

# Neutrino Oscillation Experiments and KEK-PS

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29 November 2002@RPIA2002

## Outline

1. Status of neutrino oscillations
2. Present neutrino oscillation experiments
3. Summary

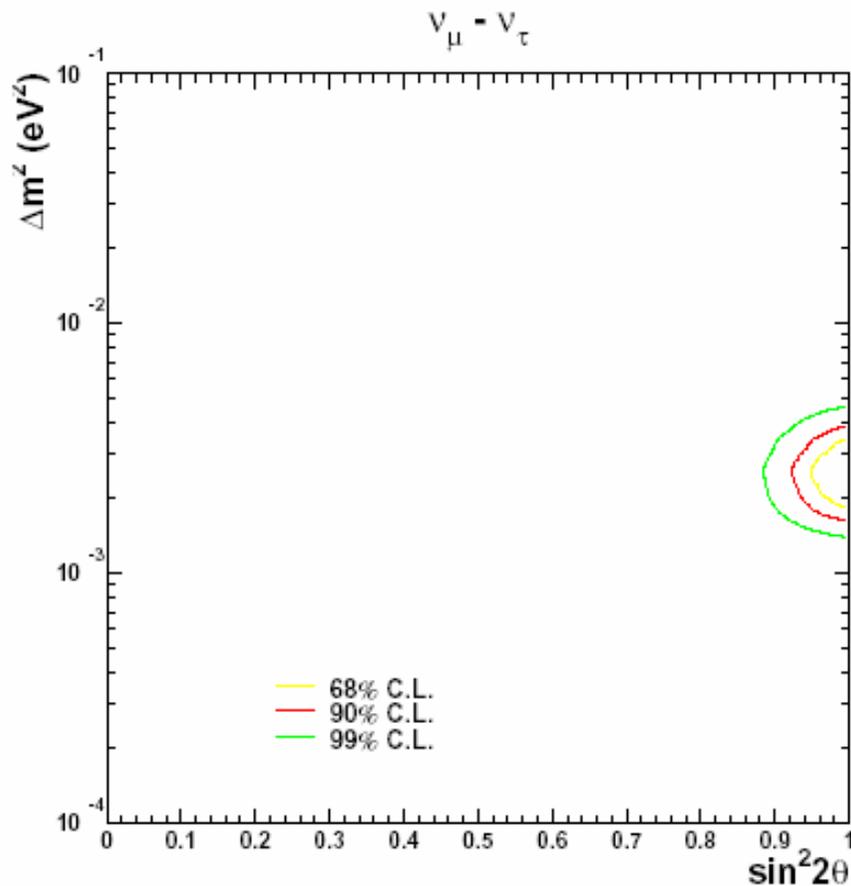
# 1. Status of neutrino oscillations (ICHEP02)

- Atmospheric  $\nu_\mu \rightarrow \nu_\tau$  oscillations at  $\Delta m^2 \sim 3 \times 10^{-3} \text{ (eV)}^2$  and Solar neutrino oscillations  $\nu_e \rightarrow \nu_\mu / \nu_\tau$  at  $\Delta m^2 \sim 10^{-4} - 10^{-7} \text{ (eV)}^2$  are almost established. K2K is confirming  $\nu_\mu \rightarrow \nu_\tau$  oscillations at  $\Delta m^2 \sim 3 \times 10^{-3} \text{ (eV)}^2$ .
- We are waiting for **KamLAND** giving a conclusion on LMA. MiniBooNE is taking data. Results from SNO, BOREXINO, MINOS, and CNGS are very interesting over the next few years.
- Questions:
  - $\theta_{13} \neq 0$  ?
  - Why is mixing matrix of lepton sector so different from that of quark sector ?
  - CPV ?

# 1. Status of neutrino oscillations (ICHEP02)

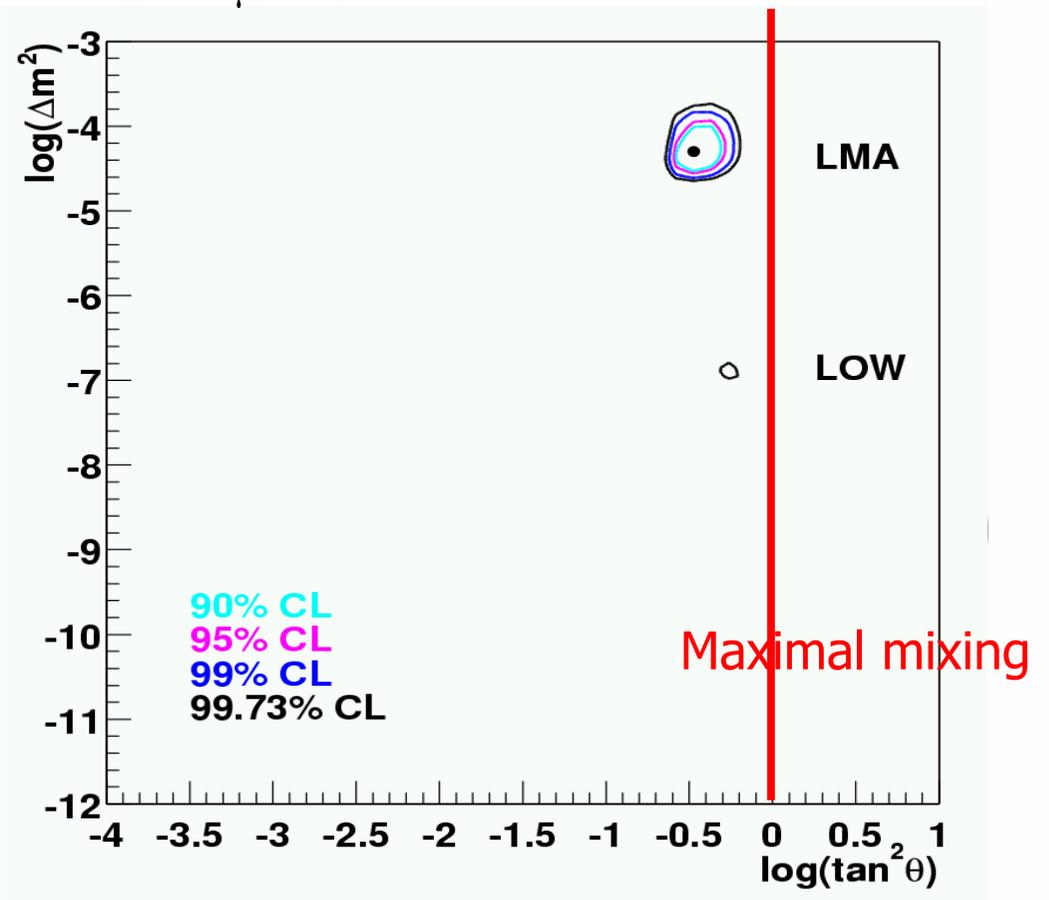
Atmospheric neutrino oscillations

$\nu_\mu \rightarrow \nu_\tau$  (SK)



Solar neutrino oscillations

$\nu_e \rightarrow \nu_\mu / \nu_\tau$  (SNO, SK, Ga, Cl).



K2K and KamLAND are the confirming experiments.

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## Solar + Atmospheric $3\nu$ Oscillations

The emerging:  $|U_{\text{LEP}}| = \begin{pmatrix} 0.73 - 0.89 & 0.44 - 0.66 & < 0.24 \\ 0.23 - 0.66 & 0.24 - 0.75 & 0.51 - 0.87 \\ 0.06 - 0.57 & 0.40 - 0.82 & 0.48 - 0.85 \end{pmatrix}.$

with structure  $|U_{\text{LEP}}| \simeq \begin{pmatrix} \frac{1}{\sqrt{2}}(1 + \mathcal{O}(\lambda)) & \frac{1}{\sqrt{2}}(1 - \mathcal{O}(\lambda)) & \epsilon \\ -\frac{1}{2}(1 - \mathcal{O}(\lambda) + \epsilon) & \frac{1}{2}(1 + \mathcal{O}(\lambda) - \epsilon) & \frac{1}{\sqrt{2}} \\ \frac{1}{2}(1 - \mathcal{O}(\lambda) - \epsilon) & -\frac{1}{2}(1 + \mathcal{O}(\lambda) - \epsilon) & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{matrix} \lambda \sim 0.2 \\ \epsilon < 0.25 \end{matrix}$

very different from quark's  $|U_{\text{CKM}}| \simeq \begin{pmatrix} 1 & \mathcal{O}(\lambda) & \mathcal{O}(\lambda^3) \\ \mathcal{O}(\lambda) & 1 & \mathcal{O}(\lambda^2) \\ \mathcal{O}(\lambda^3) & \mathcal{O}(\lambda^2) & 1 \end{pmatrix} \quad \lambda \sim 0.2$

Still open questions

Is  $\theta_{13} \neq 0$ ?

Is there CP violation in the leptons (is  $\delta \neq 0, \pi$ )?

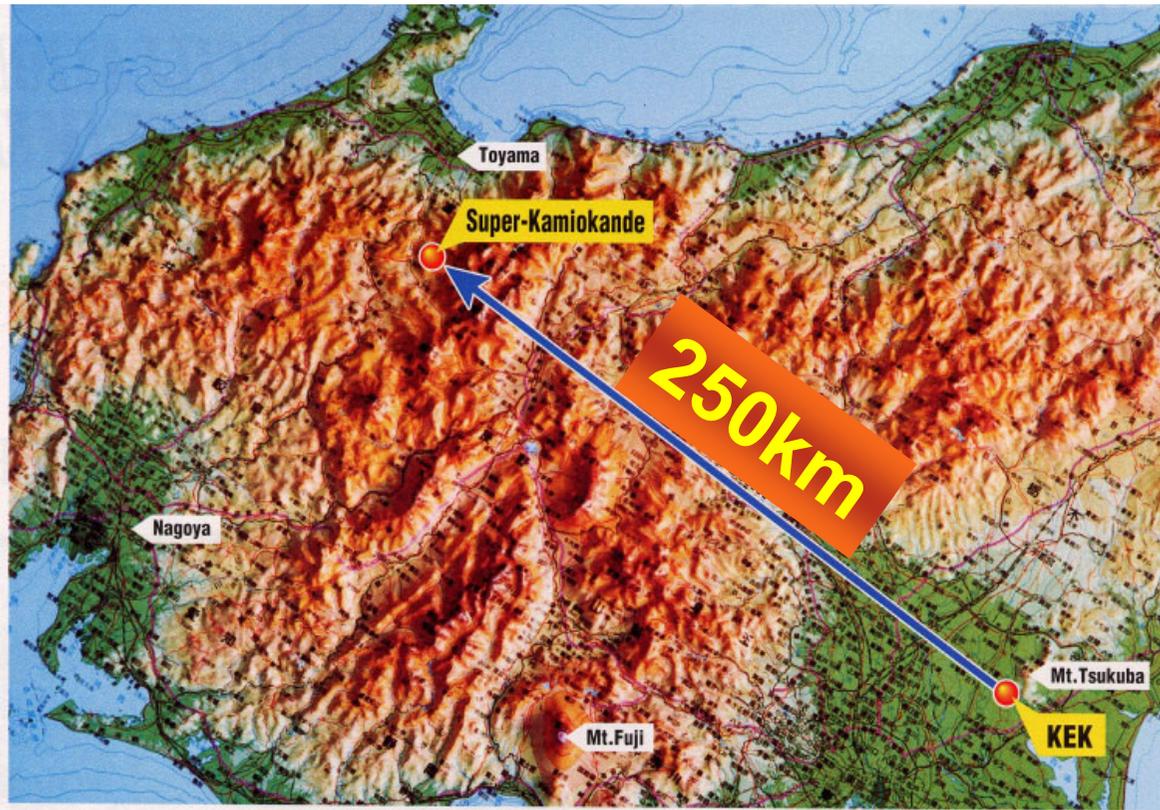
Are neutrino masses:

hierarchical:  $m_i - m_j \sim m_i + m_j$ ?

degenerated:  $m_i - m_j \ll m_i + m_j$ ?

