Long Baseline Neutrino Experiment at JHF

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Contents

JHF Neutrino Working Group

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Dec.99: Working group formed.
Mar.00: Letter of Intent prepared (http://neutrino.kek.jp/jhfnu)
Now : Working to prepare a proposal

Neutrino Oscillation

Neutrino Mixing

$$|\nu_l\rangle = \Sigma U_{li} |\nu_i\rangle$$

Weak eigenstates　　Mass eigenstates

Maki-Nakagawa-Sakata Matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}$$

Oscillation Probability

$s_{ij}=\sin\theta_{ij}$, $c_{ij}=\cos\theta_{ij}$

$$P_{l\to m} = \left|\langle \nu_m(t) | \nu_l(0) \rangle\right|^2 = \delta_{ml} - 2\sum_{i<j} \mathrm{Re}\left[\left(U^*_{mi} U_{li}\right) \cdot \left(U_{mj} U^*_{lj}\right) \cdot \left\{1 - \exp\left(-i\frac{\Delta m^2_{ij}}{2E} L\right)\right\}\right]$$

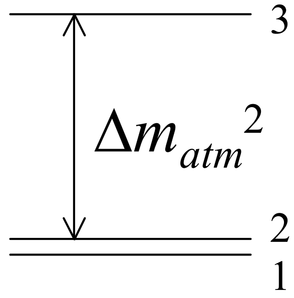
L : flight length, E : neutrino energy, $\Delta m^2_{ij} \equiv m^2_i - m^2_j$, m_i : mass eigenvalues

$$P_{l\to m} \neq \delta_{ml} \Leftrightarrow \Delta m_{ij} \neq 0$$

LFV

Oscillation probabilities

when $\begin{cases} \Delta m_{12}^2 << \Delta m_{23}^2 \approx \Delta m_{13}^2 \equiv \Delta m_{atm}^2 \\ E_\nu \approx \Delta m_{atm}^2 \cdot L \end{cases}$ contribution from Δm_{12} is small



ν_e appearance

$$P_{\mu\to e} \approx \boxed{\underbrace{\sin^2\theta_{23}}_{\sim 0.5} \cdot \sin^2 2\theta_{13}} \cdot \sin^2\left(1.27\Delta m_{atm}^2 / E_\nu\right)$$

$\sin^2 2\theta_{\mu e}$

ν_μ disappearance

$$P_{\mu\to x} = 1 - (P_{\mu\to e} + P_{\mu\to\tau} + P_{\mu\to sterile}) \approx P_{\mu\to\tau}$$

$$P_{\mu\to\tau} \approx \underbrace{\cos^4\theta_{13}}_{\sim 1} \cdot \sin^2 2\theta_{23} \cdot \sin^2\left(1.27\Delta m_{atm}^2 / E_\nu\right)$$

Neutral Current (NC) measurement

$$N_{NC} \propto P_{\mu\to active} = 1 - P_{\mu\to sterile}$$

Cf. Chooz (ν_e disappearance)

$$P_{e\to x} \approx 1 - \sin^2 2\theta_{13} \cdot \sin^2\left(1.27\Delta m_{atm}^2 / E_\nu\right)$$

$\nu_\mu \rightarrow \nu_e$ oscillation probability(1)

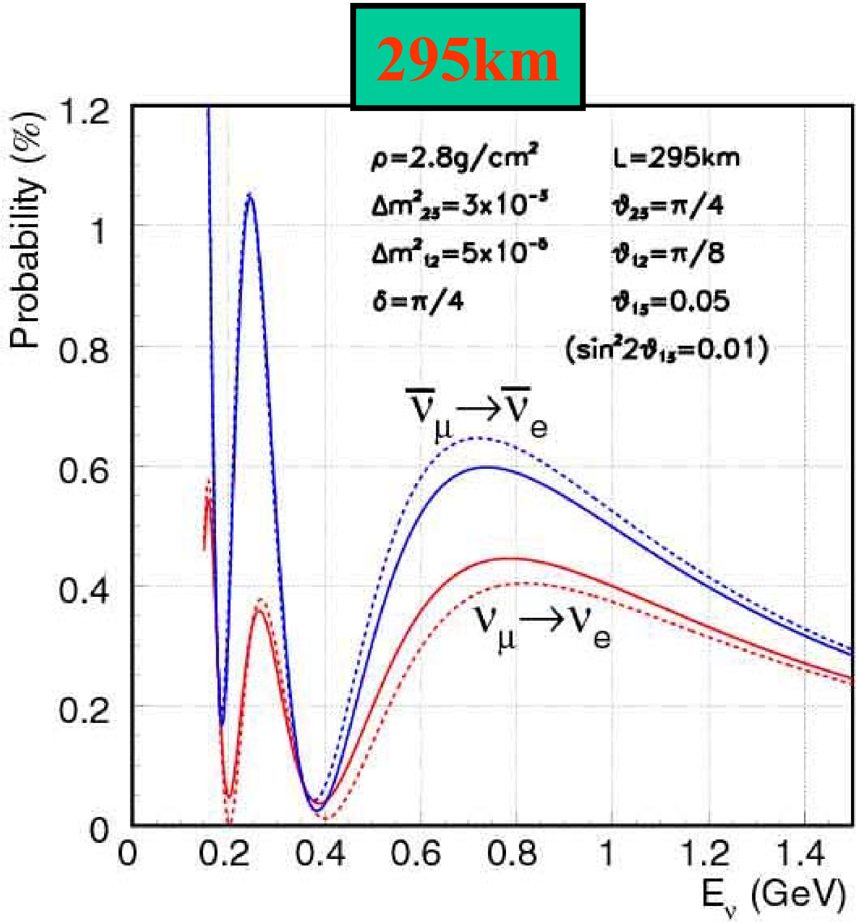
w/ CPV phase and matter effect

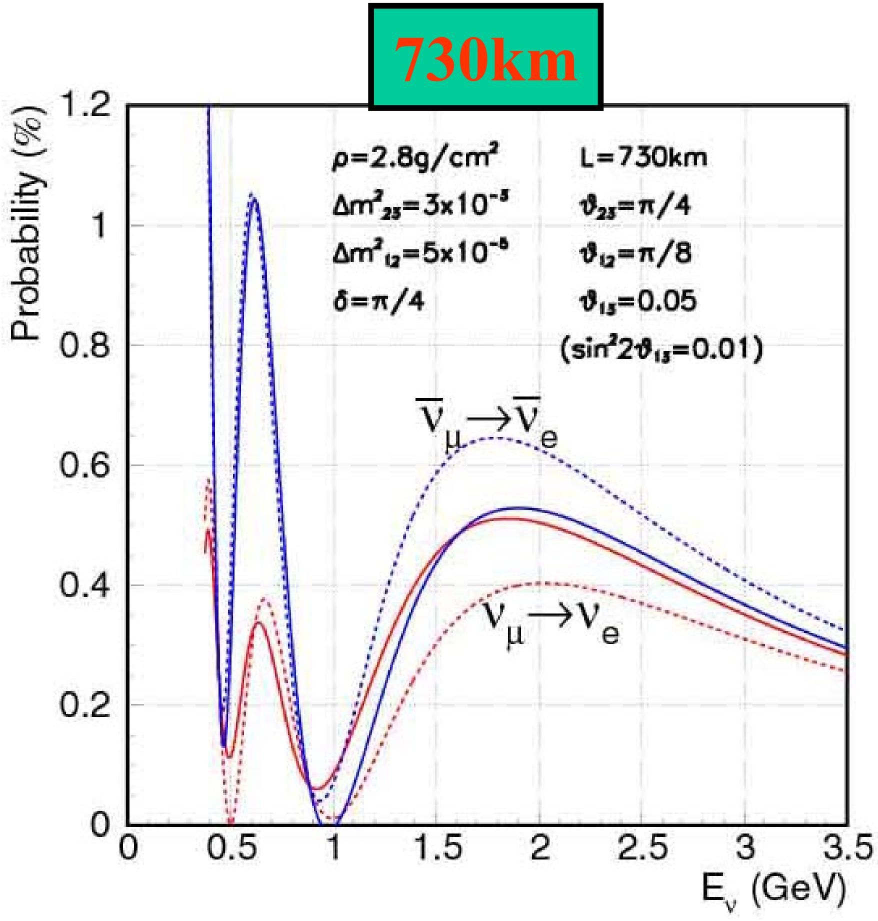
$$
\begin{aligned}
P(\nu_\mu \to \nu_e) &= 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \left(1 - 2S_{13}^2\right)\right) \\
&+ 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E}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

Matter eff.: $a = 7.56 \times 10^{-5} [\mathrm{eV}^2] \cdot \left(\frac{\rho}{[\mathrm{g/cm}^3]}\right) \cdot \left(\frac{E}{[\mathrm{GeV}]}\right)$

$\delta \rightarrow -\delta$, $a \rightarrow -a$ for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$\nu_\mu \rightarrow \nu_e$ oscillation probability(2)





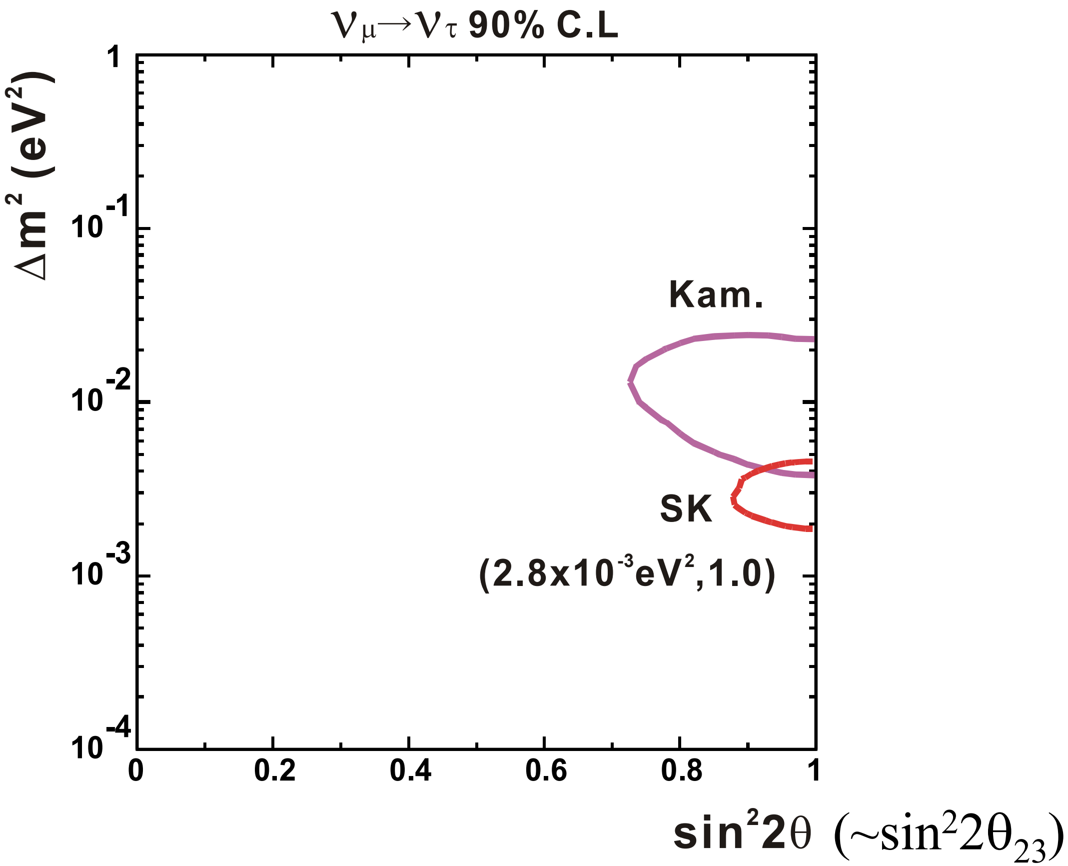
Solid line: w/ matter
Dashed line: w/o matter

