DANSS experiment: current status and future plans

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***ITEP (**Alikhanov Institute for Theoretical and Experimental Physics**)**

5TH INTERNATIONAL CONFERENCE ON PARTICLE PHYSICS AND ASTROPHYSICS

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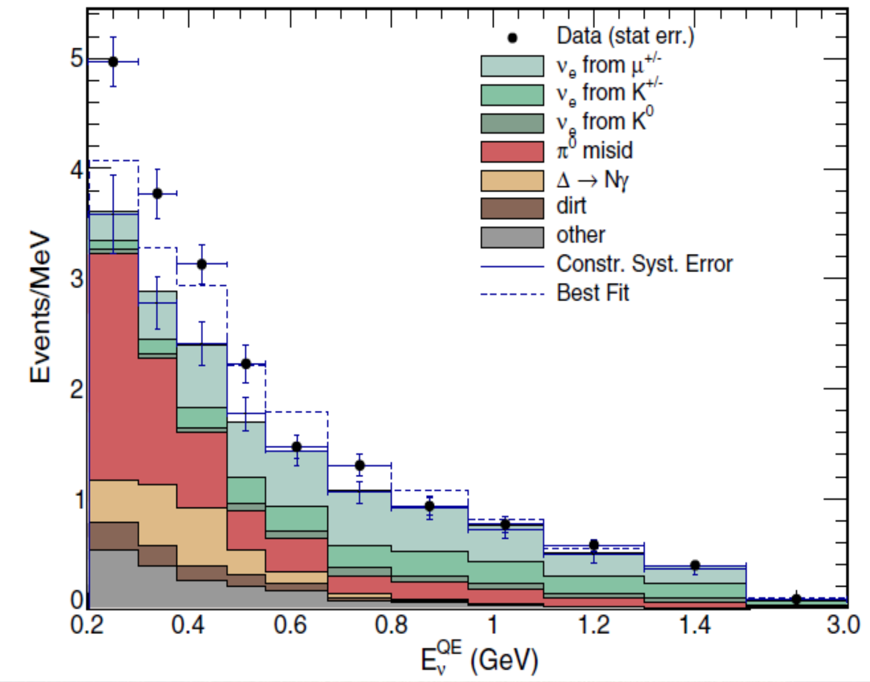
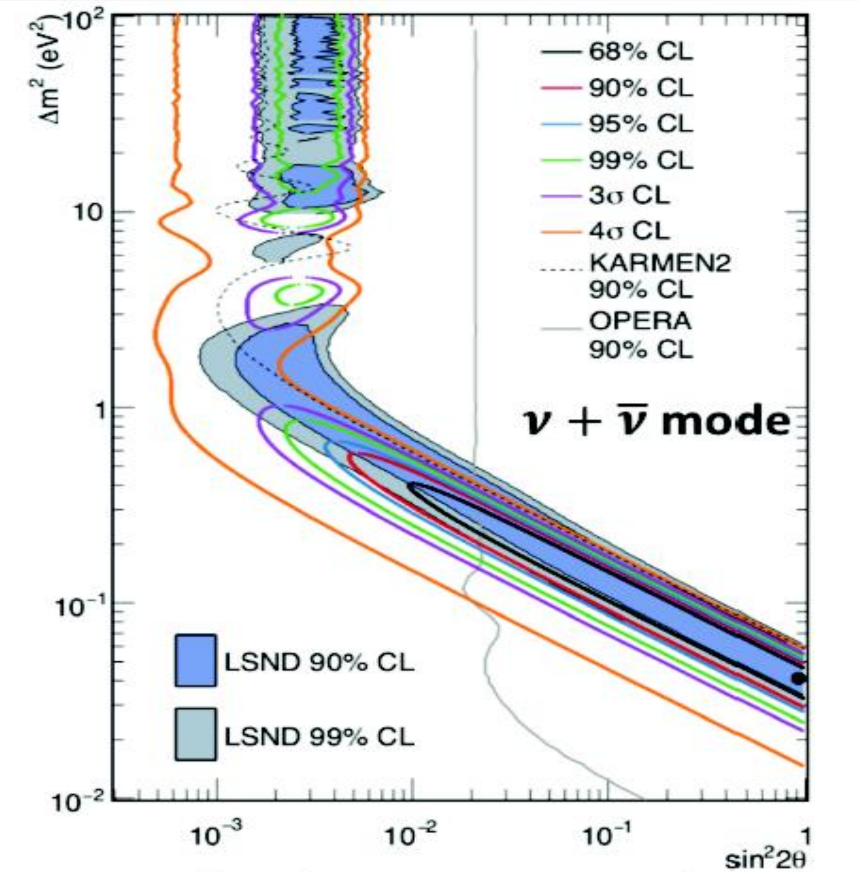
There are several indications in favor of existence of the 4th neutrino flavor - “sterile” neutrino seen in short distance oscillations

LSND + MiniBooNE – accelartor anomaly: appearance of ν_e ($\overline{\nu_e}$)
6σ combined result



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



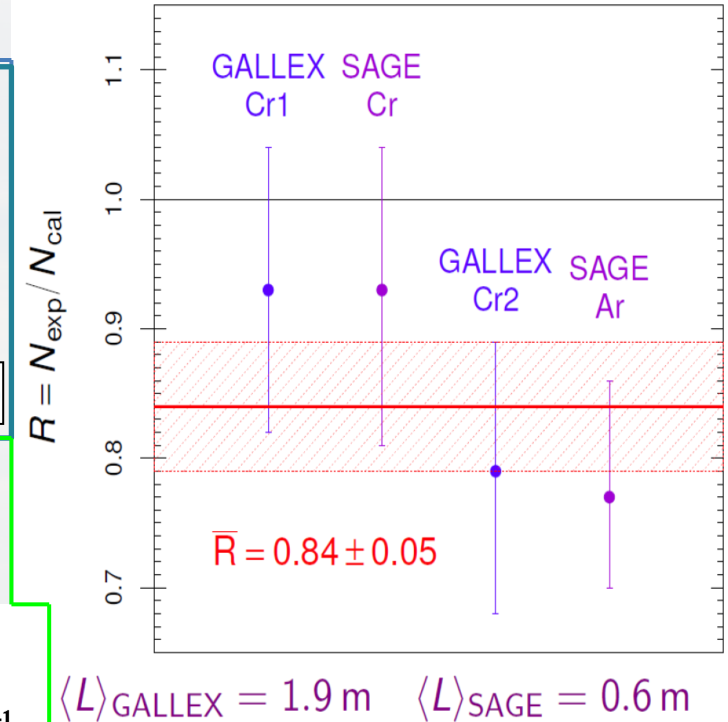
$$(\Delta m^2, \sin^2 2\theta) = (0.041\ \mathrm{eV}^2, 0.958)$$
$$\chi^2/ndf = 19.5/15.4\ (\text{prob} = 20.1\%)$$

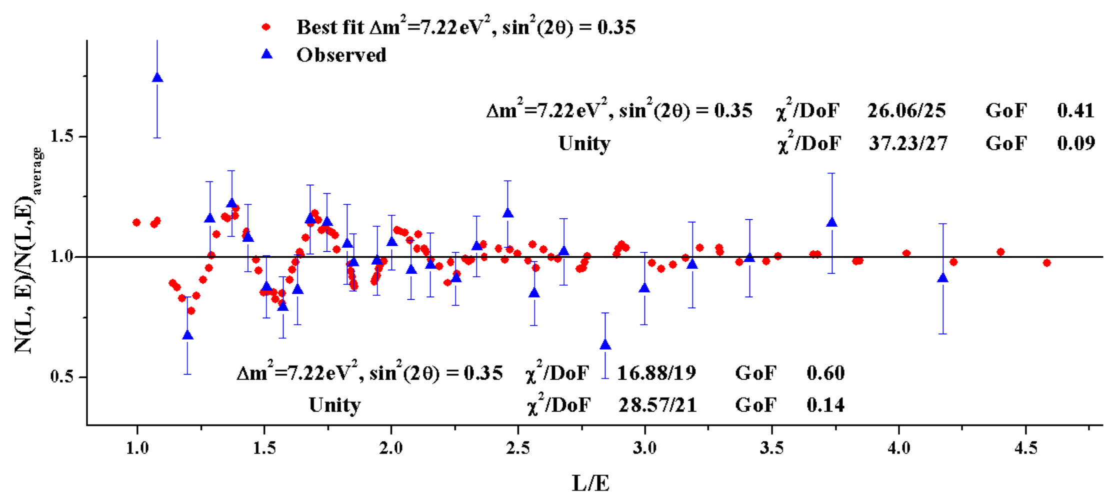
GALEX (Gran Sasso) and SAGE (Baksan) – gallium anomaly: deficit of ν_e from neutrino source in gallium detectors calibration. Phys. Rev. C 80 (2009) 015807

Reactor anomaly – deficit of $\overline{\nu}_e$ in combined analysis of reactor experiments. G. Mention et al. Phys. Rev D83 073006 (2011)

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

Neutrino-4: 2.8σ @ Δm^2~7eV^2 $\sin^2 2\theta$~0.35
JETP Lett. 109 (2019) no.4, 213



