Семинар ИЯИ
26 марта 2018

Search for sterile neutrinos at the DANSS experiment

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for the DANSS Collaboration

There are several ~3σ indications of 4^{th} neutrino

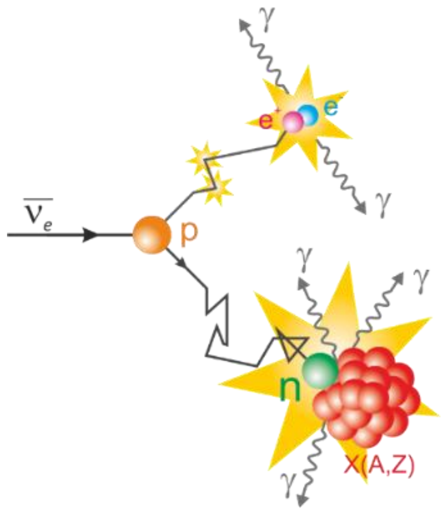
LSND, MiniBoone: $\bar{\nu}_e$ appearance
SAGE and GALEX ν_e deficit
Reactor $\bar{\nu}_e$ deficit

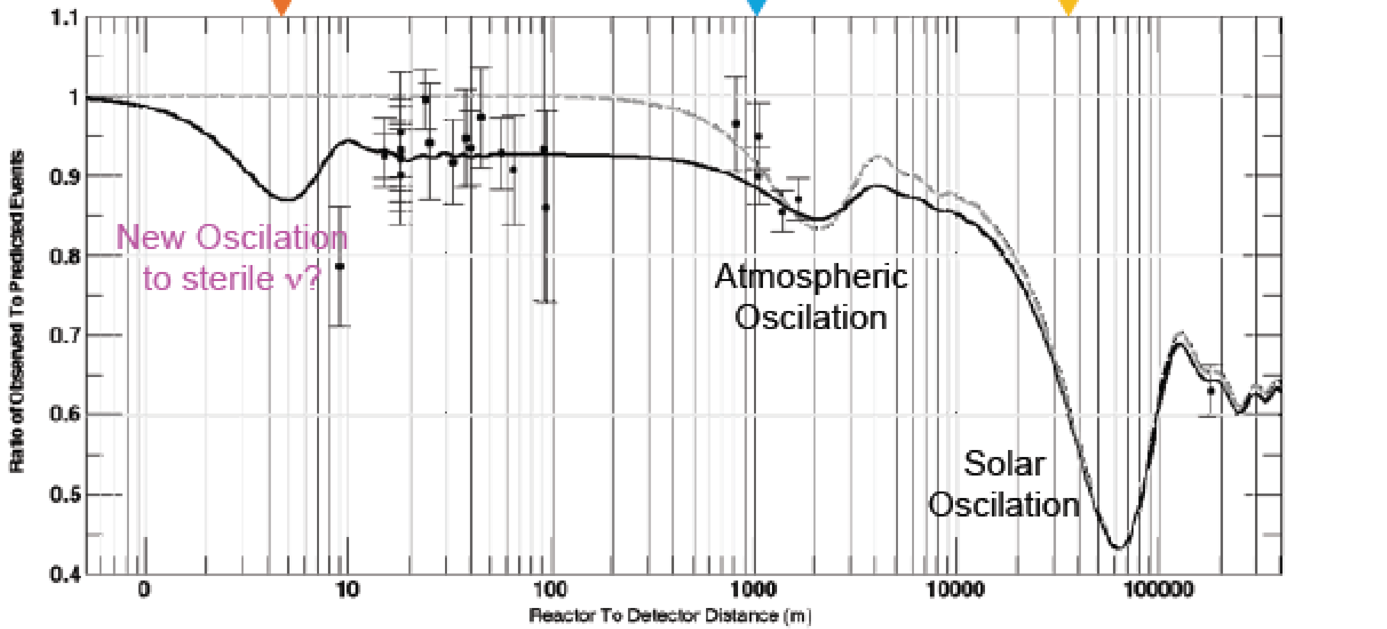
→

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



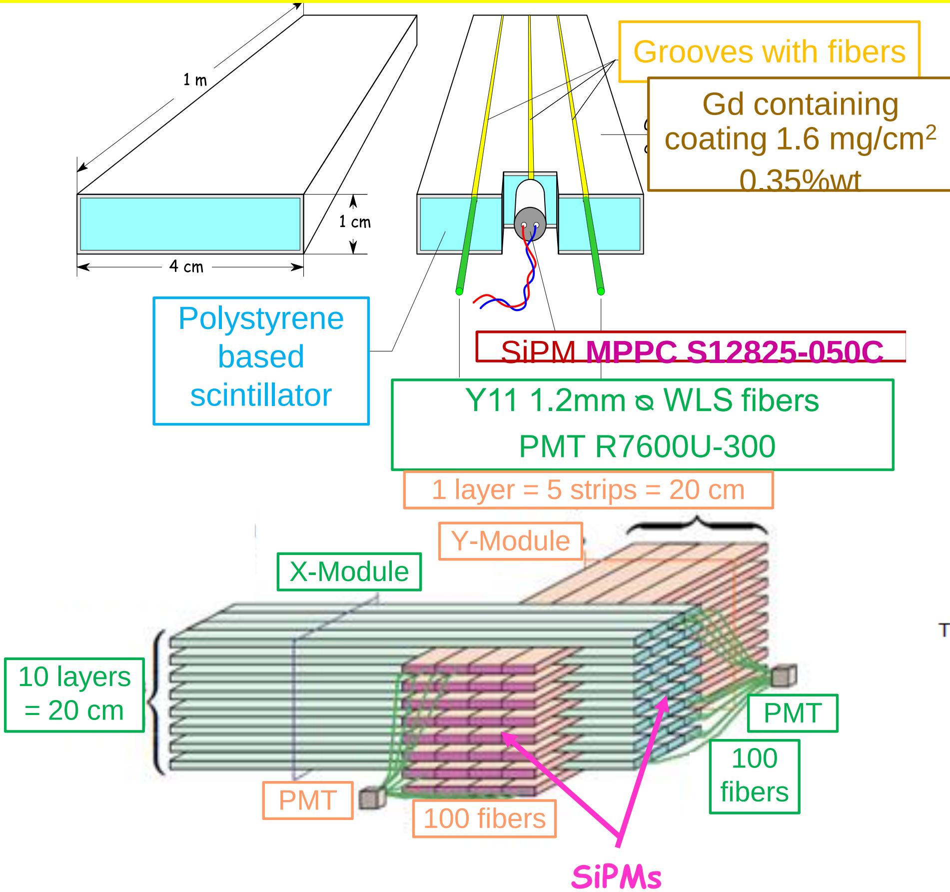


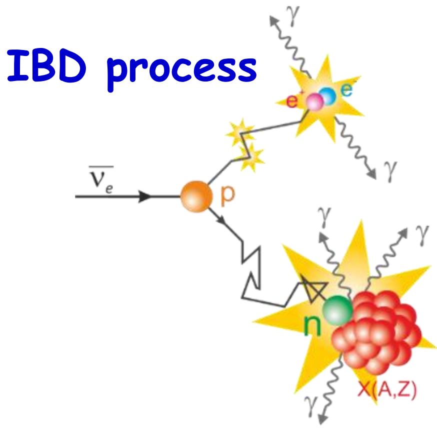
G. Mention et al. Phys Rev D 83 073006 (2011)

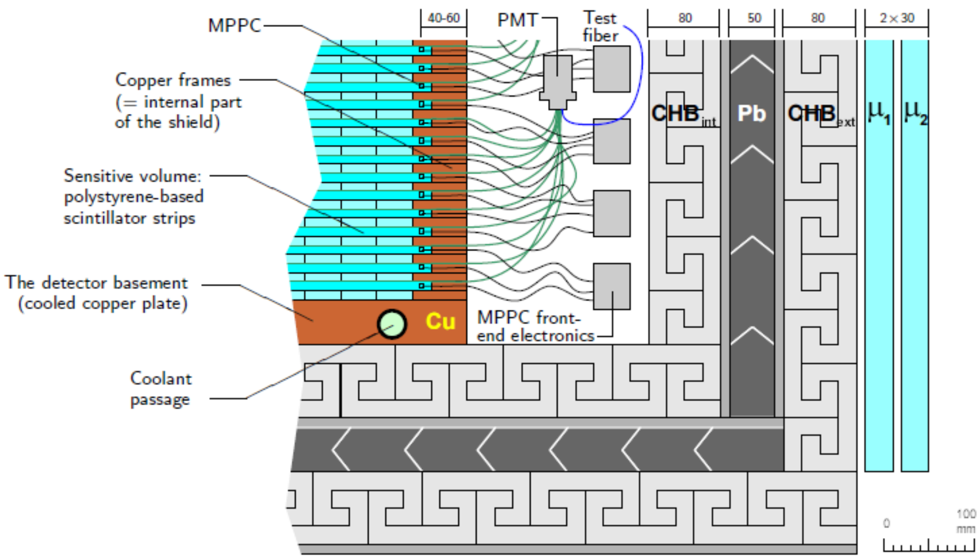
Reactor models do not describe well neutrino spectrum

Measurements at only 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

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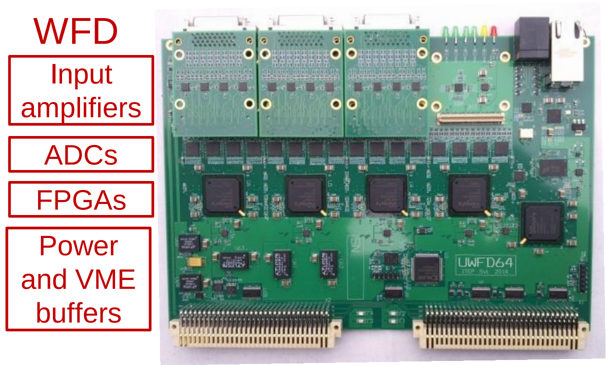
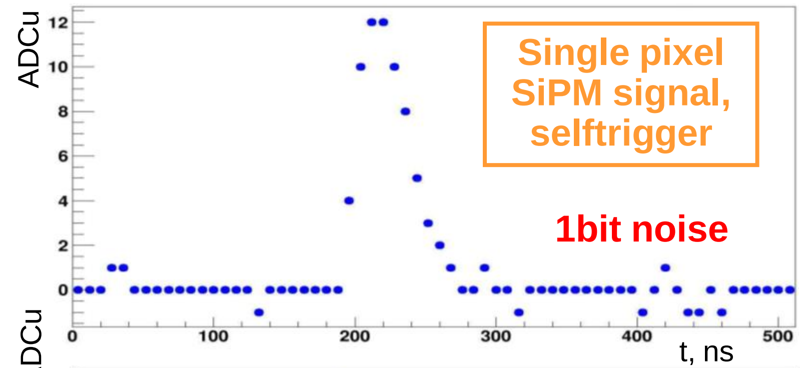
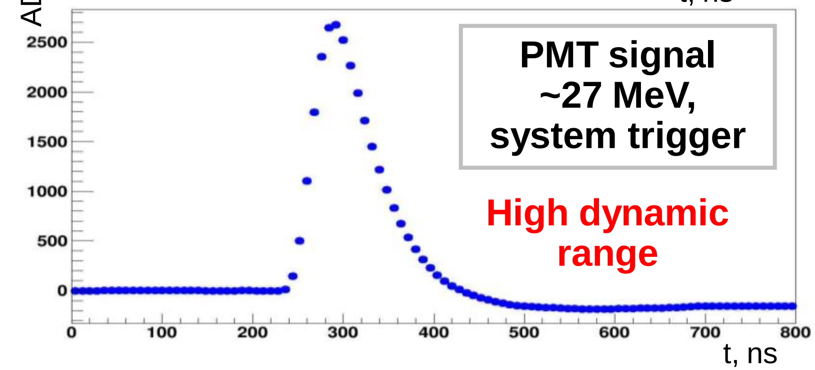
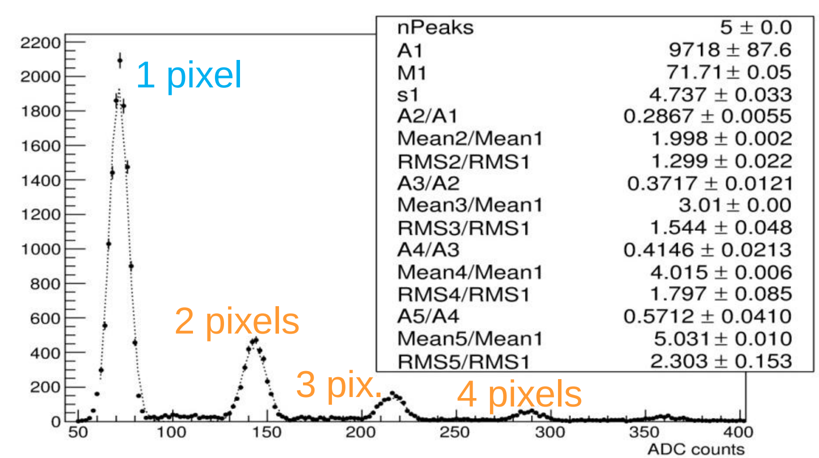


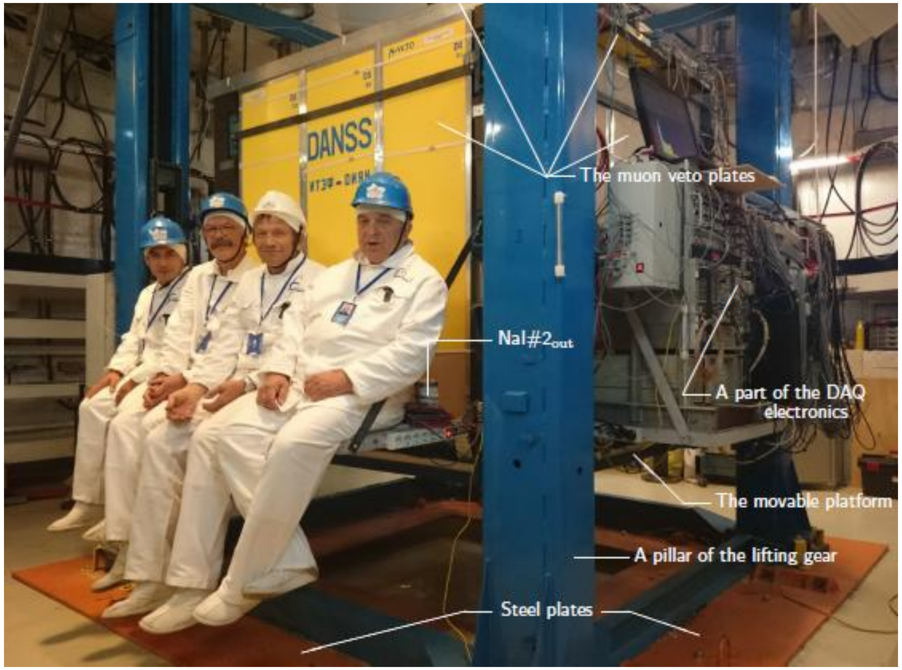
- Preamplifiers PA in groups of 15 and SiPM power supplies HVDAC for each group inside shielding, current and temperature sensing
- Total 46 Waveform Digitisers WFD in 4 VME crates on the platform
- WFD: 64 channels, 125 MHz, 12 bit dynamic range, signal sum and trigger generation and distribution (no 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.

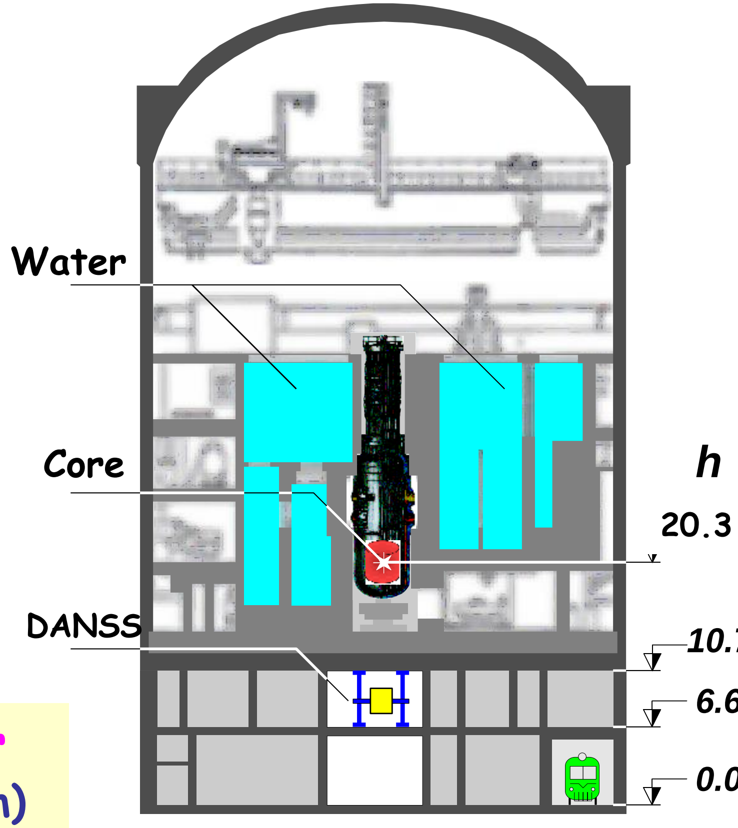






DANSS at Kalinin Nuclear Power Plant





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)

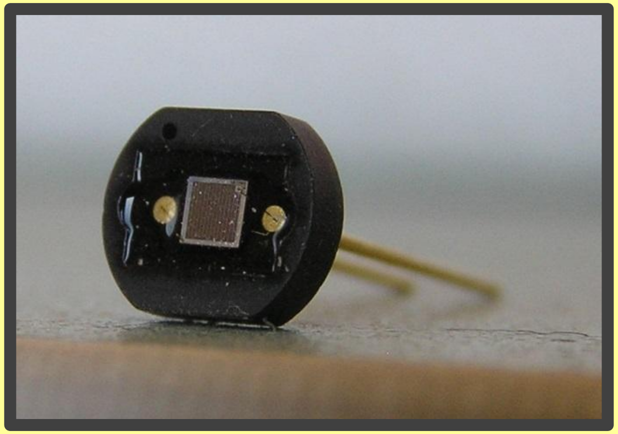
Trigger: ΣE(PMT)>0.7MeV => Read 2600 wave forms (125MHz), look for correlated pairs offline.

