EPS-HEP 2019
Ghent, Belgium
July 13, 2019

New results from the DANSS experiment

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for the DANSS Collaboration

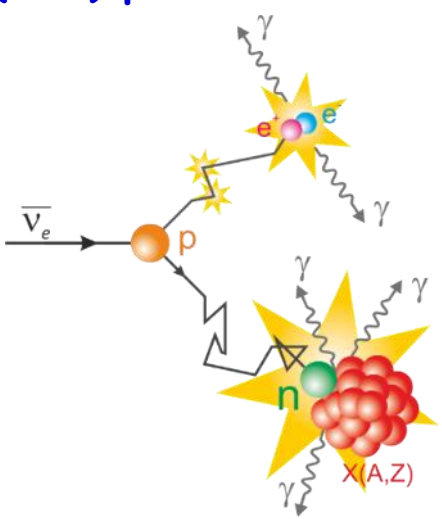
There are several ~3σ indications of 4th neutrino

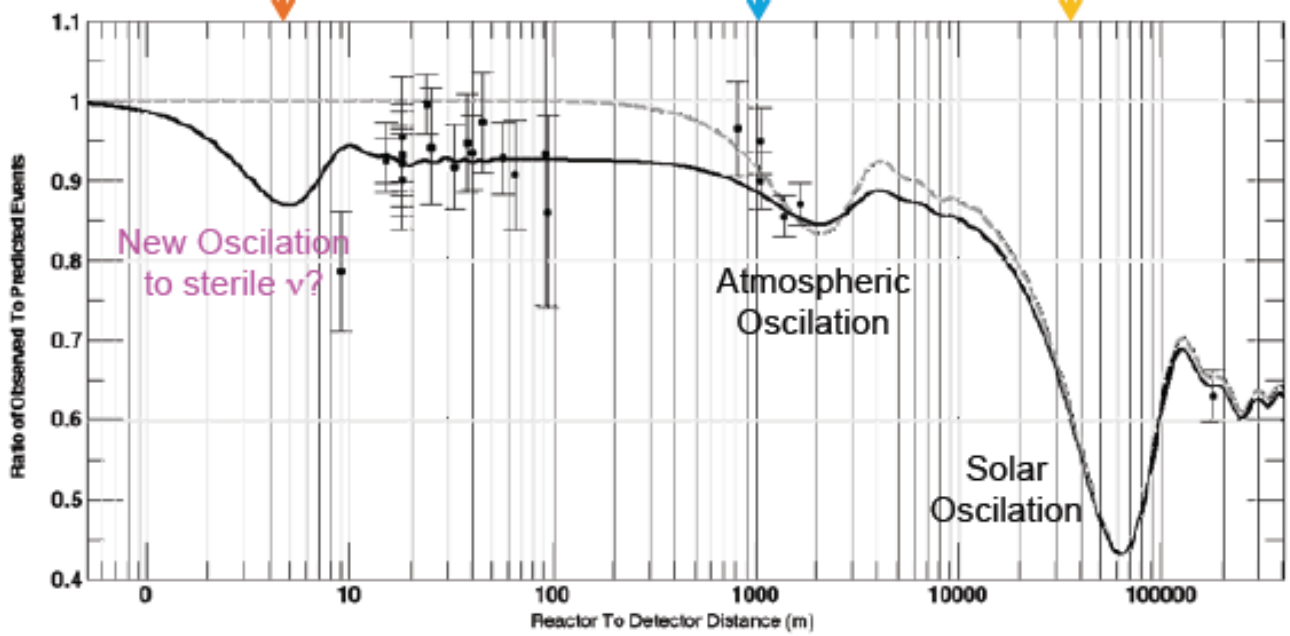
LSND, MiniBoone: $\bar{\nu}_e$ appearance
SAGE and GALEX ν_e deficit
Reactor $\bar{\nu}_e$ deficit

Indication of a sterile neutrino
$\Delta m^2 \sim 1\ eV^2$
$\sin^2 2\theta_{14} \sim 0.1$
=> Short range neutrino oscillations

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{14} \sin^2(1.27\Delta m^2_{41} \frac{L}{E}) - c^4_{14} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} \frac{L}{E}) - c^4_{14} c^4_{13} \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{21} \frac{L}{E})$$

Inverse Beta Decay (IBD) process





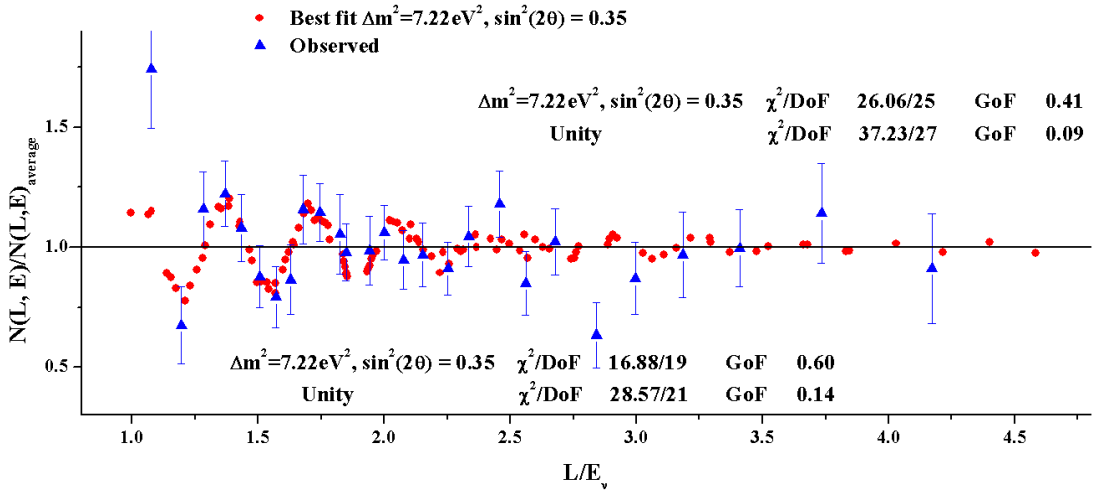
G. Mention et al. Phys Rev D 83 073006 (2011)

Reactor models do not describe well neutrino spectrum

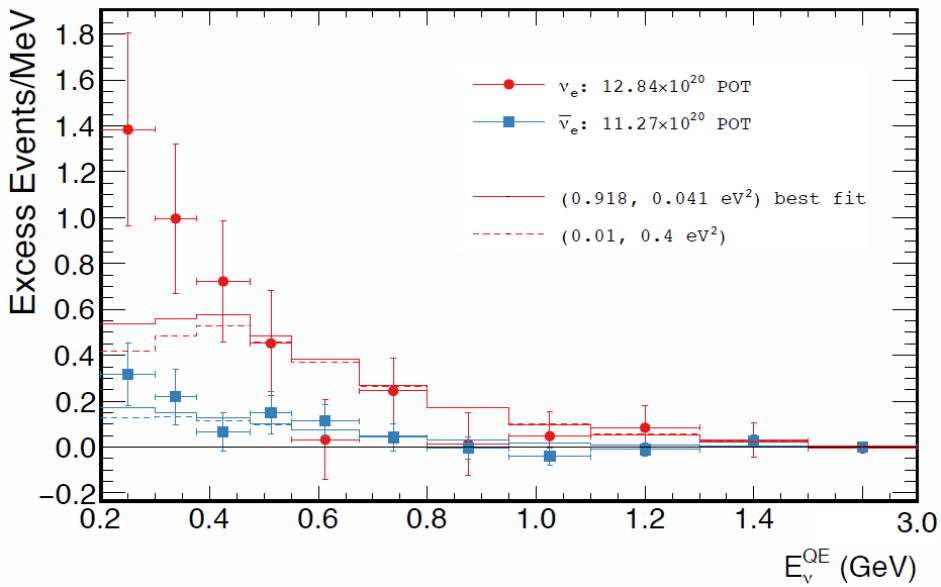
Measurements at one distance are not sufficient!

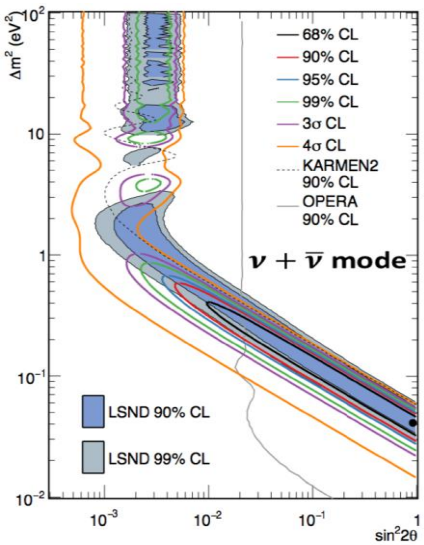
New (2018) indications of sterile neutrinos

NEUTRINO-4: $\Delta m^2 \sim 7 eV^2$ and $\sin^2 2\theta \sim 0.35$! JETP Lett. 109 (2019) no.4, 213

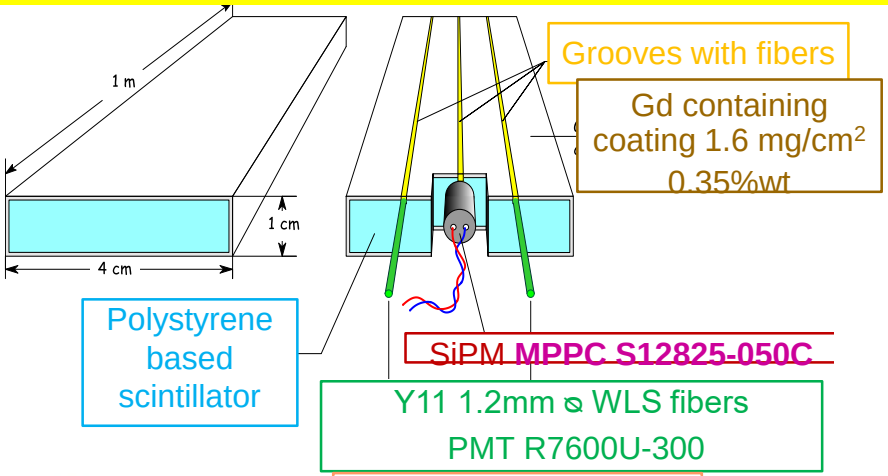


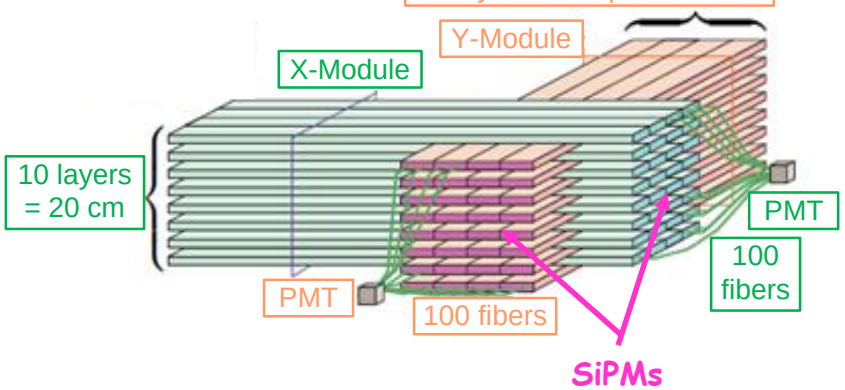
MiniBooNE ν_e excess of 4.8σ (6σ with LSND) Phys.Rev.Lett. 121 (2018) no.22, 221801

