The Neutrino Physics Summer School
Fermilab, July 2007

The Evidence for Flavor Change and Oscillations III

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Overall Outline

Lecture 1:

Discovery of atmospheric neutrino oscillations

Lecture 2:

Solving the Solar Neutrino Problem with Solar neutrino oscillations

Lecture 3:

Studies of neutrino oscillations with accelerator and reactor neutrinos

Outline - Lecture 3 -

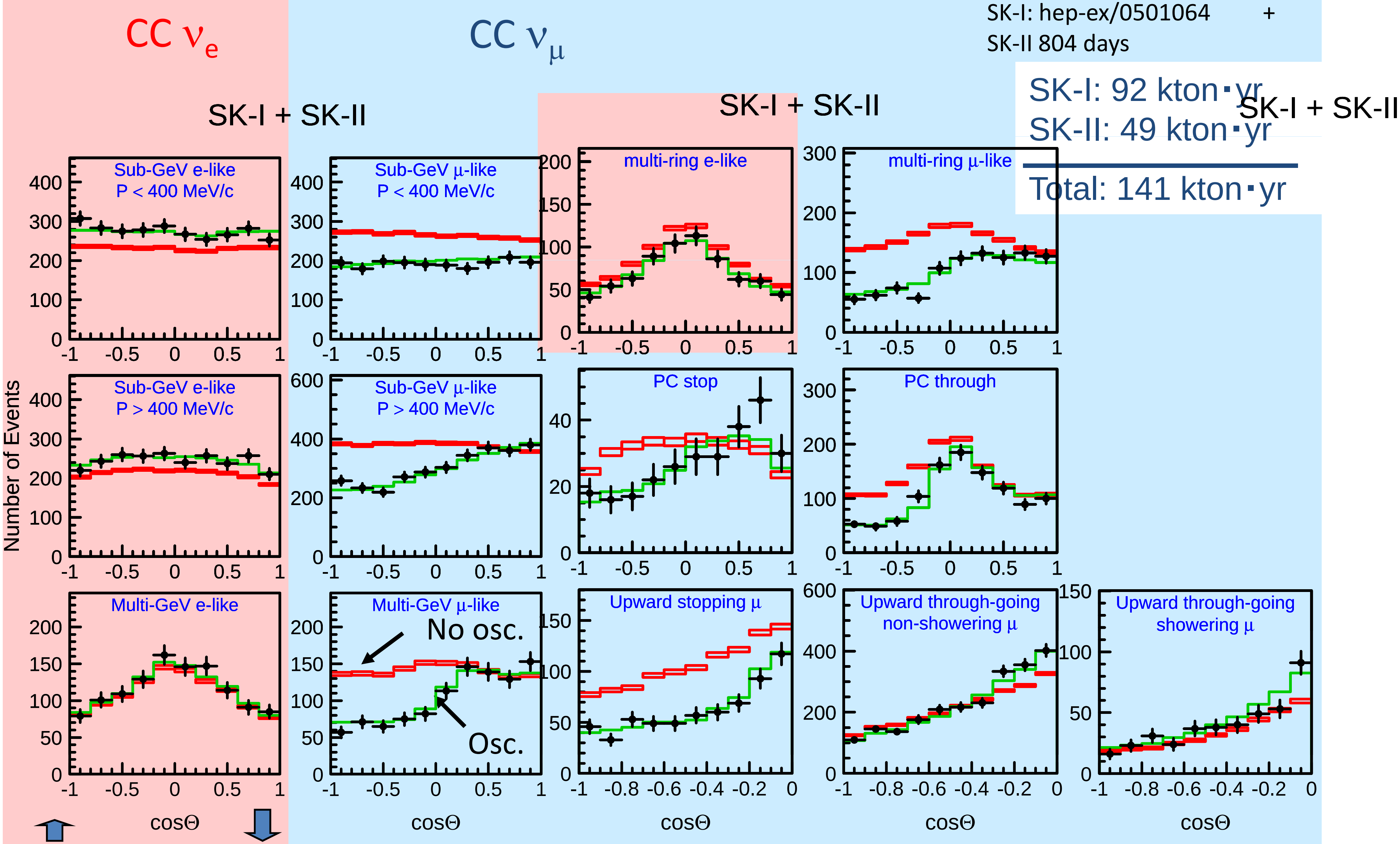
- Determination of oscillation parameters
  - Atmospheric neutrino
  - Accelerator neutrino oscillation experiments
  - KamLAND reactor neutrino experiment
- Really oscillations ?
- ν_μ to ν_τ or ν_μ to $\nu_{sterile}$?
- Tagging appeared neutrino flavor ?
- Summary

Determination of oscillation parameters

SK-I+II atmospheric neutrino data

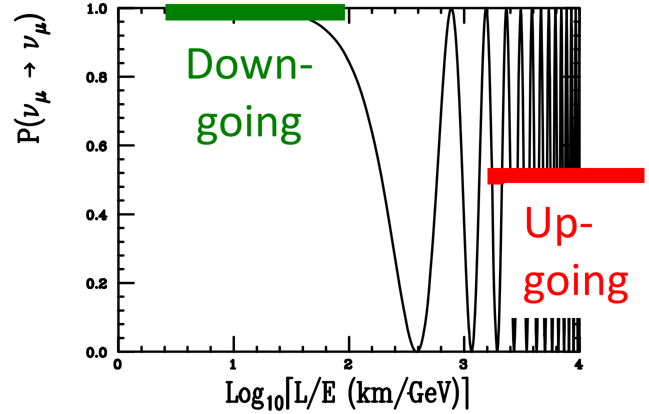
SK-I: hep-ex/0501064 +
SK-II 804 days

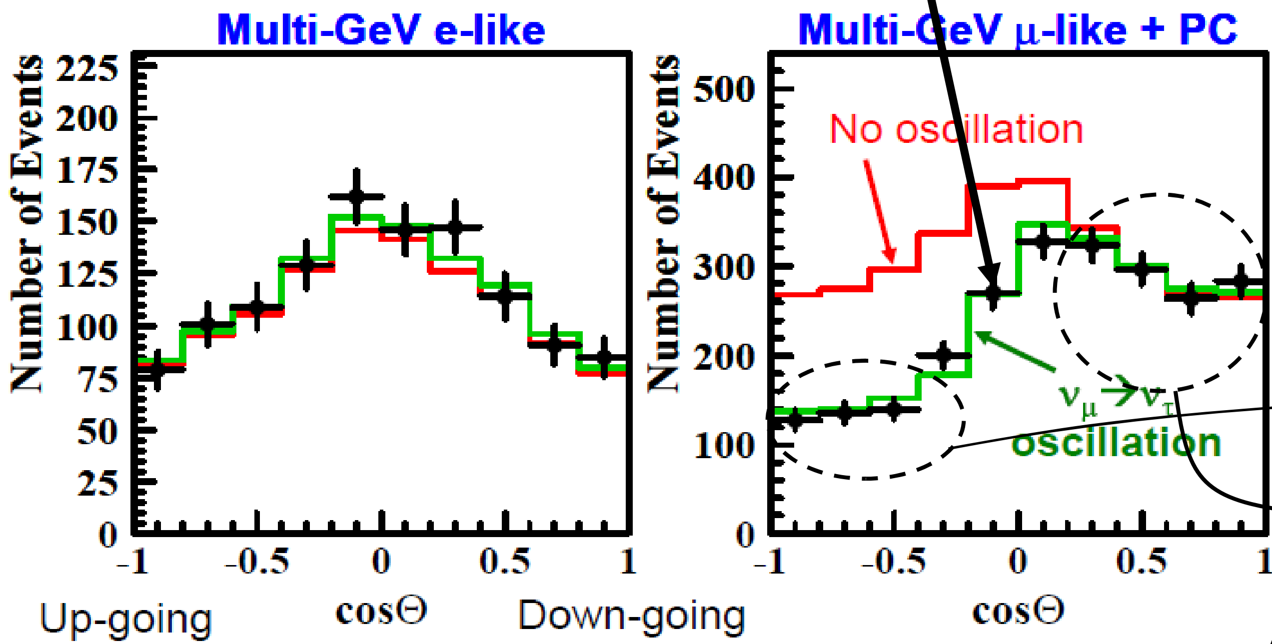
SK-I: 92 kton·yr
SK-II: 49 kton·yr
Total: 141 kton·yr



Estimating the oscillation parameters

Transition point
(as a function of energy)
➔ Δm^2



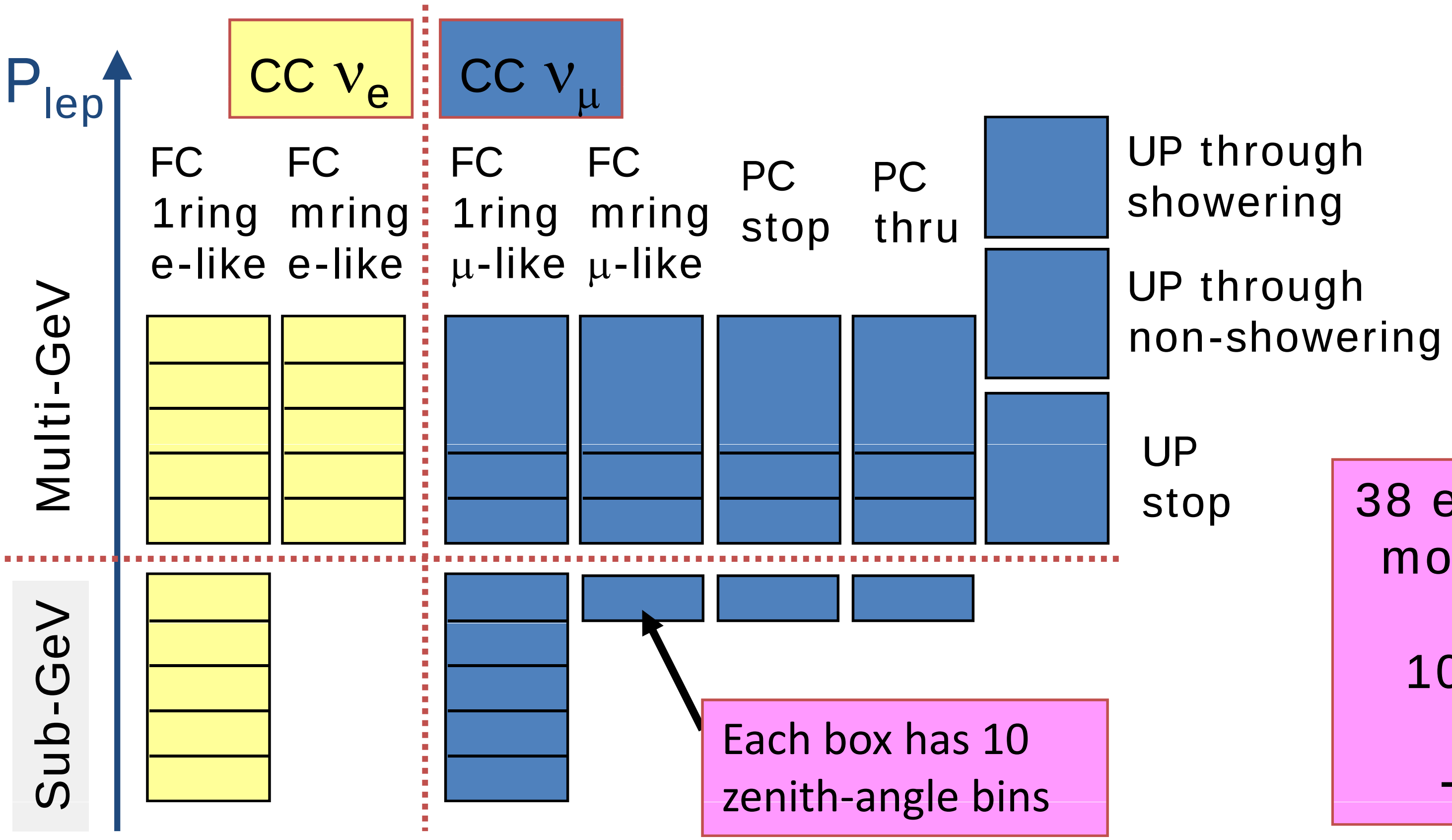


$$\frac{Up}{Down} = 1 - \sin^2 2\theta$$

Confirmation of non-oscillated flux

Accurate measurement possible due to small syst. in up/down (2% or less)

$\nu_\mu \to \nu_\tau$ 2-flavor oscillation analysis (SK-I + SK-II combined analysis)



38 event type and momentum bins
x
10 zenith bins

→ 380 bins

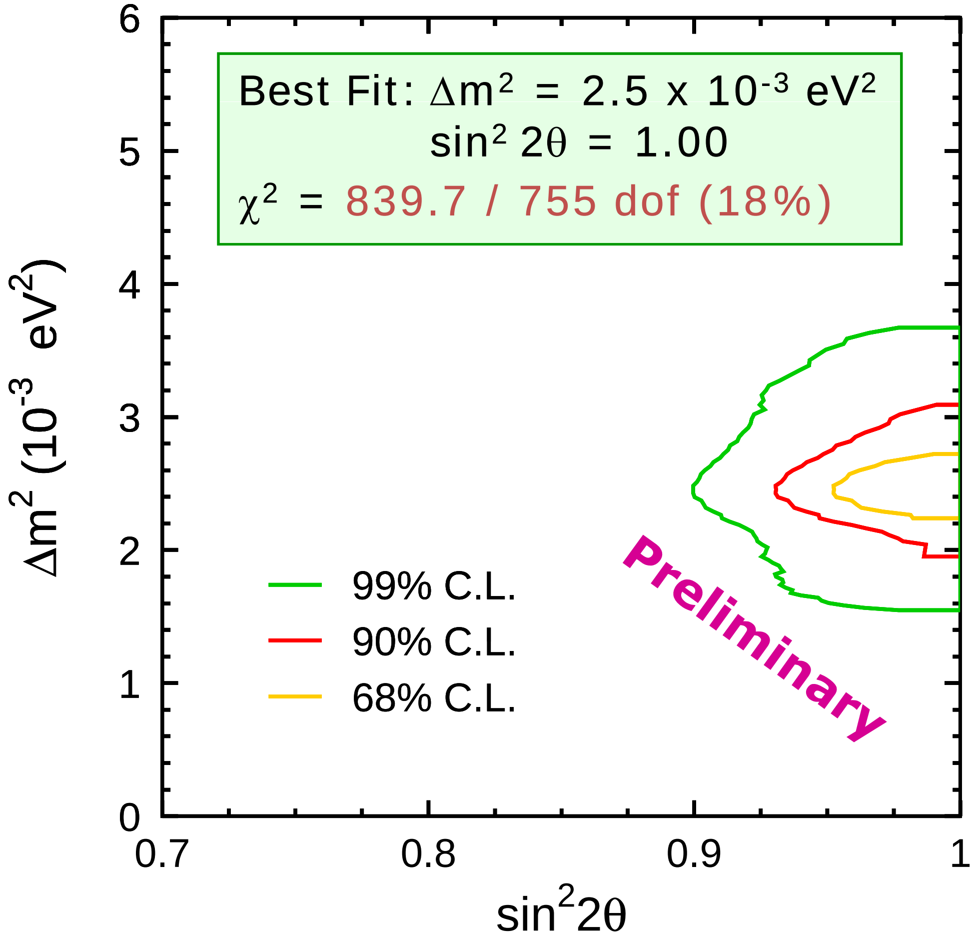
Since various detector related systematic errors are different, SK-I and SK-II data bins are not combined.

380 bins for SK-I + 380 bins for SK-II → 760 bins in total

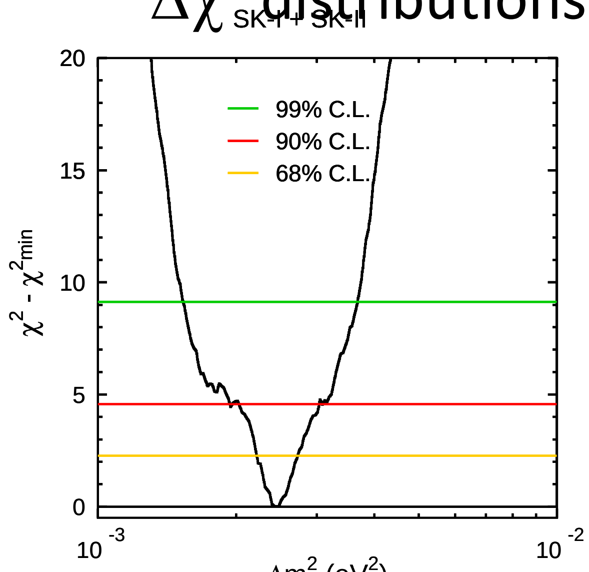
$\nu_\mu \rightarrow \nu_\tau$ 2 flavor allowed region

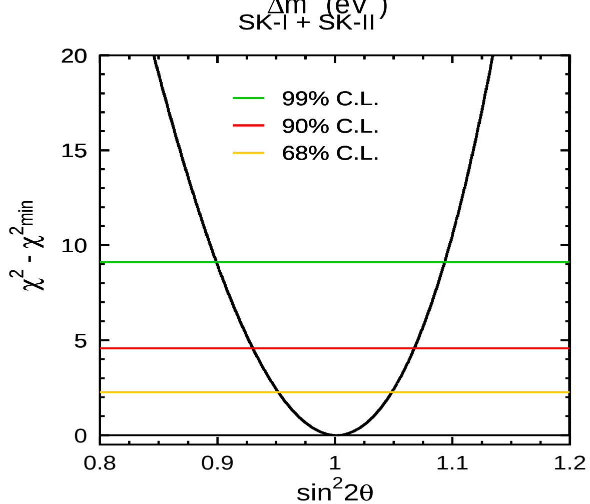
SK-I + SK-II

1489 days (SK-1)+ 800 days (SK-II)



$\Delta\chi^2$ distributions





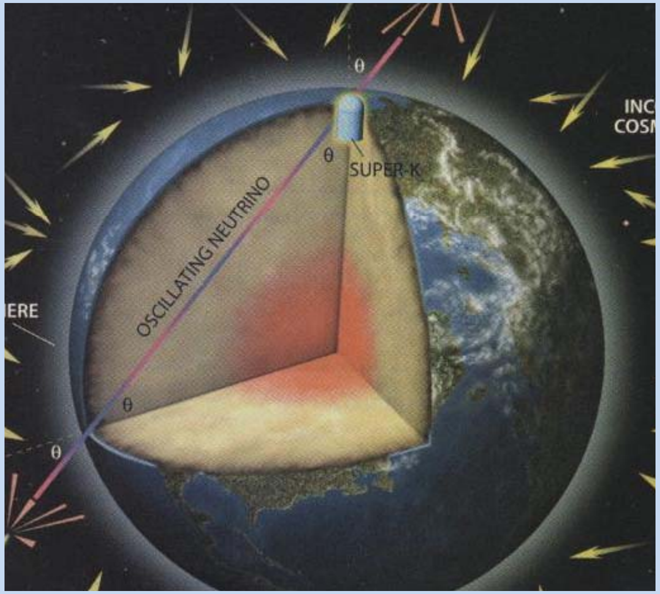
$1.9 \times 10^{-3}\ eV^2 < \Delta m^2 < 3.1 \times 10^{-3}\ eV^2$

$\sin^2 2\theta > 0.93$ at 90% CL

Accelerator neutrino oscillation experiments

Why long baseline experiments?

