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@BNL

A 2nd Generation LBL Neutrino Experiment
- The JHF-Kamioka project -

- Physics of neutrino oscillations
- JHF project and the neutrino experiment

  Narrow band ν beam tuned at the oscillation maximum

  Neutrino energy reconstruction using QE reaction
- Sensitivities of the JHF-Kamioka experiment

  Establish ν oscillation or
  discover physics beyond MNS (e.g. sterile ν)

  ν_μ disappearance (precision measurement)

  $\nu_\mu \to \nu_e$ appearance (U_{e3})

  CP violation search
- Summary and prospects

New era in particle physics and cosmology

Big progress in the last few years (SNIa,CMB,Neutrino)

- Establishment of the big-bang cosmology (SNIa,CMB)

  1. Big Bang

  2. Inflation (flat universe according to Boomerang/Maxima)

  3. Present

  $\sim$65%: vacuum energy (the cosmological constant)
  $\sim$30%: dark matter
  $\sim$ 5%: baryonic matter

- Fundamental questions for particle physics

  - What caused the Big-Bang?
    Quantum-gravity with extra dimensions?
  - What caused the inflation?
    Scalar fields at GUT scale?
  - What is the cosmological constant?
    Higgs potential way too large
  - What is the cold dark matter?
    SUSY neutralino or axions?
  - Baryon asymmetry of the universe?
    CP violation in quarks, or Leptogenesis?

- We have tools to access GUT/Extra dimensions!

  - Energy fronteer (LHC, Linear collider, $\mu - \mu$ collider)
  - Neutrino oscillations
  - Nucleon decays

What is exciting about neutrino physics?

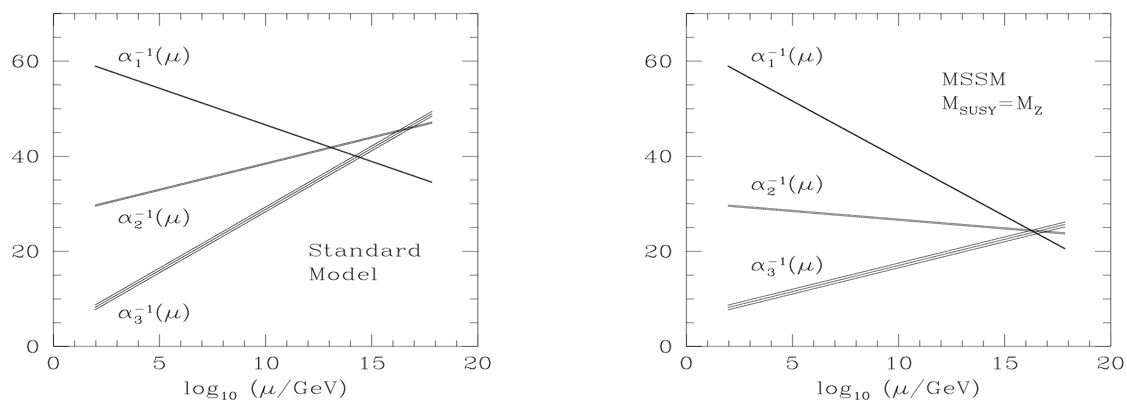
Door is open now for new physics beyond SM

- **GUT** energy scale ($\sim 10^{16}$GeV) implied by ν mass

  See-saw mechanism

  $$\frac{1}{M} = \frac{m_\nu}{v^2} \sim \frac{3\times10^{-3}(eV^2)}{(250GeV)^2} = \frac{1}{6\times10^{15}GeV}$$

  Consistent with the gauge unification



  - Explore GUT structure by ν oscillation
  - Leptogenesis $\longrightarrow$ CP violation in ν oscillation

- **Extra Dimension** implied by ν mass

  Right handed ν_R in the extra dimensional space

  $\longrightarrow$ small ν mass (small overlap between ν_R and ν_L)

  - Explore extra-dimensional space by neutrino oscillation (interaction between ν_R and ν_L)
  - Sterile neutrinos (K-K mode)?

$\Rightarrow$ **Next generation long baseline ν experiment**

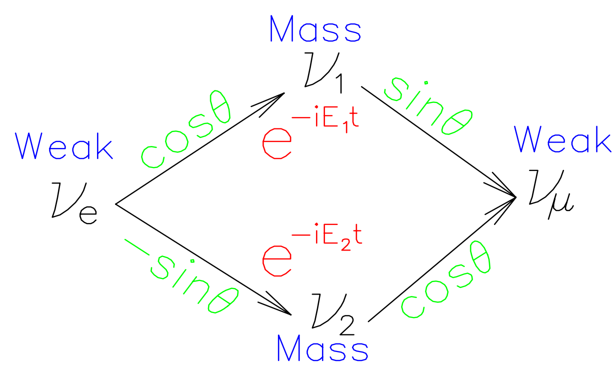
Oscillation pattern measurement (NC and CC)

Precision measurement of the oscillation parameters

Physics of neutrino oscillations

- Neutrino oscillation in 2 generations

$$\begin{pmatrix} U_{e1} & U_{e2} \\ U_{\mu 1} & U_{\mu 2} \end{pmatrix} = \begin{pmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{pmatrix}$$



$$\begin{aligned} P(\nu_e \rightarrow \nu_\mu) &= |sin\theta cos\theta(e^{-iE_1t} - e^{-iE_2t})|^2 \\ &= sin^2 2\theta sin^2 \frac{1.27\Delta m^2 L(km)}{E(GeV)} \end{aligned}$$

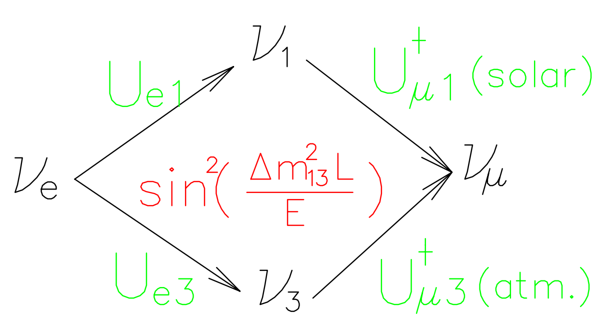
- 3 generation effect

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Leptonic CKM
(MNS matrix)

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

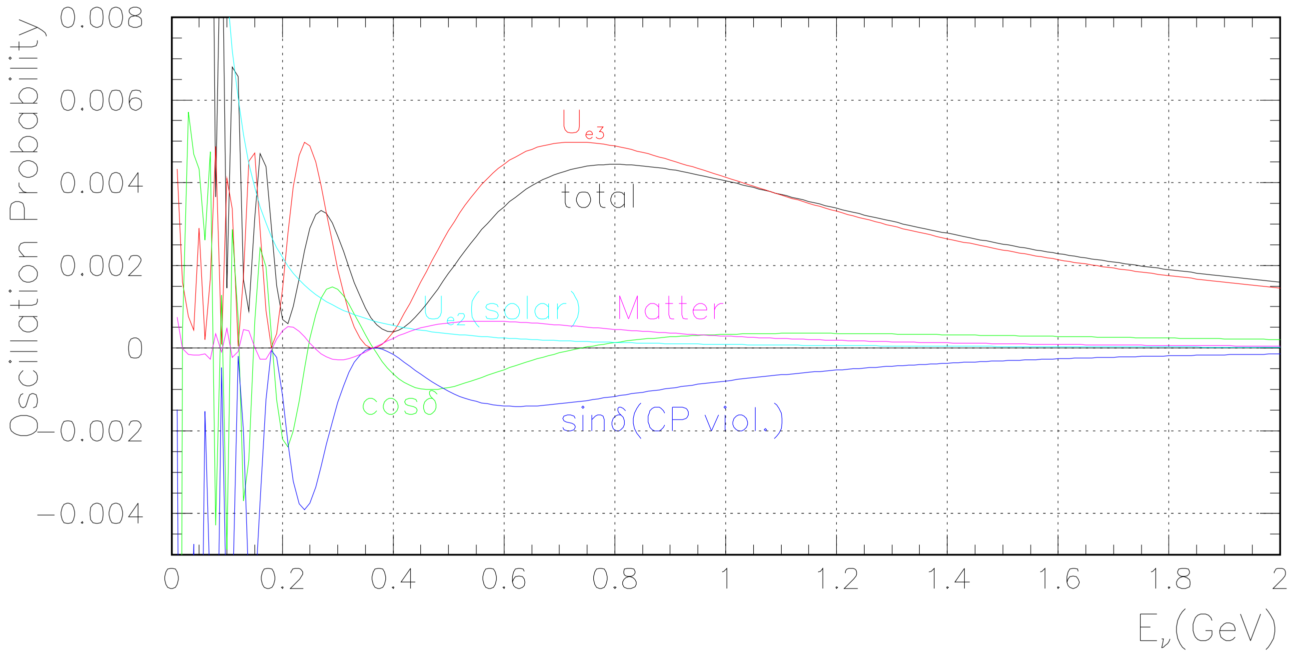
$\nu_e \leftrightarrow \nu_\mu$ is suppressed
due to small Δm^2_{12}
$\Delta m^2_{13}(\theta_{13})$ term dominates
Large CP contribution



• Large enhancement of the CP signal

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \ (1 - 2S_{13}^2)\right)$$
$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$
$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$
$$+4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$
$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \ \frac{aL}{4E} \ (1 - 2S_{13}^2)$$

Central values of LMA and 1/10 of reactor limit in $\sin^2 2\theta_{13}$



$$A_{CP} = \frac{Prob(\nu_\mu \to \nu_e) - Prob(\bar{\nu}_\mu \to \bar{\nu}_e)}{Prob(\nu_\mu \to \nu_e) + Prob(\bar{\nu}_\mu \to \bar{\nu}_e)}$$
$$= \frac{\Delta m_{12}^2 L}{4E} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot sin\delta$$

- Common oscillation maximum

Two independent mass square differences:

$$\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2,\ \Delta m_{23}^2 >> \Delta m_{12}^2 \quad \Rightarrow \quad \Delta m_{13}^2 \simeq \Delta m_{23}^2$$

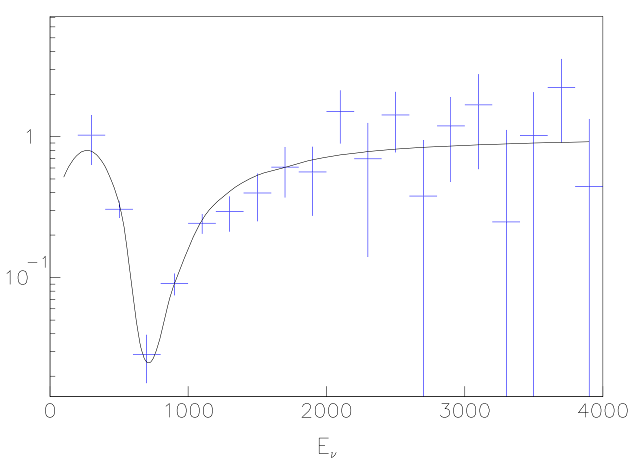
ν_μ oscillations have common oscillation maximums

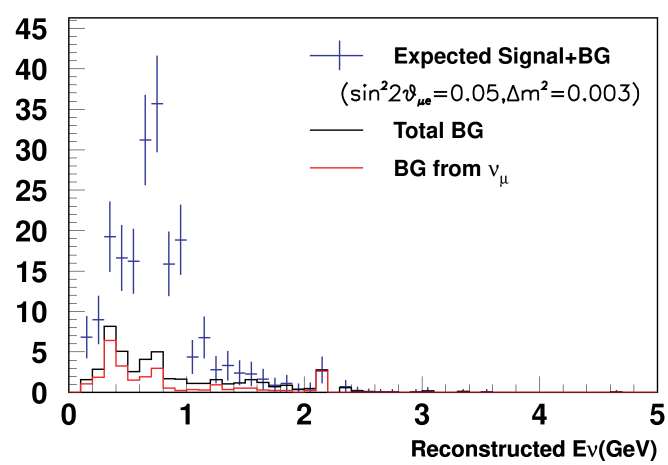
$$P(\nu_\mu \to \nu_\tau) \sim \sin^2 2\theta_{23} \sin^2 \frac{1.27\Delta m_{atm}^2 L}{E}$$

$$P(\nu_\mu \to \nu_e) \sim \cos^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{1.27\Delta m_{atm}^2 L}{E}$$

$$P(\nu_\mu \to \nu_e)_{CPV} \sim \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \frac{1.27\Delta m_{sol}^2 L}{E} \sin^2 \frac{1.27\Delta m_{atm}^2 L}{E}$$

$$\Delta m_{12}^2 \simeq \Delta m_{sol}^2 = 10^{-10} - 10^{-4}$$
$$\Delta m_{13}^2 \simeq \Delta m_{23}^2 \simeq \Delta m_{atm}^2 = (1.6 - 4.0) \times 10^{-3} eV^2$$





Notations:

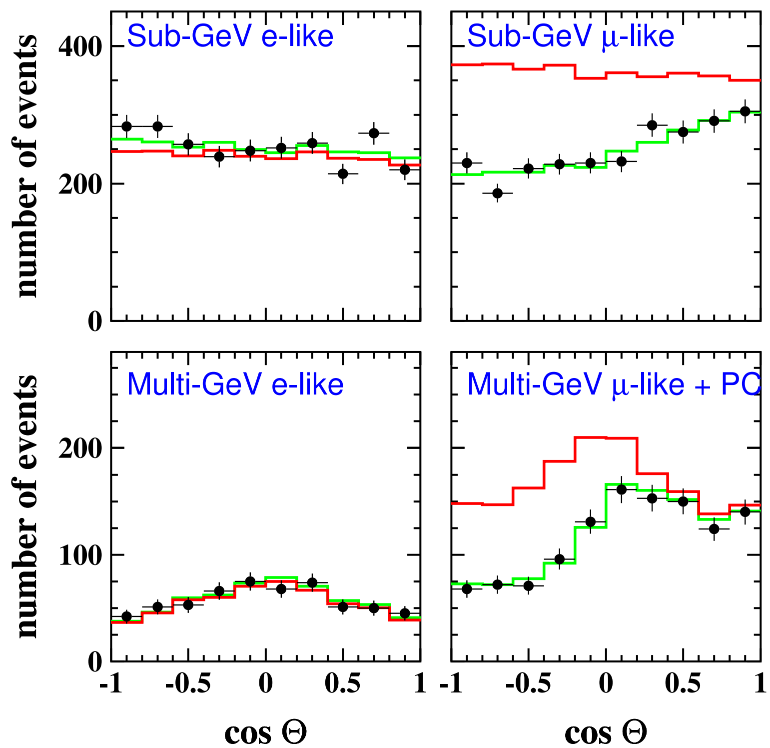
$$\sin^2 2\theta_{\mu\tau} \simeq \sin^2 2\theta_{23}$$
$$\sin^2 2\theta_{\mu e} \simeq \frac{1}{2}\sin^2 2\theta_{13} \simeq 2\,|U_{e3}|^2$$

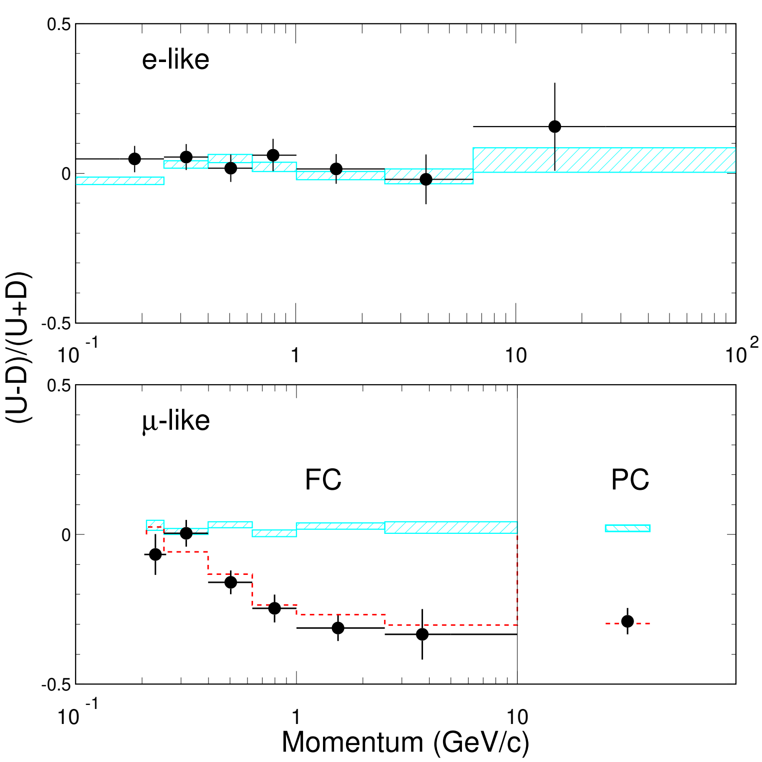
Status of neutrino oscillation experiments

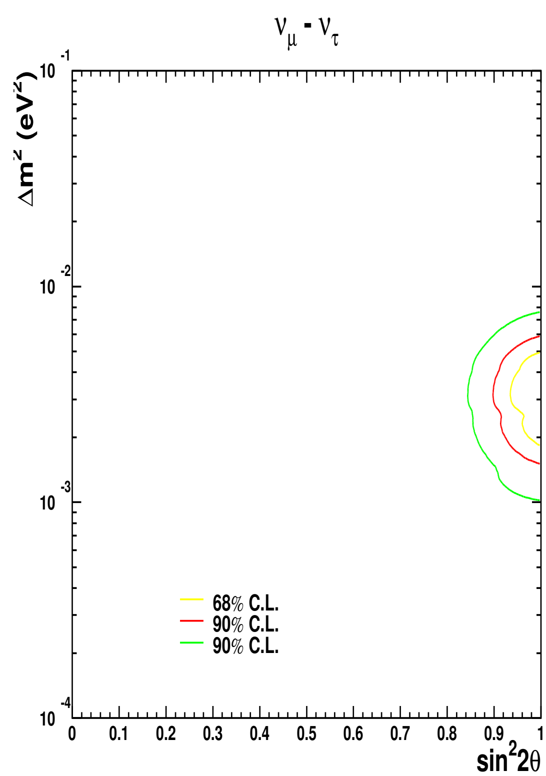
	$\Delta m^2 (eV^2)$	L(km)/E(GeV)
LSND	~ 1	4
Atmospheric	$\sim 3 \times 10^{-3}$	1300
Solar (LMA)	$\sim 5 \times 10^{-5}$	10^5
Solar (SMA)	$\sim 5 \times 10^{-6}$	2×10^6
Solar (Vac)	$\sim 10^{-10}$	7×10^{11}

- $\Delta m^2_{23}, \theta_{23}$: atmospheric ν oscillation
  - Super-Kamiokande: $\Delta m^2_{23} = 3 \times 10^{-3}, \sin^2 2\theta_{23} > 0.88$
    Not consistent with $\nu_\mu \rightarrow \nu_{sterile}$ only
  - K2K: 2σ effect observed.
  - MINOS,ICANOE,OPERA(τ appearance),MONOLITH
- $\Delta m^2_{12}, \theta_{12}$: Solar ν oscillation
  - Super-Kamiokande, Ga, Cl: LMA favored.
    Not consistent with $\nu_e \rightarrow \nu_{sterile}$ only
  - SNO+SuperK established oscillation: ES vs. CC
  - Future: Borexino, KAMLAND (confirm LMA)
- $\Delta m^2_{13}, \theta_{13}$: Reactor limit
  - $\Delta m^2_{13} \sim \Delta m^2_{23}$, $\sin^2 2\theta_{13} < 0.1$(CHOOZ)
- δ_{CP}: Large to create baryon asymmetry (Leptogenesys)
- 4th neutrino?: LSND result
  - KARMEN: null result (small allowed region remains)
  - mini-BooNE

