New results from the DANSS experiment

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on behalf of the DANSS collaboration
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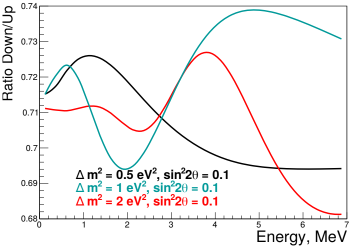
Motivation

- There are several indications in favor of existence of the 4th neutrino type — “sterile” neutrino
- Survival probability of a reactor $\tilde{\nu}_e$ at short distances in the (3+1) mixing scenario:

$$P = 1 - \sin^2 2\theta_{14} \sin^2 \left(\frac{1.27 \Delta m_{14}^2 [\mathrm{eV}^2] L[\mathrm{m}]}{E_\nu [\mathrm{MeV}]} \right)$$

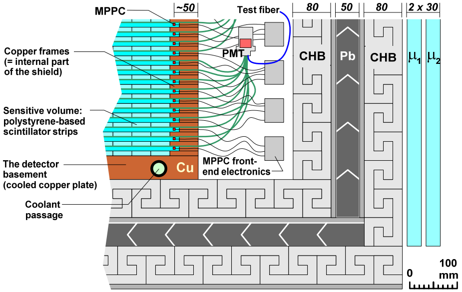
Expected $\Delta m^2 \sim 1 \ \mathrm{eV}^2$

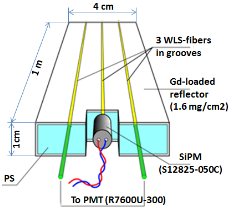
DANSS: Measure ratio of neutrino spectra at different distance from the reactor core — both spectra are measured in the same experiment with the same detector. No dependence on the theory, absolute detector efficiency or other experiments.

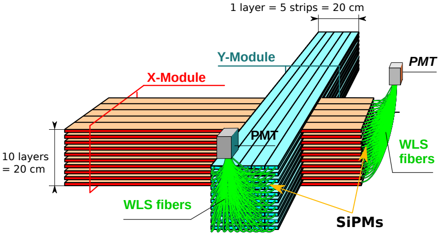


DANSS design [JINST 11 (2016) no.11, P11011]

- 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
- 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

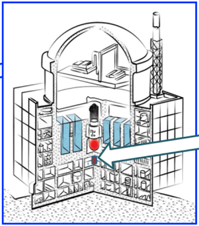




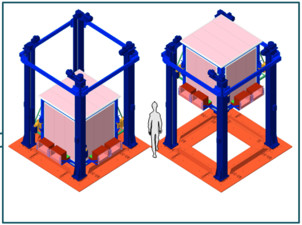


Detector site

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

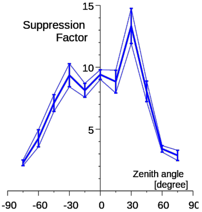


Below 3.1 GW commercial reactor ~ $5 \cdot 10^{13}$ $\nu \cdot cm^{-2} c^{-1}$ at detector position



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

- No flammable or dangerous materials – can be put just after reactor shielding
- 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 10.7 to 12.7 m on-line

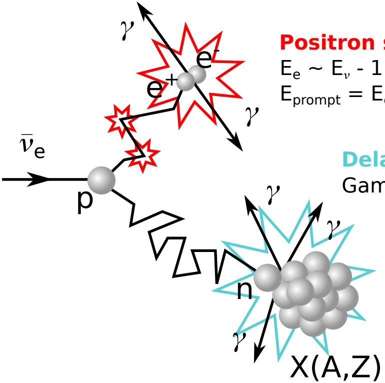


Cosmic muon suppression measured

Antineutrino registration

Inverse Beta-Decay (IBD) reaction:

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



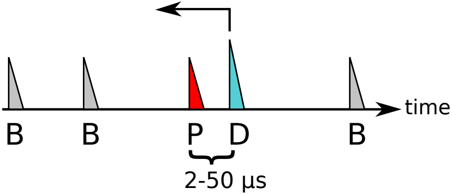
Positron signal

$E_e \sim E_\nu$ - 1.806 MeV

$E_{prompt} = E_e + E_{2\gamma}$

Delayed signal

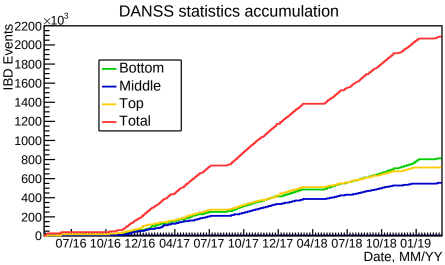
Gamma flush in the whole detector



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

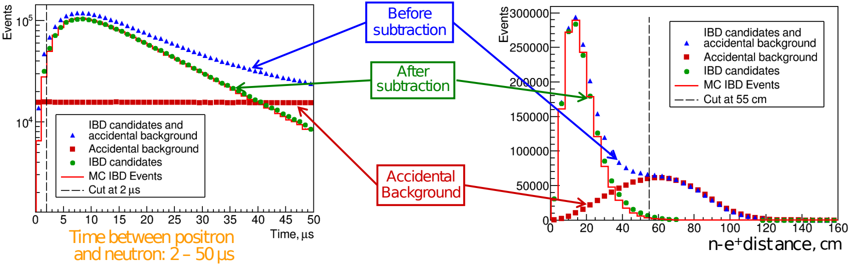
- Improvement in signal processing (use of SiPM and PMT signal shapes for T_0 and charge determination) and MC simulations (signal WF simulations, taking into account Birks effect and Cherenkov radiation).
- Cut modification (requirement for PMT-SiPM coincidences to suppress noise, requirement of annihilation photons for 1strip positron clusters to reduce accidental/neutron background for low energy positrons).
- More frequent energy calibrations (gain – each 15min, MIP – each 2 days).
- Usage of ^{12}B spectrum for energy scale calibration.
- Two lowest detector layers added to the VETO system.
- A bug in oscillation pattern numbering was corrected $\rightarrow$ tiny shifts in excluded regions.
- Four times finer grid of points on the $(\Delta m^2, \sin^2 2\theta)$ phase space.
- Increase of statistics from 966 thousand to 2.1 million IBD events.

Results of improvements



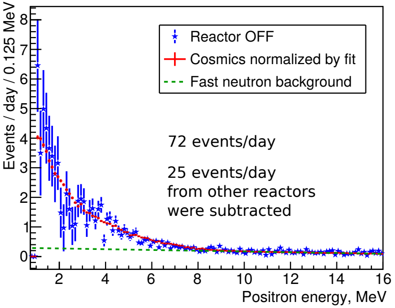
- Accidental energy in event is reduced from 100 keV to 5 keV
- Accidental background is reduced from 71% to 29% (up position)
- Cosmic background is reduced from 2.8% to 1.9%
- Energy resolution for calibration sources is still worse than in MC $\rightarrow$ additional smearing of $17\%/\sqrt{E}$ is 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 E_{e^+} without annihilation gammas!)
  We still assume $\pm$ 2% systematic uncertainty in the energy scale.
- Sensitivity of experiment is improved by a factor of ~ 1.4

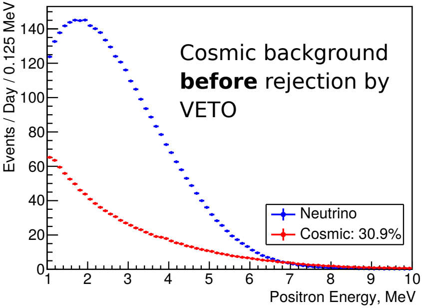
Accidental coincidence background



- 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

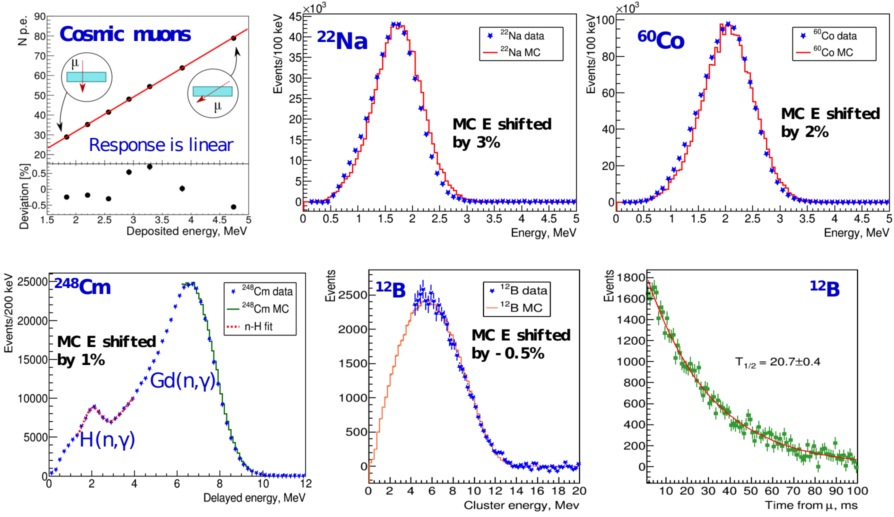
Cosmic background





- Fast neutron tails: linearly extrapolate from high energy region and subtract separately from positron and visible (i.e. rejected by VETO) cosmic spectra
- 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 $\sim$ 1.9% of neutrino signal, subtracted
- Final anti-neutrino spectrum (E_{e^+} + 1.8 MeV) has NO background!

