Measurement of Neutrino Oscillation with KamLAND: Evidence of Spectral Distortion

hep-ex 0406035 (June 2004) submitted to PRL
see also http://neutrino2004.in2p3.fr/ (G. Gratta)

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for the KamLAND collaboration

第15回「宇宙ニュートリノ」研究会、東京大学宇宙線研究所
2004年6月24日

- 4.7 times larger statistics than the first result
  (162 ton-yr -> 766.3 ton-yr)

The KamLAND Collaboration

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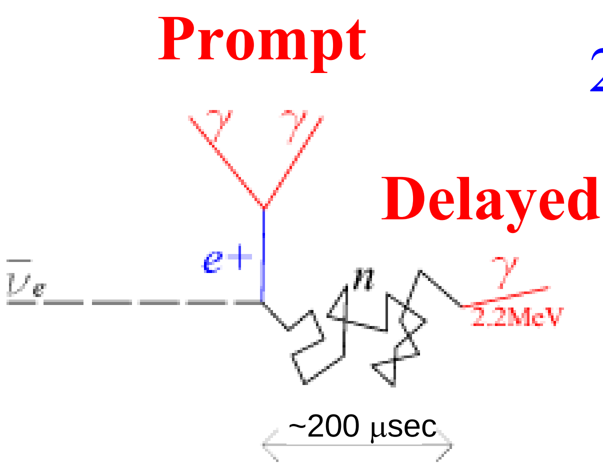
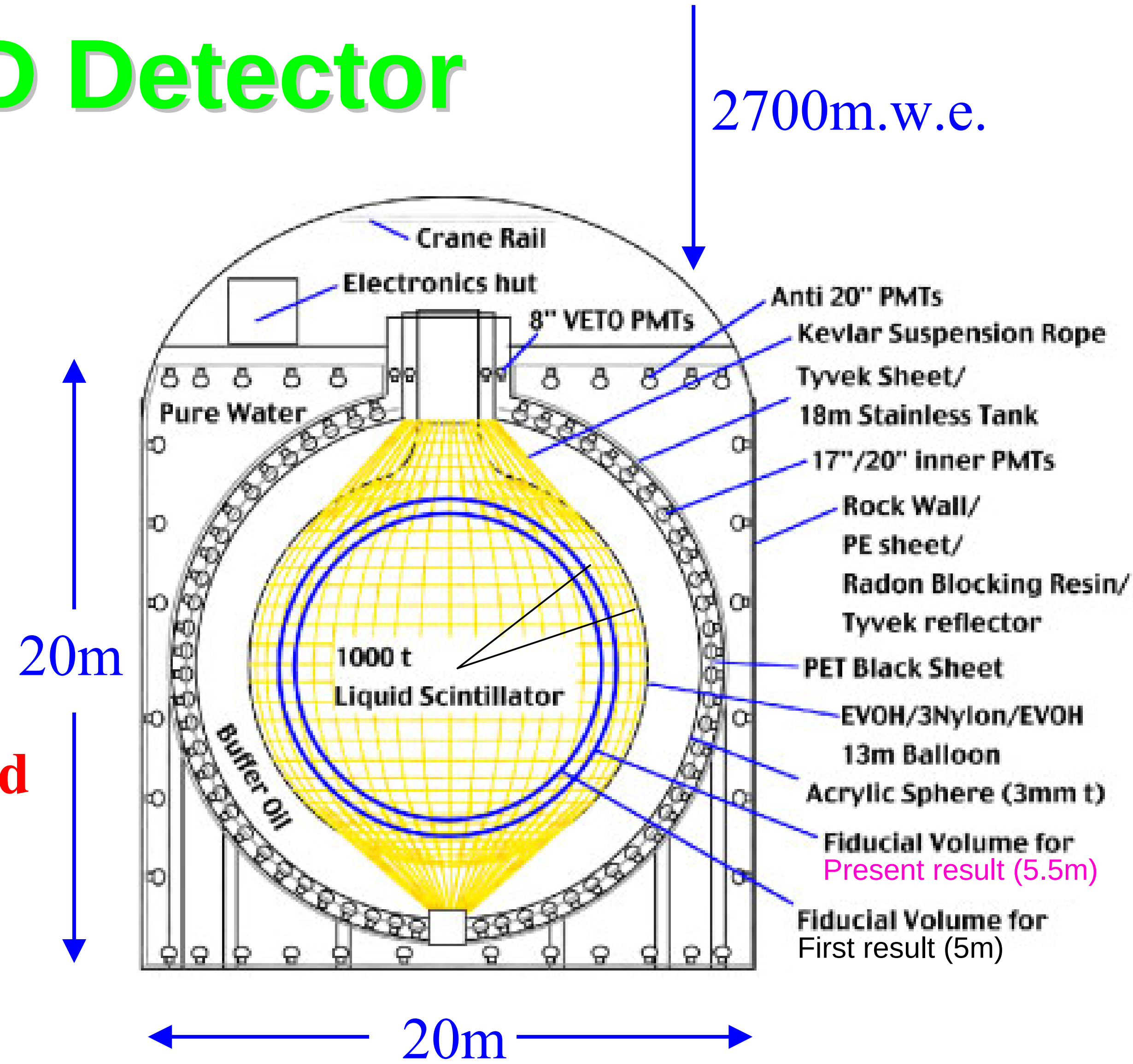
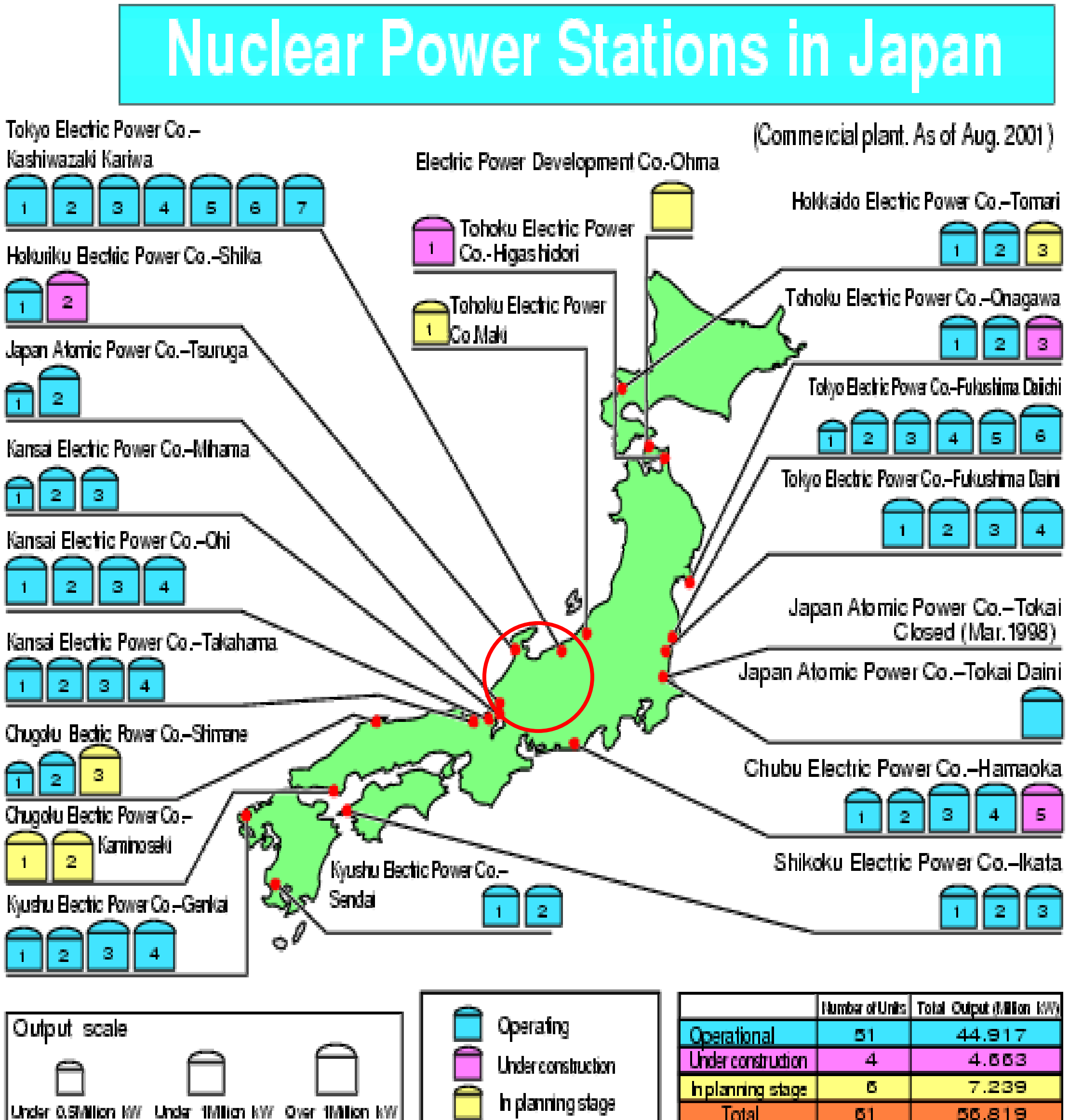
First result v.s. present result

	First res.	Present res.	
Exposure (ton-yr)	162	766.3	x 4.7
Live time (day)	145.1	515.1	x 3.55
	May 4 - Oct 6, 2002	May 9, 2002 - Jan 11, 2004	
Fiducial (radius)	5 m	5.5 m	x 1.33
Neutrino observed / no-oscillation	54 / 86.8	258 / 365.2	
Significance of Disappearance	99.95%	99.995%	
Significance of Spectral distortion	53 %	99.9 %	

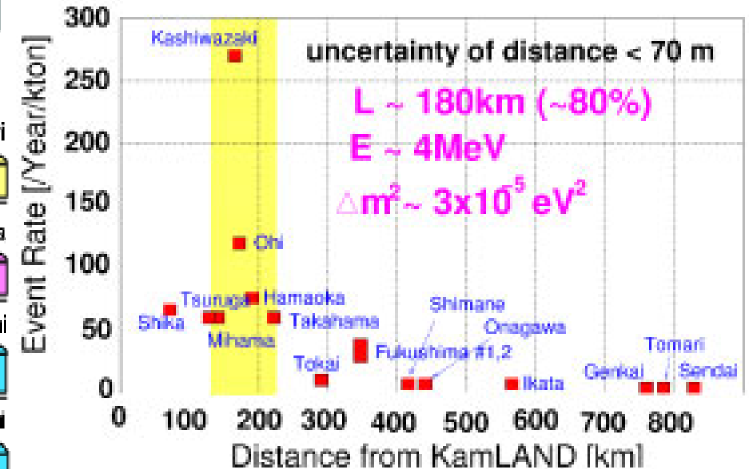
KamLAND Detector



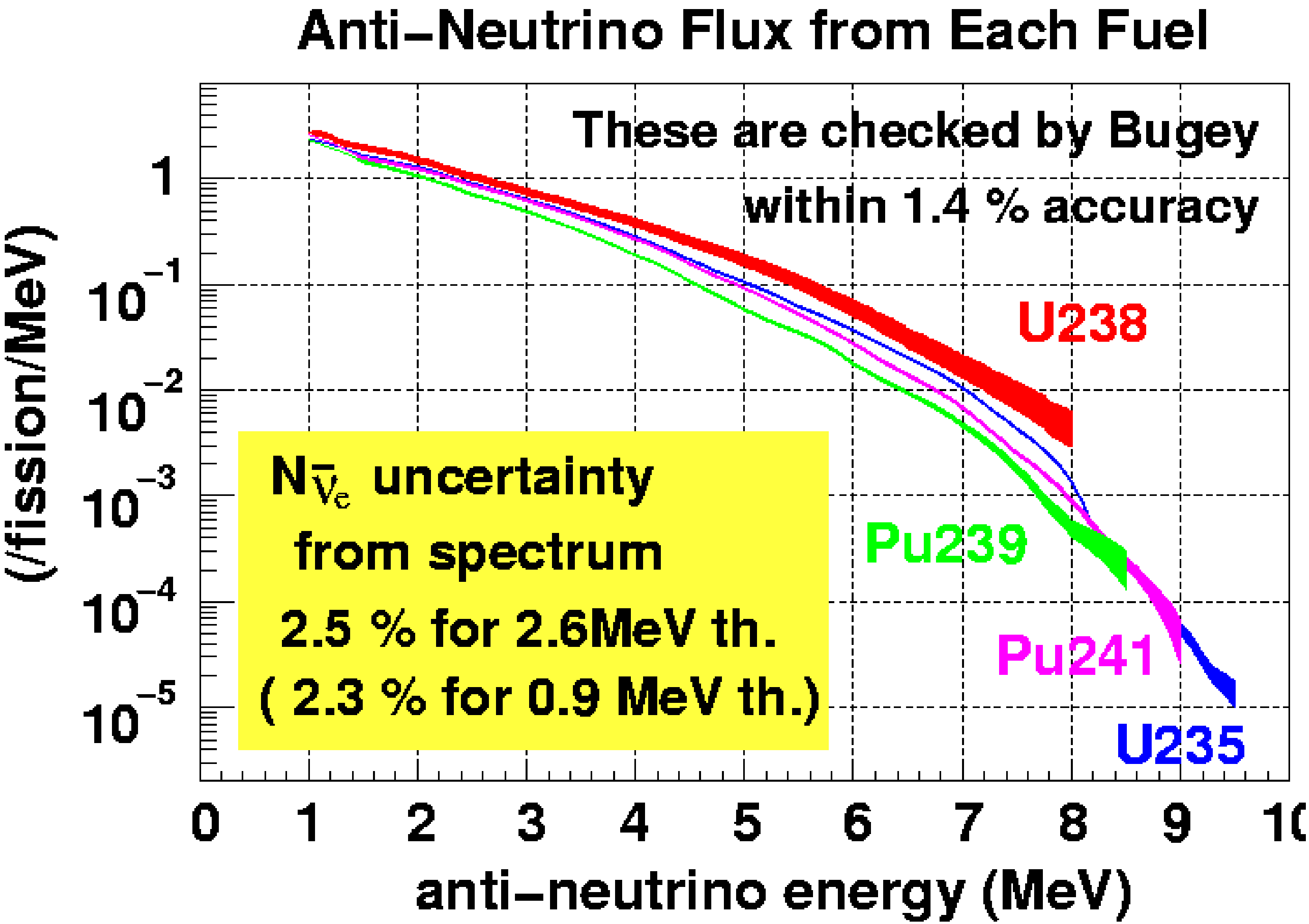




a few /day in KamLAND

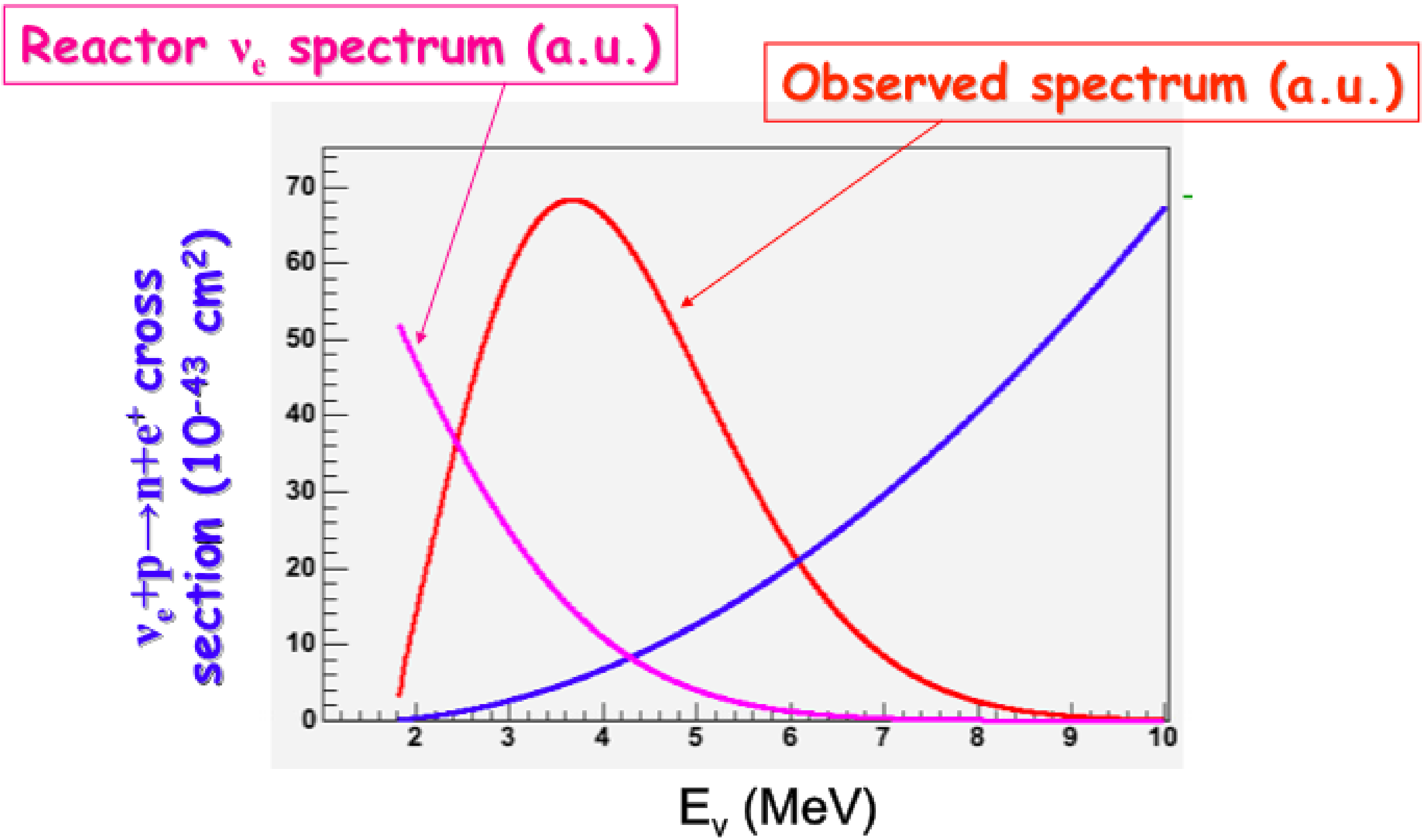


- **Thermal power, Burn-up, Fuel change record data, Simple model of reactor core.**
  - **→ fission rate**
  - **→ energy spectrum @KamLAND**
- **Korea(2.3+- 0.2% @N(ν))**

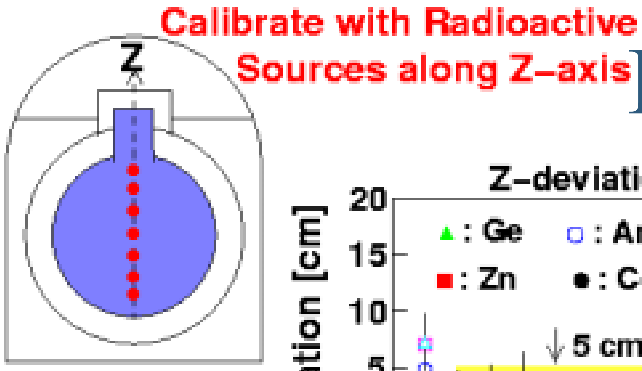


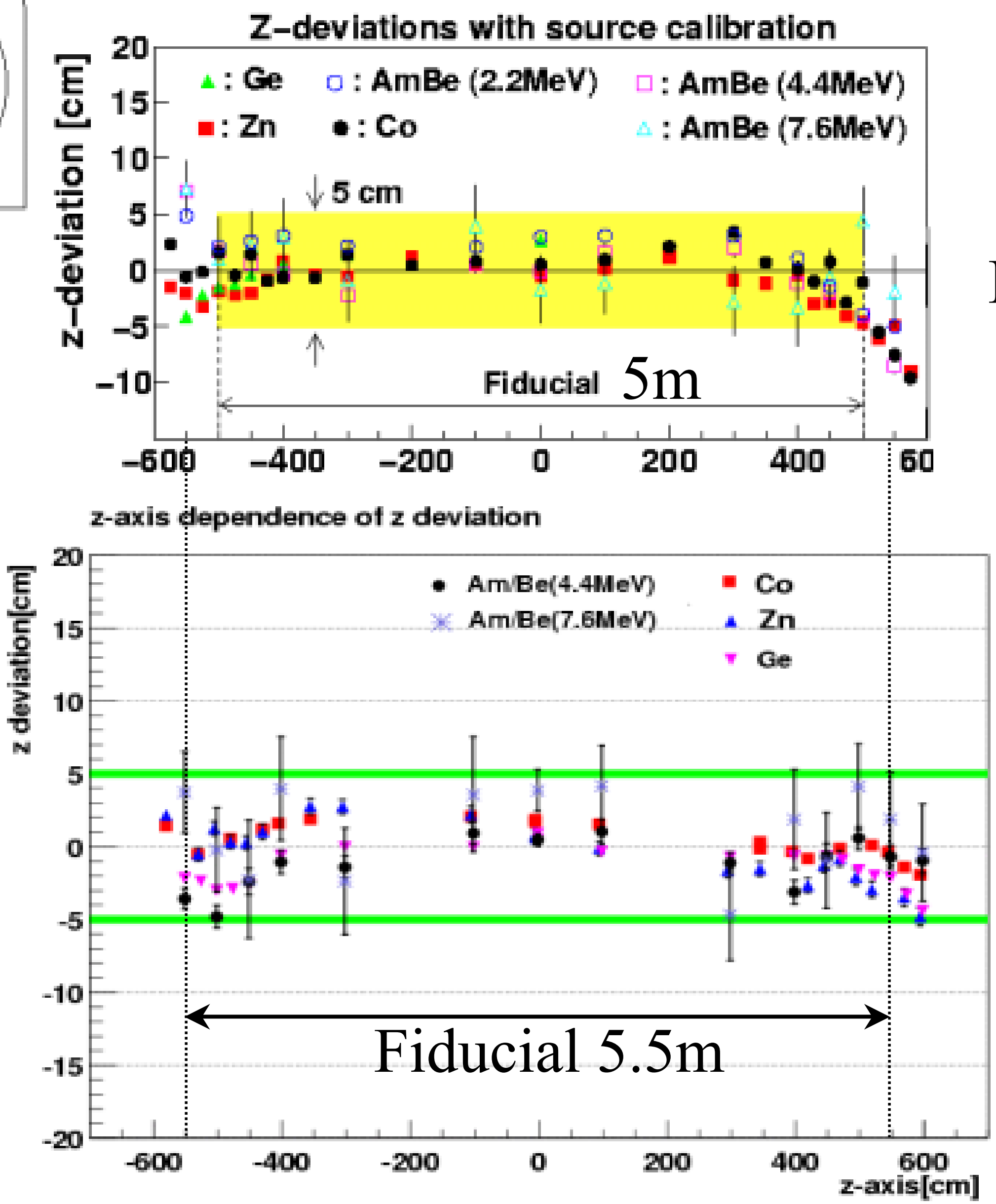
Anti-Neutrino Flux from Each Fuel
These are checked by Bugey
within 1.4 % accuracy
U238
Pu239
Pu241
U235
$N_{\bar{\nu}_e}$ uncertainty
from spectrum
2.5 % for 2.6MeV th.
(2.3 % for 0.9 MeV th.)
(/fission/MeV)
anti-neutrino energy (MeV)

