K2K and a next-generation neutrino oscillation experiment from J-PARC to Kamioka

Fujihara Seminar
"NEUTRINO MASS AND SEESAW MECHANISM“
Feb.23-25、2004

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Basic (naïve) Questions

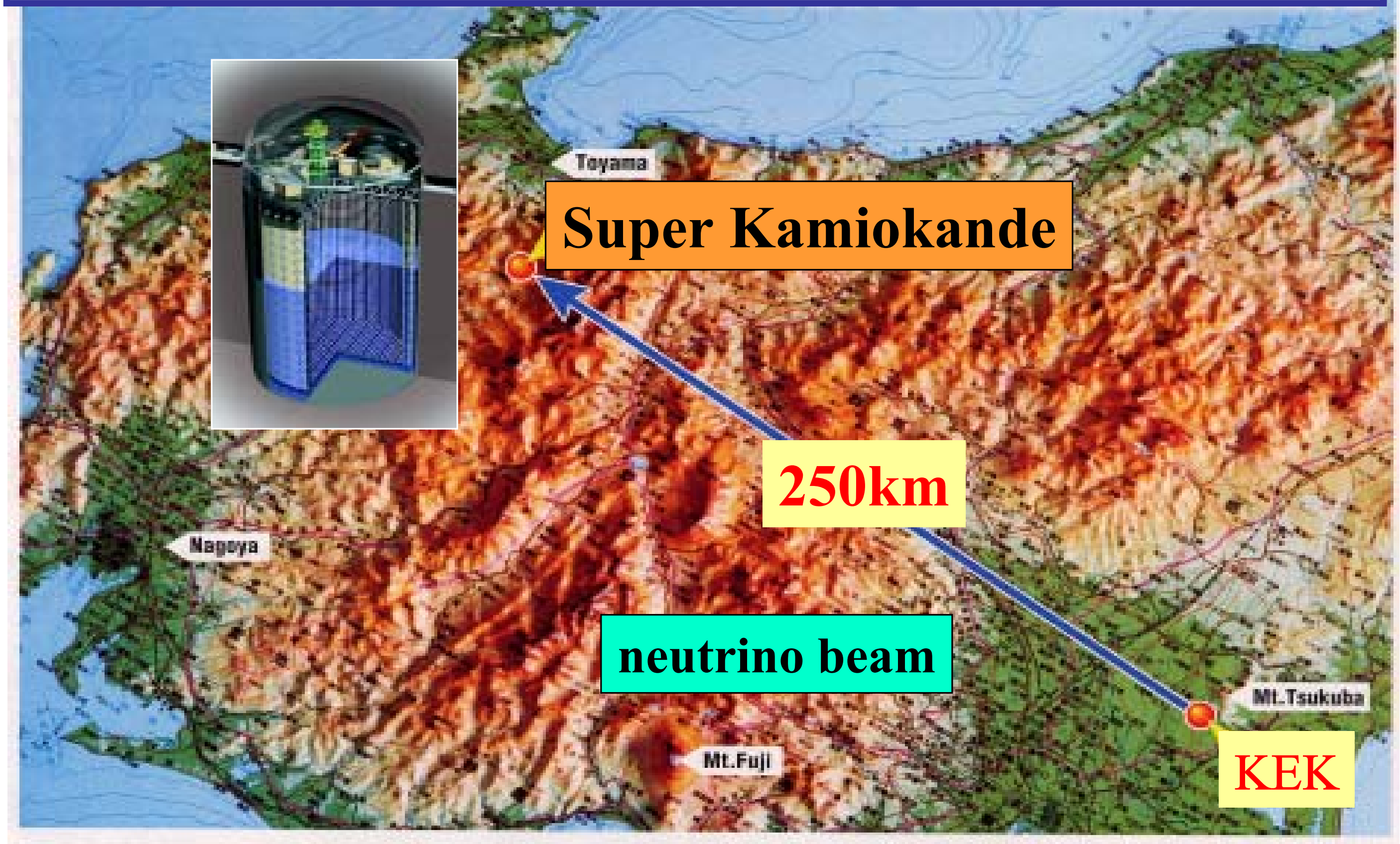
- **Larger the mass difference, larger mixing!**
  - **Three mass eigenvalues : m_1, m_2, m_3**
  - **$m_2^2 - m_1^2 \sim 6 \sim 9 \times 10^{--5}$ eV^2 $\quad$ $\sin^2 2\theta_{12} \sim 0.55 - 0.8$**
  - **$m_3^2 - m_2^2 \sim 1.6 – 3.9 \times 10^{-3}$ eV^2 $\quad$ $\sin^2 2\theta_{23} > 0.9$**

