Recent results from the DANSS experiment

Igor Alekseev for the DANSS collaboration

Kalininskaya NPP, Udomlya, 300 km NW from Moscow

XX International Workshop on Neutrino Telescopes

Istituto Veneto di Scienze, Lettere ed Arti

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There are several indications in favor of existence of the 4th neutrino flavor - “sterile” neutrino seen in short distance oscillations

LSND + MiniBooNE – **accelartor anomaly**: appearance of ν_e ($\overline{\nu}_e$)
6.1σ combined result

MiniBooNE, PRL **121**, 221801 (2018)

MicroBooNE – doesn’t confirm, but doesn’t exclude

MicroBooNE, PRL **128**, 241802 (2022)

GALEX (Gran Sasso) and SAGE (Baksan) – **gallium anomaly**: deficit of ν_e from neutrino source in gallium detectors calibration.

Phys. Rev. C **80**, 015807 (2009)

Recent results from BEST demonstrate even larger deficit of neutrinos.
The combined significance >5σ

Phys. Rev. D **105**, L051703 (2022)

Reactor anomaly – deficit of ν_e (5.7%) in combined analysis of reactor experiments.

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

Much smaller (3.7%): M. Estienne et al. PRL **123**, 022502 (2019)
No anomaly (0.6%): V. Kopeikin et al. Phys. Rev. D **104**, L071301 (2021)
^{235}U rate measurements by STEREO, Daya Bay and RENO

Neutrino-4: 2.7σ @ $\Delta m^2 \sim 7 eV^2$ $\sin^2 2\theta \sim 0.35$ Phys. Rev. D **104**, 032003 (2021)

Criticism of the Neutrino-4 analysis: M. Danilov et al. JETP Lett. **112** no. 7, 452 (2020)
C. Giunti et al. *Phys. Lett. B* 816, 136214 (2021)

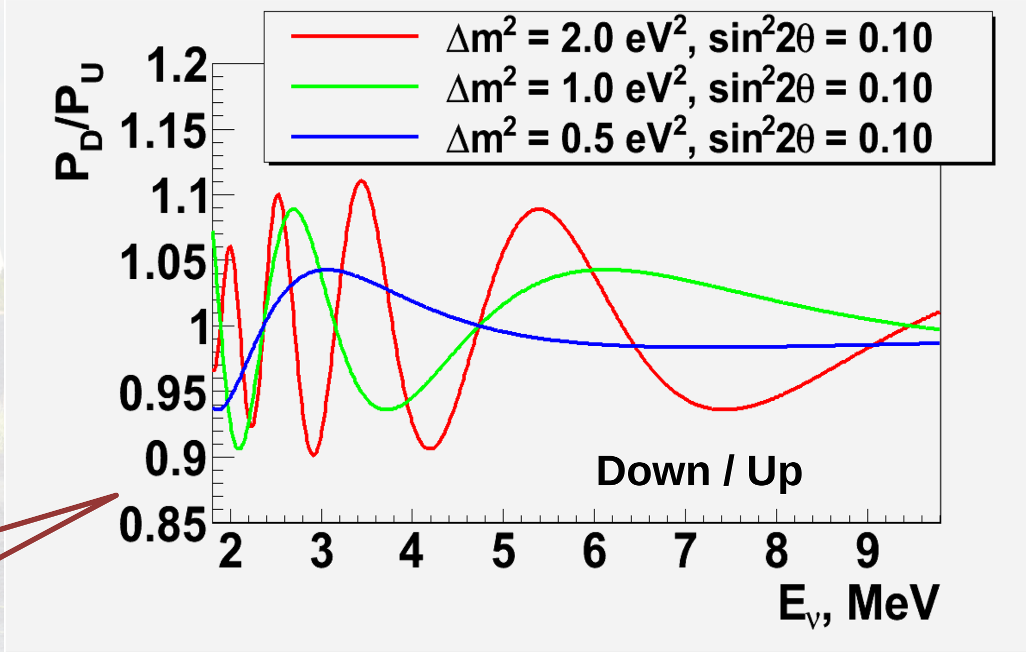
These are among of the statistically strongest indications of the New Physics

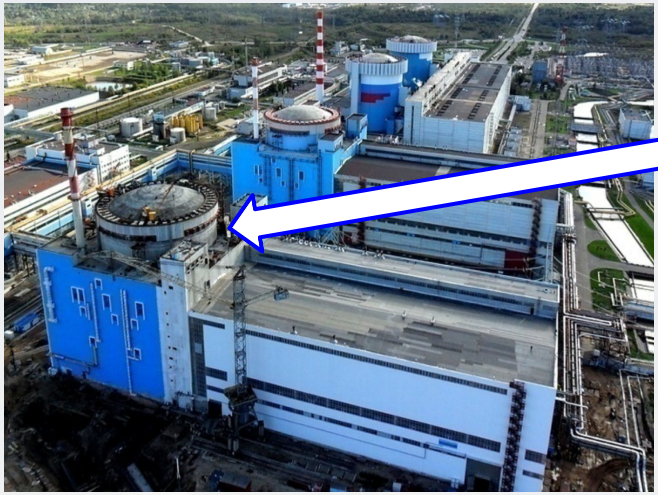
In a simple model with the 4th neutrino survival probability of electron antineutrino from the reactor is given by the formula:

$$P_{ee}^{2\nu}(L) = 1 - \sin^2(2\theta_i)\sin^2\left(1.27\frac{\Delta m_i^2[\mathrm{eV}^2]L[\mathrm{m}]}{E_{\bar{\nu}_e}[\mathrm{MeV}]}\right)$$

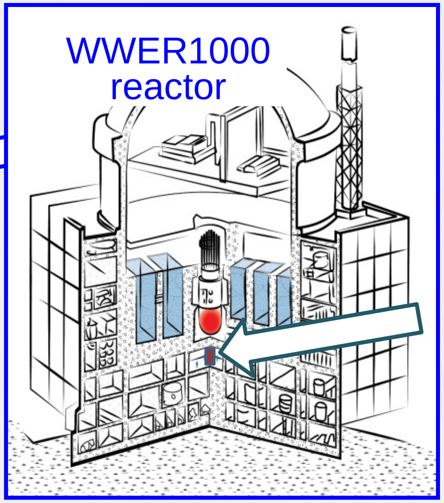
DANSS: Measure ratio of neutrino spectra at different distance from the reactor core – both spectra are measured in the same experiment with the same detector. No dependence on the theory, absolute detector efficiency or other experiments.

Naïve ratio without smearing by reactor and detector sizes and the resolution





Kalininskaya Nuclear Power Plant, Russia, ~300 km NW from Moscow



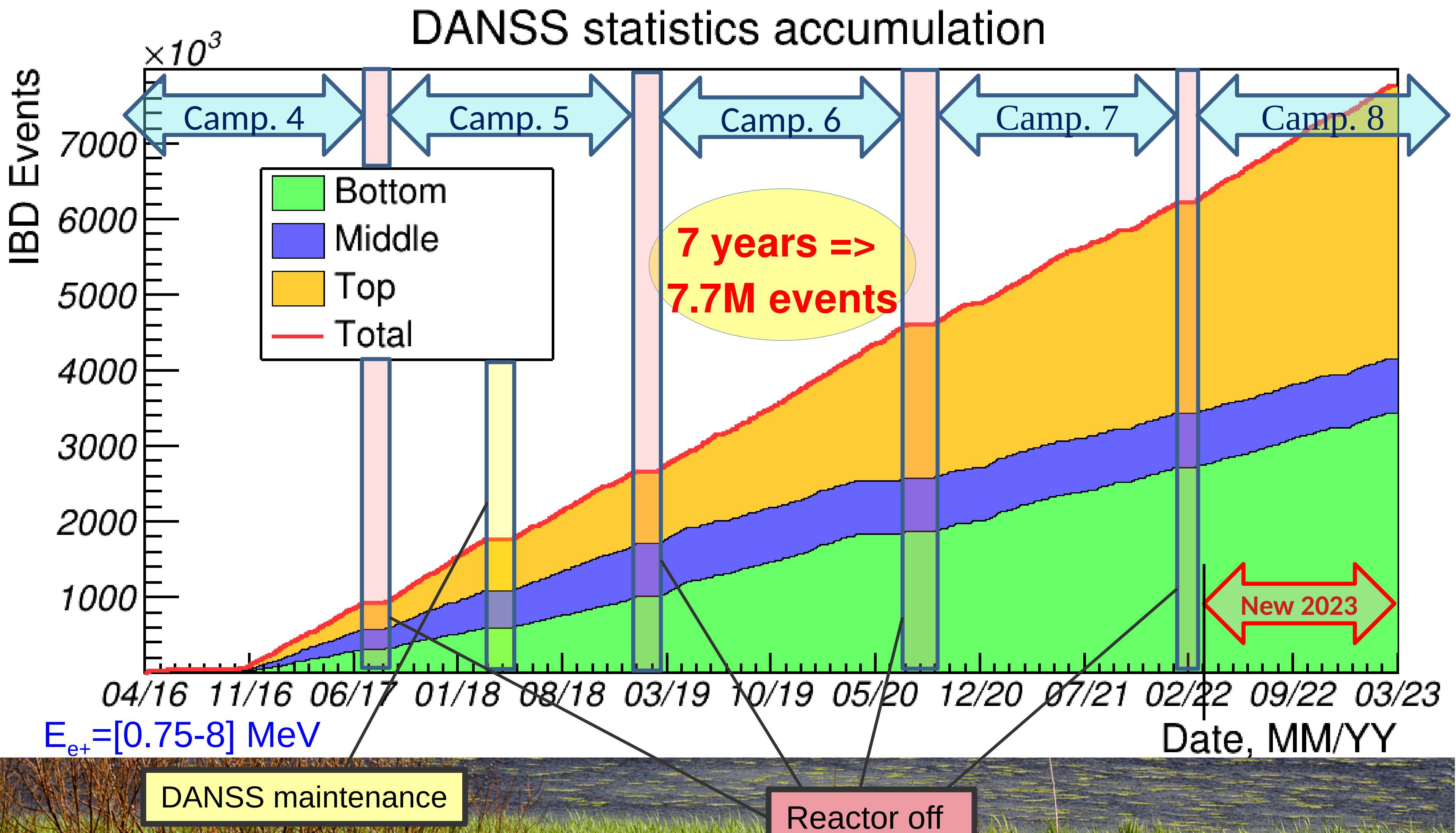
Below 3.1 GW_{th} commercial reactor $\sim 5 \cdot 10^{13}\ \nu \cdot cm^{-2} c^{-1}$@11m

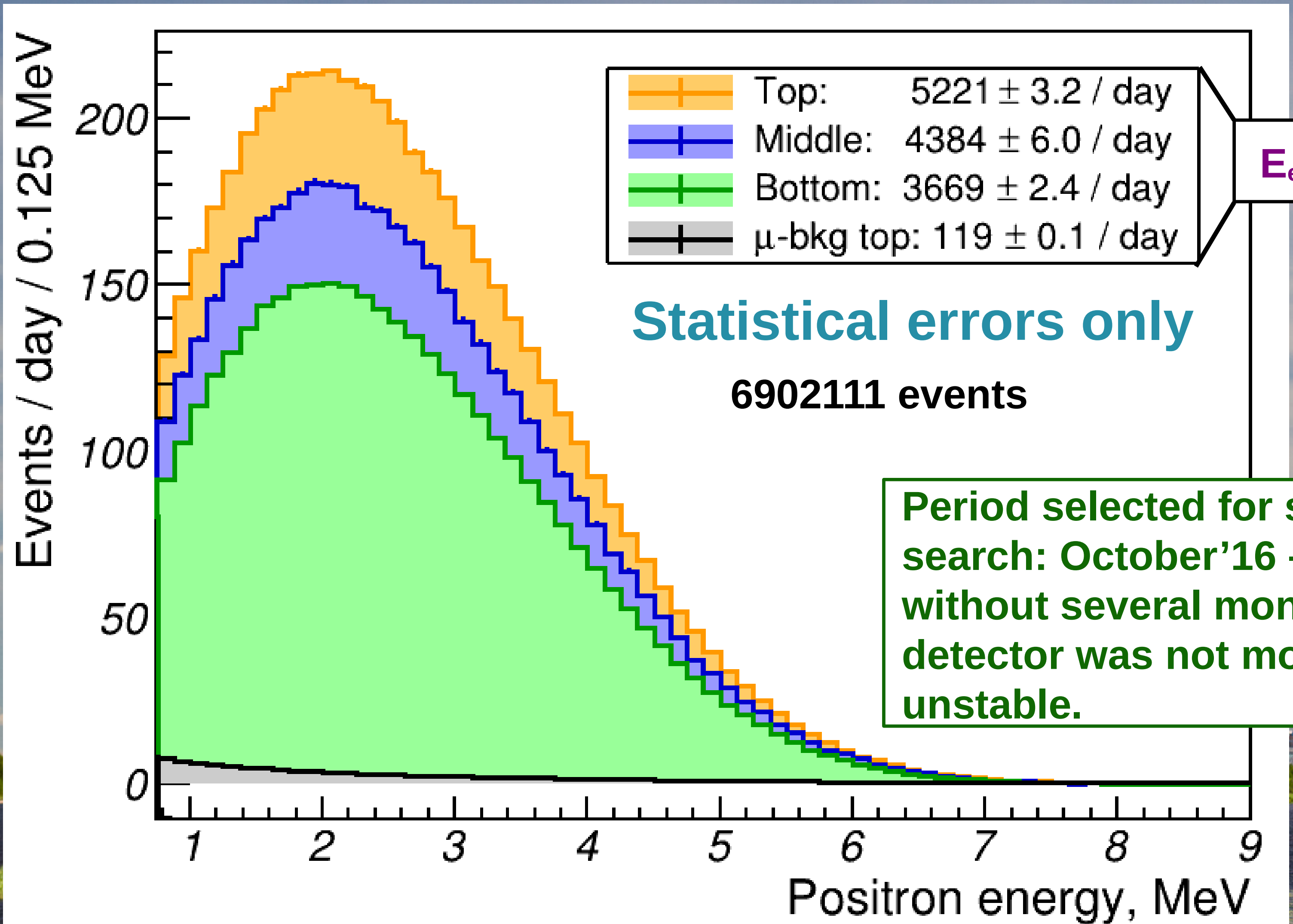
DANSS on a lifting platform
A week cycle of up/middle/down position

- Detector of the reactor AntiNeutrino based on Solid-state Scintillator - no flammable or dangerous materials – can be put just after reactor shielding
- Inverse Beta-Decay (IBD) to measure antineutrinos: $\bar{\nu}_e + p \to e^+ + n$
- Reactor fuel and body with cooling pond and other reservoirs provide overburden ~50 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
- The setup details: JINST 11 (2016) no.11, P11011
- The first results: Phys.Lett. B787(2018)56 – one year of running

This analysis covers DANSS data till March 2023
One more year to 2022 analysis release:
Igor Alekseev for the DANSS Collaboration. PoS(NOW2022)017