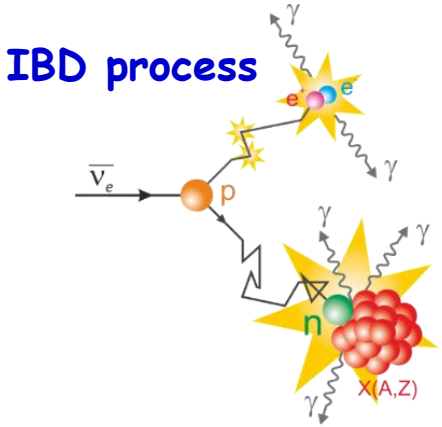


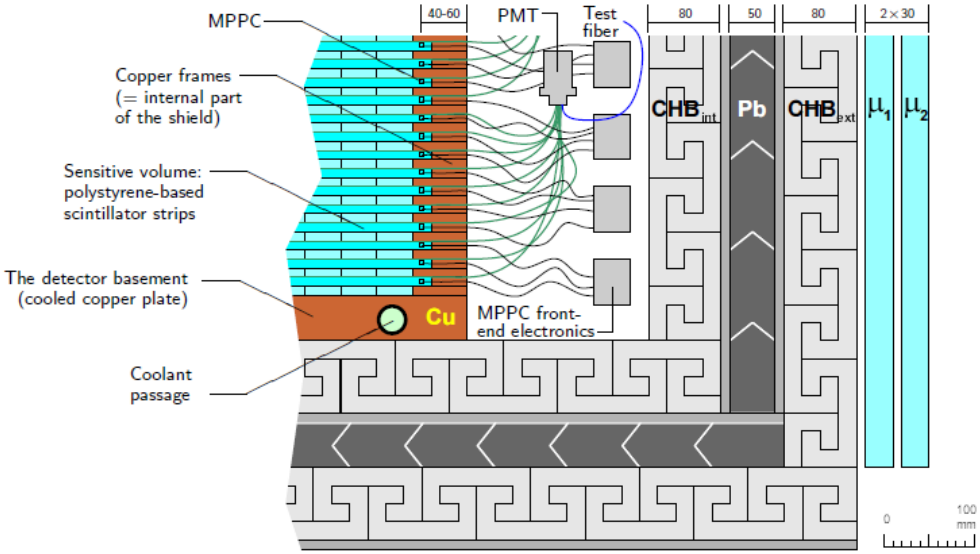


DANSS Detector design (ITEP-JINR Collaboration)





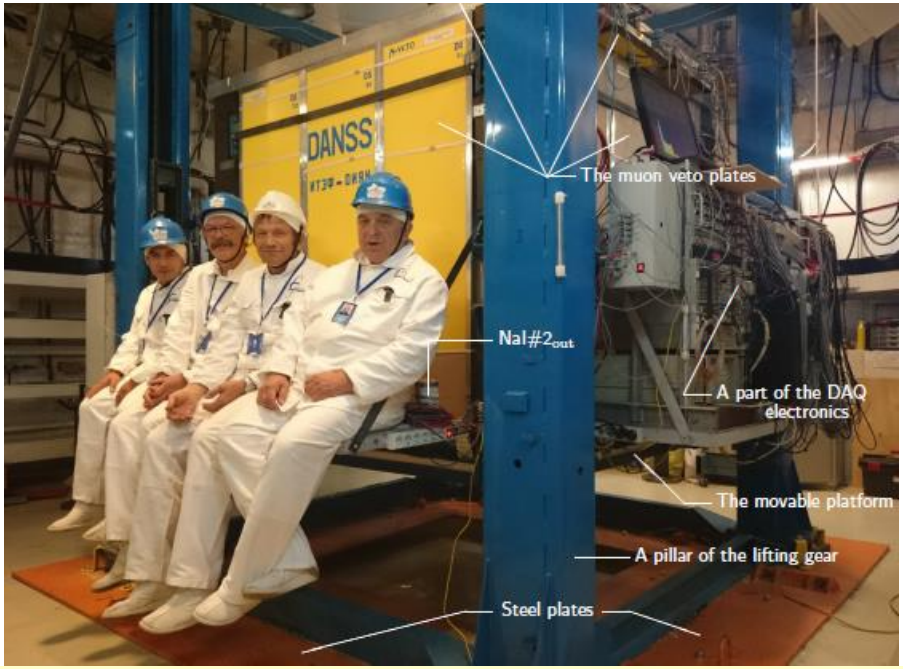


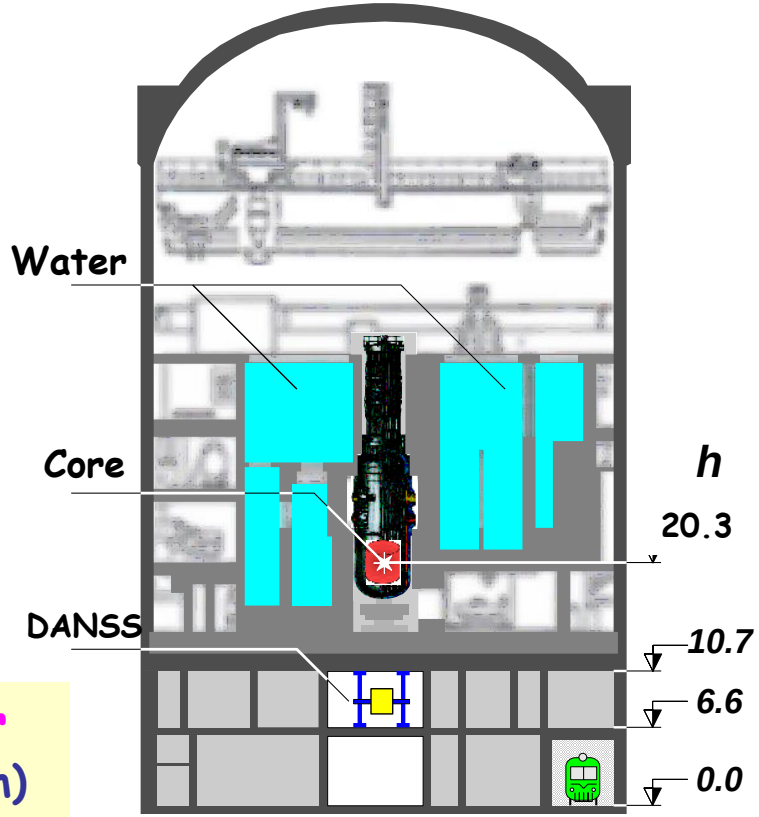


- **2500 scintillator strips with Gd containing coating for neutron capture**
- **Light collection with 3 WLS fibers**
- **Central fiber read out with individual SiPM**
- **Side fibers from 50 strips make a bunch of 100 on a PMT cathode = Module**

- **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**

DANSS at Kalinin Nuclear Power Plant





DANSS is installed on a movable platform under 3GW WWER-1000 reactor (Core:h=3.7m, ∅=3.1m) at Kalinin NPP.

~50 mwe shielding => μ flux reduction ~6!

No cosmic neutrons!

Detector distance from reactor core 10.7-12.7m (center to center)

Trigger: ΣE(PMT)>0.5-0.7MeV=>Read 2600 wave forms (125MHz), look for correlated pairs offline.

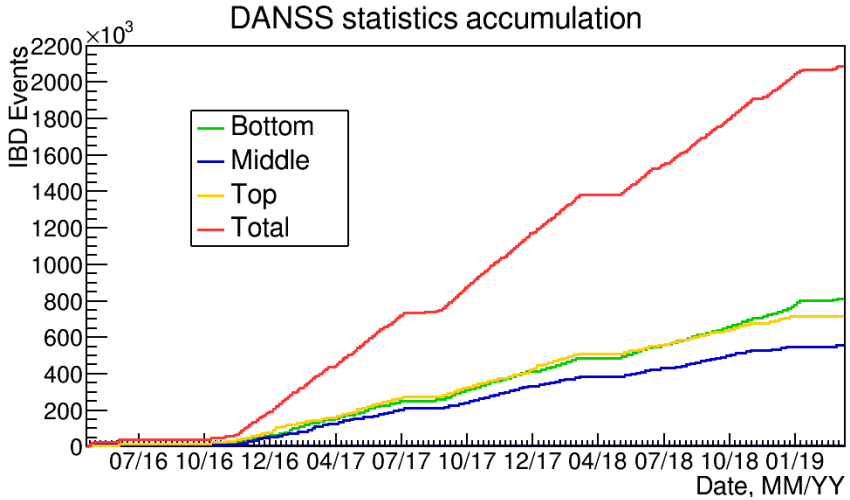
Fuel fission fractions at beginning and end of campaign

235U	63.7%	44.7%
239Pu	26.6%	38.9%
238U	6.8%	7.5%
241Pu	2.8%	8.5%

Improvements in analysis in comparison with Phys.Lett. B787(2018)56

- Use of SiPM and PMT signal shapes for T_0 and charge determination
- Signal waveform simulation in MC; Better correction on Signal-PMT(SiPM) L
- Increased frequency of calibrations of 2600Ch (Gain - 15min, MIP - 2 days)
- Requirement for PMT coincidence for all SiPM signals to suppress noise
- Improved treatment of Birks effect and Cherenkov radiation in MC
- A bug in pattern numbering was corrected → tiny shifts in excluded regions
- Requirement of annihilation photons for e+ clusters with 1 strip to reduce accidental background at low e+ energies as well as neutron background
- Comparison with ^{12}B spectrum added for MC tests and energy scale fixation
- Two lowest detector layers added to the VETO system
- Four times finer grid of points on the $(\Delta M^2, \sin^2(2\theta))$ plane
- Increase of statistics from 966 thousand to 2.1 million IBD events

Results of improvements



- Accidental energy in event is reduced from 100 keV to 5 keV
- Accidental background is reduced from 71% to 29% (up position)
- Cosmic background is reduced from 2.8% to 1.9%