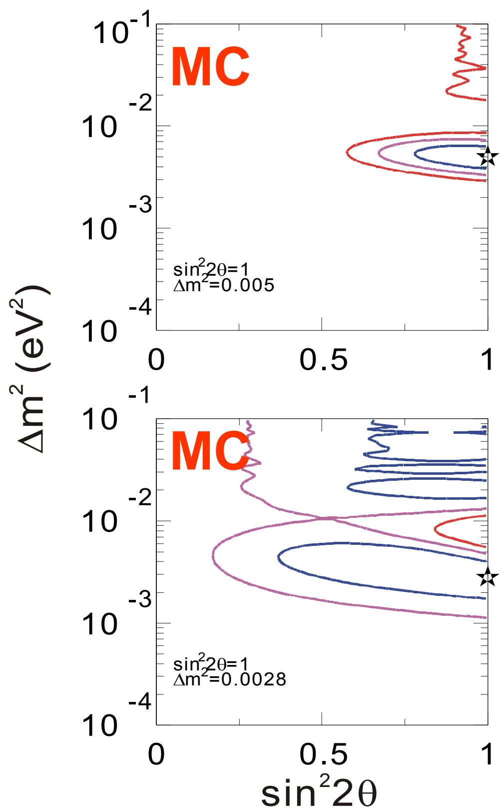
Small Matter Effect at 295km.

Current/near future constraints from ν_μ disappearance

Allowed region of SK

Expected allowed region of K2K (10^{20}POT)





$\Delta m^2 \sim (2\sim 5)\times 10^{-3}$ eV^2

$\sin^2 2\theta > 0.88$

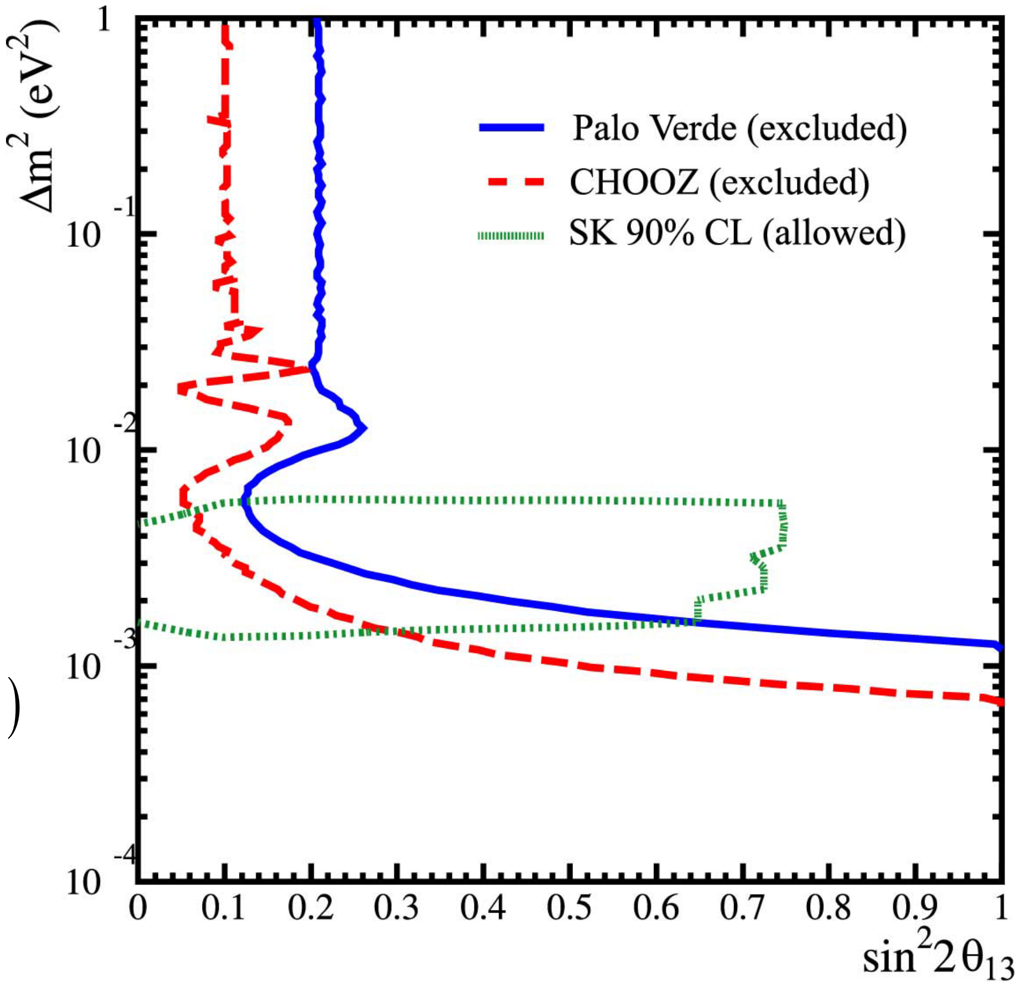
Current Limit on θ_{13}

Reactor experiment
($\bar{\nu}_e$ disappearance)

$$P_{e\to x} \approx 1 - \sin^2 2\theta_{13} \cdot \sin^2\left(1.27\Delta m^2_{atm} / E_\nu\right)$$

SK atmospheric ν obs.
ν_e appearance
(3 flavor analysis)

$$P_{\mu\to e} \approx \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(1.27\Delta m^2_{atm} / E_\nu\right)$$



Physics motivation

1. **Test our current picture of 3 flavor neutrino oscillation**
    - Spectrum shape of ν_μ disappearance
        - Test exotic models (decay, extra dimensions,….)
    - Appearance of ν_e at the same Δm^2 as ν_μ disappearance
    - NC measurements
        - No additional "neutrino"?
2. **Precise measurement of Δm^2 and mixing angles (θ_{23}, θ_{13})**
    - mixing matrix in quark sector: well known
    - understanding of mixing in lepton sector
    - understanding of mass structure

      → hints on physics beyond the SM (GUTs,…)
3. **Discovery of ν_e appearance**

    → Open possibility to detect CPV effect in lepton sector

Experiment

Overview

Super-K: 50 kton
Water Cherenkov

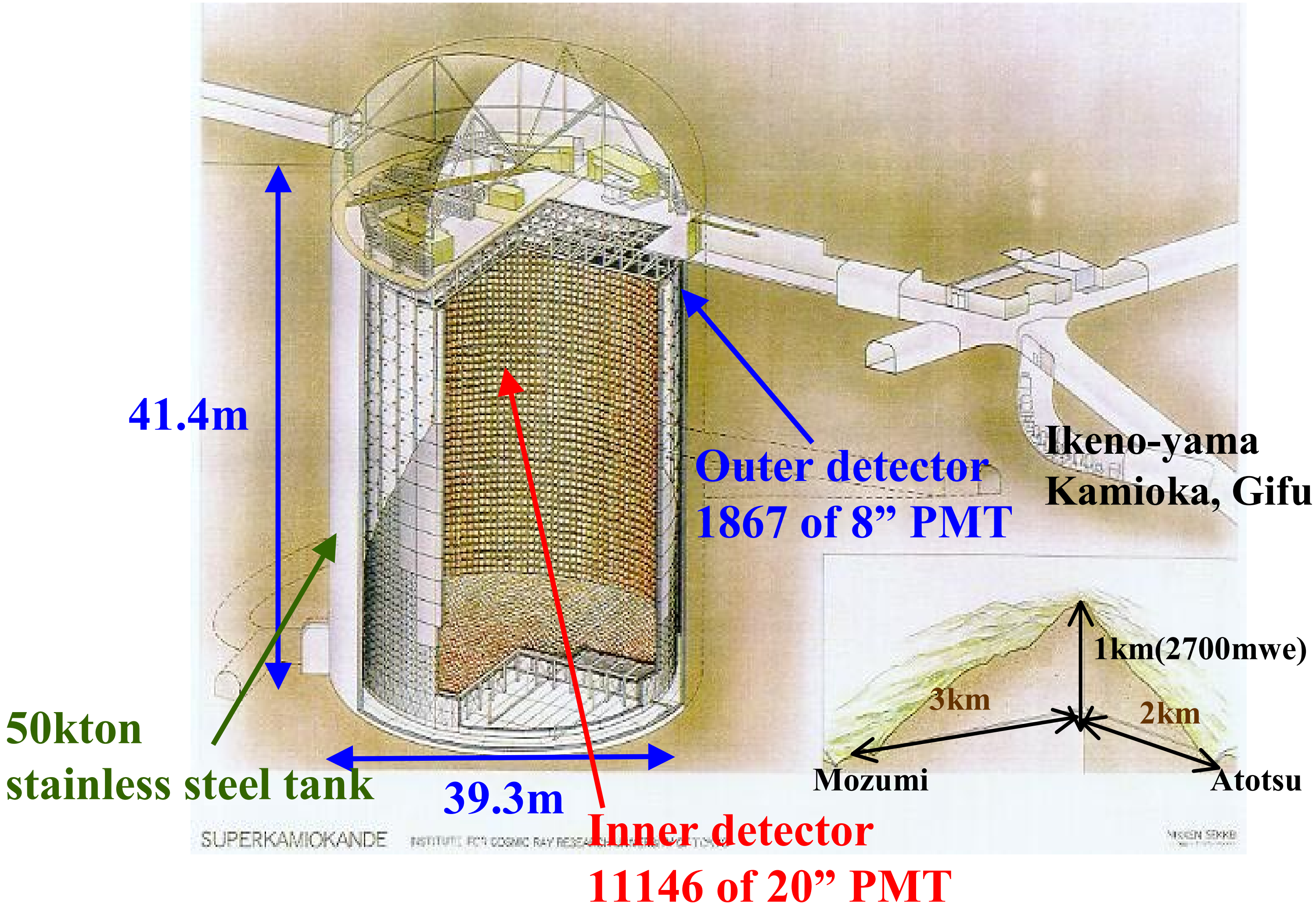
JAERI
(Tokaimura)

~1 MW 50 GeV PS

(conventional ν beam)

- $\nu_\mu \rightarrow \nu_x$ disappearance
- $\nu_\mu \rightarrow \nu_e$ appearance
- NC measurement

Super Kamiokande (far detector)



Principle

– Super-Kamiokande at 295km as far detector

– Beam energy is tuned to be at the oscillation maximum.

