JHFニュートリノ実験と超低エネルギービーム

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IPNS, KEK

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宇宙ニュートリノ第5回研究会@ICRR

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}=$\cos\theta_{ij}$

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

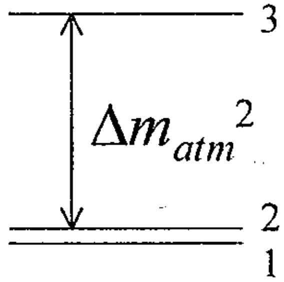
L : flight length, E : neutrino energy, $\Delta m^2_{ij} \equiv m^2_i - m^2_j$, m_i : mass eigenvalues

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

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

$P_{\mu\to e} \approx$ [redacted] $\cdot \sin^2\left(1.27\Delta m_{atm}^2 / E_\nu\right)$

~0.5 $\sin^2 2\theta_{\mu e}$

ν_μ disappearance

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

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

~ 1

Neutral Current (NC) measurement

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

Cf. Chooz (ν_e disappearance)

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

CP violation

No CPV in disappearance from unitarity

$$P_{\mu\to e}(CPV) = \sin\delta \cdot (\sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}) \cdot \cos\theta_{12}$$
$$\times \left(\sin\frac{\Delta m_{12}^2 L}{2E} + \sin\frac{\Delta m_{23}^2 L}{2E} - \sin\frac{\Delta m_{31}^2 L}{2E} \right)$$

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- LMA solution for solar neutrino
  $\Delta m^{12} \sim 10^{-4} eV^2$, $\sin^2\theta_{12} \sim 0.8$
- θ_{13} is non zero

CPV effect in lepton sector could be detectable

Physics motivation

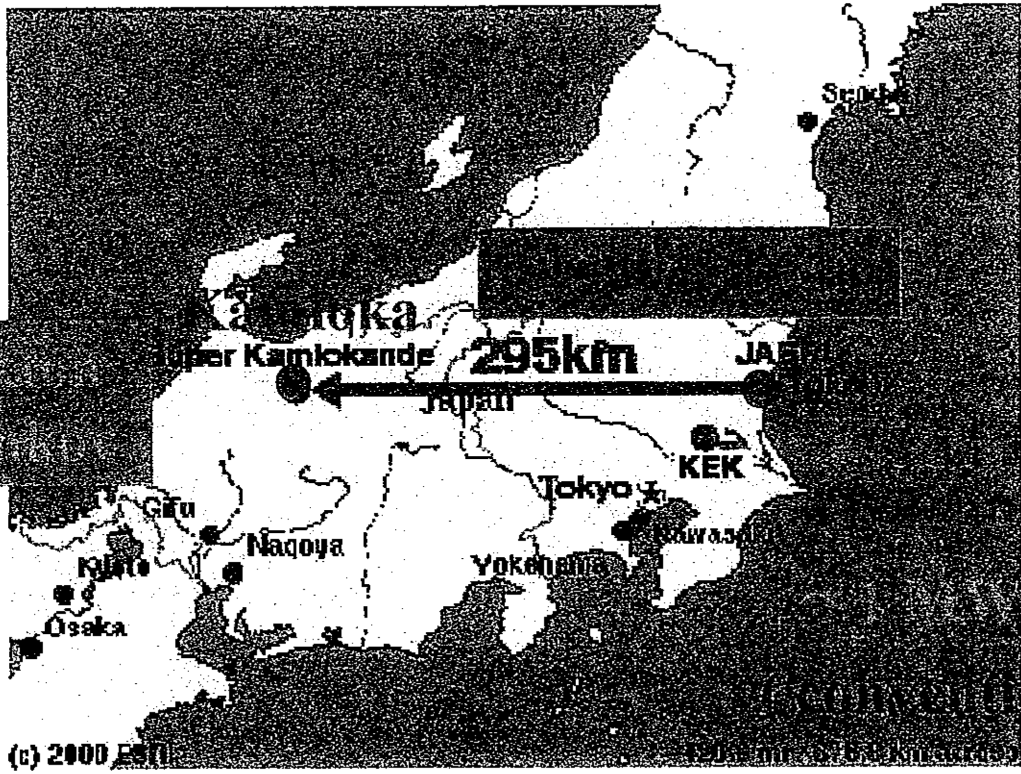
1. **Test our current picture of 3 flavor neutrino oscillation**
   - Spectrum shape of ν_μ disappearance
     - Test exotic models (decay, extra dimensions,....)
   - Appearance of ν_e at the same Δm^2 as ν_μ disappearance
   - NC measurements
     - No additional "neutrino"?
2. **Precise measurement 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

JHF ν experiment

Overview



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

Principle

- Super-Kamiokande at 295km as far detector

- Beam energy is tuned to be at the oscillation maximum.
  - High sensitivity
  - Less background

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

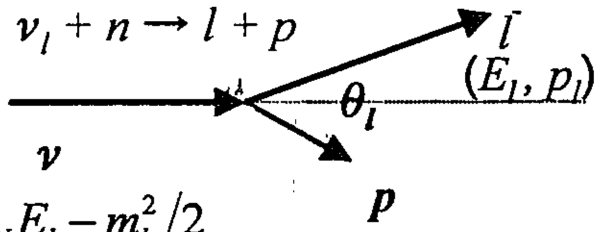
$E_\nu = 0.5 \sim 1.2\,\mathrm{GeV}$

- 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)

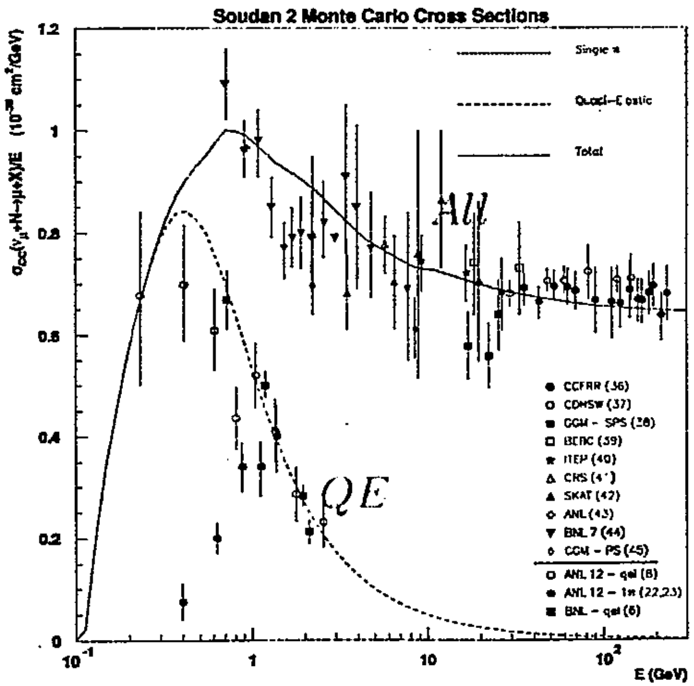
Neutrino Energy Reconstruction

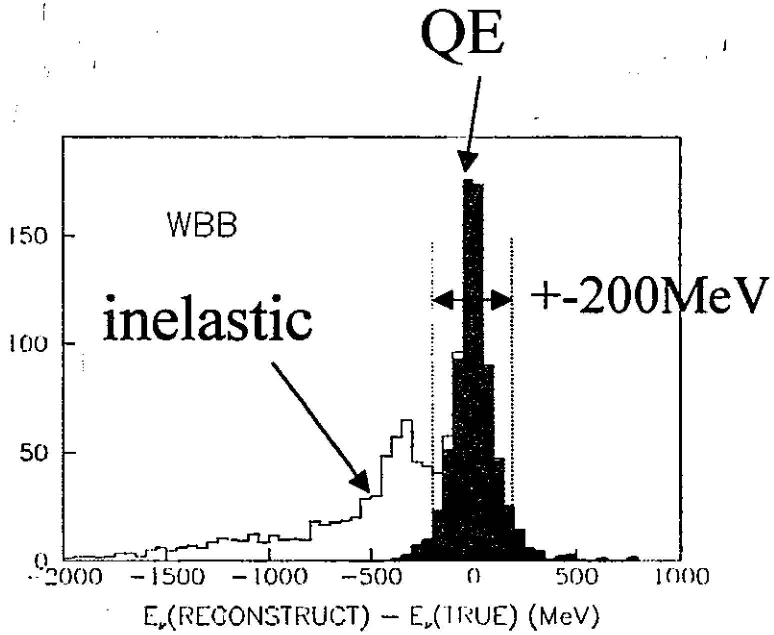
Assume CC quasi elastic (CCQE) reaction

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



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



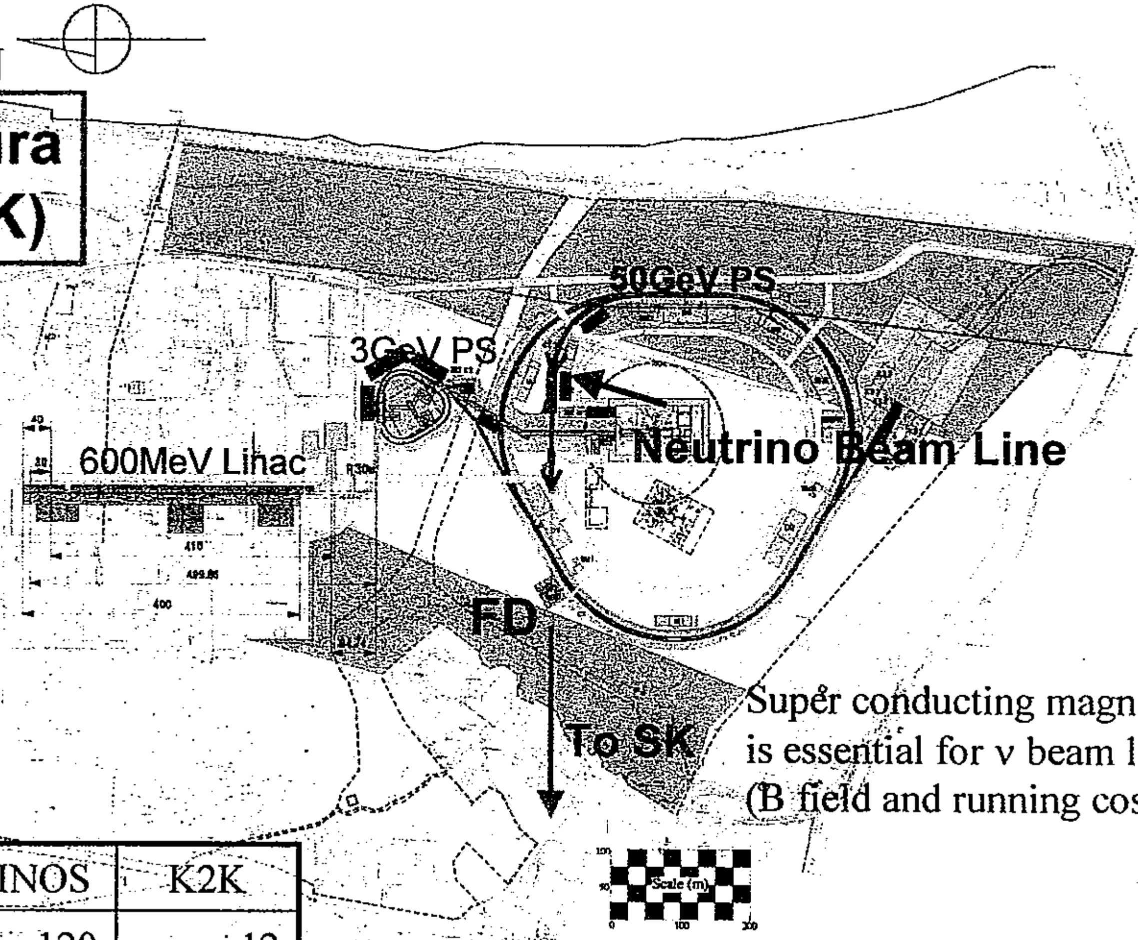


QE dominate at ~1GeV

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"