Atmospheric neutrinos



- ➔ Very wide neutrino flight length
- ➔ Wide neutrino energy
- ➔ Mixture of ν_μ, anti-ν_μ, ν_e and anti-ν_e

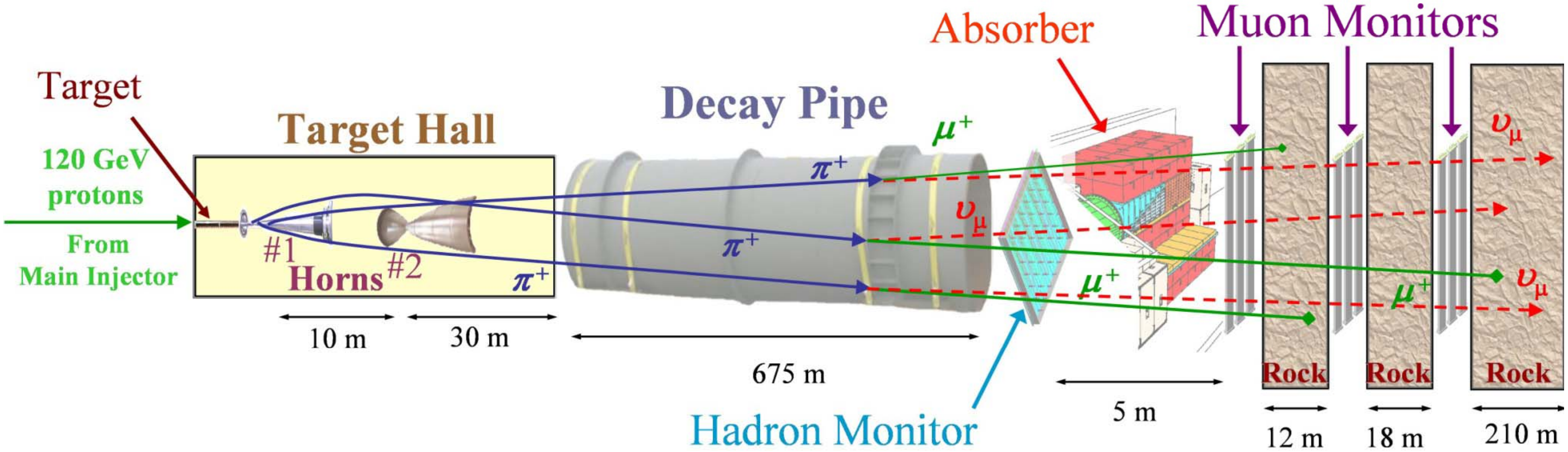
Long baseline Experiments

- ➔ Single flight length
- ➔ Controlled neutrino energy
- ➔ almost pure ν_μ (or anti-ν_μ)

Initial discovery ➔ *Precise studies*

Producing the neutrino beam

Example: MINOS



Beam line

Example: K2K

To Super-Kamiokande

250km

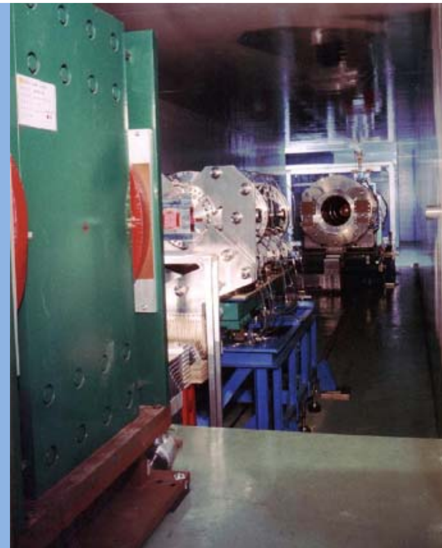
Near ν detector

12GeV proton accelerator

KEK

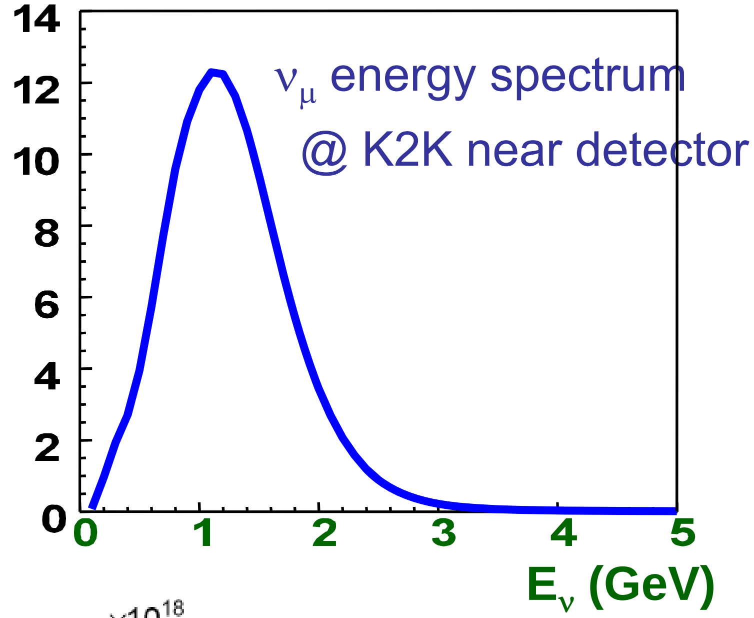
(about 30 years old, already shut down)

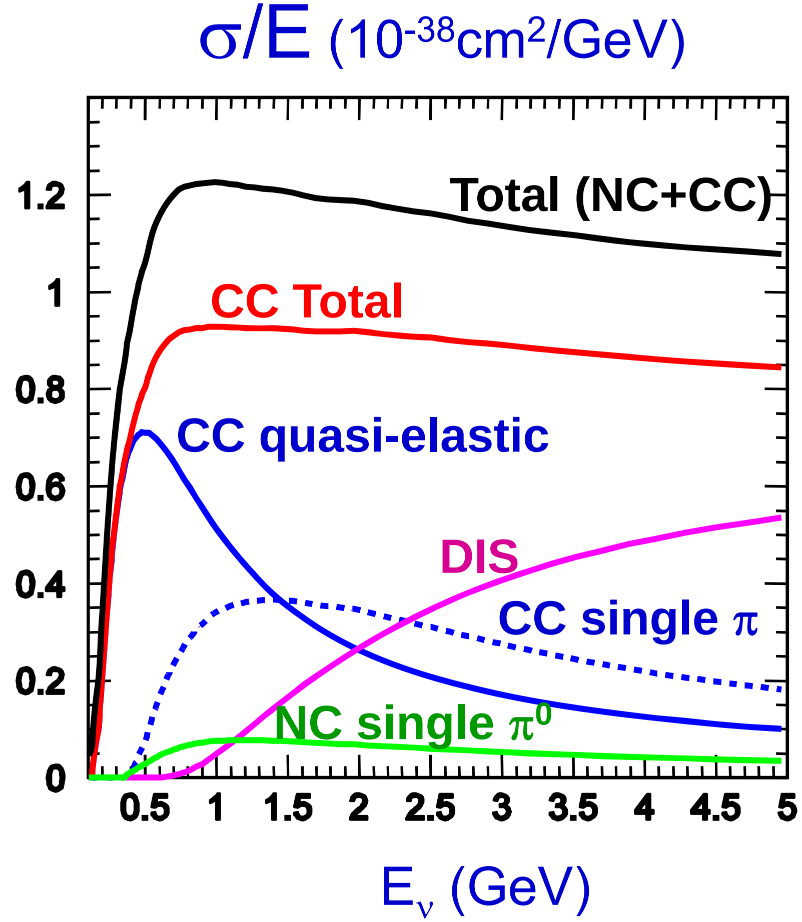
Target region (Horn)

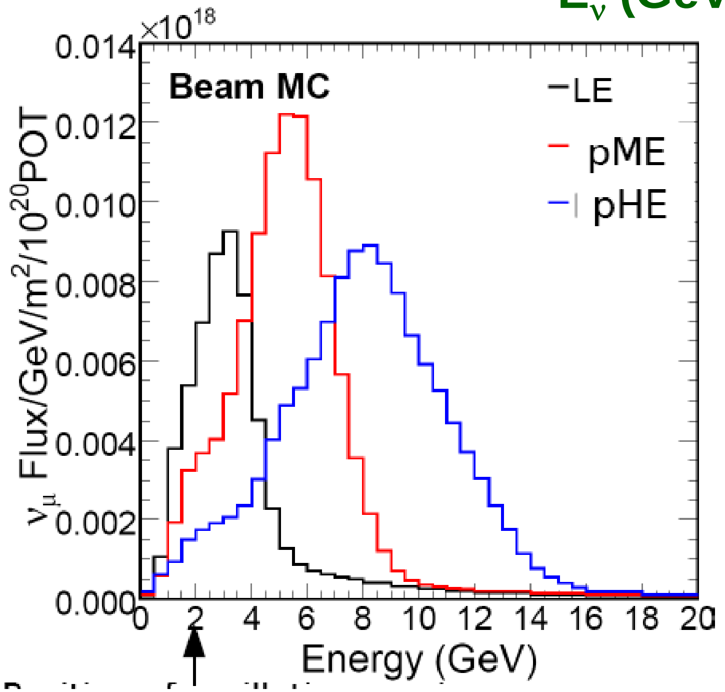


Proton beam line

Neutrino spectrum and neutrino interactions

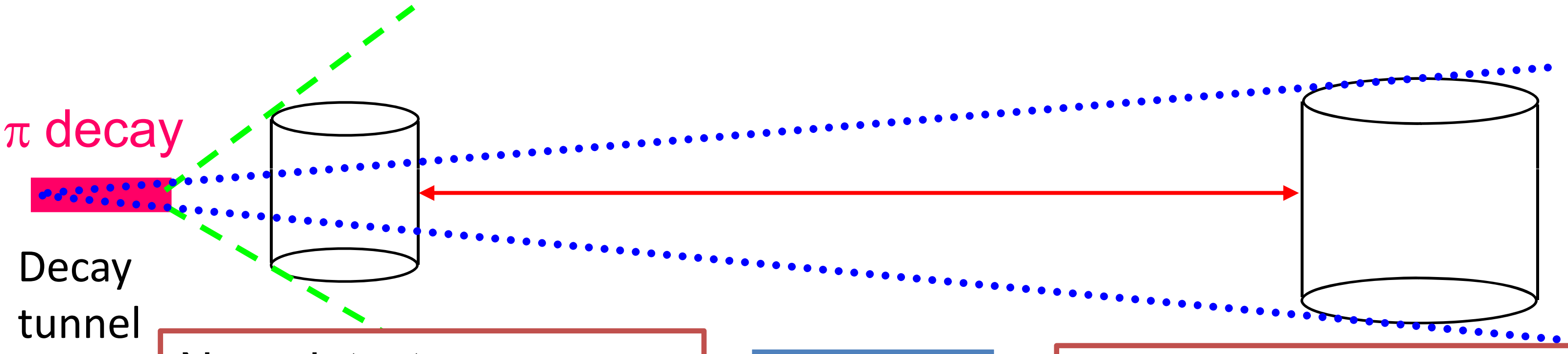






Various neutrino interaction modes are important.
➔ Good understanding of the neutrino interactions necessary.

Neutrino spectrum and the far/near ratio

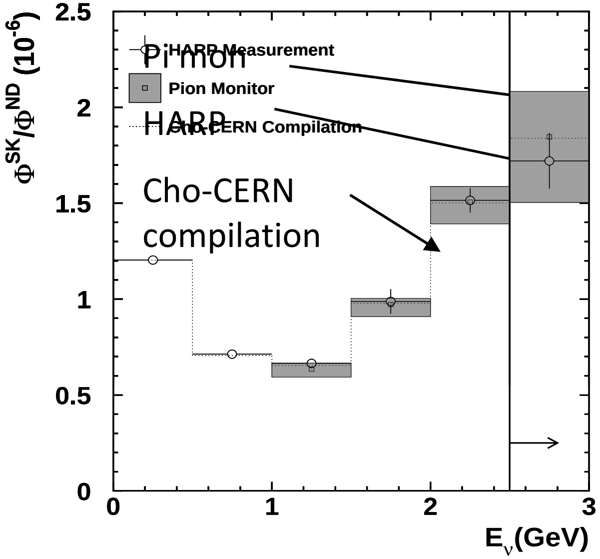


Near detector:
Neutrinos are produced by a line source.

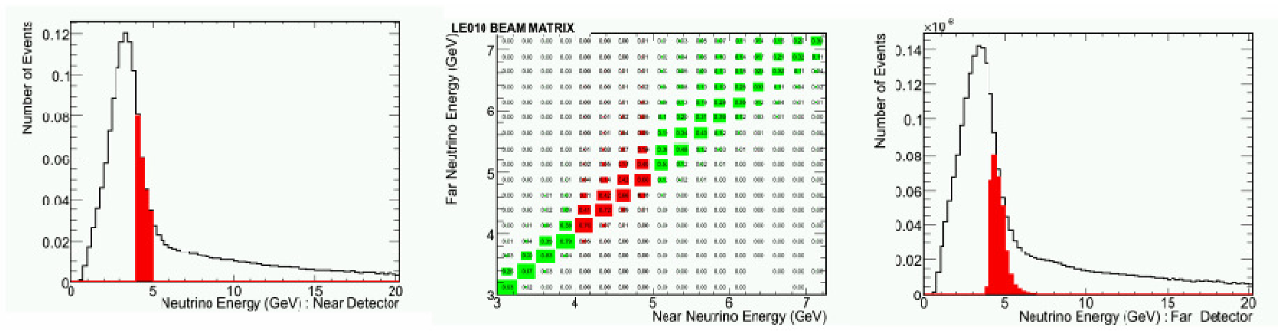
different

Far detector:
Neutrinos are produced by an approximate point source.

K2K Far/Near prediction



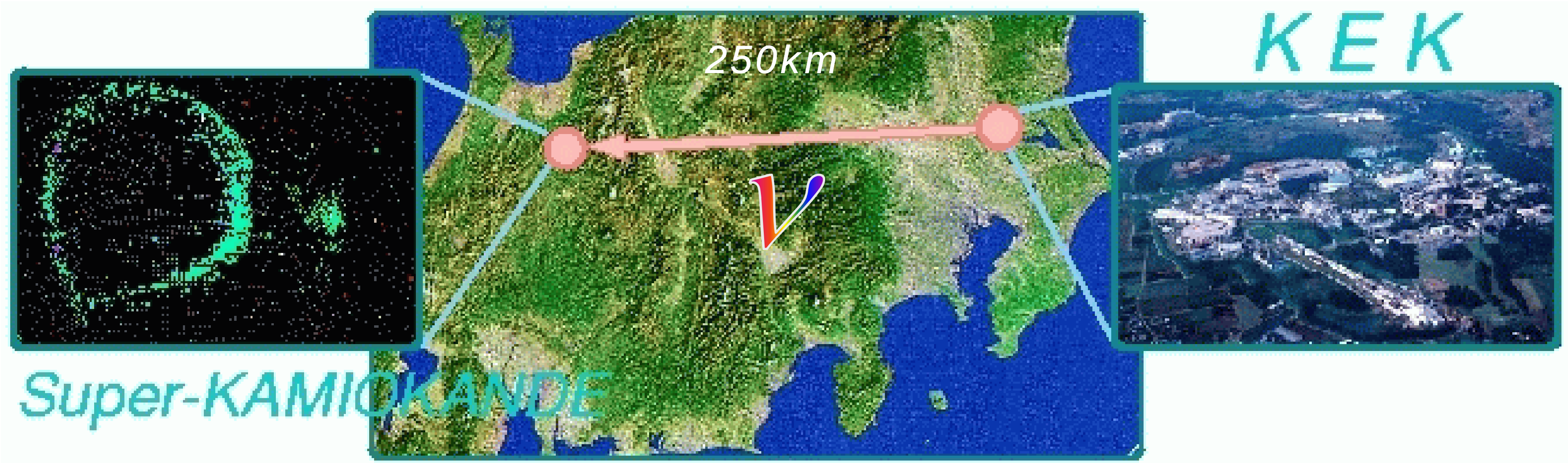
MINOS (one method)

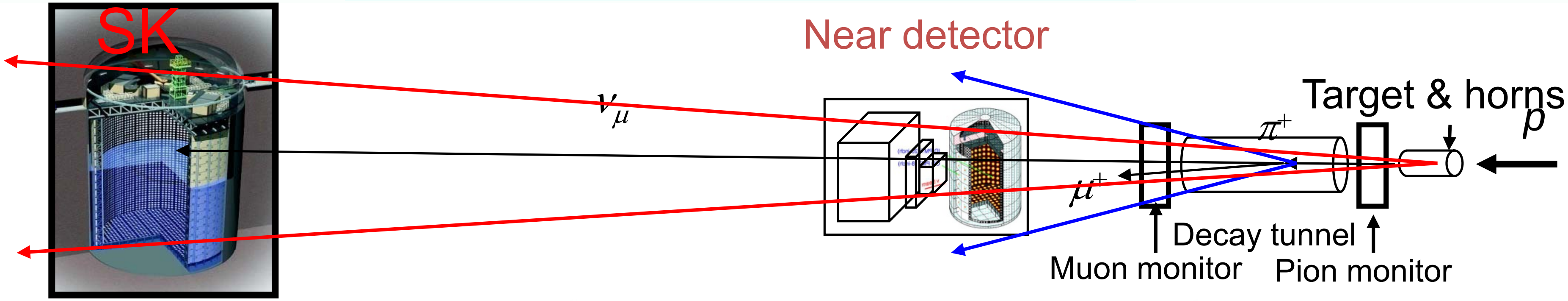


Near spectrum ➔➔ Matrix ➔ ➔ Far spectrum

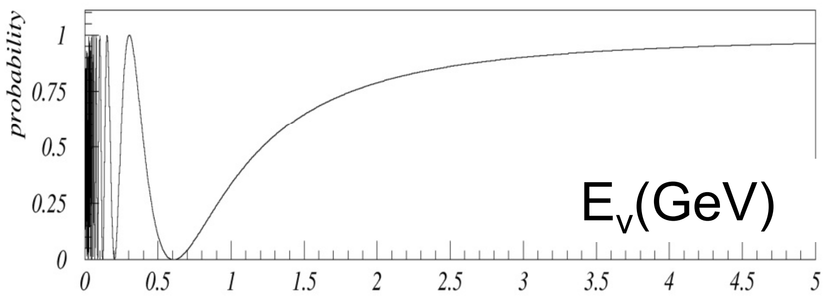
K2K experiment and its results

hep-ex/0606032





Neutrino oscillation probability for Δm^2=0.003eV^2 and at 250km.