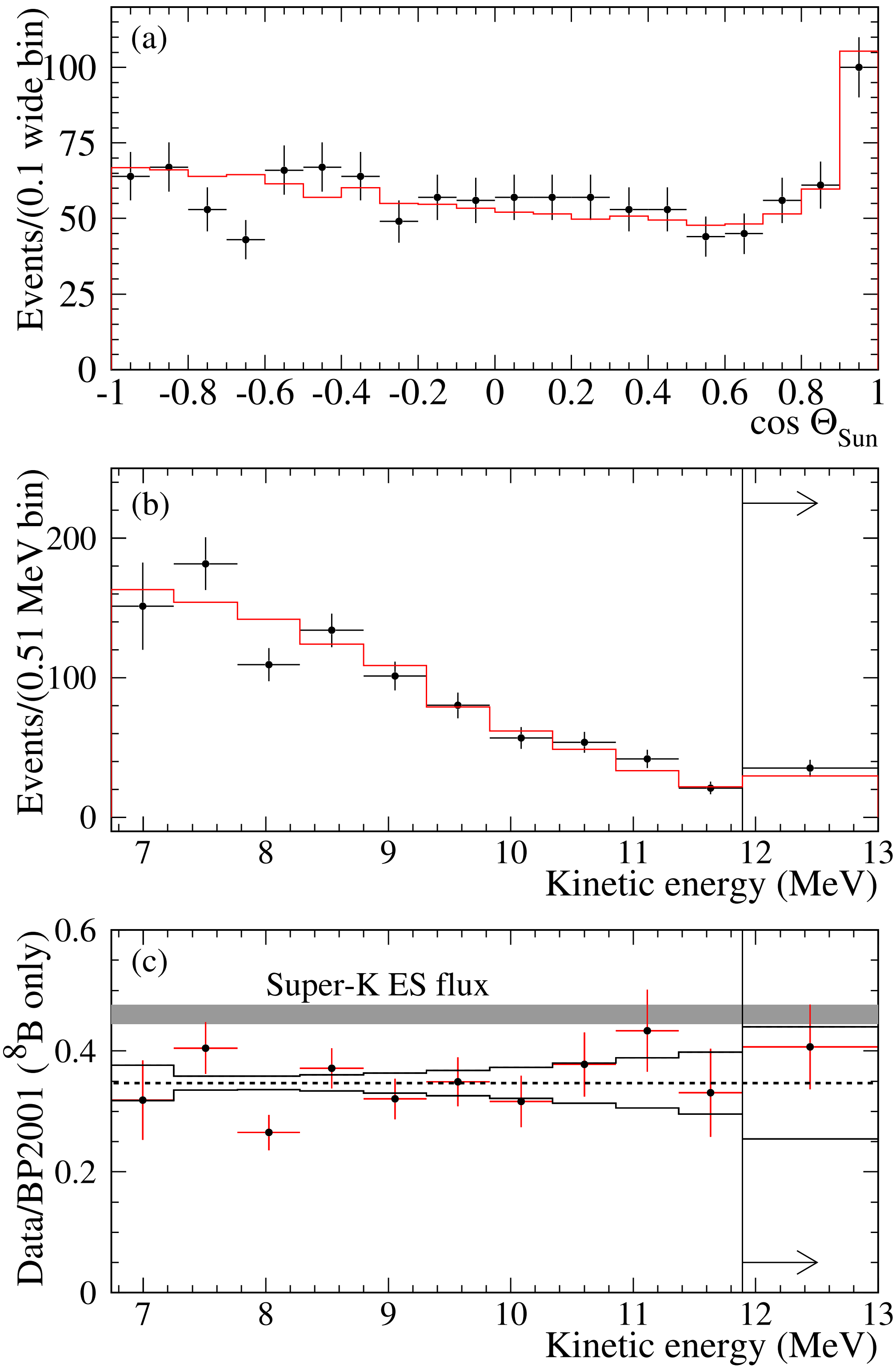
SK atmospheric results





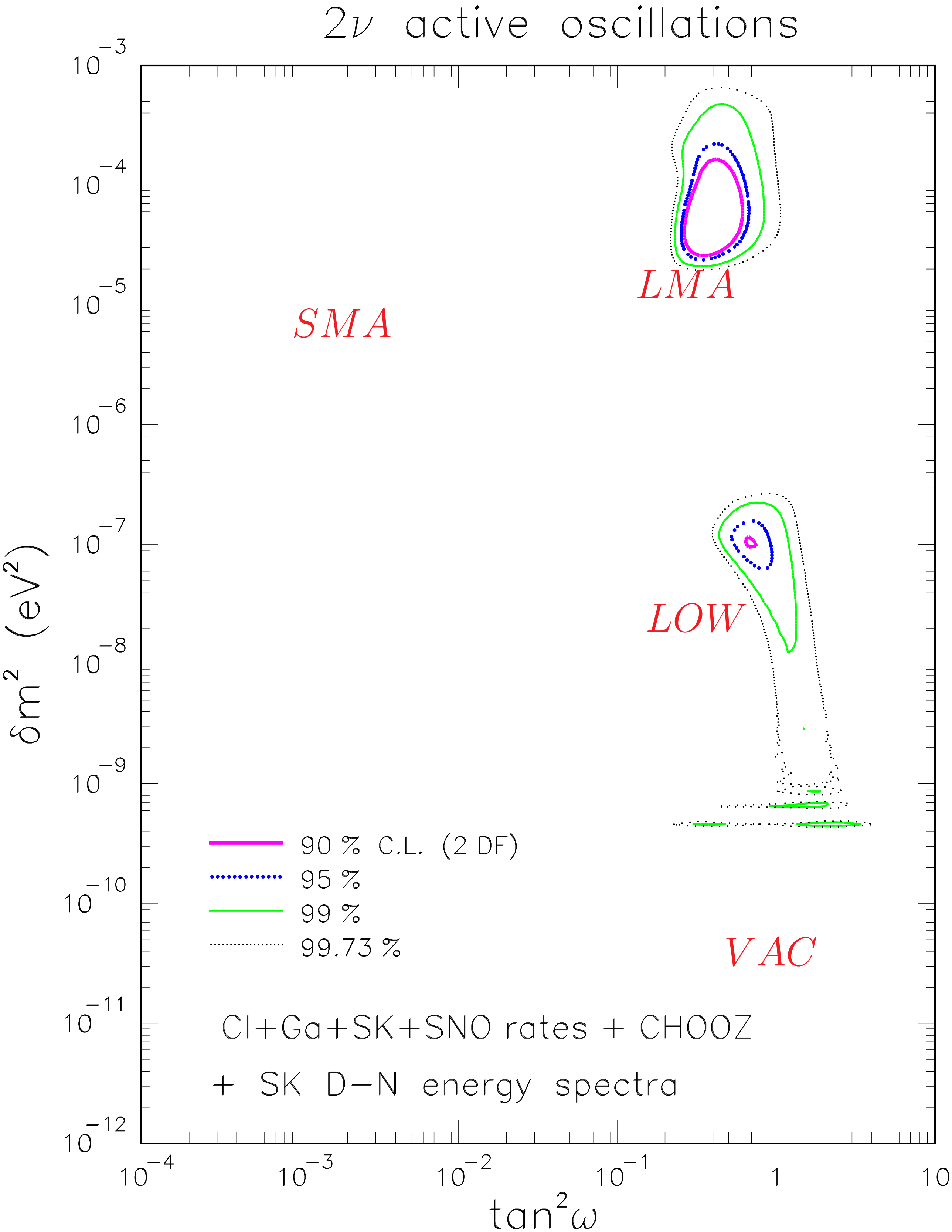


SNO result (nucl-ex/0106015)

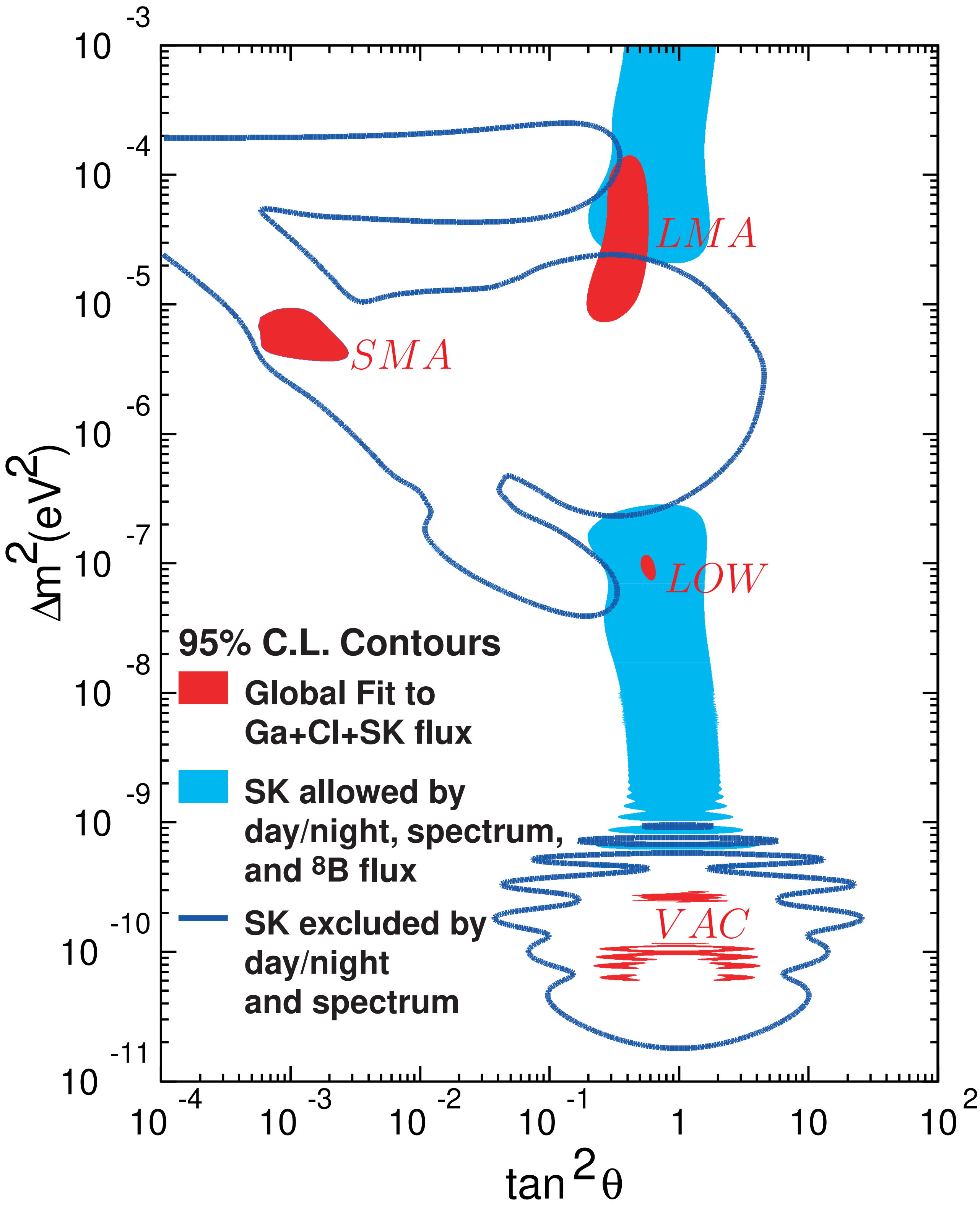


$$\Phi(\nu_{\mu\tau}) = 3.69 \pm 1.13 \times 10^6 cm^{-2}s^{-1}$$

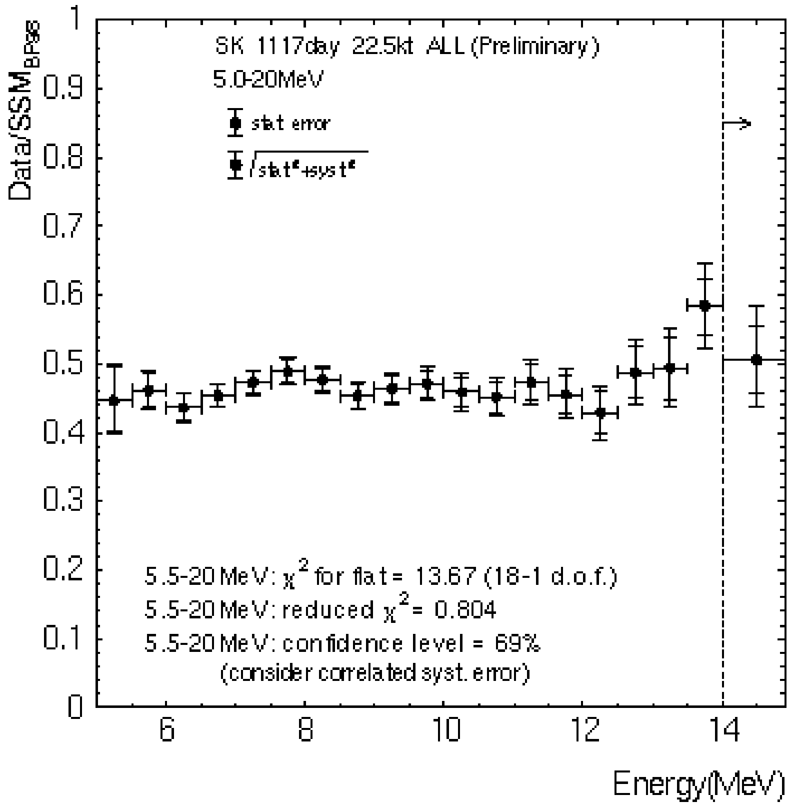
Solar ν allowed regions after SNO (hep-ph/0106247)



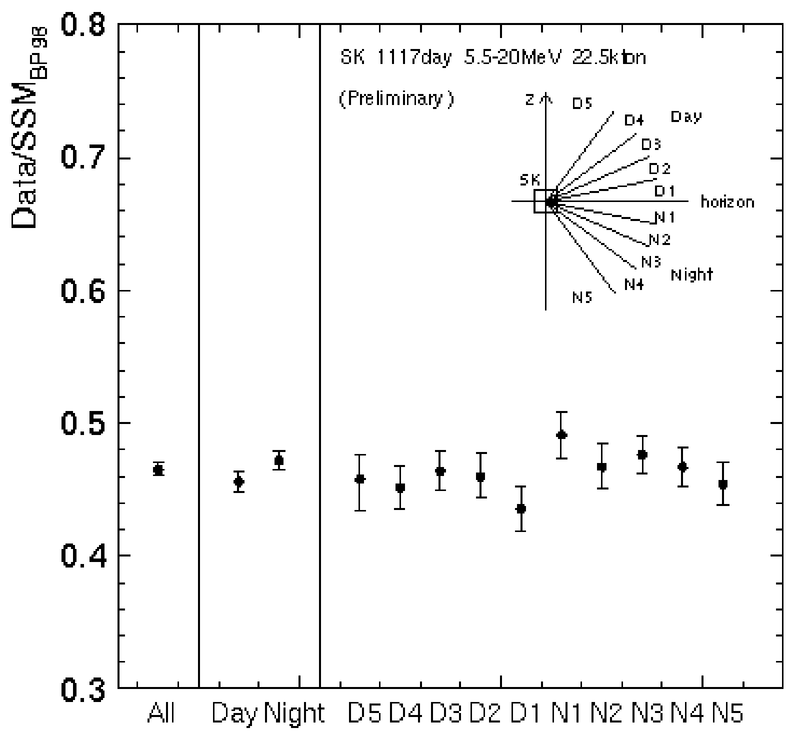
Solar ν allowed regions



SK solar results



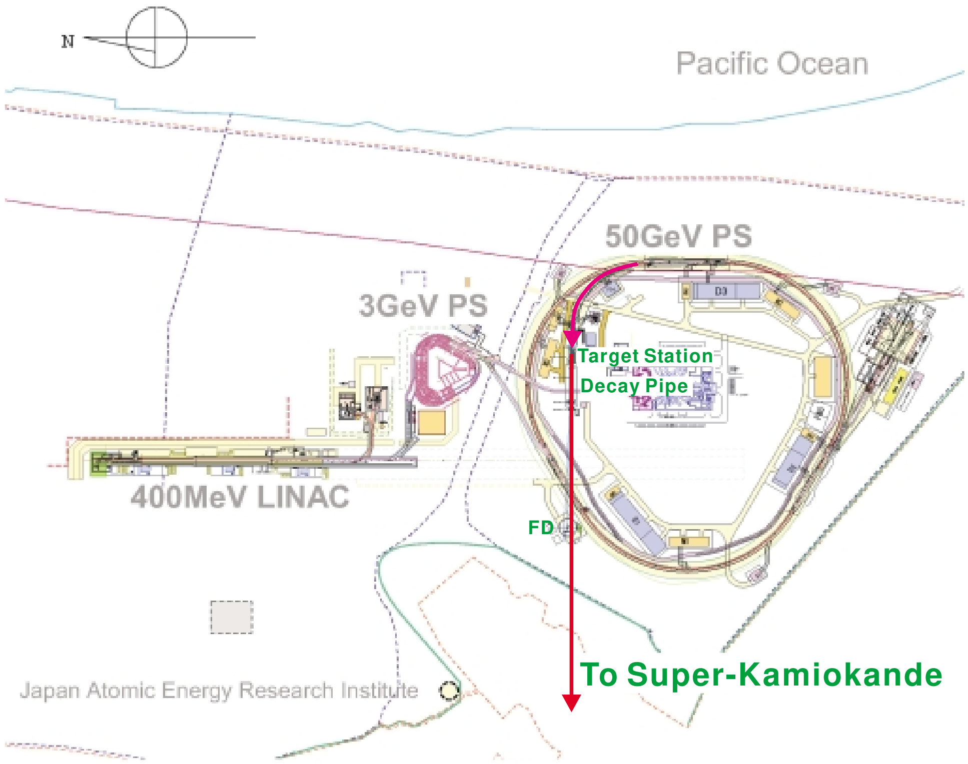
Spectrum is flat at lower energy



No significant day/night effect seen

JHF project and the neutrino experiment

JAERI@Tokai (60km N.E. of KEK)
Construction: 2001-2006 (budget approval in Dec.2000 !)