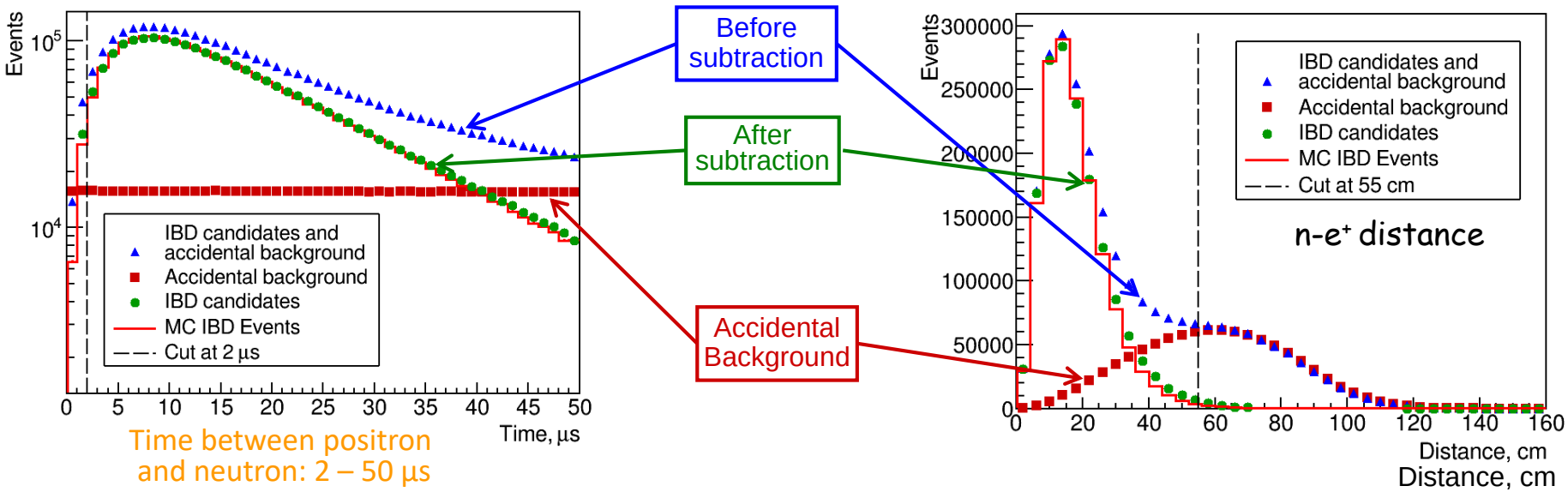
- Energy resolution for calibration sources is still worse than in MC
  → additional smearing of 17%/√E is added to MC (as in published results)

- Energy scale is determined using mainly ^{12}B signals since they are similar to e+ signals (we measure Ee+ without annihilation gammas!)

We still assume +/-2% systematic uncertainty in the energy scale.

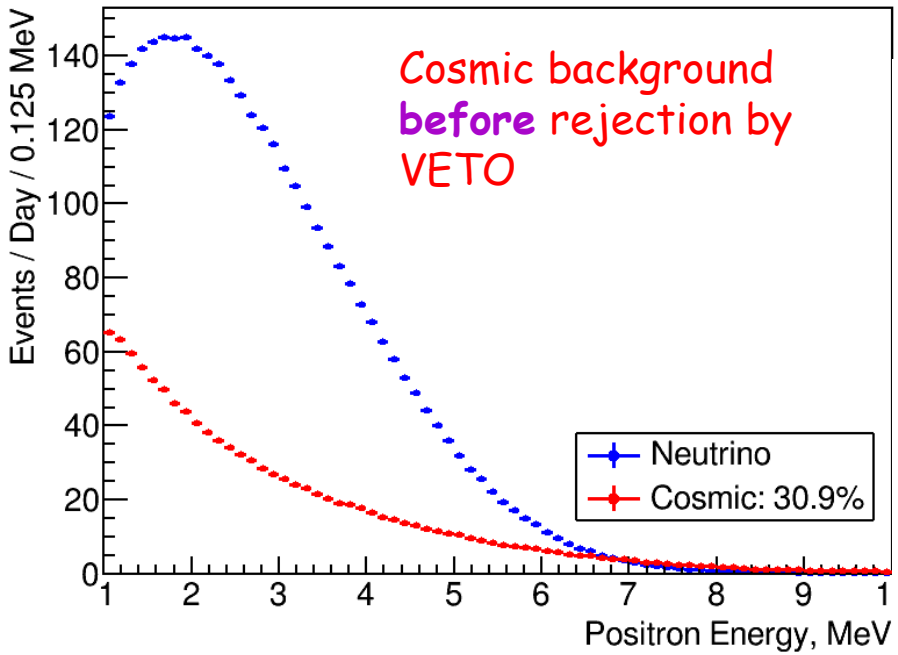
- Sensitivity of experiment is improved by a factor of ~ 1.4

Accidental coincidence background

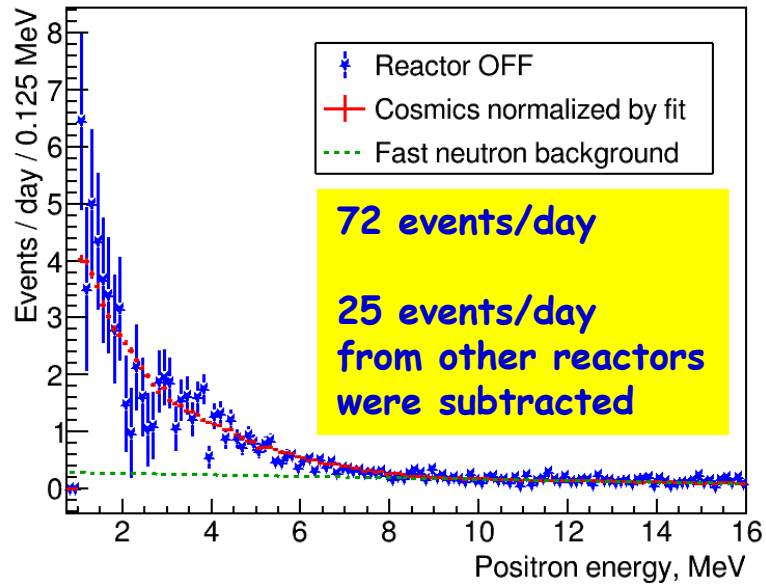


- **Fake e+ or neutron in IBD events by uncorrelated triggers → accidental background**
- **Background events from data: search for a positron candidate where it can not be present – 50 μs intervals far away from neutron candidate (5, 10, 15 etc millisec)**
- **Enlarge statistics for accidentals by searches in numerous non-overlapping intervals**
- **Cuts for the accidental coincidence exactly the same as for physics events**
- **Accidental rate is ~29% of IBD rate (up detector position)**
- **Mathematically strict procedure, but it increases statistical errors**
- **Selection of cuts to reduce accidental contribution => smaller statistical errors**

Residual background subtraction

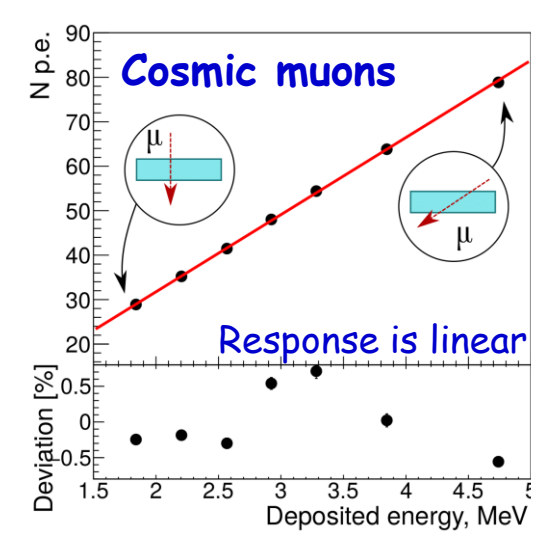


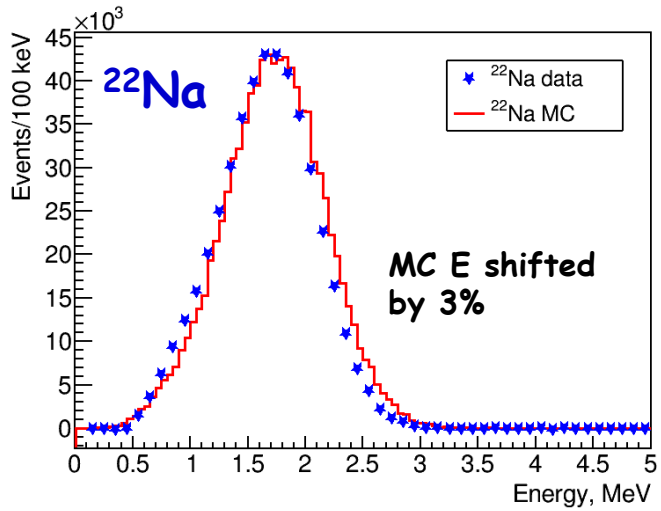
Reactor OFF Background Spectrum consistent with Cosmic background

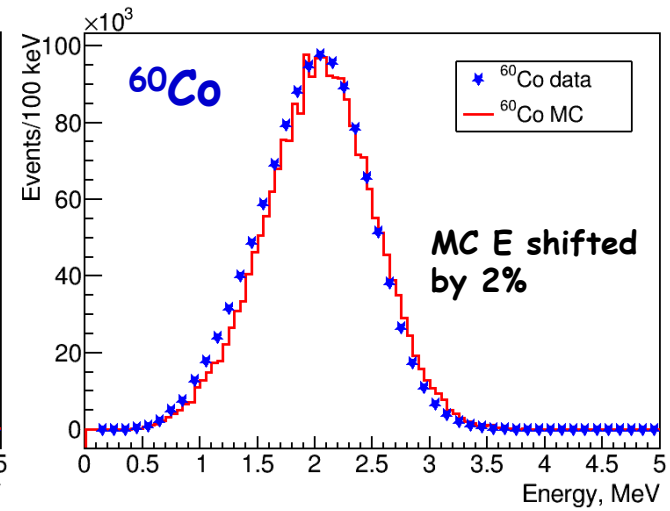


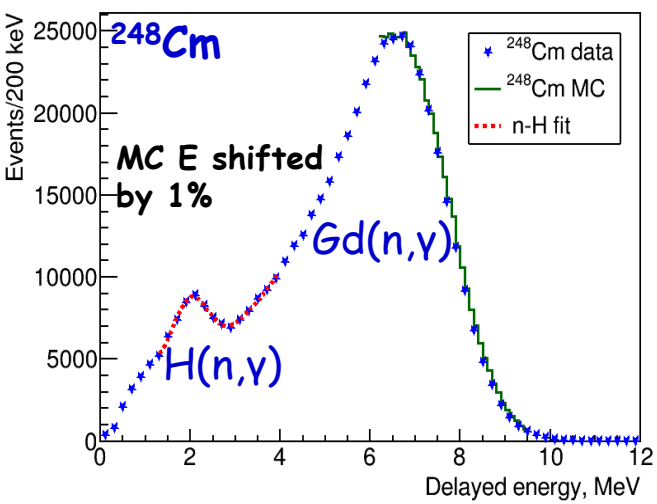
- **Fast neutron tails: linearly extrapolate from high energy region and subtract separately from positron and visible (i.e. rejected by VETO) cosmic spectra**
- **Subtract fraction of visible cosmics based on VETO inefficiency**
- **Amount of visible (rejected by VETO) cosmics 30.9% of neutrino signal (up position)**
- **VETO inefficiency - 6.2% from 'reactor OFF' spectra.**
- **Not vetoed cosmic background fraction is ~1.9% of neutrino signal, subtracted**
- **Final anti-neutrino spectrum (Ee^+ + 1.8 MeV) has No background!**