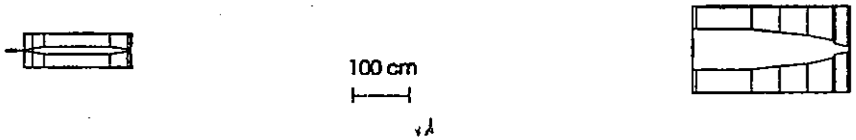
Neutrino Beam @ JHF

Three beam configurations

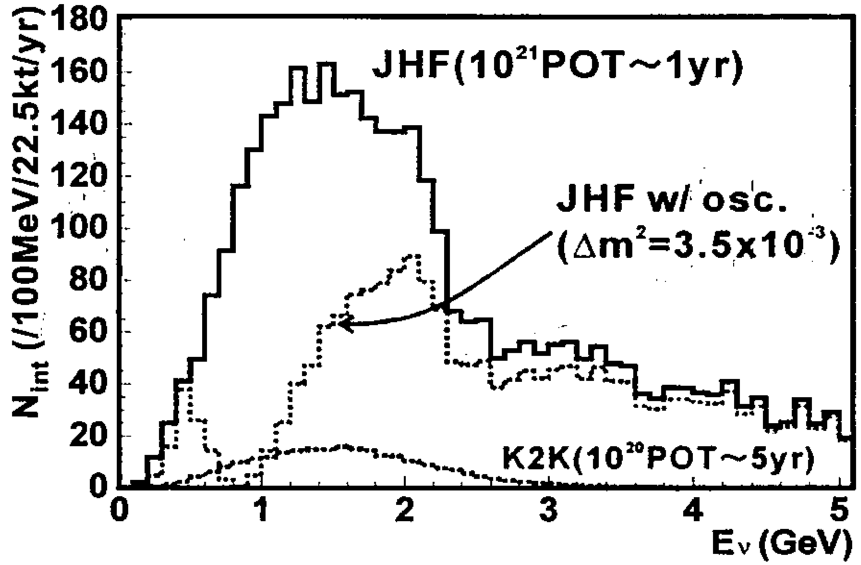
- ➢ **Wide Band Beam (WBB)**
  - – 2 Horns almost the same as K2K
- ➢ **Narrow Band Beam (NBB)**
  - –Horn(s) + Bending
- ➢ **Off Axis Beam (OAB)**
  - –Another option of NBB

Wide Band Beam

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

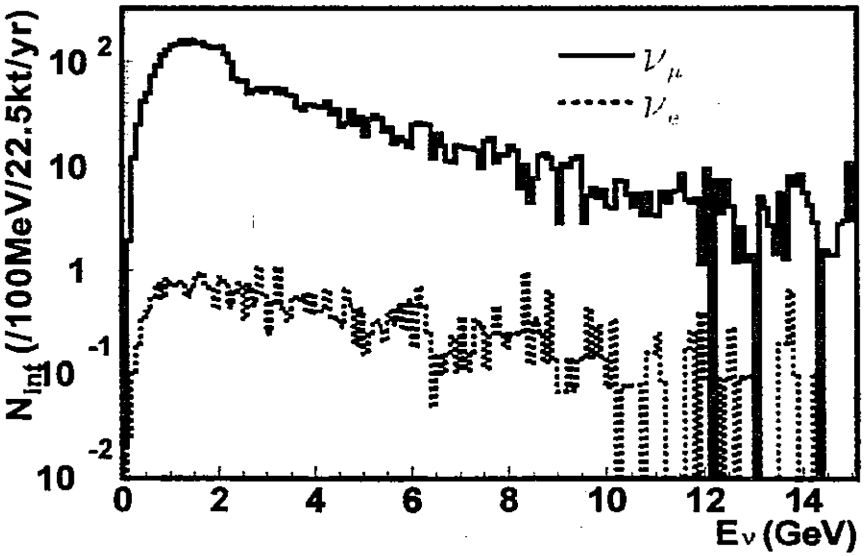


2 horns (almost same design as K2K)



$\sim$4200 ν_μ int./22.5kt/yr

ν_e:0.8%



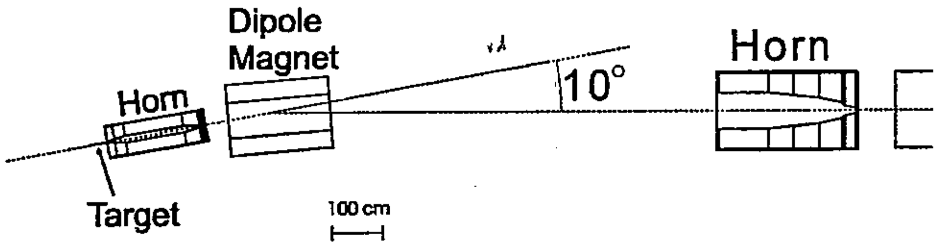
Intense
Wide sensitivity in Δm^2
BG from HE tail
Syst. err from spectrum extrapolation

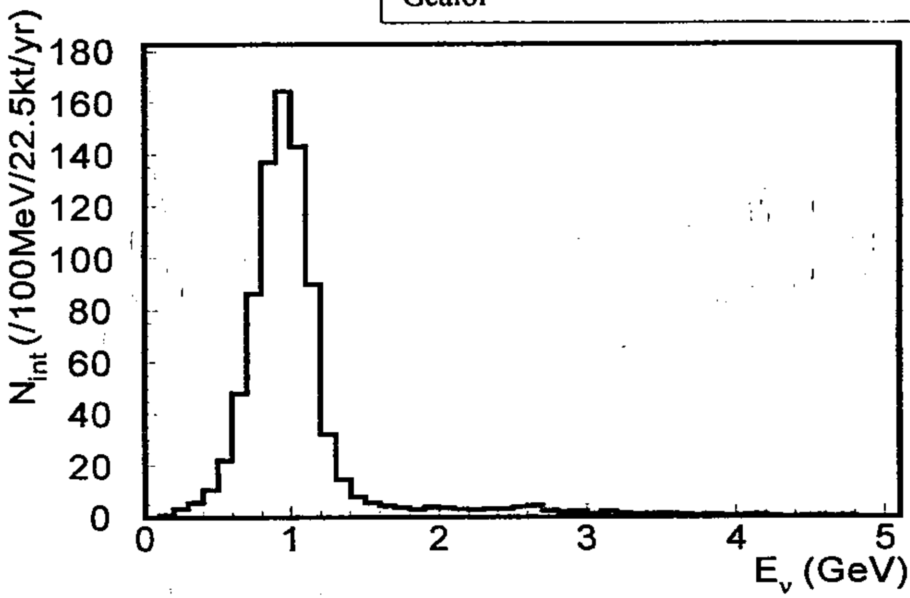
Narrow Band Beam

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	





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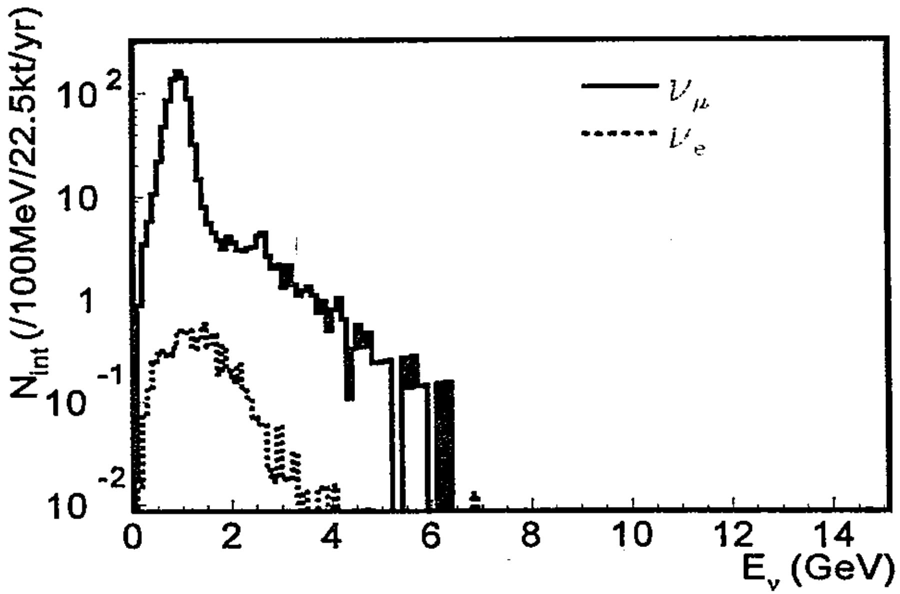
~830 int./22.5kt/yr

ν_e:0.8%(0.3% @ peak)



Less HE tail

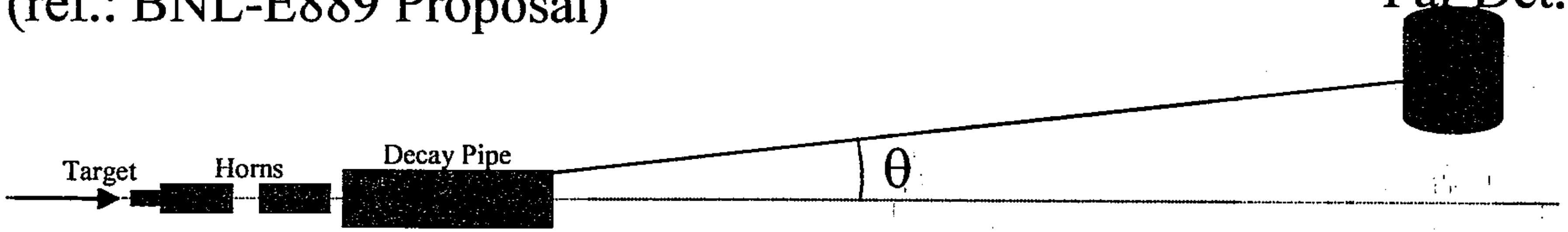
Less sys err from spectrum

"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

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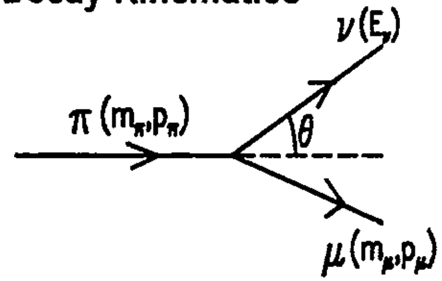
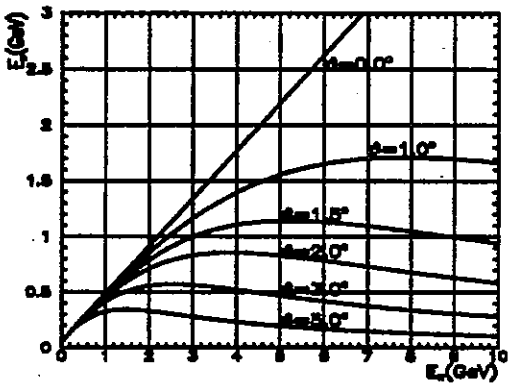
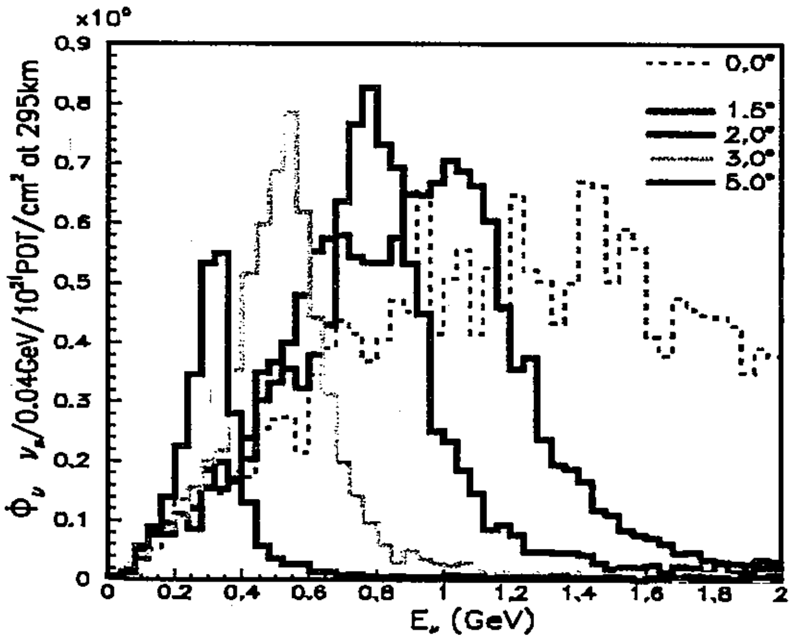
Decay Kinematics