- High sensitivity
- Less background

$\Delta m^2 = 2 \sim 5 \times 10^{-3}\,\mathrm{eV}^2$

$E_\nu = 0.5 \sim 1.2\,\mathrm{GeV}$

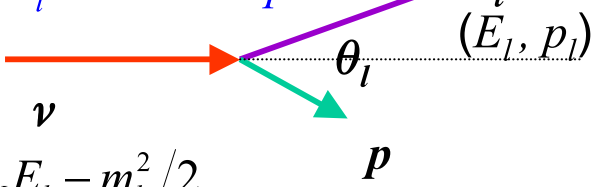
– Neutrino energy reconstruction by using **Quasi-elastic** (QE) interaction.

- Oscillation pattern measurement
- BG due to miss-reconstruction of inelastic interaction
  - Greatly improved by using narrow band beam (NBB)

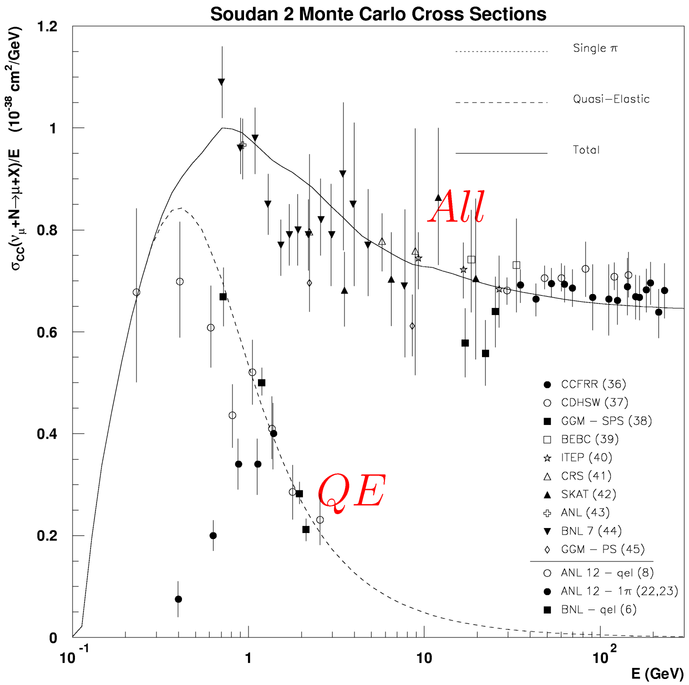
Neutrino Energy Reconstruction

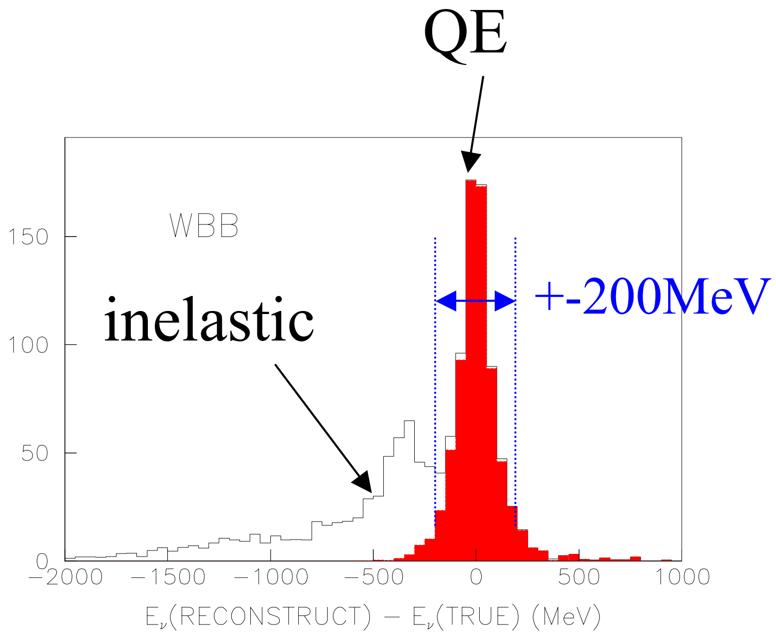
Assume CC quasi elastic (CCQE) reaction

$$\nu_l + n \rightarrow l + p$$



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





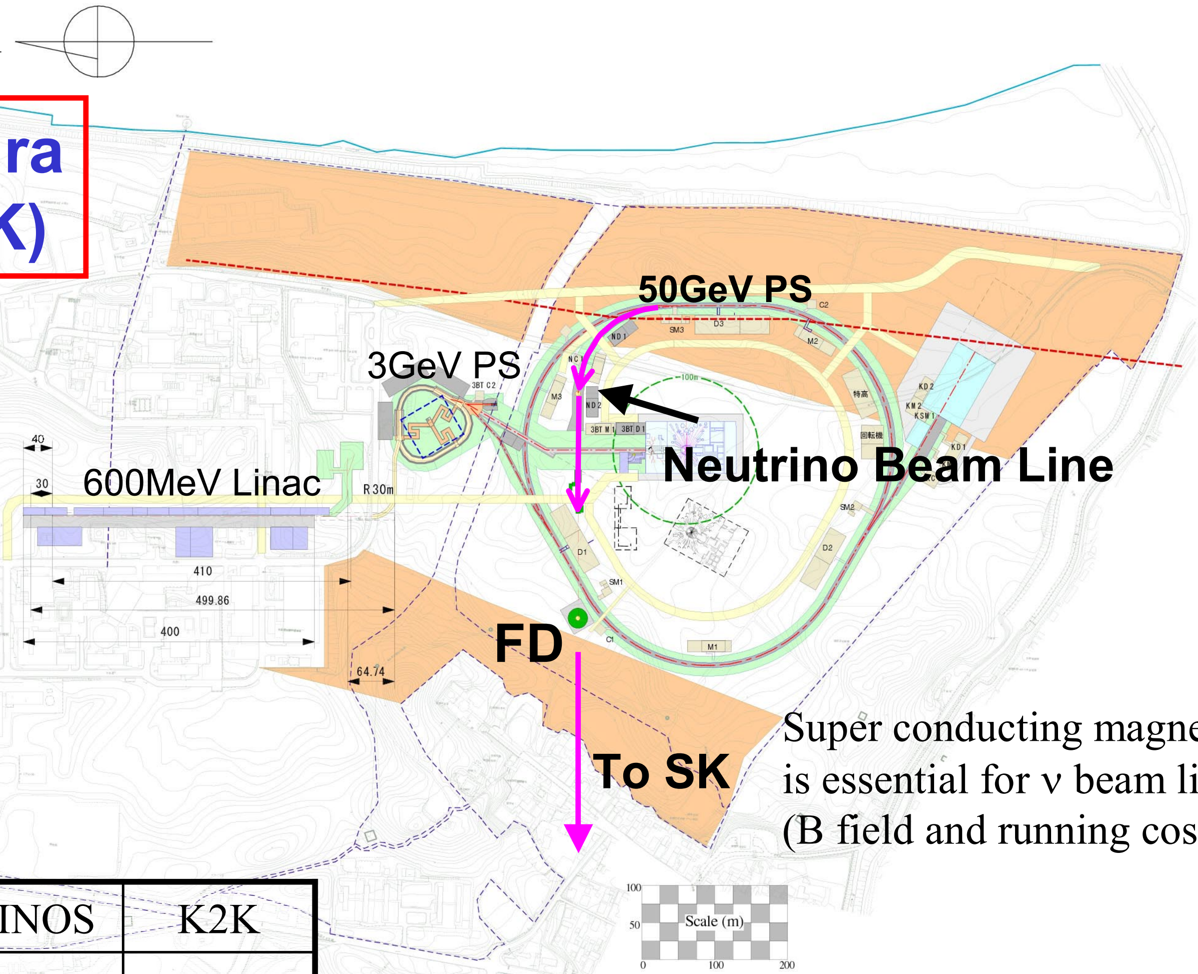
QE dominate at ～1GeV

JHF project and neutrino beam line

JAERI@Tokai-mura (60km N.E. of KEK)

Construction 2001～2006

(Expect approval in Dec.2000)



Super conducting magnet is essential for ν beam line (B field and running cost)

	JHF	MINOS	K2K
E(GeV)	50	120	12
Int.(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(130day)≡ "1 year"

Neutrino Beam @ JHF

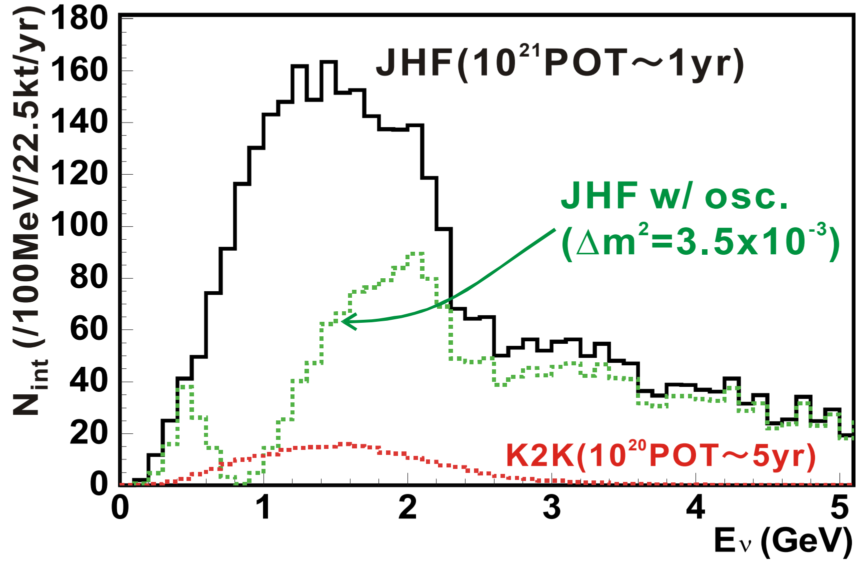
Three beam configurations

- **Wide Band Beam (WBB)**
  - 2 Horns almost the same as K2K
- **Narrow Band Beam (NBB)**
  - Horn(s) + Bending
- **Off Axis Beam (OAB)**
  - Another option of NBB

