

Solvay Workshop
ULB Bruxelles
December 1st 2017



**Search for sterile neutrinos at the
DANSS experiment**

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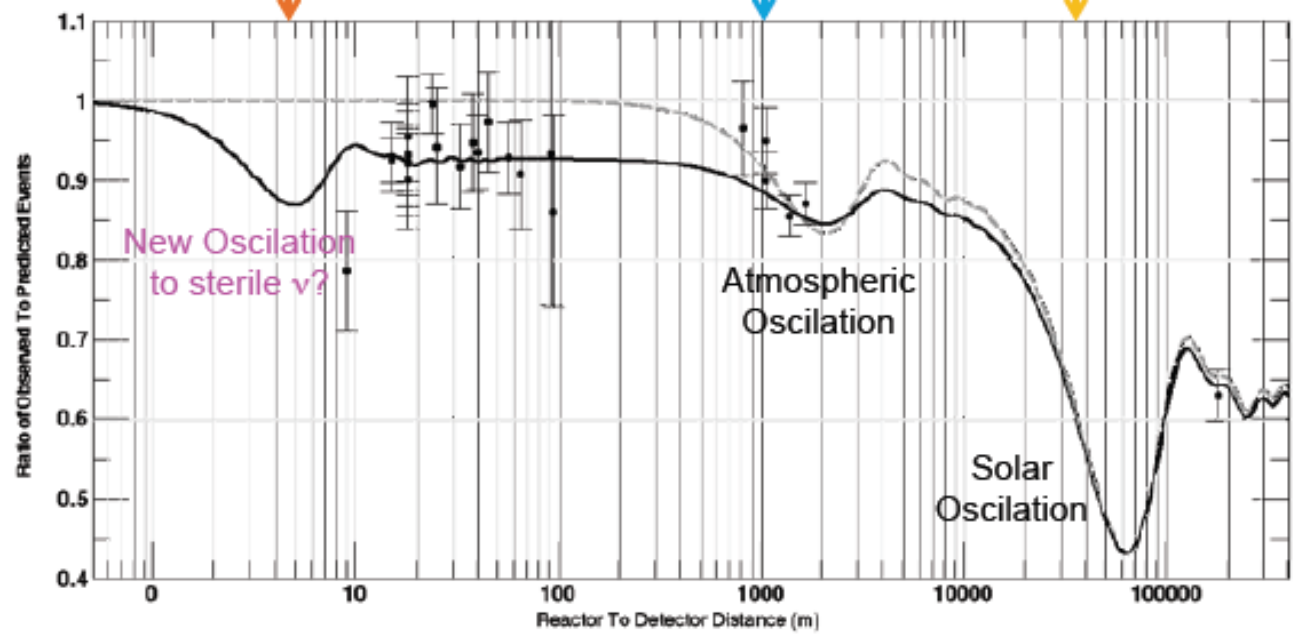
There are several $\sim 3\sigma$ indications of 4th neutrino

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



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

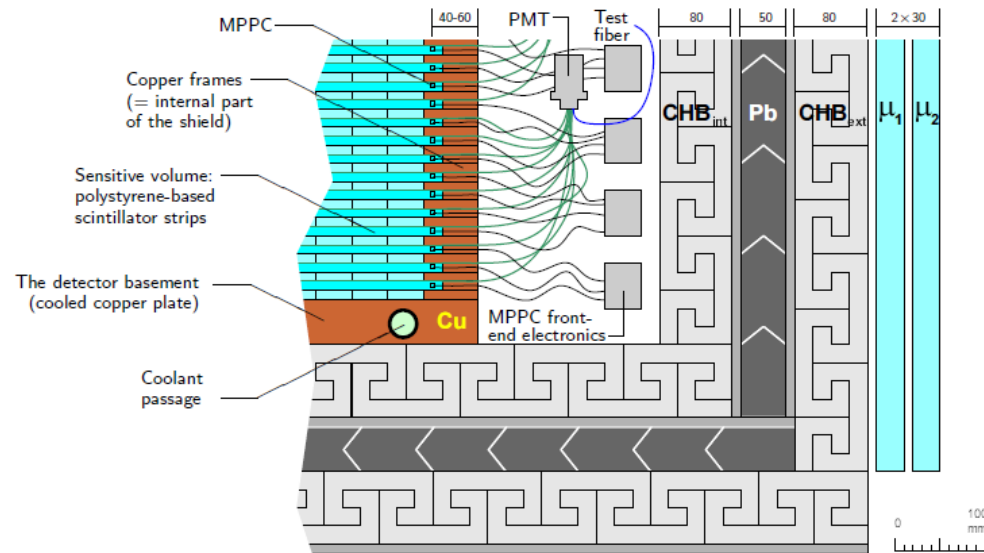
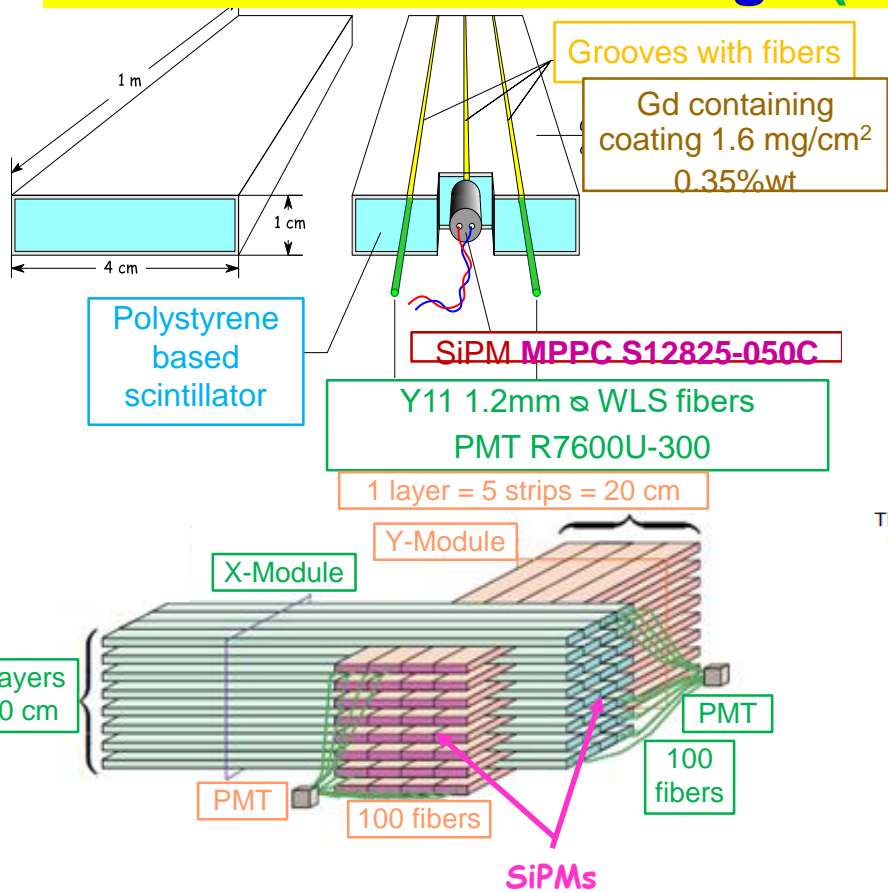
$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \boxed{\sin^2 2\theta_{14} \sin^2 \left(1.27 \Delta m_{41}^2 \frac{L}{E} \right)} - \boxed{c_{14}^4 \sin^2 2\theta_{13} \sin^2 \left(1.27 \Delta m_{31}^2 \frac{L}{E} \right)} - \boxed{c_{14}^4 c_{13}^4 \sin^2 2\theta_{12} \sin^2 \left(1.27 \Delta m_{21}^2 \frac{L}{E} \right)}$$



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!

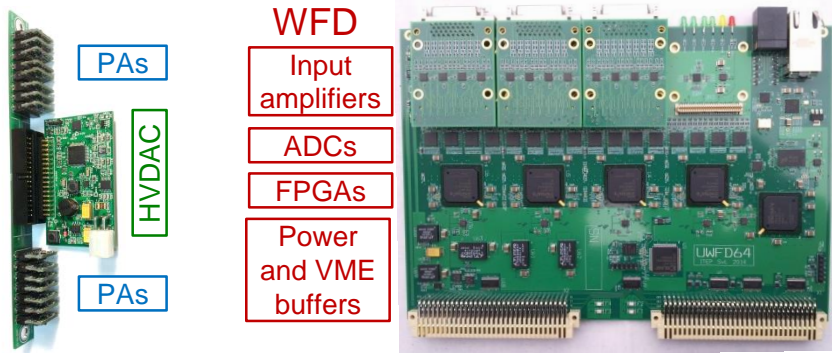
DANSS Detector design (ITEP-JINR Collaboration)



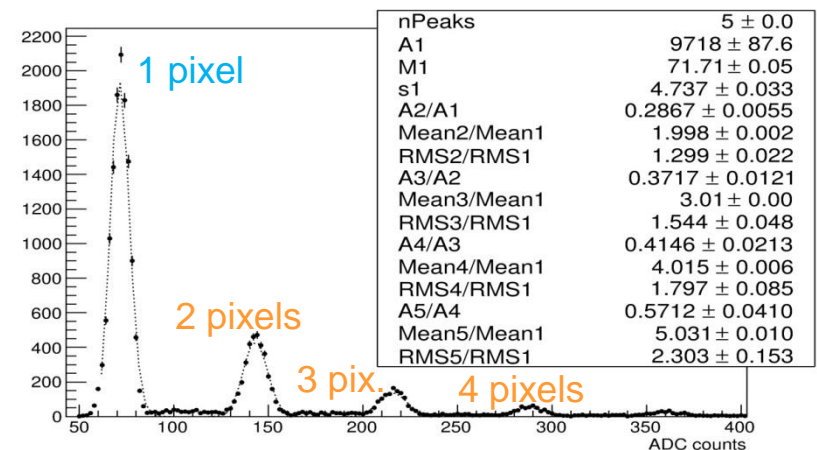
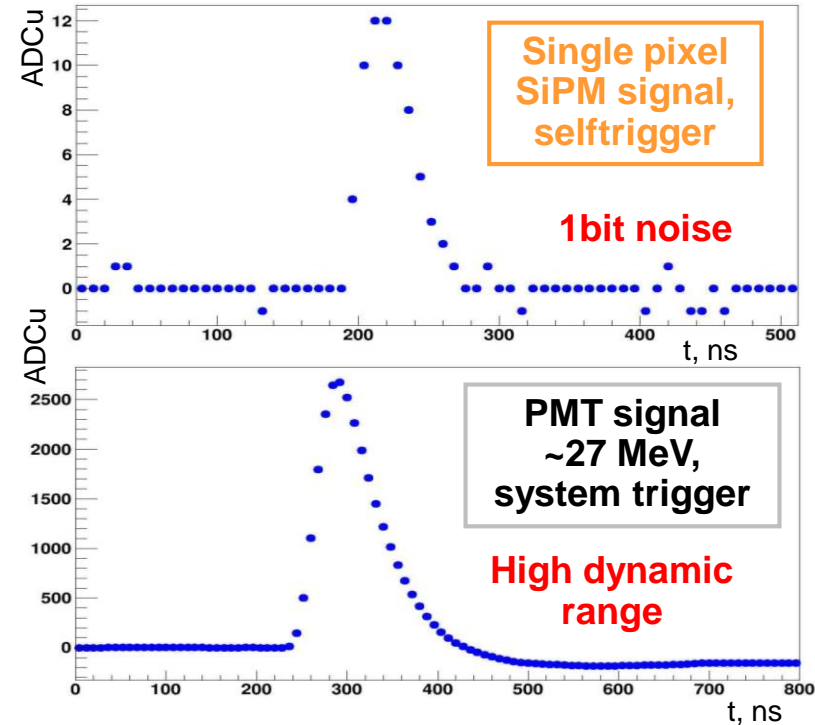
- 2500 scintillator strips with Gd containing coating for neutron capture
- Light collection with 3 WLS fibers
- Central fiber read out with individual SiPM
- Side fibers from 50 strips make a bunch of 100 on a PMT cathode = Module