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





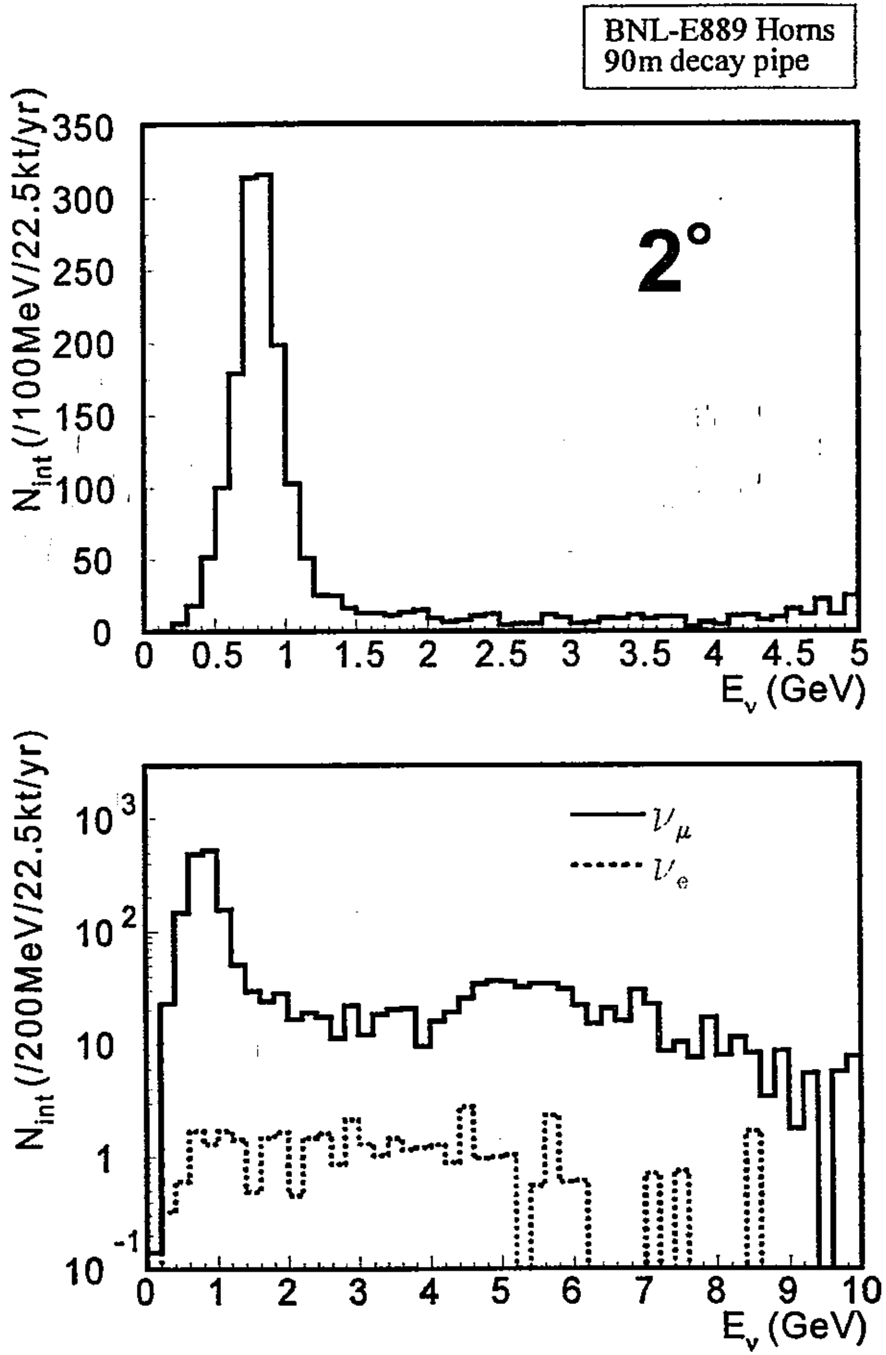
Quasi Monochromatic Beam

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



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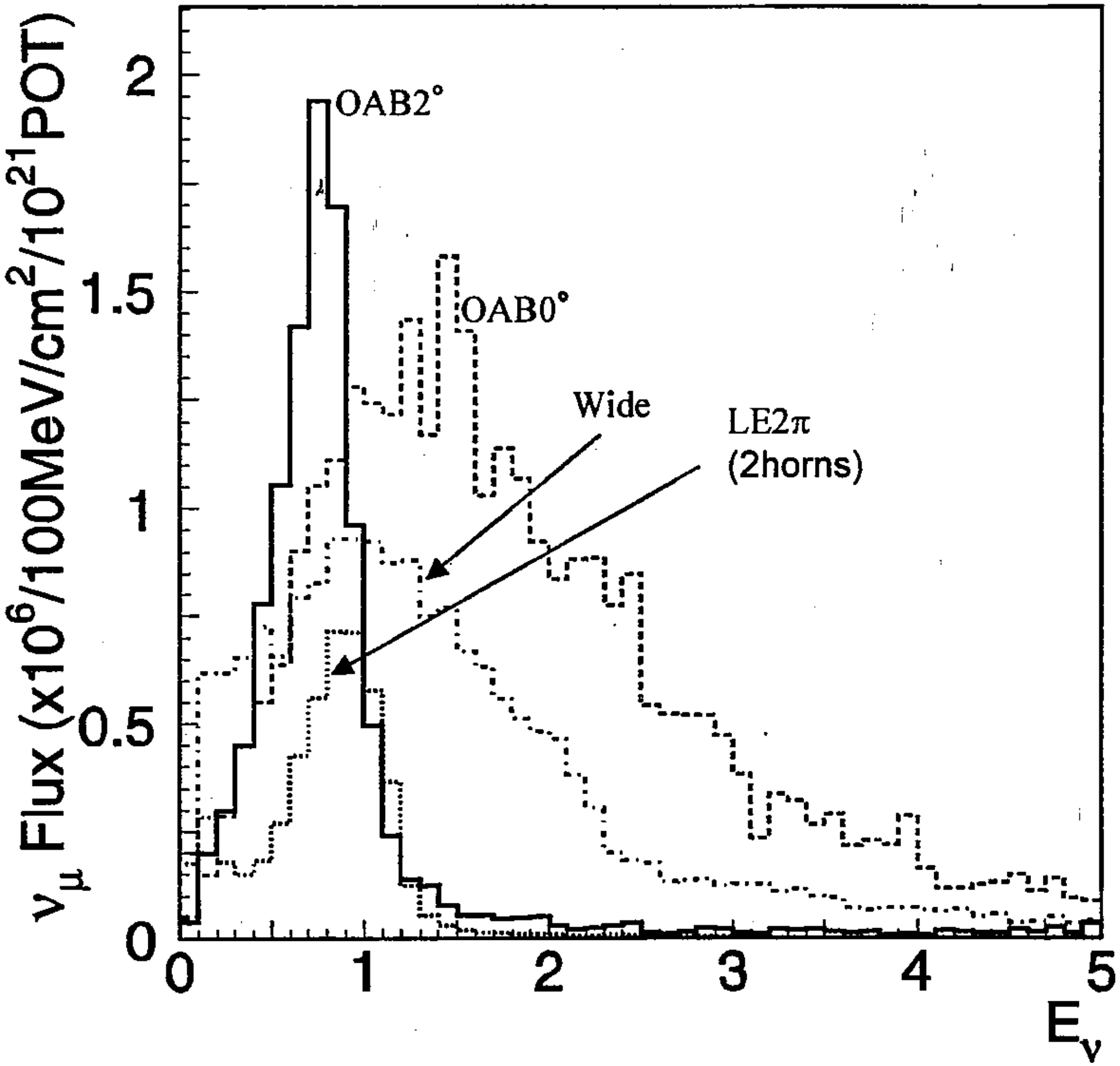
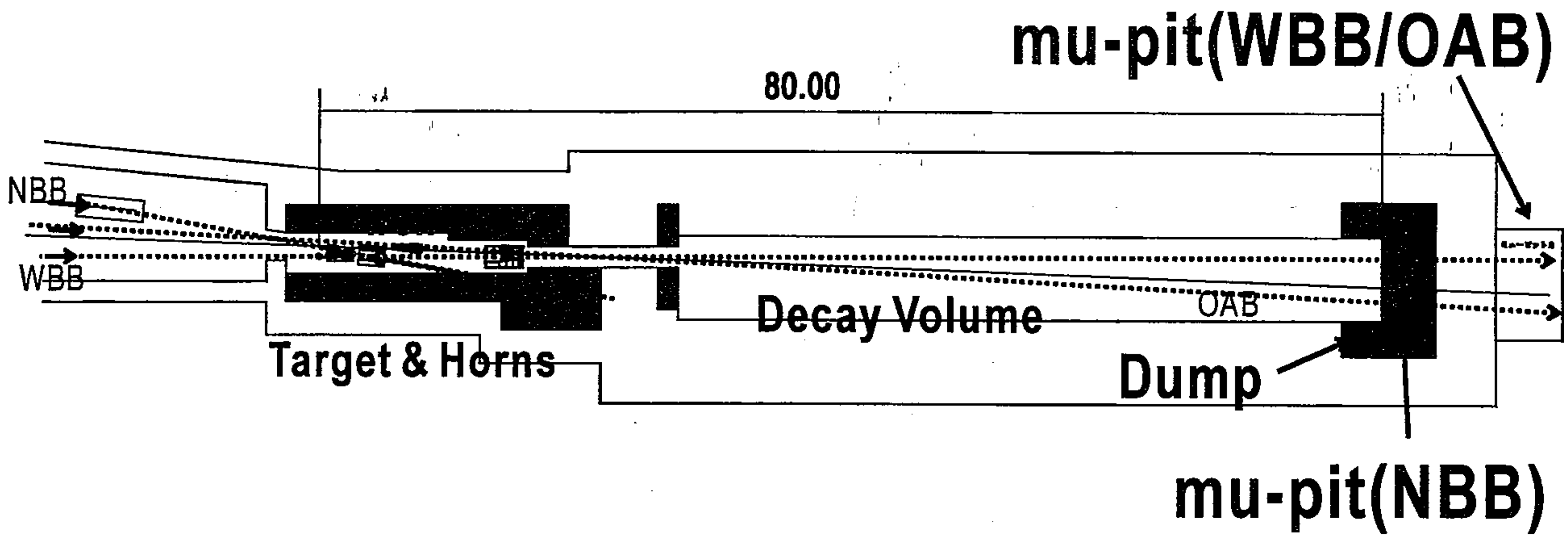
Comparison of Beams



(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

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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}.

