

# **Results from K2K and Plan for JHF-SK**

**YITP Conference**

**"Neutrinos and Implications for Physics Beyond the  
Standard Model"**

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# **K2K Collaboration**

**High Energy Accelerator Research Organization(KEK)  
Institute for Cosmic Ray Research(ICRR), University of Tokyo  
Kobe University  
Kyoto University  
Niigata University  
Okayama University  
Tokyo University of Science  
Tohoku University**

**Chonnam National University  
Dongshin University  
Korea University  
Seoul National University**

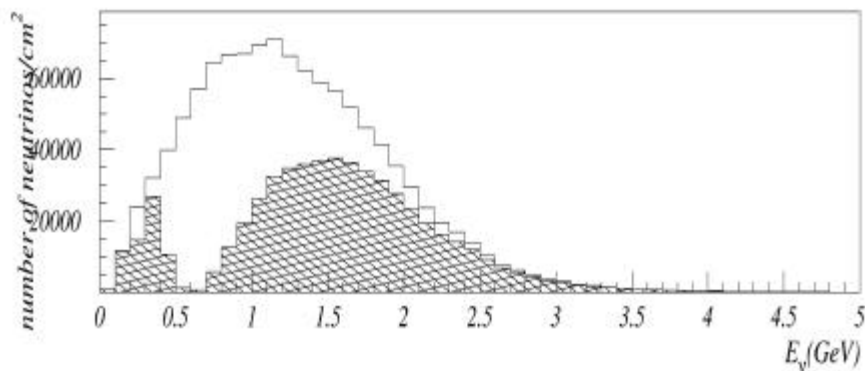
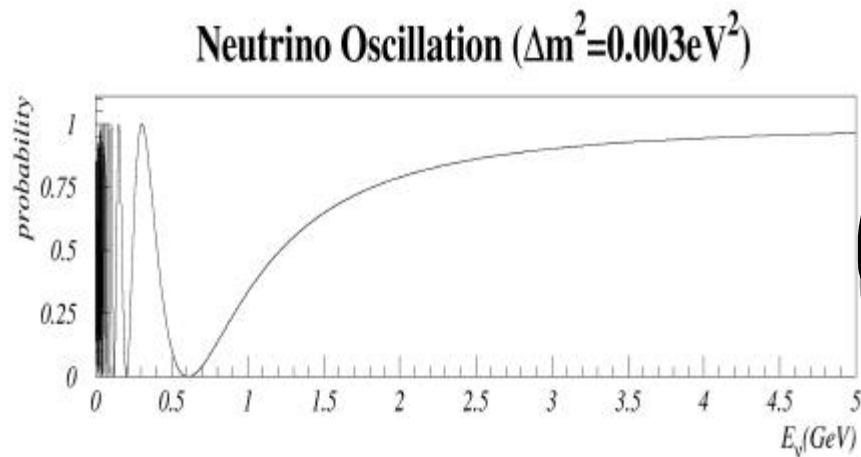
**Boston University  
University of California, Irvine  
University of Hawaii, Manoa  
Massachusetts Institute of Technology  
State University of New York at Stony Brook  
University of Washington at Seattle**

**Warsaw University  
Solton Institute for Nuclear Study**

# K2K

Fixed distance, direction  
( $E_\nu \sim 1.3$  GeV,  $L=250$ km)  
(99%  $\nu_\mu$ ,  $\sigma_\tau \ll \sigma_\mu$ )

$$\text{prob.} = \sin^2 2q \times \sin^2 \left( \frac{1.27 D m^2 L}{E_n} \right)$$



$E_n$

## Observations

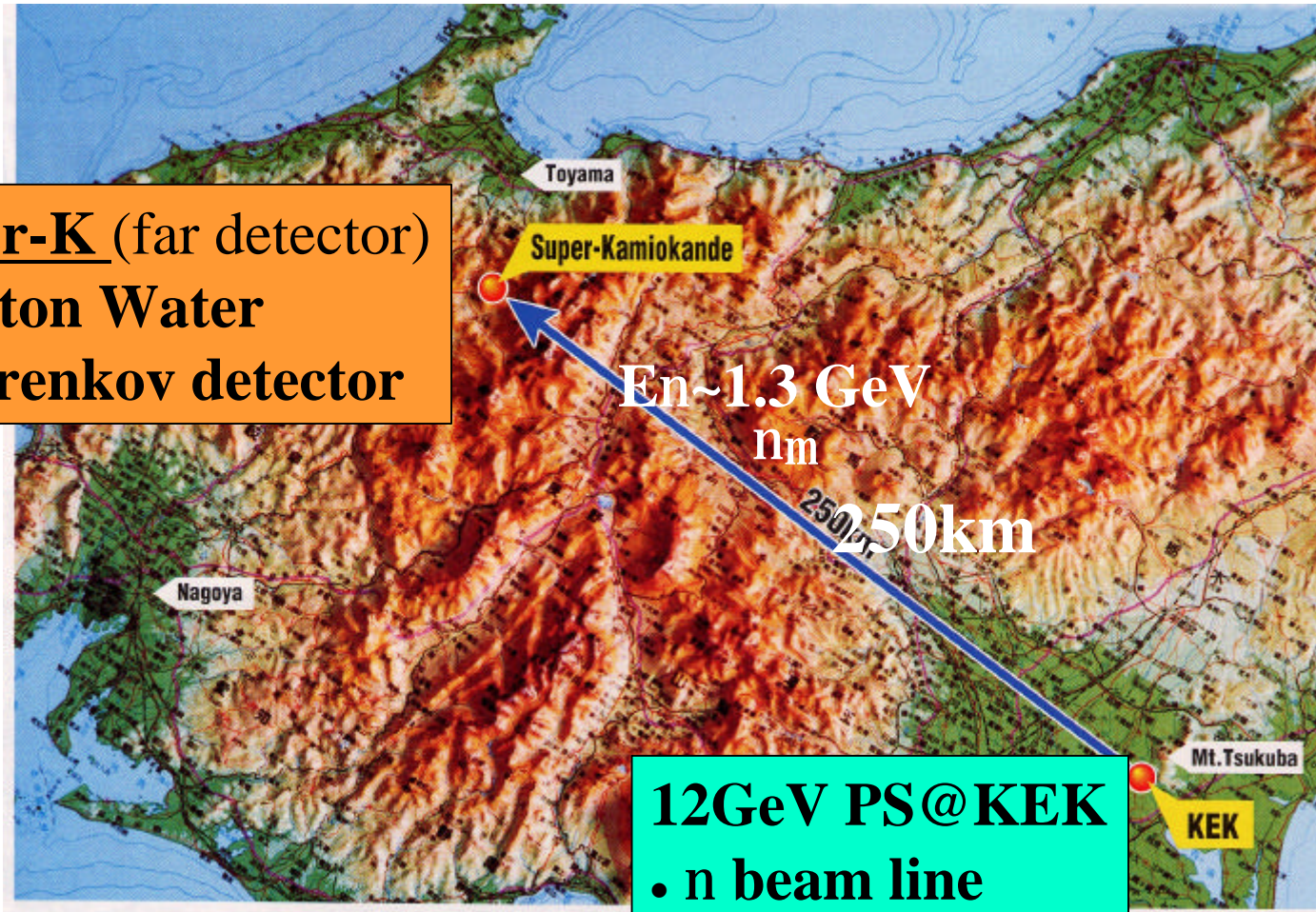
- Reduction of events
- Spectrum distortion

Goal: Atm. n results are indeed due to n oscillation

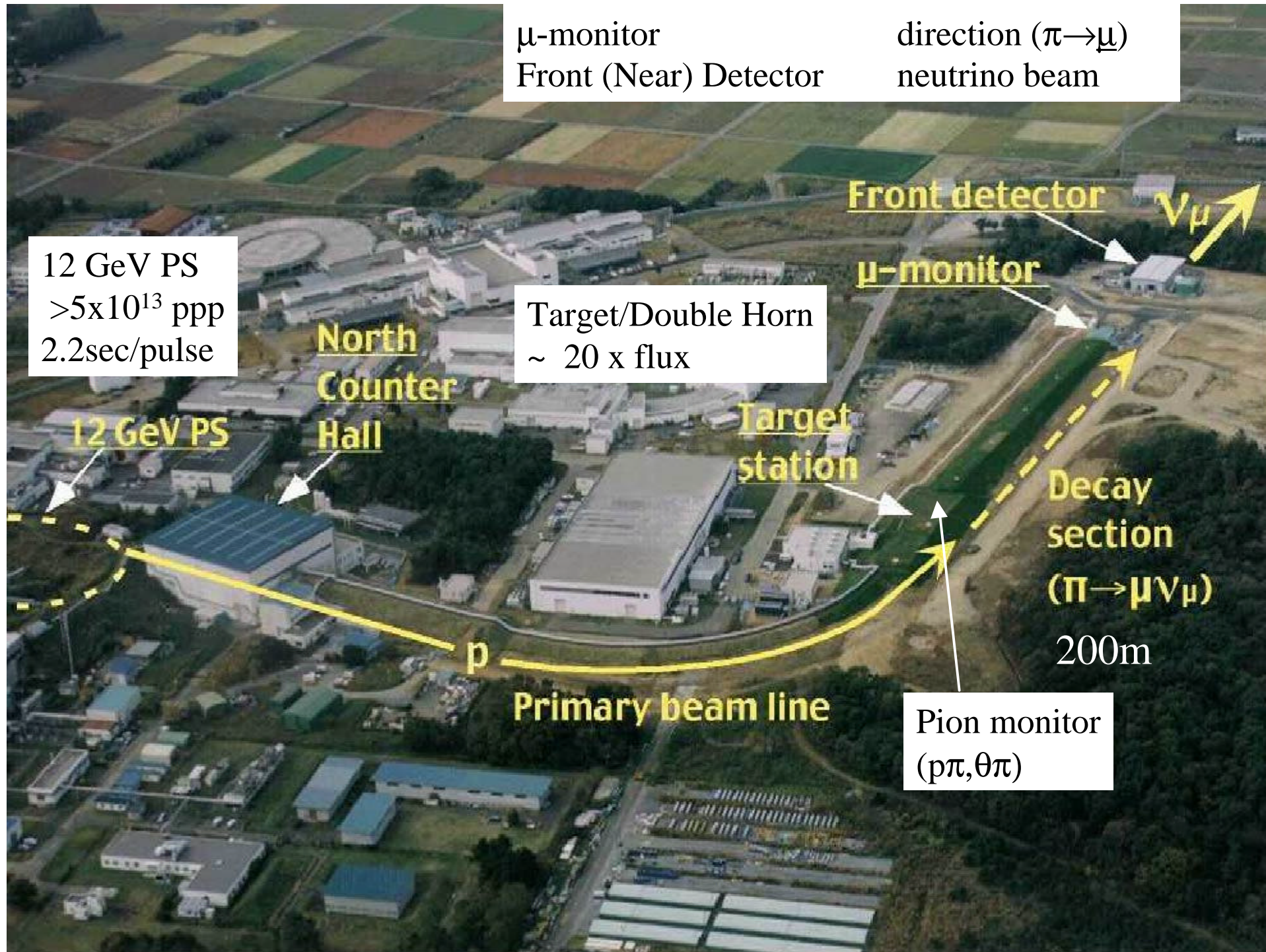
- Does  $n_m$  decrease ?
- Does it depend on  $E_n$  ?
- Is it consistent to  $\sin^2(1/E_n)$ ?
- What is  $Dm^2$ ?