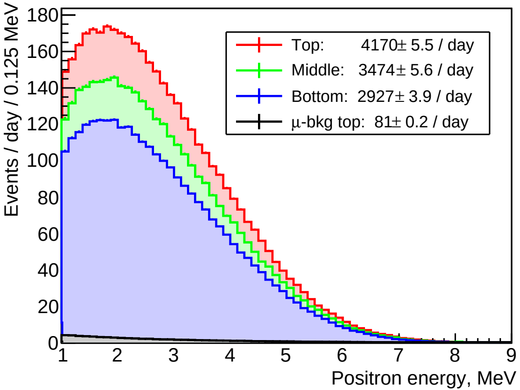
Calibration



E scale is based on ^{12}B signal which is similar to e^+ signal (we measure E_{e^+}, not E_{prompt})

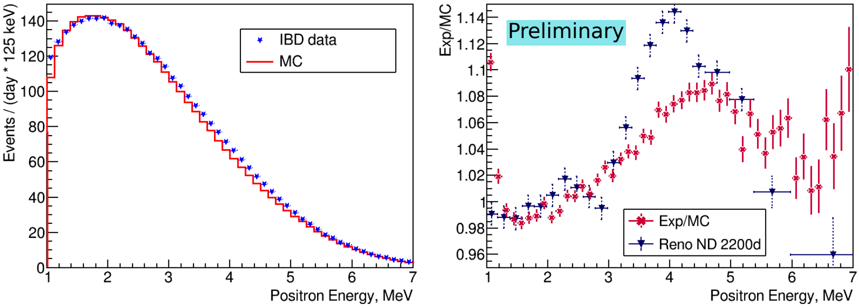
Systematic error on E scale of $\pm 2\%$ added to take into account shifts in source responses

Positron spectrum



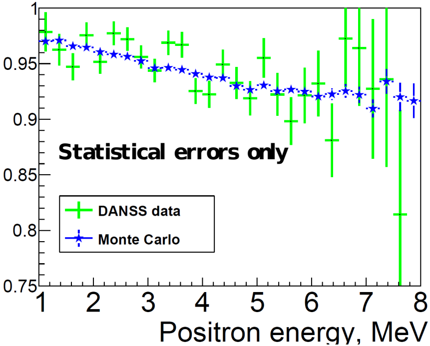
- 3 detector positions
- Pure positron kinetic energy (annihilation photons not included)
- More than 4000 neutrino events/day in detector fiducial volume of 78% (‘Up’ position closest to the reactor)
- μ - induced neutron background not rejected by VETO system is 1.9% only

Positron energy spectrum and H-M MC predictions



- Experimental spectrum is in rough agreement with MC using Huber-Muller theoretical neutrino spectrum.
- Indication of a bump (normalization in 1.5-3 MeV), but no conclusion on the bump existence now due to strong sensitivity to energy scale.
- More work on calibration is needed before quantitative comparison.

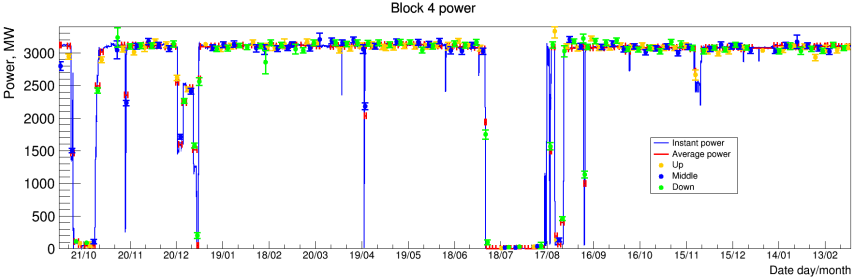
Spectrum evolution



	end	start
^{235}U	45.8%	61.7%
^{238}U	7.7%	7.1%
^{239}Pu	38.3%	28.0%
^{241}Pu	7.9%	3.1%

- Ratio of positron energy spectra collected during the last 4 months of the reactor campaign and during the $2^{nd} - 5^{th}$ months from the beginning of the next campaign
- Clear evidence for spectrum evolution, which is consistent with MC
- Not all data and old analysis. More work is needed for absolute efficiency calibration of new data (canceled in oscillation analysis)