- 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

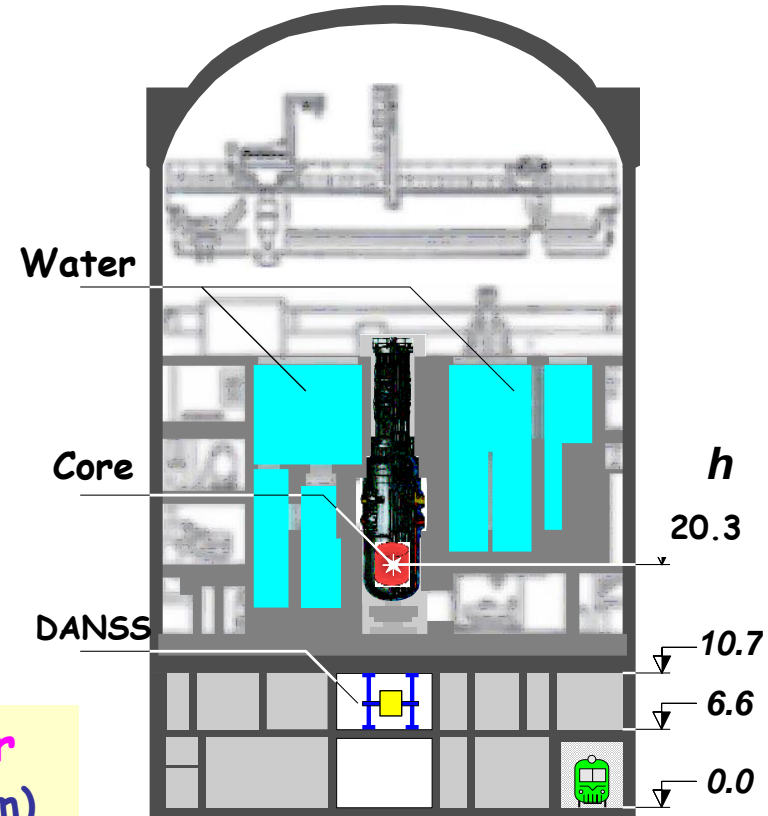
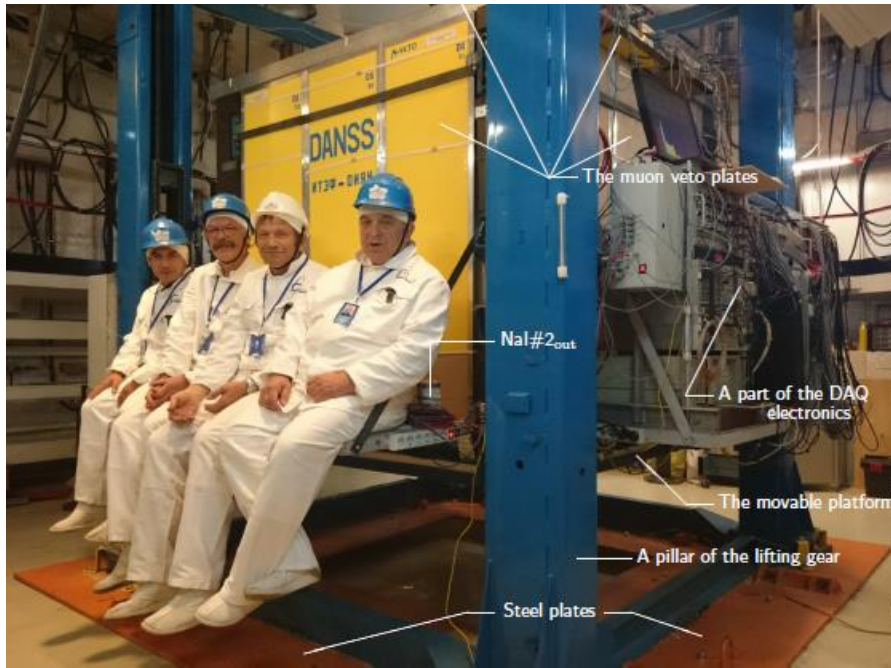
Data acquisition system



- 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 $\sim 1/12$ p.e.



DANSS at Kalinin Nuclear Power Plant



DANSS is installed on a movable platform **under** 3GW WWER-1000 reactor (Core:h=3.7m, Ø=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: $\Sigma E(\text{PMT}) > 0.7 \text{ MeV} \Rightarrow$ Read 2600 wave forms (125MHz), look for correlated pairs offline.

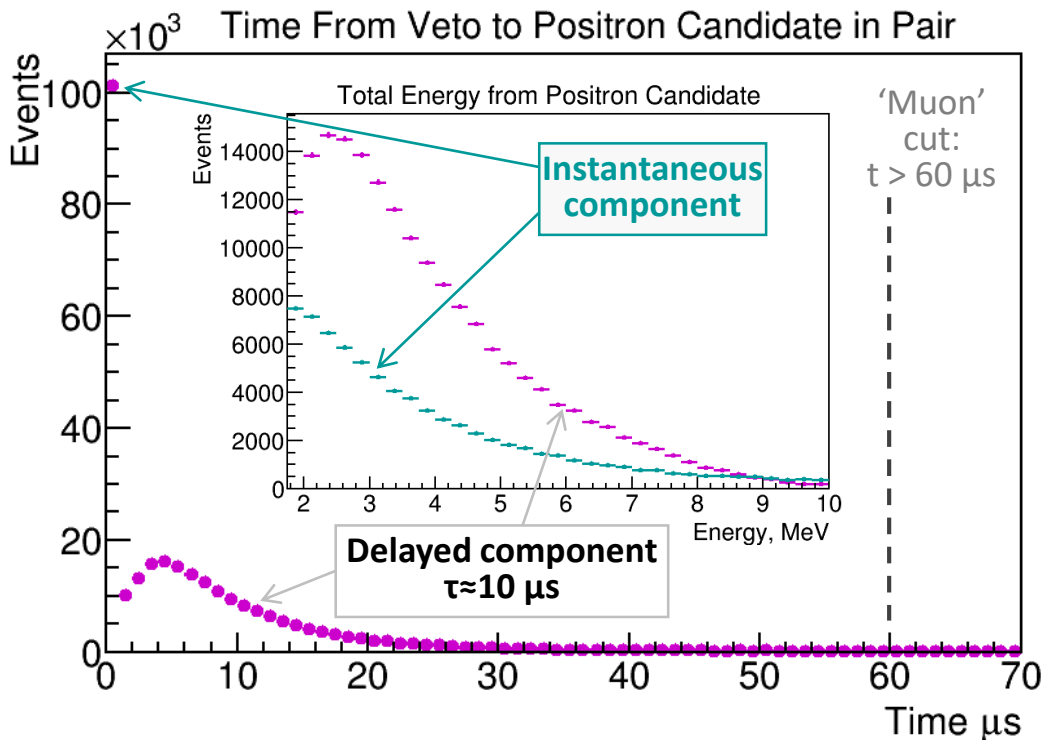
Fuel contribution to ν flux at beginning and end of campaign

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

Event building and muon cuts

Building Pairs

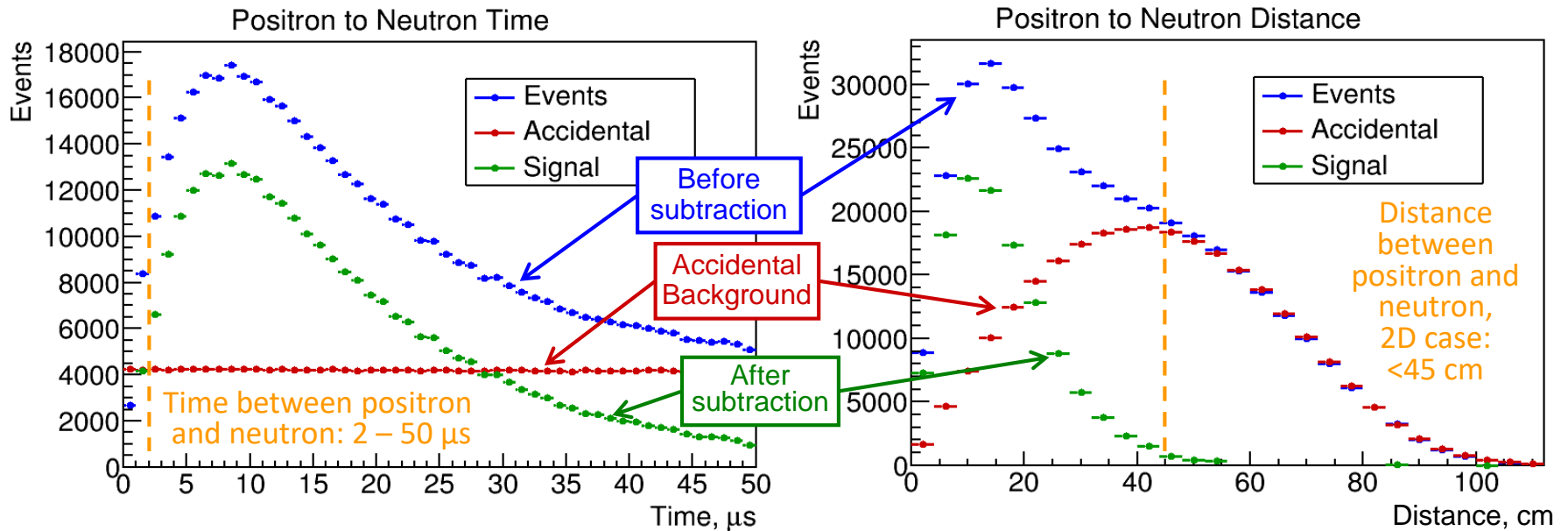
- Positron candidate: 1-20 MeV in continuous ionization cluster
- Neutron candidate: 3-15 MeV total energy (PMT+SiPM), SiPM multiplicity >3
- Search positron 50 μ s backwards from neutron