	JHF	MINOS	K2K
E(GeV)	50	120	12
Intensity (10^{12}ppp)	330	40	6
Rate (Hz)	0.292	0.53	0.45
Power (MW)	0.77	0.41	0.0052

10^{21}POT/year
Beam power is expected to be upgraded up to 4MW
(upgrades in power supplies and the barrier bucket scheme)

Letter of Intent: June 5, 2001 (hep-ex/0106019)

The JHF-Kamioka neutrino project

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Abstract

The JHF-Kamioka neutrino project is a second generation long base line neutrino oscillation experiment that probes physics beyond the Standard Model by high precision measurements of the neutrino masses and mixing. A high intensity narrow band neutrino beam is produced by secondary pions created by a high intensity proton synchrotron at JHF (JAERI). The neutrino energy is tuned to the oscillation maximum at $\sim$1 GeV for a baseline length of 295 km towards the world largest water Čerenkov detector, Super-Kamiokande. Its excellent energy resolution and particle identification enable the reconstruction of the initial neutrino energy, which is compared with the narrow band neutrino energy, through the quasi-elastic interaction. The physics goal of the first phase is an order of magnitude better precision in the $\nu_\mu \to \nu_\tau$ oscillation measurement ($\delta(\Delta m^2_{23}) = 10^{-4}$ eV^2 and $\delta(\sin^2 2\theta_{23}) = 0.01$), a factor of 20 more sensitive search in the $\nu_\mu \to \nu_e$ appearance ($\sin^2 2\theta_{\mu e} \simeq 0.5 \sin^2 2\theta_{13} > 0.003$), and a confirmation of the $\nu_\mu \to \nu_\tau$ oscillation or discovery of sterile neutrinos by detecting the neutral current events. In the second phase, an upgrade of the accelerator from 0.75 MW to 4 MW in beam power and the construction of 1 Mt Hyper-Kamiokande detector at Kamioka site are envisaged. Another order of magnitude improvement in the $\nu_\mu \to \nu_e$ oscillation sensitivity, a sensitive search of the CP violation in the lepton sector (CP phase δ down to $10^\circ - 20^\circ$), and an order of magnitude improvement in the proton decay sensitivity is also expected.

- Super-Kamiokande as a far detector: L=295km
- Narrow band beam tuned at the oscillation maximum.
  ⇒ 2nd generation long baseline neutrino experiment

$$\Delta m^2 = (1.6 - 4) \times 10^{-3} eV^2 \Rightarrow E_\nu = (0.4 - 1.0) GeV$$

- Reconstruct the neutrino energy event by event (QE events).
  ⇒ Oscillation pattern measurement
- Goal of the experiment

  ×10 improvement in ν_μ disappearance:
  $\delta(\sin^2 2\theta_{23}) \sim 0.01$, $\delta(\Delta m^2_{23}) \sim 2 \times 10^{-4} eV^2$

  Search for $\nu_\mu \rightarrow \nu_e$ appearance ×20 beyond CHOOZE:
  $\sin^2 2\theta_{\mu e} \simeq 0.5 \sin^2 2\theta_{13} > 0.003$

  Search for a small admixture of sterile ν

  CP violation and a test of the unitarity (2nd phase)

Narrow band beam at the oscillation max.

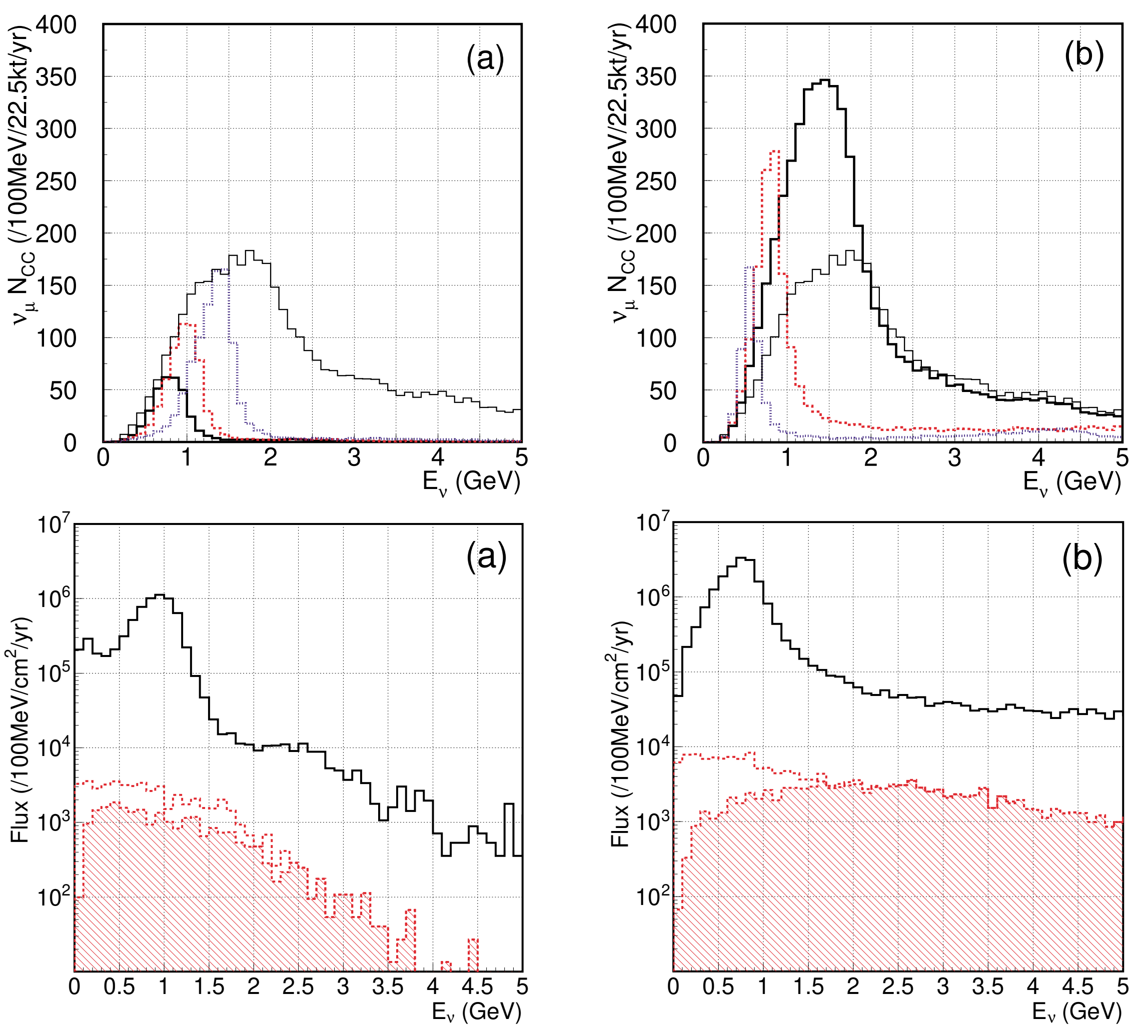
- Maximum oscillation ⇒ maximum signal enhancement

- Neutrnio energy at the oscillation maximum for JHF-Kamioka:
$$\frac{1.27\Delta m^2_{atm}L}{E} = \frac{\pi}{2} \quad \Rightarrow \quad E_\nu\text{=0.4-1.0GeV for L=295km}$$

- Tuning the narrow band beam energy

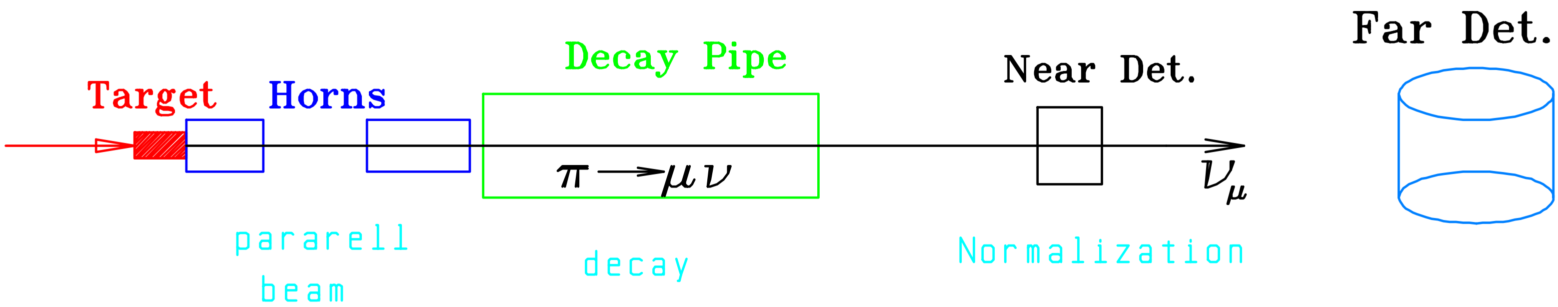
  Narrow band beam (NBB): Dipole current

  Off axis beam (OAB): Offset angle

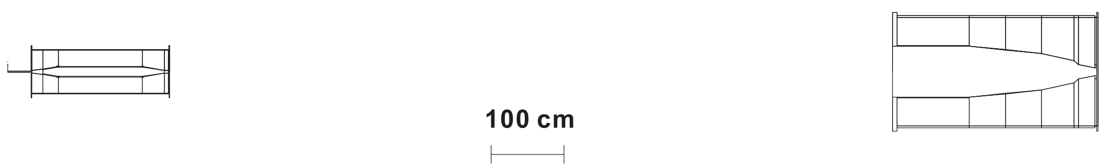


High intensity low energy ν beam

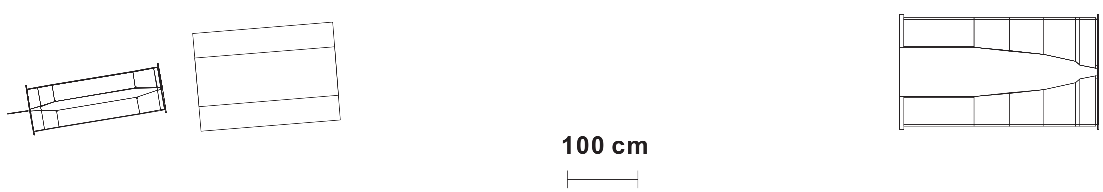
- Conventional ν_μ beam using horns



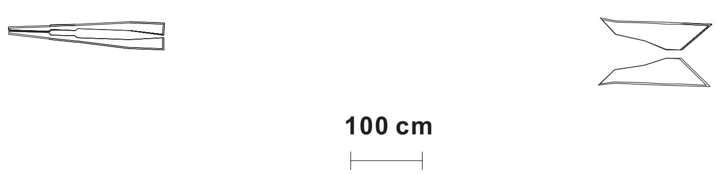
Wide band beam (similar to K2K, NUMI, CNGS)



Narrow band "dichromatic" beam



Off axis beam (ala BNL-E889 proposal)



- Critical points in the beam design

High intensity

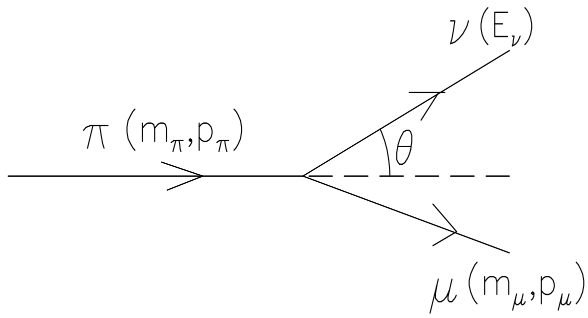
Suppression of high energy tail (narrow band)

Suppression of ν_e contamination

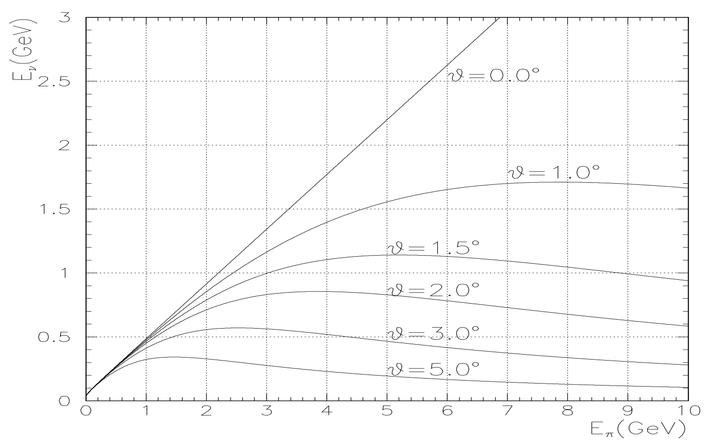
Understanding the beam systematics (beam monitoring)

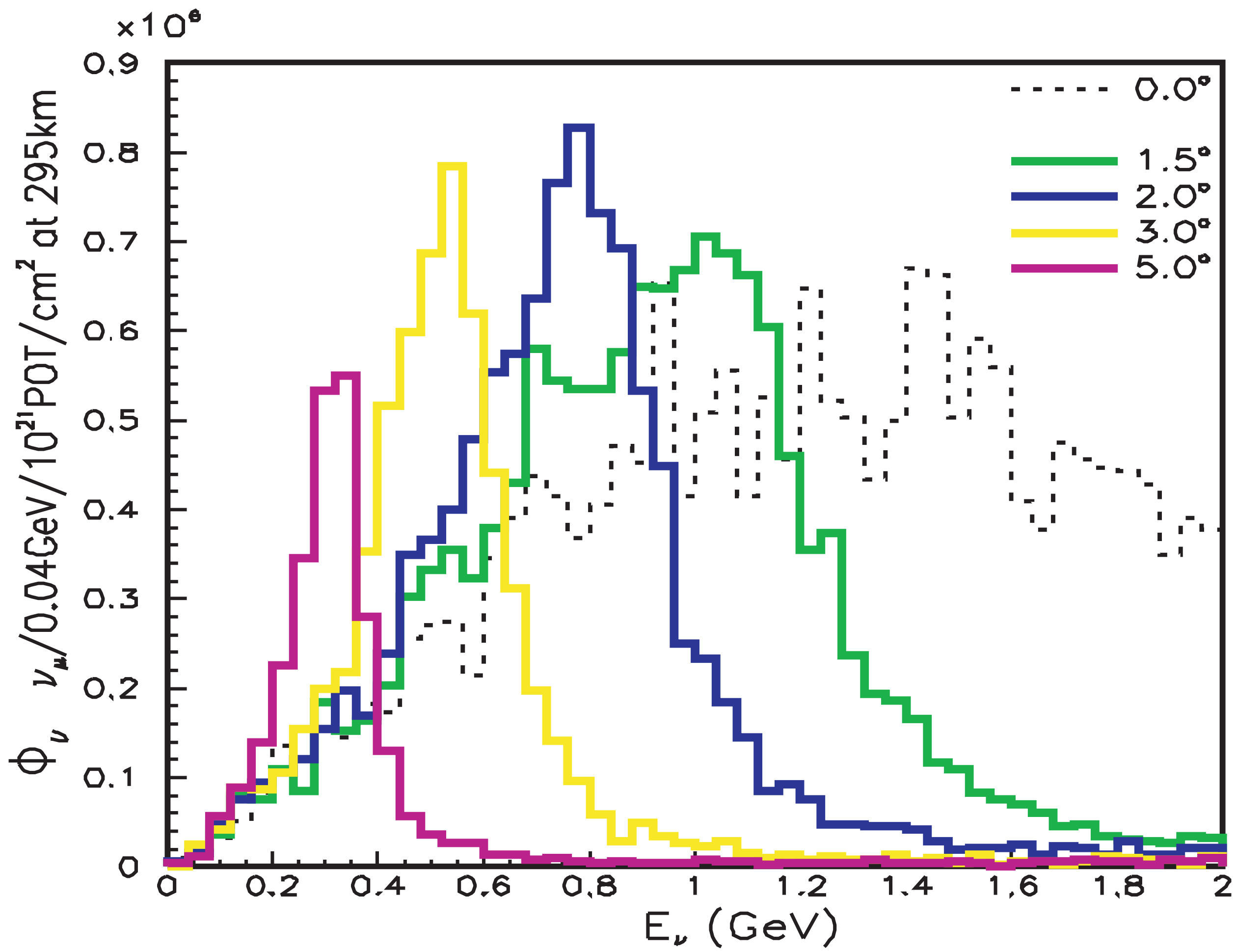
Off axis neutrino beam

BNL-E889 proposal, April 1995

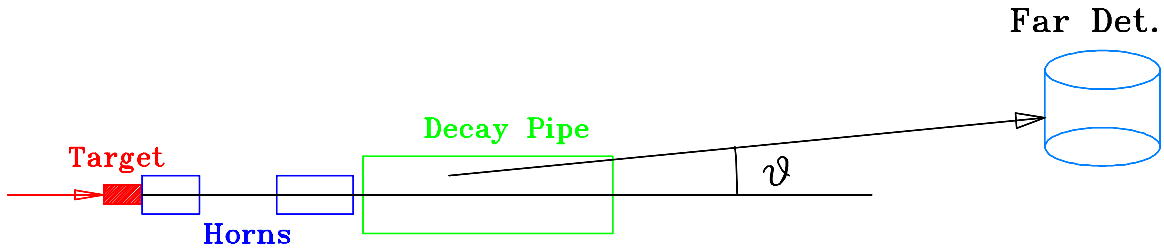


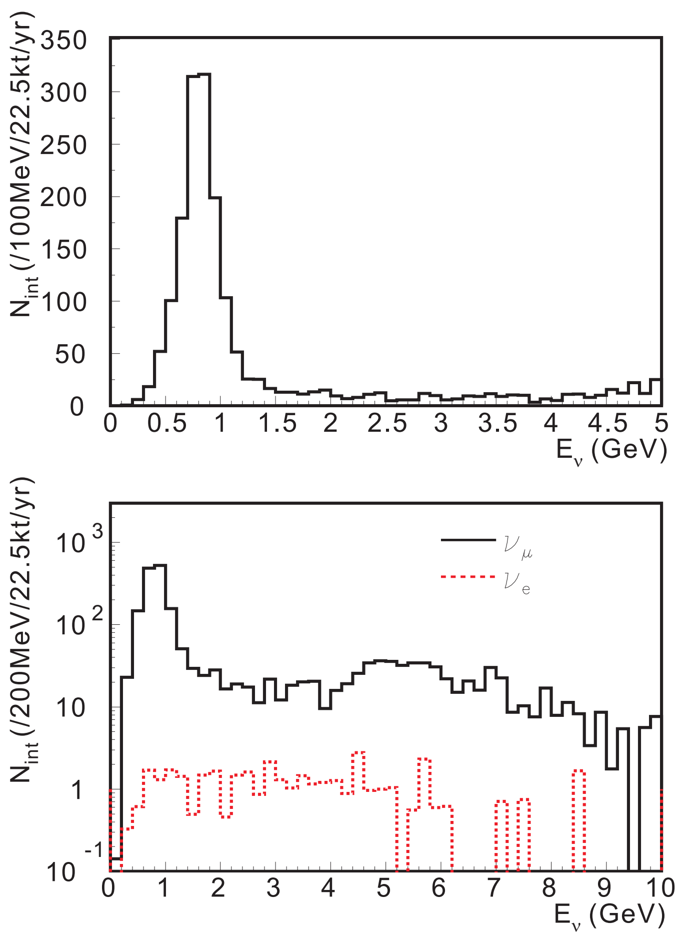
$$E_\nu = \frac{m_\pi^{\,2} - m_\mu^{\,2}}{2(E_\pi - p_\pi \cos\theta)}$$