The $\bar{\nu}_e$ energy spectrum



Improvement of Vertex Fitter





First result

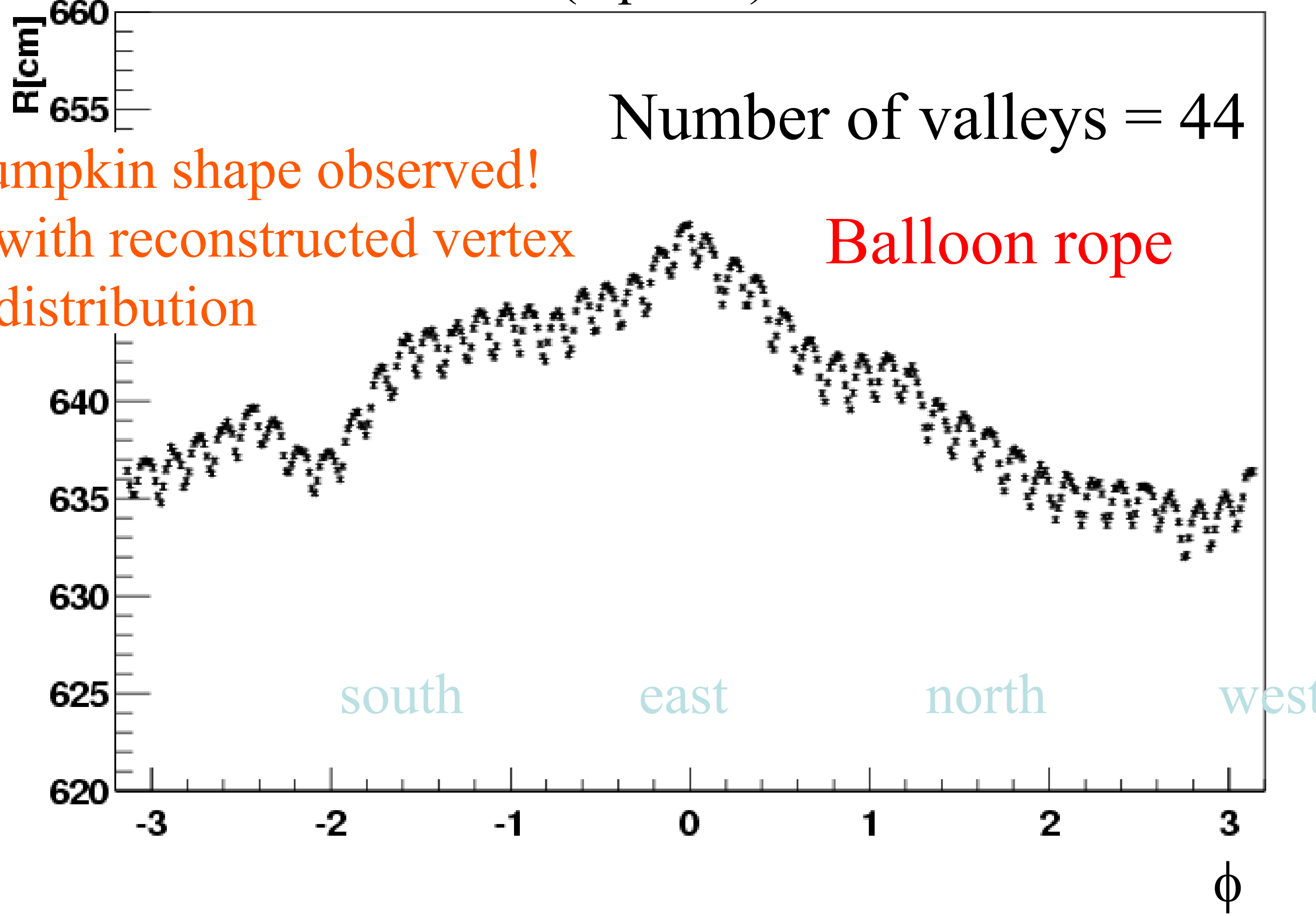
Present result

Balloon shape

1.2 < E < 1.6MeV (^{40}K γ energy region)
−2 < z < 2m (equator)

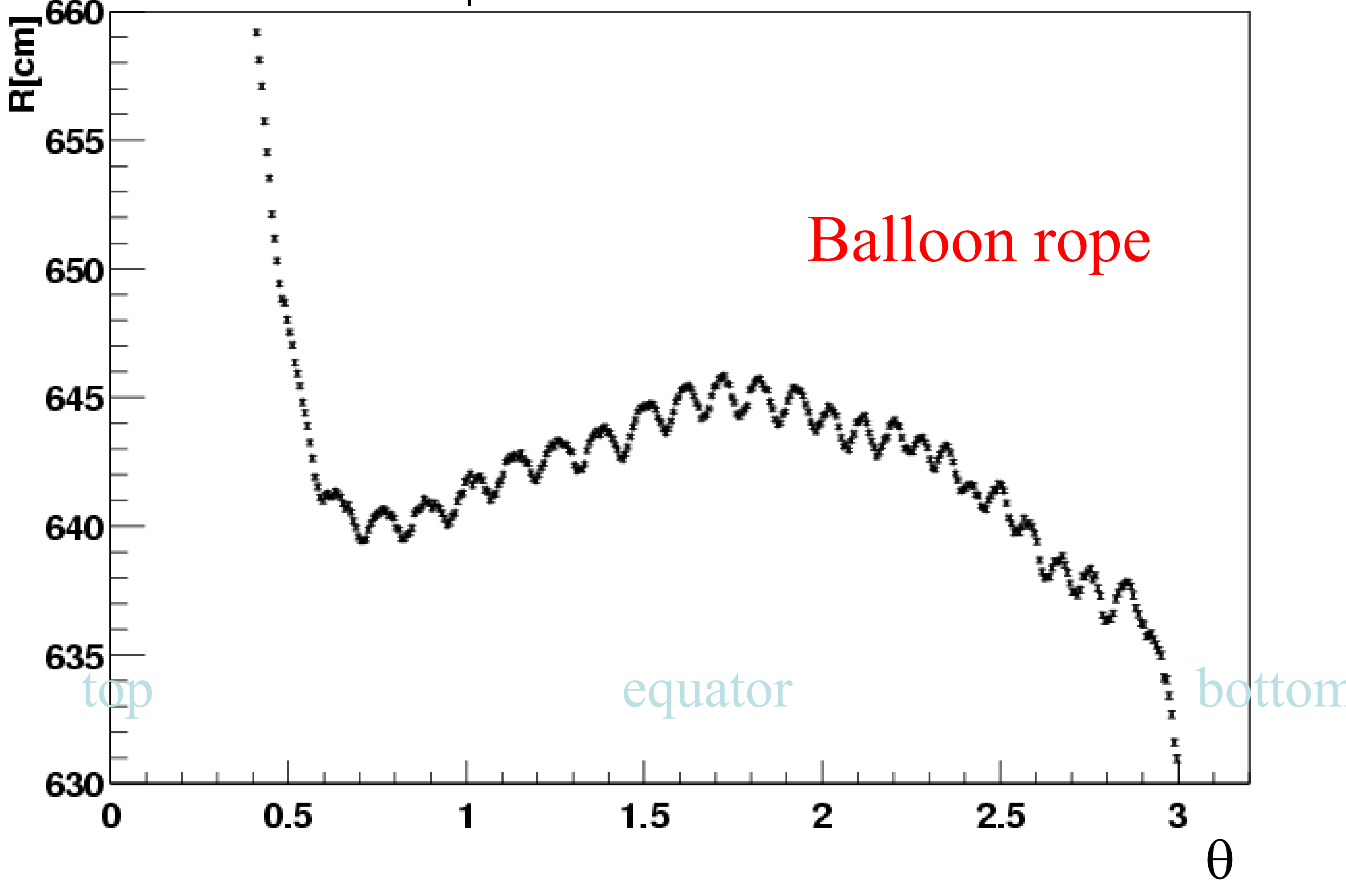
K. Ichimura, I. Shimizu, K. Inoue

Pumpkin shape observed!
with reconstructed vertex distribution



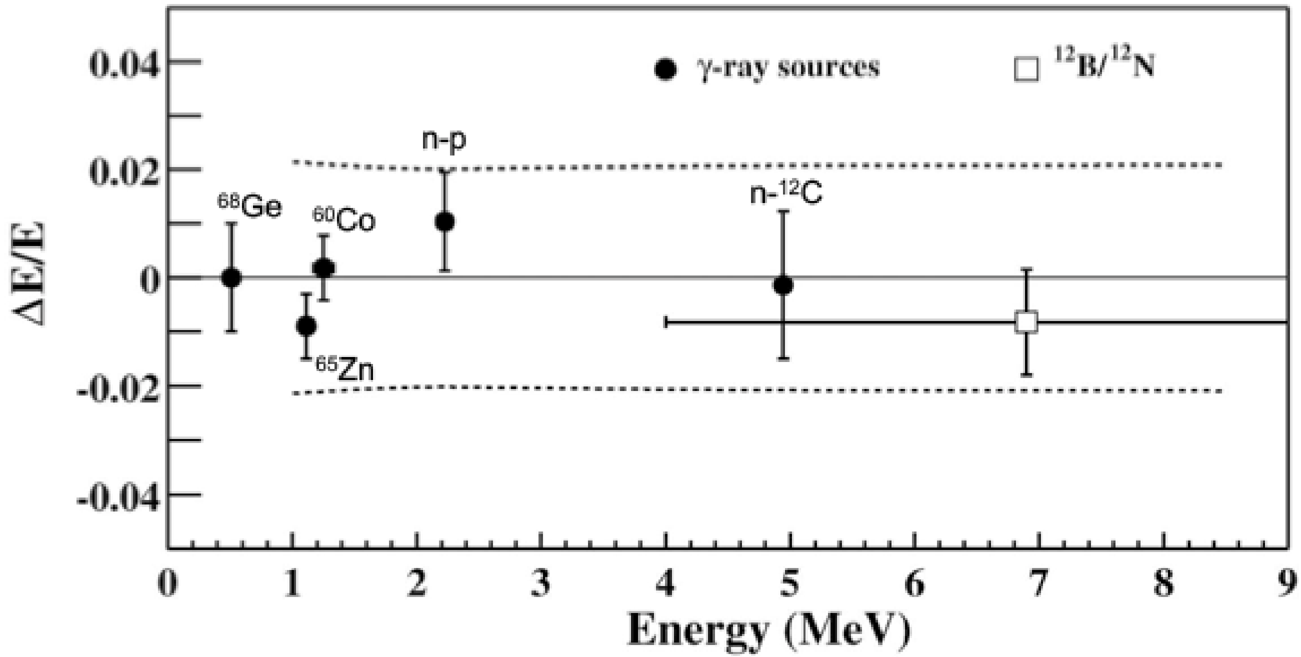
$1.2 < E < 1.6\,\mathrm{MeV}$ (^{40}K γ energy region)

$-90^\circ < \phi < 90^\circ$



Improvement of Energy Fitter

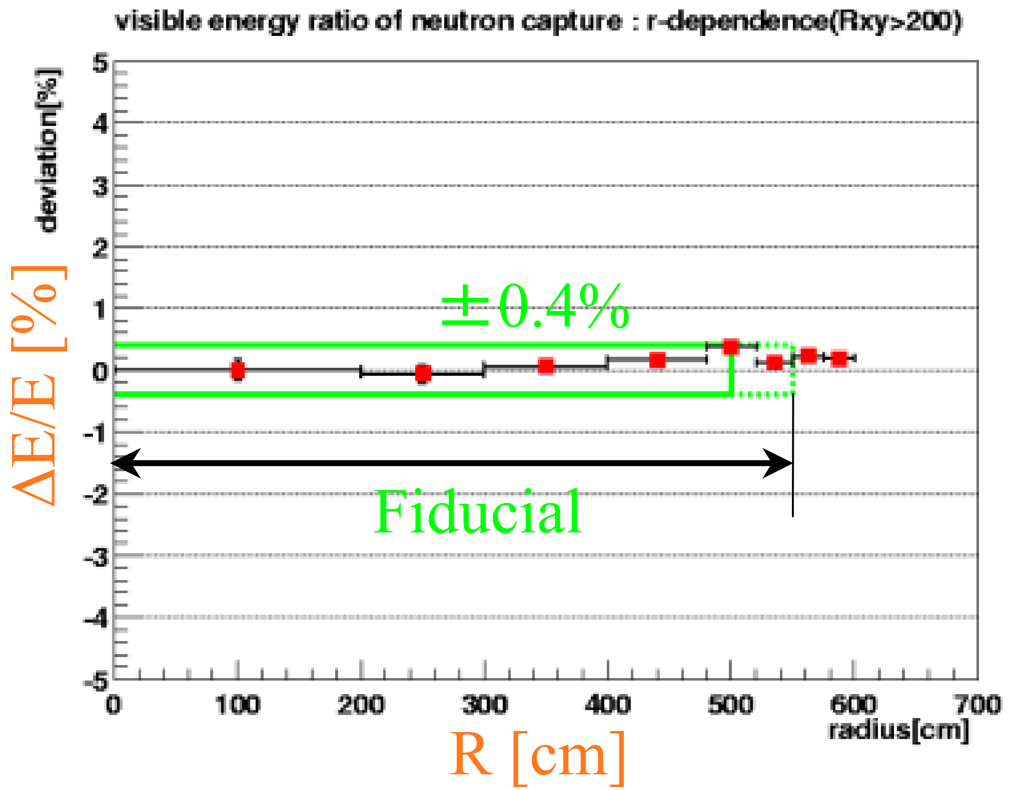
Energy calibration uses discrete γ and $^{12}B/^{12}N$



Carefully include Birks law, Cherenkov and light absorption/optics to obtain constants for γ and e-type depositions

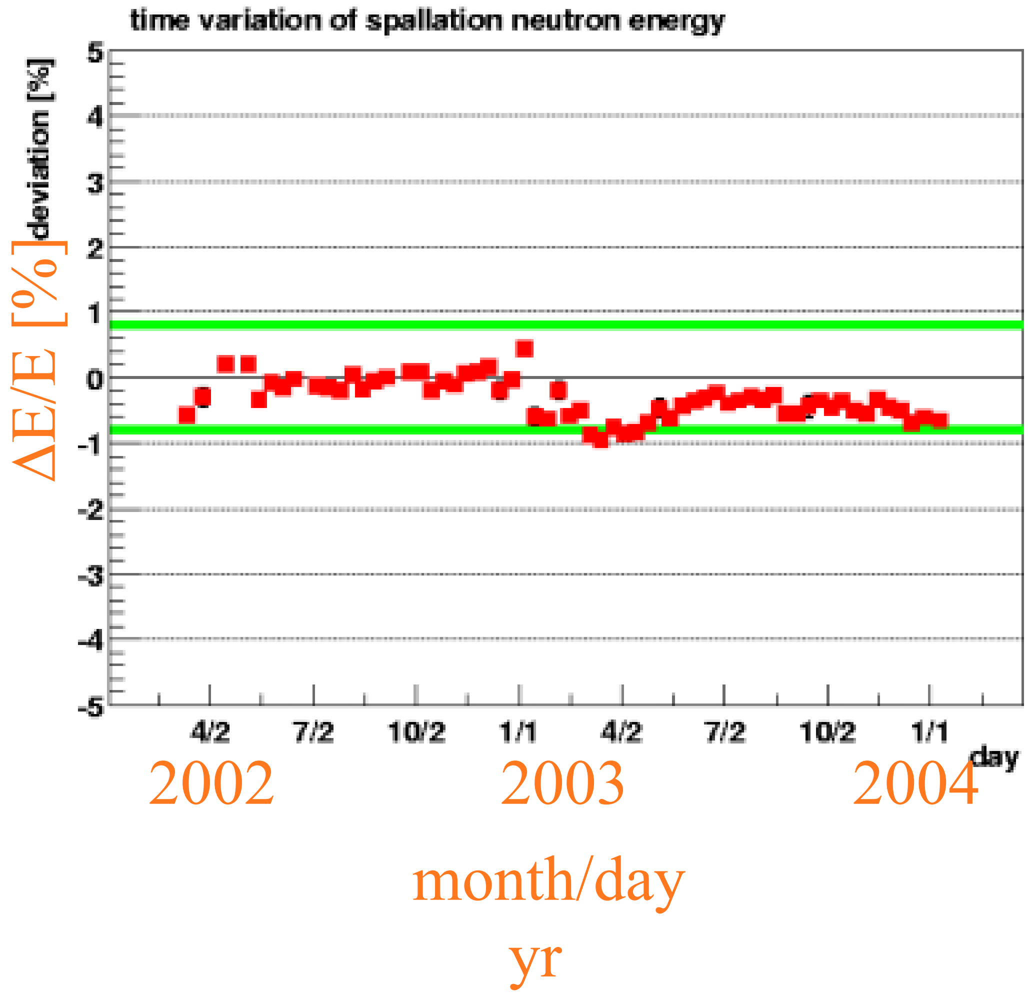
$\sigma/E \sim 6.2\%$ at 1MeV

Position dependence (spallation neutron)



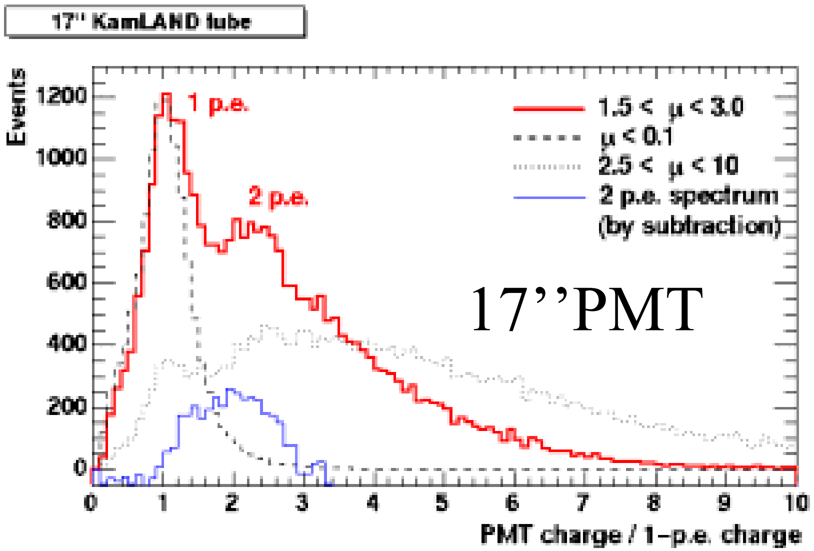
All effects are 3-dimensionally understood, calibrated:
R^2, transparency of scintillator, shade of balloon ropes, etc

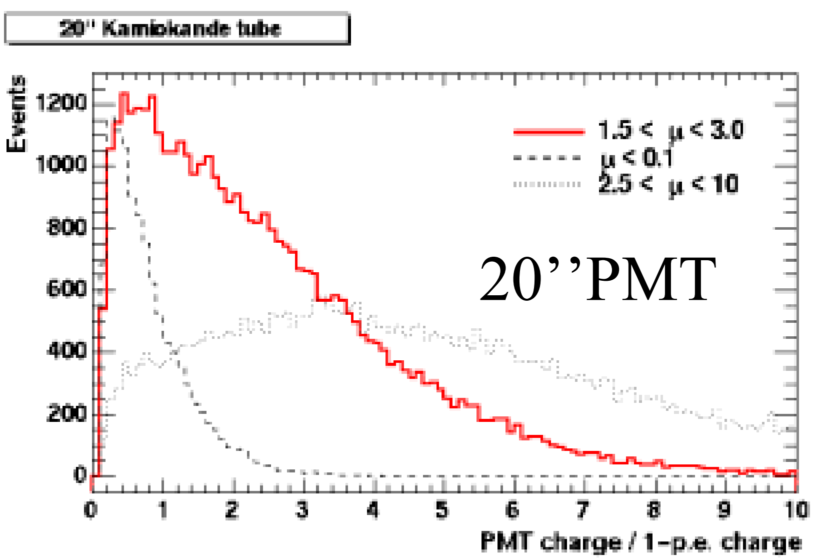
Time dependence (Spallation neutron)



- Relative calibration is performed for each run (1 run ~= 1 day) using ^{40}K peaks
- Stable for 2 years

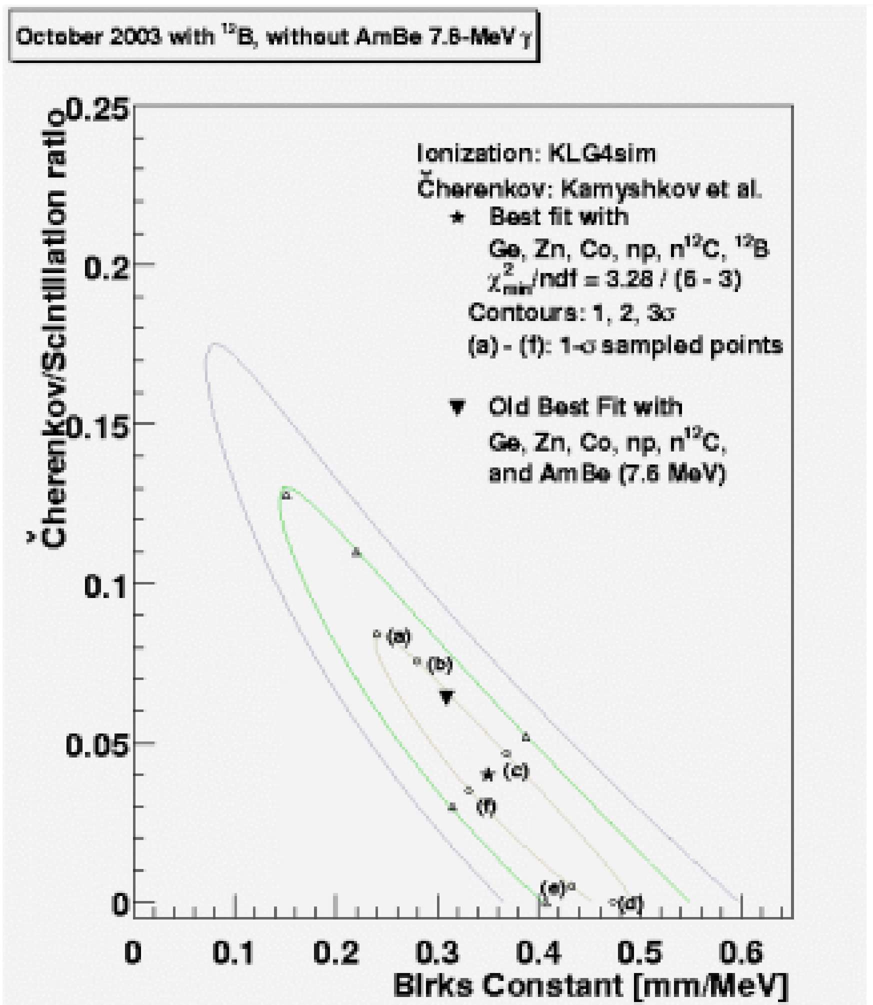
Two-photoelectron peak found by energy fitter

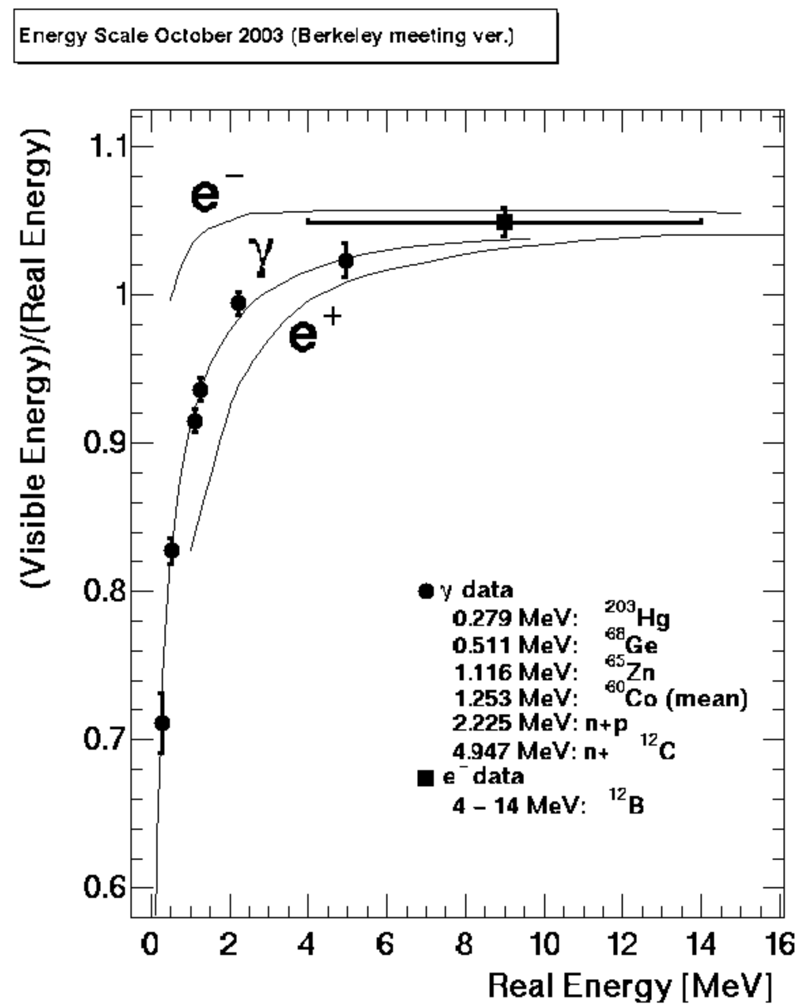




- Energy fitter knows expected number of photoelectrons for each event, each PMT, because he fits energy by comparing it with actually observed.
- Energy fitter detected a 2-p.e. peak for the first time, by choosing $\mu \sim 2$ events, showing that his expectation is very accurate.