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%

DANSS: система кремниевых ФЭУ

- SiPm важны для уточнения пространственной и энергетической структуры события, отобранного по суммарному отклику обычных фотоумножителей
- DANSS использует MPPC S12825-050C производства HAMAMATSU:
  - чувствительная зона 1.3 mm²;
  - 667 ячеек (пикселей) 50x50μ²;
  - усиление ~10^6;
  - эффективность к зелёному свету ~ 35%;
- Преимущества:
  - разрешение на уровне 1 фотоэлектрона;
  - малый размер;
  - дешевизна;
- Недостатки:
  - темновой шум с частотой ~130 kHz на уровне 50 кэВ, имитирующий сигналы мягких фотонов;
  - наличие оптической связи между соседними пикселями;
  - температурная зависимость параметров;
  - нелинейность отклика при больших числах сработавших пикселей;



Обработка сигнала кремниевых ФЭУ

Записываемый отклик SiPm: временная форма сигнала, оцифрованного с шагом 8 ns во временном окне 520 ns, которое формируется после получения триггера на данное событие

Последующий анализ позволяет:

- пособытийно компенсировать остаточное смещение базовой линии (± 1 канал АЦП);
- вычленить сигнальный импульс по времени прихода сигнала t_0 и устранить возможные паразитные импульсы, попавшие во временное окно;
- сгладить флуктуации пьедестала путём аппроксимации сигнального импульса и получить уточнённые значения интегральной величины сигнала I и времени его прихода t_0;

Шумовые спектры кремниевых ФЭУ

Связь между свойствами пиков:

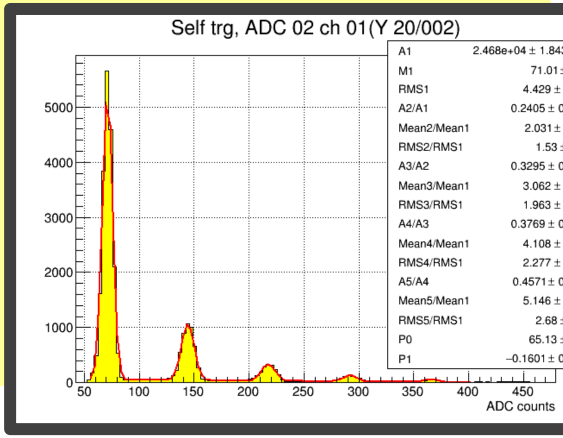
- Интегралы(статистика в пике): $I_{N+1} = I_N * \frac{P_{N+1}}{P_N}$
- Позиция(максимум): x_N = N*x_1, $x_{N+1} = x_N$*(1+1/N)
- Среднее число сработавших пикселей: $\langle N \rangle = 1 + \varepsilon + \varepsilon^2 * 3(n-1)/2n + o(\varepsilon^2)$

где N – номер пика, P_N – вероятность срабатывания N пикселей, ε - общая вероятность срабатывания больше чем одного пикселя в SiPm, n – эффективное число соседей первого сработавшего пикселя[L. Gallego, J. Rosado, F. Blanco and F. Arqueros].

Таким образом, шумовые спектры SiPm позволяют определить все параметры, необходимые для калибровки отклика SiPm в линейной области низких амплитуд:

- коэффициент усиления SiPm в форме коэффициента пересчёта каналов АЦП в число сработавших пикселей;
- вероятность оптического перекрёстного срабатывания других пикселей SiPm и производный параметр в форме среднего количества темновых гейгеровских разрядов, что эквивалентно среднему количеству пикселей, срабатывающих от одного фотоэлектрона;

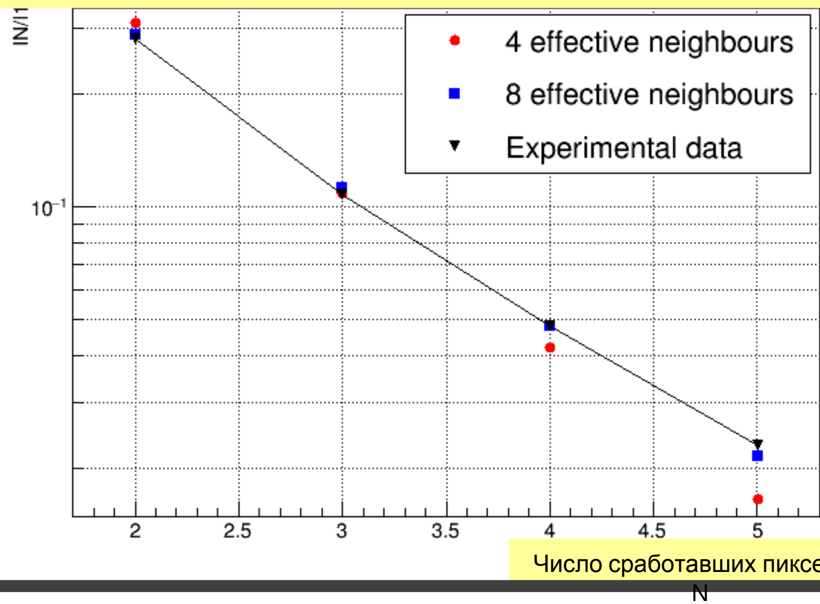
С целью калибровки SiPm и непрерывного мониторинга калибровочных параметров параллельно с набором физических данных ведётся запись шумовых событий, используя автотриггер с низким порогом (прореживание 50000). Набираемой статистики достаточно, чтобы производить независимую индивидуальную калибровку SiPm каждые двадцать минут.



Проверка математической модели

Математические модели оптической связи между пикселями [L. Gallego, J. Rosado, F. Blanco and F. Arqueros] базируются на допущении, что первый сработавший пиксель может спровоцировать лавины в конечном числе соседних ячеек. Этот параметр n, называемый эффективным числом соседей, входит в формулу для вычисления среднего числа пикселей, срабатывающих от одного фотоэлектрона. Величину n можно оценить по соотношению статистики в пиках с разным N

Среднее отношение чисел событий в пиках $\langle I_N / I_1 \rangle$



Число сработавших пикселей

N	2	3	4	5
I_N / I_1, n=4	0.310	0.108	0.042	0.016
I_N / I_1, n=8	0.288	0.112	0.048	0.022
I_N / I_1, Экс	0.281	0.108	0.049	0.023

Экспериментальные данные: 4 часа набора в стабильных температурных условиях (118M шумовых триггеров).

Используемые в DANSS SiPm хорошо описываются моделью с n=8.

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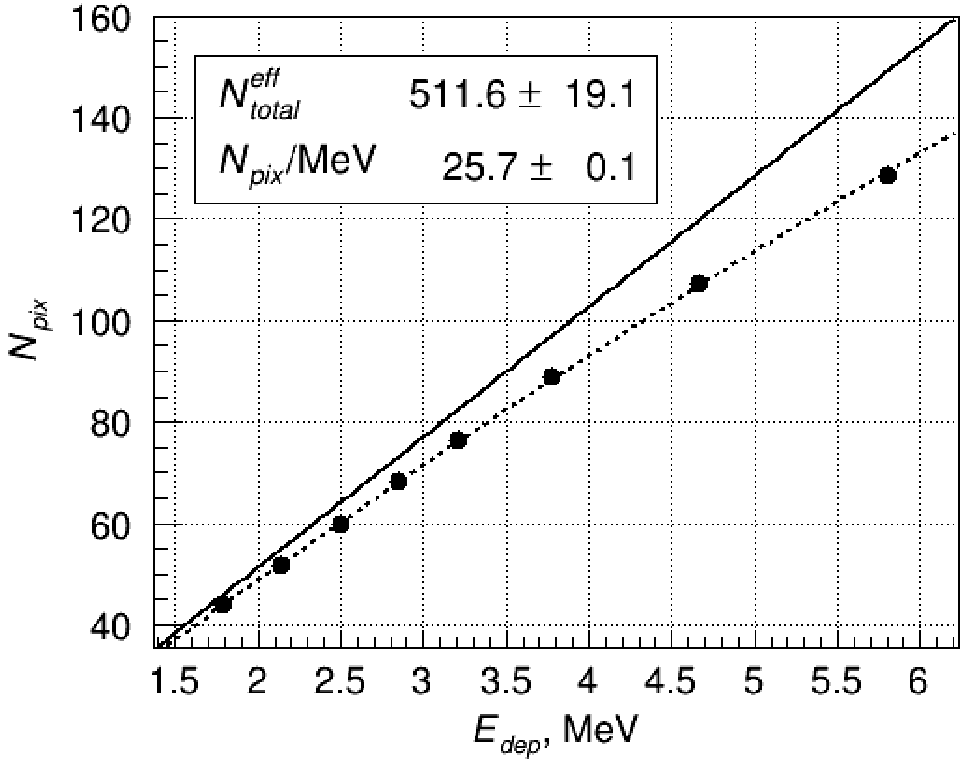
Determination of effective number of pixels

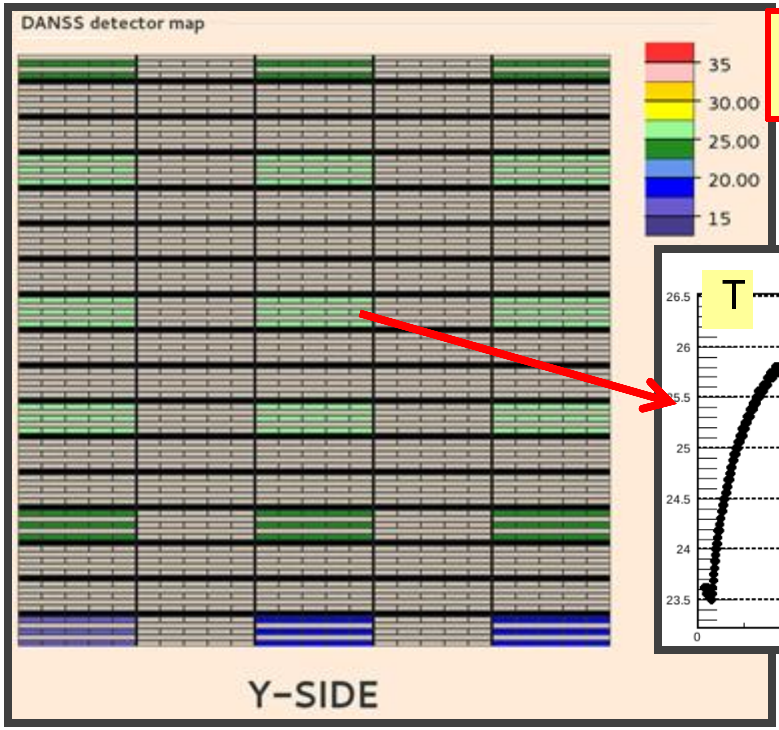
WLS Fiber illuminates SiPM non-uniformly
Effective number of pixels is determined from response nonlinearity

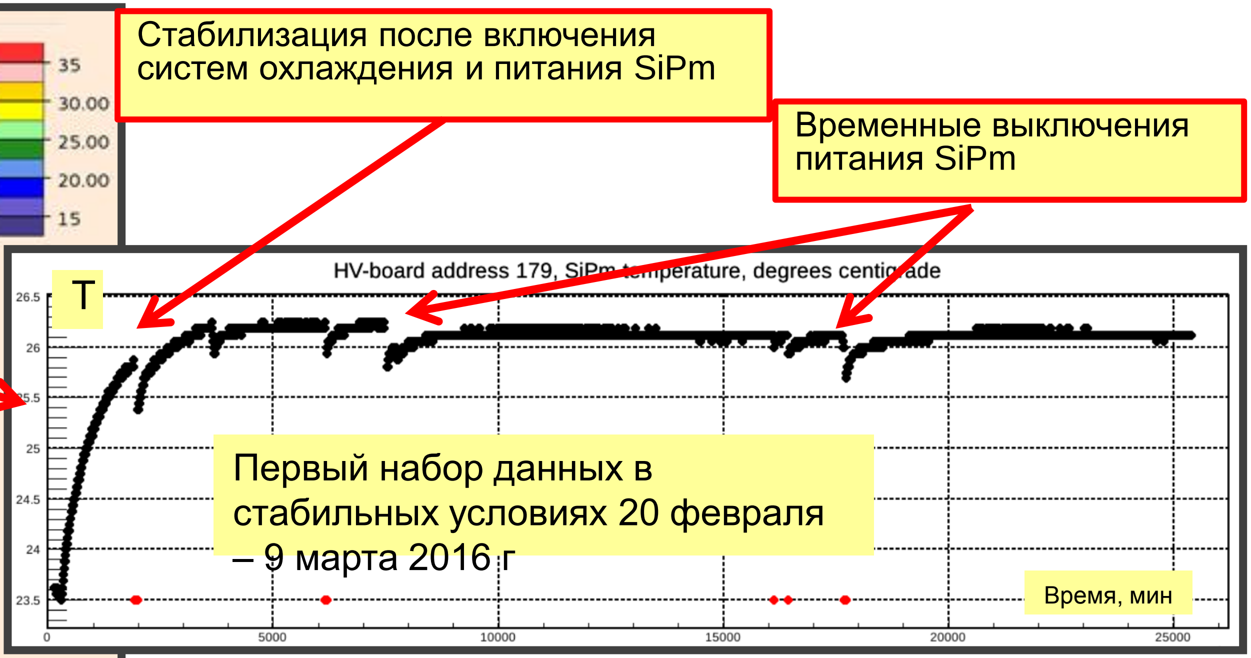


Neff=512±19

Ntot=667

DANSS: температура детектора





Температура непрерывно контролируется при помощи 36 датчиков, равномерно распределённых по поверхностям обеих считываемых сторон куба в непосредственной близости от SiPm.

При измеренной температурной стабильности статистики набираемых калибровочных данных заведомо достаточно для отслеживания и компенсации влияния возможных температурных эффектов.

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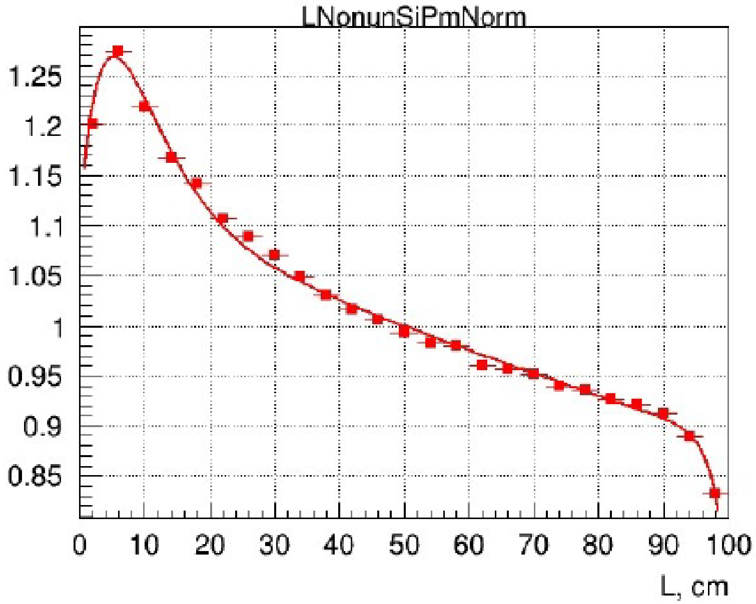
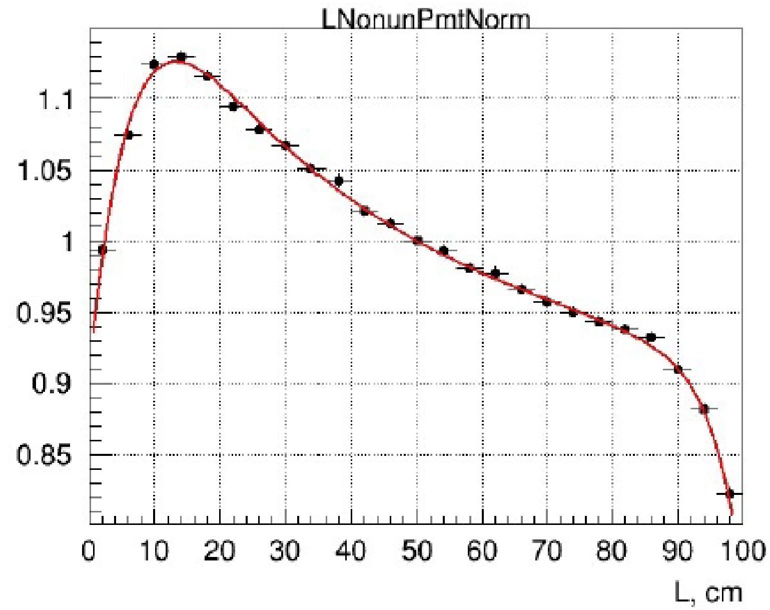
Light yield profiles