Muon Cuts

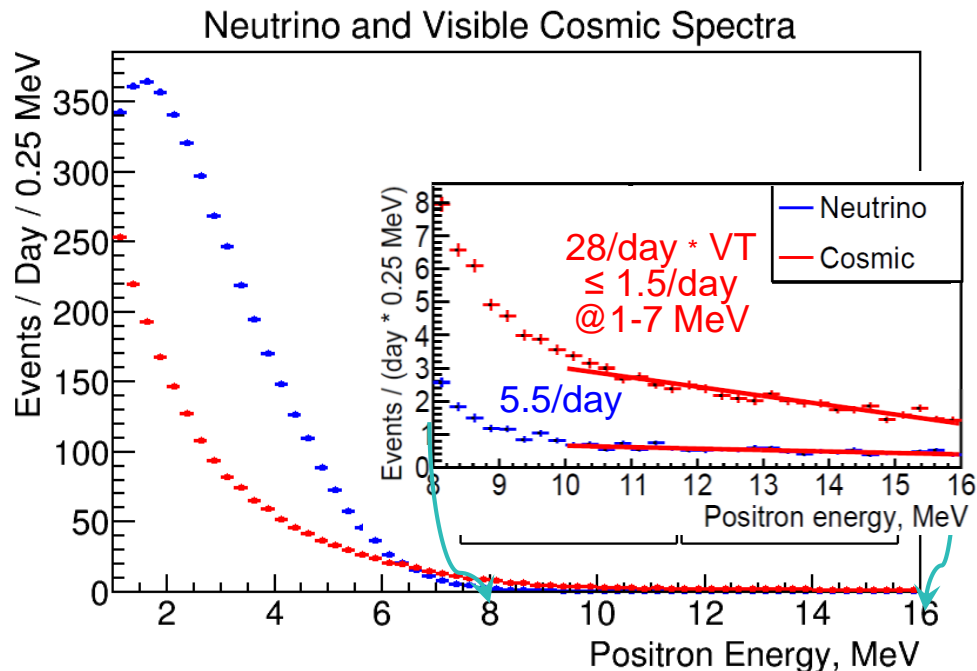
- VETO 'OR':
 - 2 hits in veto counters
 - veto energy >4MeV
 - energy in strips >20 MeV
- Two distinct components of muon induced paired events with different spectra:
 - 'Instantaneous' – fast neutron
 - 'Delayed' – two neutrons from excited nucleus
- 'Muon' cut : NO VETO 60 μ s before positron
- 'Isolation' cut : NO any triggers 45 μ s before and 80 μ s after positron (except neutron)
- 'Showering' cut : NO VETO with energy in strips >300 MeV 200 μ s before positron

Accidental coincidence background

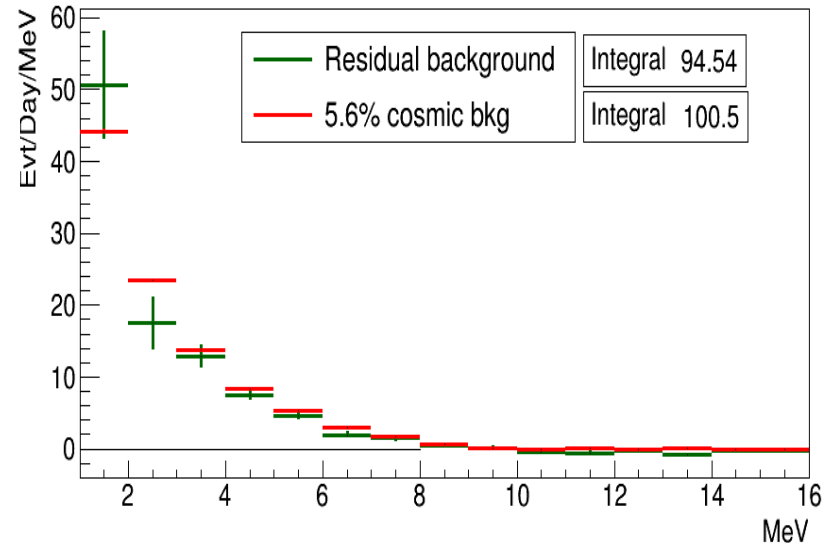


- Fake one of the IBD products by uncorrelated triggers
- Background events from data: search for a positron candidate where it can not be present – 50 μs intervals far away from neutron candidate (5, 10, 15 etc millisecc)
- Enlarge statistics for accidentals by searches in numerous non-overlapping intervals
- Accidentals rate is smaller but comparable to that of the IBD events
- Mathematically strict procedure, does not increase statistical error
- Cuts for the accidental coincidence exactly the same as for physics events
- Optimization of cuts to reduce accidental contribution => smaller statistical error

Residual background subtraction

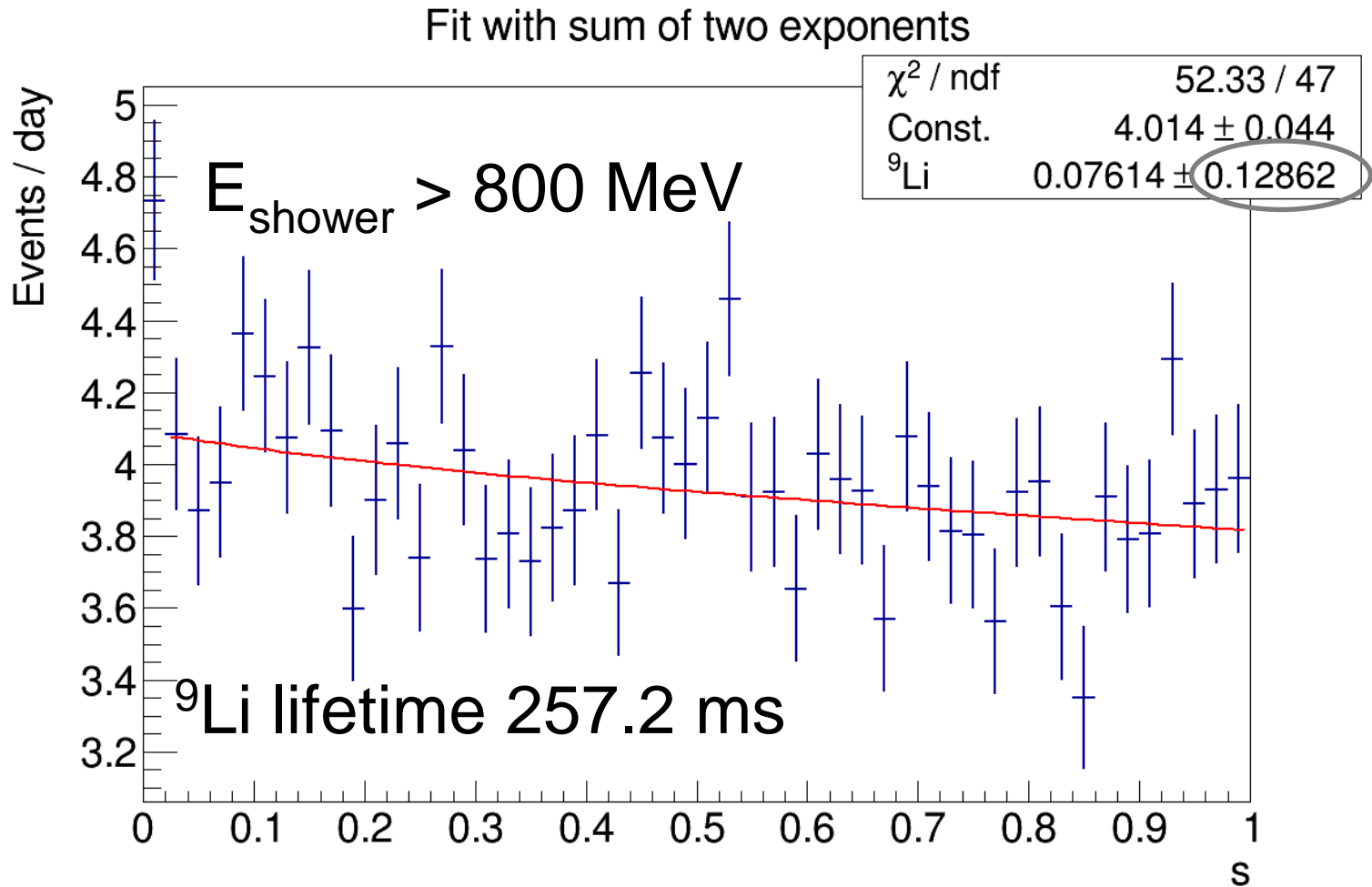


Reactor OFF Background Spectrum and old Fit of Cosmic Fraction



- **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 <50% of neutrino signal**
- **VETO inefficiency :**
 - **2.5% from muon count in sensitive volume, missed by VETO - underestimate**
 - **5.6% from 'reactor OFF' spectra.**
- **Not vetoed cosmic background fraction < 3% of neutrino signal, subtracted**
- **Final neutrino spectrum (Ee+ + 1.8 MeV) has No background!**

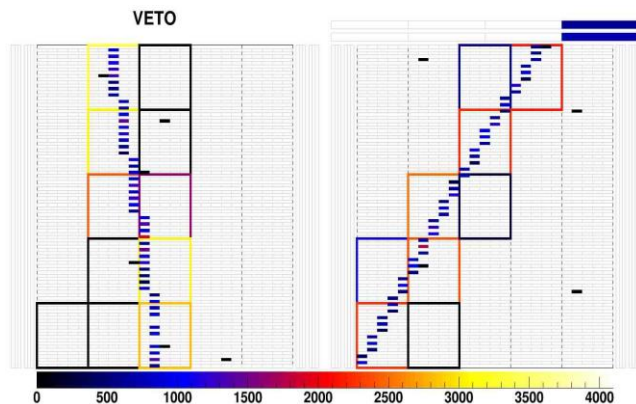
${}^9\text{Li}$ and ${}^8\text{He}$ background consistent with 0