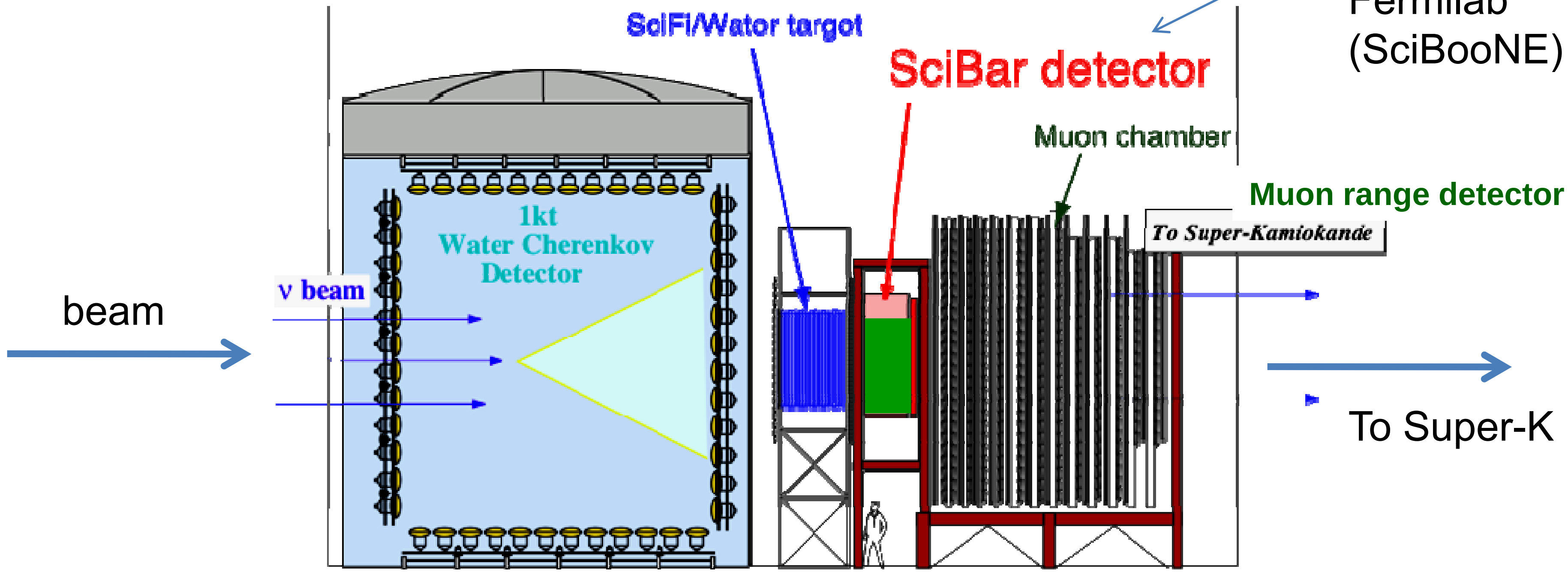


Near detector measurements

- 1KT Water Cherenkov Detector (1KT)
- Scintillating-fiber/Water sandwich Detector (SciFi)
- Lead Glass calorimeter (LG) before 2002
- Scintillator Bar Detector (SciBar) after 2003
- Muon Range Detector (MRD)

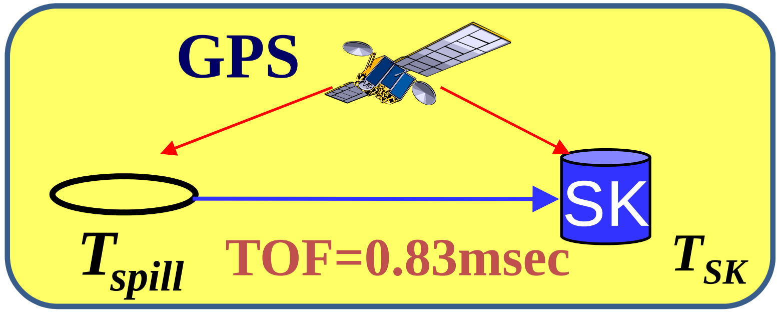
They predict the event rate and spectrum @ Super-K

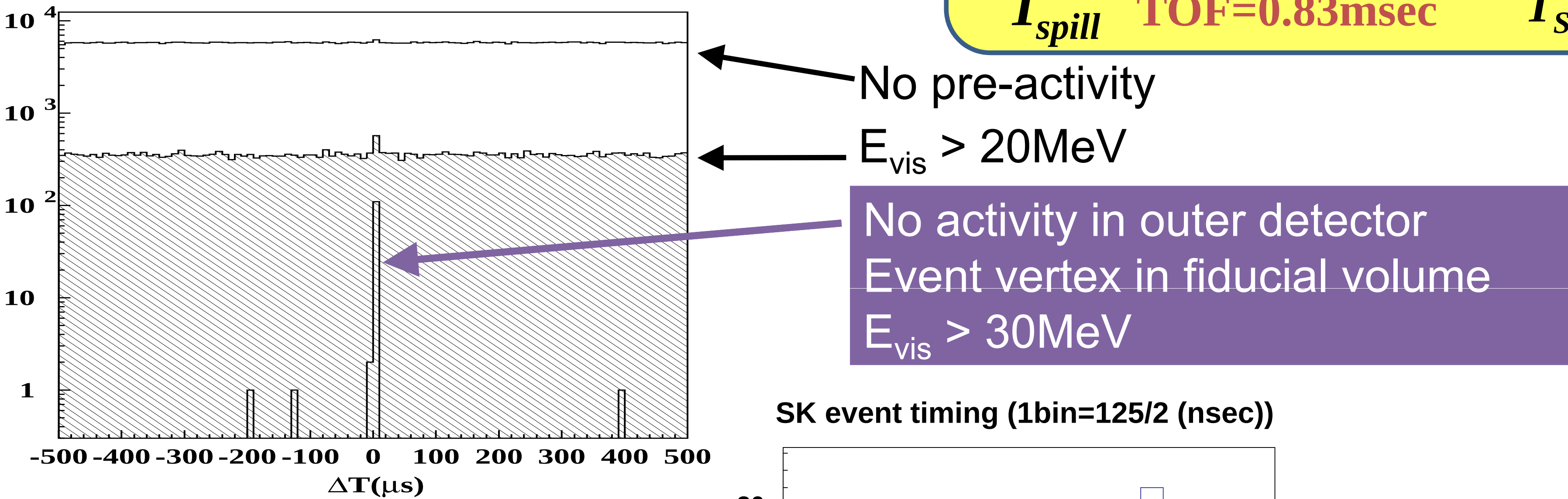
Now in Fermilab (SciBooNE)

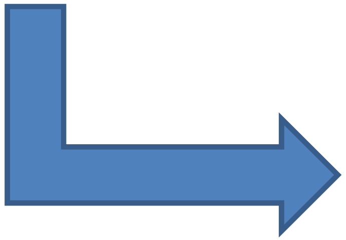


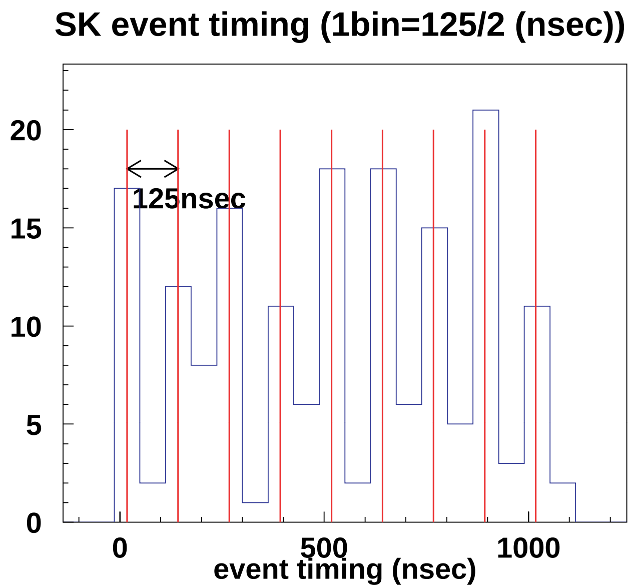
K2K events in Super-Kamiokande

K2K Neutrino events were searched for using timing.









112 events observed.

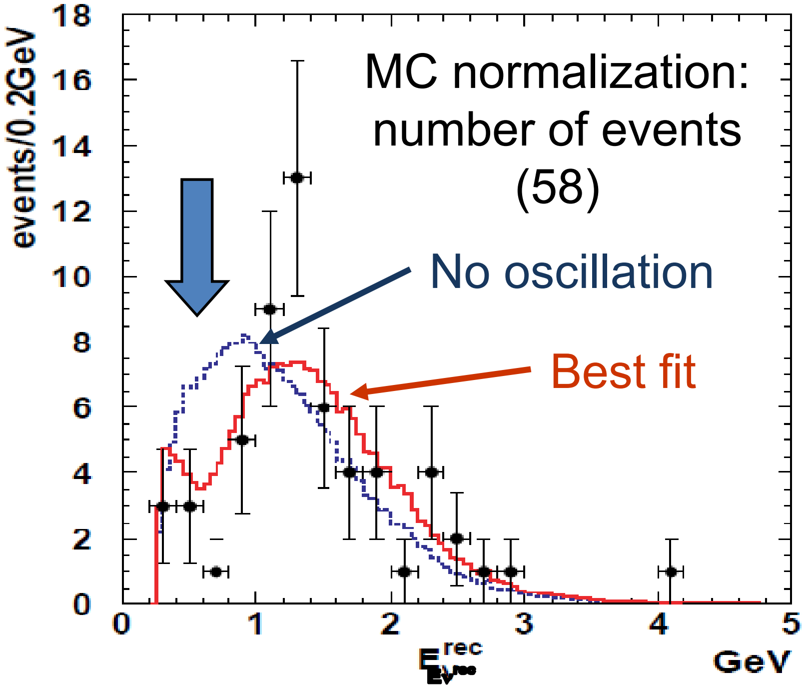
K2K events in Super-Kamiokande

K2K-I + II	DATA	MC
FC 22.5kt	112	$158.1^{+9.2}_{-8.6}$
1ring	67	
μ-like	58	
e-like	9	
Multi Ring	45	

Number

Energy spectrum

Osc. analysis

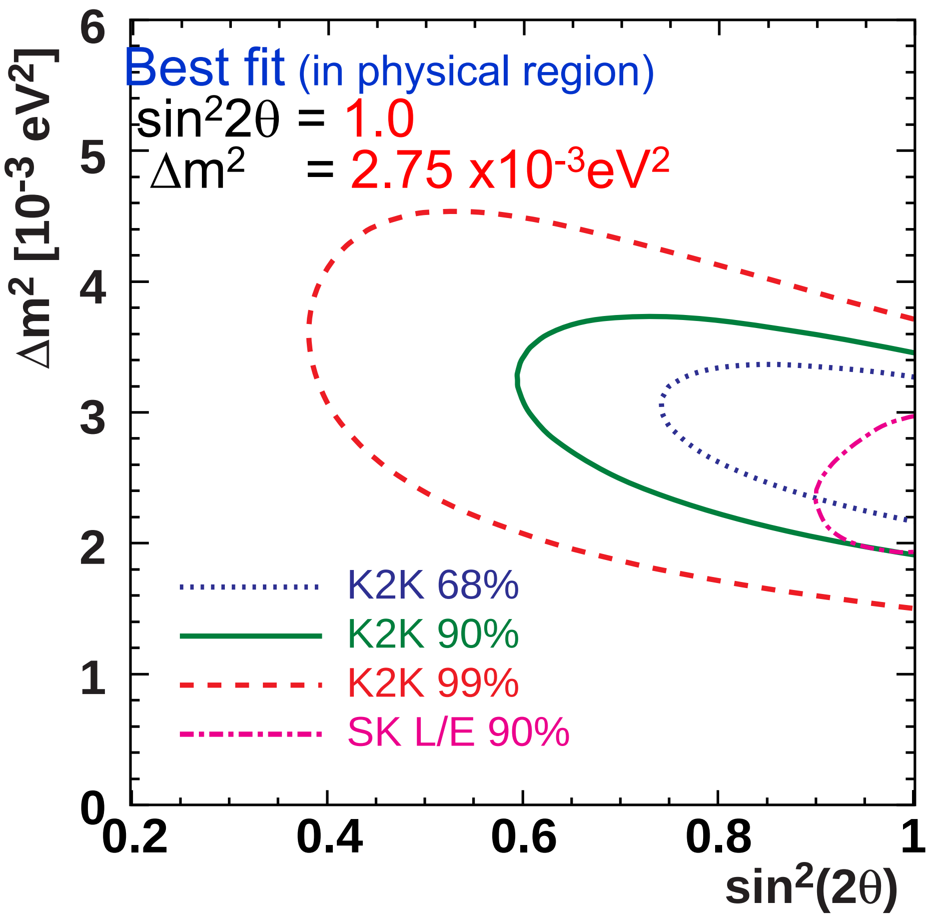


reconstructed Eν (GeV)

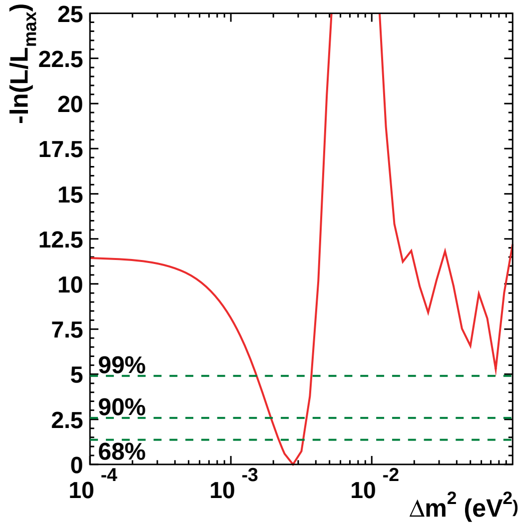
$\nu_\mu \to \nu_\tau$ oscillation fit in K2K

Hep-ex/0606032

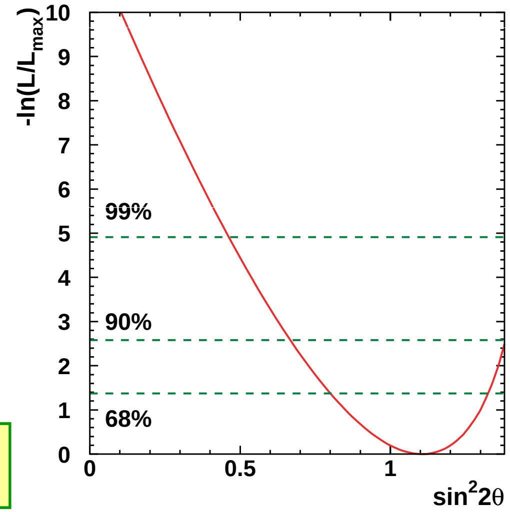
Based on **Number of events** + **Spectrum shape**



Δlikelihood @ $\sin^2 2\theta=1.0$

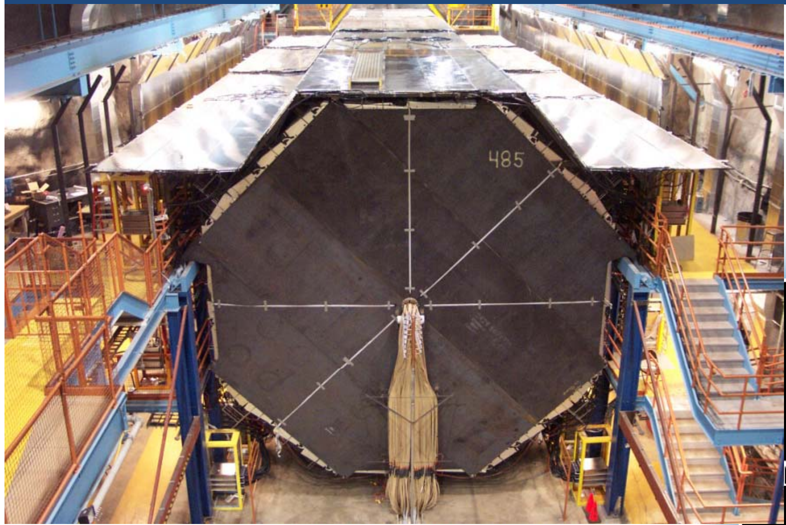


Δlikelihood @ $\Delta m^2=2.8\times10^{-3}$



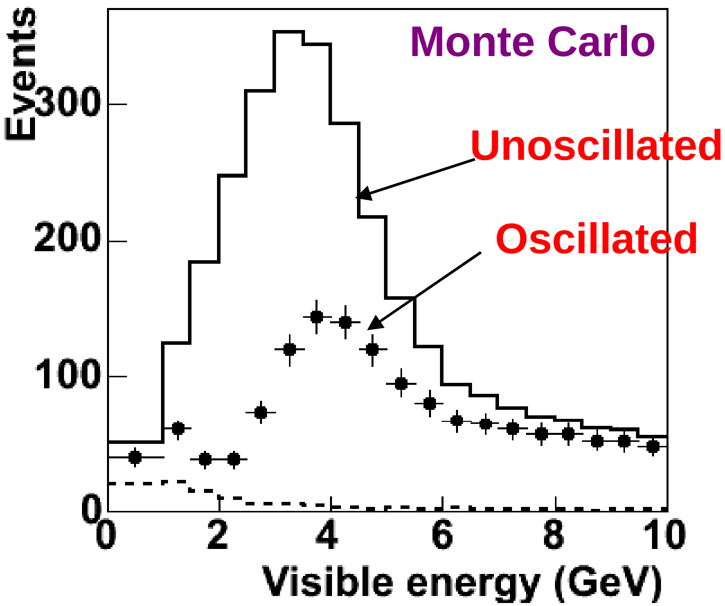
Consistent with the SK atmospheric neutrino result.