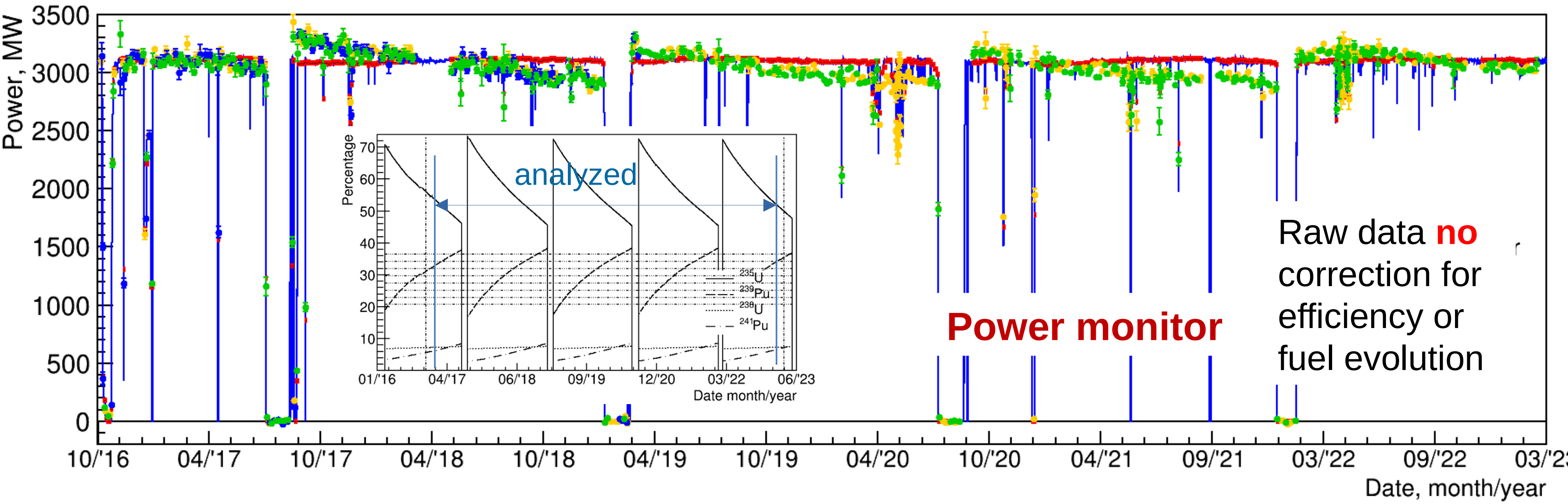
+1.5M IBD events

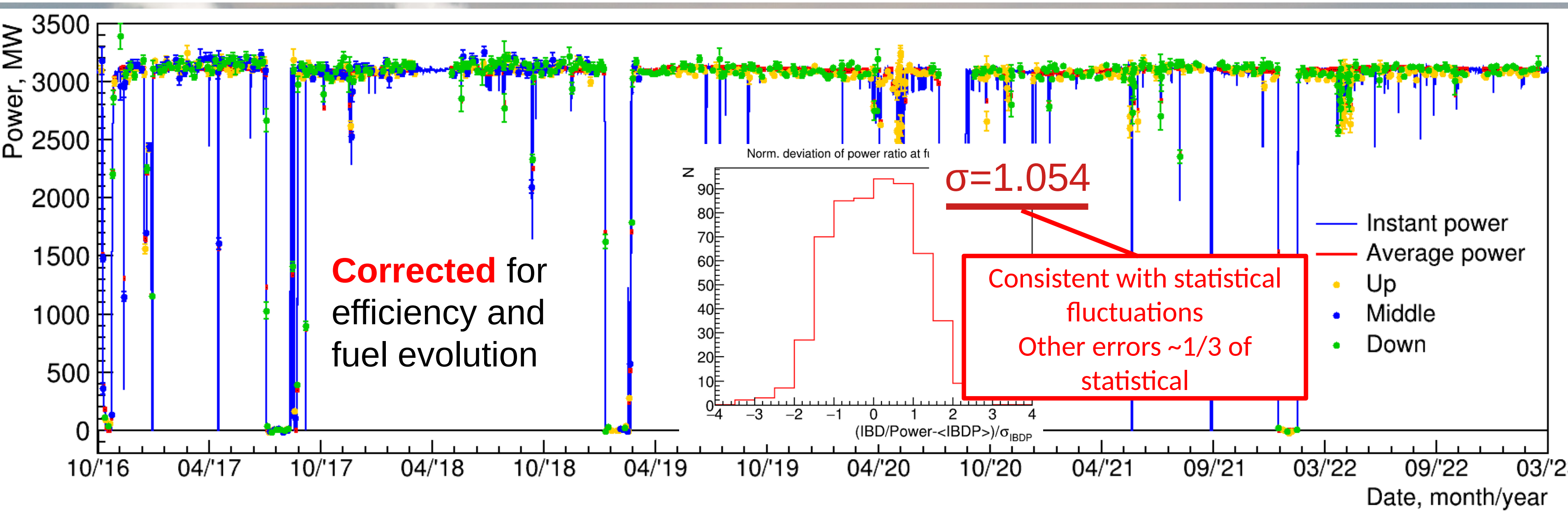




Period selected for sterile neutrino search: October'16 – March'23 without several months, when detector was not moved or was unstable.

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

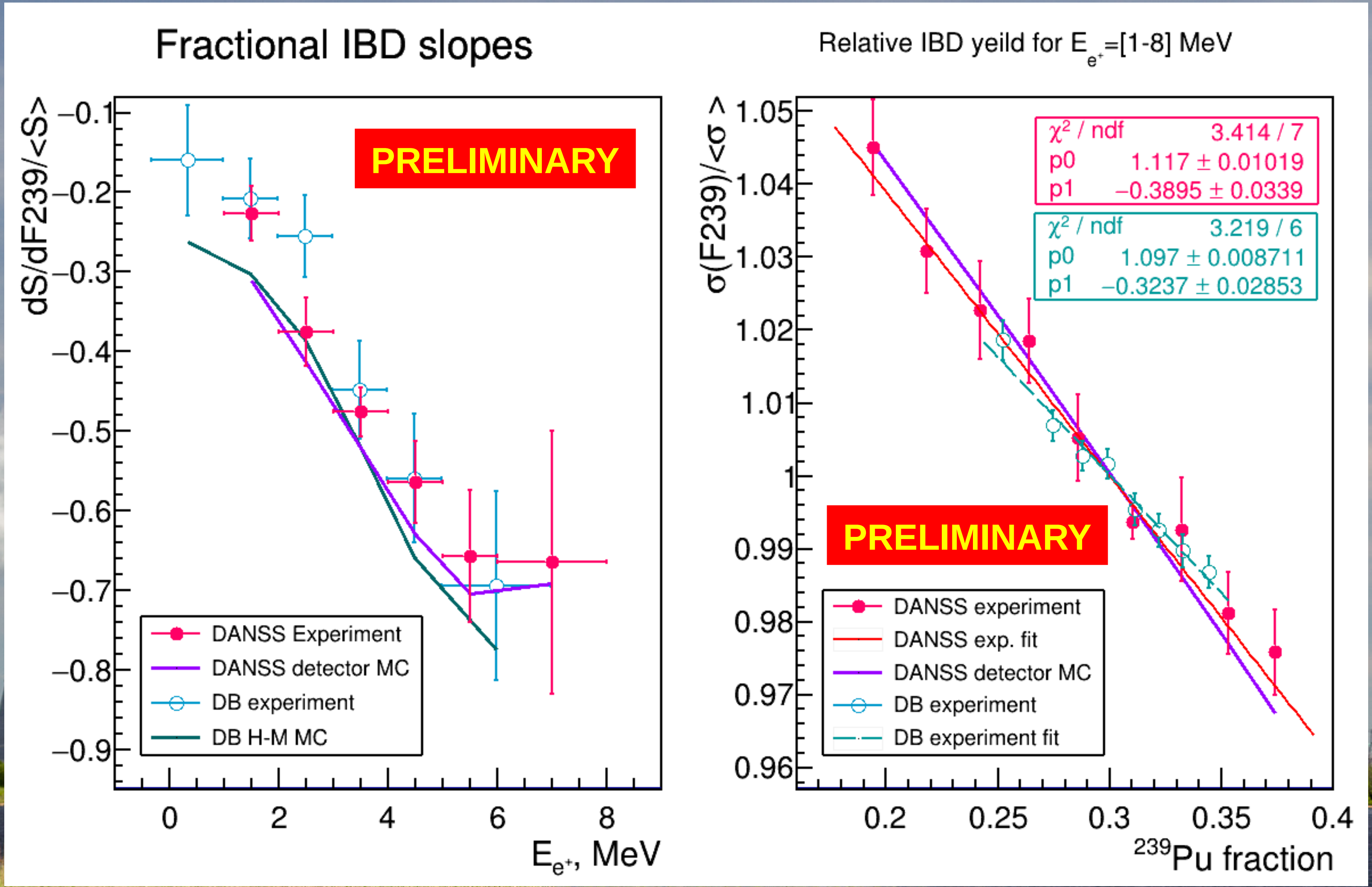




Reactor power is measured by neutrino flux with 1.5% statistical accuracy in 2 days for 6.5+ years.

Changes in absolute detector efficiency are known with accuracy better than 1% during 6.5+ years.

Relative efficiency is even more stable (<0.2%) because of frequent changes of detector positions.



- Positron spectrum dependence over fuel composition is clearly seen.
- Main contribution to the error bars comes from systematics, estimated from variation between the campaigns. Could be overestimated.
- Fractional IBD slopes are in reasonable agreement with H-M model, but are slightly higher than slopes obtained by Daya Bay experiment.

We can use obtained slope to determine ratio of 235U to 239Pu contributions:

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

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

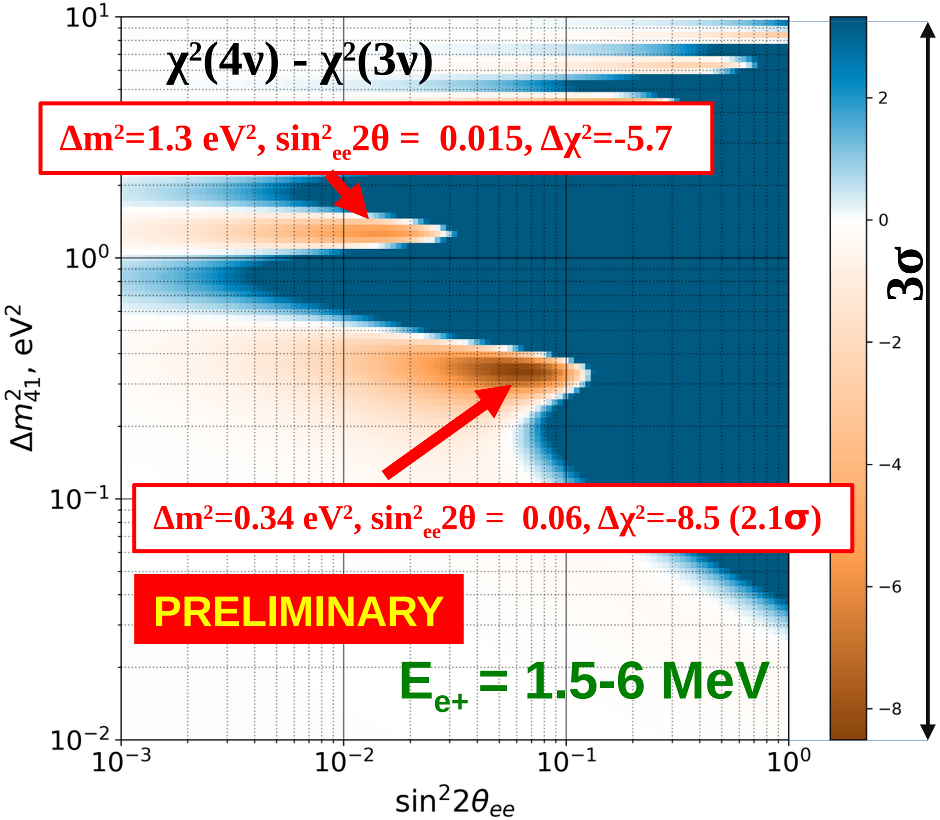
Slope $Sl = \left(\frac{dN}{df_9} \right) / N = \frac{\frac{\sigma_8}{\sigma_9}\frac{df_8}{df_9} + \frac{\sigma_1}{\sigma_9}\frac{df_1}{df_9} + \frac{\sigma_5}{\sigma_9}\frac{df_5}{df_9} + 1}{\frac{\sigma_8}{\sigma_9} f_8 + \frac{\sigma_1}{\sigma_9} f_1 + \frac{\sigma_5}{\sigma_9} f_5 + f_9}$

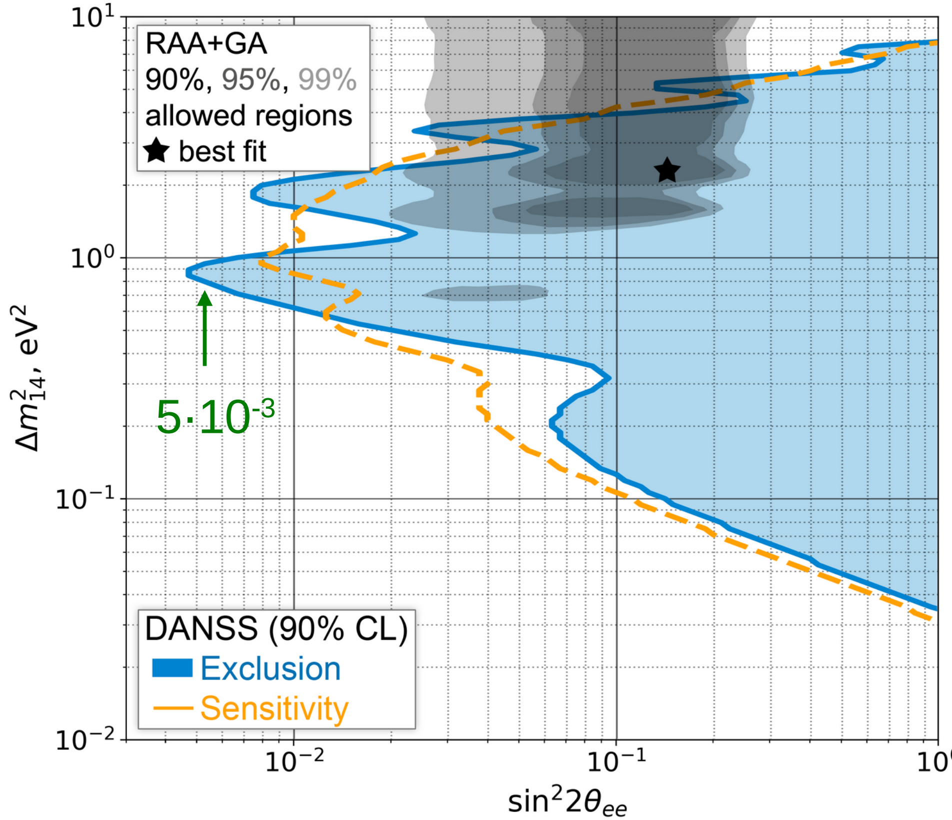
$$\frac{\sigma_5}{\sigma_9} = -\frac{\frac{\sigma_8}{\sigma_9}\left(Sl \cdot f_8 - \frac{df_8}{df_9}\right) + \frac{\sigma_1}{\sigma_9}\left(Sl \cdot f_1 - \frac{df_1}{df_9}\right) + (Sl \cdot f_9 - 1)}{Sl \cdot f_5 - \frac{df_5}{df_9}}$$

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

	σ_5/σ_9
From DANSS data	1.53±0.06
HM-model	1.53±0.05
Daya Bay result (A.C. Hayes et al. PRL **120** (2018) 2, 022503)	1.445±0.097
Our calculation from Daya Bay slope	1.459±0.052

It could be a bit too early to consider RAA solved with new σ_5/σ_9 ratio





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

Using Gaussian CLs method

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

- ✓ **5.5 M events with 1.5 MeV < E < 6 MeV (conservative energy range)**
- ✓ **$\Delta\chi^2$=-8.5 (2.1σ) - No statistically significant hint of 4ν oscillationsant hint of 4ν oscillations**
- ✓ **RAA is excluded with $\Delta\chi^2$=194 (5σ level reached in 2018** [PLB **787** (2018) 56]**)**

Using absolute counting rates

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

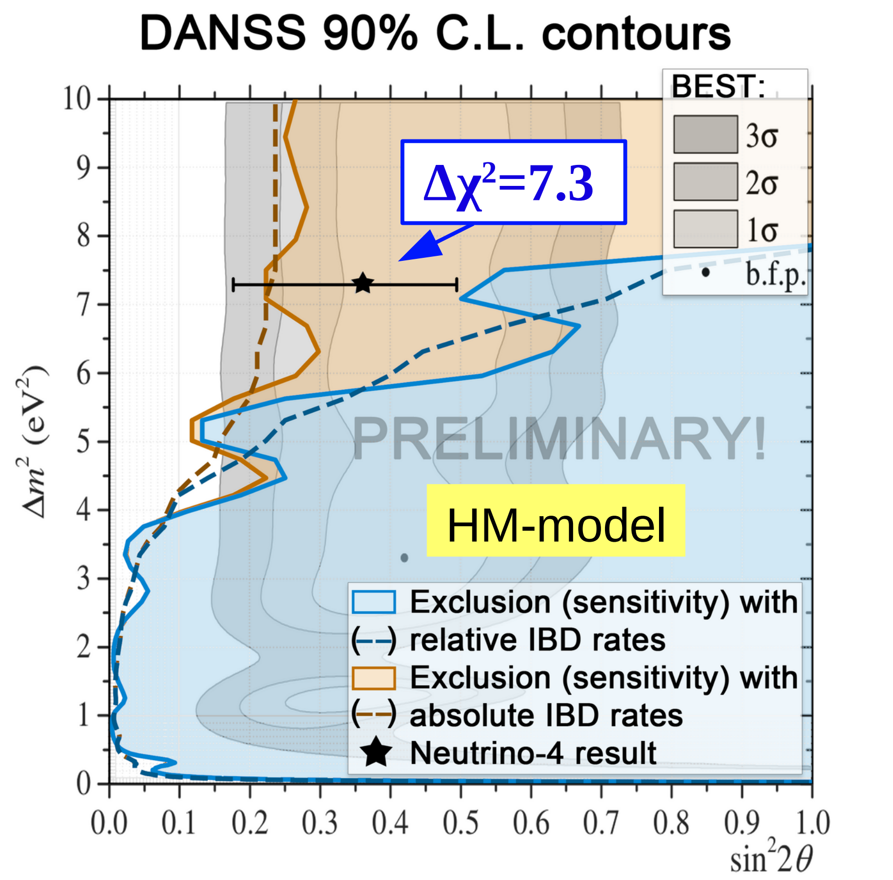
χ^2_{rel} — χ^2 using counts ratios only

$N_{top/mid/botom}$ — total counts in the corresponding detector positions

σ_{abs} — systematic uncertainty taken as **7%** (very conservative)

