Vertex reconstruction improvement in KamLAND and prospects for geoneutrino directionality analysis

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Motivation for directionality analysis in geoneutrino study

- ❖ Testing geo-reactor hypothesis
- ❖ Verification of geological models
- ❖ Additional background suppression
- ❖ More comprehensive use of experimental data

Generic unloaded scintillator-based antineutrino experiments

Main detection method: double coincidence

$$\overline{\nu}_e + p \rightarrow e^+ + n \xrightarrow{\text{capture on a hydrogen}} d + \gamma\,(2.2MeV)$$

Ionization losses and annihilation (prompt signal)

Compton scattering (delayed signal)

Typical time separation between prompt and delayed: ~200 μs

- The vertices of the prompt and the delayed signals are close but different
- The prompt-to-delayed vector direction is correlated with the direction of incident antineutrino

Quantitative study of the kinematics

Relativistic kinematics determines the following 4-vector equation for the inverse beta decay:

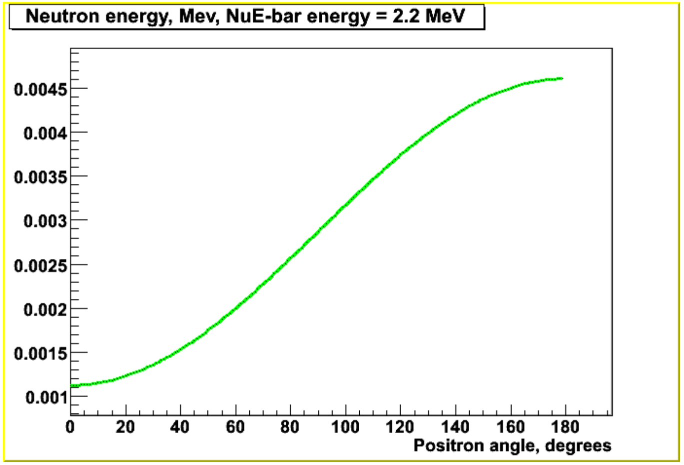
$$\hat{p}_{\nu} + \hat{p}_{p} = \hat{p}_{e^{+}} + \hat{p}_{n}$$

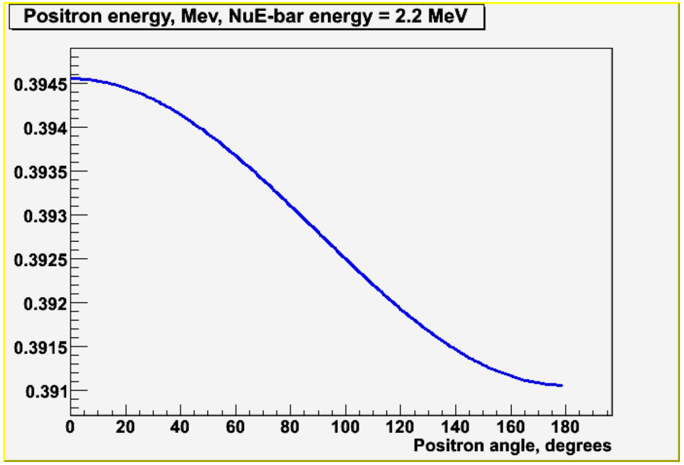
The two resulting 4-vectors can be represented in terms of:
(a) positron energy, (b) neutron energy, (c) positron angle (relative to incident antineutrino), (d) neutron angle

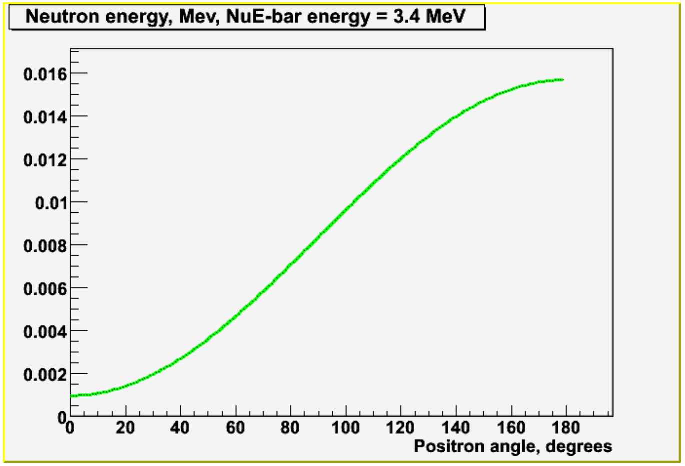
4 remaining parameters are electron and neutron mass; the two “meridian” angles

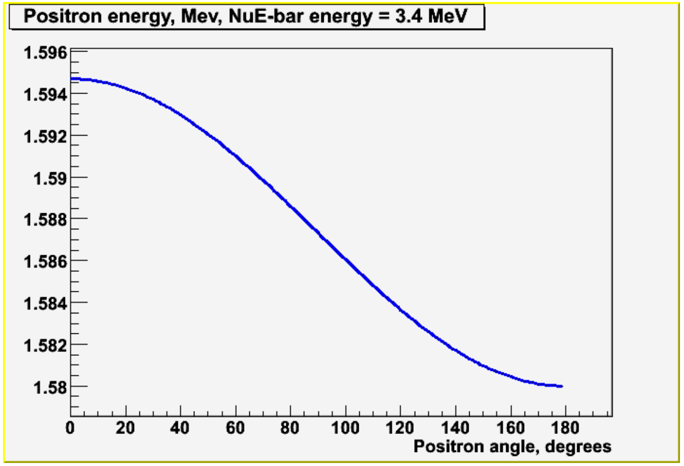
The equation can be satisfied for any positron angle but ***not*** any neutron angle