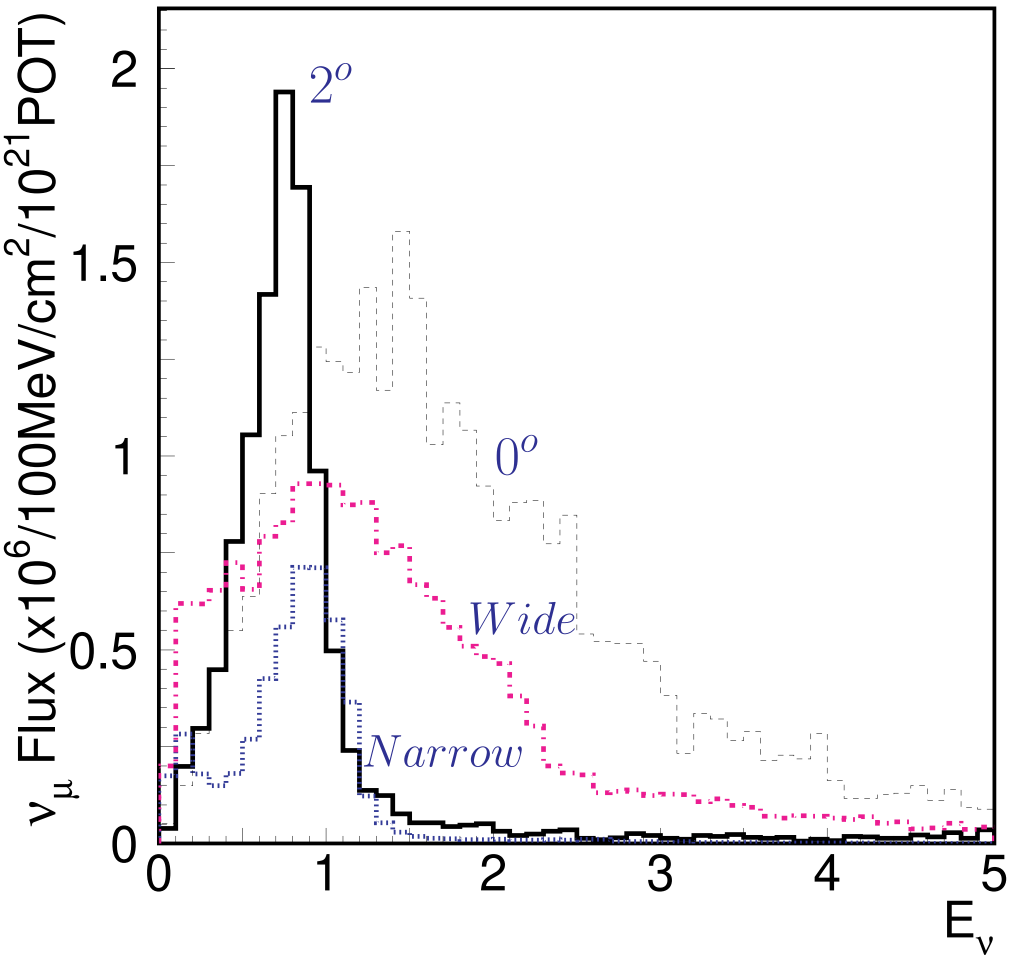


Off axis beam





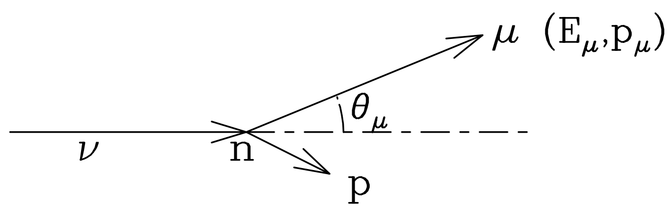
- High intensity (2200 int./22kt/year)
  More than wide band at the peak energy
- Small backgrounds from high energy tail
- 0.2% ν_e contamination (peak)
- Beam systematics under control
  Large oscillation signal

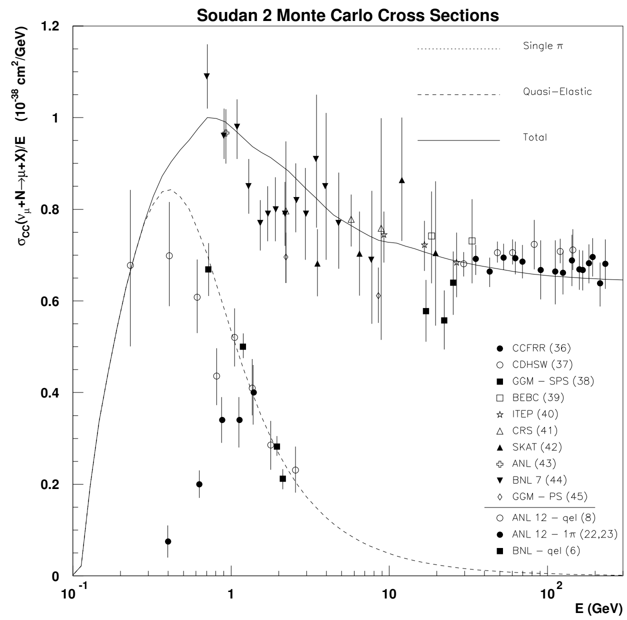


- Intensity of 2^o off axis beam is higher than 0^o wide band.

Neutrino energy reconstruction

- Tow body Quasi-elastic (QE) reaction for E_ν reconstruct.

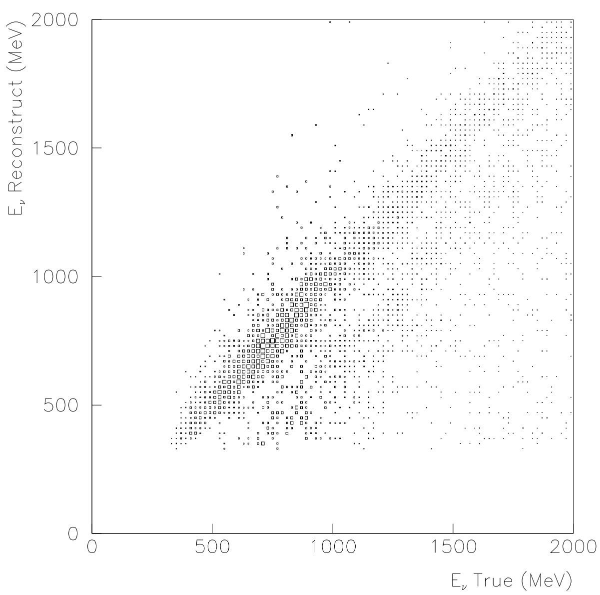


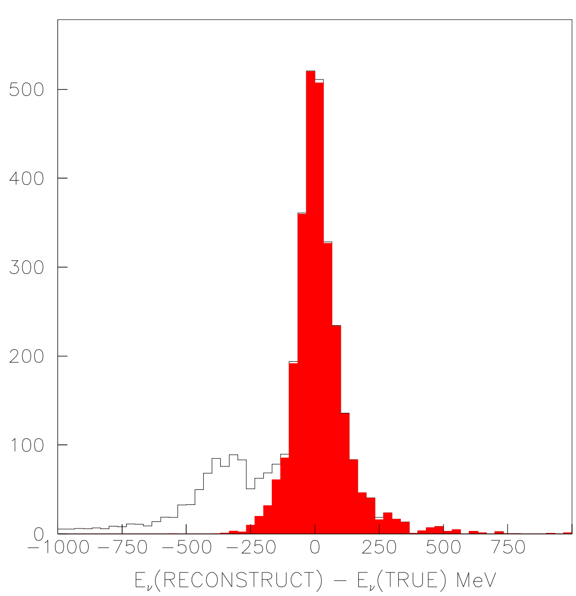


$$E_\nu = \frac{m_N E_l - m_l^2/2}{m_N - E_l + p_l cos\theta_l}$$

QE dominates in E_ν=0.4-1.0GeV region.
QE cross sections for ν_μ and $\bar{\nu}_\mu$ are reasonably high.

- Resolution of the reconstructed energy
  ΔE_ν=80MeV ($\Delta E_\nu/E_\nu$=10%): limited by Fermi motion

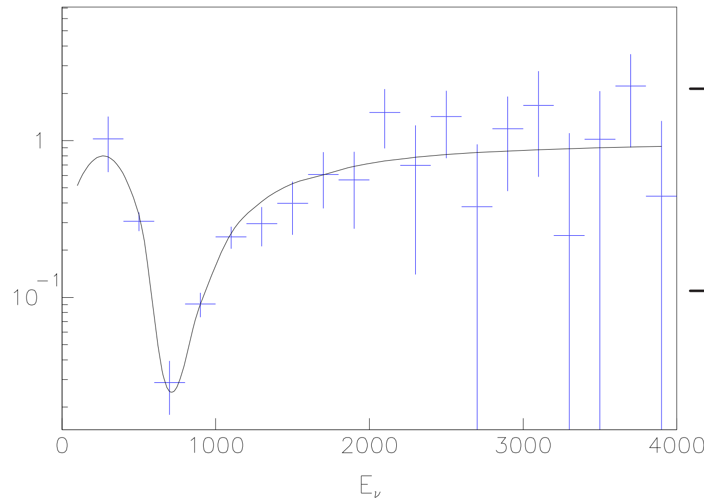




⇒ Precise oscillation pattern measuement

Oscillation pattern measurement at the oscil. max.

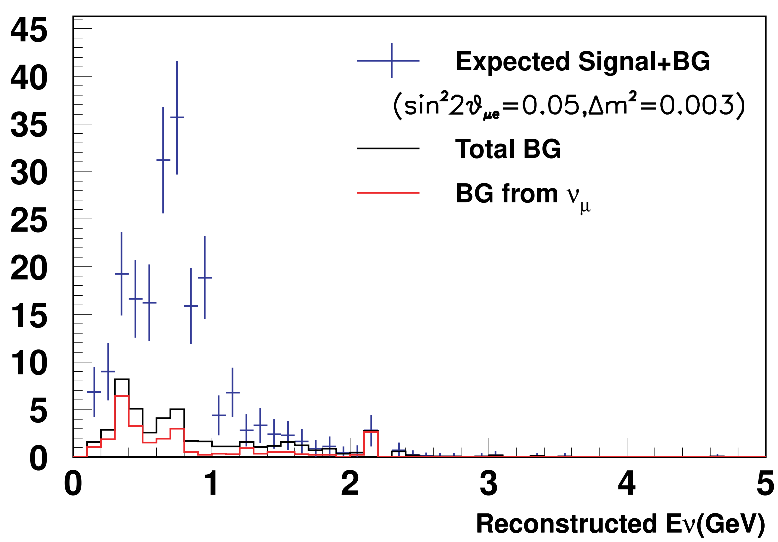
- Signal enhancement



+ Depth of the dip $= 1 - \sin^2 2\theta_{23}$:
  10% measurement of the dip
  $\Rightarrow$ 0.03·10%=0.3% in $\sin^2 2\theta_{23}$

+ Position of the dip:
  $\Rightarrow \Delta m^2 = \frac{\pi}{2} \cdot \frac{1}{1.27} \cdot \frac{E_\nu}{L}$

- Background suppression
  - Energy window around the oscillation maximum

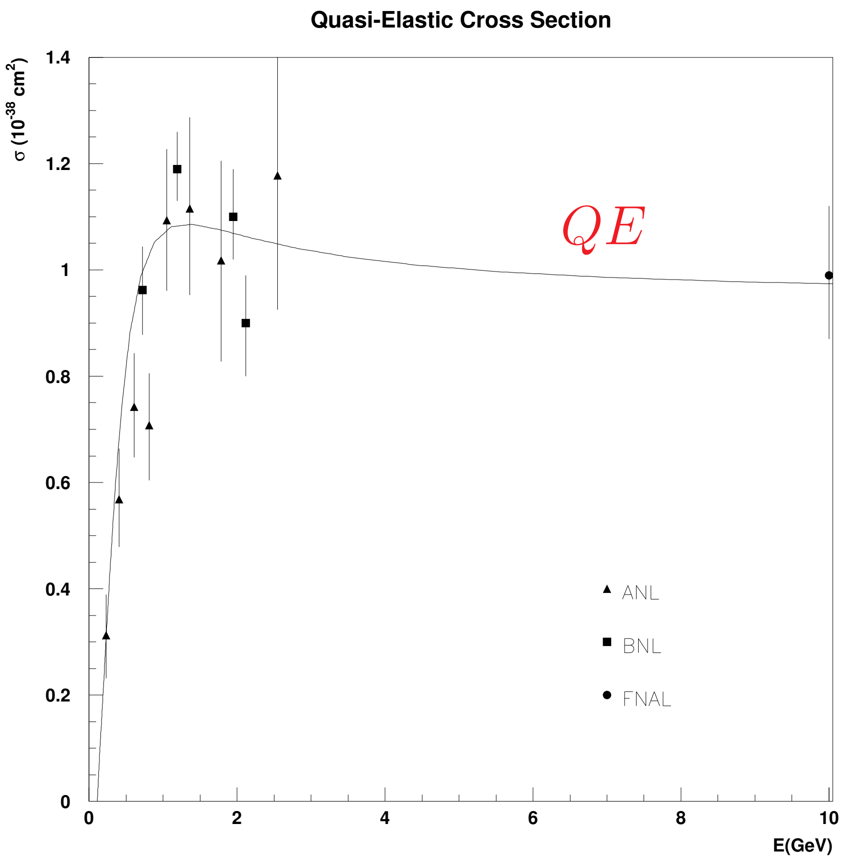


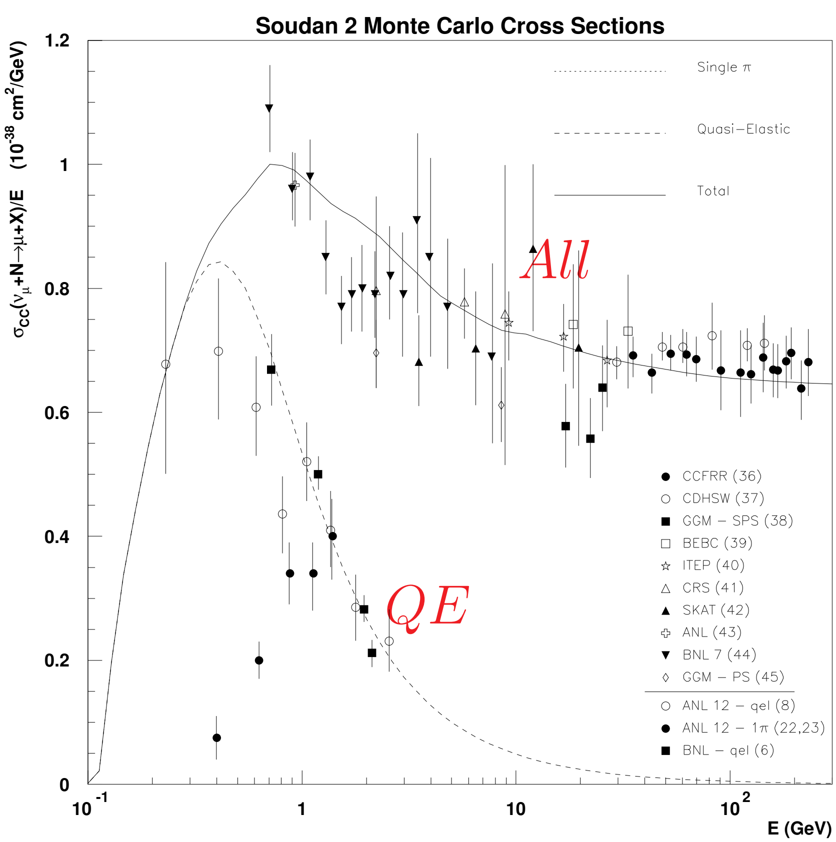
- Suppression of the systematic uncertainties
  - Enhancement of signals and suppression of backgrounds
  - Positive ID of the signal by the oscillation pattern
  - Events outside the energy window to monitor backgrounds.

Low energy neutrino beam

- Baseline length of 295km $\Rightarrow$ Oscil. max. at 0.4-1.0GeV
- Quasi-elastic reaction dominates
  - Neutrino energy reconstruction
  - Flux measurement (Q^2 dependence of the cross section)
  - High enough energy for
    - $\bar{\nu}$ detection and
    - acceptable resolution smearing due to Fermi motion (80MeV)
- Water Čerenkov detector is available
  - Large fiducial mass is possible
  - Good energy and angular resolutions
    $\Delta E/E \sim 3\%$, $\Delta\theta \sim 3^\circ$ for 1GeV μ
  - Excellent particle identification
    R(e/μ)$\sim$500, R($NC-\pi^0/e$)$\sim$100
- Intense narrow band neutrino beams are available
- Advantages in CP measurements
  - Enhancement of CP asymmetry at low energy
  - Suppression of the fake matter asymmetry

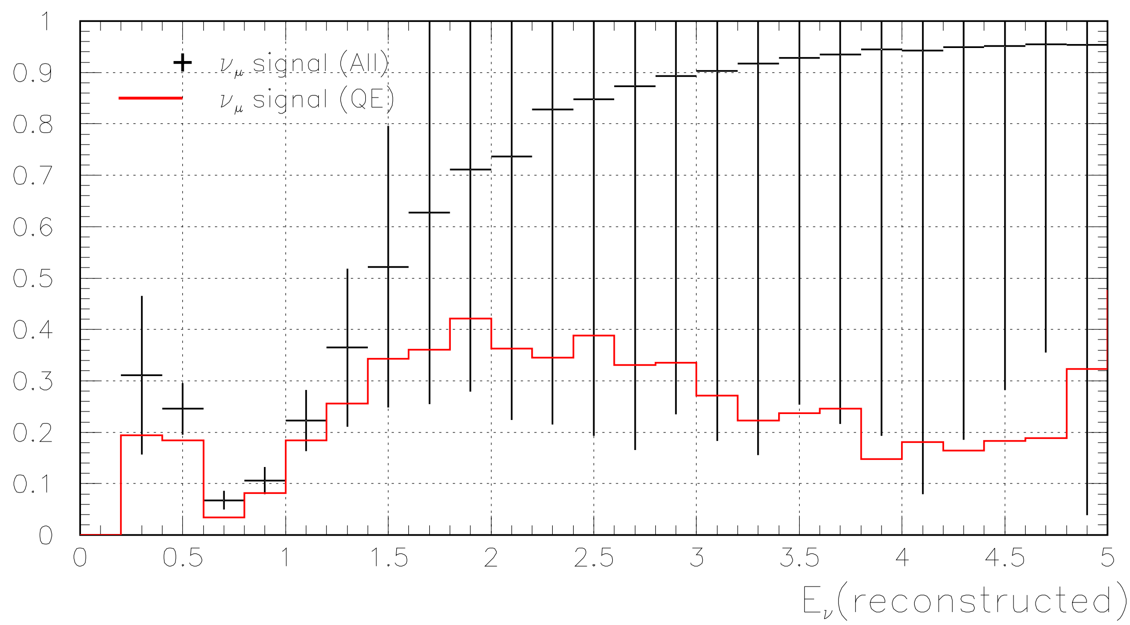
QE dominates for $E_\nu < 1\text{GeV}$





Sensitivities of the JHF-ν experiment

- ν_μ disappearance (precision measurement)