Dirac or Majorana? what about the Majorana Phases?

# The K2K experiment

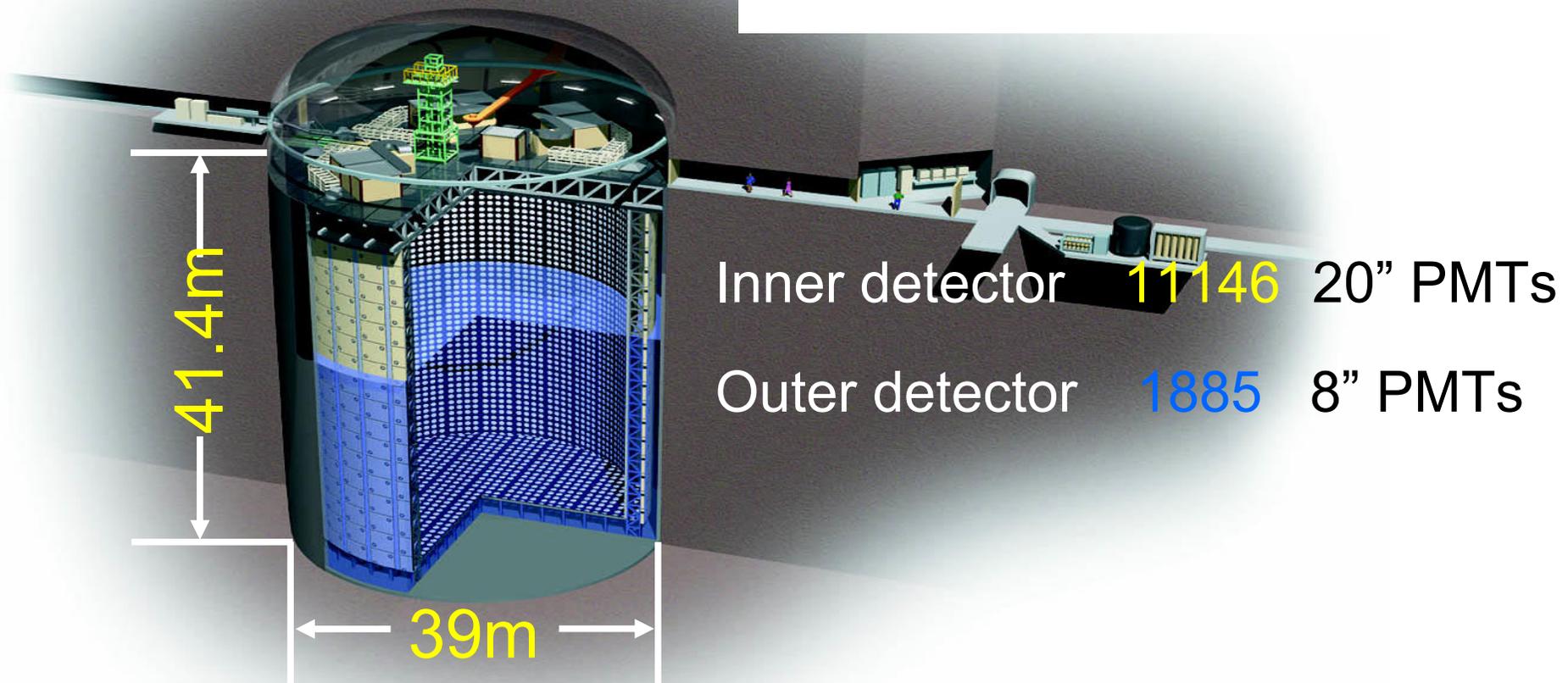


$\langle E_\nu \rangle \sim 1.3\text{GeV}$   
almost pure  $\nu_\mu$  ( $\sim 98\%$ )