Neutron and positron energies for different positron angles



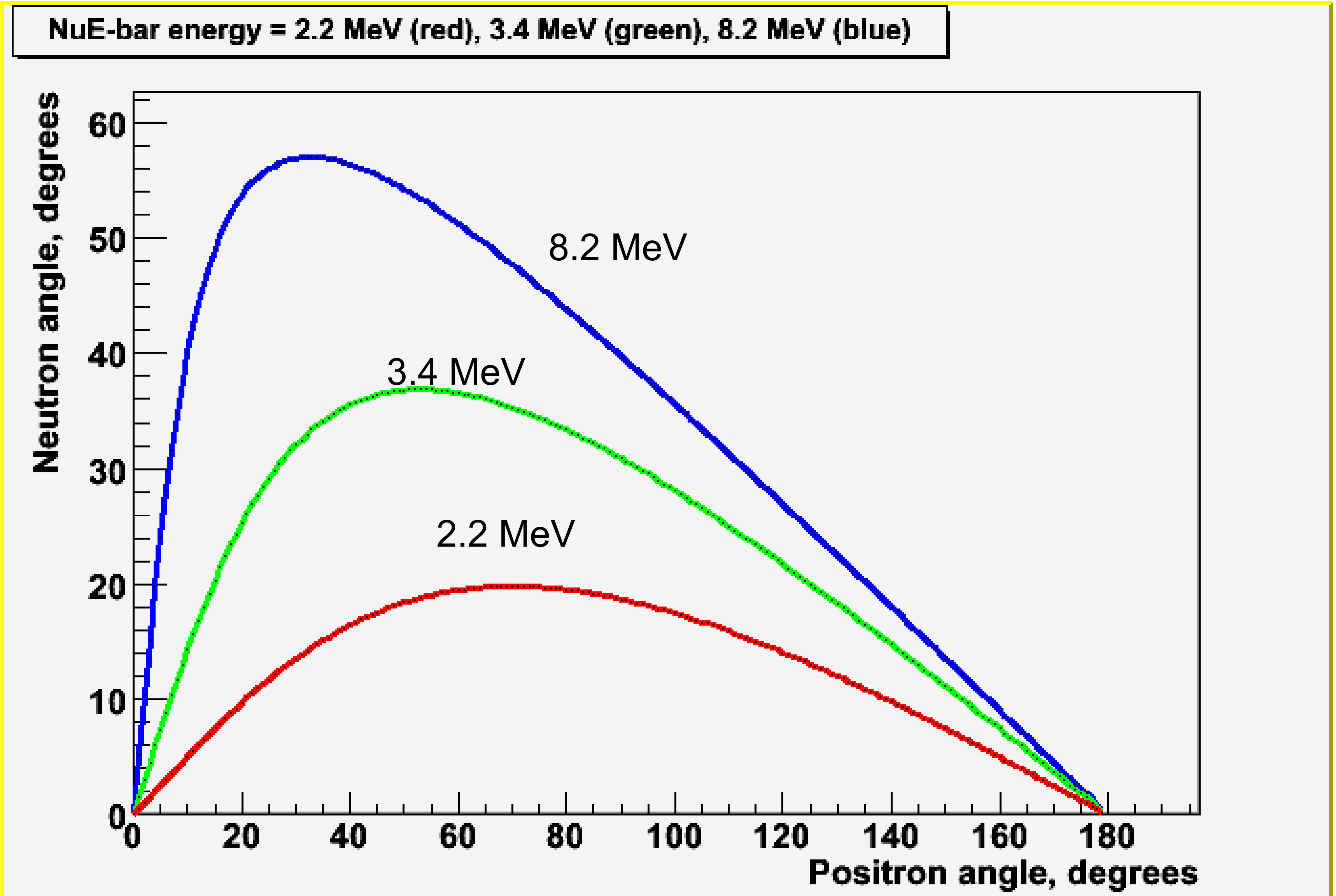






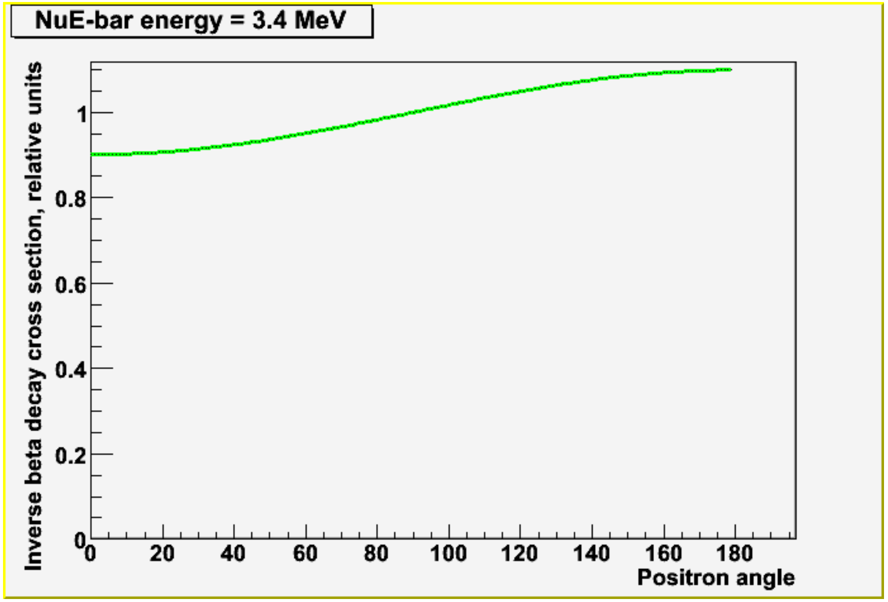
- Most of the kinetic energy is taken by the positron
- The bigger the angle of positron "scattering" ξ, the more energy neutron obtains
- Even for most energetic reactor antineutrinos and ξ=180deg, neutron gets less than 0.2 MeV