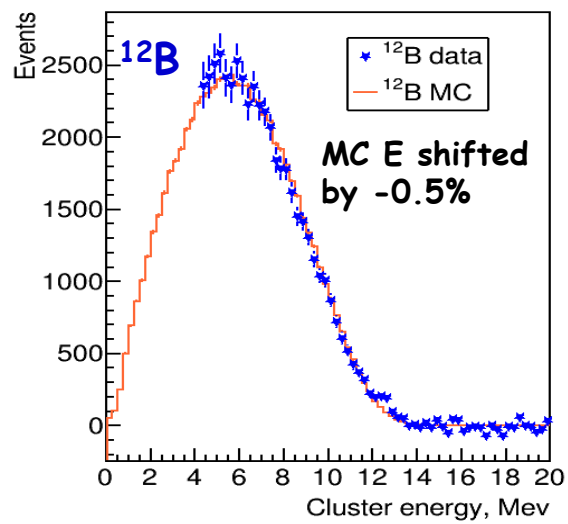
Calibration

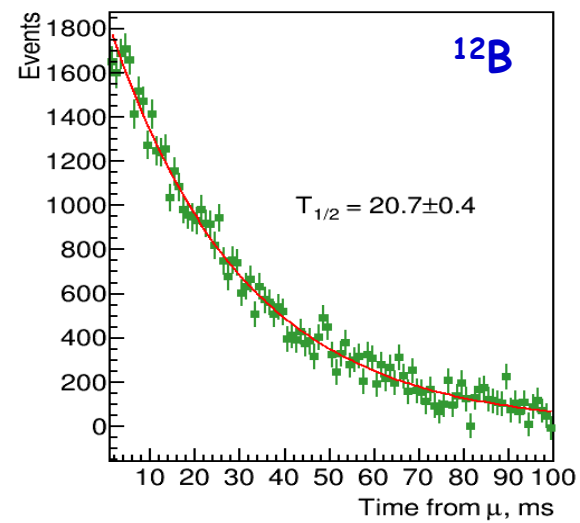






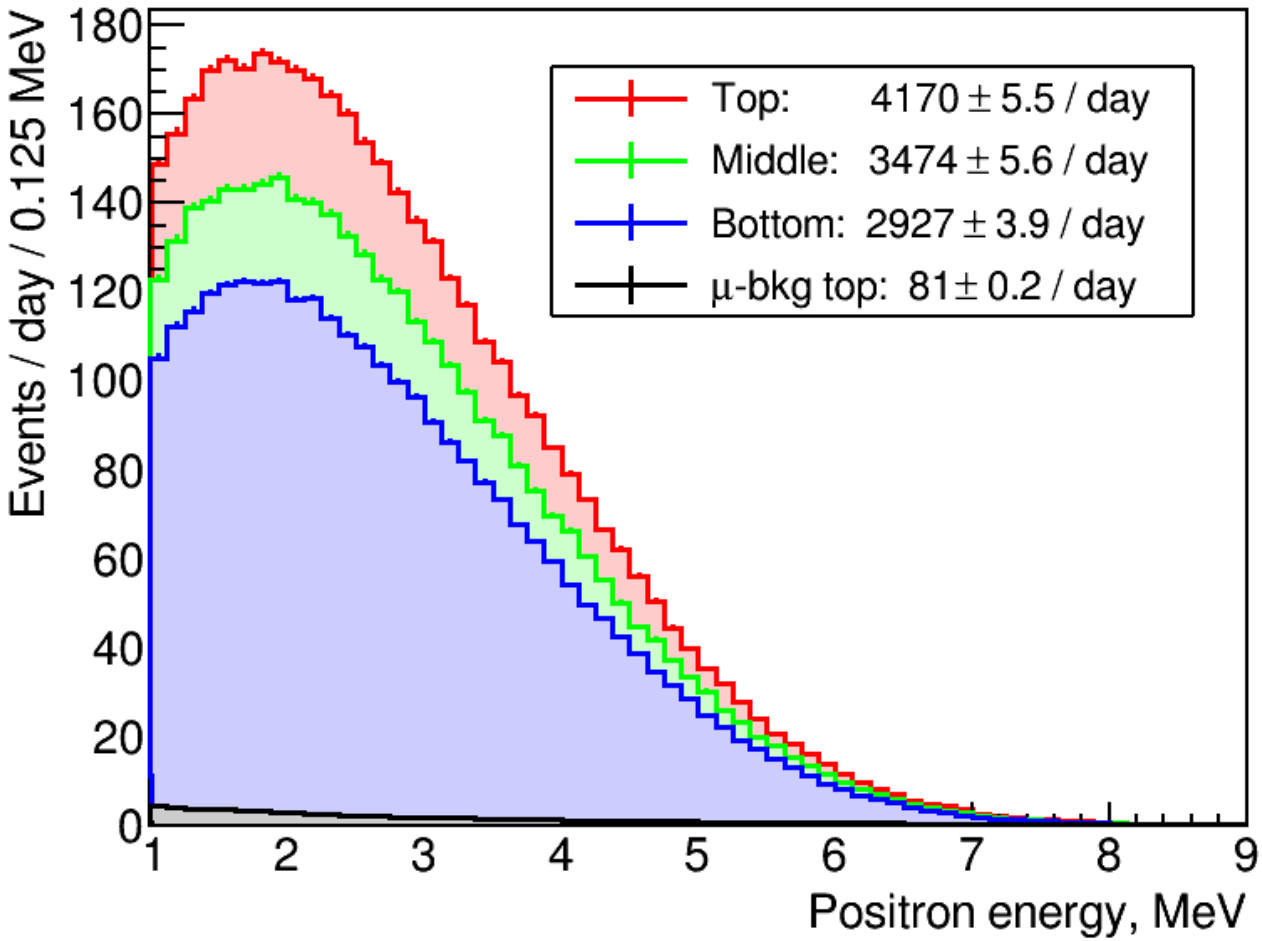






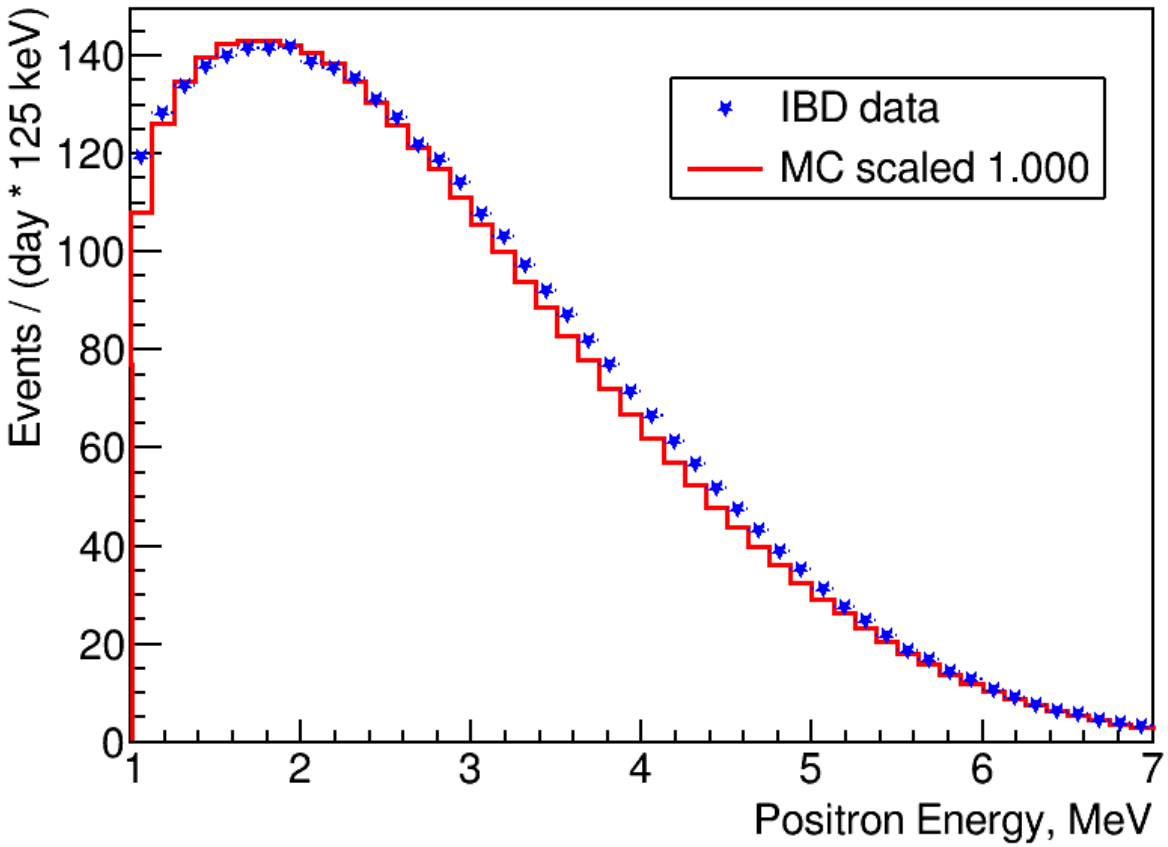
E scale is based on ^{12}B signal which is similar to e^+ signal (we measure Ee+, not Eprompt)
Systematic error on E scale of +/-2% added to take into account shifts in source responses

Positron spectrum



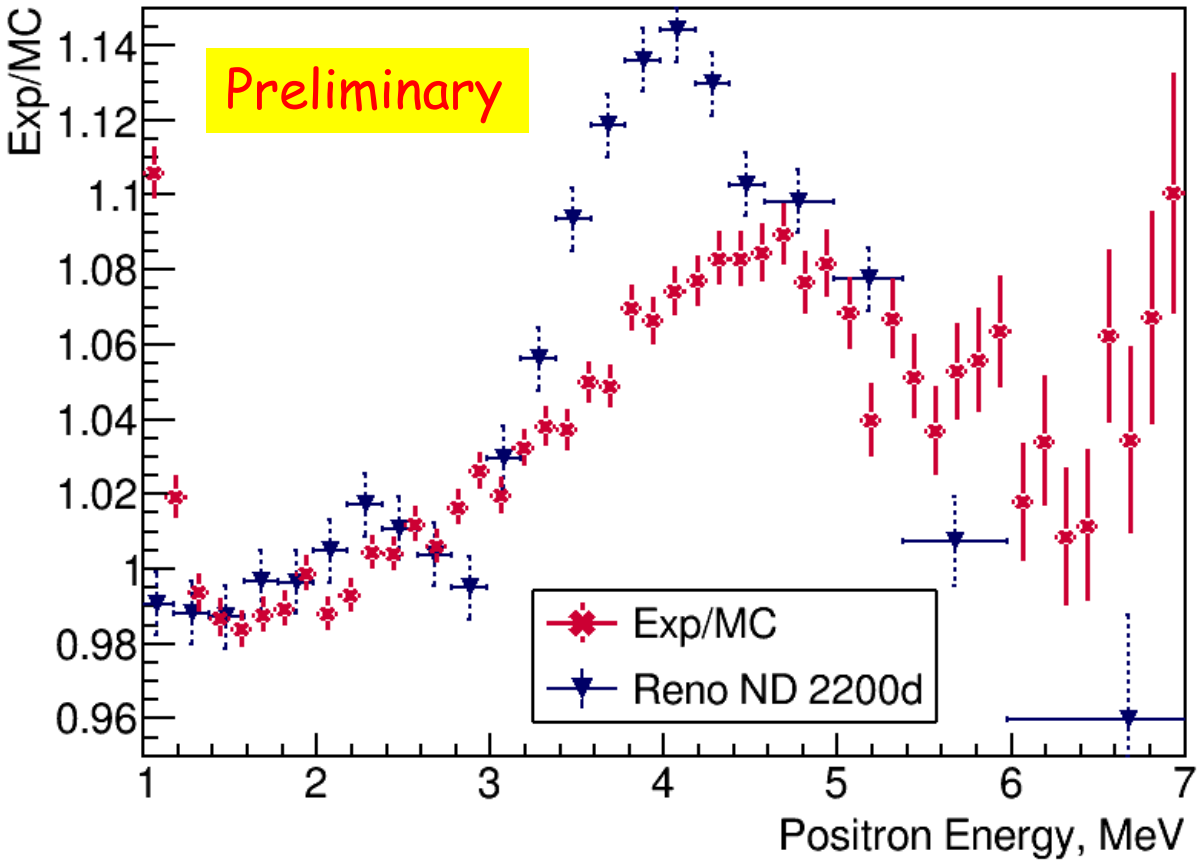
- **3 detector positions**
- **Pure positron kinetic energy (annihilation photons not included)**
- **> 4000 neutrino events/day in detector fiducial volume of 78% ('Up' position closest to the reactor)**