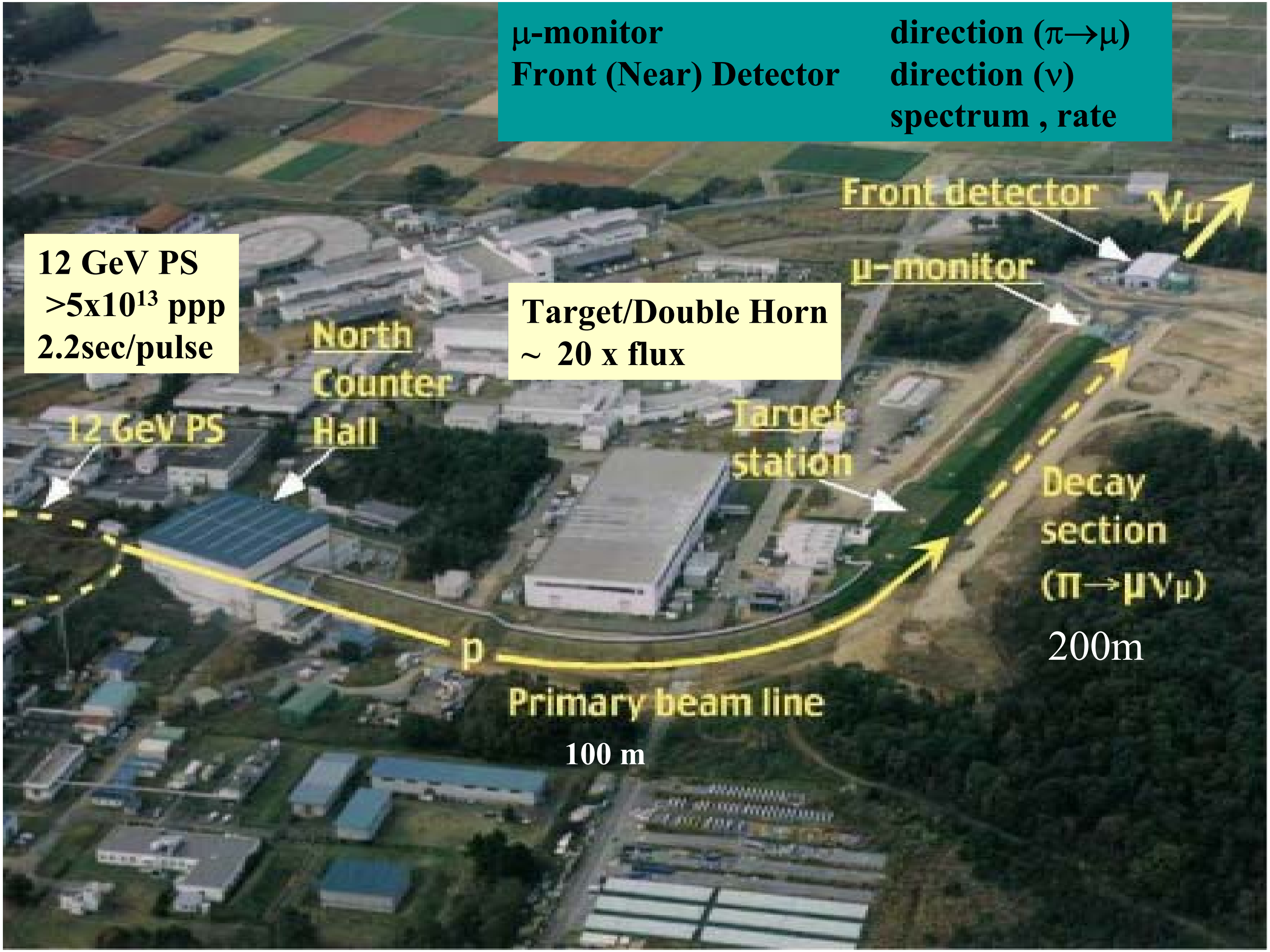
- **Quark : Larger the mass difference, smaller mixing**
  - **$\sin\theta_{12} \sim 0.2$ $\quad$ $\sin\theta_{23} \sim 0.2^2$ $\quad$ $\sin\theta_{13} \sim 0.2^3$**
- **Meson**
  - **φ(ss), ψ(cc), Υ(bb)**
  - **……..**