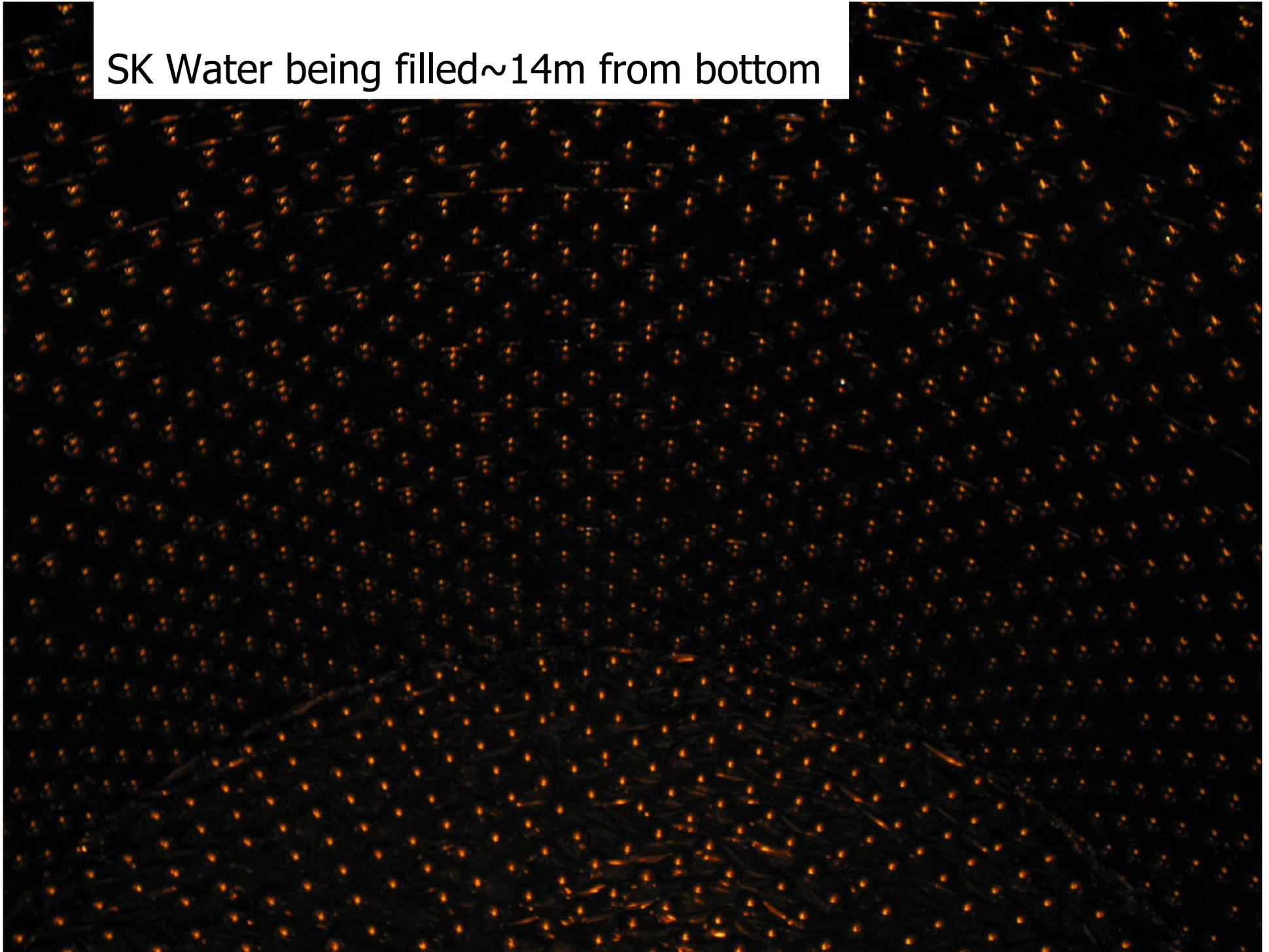
# Super-Kamiokande

50kt water Cherenkov detector

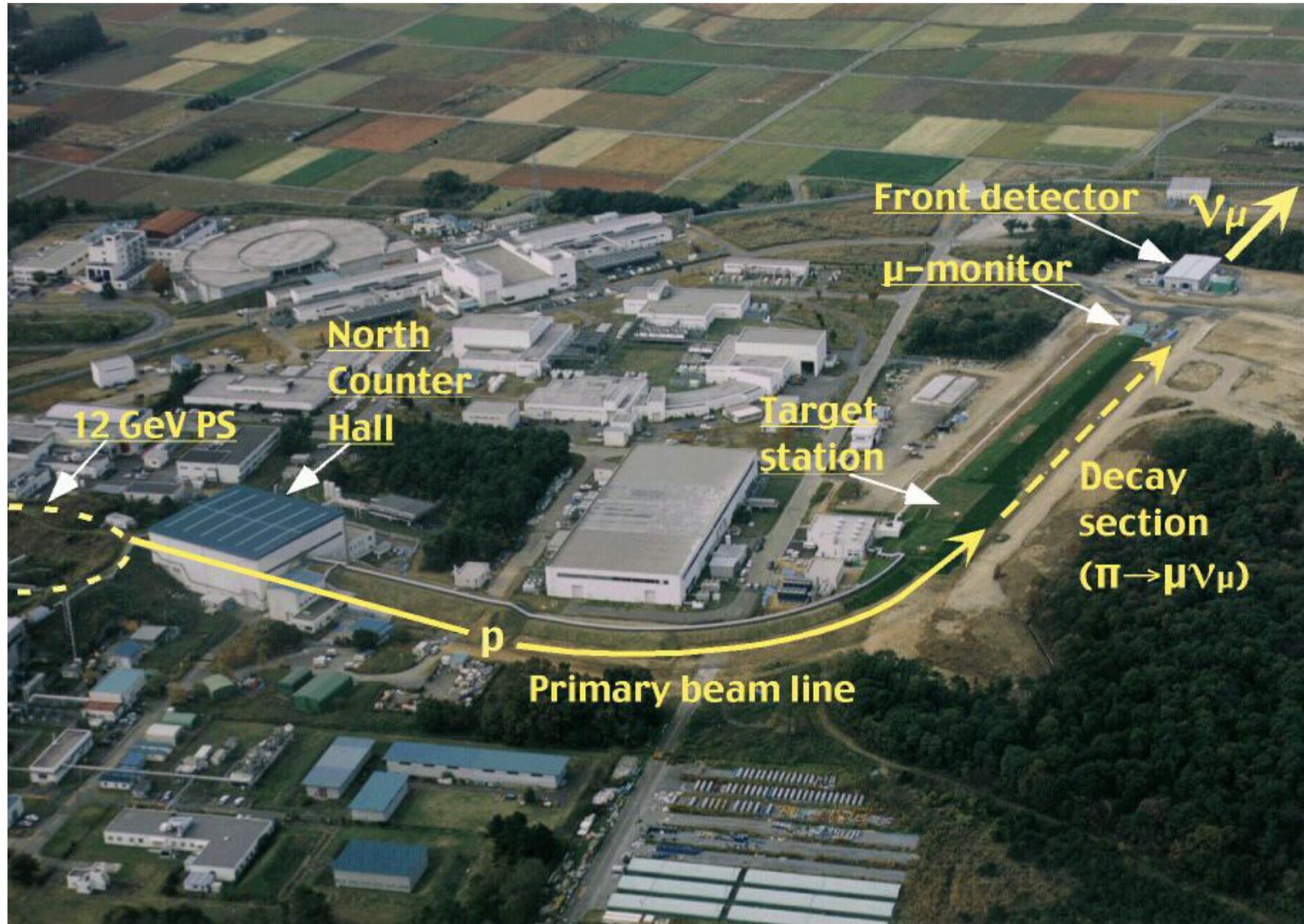
Fiducial volume 22.5kt



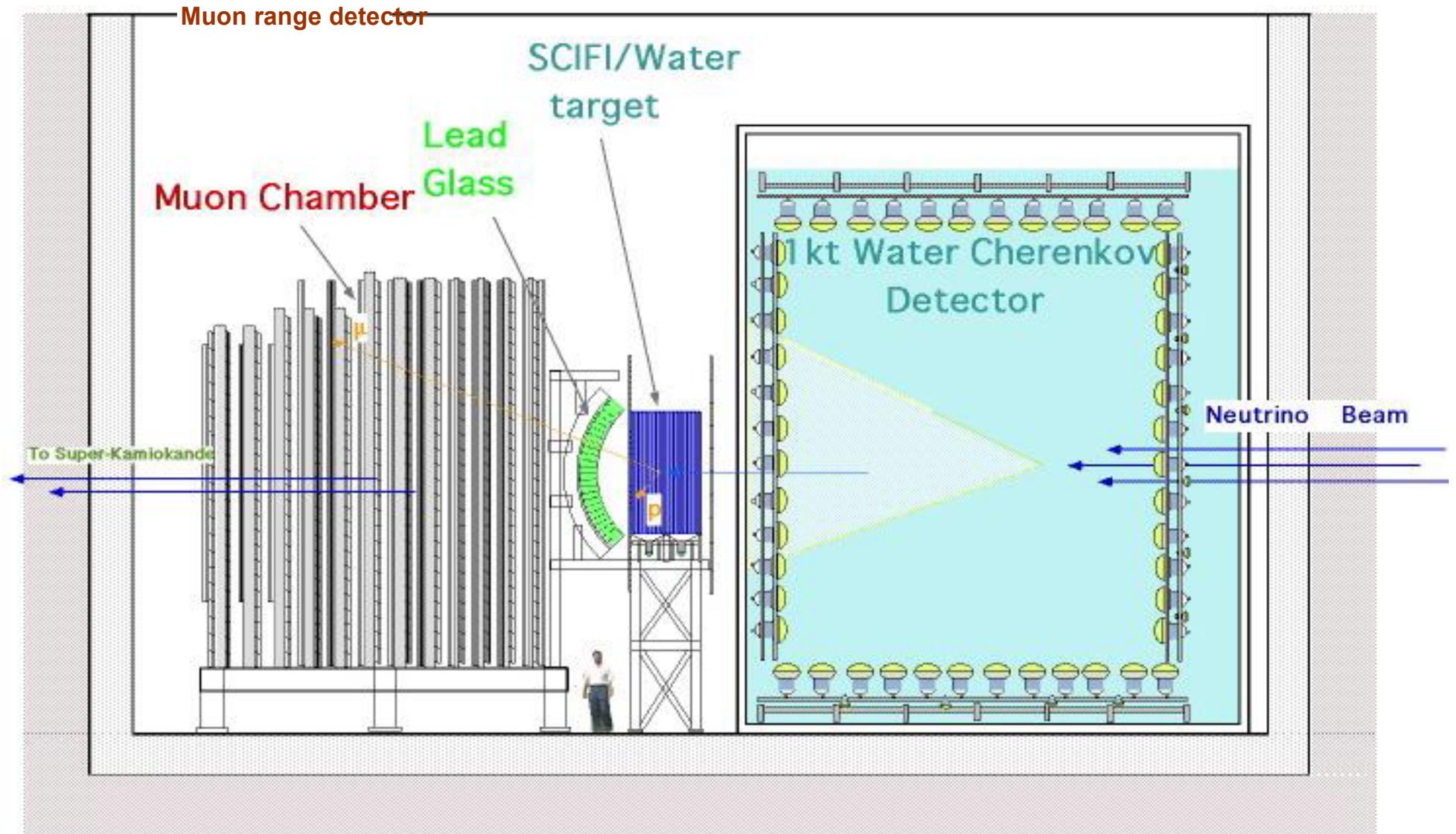
SK Water being filled ~14m from bottom



# Neutrino Beamline



# Near neutrino detectors



# Typical Events at Near Detector

1kton

Mass 25 ton (water)

Event Selection

Single event,  
Q > 1000 p.e.

Event Rate

~0.02 events/spill<sub>Rur</sub>

Scifi

5.9 ton

(70%water + 30%Al+C)

1 SciFi & MUC track +X

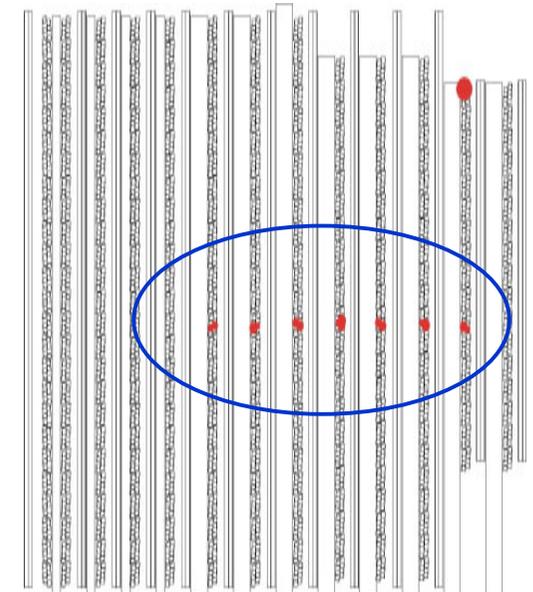
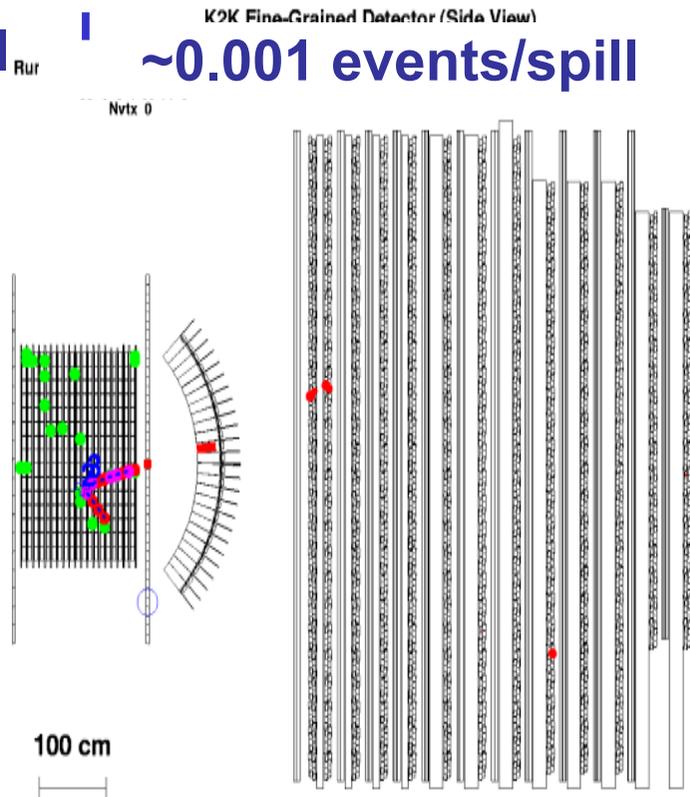
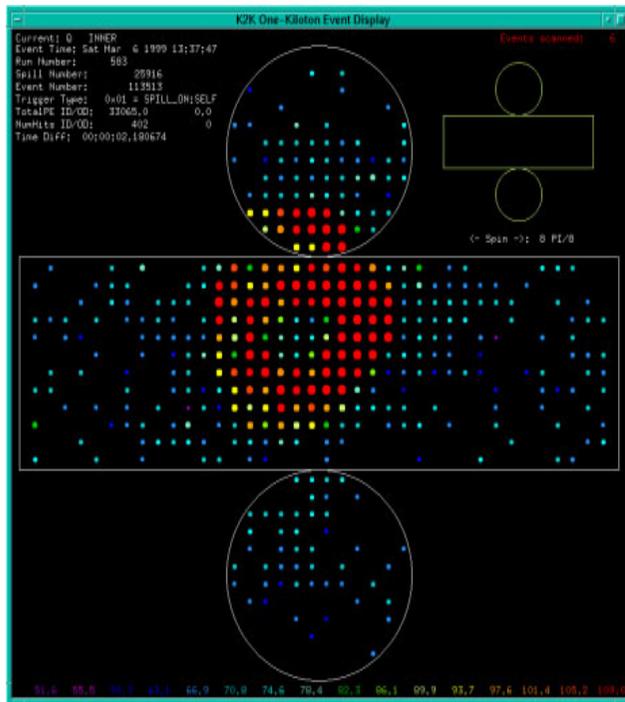
~0.001 events/spill

MUC/Fe

330 ton (Fe)

1 MUC track

~0.05 events/spill



# Neutrino oscillation analysis (MC)

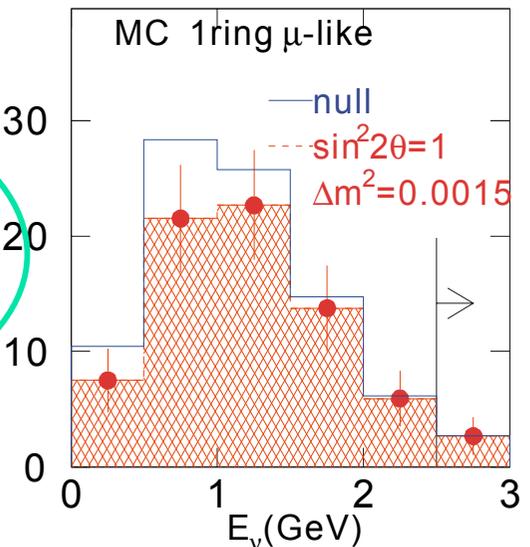
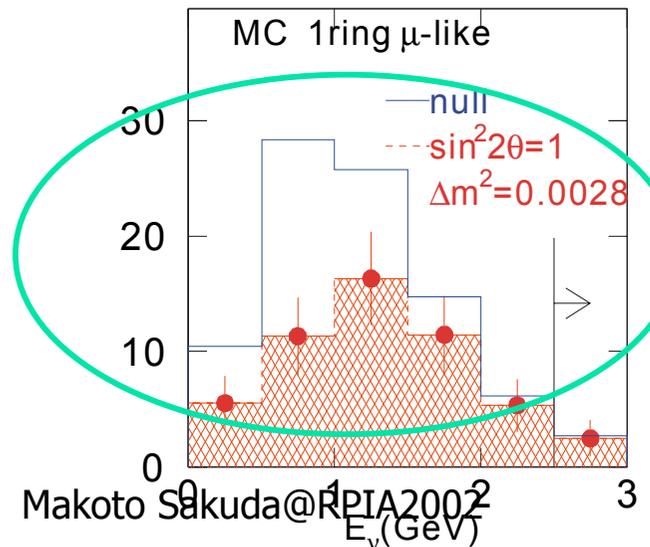
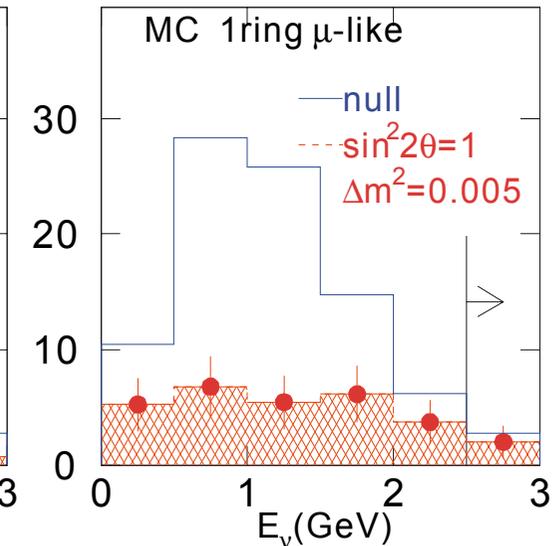
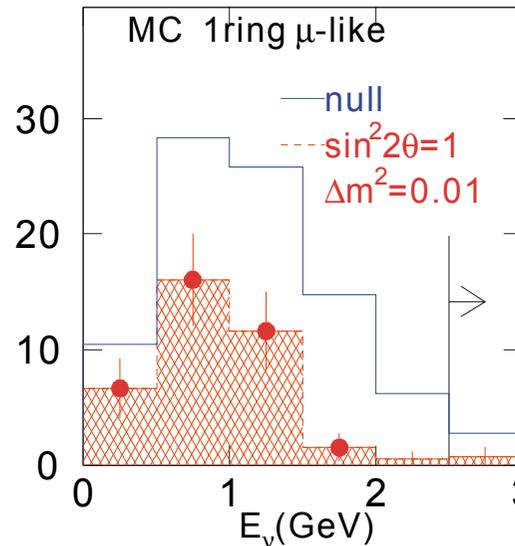
$$P = \sin^2 2\theta \cdot \sin^2(1.27\Delta m^2 L / E_\nu)$$

It is important to measure the neutrino energy spectrum with Near detector.

