV	~ 8 GeV	9.3 GeV
Hobart	42	~ 9 GeV	~ 7 GeV	9.8 GeV
London	60	12-14 GeV	12-14 GeV	14.3 GeV



Journal of Atmospheric and Terrestrial Physics. 1965. T. 27, № 3. C. 349—358.

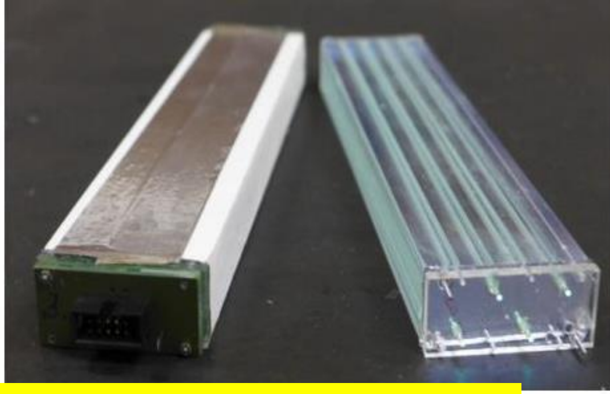
Difference between E_{thr} is up to ~ 30%!!!

If we shift our results to the left on 30% it would be much closer to theory;



Il Nuovo Cimento C.1986. Vol. 9. P. 809—828.

Plans for the DANSS upgrade

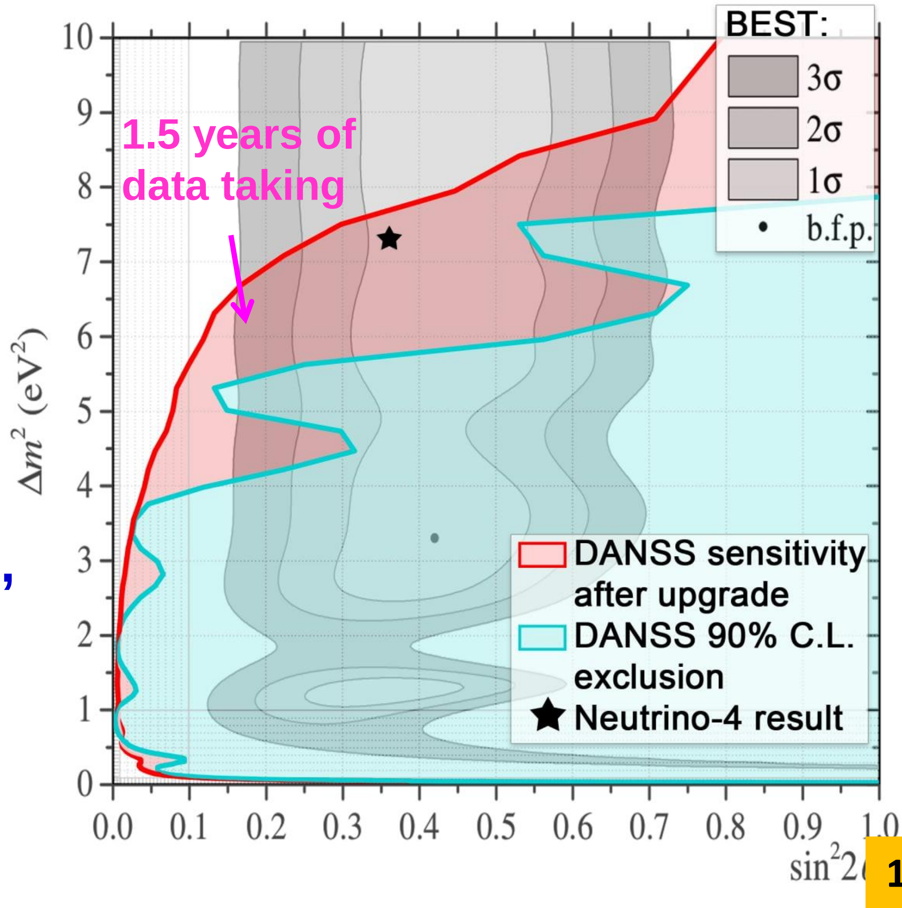


Main goal is to reach energy resolution $12\%/\sqrt{E}$ (now it only $33\%/\sqrt{E}$)

New design:

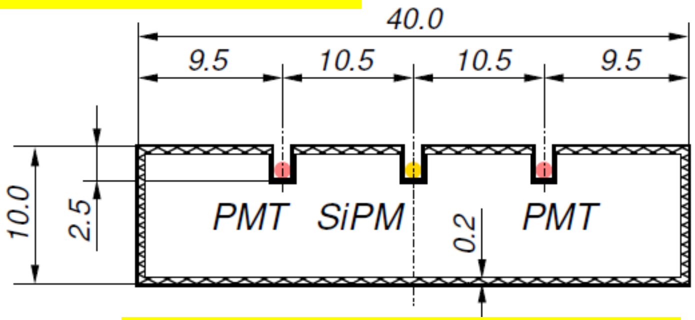
- **Same passive shielding;**
- **Same lifting system;**
- **Same digitizing system;**
- **No PMT readout;**
- **New strips – 2x5x120 cm, with 2-side 4SiPM readout;**
- **New structure: 60 layers x 24 strips, sensitive volume – 1.7 m^3;**
- **Gd-contained film between layers;**

DANSS sensitivity after the upgrade



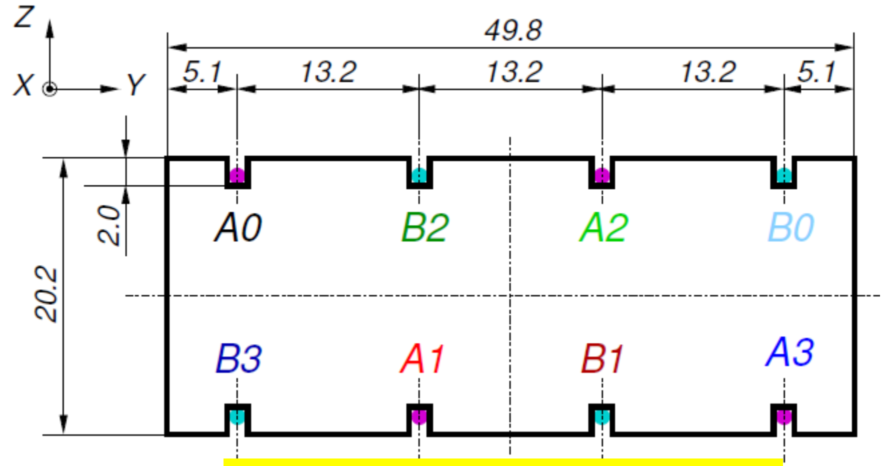
New strip design

JINST 17(2022) P04009



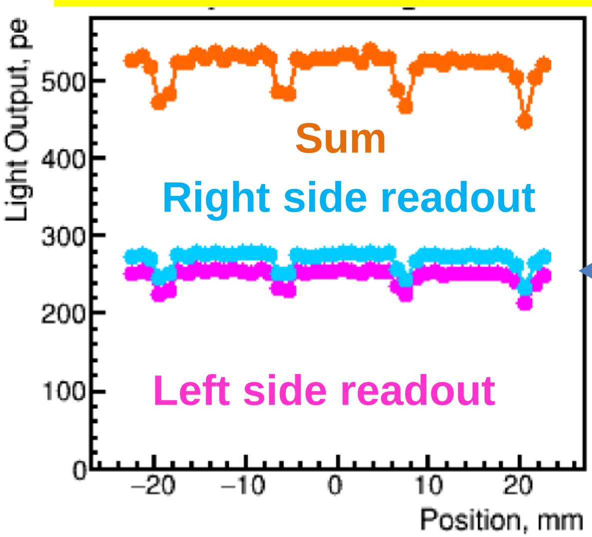
Old strip

Size: 1x4x100 cm
3 grooves for fibers
Coating with Gd
Coating with TiO2
One side readout
Y11 WSF