The MINOS experiment and its results

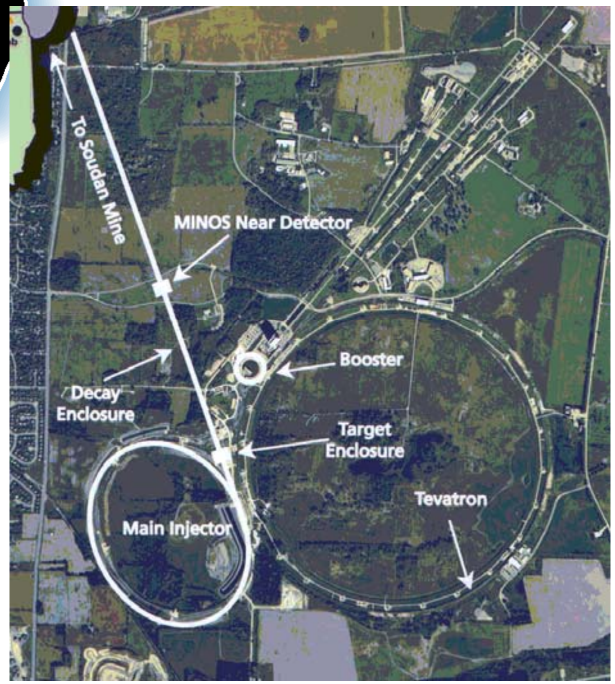


5.4 kton MINOS far detector

1 kton near detector



NuMI
beam line

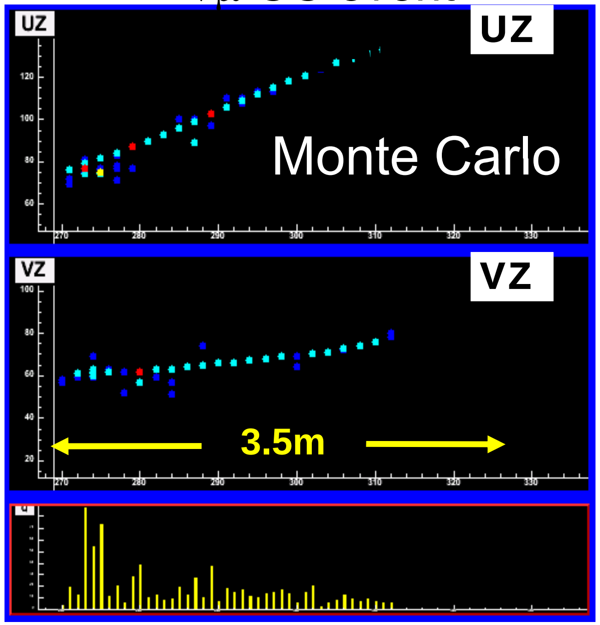


MINOS near and far detectors

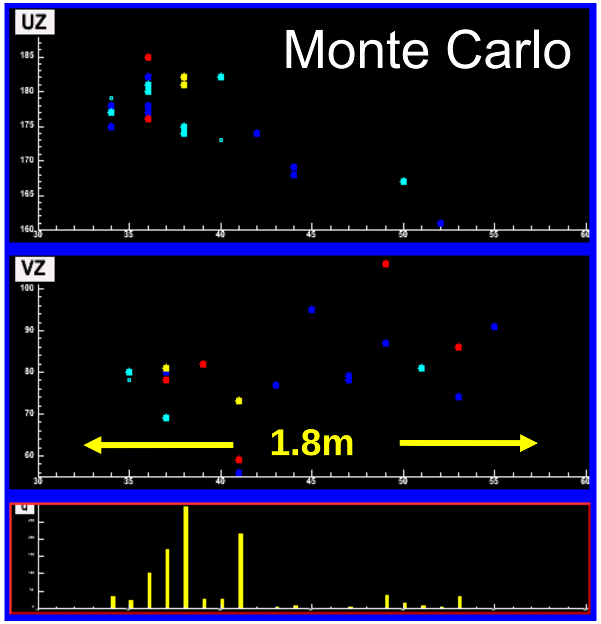
1	mass (kt)	5.4
3.8x4.8	plane size (m^2)	8x8
282/153	# steel/scint pl.	486/484
front: all pl. instrumented back: 1/5 pl. instrumented fast QIE electronics	specifics	veto shield for cosmics 8x optical multiplexing

MINOS event topologies

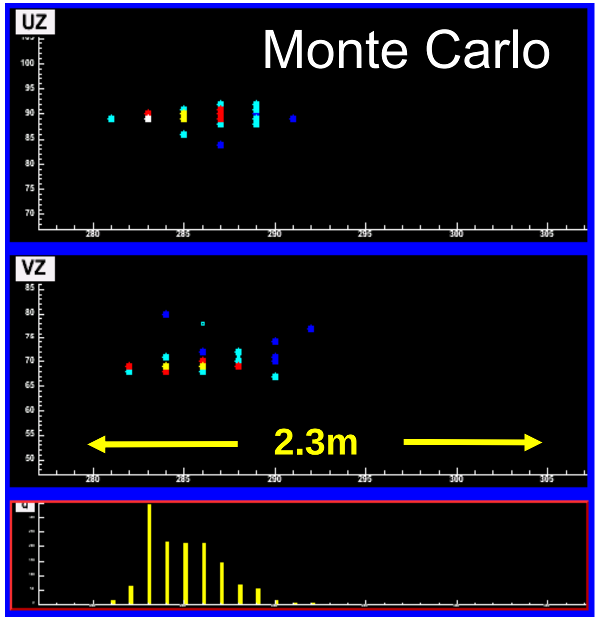
νμ CC event



NC event



νe CC event



- Long muon track + hadronic activity at vertex

- Short showering event, often diffuse

- Short event with typical EM shower profile

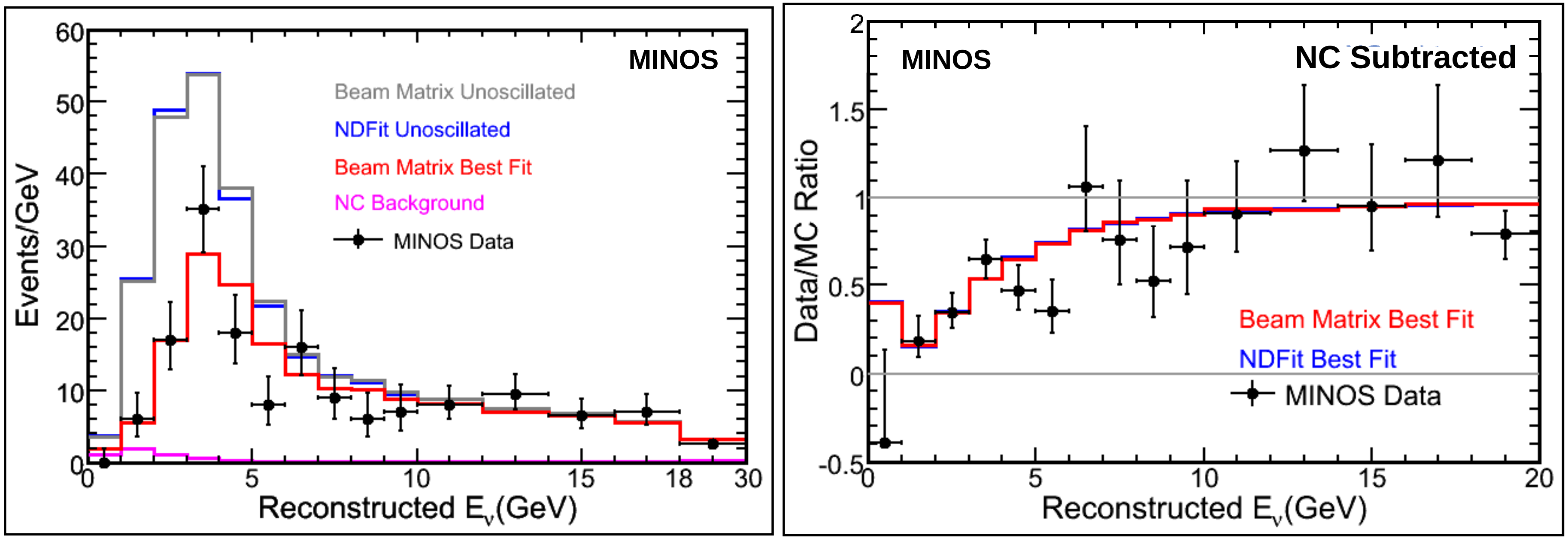
ν_μ CC is selected by;

- >=1 track
- Negative charge (curvature)
- Likelihood based on
  - Track length
  - Fraction of pulse height in a track
  - dE/dx

Number of events and energy spectrum

From May 2005 to March 2006 (1.27×10^{20} pot)

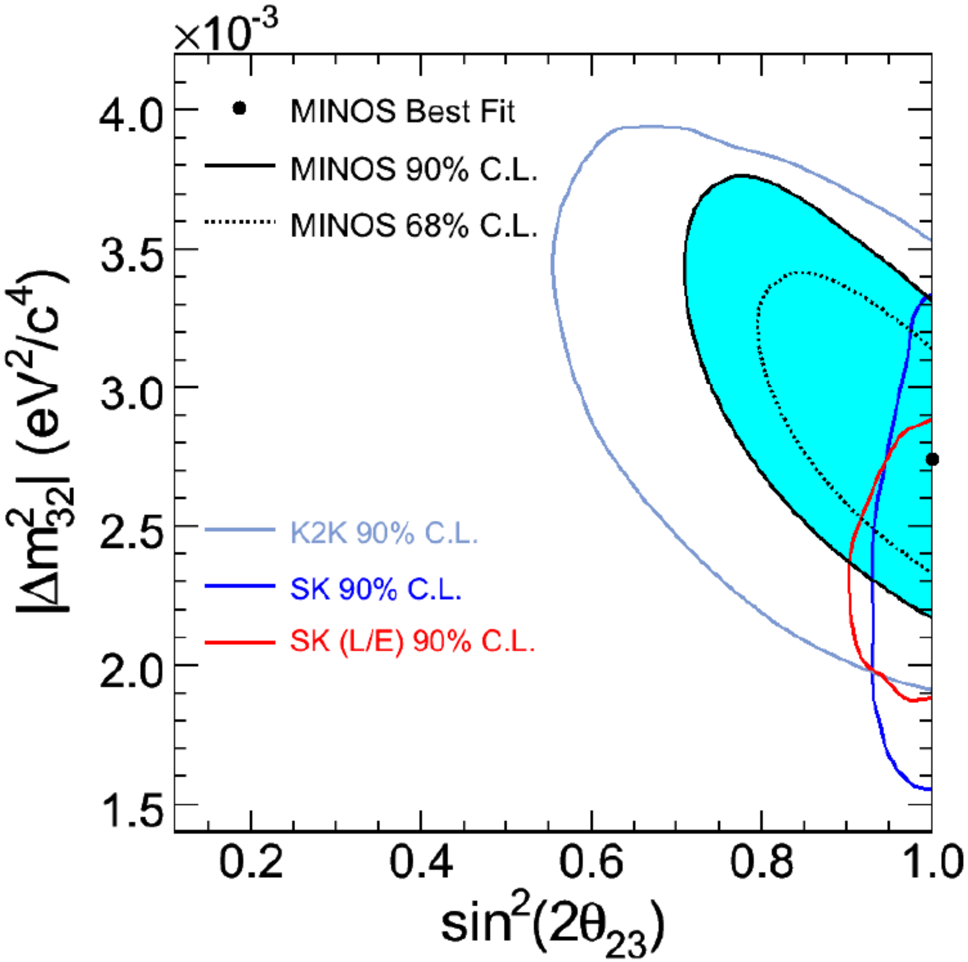
Data sample	observed	expected	ratio
ν_μ only (<30 GeV)	215	336±14	0.64±0.05
ν_μ only (<10 GeV)	122	239±11	0.51±0.05



Clear energy dependent deficit was observed !

MINOS oscillation result

hep-ex/0607088



$$\Delta m^2_{23} = 2.74^{+0.44}_{-0.25} \times 10^{-3} eV^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}$$

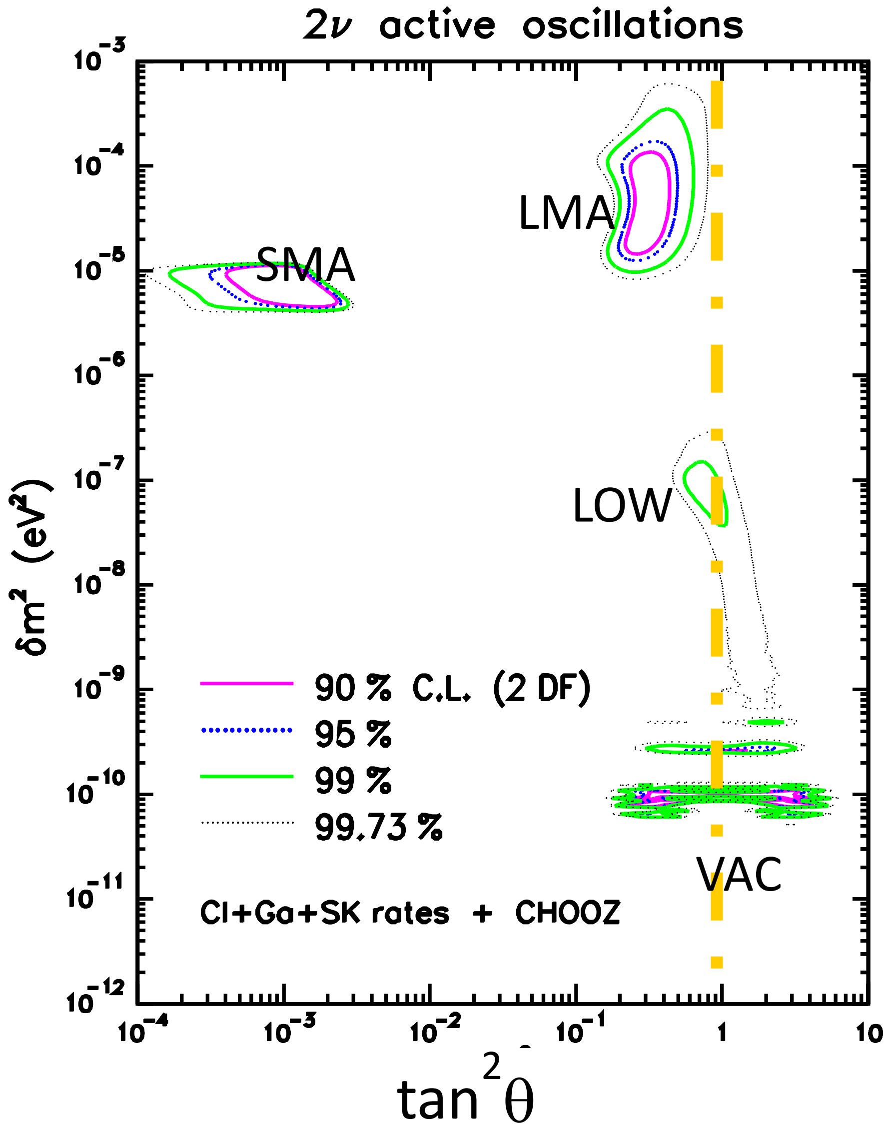
Results from SK atmospheric, K2K and MINOS agree well.
At this moment, $\sin^2 2\theta_{23}$: atmospheric, Δm_{23}^2: atmospheric
➔ LBL.

KamLAND reactor neutrino oscillation experiments

The idea of KamLAND

Atsuto Suzuki

Fogli et al.



SMA and LMA solutions were equally likely in the 1990's (although many people believed that mixing angles should be small).