# KEK to Kamioka Neutrino Oscillation Experiment

**Super-K** (far detector)  
50 kton Water  
Cherenkov detector

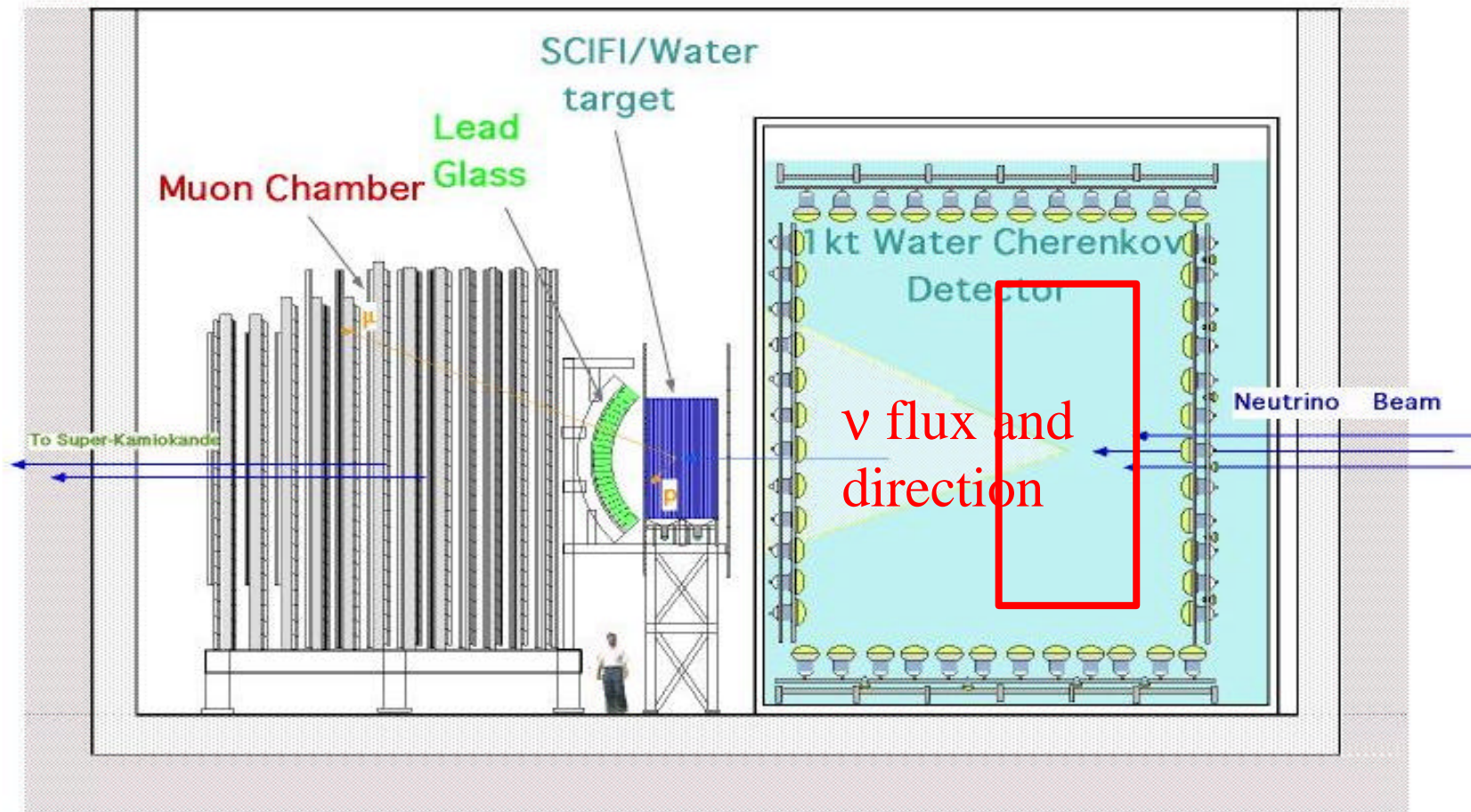


- 12GeV PS@KEK**
- n beam line
  - Beam monitor
  - Near detectors

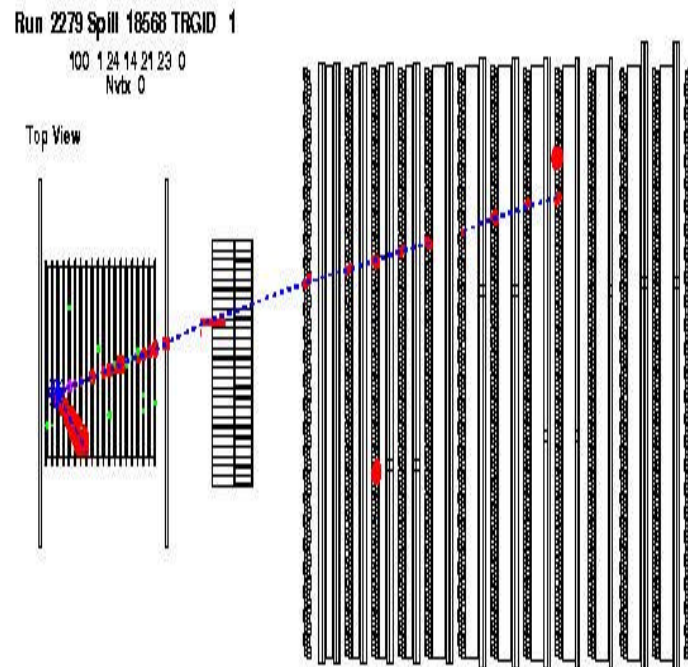


# Near Detectors at KEK

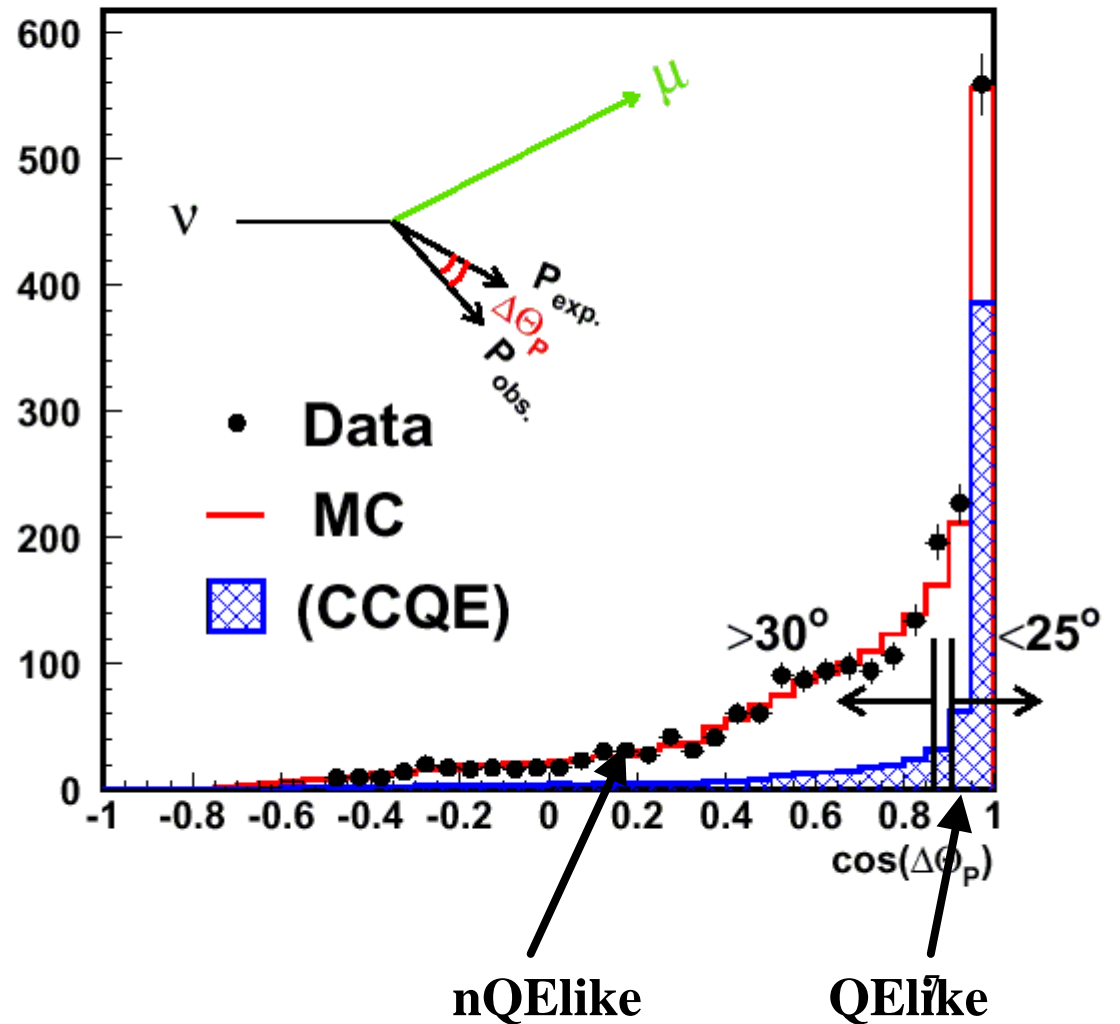
	fiducial	
1kt Water Cherenkov detector (KT)	25 ton	4p, low E
Water tube + Scintillation fiber detector (SciFi)	6 ton	1, 2, >2 tracks
Muon range detector(MRD) (Lead glass detector (LG))	~700 ton	n beam monitor



