Recent results from DANSS

Igor Alekseev for the DANSS collaboration

NOW 2022

Neutrino Oscillation Workshop 2022

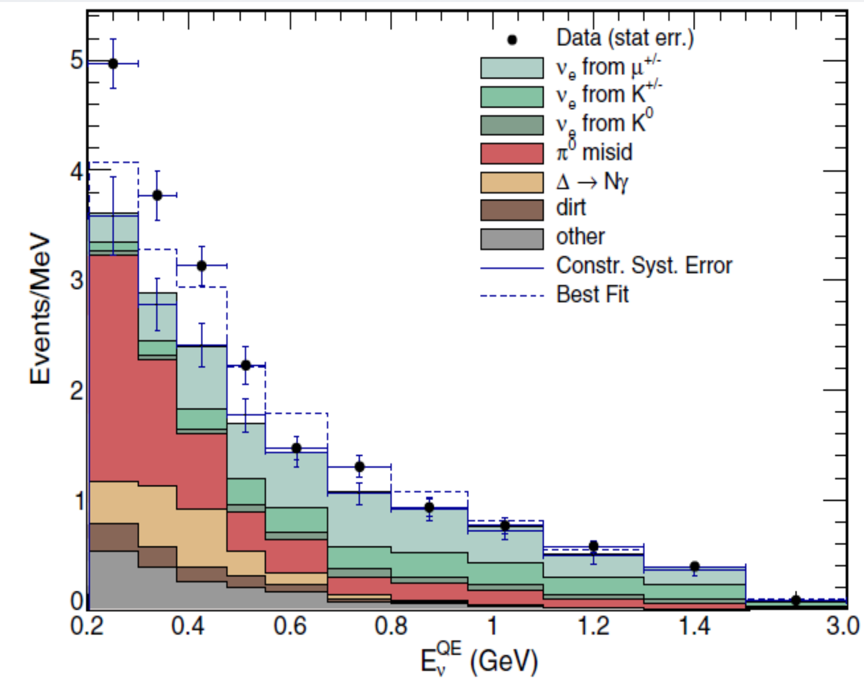
Rosa Marina (Ostuni, Brindisi, Italy)

4-11 September 2022

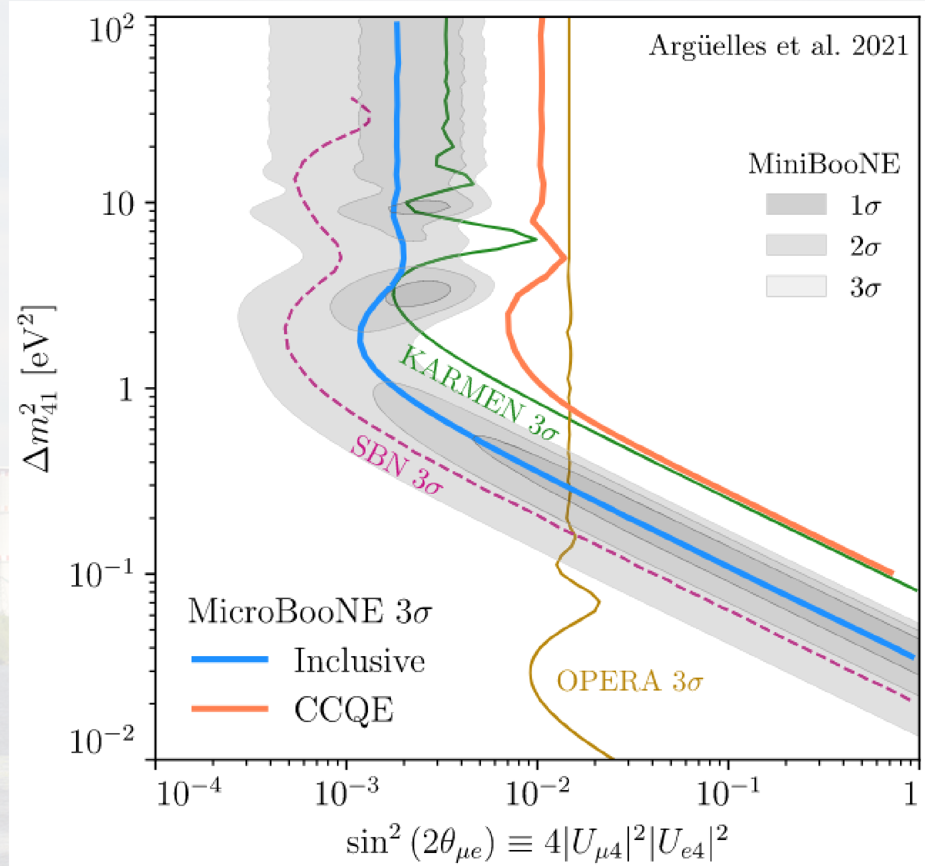
There are several indications in favor of existence of the 4th neutrino flavor - "sterile" neutrino seen in short distance oscillations

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

6.1σ combined result



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

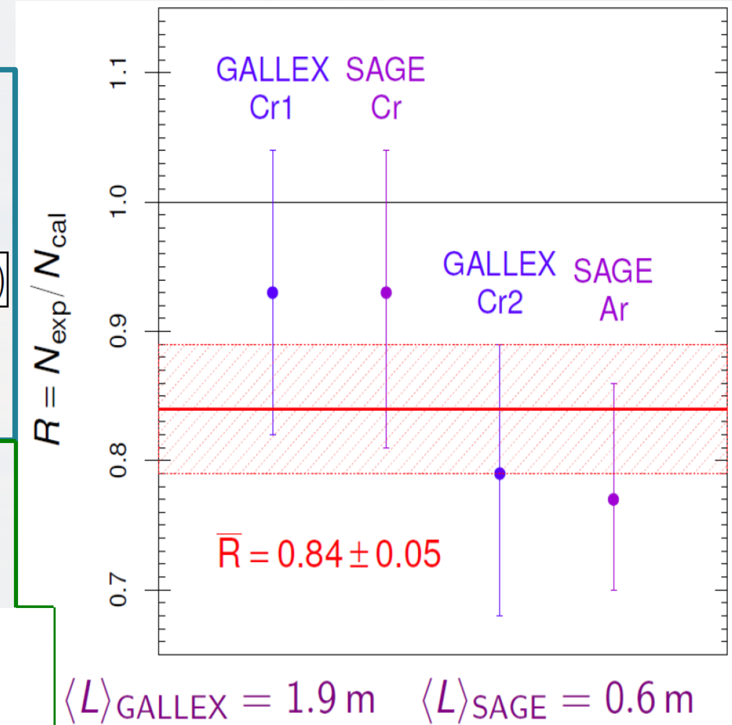


MicroBooNE, PRL **128**, 241802 (2022)

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)

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

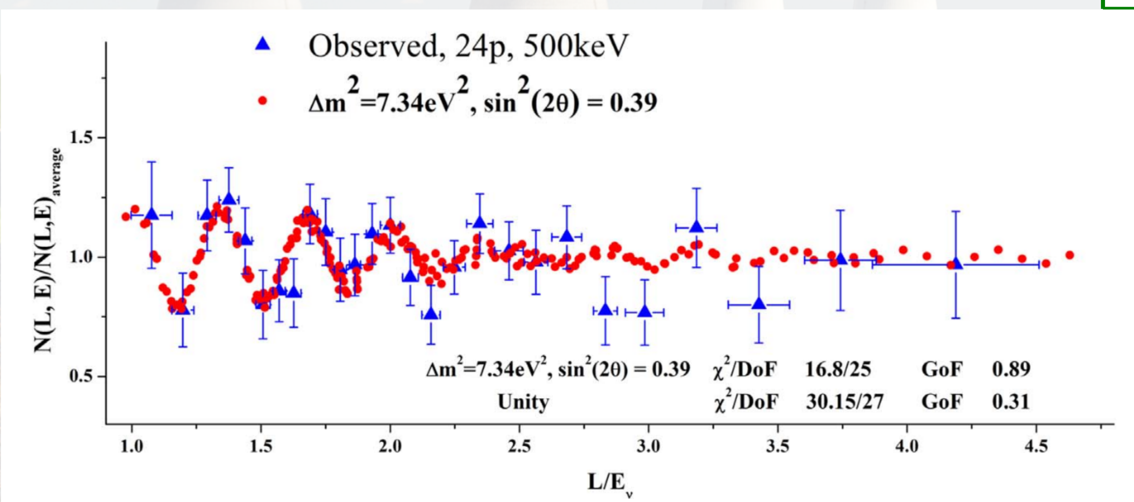
Much smaller (3.7%): M. Estienne et al. PRL 123, 022502

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

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

Neutrino-4: 2.7σ @ $\Delta m^2 \sim 7 eV^2$ $\sin^2 2\theta \sim 0.35$

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

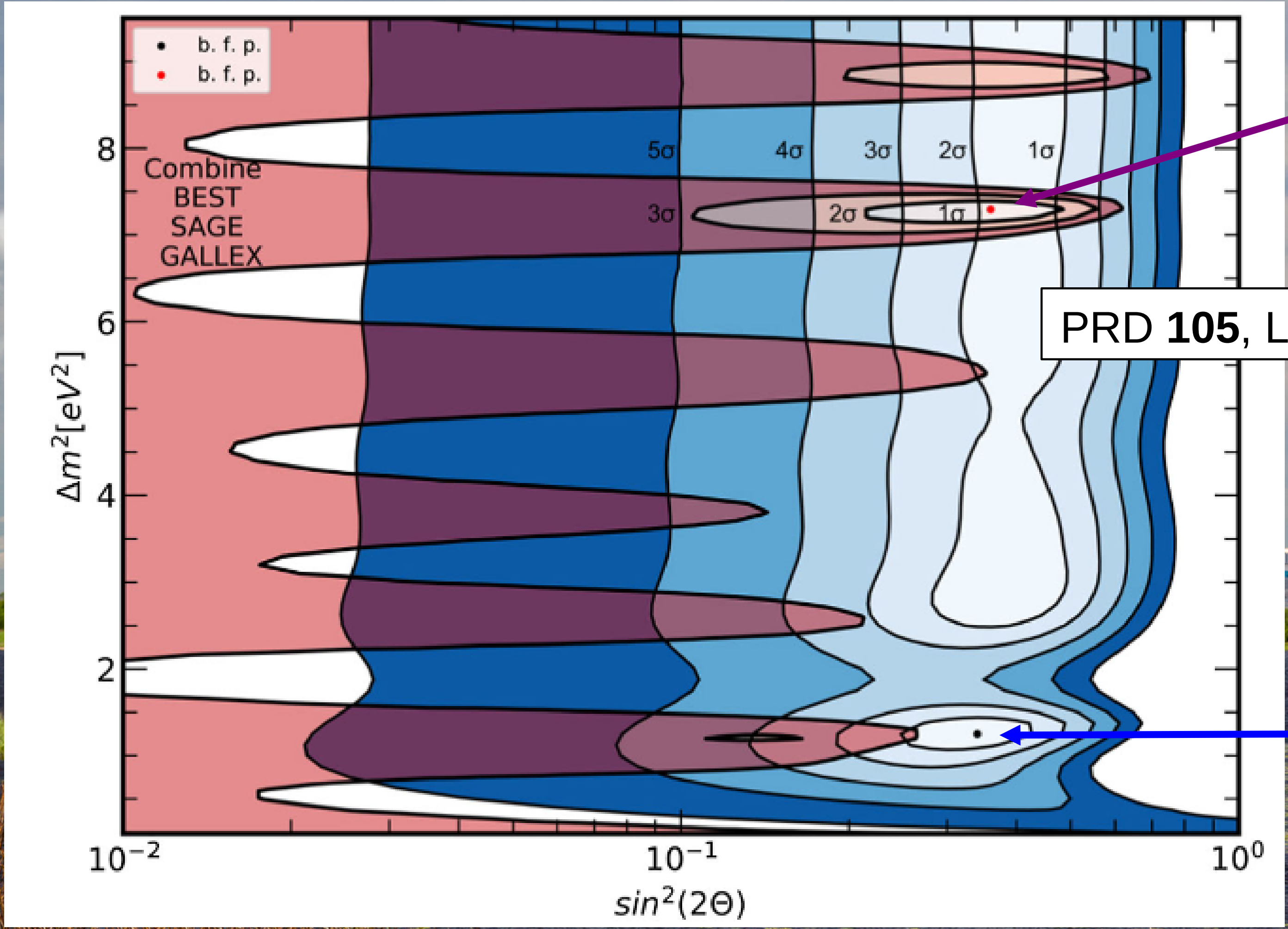


Criticism of the Neutrino-4 analysis:

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 best point

PRD **105**, L051703 (2022)

BEST + SAGE + GALLEX best point

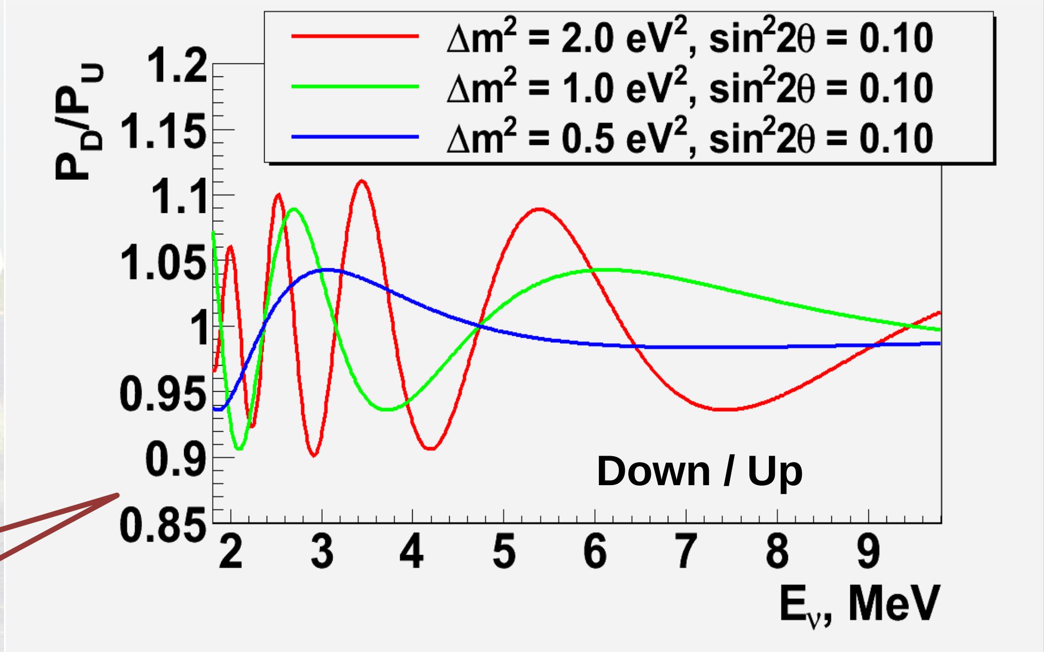
Neutrino-4 — tints of red

BEST+SAGE+GALLEX — tints of blue

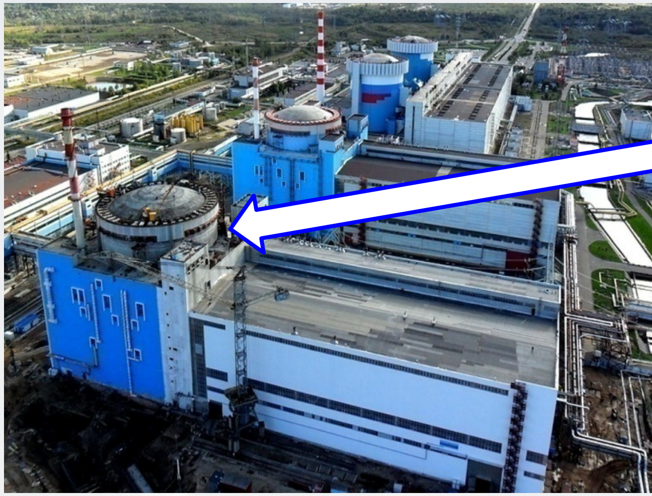
In a simple model with the 4th neutrino survival probability of electron antineutrino from the reactor is given by the formula:

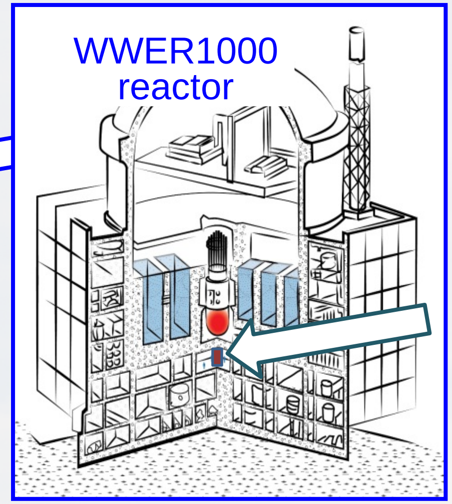
$$P_{ee}^{2\nu}(L) = 1 - \sin^2(2\theta_i)\sin^2\left(1.27\frac{\Delta m_i^2[\mathrm{eV}^2]L[\mathrm{m}]}{E_{\bar{\nu}_e}[\mathrm{MeV}]}\right)$$

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





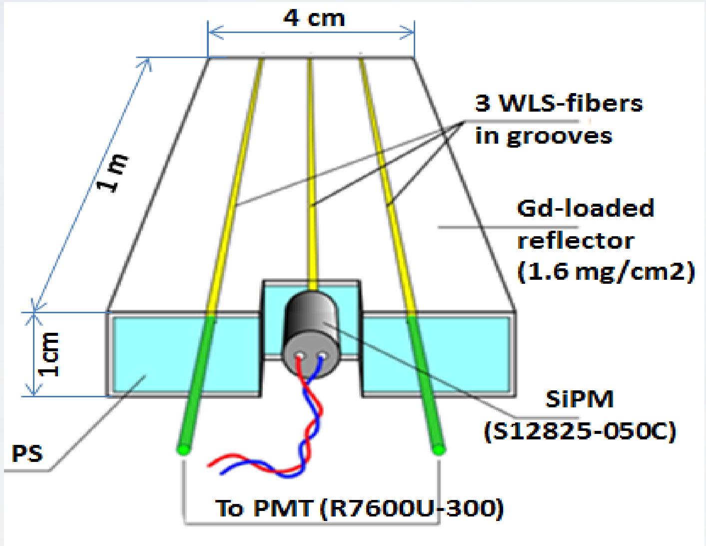
Kalininskaya Nuclear Power Plant, Russia, ~350 km NW from Moscow

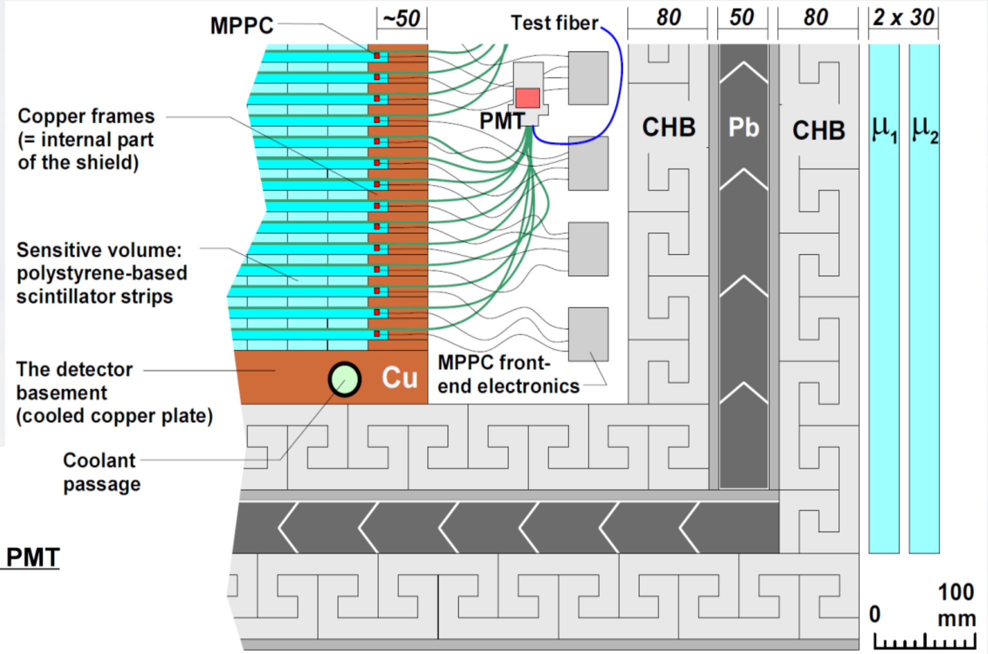
Below 3.1 GW_{th} commercial reactor ~$5 \cdot 10^{13}$ $\nu \cdot cm^{-2} c^{-1}$@11m

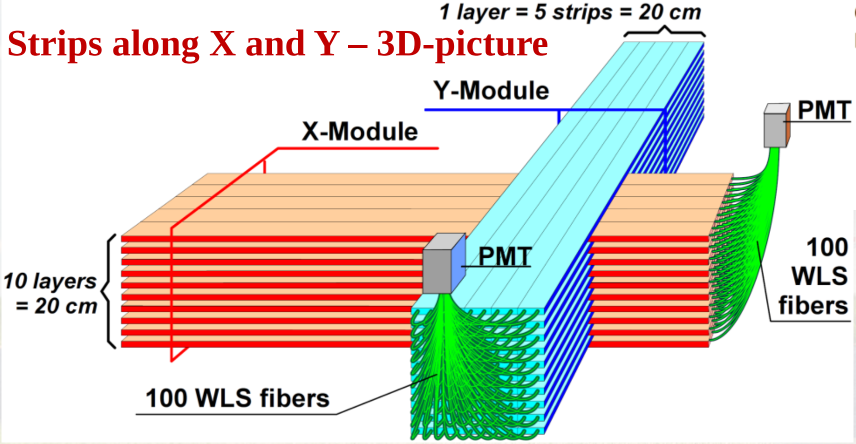
DANSS on a lifting platform A week cycle of up/middle/down position

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

Detector of the reactor AntiNeutrino based on Solid-state Scintillator







- Scintillation strips 10x40x100 mm³ 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 m³ of sensitive volume

- 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)

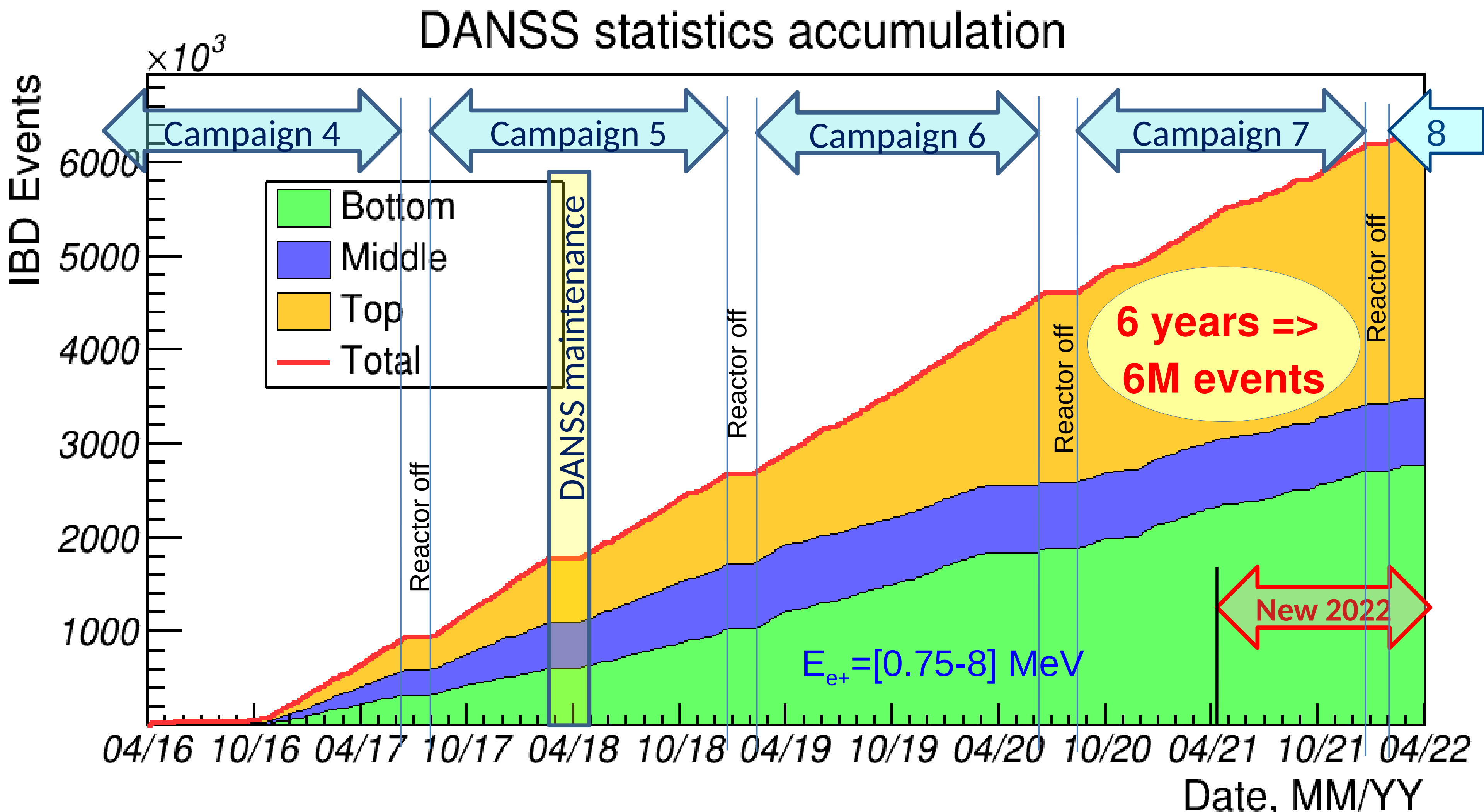
JINST 11 (2016) no.11, P11011

This analysis covers DANSS data till March 2022

One more year and one more reactor off period to 2021 analysis release:

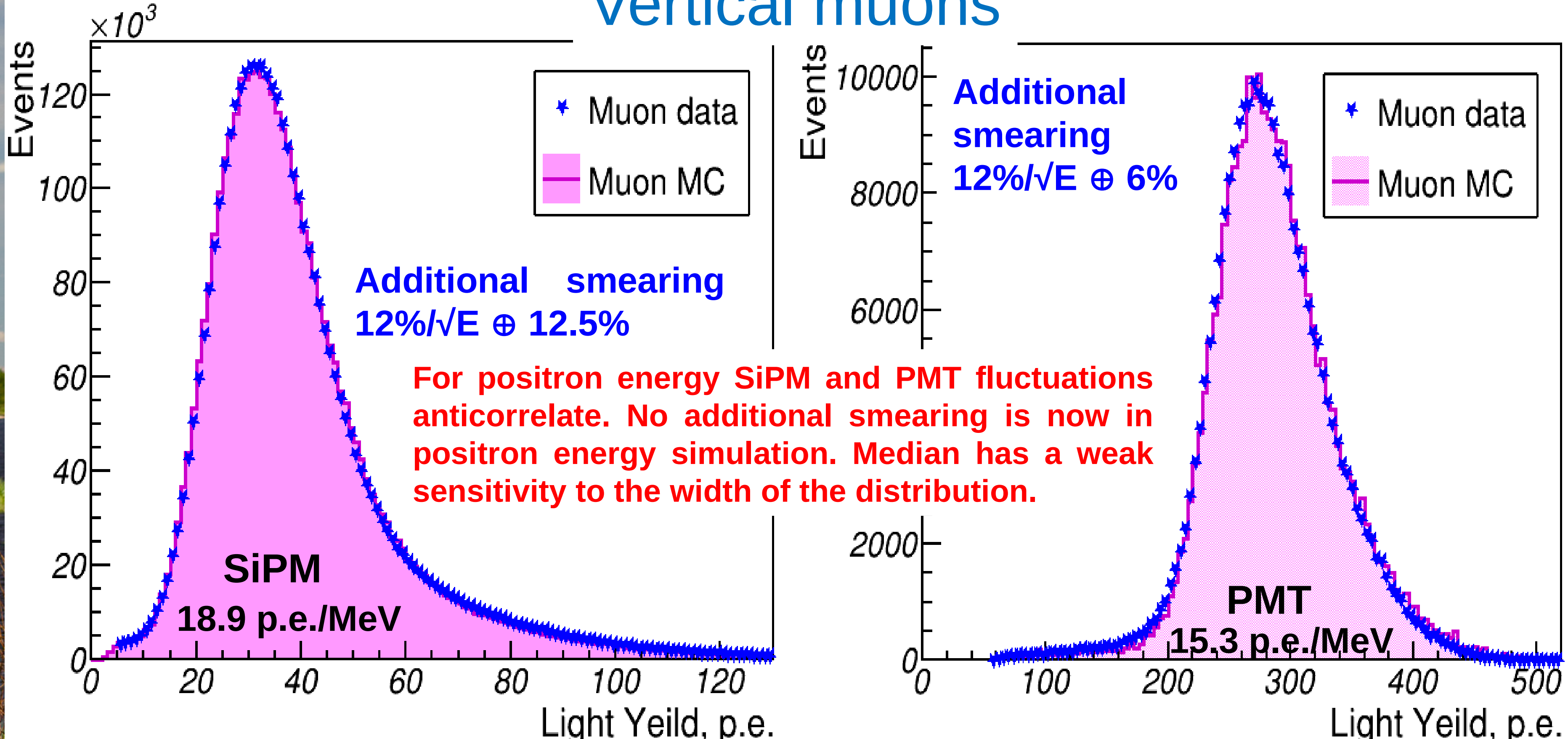
Igor Alekseev for the DANSS Collaboration. Journal of Physics: Conference Series 2156 (2021) 012100;

I.G. Alekseev and N. Skrobova. PoS 402 (NuFact2021) 143 (2022)



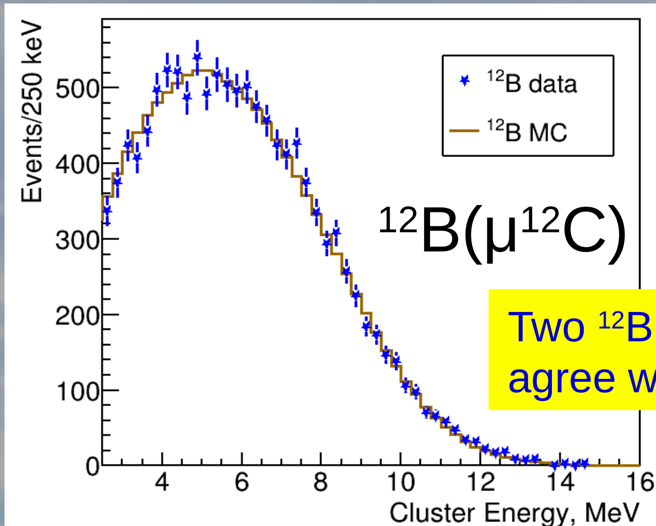
- Initial calibration is done by cosmic muons using median of the distribution. SiPM gain and X-talks are calibrated every 30-40 min. Scale for all photo-sensors is calibrated every 2 days.
- MC uses individual light yields for each SiPM and PMT channel.
- Final energy scale is fixed by ^{12}B-decay, which is similar to e^+ signal we measure: -4.6% to the muon scale. [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.