Systematic uncertainties

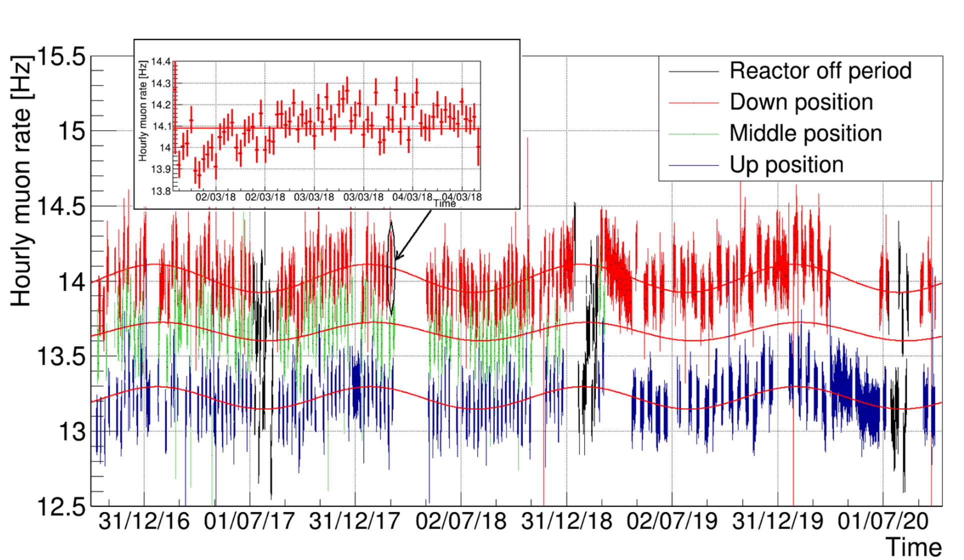
Source	Uncertainty
Number of protons	2%
Selection criteria	2%
Geometry (distance and fission points distribution)	1%
Fission fractions (from KNPP)	2%
Average energy per fission (Phys. Rev. C **88**, 014605)	0.3%
Reactor power (from KNPP)	1.5%
Backgrounds	0.5%
Total without flux predictions	**4%**
Flux predictions	2-**5%**
Total	5-**7%**



KI model exclusions are slightly stronger

Muon flux through the detector

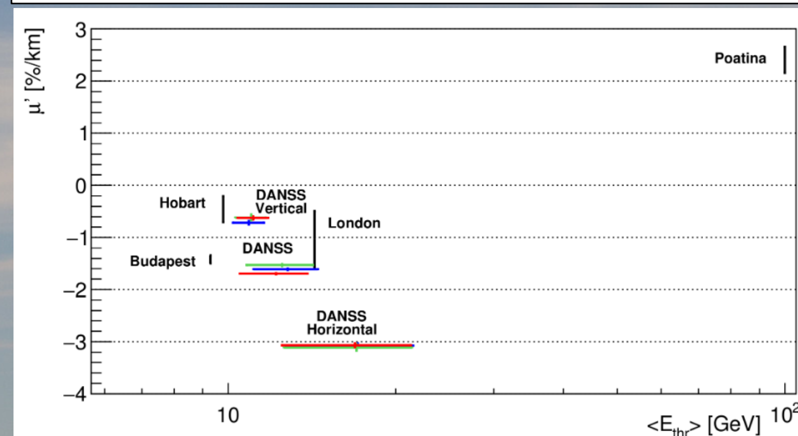
Weather data obtained from ERA5 database of European Center for Medium-Range Weather Forecasts (ECMWF).

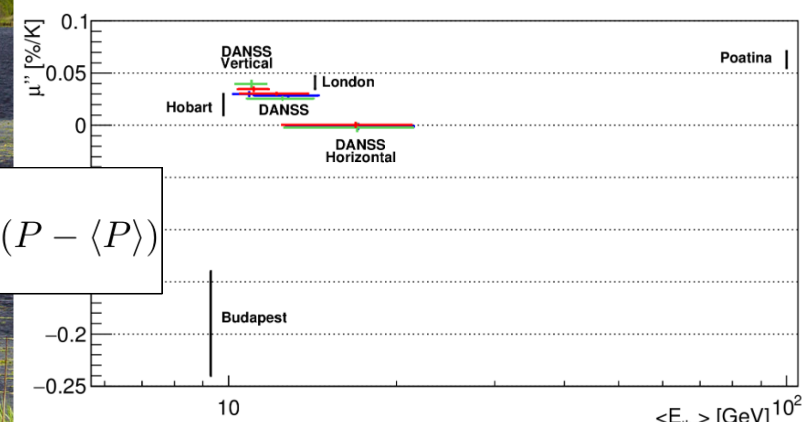


Effective level of generation

JETP Letters **118**(3) (2023) 165

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

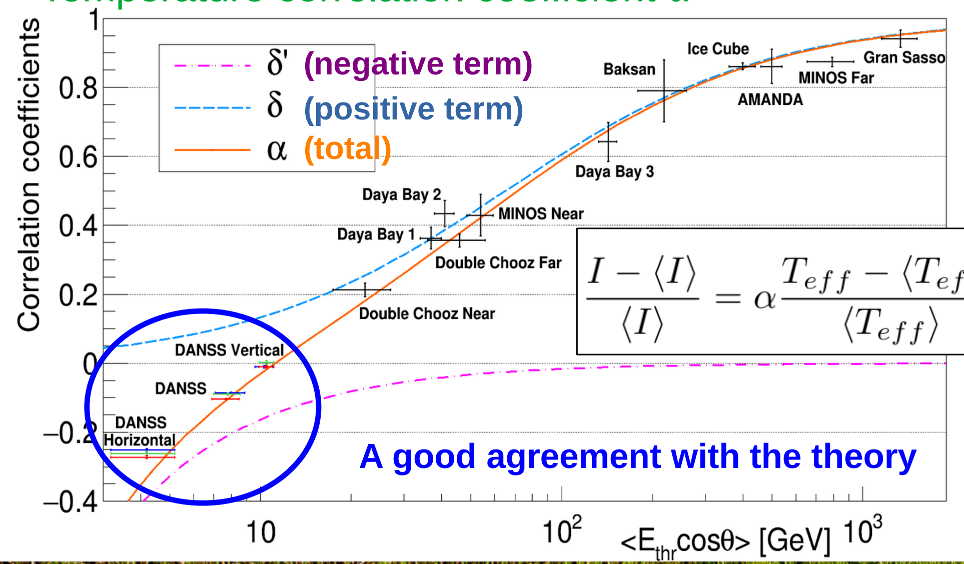




Effective temperature

EPJ C **82** (2022) 515

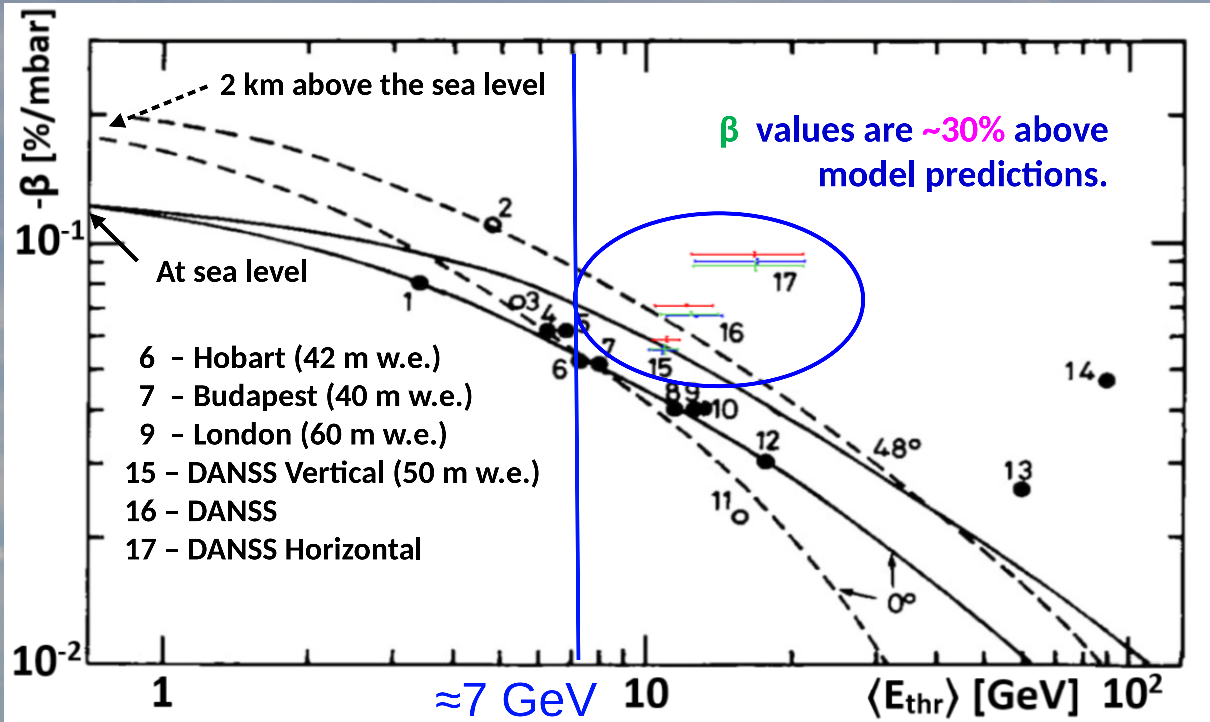
Temperature correlation coefficient α



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

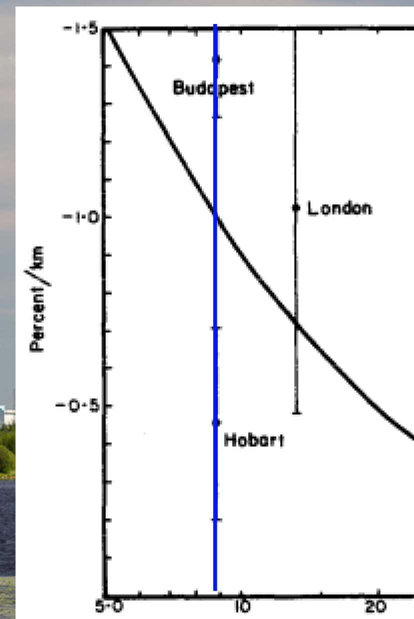
A good agreement with the theory

Pressure correlation coefficient β



S. Sagisaka Nuovo Cimento C, **9**, 809 (1986)

Both effective temperature and effective level of generation approaches give very close result for the pressure correlation coefficient β



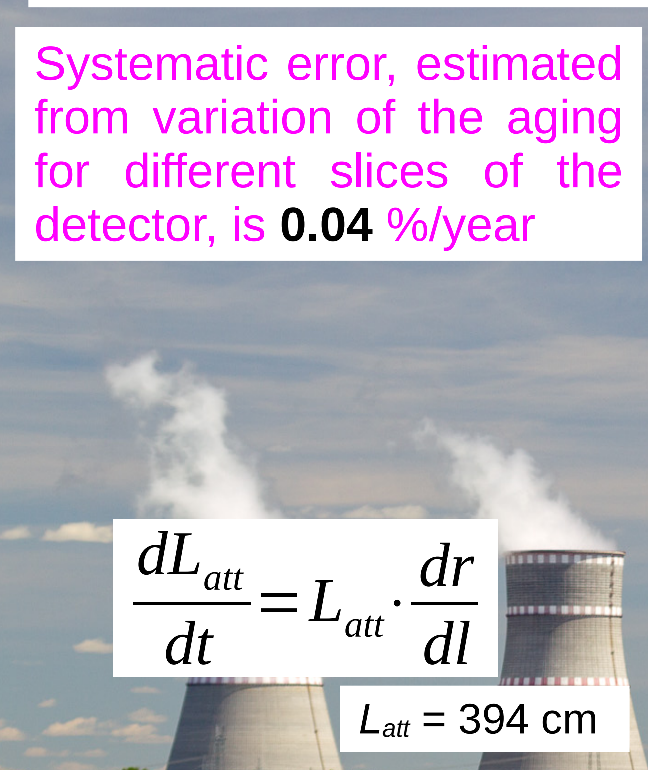
≈9 GeV

But, our calculations as well as J. Dutt and T. Thambyahpillai [Journal of Atmospheric and Terrestrial Physics, **27**(3),349 (1965)] assign to experiments Hobart, Budapest and London upto 30% larger E_{thr}.

Aging of DANSS scintillator

- T2K (several detectors) — 0.9-2.2 %/year; MINOS — 2 %/year; MINERvA — 7-10 %/year @ 80F(27.6^{o}C)
- 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 Multi
- 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.

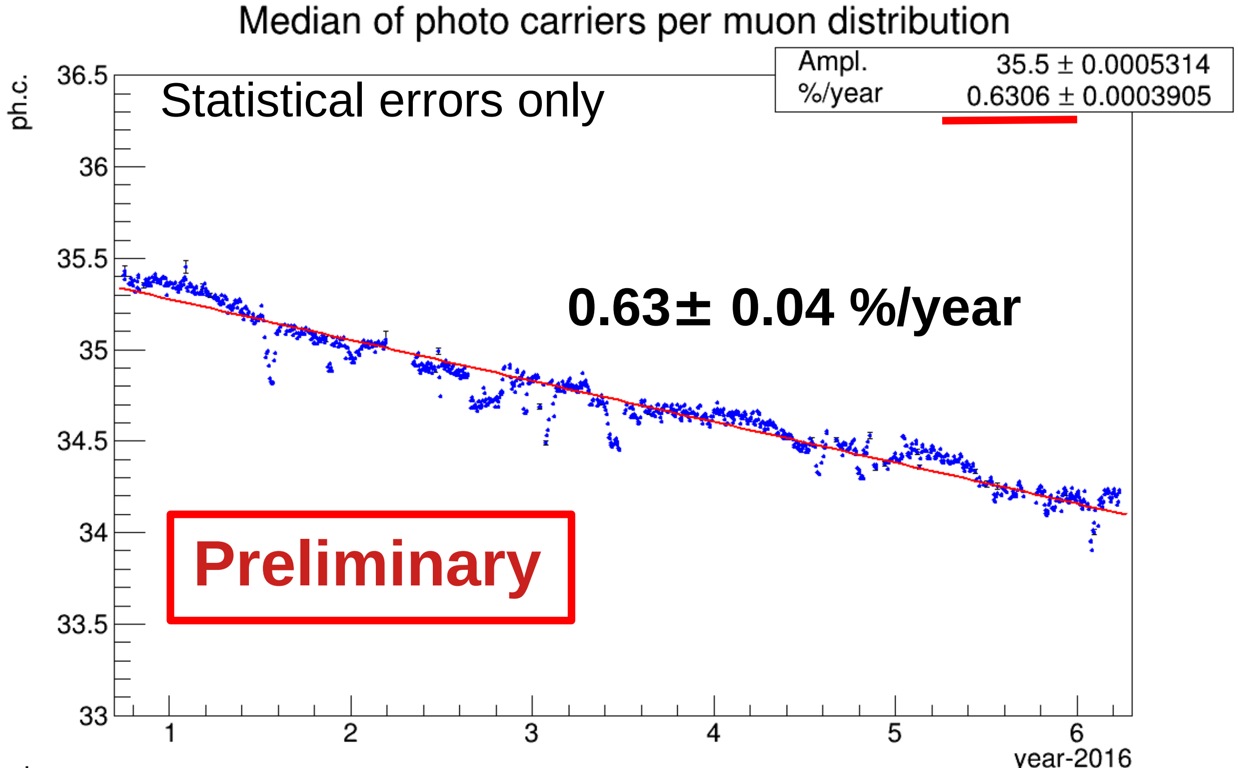
Aging of DANSS scintillator

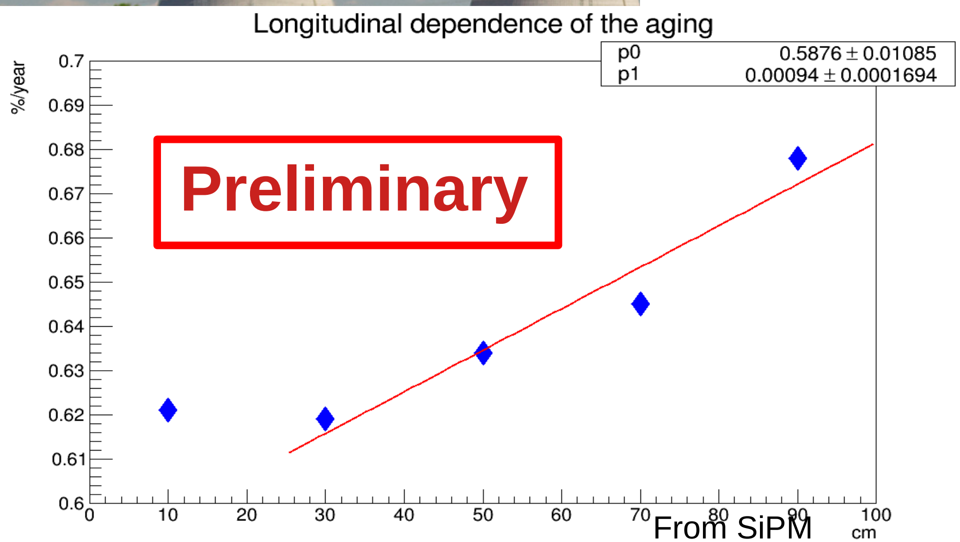


Systematic error, estimated from variation of the aging for different slices of the detector, is **0.04** %/year

$$\frac{dL_{att}}{dt} = L_{att} \cdot \frac{dr}{dl}$$

L_{att} = 394 cm





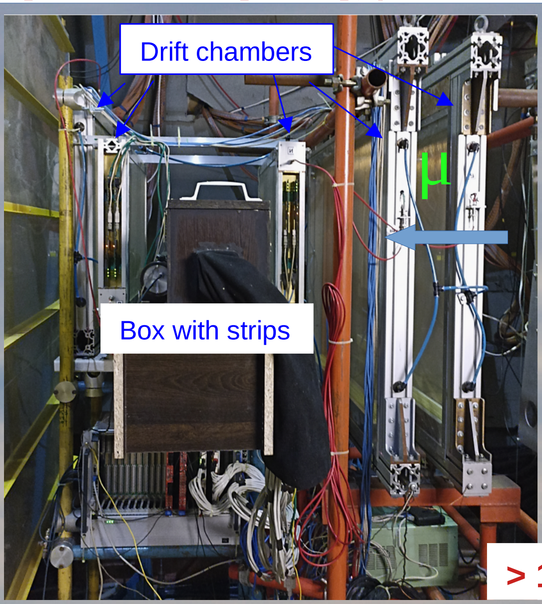
We can not separate aging of the scintillator and of the conversion efficiency of the WLS fiber. But we observe a hint of some decrease in its attenuation length. The increase of aging effect with the distance from SiPM gives an estimation of WLS attenuation length shortening *$-dL_{att}/dt$* = **0.37 ± 0.07**(stat.) %/year