Nonlinearity calibration (Cherenkov/Birks)

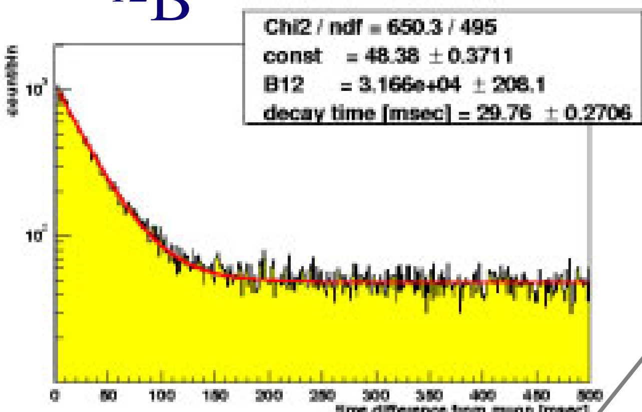


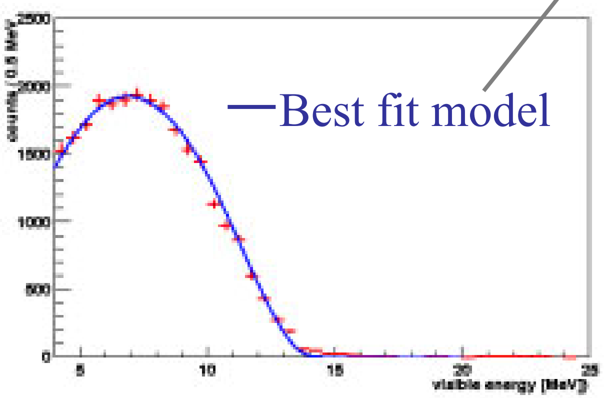


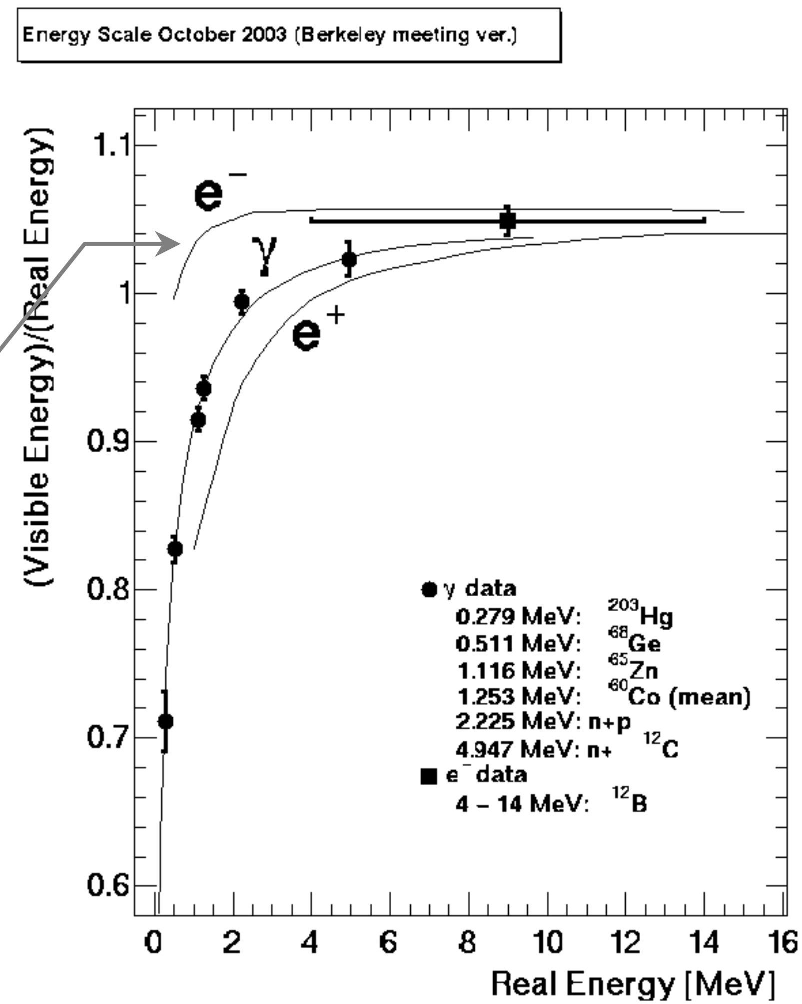
^{12}B β^- spectrum is used: good for e^+

(previously, only gammas)

^{12}B





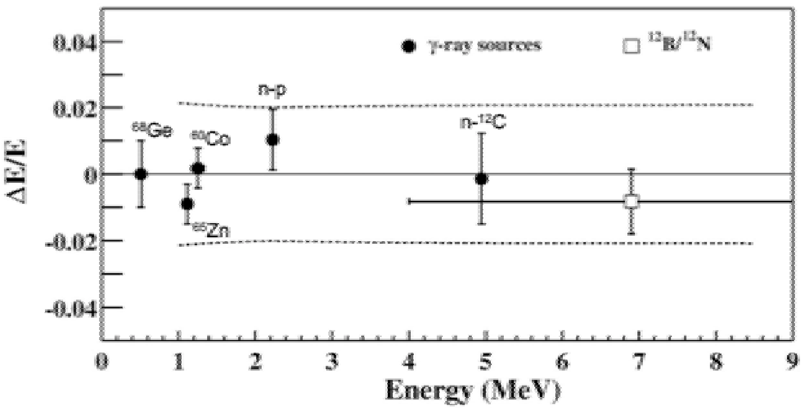


Energy scale error of 2.6-MeV e^+

	5-m fiducial	5.5-m fiducial
Cherenkov/Birks (statistic)	0.35	0.35
Cherenkov/Birks (systematic)	0.93	0.93
Time dependence	1.3	1.3
Position dependence	0.85	0.92
20’’ PMT non-linearity	0.8	0.8
Total	2.01 %	2.04 %

Improvement of Energy Fitter

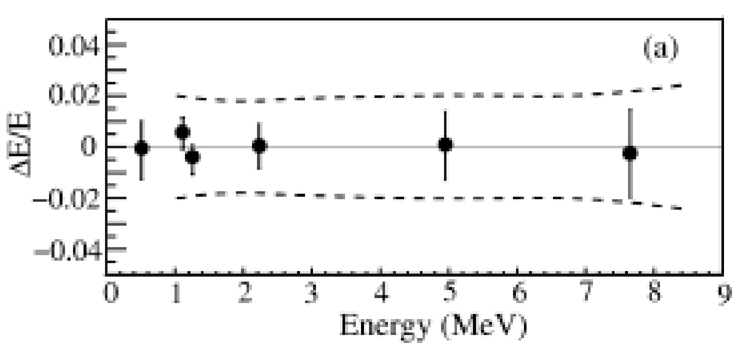
Energy calibration uses discrete γ and $^{12}B/^{12}N$



Carefully include Birks law, Cherenkov and light absorption/optics to obtain constants for γ and e-type depositions

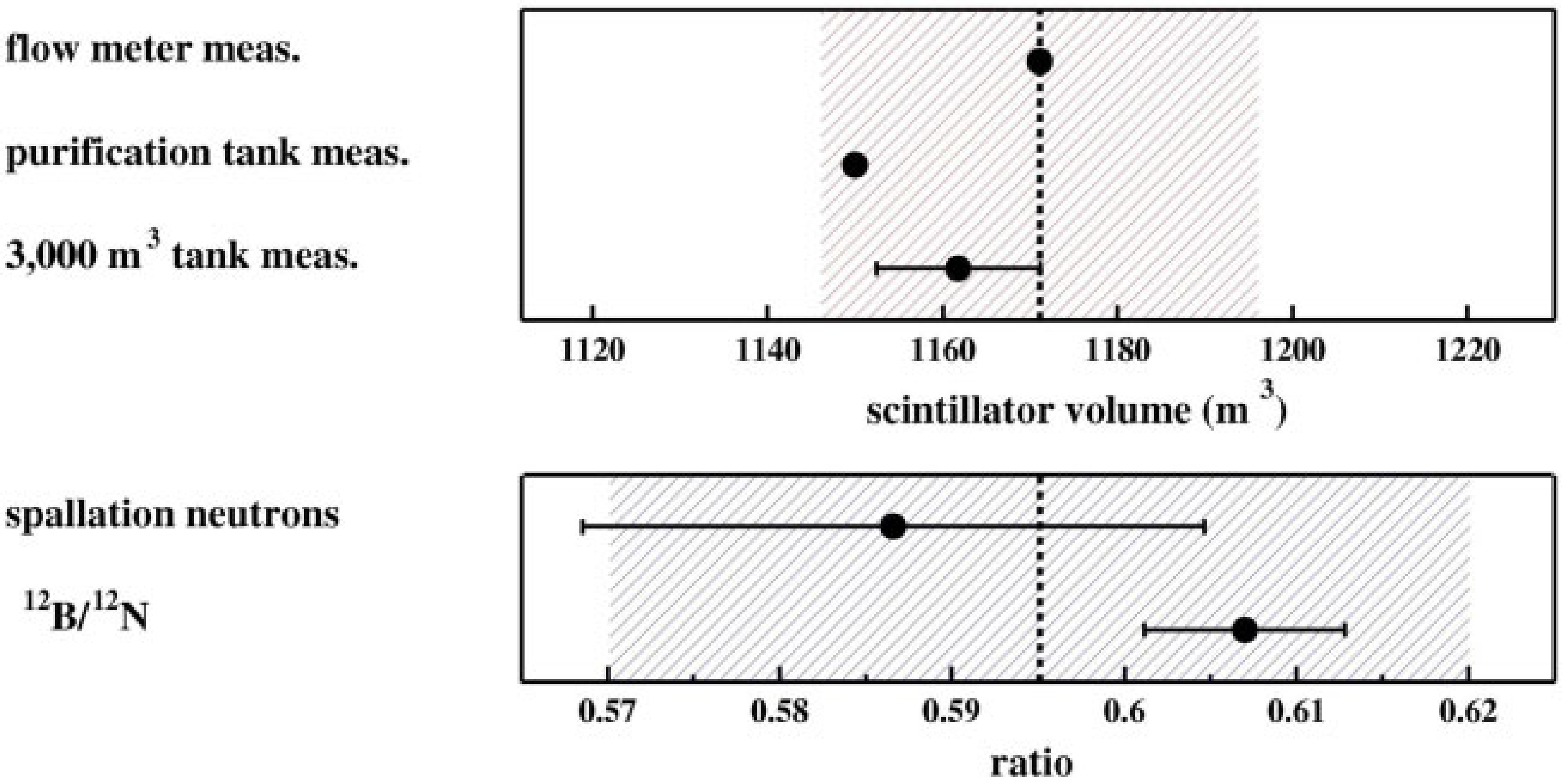
σ/E ~ 6.2% at 1MeV

- Systematic error: almost same as the first result
- Reliability increased by employing ^{12}B β^- calibration
- Position uniformity and its reliability increased

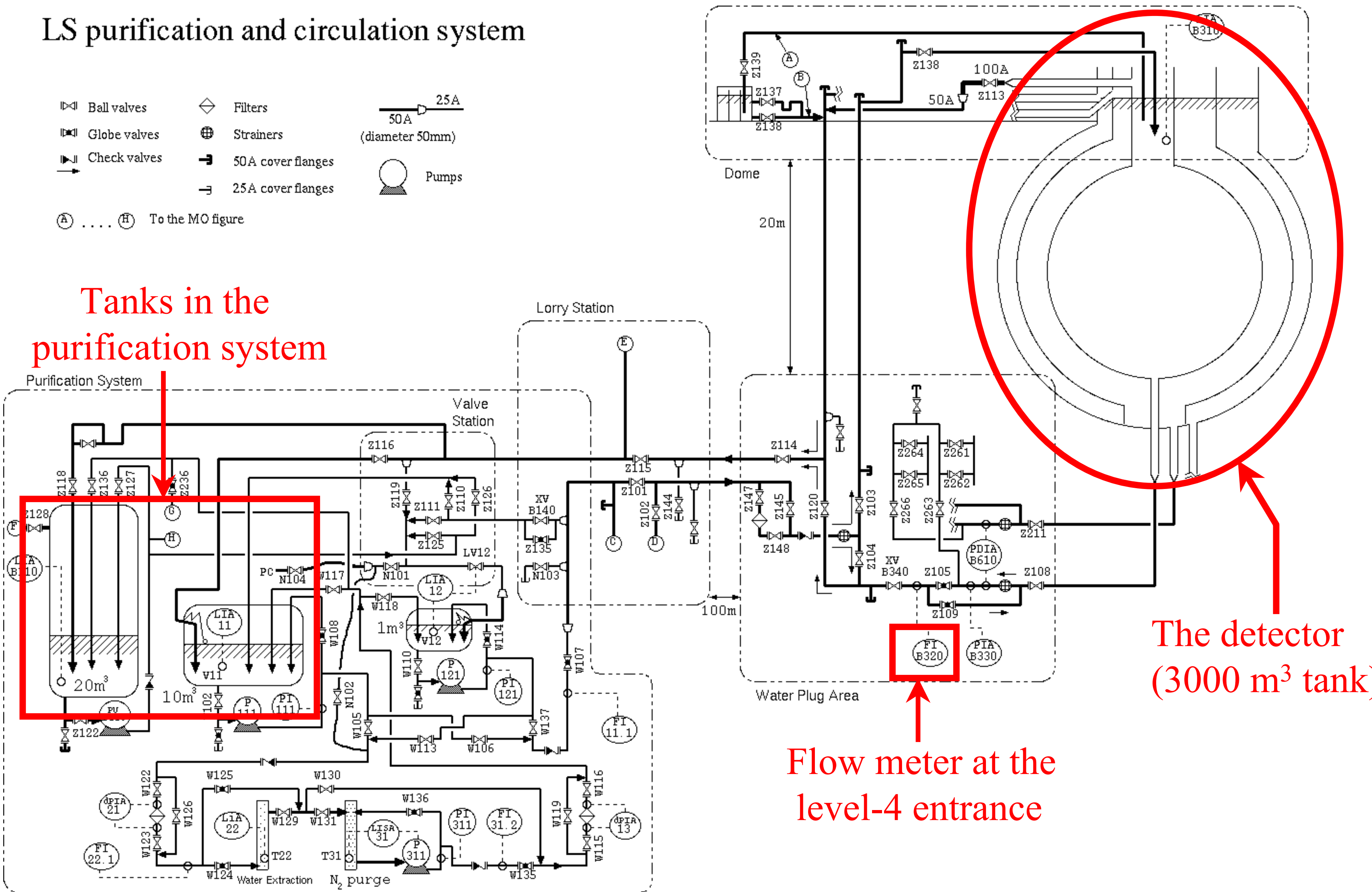


First result

Estimate of total volume and fiducial fraction

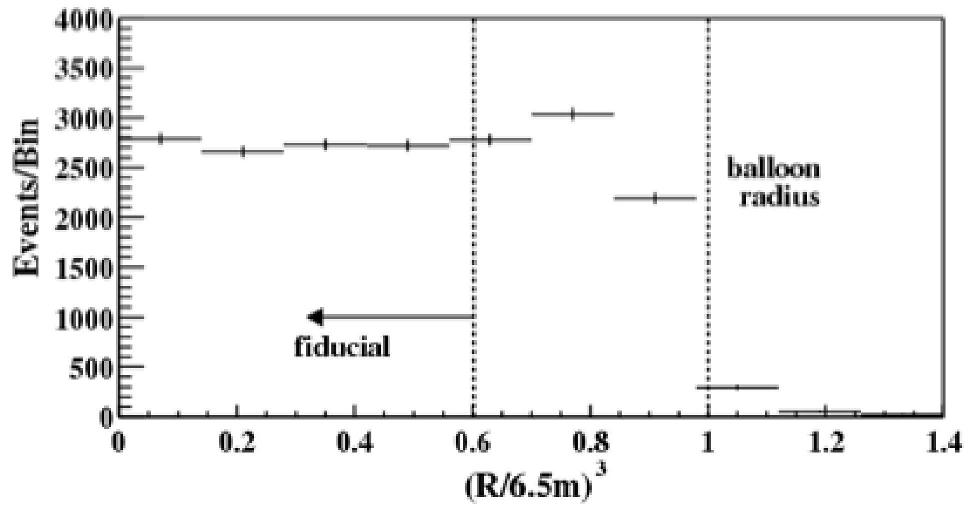


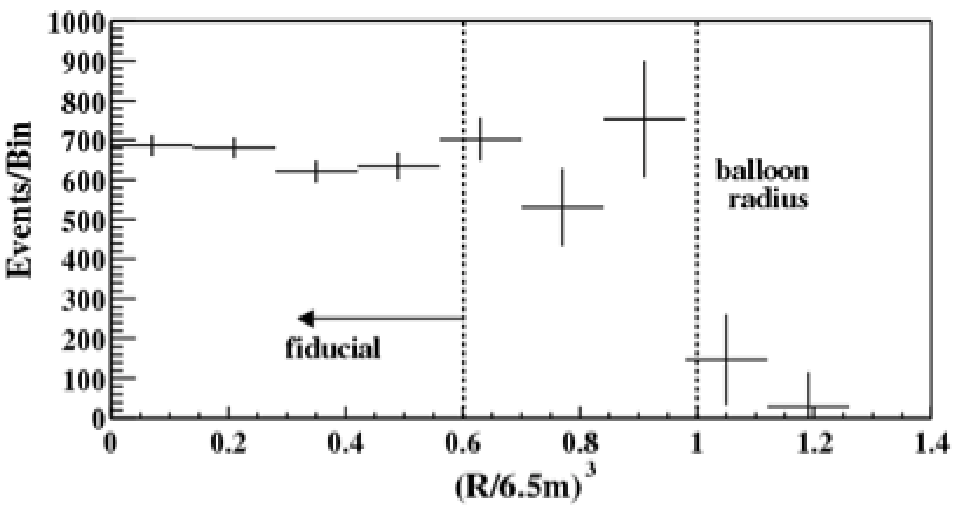
Scintillator volume measured 3 times



Fraction of volume *inside* the fiducial radius verified using μ-produced $^{12}B/^{12}N$ and n (assumed uniform)

$^{12}B/^{12}N$

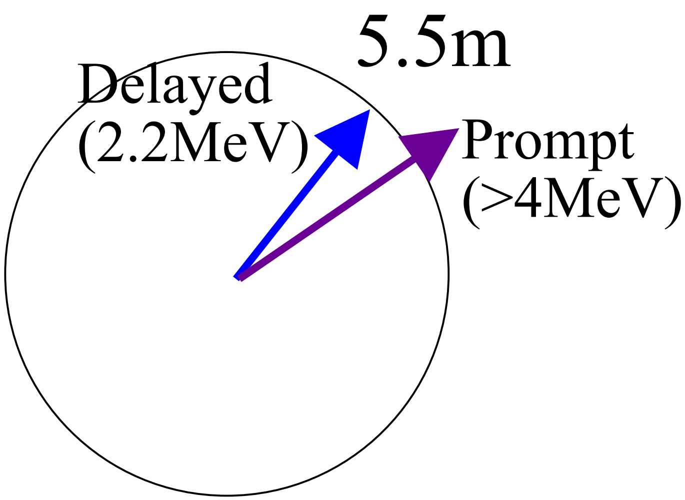


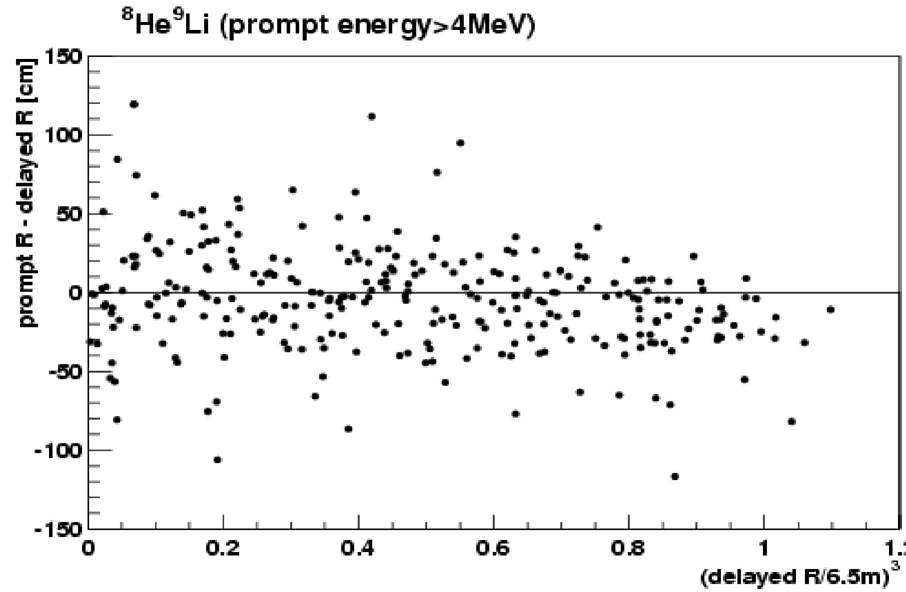


neutrons

Energy dependence of fiducial volume

$^8He^9Li$ coincidence

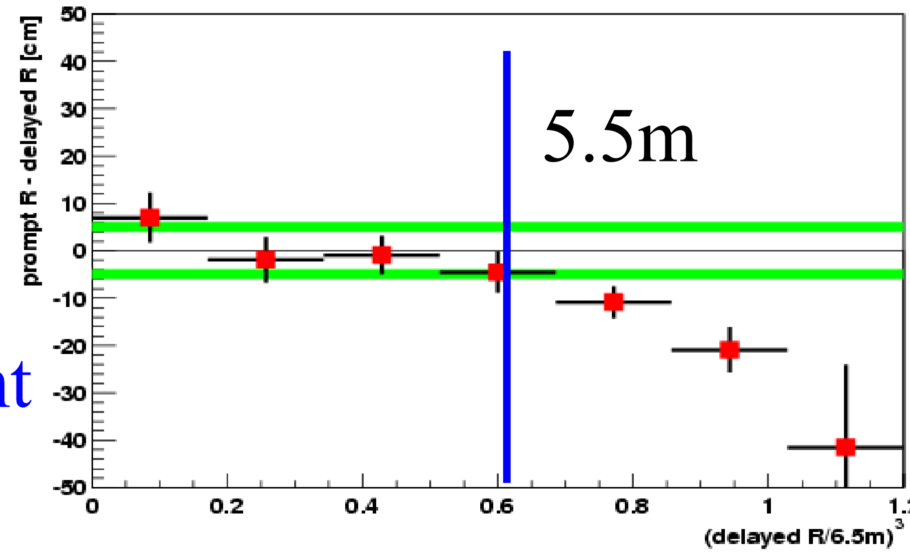




Energy dependence of vertex at 5.5m

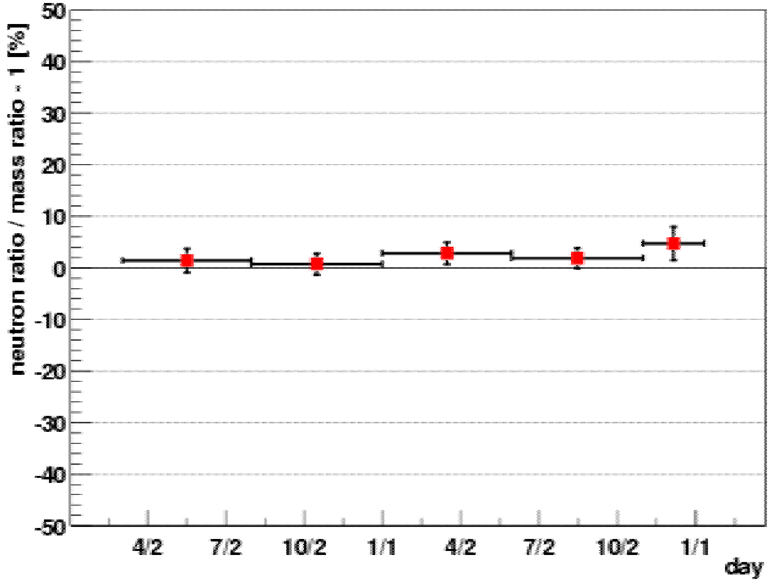
< 5cm

±2.7% energy-dependent volume error



Time variation of fiducial volume

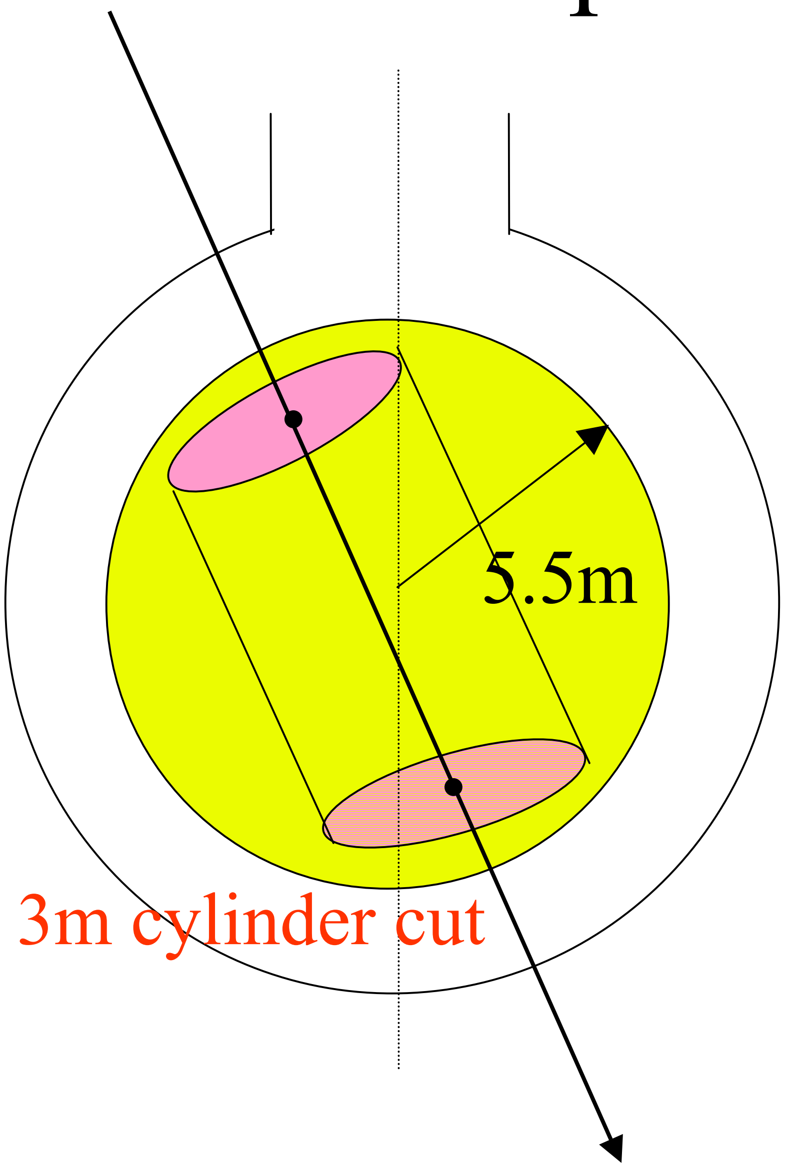
^{12}B



<±1.5%

Stable for 2 years

Spallation cut



"showering muon"