# QE and non-QE in SciFi 2track events



## SciFi 2 track $\cos(\Delta\Theta_P)$ distribution



# Neutrino Energy Reconstruction

$n_m + \nu$   
 $n$

$m + p$   
 $q_m$   
 $(E_m, p_m)$   
 $\bar{\nu}_m$   
 $p$

- ✧ CC QE
- ✧ ~100% efficiency for  $N_{SK}$
- ✧ can reconstruct  $E_\nu \leftarrow (\theta_\mu, p_\mu)$

$n_m + \nu$   
 $n$

$m + p + n$   
 $q_m$   
 $(E_m, p_m)$   
 $\bar{\nu}_m$   
 $p's$   $p$

- ✧ CC nQE
- ✧ ~100% efficiency for  $N_{SK}$
- ✧ Bkg. for  $E_\nu$  measurement

$n_m + \nu$   
 $n$

$n + p + n$   
 $q_m$   
 $(E_m, p_m)$   
 $\bar{\nu}_m$   
 $p's$   $p$

- ✧ NC
- ✧ ~40% efficiency for  $N_{SK}$

# Data set

- Data sets
  - Number of events
    - June 99-July 01
    - events fully contained in fiducial volume (FCFV)
    - 56 events observed
  - Shape of energy spectrum
    - Nov 99-July 01
    - Single  $\mu$ -like ring (1R $\mu$ ) events
    - 29 events observed
    - Reconstructed neutrino energy assuming QE ( $E_{\nu}^{\text{rec}}$ )
- Running condition
  - June '99
    - Target=2 cm $\phi$  Horn current=200kA (~6.5% of POT)
    - Larger systematic errors in 'near' measurements
  - Nov '99~July '01
    - Target=3cm $\phi$  Horn current=250kA
    - Full analysis of systematic errors

# Neutrinos at Near Detector $f_{\text{near}}(\text{En})$

Observation = **Flux(E)** x  $\sigma(\text{E})$  x Detector response

## KT

• No. of events

**Fully Contained Fiducial  
Volume (FCFV) events**

**(1) Single m-like events**

## SciFi

**(2) 1-track m events**

**(3) 2-track QE-like events**

**(4) 2-track nonQE-like events**

**4 sets of  $(p_m, q_m)$  distributions**

## Pion monitor & Beam simulation constraint

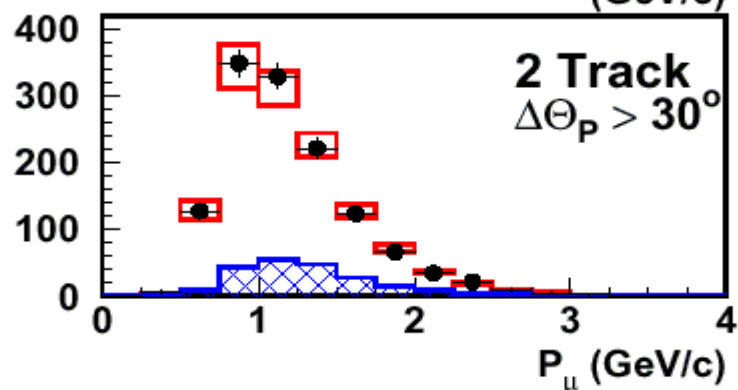
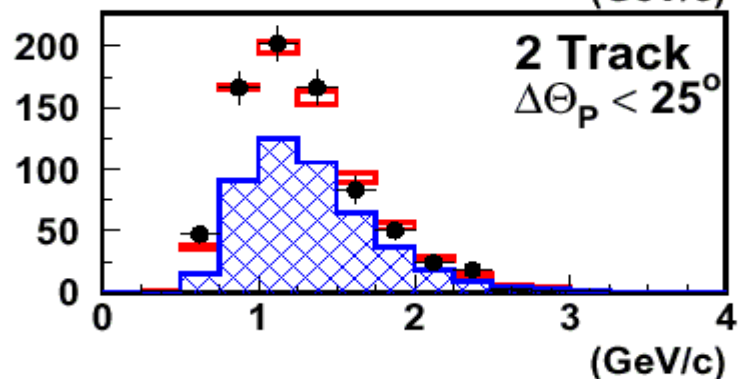
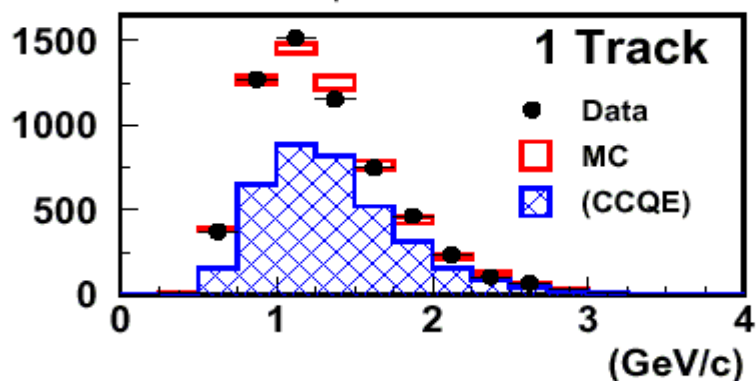
• p distribution in  $(p_p, q_p)$   $\otimes$  flux estimate  $f_{\text{near}}(\text{En})$  w. error

• n flux  $f_{\text{near}}(\text{En})$  (8 bins)

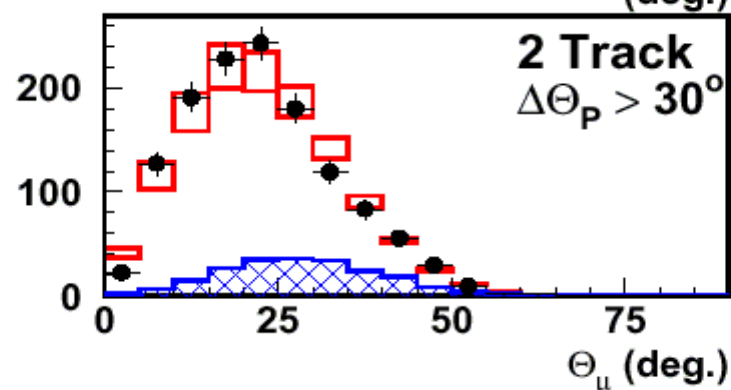
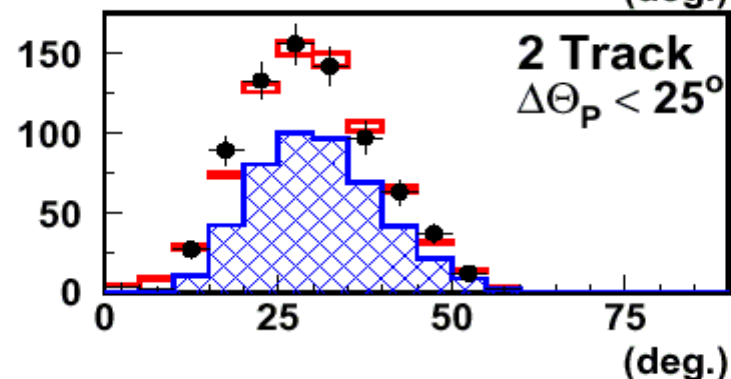
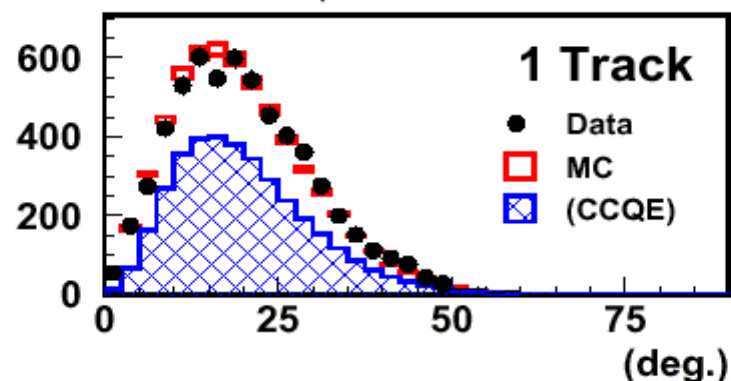
• n interaction model (param. as **nQE/QE** ratio)

# $p_m, q_m$ distributions using $f_{near}$

## SciFi $P_\mu$ distributions



## SciFi $\Theta_\mu$ distributions



# Flow of Neutrino Oscillation Analysis

Neutrino Spectrum at Near detector  $f_{near}(En)$ ,

-

Far/Near Extrapolation vs  $En$   $R_{FN}(En)$

Neutrino Spectrum w/o oscillation at SK  $f_{SK}(En)$

$f_{SK}(En)$   $\Delta$  Oscillation ( $\sin^2 2q, Dm^2$ )  $\Delta$  *Int. Model*