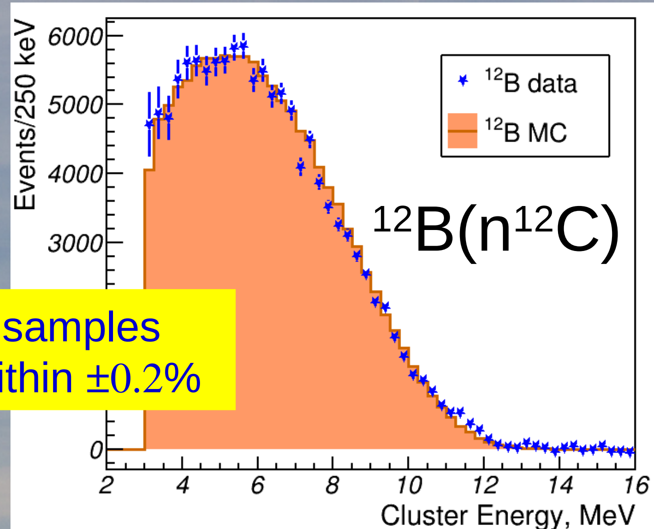
Vertical muons



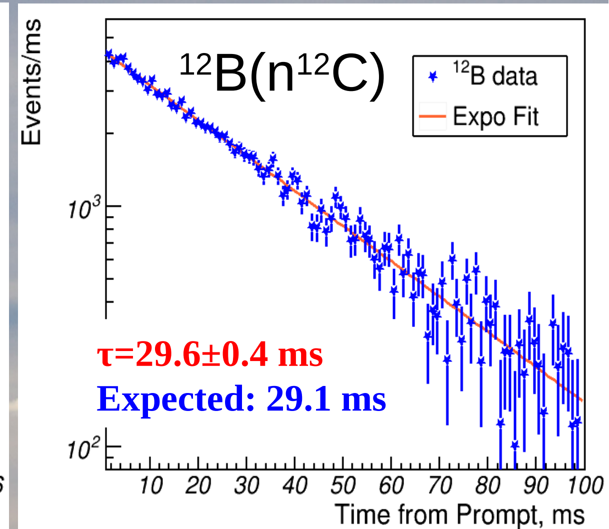
For positron energy SiPM and PMT fluctuations anticorrelate. No additional smearing is now in positron energy simulation. Median has a weak sensitivity to the width of the distribution.