Q - $(dE/dx)_{MIP}$ x (track length)

> 10^6 photoelectrons (~3 GeV)

~ 1/30 of all muons

---> all volume 2 sec veto

"non-showering muon"

other muon good reconstructed

---> 2 sec 3-m cylinder

"bad reconstructed muon"

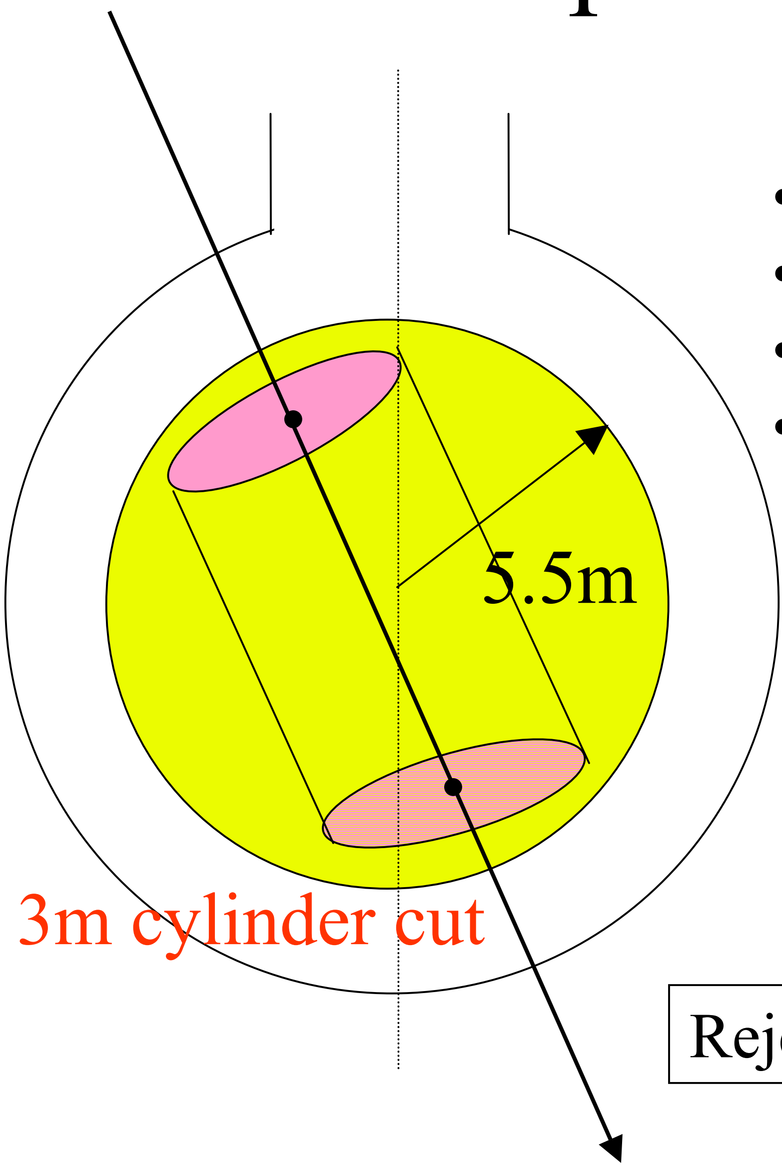
track reconstruction failed

but, from charge, Nhit,

it should be a muon

---> all volume 2 sec veto

Spallation cut



Vetotime by muon

- ID muon veto (2msec)
- Bad reconstructed muon veto (2sec)
- Showering muon veto (2sec)
- Non-showering muon veto
  (2sec, 3m cylinder cut)

Spallation events ($^8He^9Li$)

Showering muon

350 → 0.2

Non-showering muon

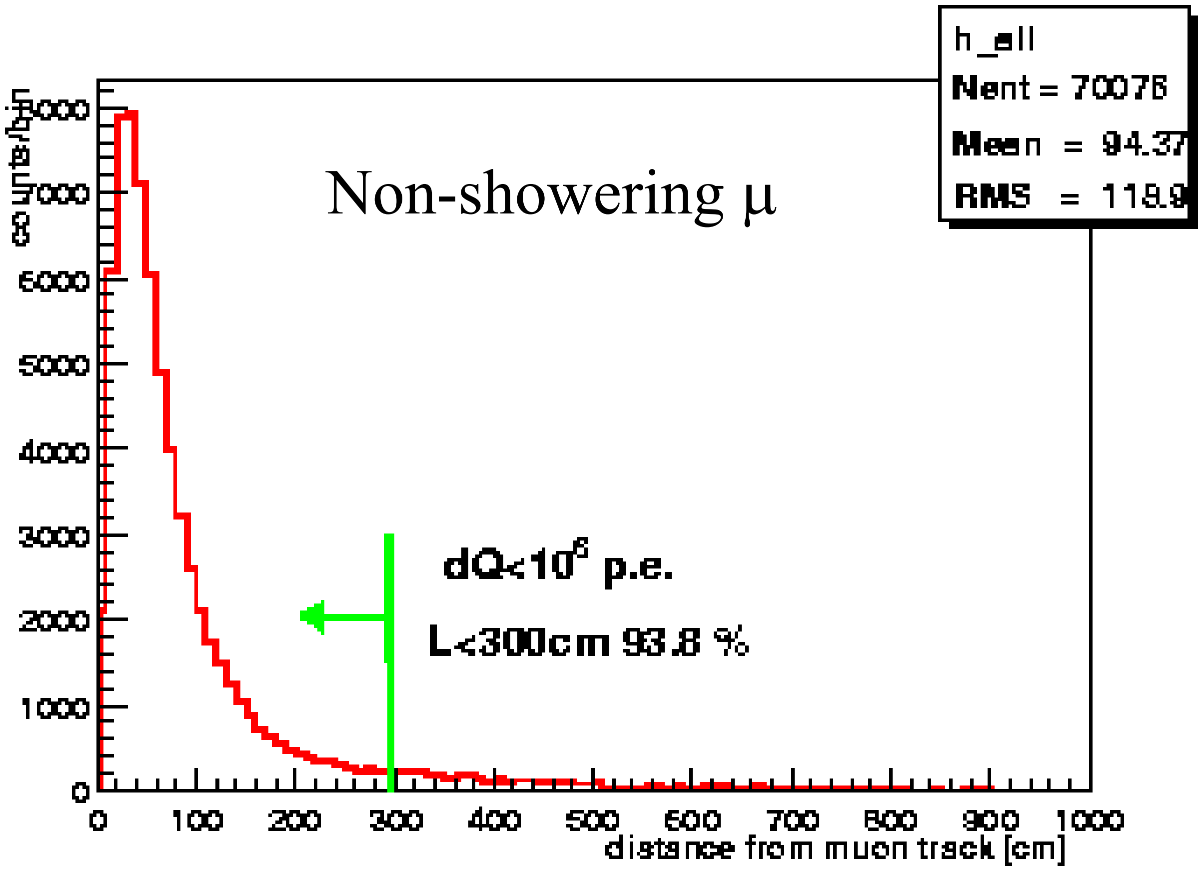
86 → 5.7

Rejection efficiency for $^8He^9Li$ = 98.7%

Dead time (x volume ratio) = 9.7%

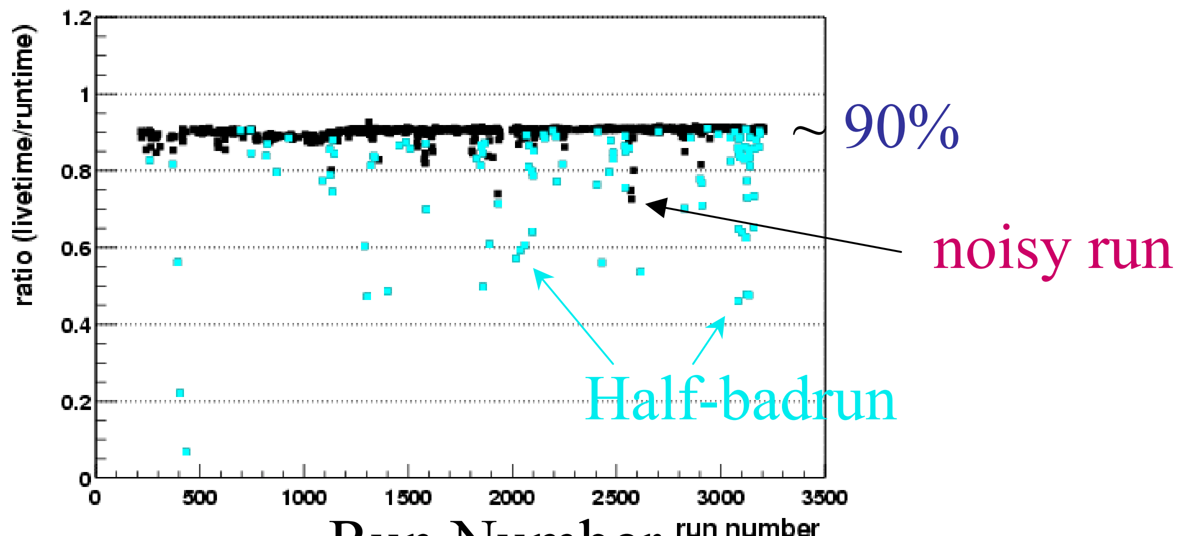
Muon fitter improved

93.8% neutrons are in r=3m column from the previous muon



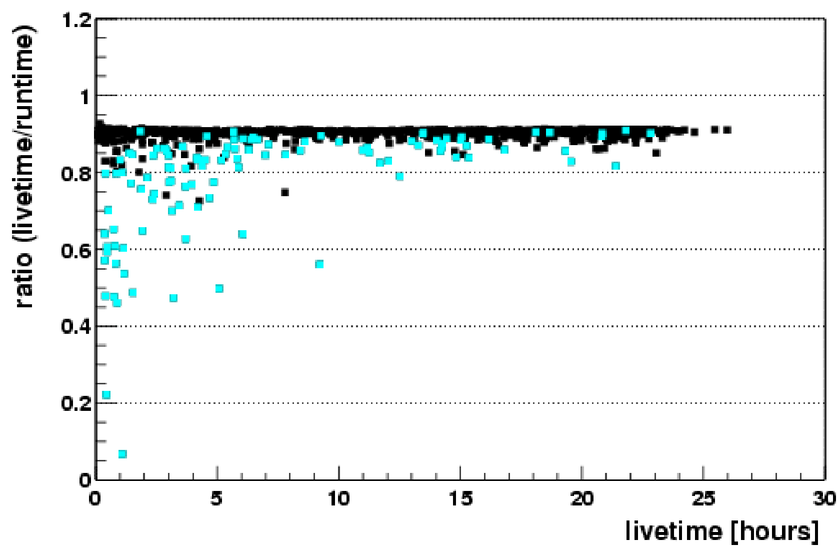
Livetime for each run

$\frac{\text{Livetime}}{\text{Runtime}}$



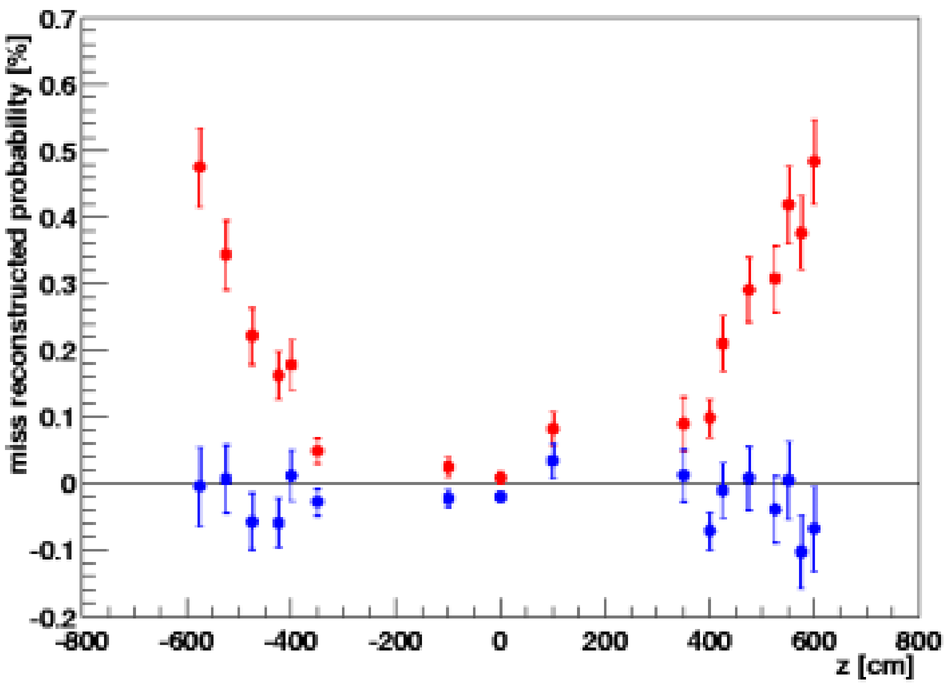
Run Number

$\frac{\text{Livetime}}{\text{Runtime}}$



Livetime

Vertex fitter efficiency



- Probability of vertex failure < 0.1 %
- Simple algorithm (vertex should be near to the early-hit PMT) assures high reliability of vertex reconstruction

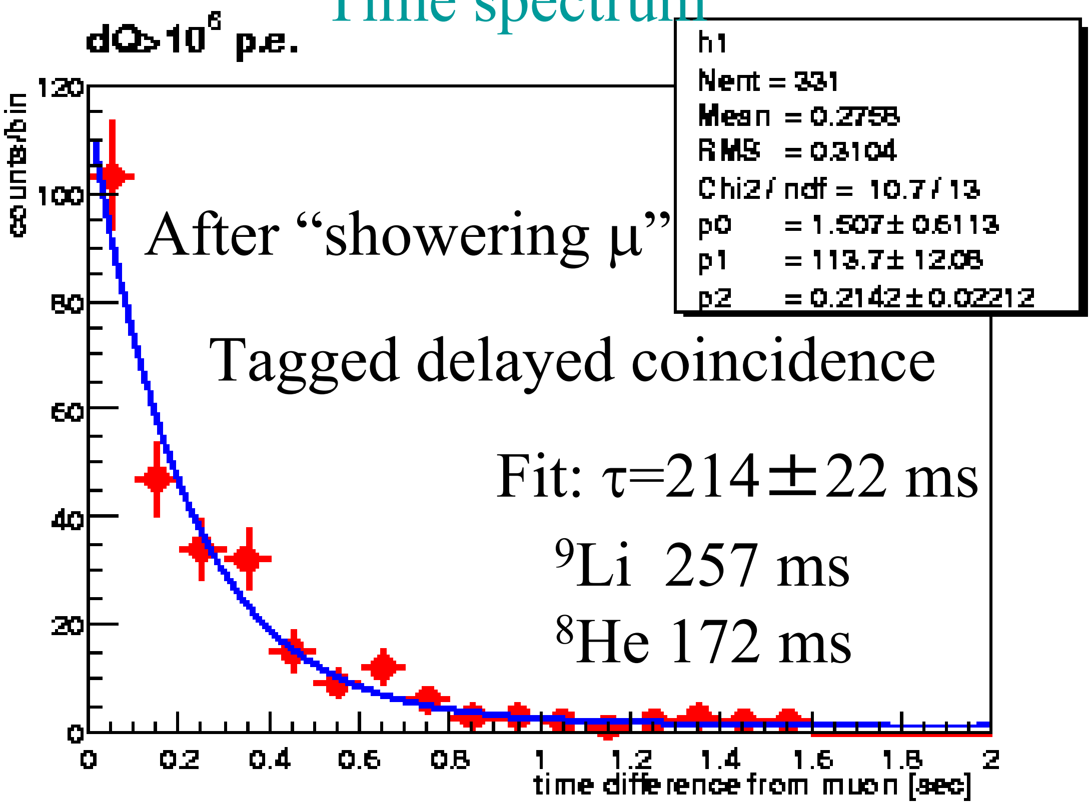
Systematic Error

Systematic	%
Scintillator volume	2.1
Fiducial fraction	4.2
Energy threshold	2.3
Cuts efficiency	1.6
Live time	0.06
Reactor $P_{thermal}$	2.1
Fuel composition	1.0
Time lag	0.01
Antineutrino spectrum	2.5
Antineutrino x-section	0.2
Total	6.5

- Almost same as the first result (6.4 %)

Background: long-lived delayed-n β-decay ^{9}Li (^{8}He)

Time spectrum

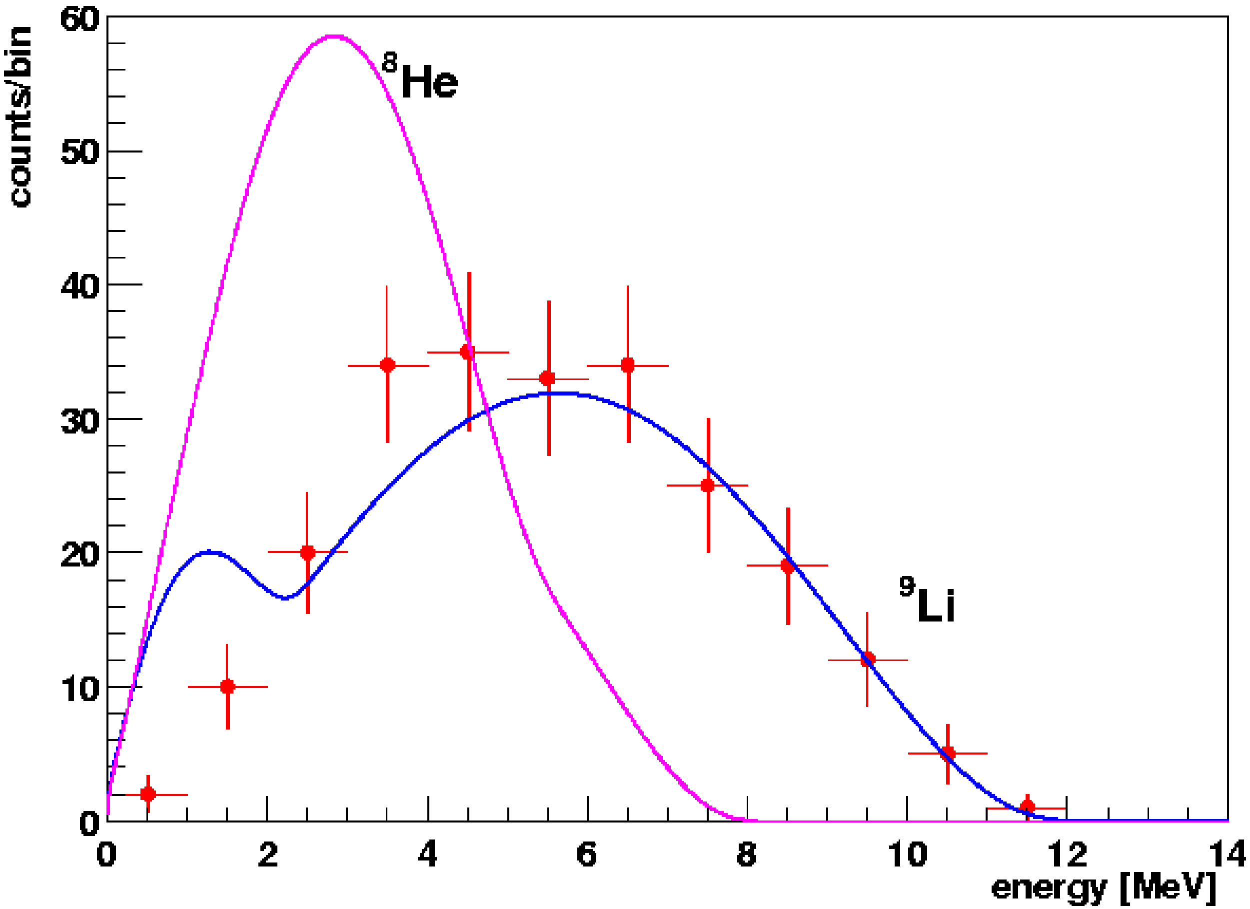


- Large statictics -> found that most are ^{9}Li ($^{8}He < 15\%$ @90% C.L.)

  both from time and energy spectra

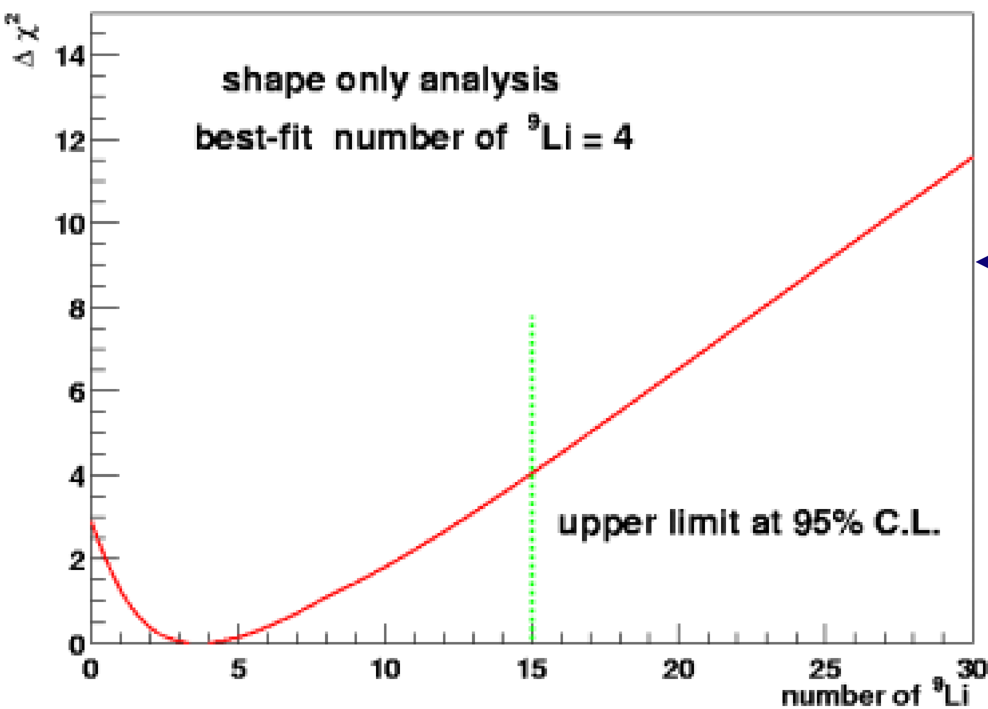
Energy spectrum of ^{9}Li

After “showering μ”