The key property making the directionality possible



Neutrons can't backscatter

Differential cross section of the process as a function of positron energy

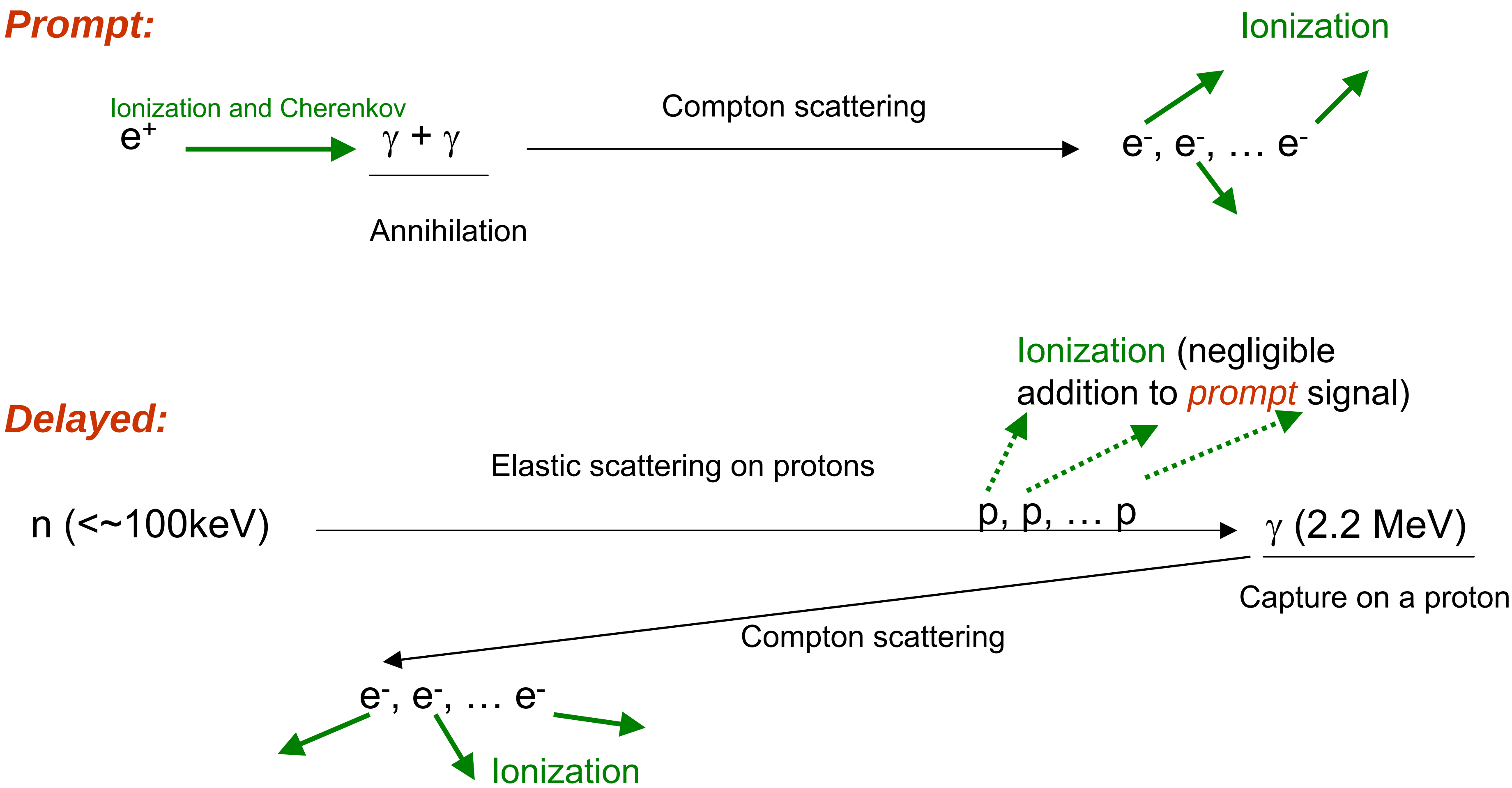


Based on the formula from the article by P.Vogel and J. F. Beacom (Phys. Rev D, v 60, 053003)

Only 0-th order of approximation was used to calculate the cross section
Approach is equivalent, both qualitatively and quantitatively, to the one use CHOOZ experiment
Regardless of the accuracy level, the positron has a slight preference for backscattering in the energy range studied but the distribution is largely uniform

$$\frac{d\sigma}{d\cos\xi} \propto 1 - 1.02\beta\cos\xi$$

Physics of event detection in scintillator



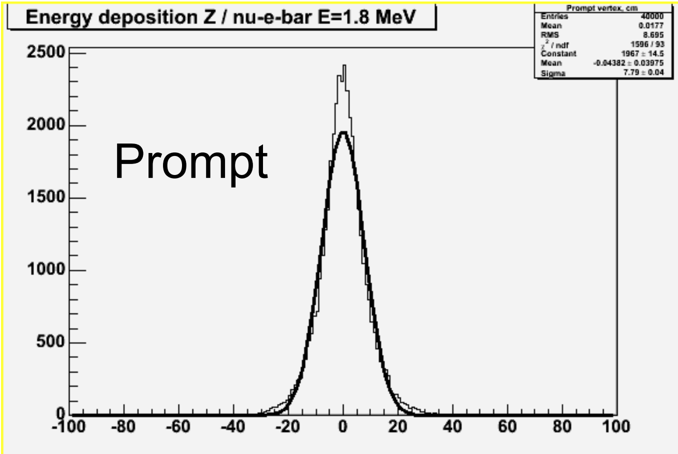
There is no point-like vertex for either prompt or delayed event

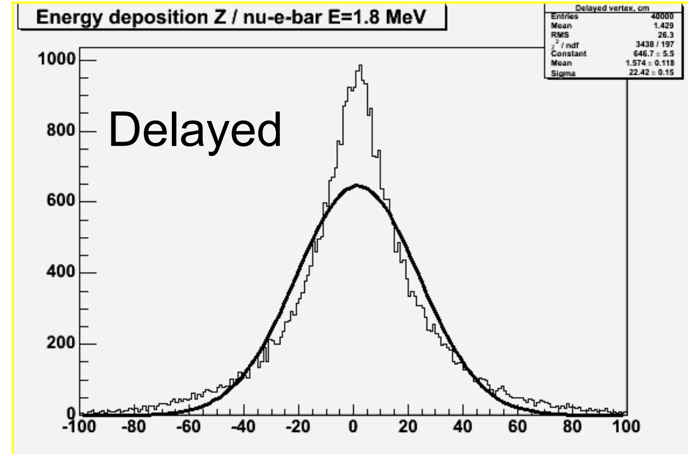
Assumption: vertex fitter reconstructs the CM of energy deposition by ionization

Quantitative simulation of the process

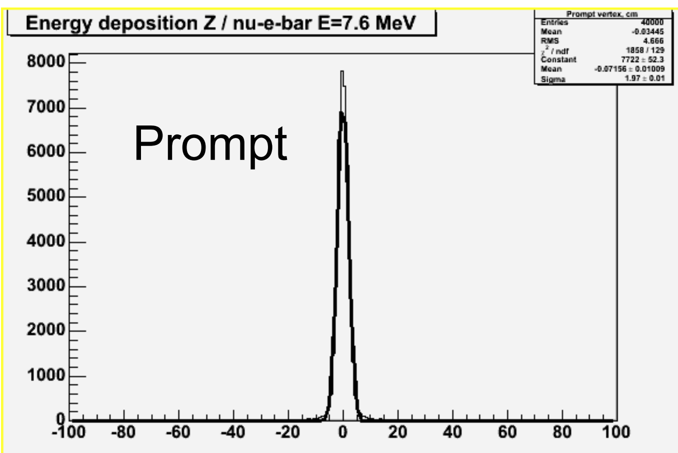
- GEANT4-07-1
- G4NDL3.7 as a database for neutron scattering cross sections
- Hadron model taken from KLG4sim (KamLAND MC package)
- Isotope composition: ($C_{12}H_{26}$)
- Suppose that an electron antineutrino of given energy travels along z direction
- For prompt signal: start with a positron, angle ξ being simulated according to distribution and energy calculated from it
- For delayed signal: start with a neutron, its angle θ and energy calculated from the parameters of the corresponding positron
- Start with both the positron and the neutron originating from the (0,0,0)