$\Delta m^2 = (2-3) \times 10^{-3} \text{ (eV)}^2$   
means a reduction  
at  $0.5 < E_\nu < 1.5 \text{ GeV}$ .

**10<sup>20</sup>POT (2004)**

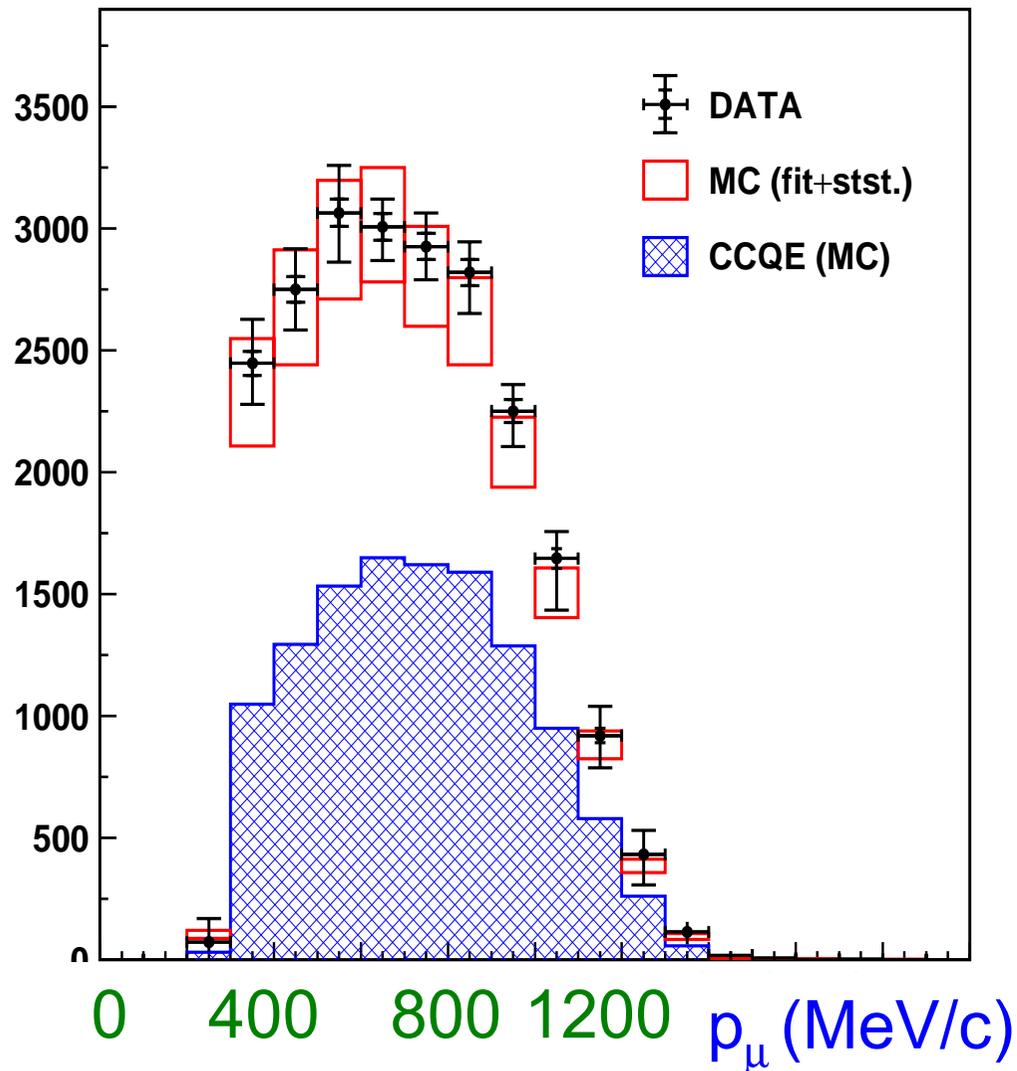
Reconstructed Neutrino Energy (MC)



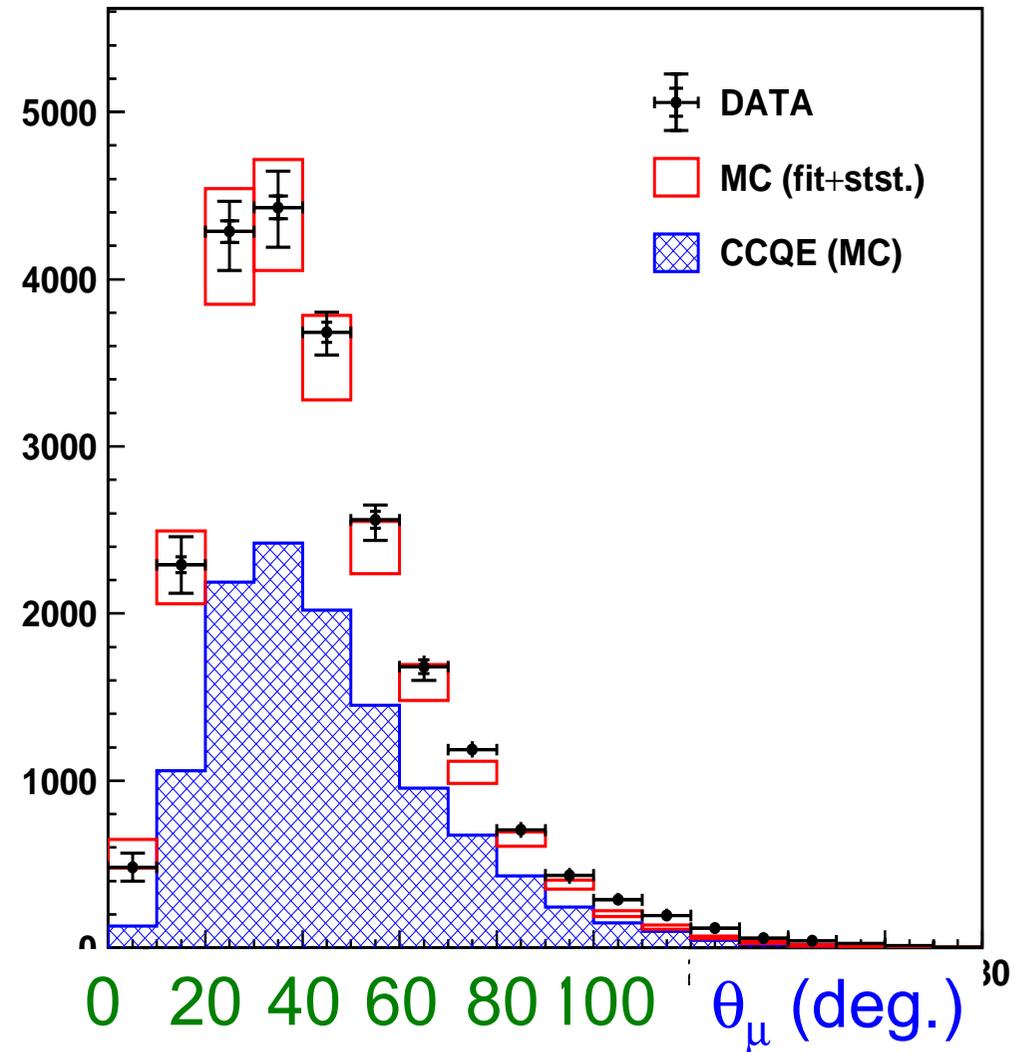
# Near Detector Spectrum (1kt)

$p_\mu$  and  $\theta_\mu$  distributions of 1kt 1ring  $\mu$ -like FCFV events

1kt:  $\mu$ -momentum Distribution (Fid.25t FC 1-Ring  $\mu$ -like)

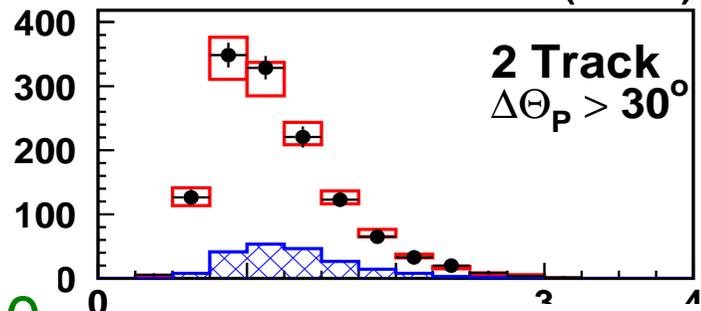
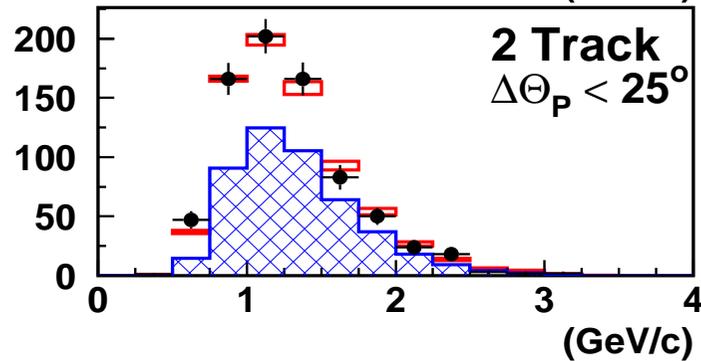
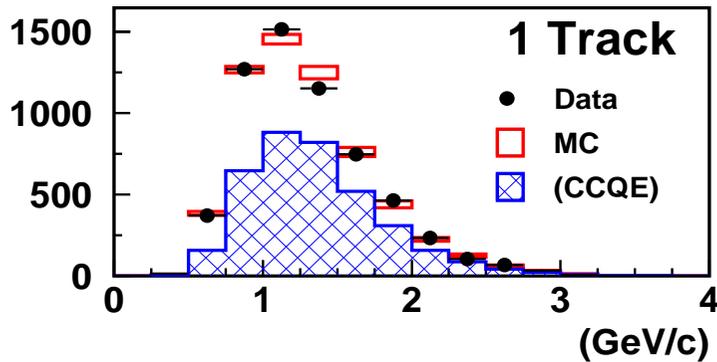


1kt:  $\mu$ -angular Distribution (Fid.25t FC 1-Ring  $\mu$ -like)