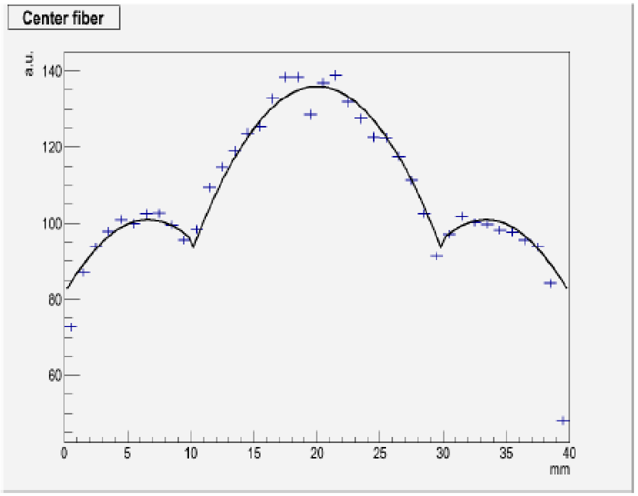
SiPM



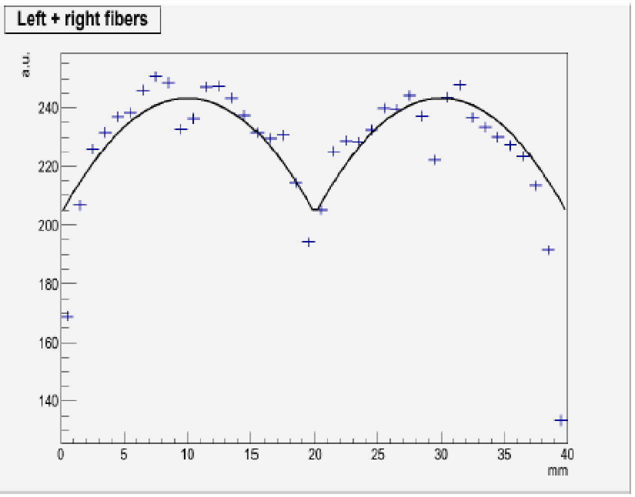
PMT



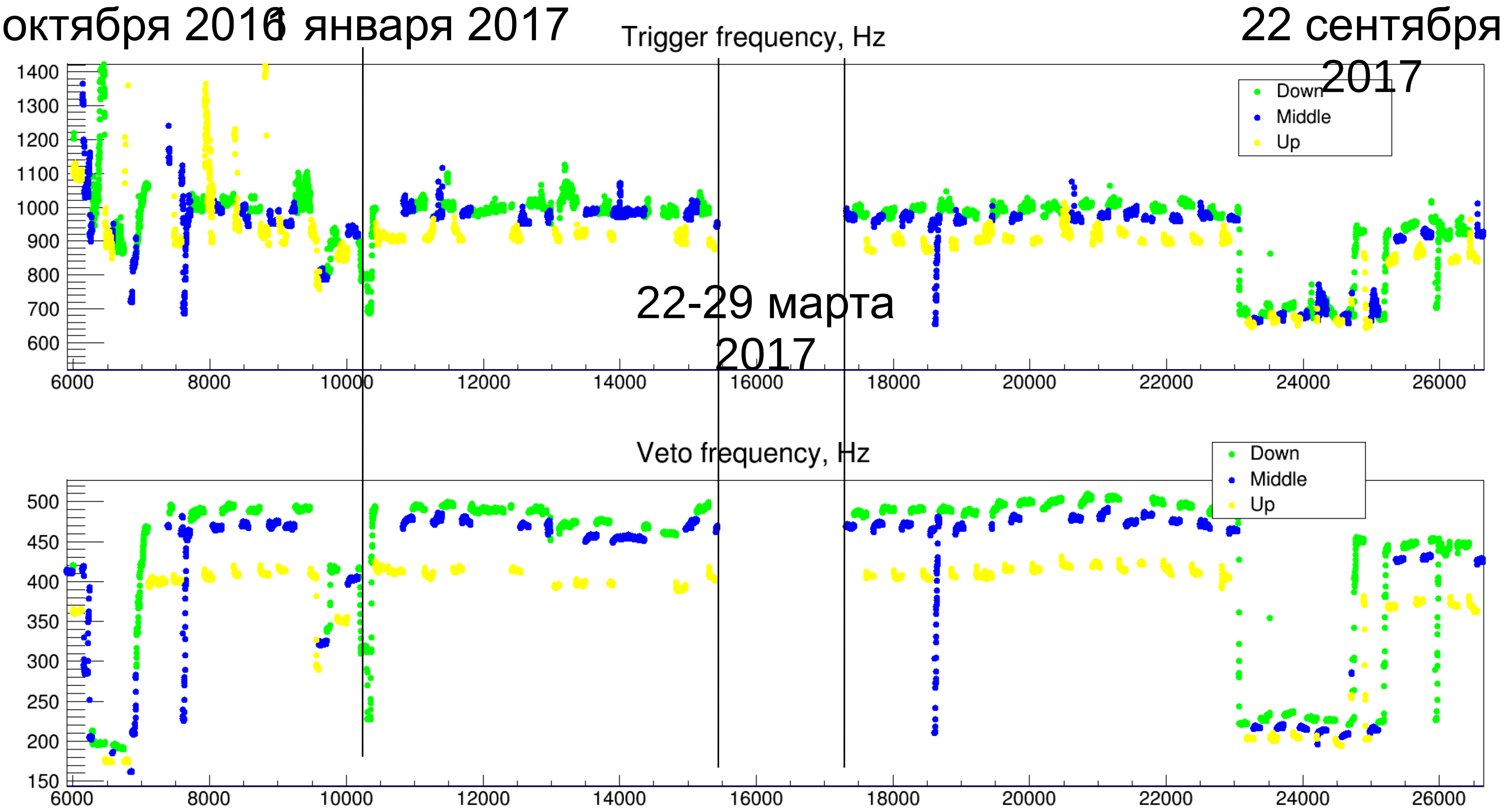
SiPM



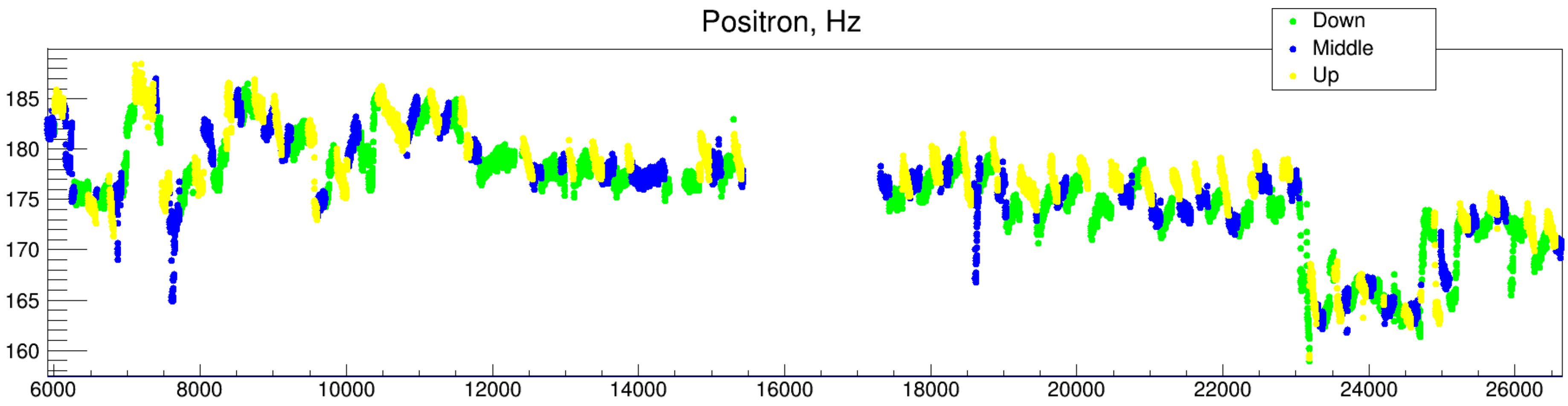
PMT

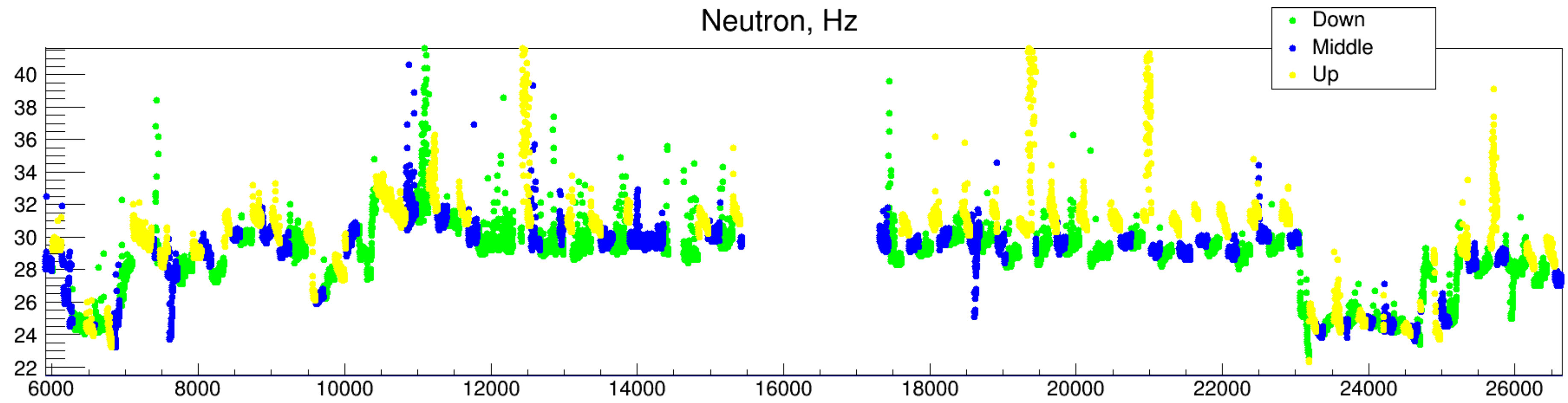


Стабильность



Стабильность





Data analysis

Raw data:
wafeforms
~500 Gb/day

Extract hit parameters

"digi"-files:
hit parameters
~50 Gb/day

Calculate trigger parameters

root-files:
trigger parameters
~5 Gb/day

Make events and random events

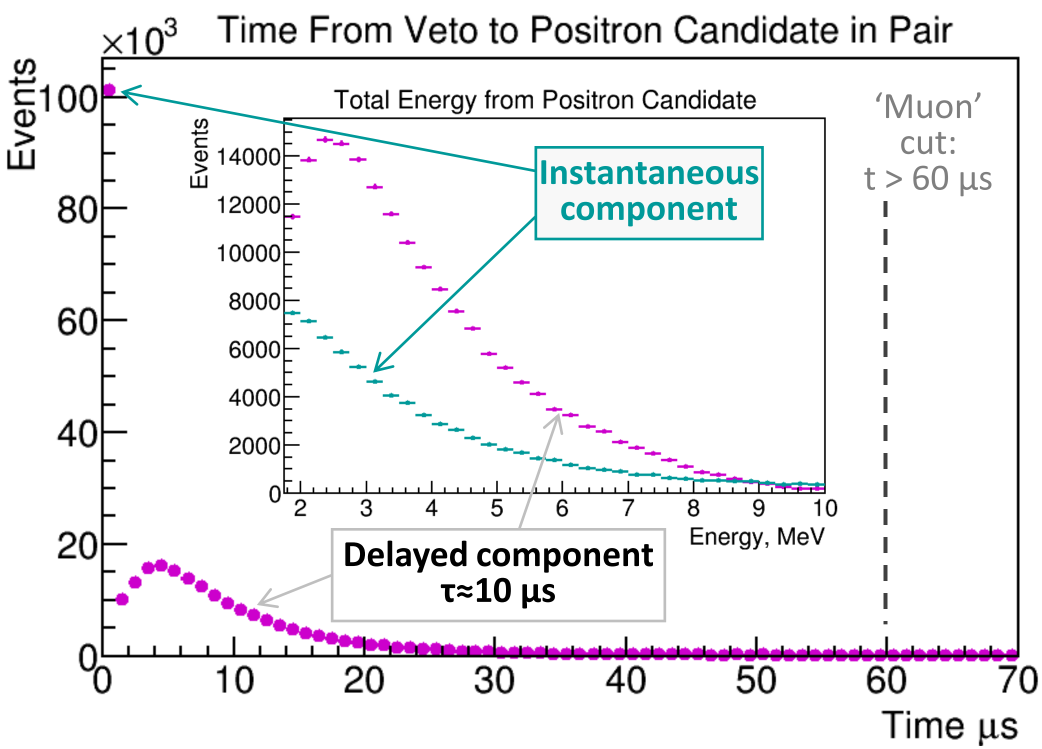
root-files:
event parameters
~30 Mb/day

Make physics distributions

Monte Carlo and Data analyses are identical

Event building and muon cuts

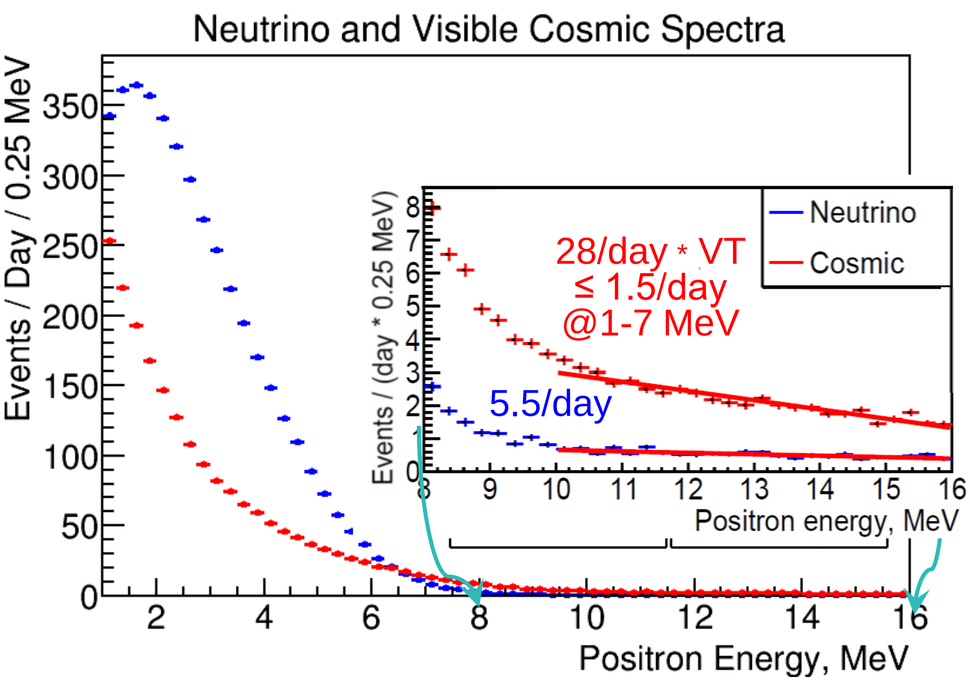
- **Building Pairs**
  - **Positron candidate: 1-20 MeV in continuous ionization cluster**
  - **Neutron candidate: 3.5-15 MeV total energy (PMT+SiPM), SiPM multiplicity >3**
  - **Search positron 50 μs backwards from neutron**

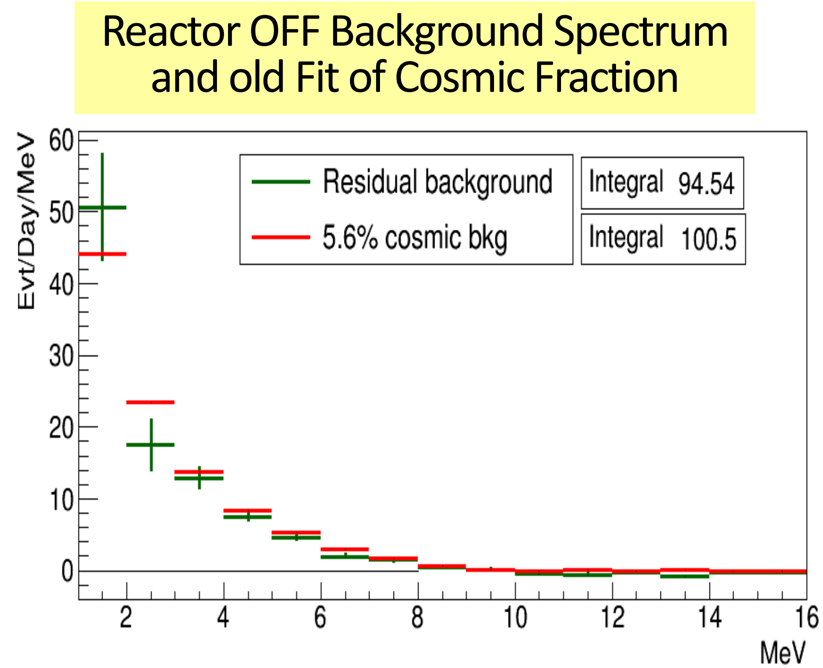


Muon Cuts

- **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**

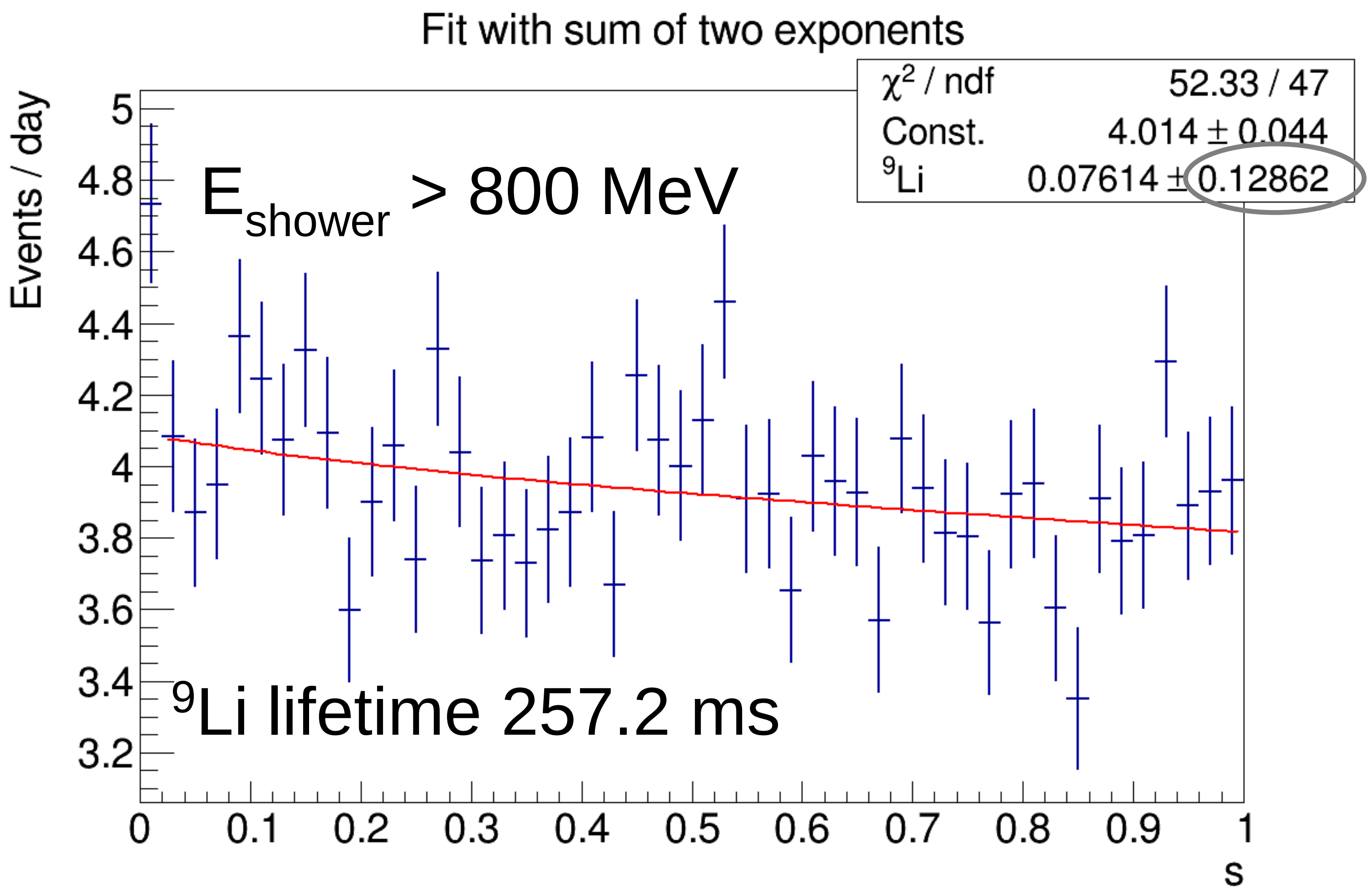
Residual background subtraction



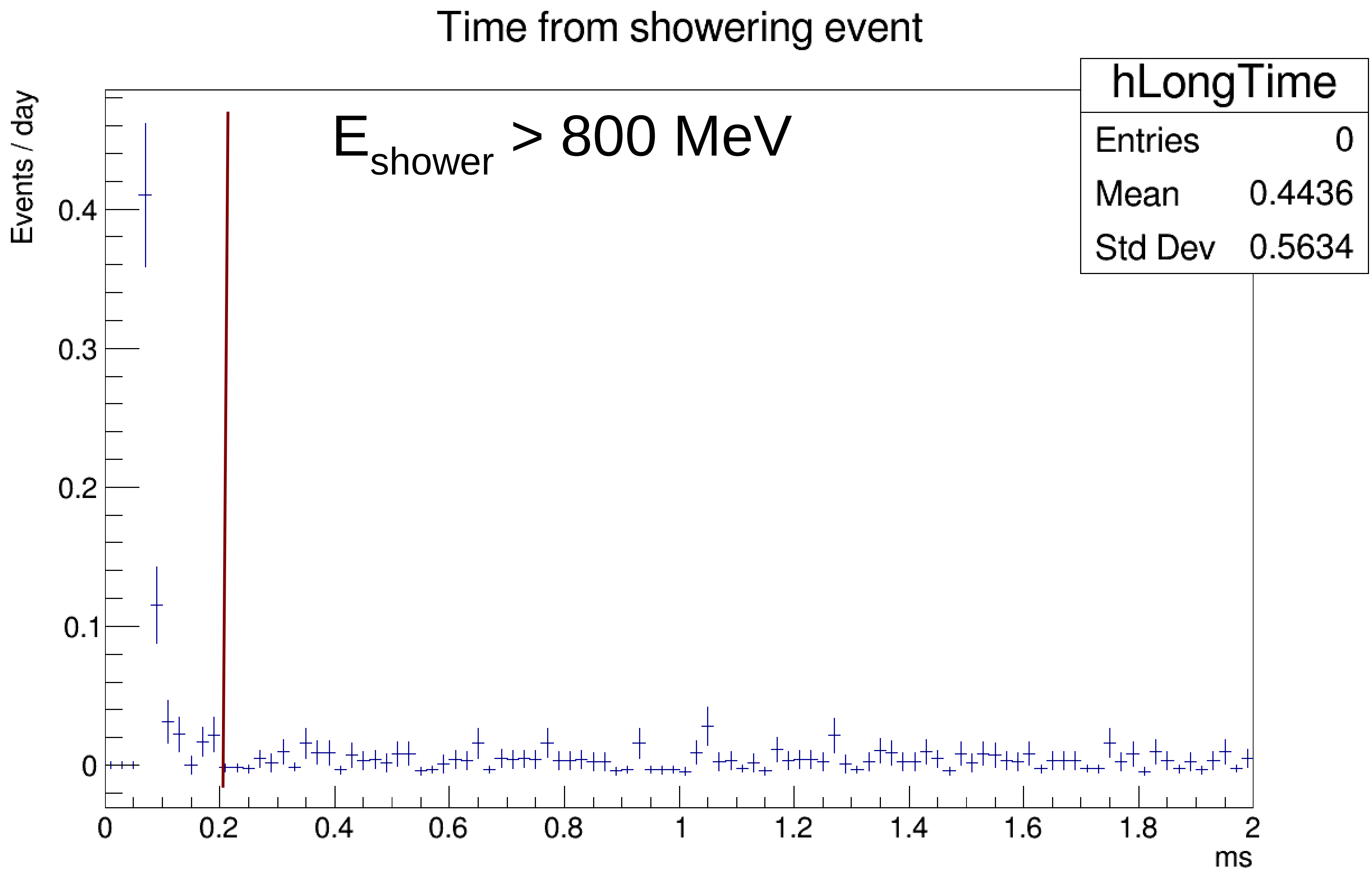


- **Fast neutron tails: linearly extrapolate from high energy region and subtract separately from positron and visible (i.e. rejected by VETO) cosmic spectra**
- **Subtract fraction of visible cosmics based on VETO inefficiency**
- **Amount of visible (rejected by VETO) cosmics <50% of neutrino signal**
- **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 is 2.8% of neutrino signal, subtracted**
- **Final neutrino spectrum (Ee+ + 1.8 MeV) has No background!**