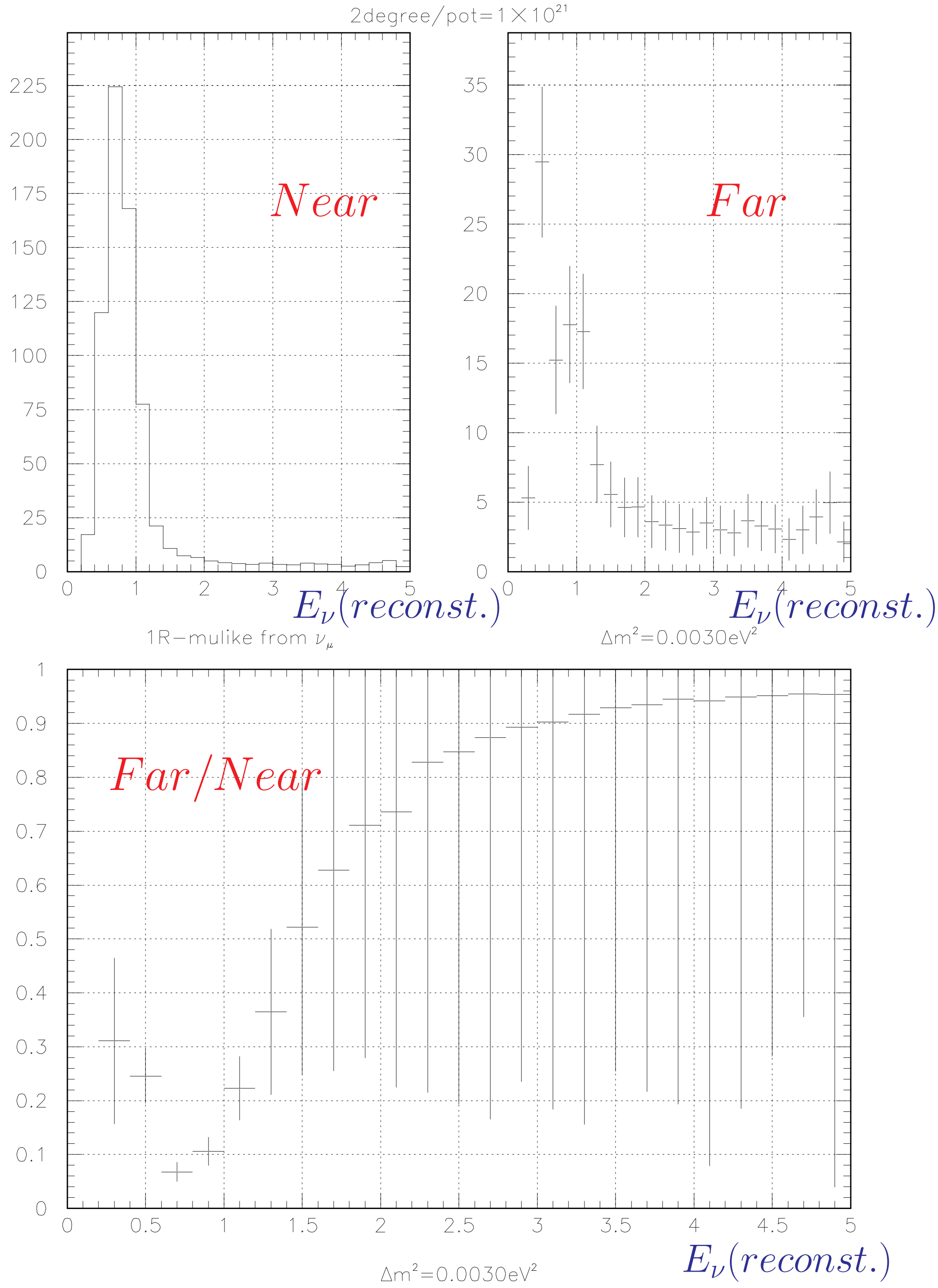


(Error bar corresponds to statistical error of 1year)

- Depth of the dip corresponds to $1 - \sin^2 2\theta_{23}$:
  10% (stat.,syst.) error in the dip measurement
  $\Rightarrow 0.07 \times 10\% = 0.7\%$ measurement in $\sin^2 2\theta_{23}$
- Position of the dip provides Δm^2
  $\Delta m^2 = \frac{\pi}{2} \cdot \frac{1}{1.27} \cdot \frac{E_\nu}{L}$

Big advantage of narrow band beam with E_ν reconst.

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

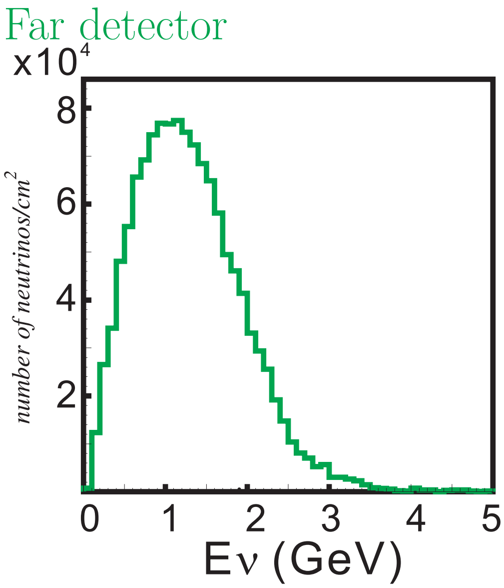

2degree/pot=1×10^21
Near
Far
Eν(reconst.)
Eν(reconst.)
1R−mulike from νμ
Δm²=0.0030eV²
Far/Near
Eν(reconst.)
Δm²=0.0030eV²

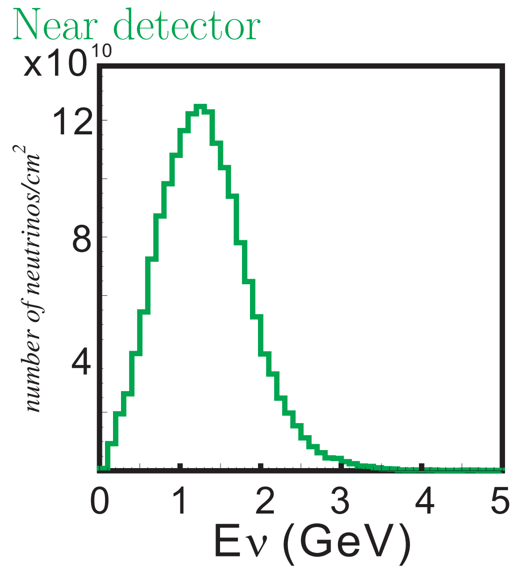
- Systematic uncertainty of the K2K experiment

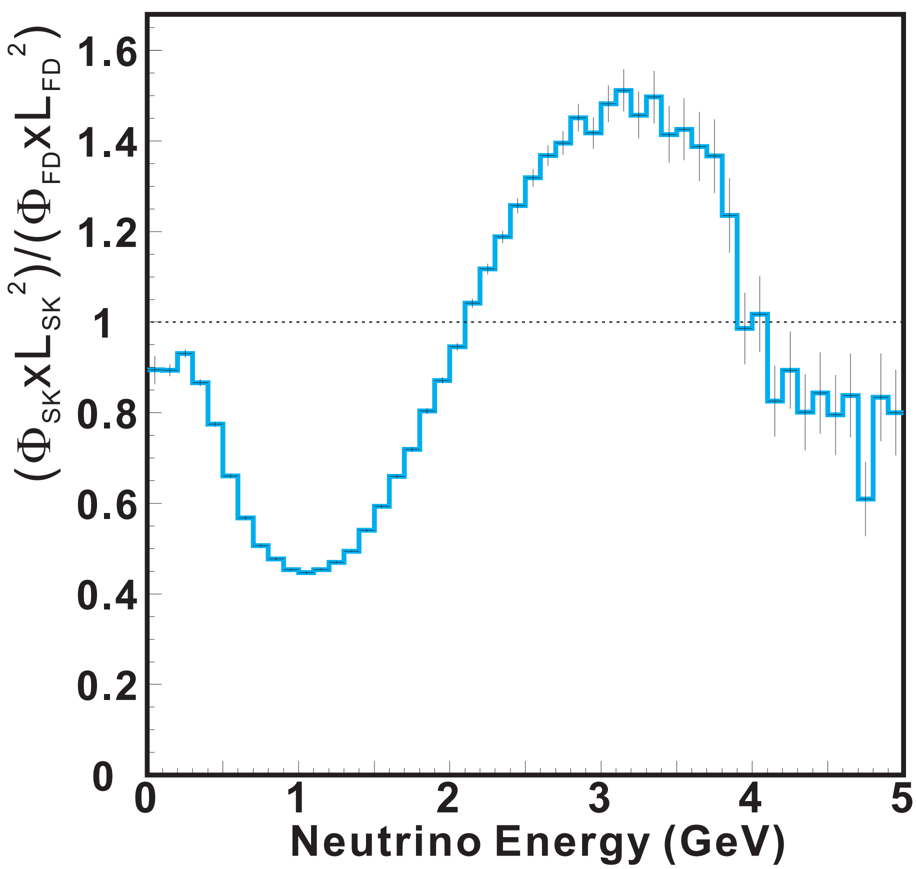
	1kt	Fe	SFT
Flux	+1.3% -1.7%	3%	3-4%
ΔR(Far/Near ratio)	+6% -7%	+6% -7%	+6% -7%
Background	1%		1%
NC/CC(±30%)	+0.8% -0.9%	6%	5%
Detection Eff.		3%	5%
Cross section		10%	3%
Multi event	3%		
$\Delta V/V$(FD)	6%	<2%	3%
$\Delta V/V$(SK)	3%	3%	3%
Total	+10% -11%	15%	13%

- Systematic uncertainty of K2K is enough for JHF-ν.
- ΔR(Far/Near) and $\Delta V/V$(FD) dominates for K2K.
- $\Delta V/V$(FD) can be improved by fine grained detector.
- ΔR(Far/Near) variation is smaller for JHF-ν.

Near/Far ratio of the K2K experiment



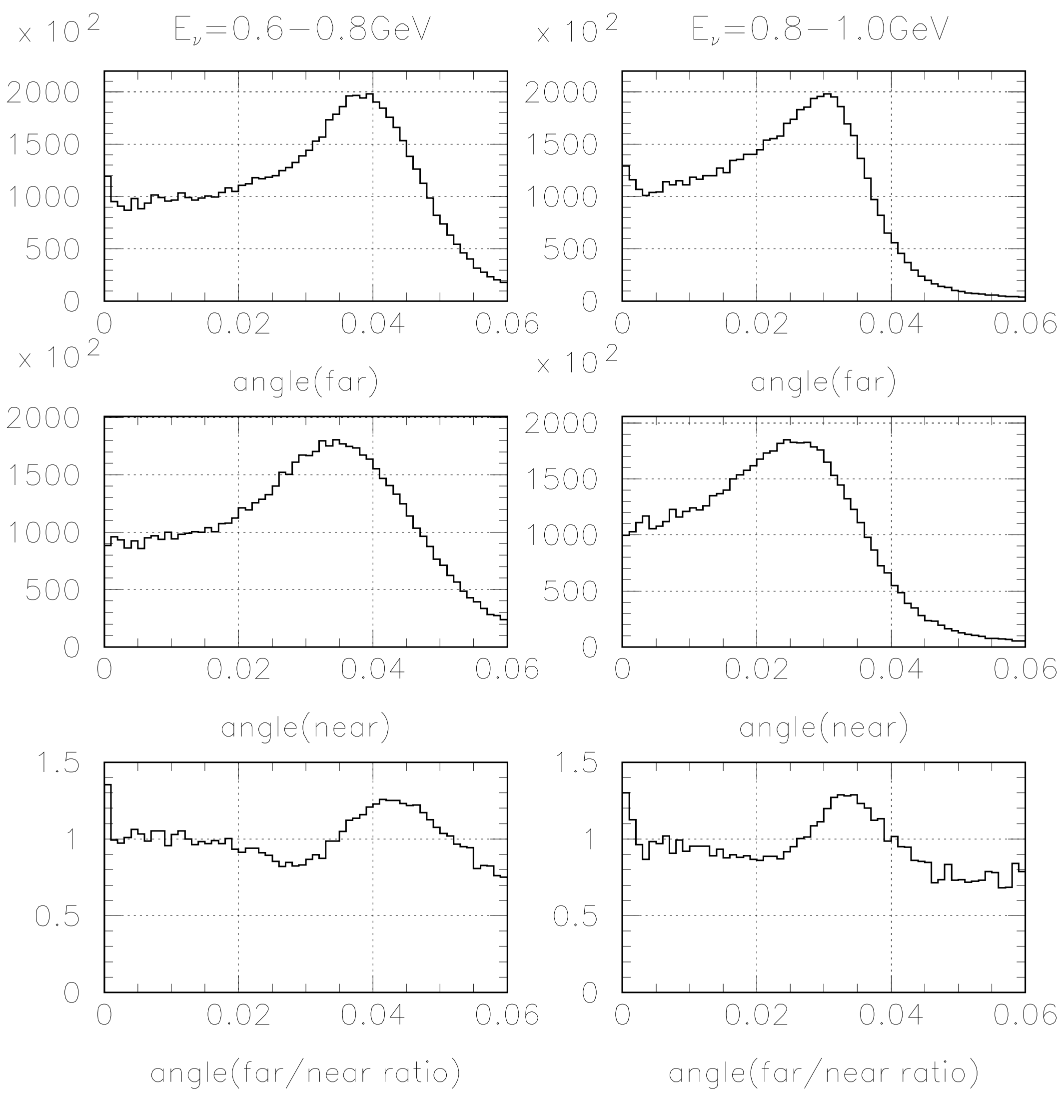


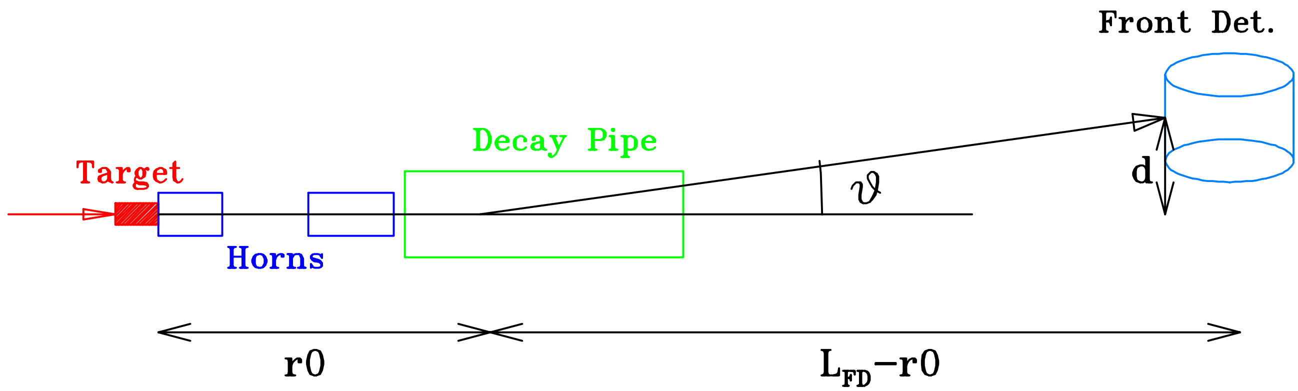


Energy dependence of the Z decay vertex

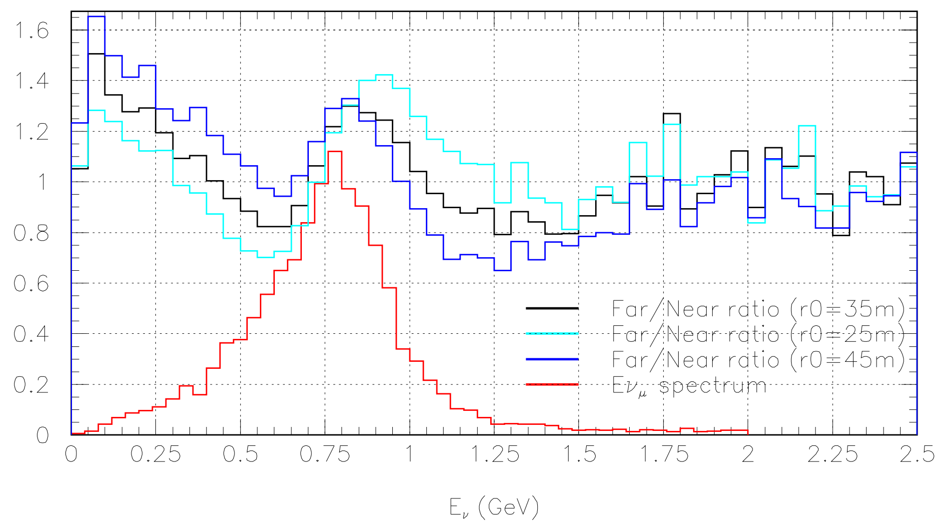
Off axis component in the near detector due to larger Ω

- Systematic uncertainty of the JHF neutrino experiment
  - Enhancement of the signal
    (Oscillation maximum)
  - Cancellation mechanism
    (Near/Far ratio insensitive to E_π)
  - Monitoring and checking of the systematics
    (E_ν versus angle distribution)

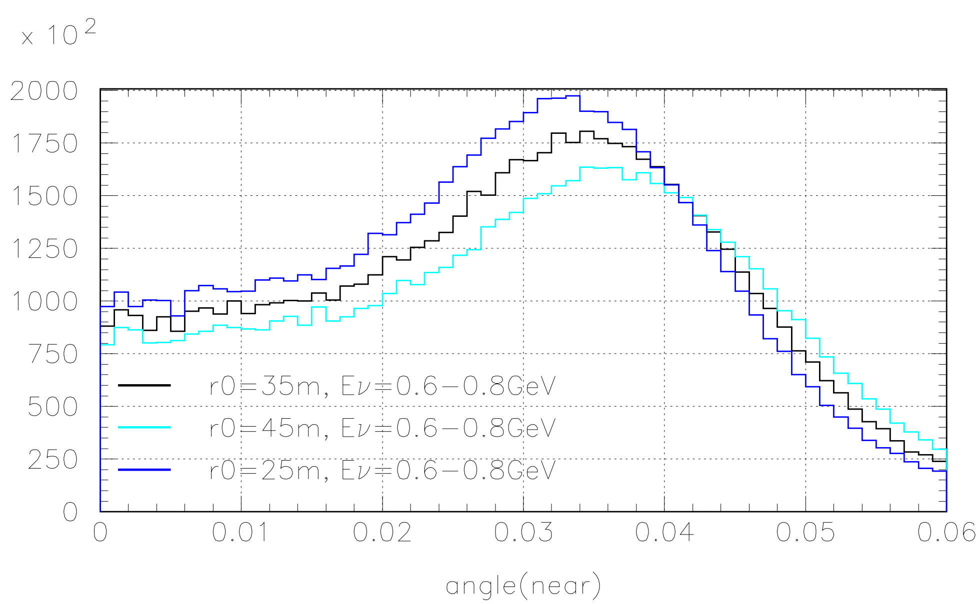




- Variation in Far/Near ratio due to r0 is less than 20%.

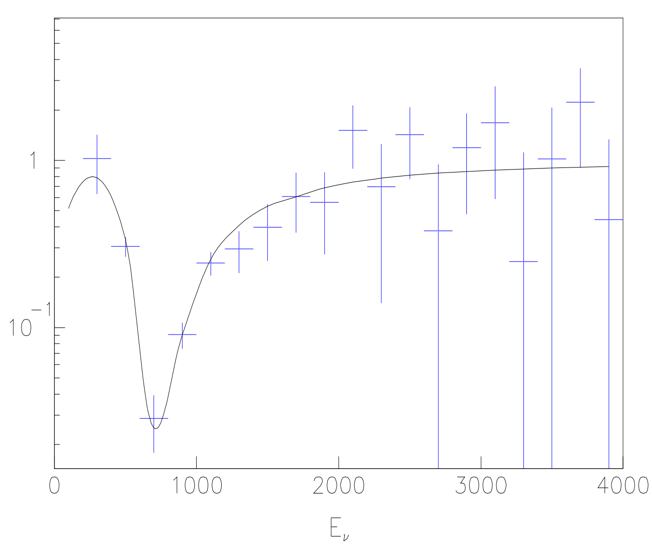


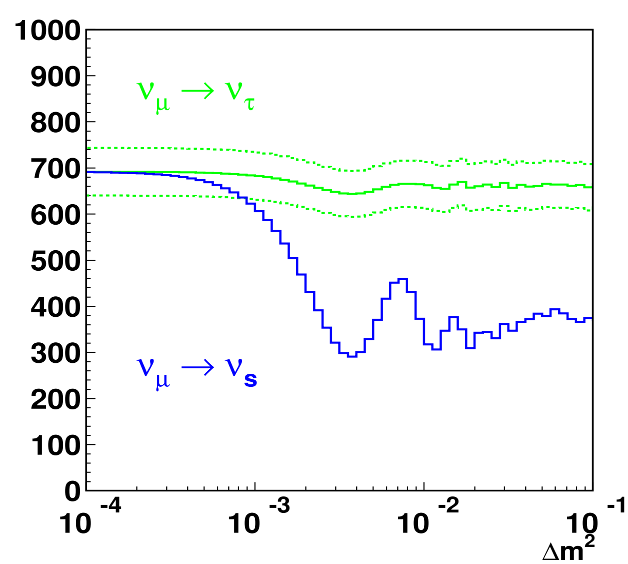
- The r0 can be checked and monitored in the front detector.