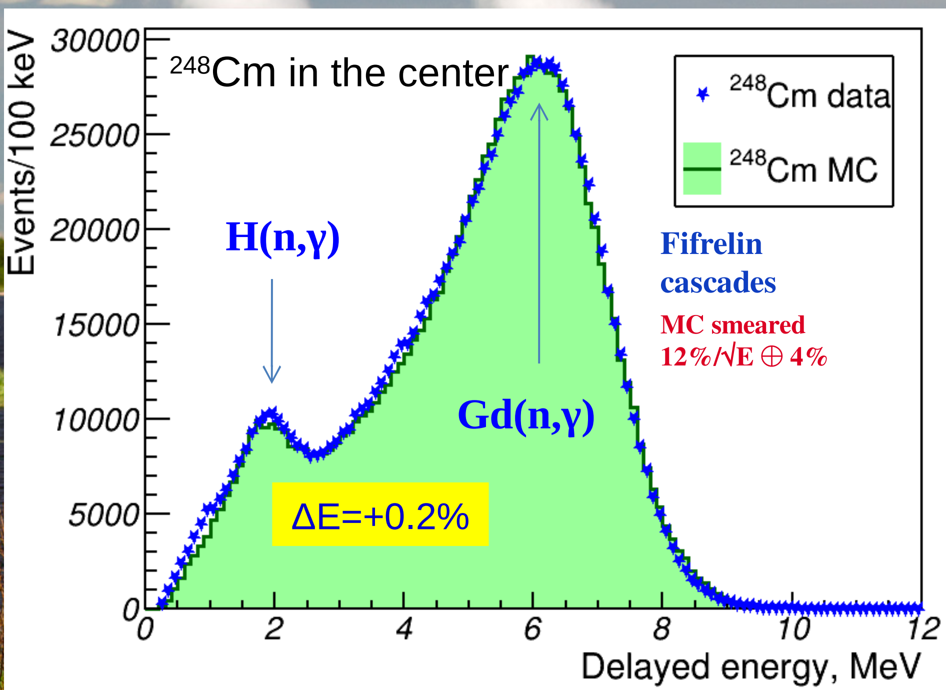
Calibration

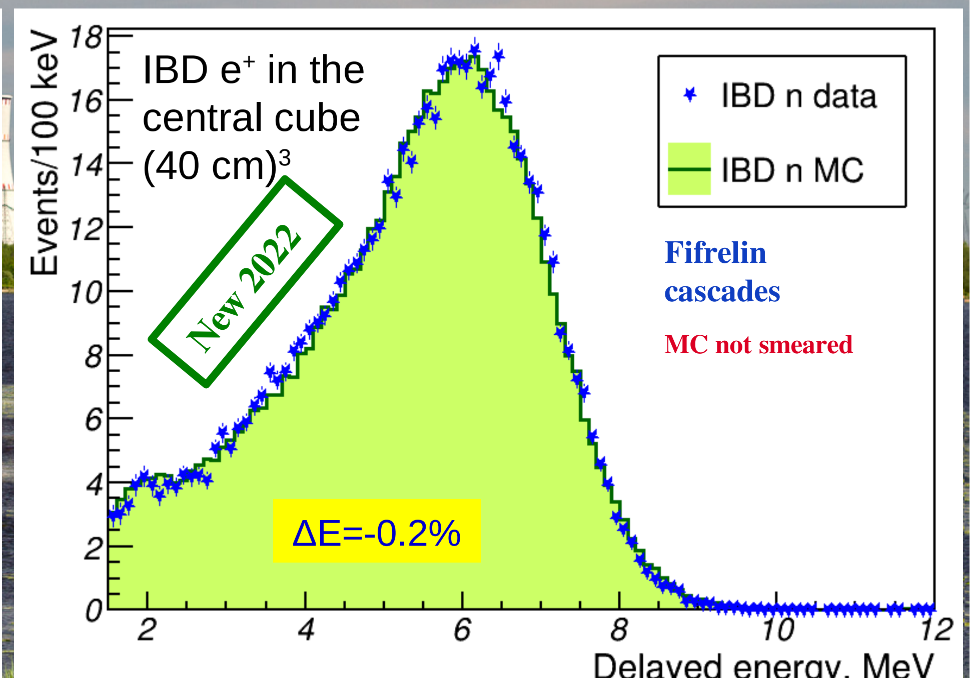




Two ^{12}B samples agree within ±0.2%

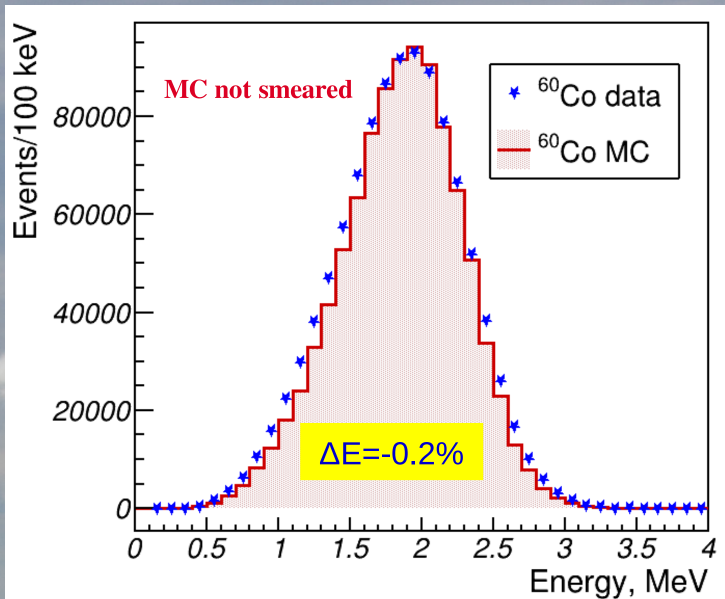


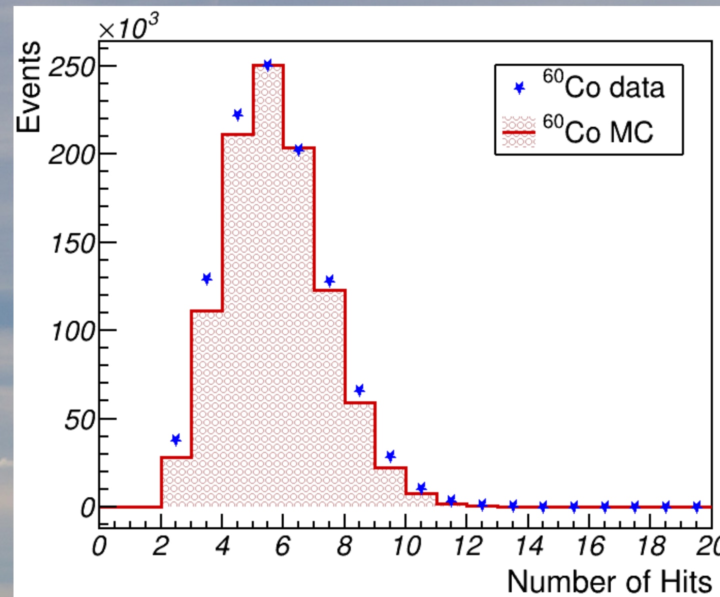




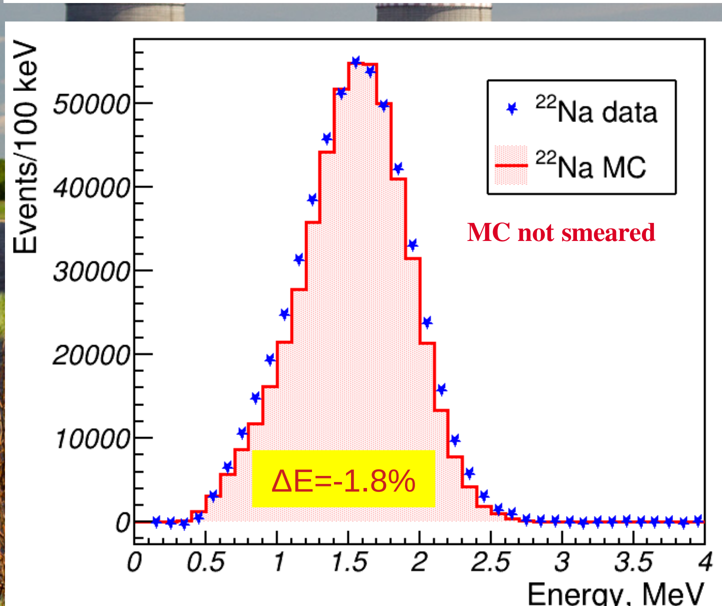
Calibration

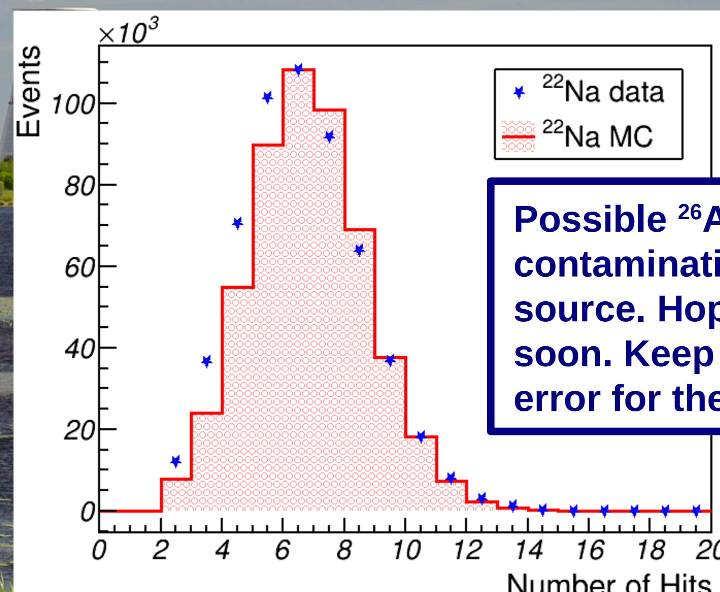
^{60}Co in the center





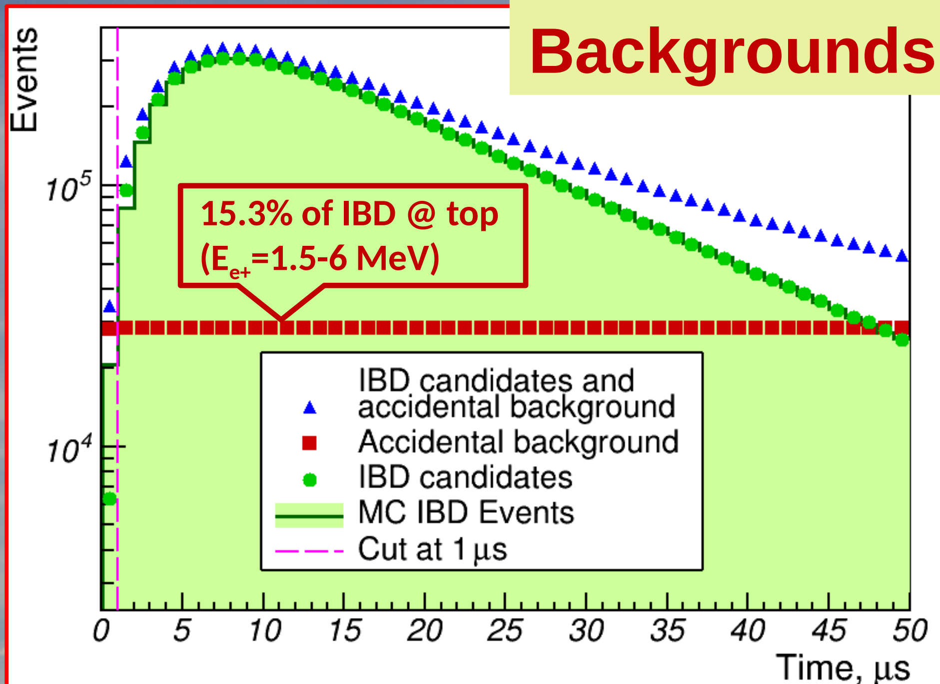
^{22}Na in the center

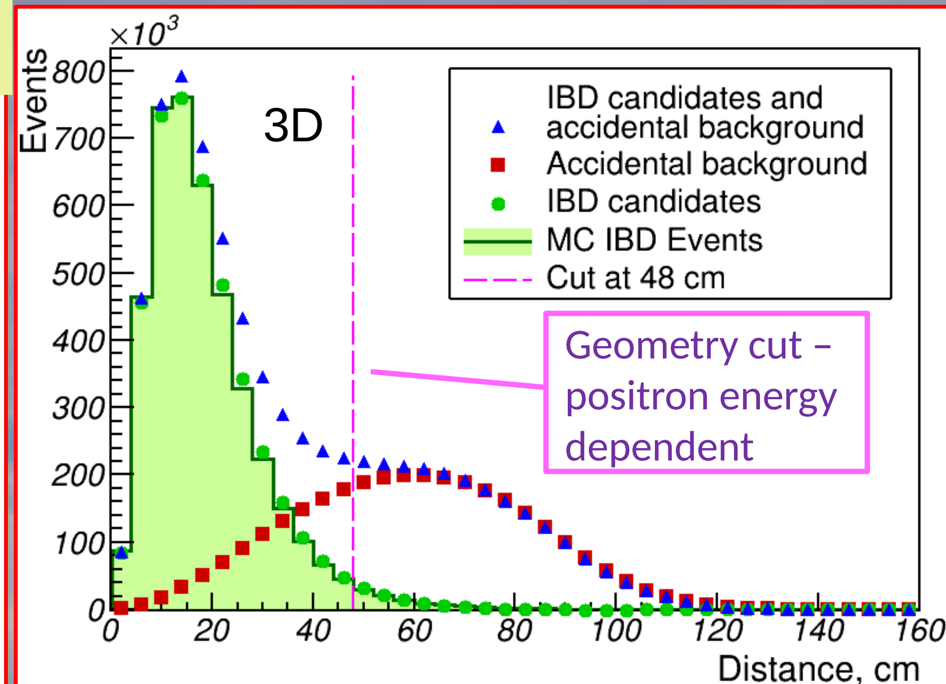


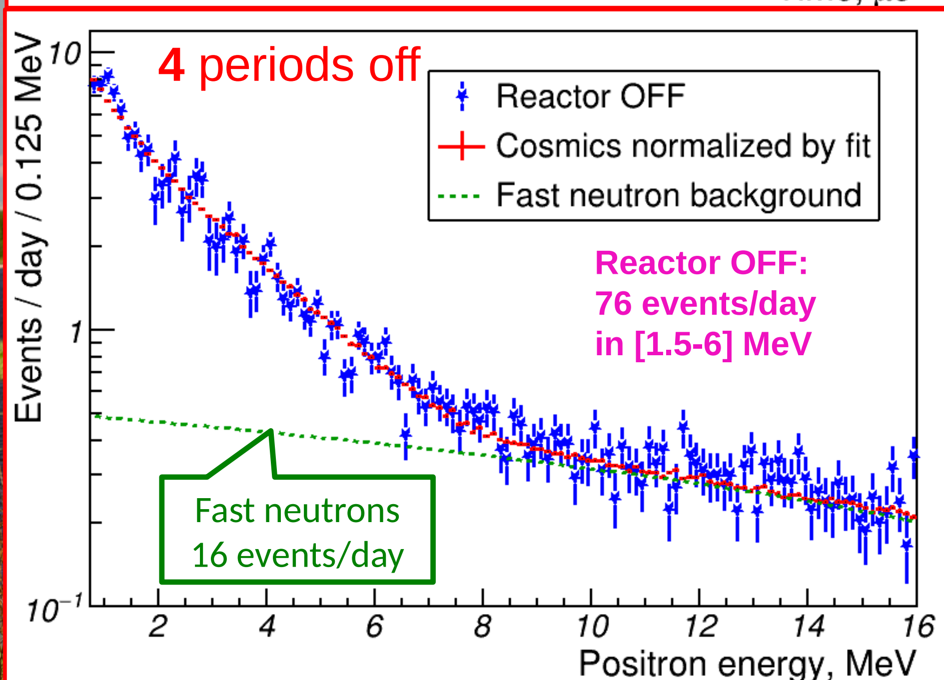


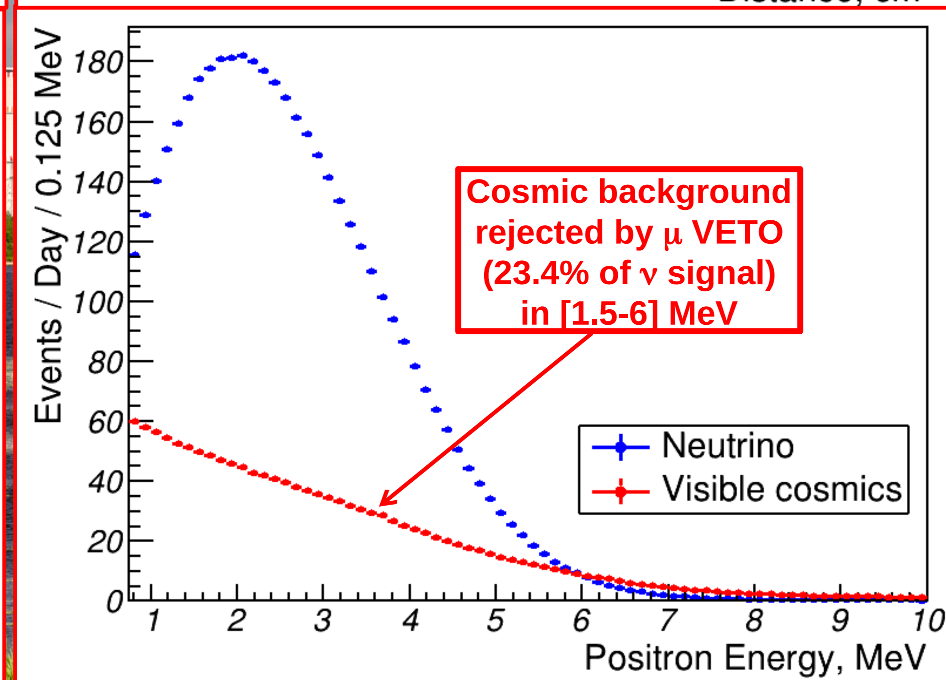
Possible ^{26}Al contamination in the ^{22}Na source. Hope to solve soon. Keep 2% systematic error for the scale.