Goals in the near future

- **1^{st} and 3^{rd} generation mixing**
  - **m_3^2-$m_1^2 \sim 1.6 – 3.9 \times 10^{-3}$ eV^2 $\sin^2 2\theta_{13} < 0.1$-$0.2$**
  - **Is θ_{13} smaller by a factor or order of magnitude?**
- **2^{nd} and 3^{rd} generation mixing**
  - **high precision measurements of θ_{23}**
  - **how close to the maximal?**
- **Look for unexpected by high precision measurements of oscillation pattern, 4^{th} 'ν'……**
- **Key measurements in K2K and improvements for future**

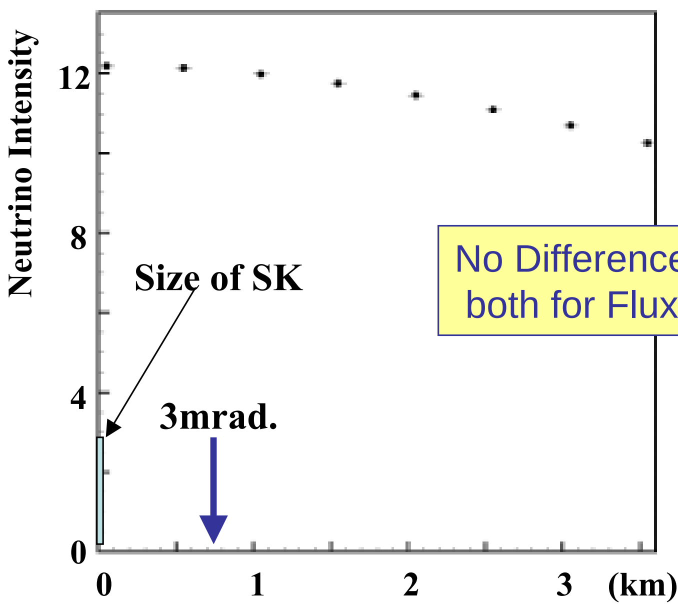
K2K（*KEK* to *Kamioka*）experiment



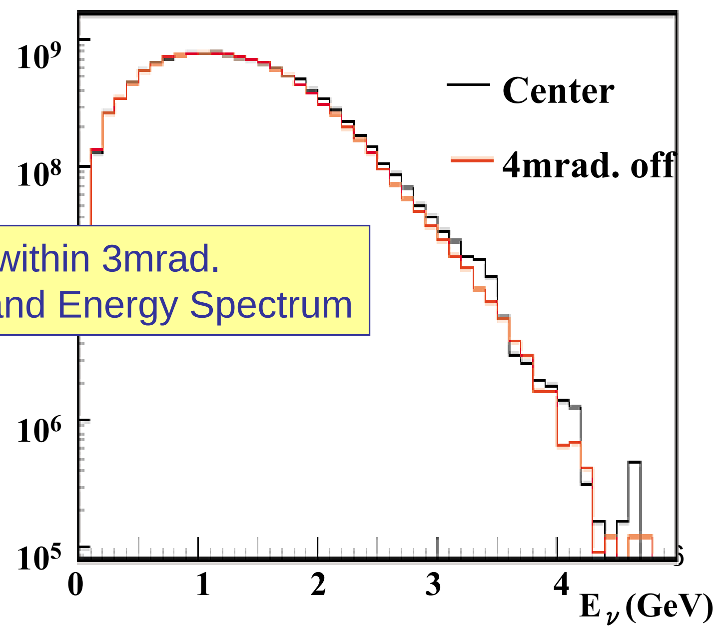

μ-monitor
Front (Near) Detector
direction (π→μ)
direction (ν)