## Prediction

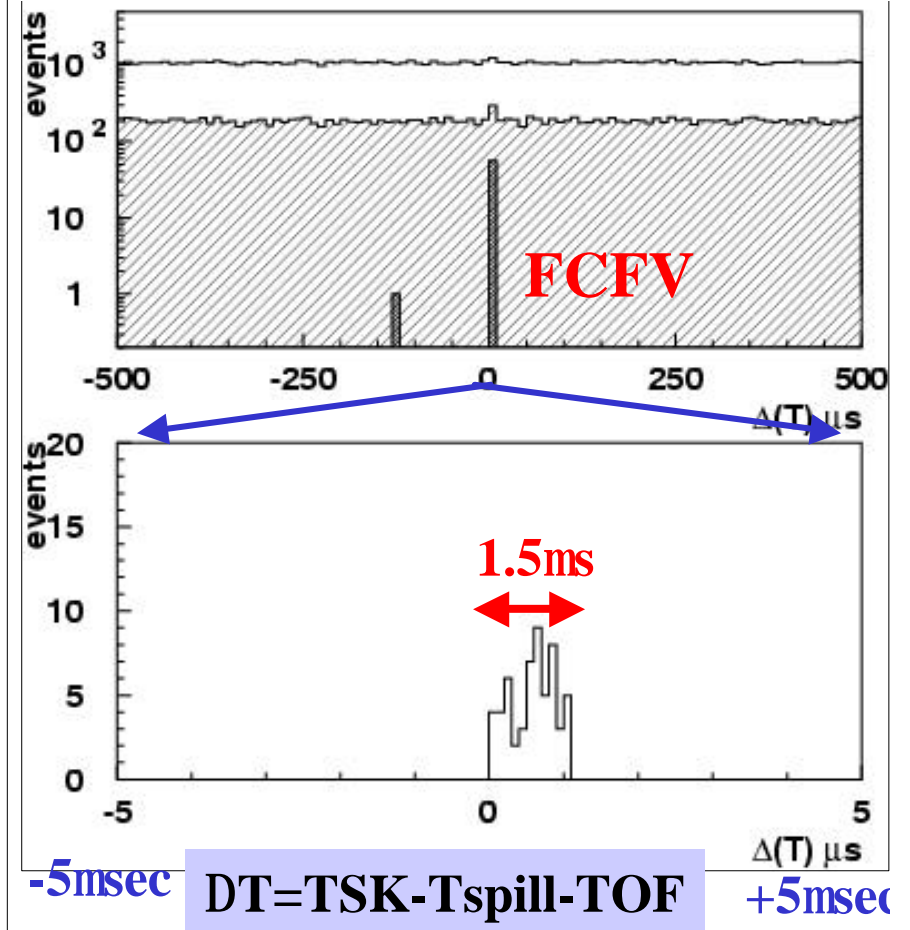
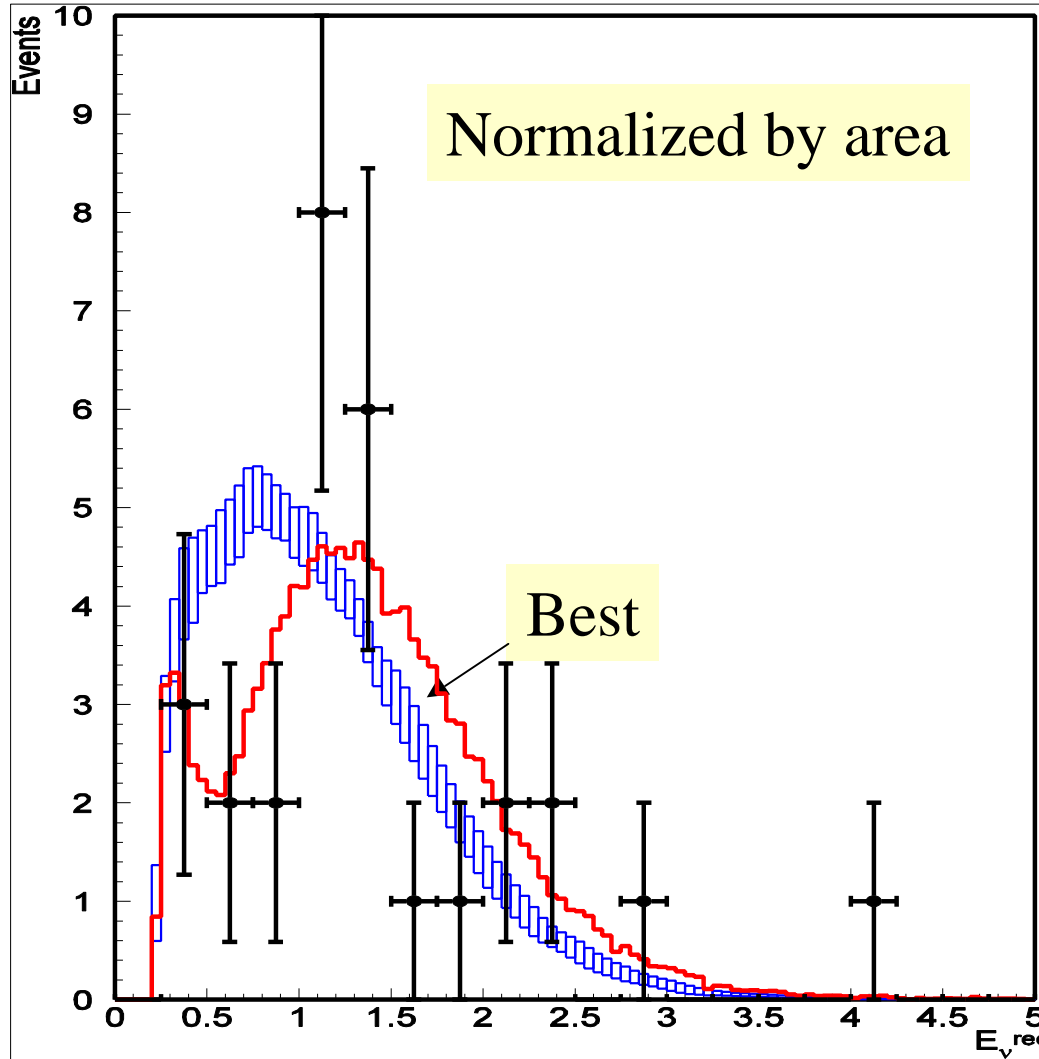
- $N_{SK}(\text{exp't})$  : Expected no. of SK events
- $S_{SK}(E_n^{rec})$  : 1Rm  $E_{rec}$  distribution(shape)

## SK observation

- $N_{SK}(\text{obs})$
- 1Rm  $E_{rec}$  distribution

Maximum Likelihood Fit in ( $\sin^2 2q, Dm^2$ )

# Rate and spectrum shape in K2K



KS test prob.(shape)= 79%

$N_{SK}$  prediction =54 (obs 56) at best fit

**56 events obs. exp.  $80.1^{+6.2}_{-5.4}$**

# Null Oscillation Probability

## Null Oscillation Probability

	method-1	method-2
$N_{SK}$ only	1.3%	0.7%
Shape only	15.7%	14.3%
$N_{SK}$ +Shape	0.7%	0.4%

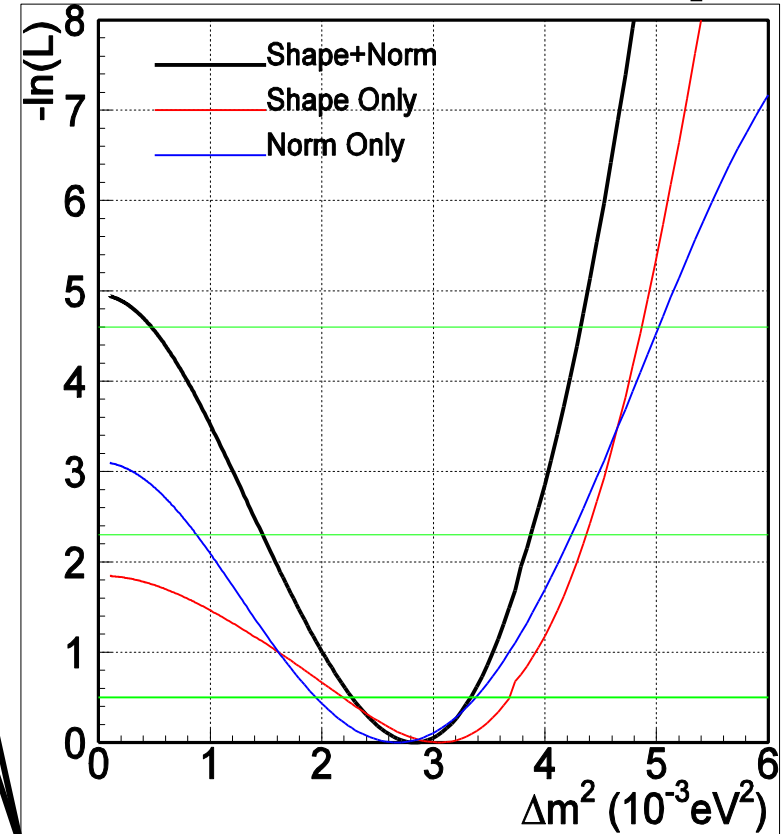
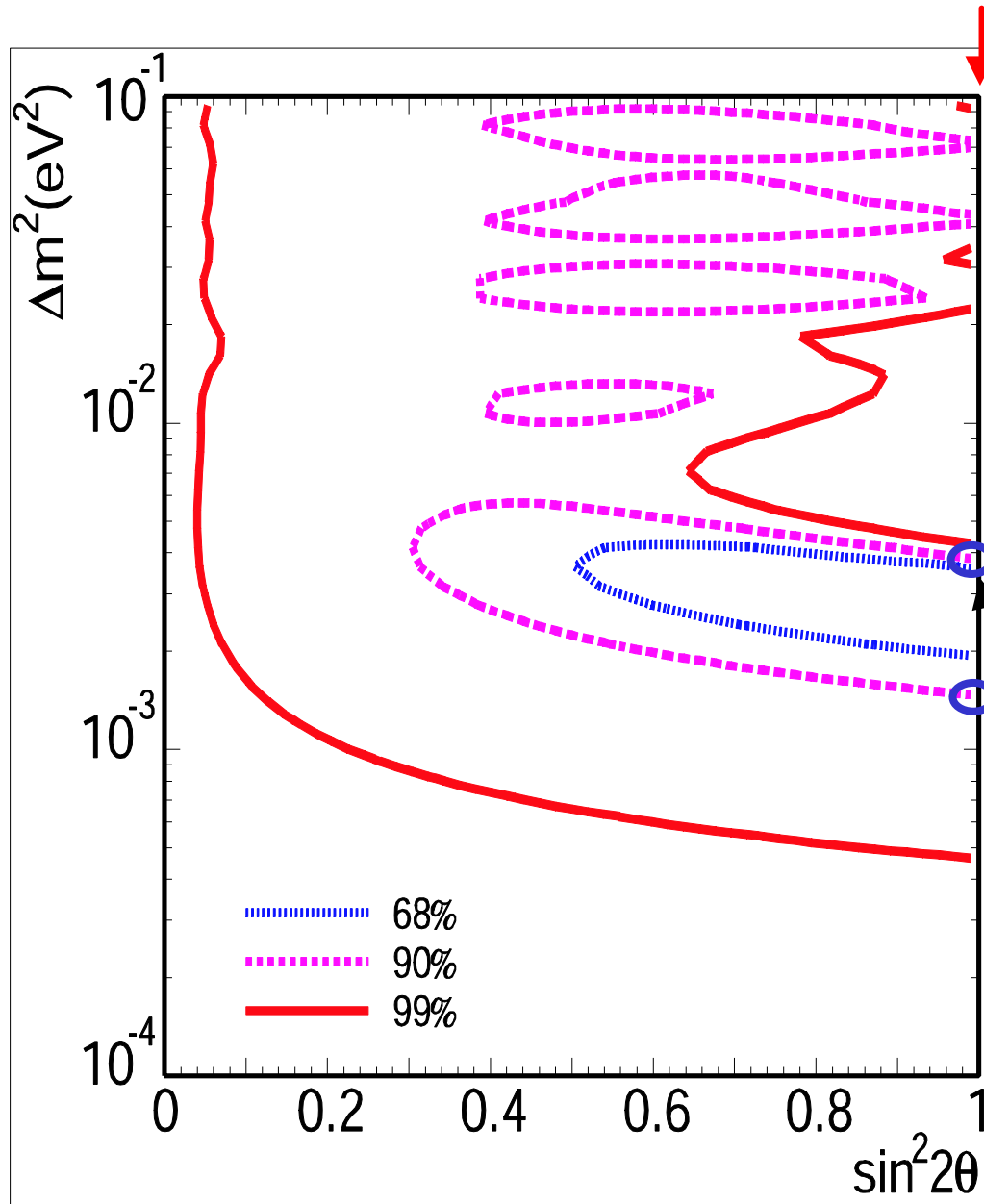
## Best fit ( $\sin^2 2q$ , $Dm^2$ )