Search for sterile ν and other physics beyond MNS

- Oscillation pattern: Confirmation of ν oscillation
  - Neutrino decay-in-flight?
  - New FCNC interaction for ν's?
  - Sterile ν's? Extra dimension?
- Single π^0 (neutral current) production: NC/CC ratio
  - Both ν_μ (oscil. max) and ν_e (θ_{13}) are suppressed
    $\Rightarrow$ Created by active ν but not ν_e or ν_μ.
  - A few hundred single π^0 events are expected.
    $\Rightarrow$ Sensitive to small admixture of sterile neutrinos.
- Precision test of CPT
  $\Delta m^2(\nu_\mu) = \Delta m^2(\bar{\nu}_\mu)$?

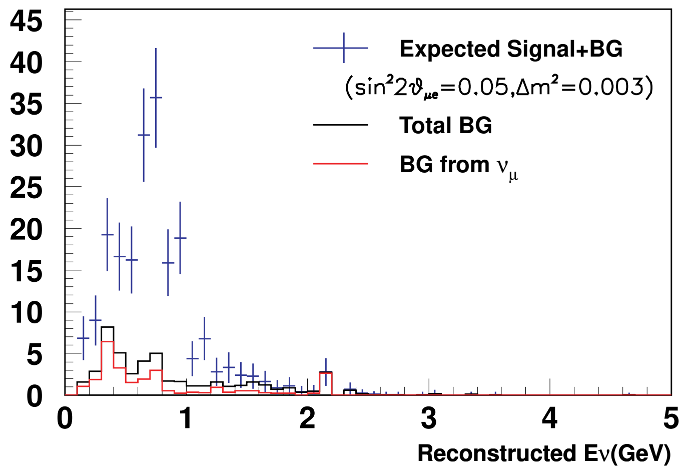




- $\nu_\mu \to \nu_e$ appearance (U_{e3})

- Signal: ν_e(Far)/ν_μ(near)

Expected to appear at the ν_μ disappearance dip.



- Backgrounds

ν_μ misidentification: negligible

ν_e contamination: $\sim$ 0.2-0.3%

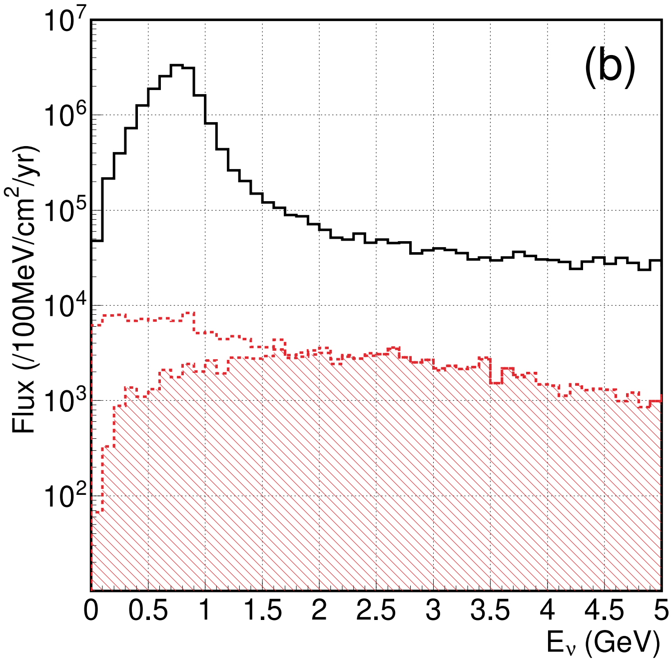
π^0 (neutral current) background: $\sim$ 0.3%

Helped by large $\pi^0 \to \gamma\gamma$ opening angle

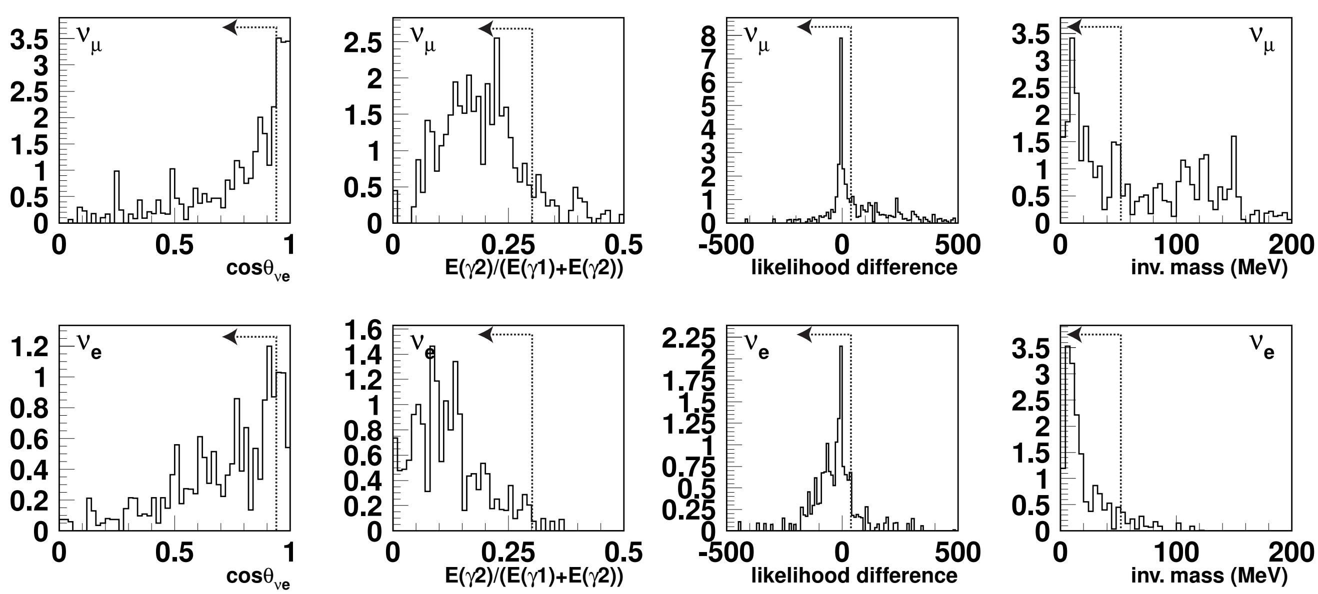
Limited by lower energy γ hidden in the scattered light

OAB 2°	ν_μ C.C.	ν_μ N.C.	Beam ν_e	Oscillated ν_e
1) Generated in F.V.	10713.6	4080.3	292.1	301.6
2) 1R e-like	14.3	247.1	68.4	203.7
3) e/π^0 separation	3.5	23.0	21.9	152.2
4) 0.4 GeV< E_{rec} < 1.2 GeV	1.8	9.3	11.1	123.2

- ν_e contamination dominated by μ decay at energy peak



- Full fit of hit patterns with single/double ring hypotheses
  - Angle between ν and e ($\cos\theta_{\nu e}$)
  - Energy fraction of lower energy ring ($\frac{E(\gamma_2)}{E(\gamma_1)+E(\gamma_2)}$)
  - Difference between double and single ring likelihood
  - Invariant mass of 2 photons

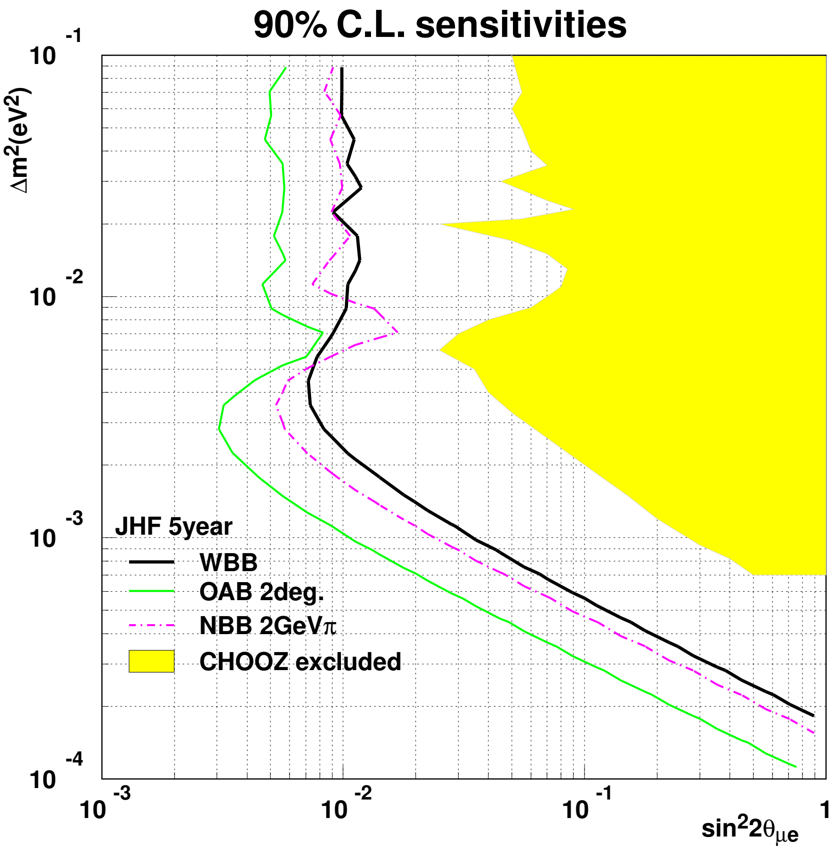


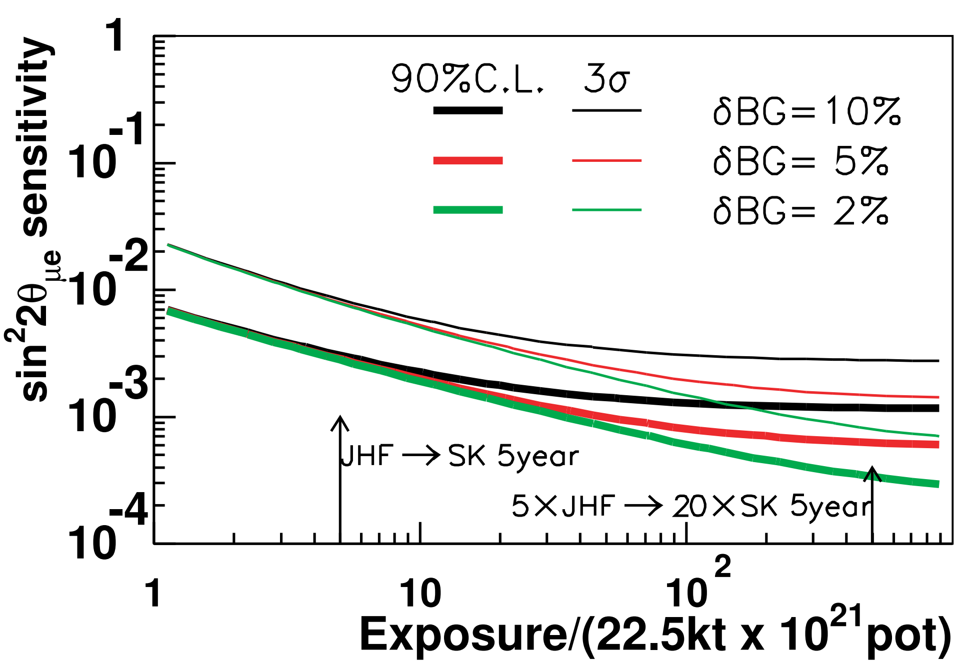
- Systematic uncertainty

  Due to background subtraction

  Smaller than the statistical error in the 1st phase.

- Sensitive to $\sin^2 2\theta_{\mu e} > 0.003$

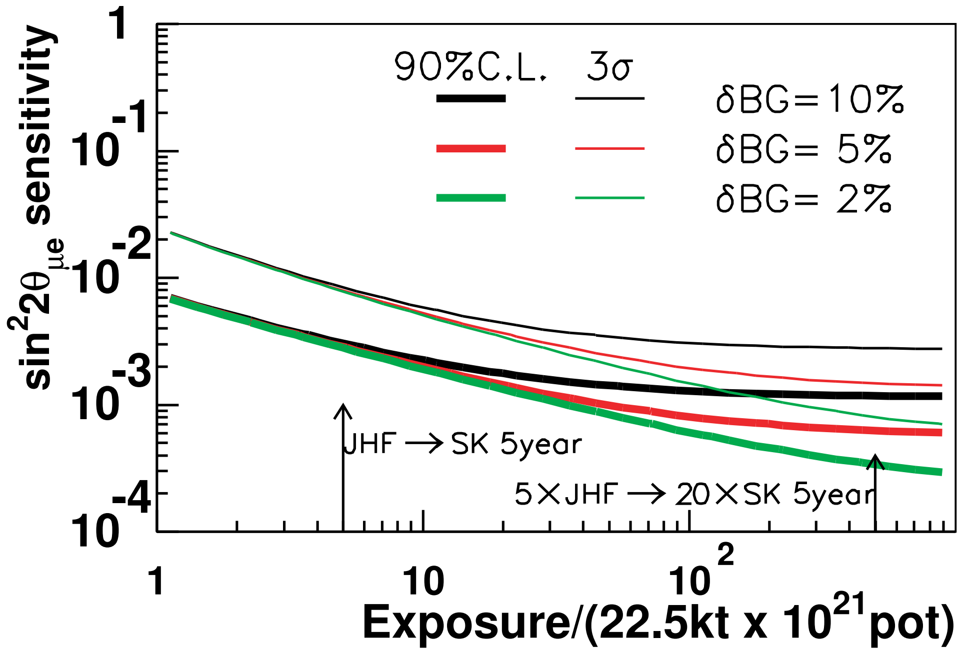




The 2nd phase of JHF-Kamioka project

- Hyper-K and JHF upgrade
  - $\times 200$ ν statistics: 1Mt detector and 4MW beam
  - Goal of the 2nd phase:
    * $sin^2 2\theta_{13}$ sensitivity below 10^{-3}
    * CP phase δ to 10-20 degrees
    * Test of the lepton unitarity triangle
    * Proton decay ($p \to K\nu, e^+\pi^0$)

- If θ_{13} not discovered in the 1st phase



  - A factor of $\sqrt{200} = 14$ improvement in statistical uncert.
    $\Rightarrow 2 \times 10^{-4}$ in $sin^2 2\theta_{\mu e}$
  - Systematic uncertainty becomes important.
  - "Peak search" in the oscillation pattern
    $\Rightarrow$ hope to get around the limit due to systematics.

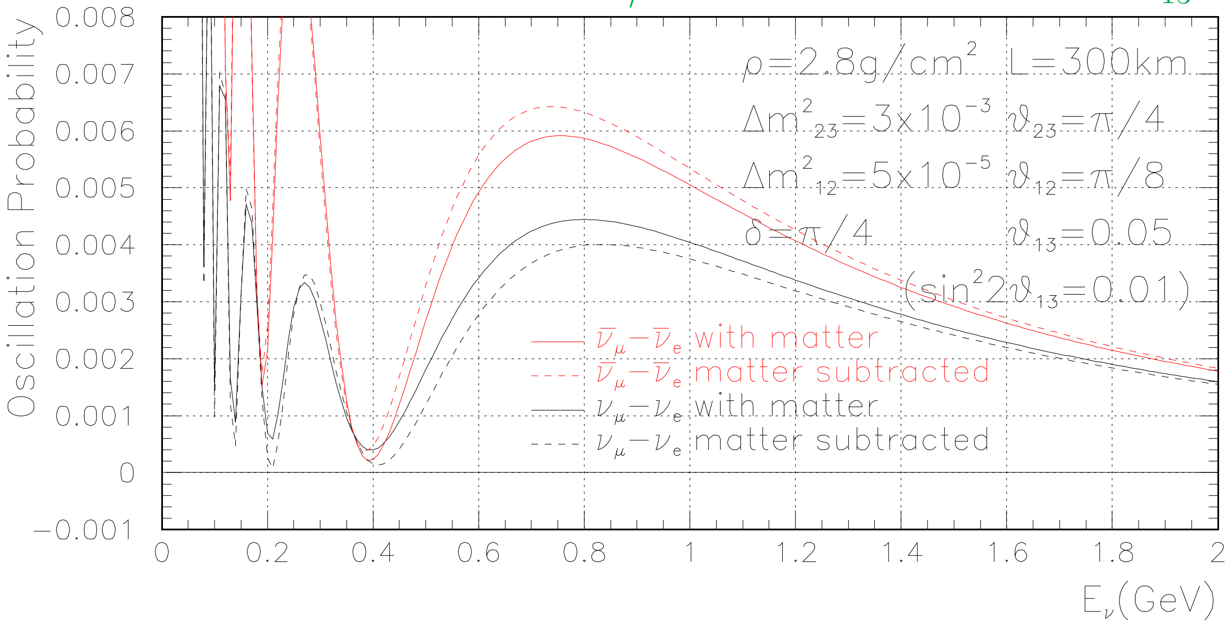
- If θ_{13} is discovered in the 1st phase $\Rightarrow$ CP study

The Hyper-Kamiokande detector

CP violation in the neutrino oscillation

$$
\begin{aligned}
A_{CP} &= \frac{Prob(\nu_\mu \to \nu_e) - Prob(\bar{\nu}_\mu \to \bar{\nu}_e)}{Prob(\nu_\mu \to \nu_e) + Prob(\bar{\nu}_\mu \to \bar{\nu}_e)} \\
&= \frac{1.27\Delta m^2_{12} L}{E} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot sin\delta
\end{aligned}
$$

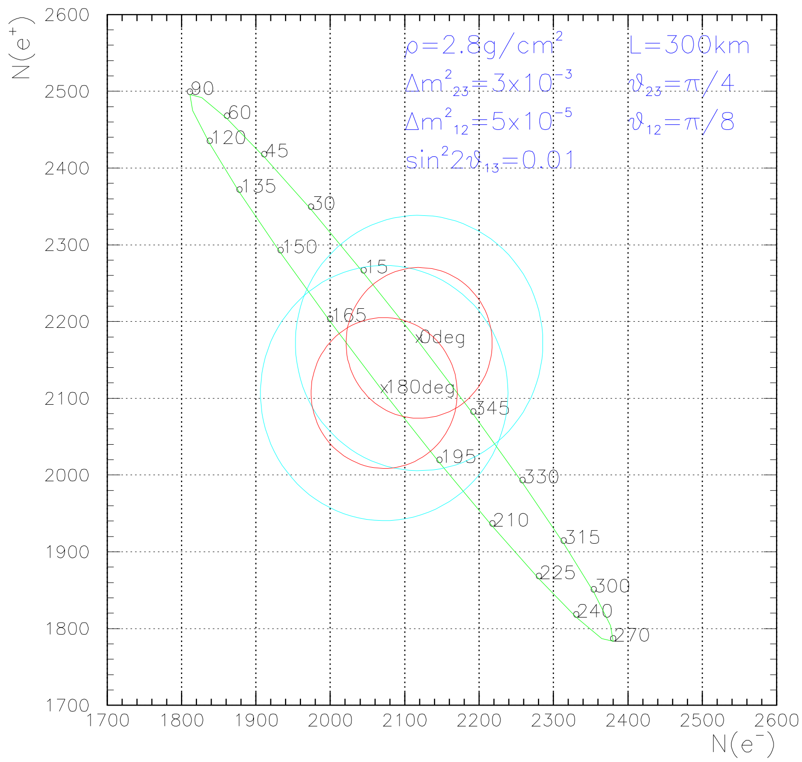
Central values of LMA and 1/10 of reactor limit in $\sin^2 2\theta_{13}$



- Large A_{CP} (25%) for a typical LMA parameter.
- Fake asymmetry due to matter effect is small because of small E and L for JHF-SK experiment.

$$
\begin{aligned}
A_{matter} &= \frac{2a}{\Delta m^2_{31}} + 2\frac{aL}{4E} \frac{< cos\frac{\Delta m^2_{32} L}{4E} >}{< sin\frac{\Delta m^2_{31} L}{4E} >} \\
&\sim 0.07E(GeV) + 5.3 \times 10^{-4} L(km) \frac{< cos\frac{\Delta m^2_{32} L}{4E} >}{< sin\frac{\Delta m^2_{31} L}{4E} >}
\end{aligned}
$$

CP sensitivity



- Ocillation maximum and low neutrino energy
  Signal enhancement relative to the backgrounds.