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



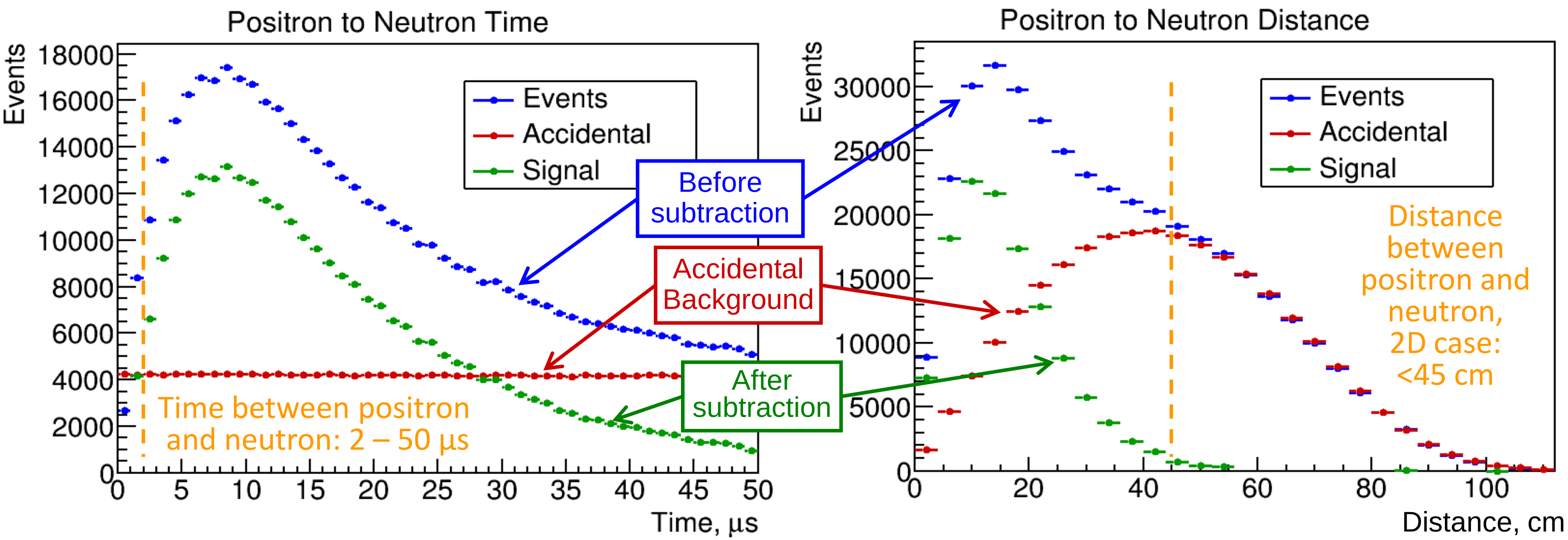
90% CL upper limit = 3 events/day



Time from showering event
hLongTime
Entries 0
Mean 0.4436
Std Dev 0.5634
E$_{shower}$ > 800 MeV
Events / day
0
0.1
0.2
0.3
0.4
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
ms

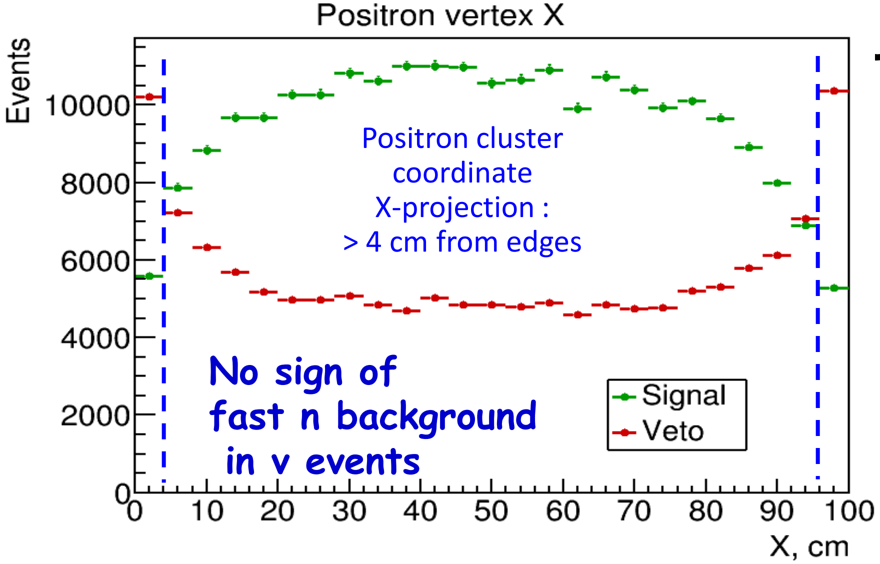
8

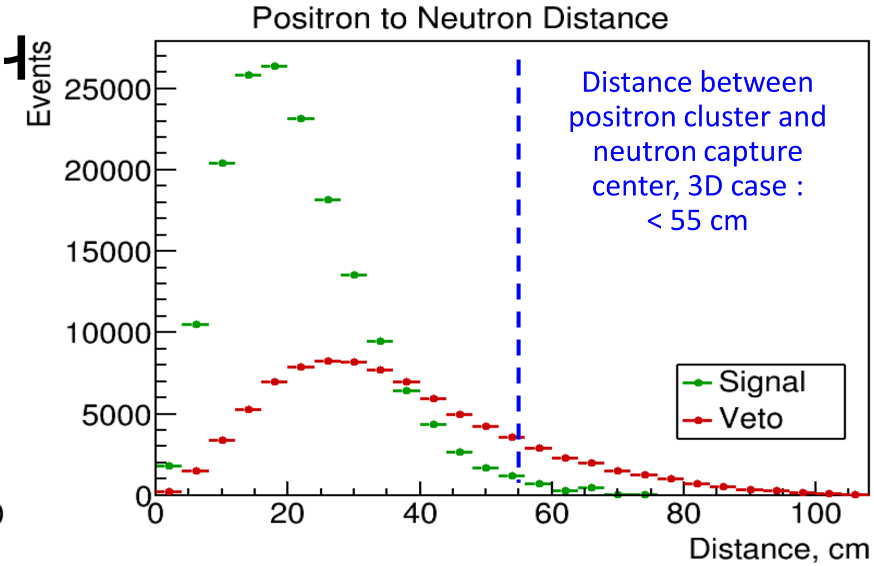
Accidental coincidence background



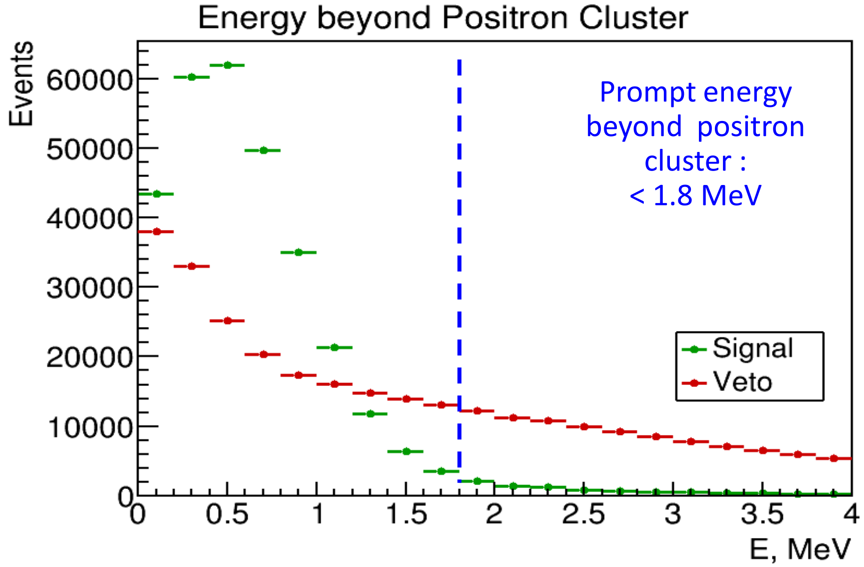
- Fake one of the IBD products by uncorrelated triggers
- Background events from data: search for a positron candidate where it can not be present – 50 μs intervals far away from neutron candidate (5, 10, 15 etc millisec)
- Enlarge statistics for accidentals by searches in numerous non-overlapping intervals
- Accidental rate is smaller but comparable to IBD rate
- 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

Additional cuts using fine segmentation



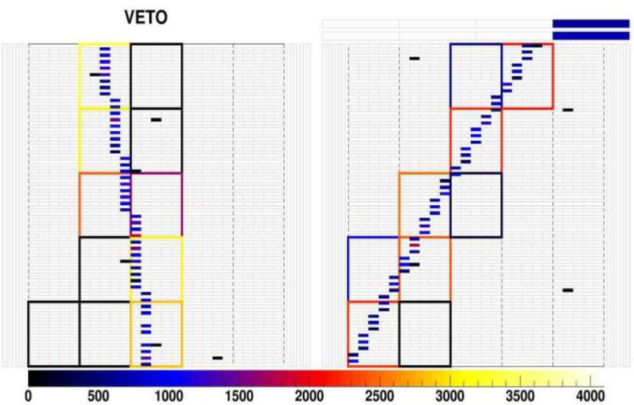


- Comparison of the distributions for the events which passed the muon cut with similar for those accompanied by muons
- Positron cluster position: 4 cm from all edges
- Vertical projection of the distance: <40 cm
- Multiplicity beyond positron cluster: <11
- Totally 8 cuts of this kind
- Reject cosmic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

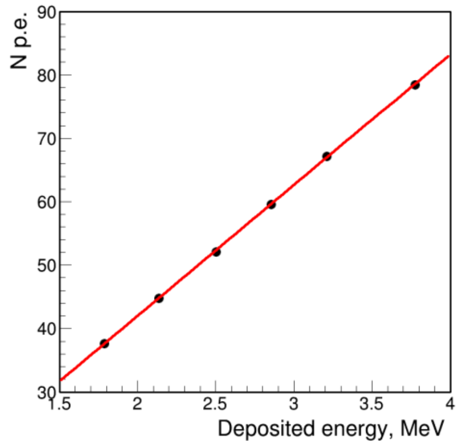


Calibration

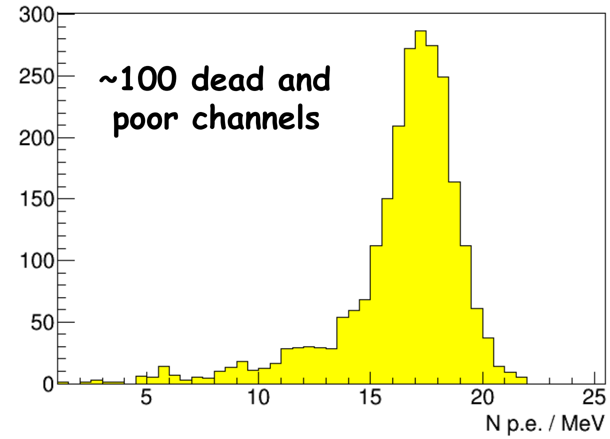
With cosmic muons



Response is linear with energy

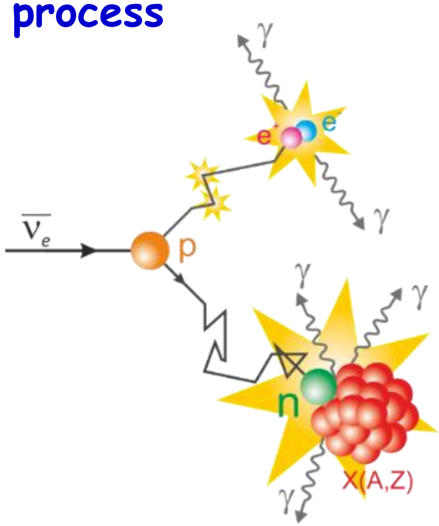


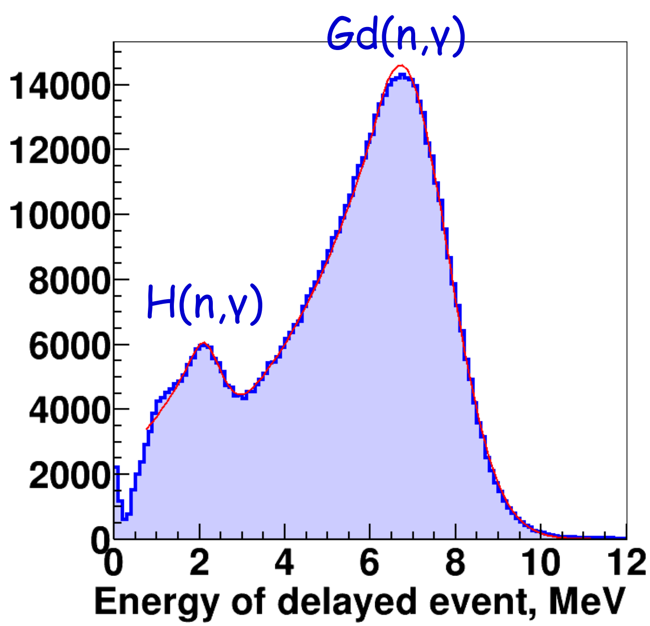
Uniformity of SiPM response before calibration

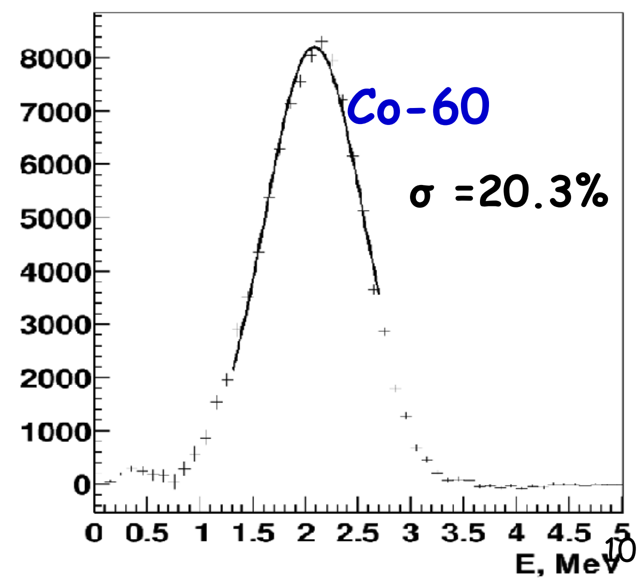


With radioactive sources. 248Cm n source is similar to IBD process

Inverse Beta Decay (IBD) process

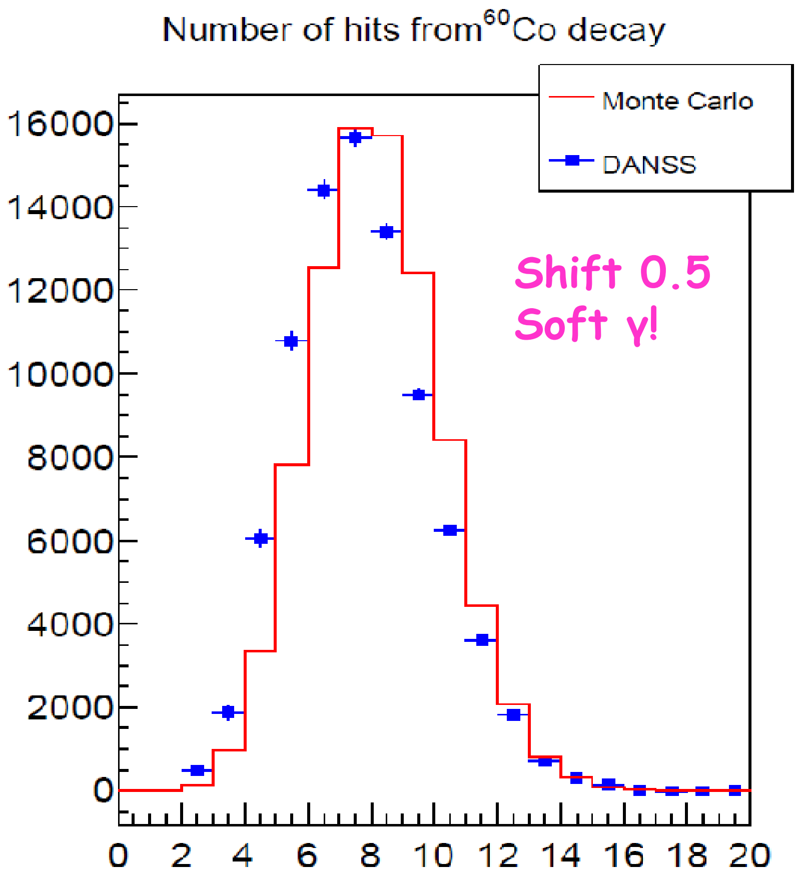






MC simulation (GEANT4 V4.10.4) of DANSS is very detailed

Longitudinal and transverse profiles of light collection
Losses in dead material and dead channels
Fluctuations in number of p.e. at first 2 dinodes
Excess noise factor for SiPMs due to X-talk
Measured cosmic muon angular distribution

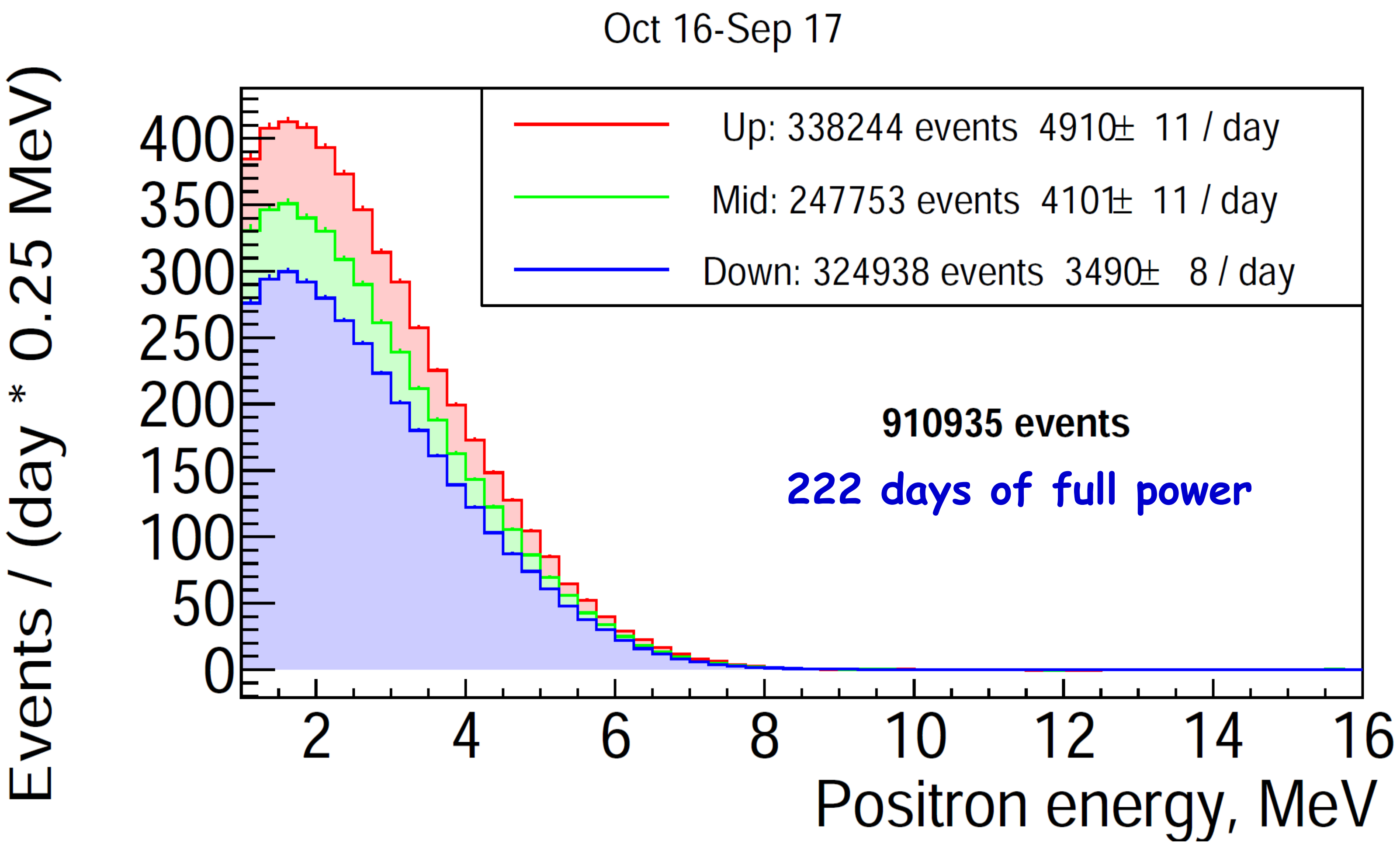


MC reproduces sensitive distributions

However MC underestimates energy resolution by 15%.