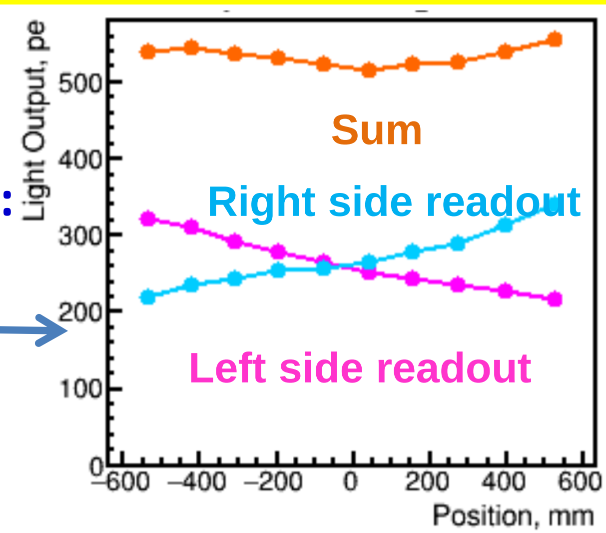


New strip

Size: 2x5x120 cm
8 grooves for fibers with 8 SiPM
Gd-contained film between layers
Chemical foaming
Two side readout
New WSF (JINST 17 P01031, 2022)

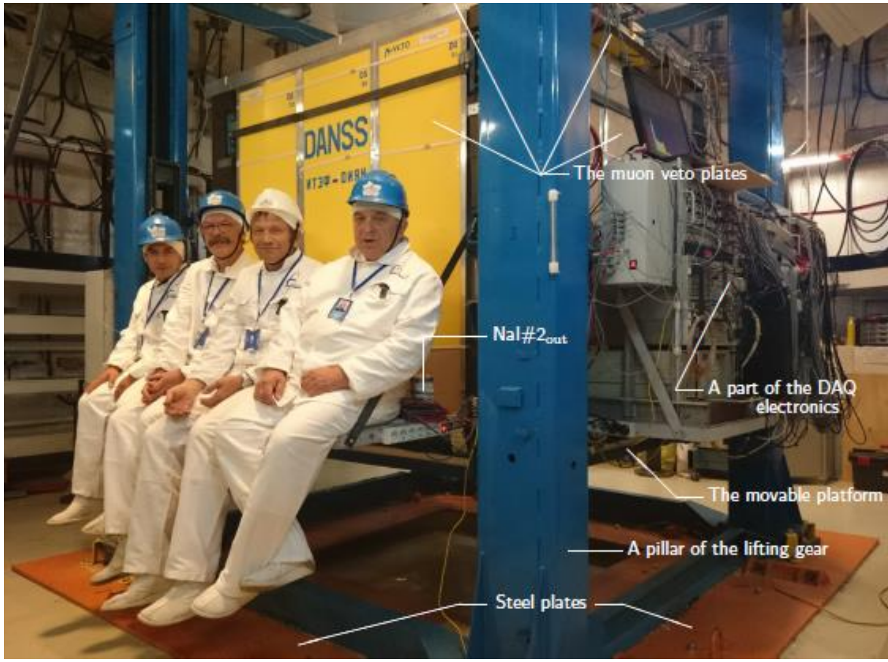


Strip scanning on μ-beam:
Transverse profile
Longitudinal profile



Summary

- DANSS collects more than 7.7M of IBD events;
- The σ235/σ239 was measured. It's consistent with H-M model and larger than DayaBay result;
- Indication of 5 MeV bump, but not conclusive;
- Big part of the available parameters of sterile neutrino was excluded in model independent way, including large fraction of the BEST preferred area and its best fit point;
- Analysis with absolute neutrino counting rate excluded almost all sterile neutrino parameter space preferred by BEST;
- We found possible explanation of discrepancy between experimental value of barometric correlation coefficient for cosmic muons β and model predictions;



Our plans:

To take data till the start of the upgrade

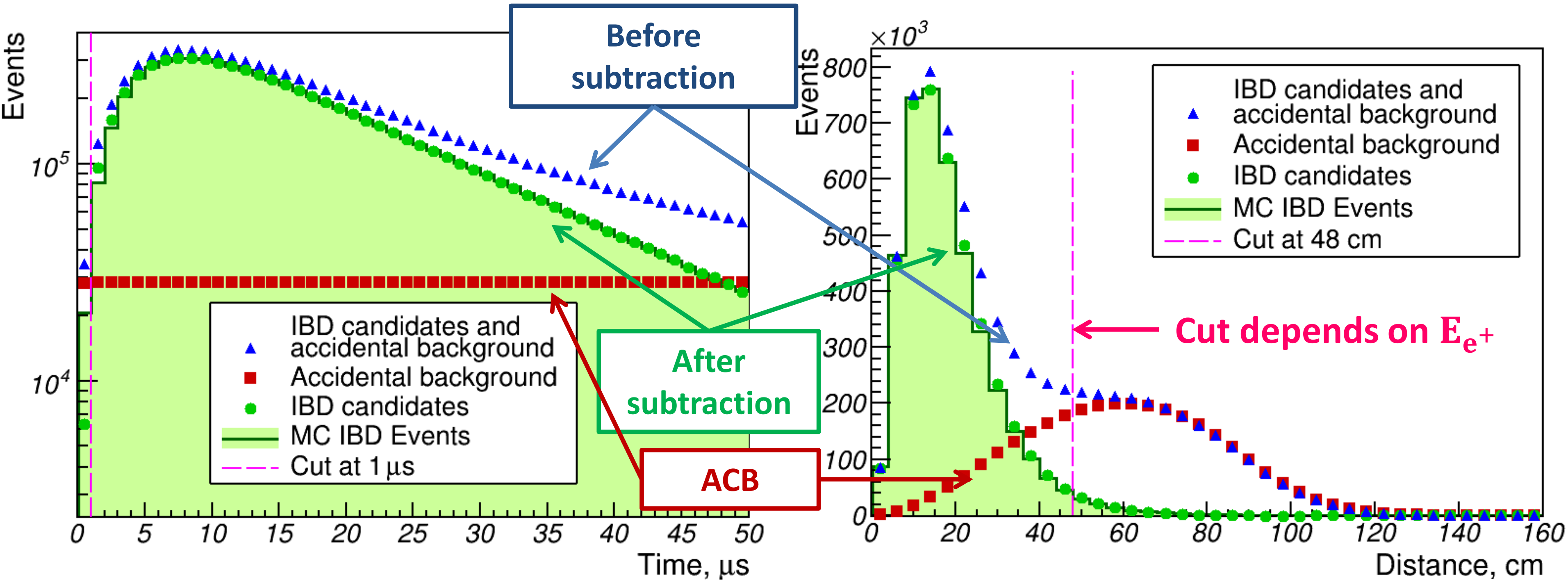
To upgrade detector

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

To measure reactor characteristics using ν

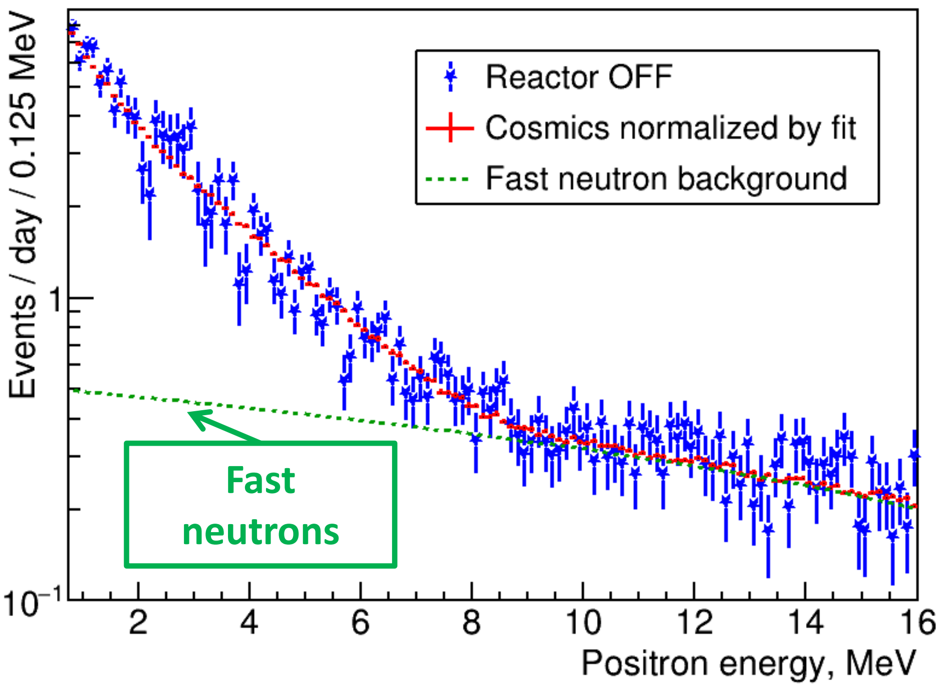
Backup slides

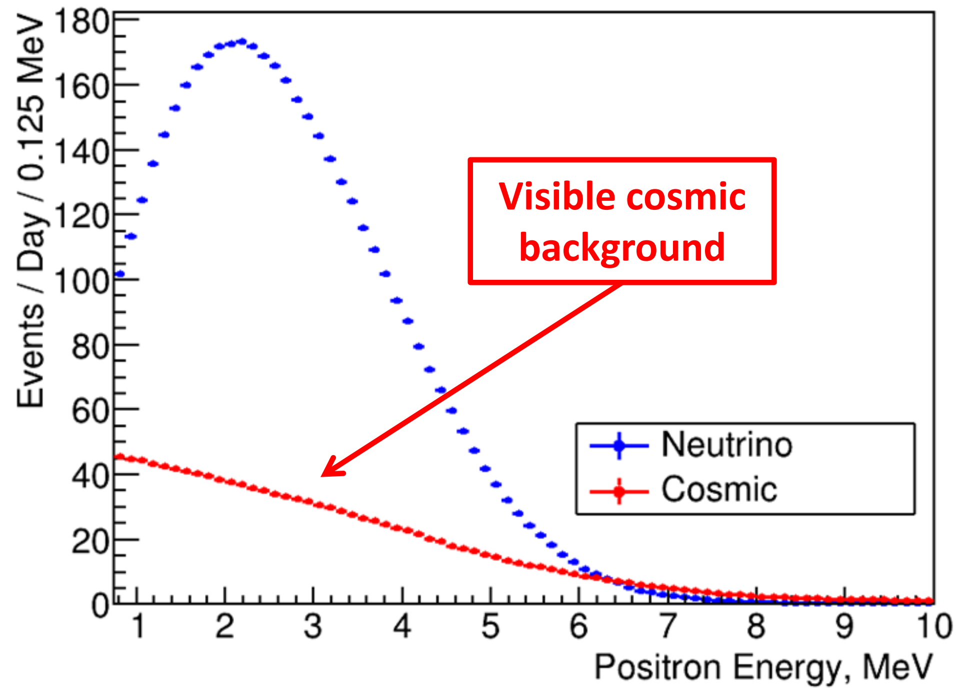
Accidental coincidence background



- Accidental coincidence background (ACB) is the coincidence of 2 uncorrelated e^+-like and n-like signals in IBD time window (1-50 μs);
- 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;
- ACB rate is 15.3% of IBD rate (in Top position and time window 1-50 μs, for $1.5\ \mathrm{MeV} < \mathrm{E}_{e^+} < 6\ \mathrm{MeV}$);
- Cuts (like geometric) allow to reduce ACB;