spectrum , rate
12 GeV PS
>5x10^13 ppp
2.2sec/pulse
Target/Double Horn
~ 20 x flux
Front detector
νμ
μ-monitor
North
Counter
Hall
12 GeV PS
Target
station
Decay
section
(π→μνμ)
200m
p
Primary beam line
100 m

Beam direction and its stability

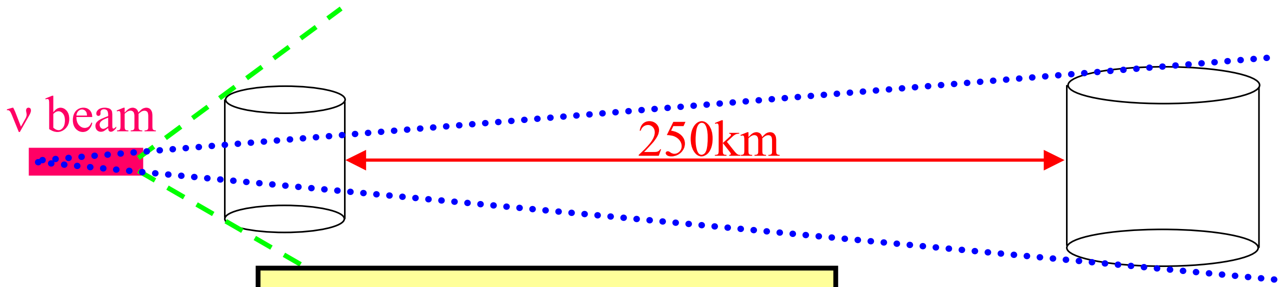
- **Long 'expensive' beam line**
  - **accommodate change in extraction and stabilize targeting <2mm**
- **Neutrino Beam Steering and its Stability**
  - **Measurement by neutrino interaction vertex profile <1mrad.**
  - **Muon profile (from π−μ decay >5GeV μ , spill-by-spill) <1mrad.**



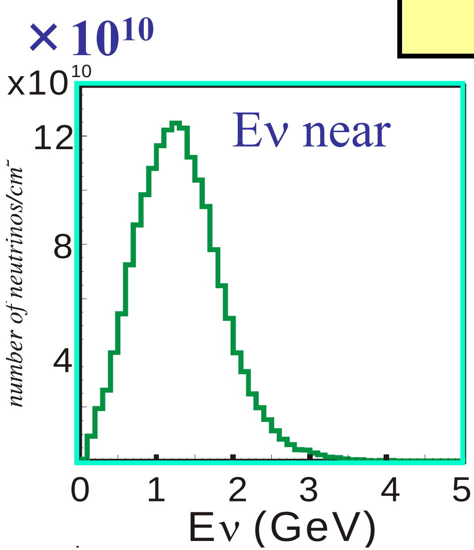
No Difference within 3mrad.
both for Flux and Energy Spectrum