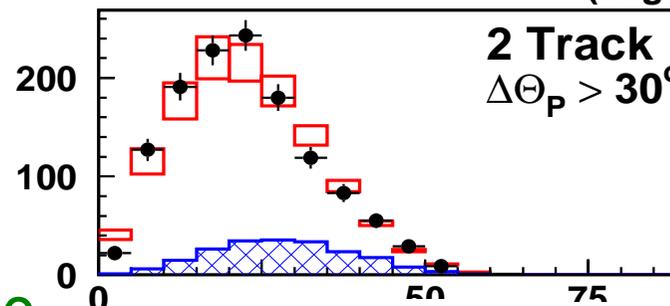
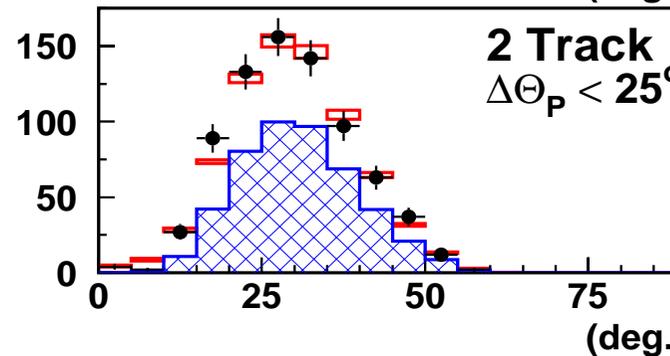
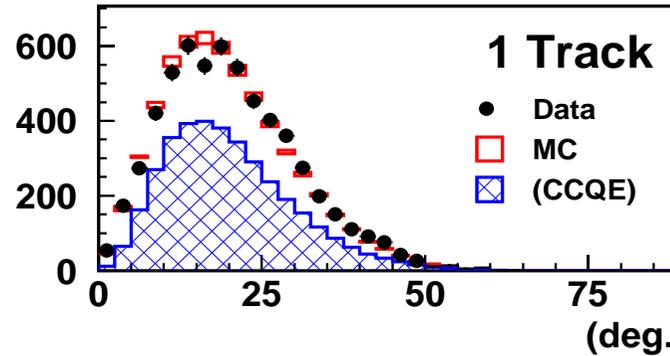


# Near Detector Spectrum (SciFi)

SciFi  $P_{\mu}$  distributions



SciFi  $\Theta_{\mu}$  distributions



1track

2track  
 QE like

2track  
 non-QE  
 like

0

1

2

$p_{\mu}$  (GeV/c)

0

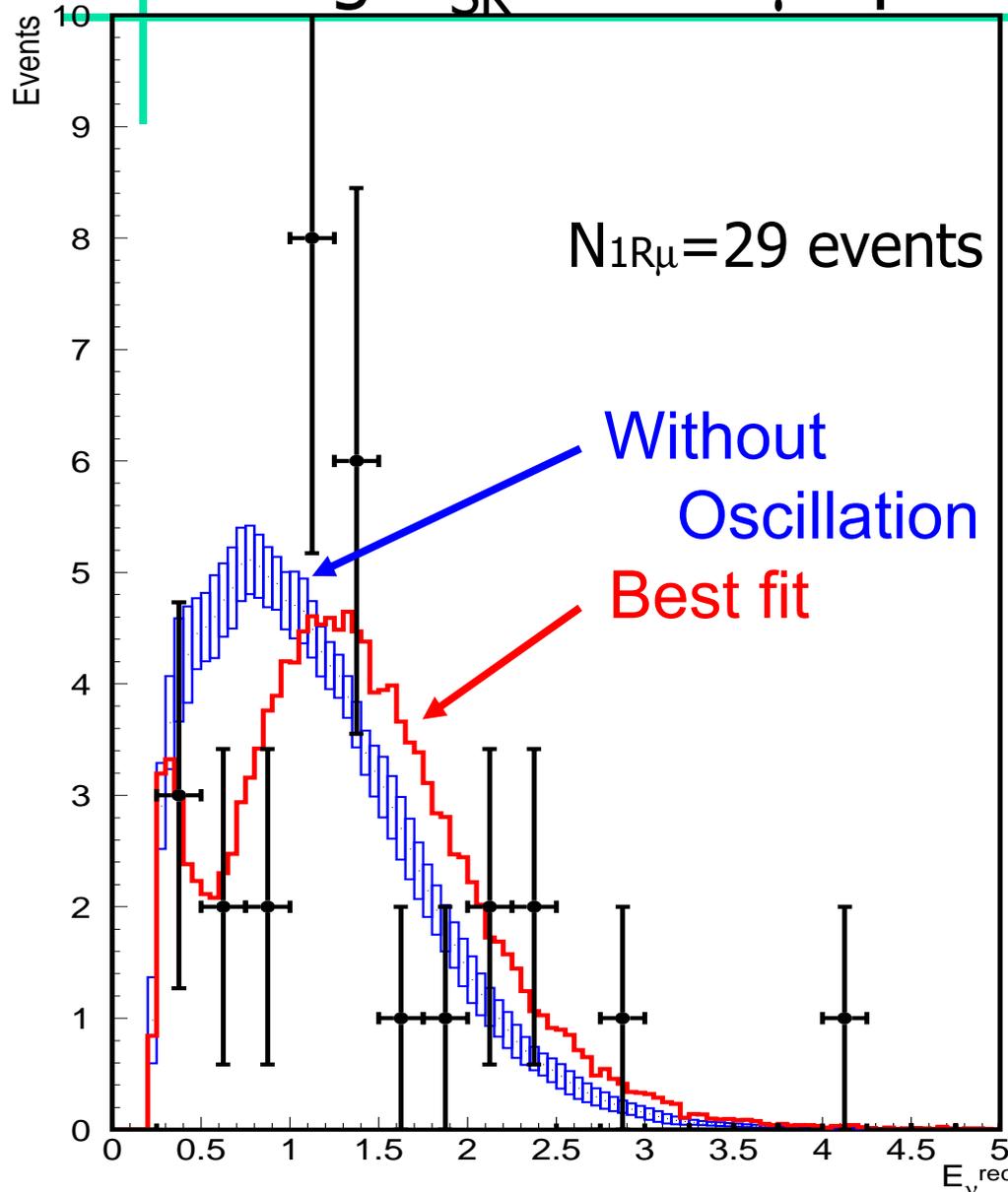
25

50

$\theta_{\mu}$  (deg.)

# Oscillation analysis

using  $N_{SK}$  and  $1R\mu$  spectrum shape



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1.  $N_{SK}$

Observed = 56 events

Expected =  $80.1 + 6.2 - 5.4$

2. Spectrum shape

June '99 - July '01

$1R\mu$  events

(29 events)

**Best fit parameters**  
**( $\sin^2 2\theta, \Delta m^2$ )**

**$= (1.0, 2.8 \times 10^{-3} \text{ eV}^2)$**

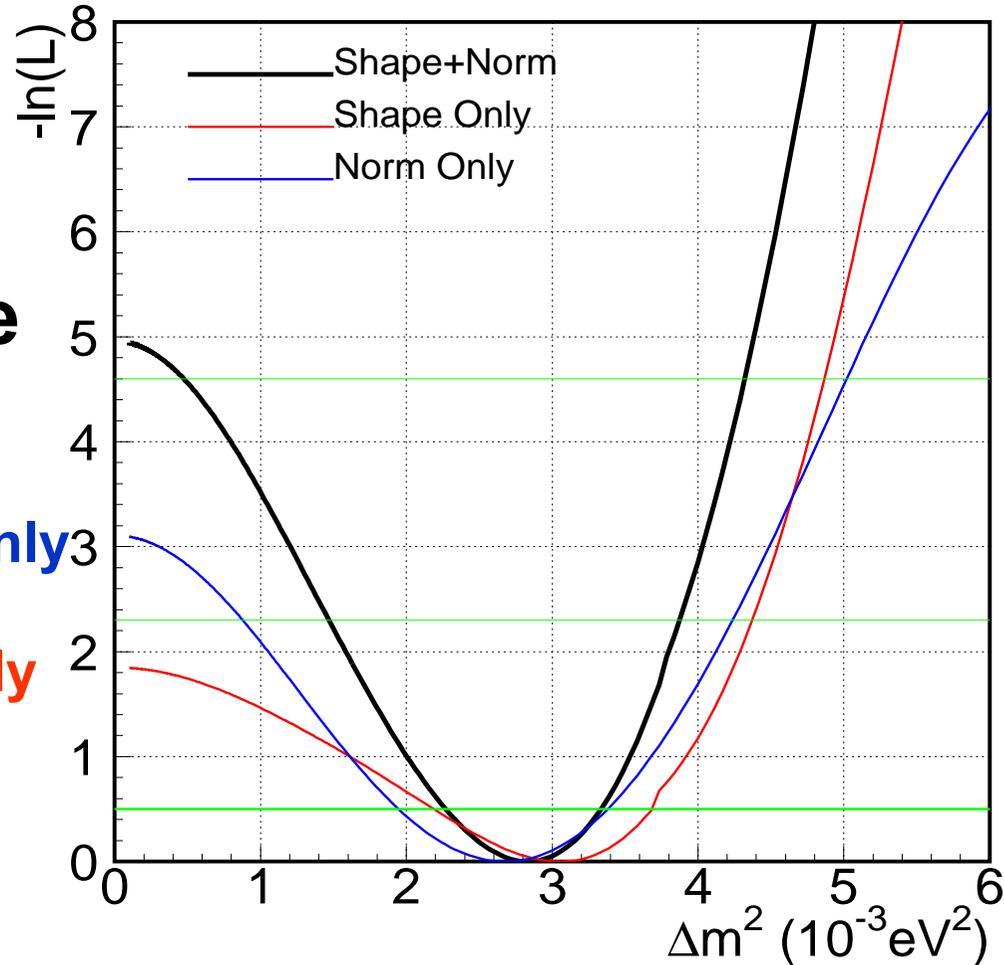
# Allowed $\Delta m^2$

by  $N_{SK}$  and shape analysis

$N_{SK}$  + Shape

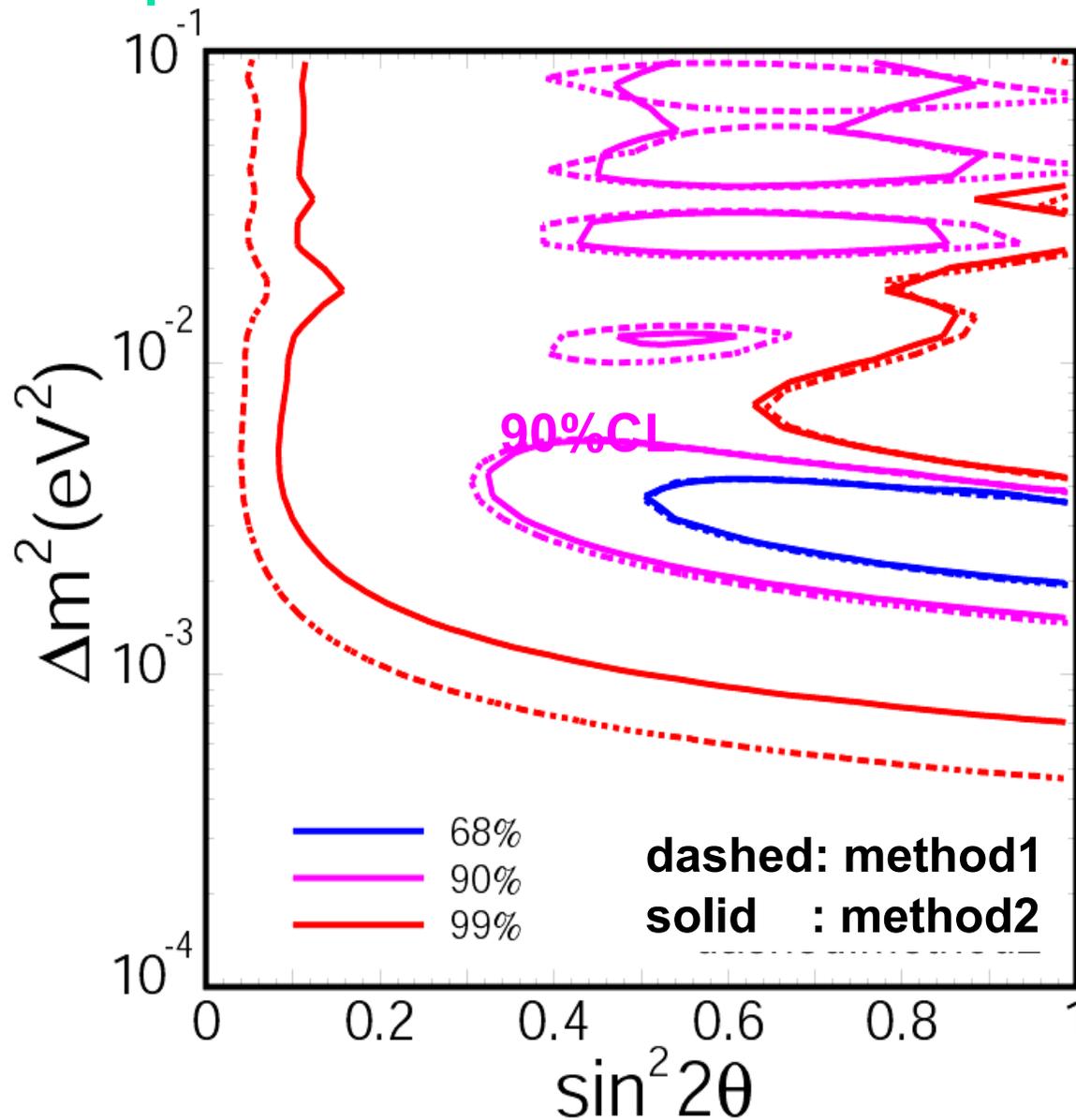
Number of Events only

Spectrum Shape only



$N_{SK}$  and shape analysis indicate  
the same  $\Delta m^2$  region for  $\sin^2 2\theta = 1$