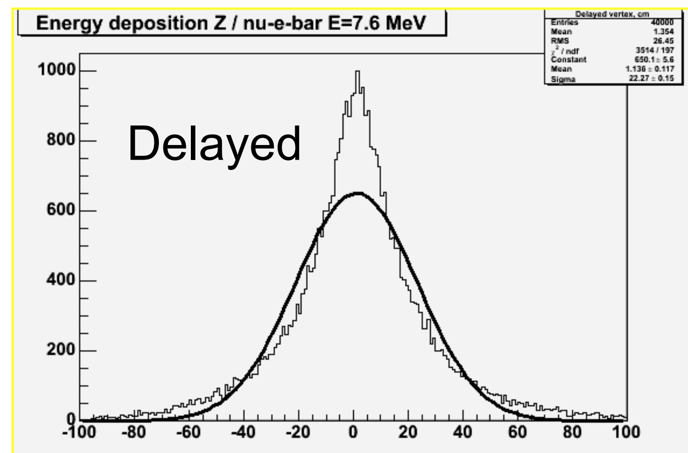
Simulation results





Antineutrino energy = 1.8 MeV (lowest detectable by inverse beta decay)

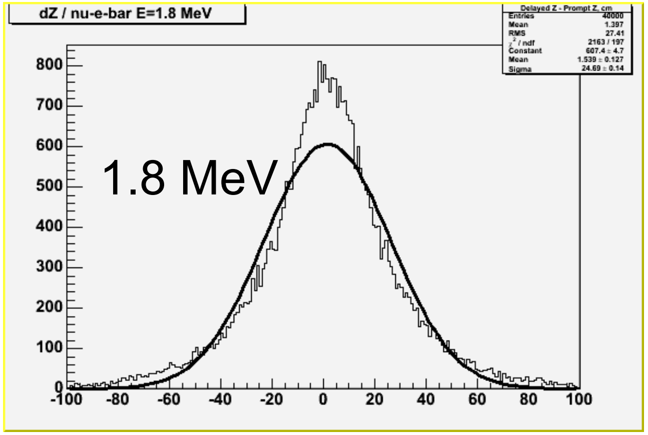


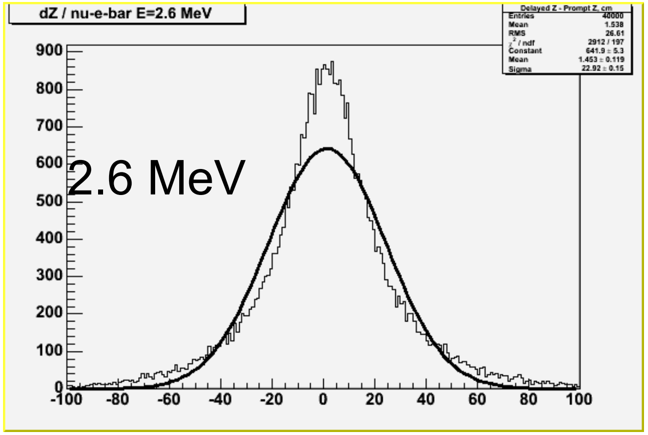


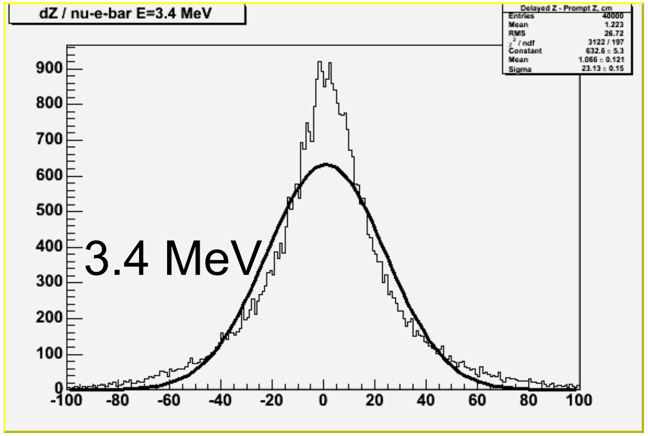
Antineutrino energy = 7.6 MeV (high energy reactor antineutrino)

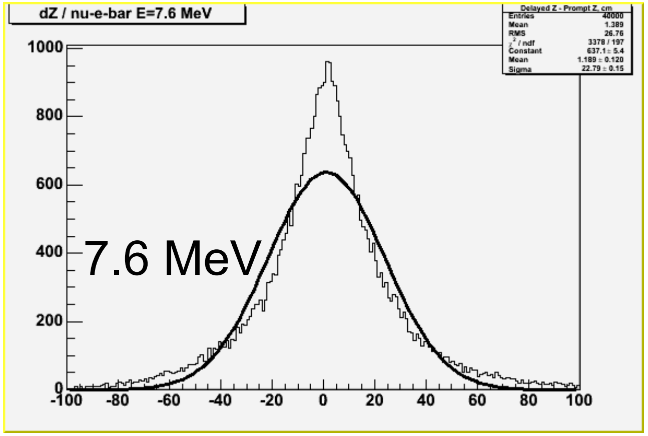
In real experiment, the origin is unknown

What is known: the ***difference*** between the prompt and the delayed vertices









Depending on the antineutrino energy, the simulated prompt-to-delayed Z-difference is 1.1-1.5cm

Estimation quoted by CHOOZ was 1.7 cm (arXiv:hep-ex/0301017)

Disagreement is small enough to be attributable to the difference in the scintillator composition

Reconstruction resolution effect

Still two omissions from the real-world picture…

1. We are not expecting 40000 geoneutrino events from the existing experiments
2. There is always a statistical error in vertex reconstruction due to finite resolution

Vertex errors smear the vertex distribution ***in addition*** to the natural spread
The effect is that higher number of events is needed to achieve the same statistical significance than it would have been with a perfect fitter