Measurements in K2K

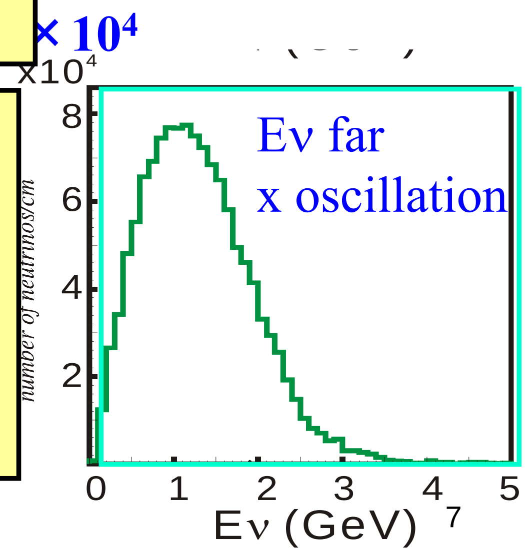


Spectrum measurements at two locations

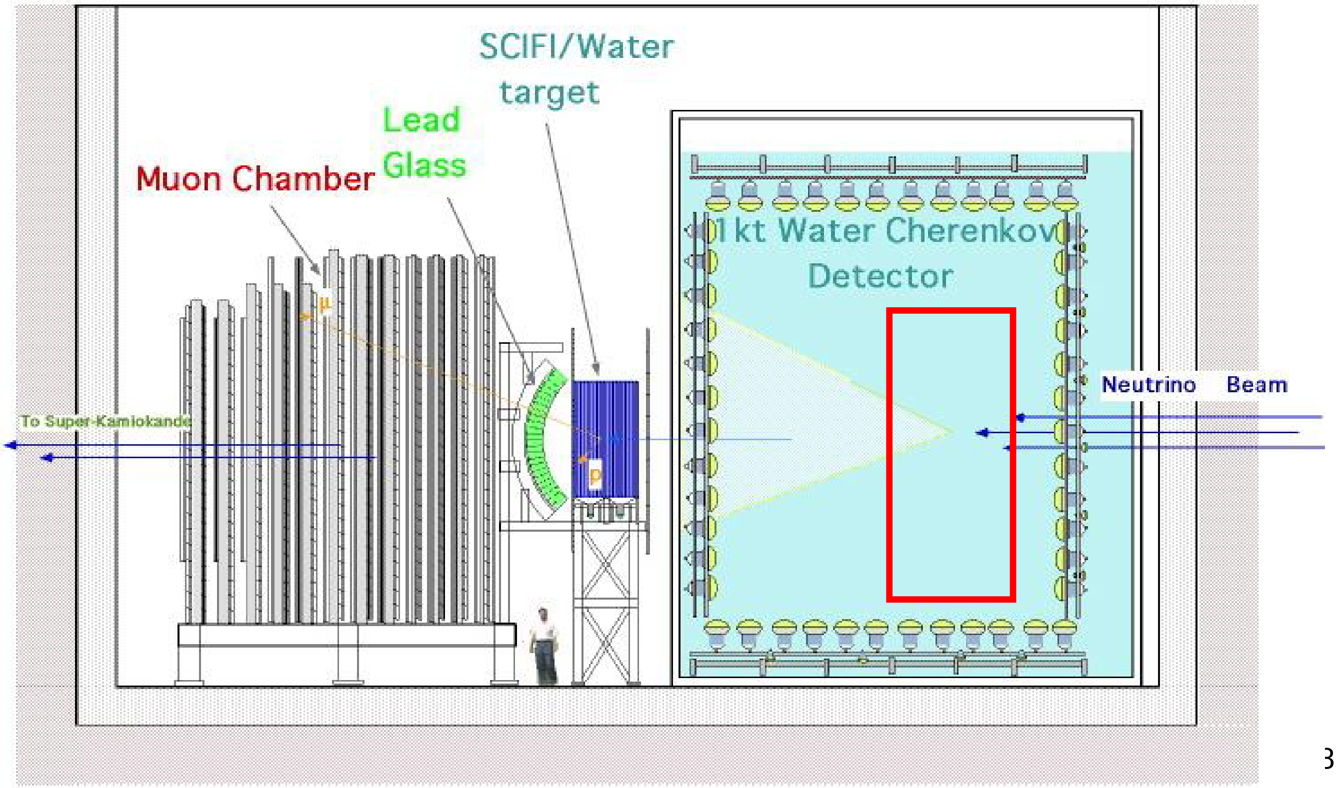


Two reasons of different spectrum

- **line ↔ point source**
- **Oscillation**



Near Detectors at KEK



Prediction of Neutrino events at Far Site

- **Near Detectors**
  - **Intensity**
  - **Energy Spectrum at near**

  } **neutrino int. de-convolution**

- **Beam MC with pion production model**
  - **$Flux_{far}$ (E)/$Flux_{near}$ (E)**
  - **Prediction of neutrino beam at SK**
  - **Oscillation**
  - **Prediction of total number of events**
  - **E_ν distribution**

  } **neutrino int convolution** ⇔ **SK events**

- **Pion production model**
  - **Pion production measurements at ANL in '70**
    - ν Spectrum at near
    - pion (p,θ) distribution measurement with gas Cherenkov detector

Expected No. of ν_μ Interactions at Far Site

$$N_{far}^{exp} = N_{near}^{obs} \cdot \frac{\int Flux_{far} \cdot \sigma_{far} \cdot \varepsilon_{far} \cdot dE_\nu}{\int Flux_{near} \cdot \sigma_{near} \cdot \varepsilon_{near} \cdot dE_\nu} \cdot \frac{Mass_{far}}{Mass_{near}}$$

- **Measurement by 1KT is Used as normalization**

  1KT is 'Same' Type as SK **nuclear effects and Same Detection Energy Threshold**

→ Cancellation of Systematics errors

$$\frac{\sigma_{Far}}{\sigma_{near}} \approx 1 \qquad \frac{\varepsilon_{Far}}{\varepsilon_{near}} \approx 1$$