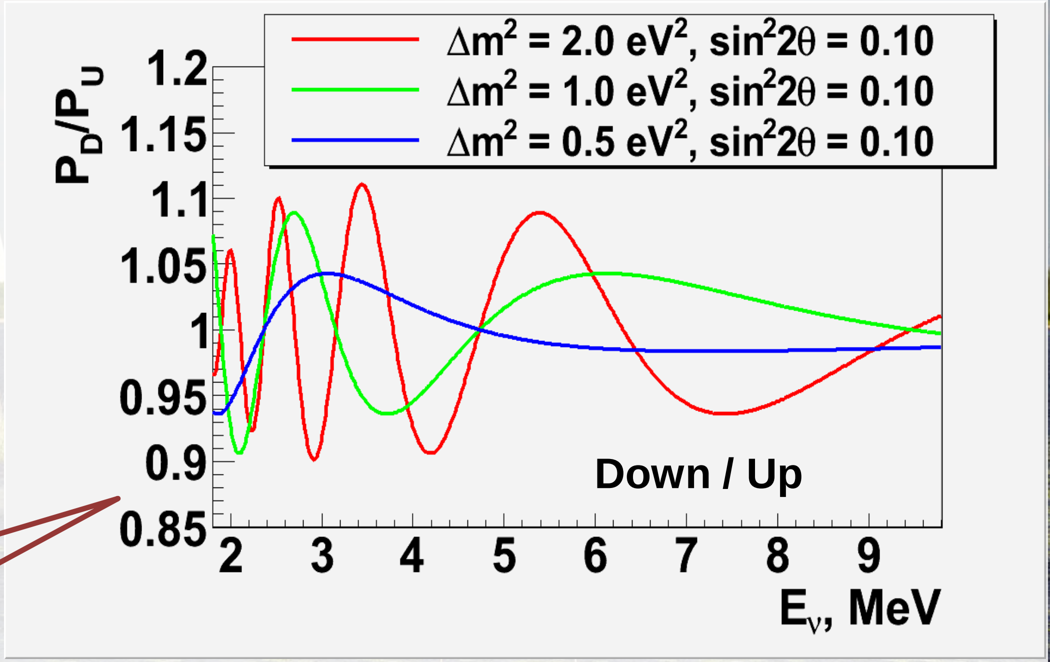


In a simple model with the 4th neutrino survival probability of electron antineutrino from the reactor is given by the formula:

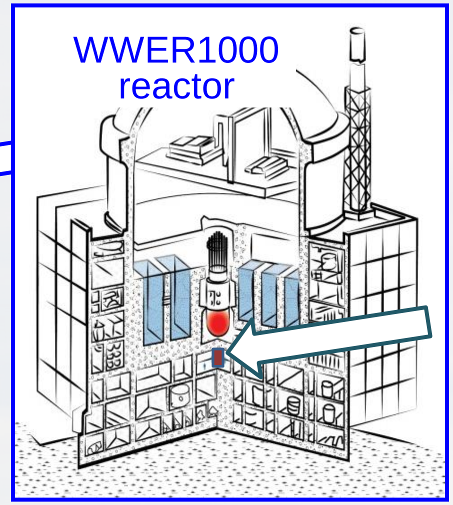
$$P_{ee}^{2\nu}(L) = 1 - \sin^2(2\theta_i)\sin^2\left(1.27\frac{\Delta m_i^2[\mathrm{eV}^2]L[\mathrm{m}]}{E_{\bar{\nu}_e}[\mathrm{MeV}]}\right)$$

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



KNPP - Kalinin Nuclear Power Plant, Russia, ~350 km NW from Moscow



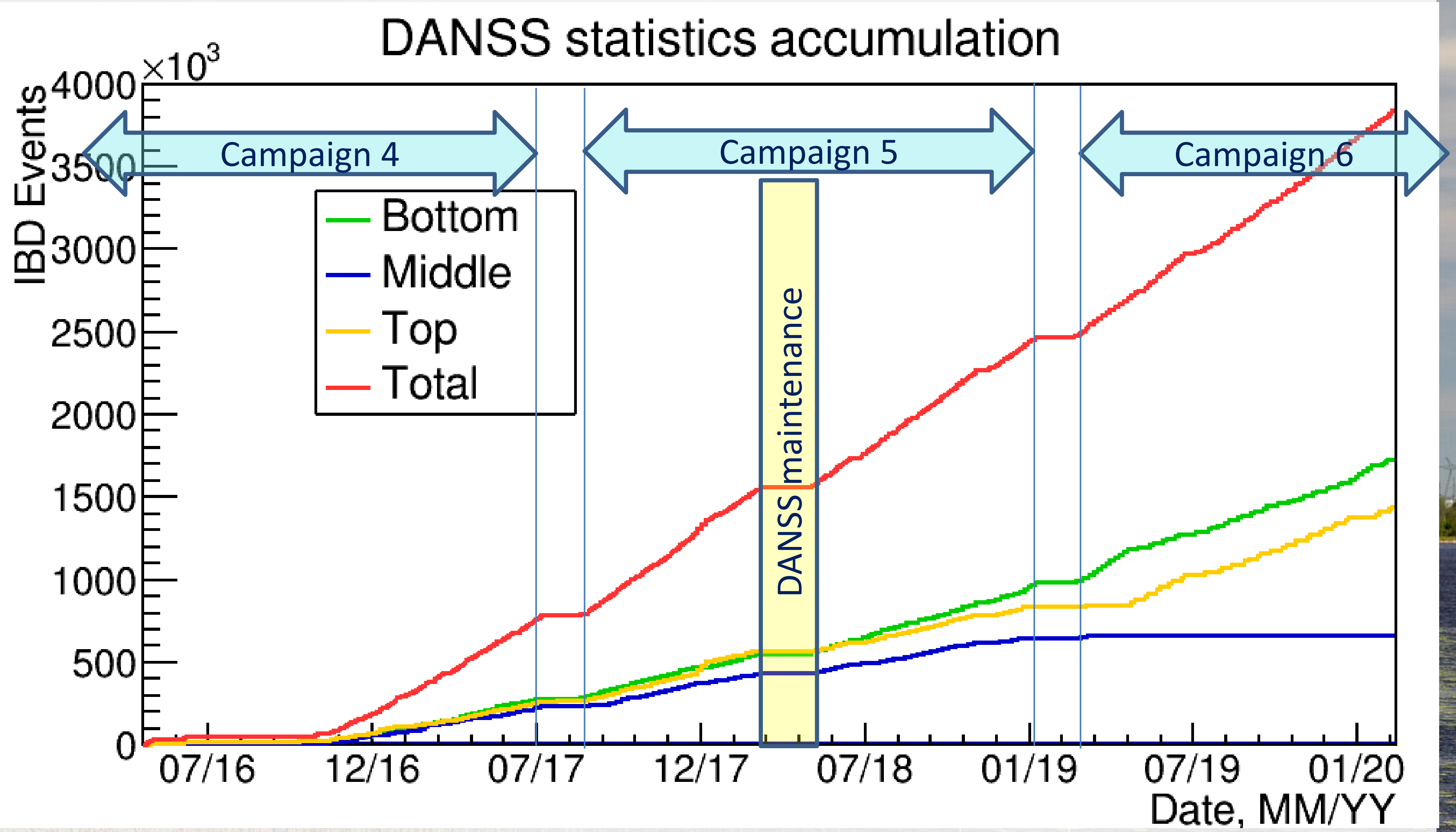
Below 3.1 GW_{th} commercial reactor ~ $5\cdot10^{13}$ $\nu\cdot cm^{-2}c^{-1}$

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**

One year old analysis details are here: I. Alekseev, JPCS Vol. 1468, 012156 (2020).

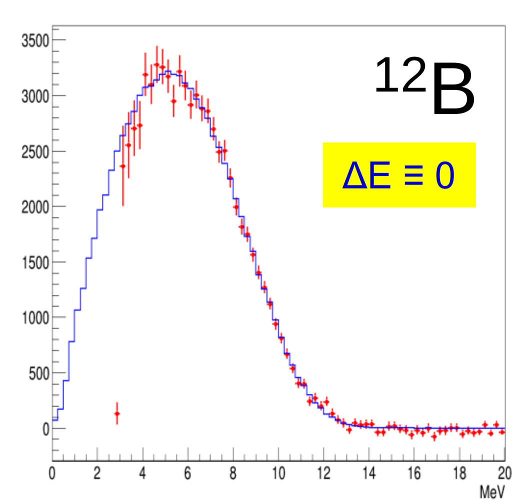
4 years of stable operation since October 2016

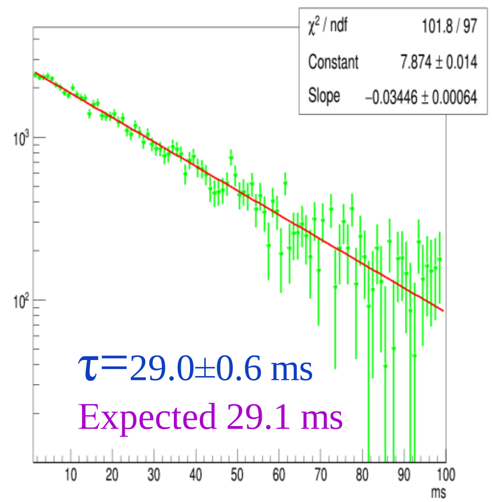


- Initial calibration is done using cosmic muons
- Energy scale is fixed by ^{12}B-decay, which is similar to e^+ signal we measure.