Wide Band Beam

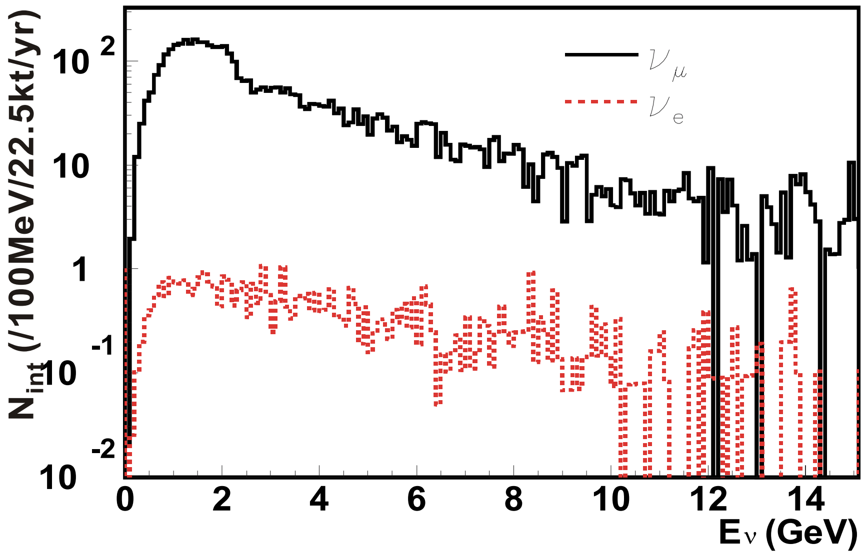
Target : Cu 1cm$^{\phi}$ x 30cm
Horn : 250kA
Decay Pipe : 50m x 1.5m$^{\phi}$
Gcalor

2 horns (almost same design as K2K)



~4200 ν_μ int./22.5kt/yr

ν_e:0.8%



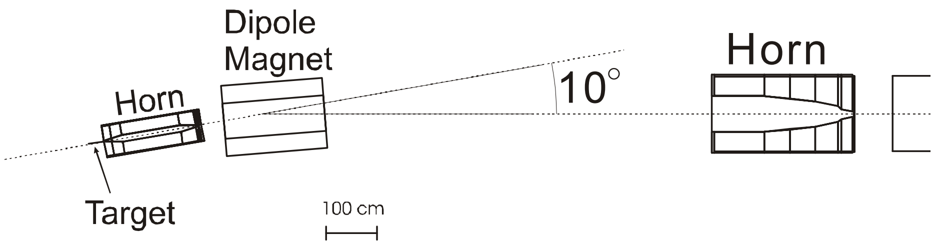
Intense
Wide sensitivity in Δm^2
BG from HE tail
Syst. err from spectrum extrapolation

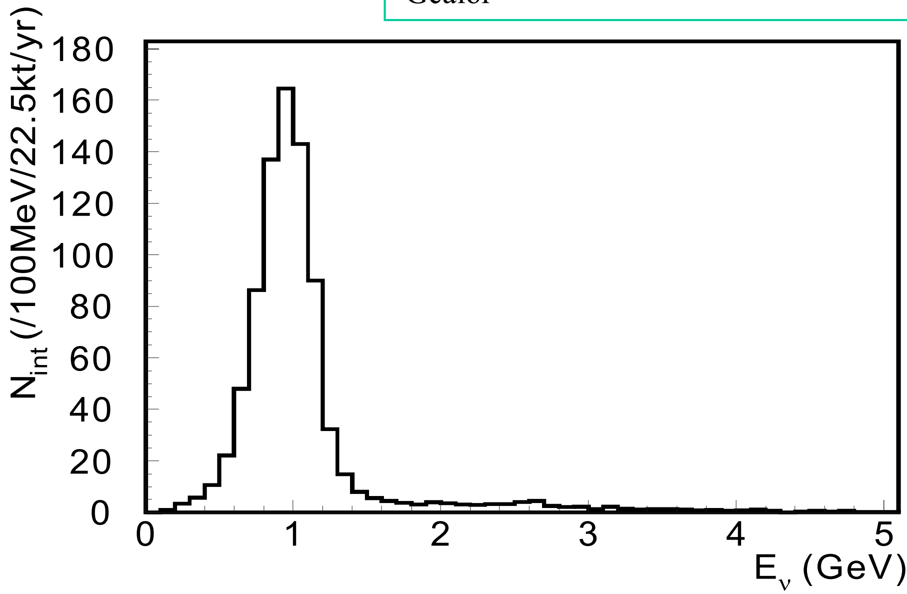
Narrow Band Beam

Updated from LOI

(factor ～2 increased by adding 2nd horn)

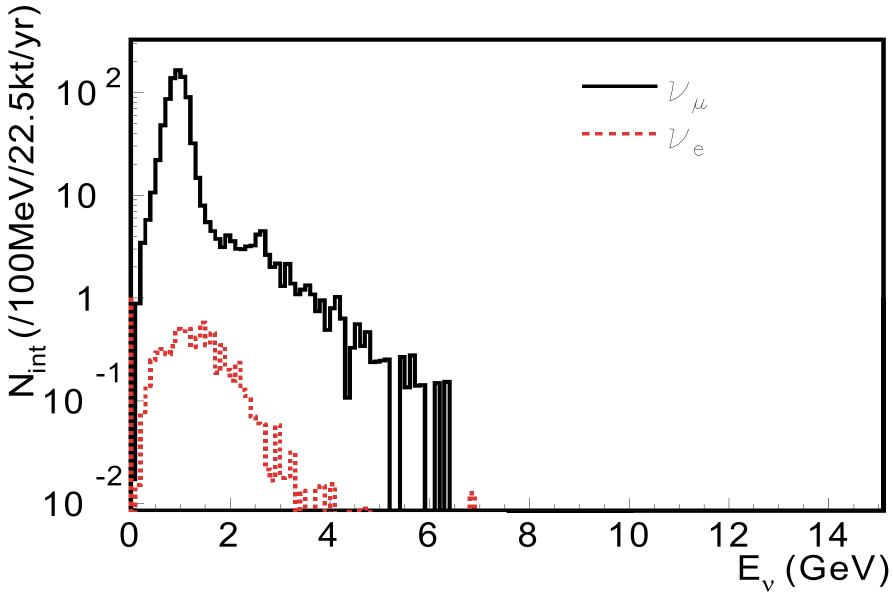
Target	: Cu 1cm$^{\phi}$ x 30cm
Horn	: 250kA
Decay Pipe	: 155m x 1.5m$^{\phi}$
Dipole	: 50cm(V)x70cm(H)x2m(L) 0.58T (10deg@2GeV/c)
Gcalor	





～830 int./22.5kt/yr

ν_e:0.8%(0.3% @ peak)



Less HE tail

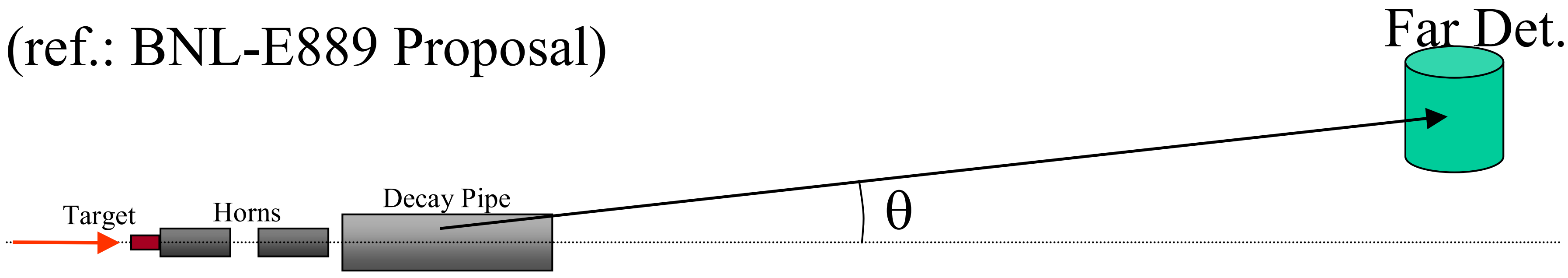
Less sys err from spectrum

"counting experiment"

Easy to tune E_ν

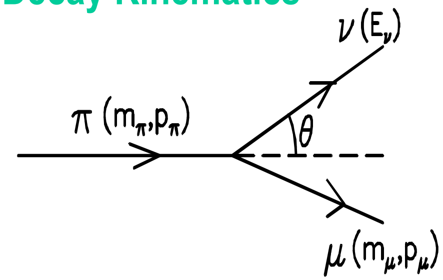
Off Axis Beam (another NBB option)

(ref.: BNL-E889 Proposal)

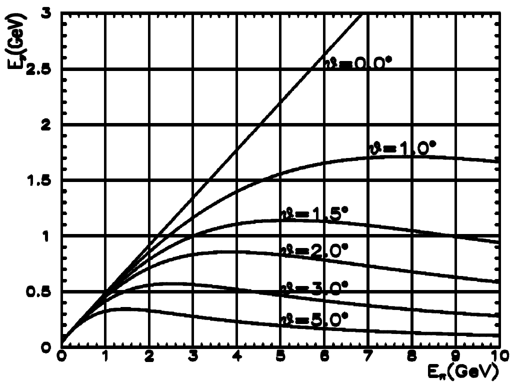


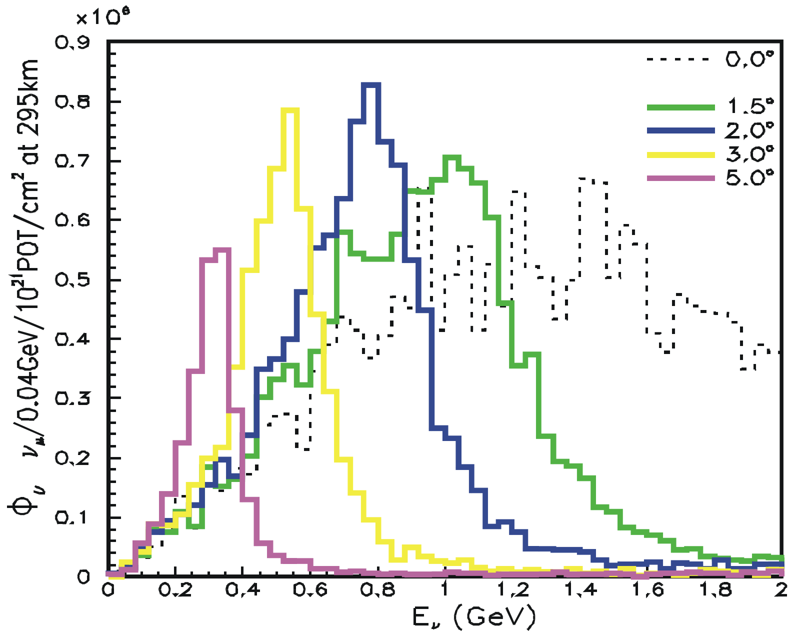
WBB w/ intentionally misaligned beam line from det. axis