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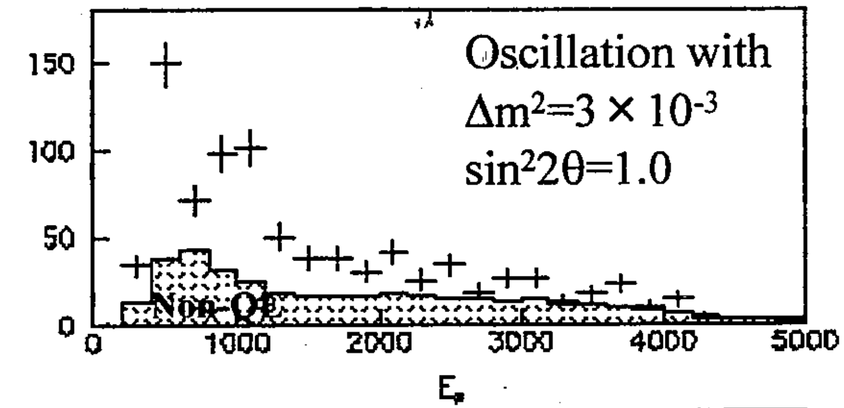
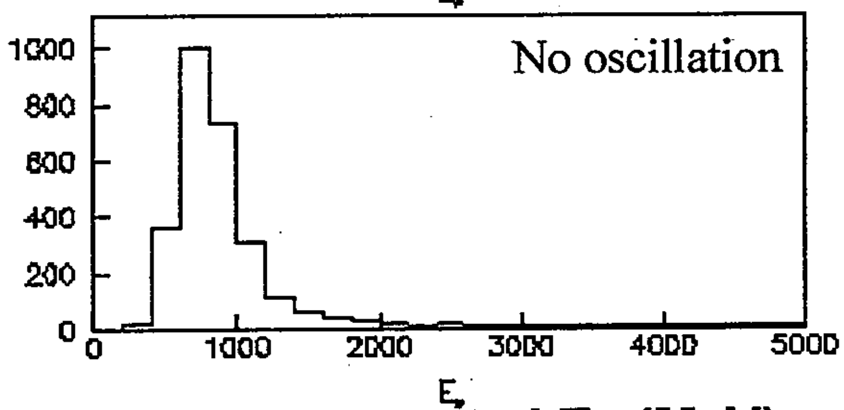
Sensitivity (goal):

$\delta\sin^2 2\theta_{23} \sim 0.01$
$\sin^2 2\theta_{13} \sim 5 \times 10^{-3}$ (90% CL)
$\delta\Delta m_{23}^2 \sim 1.5 \times 10^{-4} eV^2$
at ($\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.2 \times 10^{-3} eV^2$)

ν_μ disappearance

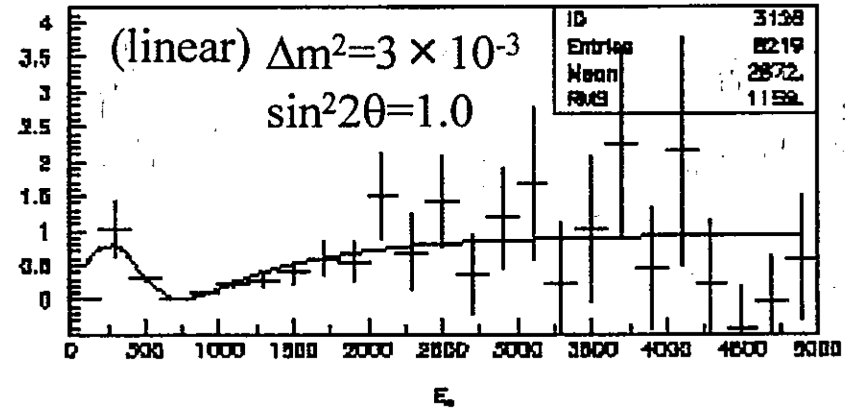
1ring FC μ-like

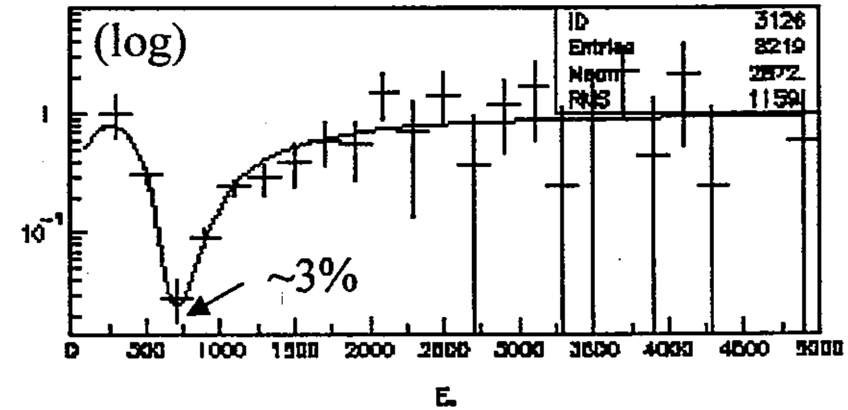




Reconstructed Eν (MeV)

Ratio after BG subtraction

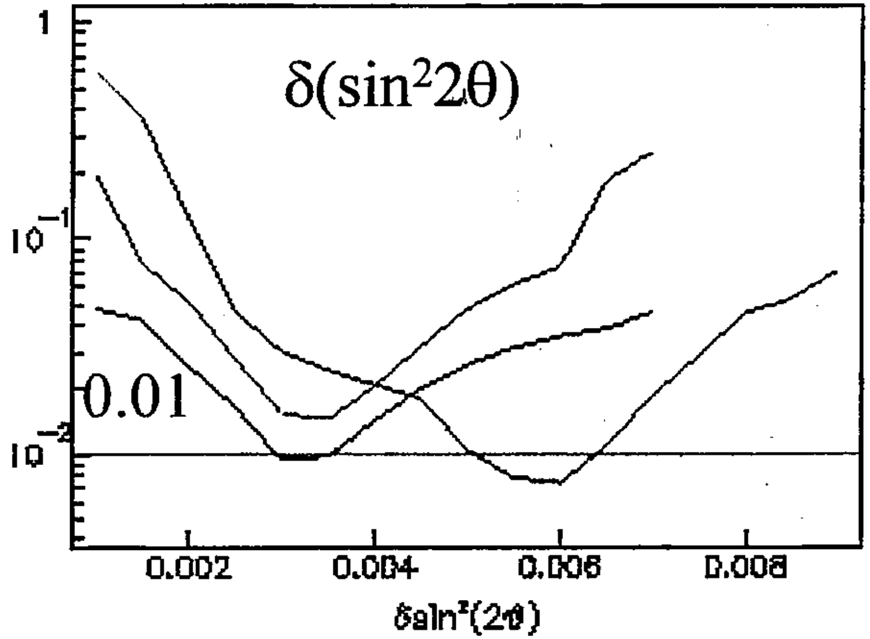


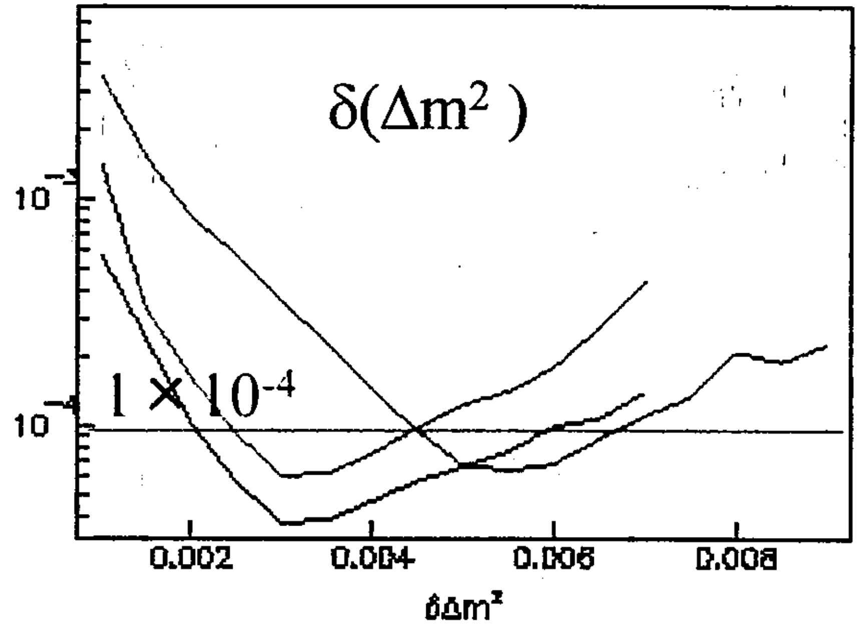


Fit with $1-\sin^2 2\theta \cdot \sin^2(1.27\Delta m^2 L/E)$

5 years precision

NBB-3GeVπ, OAB-2degree, NBB-1.5GeVπ





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

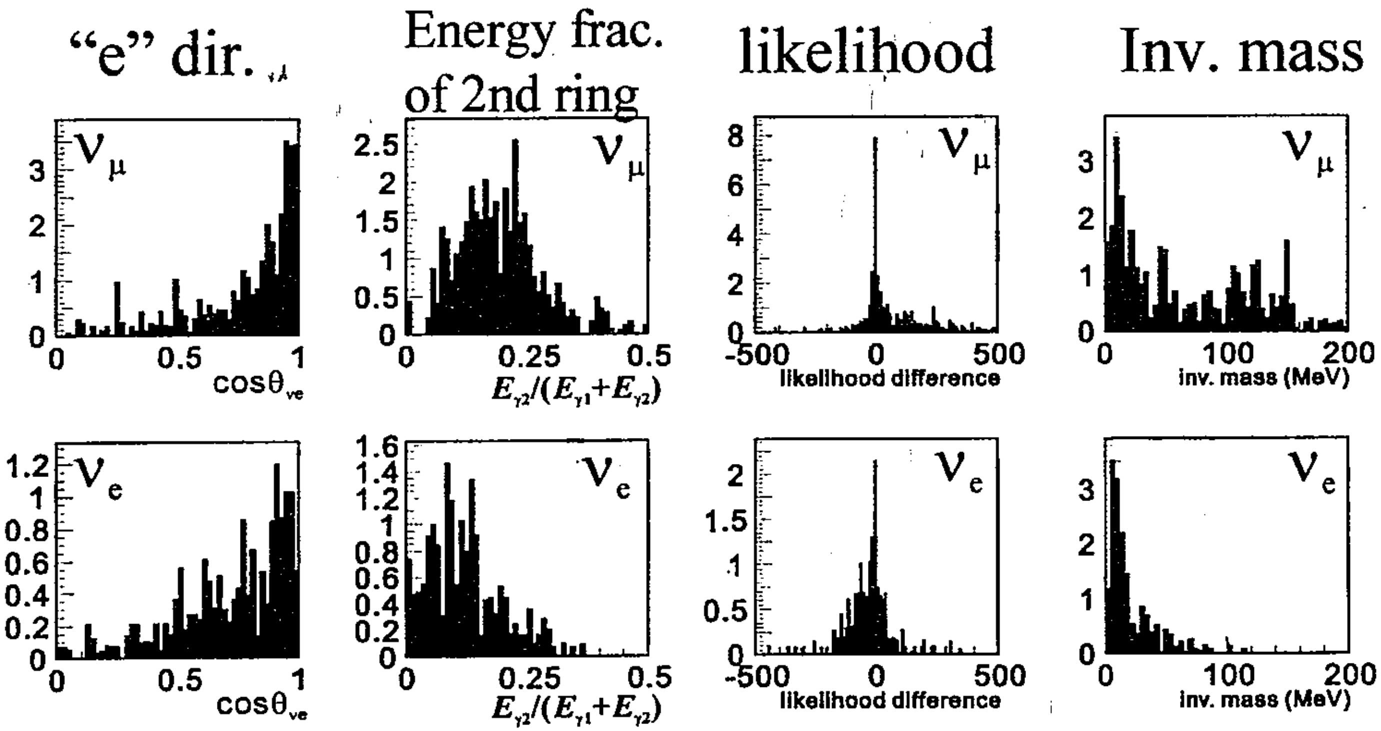
$\delta(\Delta m^2) \sim < 1 \times 10^{-4}$ in 5 years

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

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Expected signal

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

WBB

[illegible]