The DANSS upgrade

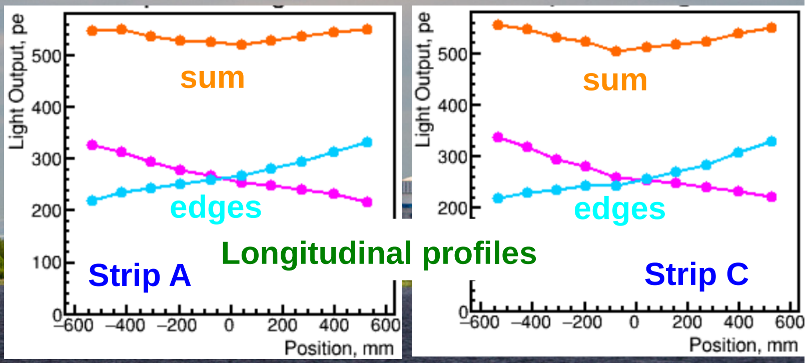
Main goal of the upgrade is to improve energy resolution:
34%/√E --> 12%/√E

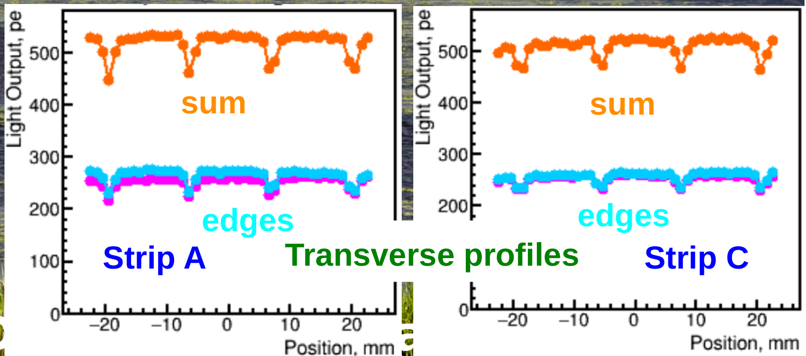
- ✓ New scintillation strips: 20x50x1200 mm³;
- ✓ 60 layers x 24 strips — cube (120 cm)³ → 1.7 times larger fiducial volume;
- ✓ **No PMT** – SiPM readout from both sides of each WLS;
- ✓ 8 grooves with WLS, 16 SiPM per strip to get high light yield and uniformity;
- ✓ TOF to get longitudinal coordinate 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 SiPMs to 10°C.
- ✓ Keep platform, passive shielding and digitization.

New strip test (16 SiPM per strip) μ-beam at U-70 (Protvino)

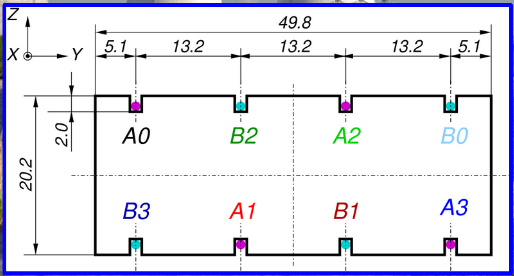


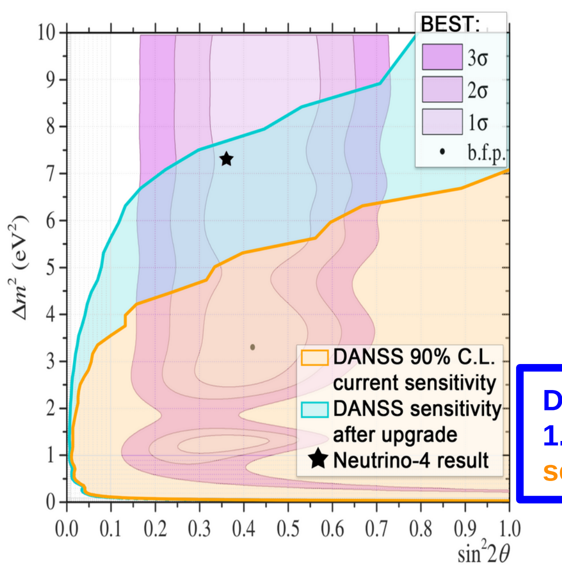
> 140 p.e./MeV





Strip cross section





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

- DANSS recorded the first data in April 2016 and is running now. More than 7.7 million IBD events collected. The experiment is still running.
- We record more than 5 thousand antineutrino events per day in the closest position. 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 6.5 years of operation.
- Relative IBD rate dependence on ^{239}Pu fraction was measured in the fraction range from 26 to 38%. It agrees with HM model. Measured $\sigma_{235}/\sigma_{239}$ ratio is slightly larger than measured by Daya Bay and consistent with HM. Is RAA still alive?
- 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 for both effective temperature and effective generation level approaches. But it could be explained by a different assignment of the threshold energy in the theoretical paper.
- 5.5 million 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.
- Preliminary 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 (2016-2023) has two close best points:

$$\Delta m^2=0.34\ \mathrm{eV}^2,\ \sin^2_{ee}2\theta=0.06:\ \Delta\chi^2=-8.5\ (2.1\sigma)$$

$$\Delta m^2=1.3\ \mathrm{eV}^2,\ \sin^2_{ee}2\theta=0.015:\ \Delta\chi^2=-5.7$$

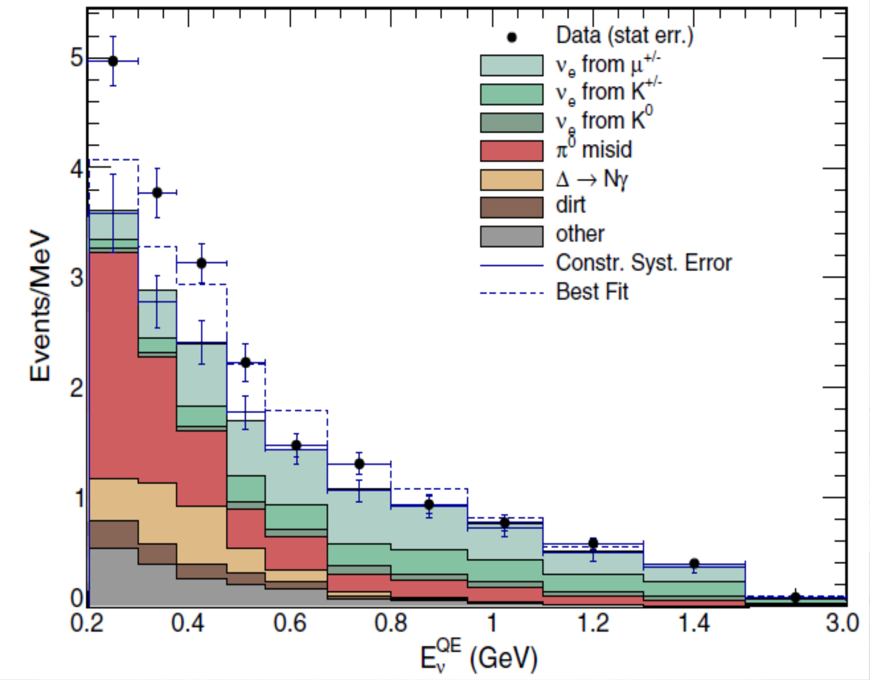
This is not statistically significant (2.1σ) to claim even the indication of sterile neutrino

- Analysis using absolute rates allows further (though model dependent) advance into larger Δm^2. It practically excludes all sterile neutrino parameter space preferred by BEST.
- Aging of DANSS scintillator detectors was studied. We observe average aging 0.63±0.04 %/year and a hint of WLS attenuation length shortening at the level of 0.37±0.07 %/year.
- Our analysis plans are to finalize the energy calibration and to include larger E_{e+} range in the analysis.
- The work on the DANSS upgrade with installation of new strips with SiPM only readout from both ends goes though not as fast as we would like. The upgraded setup will provide much better energy resolution and higher counting rate and allow to scrutinize Neutrino-4 and BEST results. New strip design with 16 SiPM per strip was successfully tested at muon beam. New strips have high light yield more than 140 ph.c./MeV with good uniformity. We plan to continue data taking till the upgrade starts.

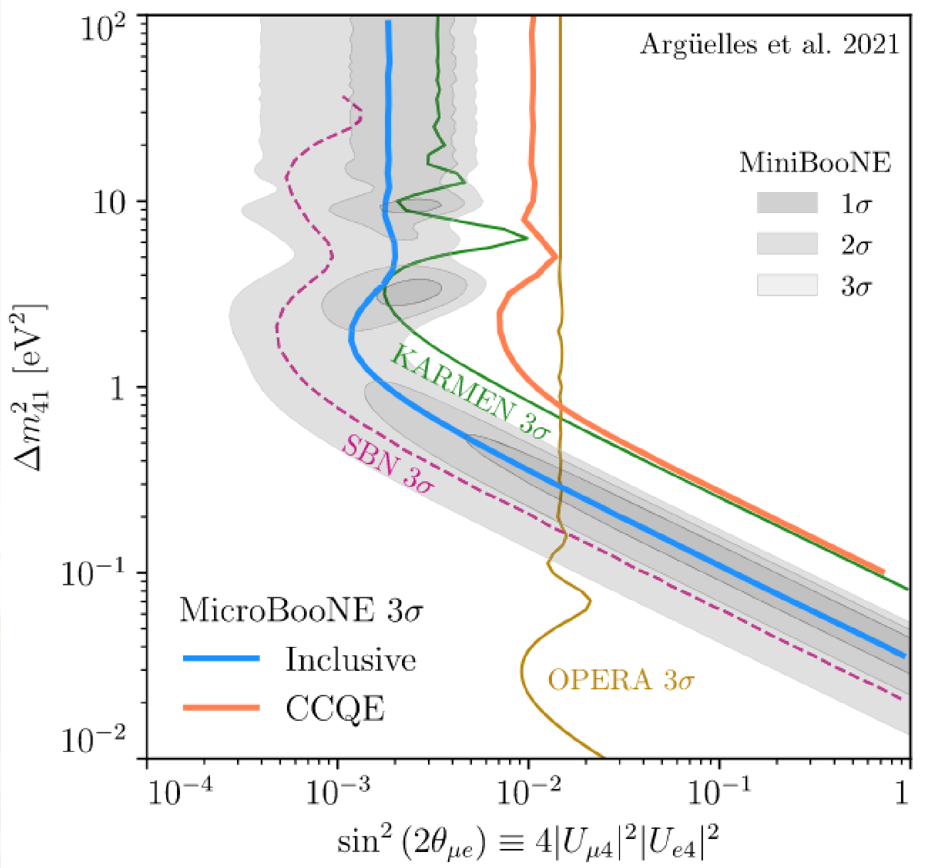
There are several indications in favor of existence of the 4th neutrino flavor - “sterile” neutrino seen in short distance oscillations

LSND + MiniBooNE – accelartor anomaly: appearance of ν_e ($\bar{\nu}_e$)

6.1σ combined result



MiniBooNE, PRL **121**, 221801 (2018)

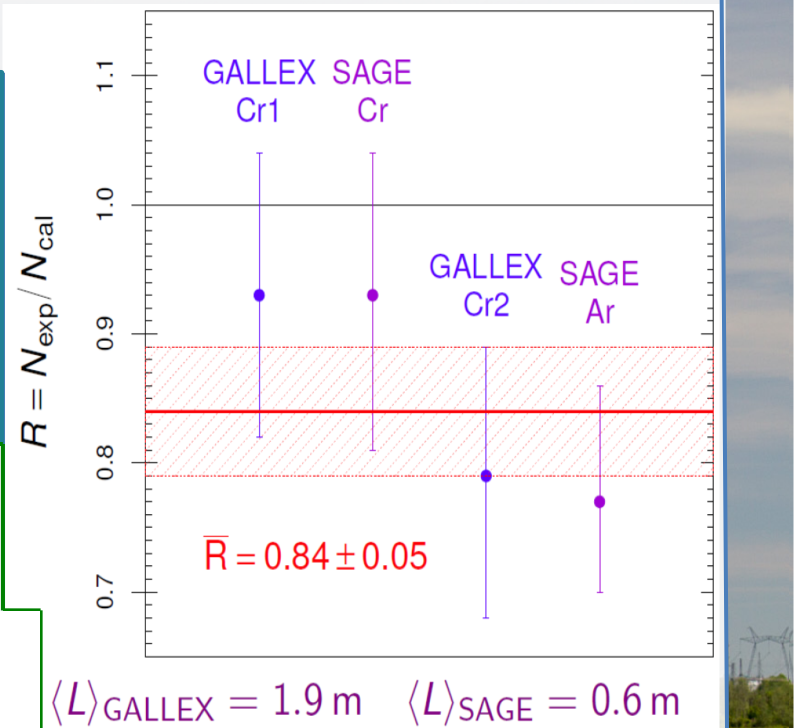


MicroBooNE, PRL **128**, 241802 (2022)

MicroBooNE – doesn’t confirm MiniBooNE, but doesn’t exclude

GALEX (Gran Sasso) and SAGE (Baksan) – gallium anomaly: deficit of ν_e from neutrino source in gallium detectors calibration.

Phys. Rev. C 80 (2009) 015807



Reactor anomaly – deficit of ν_e (5.7%) in combined analysis of reactor experiments.

G. Mention et al. Phys. Rev D83 073006 (2011)

$$|\Delta m^2_{\rm new}| > 1.5\ {\rm eV}^2\ (95\%)\ \text{and}\ \sin^2(2\theta_{\rm new}) = 0.14 \pm 0.08\ (95\%)$$

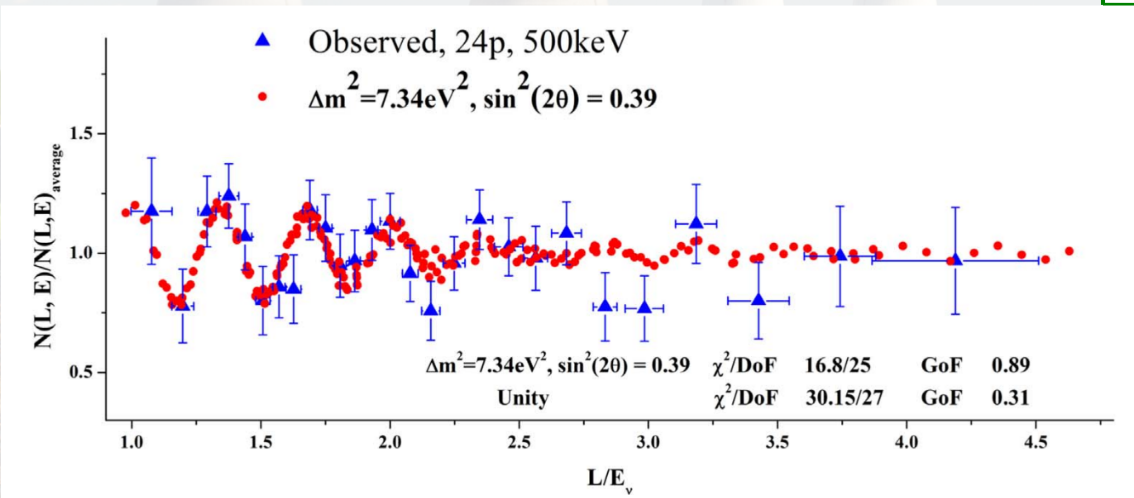
Much smaller (3.7%): M. Estienne et al. PRL 123, 022502