- **Neutrino Flux Ratio $Flux_{far}/Flux_{near}$ is Calculated with beam MC**

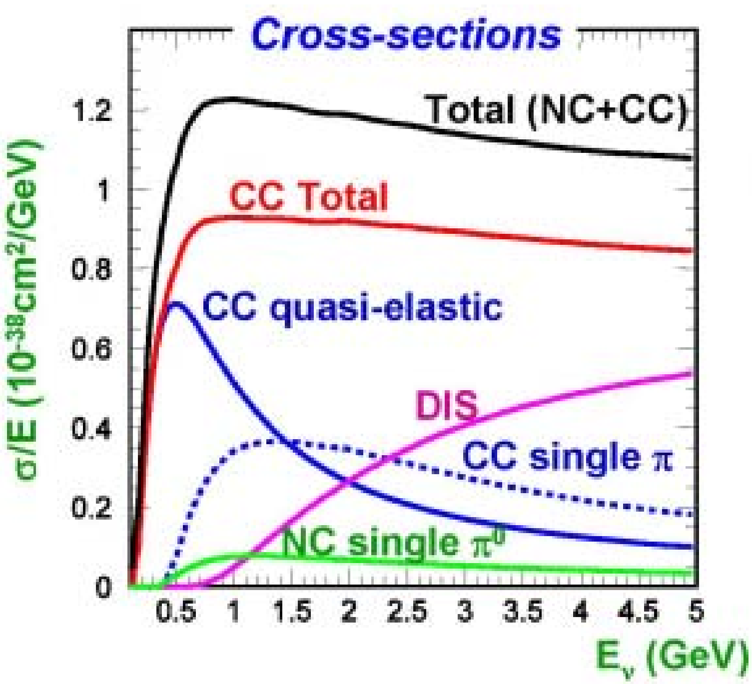
  Tested by Pion Monitor Measurement

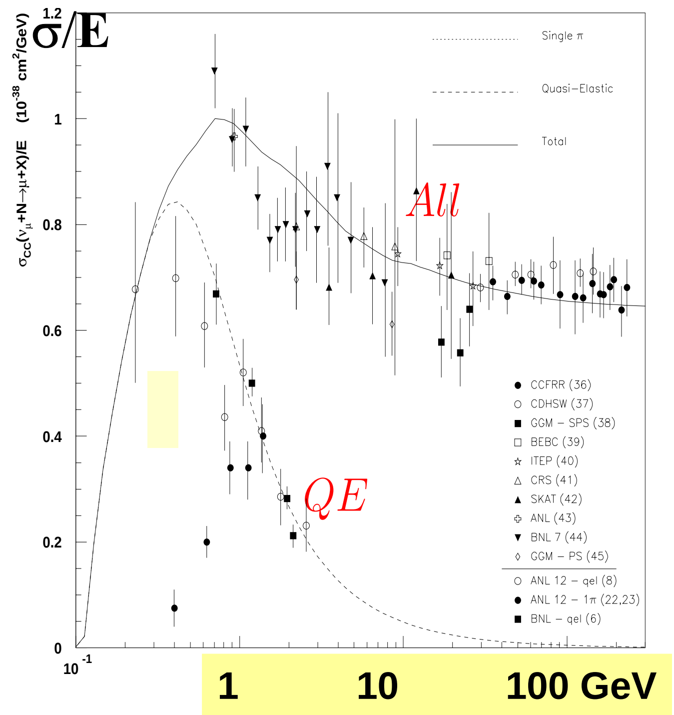
- **Dominant Systematic Errors are an uncertainty of far-near ratio (~7%) and an uncertainty of 1kt fiducial volume (~4%)**
- **to go further….. various type of detectors**

ν_μ Spectrum measurement at Near

Only Flux(Eν) x σ(Eν) will be measured

ν Int. Model QE/nonQE ratio and NC/CC

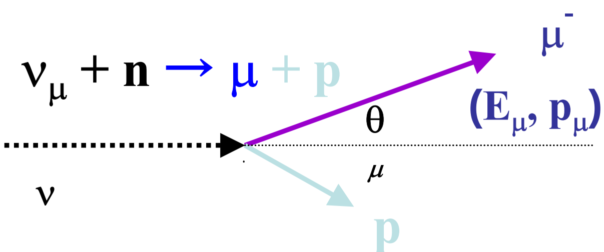




E_ν reconstruction

$$P = \sin^2 2\theta \cdot \sin\left(\frac{1.27\Delta m^2 \cdot L}{E_\nu}\right)$$

$\nu_\mu + n \rightarrow \mu + p$



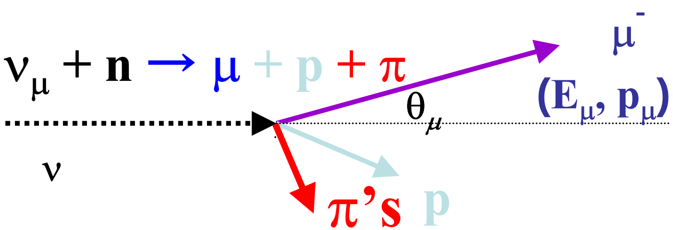
✧ CC QE

✧can reconstruct Eν ←(θ_μ,p_μ)

$$E_\nu^{rec} = \frac{m_N E_\mu - m_\mu^2 / 2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

p,n no signal in W-C
E_{had} measurement!