Background from the other sources

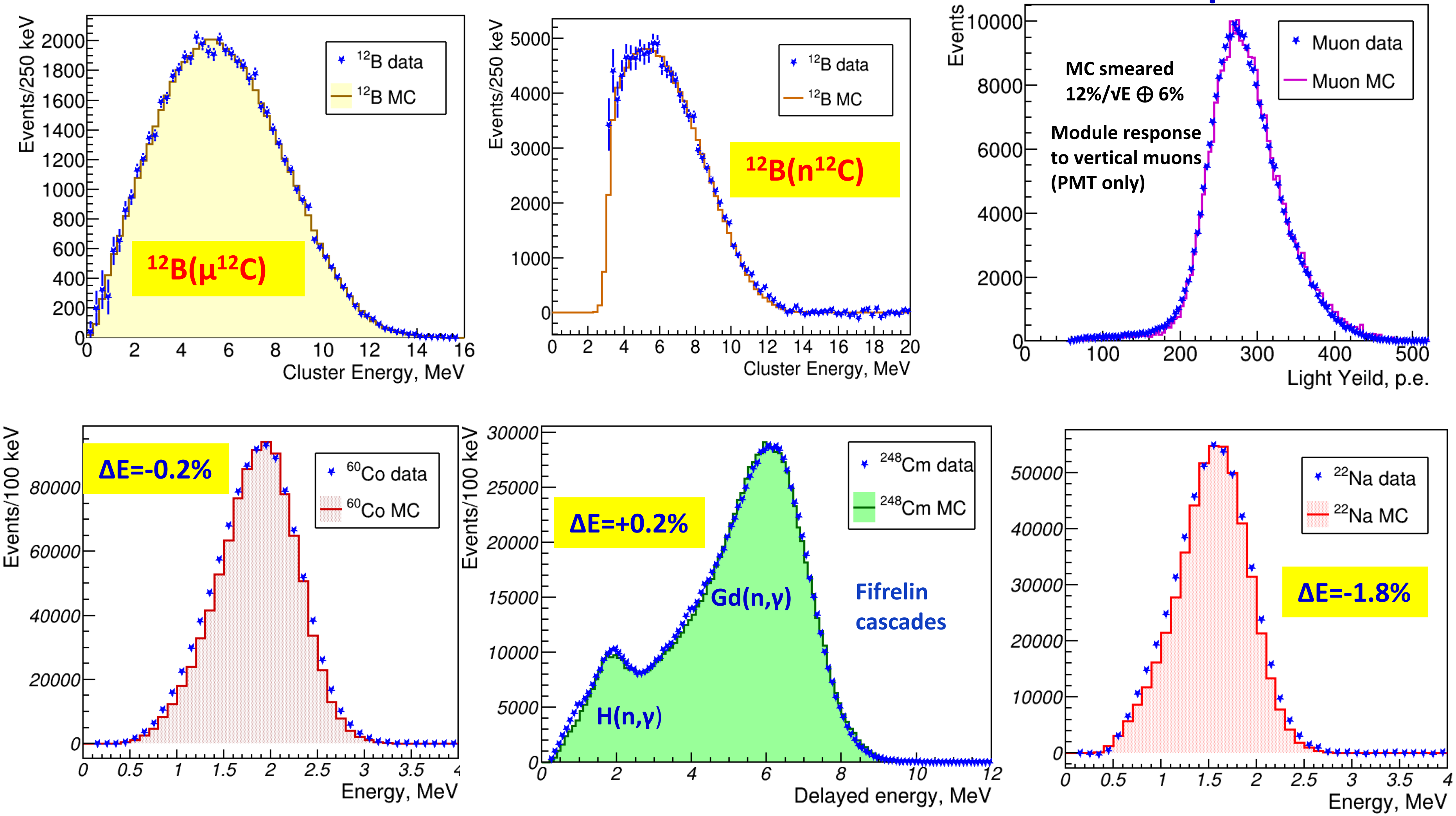




- **Total IBD rate in top position: 5221 event/day;**
- **Fast neutrons rate was calculated by liner extrapolation from the high energy region – 16 events/day in 1.5 – 6 MeV range;**
- **Visible cosmic background has been rejected by Muon Veto System;**
- **Due to inefficiency of the Muon Veto System small part of the cosmic background becomes invisible. The rate of it was found to be 41 event/day, from reactor off data;**
- **Neutrino from the adjacent reactors: 25 events/day;**
- **Additional 19 event/day at low energy area observed in reactor off data;**
- **Total subtracted background is 1.76% for the top detector position, S/B>50!**