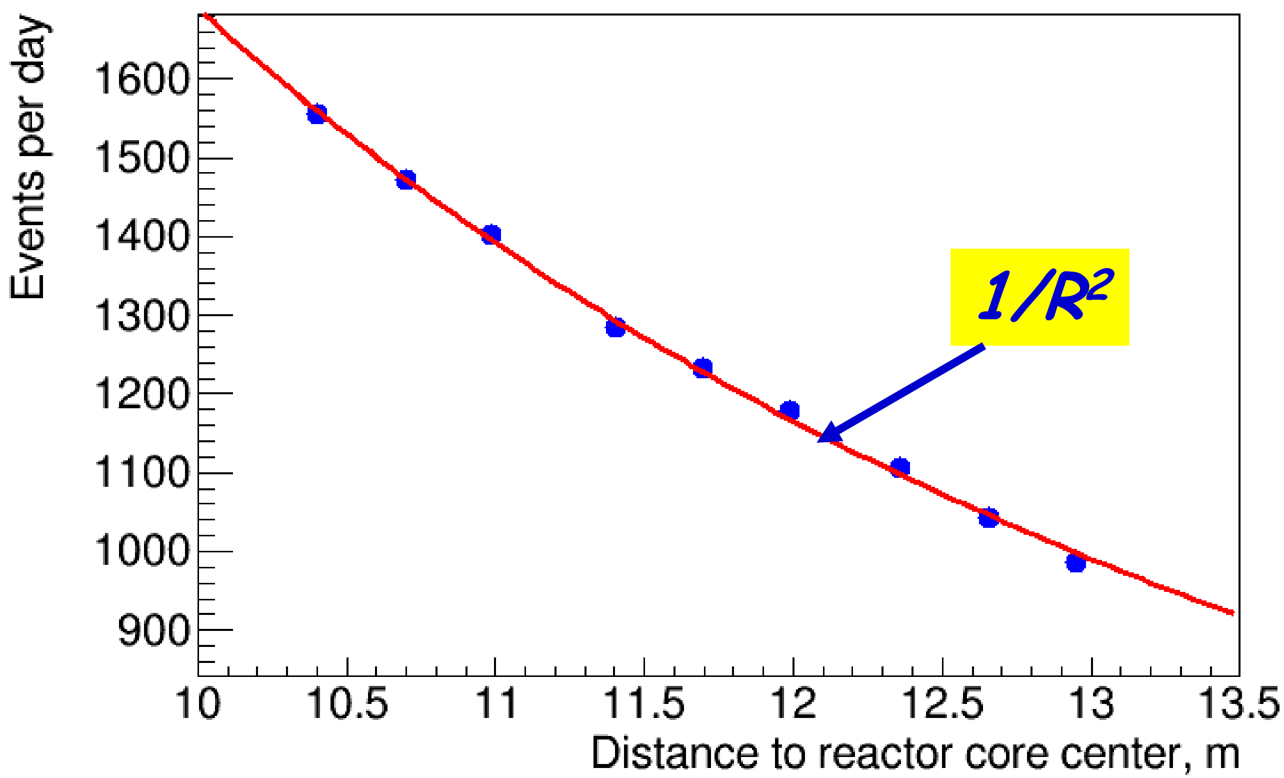
MC predictions are scaled up by 15%

Positron spectrum



- **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

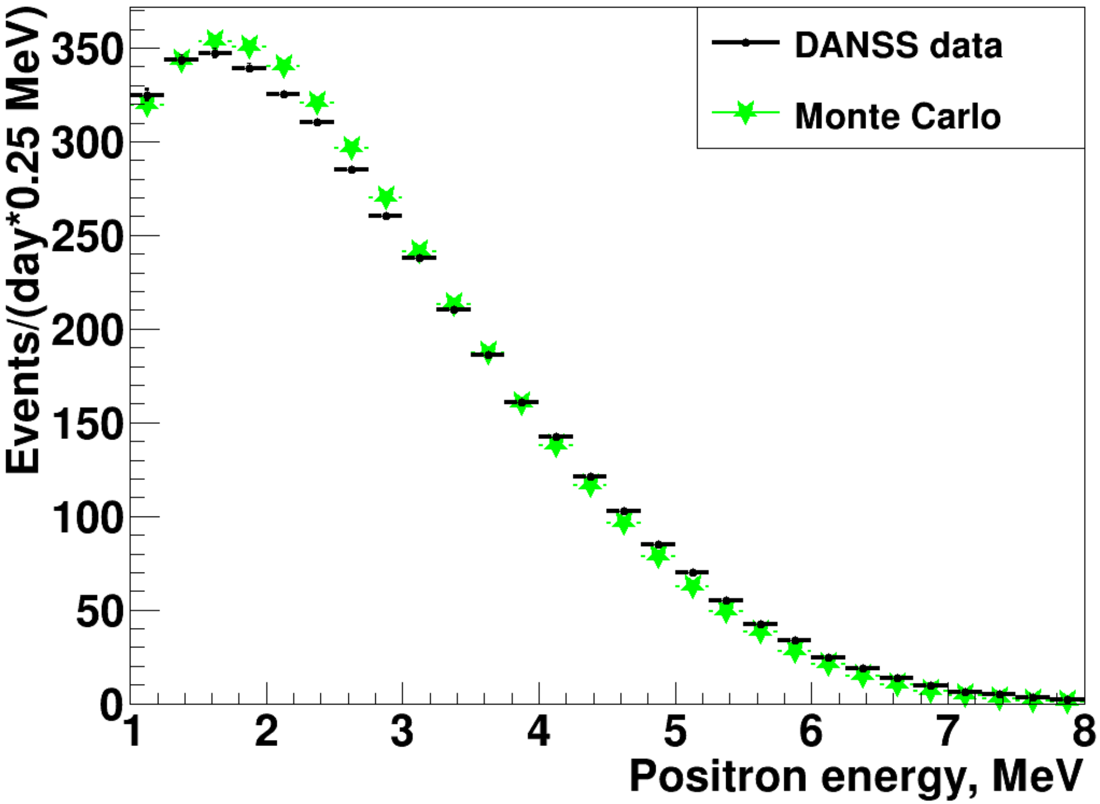


- **3 detector positions**
- **Detector divided vertically into 3 sections with individual acceptance normalization**

Rough agreement with $1/R^2$ dependence

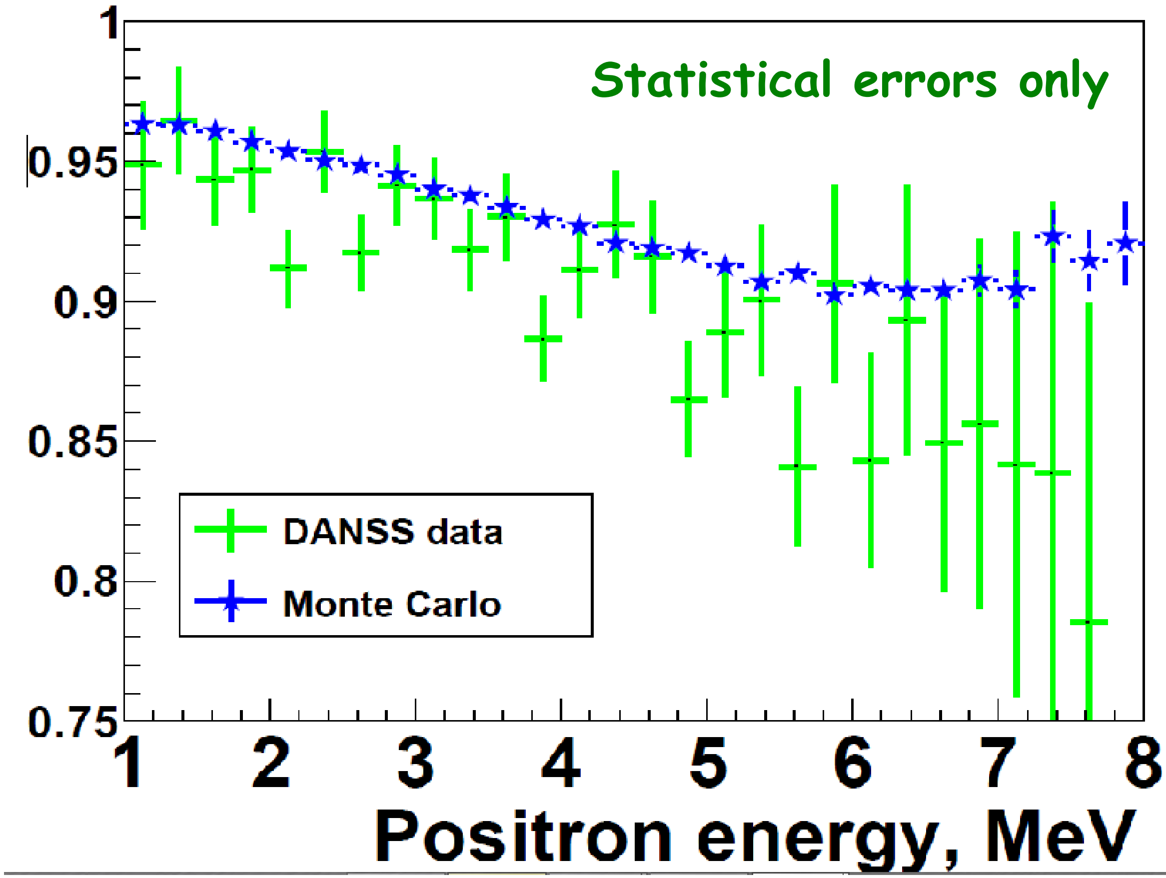
Not used so far in analysis!

Positron spectrum (last 4 months of campaign)



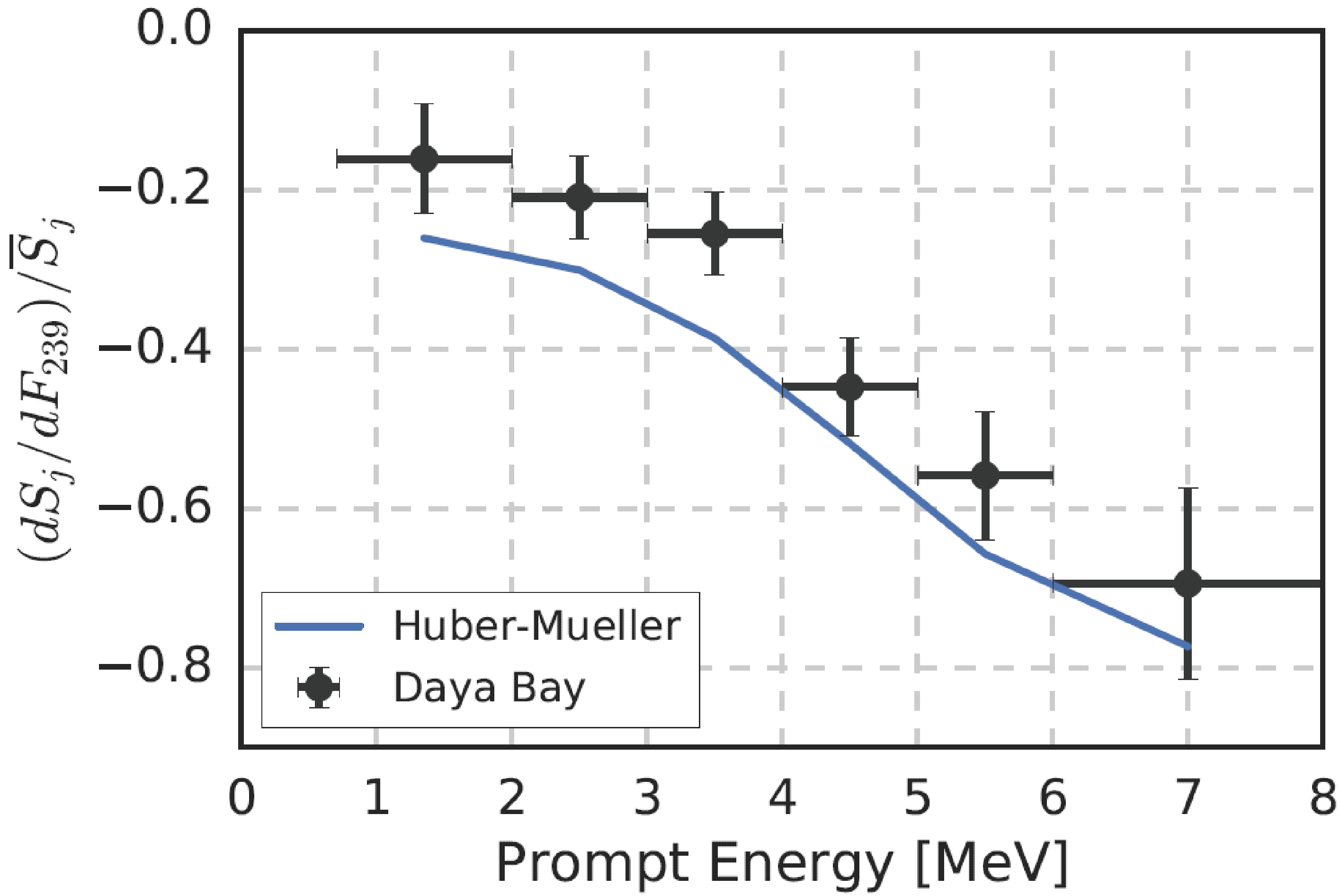
Rough agreement with MC.
(Theoretical neutrino spectrum was taken from Huber and Mueller)
More work on calibration is needed before quantitative comparison

Ratio of positron spectra at the end and beginning of campaign (Δ239Pu=11%)

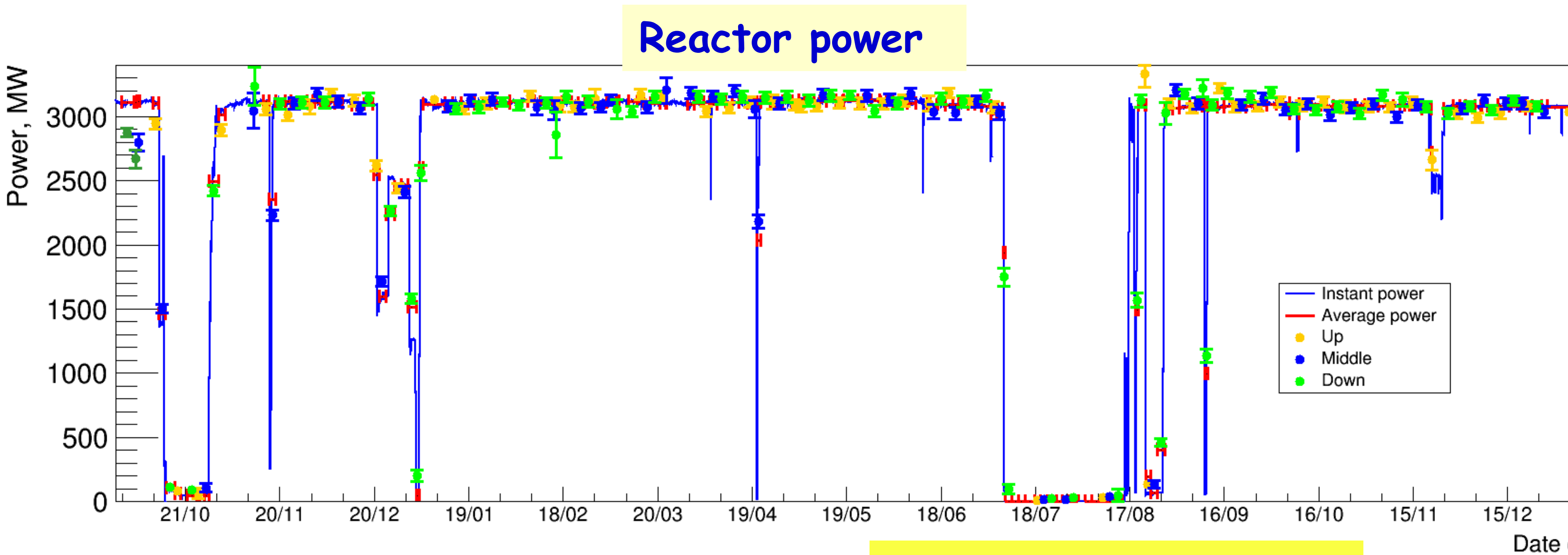


Clear evidence for spectrum evolution
Spectrum evolution is consistent with MC contrary to Daya Bay measurements

Daya Bay measurements of spectrum evolution (smaller than MC predictions for 25-35% 239Pu)