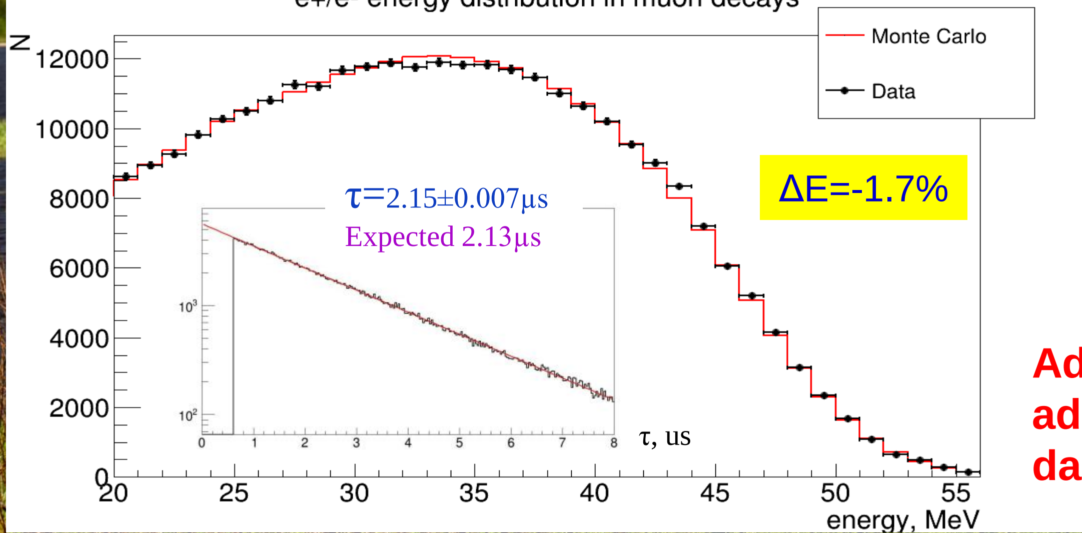
[We measure the positron energy, not the total prompt event energy]

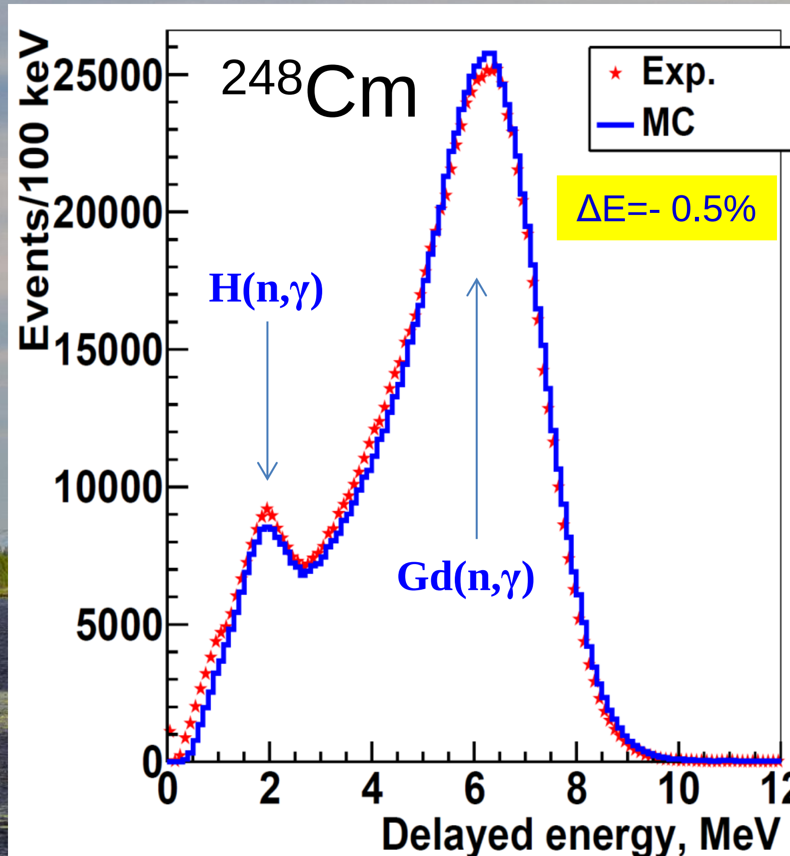
- STEREO Gd(n,γ) data set based on FIFERELIN library arXiv: 1905.11967
- Analysis of Michel electrons from muon decays
- Energy scale uncertainty estimated as 2% is added to systematical error.





e+/e- energy distribution in muon decays

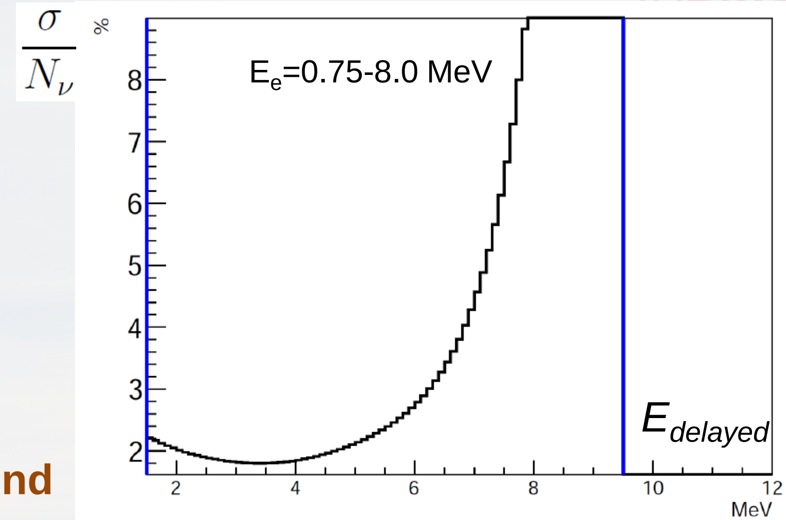




Additional smearing 12%/√E ⊕ 4% is added to MC to reach satisfactory source data description.

An optimization of cuts was done minimizing the relative error:

$$\frac{\sigma}{N_\nu} = \frac{\sqrt{N_\nu + N_R + k_C \cdot N_C}}{N_\nu}$$



σ – **expected statistical error**

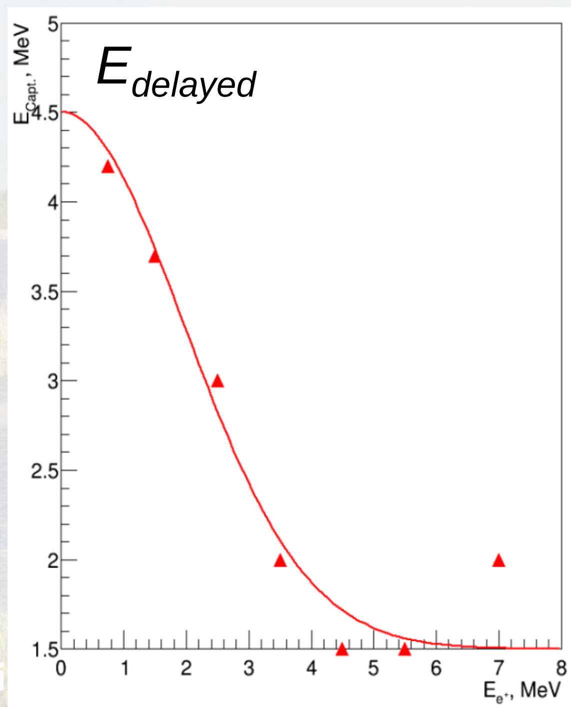
N_ν – **number of neutrino events after all cuts and background subtraction**

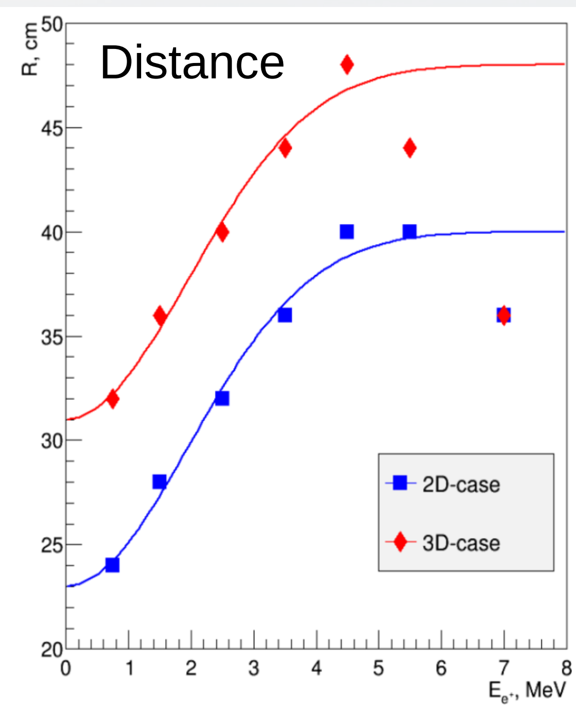
N_R – **number of events of the accidental background**

N_C – **number of tagged cosmic induced events**

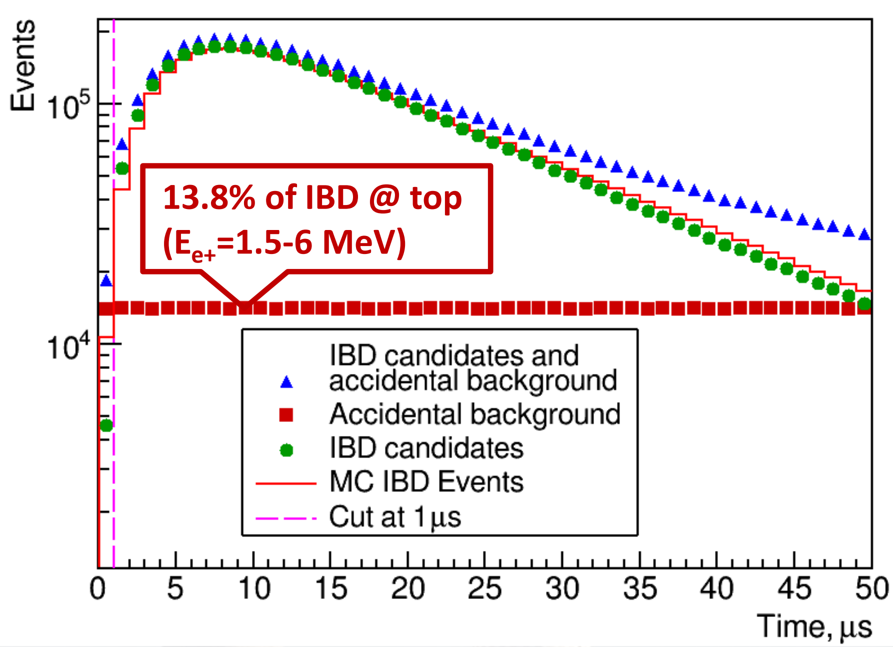
k_C – **veto "transparency" - relative background rate from the reactor off measurements**