Shape only	(1.0, $3.0 \times 10^{-3} eV^2$ )	(1.0, $3.2 \times 10^{-3} eV^2$ )
(Allowing unphys.)	(1.09, $3.0 \times 10^{-3} eV^2$ )	(1.05, $3.2 \times 10^{-3} eV^2$ )
$N_{SK}$ +Shape	(1.0, $2.8 \times 10^{-3} eV^2$ )	(1.0, $2.7 \times 10^{-3} eV^2$ )
(Allowing unphys. )	(1.03, $2.8 \times 10^{-3} eV^2$ )	(1.05, $2.7 \times 10^{-3} eV^2$ )

- method-1 Maximize L by adjusting systematic parameters.
- method-2 The MC generation of the systematic parameters & L=the mean

# Allowed region from K2K

for  $\sin^2 2q=1$



$\Delta m^2 = 1.5 \sim 3.9 \times 10^{-3} \text{eV}^2$   
 @  $\sin^2 2q=1$  @ 90% CL

c.f. atm n from SK  
 $1.6 \sim 3.9 \times 10^{-3} \text{eV}^2$  (90% CL)

**Next step**

# Three Generations MNS matrix

- 3 angles and 1 phase (+ Majorana phases)

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \begin{pmatrix} c_{13} & s_{13} \\ 0 & 1 \\ 0 & 0 \end{pmatrix}$$

**solar**

$n_e \text{ (R) } n_m, n_t$

with  $(m_2^2 - m_1^2)$

**atmospheric**

$n_m \text{ (R) } n_t$

with  $(m_3^2 - m_2^2)$

**reactor limit**

$n_e \text{ (R) } n_x$  with  $(m_3^2 - m_1^2)$

$n_m \text{ (R) } n_e$  with  $(m_3^2 - m_1^2)$

**NOT OBSERVED**

$$n_m \textcircled{R} n_e$$

- LMA  $\textcircled{R}$  (1-2) oscillation compete with (1-3) at  $E/L \sim Dm_{atm}^2$   
 $\sin^2 2q_{12} L Dm_{12}^2/E \quad \hat{U} \quad \sin^2 2q_{13} L Dm_{13}^2/E$

- $\sin^2 2q_{13}$

$$n_m \textcircled{R} n_e = \sin^2 2q_{23} \sin^2 2q_{13} \sin^2 \frac{Dm_{23}^2 L}{E_n}$$

- Particle- anti-Particle asymmetry

$$A_{CP} \circ \frac{P - \bar{P}}{P + \bar{P}} \gg \frac{Dm_{12}^2 L}{E} \times \frac{\sin 2q_{12}}{\sin q_{13}} \times \sin d$$

in vacuum

parameters in solar

- $q_{13}$  (remain to be discovered) : first step
- $d$  : second step

# Next generation of oscillation experiments

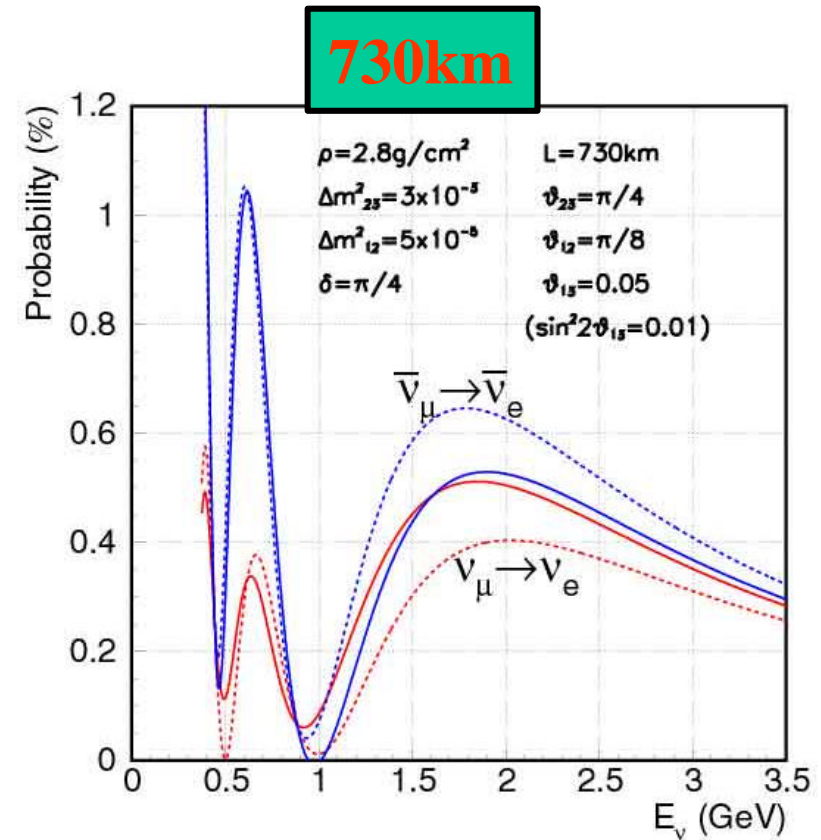
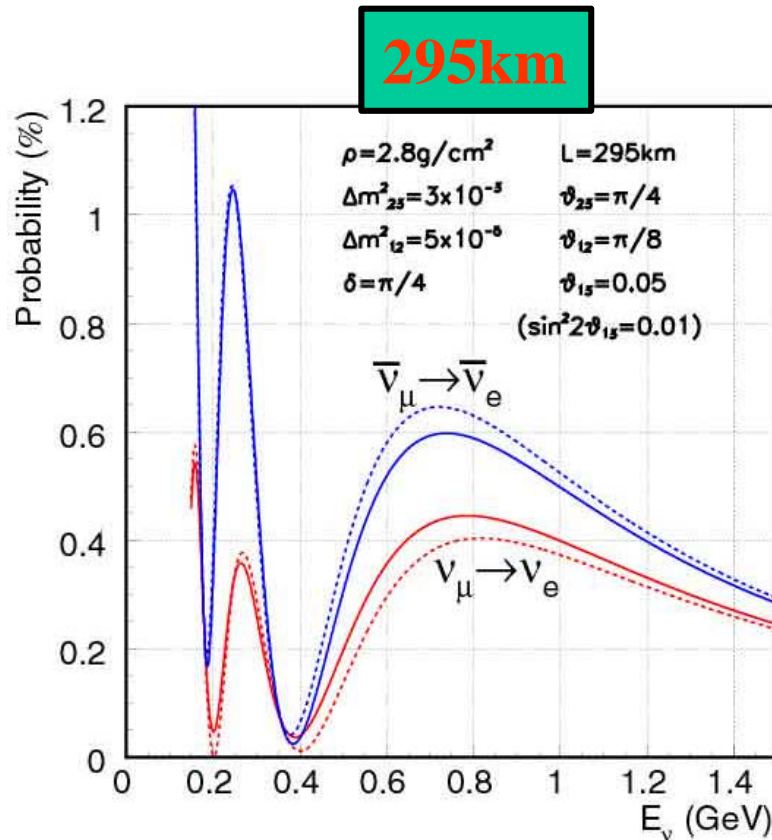
## • Measurement of $q_{13}$

- The last mixing to be discovered in three generations scheme
- $n_m \otimes n_e$  appearance at  $E/L \sim \Delta m_{\text{atm}}^2$ 
  - two competing processes (LMA & small  $q_{13}$ )  $\otimes$  CPV
- The measurement of  $q_{13}$  is made complicated by matter effects and possible CP violation (both are important in their own right)
- Keep one of the effect small

## • Experimentally

- Complicated by  $t \otimes e$  decay at high energy
- Narrow band beam to extra-constrain for  $E$ (reconstructed)
- Small high energy tail to suppress NC- $p^0$

# Matter effect on $n_m \rightarrow n_e$ oscillation



$E_n$  a  $L/n$  ( $n=1,3,5\dots$ ) at oscillation max.