# Allowed regions



$$\Delta m^2 = 1.5 \sim 3.9 \times 10^{-3} \text{ eV}^2$$

$$\text{@} \sin^2 2\theta = 1 \text{ (90\% CL)}$$

## Best fit parameters

$$(\sin^2 2\theta, \Delta m^2)$$

$$\left\{ \begin{array}{l} = (1.0, 2.8 \times 10^{-3} \text{ eV}^2) \\ \text{[Method-1]} \\ = (1.0, 2.7 \times 10^{-3} \text{ eV}^2) \\ \text{[Method-2]} \end{array} \right.$$

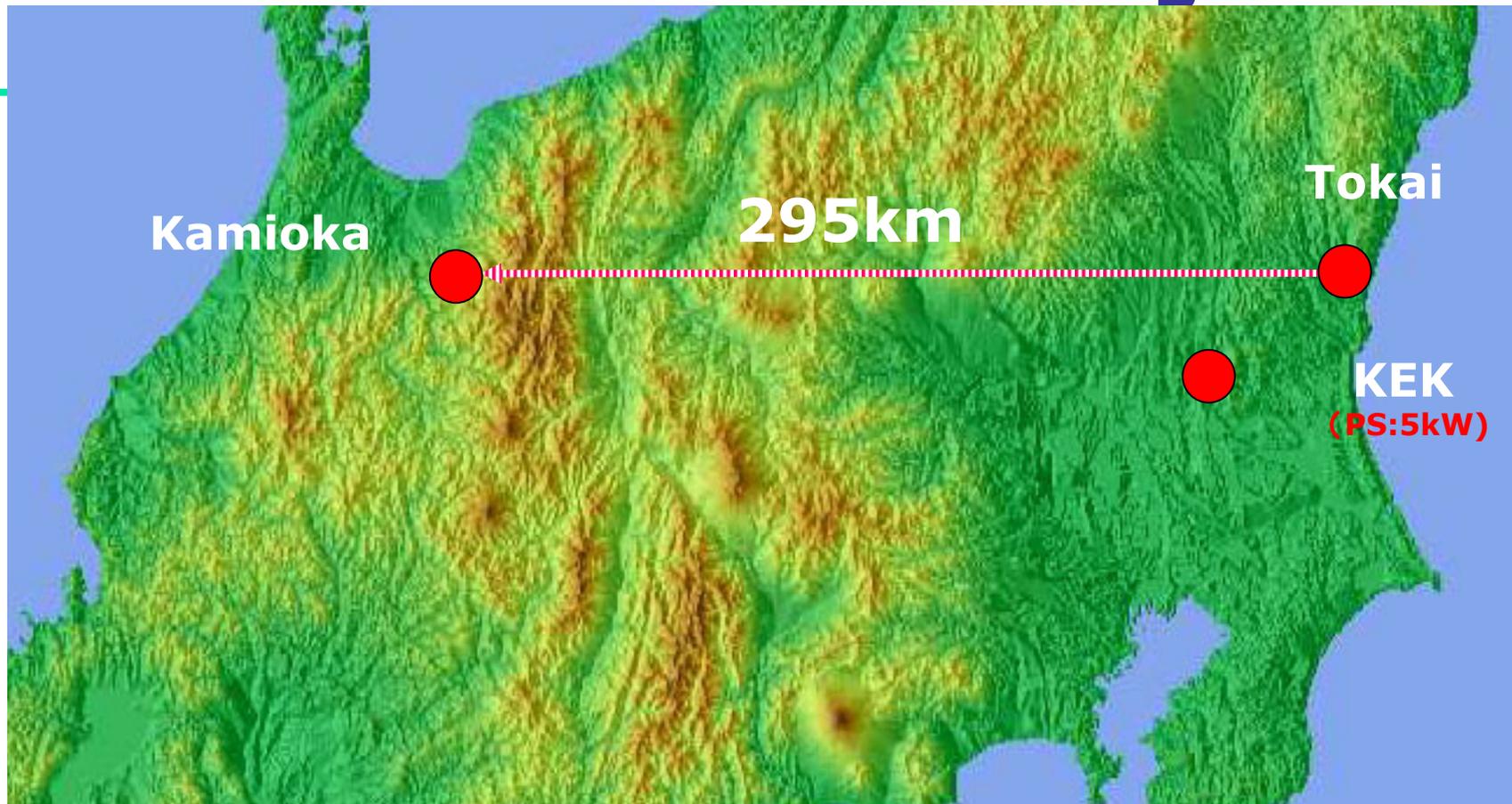
Prob. of null oscillations < 1%

### 3. Summary (1)

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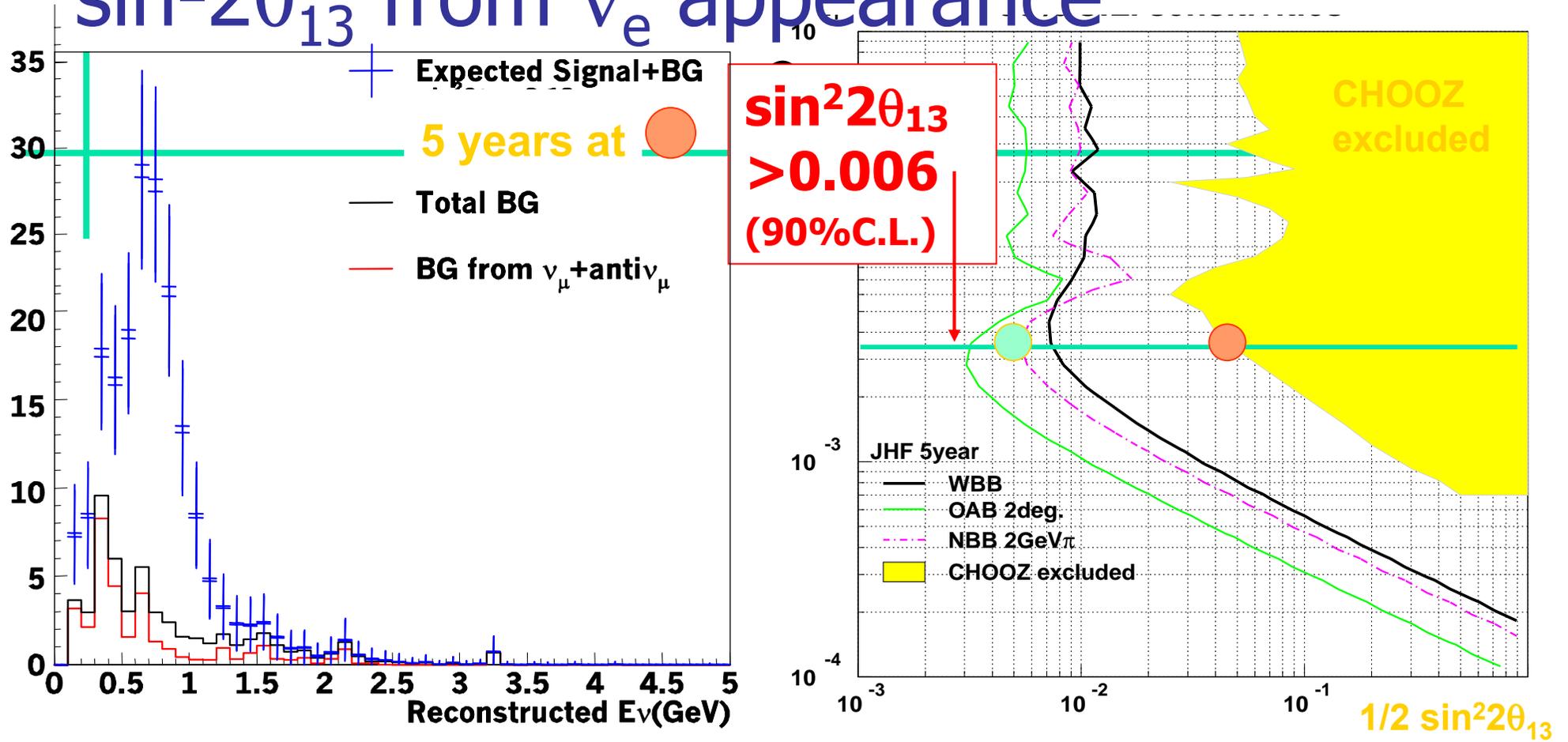
- K2K is confirming SK results on  $\nu_{\mu}$  oscillations. This is made possible by steady efforts of KEK-PS crew. We hope that KEK-PS will improve the intensity by 20% from the next K2K runs in 2003, since the radiation safety limit has been officially relaxed by 20%. K2K will restart this December.
- A proof-of-principle experiment for Superbunch Acceleration scheduled next year will be important. This scheme will give a concrete method to increase the beam intensity of any existing proton synchrotrons. Increase of the intensity by a factor 3-4 should have a big impact on future neutrino oscillation experiments and on Tevatron collider experiments.

## 2. JHF-Kamioka $\nu$ Project



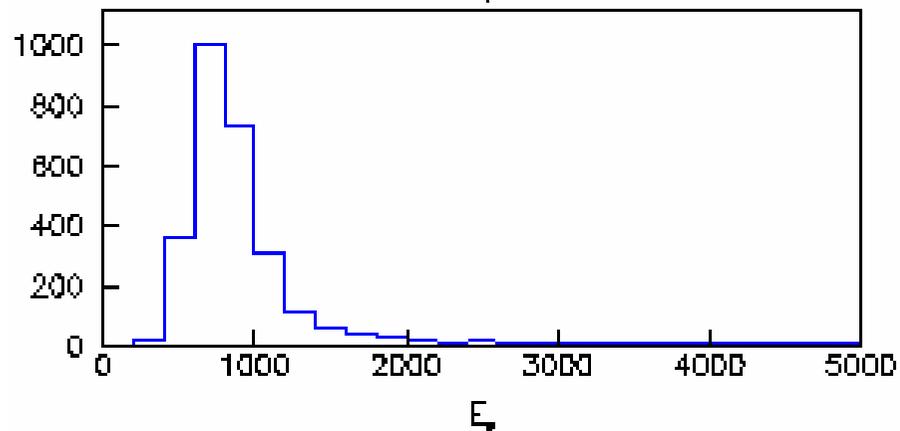
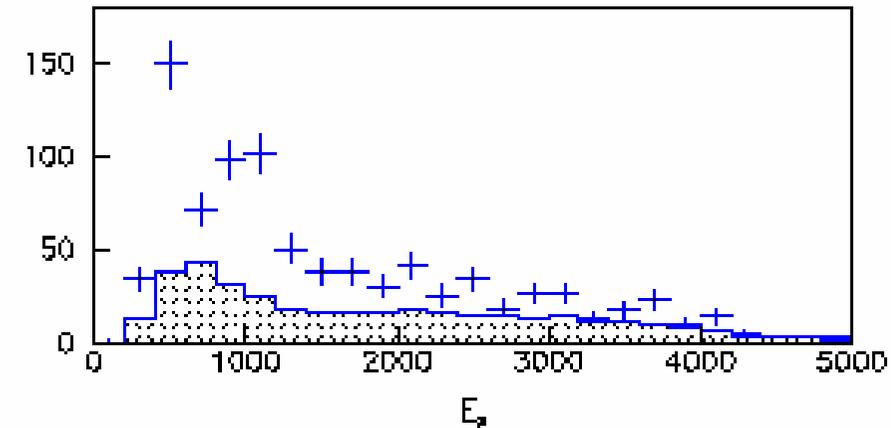
- ***JHF 50GeV PS  $\rightarrow$  Super-Kamiokande***  
(0.75MW) (22.5kt fid.)
- $\times \sim 100$  of K2K
- $\nu_{\mu} \rightarrow \nu_x$  disapp. /  $\nu_{\mu} \rightarrow \nu_e$  **app.** / NC