Decay Kinematics



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





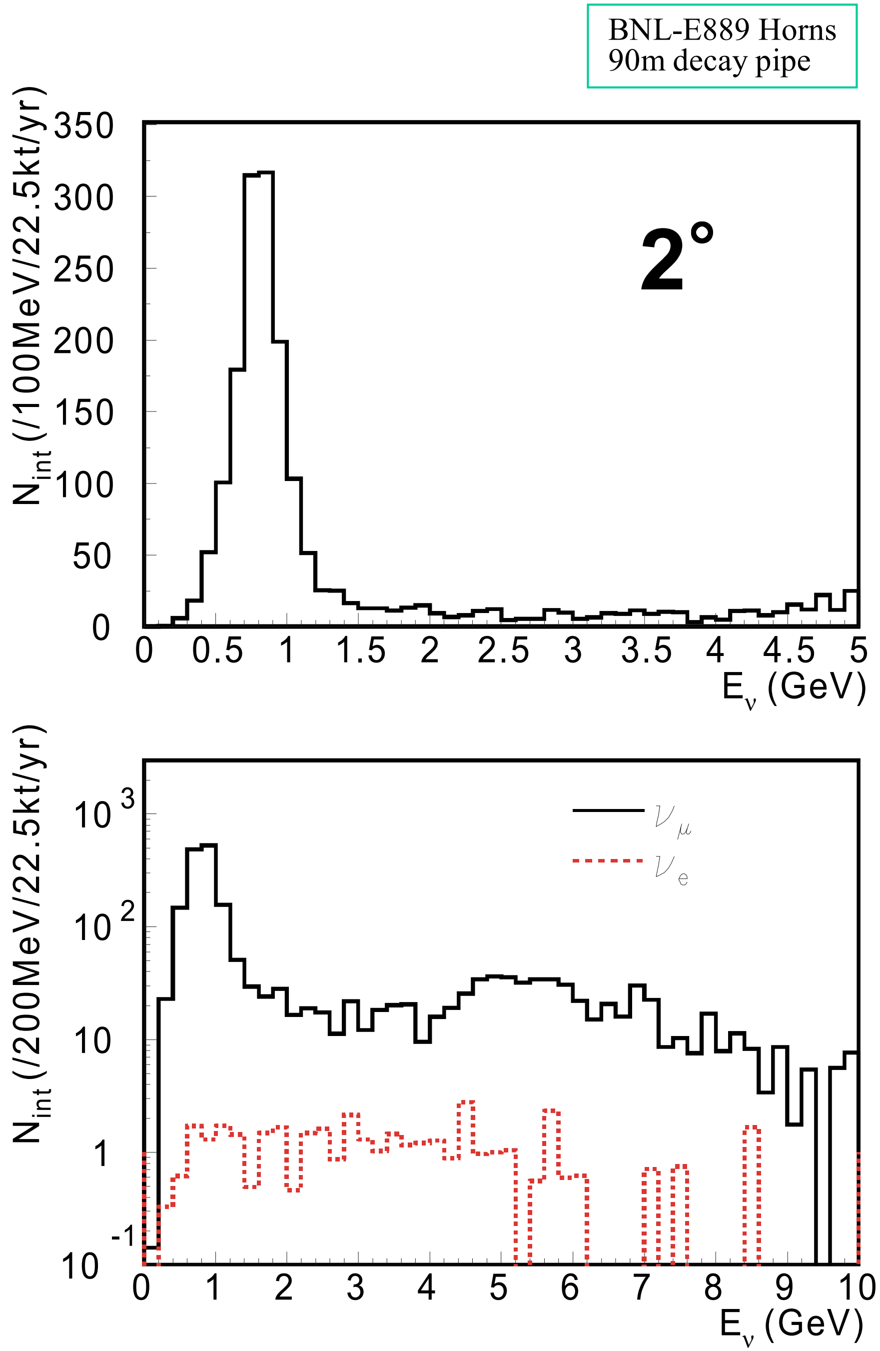
Quasi Monochromatic Beam

Off axis beam

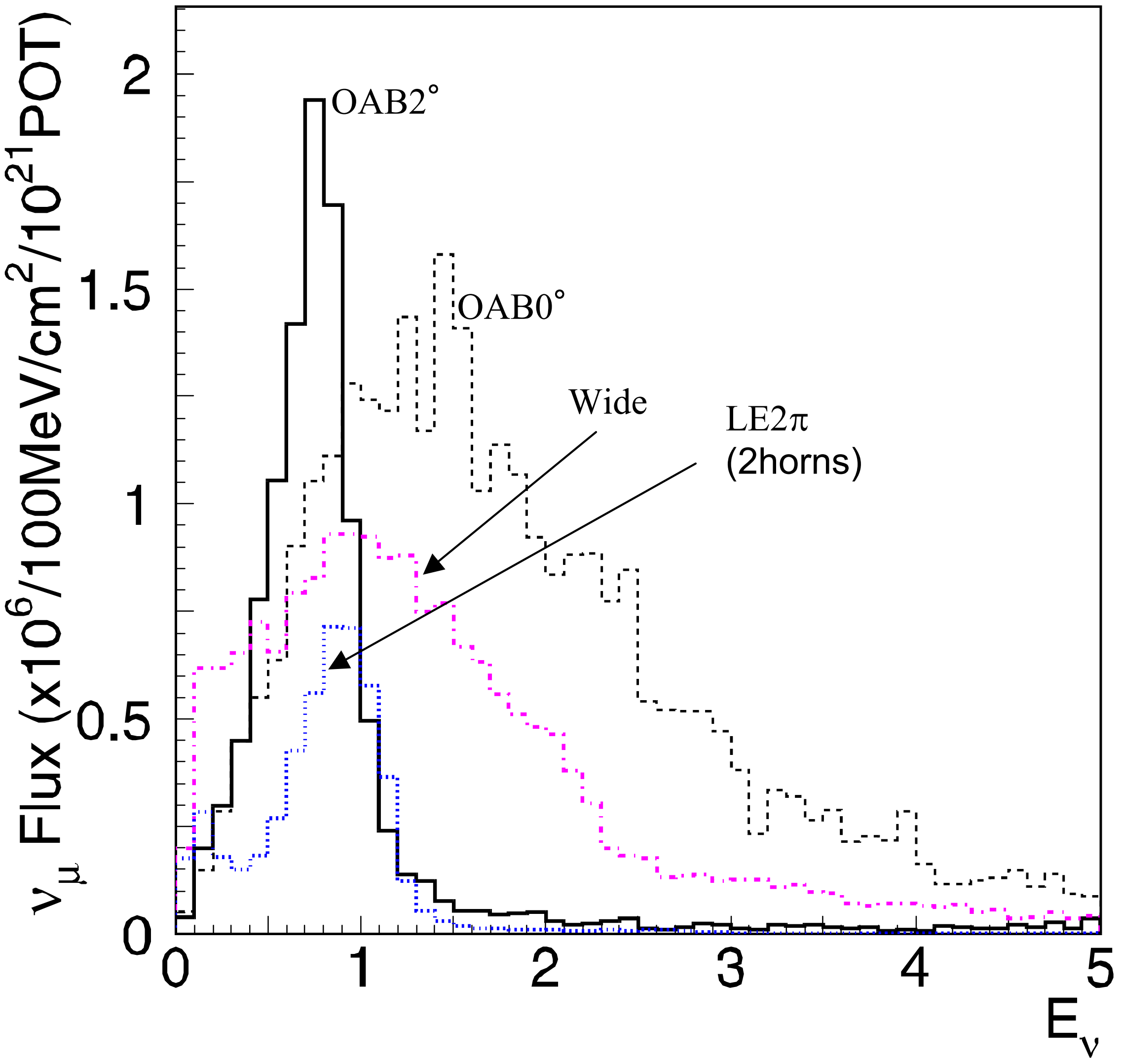
~2200 int./22.5kt/yr

ν_e: 0.8% (0.2% @ peak)

High int. narrow band beam
More HE tail than NBB
Hard to tune E_ν

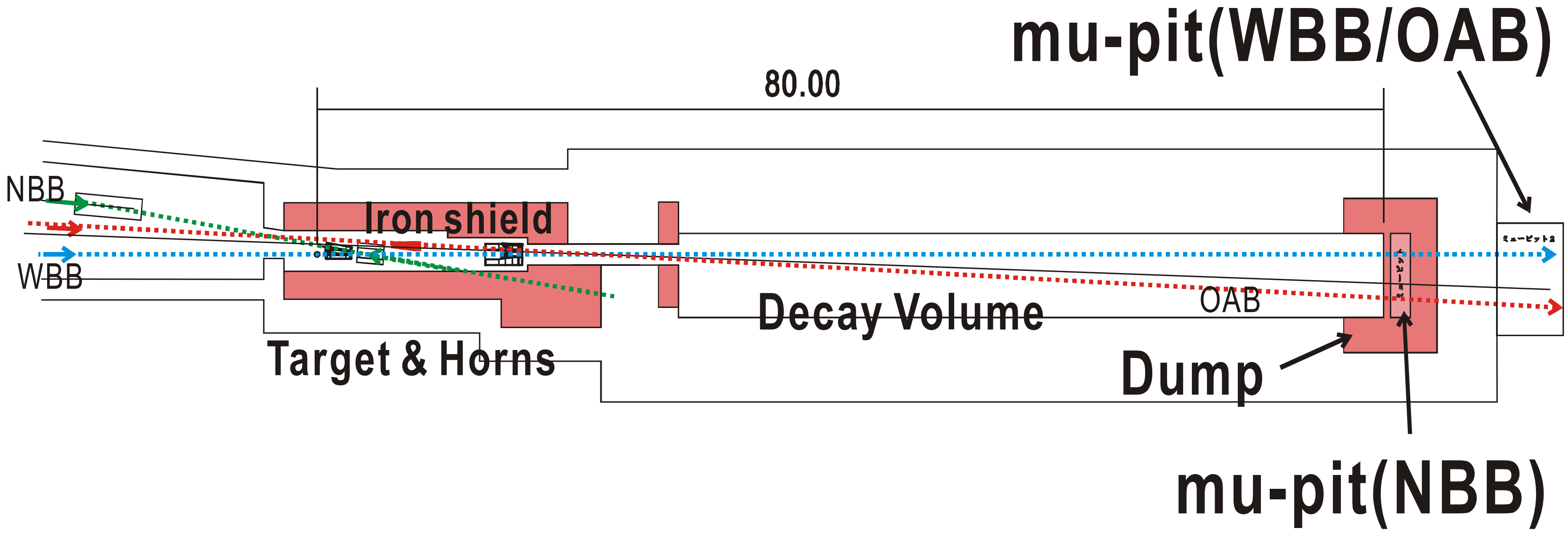


Comparison of Beams



(same decay pipe length=50m)

Current design of target station and decay volume



WBB/NBB/OAB can be switched by replacing optics
Decay volume is shared (flat pipe)

Design being optimized: flux, radiation shielding, cost

Physics Sensitivity

Strategy and Goal

- First 1 year WBB
  - → pin down Δm_{23}^2 to $\pm 10\%$ level
  - → NC measurement
- 5year NBB or OAB
  - → precise measurement of θ_{23} and θ_{13}.