Matter effect a  $q_{13}^2 L/n \hat{U}$  CPV a  $q_{13} \Delta m_{12}^2 n$

**The effect depends on oscillation parameters.**

**Condition where the matter effect is small**

**Cross section(E)**

Solid line: w/ matter

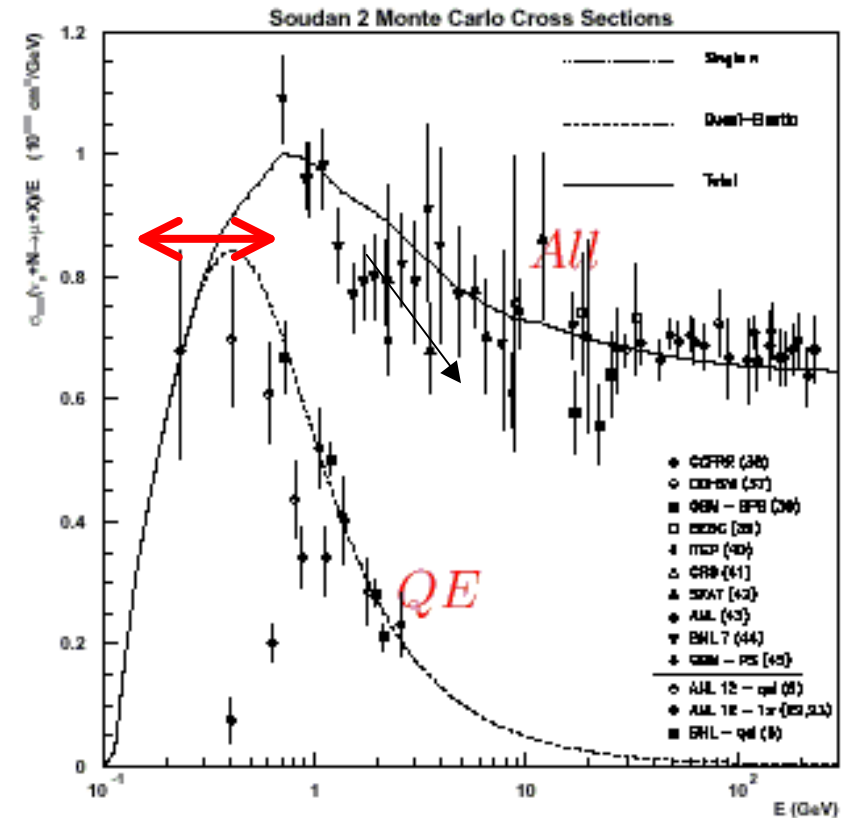
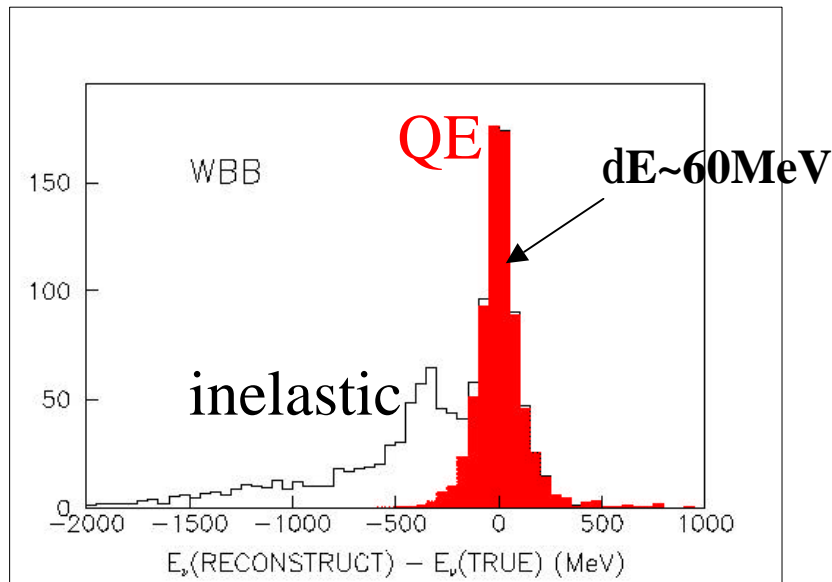
Dashed line: w/o matter

# Possible $n_m \textcircled{R} n_e$ experiment

1. Neutrino energy measurement
  - $E_\mu + E_{\text{had}}$  Good calorimetry at high energy
  - Two-body kinematics (QE) (low energy)
    - sub-GeV neutrino beam
    - small high energy tail
2. PID (neutrino flavor ID) and beam contamination
  - single particle or fine segmentation for high energy jets
  - narrow band beam gives extra-constraint for rejecting backgrounds (NC- $\pi^0$ , beam contamination)
3. Matter effect  $\propto E_\nu, L$  and depends on other oscillation parameters
  - better with low energy, keeping correction by matter effect to be small

# Low Beam Energy

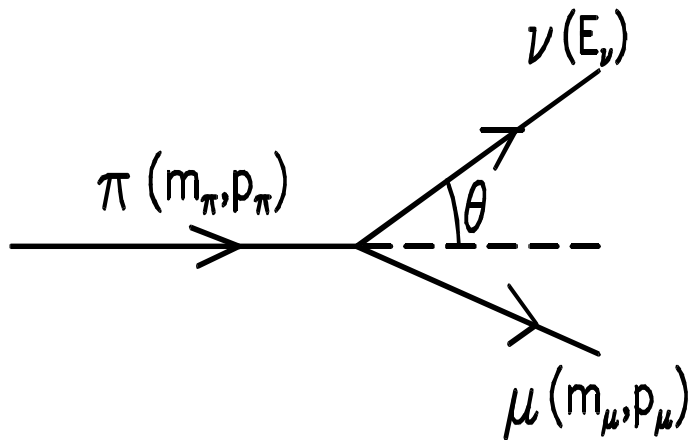
- Large QE fraction for <1 GeV
- Need good knowledge of cross sections
- Beam with small high energy tail



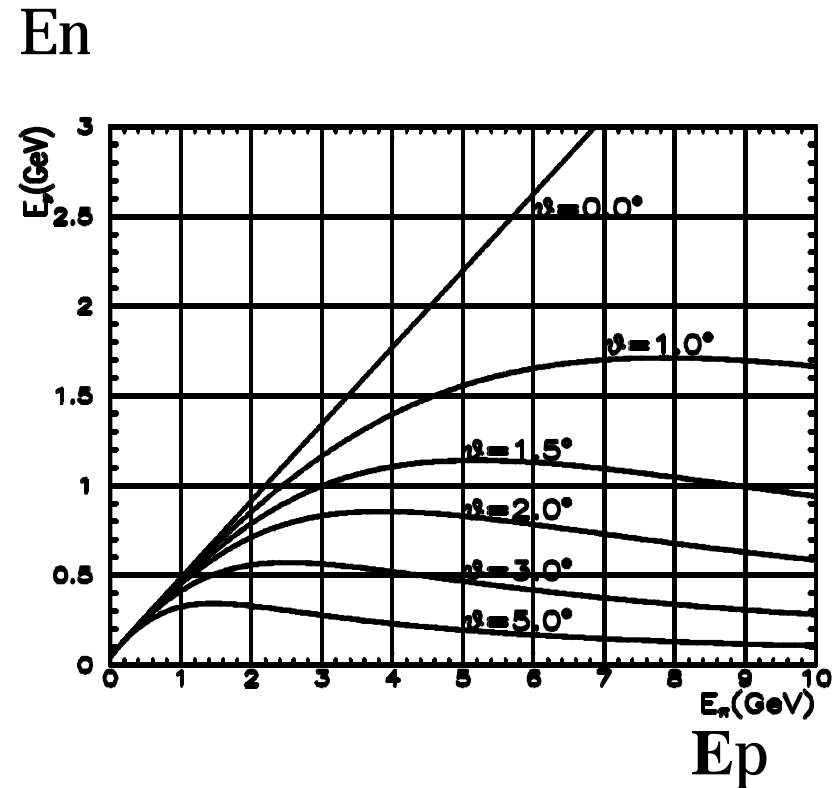
# Off-axis beam

(ref.: BNL-E889 Proposal)