No anomaly (0.6%): V. Kopeikin et al. ArXiv:2103.01684

^{235}U rate measurements by Daya Bay and RENO

Neutrino-4: 2.7σ @ Δm^2~7eV^2 $\sin^2 2\theta$~0.35

JETP Lett. 109 (2019) no.4, 213

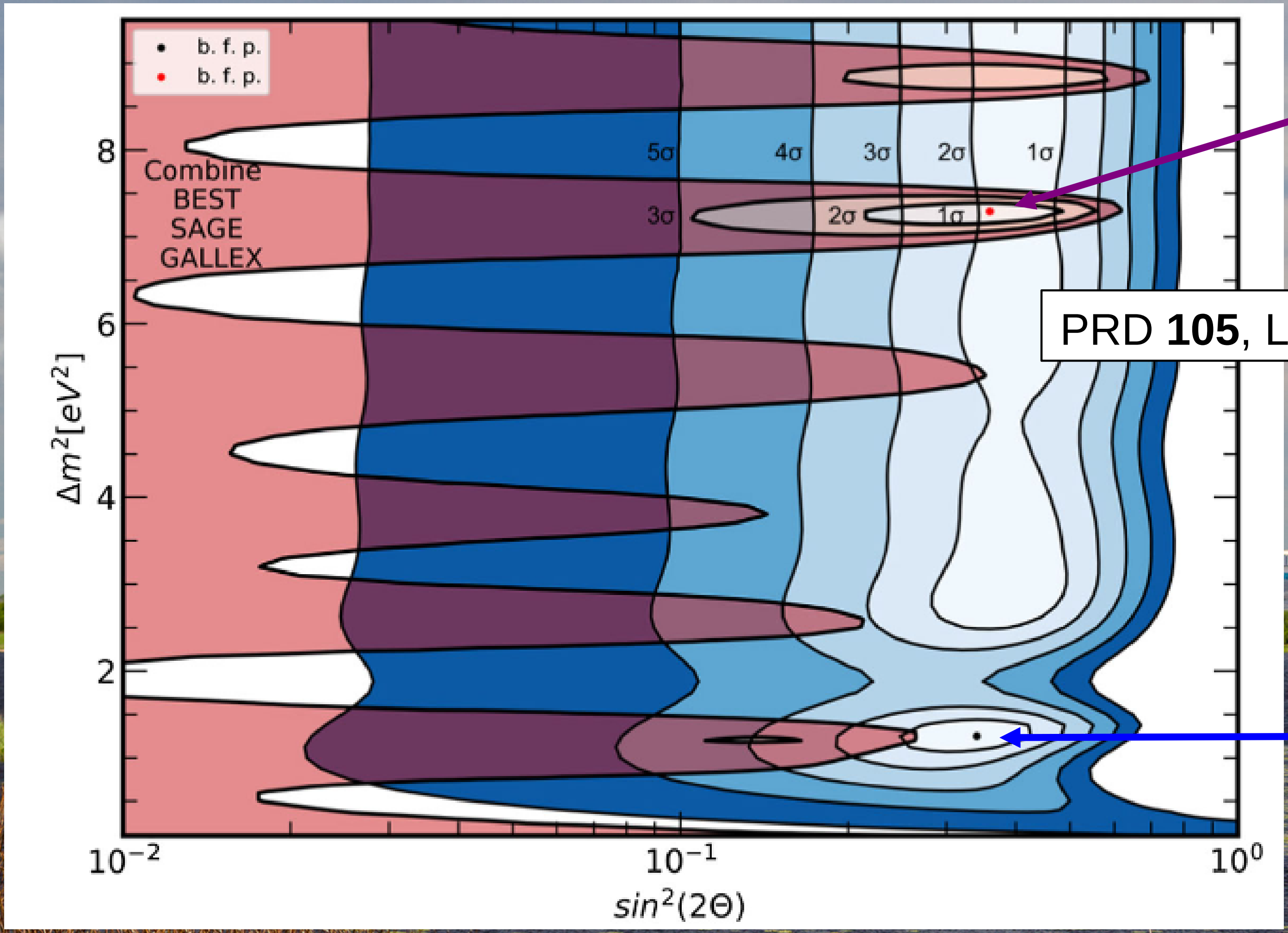


Criticism of the Neutrino-4 analysis:

M. Danilov et al. JETP Lett. 112 (2020) 7, 452-454;

C. Giunti et al. *Phys.Lett.B* 816 (2021) 136214

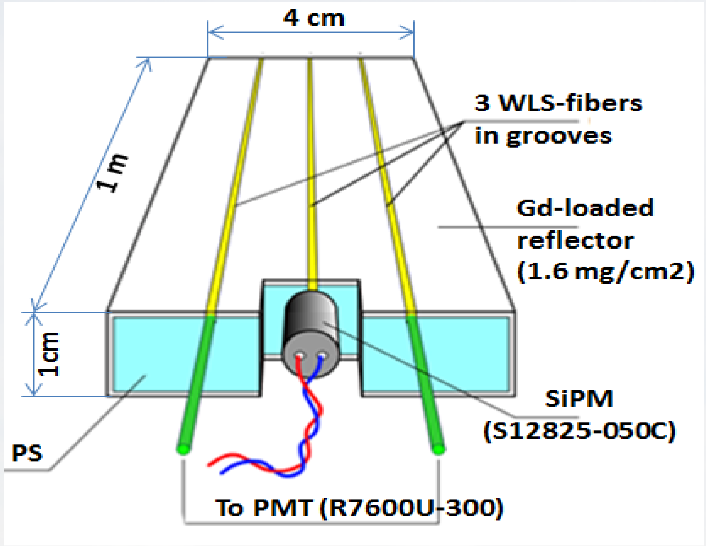
Recent results from BEST demonstrate event larger deficit of neutrinos.
Inner vessel 0.791±0.05 and outer vessel 0.766±0.05.
The combined significance >5σ.

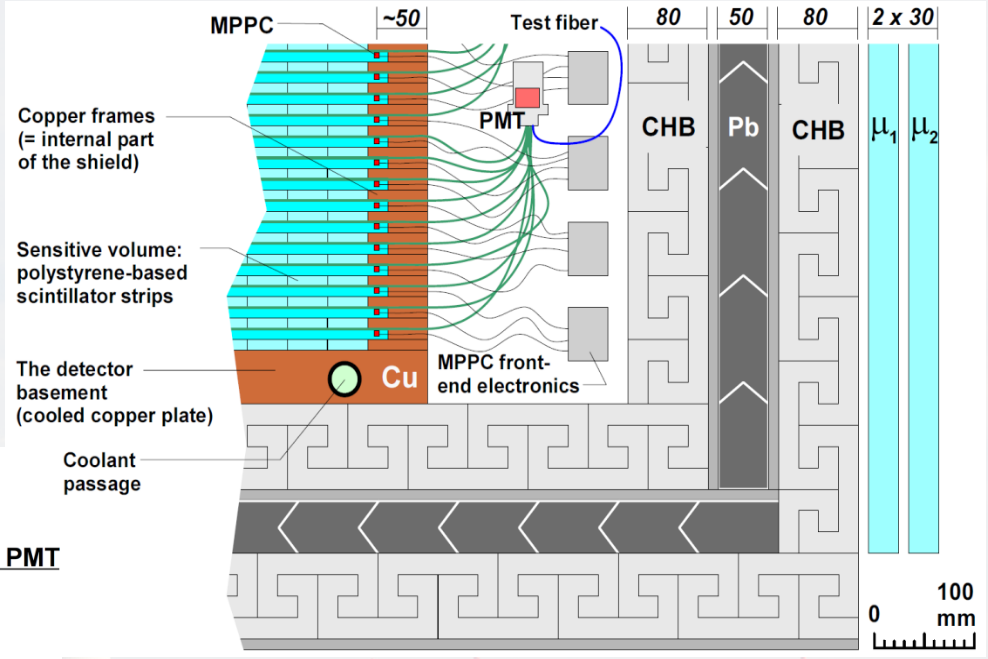


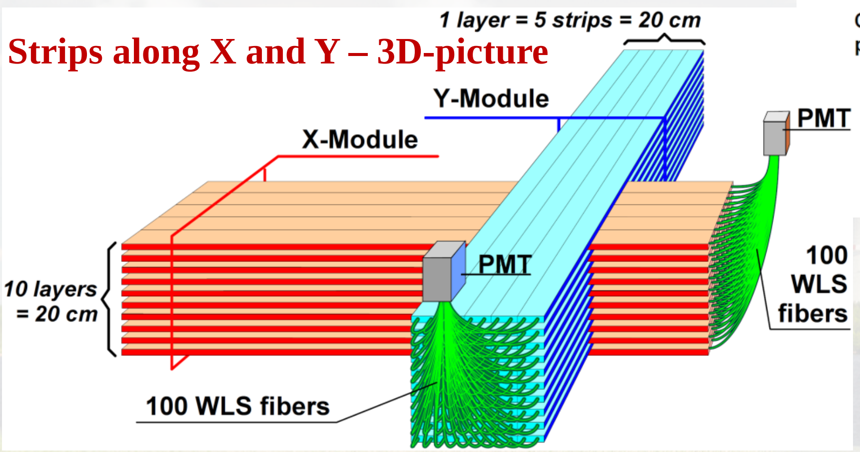
Neutrino-4 — tints of red

BEST+SAGE+GALLEX — tints of blue

Detector of the reactor AntiNeutrino based on Solid-state Scintillator







- 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
- Dedicated WFD-based DAQ system
- Total 46 64-channel 125 MHz 12 bit Waveform Digitisers (WFD)
- System trigger on certain energy deposit in the whole detector (PMT based) or μ-veto signal
- Individual channel selftrigger on SiPM noise (with decimation)

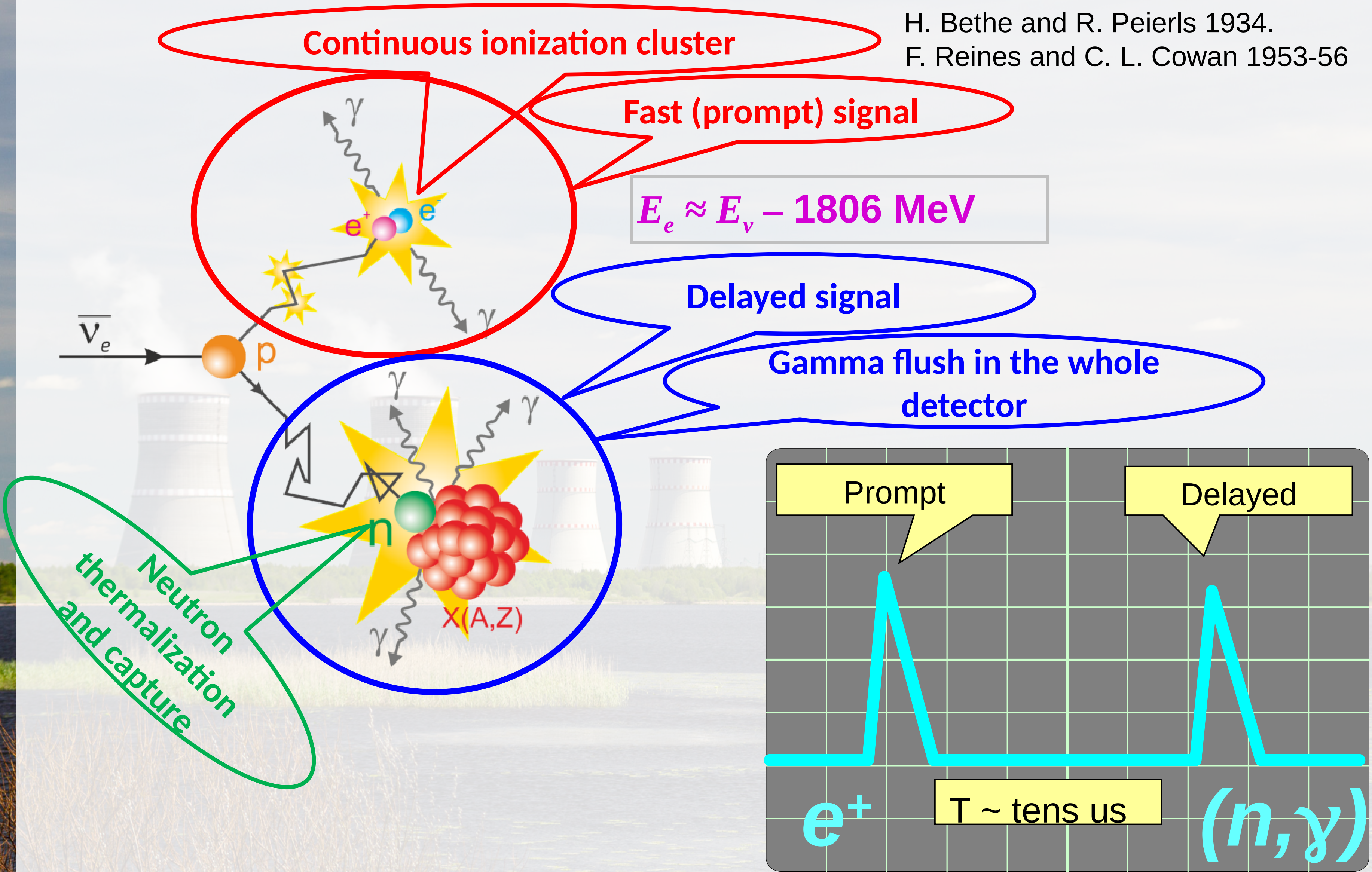
JINST 11 (2016) no.11, P11011

- Scintillation strips 10x40x100 mm^3 with Gd-dopped coating (0.35%wt)
- 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

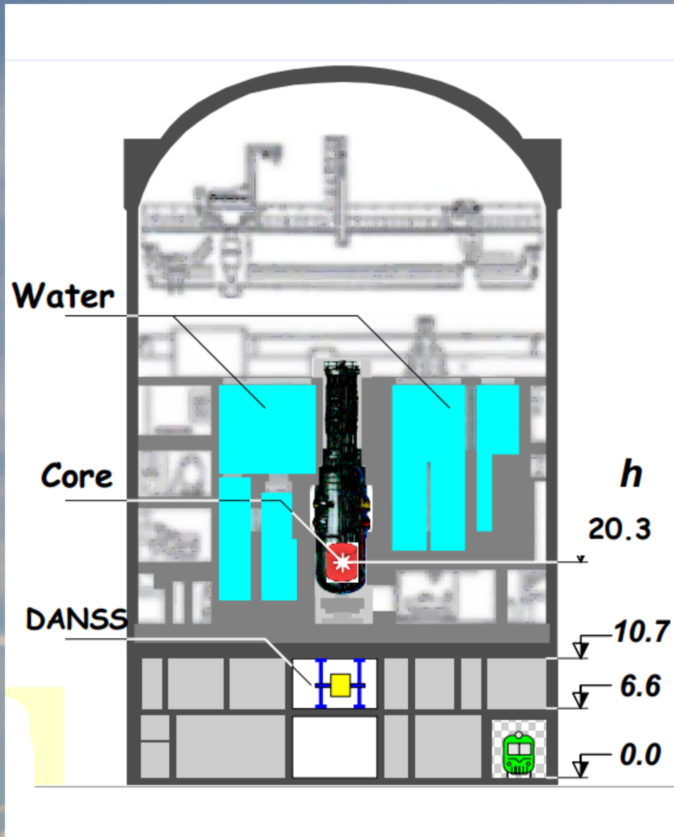
Inverse Beta-Decay (IBD)

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

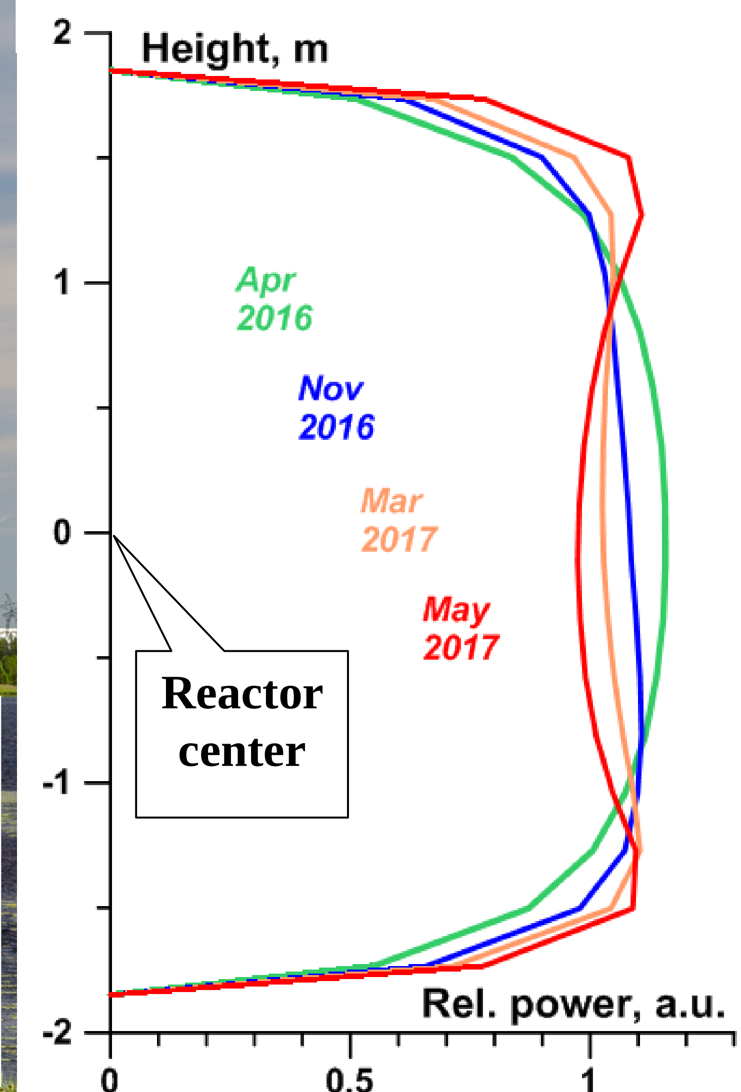
H. Bethe and R. Peierls 1934.
F. Reines and C. L. Cowan 1953-56