# $\sin^2 2\theta_{13}$ from $\nu_e$ appearance

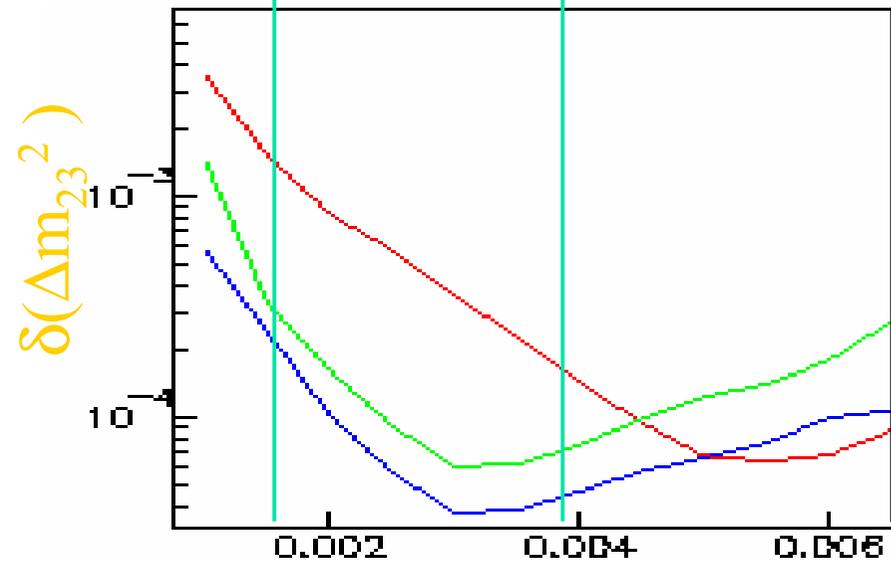
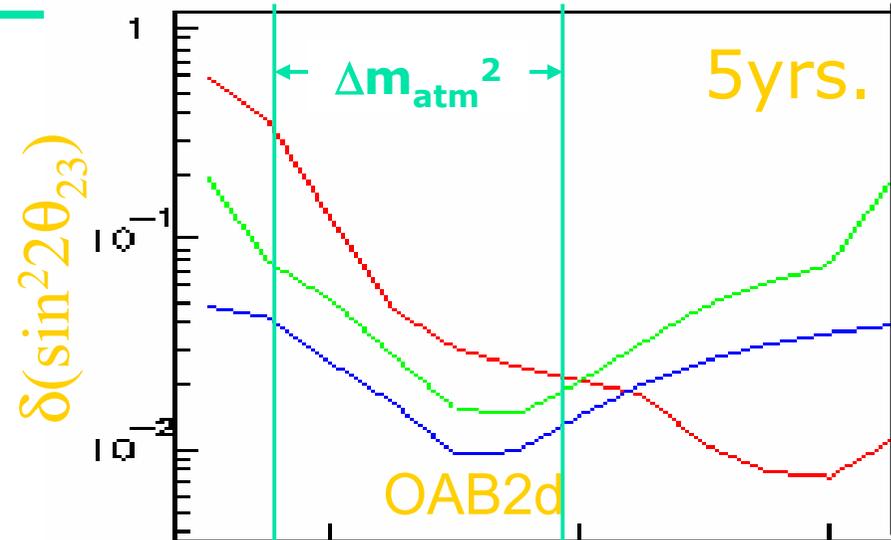


$\sin^2 2\theta_{13}$	Backgrounds					Signal	Signal + BG
	$\nu_\mu$	$\nu_e$	$\bar{\nu}_\mu$	$\bar{\nu}_e$	total		
0.1	12.0	10.7	1.7	0.5	24.9	114.6	139.5
0.01						11.5	36.4

# $\nu_\mu$ disappearance ( $\sin^2 2\theta_{23}$ , $\Delta m_{23}^2$ )



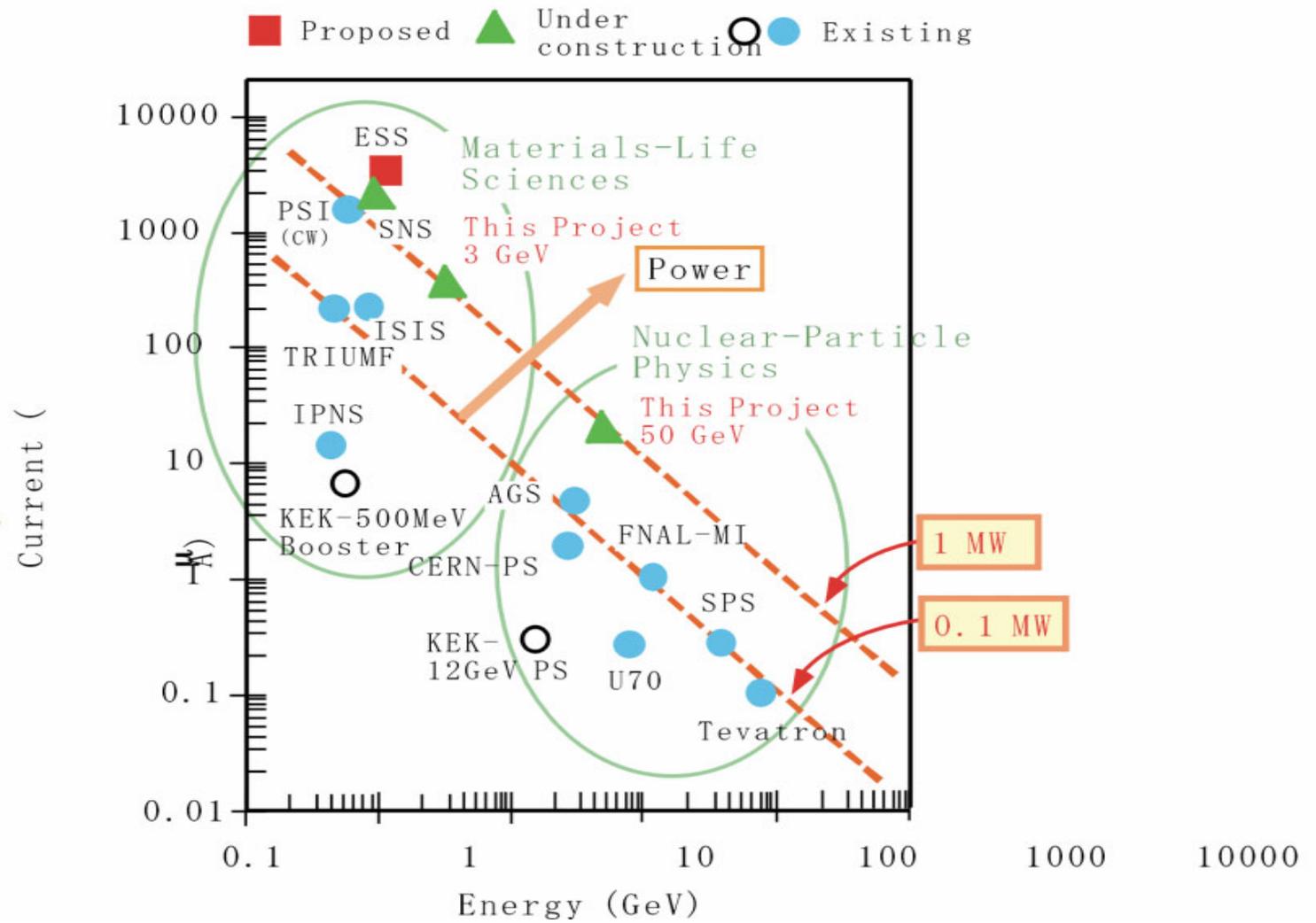
$\delta(\sin^2 2\theta_{23}) \sim 0.01$   
 $\delta(\Delta m_{23}^2) < 1 \times 10^{-4}$



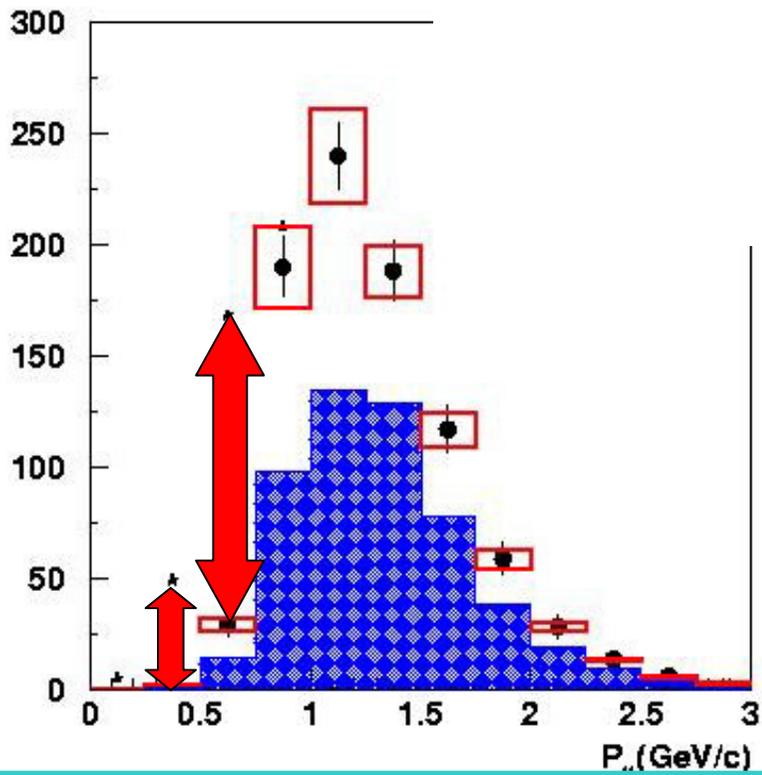
$\Delta m_{23}^2$  (eV<sup>2</sup>)