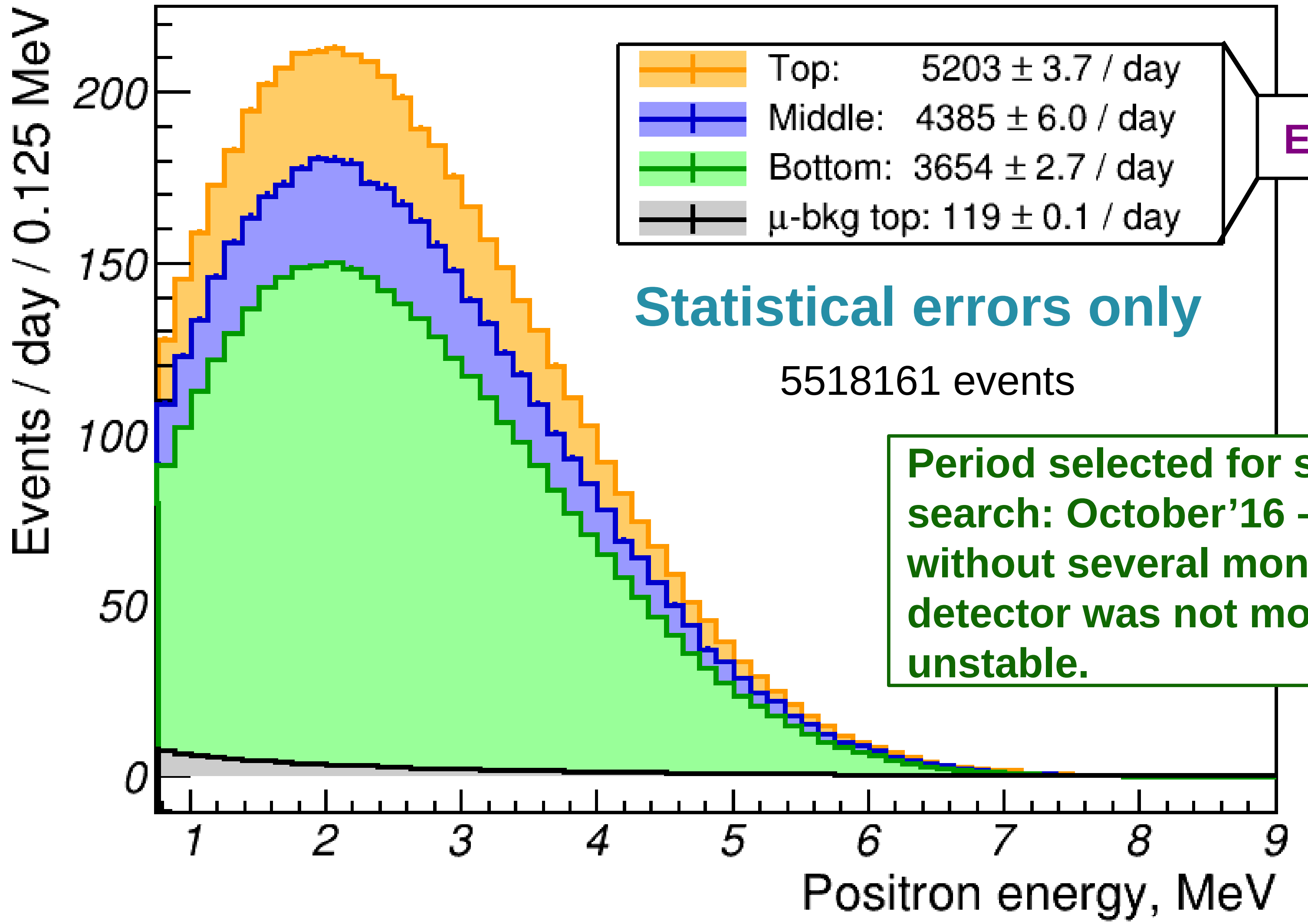
Backgrounds









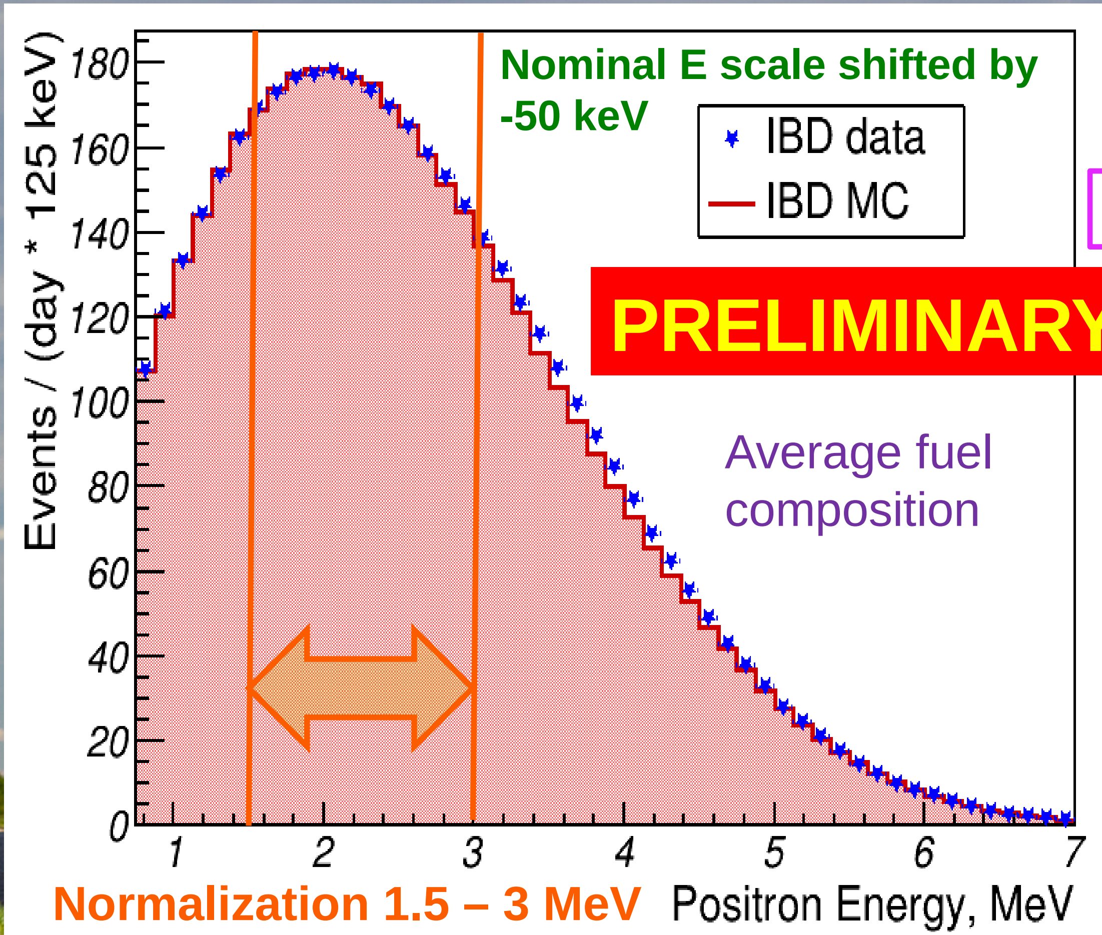


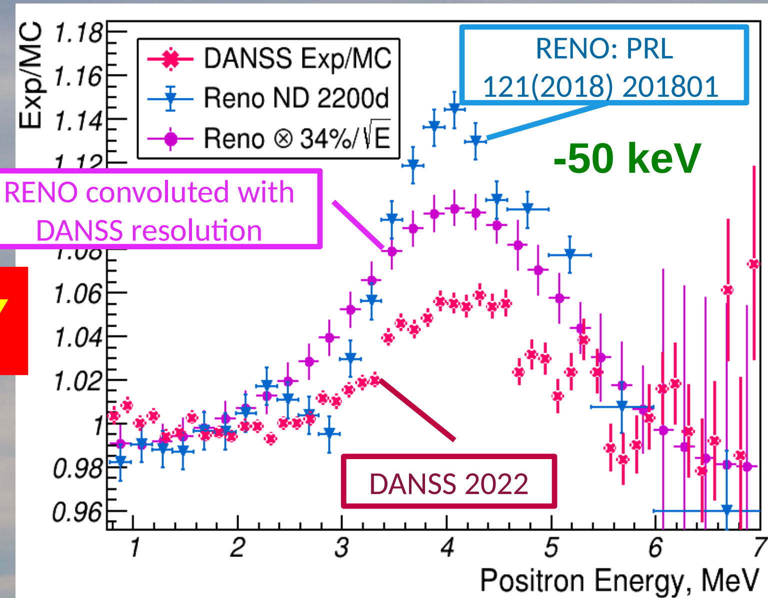
E_{e+}=[0.75-8] MeV

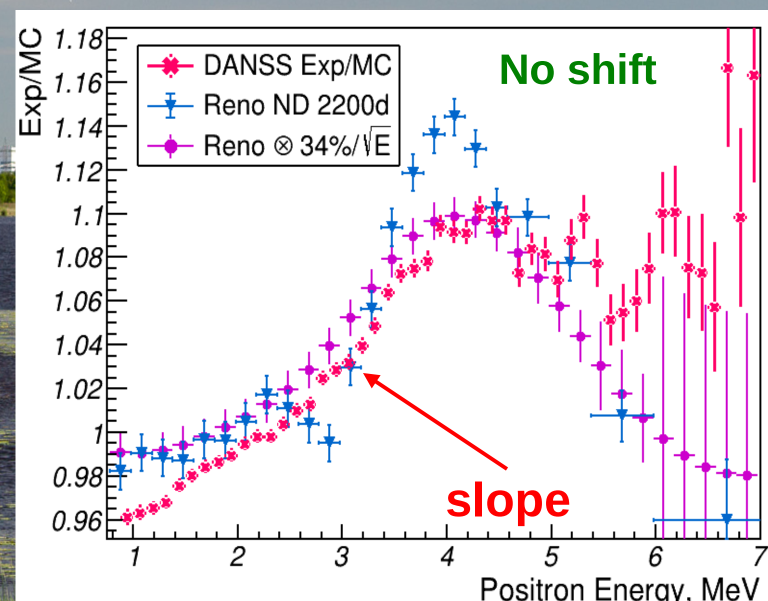
Period selected for sterile neutrino search: October'16 – March'22 without several months, when detector was not moved or was unstable.

- ✓ **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 = 1.76% in top position: S/B > 50 !**

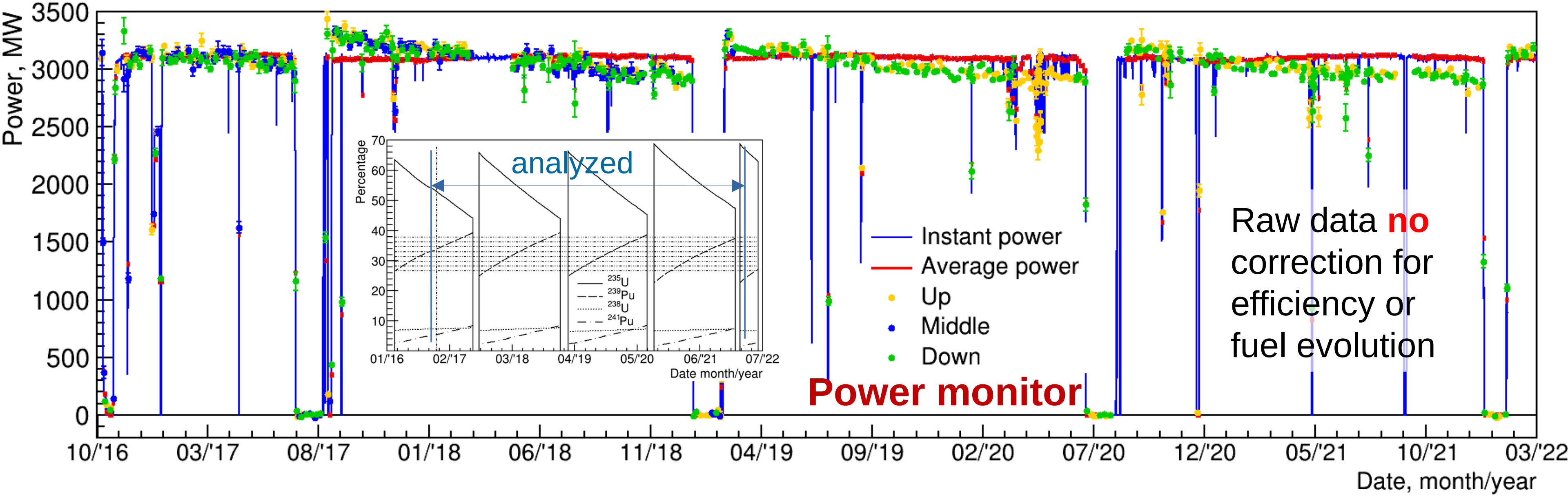
Positron spectrum comparison to H-M model

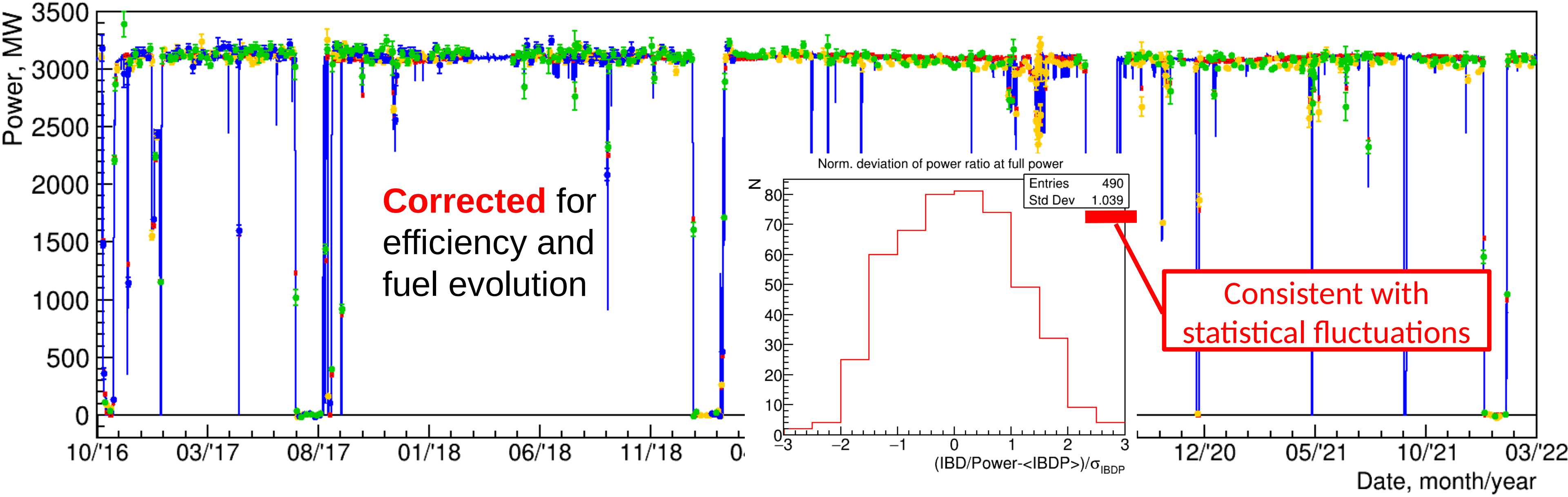






- New energy calibration
- Strong dependence on energy shift and scale
- Effect (if does exist) looks twice smaller than expected from other measurements

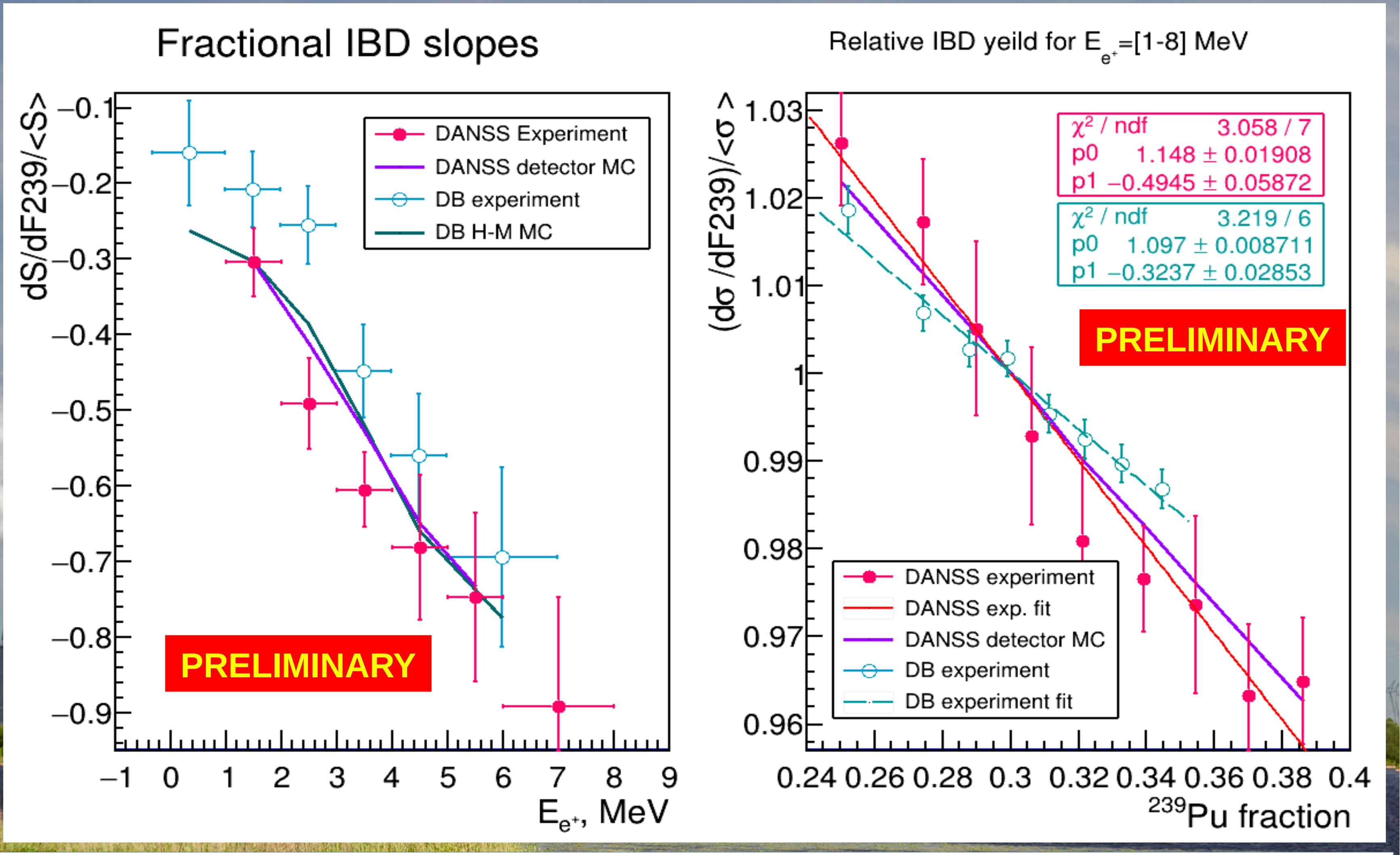




Reactor power is measured by neutrino flux with 1.5% statistical accuracy in 2 days for 5.5+ years.

Changes in absolute detector efficiency are known with accuracy better than 1% during 5.5+ years.

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



- 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.

χ^2 - calculation

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

3-position 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;

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

additional smearing in energy resolution - 3%

distance to fuel burning profile center - 5 cm

fast neutron background - 30%

energy scale - 2%

energy shift - 50 keV

cosmic background - 25%

$\chi^2(4\nu)$ - $\chi^2(3\nu)$

E_{e+} = 1.5-6 MeV

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

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

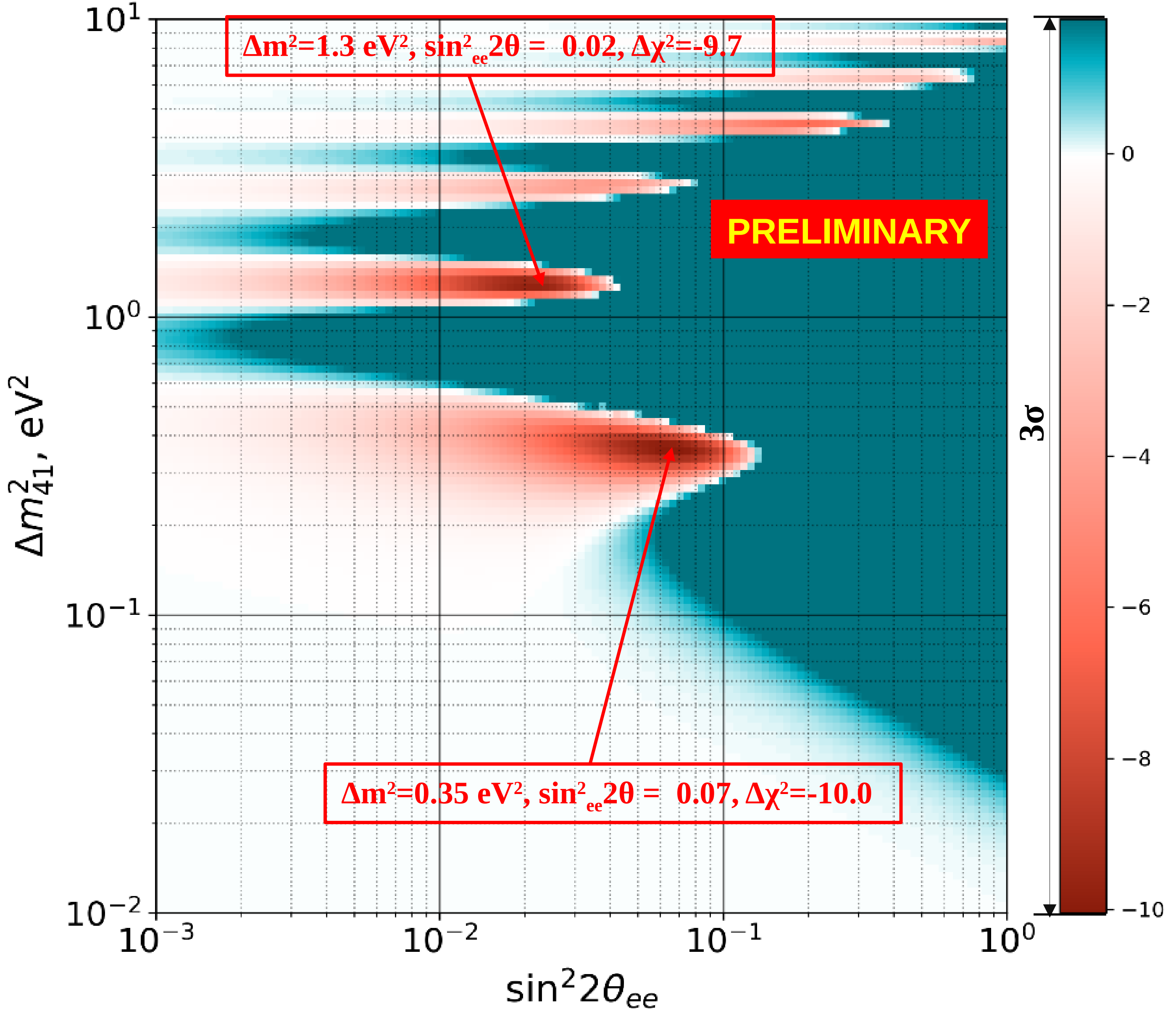
Dark blue:

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

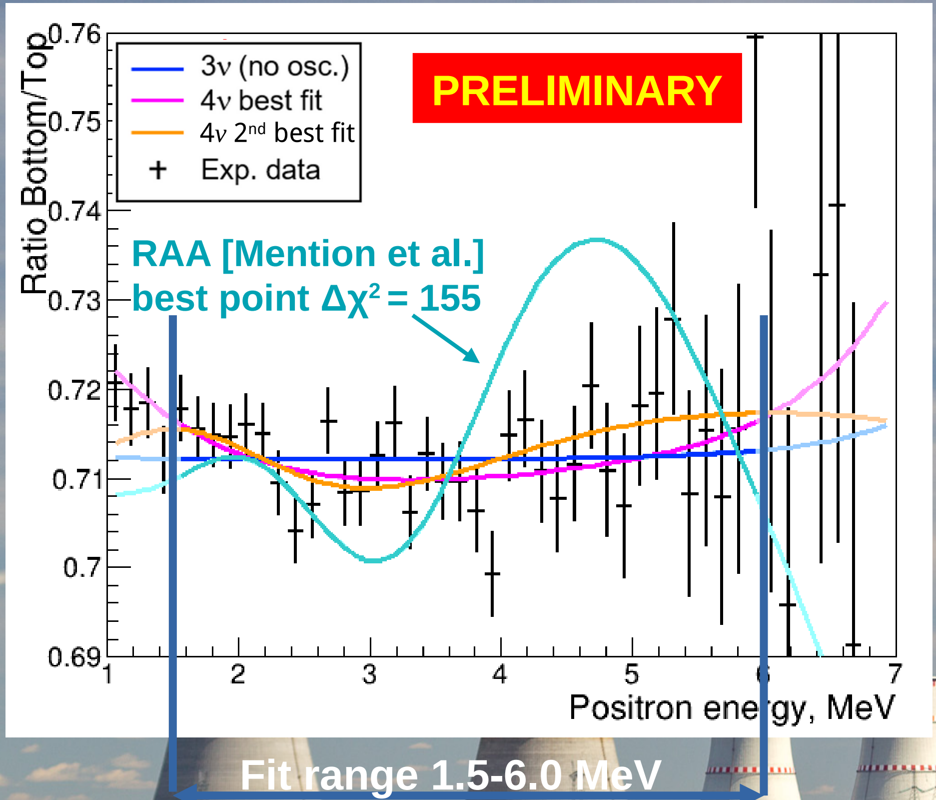
Exclusion at 3σ CL for 2 DoF χ^2-distribution, but in our case the distribution is degenerated at $\sin^2_{ee}2\theta \rightarrow 0$.

Using Gaussian CLs method

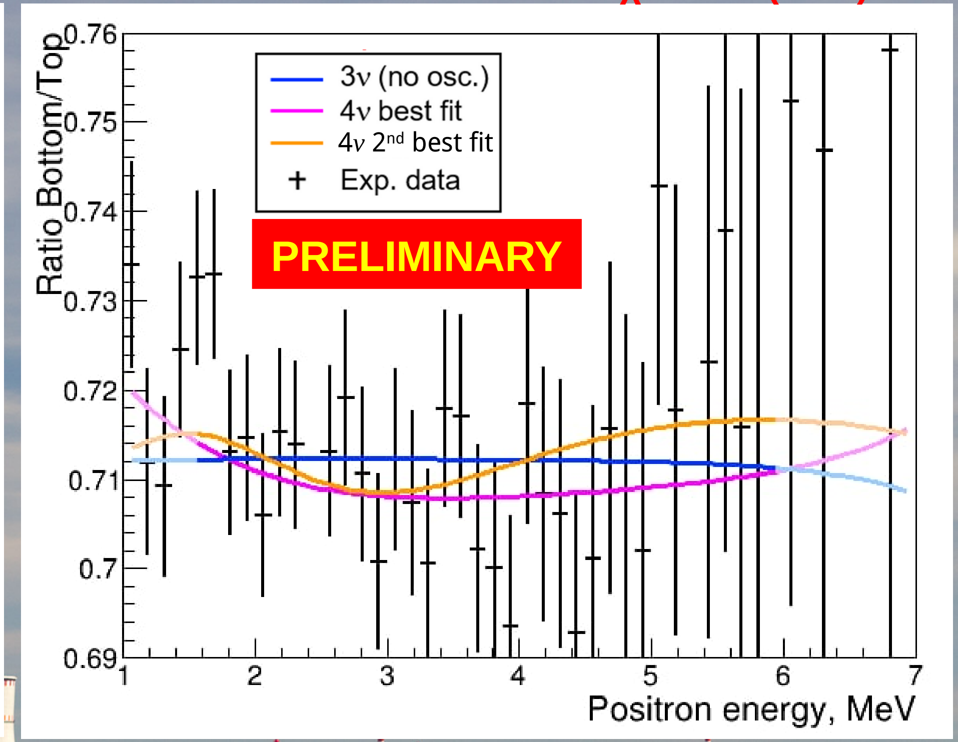
X. Qian et al. Nucl.Inst. Meth. A 827 (2016) 63



All data 2016-2022 $\Delta\chi^2 = -10.0$ (2.35σ)



New data 2021-2022 $\Delta\chi^2 = -8.0$ (2.0σ)



2016-2020: ~2.8 mln IBD events* - best point Δm^2=1.3 eV^2, $\sin^2_{ee}2\theta$=0.02: $\Delta\chi^2$=-5.5 (1.5σ)

2016-2021: ~3.8 mln IBD events* - best point Δm^2=1.3 eV^2, $\sin^2_{ee}2\theta$=0.014: $\Delta\chi^2$=-3.2 (<1.3σ)

2021-2022: ~0.6 mln IBD events* - best point Δm^2=0.42 eV^2, $\sin^2_{ee}2\theta$=0.09: $\Delta\chi^2$=-8.0 (2.0σ)

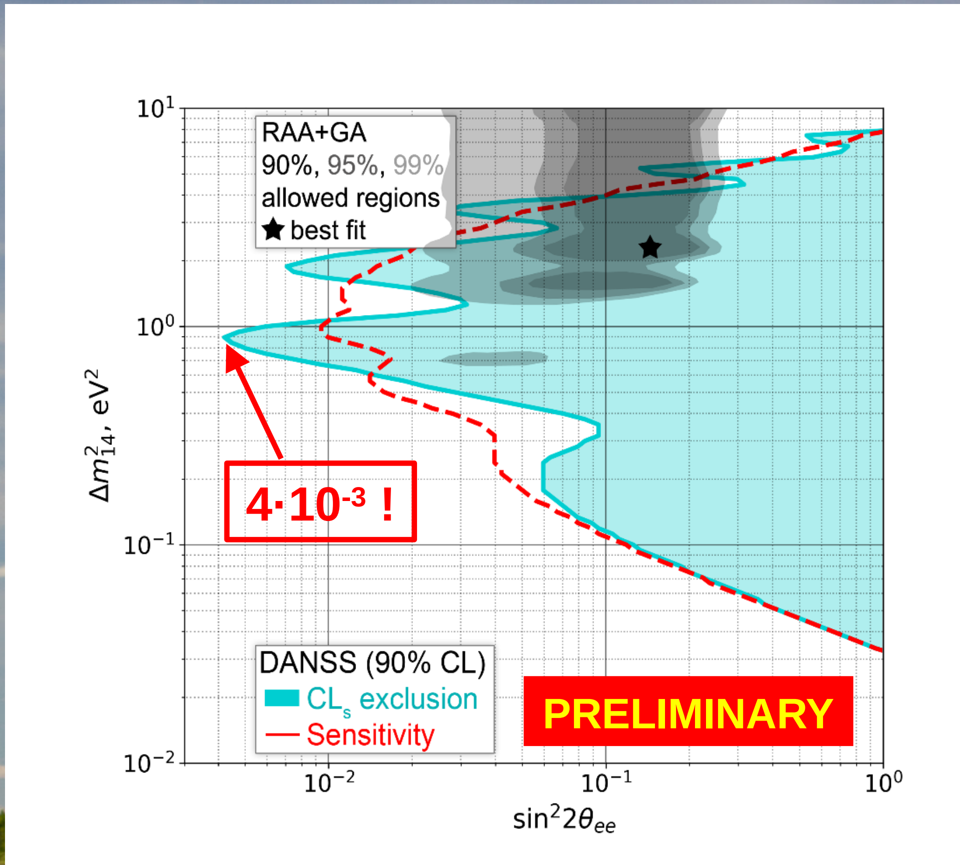
2016-2022: ~4.4 mln IBD events* - best point Δm^2=0.35 eV^2, $\sin^2_{ee}2\theta$=0.07: $\Delta\chi^2$=-10.0 (2.35σ)

- 2nd best point Δm^2=1.3 eV^2, $\sin^2_{ee}2\theta$=0.02: $\Delta\chi^2$=-9.7

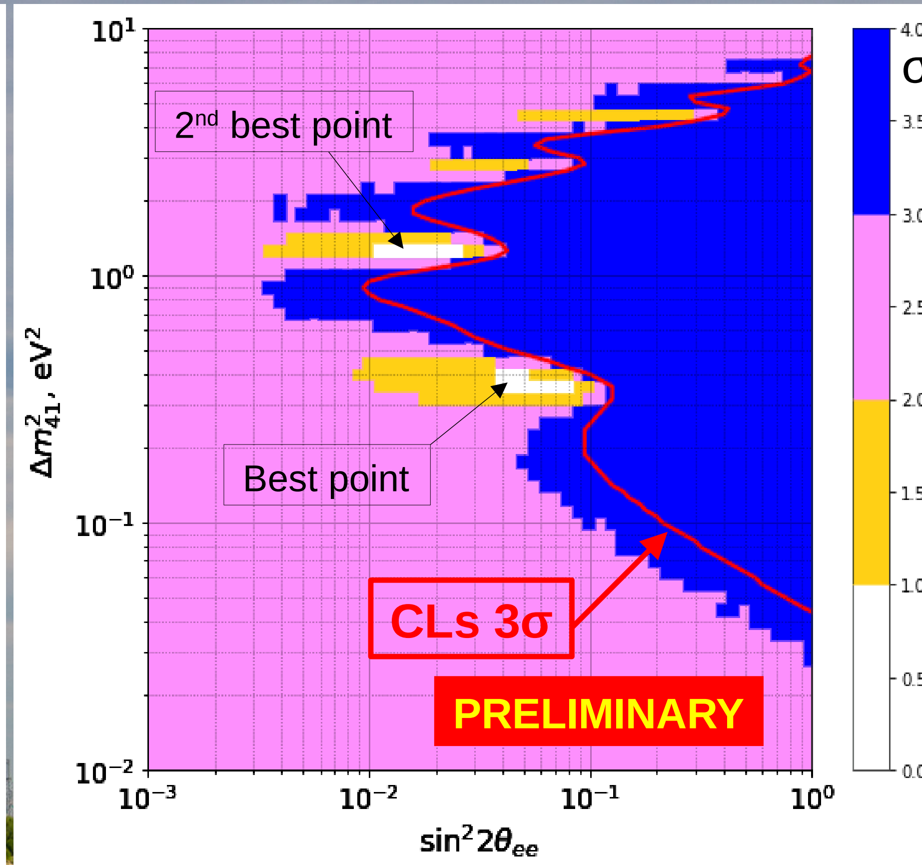
* - IBD events in the range E_{e+} = 1.5-6 MeV used for the fit

No statistically significant hint of 4ν signal

Gaussian CLs



Feldman and Cousins



4.4 mln IBD events in the E_{e+} range 1.5-6 MeV included in the χ^2 (very conservative).

Gaussian CLs method – the most stringent limit reaches $\sin^2 2\theta < 4\text{x}10^{-3}$ level.

A very interesting region of 4ν parameter space excluded.

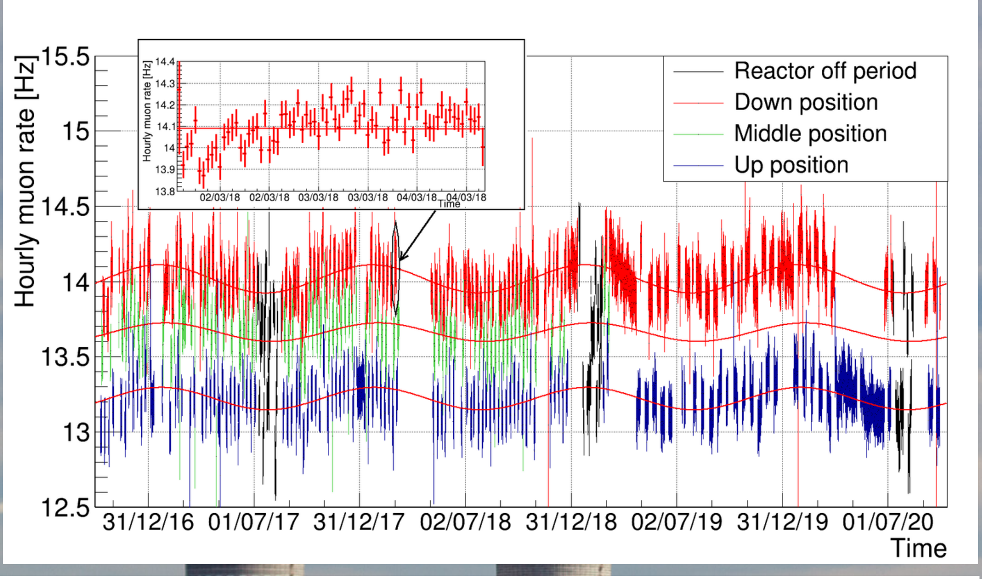
Two F-C allowed regions with close significance more than 2σ.