Vertex reconstruction error asymptotics:

Upon fairly wide assumptions, the vertex resolution goes like:

$$R = k / \sqrt{E_{vis}(MeV)}$$

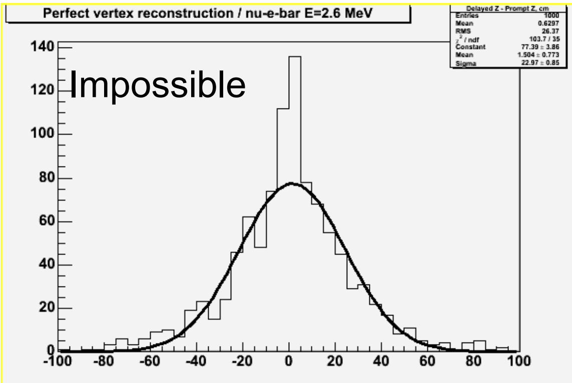
Where:

- **E_{vis}** – visible energy of the event proportional to the number of PMT hits
- ***k*** – proportionality coefficient determined by detector physical properties (photocathode coverage, scintillator characteristics), and the reconstruction algorithm, representing the quality of the latter

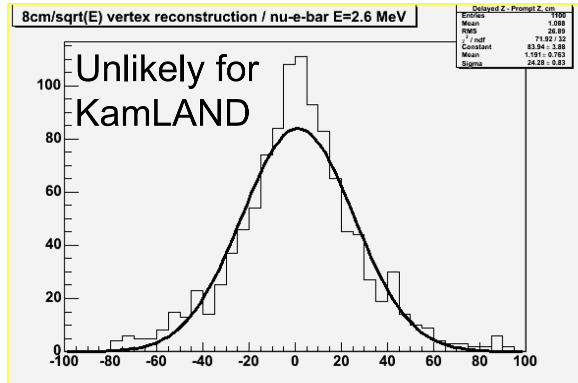
- **The effect of resolution is more significant for the lower energy events**

Simulation with finite resolution

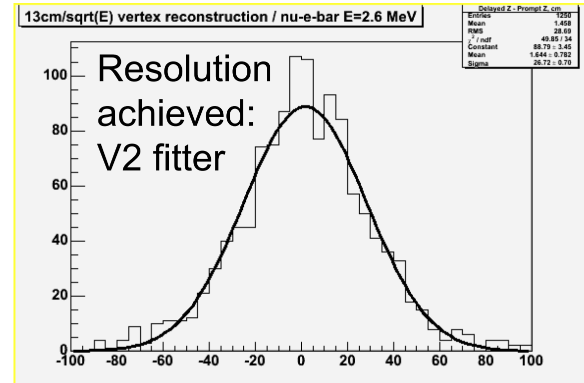
Question: for an average geoneutrino energy, *how many events* do we have to achieve the ***same*** statistical error in Δz estimation?



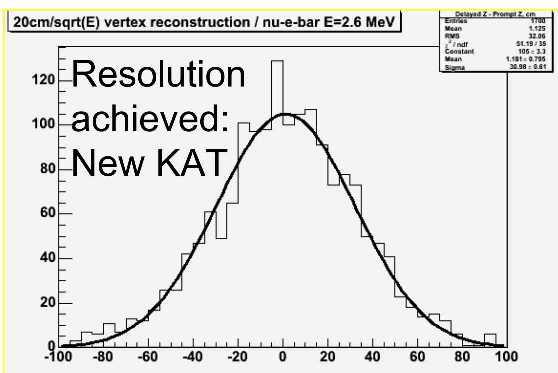
Perfect fitter (k=0): 1000



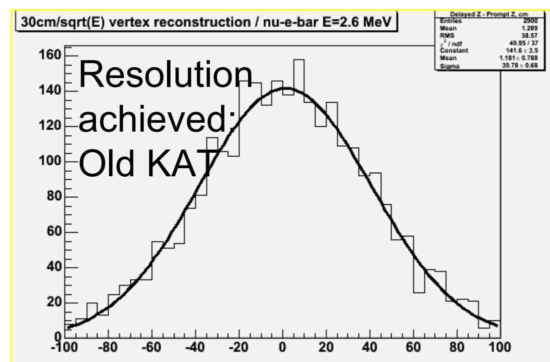
k=8cm/sqrt(E_{vis}):1100



k=13cm/sqrt(E_{vis}):1250



k=20cm/sqrt(E_{vis}):1700



k=30cm/sqrt(E_{vis}):2900

Improving resolution: down to 20 cm and some way below – very efficient for geo-nu
Below 13 cm – quickly diminishing returns

Even with perfect reconstruction, 1000 candidates give σ more than half the z-axis shift

Other motivations for having better resolution

1. Studies of the low-energy backgrounds
2. Possibility to use tighter cuts not compromising the selection efficiency to better suppress accidental backgrounds
3. For KamLAND and similar experiments, solar neutrino studies where the event energies are going to be less than 1 MeV

Vertex reconstruction approaches

3 flavors of information from events:

1. Timing (tubes closer to the signal are likely to get signal earlier)
2. Hit pattern (tubes closer to the source are more likely to be hit)
3. Charge pattern (tubes closer to the source tend to have more charge)

Normally, this information is combined in a likelihood model and the likelihood functional is maximized with x, y, z being the free parameters

For smaller detectors approaches 2, 3 are preferable, the hit-based one being better for lower energies and the charge-based – for higher energies

For bigger detectors, time-based approach yields better resolution and its advantage increases with the detector size indefinitely