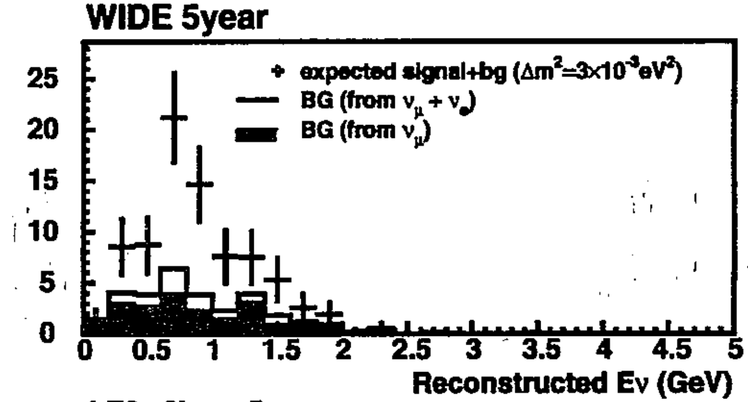
e/π^0 cut tightened to reduce BG

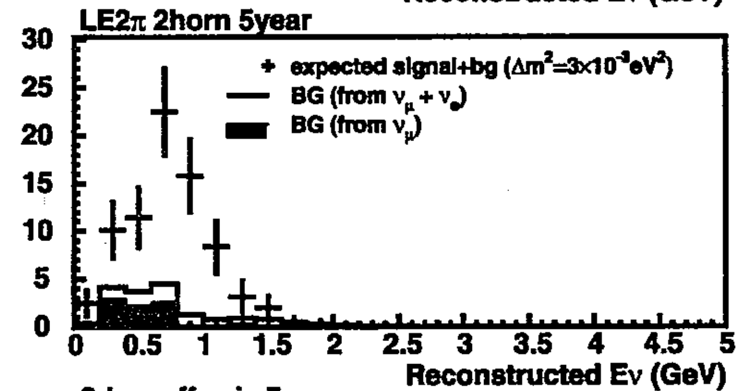
NBB

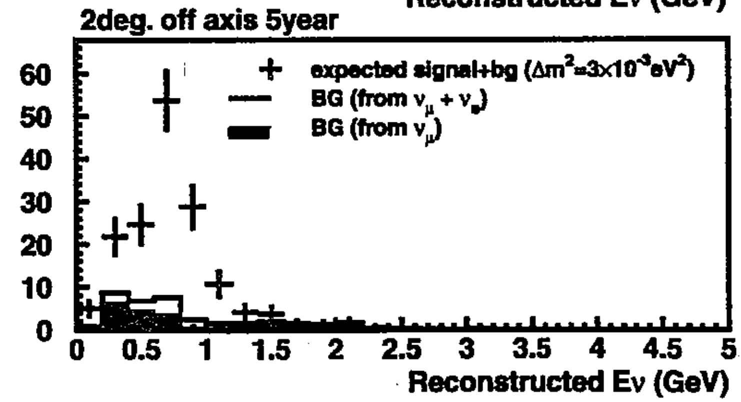
[illegible]

OAB(2deg)

[illegible]

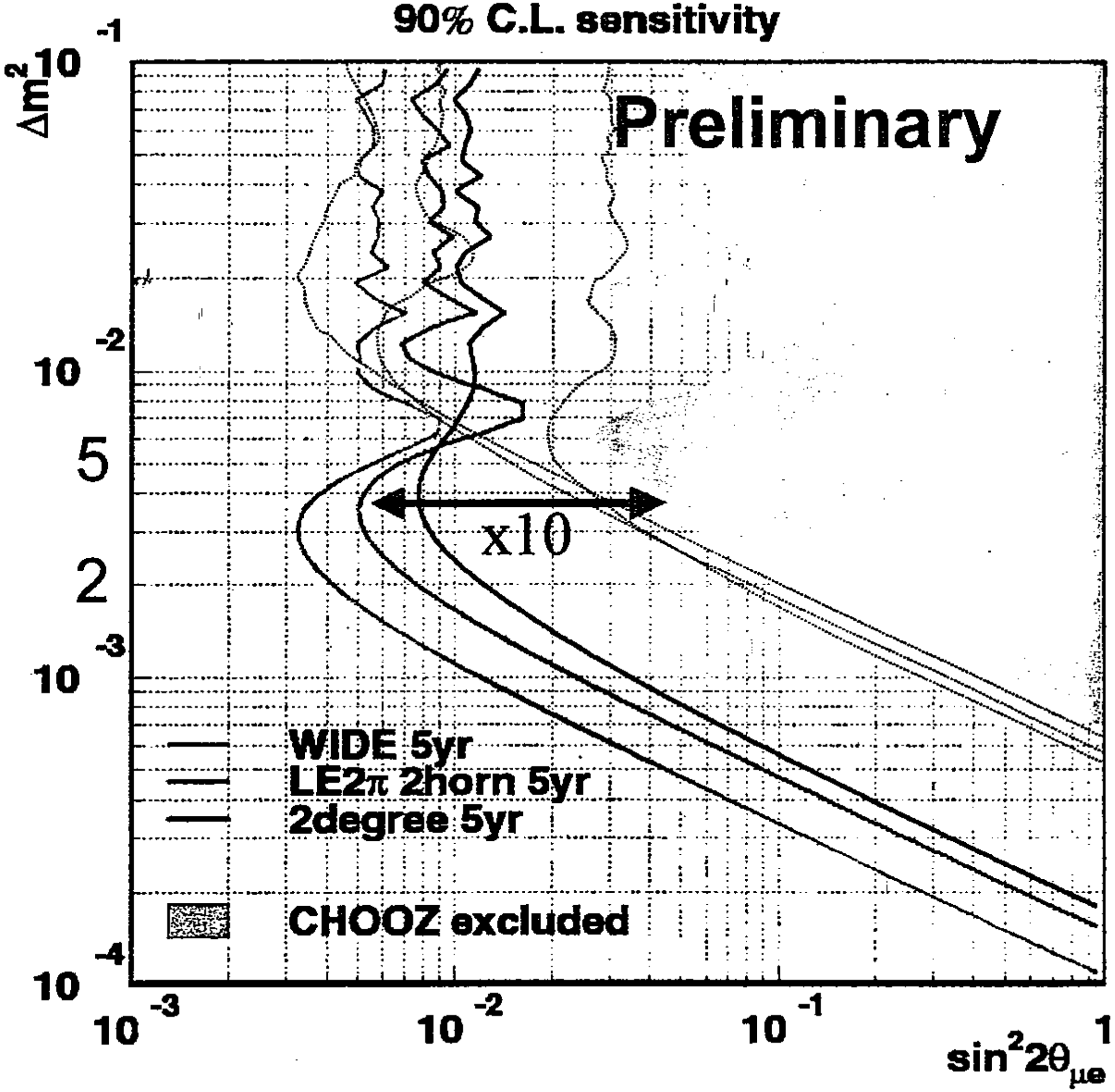






Preliminary

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

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

- NC/CC sensitive to ν_s
- NC Enriched Sample

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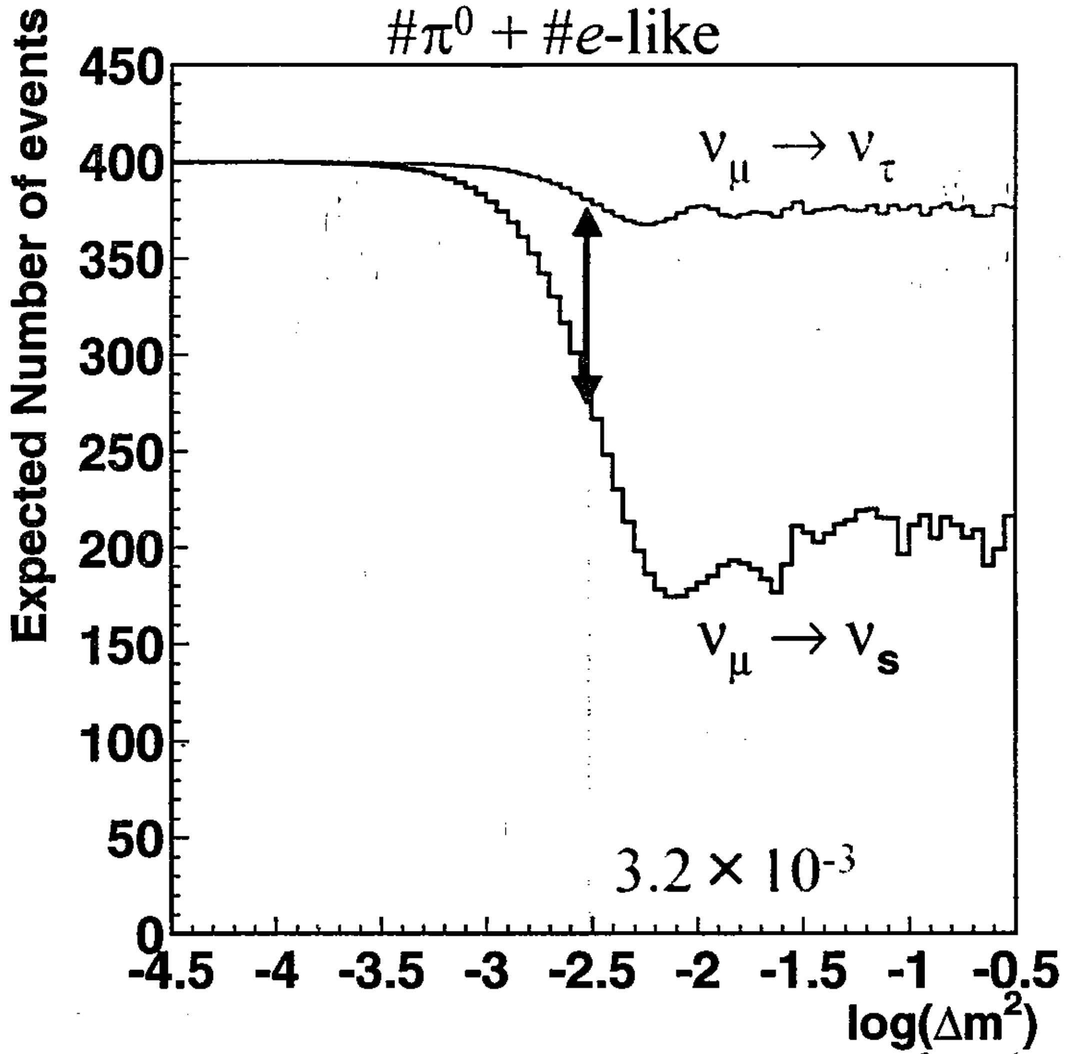

log(Δm²)

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: $\delta(\Delta m^2) \sim 2.4\times10^{-4}eV^2$, $\delta(\sin^2 2\theta_{23}) \sim 0.06$
  - ν_e appearance : $\delta(\sin^2 2\theta_{\mu e}) > 0.04$ @$\Delta m^2=3\times10^{-3}eV^2$

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

Complementary to JHFν

	Beam	E_ν	$(E/L)(\pi/2)/1.27$	Det.	E_ν rec'nst	CC event
JHFν	NBB/WBB /OAB	~1GeV	$3.8\times10^{-3}eV^2$	Water Cherenkov	QE	3200/yr(WBB)
MINOS	WBB	>3GeV*	$5\times10^{-3}eV^2$	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