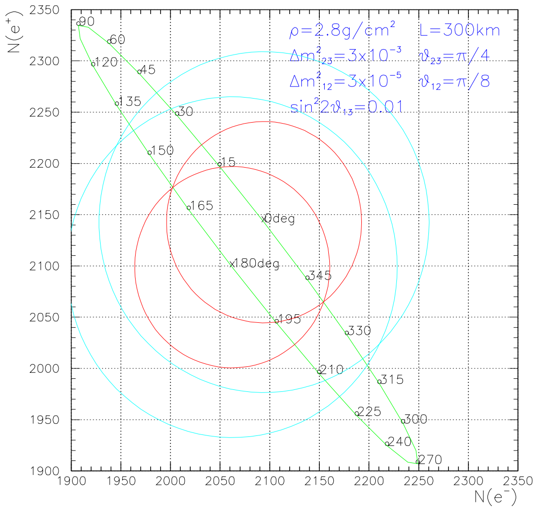
- Double ratio: **cancellation of systematic errors**

$$\frac{P_{\nu_\mu \to \nu_e}(far)}{P_{\nu_\mu}(near)} / \frac{P_{\bar{\nu}_\mu \to \bar{\nu}_e}(far)}{P_{\bar{\nu}_\mu}(near)}$$

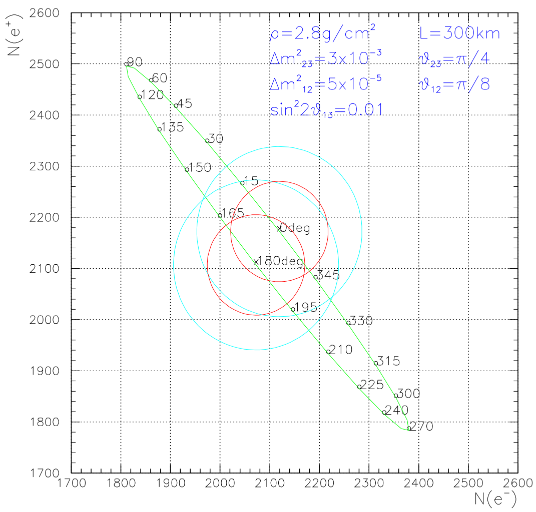
- CP phase δ can be measured down to 10-20 degrees.

CP sensitivity goes up linearly with Δm_{12}^2

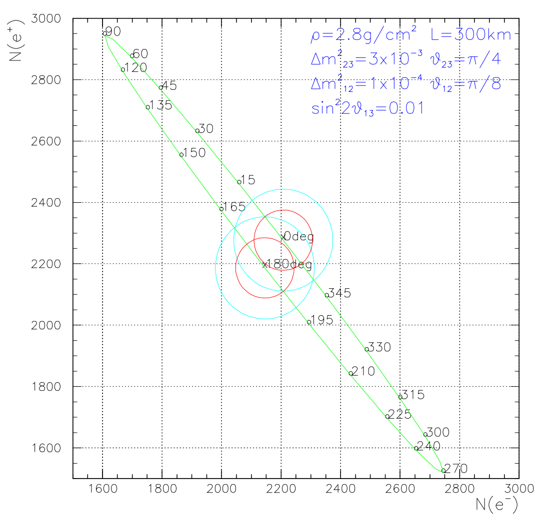
$$\Delta m_{12}^2 = 3 \times 10^{-5}$$



$$\Delta m_{12}^2 = 5 \times 10^{-5}$$

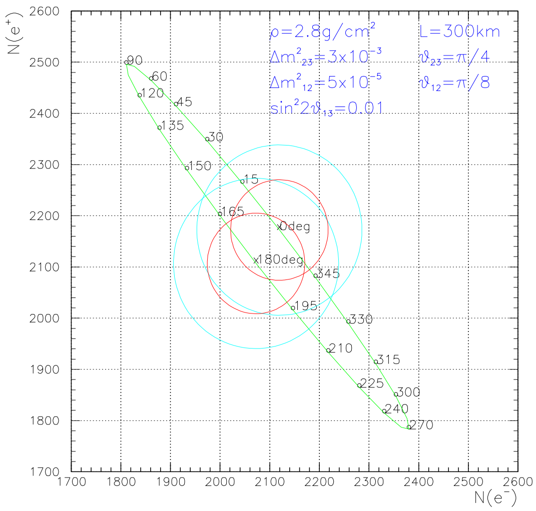


$$\Delta m_{12}^2 = 10 \times 10^{-5}$$

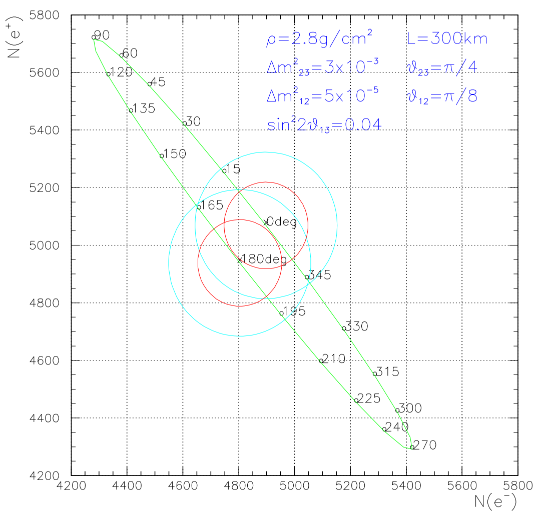


CP sensitivity does not depend much on $sin^2 2\theta_{13}$

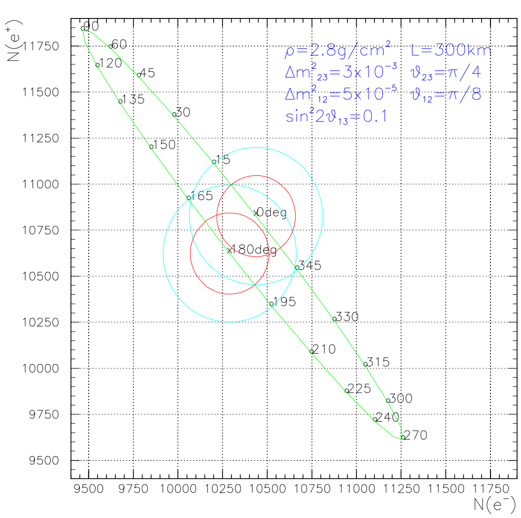
$sin^2 2\theta_{13} = 0.01$



$sin^2 2\theta_{13} = 0.04$

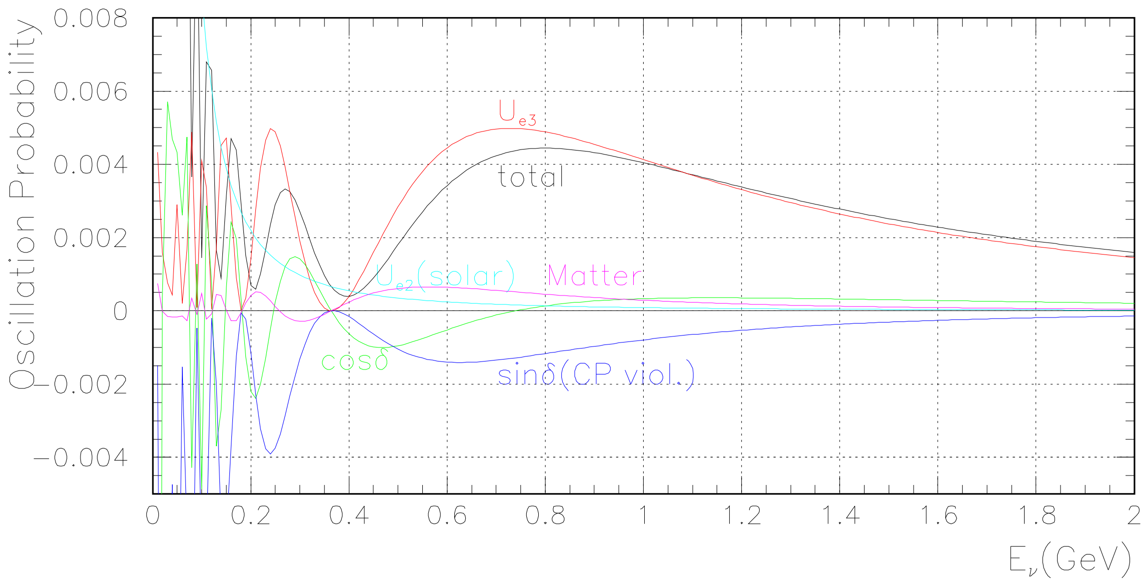


$sin^2 2\theta_{13} = 0.1$

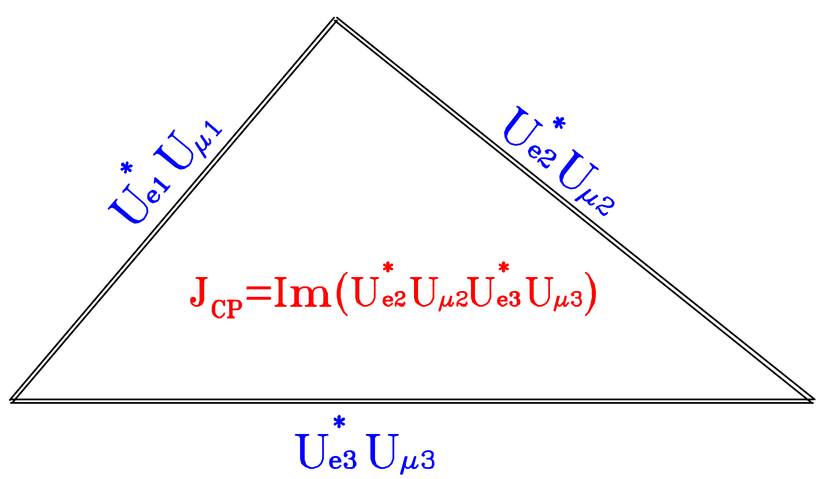


Overconstrain the Unitarity Triangle

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \;=\;& 4|U_{e3}U^*_{\mu 3}|^2 \sin^2 \frac{\Delta m^2_{31}L}{4E} \;\; {\color{red}[U_{e3}]} \\
&+8\mathrm{Re}(U^*_{e3}U_{\mu 3}U_{e2}U^*_{\mu 2}) \cos\frac{\Delta m^2_{32}L}{4E} \sin\frac{\Delta m^2_{31}L}{4E} \sin\frac{\Delta m^2_{21}L}{4E} \;\; {\color{red}[cos\delta]} \\
&-8\mathrm{Im}(U^*_{e3}U_{\mu 3}U_{e2}U^*_{\mu 2}) \sin\frac{\Delta m^2_{32}L}{4E} \sin\frac{\Delta m^2_{31}L}{4E} \sin\frac{\Delta m^2_{21}L}{4E} \;\; {\color{red}[sin\delta]} \\
&-4\mathrm{Re}(U^*_{e2}U_{\mu 2}U_{e1}U^*_{\mu 1}) \sin^2\frac{\Delta m^2_{21}L}{4E} \;\; {\color{red}[U_{e2}]} \\
&+(Matter\ effect) \qquad {\color{red}(Joe\ Sato,\ hep-ph/0008056)}
\end{aligned}
$$



- The 4 coefficients overconstrain the unitarity triangle:
  $U^*_{e1}U_{\mu 1} + U^*_{e2}U_{\mu 2} + U^*_{e3}U_{\mu 3} = 0$



Comments on other studies (clarification)

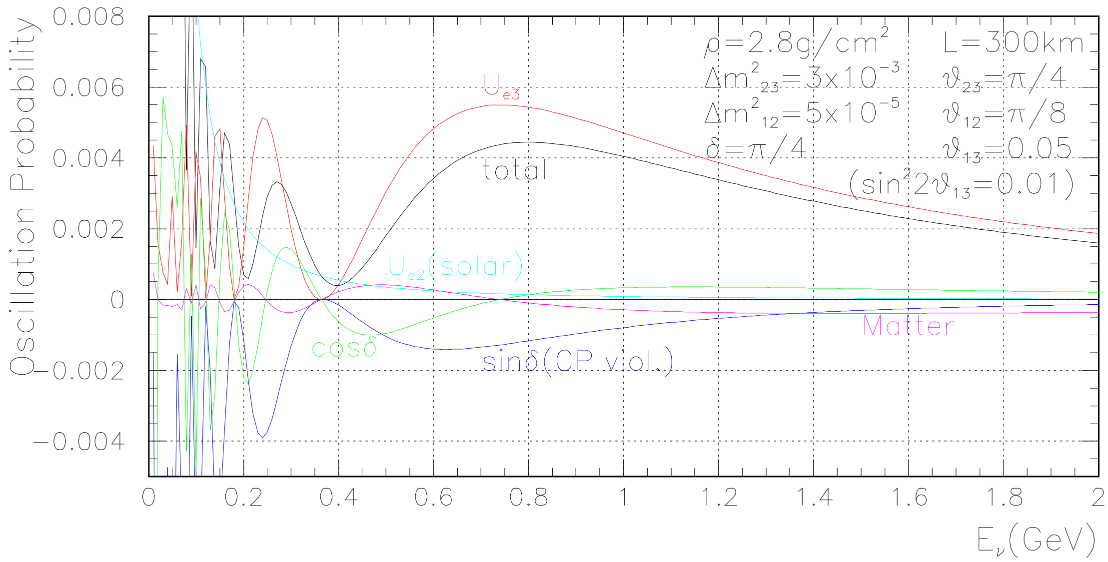
Different results on the "optimum E_ν/baseline length":

- Comparing $\delta = 90^\circ$ only with $\delta = 0^\circ$ but not $\delta = 180^\circ$
  $\delta = 180^\circ$ simply corresponds to $\theta_{13} \to -\theta_{13}$:

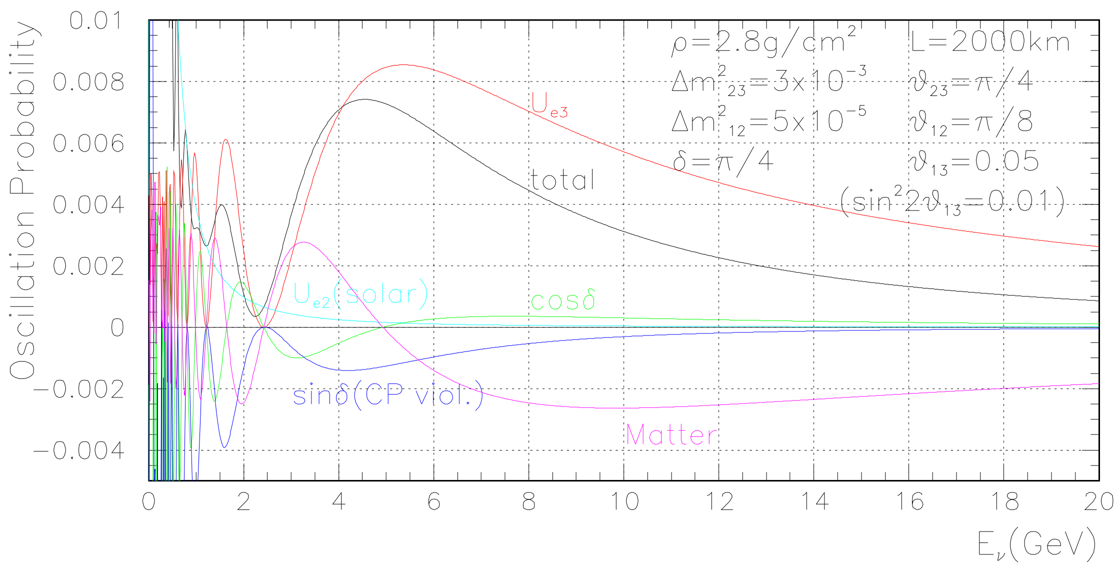
$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Comparing $\delta = 90^\circ$ with $\delta = 0^\circ$ and $\delta = 180^\circ$
  Optimization favours CP-conserving $\cos\delta$ term at high E_ν
- Systematic uncertainties are not accounted for:
  - Uncertainties due to other oscillation parameters: e.g.θ_{12},θ_{13}
    Important in comparing $\delta = 90^\circ$ with $\delta = 0^\circ$ and $\delta = 180^\circ$.
  - Uncertainty due to matter effect:
    Fake CP asymm. much larger than signal at high E_ν.
    $\Rightarrow$ Careful study of systematic uncertainty required.
- E_ν dependence of backgrounds are not accounted for:
  - Suppressed ν_e contamination at low E_ν (less Kaon)
  - NC(π^0) rejection is higher at low E_ν due to
    lower cross section & larger opening angle for $\pi^0 \to \gamma\gamma$.
- E_ν dependence of the detector mass is not accounted for:
  Large mass water Čerenkov is good at low E_ν

- ~1GeV neutrino beam



- ~10GeV neutrino beam

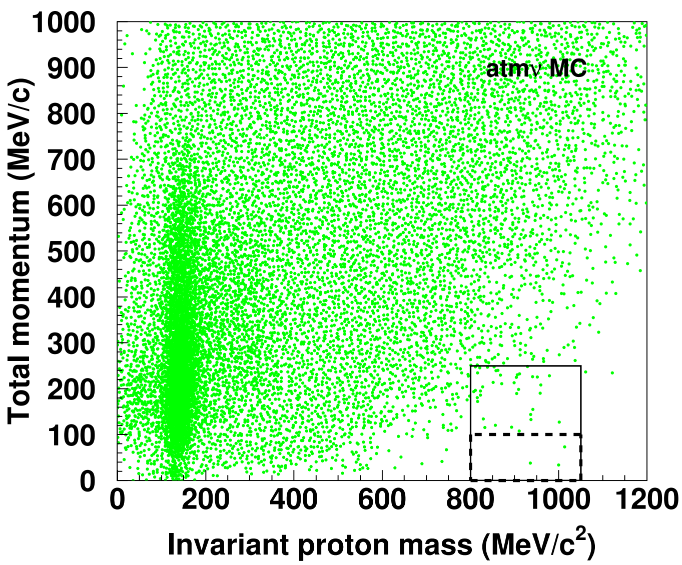


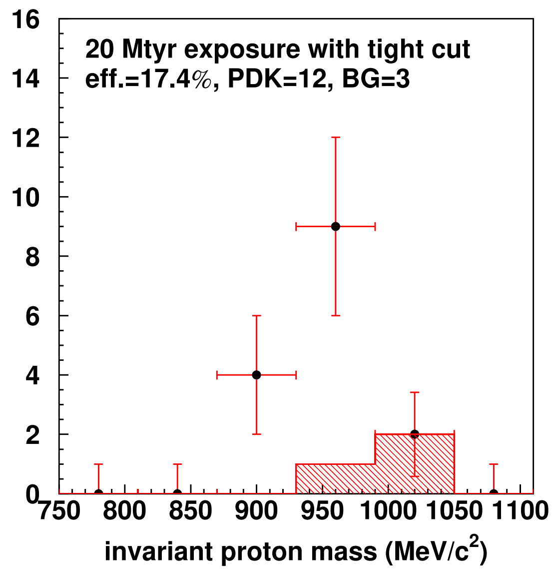
- Good for studying the matter effect
- Matter effect dominates the ν-$\bar{\nu}$ asymmetry (A_{fake})
- $\cos\delta$ term becomes larger than $\sin\delta$ term
  $\Rightarrow$ δ measurement through $\cos\delta$ term?