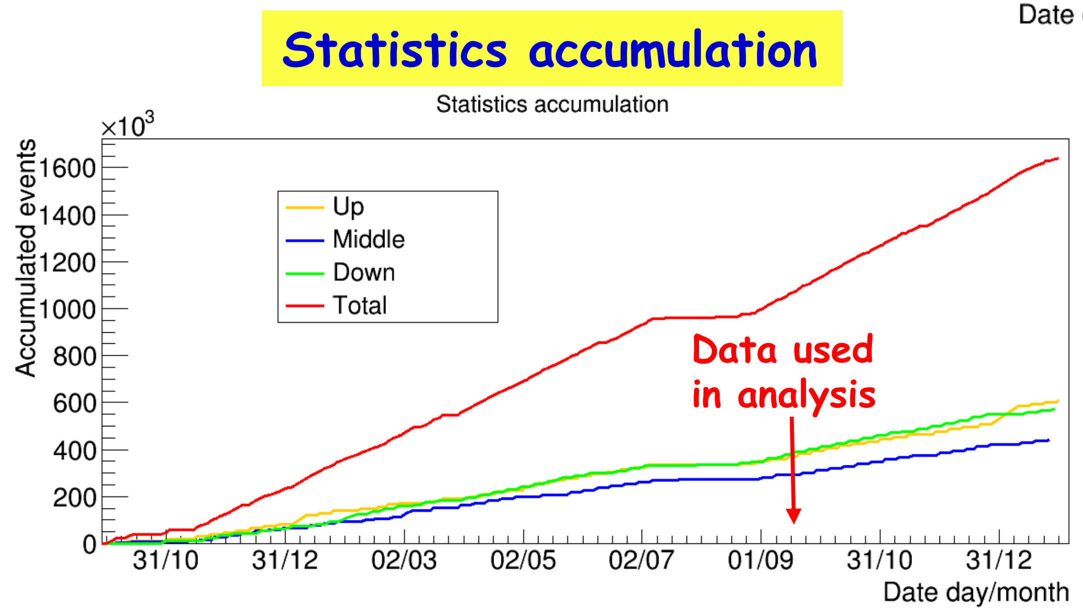


Comparison of reactor power and DANSS rate



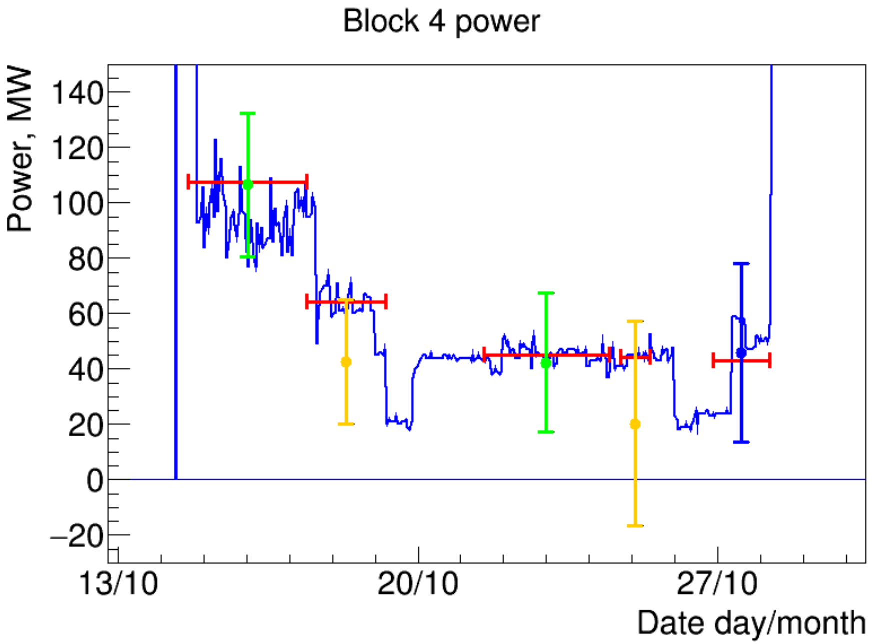
- **On power graph:**
  - **Points at different positions equalized by $1/r^2$**
  - **Normalization by 12 points in November-December 2016**
  - **Adjacent reactor fluxes subtracted (0.6% at Up position)**
  - **Spectrum dependence on fuel composition is included**

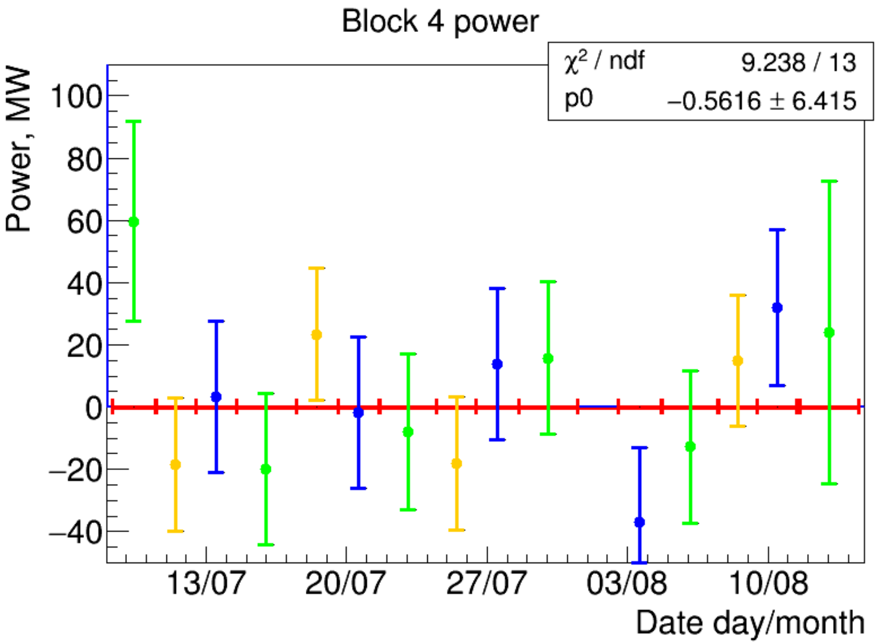
  MC underestimates changes a bit
- **Statistics @100% power, ~222 days after QA**



Comparison of reactor power and DANSS rate

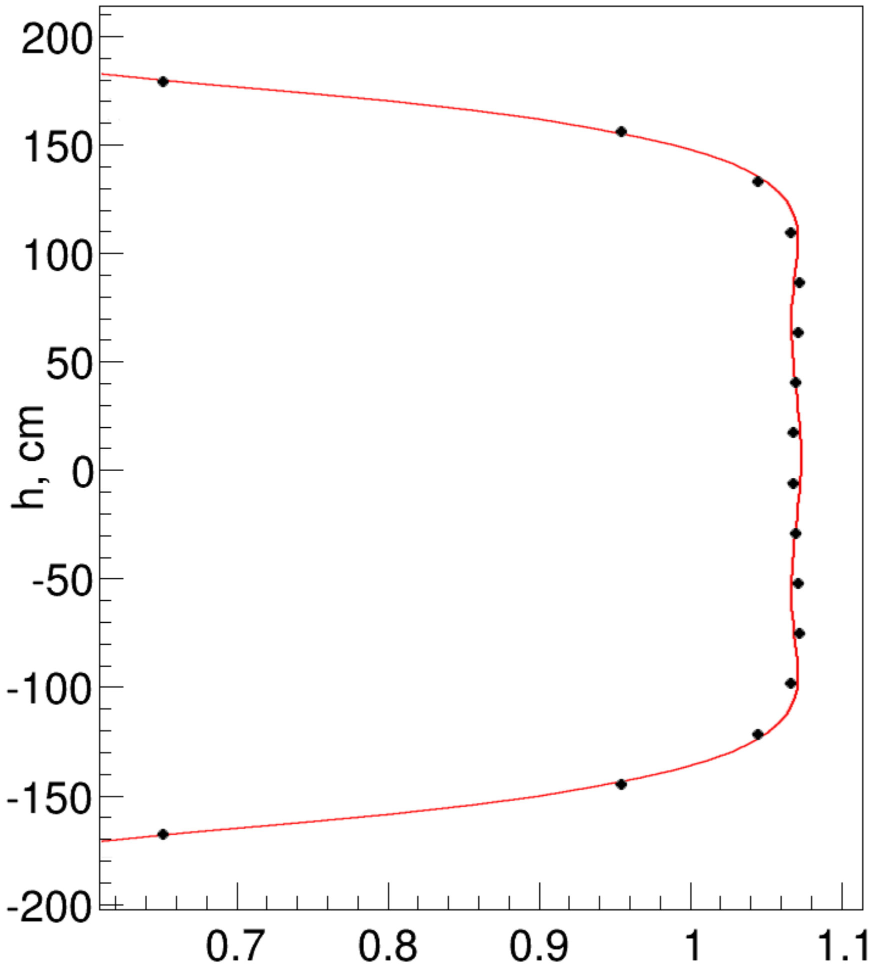
Cosmic VETO system inefficiency (5.6%)
was determined during the first reactor OFF period





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

Reactor core burning profile averaged over campaign

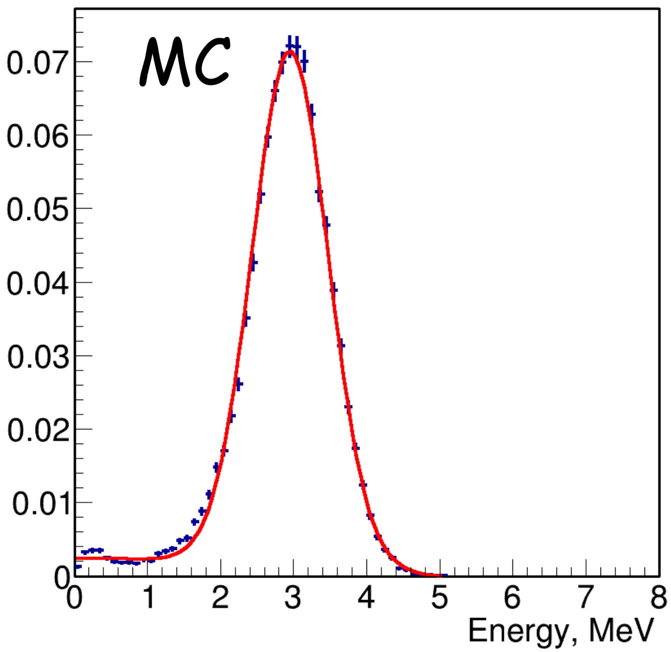


Data Analysis

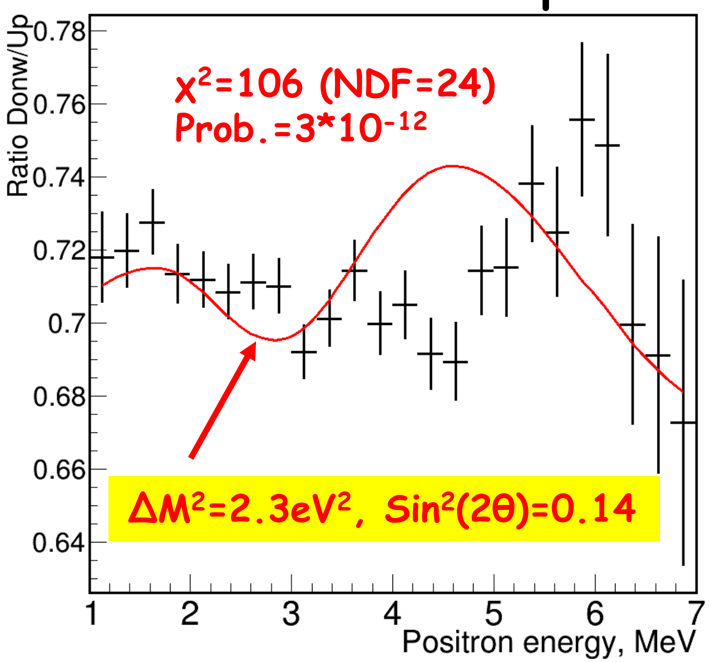
For every ΔM^2 and $Sin^2(2\theta)$ e^+ spectrum was calculated for Up and Down detector positions taking into account reactor core size and detector energy response including tails (obtained from cosmic muon calibration and GEANT-4 MC simulation identical to data analysis)

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



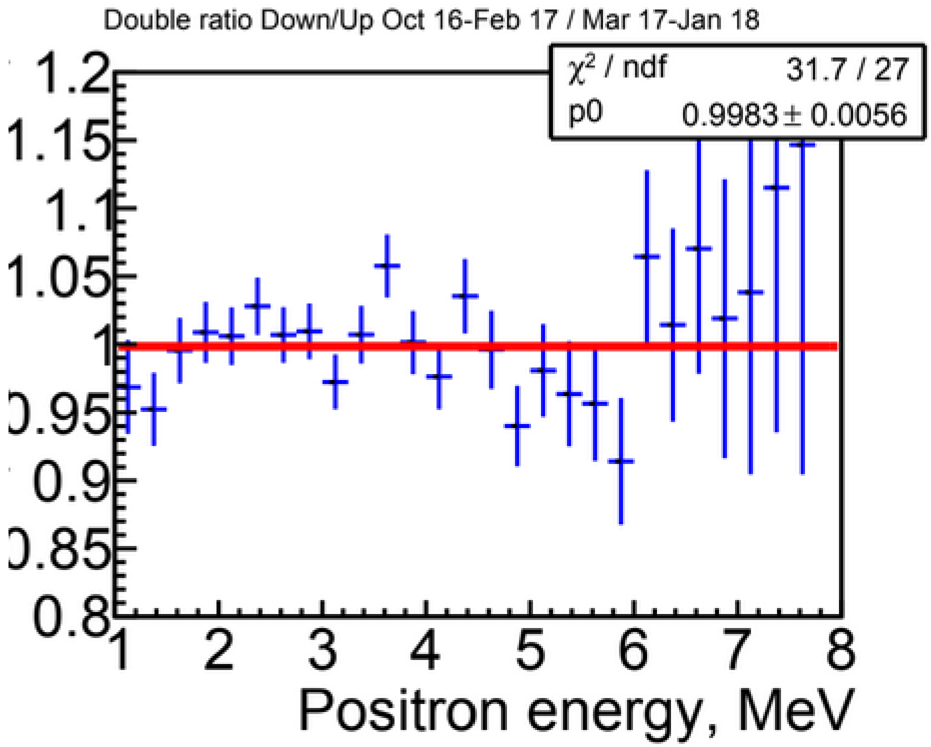
3 ν hypothesis:
χ^2=35
Prob.=0.064

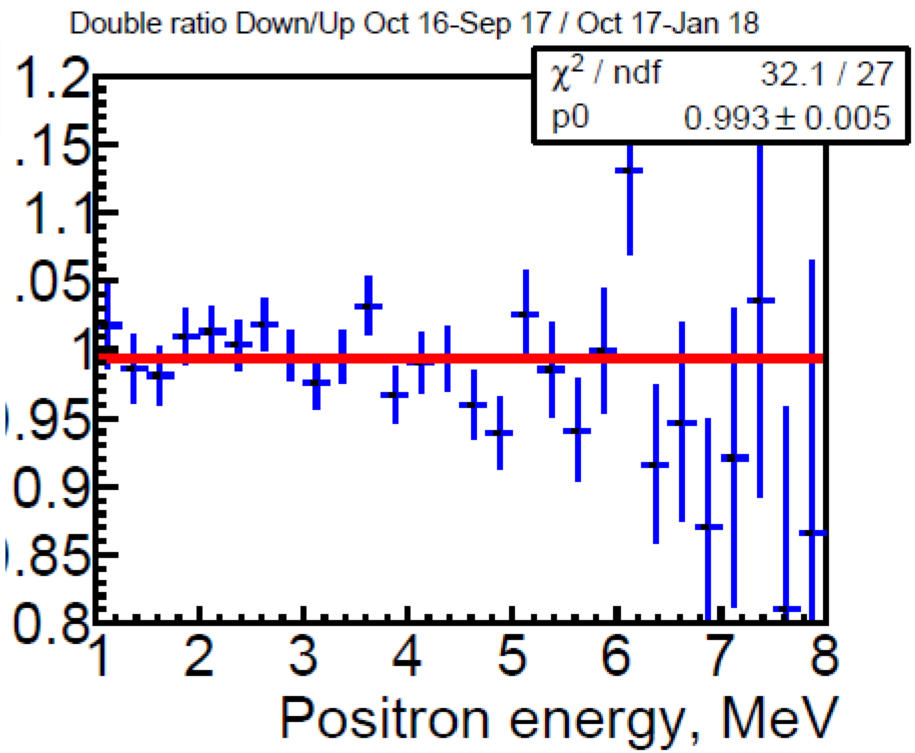
Most plausible parameter set from Reactor and Galium anomalies is excluded!

Stability of results

We checked that results are stable in time and against variations of selection criteria

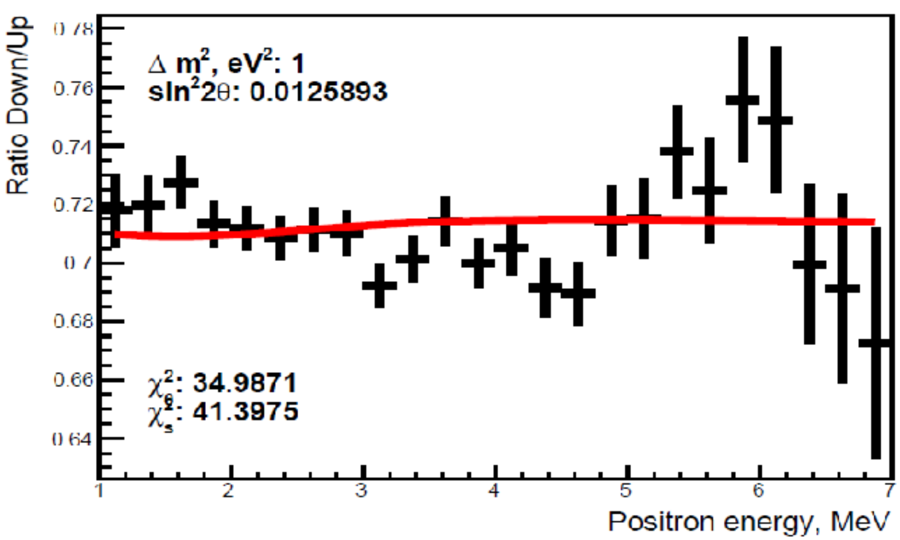
Ratio of bottom/up ratios for different time periods
Probabilities of χ2 about 25%

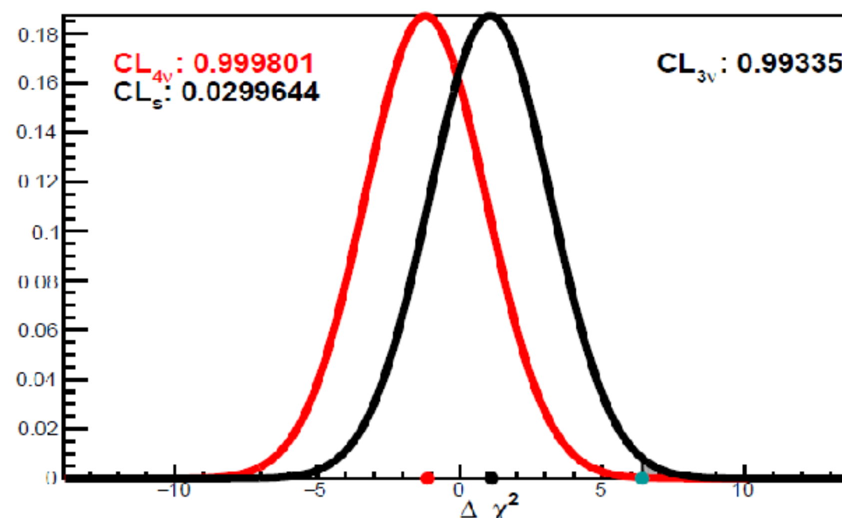




Gaussian CL_s (arXiv:1407.5052v4 [hep-ex])