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Sensitivity to CPV

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

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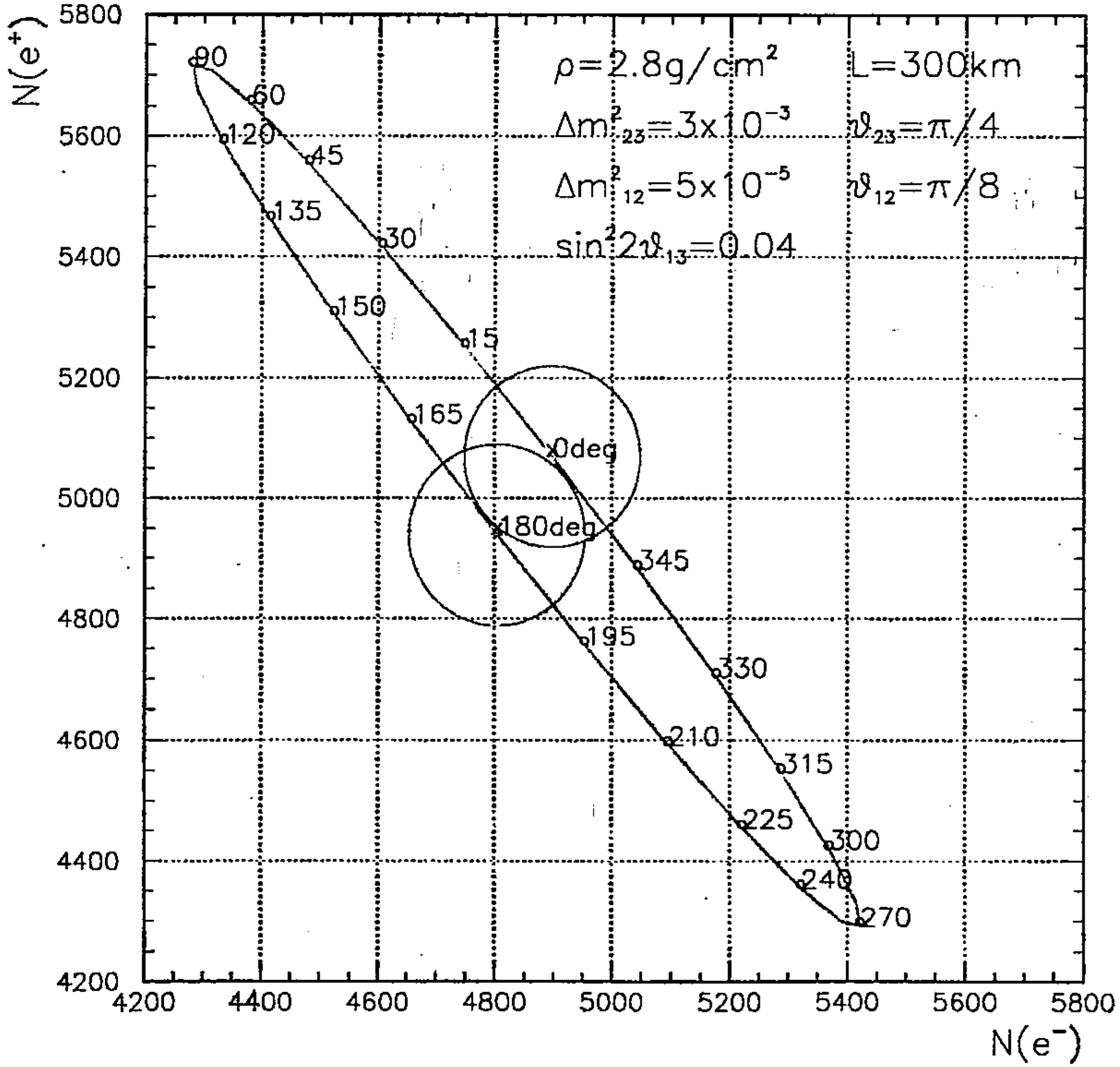


Summary

- **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)
  - ✓ $\delta\Delta m_{23}^2 \sim 1 \times 10^{-4}$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

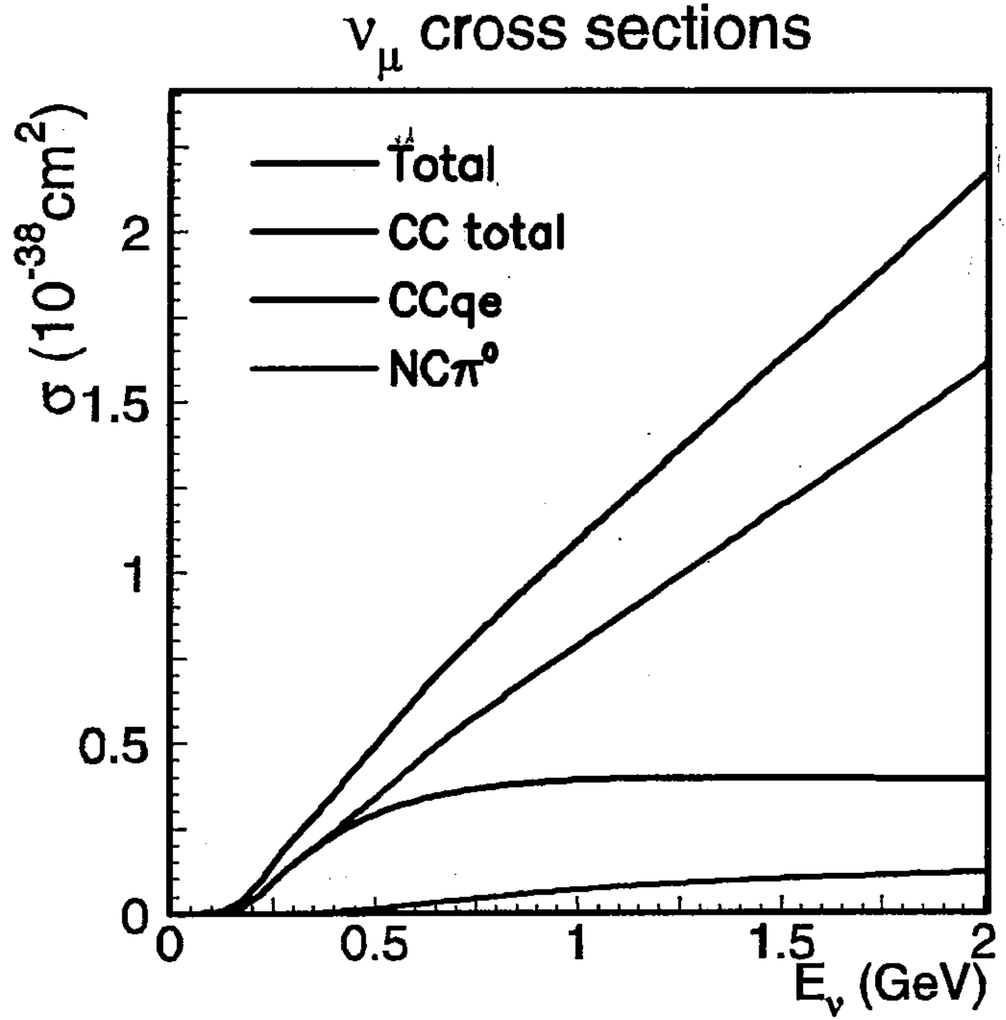
  Data taking in 2006-7

A study on possibility of Super LowE Super Convensional Beam

- Possible advantages
  - Below π^0 threshold → expect low BG
  - 2nd osc. max. → expect large CP asym.
  - Small contribution from matter effect
- Questions
  - Statistics
    - neutrino flux enough? Spectrum?
  - Backgound
    - Really no π^0 BG?
    - e/μ separation at low energy? ν_e BG?
  - Systematics
    - cross section, ……

24/Feb/2001
T.Kobayasi

ν_μ cross sections



SLE Region(<500MeV)

- ➢Small cross section
- ➢Rapidly changing
- ➢CCqe dominates CCint.
- ➢Small π^0 prod. cross sect.

$\nu_\mu \rightarrow \nu_e$ oscillation probability

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

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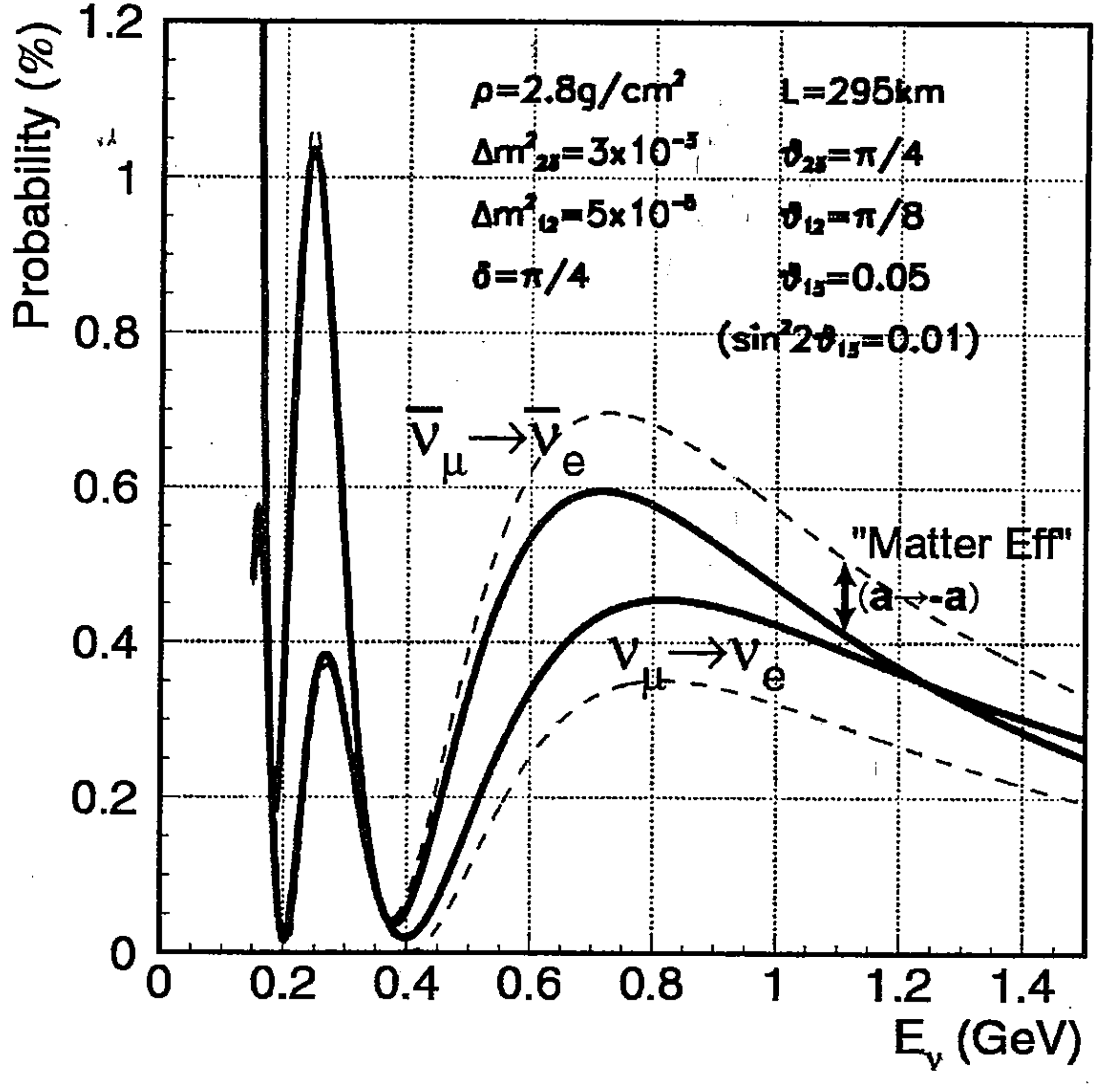
$$a = 7.56\times 10^{-5}[\mathrm{eV}^2]\cdot\left(\frac{\rho}{[\mathrm{g/cm}^3]}\right)\cdot\left(\frac{E}{[\mathrm{GeV}]}\right)$$