Proton decays

- **GUT** $p \rightarrow e^+\pi^0$: $\tau(p \rightarrow e^+\pi^0) = 10^{35\sim37} years$

  Background free measurement by tagging free proton decays

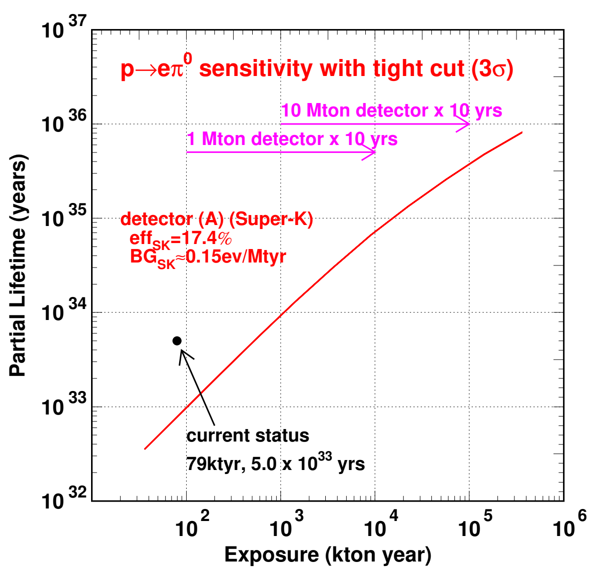


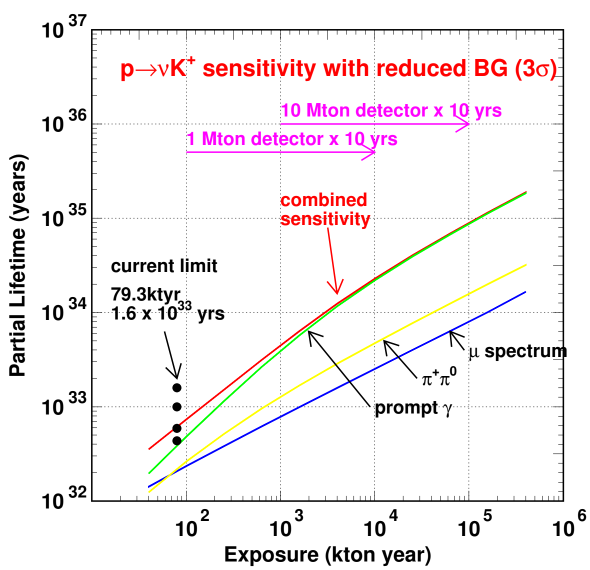


- **SUSY-GUT** $p \rightarrow K^+\bar{\nu}$: $\tau(p \rightarrow K^+\bar{\nu}) = 10^{29\sim35} years$

  Background free measurement by γ tag from residual ^{15}N

- **Sensitivities**





$\tau(p \rightarrow e^+\pi^0) > 10^{35} years$ $\tau(p \rightarrow K^+\bar{\nu}) > 3 \times 10^{34} years$

Summary and prospects

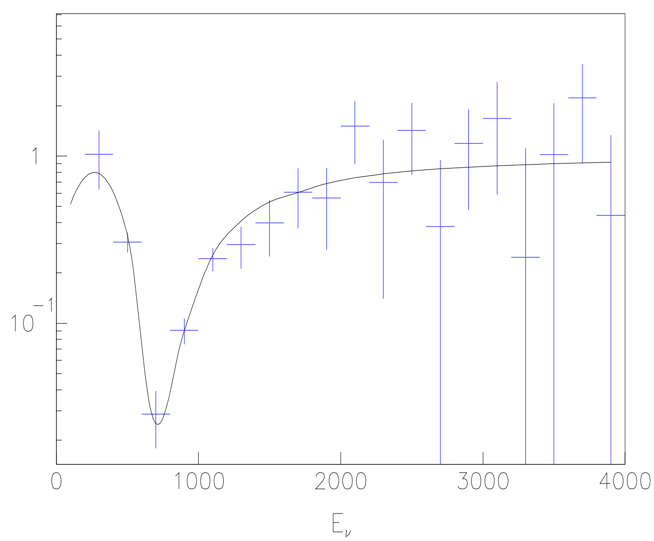
- **Strategy of the experiment**
  - Super-Kamiokande as a far detector: L=295km
  - Low energy ν_μ beam tuned at the oscillation maximum.
    Off-axis neutrino beam
  - Reconstruct the neutrino energy event by event (QE).
    Oscillation pattern measurement

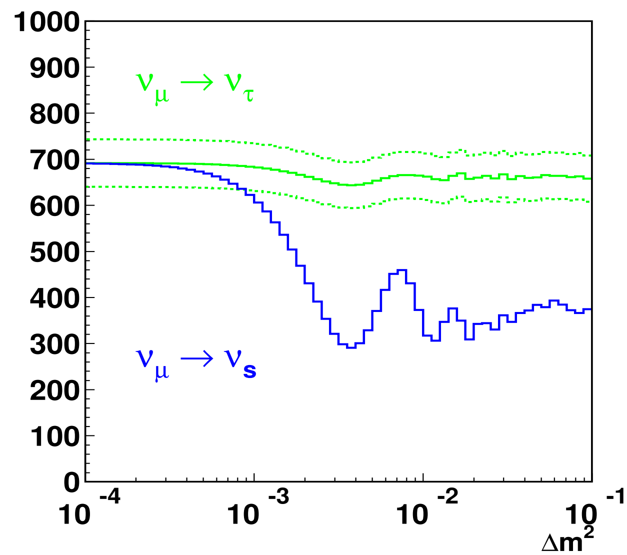
Discovery of Z^0 (SPS) $\Rightarrow$ Precision measurements of EW int. at Z^0 pole (LEP) Discovery of ν oscillation (Super-Kamiokande) $\Rightarrow$ Precision measurements of ν oscil. at oscil. max.

- **Physics goals of future neutrino experiments**
- **Examination of the experimental approach**
  1. Background suppression (S/N ratio)
  2. Statistical sensitivity
  3. Systematic Uncertainties
  4. Feasibility
- **Prospects**

Physics goals of future neutrino experiments

- **Establish the neutrino oscillation or discover physics beyond MNS (sterile ν)**
  - Oscillation pattern measurement **JHF-SK**
    ν_μ **disappearance-reappearance pattern**
  - ν_τ appearance (direct) e.g. OPERA
  - ν_τ appearance (NC measurement) **JHF-SK**



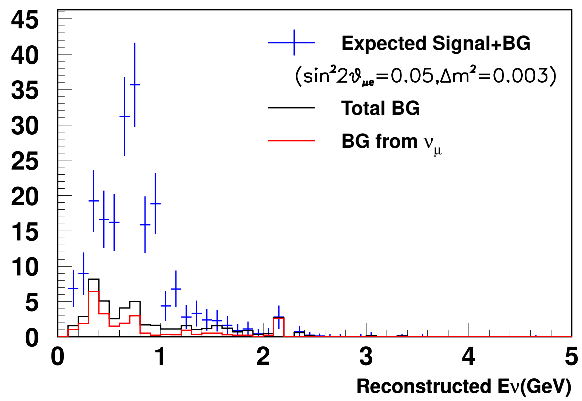


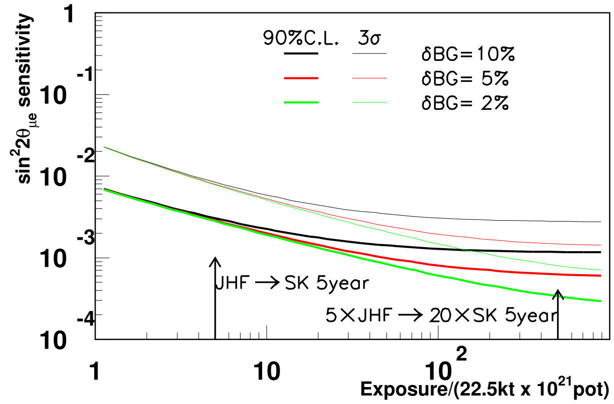
- **Atmospheric neutrino oscillation** $(\theta_{23}, \Delta m^2_{23})$
  - Precision measurement of the parameters **JHF-SK**
    An order of magnitude better precision:
    $\delta(\sin^2 2\theta_{23}) \sim 0.01$, $\delta(\Delta m^2_{23}) \sim 1 \times 10^{-4} eV^2$
  - Sign of Δm^2_{23} Future very long baseline experiment
    Measurement of the matter effect

- **Solar neutrino oscillation** $(\theta_{12}, \Delta m^2_{12})$
  - Establish the oscillation and fix parameters e.g.SK,SNO,Kamland

- **Search for θ_{13}**

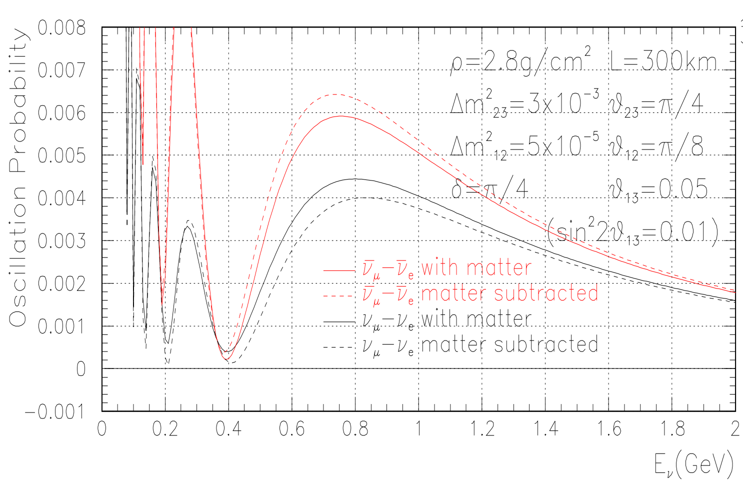
  – $\nu_\mu \to \nu_e$ appearance **JHF-SK**
  A factor of 20 improvement beyond CHOOZ limit
  $\sin^2 2\theta_{\mu e} \simeq 0.5 \sin^2 2\theta_{13} \simeq |U_{e3}|^2 > 0.003$

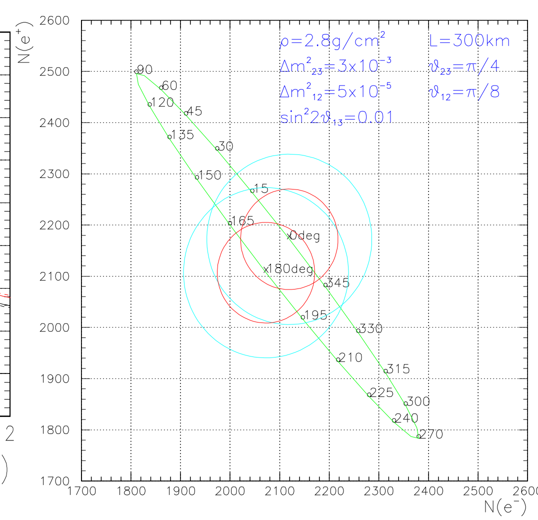




- **CP violation search**

  – $\nu_\mu \to \nu_e$ vs. $\bar{\nu}_\mu \to \bar{\nu}_e$ **JHF-HyperK**
  $|\delta| > 10 - 20°$ for most of the LMA parameter region.





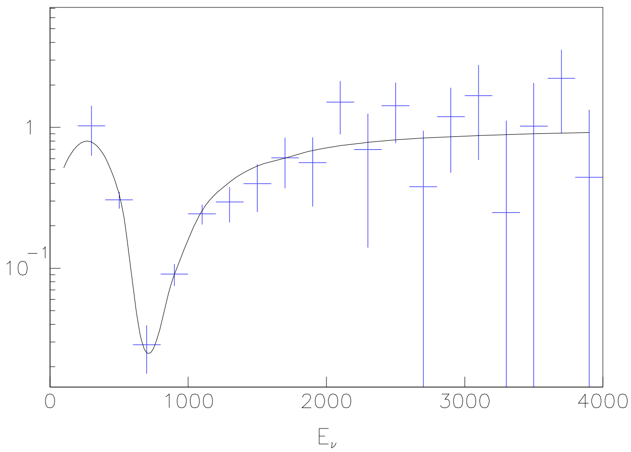
- **LSND type neutrino oscillation**

  – Short baseline $\nu_\mu \to \nu_e$ appearance miniBooNE

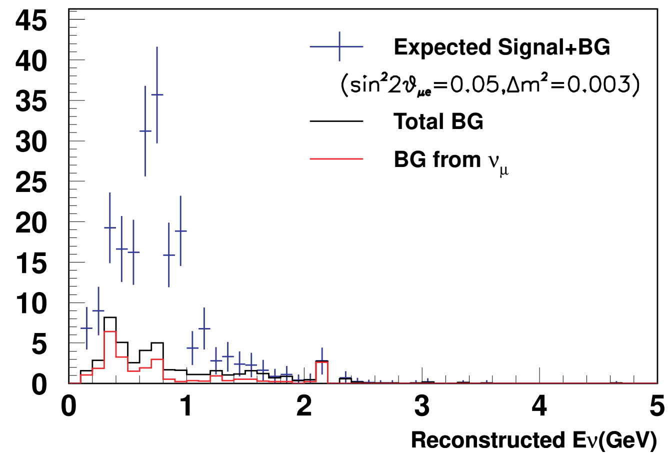
  – Detailed parameter studies if discovered **JHF-SK** ?

1. Background suppression (S/N ratio)

"Background" statistics limits at the sensitivity limits
$\Rightarrow$ Improvements in S/N linearly enhace the sensitivities:



+ non-QE backgr. (peak): 3%
+ resolution tail (peak): 3%
10% measurement
$\Rightarrow$ 0.6% in $\sin^2 2\theta_{\mu\tau}$



+ ν_e contamination: 0.2%
+ NC-π^0 background: 0.3%
50% measurement
$\Rightarrow$ 2.5×10^{-3} in $\sin^2 2\theta_{\mu e}$

How are these achieved?

- Signal enhancement: Oscillation maximum
- Excellent particle ID by water Čerenkov
  R(e/μ)~500, R($NC(\pi^0)/e$)~100
- E_ν reconstruction and the narrow band beam
  Background suppression by the E_ν window
- CP measurement: additional advantages at low energy
  – Enhancement of the asymmetry

$$A_{CP} = 1.27\Delta m^2_{12}\frac{L}{E} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot sin\delta$$

  – Fake asymmetry due to matter effect is small

2. Statistical Sensitivity

- **Neutrino beam**
  High intensity narrow band beam at low energy

- **Neutrino yield** Y_ν: small dependence on E and L

$$
\begin{aligned}
Y_\nu &= \Phi_{\nu flux} \cdot P_{\pi decay} \cdot \sigma_\nu \cdot P_{oscil} \\
&\propto \frac{E^2}{L^2} \cdot \frac{1}{E} \cdot E \cdot \sin^2 \frac{1.27 \Delta m^2_{atm} L}{E}
\end{aligned}
$$

- **Signal enhancement** at the oscillation maximum

Equivalent statistics for 10^{21} 50GeV-POT per 1kton detector

Beam	(GeV, km)	$\Phi_{\nu flux} \cdot P_{\pi decay} \cdot \sigma_\nu$	P_{oscil}	Y_ν	$Y_\nu \cdot P_{oscil}$
OAB2°	(0.7, 295)	100	1.0	100	100
WBB	(1.1, 295)	230	0.7	161	112
MINOS LE	(3.5, 730)	500	0.5	250	125
MINOS ME	(7.0, 730)	1830	0.15	274	41
MINOS HE	(15.0, 730)	3555	0.034	120	4

Further advantages:

- **Excellent background suppression** (good S/N)
- **Large fiducial mass** with Water Čerenkov
- **CP asymmetry** enhancement at low energy

3. Systematic Uncertainties

- **Signal enhancement and backgr. suppression**

  ν_μ disapperance: Systematics in normalization

  10% uncertainty $\Rightarrow 6\% \cdot 0.1 = 0.6\%$ in $\sin^2 2\theta_{\mu\tau}$

  ν_e disapperance: Systematics in BG subtraction

  20% uncertainty $\Rightarrow 0.25\% \cdot 0.2 = 5\times 10^{-4}$ in $\sin^2 2\theta_{\mu e}$

- **Cancellation of systematics**

  Far/near ratio (signal, background)

  Double ratio in CP measurement: $\frac{P_{\nu_\mu\to\nu_e}(far)}{P_{\nu_\mu}(near)} / \frac{P_{\bar{\nu}_\mu\to\bar{\nu}_e}(far)}{P_{\bar{\nu}_\mu}(near)}$

- **Monitorings and Checks of syetematics**

  Muon beam monitor: beam stability checks

  Monitor ν flux as a function of E_ν and θ_ν

  Constrain systematics in Far/near ratio

  BG estimation by events outside E_ν window.

- **Additional studies on syst. uncertainties**

  Hadron production measurements (HARP3?)

  ν cross section measurements using NBB

- **Redundancy**

  Positive ID of the signal by the oscillation pattern

4. Feasibilities

- JHF approved and in construction
- Far detector(Super-K) exists
- Existing beam technology (conventional ν beam)
- Full simulation/analysis proven by SK/K2K
- Realistic experimental requiements
  Systematics and background rejection
- Staging to Hyper-K/upgraded JHF
- Redundancies (oscillation pattern measurement)
- Step towards neutrino factory

Prospects

2000 –

- JHF project approved (December)

2001 –

- JHF (KEK-JAERI) started (April)
- International workshop on JHF-Kamioka project (May)
  http://neutrino.kek.jp/jhfnu/workshop2/index.html
- Release of the Letter of Intent (hep-ex/0106019)
  Conceptual design of the JHF-Kamioka project
- Second international workshop (November)
- Technical design of the JHF-SK experiment
- Grant request of the ν beamline
- Forming the collaboration
- Proposal of the JHF-SK experiment

2002 –

- Construction of the tunnels starts

2006 –

- Accelerator construction will be completed

2007 –

- Start taking data of the first phase

2012 –

- Start taking data of the second phase