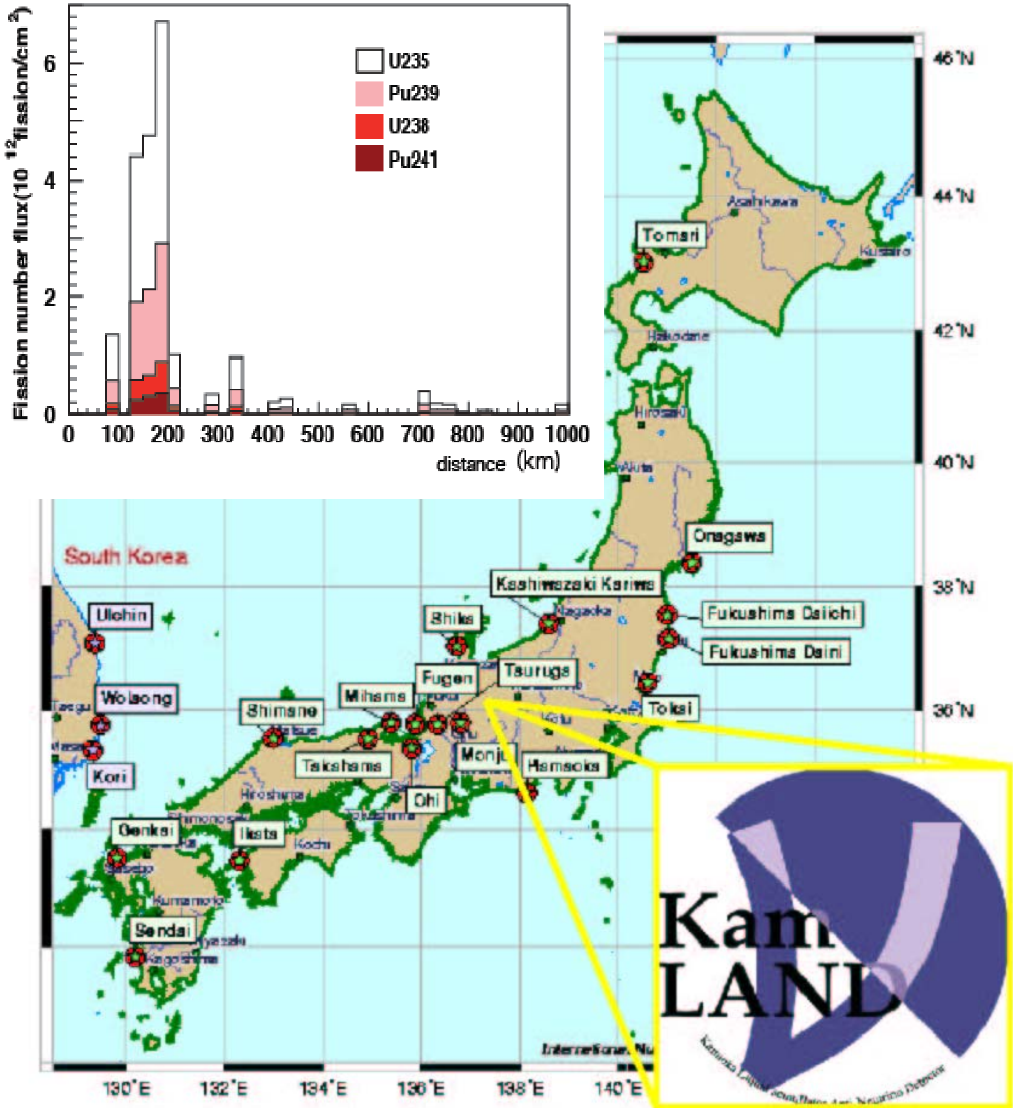
If LMA is the real solution, a reactor long baseline experiment can observe the oscillation.

Even if LMA is not the solution, this experiment can clearly exclude LMA.

➔Found there are many reactors in Japan…

➔ Kamiokande no more used...

Reactors around KamLAND



$$\langle L_\nu \rangle = 180km$$
$$\langle E_\nu \rangle = a\ \ few\ MeV$$

Sensitive to $\Delta m^2 > 10^{-5} eV^2$

However, the cross section is small…. ⇒ need a lot of power.

Fortunately,

68GW available

(4% of the world's manmade power)
(20% of the world's nuclear power)

with no cost.

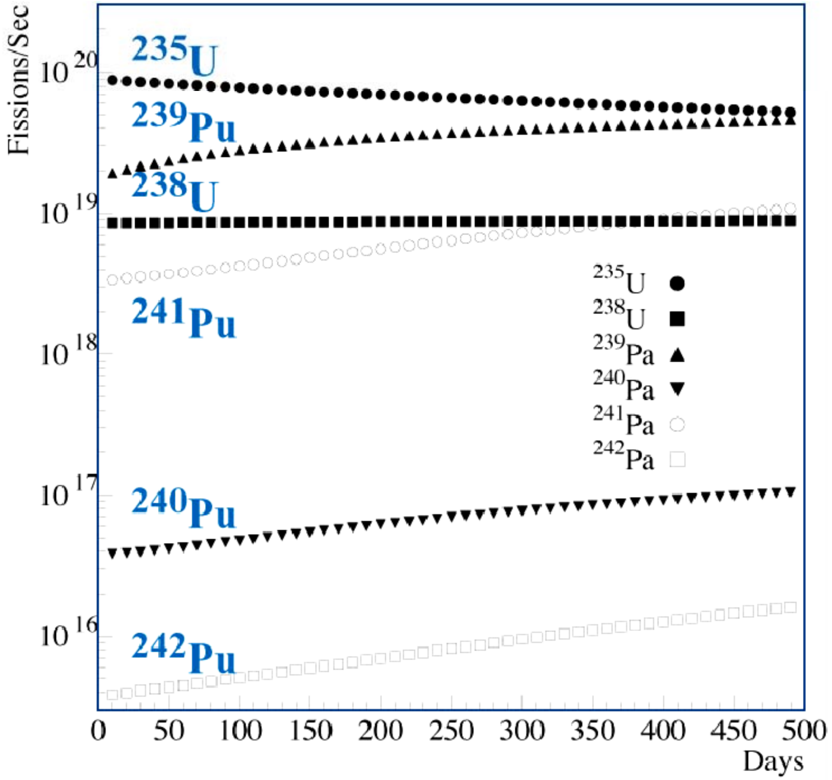
Anti-ν_e production in reactors

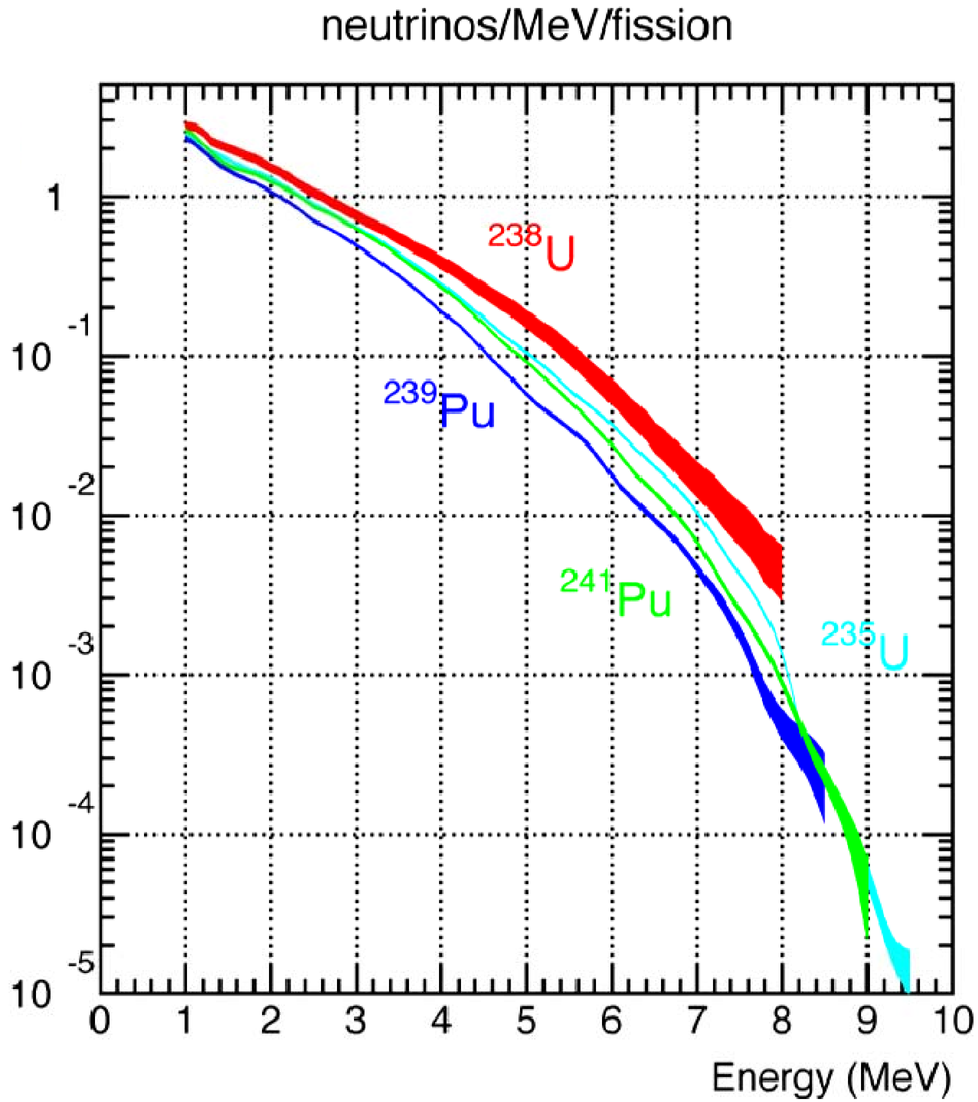
Fission reaction:

$$U + n \rightarrow \underline{X_1} + \underline{X_2} + \ldots$$

neutron rich

$$X_i \rightarrow Y + e^- + \underline{\overline{\nu}_e}$$





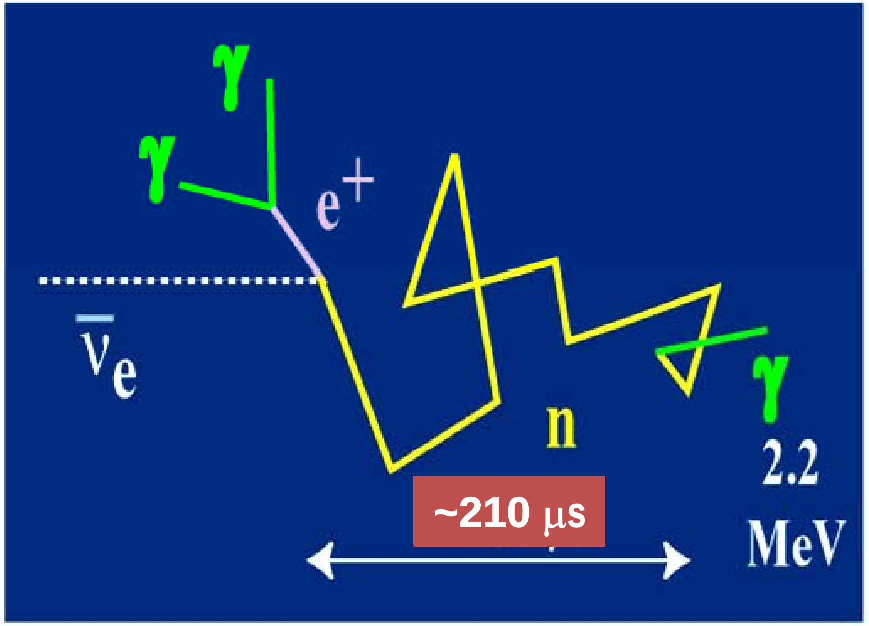
Detecting reactor neutrinos in Liq. scintillators

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

$$\bar{\nu}_e + C \rightarrow e^+ + {}^{12}B$$

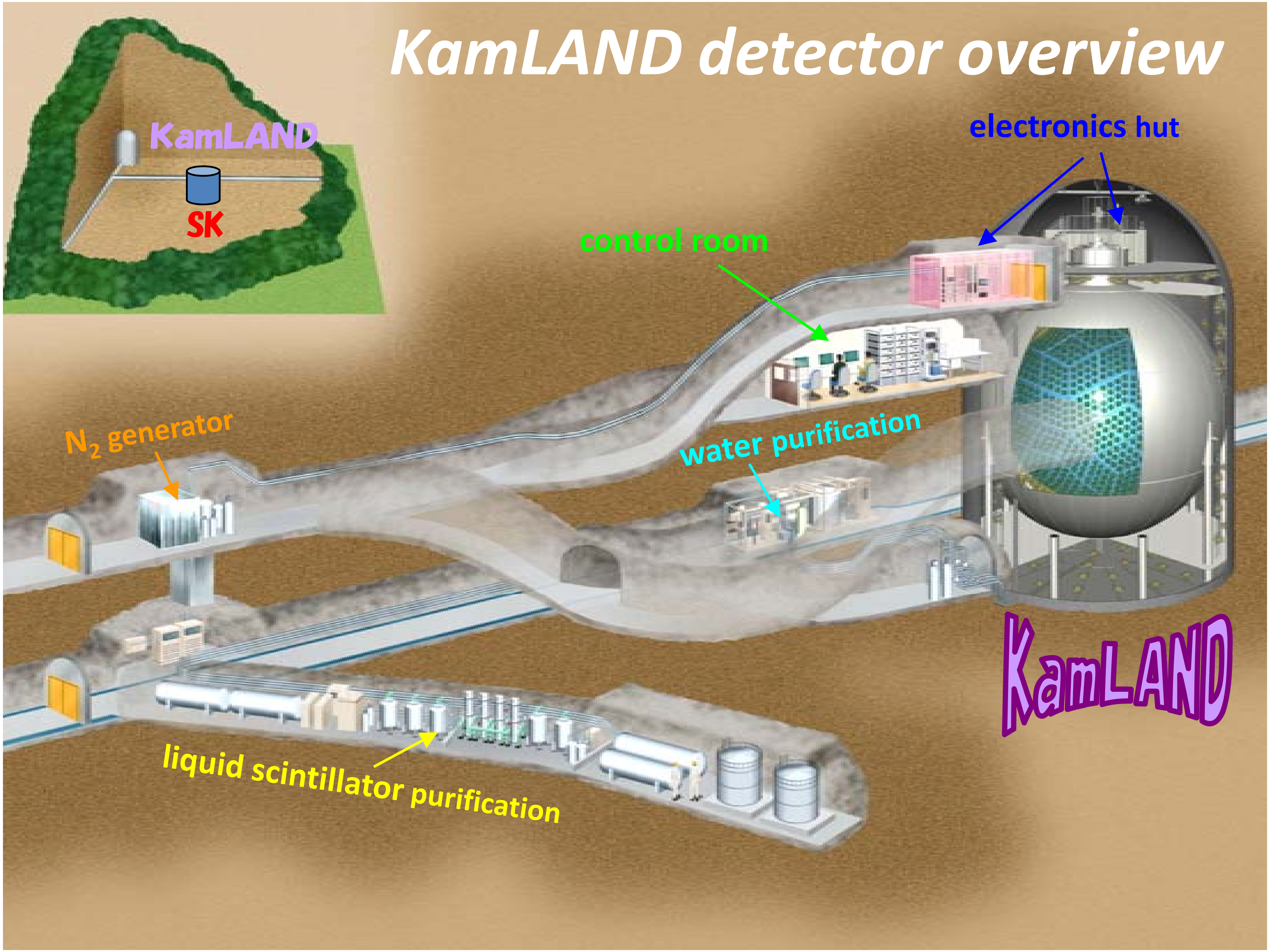
(energy, Eν<8MeV)

$$n + p \rightarrow d + \underline{\gamma(2.2MeV)}$$

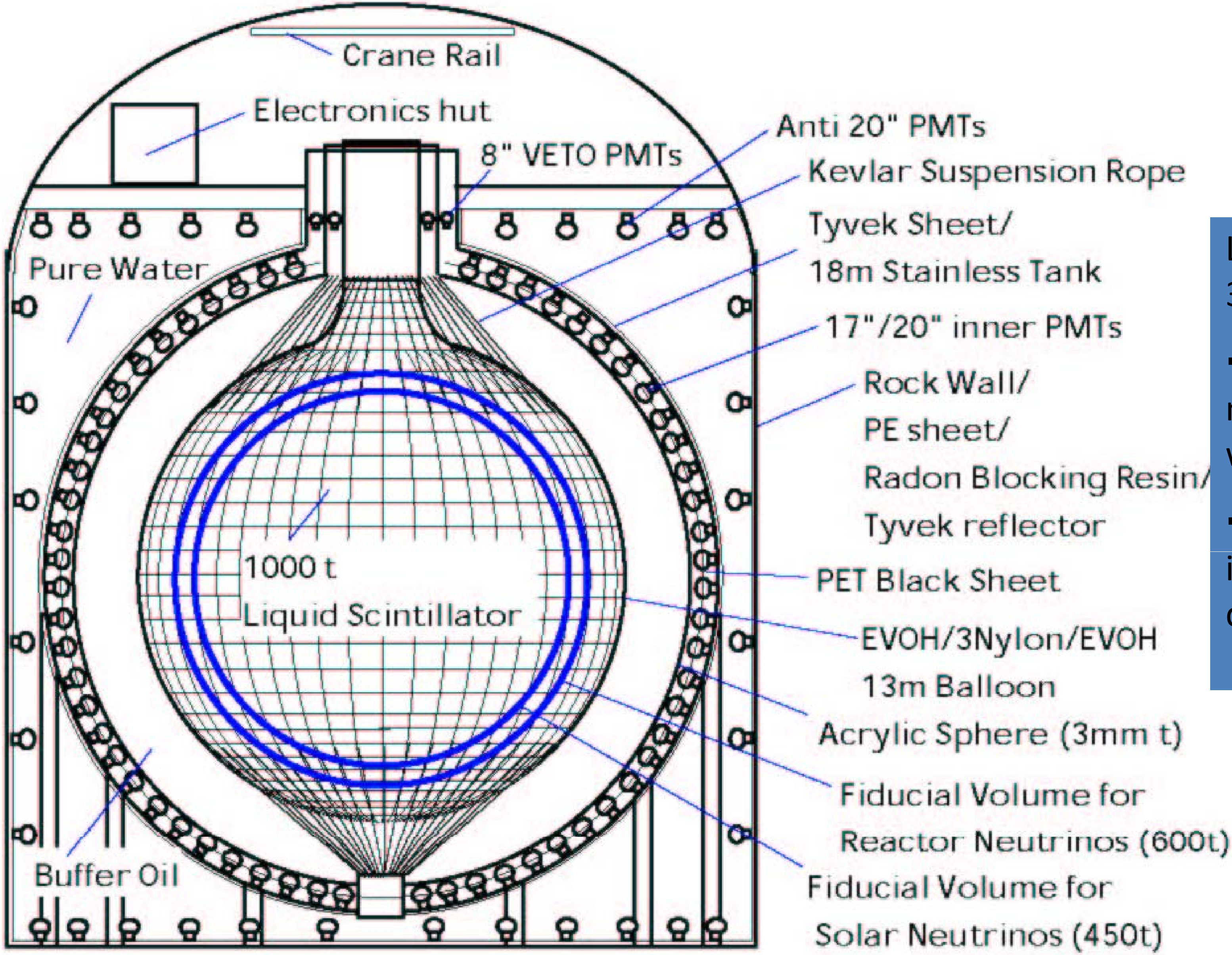


Coincidence of e^+ and γ reduces the BG substantially

KamLAND detector overview



KamLAND detector (1000 ton Liq. Sci. detector)