^{9}Li events in the final neutrino sample

used in the analysis



agree

- 4.8 ± 0.9

  estimated from spallation cut efficiency

- 4 (the best fit)

  energy spectrum of the final neutrino sample

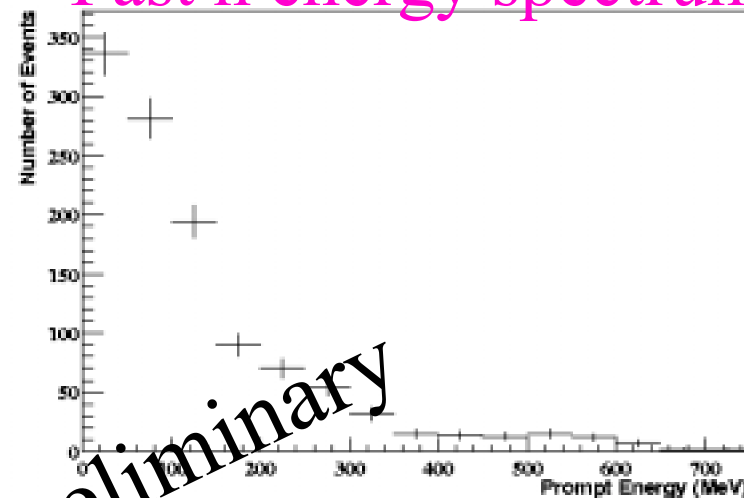
Extracting fast neutron sample

Choosing events with Outer Detector (OD) hit greater or equal to 5

Energy spectrum
Position dependence
-> OD veto efficiency
  no-OD muon (rock muon)
  (Monte Carlo)

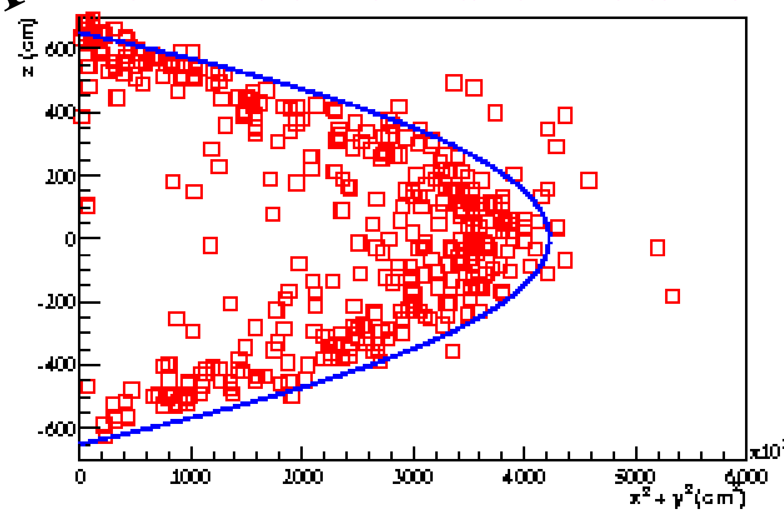
Currently, upper limit:
  < 0.89 in the data sample

Fast n energy spectrum



preliminary

Fast n vertex distribution

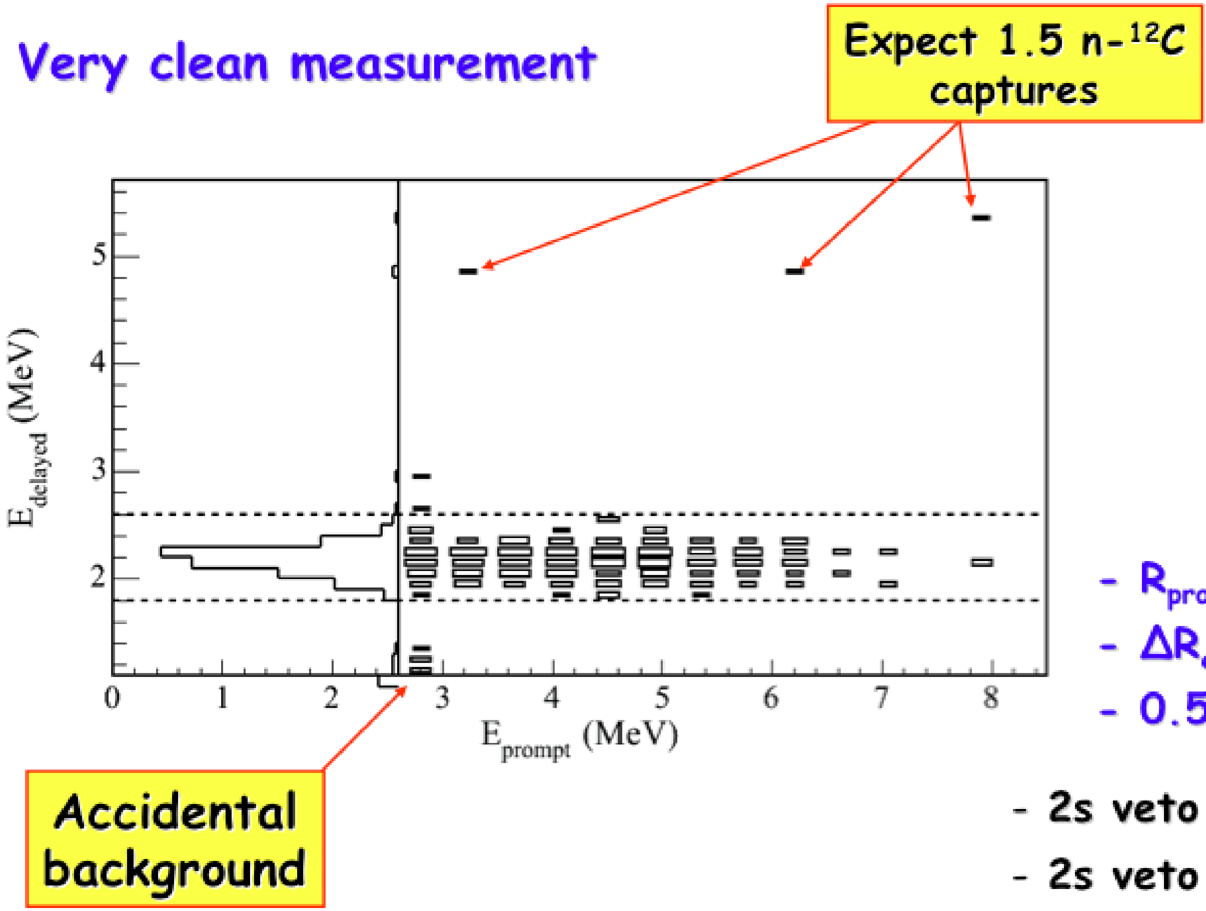


Background

Background	Events
Accidentals	2.69±0.02
$^{8}He/^{9}Li$	4.8±0.9
μ -induced n	<0.89
Total	7.5±1.3

Delayed coincidence events: the neutrino sample

Very clean measurement



- $R_{prompt,\ delayed} < 5.5$ m
- $\Delta R_{e-n} < 2$ m
- $0.5\ \mu s < \Delta T_{e-n} < 1$ ms

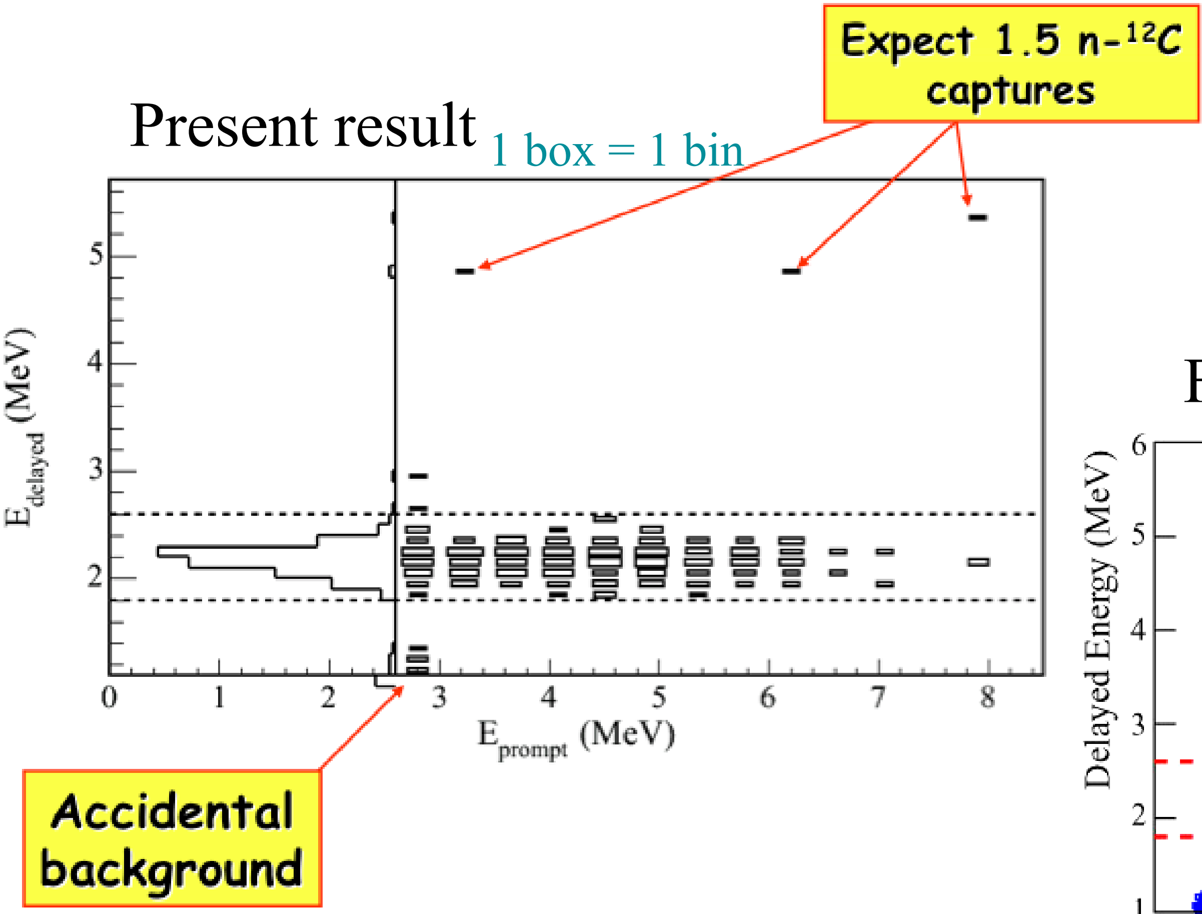
543.7 ton
33% increase

- 2s veto for showering/bad μ
- 2s veto in a R = 3m tube along track

Dead-time 9.7%

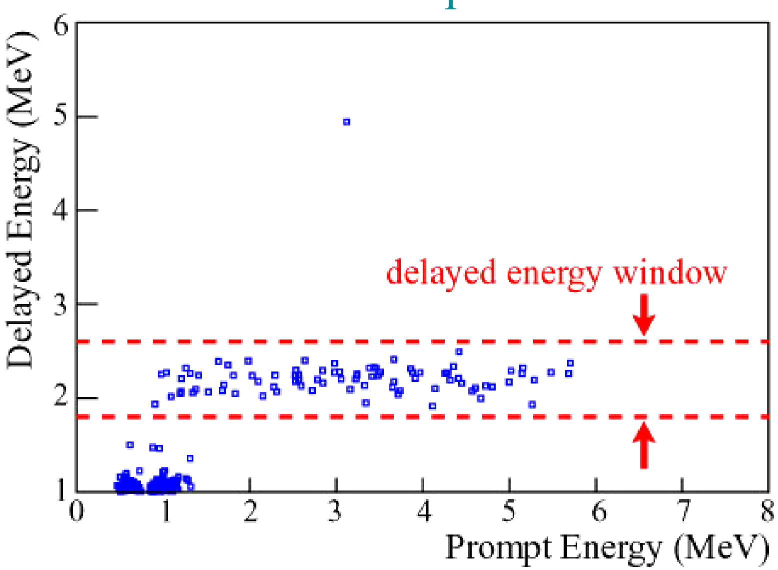
Present result v.s. first result

Present result 1 box = 1 bin



Quality: the same
Sample increased

First result 1 point = 1 event



Results

(766.3 ton·yr,
~4.7× the statistics of the first paper)

Background	Events
Accidentals	2.69±0.02
$^{8}He/^{9}Li$	4.8±0.9
μ-induced n	<0.89
Total	7.5±1.3

Observed events 258
No osc. expected 365±24(syst)
Background 7.5±1.3

Inconsistent with simple $1/R^2$ propagation at 99.995% CL

(Observed-Background)/Expected = 0.686±0.044(stat)±0.045(syst)

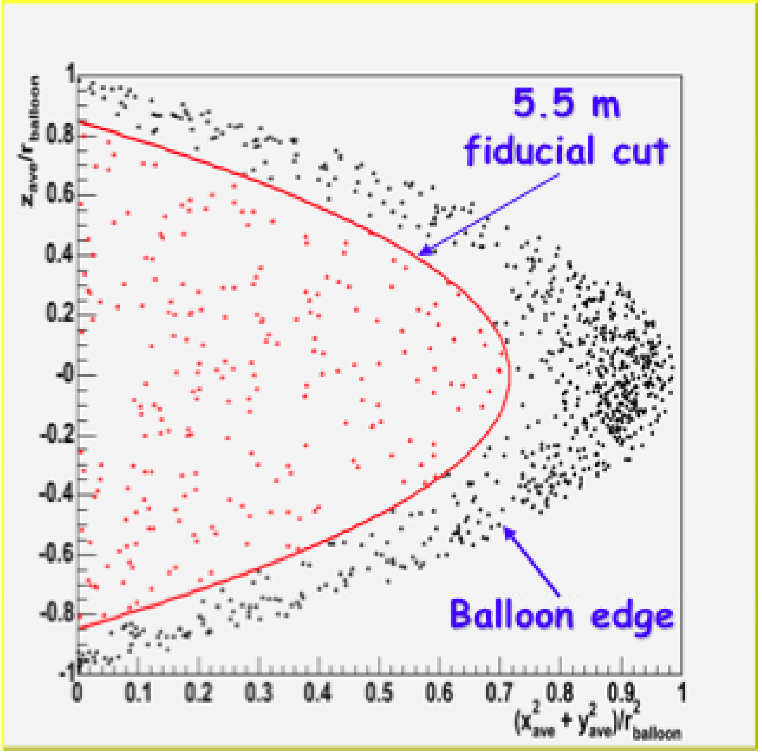
Caveat: this specific number does not have an absolute meaning in KamLAND, since, with oscillations, it depends on which reactors are on/off

Selecting antineutrinos, E_{prompt}>2.6MeV

- $R_{prompt,\ delayed}$ < 5.5 m
- ΔR_{e-n} < 2 m
- 0.5 μs < ΔT_{e-n} < 1 ms
- 1.8 MeV < $E_{delayed}$ < 2.6 MeV
- 2.6 MeV < E_{prompt} < 8.5 MeV

543.7 ton
33% increase

Tagging efficiency 89.8%

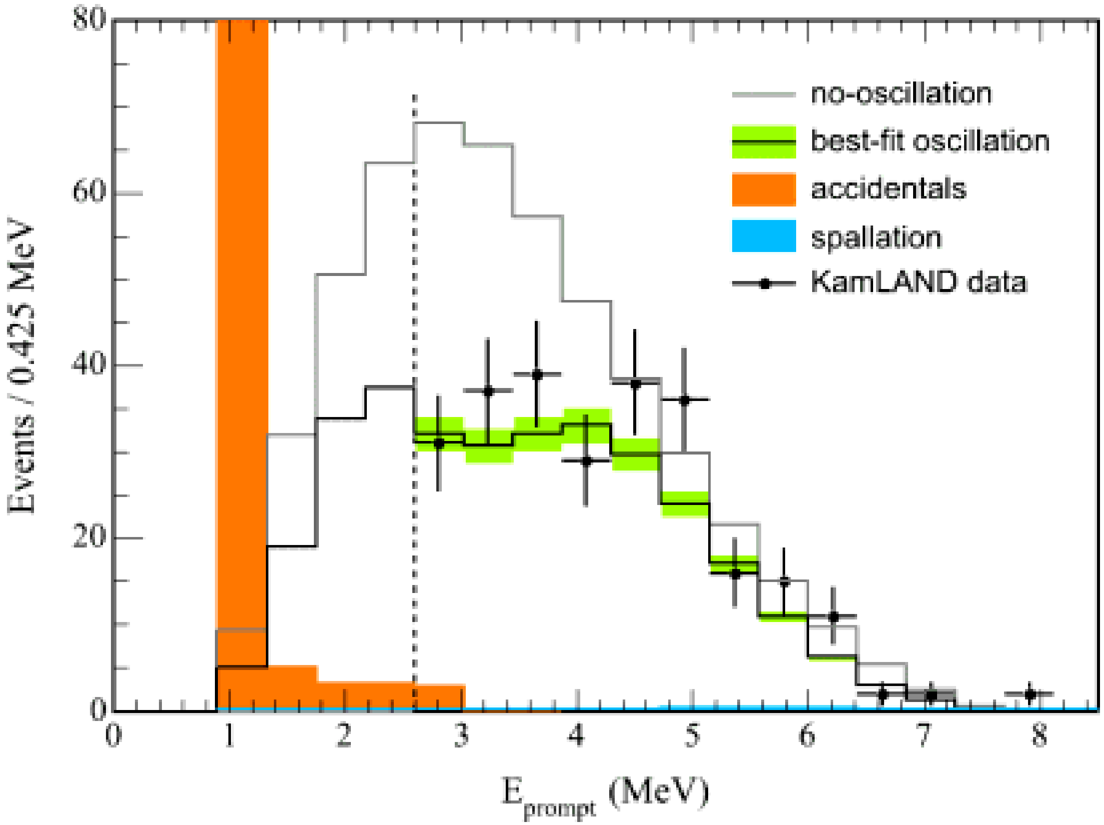


...In addition:

- 2s veto for showering/bad μ
- 2s veto in a R = 3m tube along track

Dead-time 9.7%

Energy spectrum now adds substantial information



A fit to a simple rescaled reactor spectrum is excluded at 99.89% CL (χ^2=43.4/19)

Best fit to oscillations:

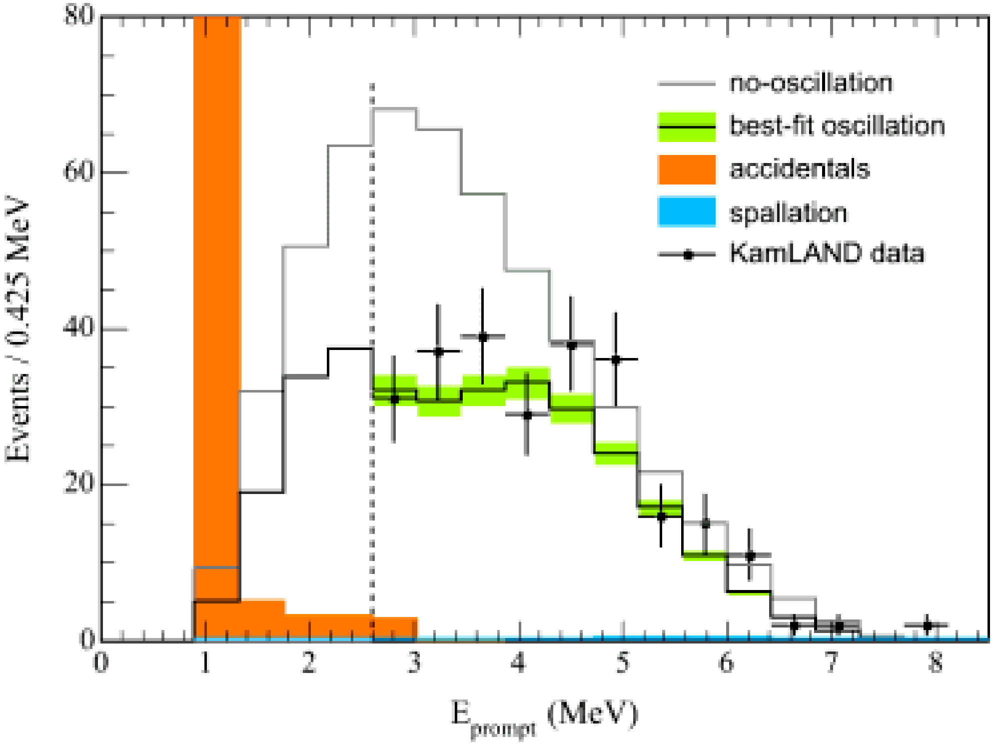
$\Delta m^2 = 8.3 \cdot 10^{-5}$ eV^2

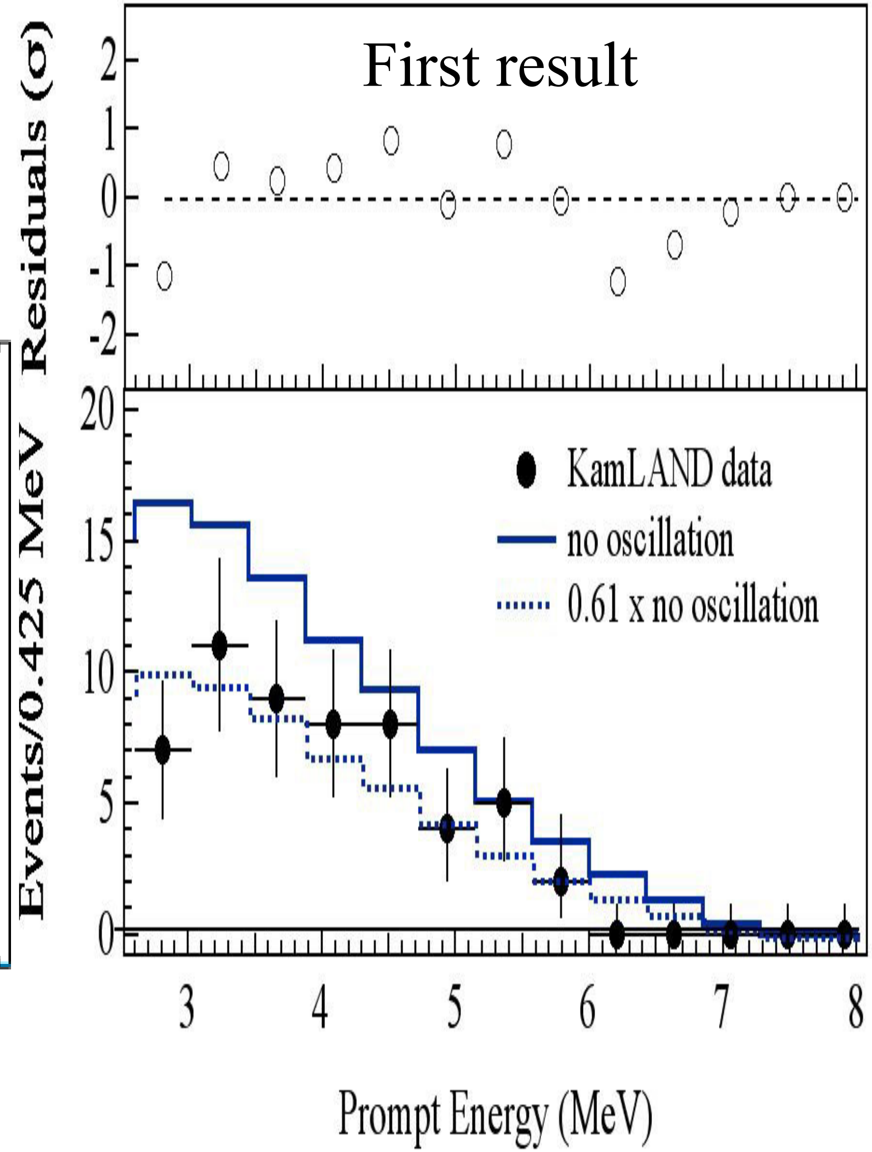
$\sin^2 2\theta = 0.83$

Straightforward χ^2 on the histo is 19.6/11

Using equal probability bins χ^2/dof=18.3/18 *(goodness of fit is 42%)*

4.7-times statistics
53 %.C.L. -> 99.89 % C.L.
(spectral distortion)