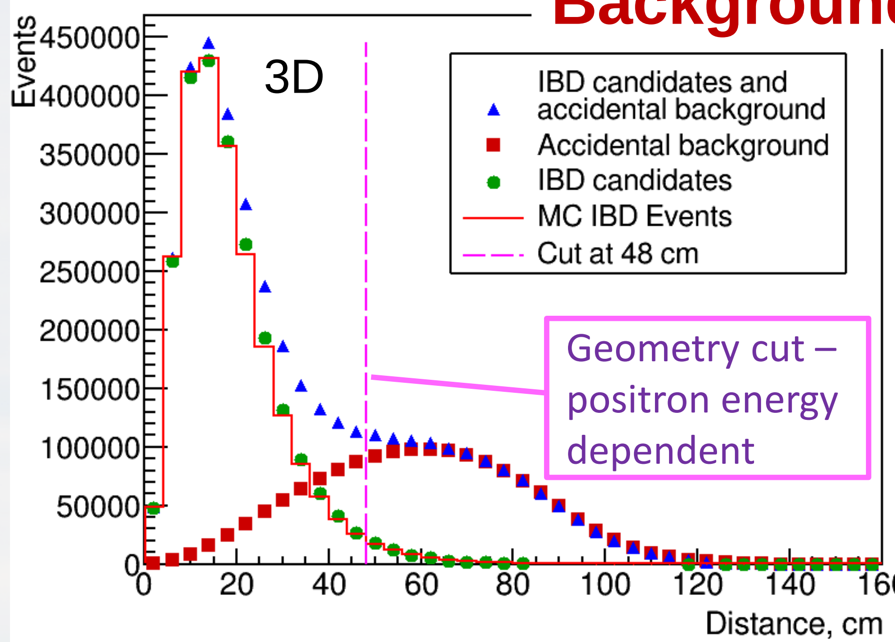
Positron **energy dependent** cuts on delayed energy and prompt to delayed vertexes distance