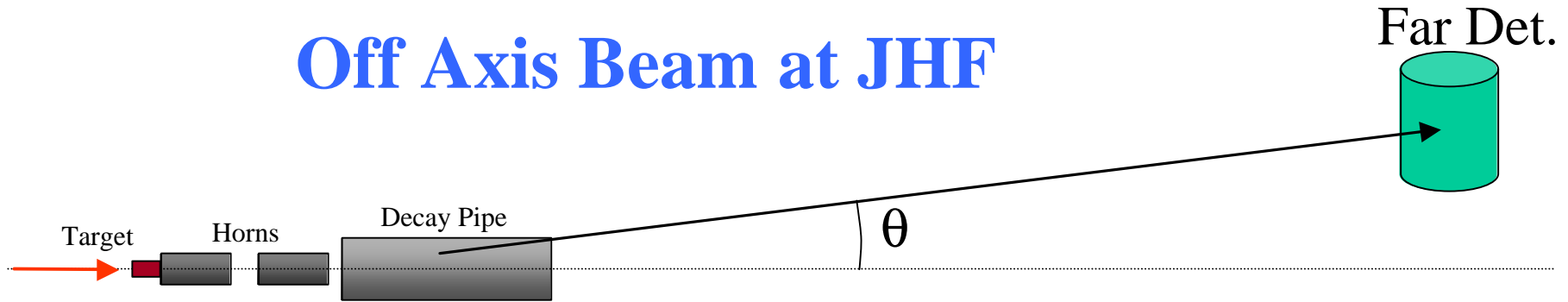
Two body decay kinematics



$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)}$$

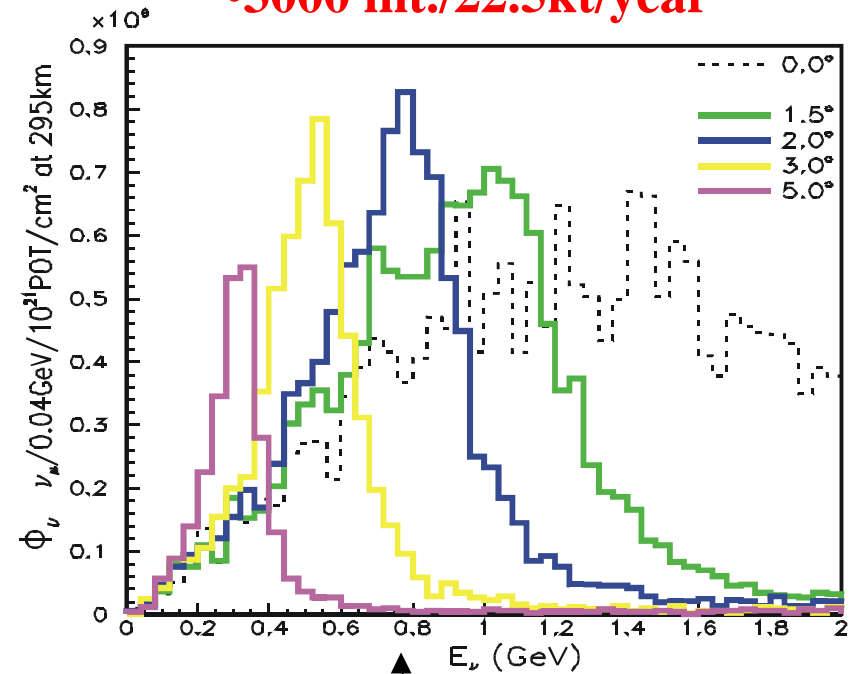
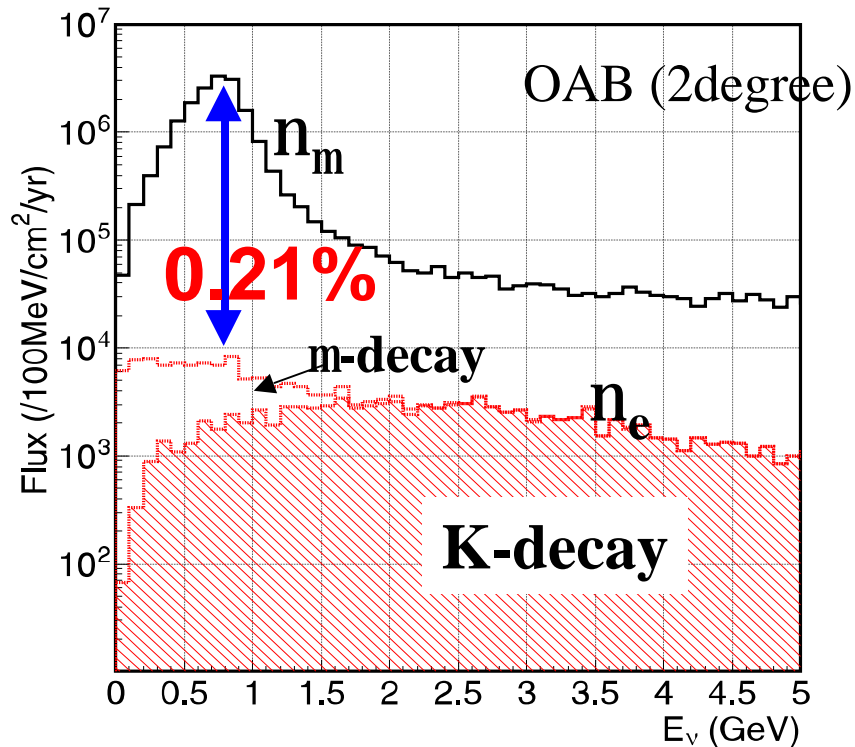


# Off Axis Beam at JHF



**WBB w/ intentionally misaligned beam line from det. axis**

- $n_e$  contamination :0.8%(0.2% @ peak)
- Highest intensity at low energy
- Even higher than  $0^\circ$  beam
- 3000 int./22.5kt/year



$3 \times 10^{-3} \text{eV}^2$  with 295km

# JHF-SK(HK) $\nu$ Experiment



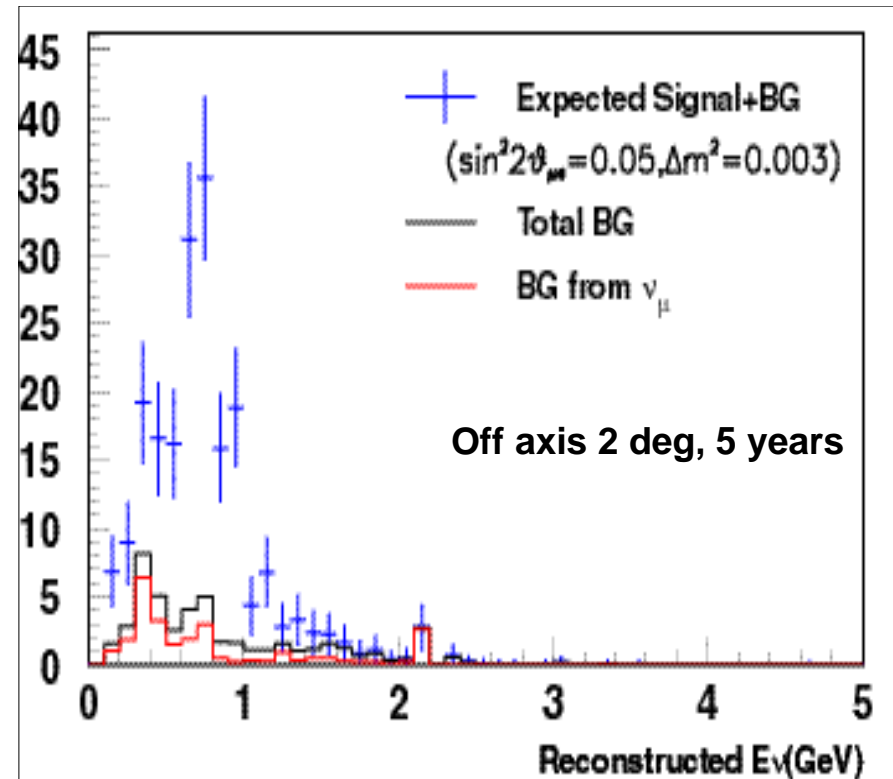
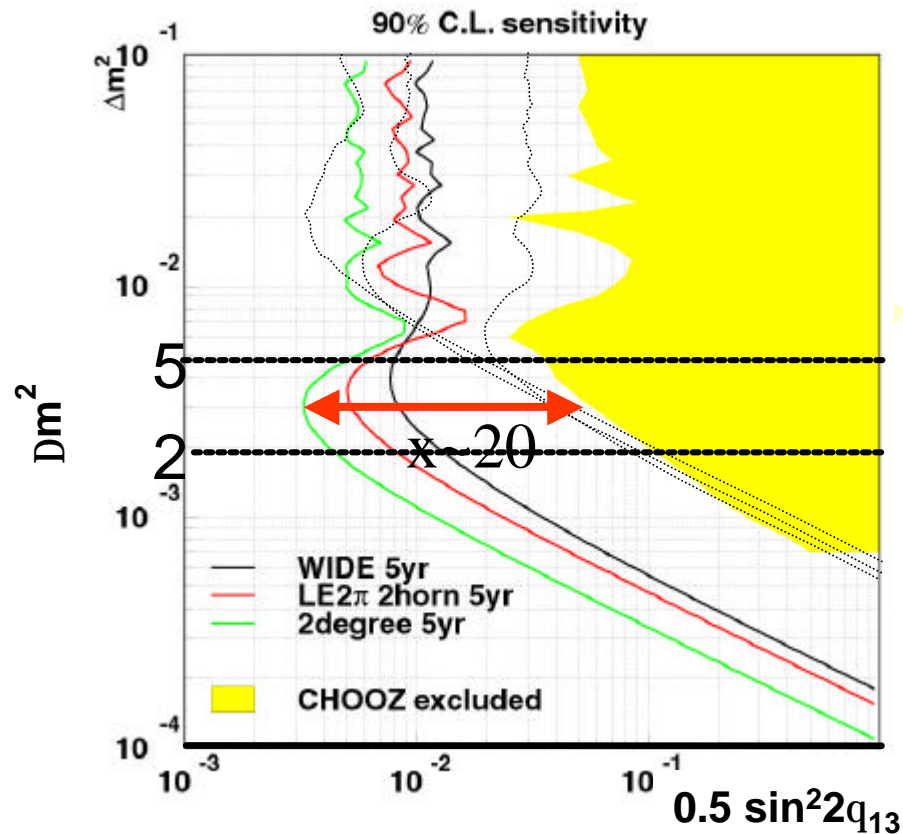
## First Phase

- nm  $n_x$  disappearance
- nm  $n_e$  appearance
- NC measurement

## Second Phase

- CPV
- proton decay (x10)

# $\sin^2 2q_{13}$ from appearance experiment $n_e + n \rightarrow e + p$



$\sin^2 2q_{13}$	Background in Super-K					Signal	Signal + BG
	$n_m$	$n_e$	$\bar{n}_m$	$\bar{n}_e$	total		
0.1	12.0	10.7	1.7	0.5	24.9	114.6	139.5
0.01	12.0	10.7	1.7	0.5	24.9	11.5	36.4