Comparison of reactor power and DANSS rate

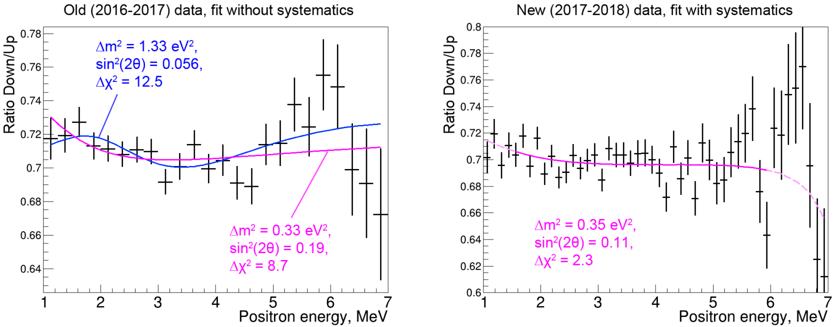


- Points at different positions equalized by $1/r^2$
- Normalization by 12 points in November-December 2016
- Adjacent reactor fluxes subtracted (0.6% at Up position)
- Spectrum dependence on fuel composition is included
- Reactor power is measured with $\tilde{\nu}_e$ flux with 1.5% accuracy in 2 days 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)

Oscillation analysis

- For a grid of points (Δm^2, $\sin^2 2\theta$) positron spectrum is calculated for Up and Down positions taking into account reactor core size and detector energy response.
- Reactor burning profile was provided by KNPP.
- Energy response (including tails) was obtained from cosmic muon calibration and GEANT-4 MC simulation analyzed identically to data analysis.
- Ratio Down/Up spectra was calculated and compared with experiment (independent on $\tilde{\nu_e}$ 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 $\sin^2 2\theta$, χ^2 for 3ν and 4ν hypotheses was calculated by minimization over nuisance parameters.
- Exclusion region was calculated using Gaussian CL_s method.

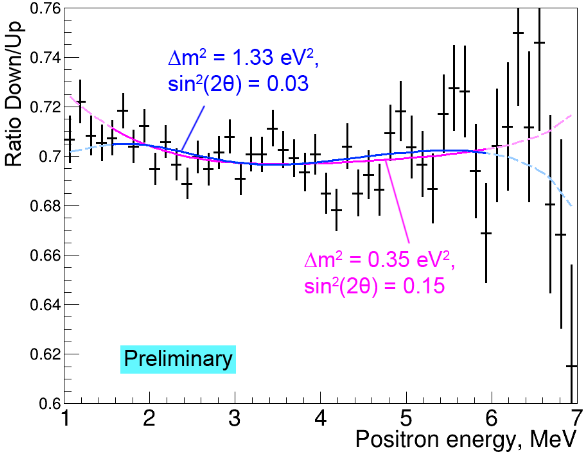
Oscillation analysis



- Obtained ratio of e^+ spectra at 2 distances for 2016-2017 data was not too smooth but still consistent with constant
- $\Delta\chi^2$ between best 3ν and 4ν hypotheses was 12.5 without systematic errors.
- There were several other points with small χ^2 for 4ν 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 $\Delta\chi^2$ between 3ν and 4ν 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)

Ratio Down/Up (full dataset)

- The best 4ν point $(\Delta m^2 = 0.35\ \text{eV},\ \sin^2 2\theta = 0.15,\ \Delta\chi^2 = 7.8)$ has CL of 1.8σ.
- Best point in the published analysis $(\Delta m^2 = 1.33\ \text{eV})$ in the full dataset has $\sin^2 2\theta = 0.03,\ \Delta\chi^2 = 4.3$



Preliminary results

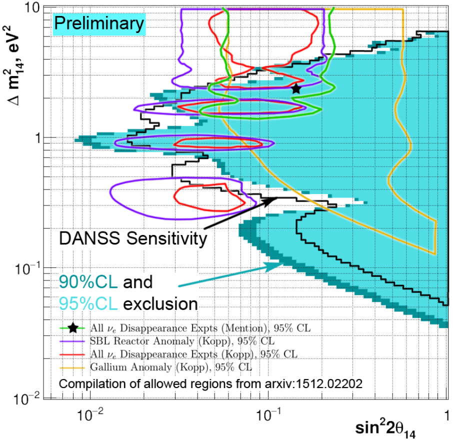
Exclusion region was calculated using Gaussian CL_s method (X.Qian et al. NIMA, 827, 63 (2016)) using fit 1.5-6 MeV interval (to be conservative)
CL_s method is more conservative than usual Confidence Interval method

Systematics include variations in:

- Energy resolution $\pm 10\%$
- Level of cosmics background $\pm 25\%$
- Level of flat background $\pm 30\%$
- Energy scale $\pm 2\%$

Systematics is small
A large fraction of allowed parameter region is excluded by DANSS results using only ratio of e^+ spectrum at different L (independent on $\tilde{\nu}_e$ spectrum, detector efficiency,. . .)