Reactor WWER1000



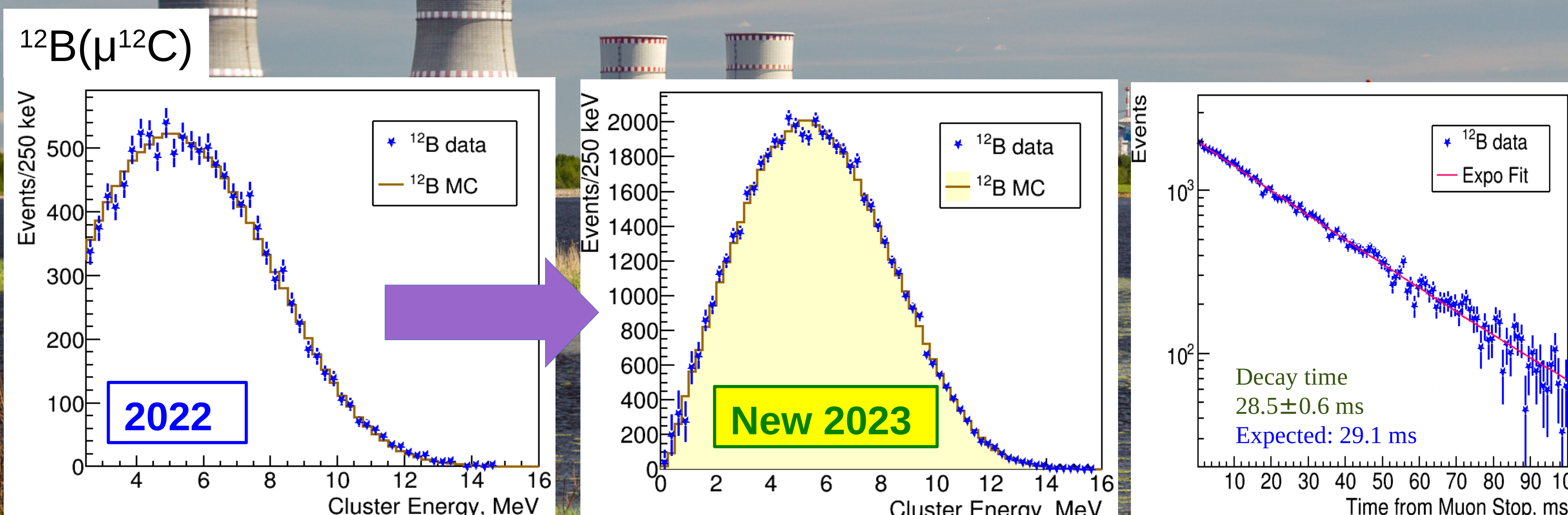
Reactor vertical burning profile for 100% power during the campaign



Fuel contribution during the campaigns

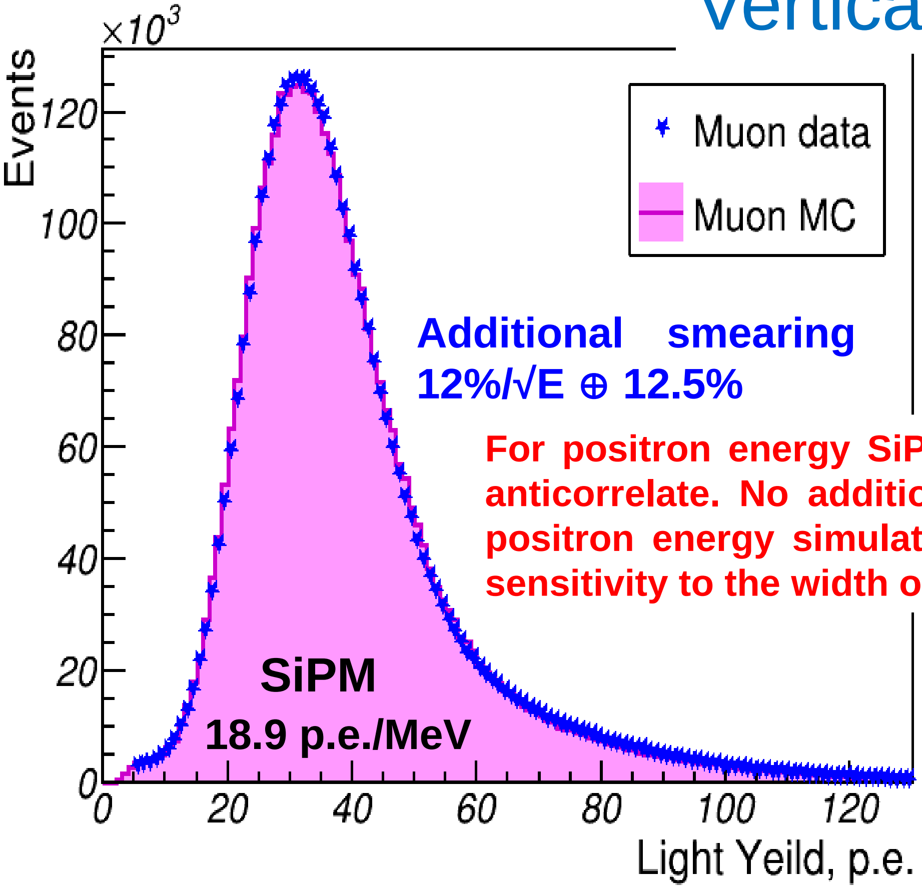
	Begin 4	End 4	Begin 5	End 5	Begin 6	End 6	Begin 7
^{235}U	63.5%	44.1%	65.8%	43.9%	66.3%	45.6%	68.7%
^{238}U	6.7%	7.8%	6.9%	7.8%	6.5%	7.3%	6.7%
^{239}Pu	26.7%	39.3%	24.9%	39.4%	24.8%	38.6%	22.8
^{241}Pu	2.7%	8.6%	2.2%	8.6%	2.3%	8.6%	1.7%

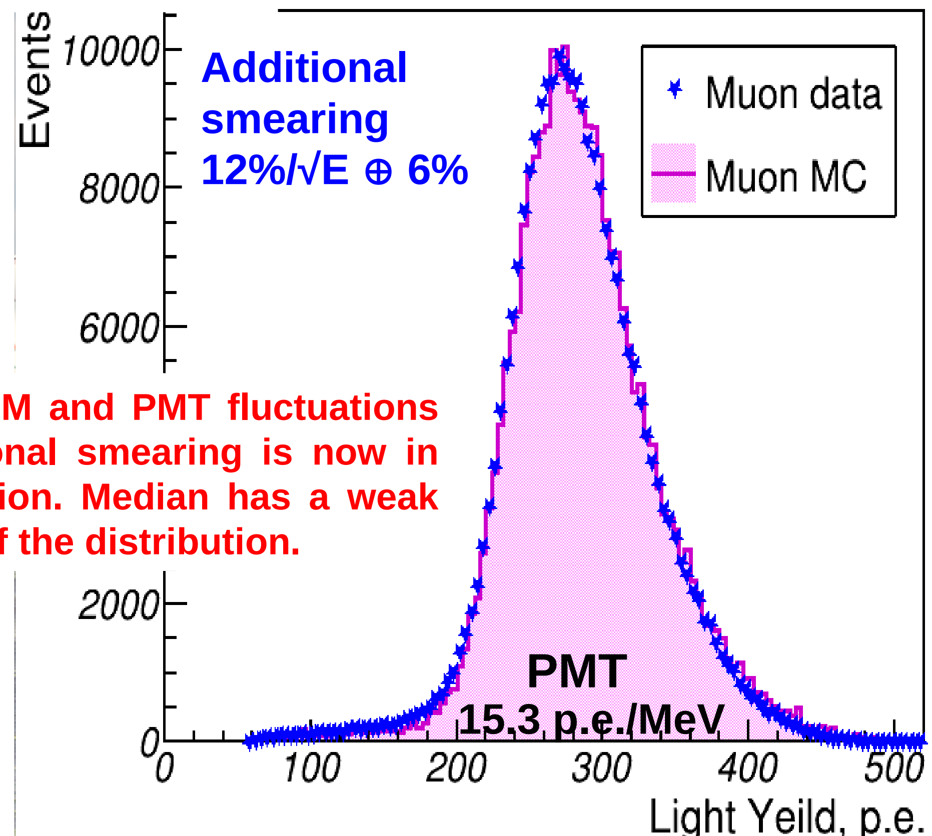
- Initial calibration is done by cosmic muons using median of the distribution. SiPM gain and X-talks are calibrated every 30-40 min. Scale for all photo-sensors is calibrated every 2 days.
- MC uses individual light yields for each SiPM and PMT channel.
- Final energy scale is fixed by ^{12}B-decay, which is similar to e^+ signal we measure. Two independent ^{12}B samples from spallation neutrons and muon capture agree wthin ±0.2%. [We measure the positron energy, not the total prompt event energy].
- Calibration check is done using ^{22}Na, ^{60}Co, ^{248}Cm (neutrons) sources and neutrons from IBD events.
- Everything with exception of ^{22}Na agree better than ±0.2%. Nevertheless we keep energy scale uncertainty estimation at 2% level and add it to the systematical error.



- Initial calibration is done by cosmic muons using median of the distribution. SiPM gain and X-talks are calibrated every 30-40 min. Scale for all photo-sensors is calibrated every 2 days.
- MC uses individual light yields for each SiPM and PMT channel.
- Final energy scale is fixed by ^{12}B-decay, which is similar to e^+ signal we measure. [We measure the positron energy, not the total prompt event energy].
- We keep energy scale uncertainty estimation at 2% level and add it to the systematical error.

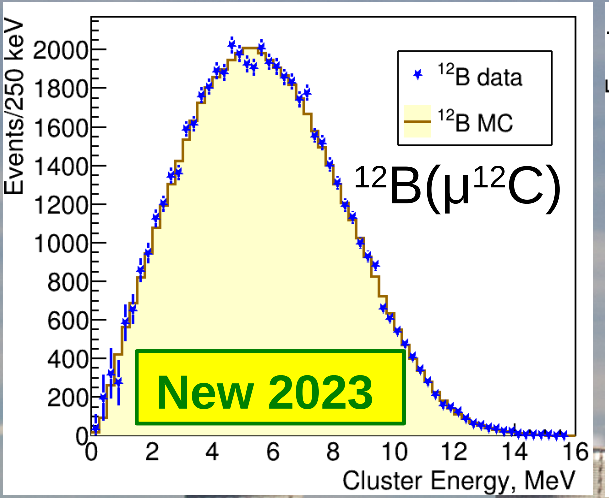
Vertical muons

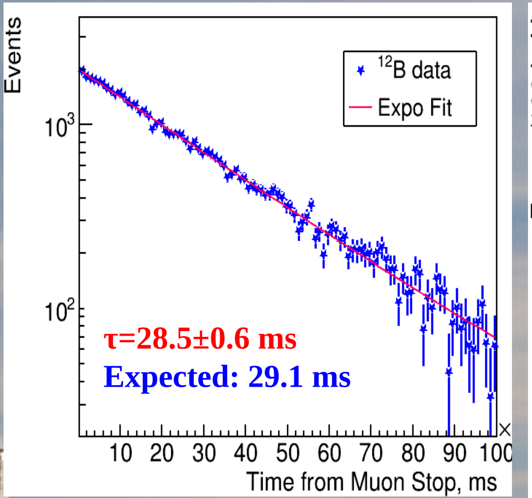


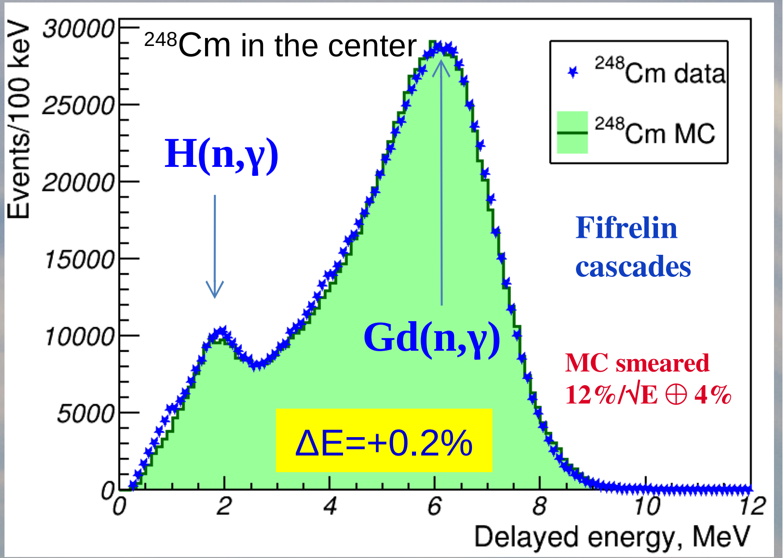


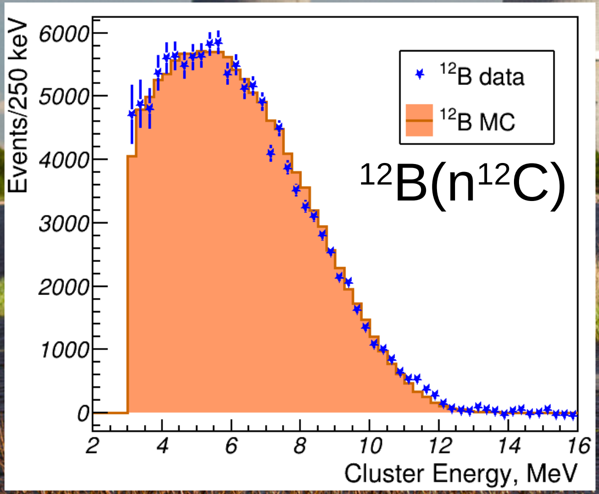
For positron energy SiPM and PMT fluctuations anticorrelate. No additional smearing is now in positron energy simulation. Median has a weak sensitivity to the width of the distribution.