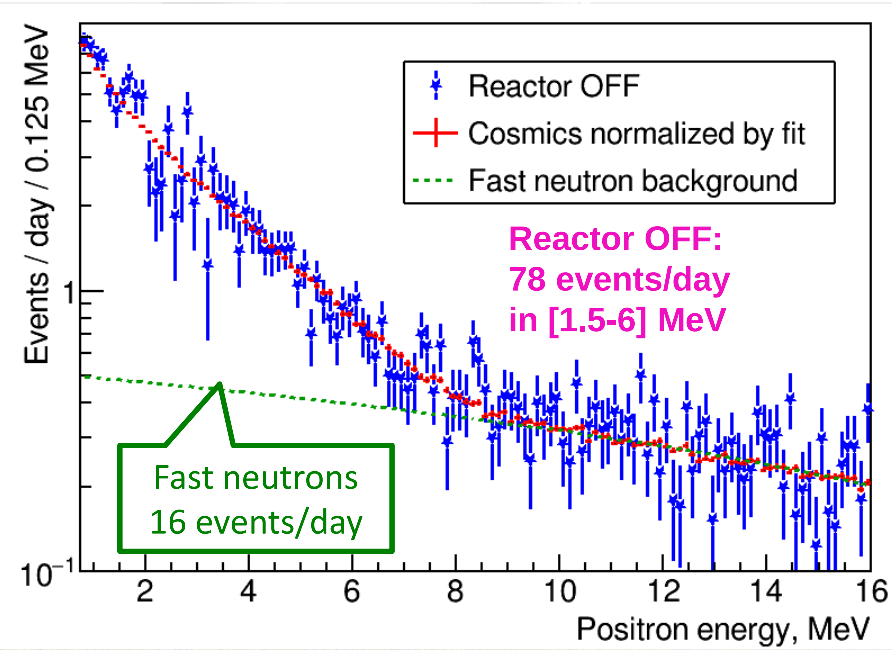


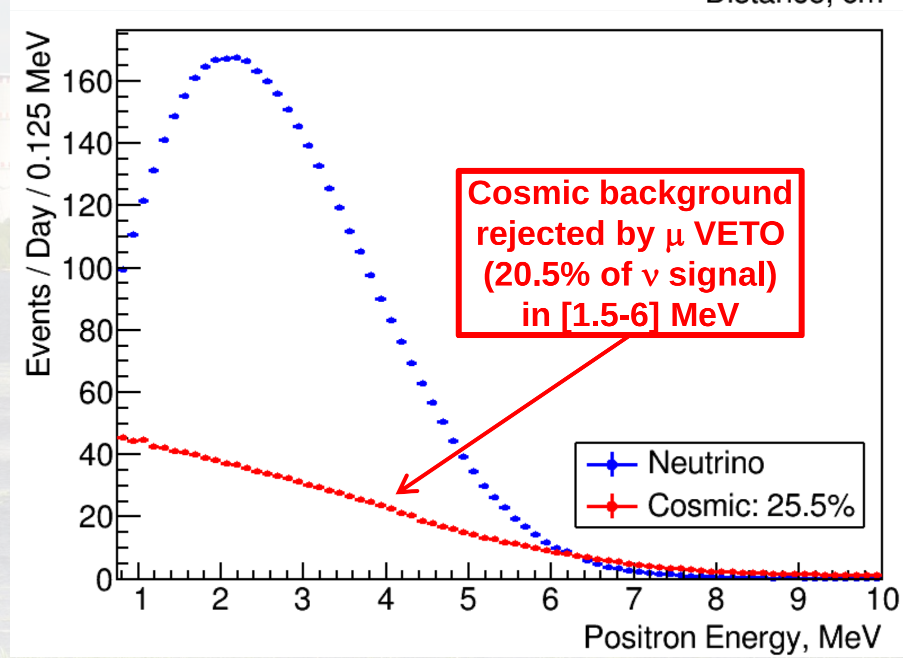


Backgrounds

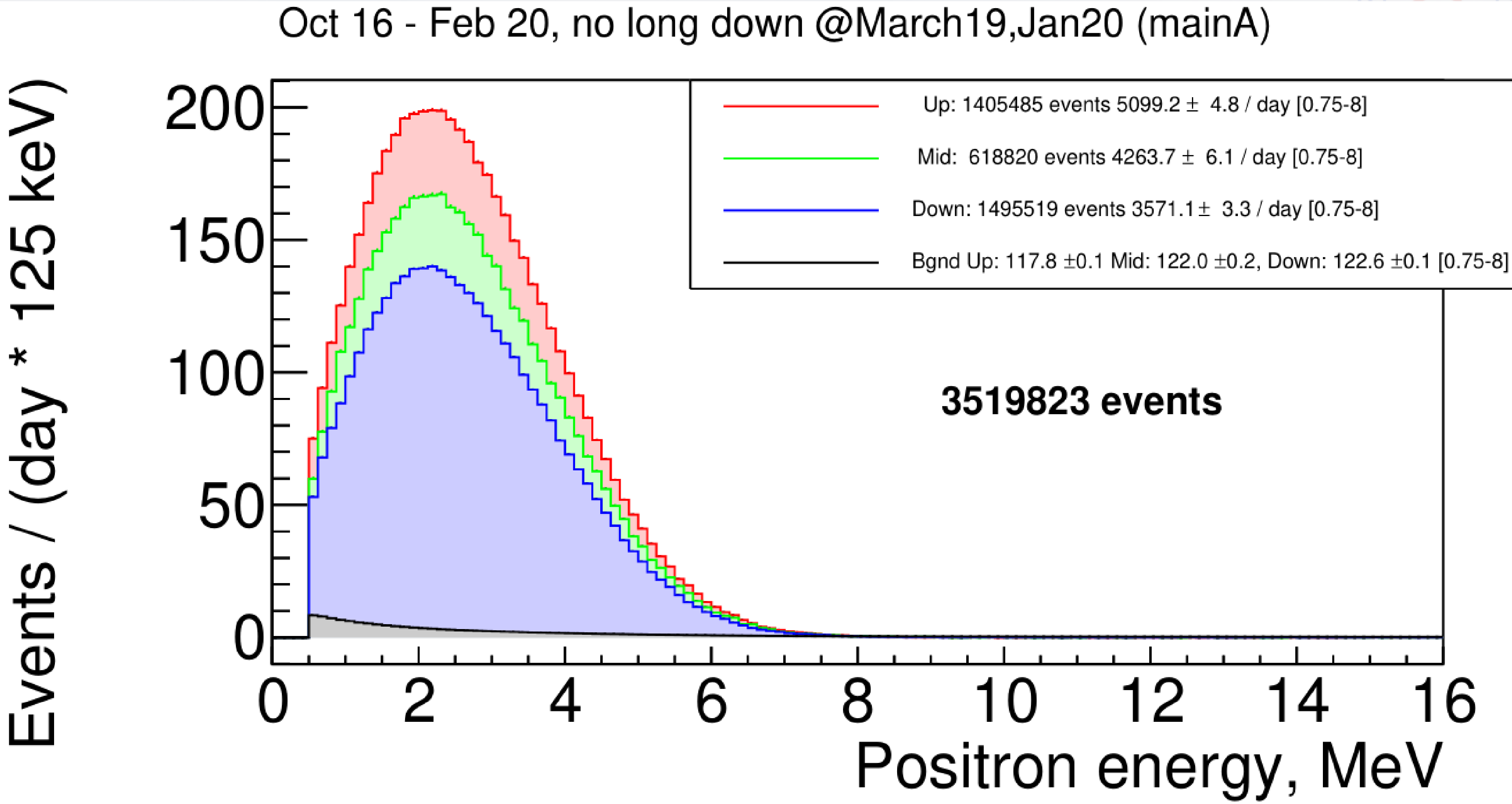








Positron spectrum

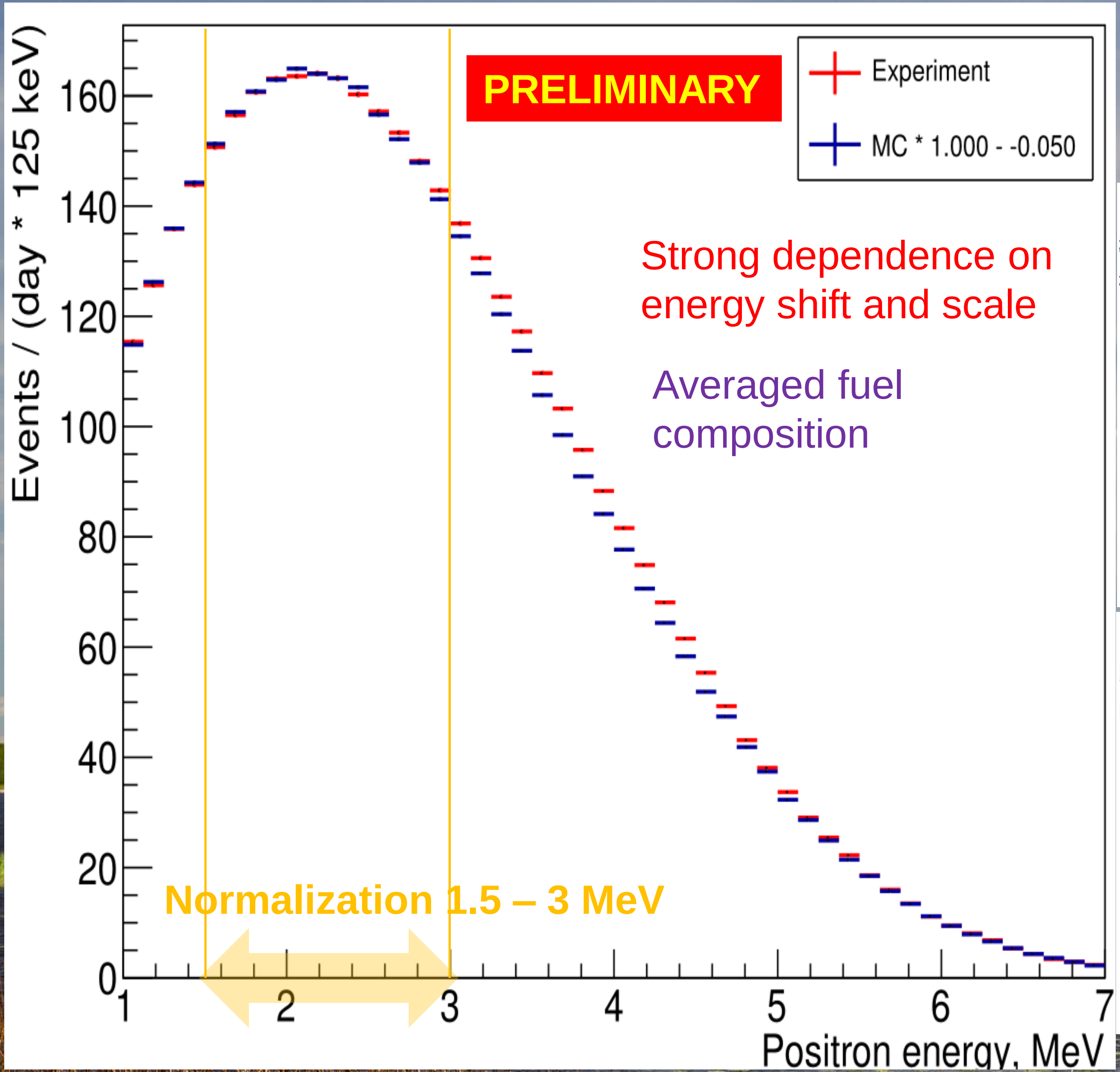


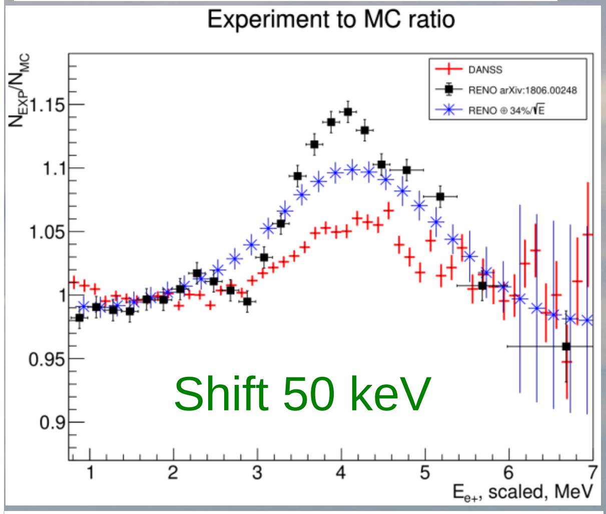
All backgrounds subtracted

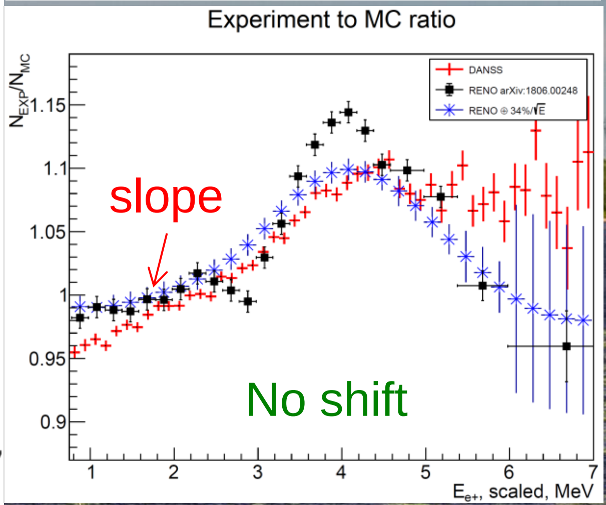
Neighbor reactors at 160 m, 334 m, and 478 m, 0.6% of neutrino signal at up position, subtracted

Statistical errors only

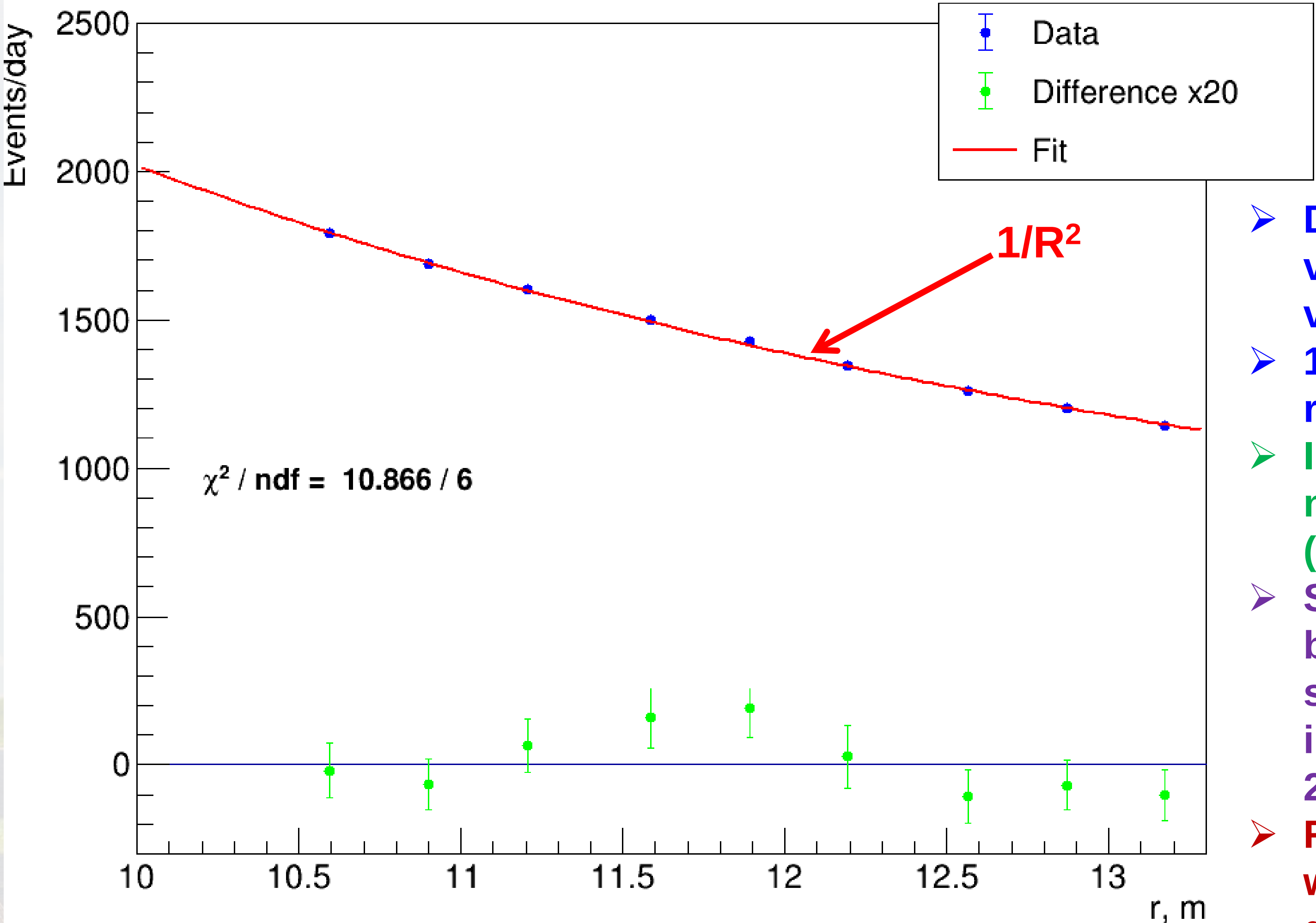
Positron spectrum comparison to H-M model