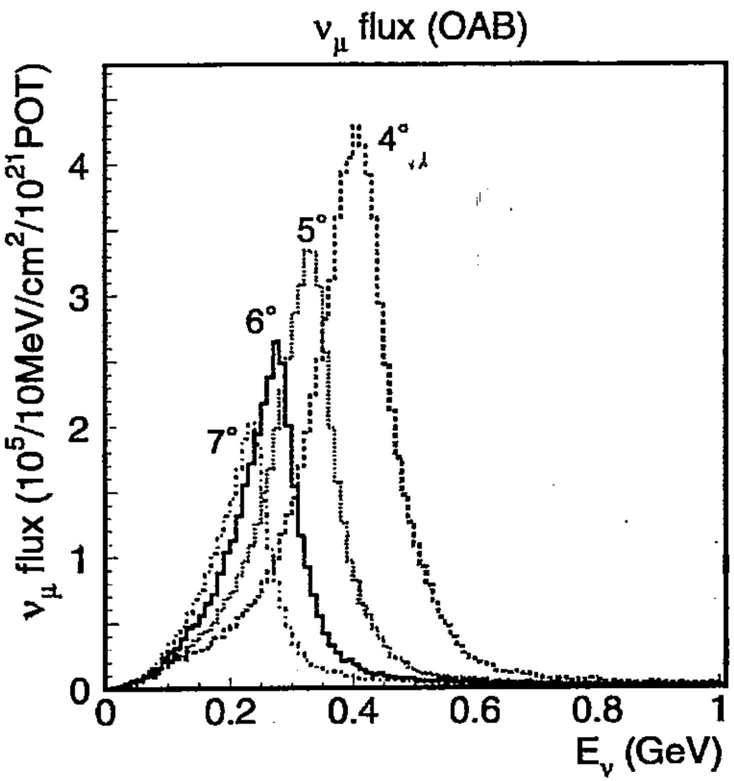
$\delta \rightarrow -\delta$, $a \rightarrow -a$ for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

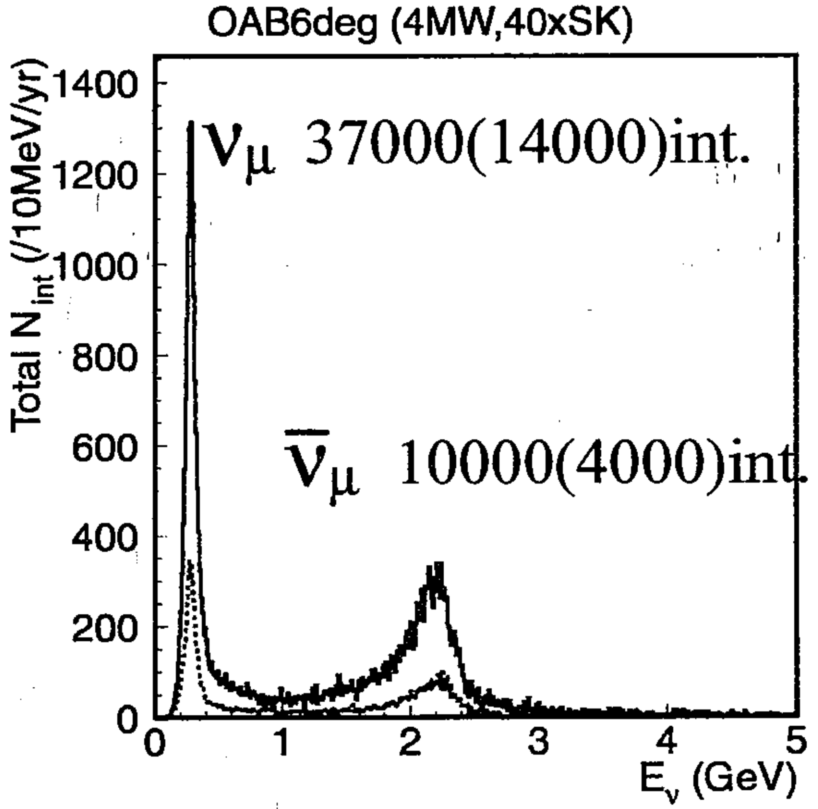
Oscillation Probabilities



Simulation of Hypothetical SLE Beam

Large angle OAB(150m decay pipe), 4MWx40SK→200xJHF1





( ):N_{int} <500MeV

Very small statistics!(c.f.~GeV beam)

Need ~3.5times running for $\bar{\nu}_\mu$

2nd peak from Kaon→ serious BG?

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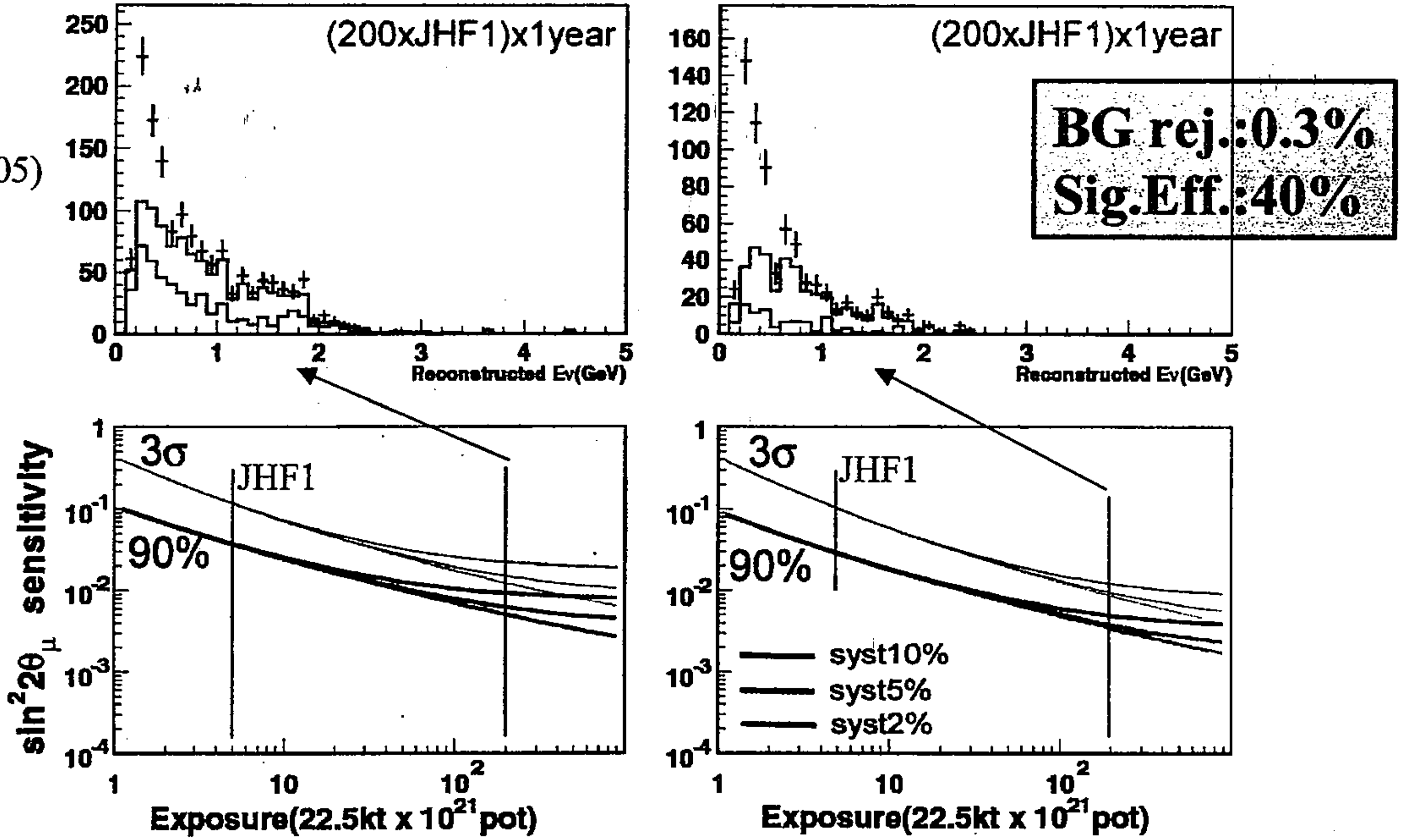
Sensitivity on ν_e appearance

OAB6deg Beam

1ring e-like **+e/π^0 separation**

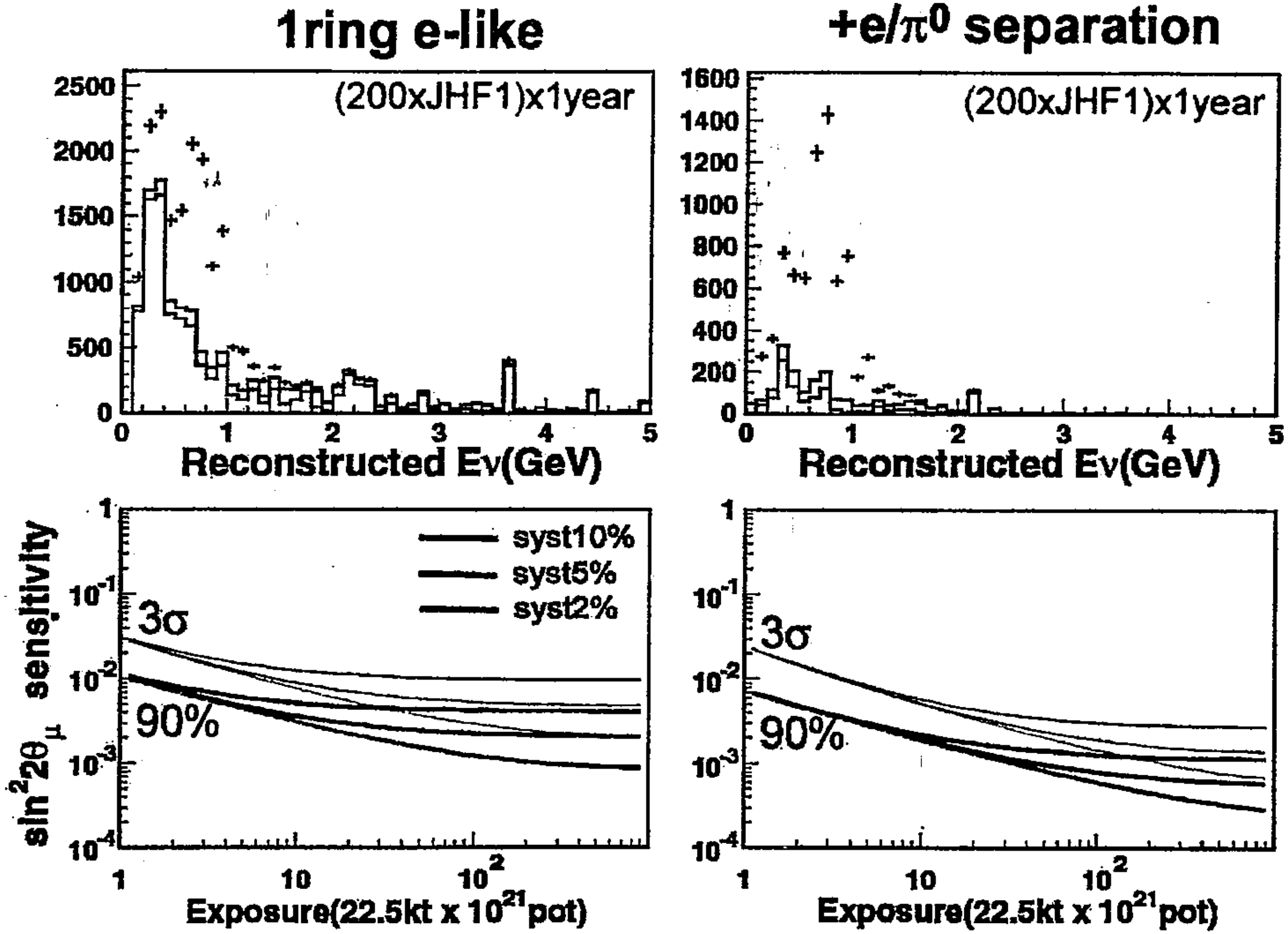
$\sin^2 2\theta_{13}=0.1$
($\sin^2 2\theta_{\mu e}=0.05$)



(Beam ν_e contamination is not negligible.)