Sensitivity (goal):

$\delta \sin^2 2\theta_{23} \sim 0.01$

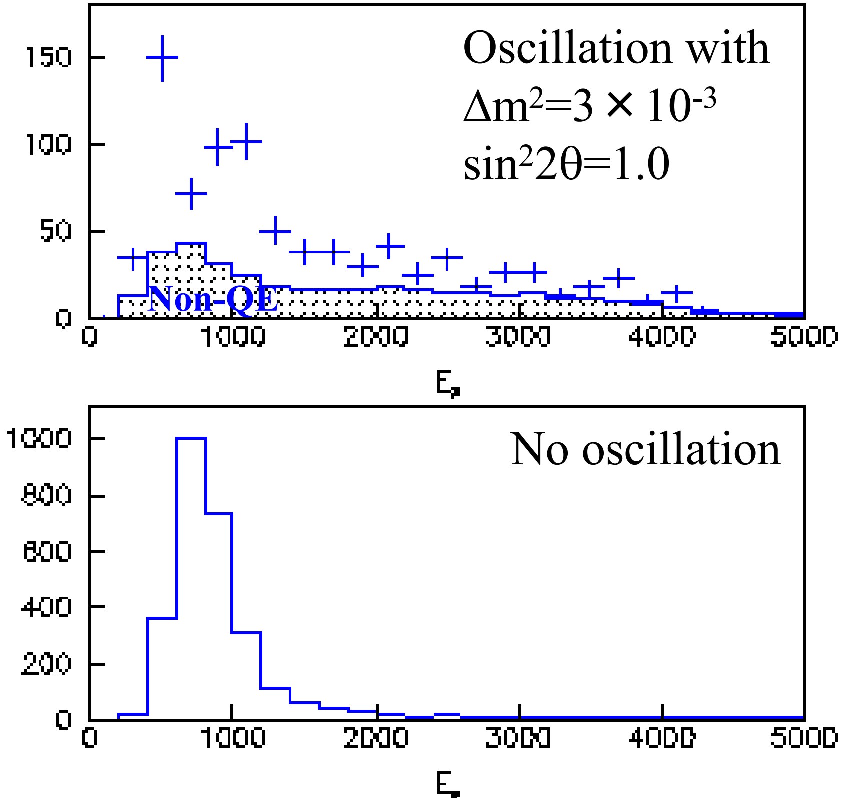
$\sin^2 2\theta_{13} \sim 5 \times 10^{-3}$ (90% CL)

$\delta \Delta m_{23}^2 \sim 1.5 \times 10^{-4} \mathrm{eV}^2$

at ($\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.2 \times 10^{-3} \mathrm{eV}^2$)

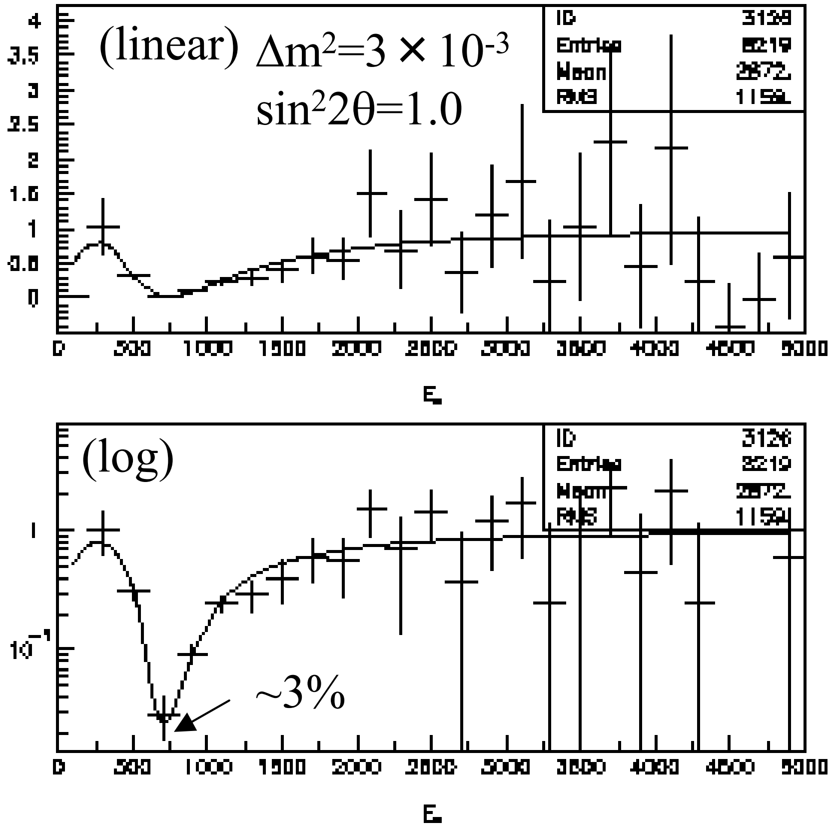
ν_μ disappearance

1ring FC μ-like



Reconstructed Eν (MeV)