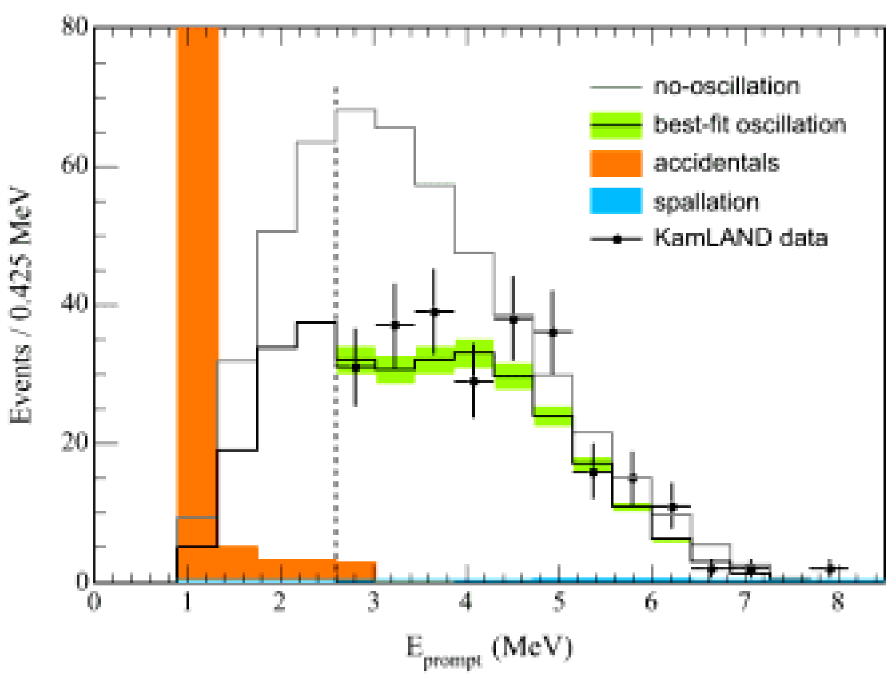


A fit to a simple rescaled reactor spectrum is excluded at 99.89% CL (χ^2=43.4/19)

Data and scaled no-oscillation shape consistent at 53% C.L

Verification of the final neutrino sample

The 258 events



- Event reconstruction quality & near-event distribution checked after the final neutrino sample fixed
- All events have been verified by physicists. (not a selection criterion)

"Reconstructed Event Display" to check event quality

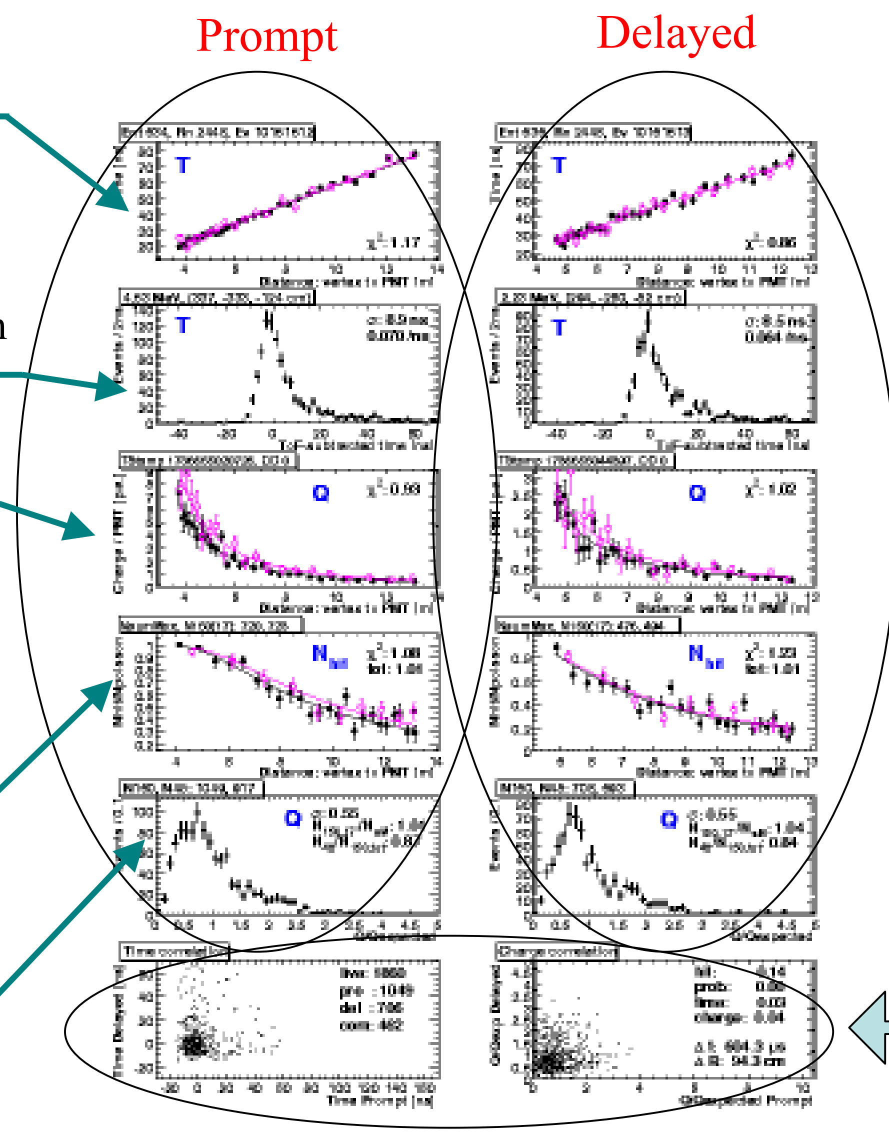
Time v.s. distance from the obtained vertex point to each PMT. Points are data, curves are expected by the vertex fitter with the universal speed of light.

ToF-subtracted time spectrum. Width is from scintillation time profile.

Charge v.s. distance. r $^{-2}$ effect is dominant, with all the effects (transparency, shade etc) are also included in the expected curves.

Occupancy v.s. distance. Saturation curve characteristic to Poisson statistics are seen in data and expected curves.

Distribution of charge divided by expected. Width is from PMT charge distribution.

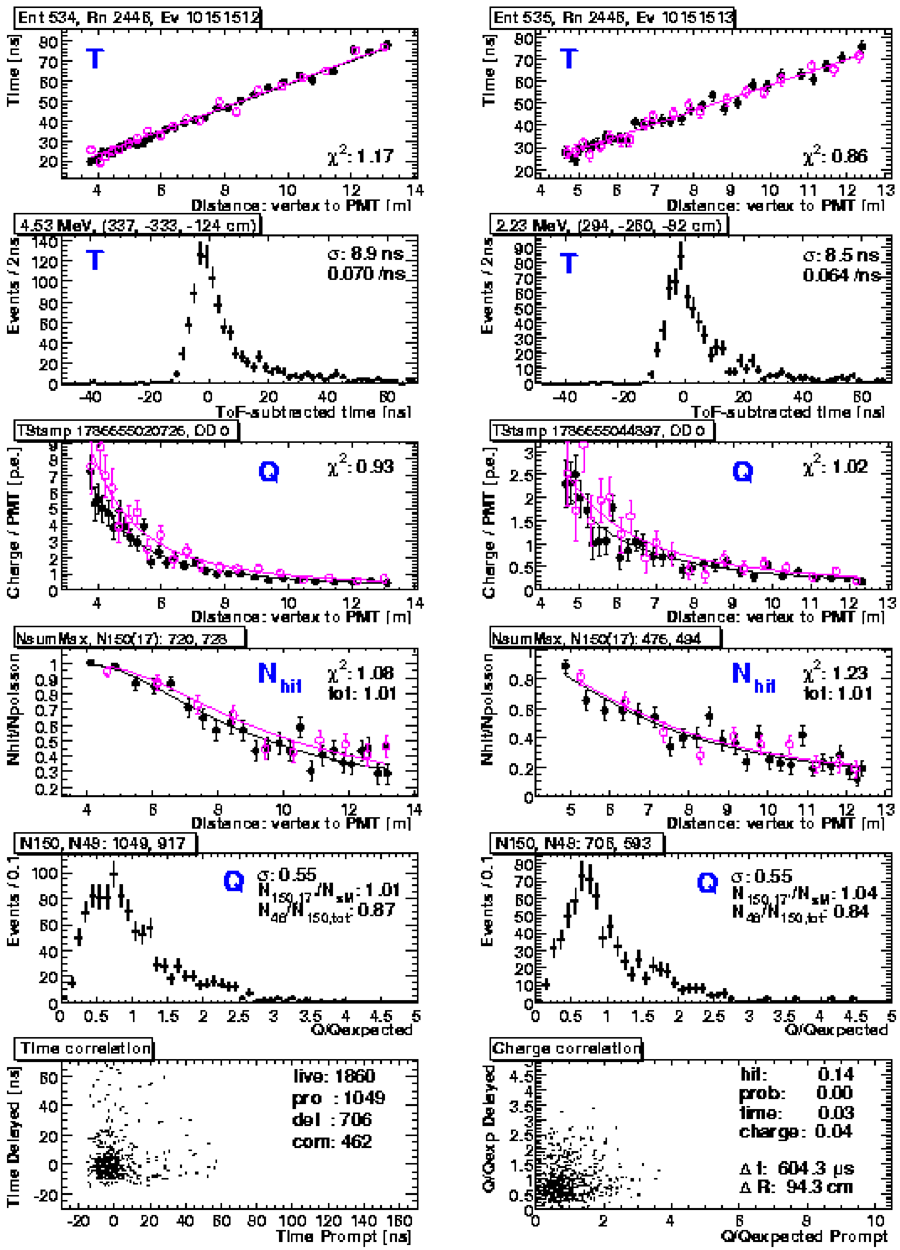


- 17''
- 20''

1 data point : 30 to 50 PMTs

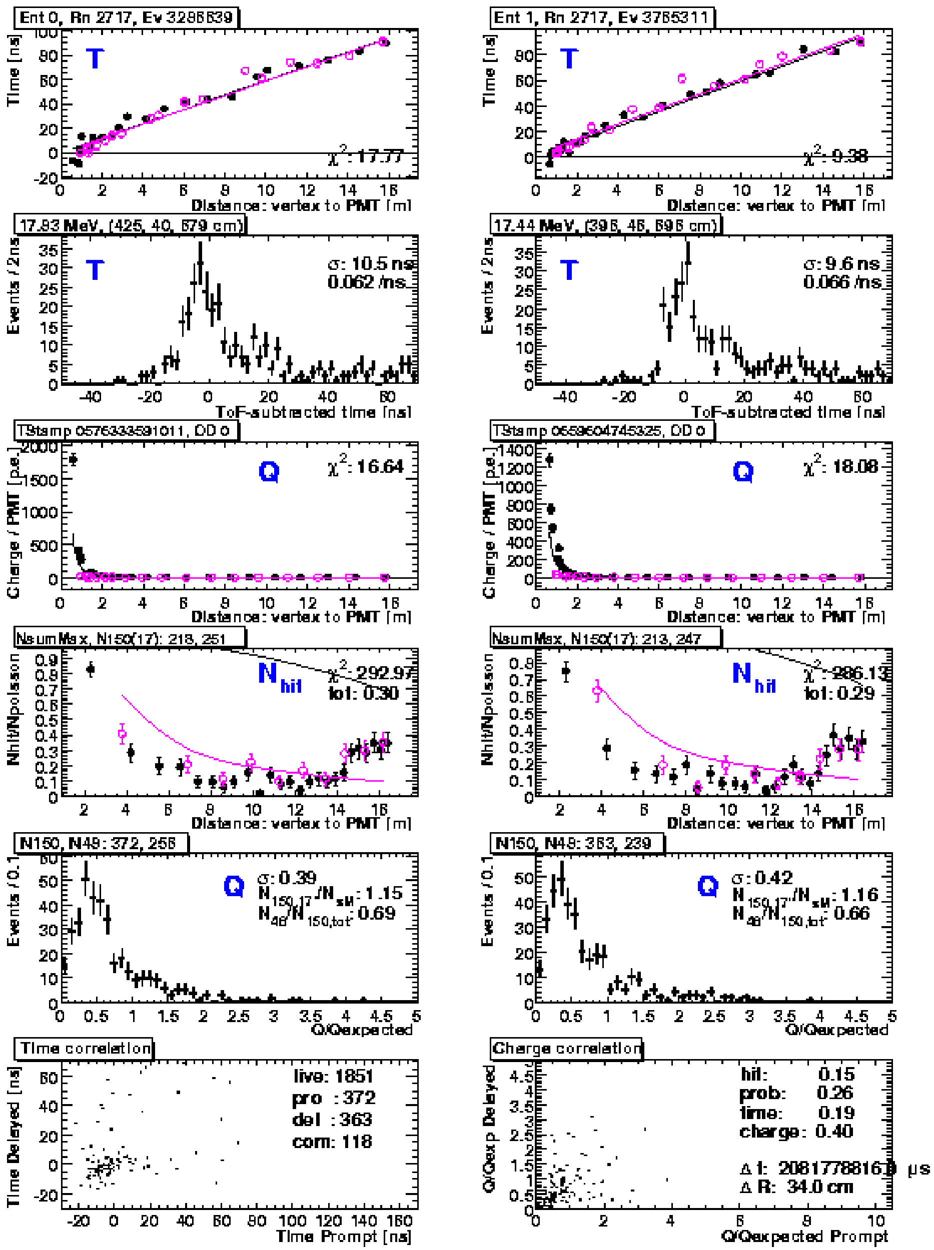
Correlation between prompt and delayed events.

ν 4.5 MeV



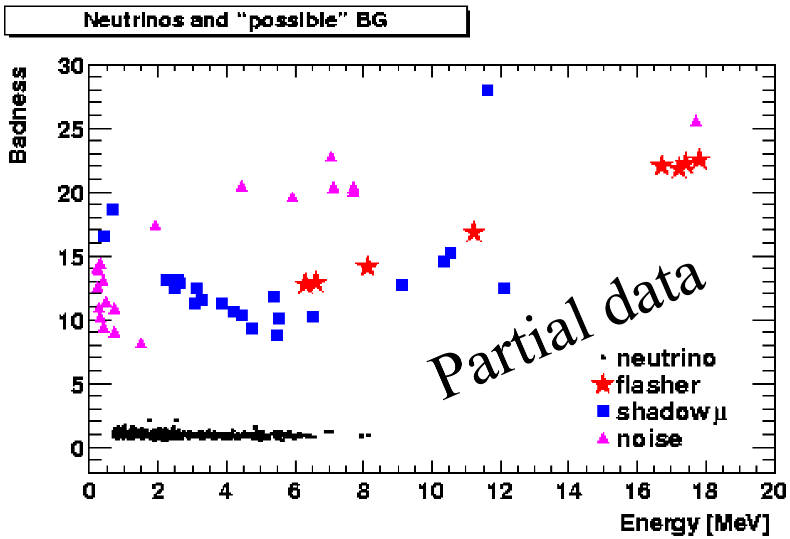
- One of neutrino candidates.
- Timing, Charge, Occupancy dependence on distance from the reconstructed vertex point are quite consistent with isotropic scintillation light emission.

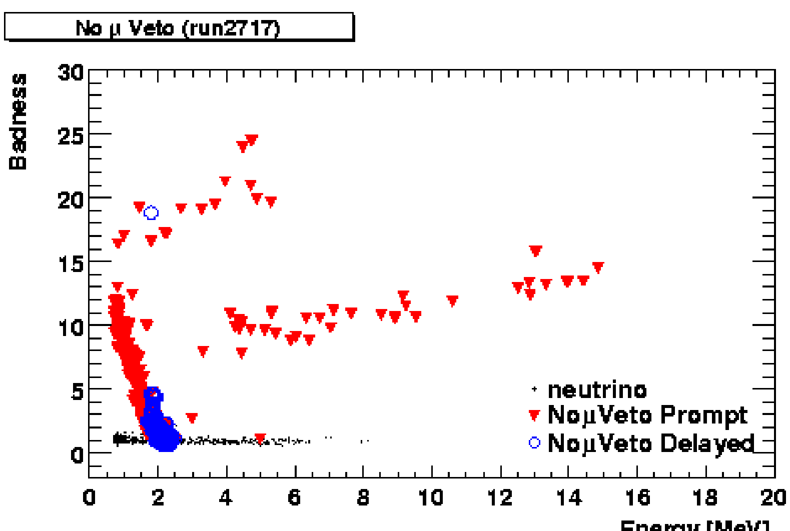
Flasher



- Flasher events can be easily distinguished from real events.
- Because flasher is real light emission, timing and charge distributions show roughly similar behavior.
- However, chi square is very bad, probably because it’s not isotropic emission, and has different wave length spectrum.
- Usually, flasher is identified with very large charge in only one PMT, but in this analysis, that “flashing PMT” is excluded from the data, and flasher can still be identified with bad distribution of other PMTs.

Badness: ν v.s. unphysical events





- All the unphysical events studied here are clearly separated from neutrino samples or AmBe calibration data.
- No veto BG shows continuous distribution. Even if muon veto fails, it doesn't fake only good background but also makes background with high badness.
- All neutrino events are good as a result (we didn't apply any cut using badness)

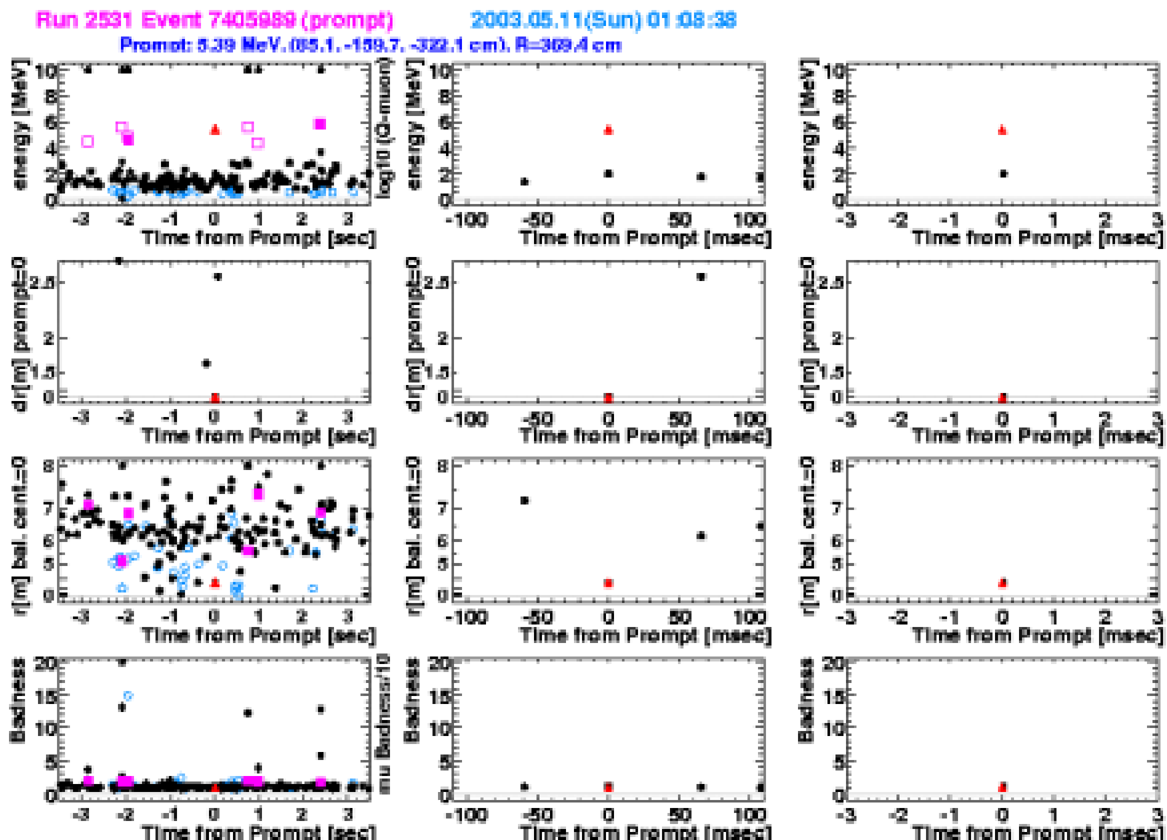
Near events distribution

energy

Δr from the prompt event

R

badness



▲ prompt

● global trigger

○ delayed trigger

□ ■ muon

■ residual charge

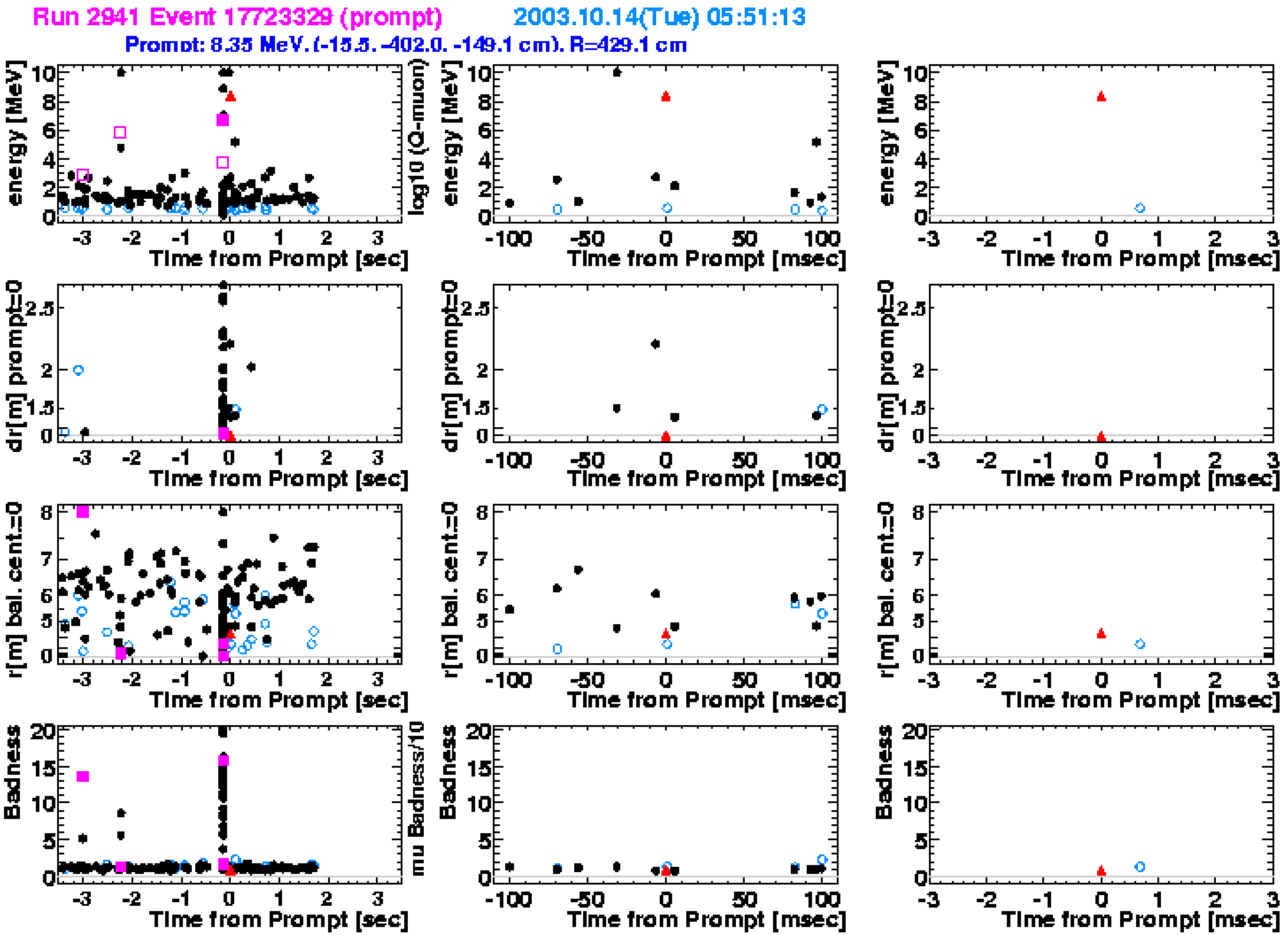
±3.5 s

±100 ms

±3 ms

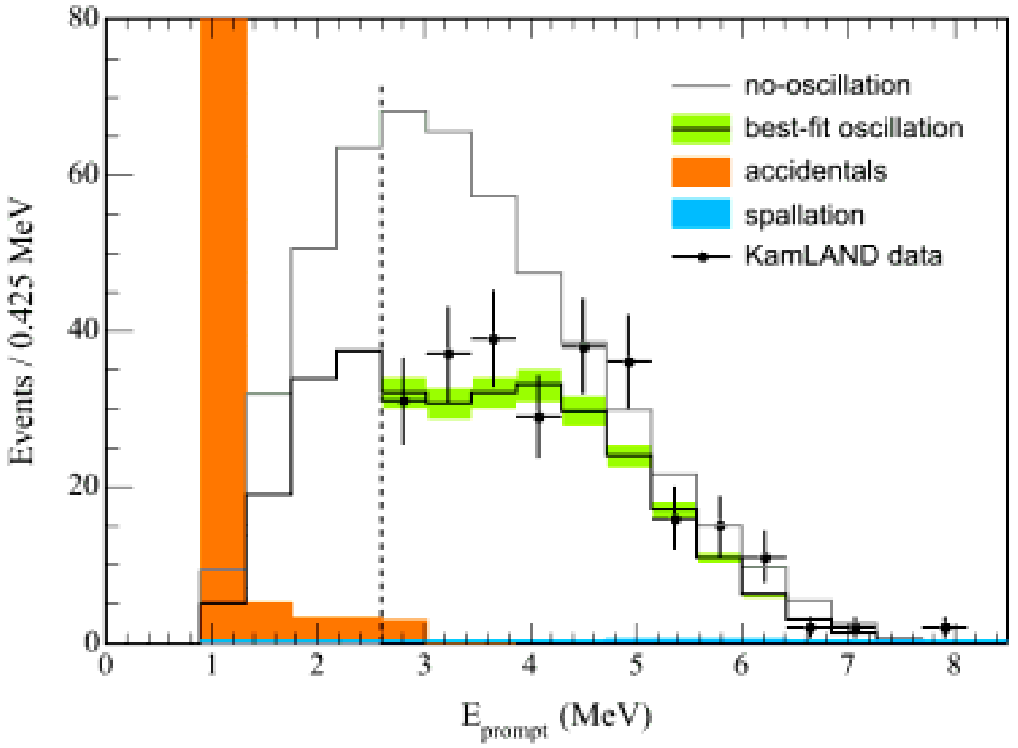
Time from the prompt

A typical spallation event



- High energy (>4MeV), and high badness event cluster near the prompt delayed pair