Positron spectrum



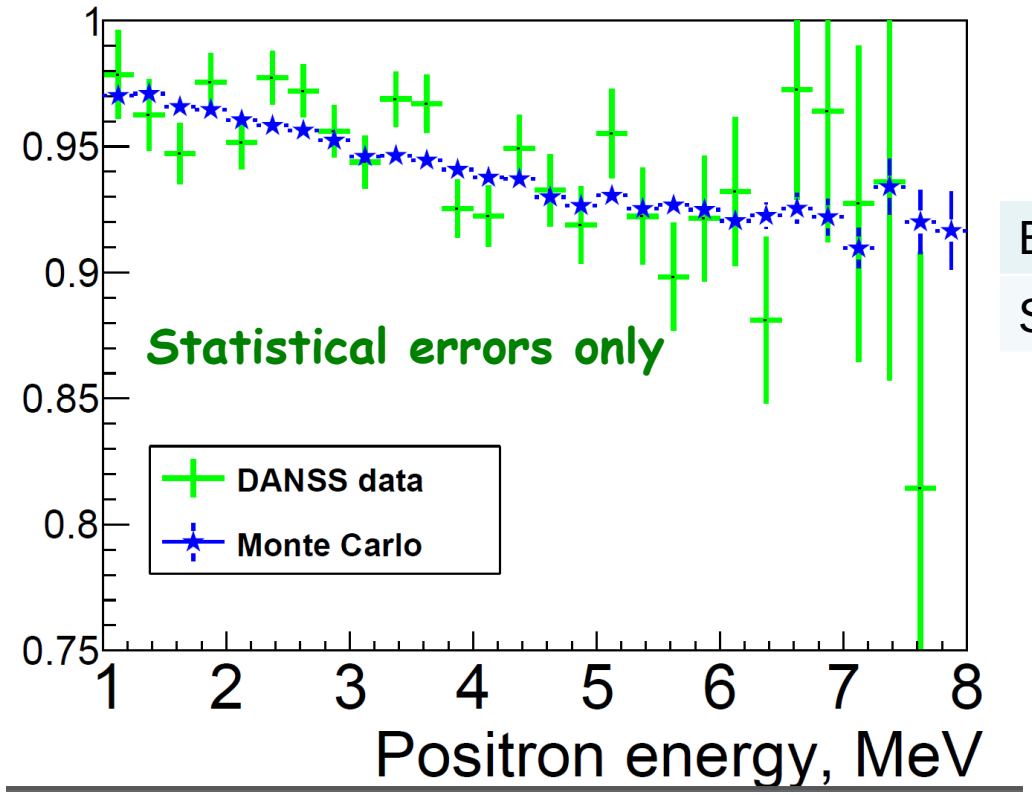
Rough agreement with MC.
(Theoretical neutrino spectrum was taken from Huber and Mueller)
Large sensitivity to energy scale
More work on calibration is needed before quantitative comparison

Ratio of positron energy spectrum to H-M MC predictions



Indication of a small bump (normalization in 1.5-3MeV)
However, shape dependence on energy scale is strong
No conclusion on the bump existence at the moment
More studies on energy scale are required

Ratio of positron spectra at the 4 last months of campaign and 2-5 months of the next campaign



Fission fractions [%]

	235U	238U	239Pu	241Pu
End	45.8	7.7	38.3	7.9
Start	61.7	7.1	28.0	3.1

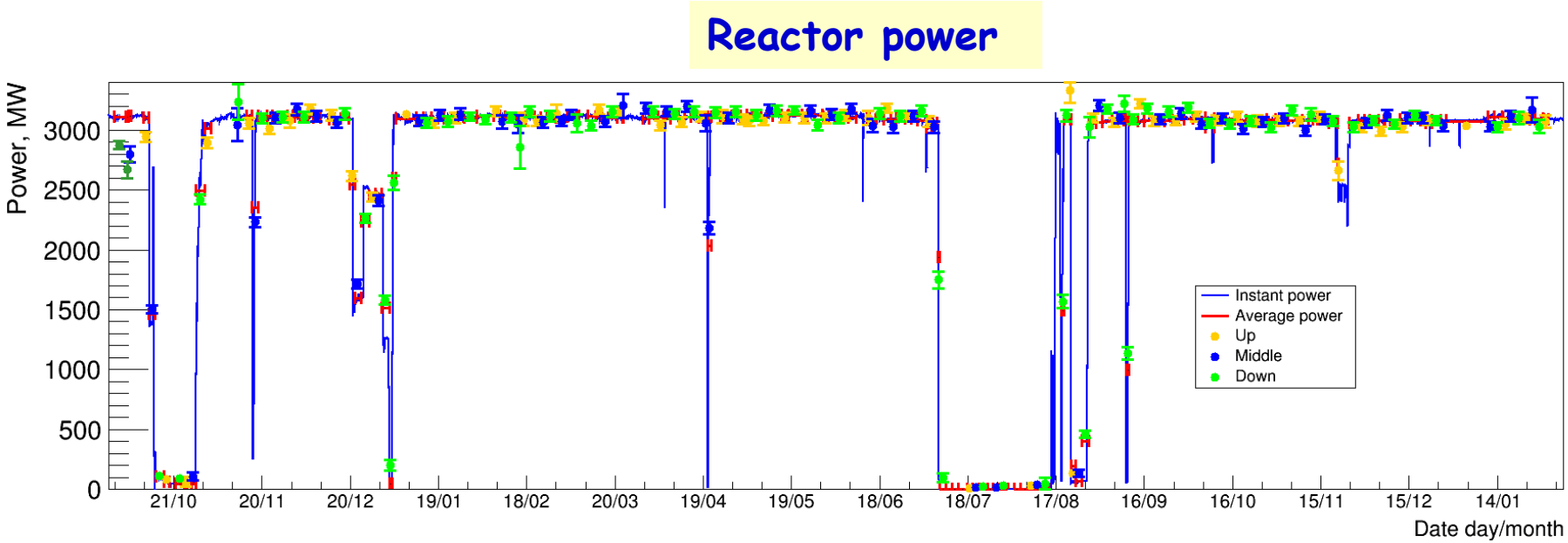
Not all data and old analysis

More work is needed for absolute efficiency calibration of new data (canceled in oscillation analysis)

Clear evidence for spectrum evolution

Spectrum evolution is consistent with MC

Comparison of reactor power and DANSS rate



- Points at different positions equalized by $1/r^2$
- Normalization by 12 points in November-December 2016
- Cosmics and adjacent reactor fluxes (0.6%) subtracted
- Spectrum dependence on fuel composition is included
- Reactor power is measured with ν flux with 1.5% accuracy in 2 days during more than a year

Not all data and old analysis

More work is needed for absolute efficiency calibration of new data (canceled in oscillation analysis)

Data Analysis

For a grid of points (ΔM^2,$Sin^2(2\theta)$) e^+ spectrum is calculated for Up and Down positions taking into account reactor core size and detector energy response

The energy response (including tails) was obtained from cosmic muon calibration and GEANT-4 MC simulation analyzed identically to data analysis.

Reactor burning profile was provided by NPP

Ratio of Down/Up spectra was calculated and compared with experiment (independent on ν spectrum, detector efficiency, and many other problems!)

Systematic errors in energy resolution, energy scale, level of cosmic background were treated as nuisance parameters

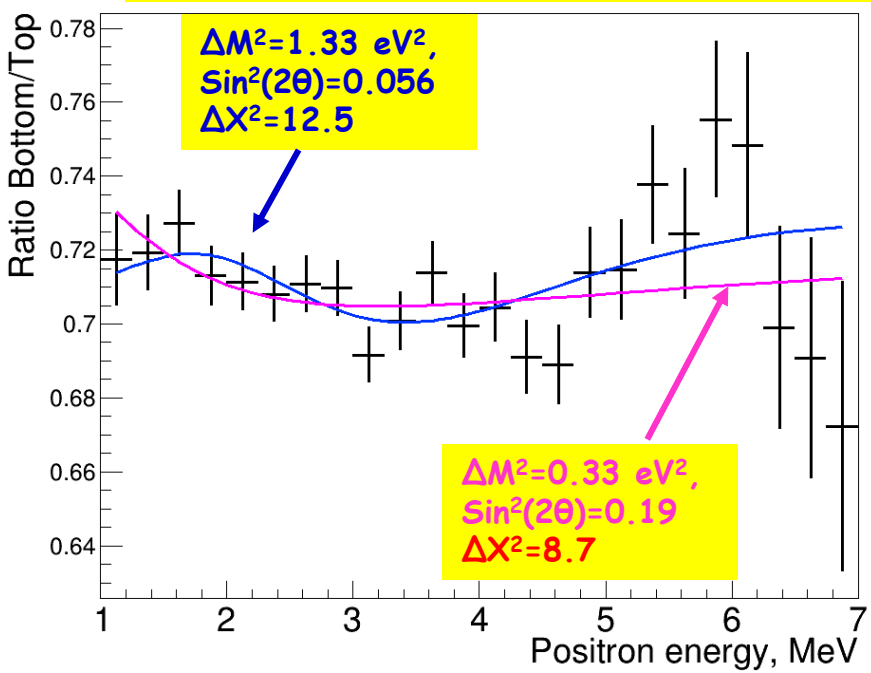
For each ΔM^2 and $Sin^2(2\theta)$, X^2 for 3ν and 4ν hypotheses were then calculated by minimization over nuisance parameters

Confidence level for considered point was calculated using obtained ΔX^2 with Gaussian CLs method which is more conservative than usual CI method