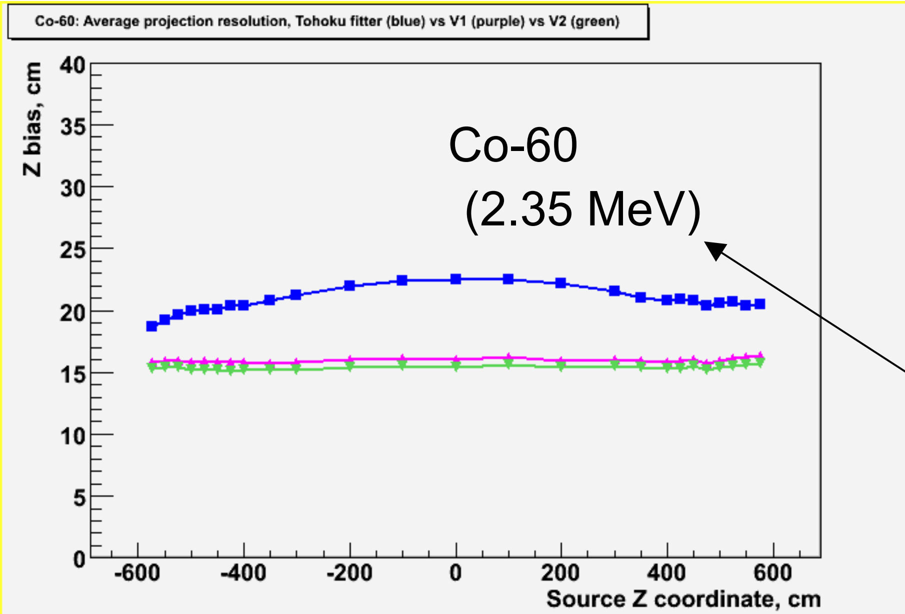
These approaches are, in principle, not mutually exclusive and the ultimate vertex fitter should use all the available information

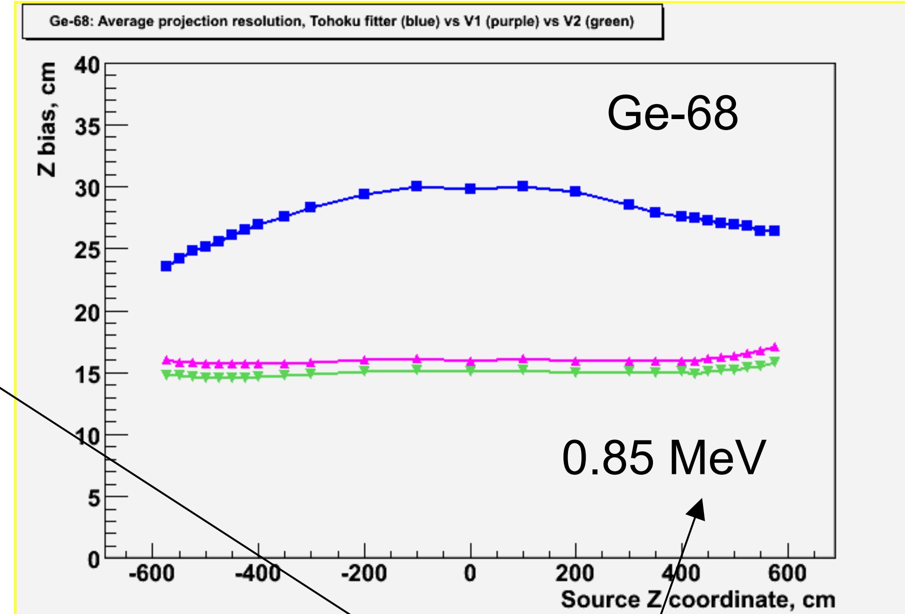
Note: these approaches are not mutually exclusive but combining them in a single tool is not an easy task

Vertex reconstruction development in KamLAND

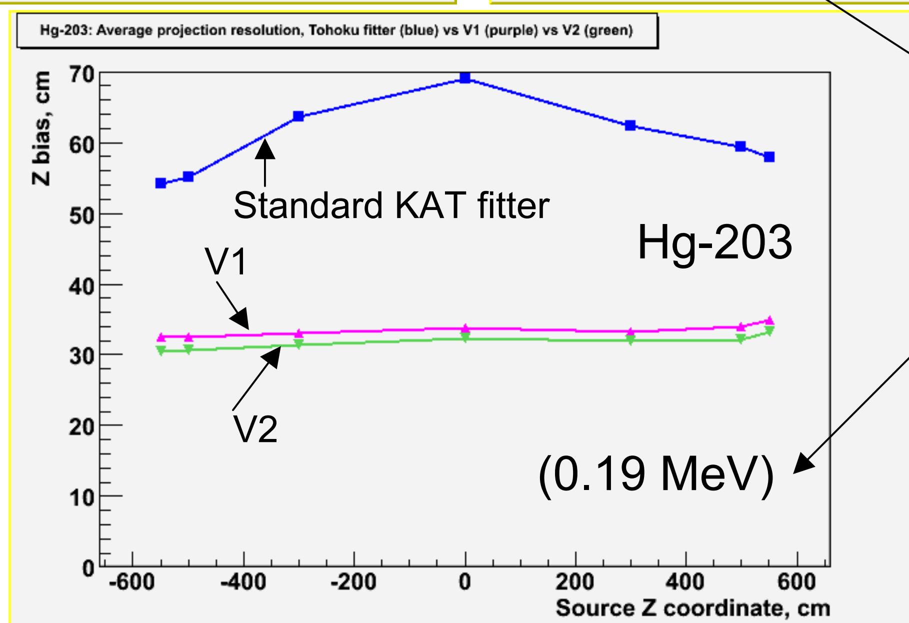
- Early experiments have shown that time-based fitters provide superior resolution for KamLAND detector.
- The old KAT fitter used in First Reactor Result was a straightforward time-based fitter providing the resolution about 30 cm per MeV (as estimated by Yu. Kamyshkov).
- In 2003, two new fitters were developed for Japanese and American branches of the analysis (new KAT and PTF, respectively) with accuracy around 18-20 cm per MeV (for new KAT fitter, the resolution is estimated by A. Kozlov). Both are currently the standard tools for the data analysis. The KamLAND geo-neutrino paper uses the new KAT fitter data.
- In 2004, the V1 fitter was the first in KamLAND to make use of real experimental PMT hit time distributions, optimizing the resolution within the same purely time-based approach.
- In 2005, the V2 fitter was written, slightly improving on the V1 in terms of resolution and systematics due to a more accurate handling of calibration data and taking more technical detail into account. The resolution is estimated as 12.9 cm per MeV.

Resolution on source calibrations





- ✓ Ge-68 calibration is a good imitation of the prompt signal from the lowest energy antineutrinos detectable by inverse-beta decay
- ✓ Delayed signals behave rather like Co-60 calibration but with bigger natural spread
- ✓ Hg-203 is more relevant for future solar neutrino studies.