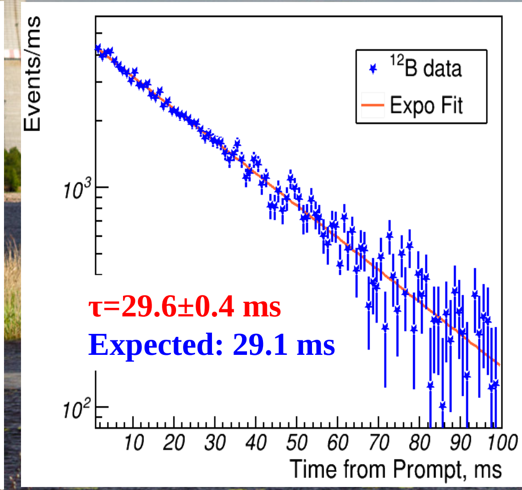
Calibration

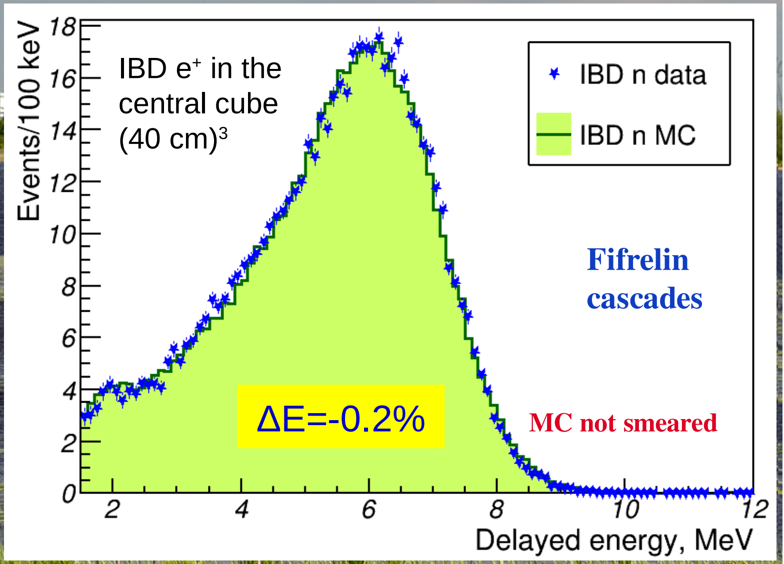






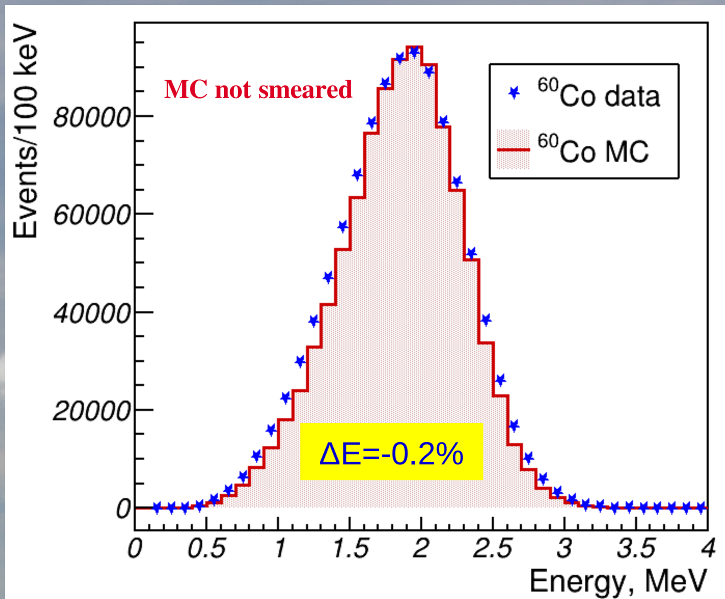


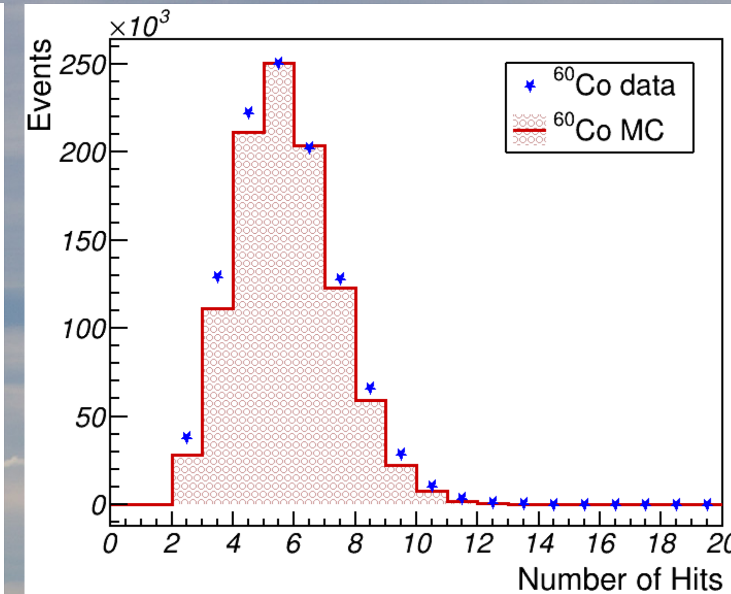




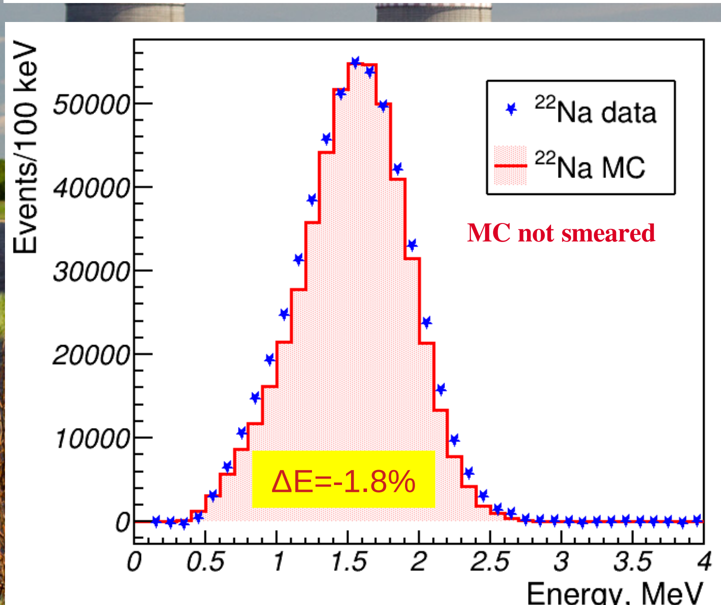
Calibration

^{60}Co in the center

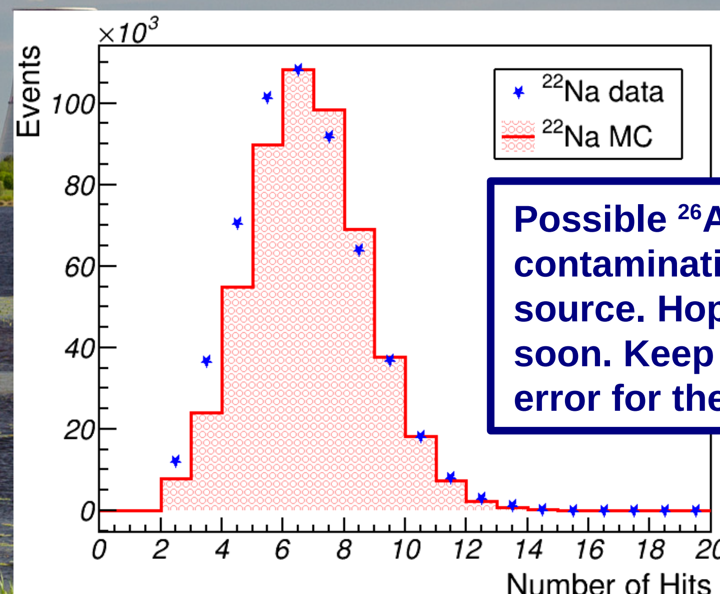




^{22}Na in the center



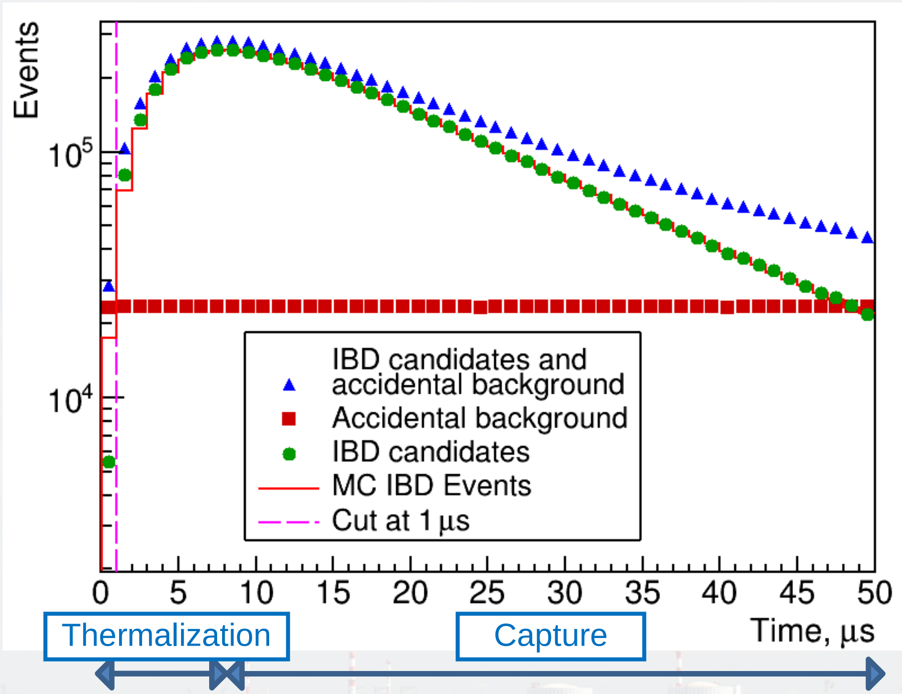
T, us



Possible ^{26}Al contamination in the ^{22}Na source. Hope to solve soon. Keep 2% systematic error for the scale.

Trigger and events

- Trigger = digital sum of PMT > 0.5 MeV or VETO
  - Total trigger rate ≈ 1.1 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: > 0.5 MeV in continuous ionization cluster (PMT+SiPM)

Neutron candidate: > 1.5 MeV total energy (PMT+SiPM), hit 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

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

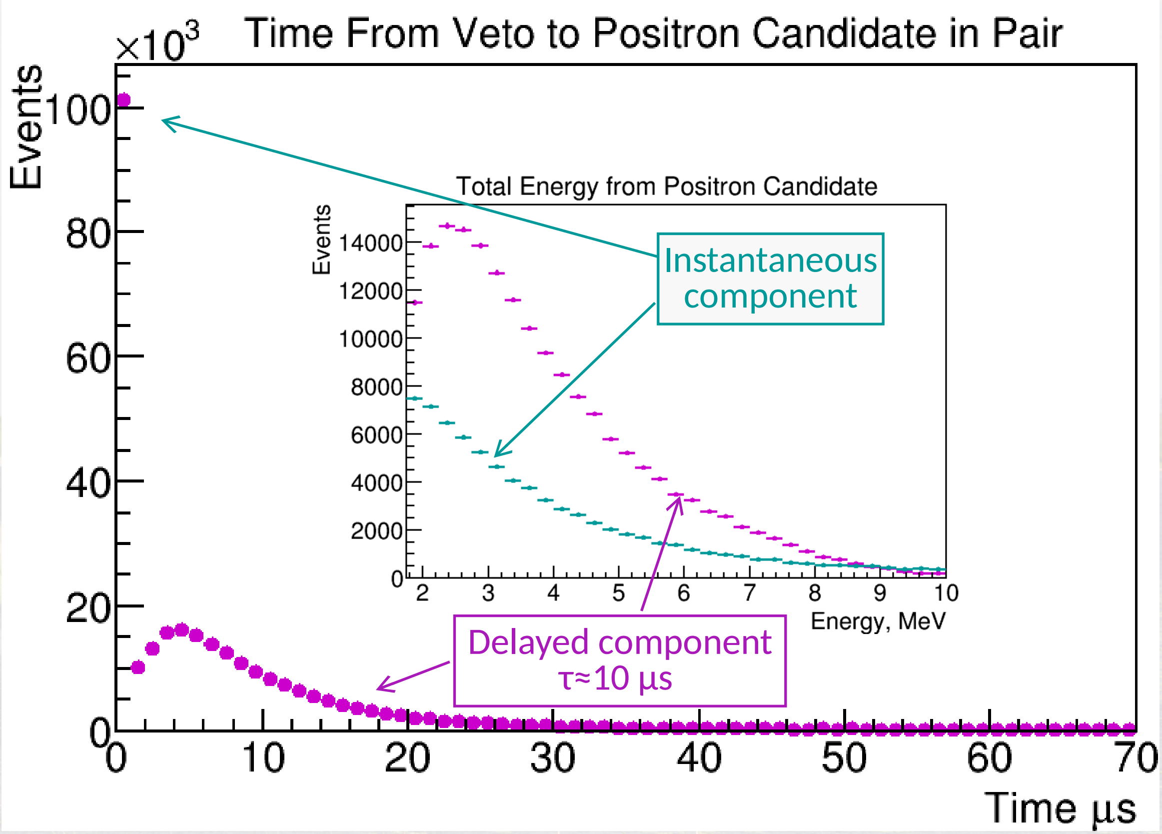
Two distinct components of muon induced paired events with different spectra:

- '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

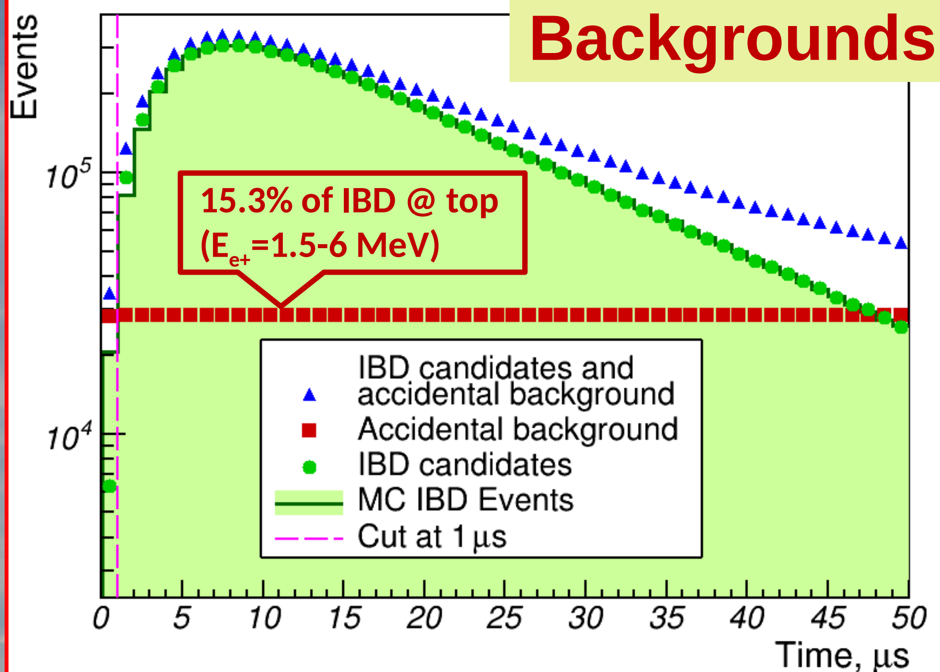
Delayed event energy is < 9.5 MeV and number of hits is < 20

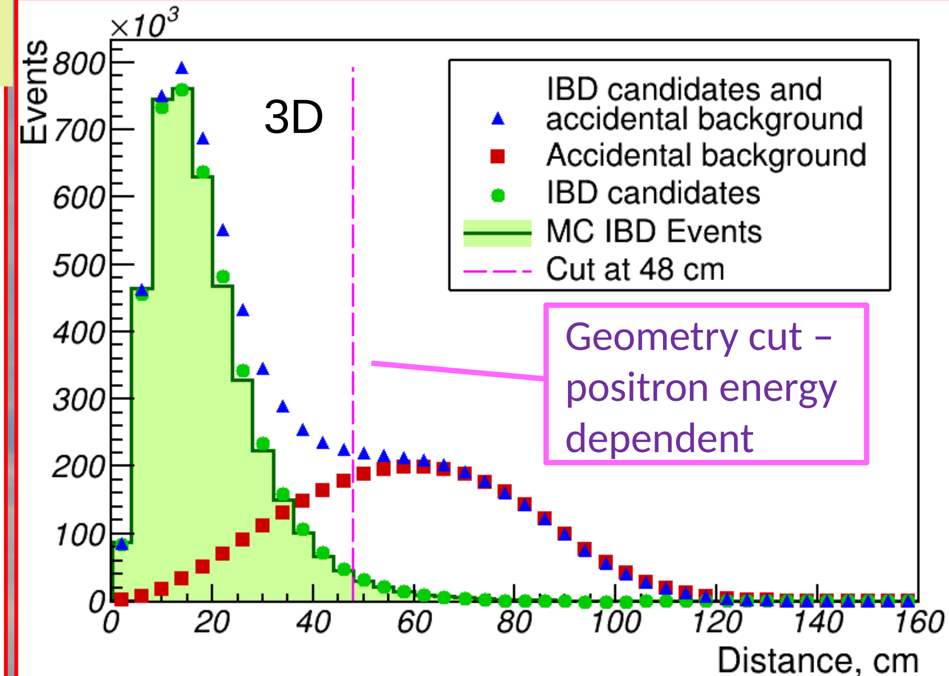
Positron (cluster) energy E_e dependent cuts on prompt to delayed cluster distance and delayed event energy:

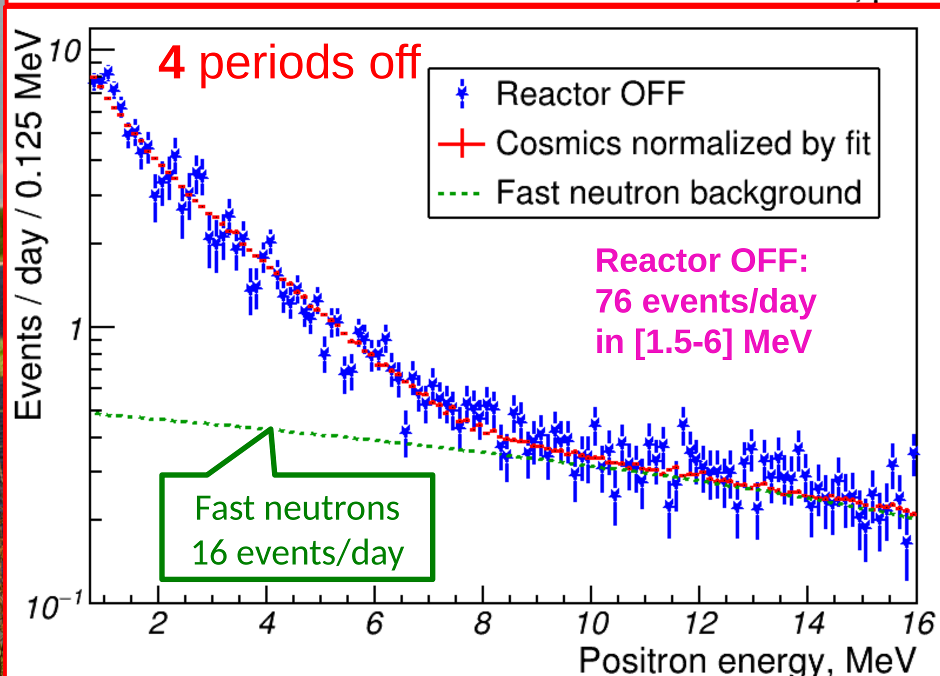
$$
\begin{aligned}
L_{2D}[cm] &< 40 - 17 \cdot e^{-0.13 \cdot E_e^2} \\
L_{3D}[cm] &< 48 - 17 \cdot e^{-0.13 \cdot E_e^2} \\
E_N[MeV] &> 1.5 + 2.6 \cdot e^{-0.15 \cdot E_e^2}
\end{aligned}
$$