- DANSS plans 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 $\sim$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% fluxfrom adjacent reactors
- Antineutrino spectrum and counting rate dependence on fuel composition is clearly observed.
- Reactor power was measured using antineutrino rate with statistical error of 1.5% in two days during $>$ 1 year of operation
- Preliminary DANSS analysis based on 2.1 million IBD events excludes a large and the most interesting fraction of available parameter space for sterile neutrino using only ratio of positron spectra at two distances (with no dependence on antineutrino 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

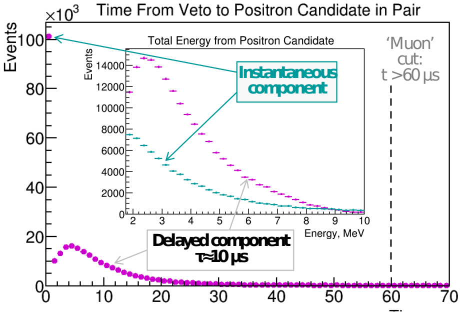
Thank you!

Event building

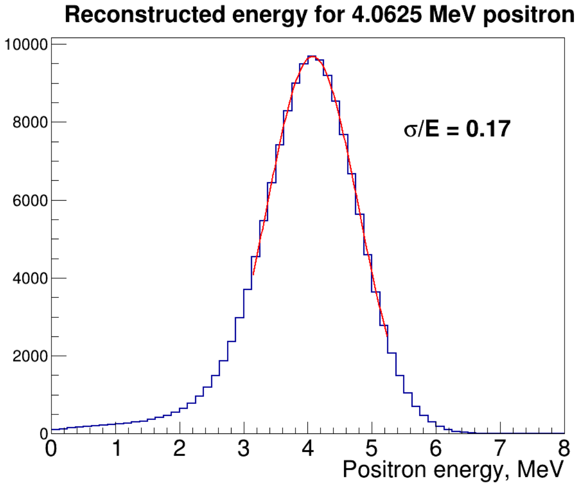
- Neutron candidate: 3.5-15 MeV total energy (PMT+SiPM), SiPM multiplicity > 3
- Search positron 50 μs backwards from neutron
- Positron candidate: 1-20 MeV in continuous ionization cluster
- No other signals in the vicinity of IBD signal

Muon cuts

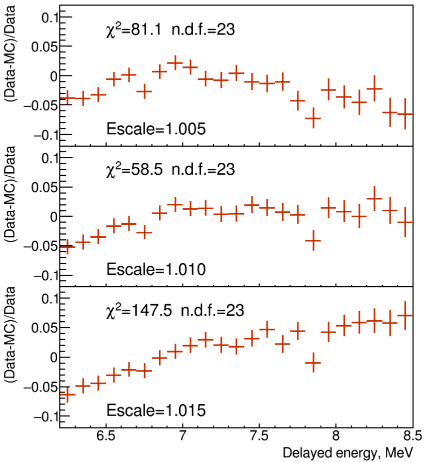
- VETO 'OR':
  - 2 hits in veto counters
  - veto energy > 4MeV
  - energy in strips > 20 MeV
- Two distinct components of muon induced paired events with different spectra:
  - 'Instantaneous' – fast neutron
  - 'Delayed' – two neutrons from excited nucleus
- 'Muon' cut : NO VETO 60 μs before positron
- '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

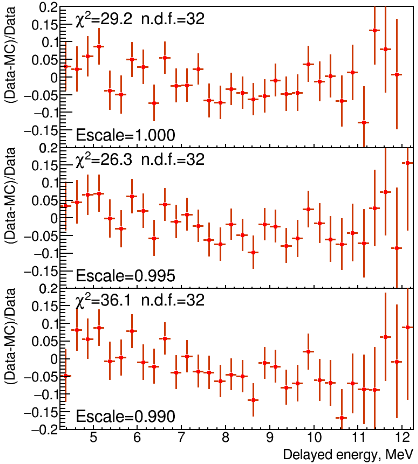


Energy resolution



Additional smearing has been added to MC





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

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

Fuel

	begin 4	end 4	begin 5
^{235}U	63.7%	44.7%	66.1%
^{238}U	6.8%	6.5%	6.7%
^{239}Pu	26.6%	38.9%	24.9%
^{241}Pu	2.8%	8.5%	2.3%

core: $h = 3.7$ m, $d = 3.2$ m