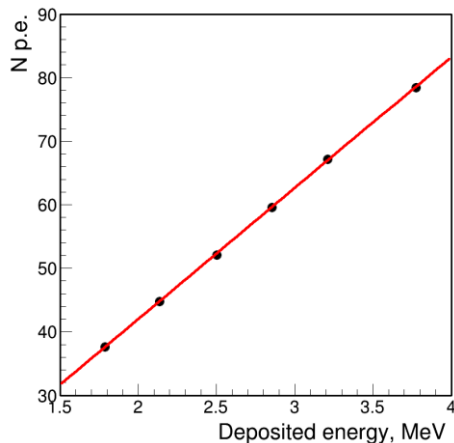
90% CL upper limit = 3 events/day

Calibration

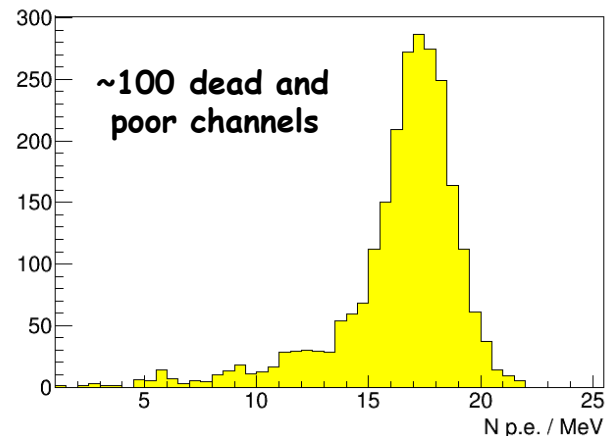
With cosmic muons



Response is linear with energy

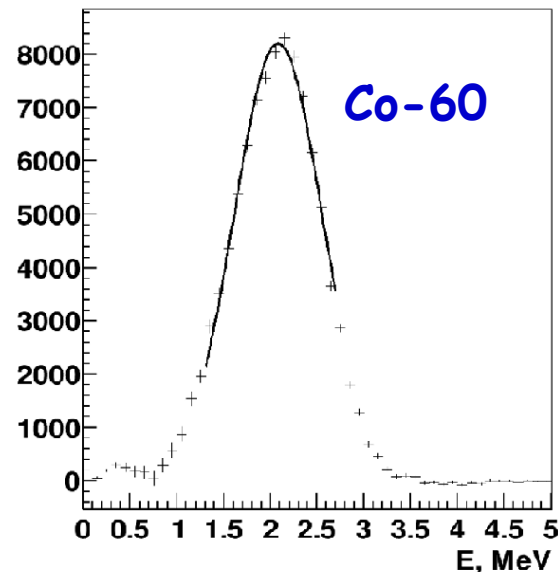
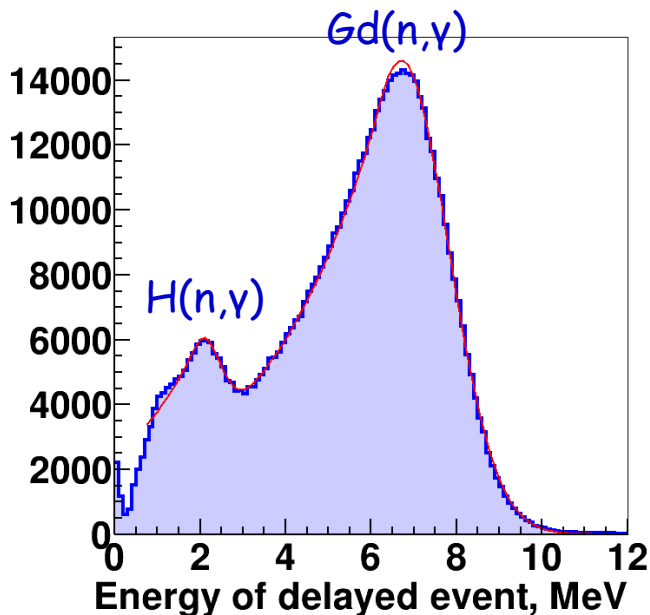
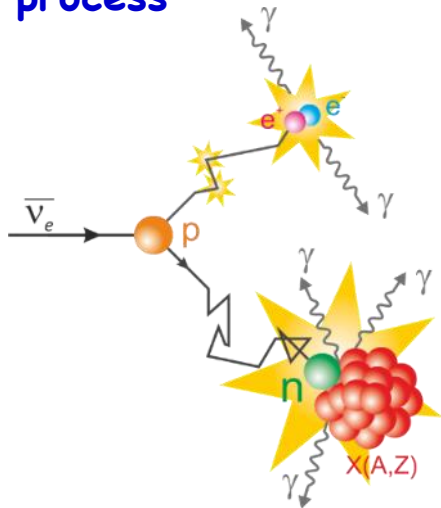


Uniformity of SiPM response before calibration



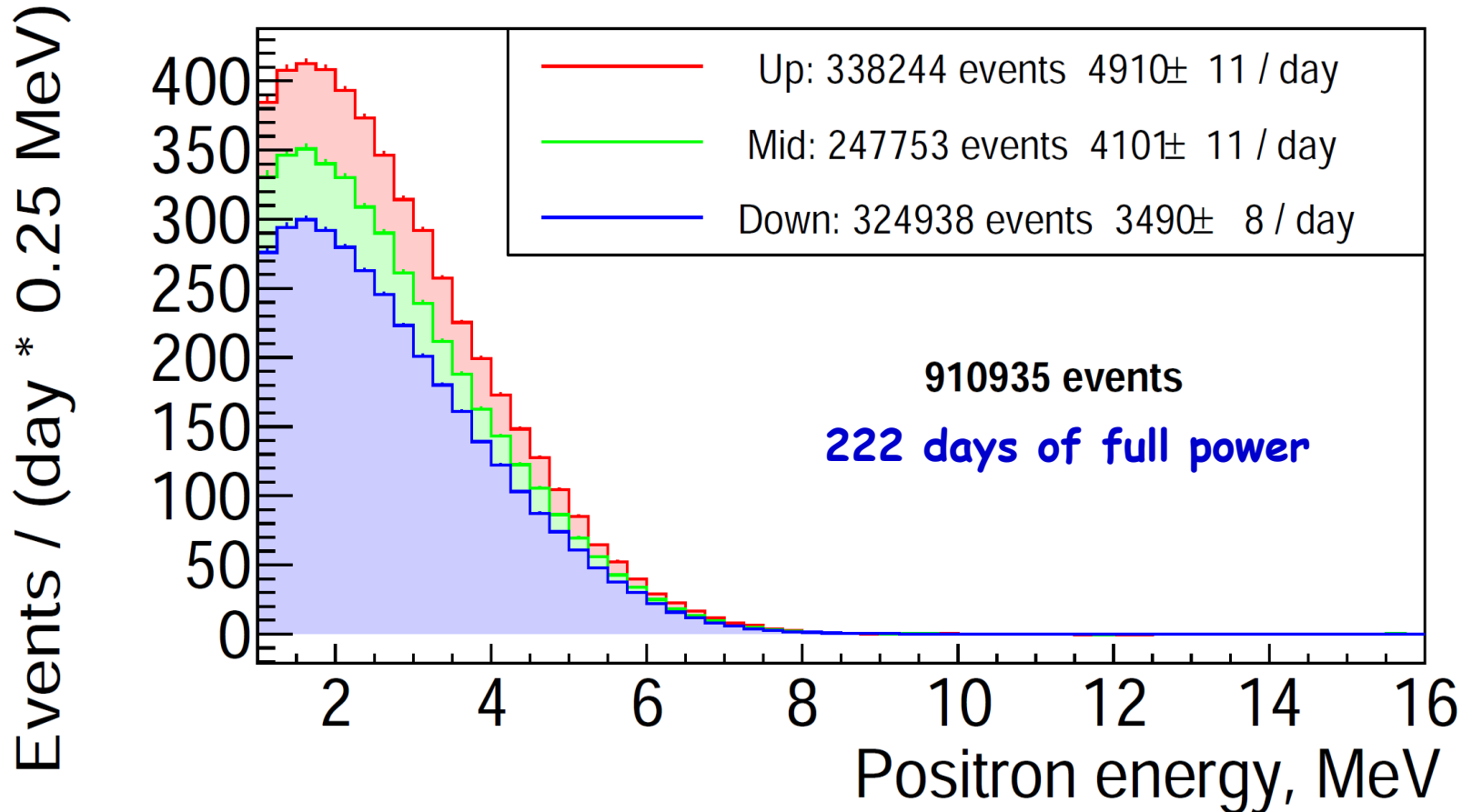
With radioactive sources. ^{248}Cm n source is similar to IBD process

Inverse Beta Decay (IBD) process



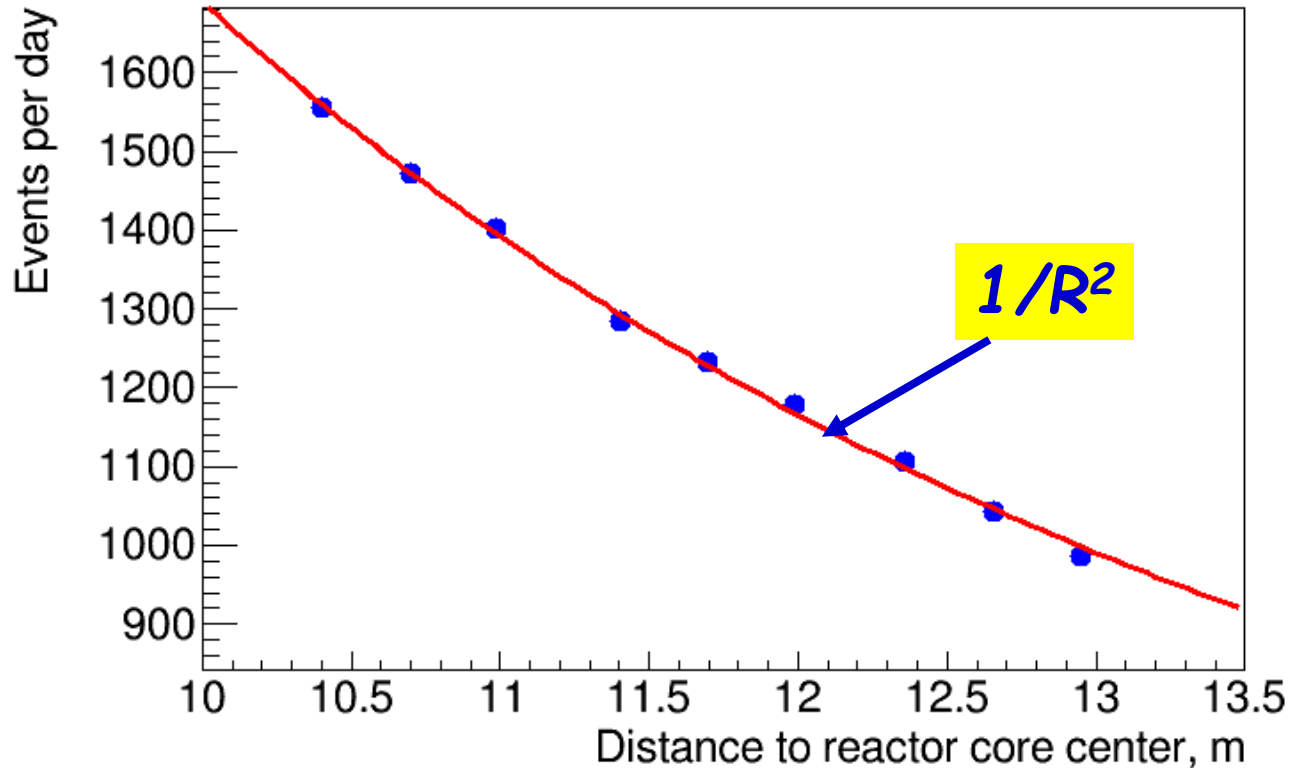
Positron spectrum

Oct 16-Sep 17



- 3 detector positions
- Pure positron kinetic energy (annihilation photons not included)
- About 5000 neutrino events/day in detector fiducial volume of 78% ('Up' position closest to the reactor)