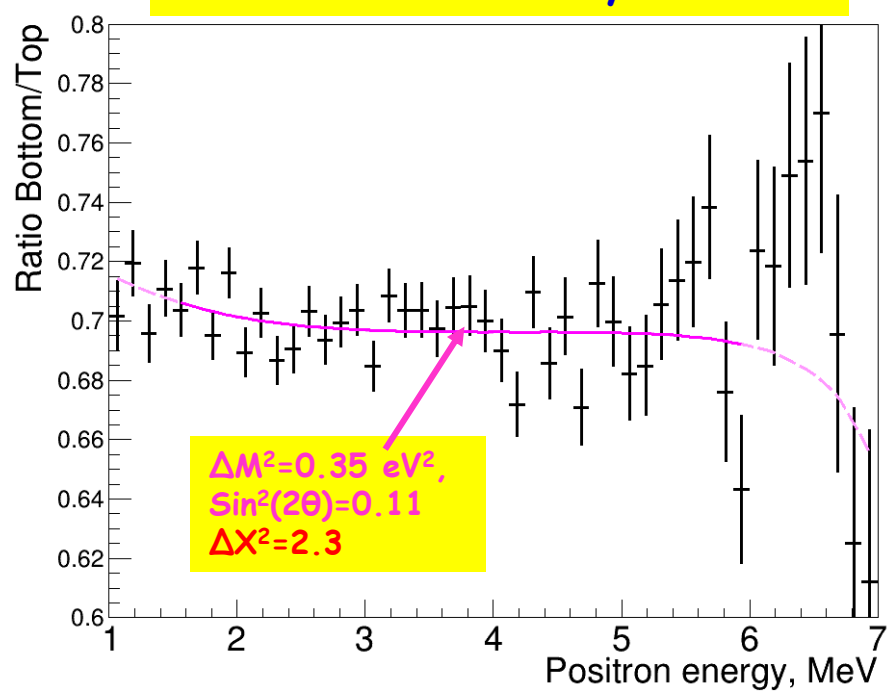
Data Analysis

- Obtained ratio of e+ spectra at 2 L for 2016-2017 data was not too smooth but still consistent with constant (p value = 0.05).
- ΔX^2 between best 4v and 3v hypotheses was 12.5 without systematic errors.
- There were several other points with small X^2 for 4v hypothesis
- This created a lot of excitement, although we clearly stated that significance of this difference would be calculated after collection of additional data
- For new data the largest ΔX^2 between 4v and 3v hypotheses is only 2.3 with systematic errors which include reduction of fit range to 1.5-6 MeV (such reduction of the fit range was used in published analysis as systematic)

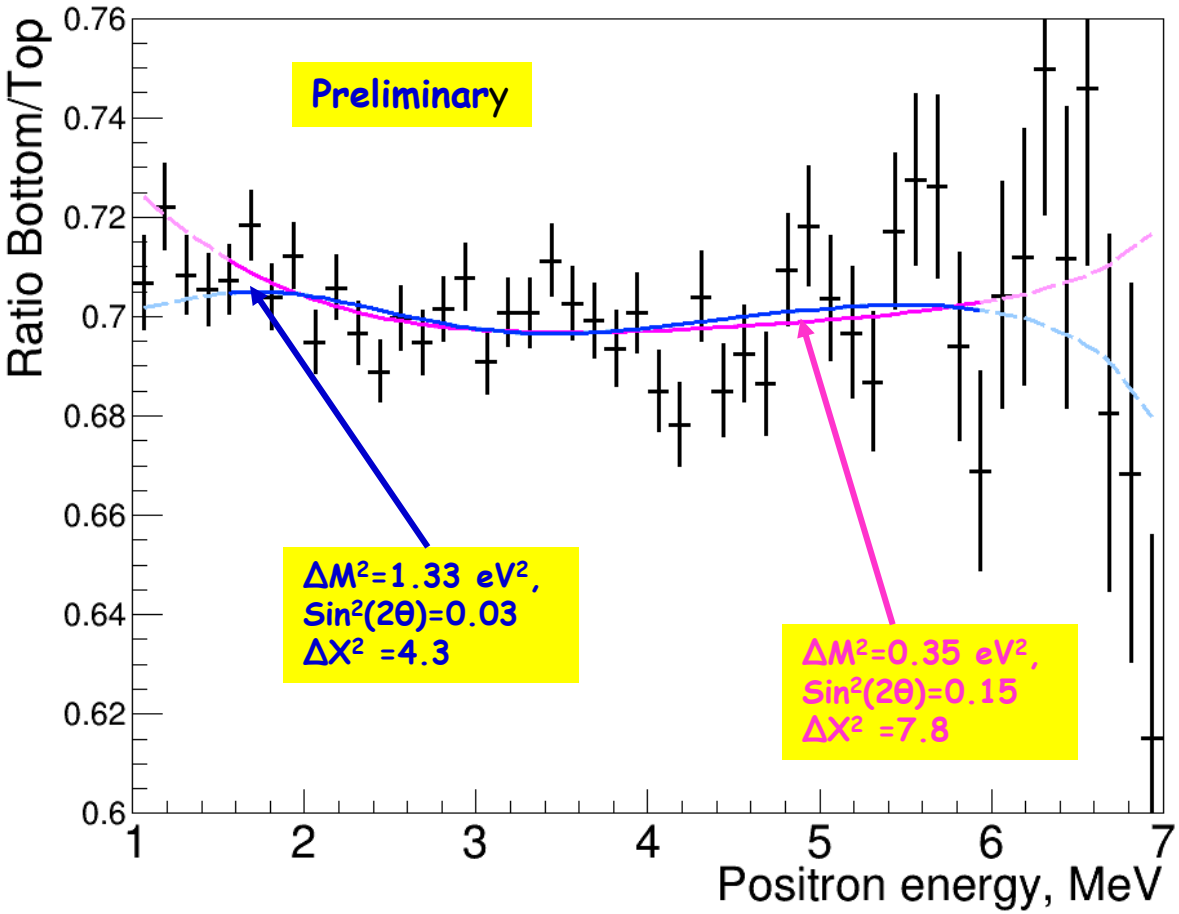
Old data; fits without systematics



New data; fit with systematics



Ratio of positron energy spectra at down and up detector positions (Full data set)



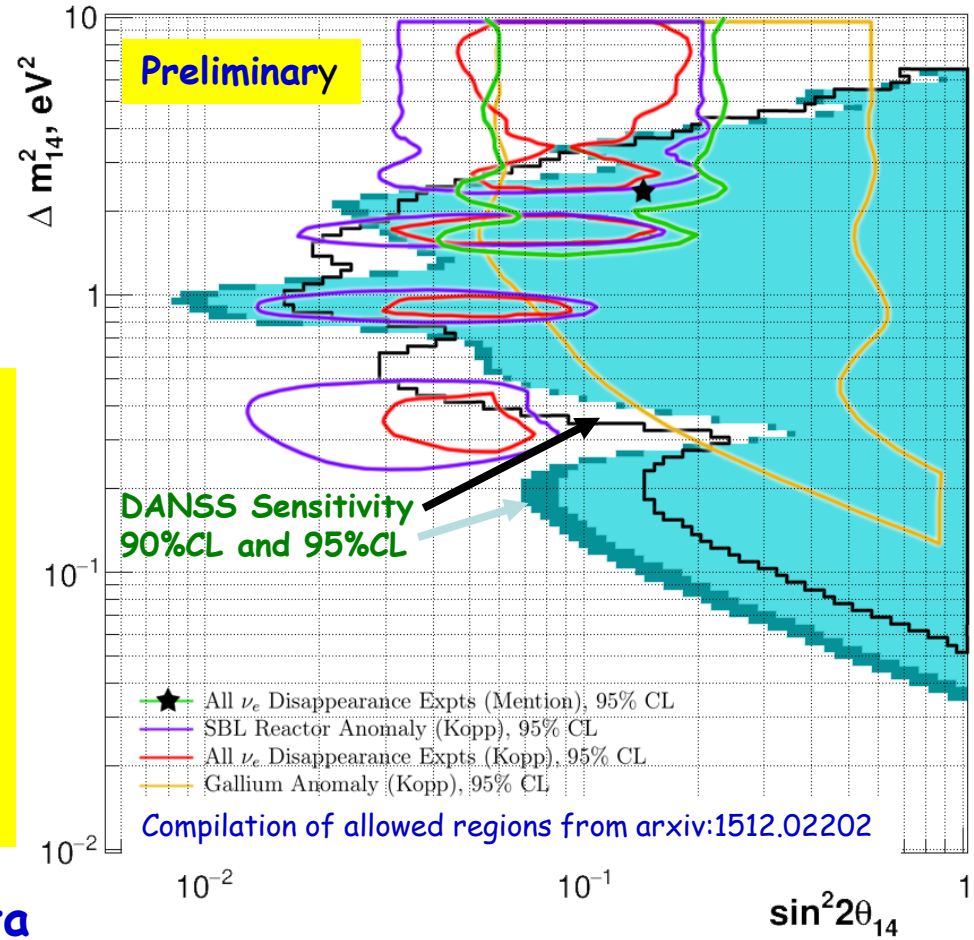
- The best 4v point (ΔM^2=0.35eV^2, $\sin^2(2\theta)$=0.15, ΔX^2 =7.8) has CL of 1.8σ.
- Best point in old data (ΔM^2=1.33 eV^2) is also shown

Results

Exclusion region was calculated using Gaussian CLs method
(X.Qian et al. NIMA, 827, 63 (2016))
using 1.5-6MeV e+ energy range only (to be conservative)
CLs method is also more conservative than usual Confidence Interval method

CLs is calculated with variations in:
-Energy resolution +/-10%
-Energy scale +/-2%
-Level of cosmic background +/-25%
-Level of flat background +/-30%
Systematics influence is small

New data allowed to extend the published DANSS excluded region (Phys.Lett. B787(2018)56)
A large fraction of allowed parameter space is excluded by DANSS results using only ratio of e+ spectrum at different L (independent on ν spectrum, detector efficiency,…)



-DANSS continues to collect more data
-Detector calibration and systematics studies will be continued

Summary

- With improved analysis DANSS records about 4 thousand antineutrino events per day with cosmic background ~1.9%.
- We doubled data set. New data have no sign of oscillations.
- During reactor shutdown DANSS counting rate is consistent with cosmic background after subtraction of 0.6% flux from adjacent reactors
- Antineutrino spectrum and counting rate dependence on fuel composition is clearly observed.
- Reactor power was measured using anti-ν rate with statistical error of ~1.5% in two days during > 1 year of operation
- Preliminary DANSS analysis based on 2 million IBD events excludes a large and the most interesting fraction of available parameter space for sterile neutrino using only ratio of e+ spectra at two distances (with no dependence on ν spectrum and detector efficiency!)