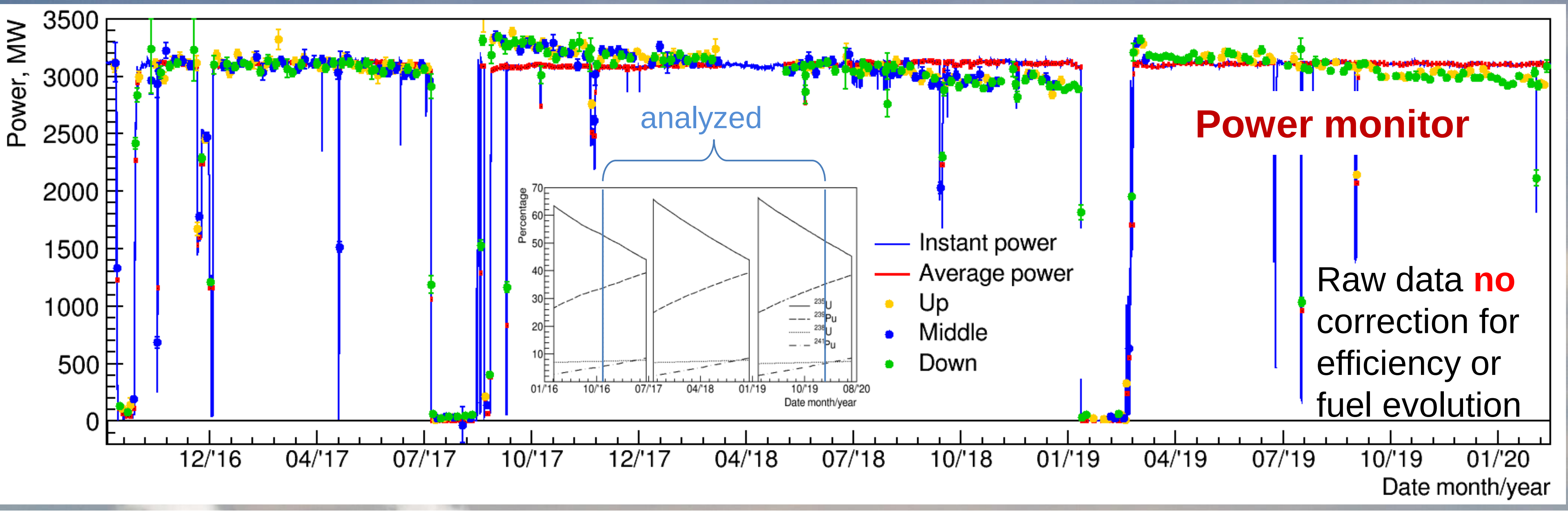


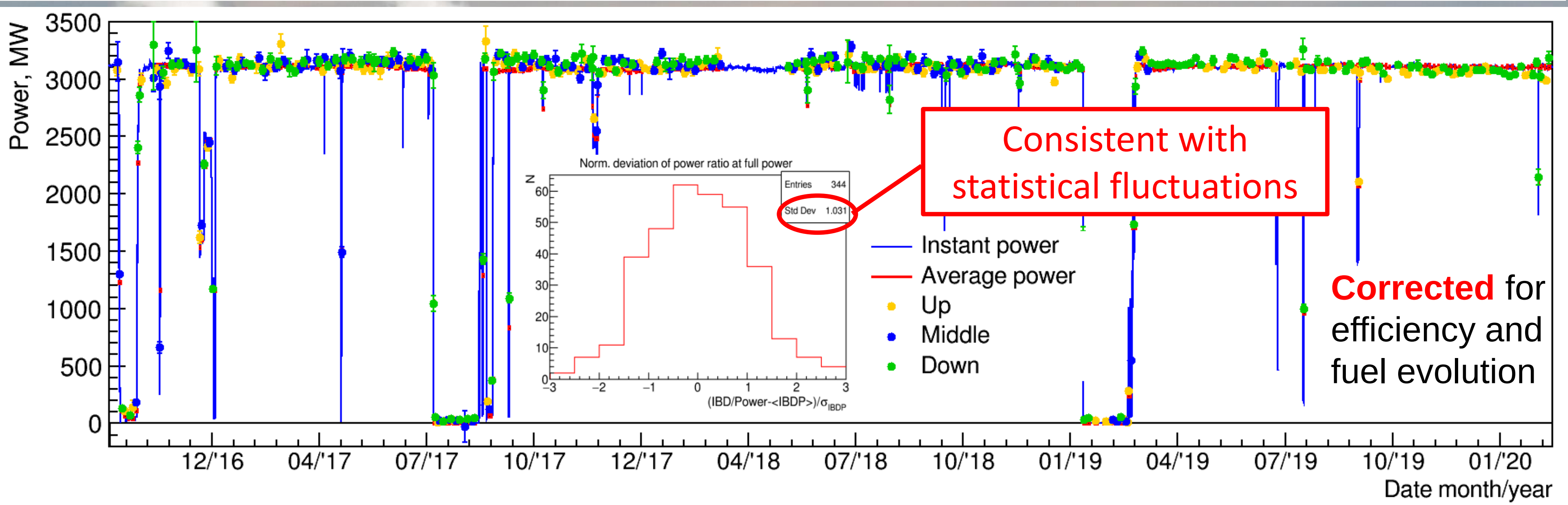
Counting rate dependence on the distance from the reactor core



- 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





Reactor power is measured by neutrino flux with 1.5% statistical accuracy in 2 days for 3+ years.
Changes in absolute detector efficiency are known with accuracy better than 1% during 3+ years.
Relative efficiency is even more stable (<0.2%) because of frequent changes of detector positions.

The DANSS upgrade

Main goal of the upgrade is to improve energy resolution: 34%/√E → 15%/√E;

New scintillation strips: 20x50x1200 mm^3;

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 SiPM per strip;

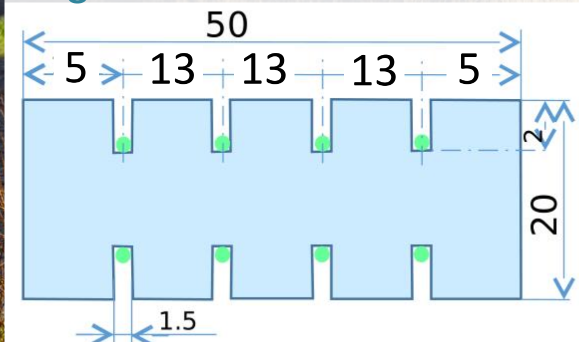
TOF to get longitudinal coordinate in each strip;

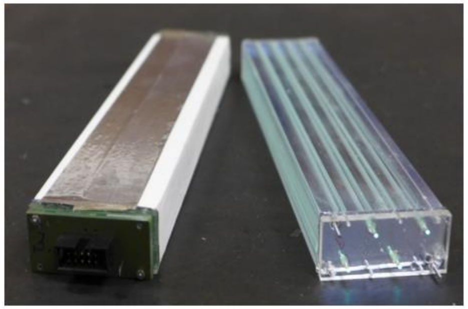
Chemical whitening of strips – no large dead layer with titanium and gadolinium;

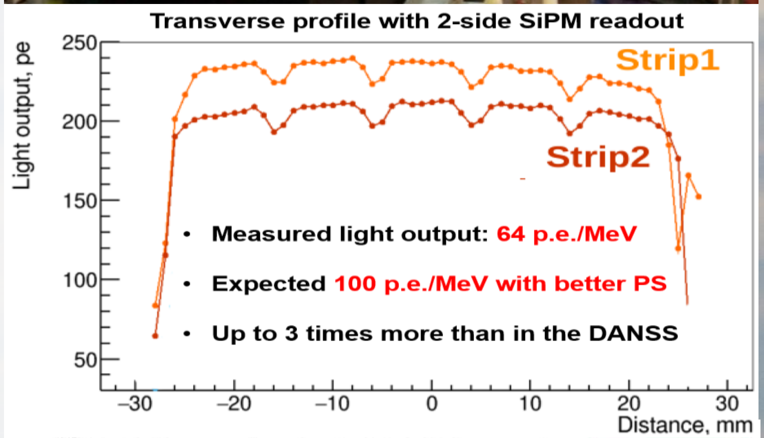
Gadolinium in polyethylene film between layers;

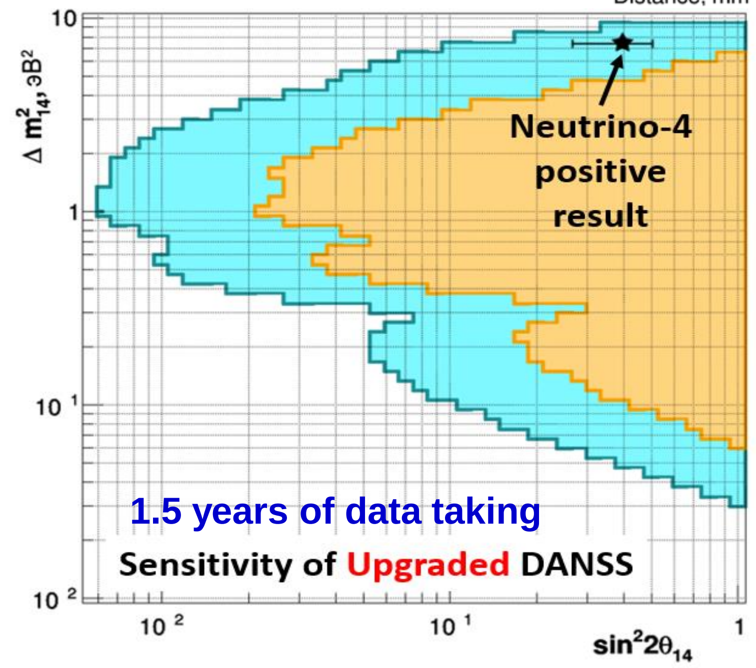
New front end electronics – low power inside passive shielding. Cool SiPMs to 10^oC.

Keep platform, passive and active shielding, digitization.









- DANSS recorded the first data in April 2016 and is running now.
- With new analysis we record more than 5 thousand antineutrino events per day in the closest position after subtraction of the muon induced background about 90 events per day.
- Our data set is already nearly 4 million IBD events.
- 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 3 years of operation.
- DANSS upgrade is planned with installation of new strips with SiPM only readout from both ends. This will allow:
  - achieve better energy resolution;
  - Get larger sensitive volume and increase counting rate.