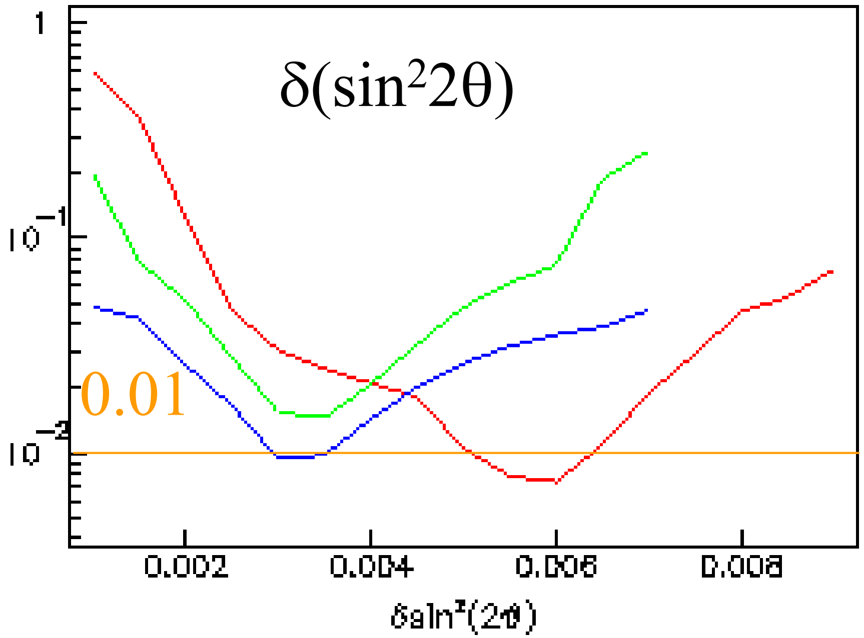
Ratio after BG subtraction

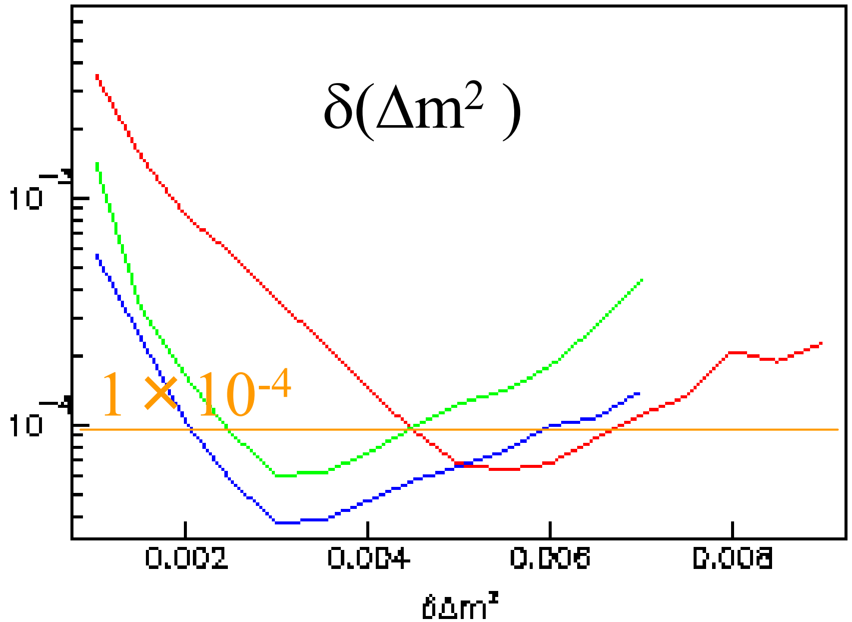


Fit with $1-\sin^2 2\theta \cdot \sin^2(1.27\Delta m^2 L/E)$

5 years precision

NBB-3GeVπ, OAB-2degree, NBB-1.5GeVπ





$\delta(\sin^2 2\theta) \sim 0.01$ in 5 years

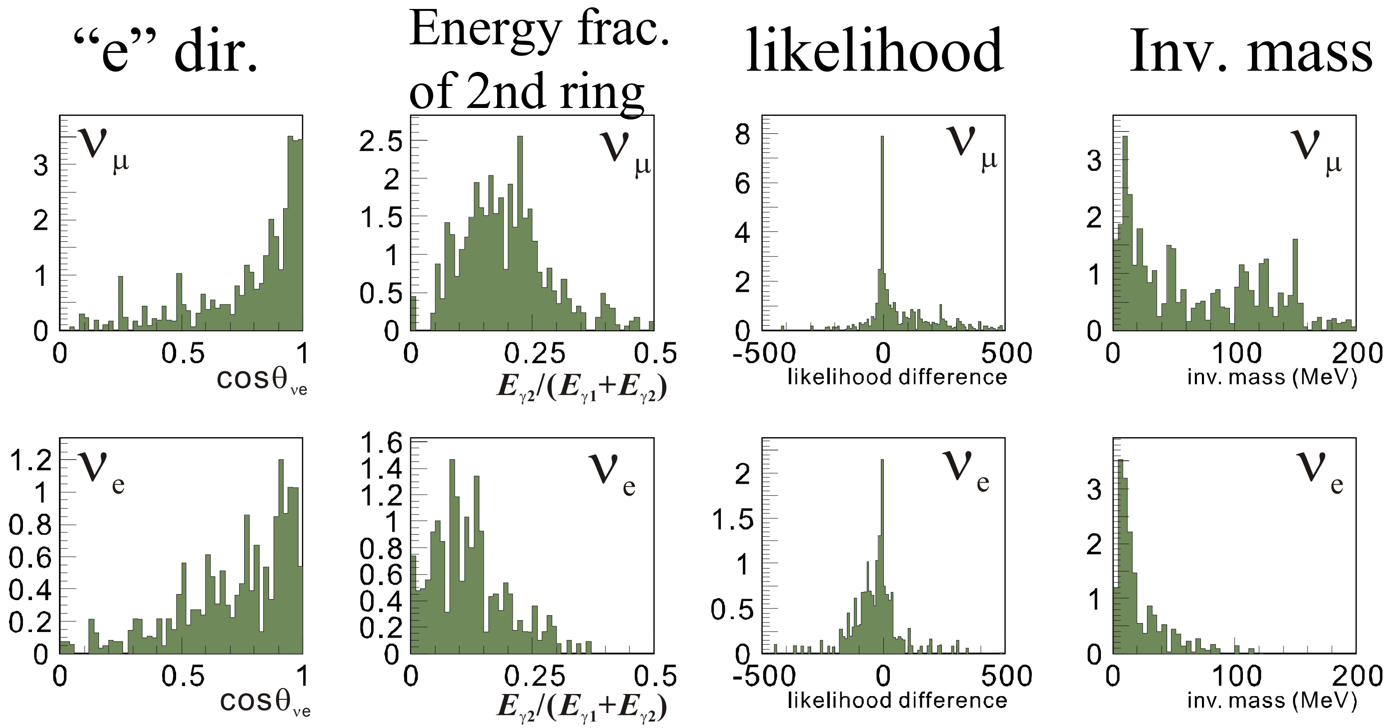
$\delta(\Delta m^2) \sim < 1 \times 10^{-4}$ in 5 years

ν_e appearance (θ_{13})

- Signal
  - 1ring e-like ring
  - At energy of ν_μ disappearance dip
- Backgrounds
  - ν_μ NC π^0 production
    - Lower E photon is missed
  - Beam ν_e comtamination
    - Broad E dist. Can be reduced w/ energy window.
    - 0.2-0.3% of ν_μ at peak of NBB/OAB

π^0 BG rejection (updated from LOI)

Force to find 2nd ring in 1-ring e-like sample



Factor ~10 improvement in BG rejection
while ν_e eff. decrease is only 30%

Preliminary

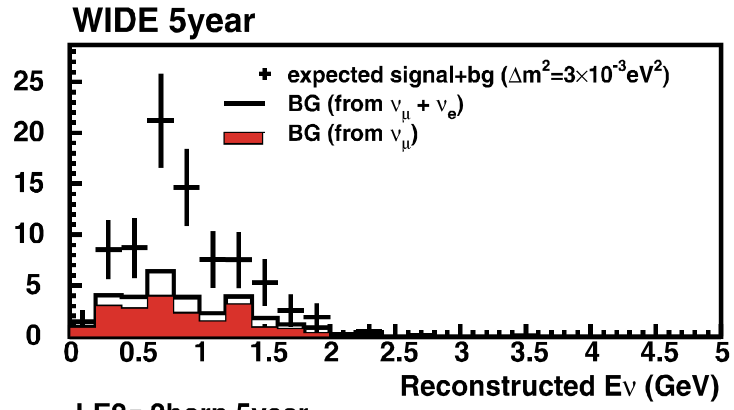
Expected signal

$\sin^2 2\theta_{\mu e}=0.05$ (Chooz limit)

WBB

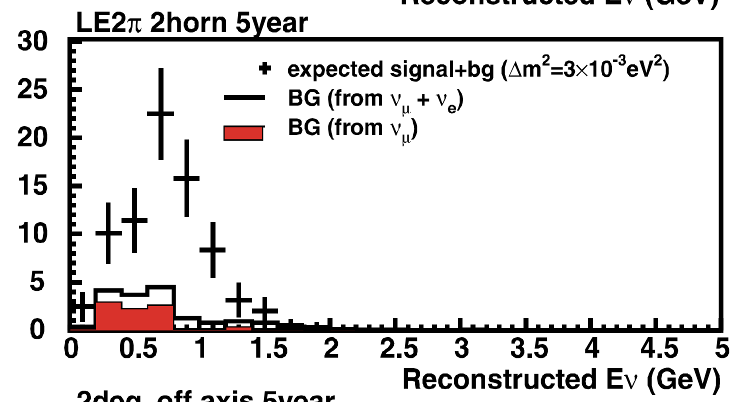
Sig: 49(ε=18.4%)
BG: 20(ε=0.1%)

e/π^0 cut tightened to reduce BG



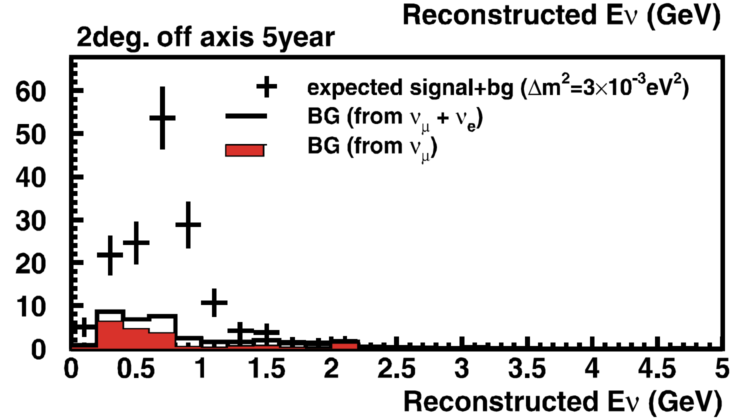
NBB

Sig: 58(ε=50.4%)
BG: 9(ε=0.2%)



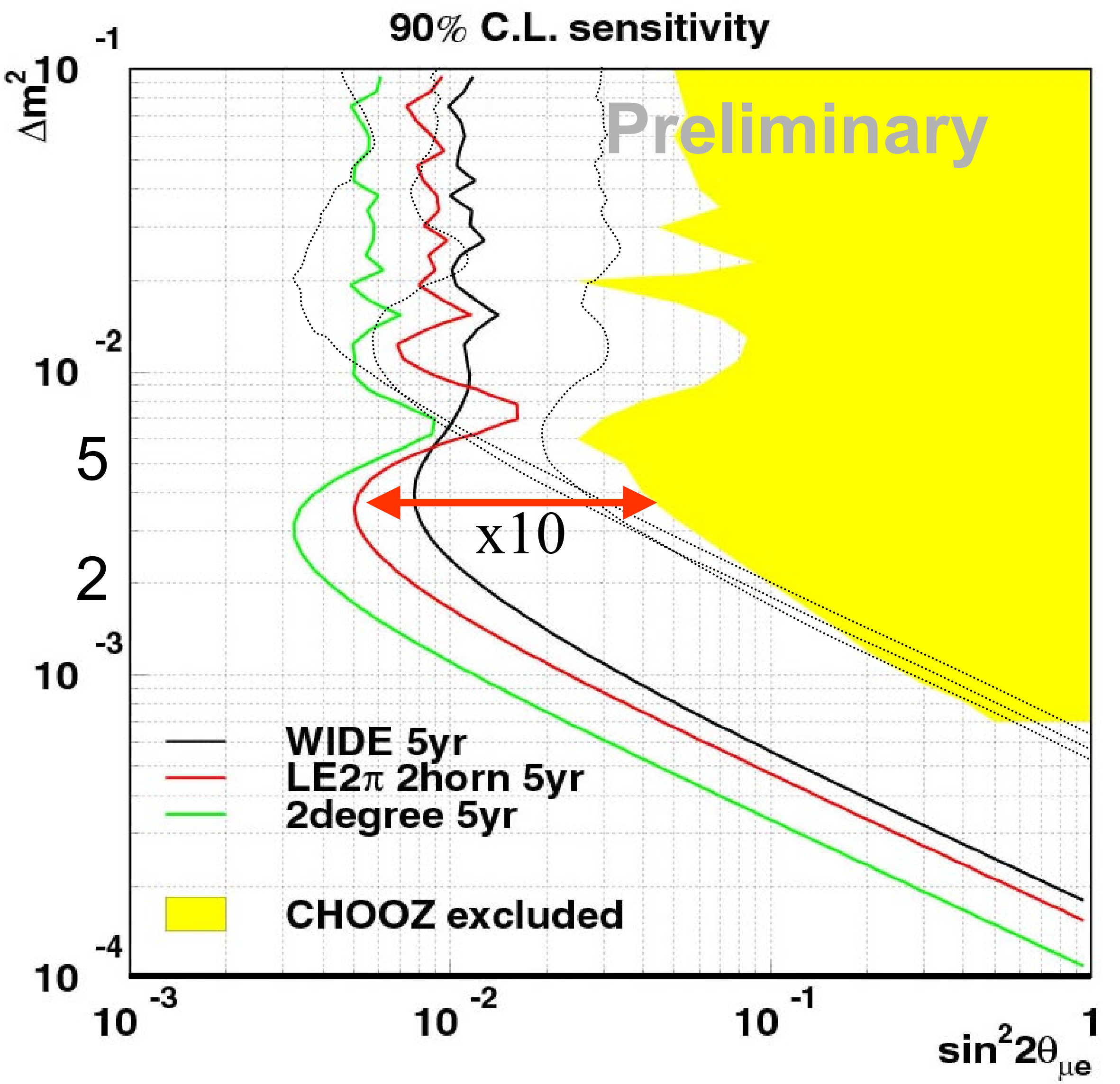
OAB(2deg)

Sig: 121.5(ε=53.4%)
BG: 19(ε=0.2%)