Energy spectrum now adds substantial information



A fit to a simple rescaled reactor spectrum is excluded at 99.89% CL (χ^2=43.4/19)

Best fit to oscillations:

$\Delta m^2 = 8.3 \cdot 10^{-5}$ eV^2

$\sin^2 2\theta = 0.83$

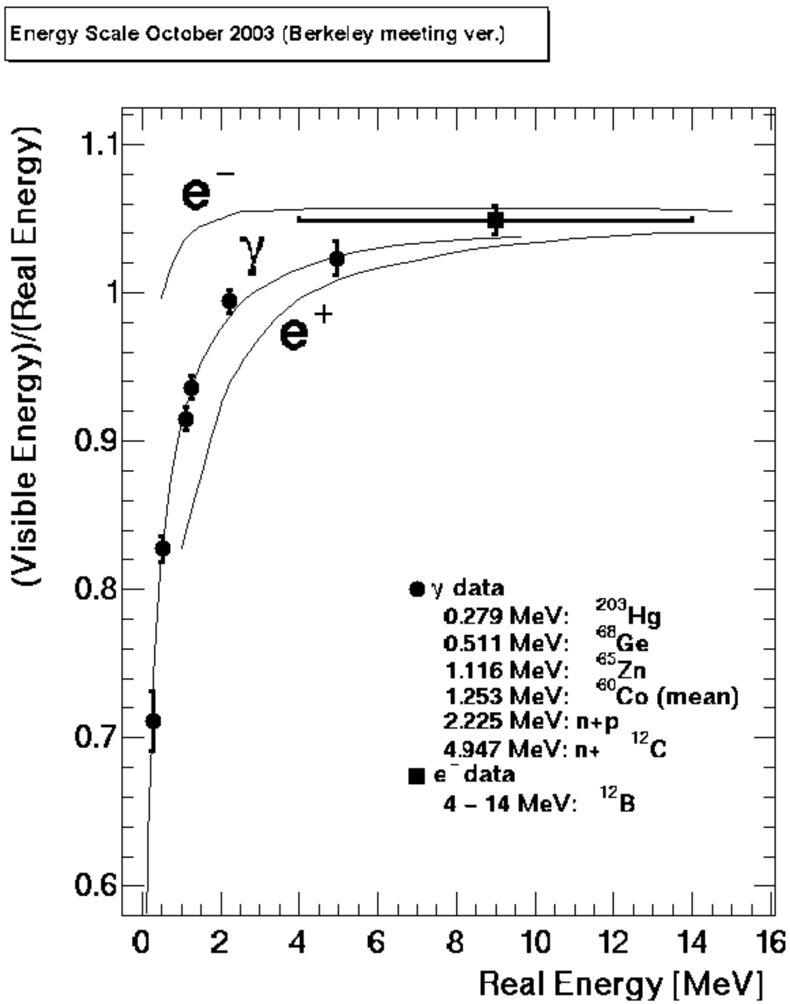
Straightforward χ^2 on the histo is 19.6/11

Using equal probability bins

χ^2/dof=18.3/18

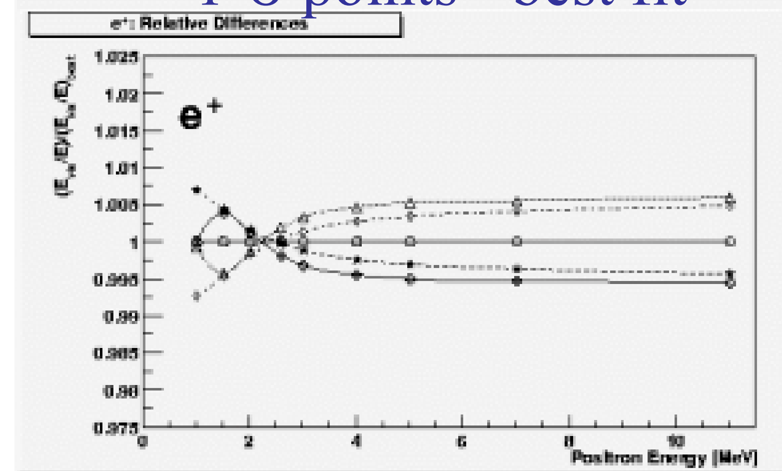
(goodness of fit is 42%)

Systematic errors of spectral shape



- 0.35% (energy scale nonlinearity)
- 2.7% (possible energy dependence of the fiducial volume, approximated by linear function)
- ~1.4 % (reactor spectrum)

1-σ points - best fit



Analysis method

- Rate analysis

$$\chi^2_{\mathrm{Rate}} = \frac{(\mathrm{Ratio}_{\mathrm{observed}} - \mathrm{Ratio}_{\mathrm{expected}}(\sin^2 2\theta\ ,\Delta m^2))^2}{\sigma_{\mathrm{stat}}{}^2 + \sigma_{\mathrm{syst}}{}^2}$$

$\sigma_{\mathrm{stat}}, \sigma_{\mathrm{syst}}$: Sigma of the observed ratio

- Shape analysis

$$\chi^2_{\mathrm{Shape}} = -2 \log L_{\mathrm{Shape}}(\sin^2 2\theta\ ,\Delta m^2, N_{BG}, \alpha) + \chi^2_{BG}(N_{BG}) + \chi^2_{\mathrm{distortion}}(\alpha)$$

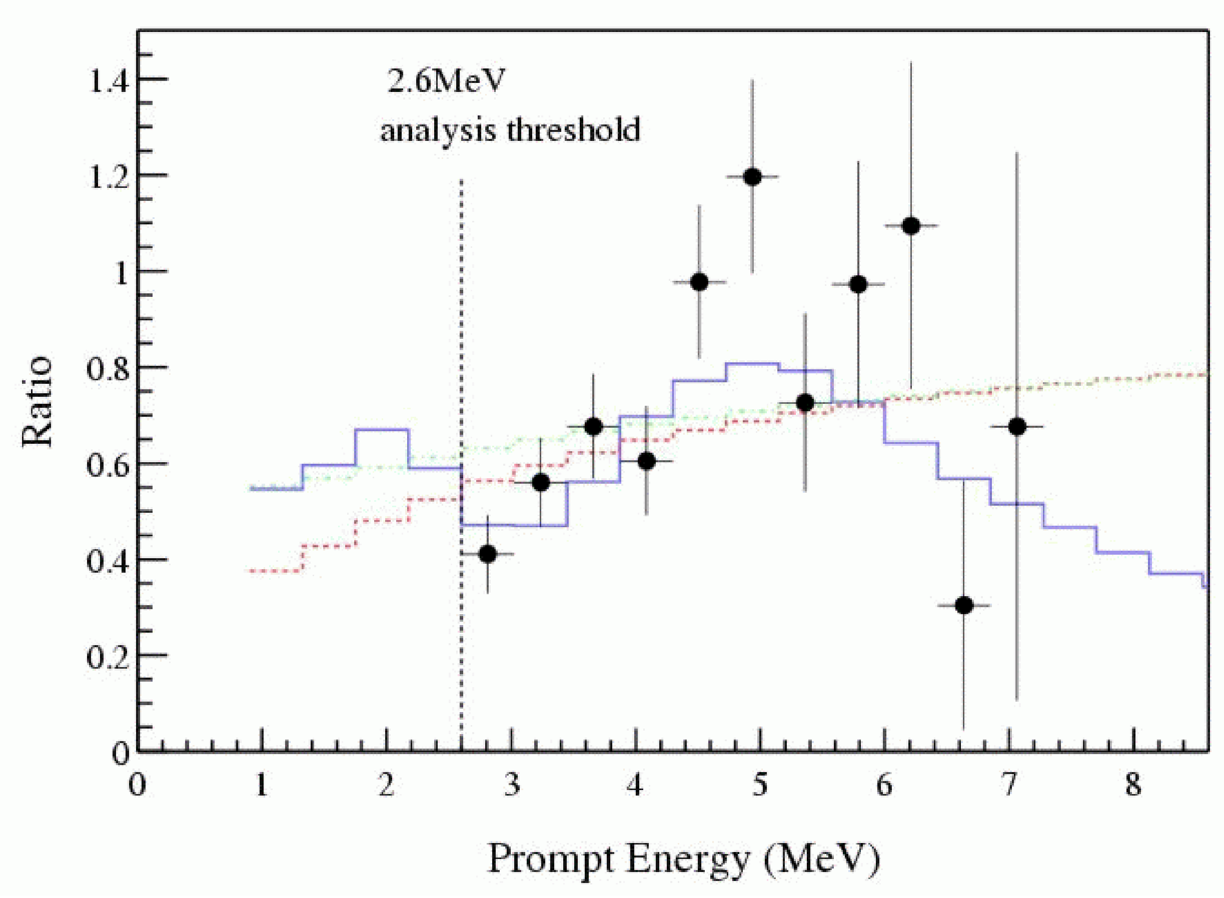
N_{BG} : accidental and spallation backgrounds

α : energy scale, ν spectrum error

- Rate+Shape analysis

$$\chi^2_{\mathrm{Rate+Shape}} = \chi^2_{\mathrm{Rate}} + \chi^2_{\mathrm{Shape}}$$

Ratio: (observed - BG) / no-oscillation

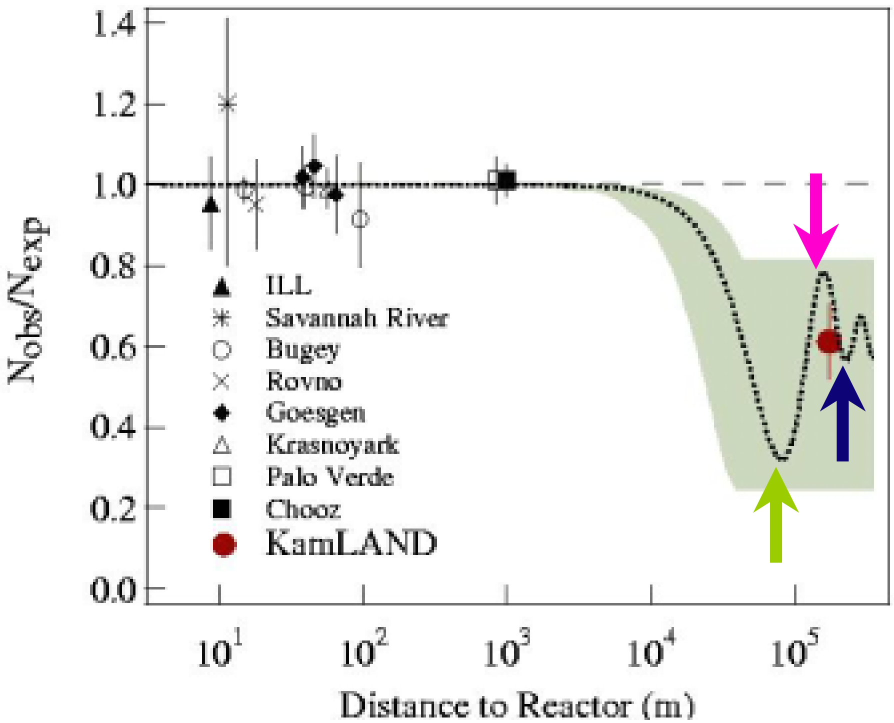


- Rescaled no-oscillation == arbitrary constant obviously doesn't fit the data

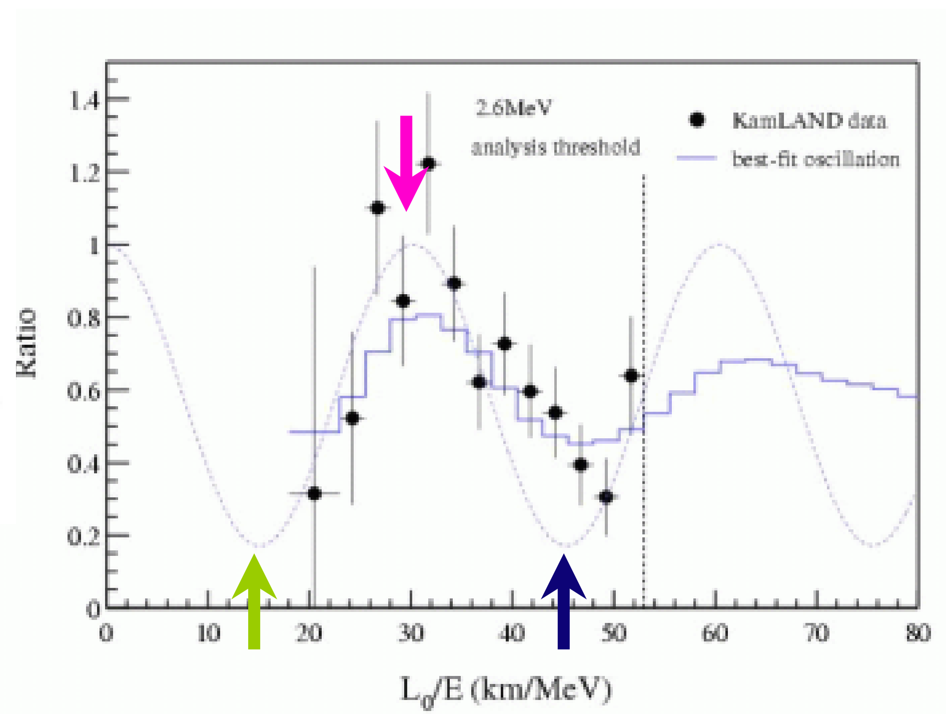
Ratio v.s. L_0/E

oscillating nearly 1 wave length
(with short-base-line data,
1.5 wave length)

Present result

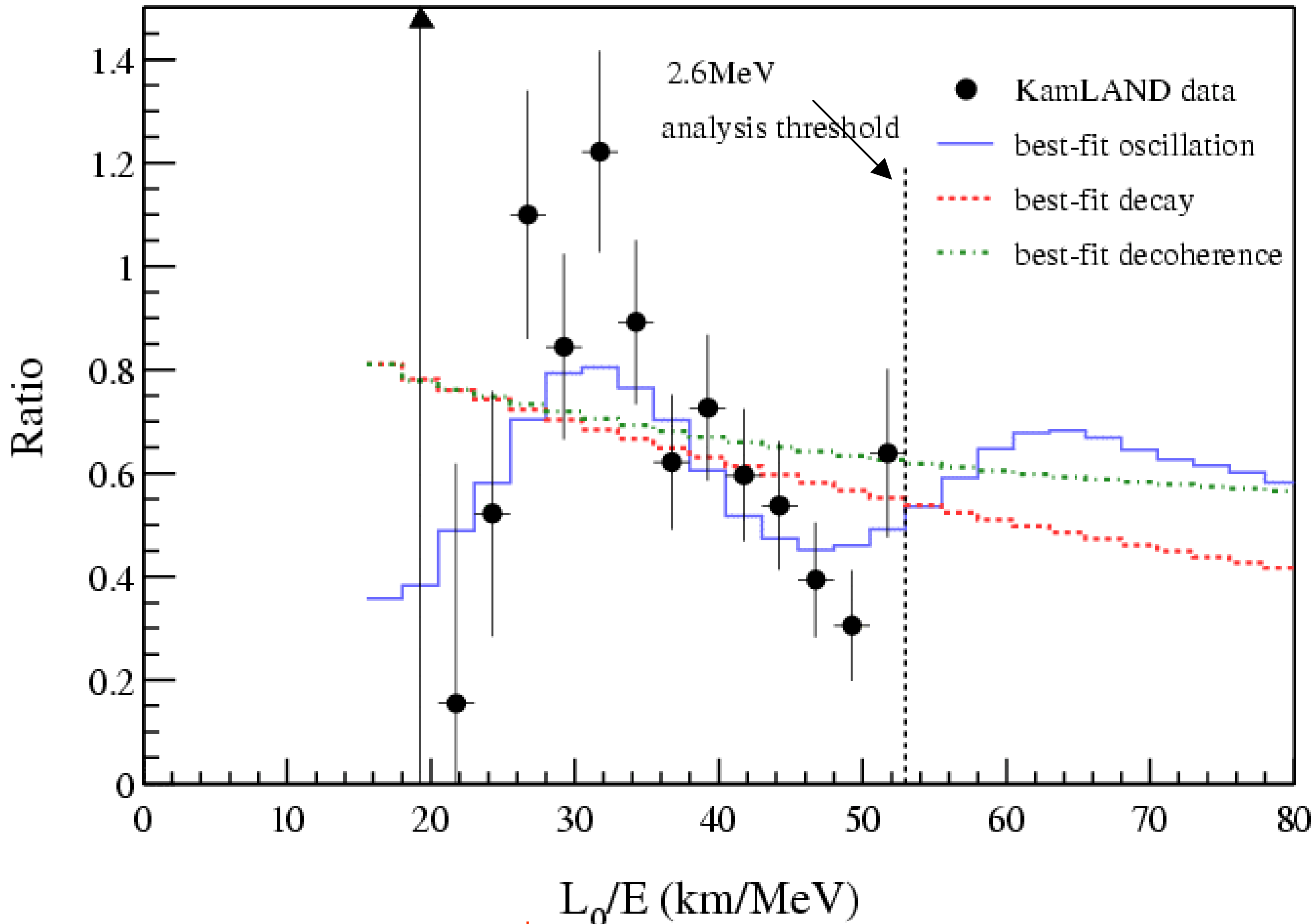


First result and
previous experiments



L_0=180 km

More exotic, non-oscillations models for the antineutrino channel start being less favored by data



Decay* excluded at 95% CL

Decoherence† excluded at 94% CL

*V.Barger et al. Phys. Rev. Lett. 82 (1999) 2640

†E.Lisi et al., Phys. Rev. Lett. 85 (2000) 1166

Neutrino decay and decoherence

- Neutrino decay

$\nu_2 \rightarrow X$ (sterile), $\Delta m_{12}^2 \sim 0$ case

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = (\cos^2\theta + \sin^2\theta \exp(-\frac{m\,L}{2\,\tau\,E}))^2$$

- Neutrino decoherence

$\Delta m_{12}^2 \sim 0$ case

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \frac{1}{2}\sin^2 2\theta\,(1 - \exp(-\gamma_0 \frac{L}{E}))$$

Shape distortion

Neutrino oscillation

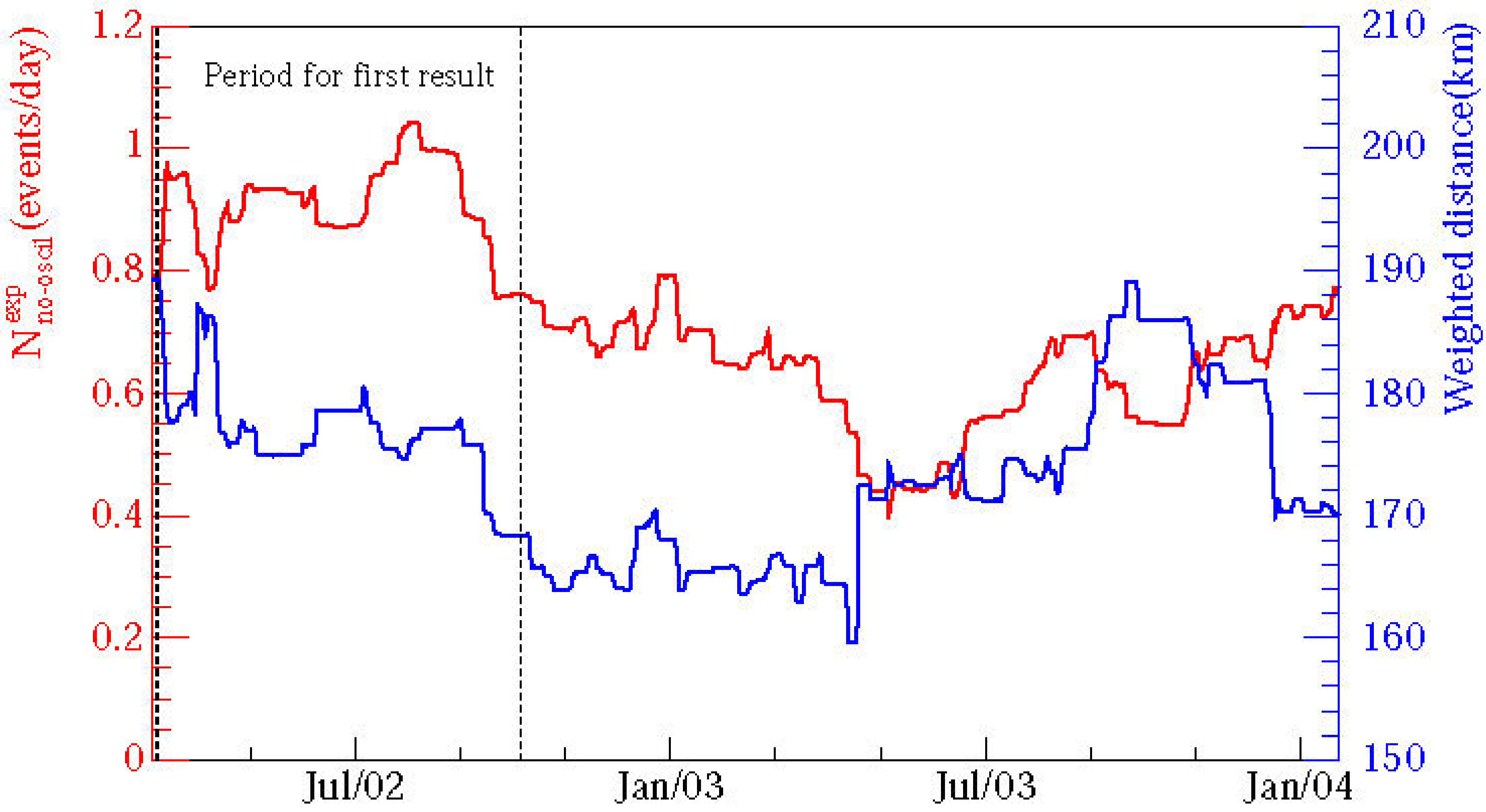
Neutrino decay

Neutrino decoherence

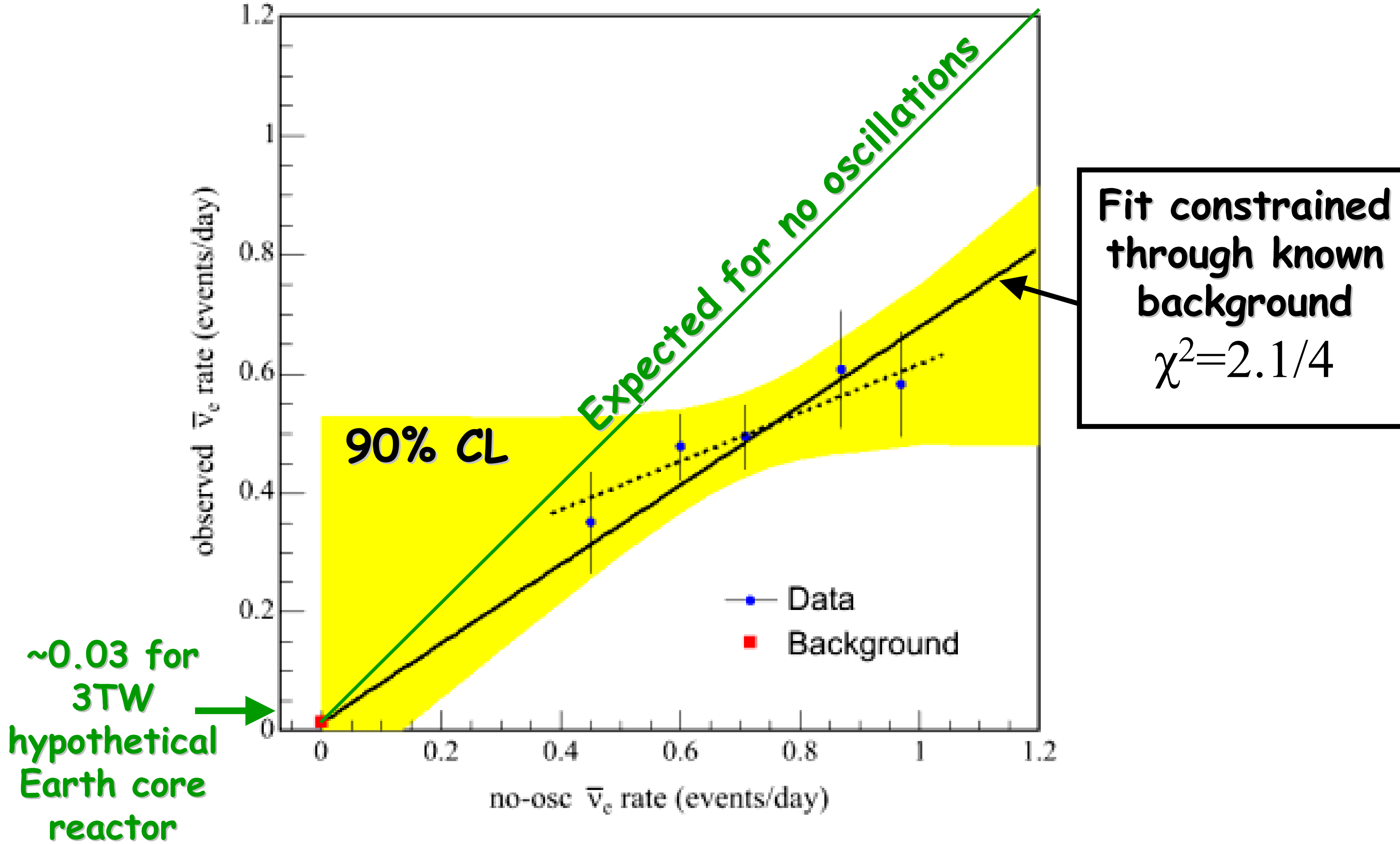
Testing good ness of fit

Which one is more likely ?