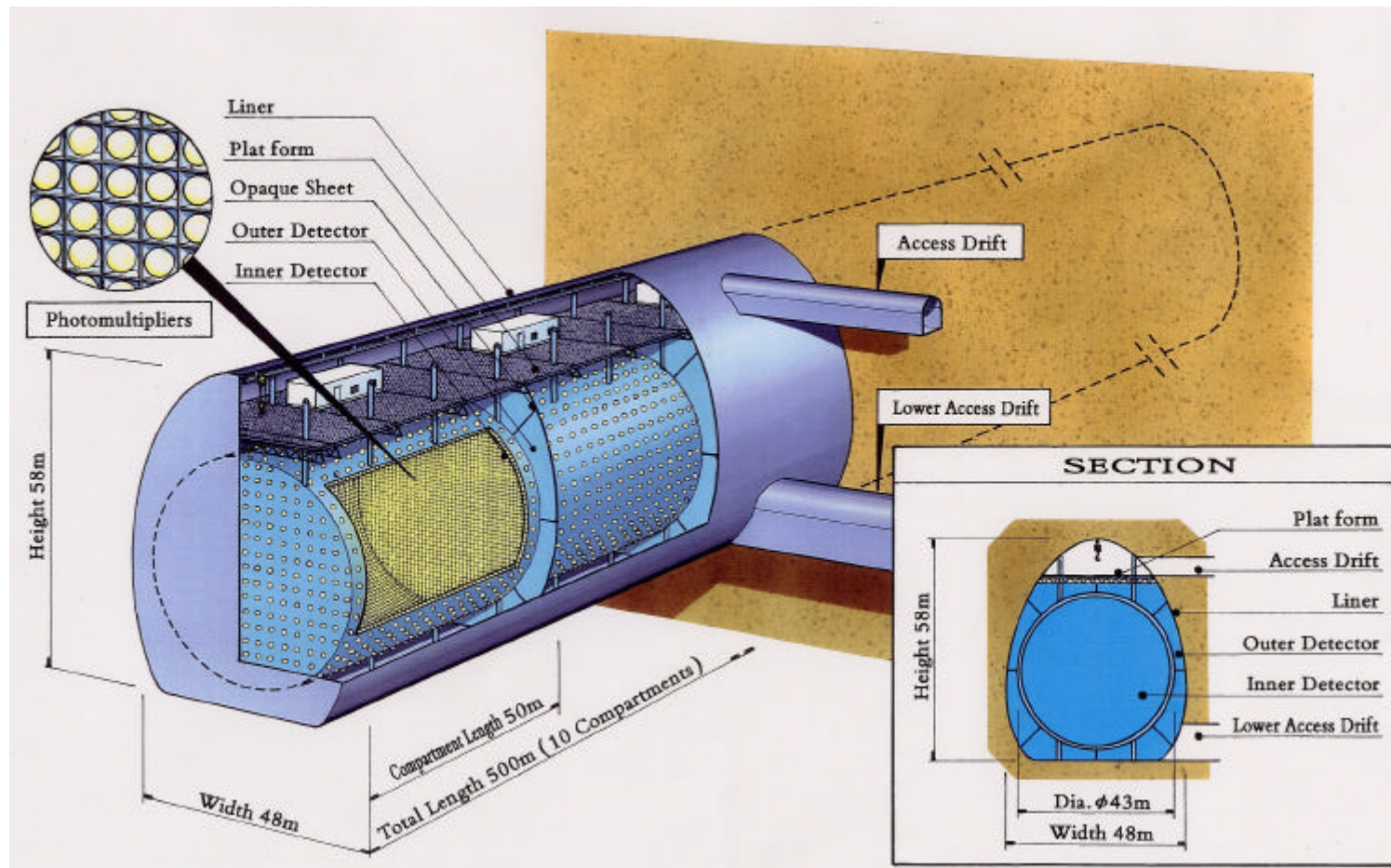
# **n Oscillation experiments**

- **Confirmation of atm., solar, and LSND**
- **Phase 1 : Precision parameter measurements**  
 $\sin^2 2q_{13} \sim 6 \times 10^{-3}$  (90% CL)  
 $d \sin^2 2q_{23} \sim 0.01$  ( $n_m$  disappearance)  
 $d D m_{23}^2 \sim 1.5 \times 10^{-4} \text{eV}^2$
- **Phase 2 : CPV and Proton decay**  
**1 Mton Water Cherenkov detector with JHF upgrade**

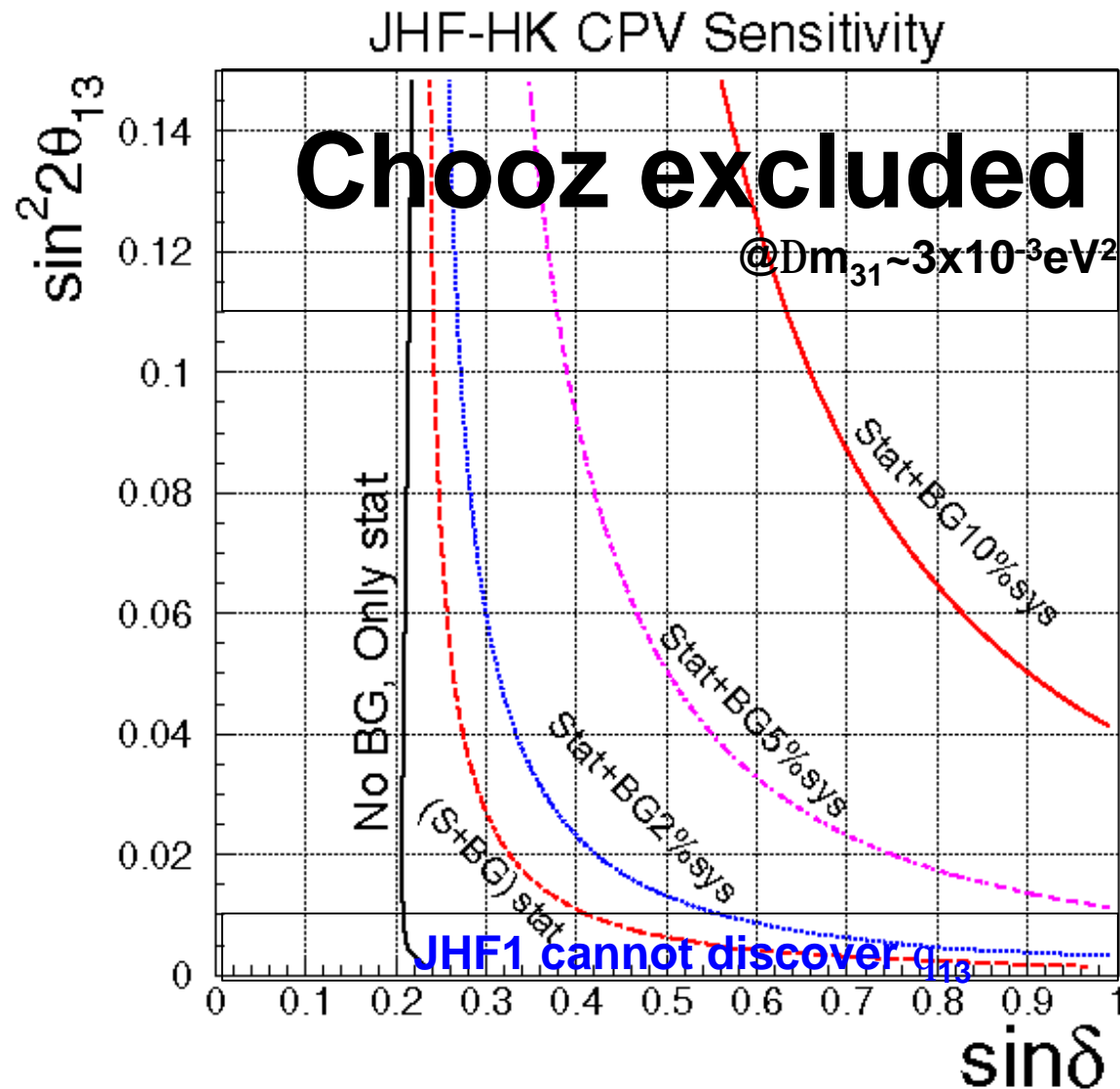
# Hyper-Kamiokande

Proton decay search

Precision neutrino oscillation study



# Future sensitivity(3s) with 4MW beam and 1 Mton Hyper-K



IF BG sys 2%

**sin<sup>2</sup>2q<sub>13</sub>=0.01  
→sind>0.55  
(33 deg)**

**large sin<sup>2</sup>2q<sub>13</sub>  
→sind>0.25  
(14 deg)**

- spectrum difference
- cross section
- detection efficiency
- matter effect 29

# Conclusion - 1

- K2K Oscillation analysis on June99 ~July01 data
  - Full error analysis

1. Null oscillation probability is less than 1%
2. Both SK rate reduction and  $E_\nu^{\text{rec}}$  shape indicate consistent oscillation parameters region
3.  $\Delta m^2 = 1.5 \sim 3.9 \times 10^{-3} \text{ eV}^2$  for  $\sin^2 2\theta = 1$  @ 90% CL
4.  $\sin^2 2\theta$ ,  $\Delta m^2$  are consistent with atmospheric neutrino results

The best fit point ( $\sin^2 2\theta = 1.0$ ,  $\Delta m^2 = 2.8 \times 10^{-3} \text{ eV}^2$ )

cf. Atmospheric neutrino results

$\Delta m^2 = (1.6 \sim 3.8) \times 10^{-3} \text{ eV}^2$  for  $\sin^2 2\theta = 1.0$

best fit ( $\sin^2 2\theta = 1.0$ ,  $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$ )

- Data taking will resume within this year

## Conclusion-2

- All observed phenomena will be checked against oscillation hypothesis in current experiments (spectrum distortion,  $\tau$  appearance, LSND effect) – Anything hidden ?
- One of the primary objectives of next generation experiment should be  $n_m - n_e$  search at  $\Delta m^2_{\text{atm}}$  region
- LMA solution in solar neutrinos made neutrino oscillation experiments exciting
  - possibility of CP violation search
  - road to lepto-genesis ?
- The precision of oscillation parameters must be improved to obtain underlying physics