See the next talk for the statistical analysis and sterile neutrino search results

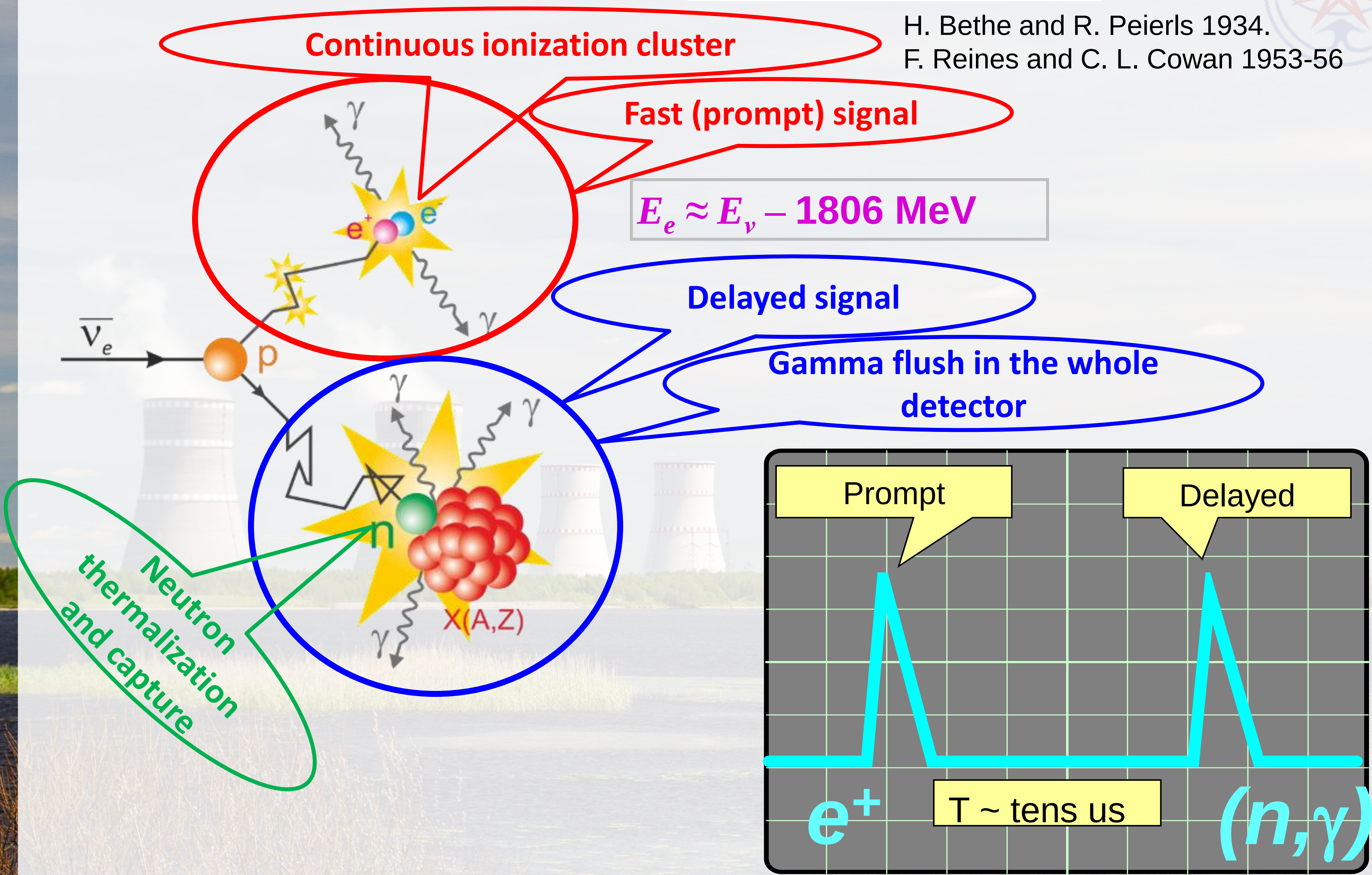
The detector construction was supported by the Russian State Corporation ROSATOM (state contracts H.4x.44.90.13.1119 and H.4x.44.9B.16.1006). The operation and data analysis became possible due to the valuable support from the Russian Science Foundation grant 17-12-01145П. The collaboration appreciate the permanent assistance of the KNPP administration and Radiation and Nuclear Safety Departments.

Thank you !

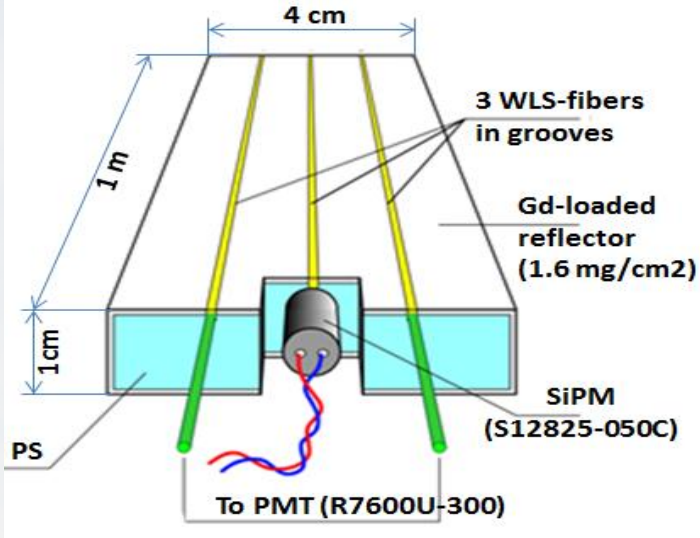
Inverse Beta-Decay (IBD)

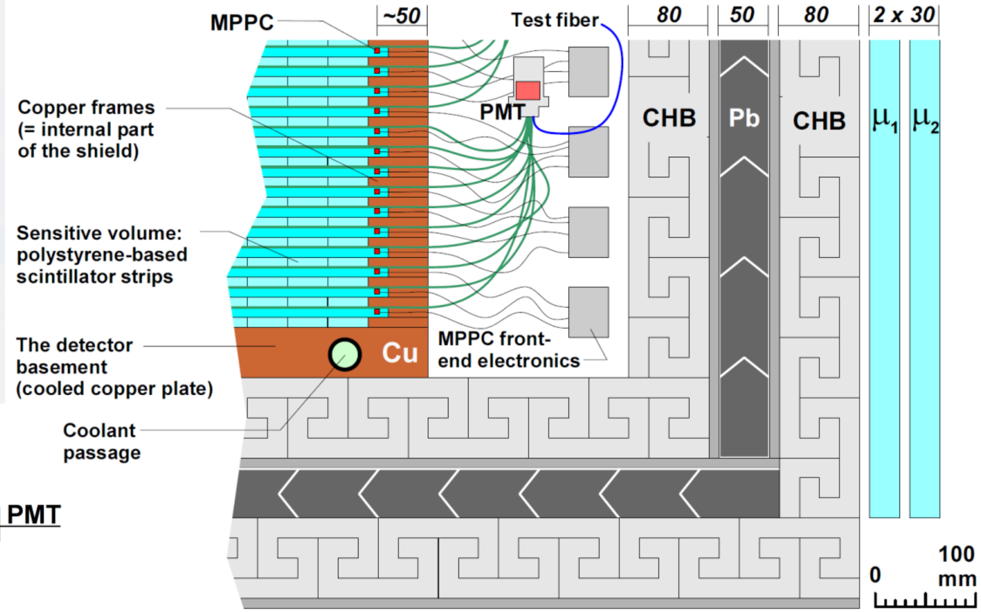
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

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

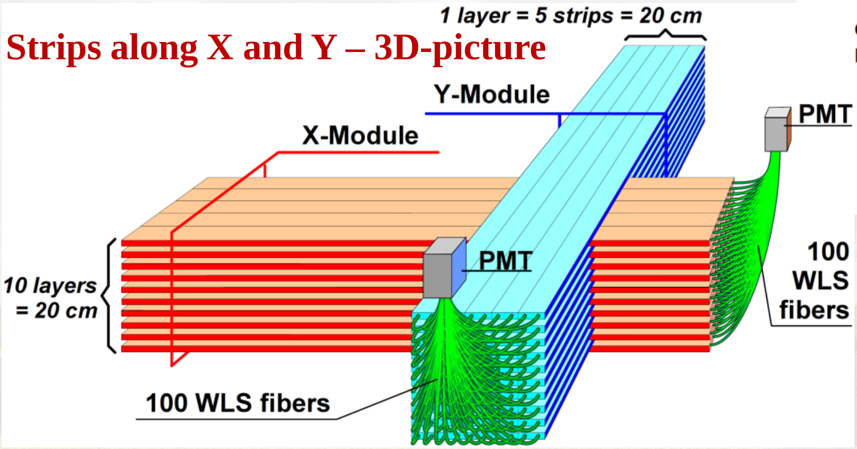


Detector of the reactor AntiNeutrino based on Solid-state Scintillator





Strips along X and Y – 3D-picture

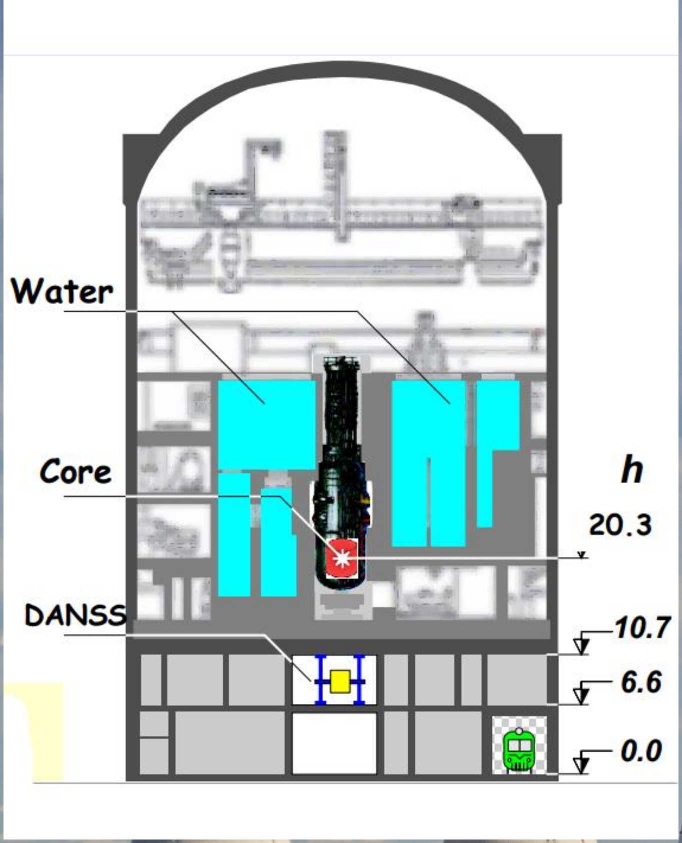


- Scintillation strips 10x40x100 mm^3 with Gd-dopped coating (0.35%wt)
- Double PMT (groups of 50) and SiPM (individual) readout
- SiPM: 17.7 p.e./MeV & 0.37 X-talk
- PMT: 15.9 p.e./MeV
- 2500 strips = 1 m^3 of sensitive volume