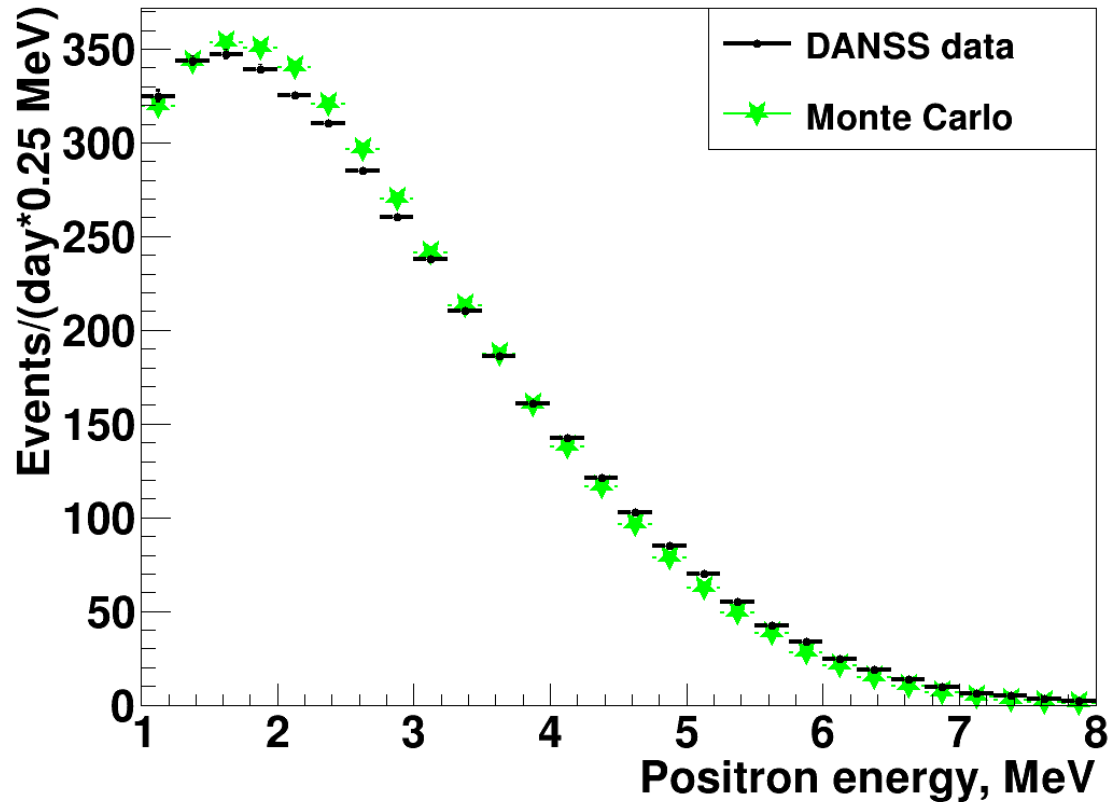
$\bar{\nu}$ counting rate dependence on distance from reactor core



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

Rough agreement with $1/R^2$ dependence

Positron spectrum (last 4 months of campaign)



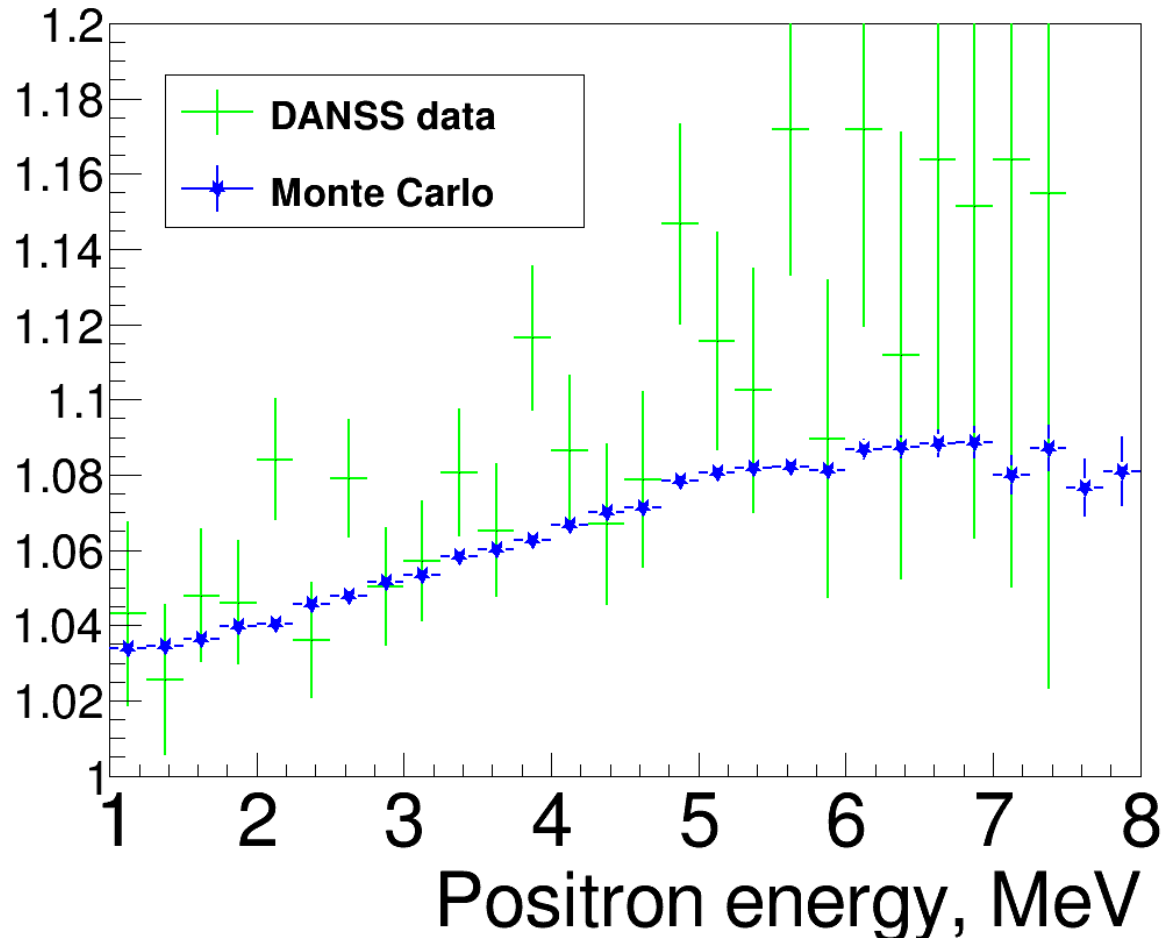
Rough agreement with MC.

(Theoretical neutrino spectrum was taken from Huber and Mueller)

More work on calibration is needed before quantitative comparison

Ratio of positron spectra at beginning and end of campaign

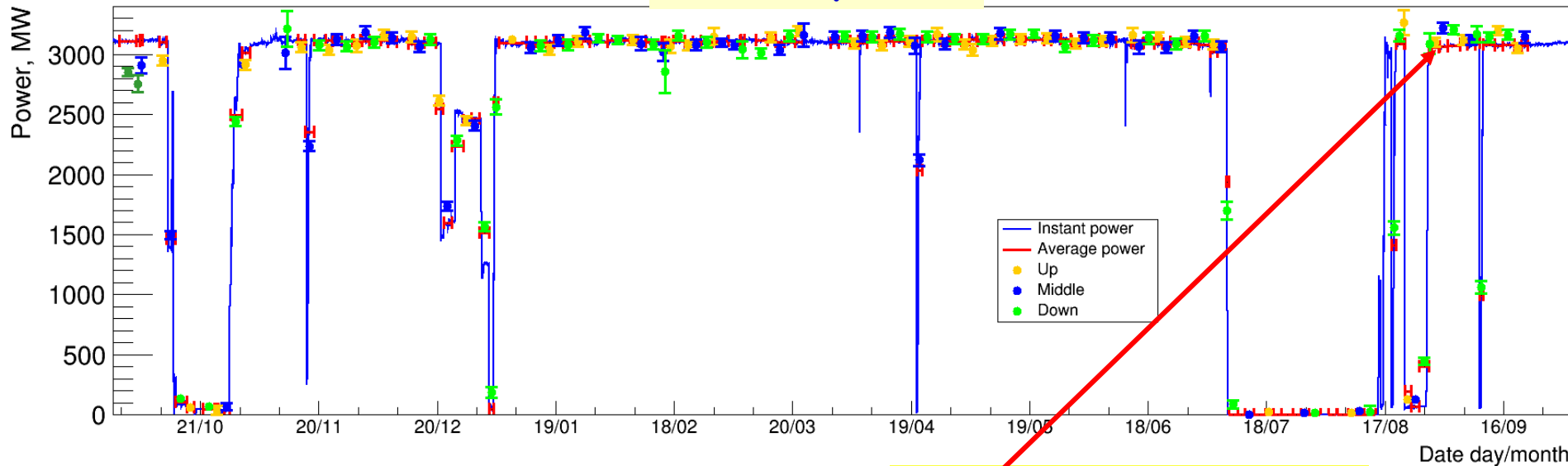
Normalized ratio after shutdown / before shutdown



Spectrum evolution somewhat larger than MC

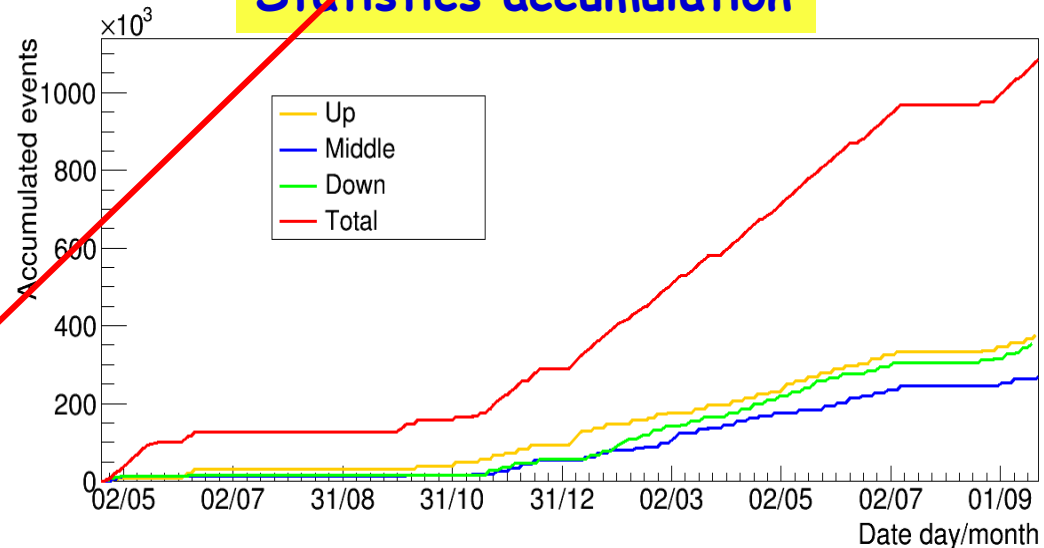
Comparison of reactor power and DANSS rate

Reactor power



- On power graph:
 - 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 (~6%) (MC underestimates changes by ~ 20%)
- Statistics @100% power, ~222 days after QA