- Помещаем точки на кривую (Asimov data set) Gauss(μ, σ): $\mu = \Delta\chi^2 = \chi^2_s - \chi^2_0 = -\chi^2_0$, $\sigma = 2\sqrt{|\Delta\chi^2|}$; $\mu_{H_0} = -\mu_{H_1}$, $\sigma_{H_0} = \sigma_{H_1}$
- Вычисляем $\Delta\chi^2$ для данных
- Определяем уровень достоверности $CL = \frac{1-CL_1}{1-CL_0}$, где $CL_i = \int_{-\infty}^{\Delta\chi^2_{data}} G_i$





Preliminary results

Exclusion region was calculated using Gaussian CLs method

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

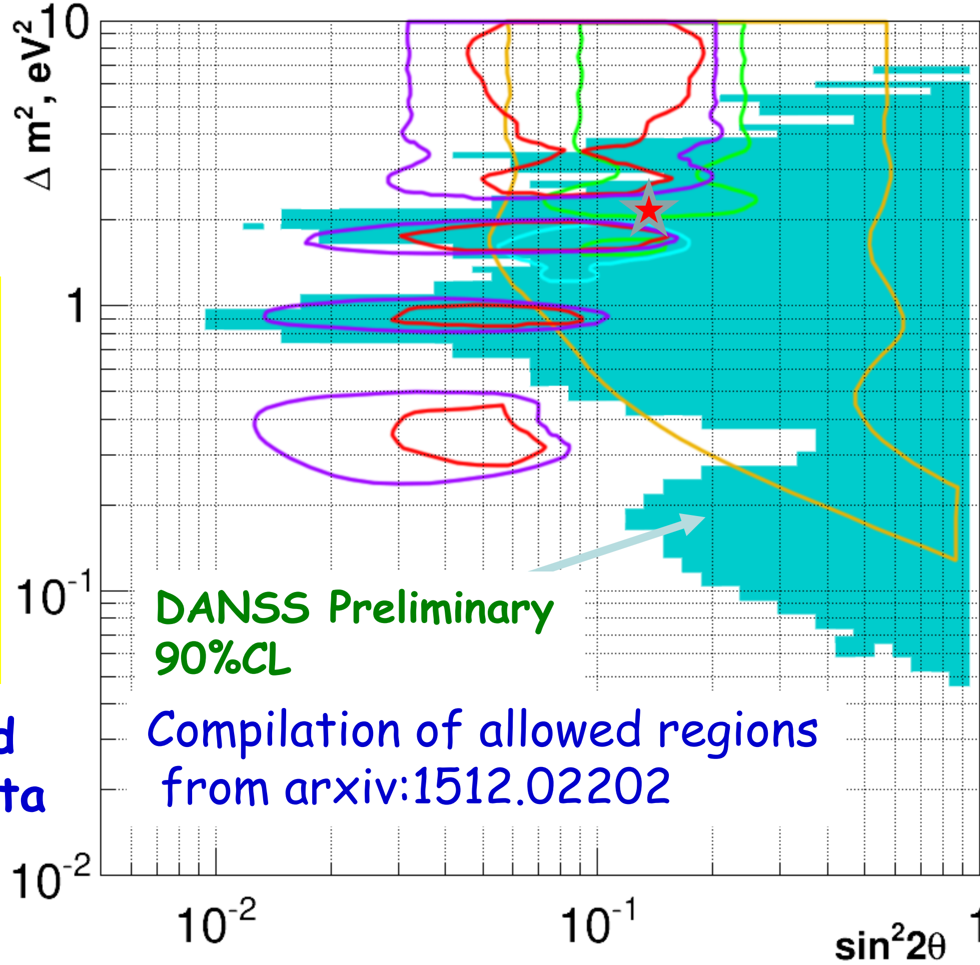
CLs method is more conservative than usual Confidence Interval method

Systematics studies include variations in:

- -Burning profile in reactor core
- -Energy resolution ±%
- -Level of cosmics background ±0.5%
- -Energy intervals used in fit (1.5-6)

Systematics influence 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,…)

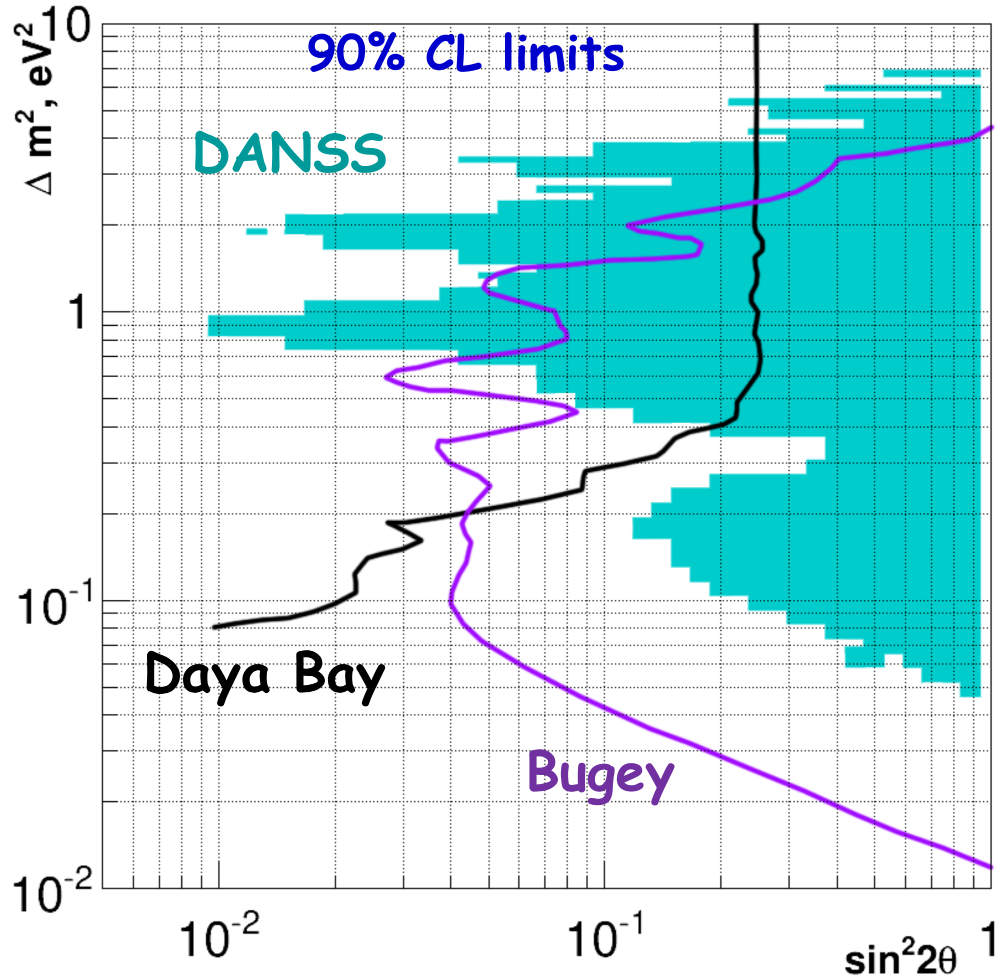


-DANSS plans to collect more data and to include into analysis all available data

-Detector calibration and systematics studies will be continued

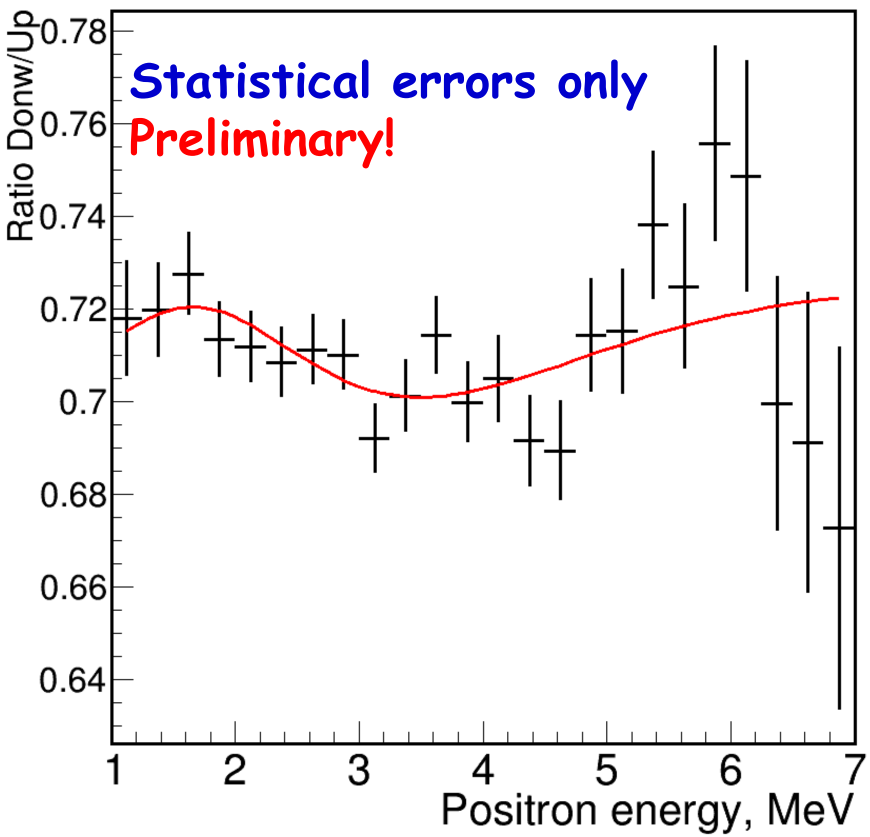
Comparison with experiments based on spectra ratio at different distances

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



Best point:

ΔM^2=1.4, $Sin^2(2\theta)$=0.045, X^2=22 Prob.=0.58 ΔX^2=13.3 (3σ)



Significance will be estimated using Feldman and Cousins method with systematic uncertainties after collection more data

Summary

- DANSS records about 5000 antineutrino events per day with cosmic background <3%

- DANSS counting rate consistent with reactor power within ~1%. During reactor shutdown It is consistent with 0 after subtraction of ~3% cosmic background and 0.6% flux from adjacent reactors

- Antineutrino spectrum and counting rate dependence on fuel composition is clearly observed

- **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 ν spectrum and detector efficiency!)**

- Significance of the best fit point will be evaluated using more elaborated methods and more statistics

We plan to collect more data,

To improve MC for perfect description of detector response

To refine detector calibration

To continue systematic studies

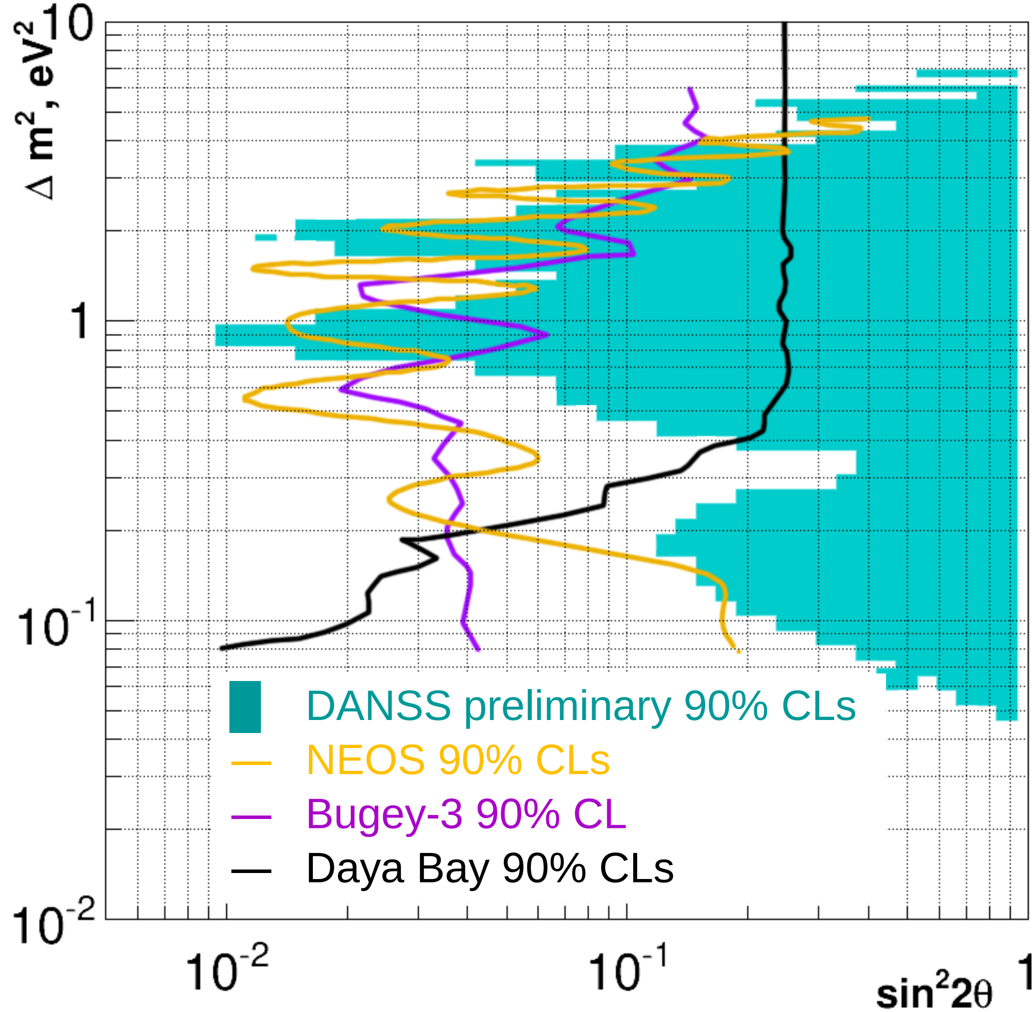
To include all available statistics into analysis

Thank you !

Backup slides

Comparison with other experiments

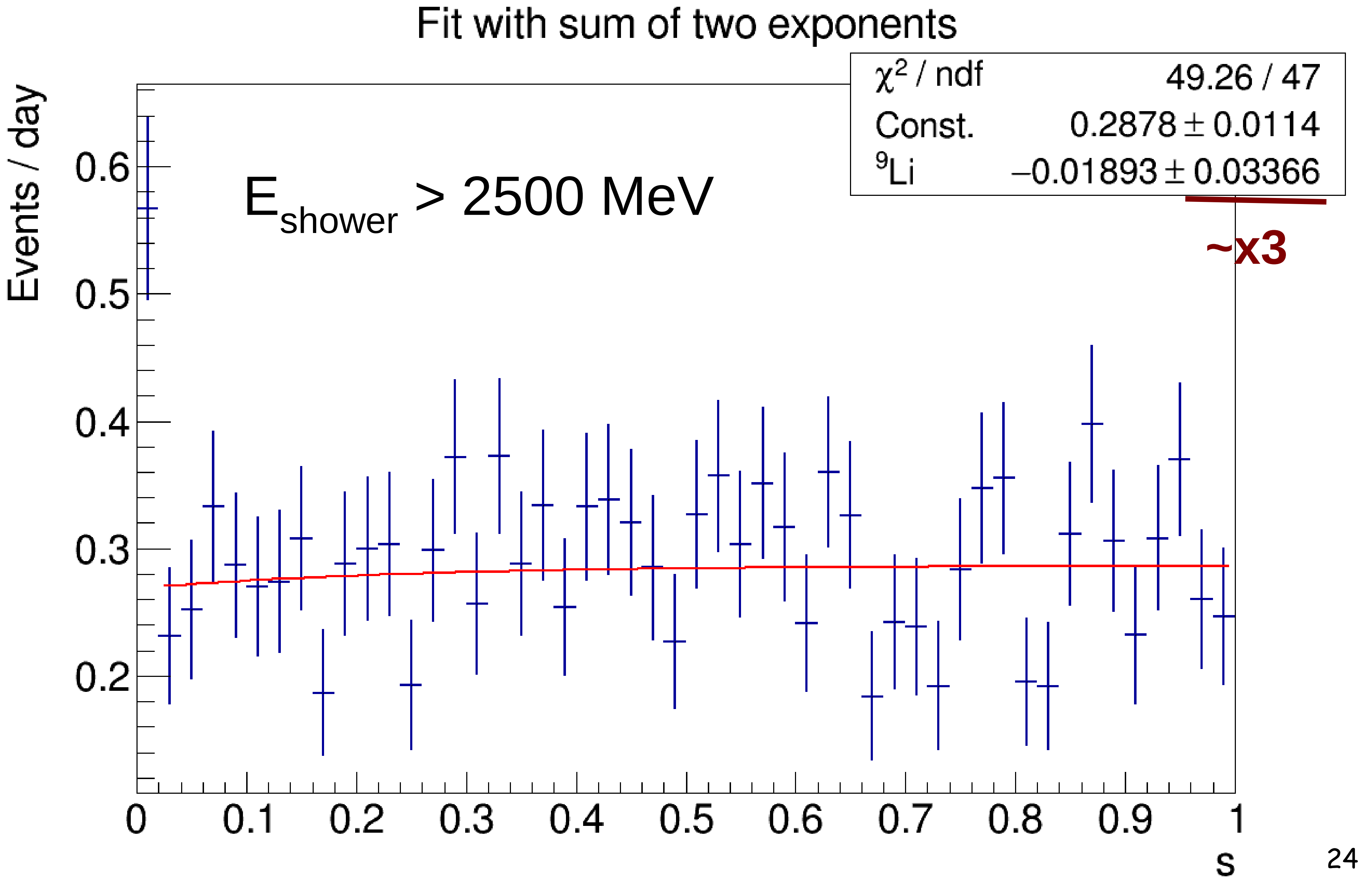
NEOS – normalization on Daya Bay → systematic errors?
Bugey – use of "old" reactor model → Systematic errors?