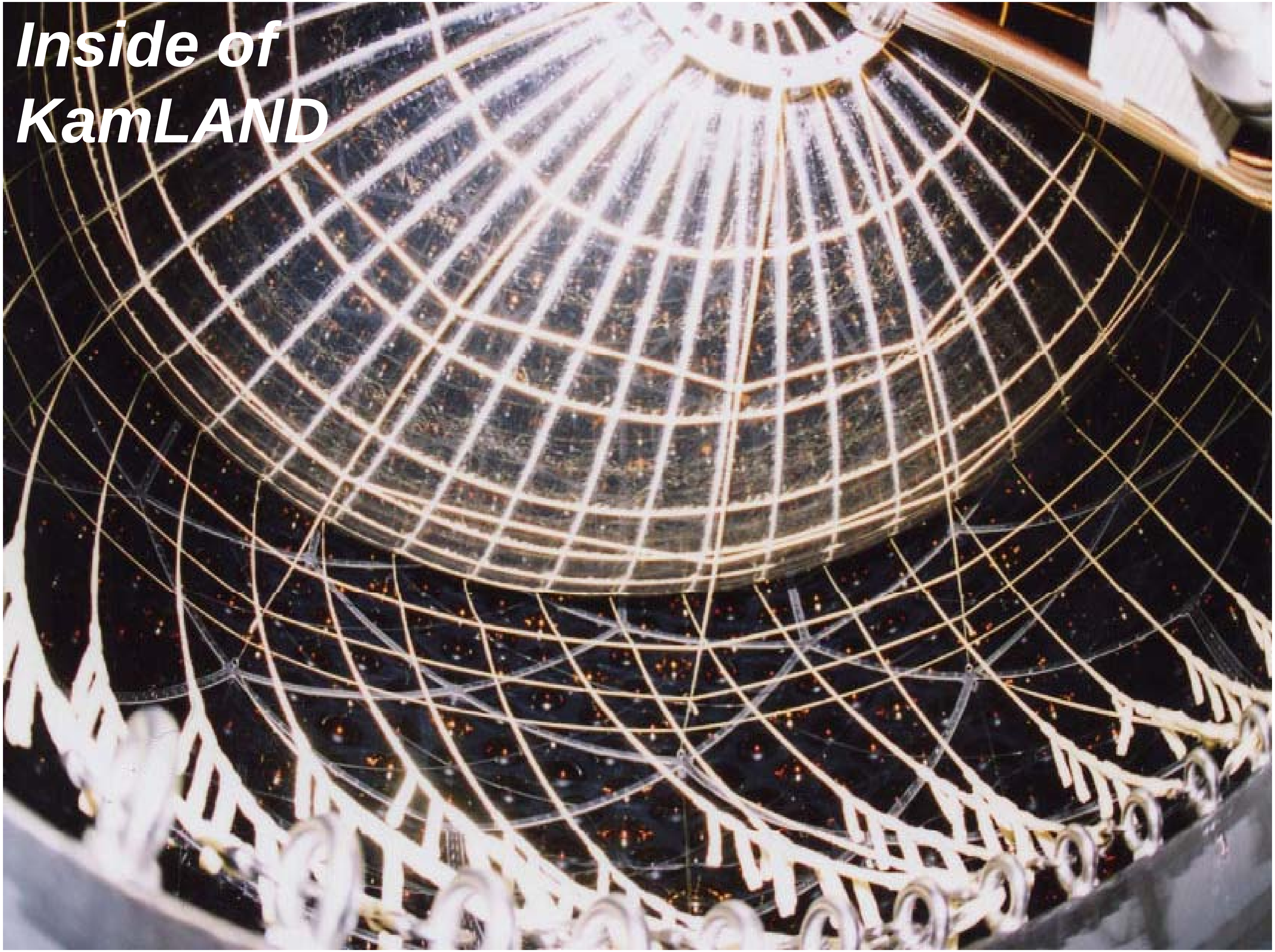


Light output = 320p.e./MeV

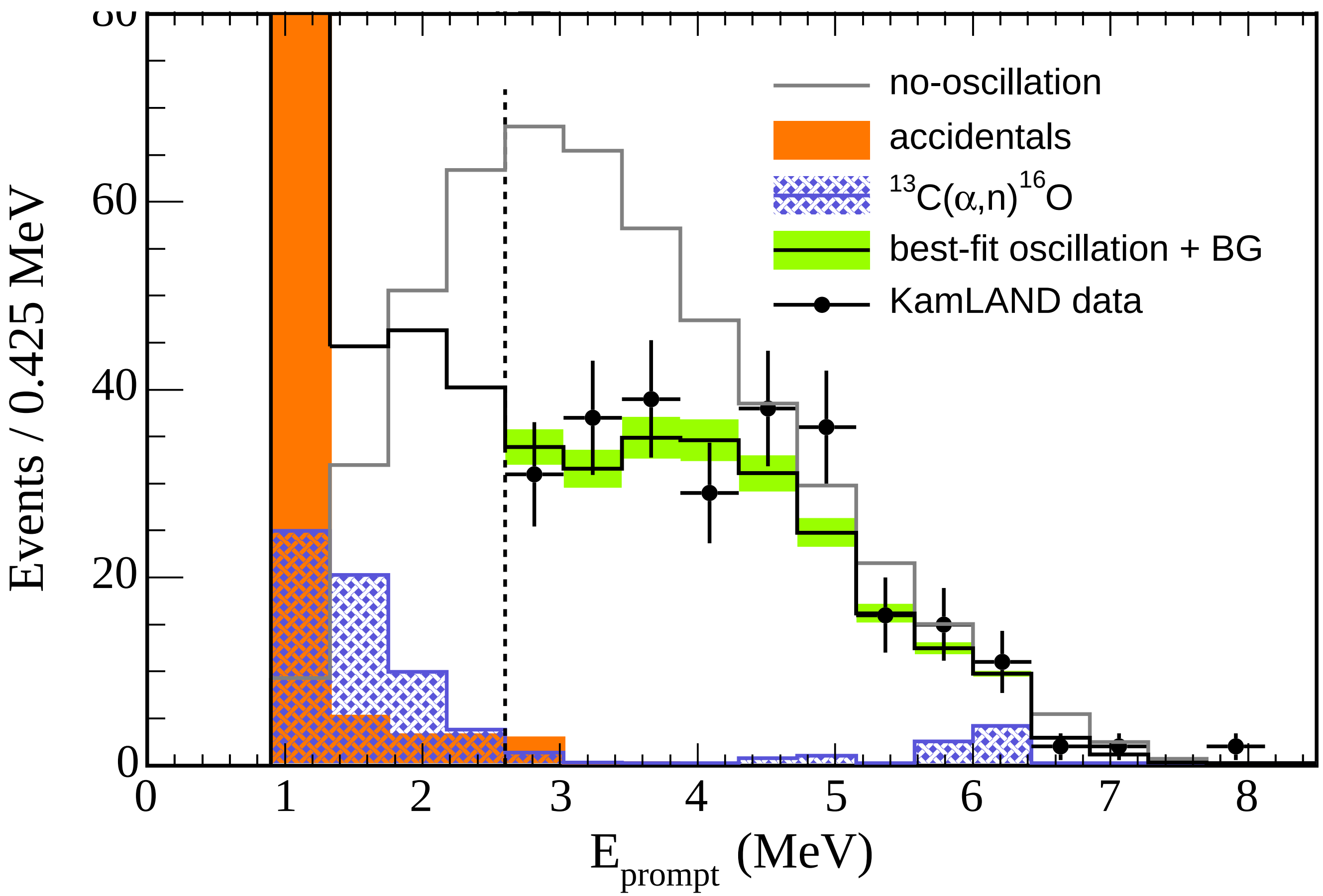
➔About 50 more light than water Cherenkov

➔But no information on direction

Inside of KamLAND



Reactor neutrino energy spectrum @KamLAND



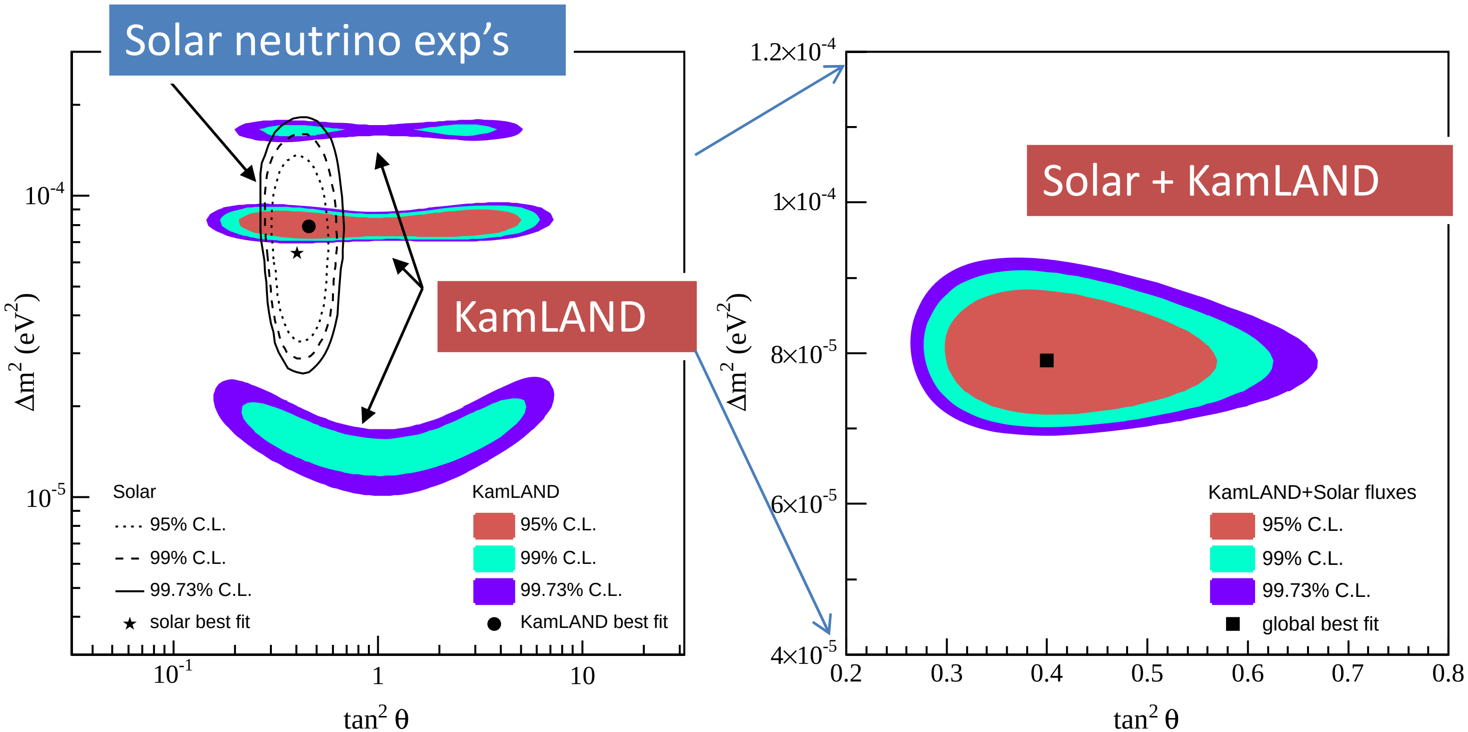
➔ Clear energy dependent deficit of reactor neutrino events.

\+

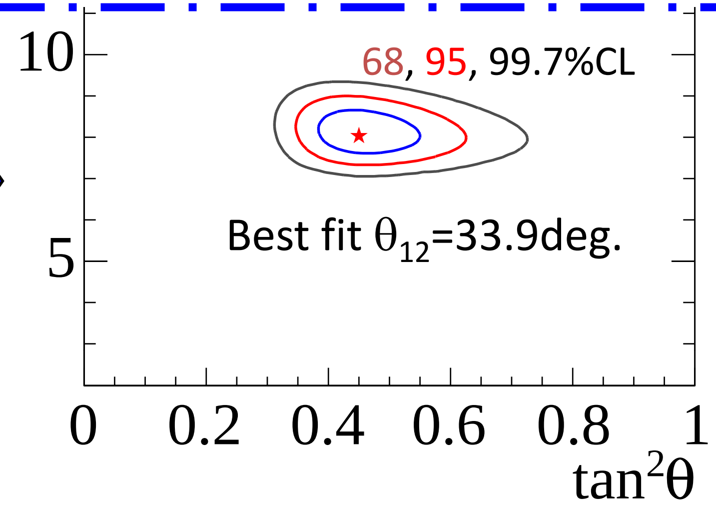
Known neutrino flight length

Accurate measurement of Δm_{12}^2

Allowed (Δm_{12}^2, θ_{12}) parameter region



With the 2005 SNO NC results



Really oscillation ?

YES !

Really oscillation ?

Before 2004, what we knew was that neutrinos change flavor if they propagate a long enough distance.

People consider other mechanisms to change the neutrino flavor. For example they were neutrino decay or neutrino decoherence models.

oscillation

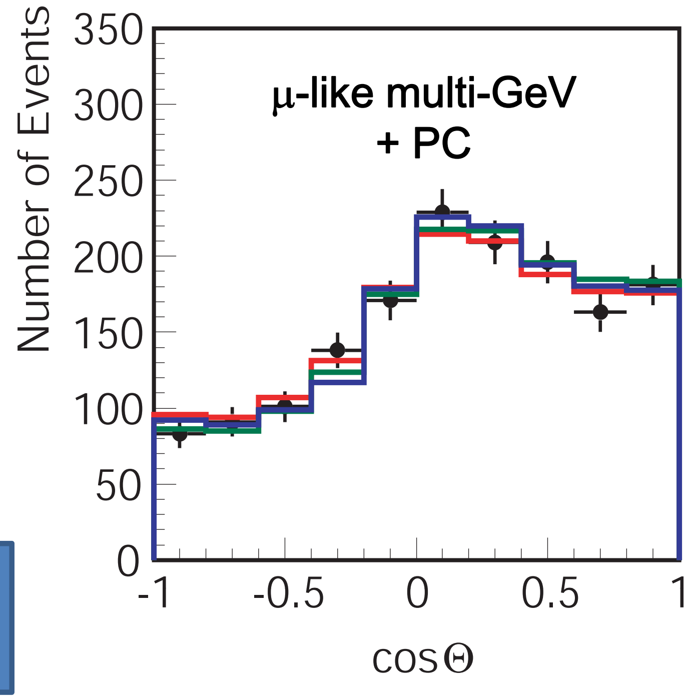
decoherence

$$P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta \cdot (1 - \exp(-\gamma_0 \frac{L}{E}))$$

decay

$$P_{\mu\mu} = (\cos^2\theta + \sin^2\theta \cdot \exp(-\frac{m}{2\tau}\frac{L}{E}))^2$$

These models explained the atmospheric neutrino data remarkably well.



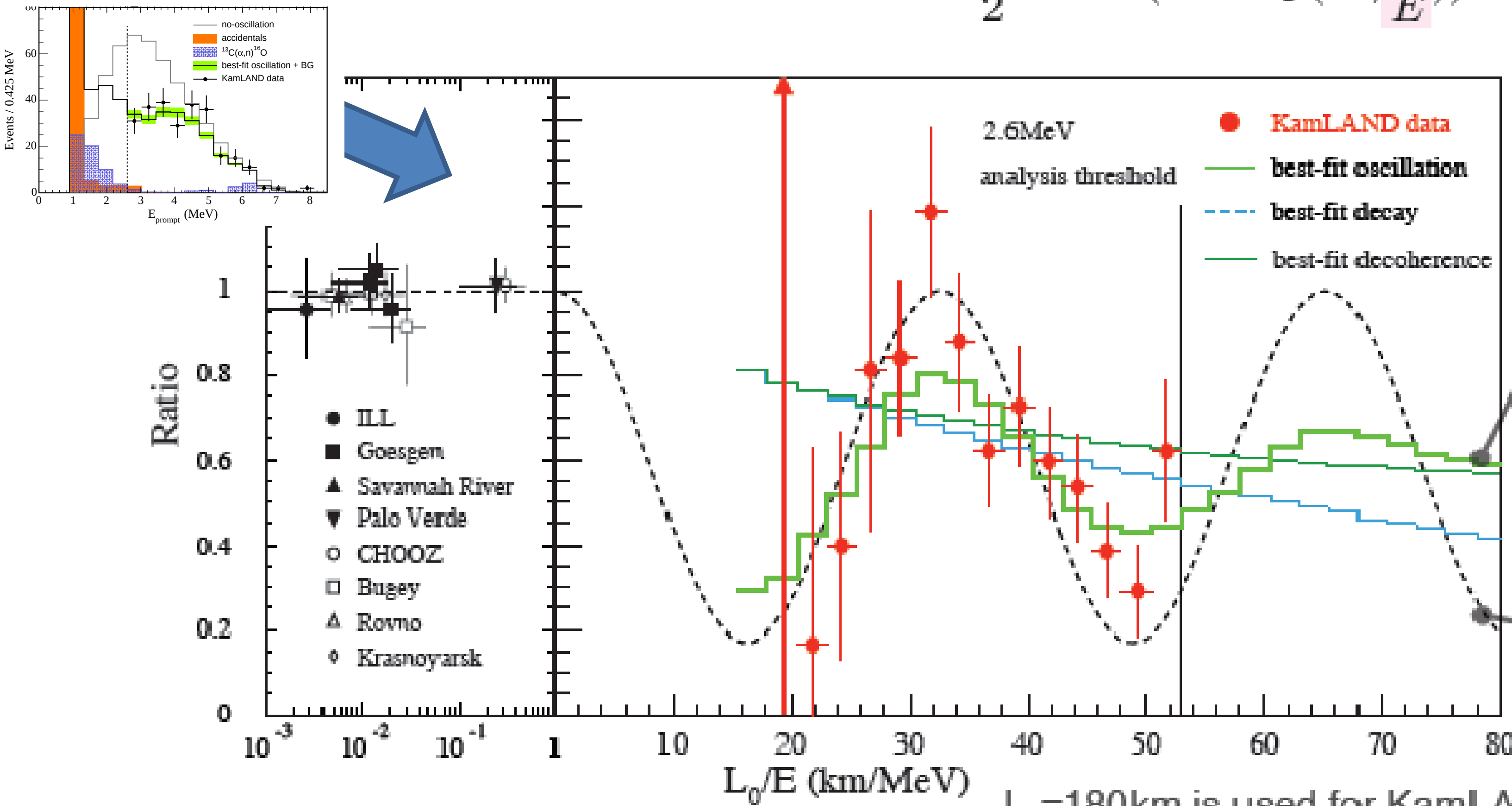
Really oscillation: YES !