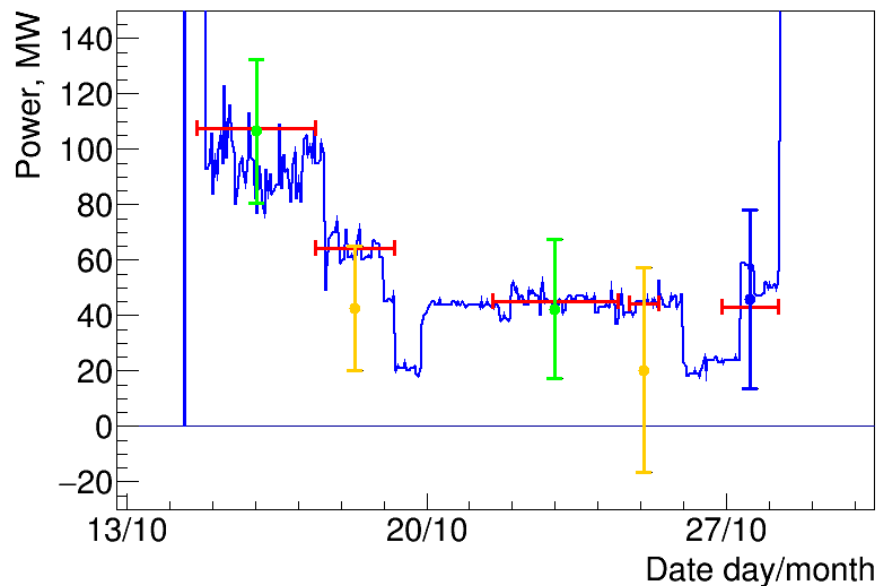
Statistics accumulation



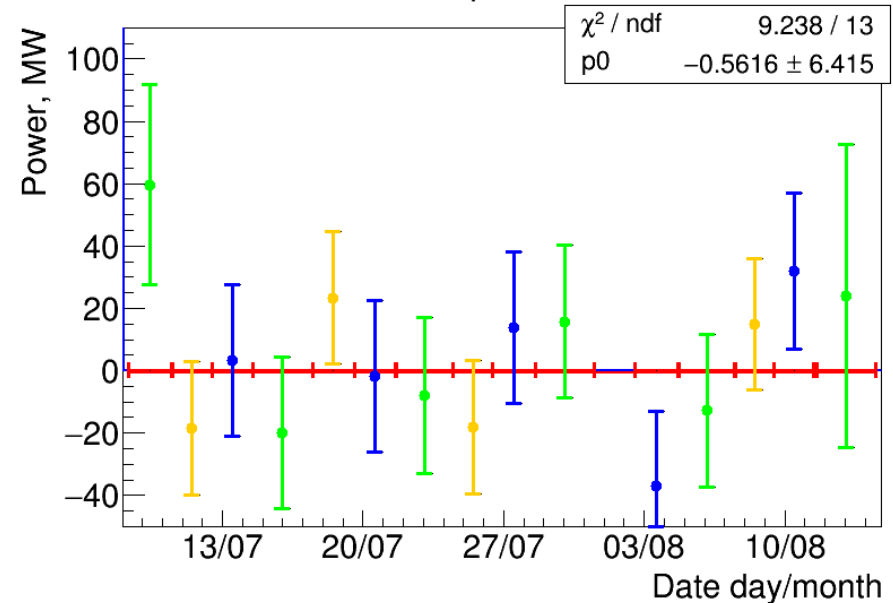
Comparison of reactor power and DANSS rate

Cosmic VETO system inefficiency (5.6%)
was determined during the first reactor OFF period

Block 4 power



Block 4 power



DANSS counting rate during the second reactor OFF period
is consistent with zero
(after ~3% cosmic background and 0.6% adjacent reactor subtraction)

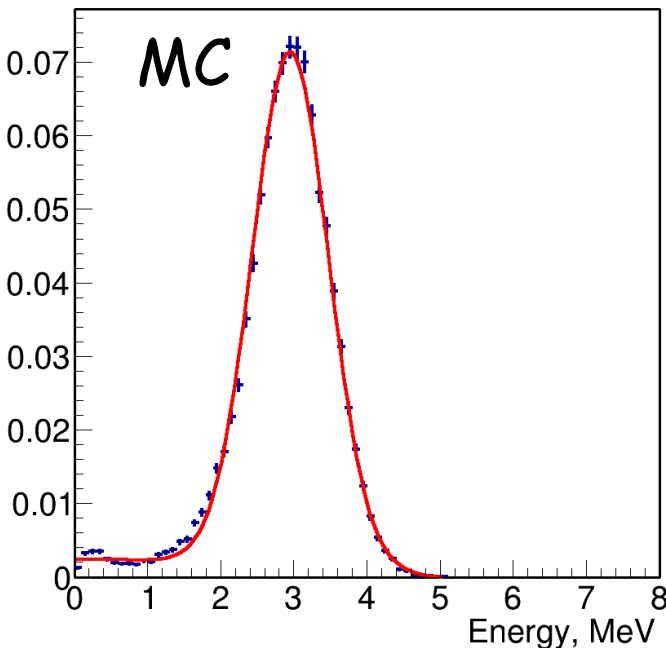
Data Analysis

For every ΔM^2 and $\text{Sin}^2(2\theta)$ e^+ spectrum was calculated for Up and Down detector positions taking into account reactor core size and detector energy response including tails (obtained from cosmic muon calibration and GEANT-4 MC simulation identical to data analysis)

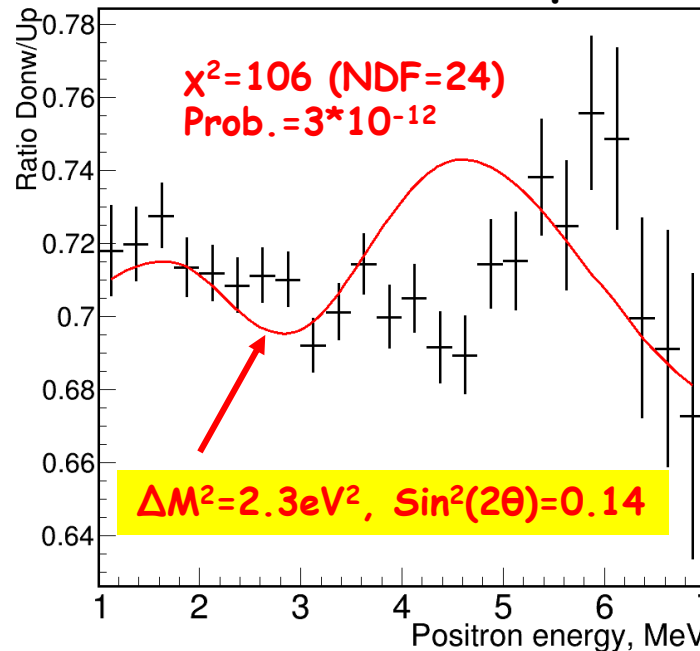
Reactor burning profile was provided by NPP

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

Response to 3 MeV e^+



Ratio Down/Up



3 ν hypothesis:
 $\chi^2=35$
Prob.=0.064

Most plausible
parameter set
from Reactor and
Galium anomalies
is excluded!

Preliminary results

Exclusion region was calculated using Gaussian CLs method

(X.Qian et al. NIMA, 827, 63 (2016))

CLs method is more conservative than usual Confidence Interval method

Systematics studies include variations in:

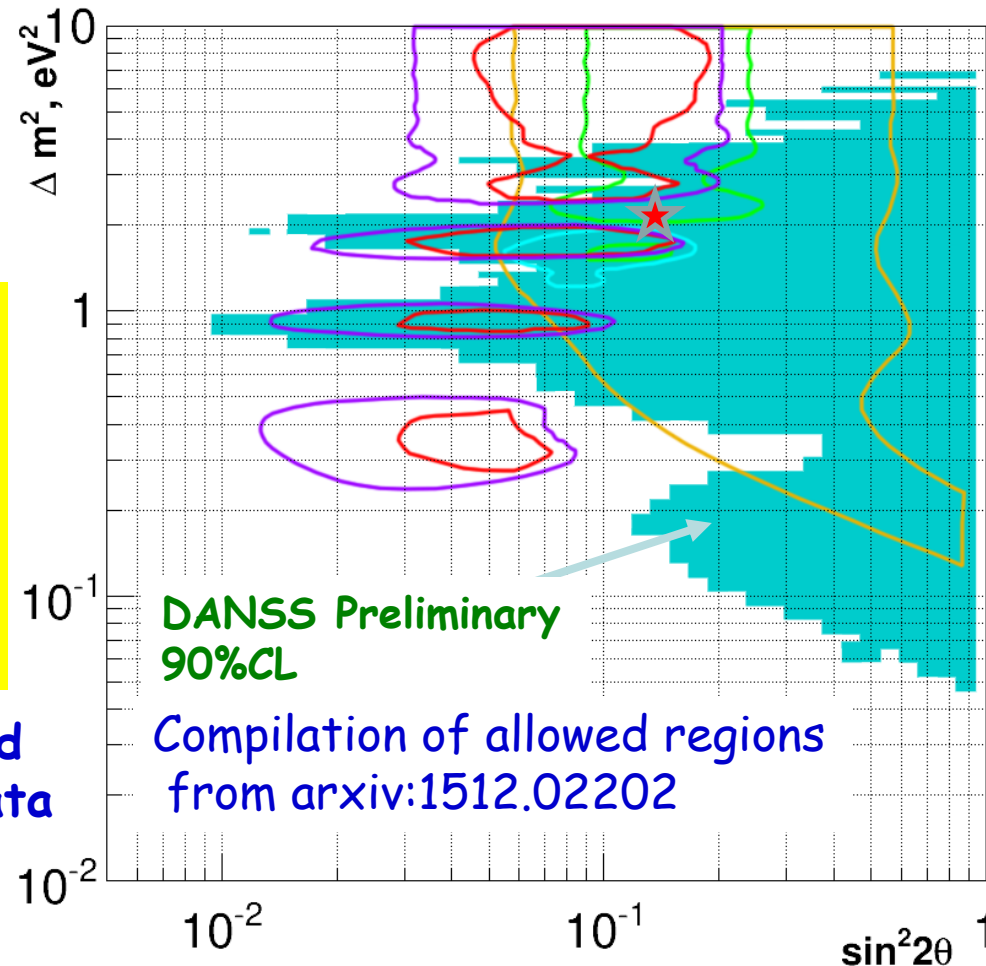
- Burning profile in reactor core
- Energy resolution +25%
- Level of cosmic background 0.7%
- Energy intervals used in fit