We plan:

To upgrade detector

To improve MC for perfect description of detector response

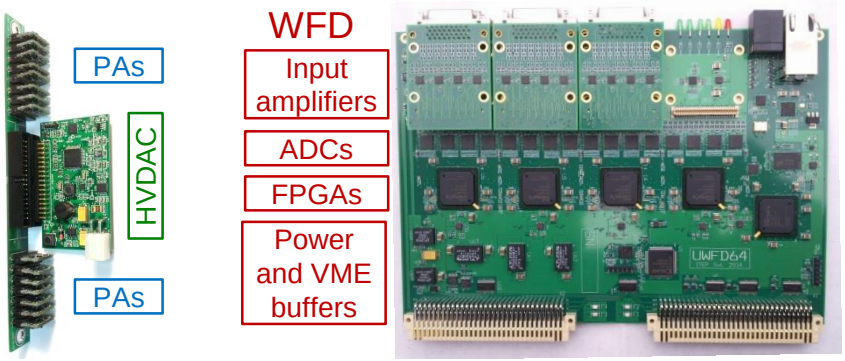
To refine detector calibration and energy scale determination

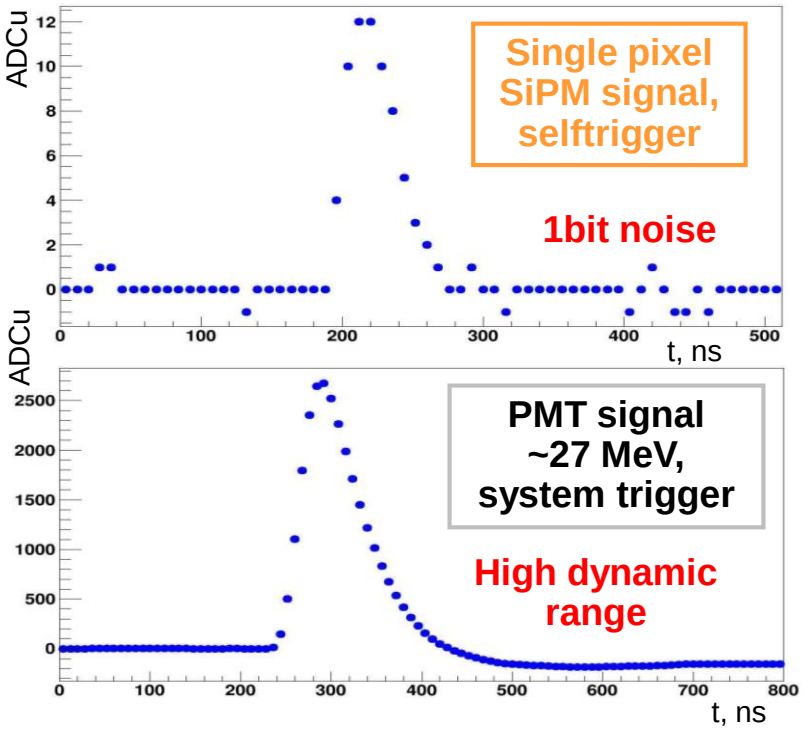
To compare e+ spectrum with theory

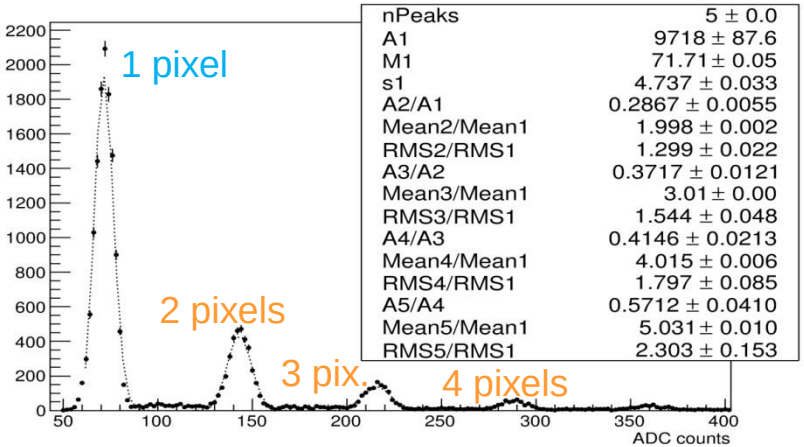
Thank you !

Backup slides

Data acquisition system



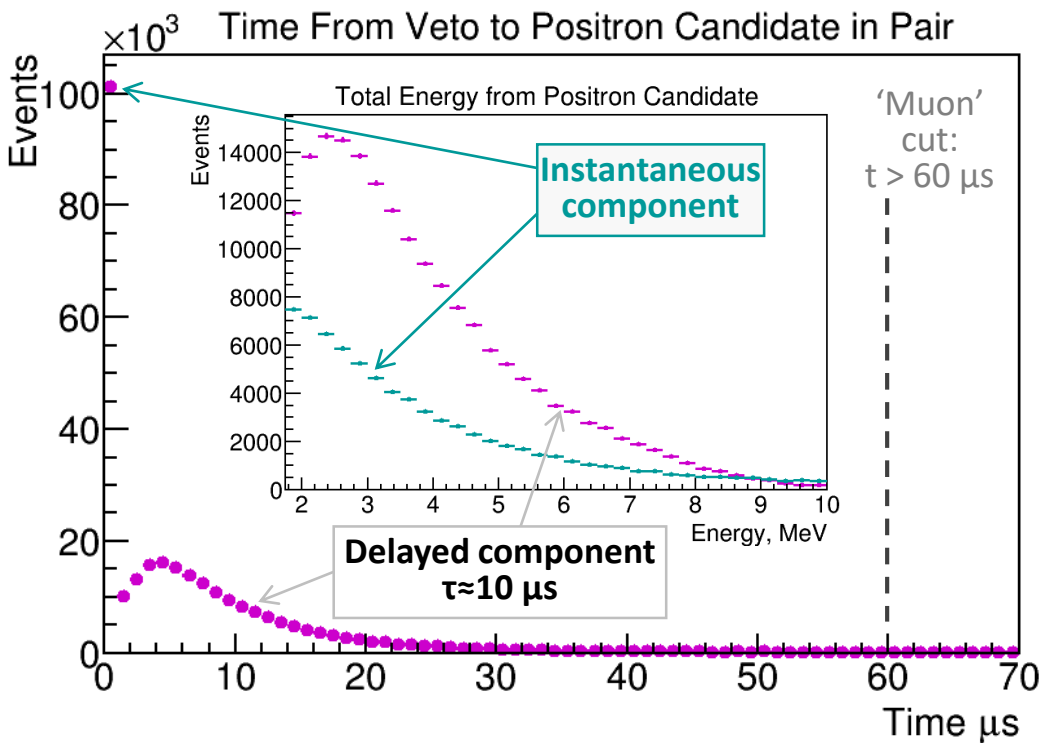




- Preamplifiers PA in groups of 15 and SiPM power supplies HVDAC for each group inside shielding, current and temperature sensing
- Total 46 Waveform Digitisers WFD in 4 VME crates on the platform
- WFD: 64 channels, 125 MHz, 12 bit dynamic range, signal sum and trigger generation and distribution (no additional hardware)
- 2 dedicated WFDs for PMTs and μ-veto for trigger production
- Each channel low threshold selftrigger on SiPM noise for gain calibration
- Exceptionally low analog noise ~1/12 p.e.

Event building and muon cuts

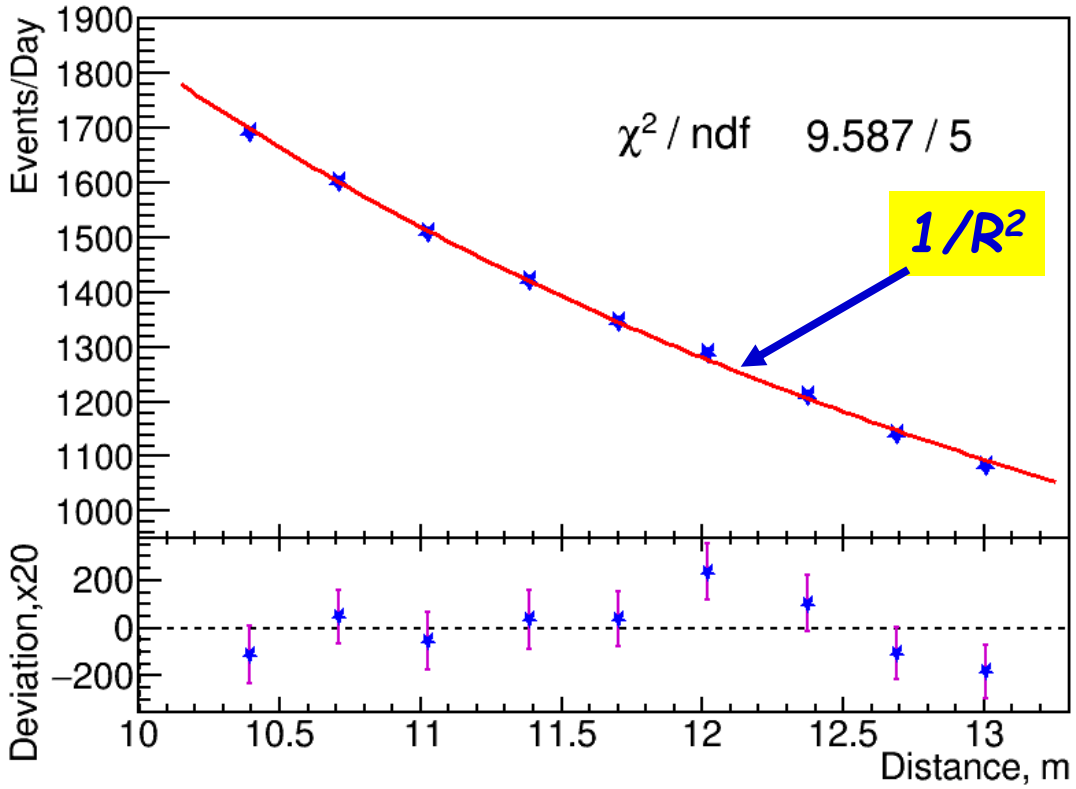
- **Building Pairs**
  - **Positron candidate: 1-20 MeV in continuous ionization cluster**
  - **Neutron candidate: 3.5-15 MeV total energy (PMT+SiPM), SiPM multiplicity >3**
  - **Search positron 50 μs backwards from neutron**



Muon Cuts

- **VETO 'OR':**
  - **2 hits in veto counters**
  - **veto energy >4MeV**
  - **energy in strips >20 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 60 μs before positron**
- **'Isolation' cut : NO any triggers 45 μs before and 80 μs after positron (except neutron)**
- **'Showering' cut : NO VETO with energy in strips >300 MeV 200 μs before positron**

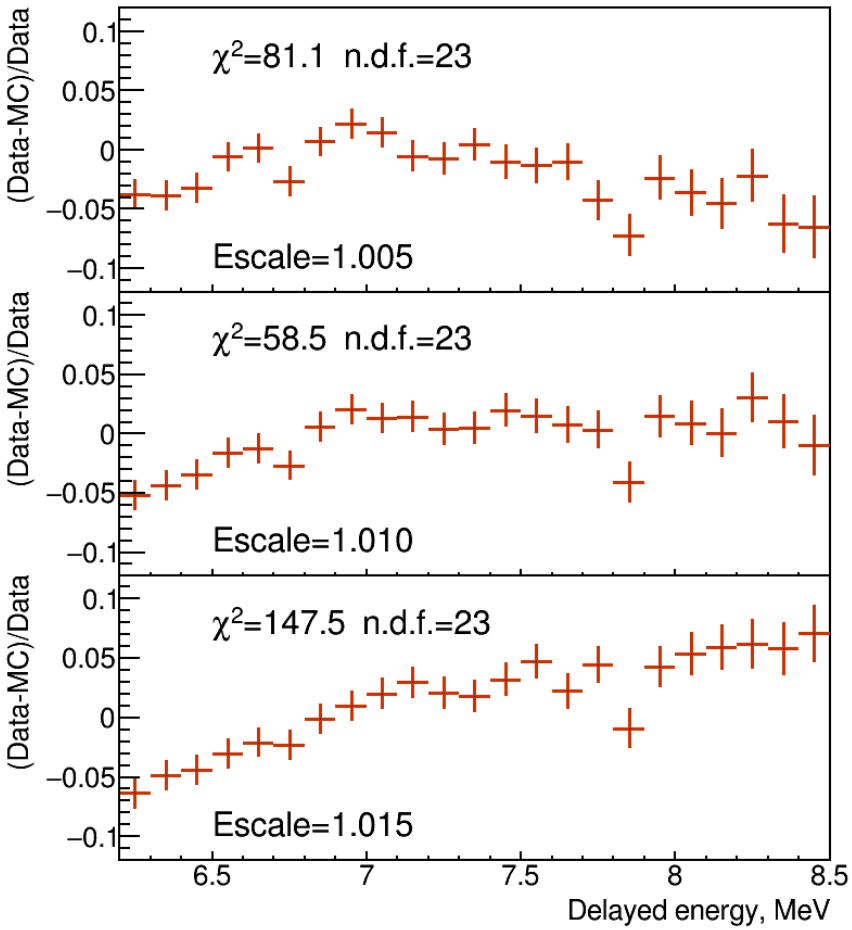
$\bar{\nu}$ counting rate dependence on distance from reactor core