2003 saw a substantial dip in reactor antineutrino flux

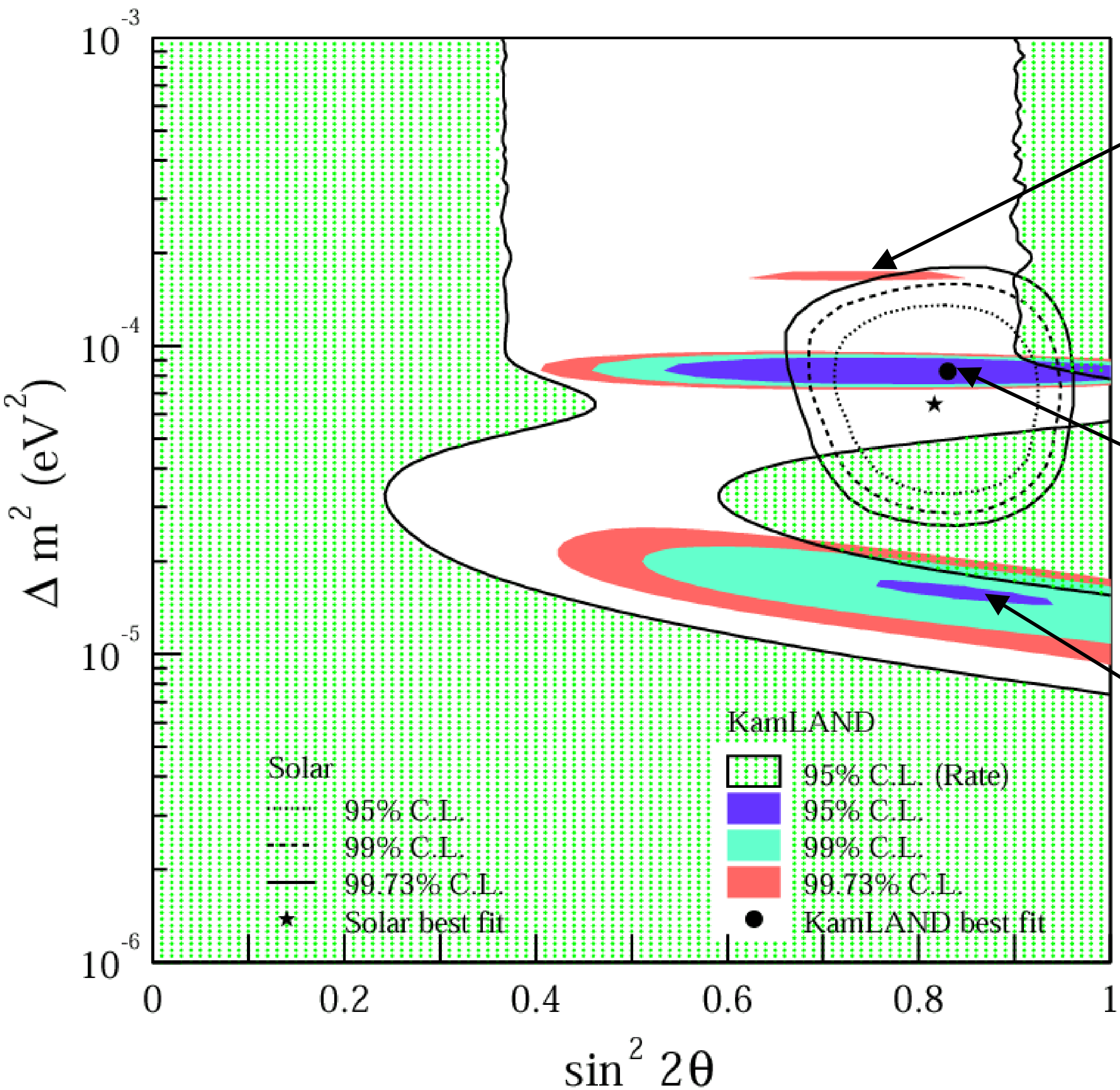


Good correlation with reactor flux



(But a horizontal line still gives a decent fit with χ^2=5.4/4)

Un-binned likelihood fit to 2-flavor oscillations



LMA2 excluded at 99.6% CL

$\Delta m^2=8.3\cdot10^{-5}$ eV^2

$\sin^2 2\theta=0.83$

$\tan^2\theta=0.41$

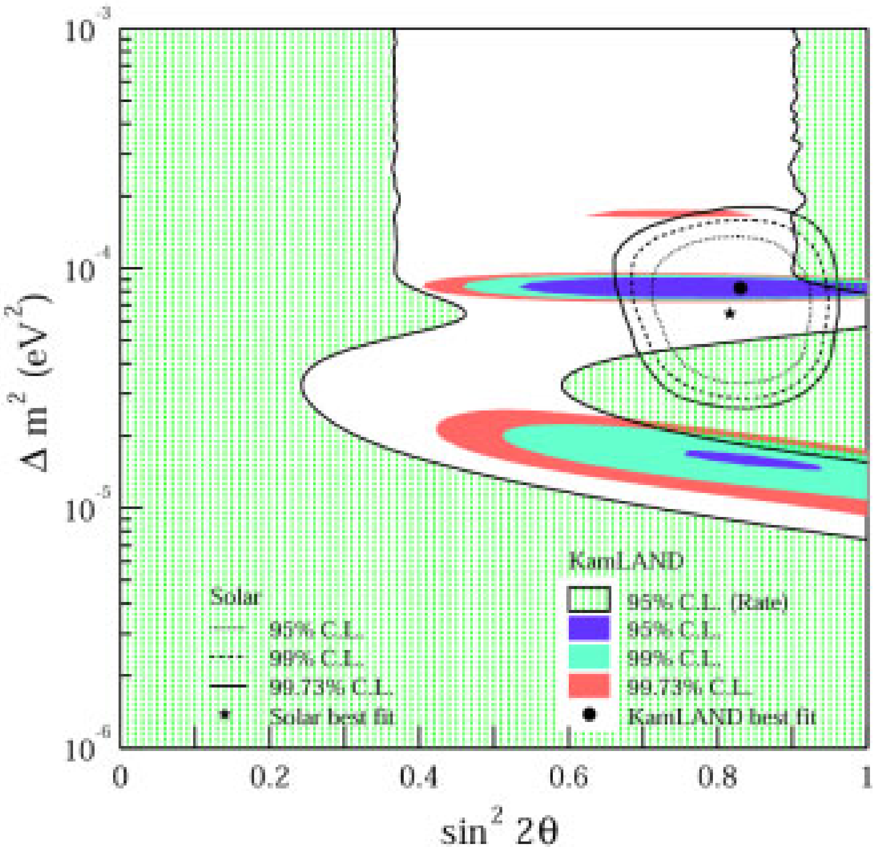
"LMA0" disfavored at 94% CL

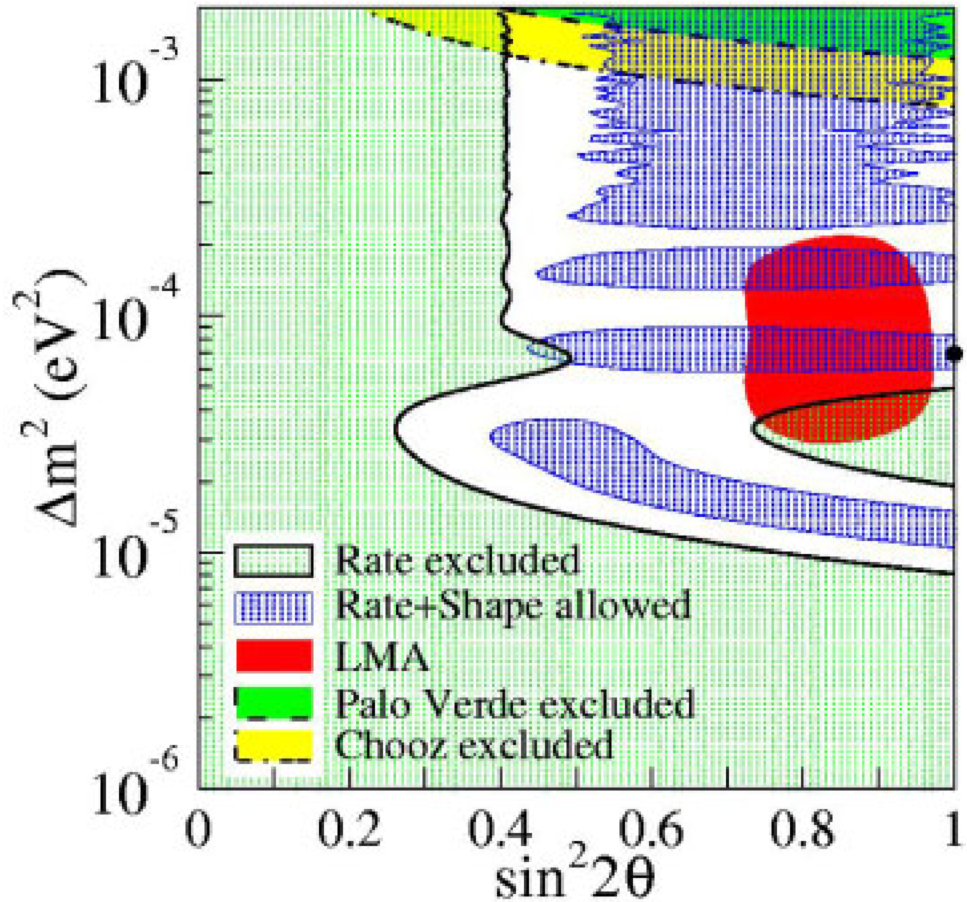
This result

$\Delta m^2 = 8.3 \cdot 10^{-5}$ eV^2
$\sin^2 2\theta = 0.83$

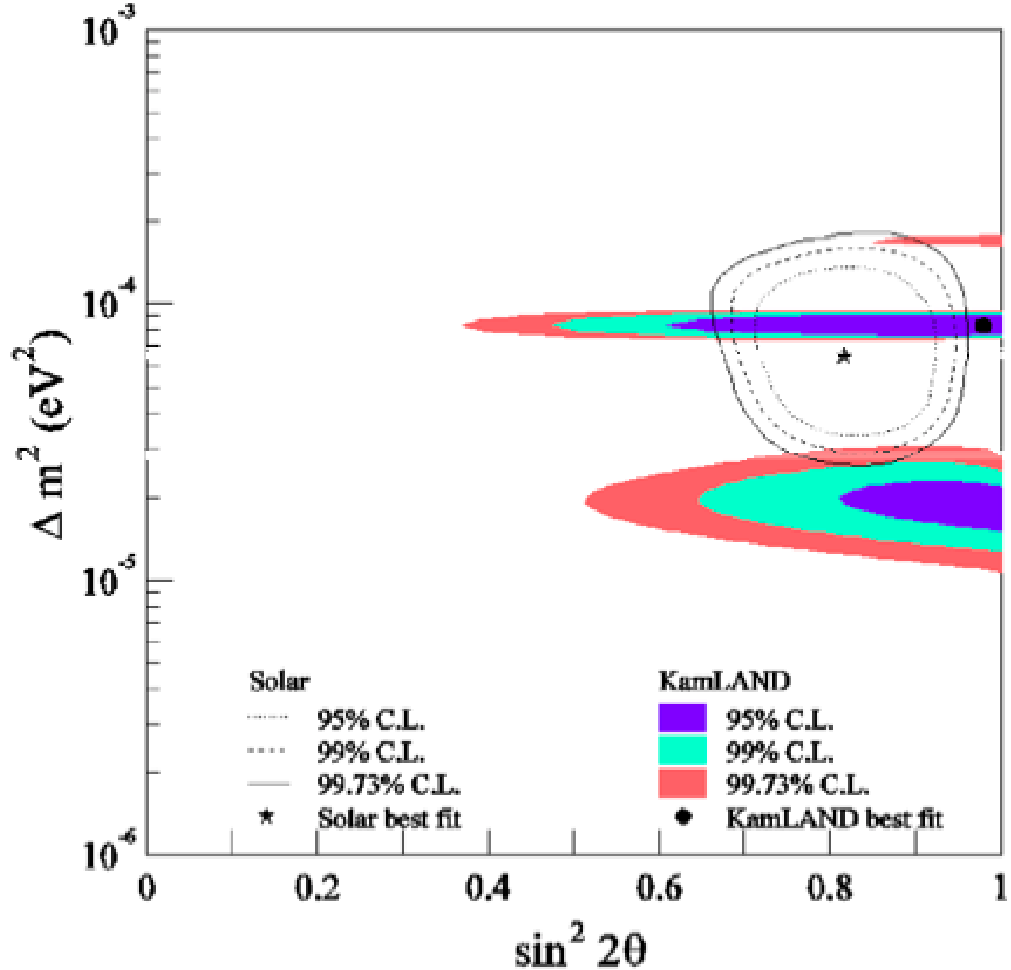
First KamLAND result

$\Delta m^2 = 6.9 \times 10^{-5}$ eV^2
$\sin^2 2\theta = 1.0$





A shape-only fit gives similar results



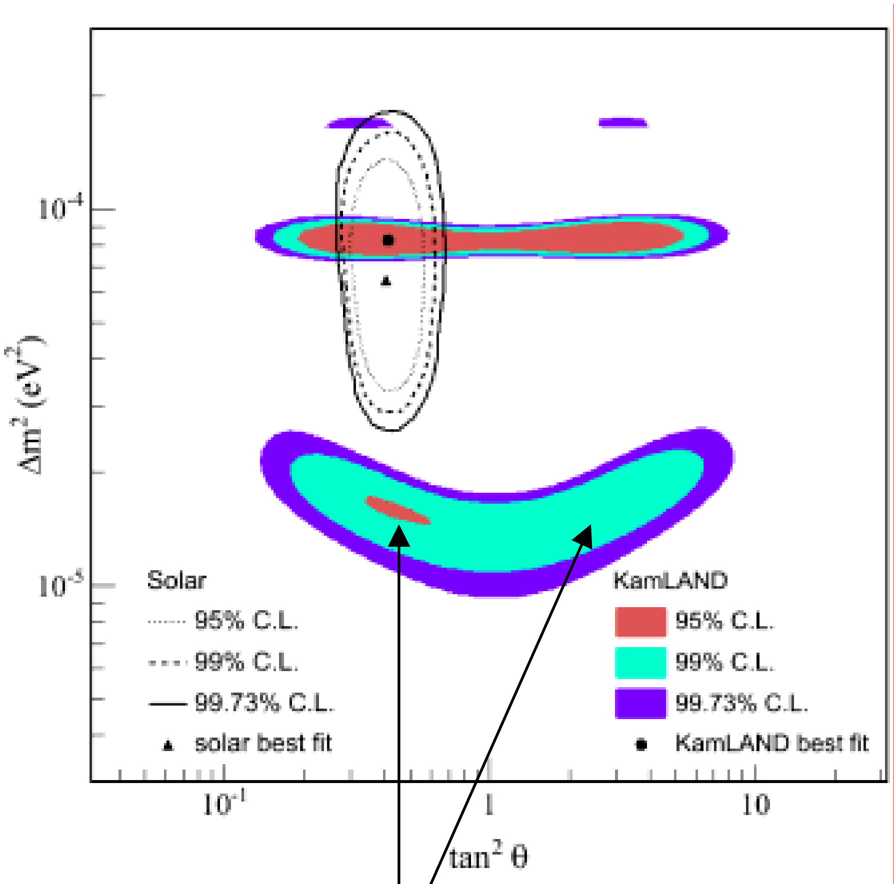
$\Delta m^2=8.3 \cdot 10^{-5}\ eV^2$

$\sin^2 2\theta=0.98$

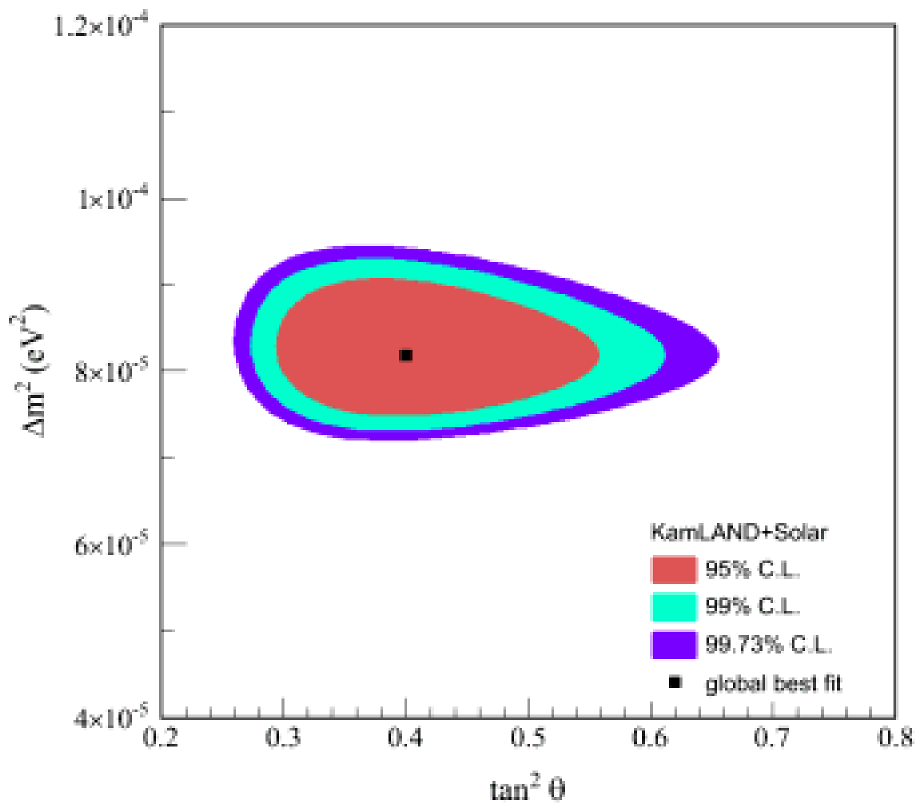
Combined solar ν – KamLAND 2-flavor analysis

$$\Delta m^2_{12} = 8.2^{+0.6}_{-0.5} \times 10^{-5}\, eV^2$$

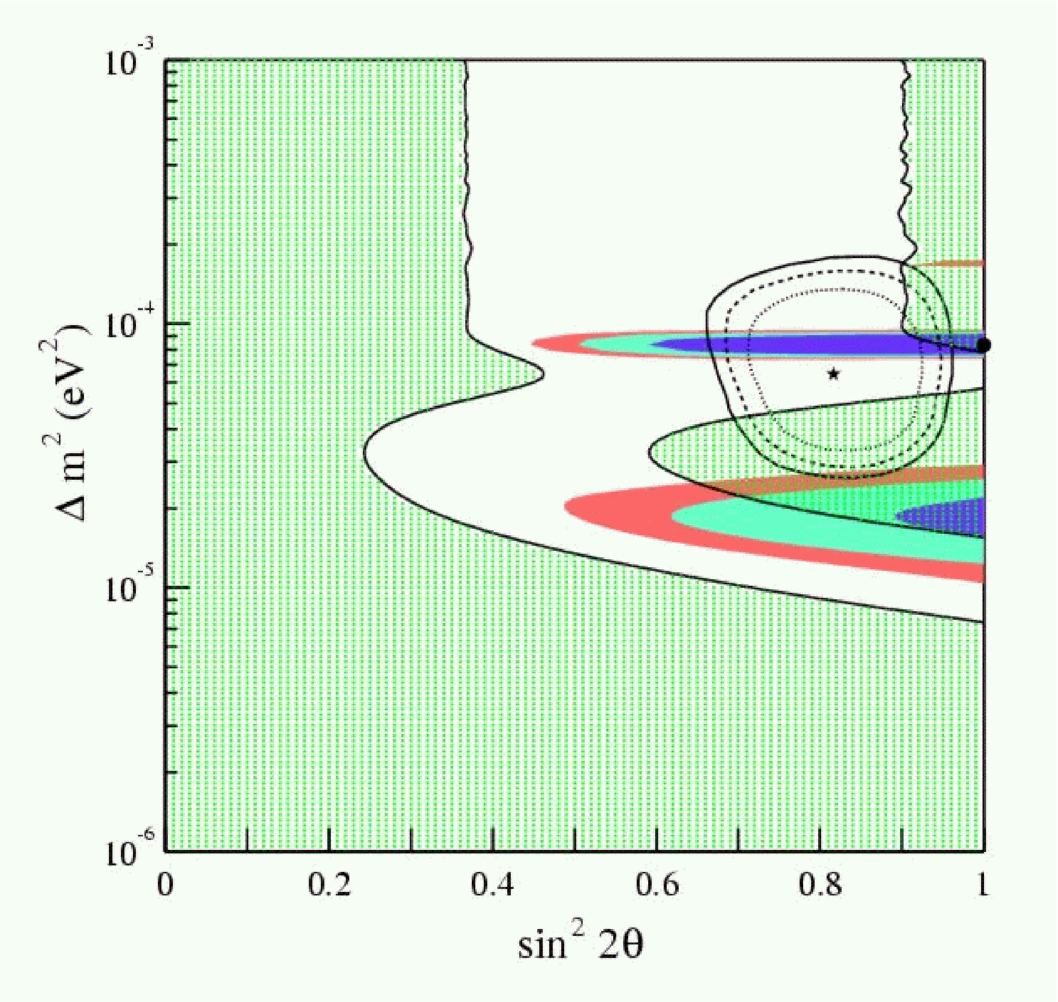
$$\tan^2\theta_{12} = 0.40^{+0.09}_{-0.07}$$



Includes (small) matter effects



Unknown very far reactor: doesn’t change the result much



- e.g. hypothetical “georeactor” at the center of the Earth
- The same energy spectrum as normal reactors but no spectral distortion because it’s very far.
- Intensity: free parameter -> result didn’t change so much

Summary of reactor $\overline{\nu}_e$ oscillation by KamLAND

- 4.7 times larger statistics than the first result
- Spectral shape distortion observed at 99.9 % C.L.
- Oscillatory behavior of shape distortion observed: other models don't fit the observed distortion

  (e.g. neutrino decay disfavored at 95 % C.L.)
- Two-flavor neutrino oscillation:
  - KamLAND best fit: $\Delta m^2 = 8.3 \times 10^{-5}$ eV^2

    $\tan^2\theta = 0.41$
  - Global analysis : $\Delta m^2 = 8.2\,^{+0.6}_{-0.5} \times 10^{-5}$ eV^2

    $\tan^2\theta = 0.40\,^{+0.09}_{-0.07}$