Systematics is small

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

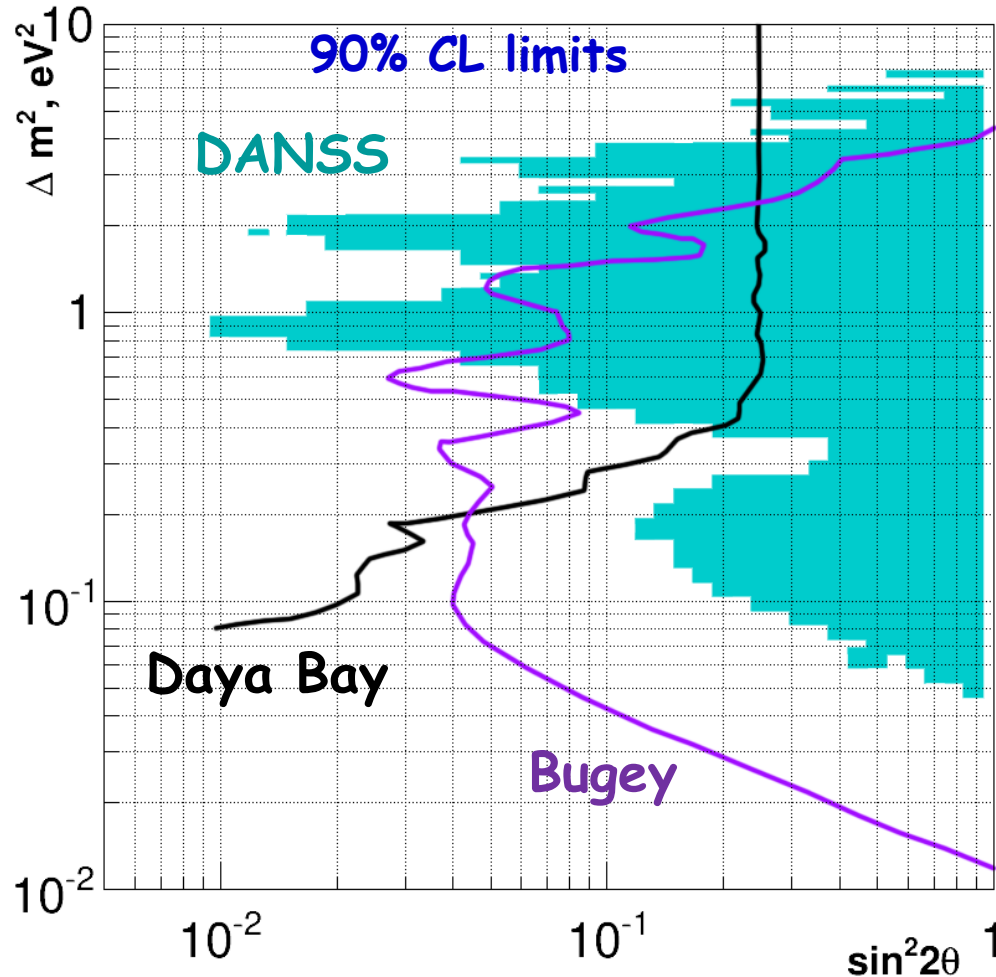
-DANSS plans to collect more data and to include into analysis all available data

-Detector calibration and systematics studies will be continued



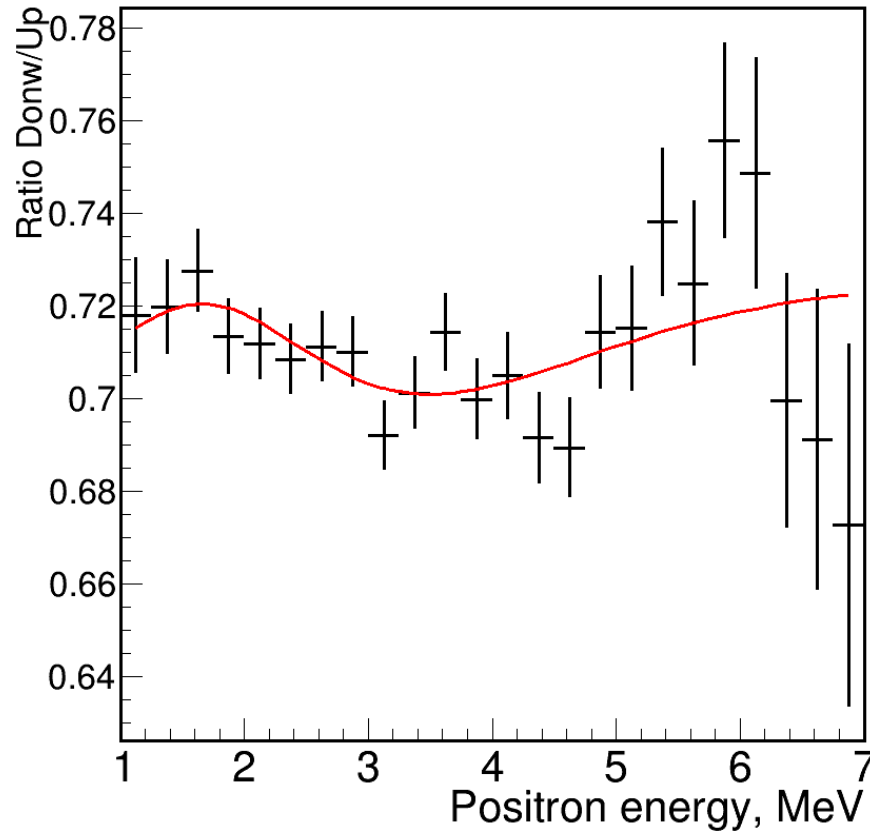
Comparison with experiments based on spectra ratio at different distances

NEOS is not included since it is normalized on spectrum from different experiment (and reactor)



Best point:

$\Delta M^2=1.4$, $\text{Sin}^2(2\theta)=0.045$, $\chi^2=22$ Prob.=0.58 $\Delta\chi^2=13.3$



Significance will be estimated using Feldman and Cousins method with systematic uncertainties

Summary

- DANSS records about 5000 antineutrino events per day with cosmic background <3%
- Antineutrino spectrum and counting rate dependence on fuel composition is clearly observed
- DANSS counting rate consistent with reactor power within ~1% if we use fuel evolution correction 20% higher than in MC. During reactor shutdown $\bar{\nu}$ rate is consistent with 0 after subtraction of ~3% cosmic background and 0.6% flux from adjacent reactors
- Preliminary DANSS analysis based on 662 thousand 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 $\bar{\nu}$ spectrum and detector efficiency!)
- Significance of the best fit point will be evaluated using more elaborated methods



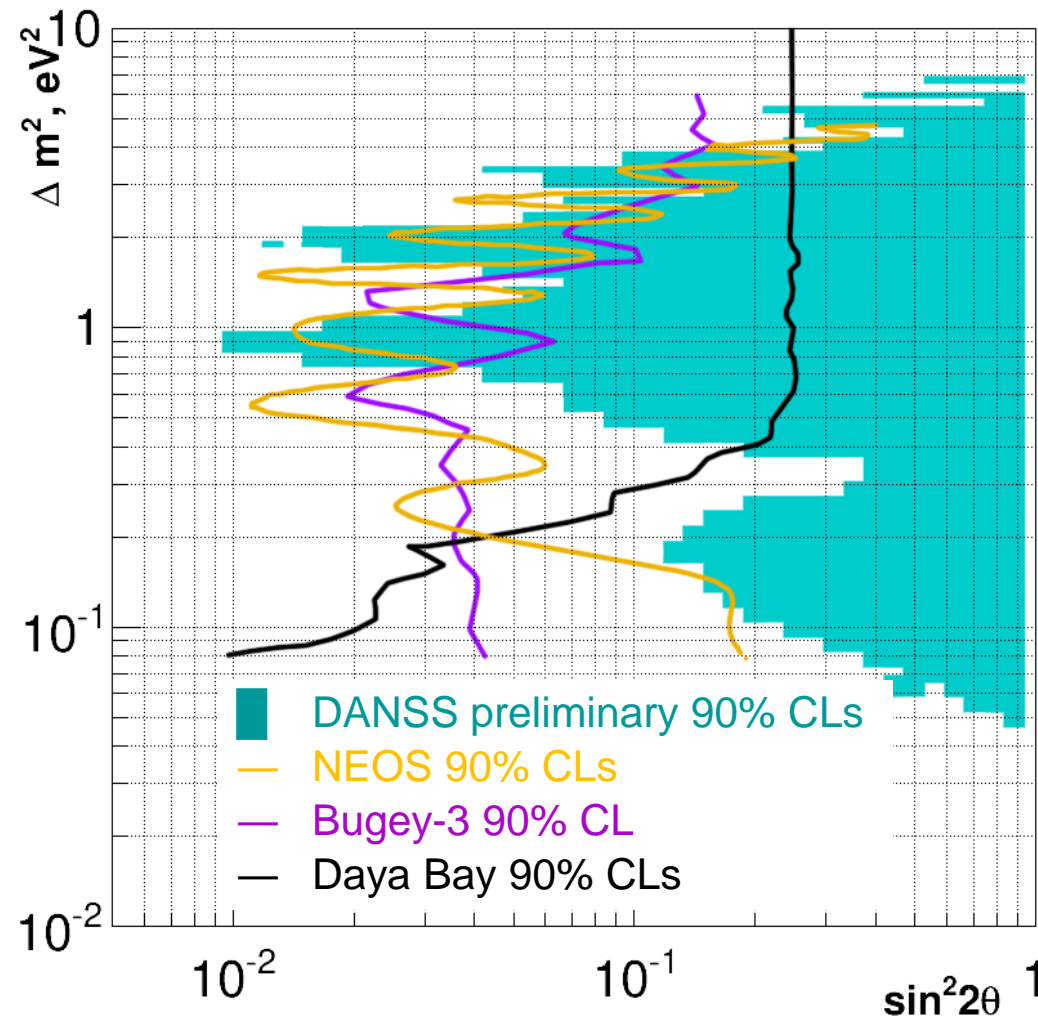
We plan to collect more data,
To improve MC for perfect description of detector response
To refine detector calibration
To continue systematic studies
To include all available statistics into analysis

Thank you !

Backup slides

Comparison with other experiments

NEOS - normalization on Daya Bay \rightarrow systematic errors?
Bugey - use of "old" reactor model \rightarrow Systematic errors?



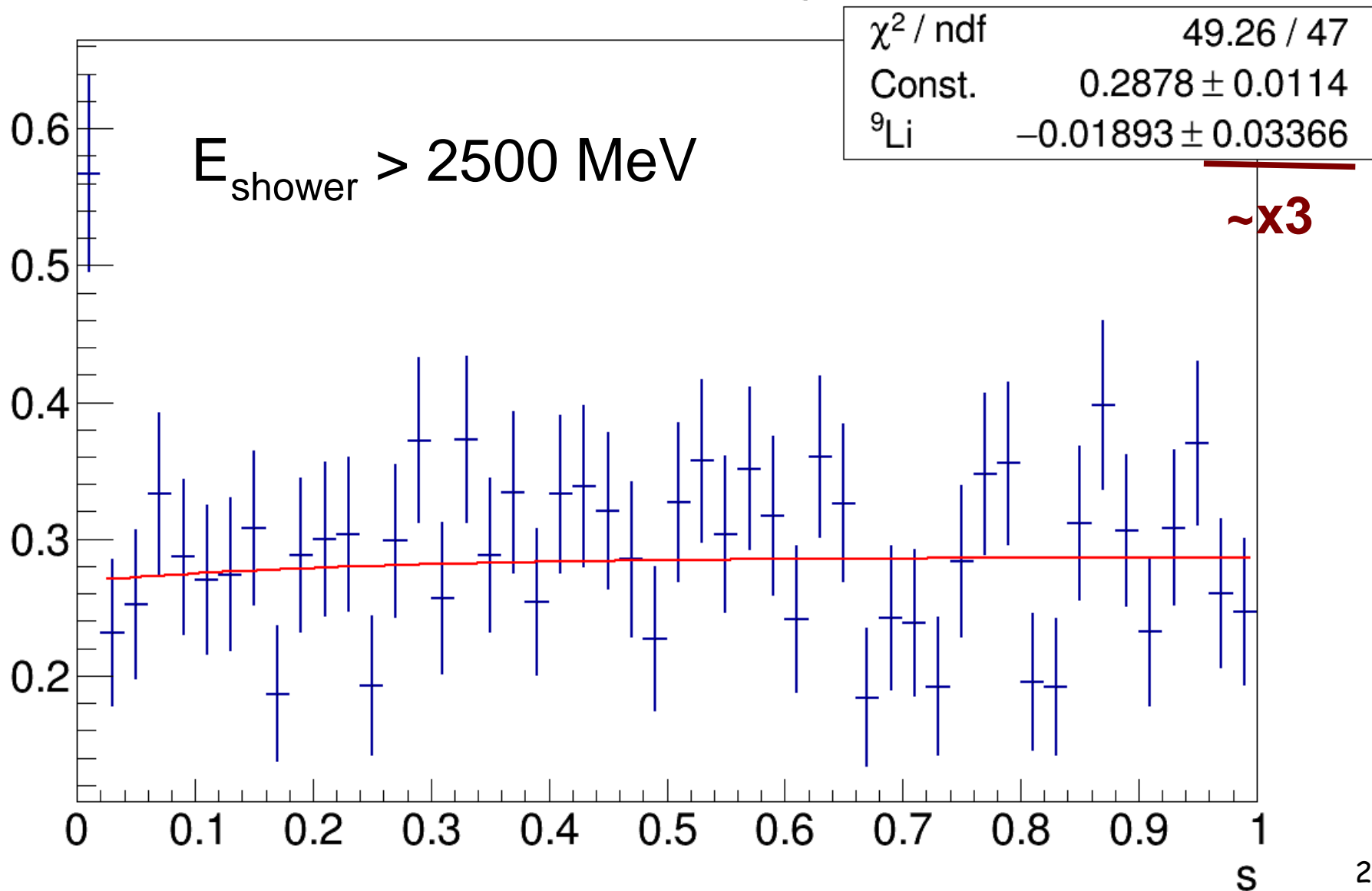
arXiv:1610.05134 [hep-ex]