KamLAND

oscillation $P_{ee} = 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2}{4} \frac{L}{E})$

decay $P_{ee} = (\cos^2\theta + \sin^2\theta \exp(-\frac{m_2}{2\tau} \frac{L}{E}))^2$

decoherence $P_{ee} = 1 - \frac{1}{2} \sin^2 2\theta (1 - \exp(-\gamma \frac{L}{E}))$

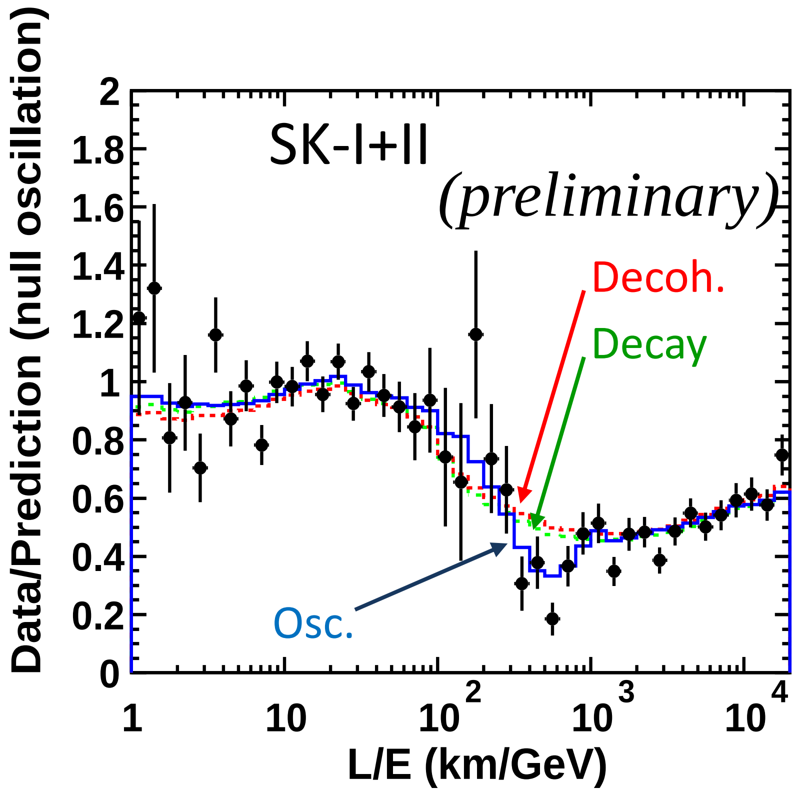


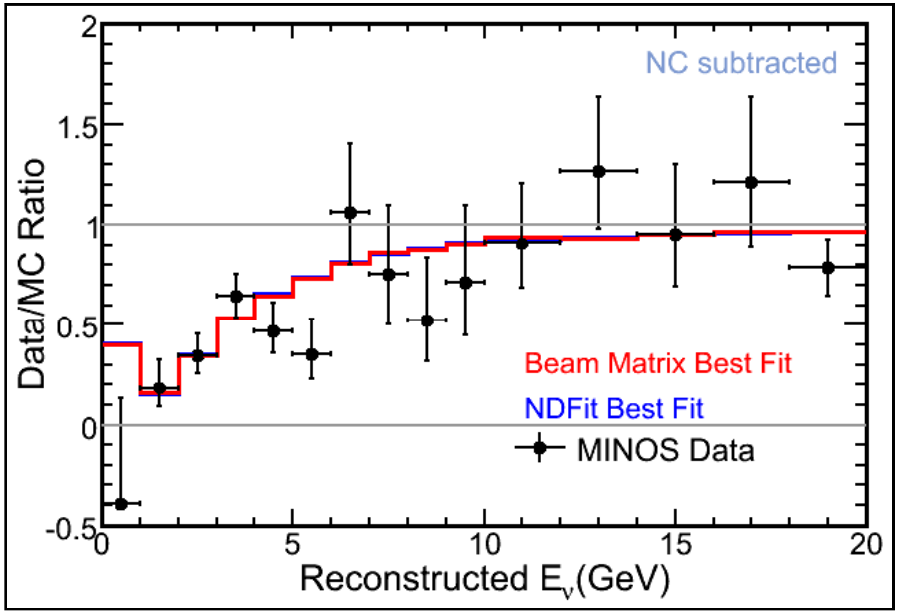
with real reactor distribution

ideal oscillation pattern

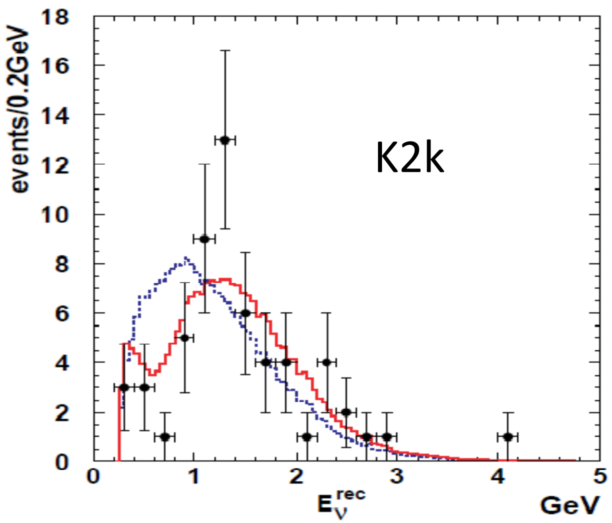
L_0=180km is used for KamLAND

Really oscillation: YES !





Oscillation gives the best fit to the data.
Decay and decoherence models disfavored by 4.8 and 5.3 σ, resp.



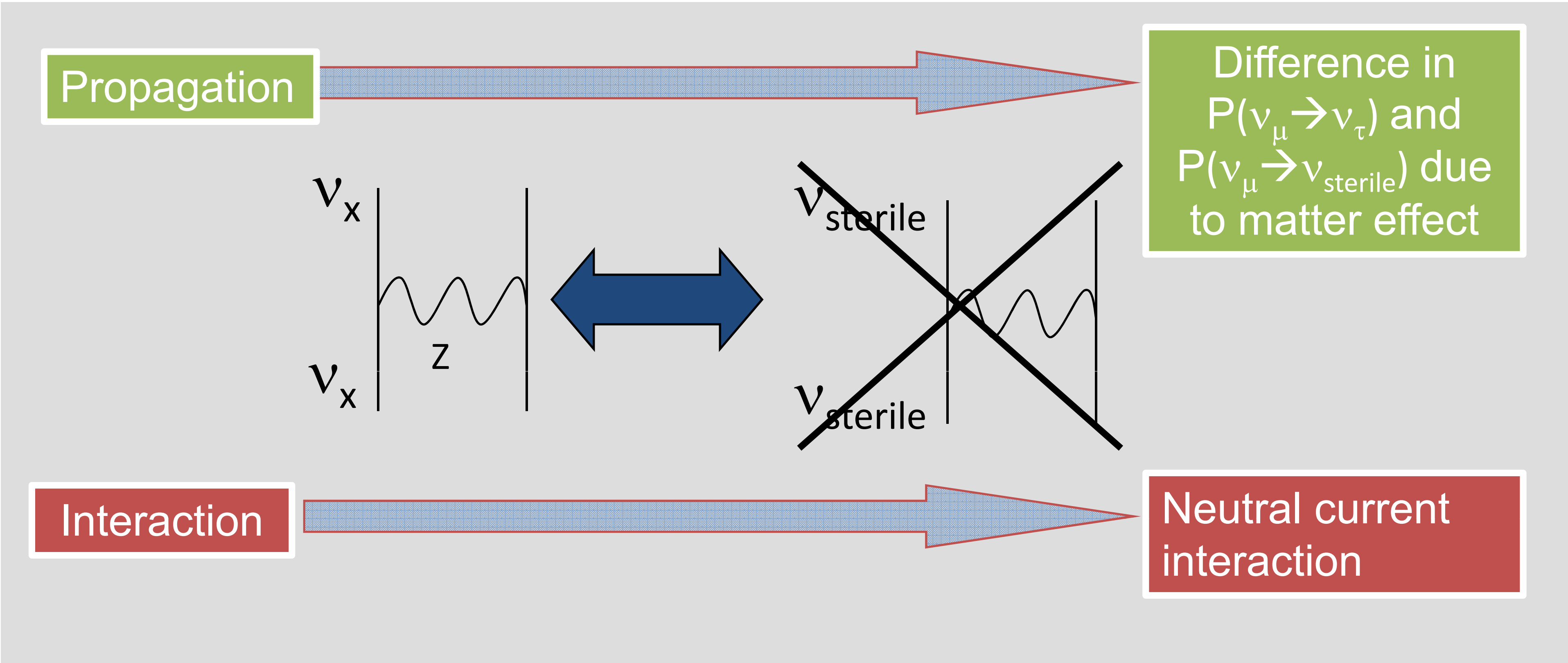
All these data consistently favor oscillations.

ν_μ to ν_τ or ν_μ to $\nu_{sterile}$?

Oscillation to ν_τ or $\nu_{sterile}$?

μ data show L and energy dependent deficit of events, while e (in atmospheric neutrino exp) data show no such effect.

$\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_{sterile}$



Testing $\nu_\mu \rightarrow \nu_\tau$ vs. $\nu_\mu \rightarrow \nu_{sterile}$

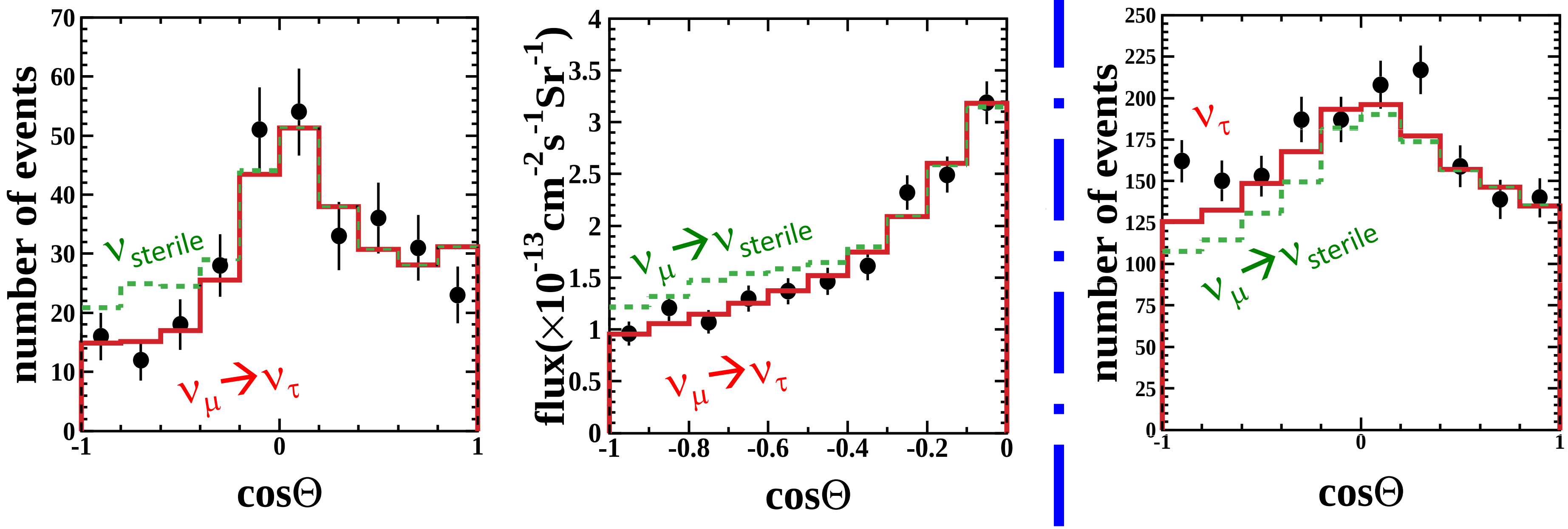
Matter effect

High E PC events (Evis>5GeV)

Up through muons

Neutral current

Multi-ring e-like, with Evis >400MeV



→ **Pure $\nu_\mu \rightarrow \nu_{sterile}$ excluded**

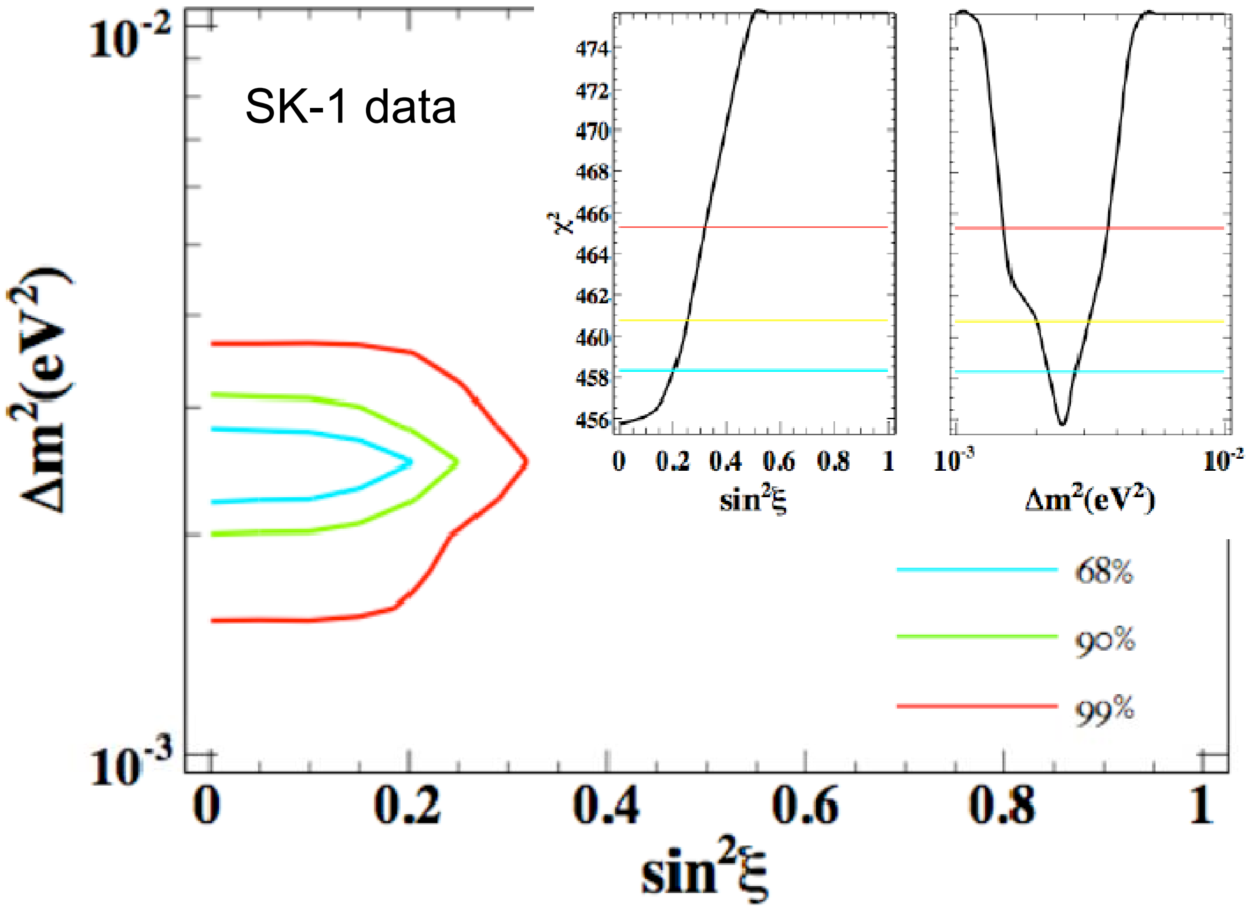
(PRL85,3999 (2000))

Limit on oscillations to $\nu_{sterile}$

$\nu_\mu \rightarrow (\sin\xi \cdot \nu_{sterile} + \cos\xi \cdot \nu_\tau)$

If pure $\nu_\mu \rightarrow \nu_\tau$, $\sin^2\xi=0$

If pure $\nu_\mu \rightarrow \nu_{sterile}$, $\sin^2\xi=1$



Consistent with pure $\nu_\mu \rightarrow \nu_\tau$

SK collab. draft in preparation

Tagging appeared neutrino flavor ?

(Here we consider only ν_τ oscillated from ν_μ.)