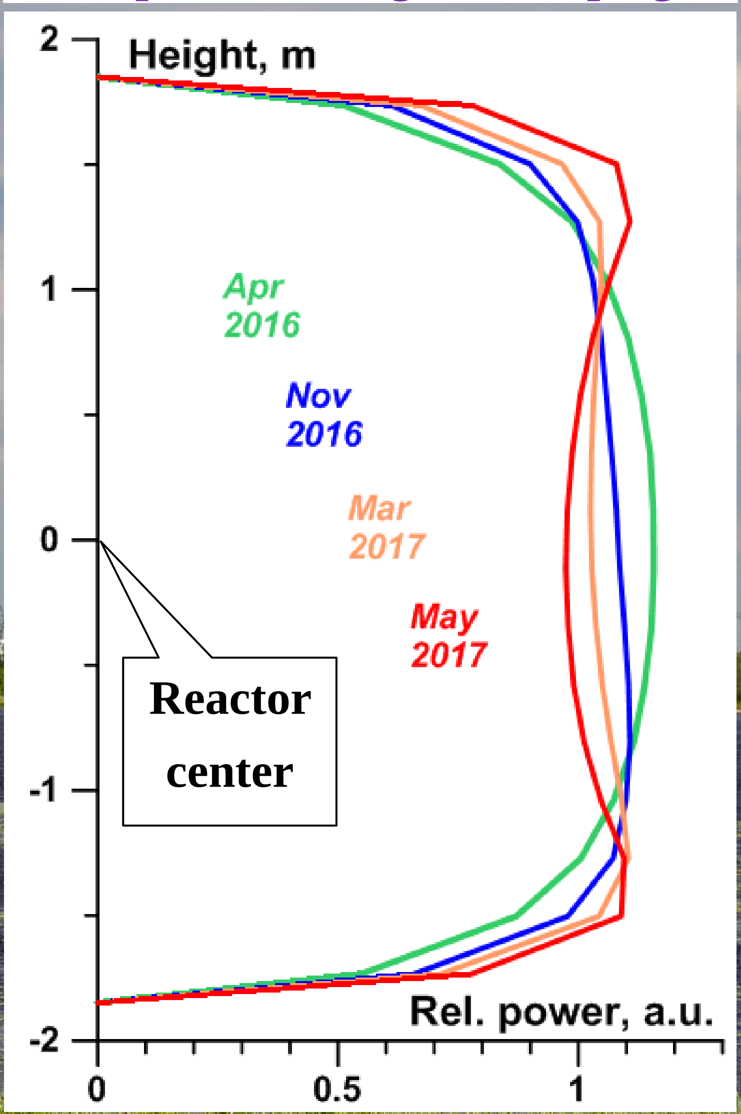
•Multilayer closed passive shielding: electrolytic copper frame ~5 cm, borated polyethylene 8 cm, lead 5 cm, borated polyethylene 8 cm
•2-layer active μ-veto on 5 sides
•Dedicated WFD-based DAQ system
•Total 46 64-channel 125 MHz 12 bit Waveform Digitisers (WFD)
• System trigger on certain energy deposit in the whole detector (PMT based) or μ-veto signal
• Individual channel selftrigger on SiPM noise (with decimation)

JINST 11 (2016) no.11, P11011

Reactor WWER1000



Reactor vertical burning profile for 100% power during the campaign 4

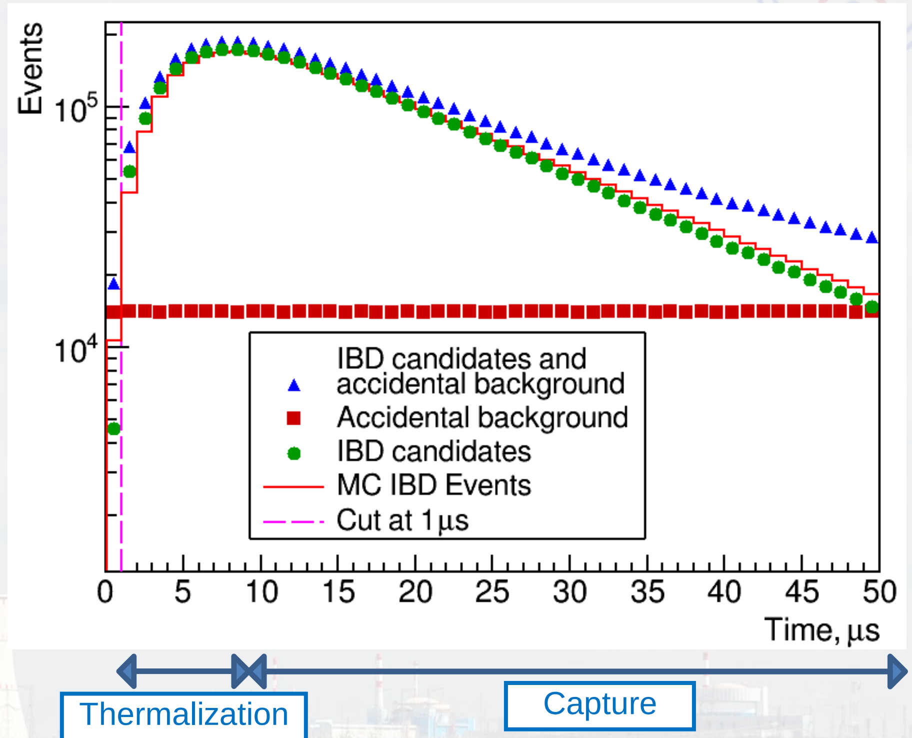


Fuel contribution during the campaigns

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

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

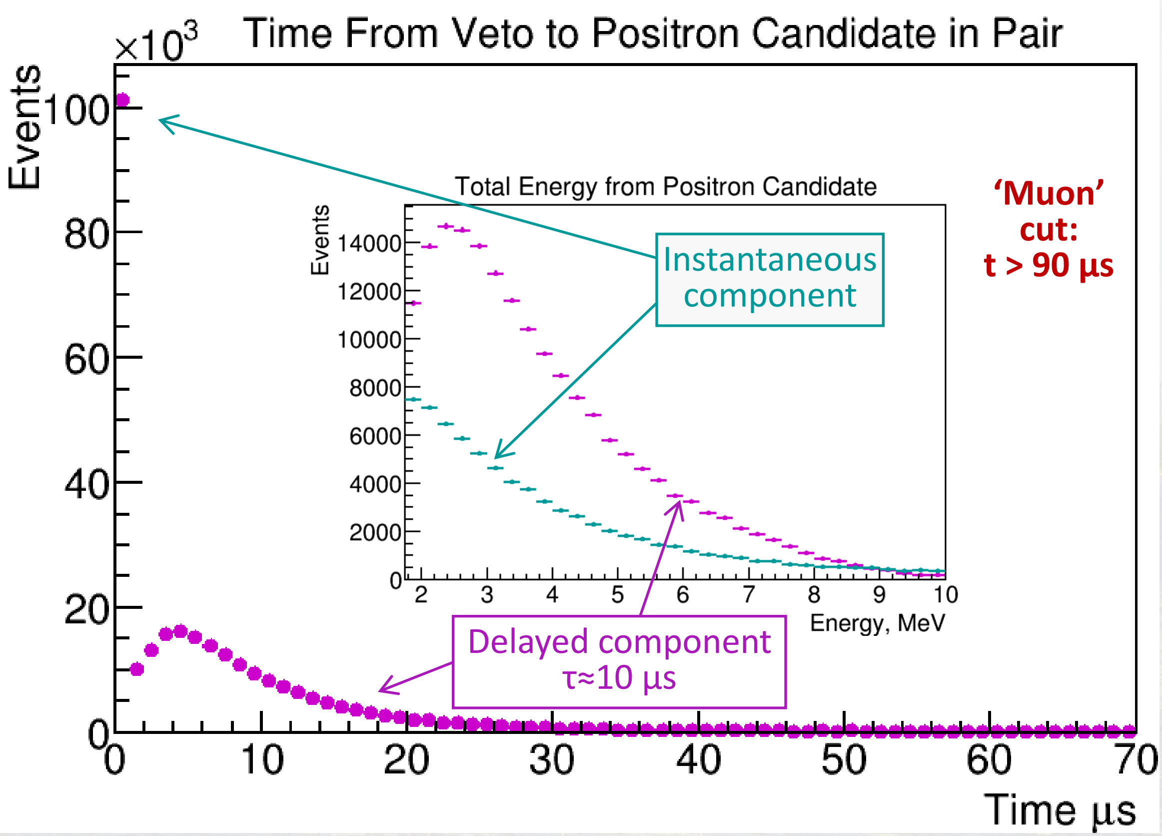
VETO 'OR':
- 2 hits in veto counters
- veto energy >4 MeV
- energy in strips >20 MeV
- energy in two bottom strip layers > 3 MeV

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:

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

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

$$E_N[MeV] > 1.5 + 3 \cdot e^{-0.13 \cdot E_e^2}$$

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

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