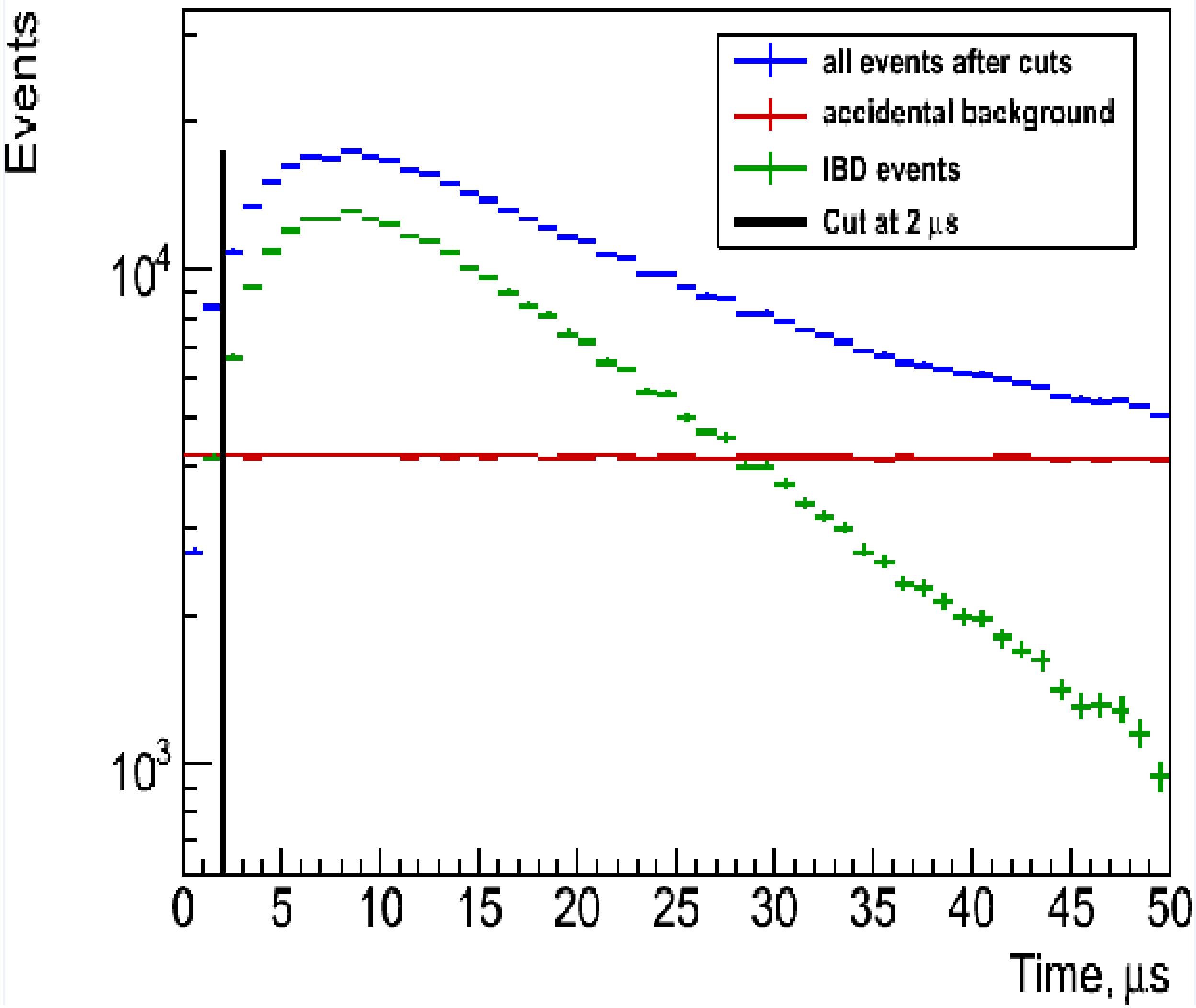
arXiv:1610.05134 [hep-ex]

^{9}Li and ^{8}He background estimation

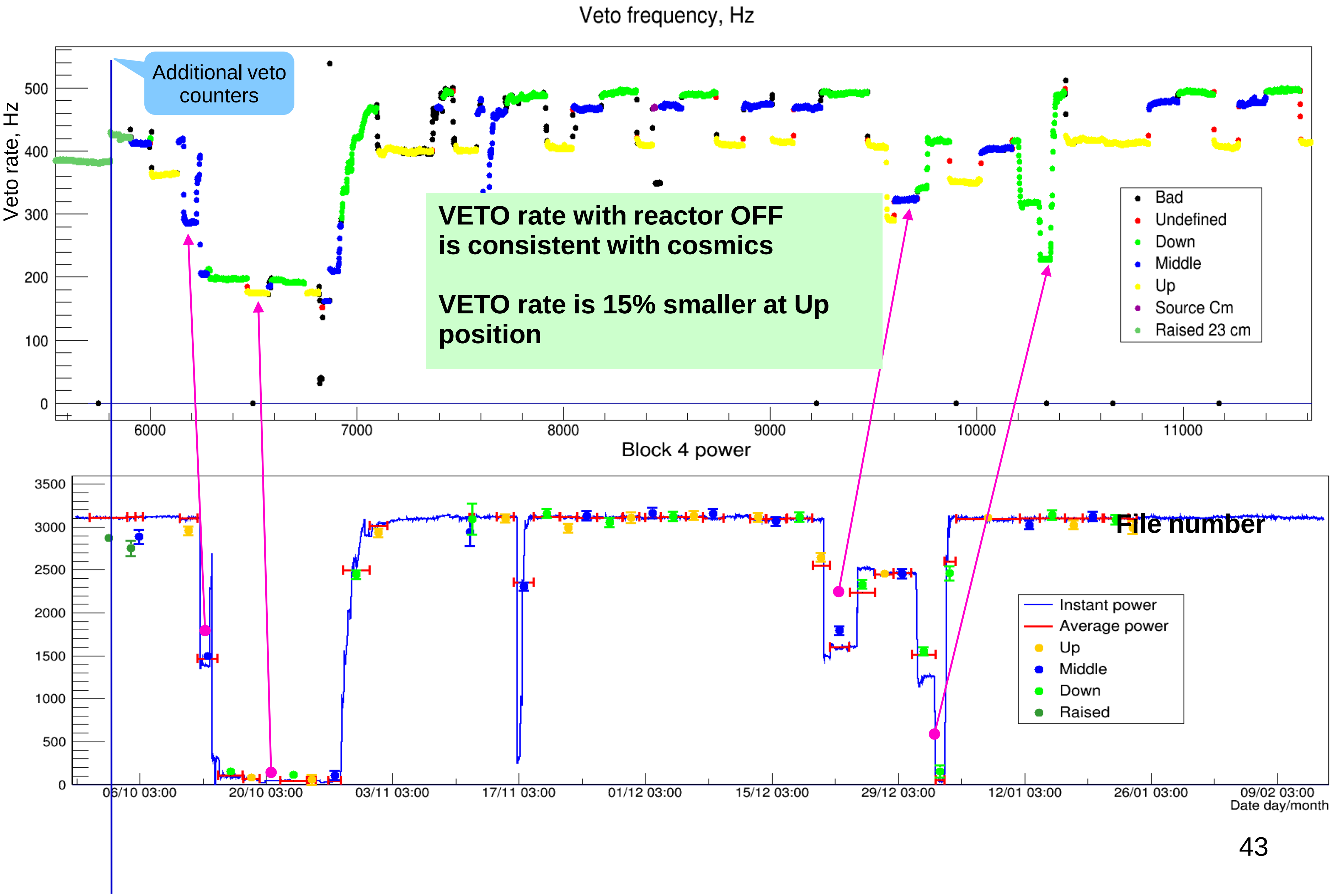
90%CL limit: 1.64 * 3 * 0.034 * 257.2 / 20 = 2.2 events/day



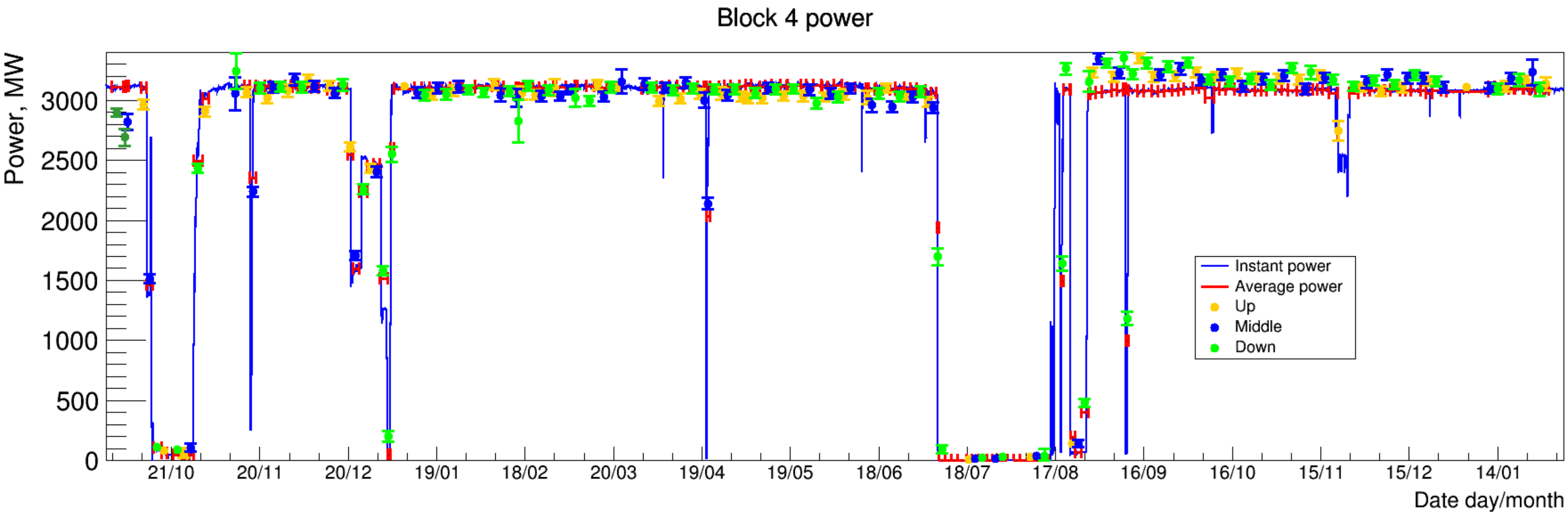
Delay time of the neutron signal



Veto

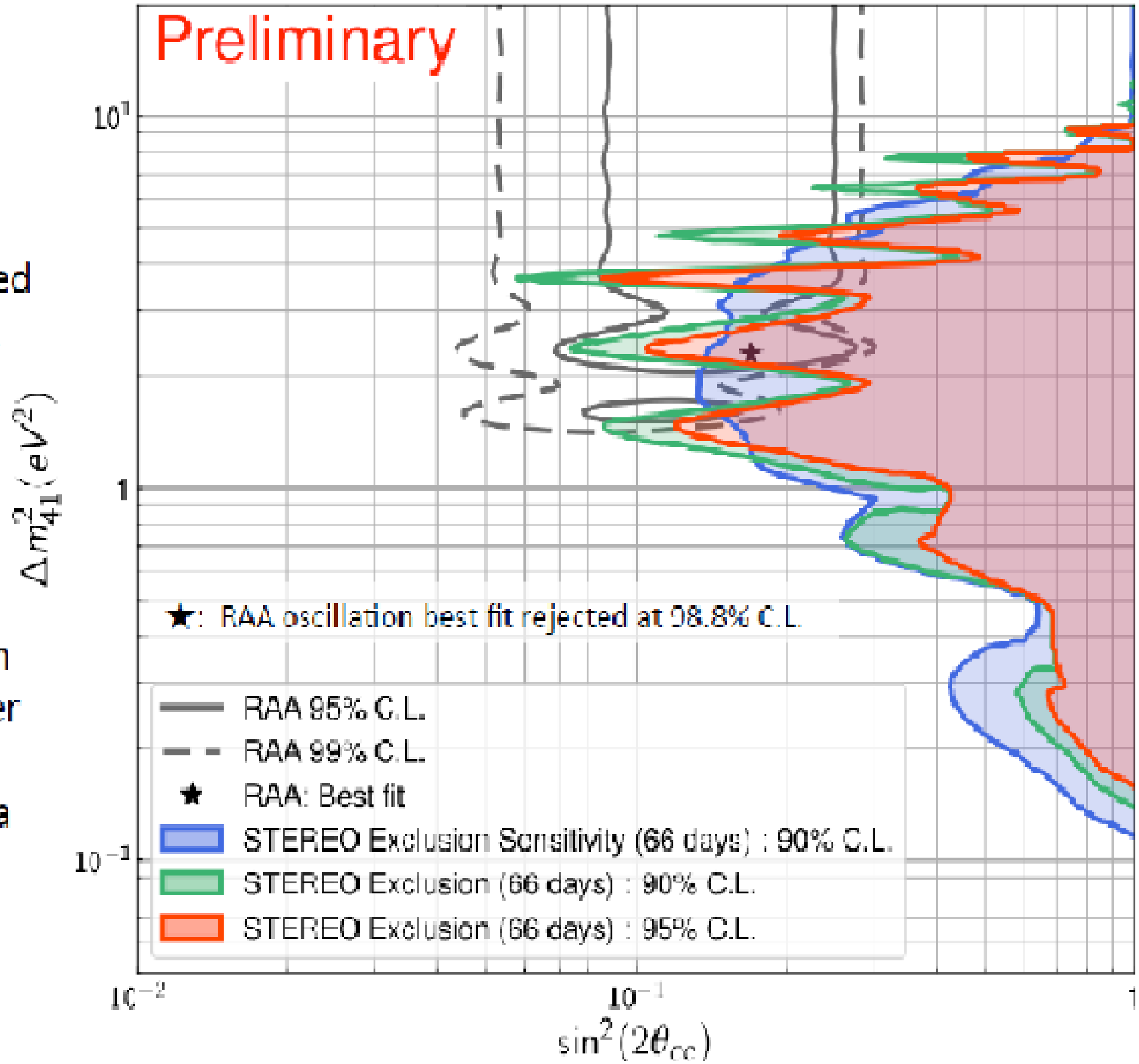

Veto frequency, Hz
Additional veto counters
Veto rate, Hz
500
400
300
200
100
0
6000
7000
8000
9000
10000
11000
Block 4 power
Bad
Undefined
Down
Middle
Up
Source Cm
Raised 23 cm
VETO rate with reactor OFF is consistent with cosmics
VETO rate is 15% smaller at Up position
3500
3000
2500
2000
1500
1000
500
0
06/10 03:00
20/10 03:00
03/11 03:00
17/11 03:00
01/12 03:00
15/12 03:00
29/12 03:00
12/01 03:00
26/01 03:00
09/02 03:00
Date day/month
File number
Instant power
Average power
Up
Middle
Down
Raised

Comparison of reactor power and DANSS rate without correction for fuel evolution



STEREO Contours

- Raster scan approach.
- $\Delta\chi^2$ law simulated in each Δm^2 bin.
- Reject oscillation amplitudes larger that statistical fluctuations for a given C.L.



arXiv:1703.01683
arXiv:1802.02884v1

SoLid at BR2

Phase-1 data taking started !

Detector technology: plastic scintillator (PVT) with LiF:ZnS(Ag) phosphor screens

High efficiency neutron ID

PVT has excellent linearity in energy range

Fine segmentation 12800 cubes to isolate positron energy

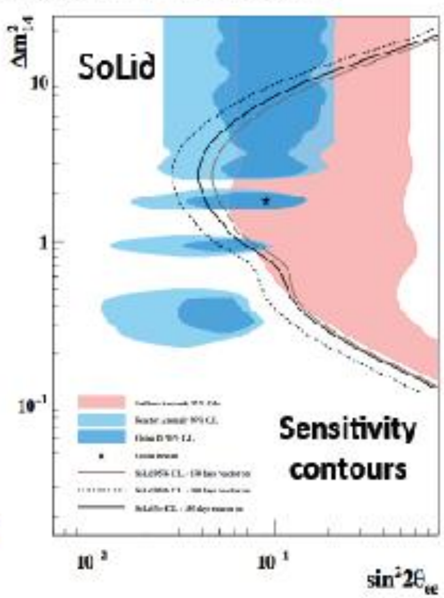
50 detector planes, 1.6 tons, 3500 read out channels


5 x 5 x 5 cm cube

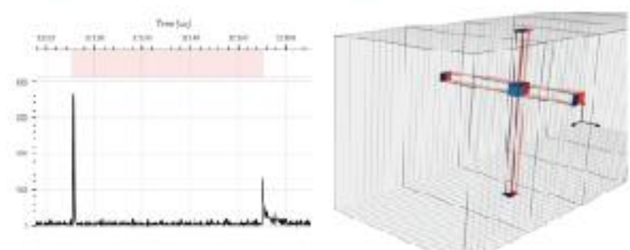

Detector on rail

Installed 6.2 m from BR2 reactor, SCK•CEN mol, Belgium

Parameters	Objectives
Total mass	1.6 t
IBD efficiency	30 %
Threshold	200 - 500 keV
Anti-neutrinos	~1000 d^{-1}
Signal/Background	~3
Energy resolution	14% à 1 MeV
Systematic uncertainty	2.5 - 4.5 %



Sensitivity contours


Antineutrino candidate in commissioning data

Commissioning completed succesfully in December 2017

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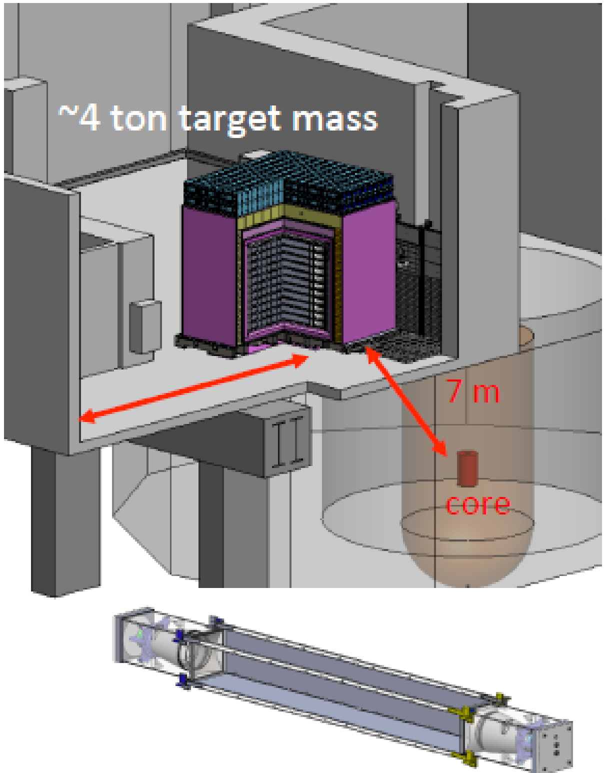
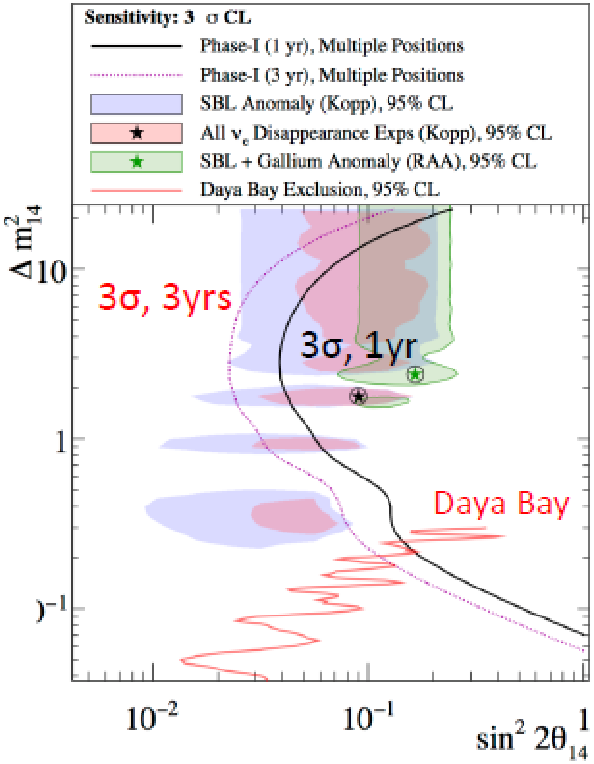
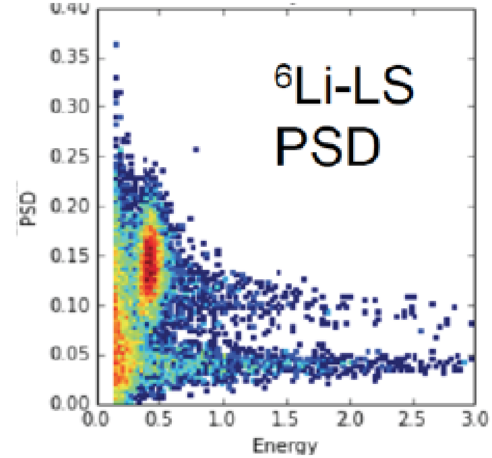
PROSPECT – HFIR@ORNL

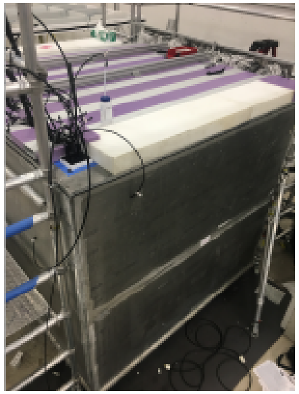
Segmented, ^{6}Li-loaded Movable Detector







Discriminant n-capture on ^{6}Li



Segmented Detector
14x11 segments
~4.5%/√E resolution

Objectives
4σ test of best fit after 1 year
>3σ test of favored region after 3 years

Detector construction complete
Installation happening now at HFIR
Online soon!