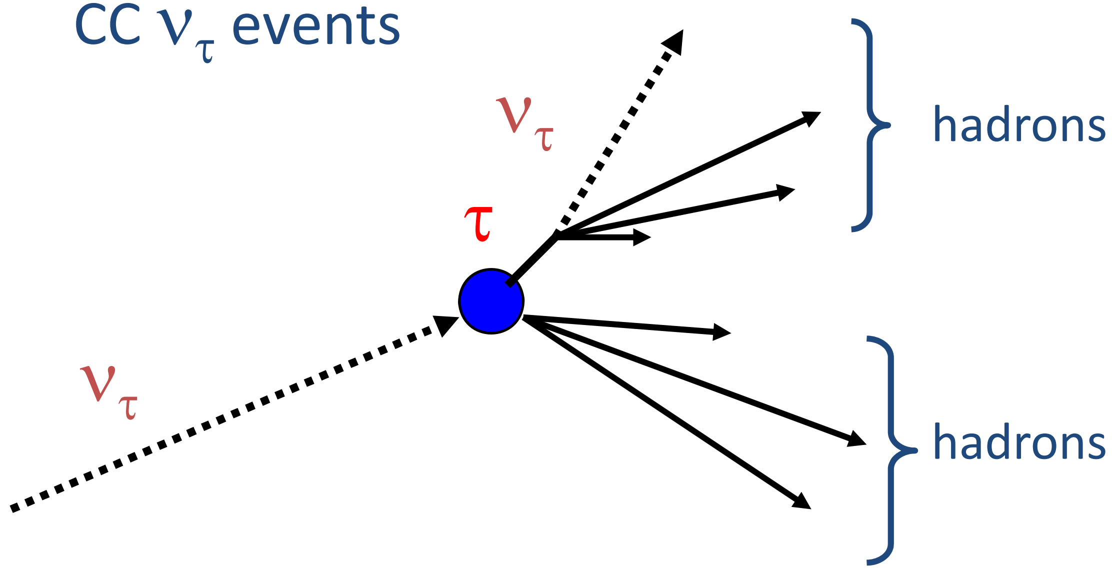
Tau neutrino appearance search

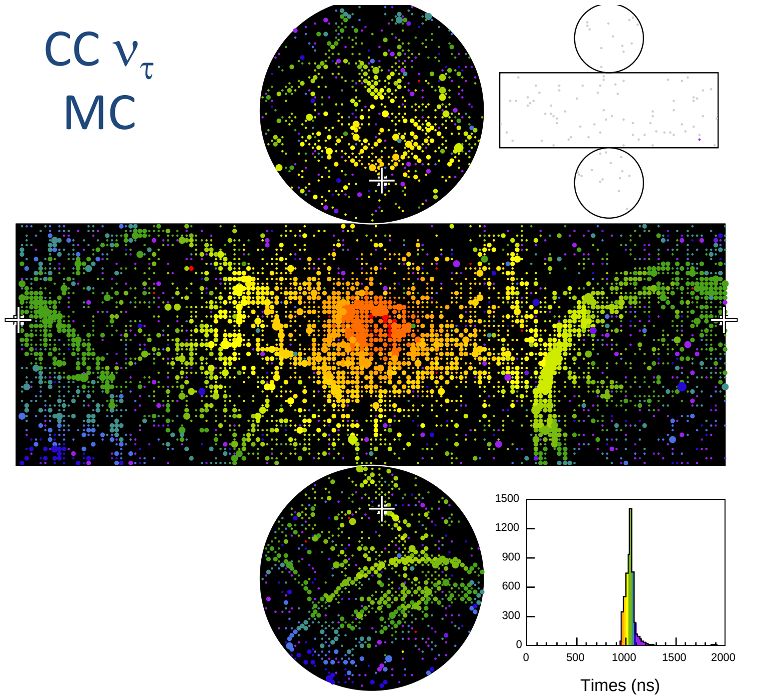
- We only consider ν_τ appearance from the initial ν_μ beam. (Solar and reactor neutrino energies are much below the ν_μ and ν_τ CC interactions.)

- The threshold for the CC ν_τ interaction is about 3.5GeV.
  - ➔ K2K cannot observe CC ν_τ interactions.
  - ➔ Atmospheric neutrino experiments could…

Search for CC ν_τ events (SK-I)

CC ν_τ events





- Many hadrons ….

(But no big difference with the other (NC) events.)

→ BAD → τ-likelihood analysis

- Upward going only

→ GOOD → Zenith angle

Only ~ 1.0 CC ν_τ FC events/kton·yr

↕

(BG (other ν events) ~ 130 ev./kton·yr)

Selection of ν_τ events

Pre-cuts: E(visible) >1,33GeV, most-energetic ring = e-like

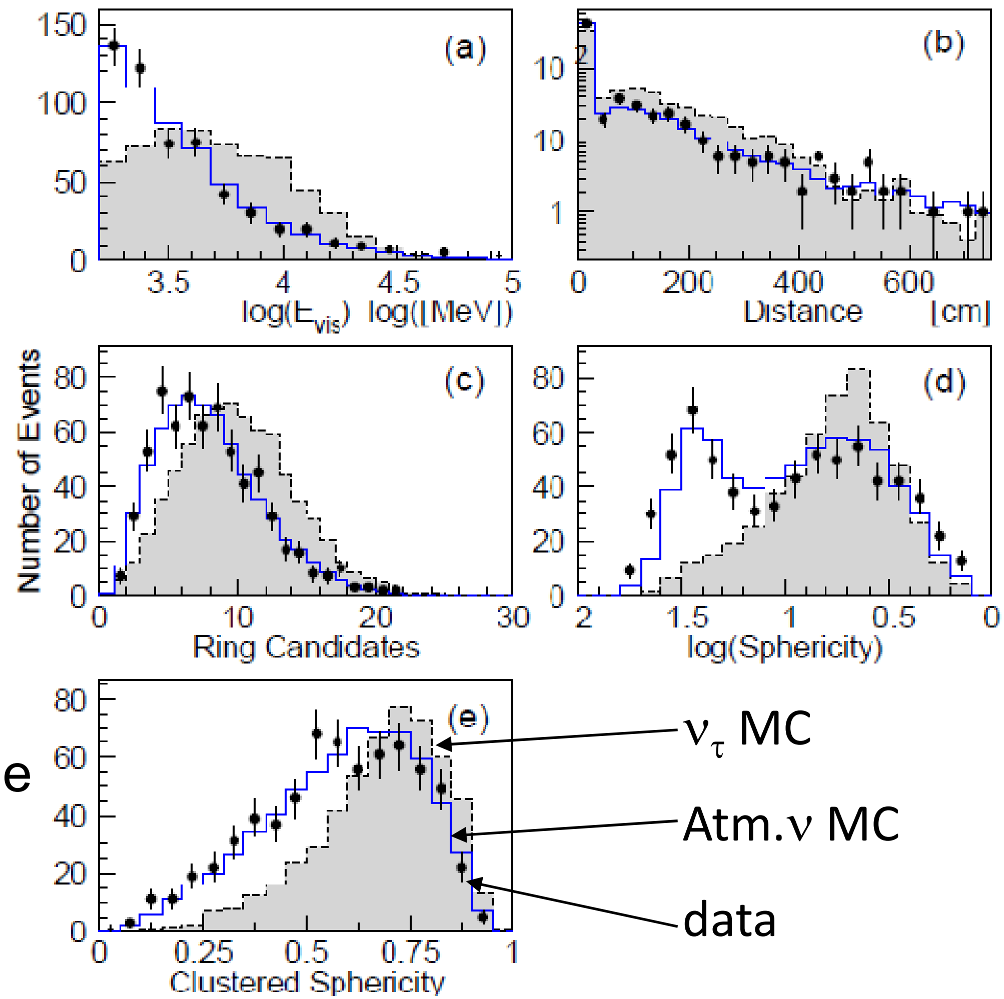
E(visible)

Max. distance between primary vertex and the decay-electron vertex

Number of ring candidates

Sphericity in the lab frame

Sphericity in the CM frame



ν_τ MC

Atm.ν MC

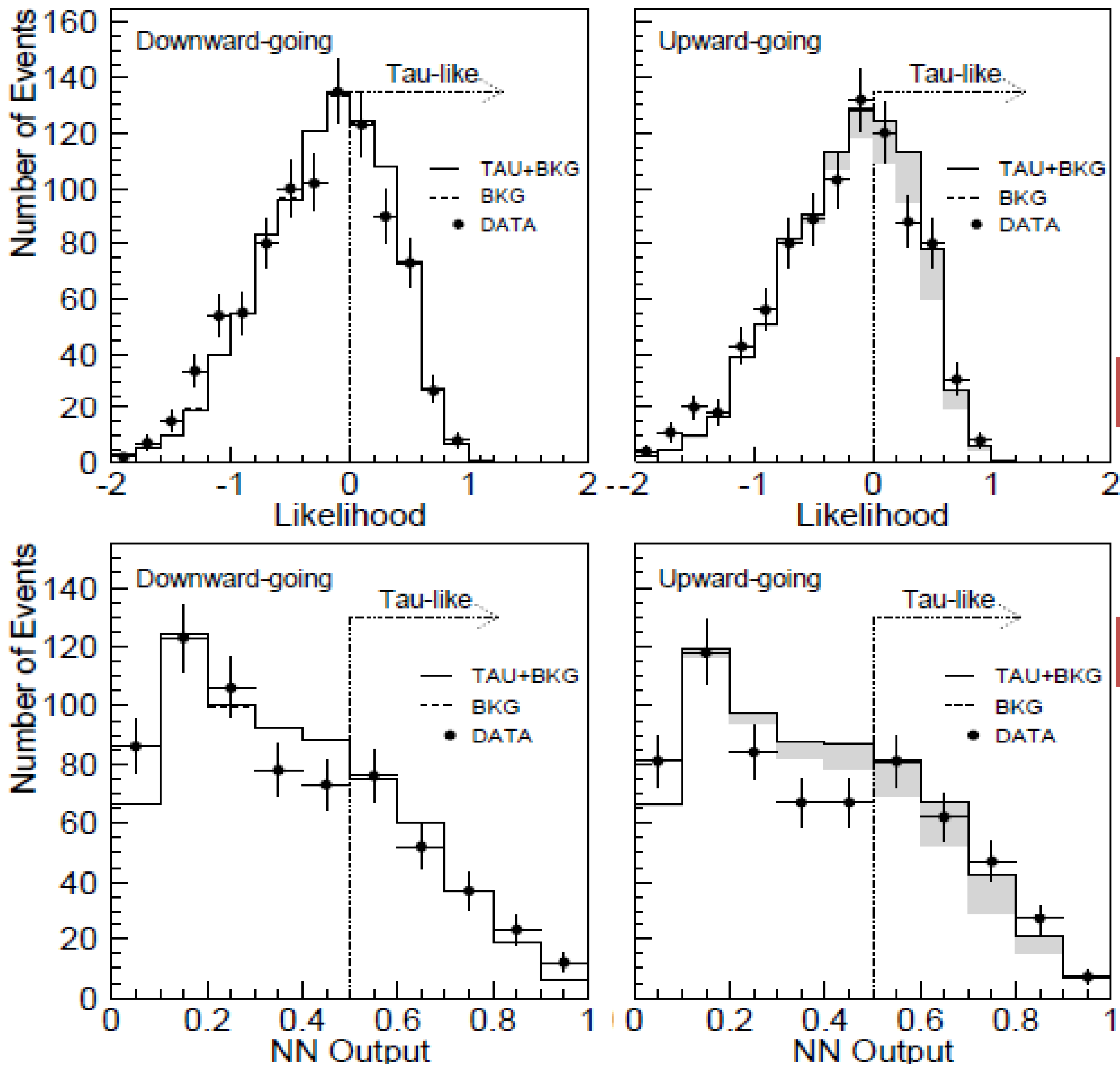
data

Likelihood / neural-net distributions

Down-going (no ν_τ) | Up-going

Likelihood

Neural-net

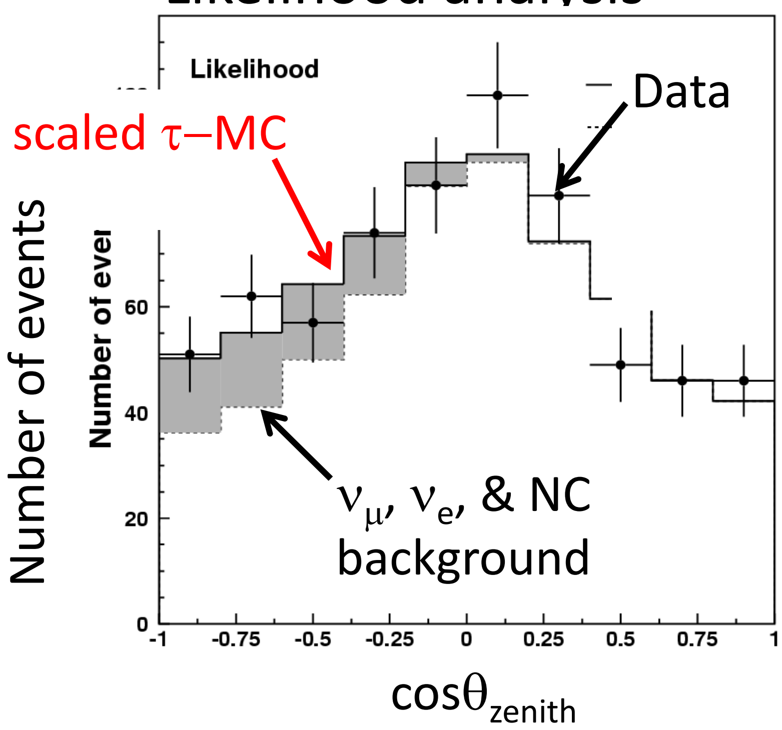


Zenith-angle

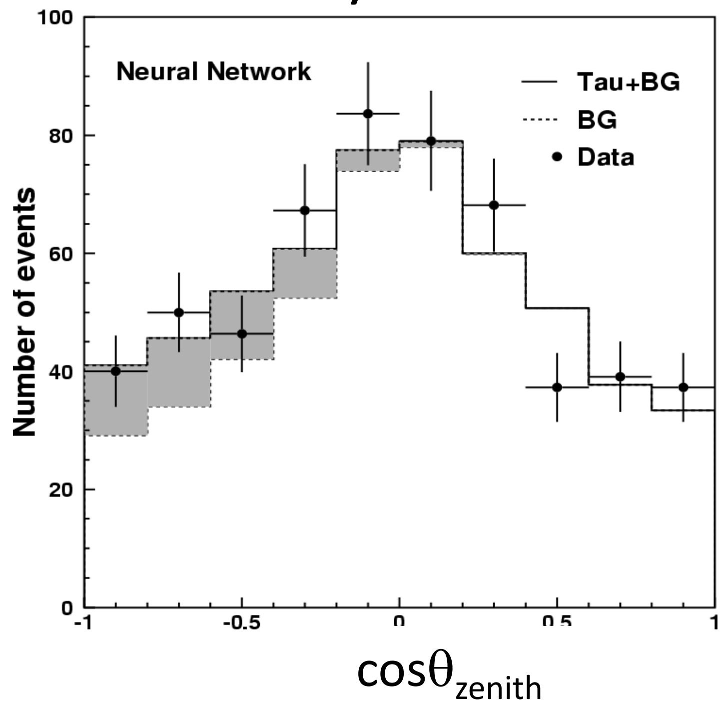
Zenith angle dist. and fit results

Hep-ex/0607059

Likelihood analysis



NN analysis



	Likelihood analysis	NN analysis
Fitted number of τ events	138±48(stat) +15 / -32(syst)	134±48(stat) +16 / -27(syst)
Exp'd number of τ events	78±26(syst)	78±27 (syst)

Zero tau neutrino interaction is disfavored at 2.4σ.

In the future, we expect a stronger evidence for ν_τ appearance (OPERA).

Summary

- Atmospheric, solar, reactor and accelerator experiments gave strong "evidence for flavor change and oscillations".
- We already know; $\Delta m_{12}{}^2$, $\sin^2\theta_{12}$, $|\Delta m_{23}{}^2|$ and $\sin_2 2\theta_{23}$ rather accurately.
- However, there are several unknown neutrino oscillation parameters.
- We believe that the neutrino masses and mixings are keys to our deeper understanding of the nature. Future experiments should measure these unknown parameters.

Enjoy the rest of the school!

Thank you!

Definition of χ^2

Number of data bins

Number of syst error terms

$$L(N_{\exp}, N_{obs}) = \prod_{n=1}^{760} \frac{\exp(-N_{\exp}^{n})(N_{\exp}^{n})^{N_{obs}^{n}}}{N_{obs}^{n}!} \times \prod_{i=1}^{70} \exp\left(\frac{-\varepsilon_i^2}{2\sigma_i^2}\right)$$

Poisson with systematic errors

$$\chi^2 \equiv -2\ln\left(\frac{L(N_{\exp}, N_{obs})}{L(N_{obs}, N_{obs})}\right) = \sum_{n=1}^{760}\left[2(N_{\exp}^{n} - N_{obs}^{n}) + 2N_{obs}^{n}\ln\left(\frac{N_{obs}^{n}}{N_{\exp}^{n}}\right)\right] + \sum_{i=1}^{70}\left(\frac{\varepsilon_i}{\sigma_i}\right)^2$$

$$N_{\exp} = N_{MC} \cdot P(\nu_\mu \to \nu_\mu\,(for\,CC\,\nu_\mu)) \cdot (1 + \sum_{j=1}^{70} f_j \cdot \varepsilon_j)$$

N_{obs} : observed number of events

N_{exp} : expectation from MC

ε_i : systematic error term

σ_i: sigma of systematic error

χ^2 minimization at each parameter point (Δm^2, $\sin^2 2\theta$, …).

Method (χ^2 version): G.L.Fogli et al., PRD 66, 053010 (2002).

70 systematic error terms

Flux (16)

- (Free parameter) flux absolute normalization
- Flux; (nu_mu + anti-nu_mu) / (nu_e + anti-nu_e) ratio (E_nu < 5GeV)
- Flux; (nu_mu + anti-nu_mu) / (nu_e + anti-nu_e) ratio (E_nu > 5GeV)
- Flux; anti-nu_e / nu_e ratio (E_nu < 10GeV)
- Flux; anti-nu_e / nu_e ratio (E_nu > 10GeV)
- Flux; anti-nu_mu / nu_mu ratio (E_nu < 10GeV)
- Flux; anti-nu_mu / nu_mu ratio (E_nu > 10GeV)
- Flux; up/down ratio
- Flux; horizontal/vertical ratio
- Flux; K/pi ratio
- Flux; flight length of neutrinos
- Flux; spectral index of primary cosmic ray above 100GeV
- Flux; sample-by-sample relative normalization (FC Multi-GeV)
- Flux; sample-by-sample relative normalization (PC + Up-stop mu)
- Solar activity during SK1
- Solar activity during SK-II

ν interaction (12)

- M_A in QE and single-π
- QE models (Fermi-gas vs. Oset's)
- QE cross-section
- Single-meson cross-section
- DIS models (GRV vs. Bodek's model)
- DIS cross-section
- Coherent-π cross-section
- NC/CC ratio
- nuclear effect in ^{16}O
- pion spectrum
- CC ν_τ cross-section

Detector, reduction and reconstruction (21 × 2) (SK-I+SK-II, independent)

- Reduction for FC
- Reduction for PC
- Reduction for upward-going muon
- FC/PC separation
- Hadron simulation (contamination of NC in 1-ring μ-like)
- Non-ν BG (flasher for e-like)
- Non-ν BG (cosmic ray muon for mu-like)
- Upward stopping/through-going mu separation
- Ring separation
- Particle identification for 1-ring samples
- Particle identification for multi-ring samples
- Energy calibration
- Energy cut for upward stopping muon
- Up/down symmetry of energy calibration
- BG subtraction of up through μ
- BG subtraction of up stop μ
- Non-ν_e contamination for multi-GeV 1-ring electron
- Non-ν_e contamination for multi-GeV multi-ring electron
- Normalization of multi-GeV multi-ring electron
- PC stop/through separation