The best point (2.35σ) is **not** significant enough to claim indication of 4ν.

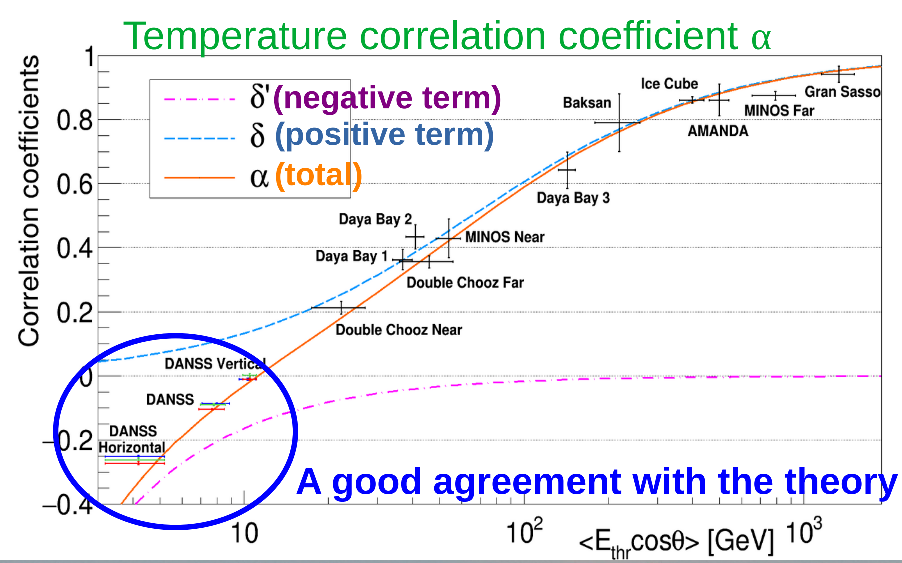
RAA+GA best point is deep in the exclusion region. 5σ exclusion already in 2018 [PLB 787 (2018) 56].

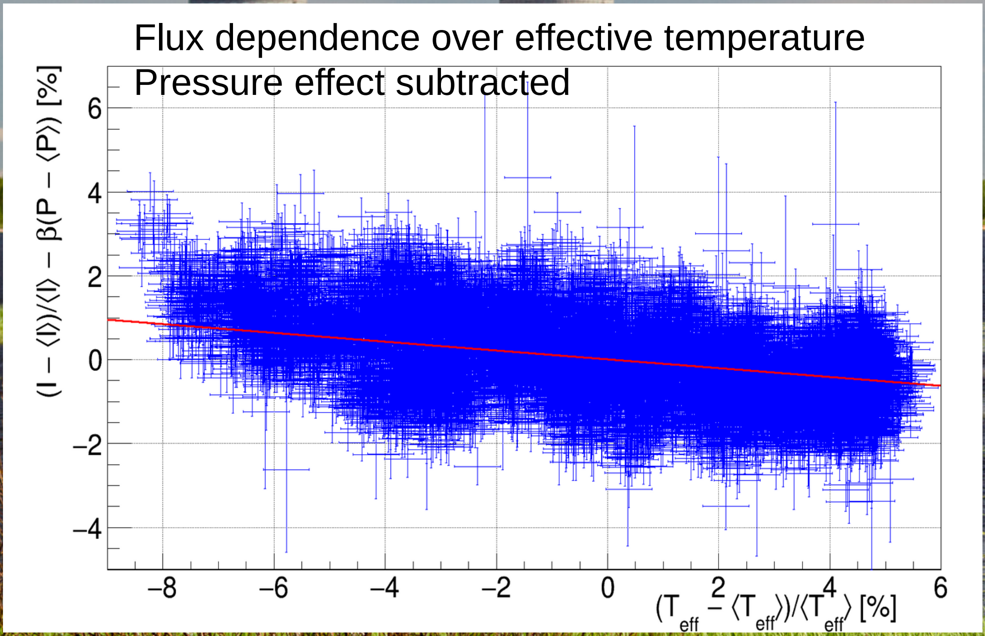
Muon flux through the detector

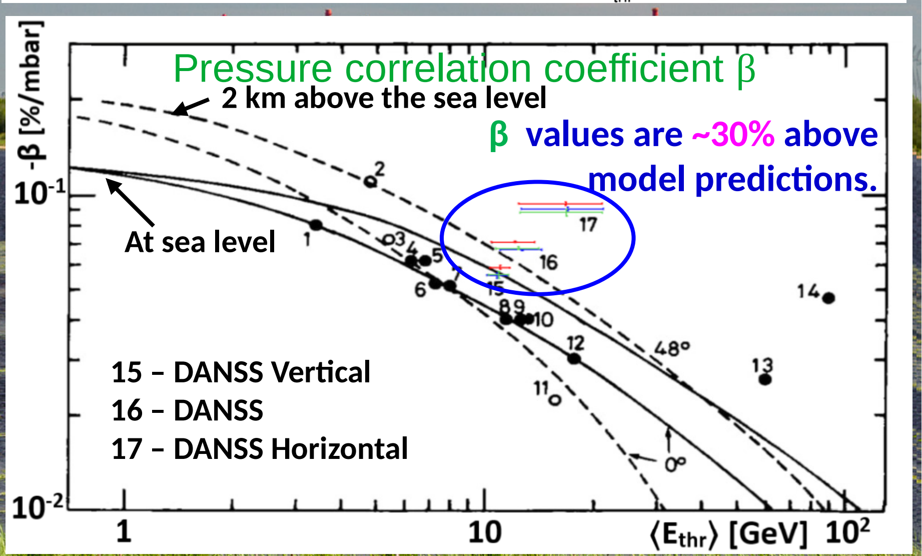
EPJ C 82 (2022) 515



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







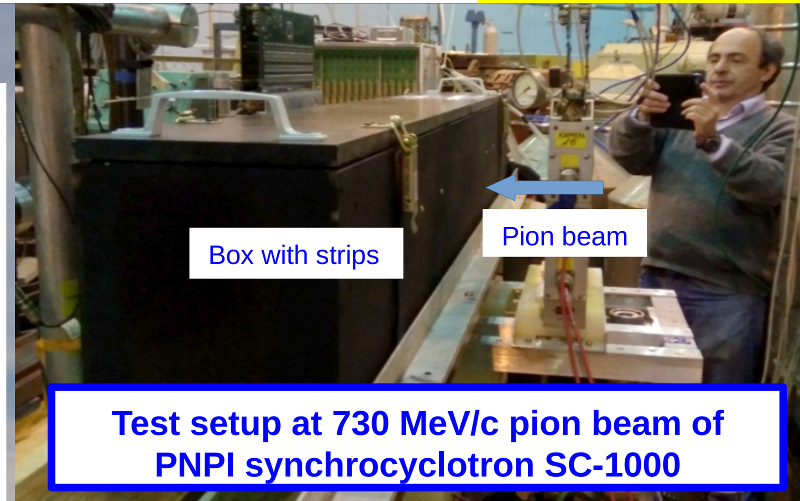
The DANSS upgrade

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

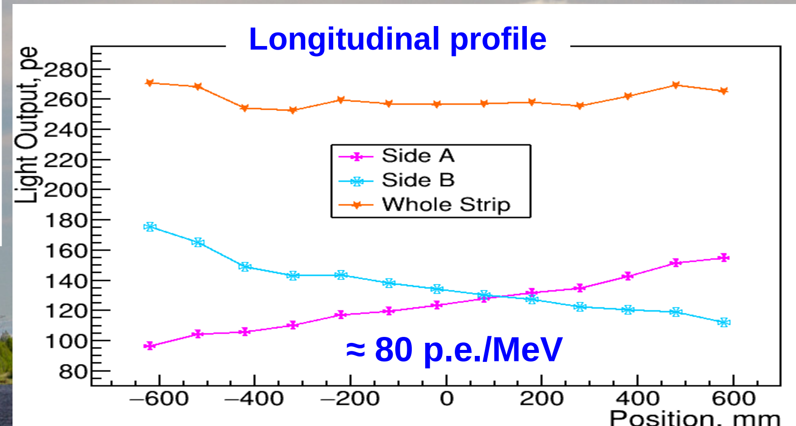
- ✓ New scintillation strips: 20x50x1200 mm³;
- ✓ 60 layers x 24 strips — cube (120 cm)³ → 1.7 times larger fiducial volume;
- ✓ **No PMT** – SiPM readout from both sides;
- ✓ 8 grooves with WLS, 8 (16 – in development) SiPM per strip to get high light yield and uniformity;
- ✓ TOF to get longitudinal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

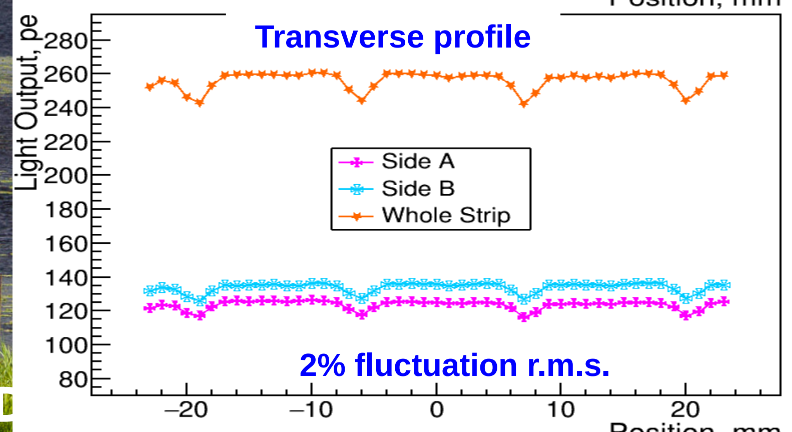
We plan to finish the upgrade in 2023.

New strip test (8 SiPM per strip) **JINST 17 (2022) P04009**

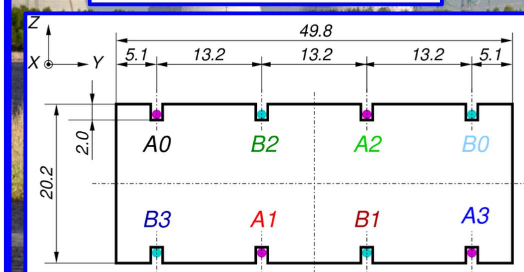


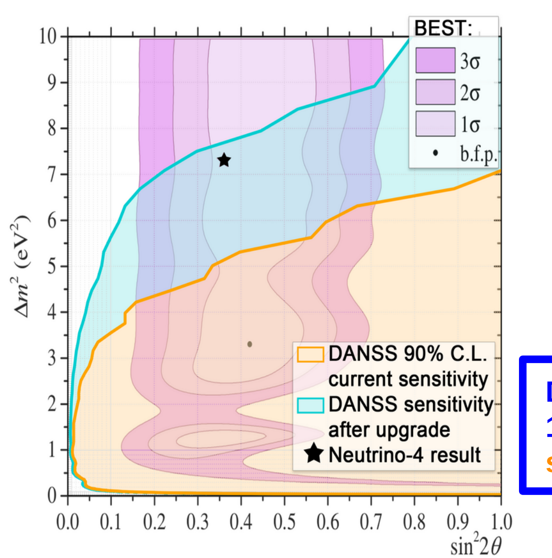
Test setup at 730 MeV/c pion beam of PNPI synchrocyclotron SC-1000





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 6 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 5.5 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.
- 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 theroretical expectations.
- 4.4 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]
- New data (2021-2022) reveals some weak hint of sterile neutrino ($\Delta\chi^2$=-8.0, 2σ). The full data set (2016-2022) has two close best points:

  Δm^2=0.35 eV^2, $\sin^2_{ee}2\theta$=0.07: $\Delta\chi^2$=-10.0 (2.35σ)

  Δm^2=1.3 eV^2, $\sin^2_{ee}2\theta$=0.02: $\Delta\chi^2$=-9.7

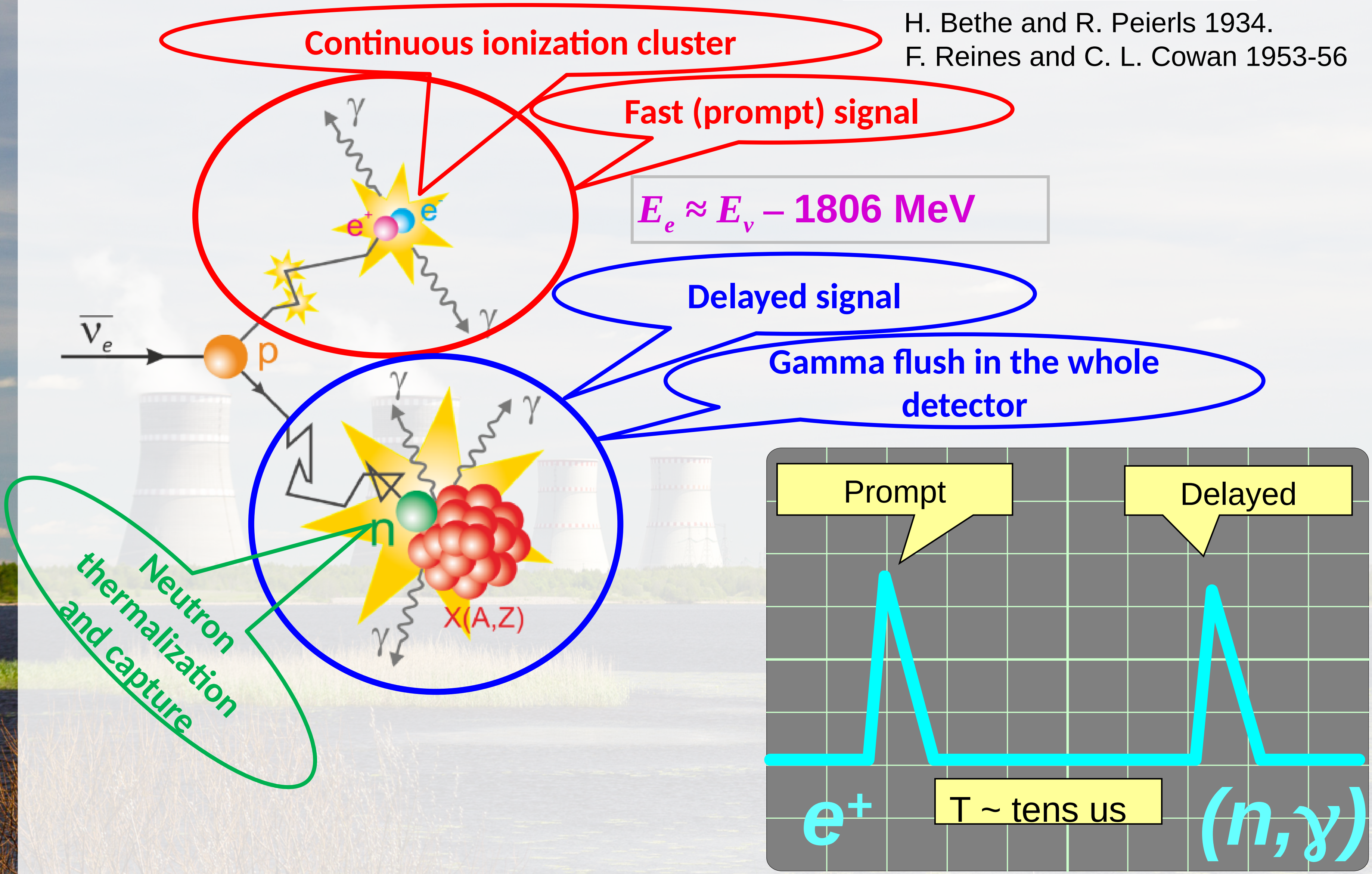
  This hint is not statistically significant (2.35σ) to claim even the indication of sterile neutrino
- Our analysis plans include finalize the energy calibration and include larger E_{e+} range in the analysis.
- DANSS upgrade is planned at 2023 with installation of new strips with SiPM only readout from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

Thank you !