Visible energies

Lower energy events are more sensitive to the fitter's own resolution

Trying to observe directionality in KamLAND

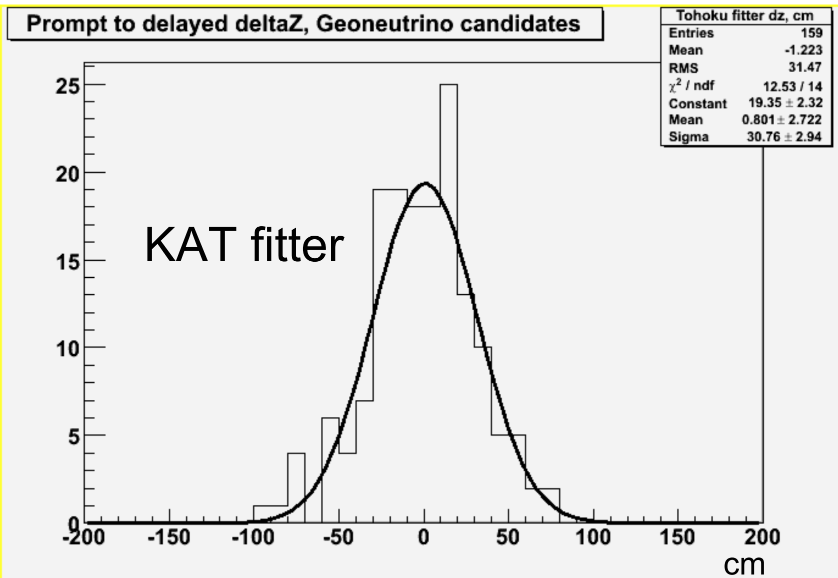
Geo-neutrino candidates:

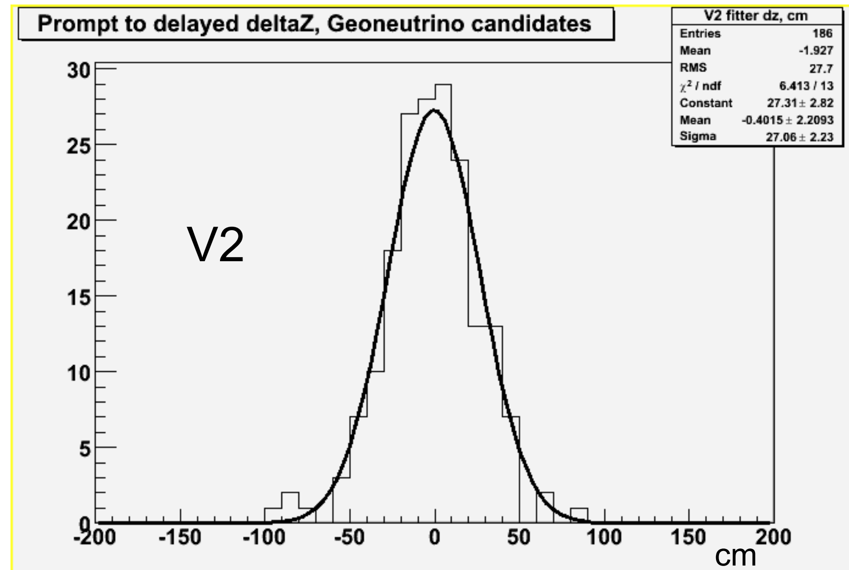
Fiducial cut: R_p < 500 cm, R_d < 500 cm
Time separation: $T_d - T_p$ < 0.5 ms
Space separation: $R_{p\text{-}d}$ < 100 cm
Prompt energy: 0.9 MeV < E_p < 2.6 MeV
Delayed energy: 1.8 MeV < E_d < 2.6 MeV

Reactor+Geo candidates:

Fiducial cut: R_p < 550 cm, R_d < 550 cm
Time separation: $T_d - T_p$ < 0.5 ms
Space separation: $R_{p\text{-}d}$ < 100 cm
Prompt energy: 0.9 MeV < E_p < 7.6 MeV
Delayed energy: 1.8 MeV < E_d < 2.6 MeV

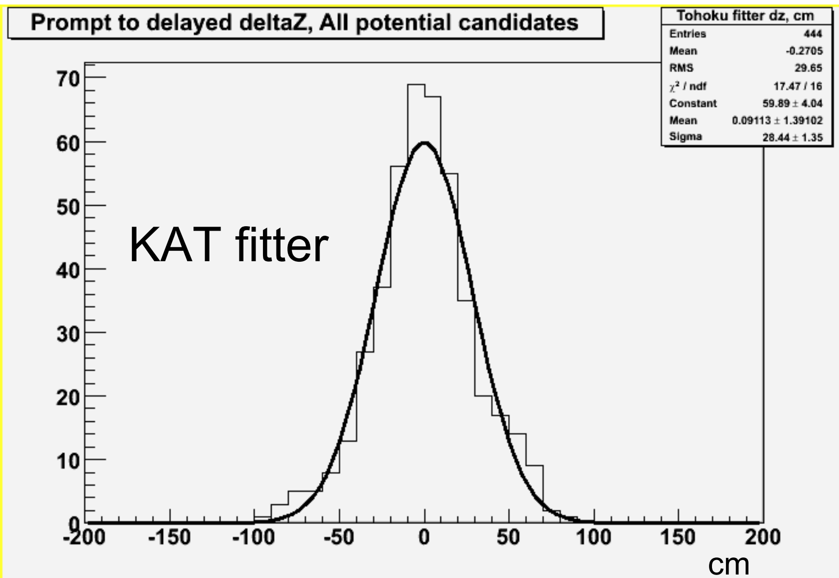
Z-difference between prompt and delayed signals on geo-antineutrinos