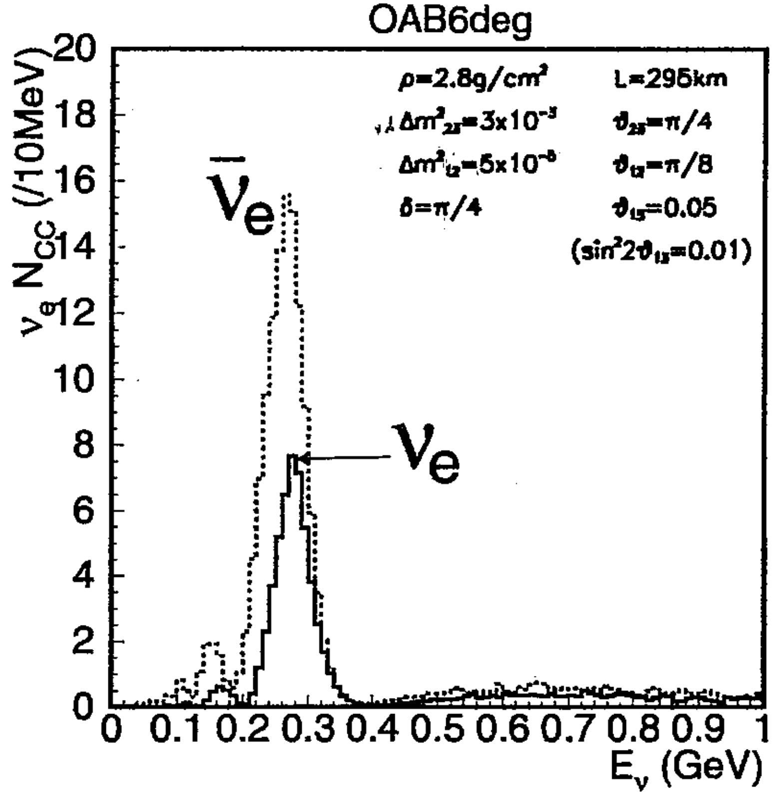
Sensitivity of ~GeV beam for **comparison**

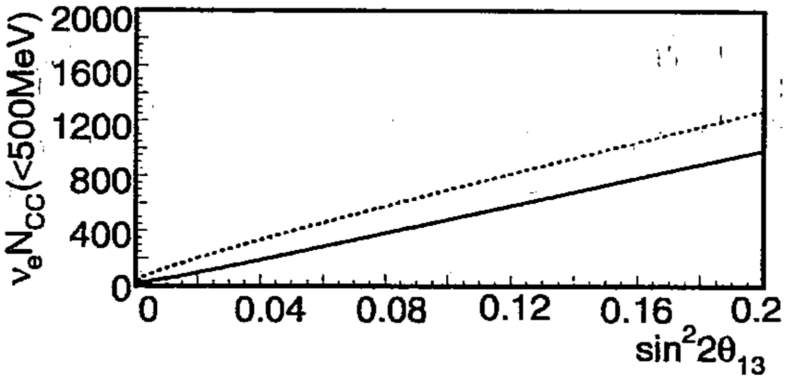
OAB2deg Beam

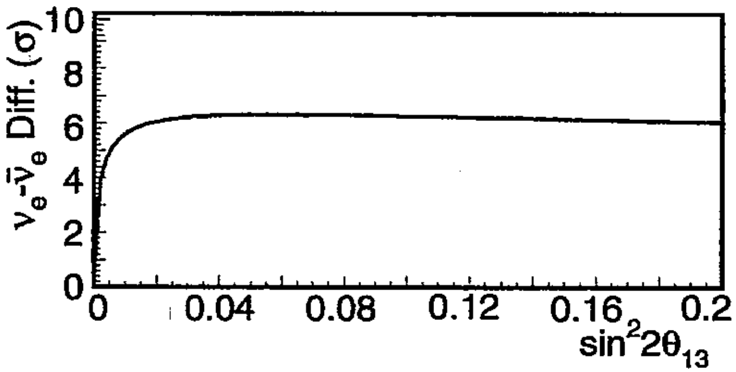


OAB2deg(w/ e/π^0) much higher sens. than SLE beam

CPV Measurement





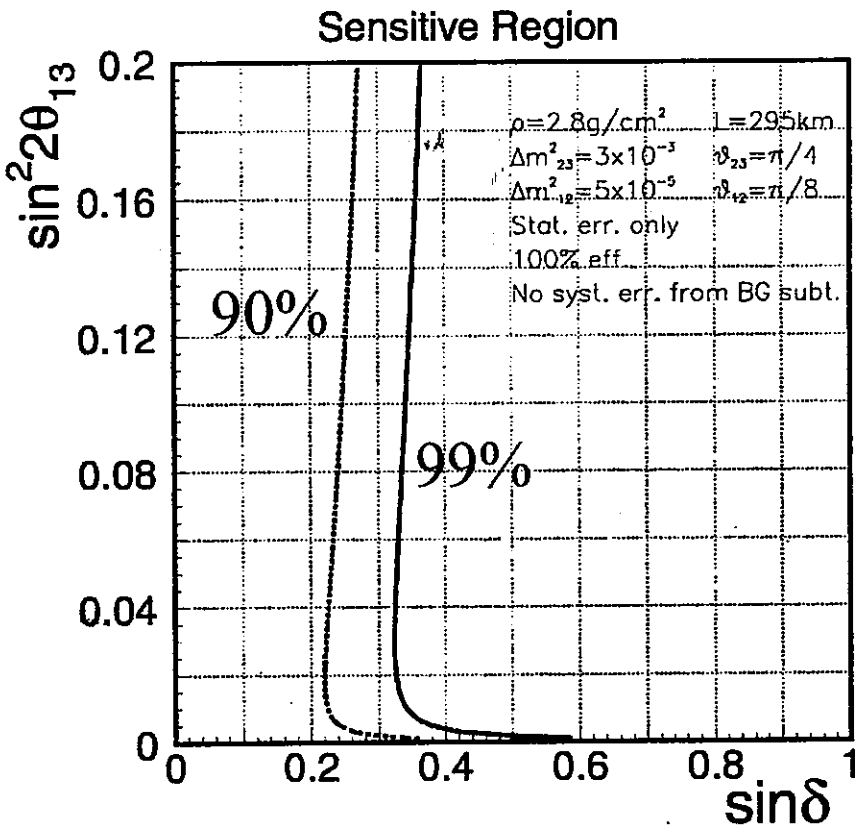


ν_μ beam: 2years

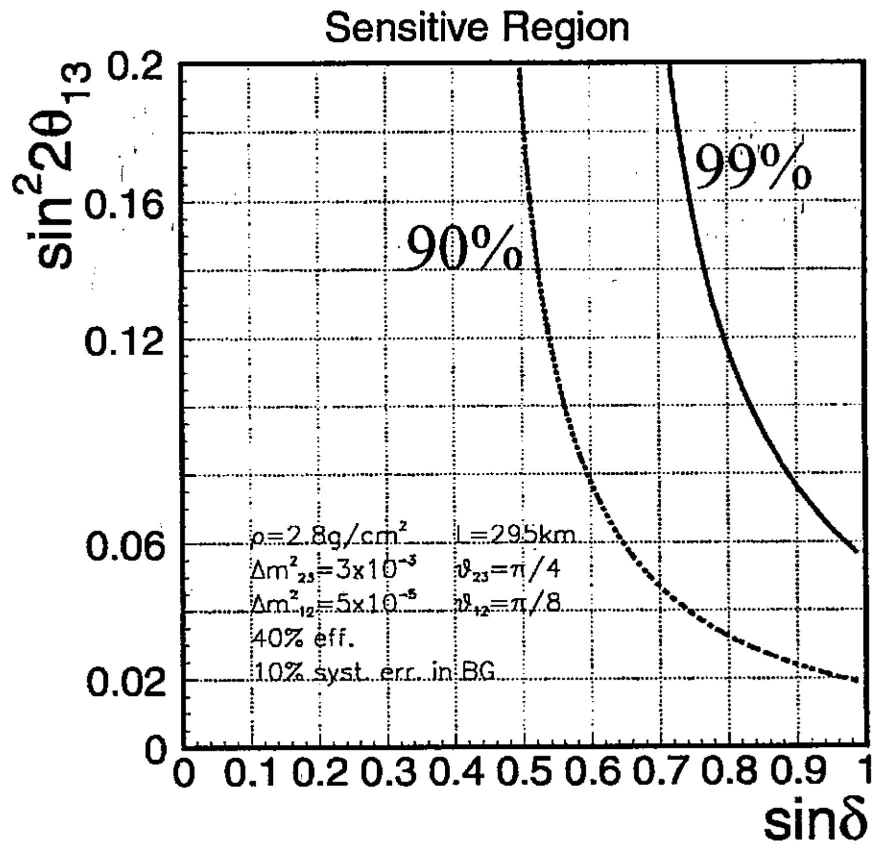
ν_μ beam: 7.5years

Sensitivity on CPV

OAB6deg Ideal Case



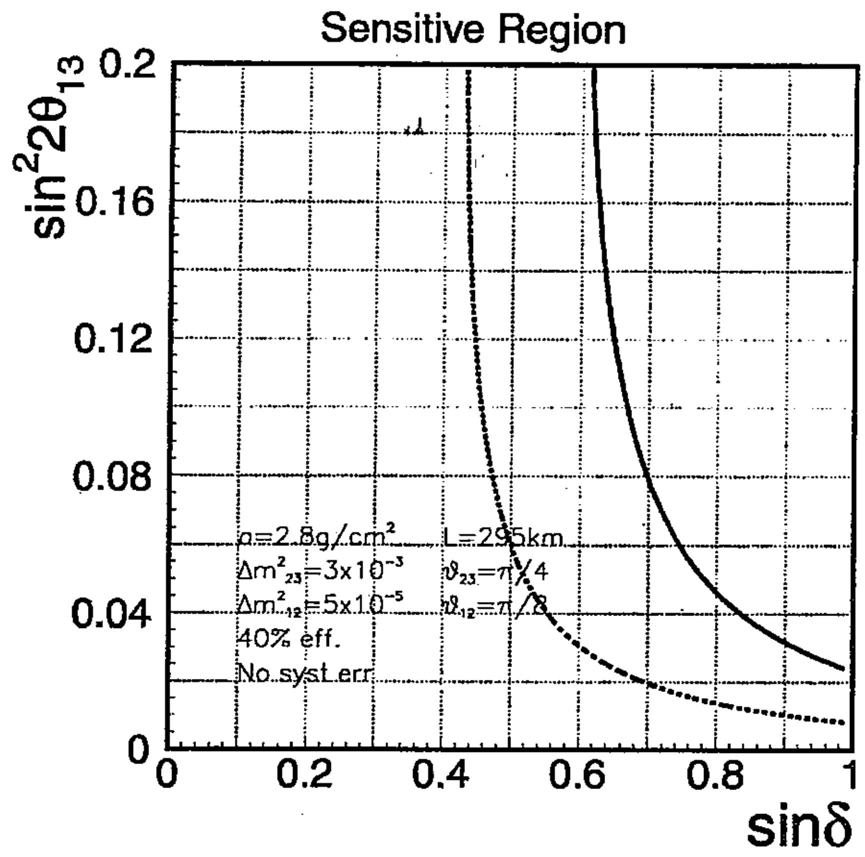
OAB6deg Realistic



200x**JHF1**
2years for ν_μ
7.5years for $\bar{\nu}_\mu$

ε=40%, BG rej:0.3%
BG syst.:10%
$\nu_\mu \mathrm{BG} = \bar{\nu}_\mu \mathrm{BG}$

Sensitivity on CPV



e=40%, BGrej.:0.3%
No BG syst. err

Slightly better than w/ BG syst error.

But, essentially, sensitivity is limited by stat. error due to bad S/N ratio.

Summary of SLE beam study

- Studied potential of SLE Super Conventional beam
- Worse sensitivity in ν_e appearance due to small statistics than ~GeV beam
- Sensitivity in CPV is limited by BAD S/N ratio.
- Possible sources of systematic error
  - ➢ rapid rise of cross section
  - ➢ ν_μ, $\bar{\nu}_\mu$ BG difference
  - ➢ π/K production ratio at target(affect both ν_μ, ν_e flux)
  - ➢ ……
- Possible improvements….
  - – go further
  - – compare 1st and 2nd osc. max (by Konaka)
  - – …..