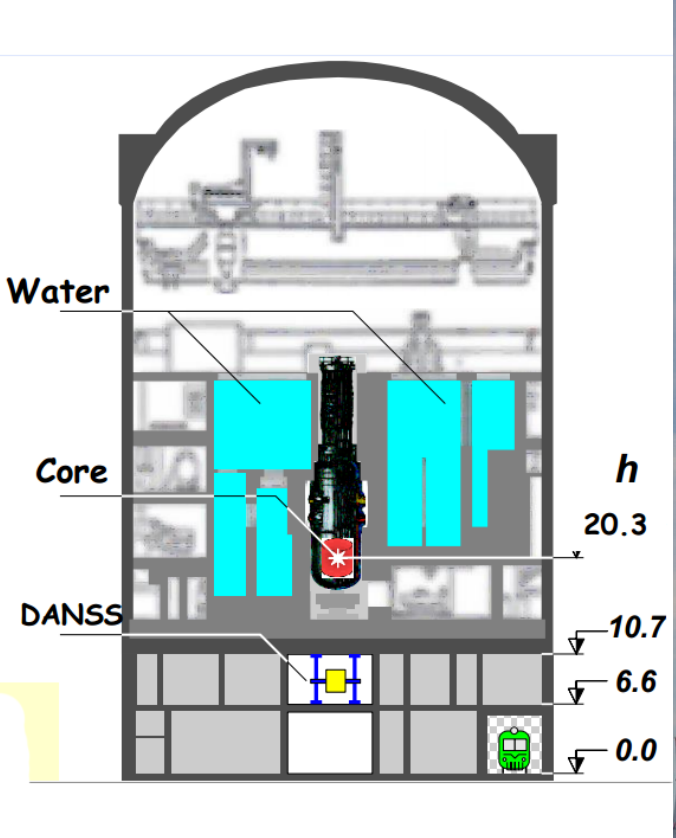
Inverse Beta-Decay (IBD)

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

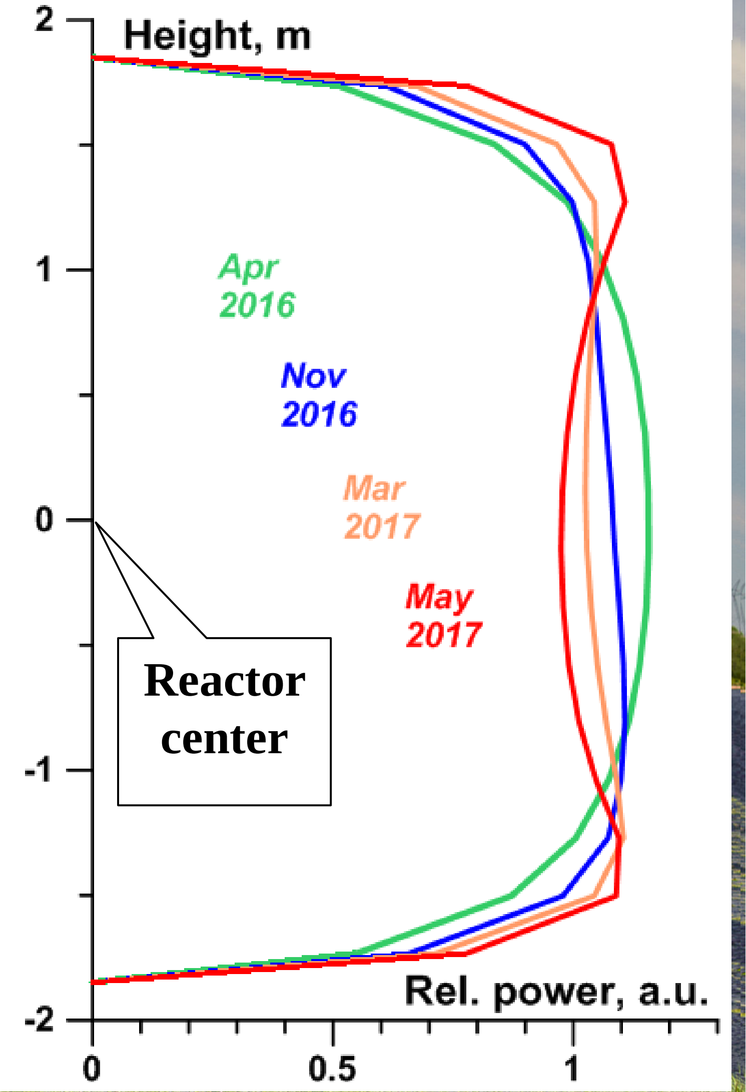
H. Bethe and R. Peierls 1934.
F. Reines and C. L. Cowan 1953-56



Reactor WWER1000



Reactor vertical burning profile for 100% power during the campaign

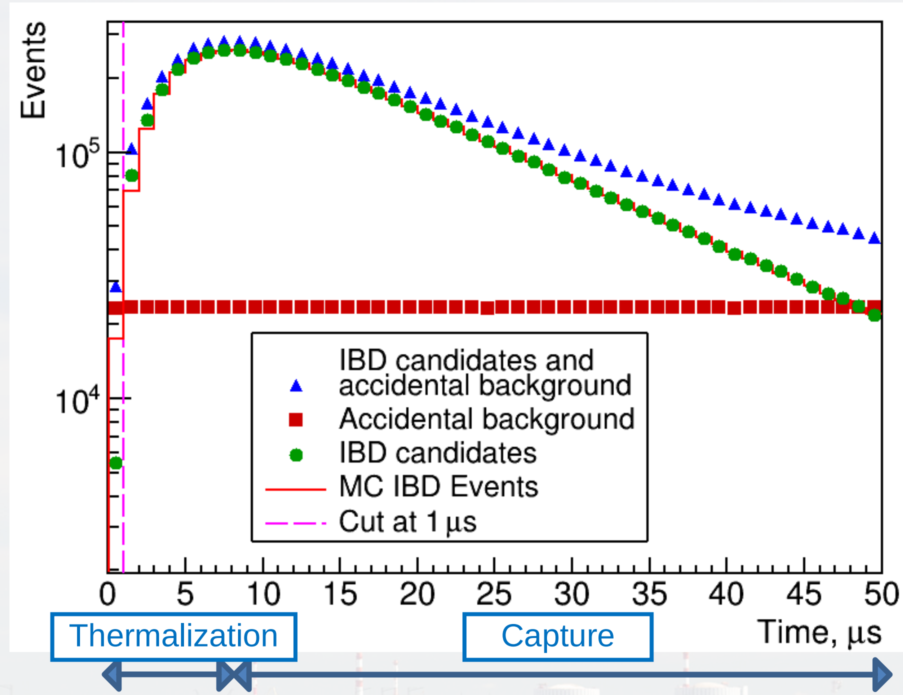


Fuel contribution during the campaigns

	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%

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

VETO 'OR':

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

Muon Cuts

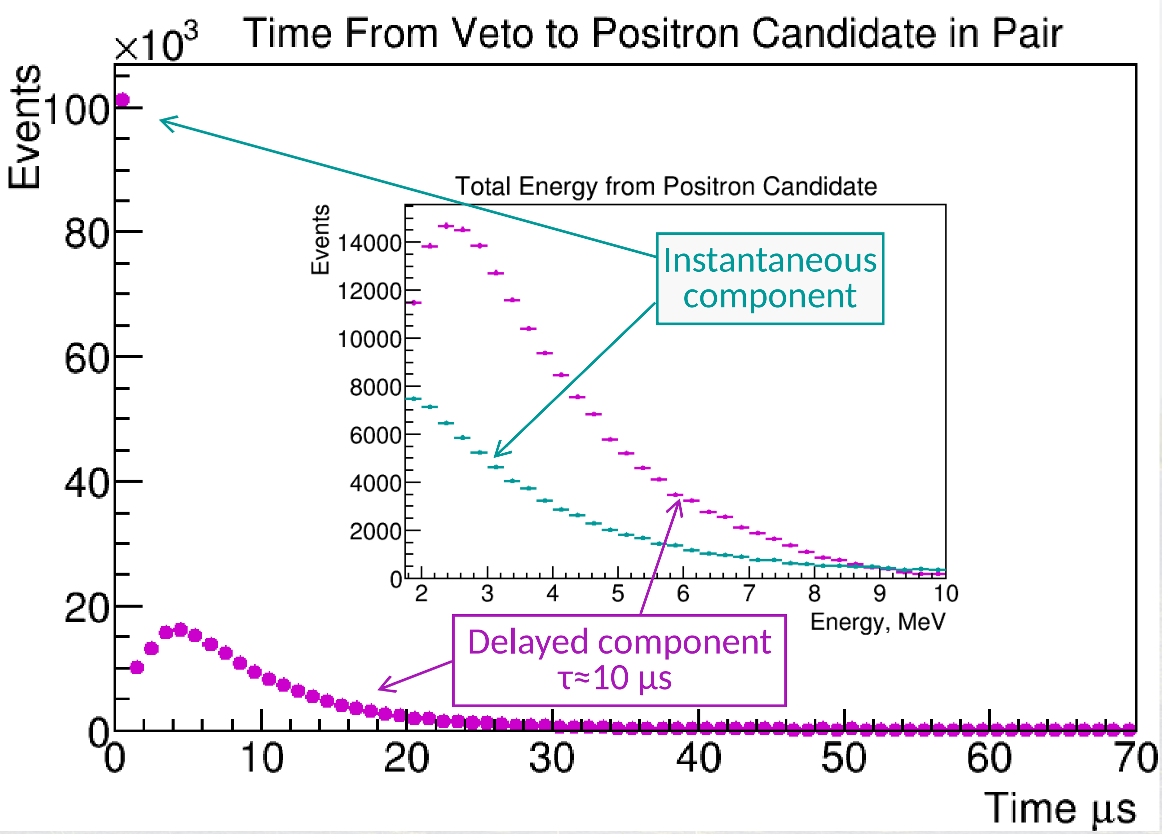
Two distinct components of muon induced paired events with different spectra:

- '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

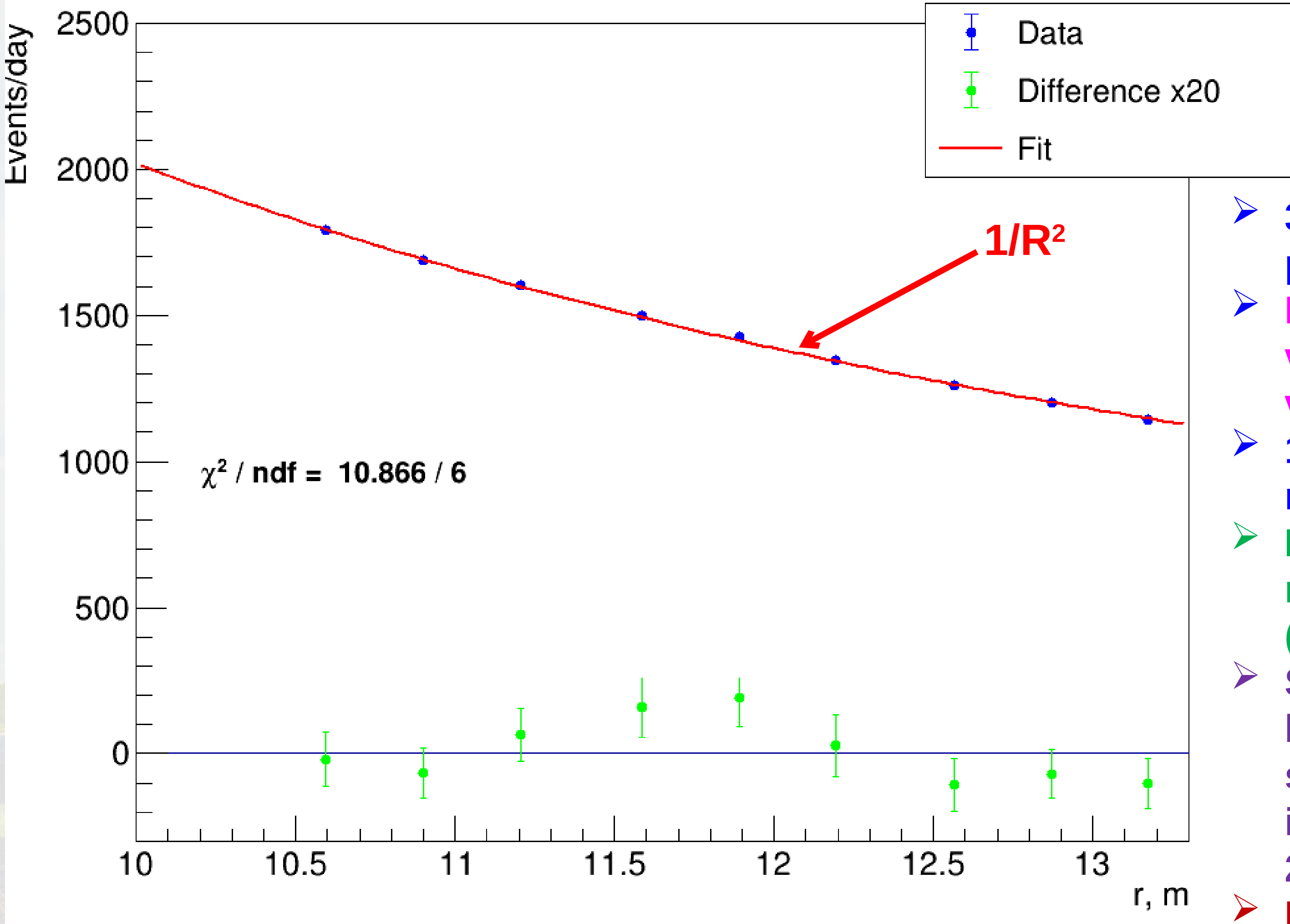
Delayed event energy is < 9.5 MeV and number of hits is < 20

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 MeV

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

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