Preliminary

Sensitivity on $\nu_\mu \rightarrow \nu_e$ appearance



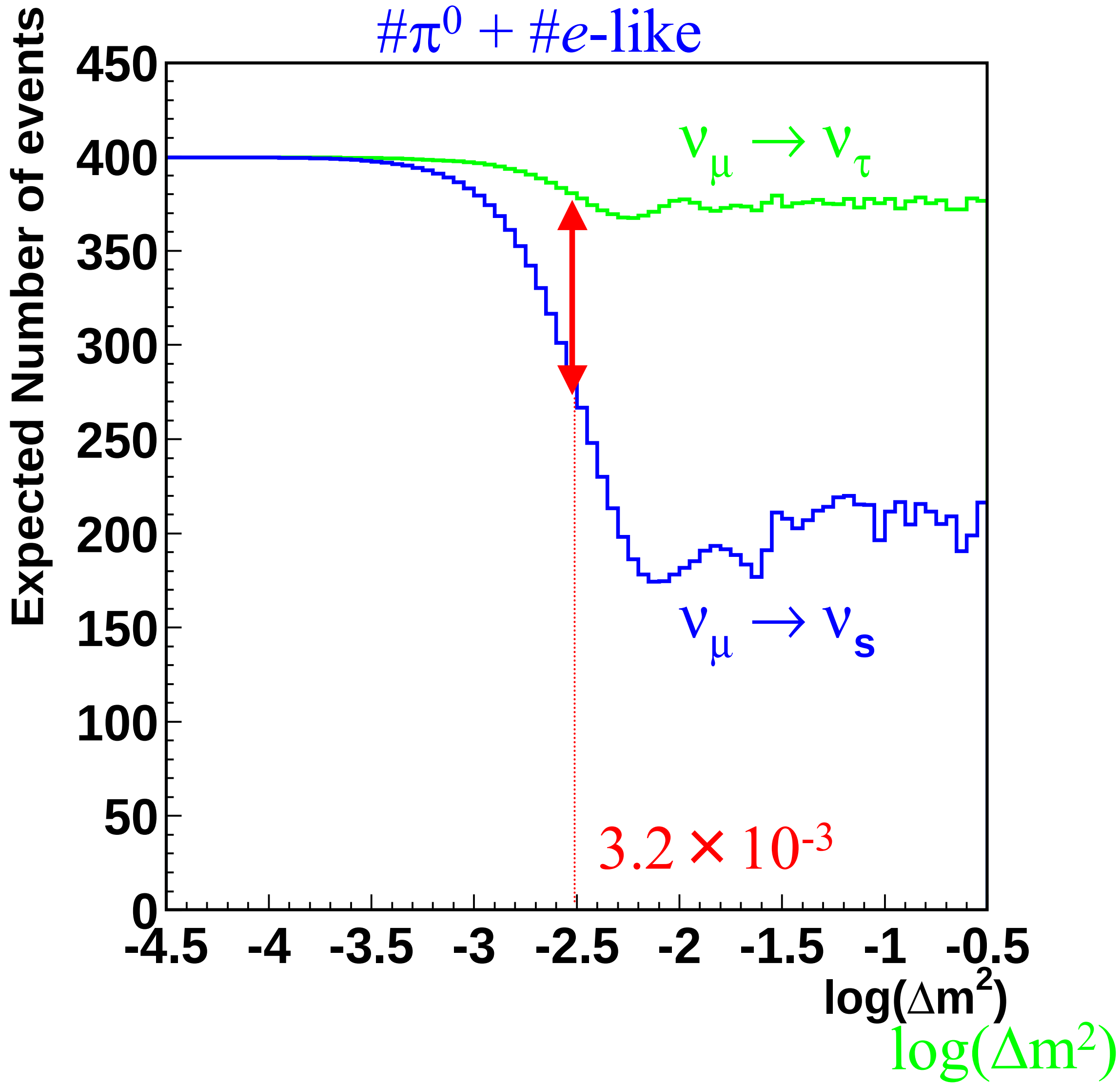
Dashed lines: MINOS Ph2le, Ph2me, Ph2he from right
(A.Para, hep-ph/0005012)

NC measurement

\# of NC events

$$N_{NC} \propto P_{\mu\to active} = 1 - P_{\mu\to sterile}$$

- NC/CC sensitive to ν_s
- NC Enriched Sample



Comparison with other LBL projects

- **ICANOE (2005～)**
  - CERN SPS(400GeV) →Gran Sasso LBL (732km)
  - E_ν ～20GeV
  - Optimized for ν_τ search
- **MINOS (2003～)**
  - Fermilab Main Injector (120GeV) → Soudan mine (730km)
  - E_ν>3GeV
  - ν_μ disappearance: $\delta(\Delta m^2)\sim 2.4\text{x}10^{-4}\text{eV}^2$, $\delta(\sin^2 2\theta_{23})\sim 0.06$
  - ν_e appearance : $\delta(\sin^2 2\theta_{\mu e})>0.04$ @$\Delta m^2=3\text{x}10^{-3}\text{eV}^2$

    (read from A.Para, ICHEP2000 by T.K.)

Complementary to JHFν

	Beam	E_ν	(E/L)(π/2)/ 1.27	Det.	E_ν rec'nst	CC event
JHFν	NBB/WBB /OAB	～1GeV	$3.8\text{x}10^{-3}\text{eV}^2$	Water Cherenkov	QE	3200/yr(WBB)
MINOS	WBB	>3GeV*	$5\text{x}10^{-3}\text{eV}^2$	Iron cal.	Hadr. Cal.	2500/yr*

JHF project has much higher potential.

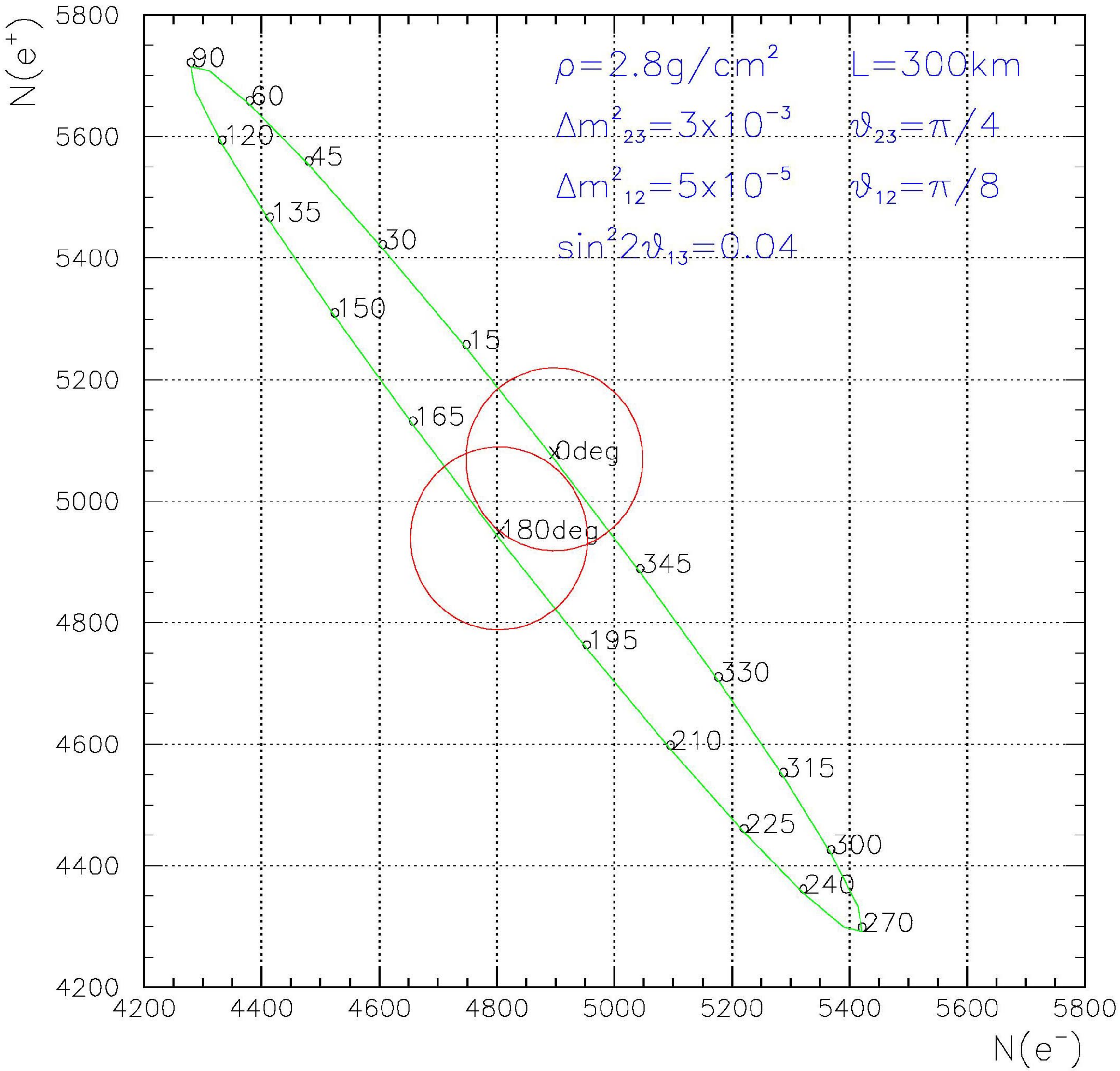
*:PH2(Low) option

Future Extensions

- **PS upgrade to 4MW and 1Mton water Cherenkov detector**
  - 2 order increase in statistics
  - CPV if ν_e appearance discovered in the 1st phase
    - O(100) ν_e events/year if θ_{13}=0.1x(Chooz limit)
  - (Proton decay)
- **Very LBL experiment (1000-2000km)**
  - ～300(1200)CC events/100kt/yr @ 2000(1000)km w/ 6GeV NBB
  - Sign of Δm^2s
  - Matter effect
  - CPV

Sensitivity to CPV

4MW PS
1Mton Hyper Kam.
2years for ν_μ
6years for ν_μ bar



Summary

- **JHFν project**
  - ✓ ∼MW 50GeV PS @ JHF
  - ✓ Super-Kamiokande@ 295km as far detector
  - ✓ Low energy(∼1GeV) conventional ν_μ beam tuned at osc. max.
  - ✓ Energy reconstruction by using QE
  - ✓ NBB/OAB to reduce background and syst. err.
- **Physics sensitivity**
  - ✓ $\delta\sin^2 2\theta_{23} \sim 0.01$
  - ✓ $\sin^2 2\theta_{13} \sim 5\times 10^{-3}$ (90% CL)
  - ✓ $\delta\Delta m_{23}^2 \sim 1\times 10^{-4}\mathrm{eV}^2$
  - ✓ ν_s existence can be tested.
- Design and R&D work have just been started.
- JHFν is not included in current budget request.
- Full approval within a few years

  Data taking in 2006-7

International Workshop on “future long baseline experiment at JHF” with Conventional Beam

May 31(just after Nufact01) at Tsukuba

Introduce JHFν project to interested people

Let’s Join!