${}^9\text{Li}$ and ${}^8\text{He}$ background estimation

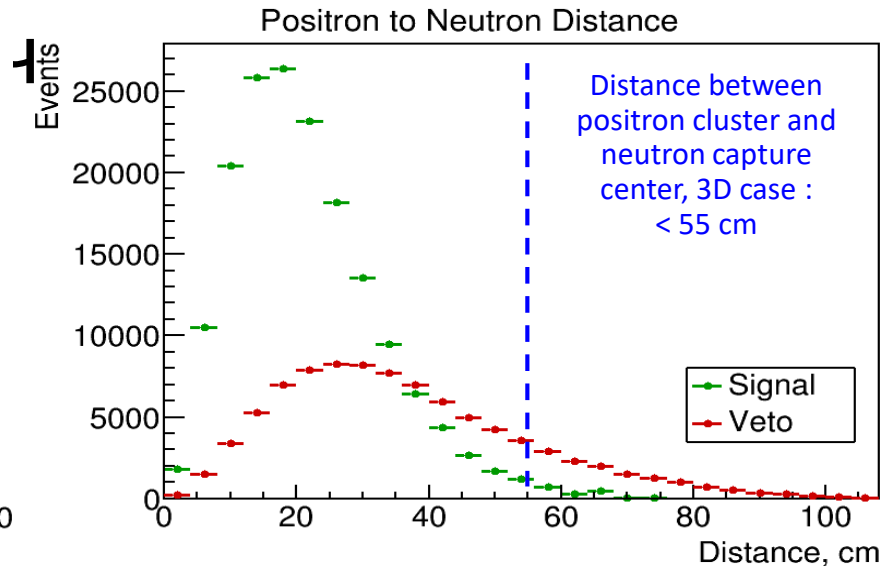
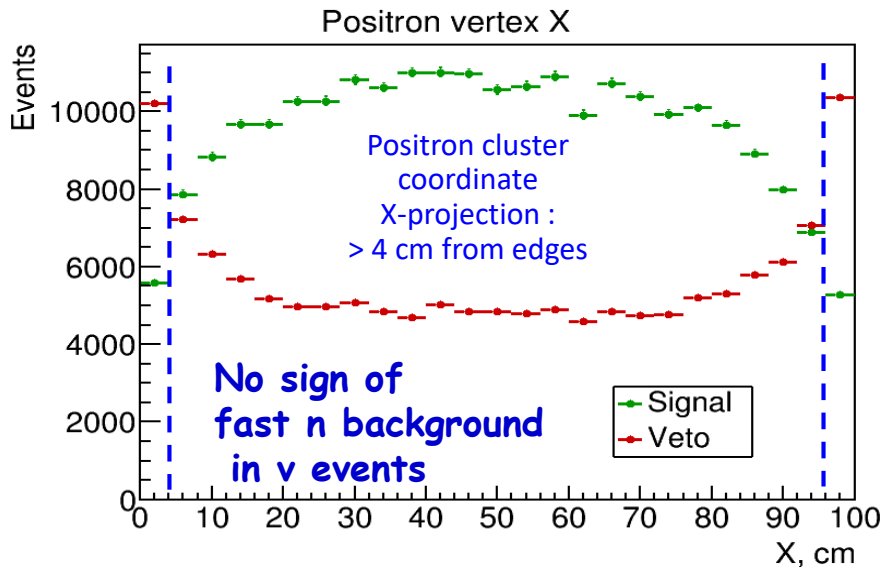
90%CL limit: $1.64 * 3 * 0.034 * 257.2 / 20 = 2.2$ events/day

Fit with sum of two exponents

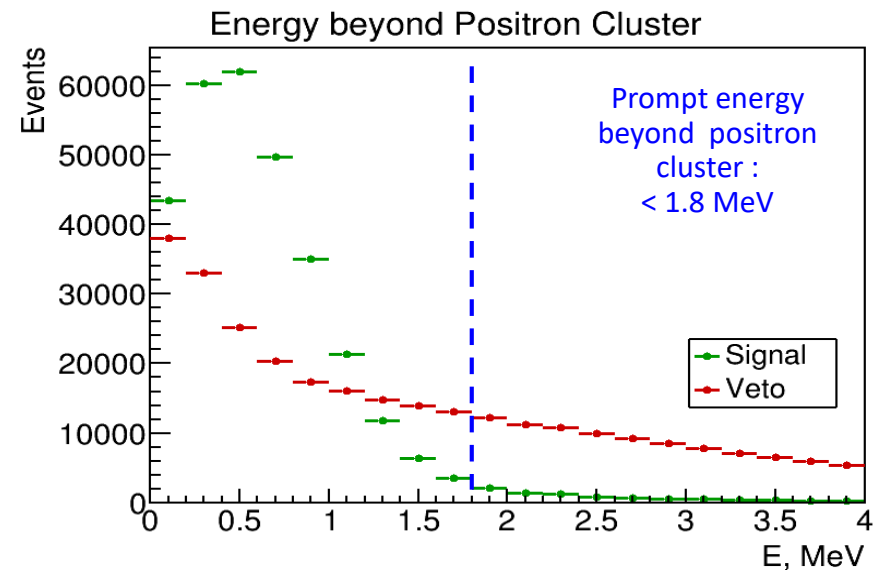
Events / day



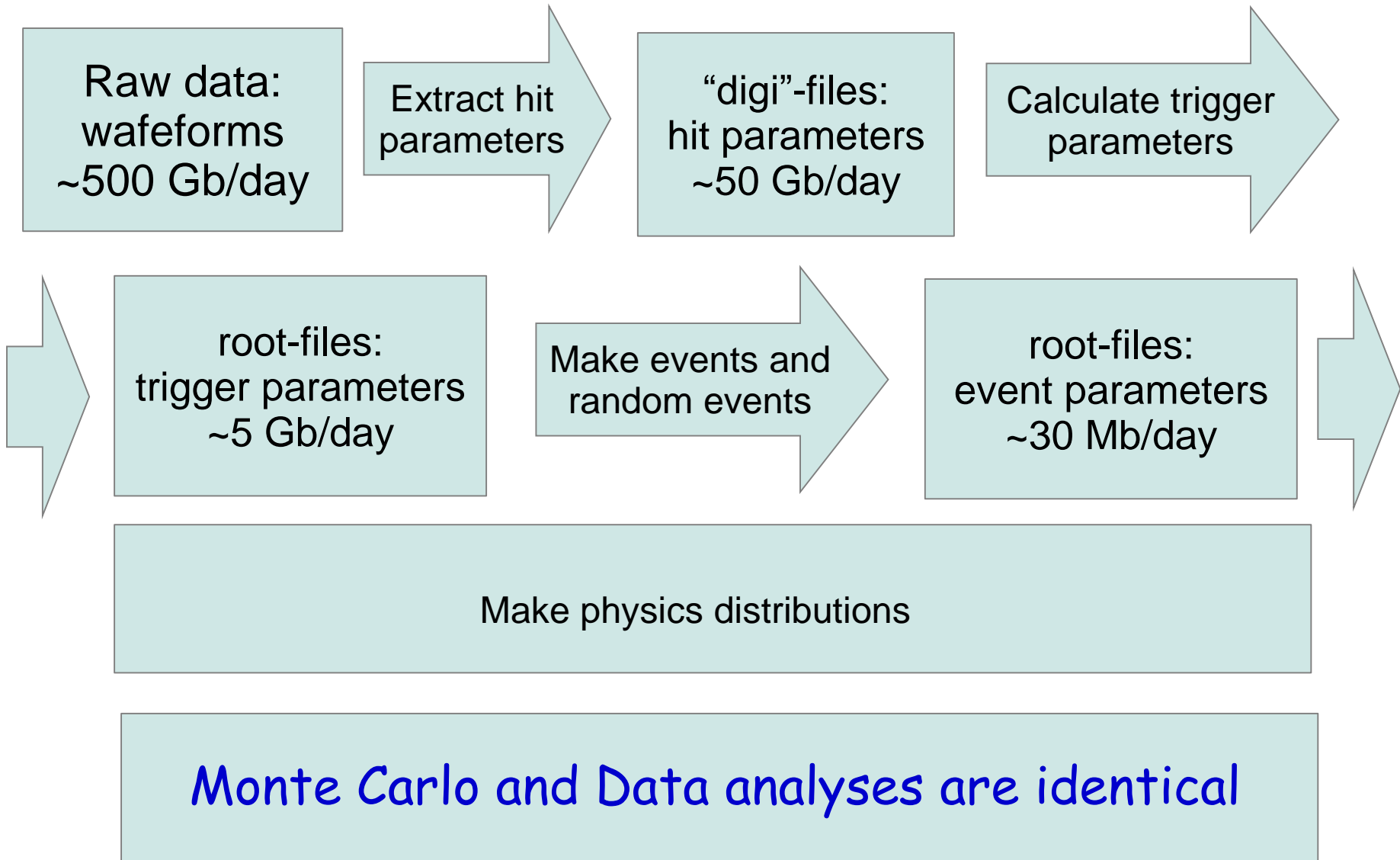
Additional cuts using fine segmentation



- Comparison of the distributions for the events which passed the muon cut with similar for those accompanied by muons
- Positron cluster position: 4 cm from all edges
- Vertical projection of the distance: <40 cm
- Multiplicity beyond positron cluster: <11
- Totally 8 cuts of this kind
- Reject cosmic background >3 times, but only 15% of the events



Data analysis



Reactor core burning profile averaged over campaign