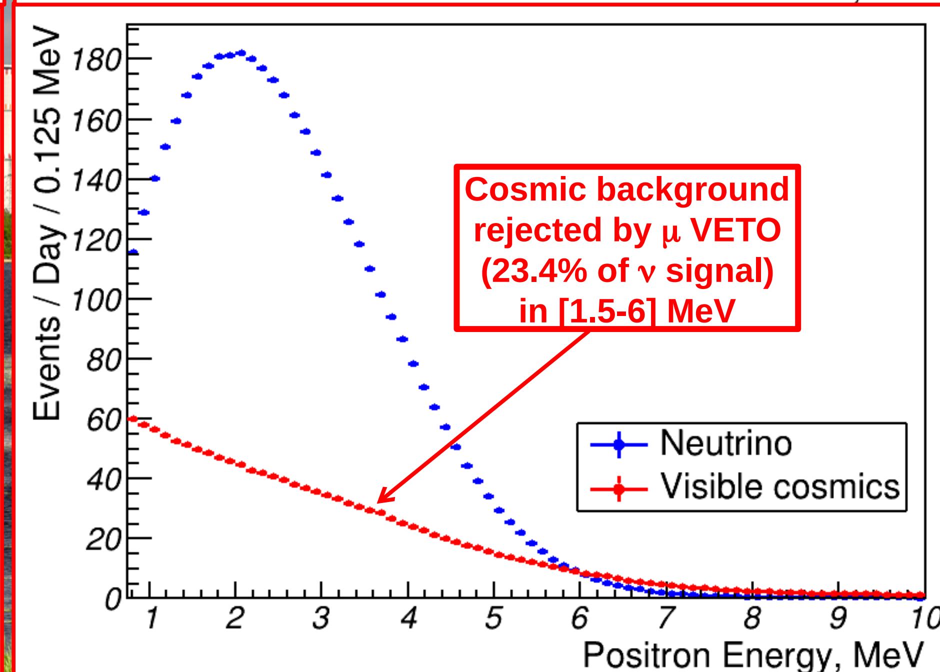
For events with single hit positron cluster additional requirement of at least a hit out of the cluster and the energy beyond the cluster > 0.1 MeV

Backgrounds

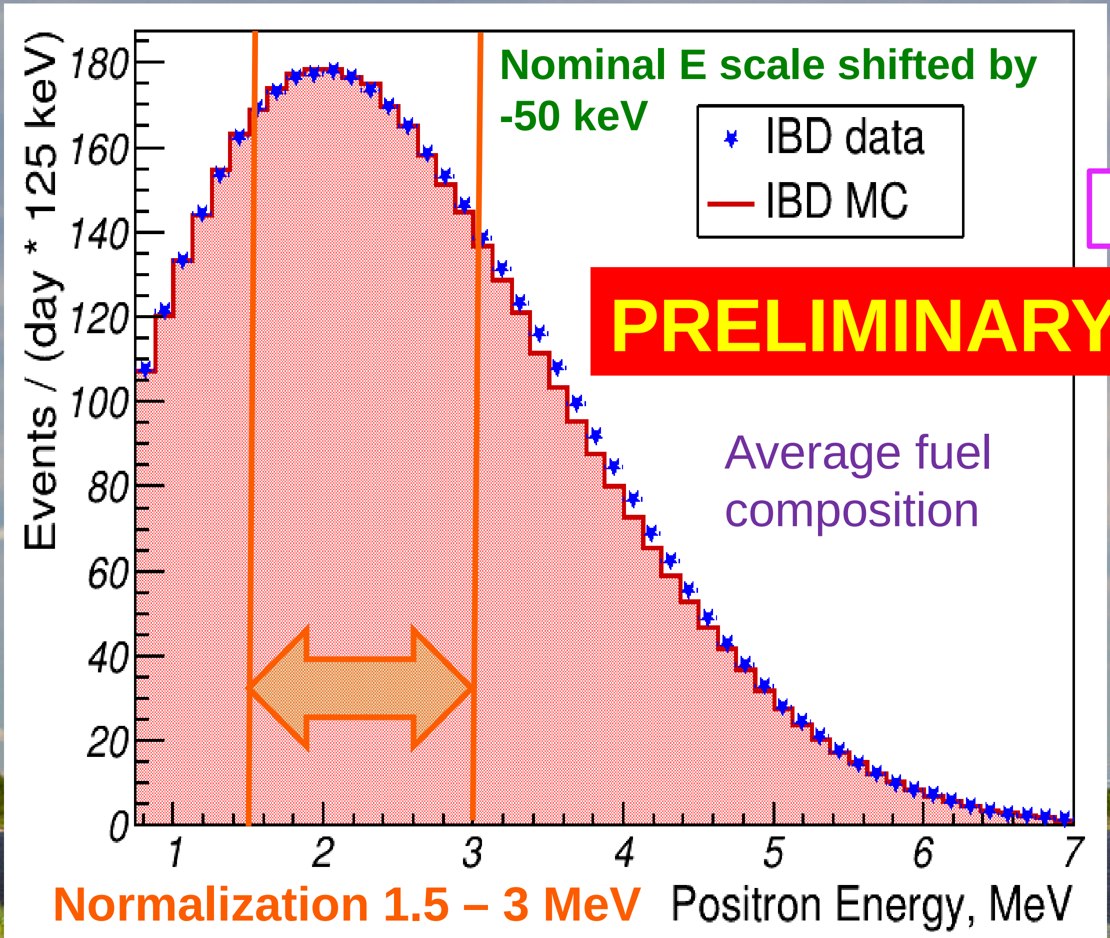


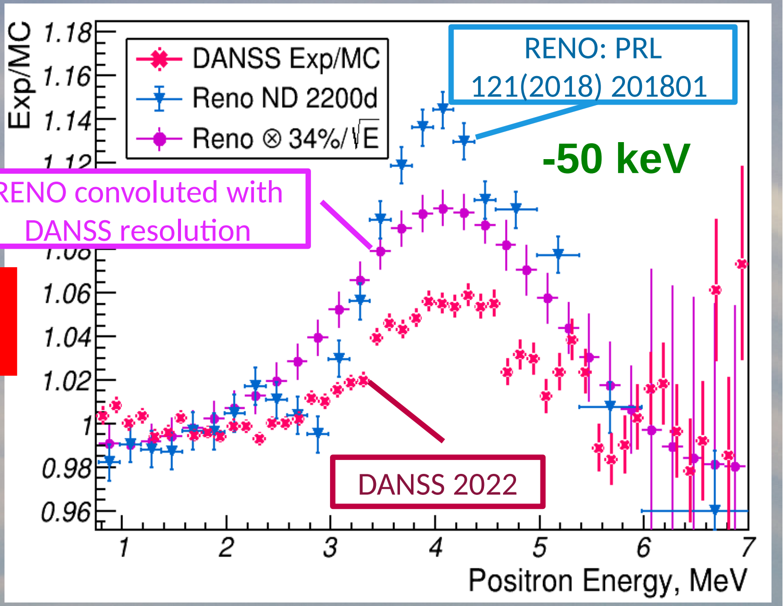


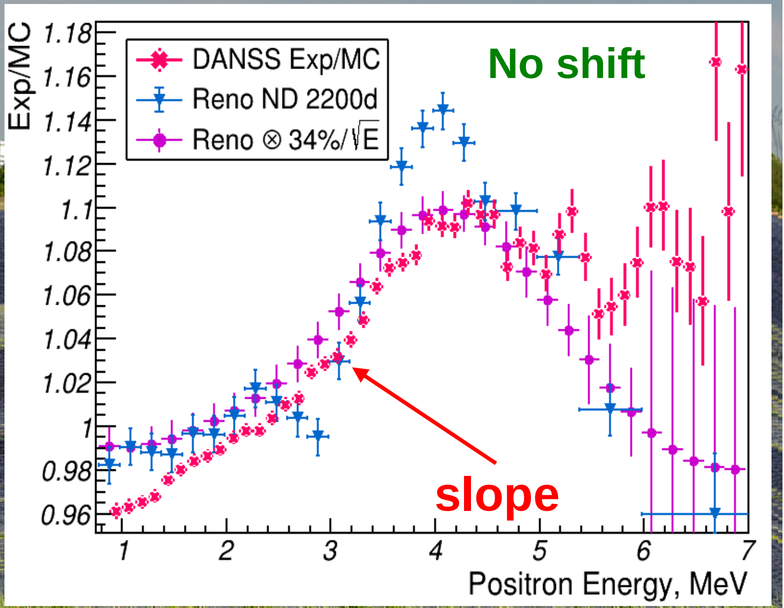




Positron spectrum comparison to H-M model







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

χ^2 - calculation

$$\chi^2 = \min_{\eta,k} \underbrace{\sum_{i=1}^{N} (Z_{1i} \quad Z_{2i}) \cdot W^{-1} \cdot \begin{pmatrix} Z_{1i} \\ Z_{2i} \end{pmatrix}}_{\text{3-position movement Oct. 16 – Dec. 18}} + \underbrace{\sum_{i=1}^{N} \frac{Z_{1i}^2}{\sigma_{1i}^2}}_{\text{2-pos. Mar. 19 – Mar. 22}} + \underbrace{\sum_{j=1,2} \frac{(k_j - k_j^0)^2}{\sigma_{kj}^2} + \sum_{l} \frac{(\eta_l - \eta_l^0)^2}{\sigma_{\eta l}^2}}_{\text{Penalty terms for nuisance parameters: relative efficiencies and systematics}}$$

3-position movement
Oct. 16 – Dec. 18

2-pos.
Mar. 19 –
Mar. 22

Penalty terms for nuisance parameters: relative efficiencies and systematics

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,

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

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

k – relative efficiency,

η – nuisance parameters;

W – covariance matrix;

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

relative detector efficiencies - 0.2%

fast neutron background – 30%

distance to the fuel burning profile center - 5 cm

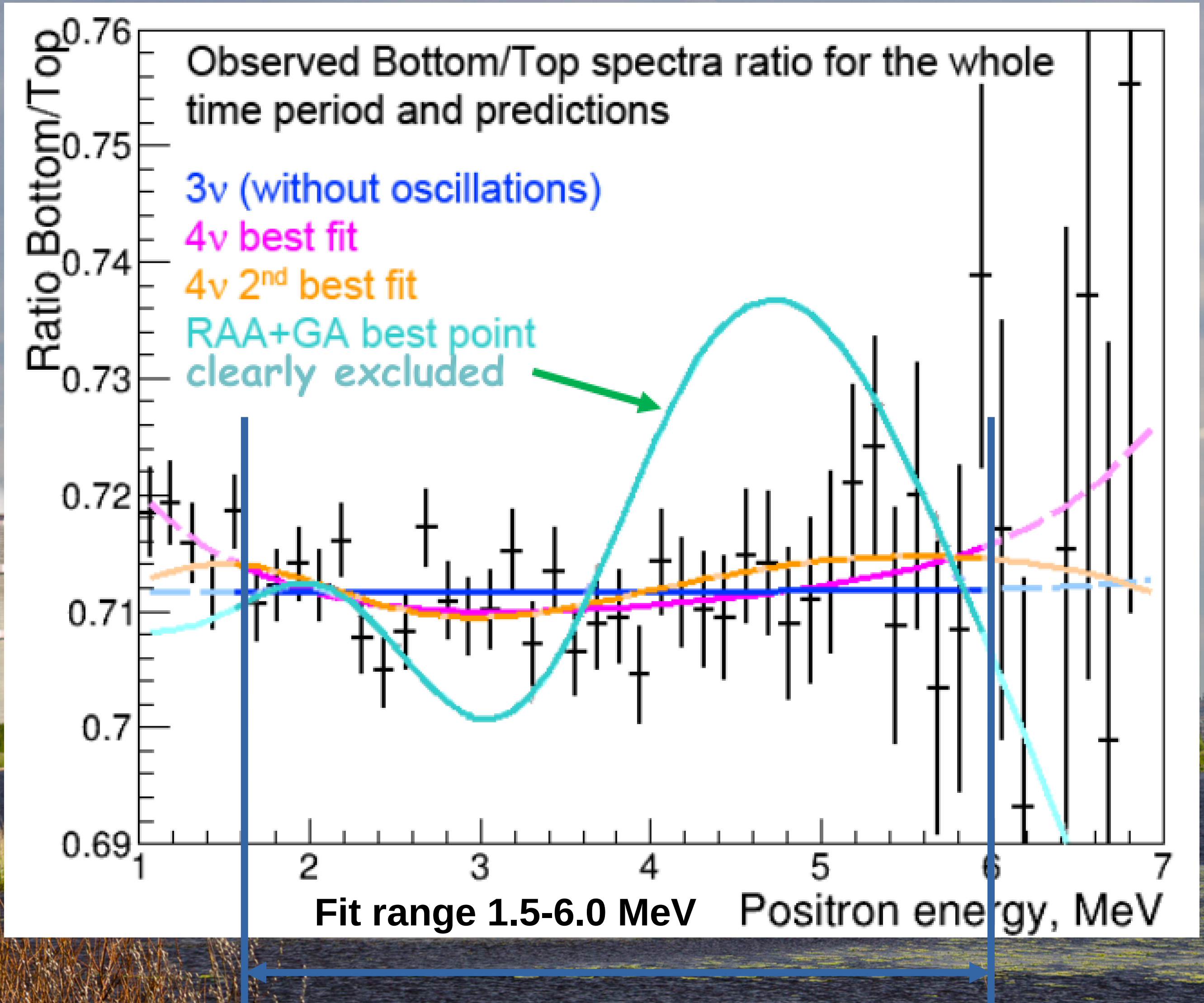
additional smearing in energy resolution – ($6\%/\sqrt{E} \oplus 2\%$)

energy scale - 2%

energy shift - 50 keV

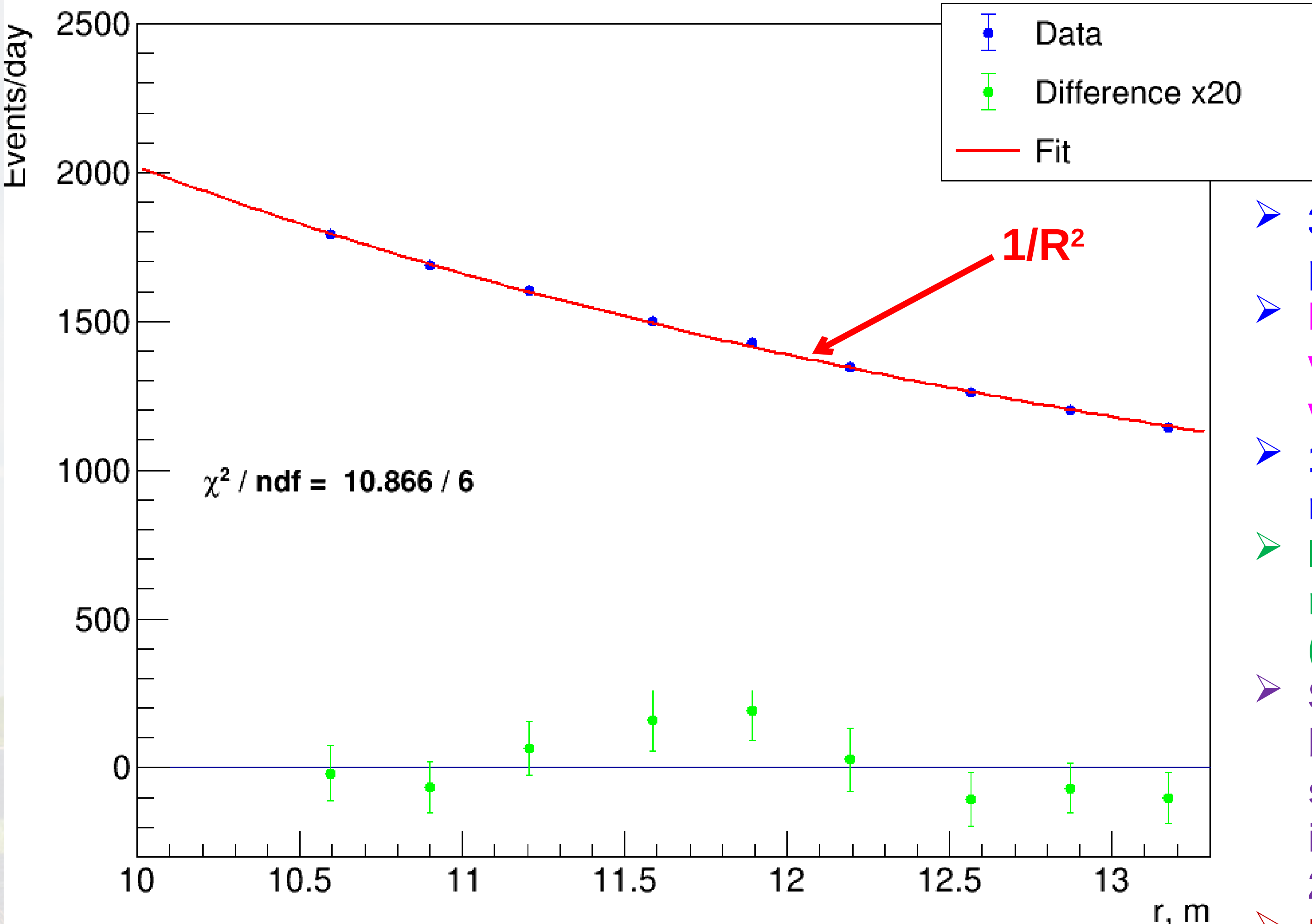
cosmic background - 25%

All data 2016-2023 $\Delta\chi^2 = -8.5$ (2.1σ)



No statistically significant hint of 4ν signal

Counting rate dependence on the distance from the reactor core



- **3 position movement period used**
- **Detector fiducial volume divided into 3 vertical sections**
- **1.5 – 6 MeV e^+ energy range**
- **Individual section normalization (efficiency etc)**
- **Section/position background subtracted individually based on 2 reactor off periods**
- **Rough agreement with $1/R^2$ dependence**

Position	Top			Mid			Bottom		
Section	U	M	D	U	M	D	U	M	D

^9Li and ^8He background ~ 4 events per day