## Summary (2)

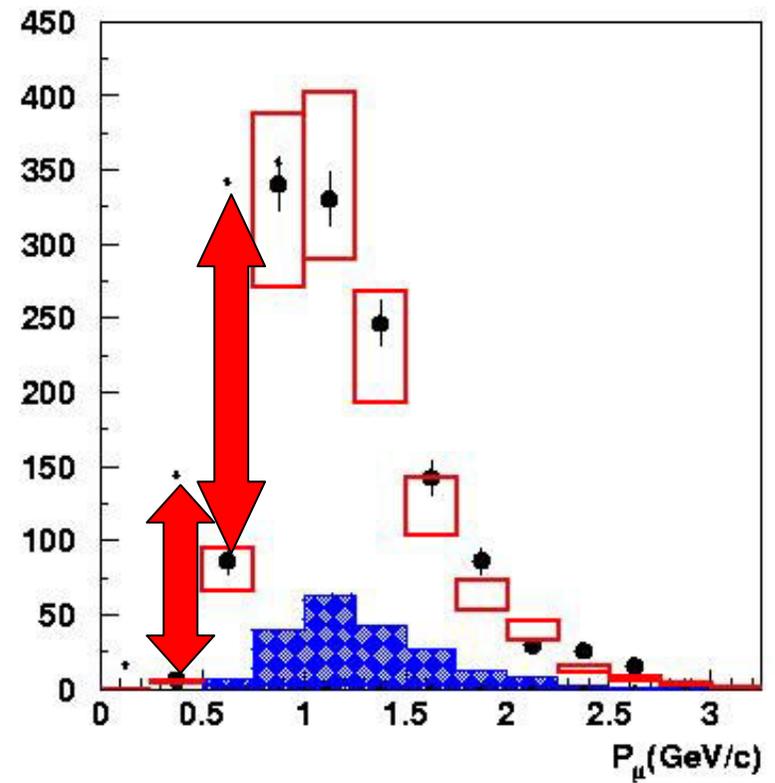
- JHF-Kamioka neutrino experiment (2007~)
  - JHF 0.75MW 50GeV-PS+Off Axis beam+Super-K
  - Narrow band beam at oscillation maximum ( $\sim 1\text{GeV}$ )
  - $\nu_e$  appearance, discovery of  $\theta_{13}$  ( $\sin \theta_{13} > 0.006, 90\% \text{CL}$ )
  - Budget request submitted, R&D started



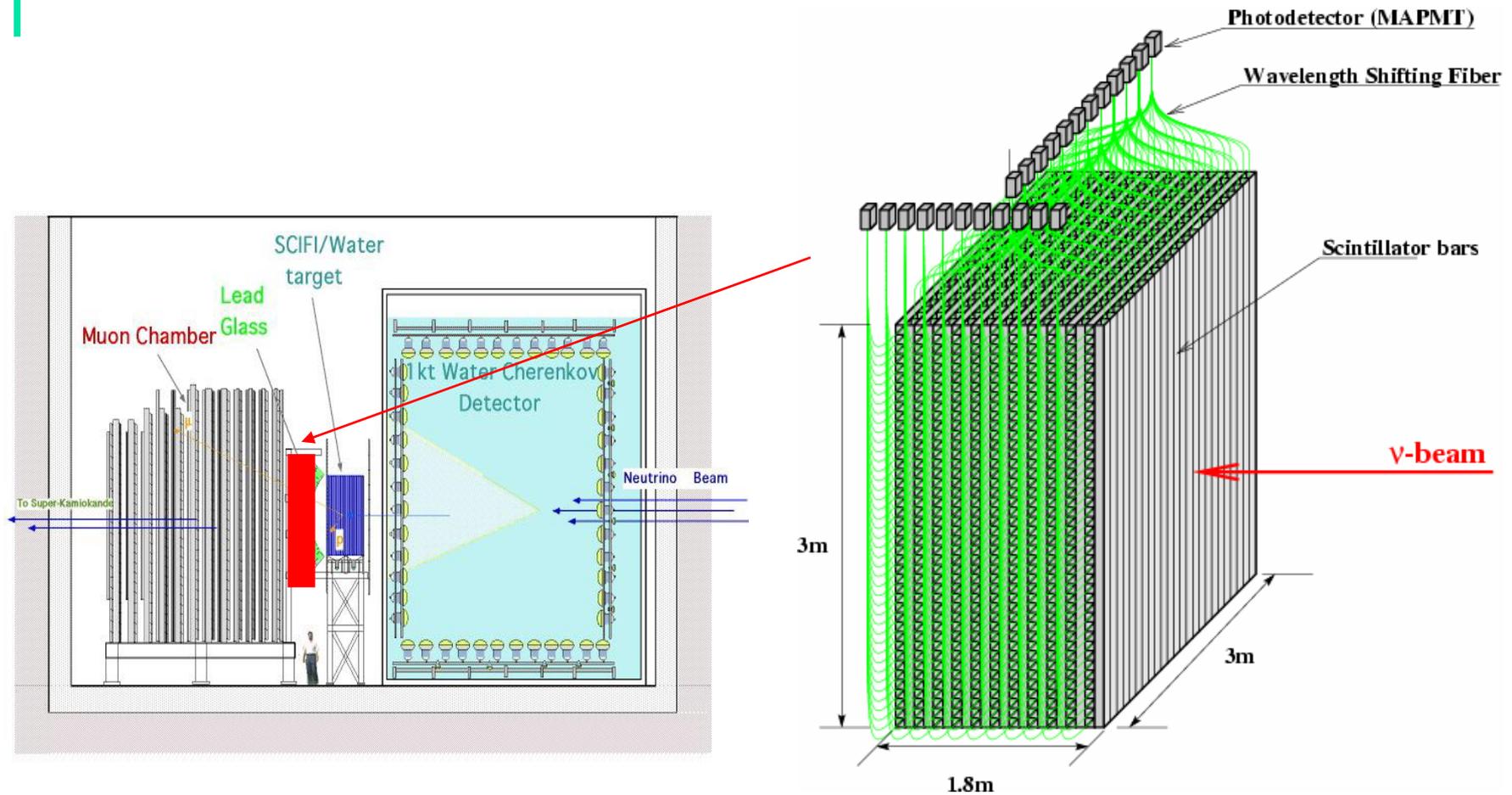
## QE-enriched



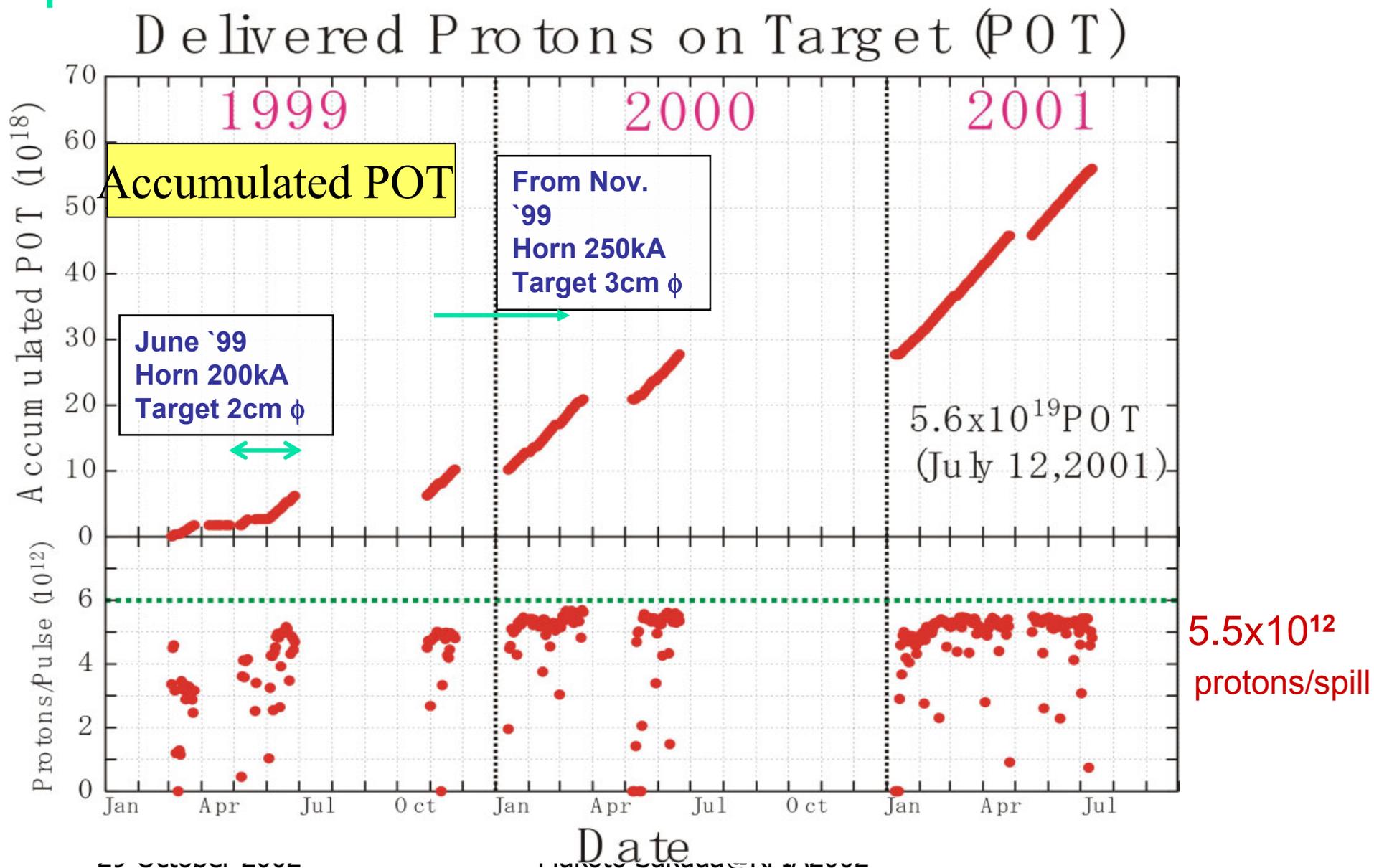
## nonQE-enriched

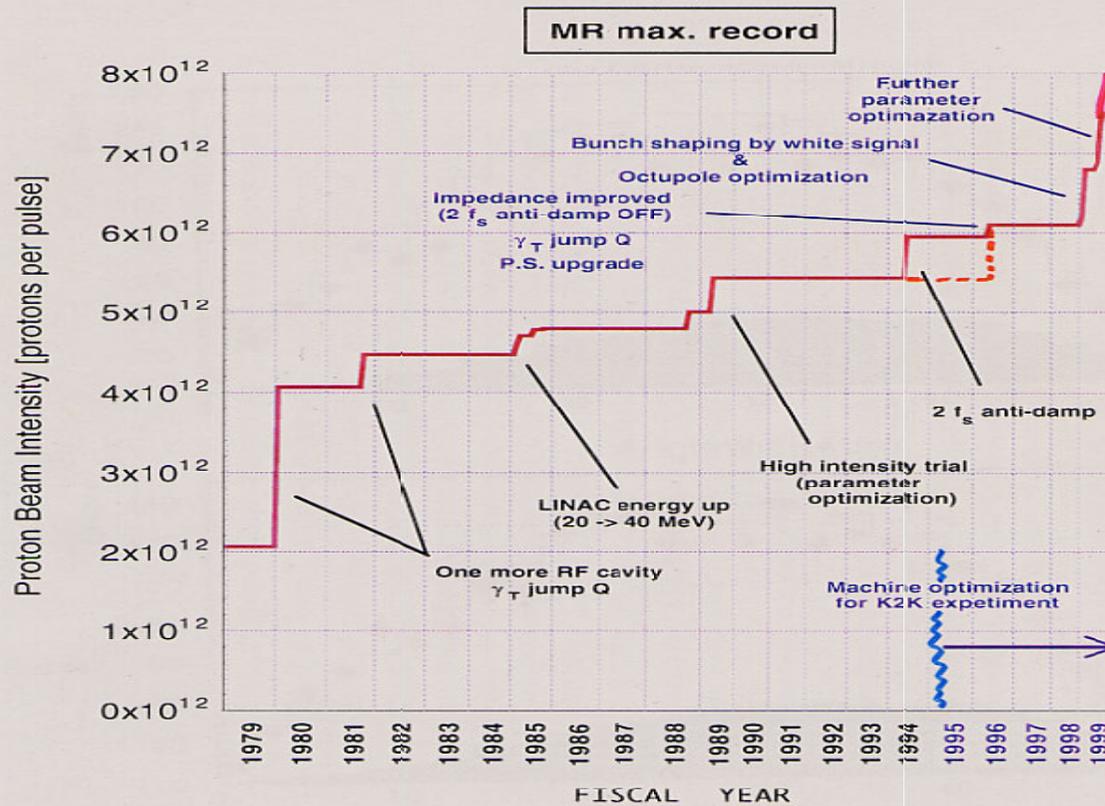


# SciBar Detector in summer 2003



# Protons on Target (POT)





# SK data as a function of zenith angle