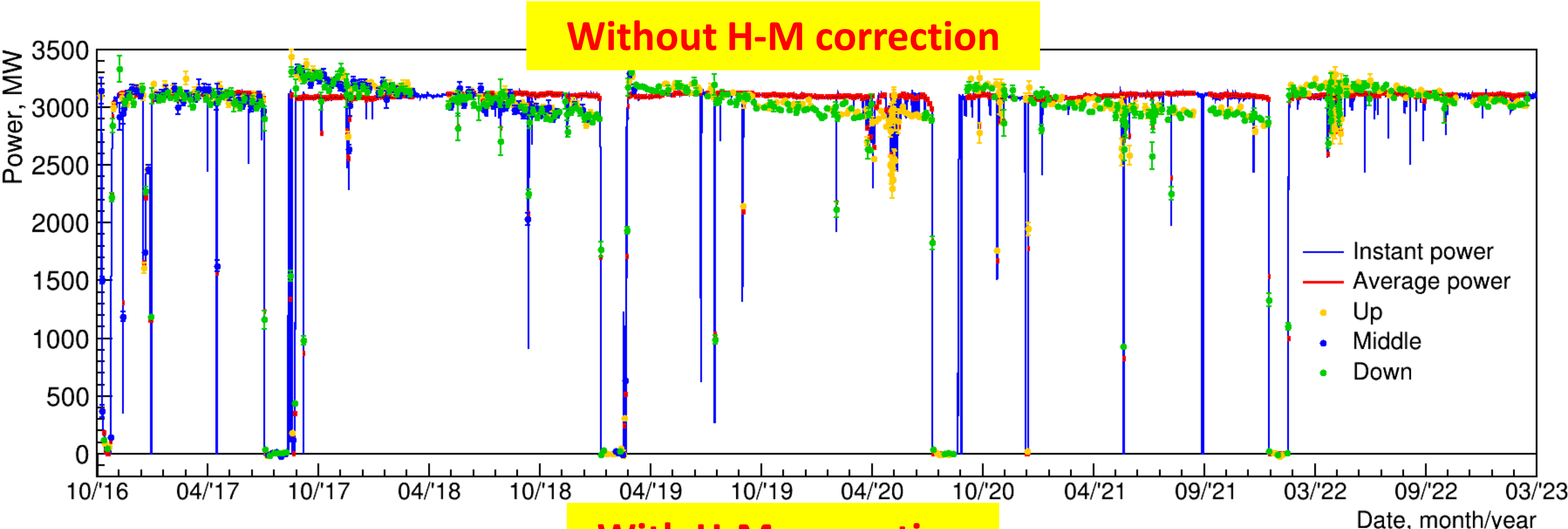
Calibration

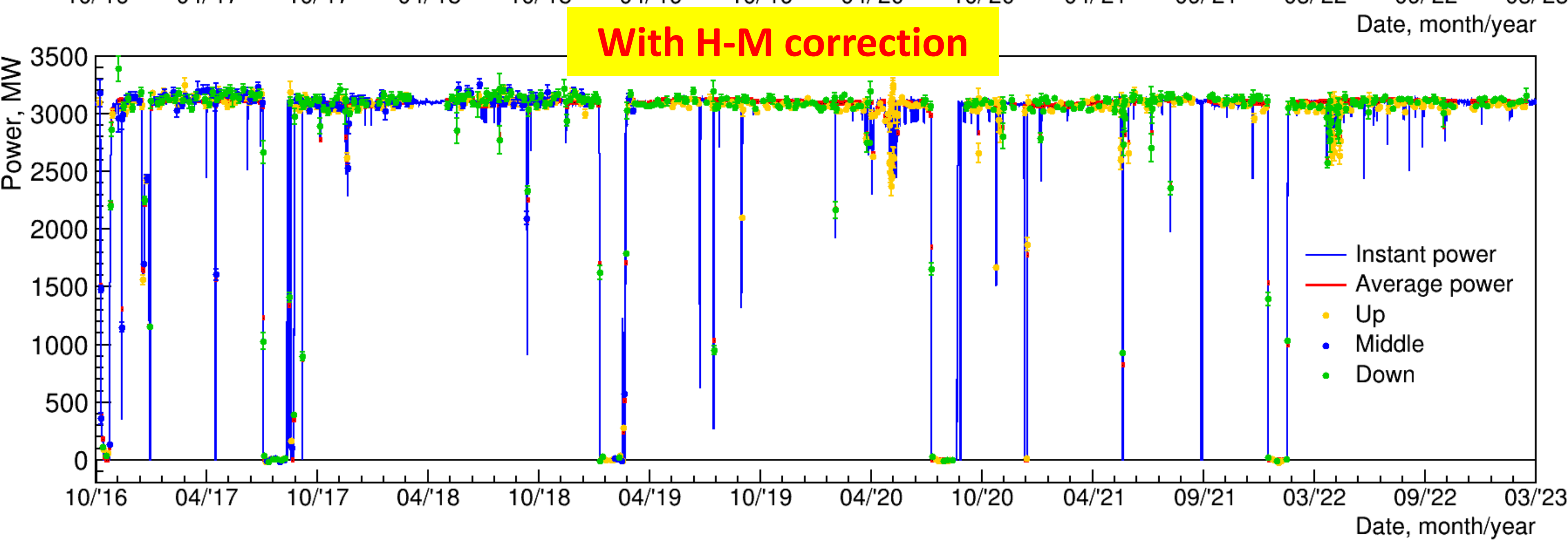
2500 SiPM gains and X-talks are calibrated every 30-40 min.
All 2550 channels are calibrated every 2 days using cosmic muons
Several calibration sources are used to check the detector response



Systematic error on E scale of +/-2% was added due to ^{22}Na disagreement

Reactor power monitoring





Fractional IBD slopes calculation