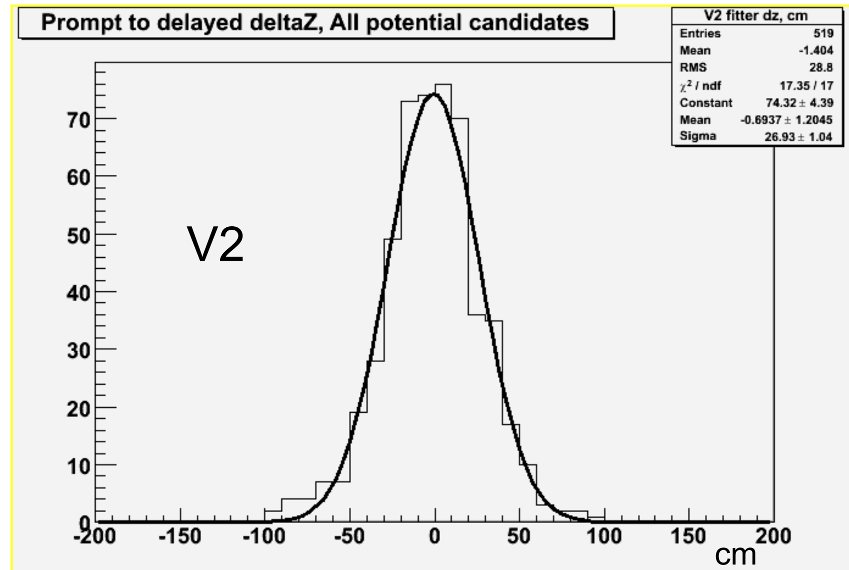




The observed deviation from zero is not statistically significant

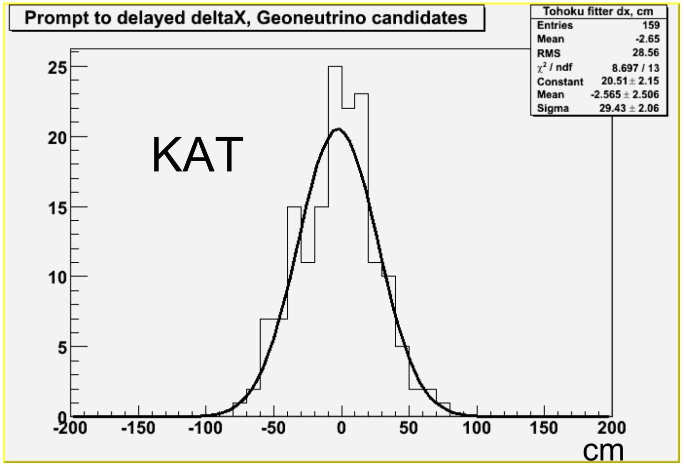
Z-difference between prompt and delayed signals on all antineutrinos

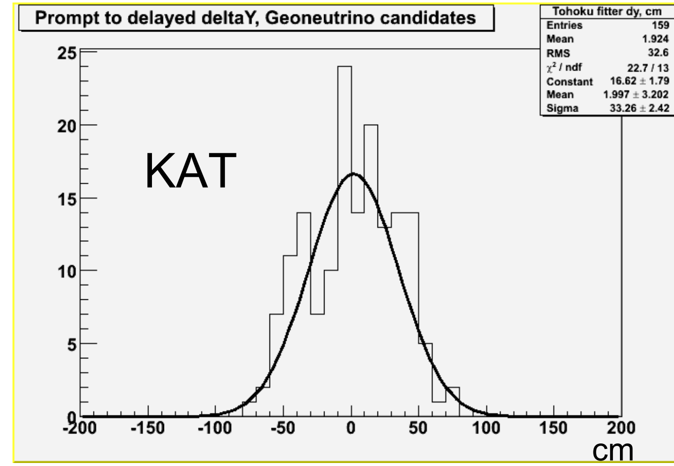


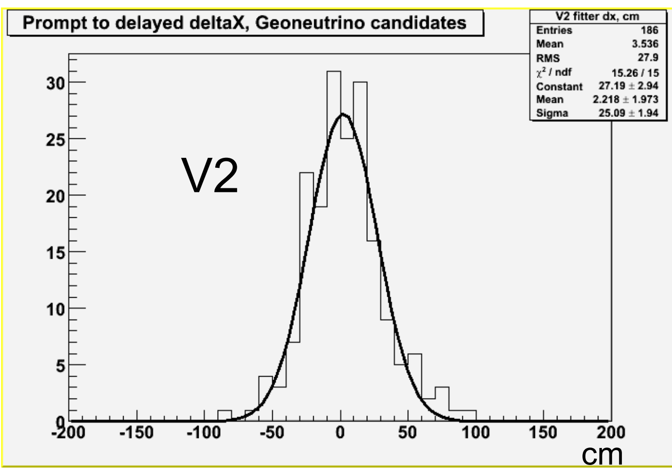


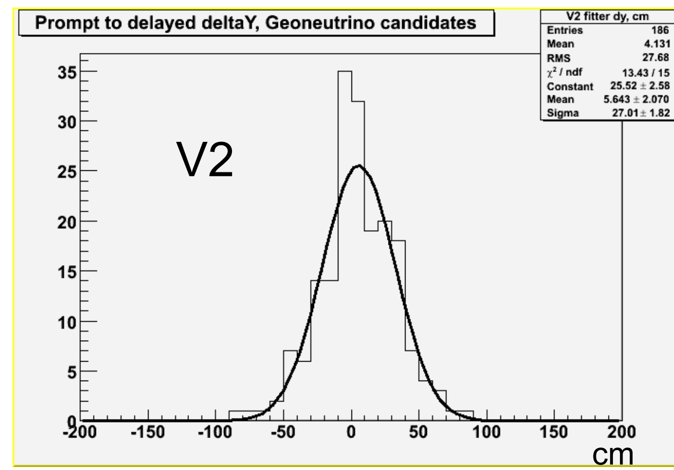
The observed deviation from zero is not statistically significant either – no test for geo-reactor hypothesis possible now

On the reliability of such study with current tools









The systematic prompt to delayed shift is:

a) Energy dependent
b) Fitter dependent
c) Exceeding the expected physical bias

So is directionality useless for detectors not big enough?

Answer:
No, it’s additional information which may be always used in the likelihood analysis. Throwing it away altogether is not optimal.

However:
It requires extremely high standards for vertex reconstruction tools, especially in terms of systematic biases. ± 5 cm or even ± 2 cm which are OK for fiducail volume studies won’t do here. Besides, comprehensive 4Pi calibration with accuracy better than 1 cm is a pre-requisite for such a study.

Summary

✓ Monte-Carlo simulations show the correlation between the direction of incident antineutrino and the prompt-to-delayed vector, mostly due to the delayed vertex shift

✓ The effect is of the order of 1-2 cm, the delayed signal being the shifted in the direction of incident antineutrino - in good agreement with the pioneering study carried out by CHOOZ collaboration

✓ The natural spread of the signal due to gamma path in scintillator sets a natural limit for the vertex accuracy

✓ Finite vertex fitter resolution gives additional smearing which requires more events for statistically significant conclusions but the better the vertex fitter, the smaller the additional overhead

✓ The magnitude of the expected vertex difference allows conclusive study only with much larger number of events than current detectors can observe

✓ Biases must be controlled down to several mm or, alternatively, reliable all-volume calibration with the same accuracy must be available

✓ With proper statistical analysis, directionality information can be useful in likelihood models for better utilization of experimental data