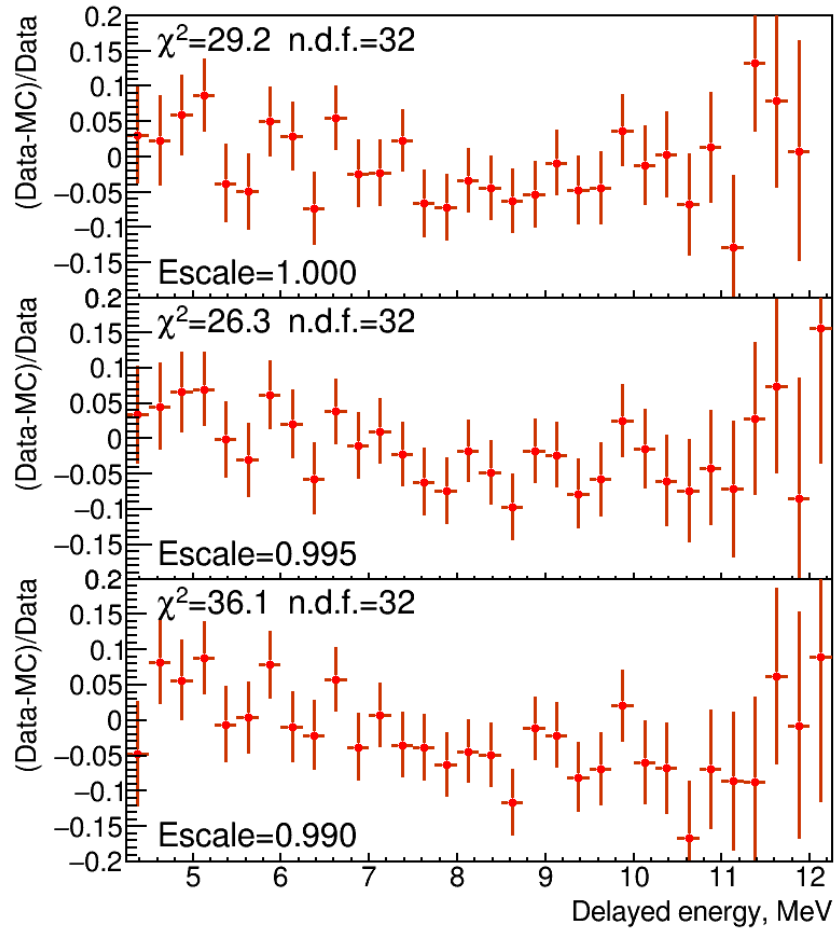
- **3 detector positions**
- **Detector divided vertically into 3 sections with individual acceptance normalization**

Rough agreement with $1/R^2$ dependence

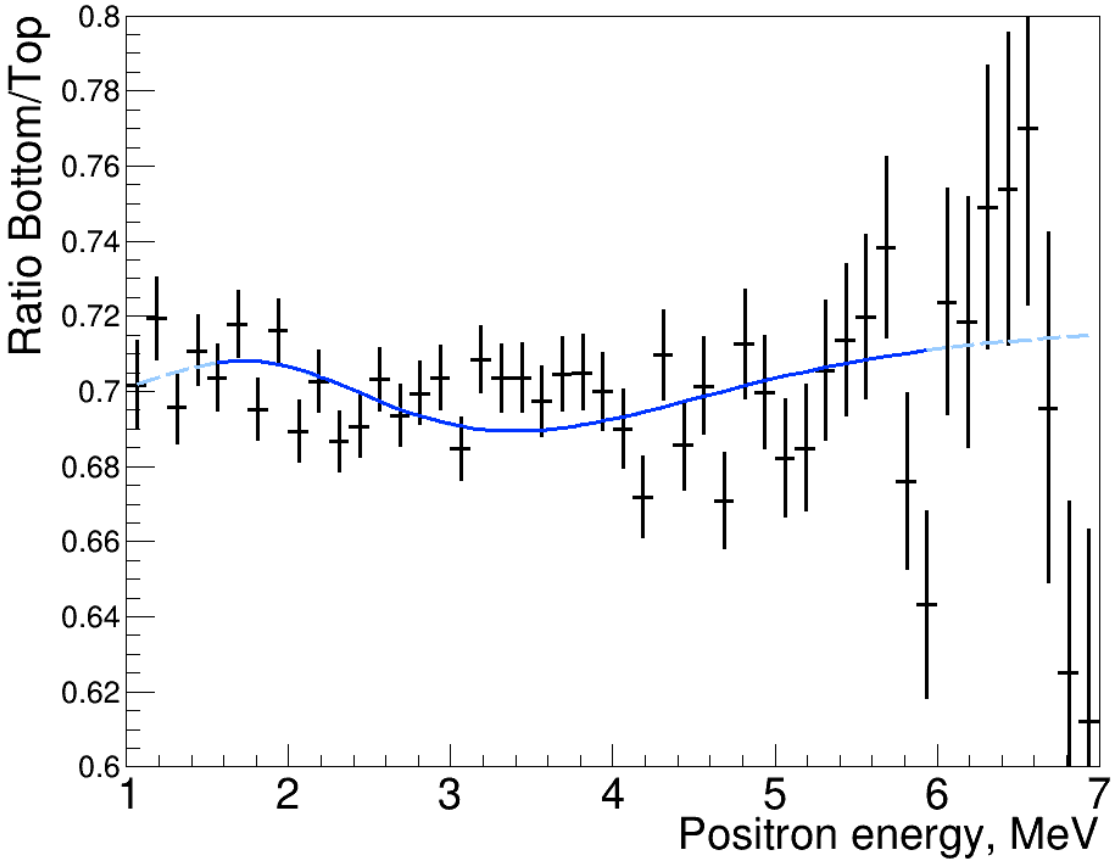
^{248}Cm: MC E shifted by 1%

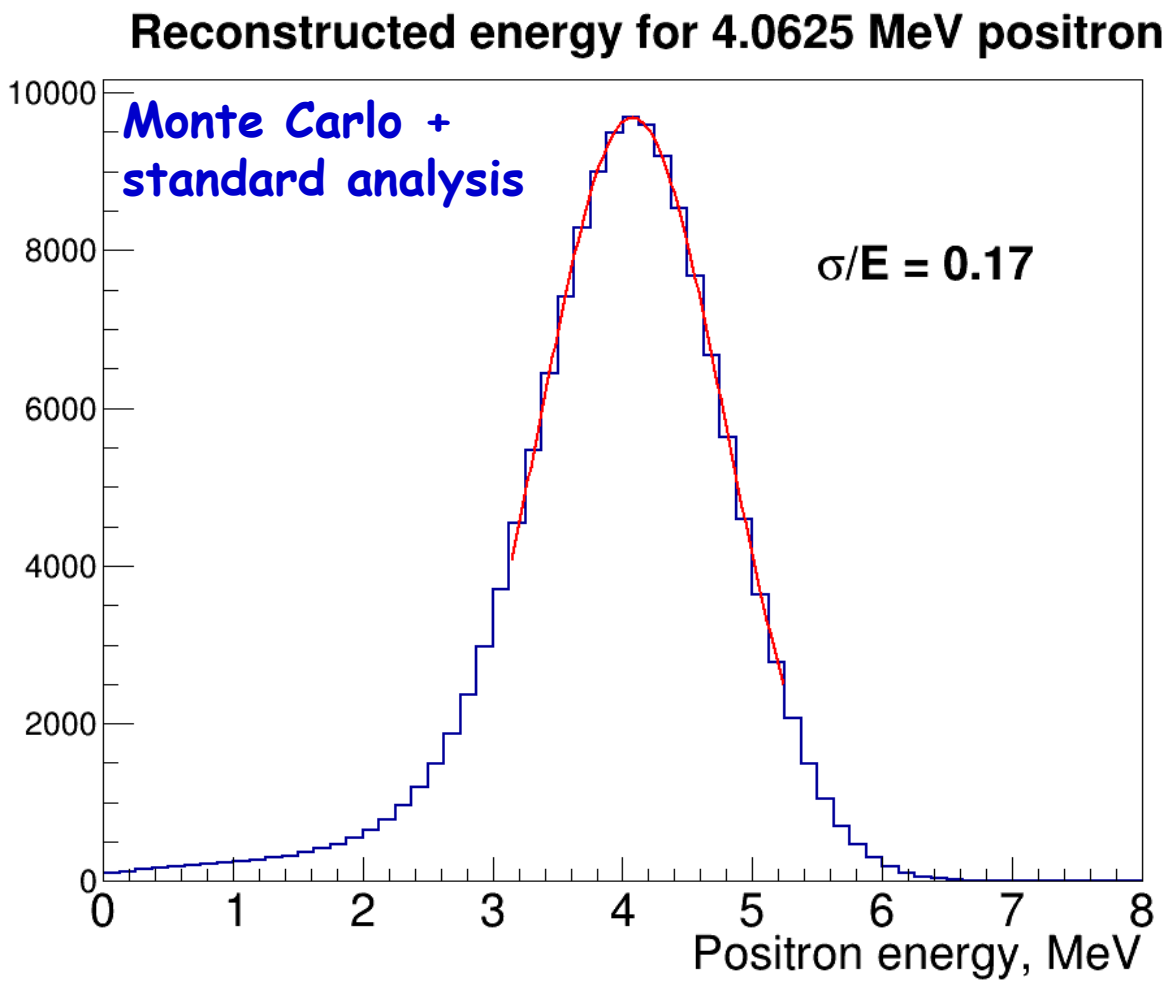


^{12}B: MC E shifted by -0.5%



Comparison of new data and the best fit in published data (fit without systematics)




Reconstructed energy for 4.0625 MeV positron
Monte Carlo +
standard analysis
σ/E = 0.17
10000
8000
6000
4000
2000
0
0
1
2
3
4
5
6
7
8
Positron energy, MeV

Reactor core burning profile averaged over campaign