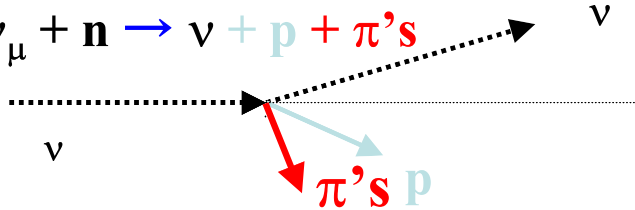
$\nu_\mu + n \rightarrow \mu + p + \pi$



✧ CC nQE

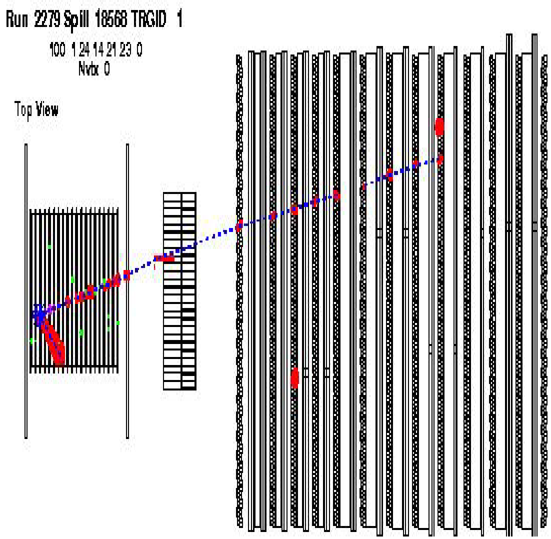
✧Bkg. for E_ν measurement

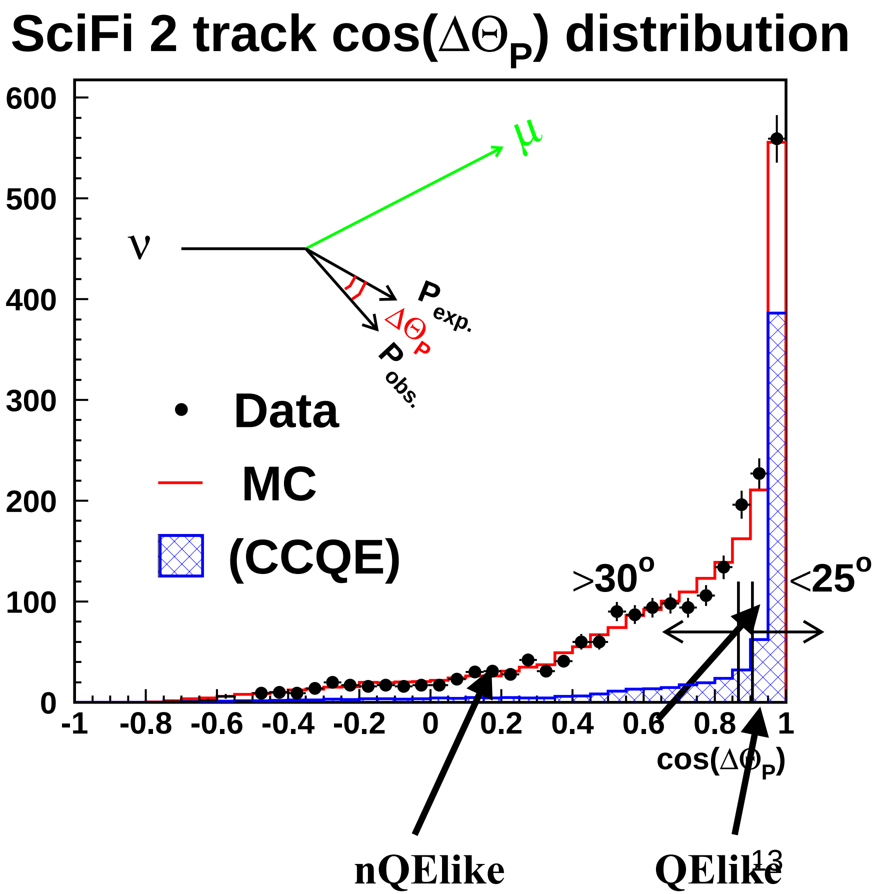
$\nu_\mu + n \rightarrow \nu + p + \pi$'s



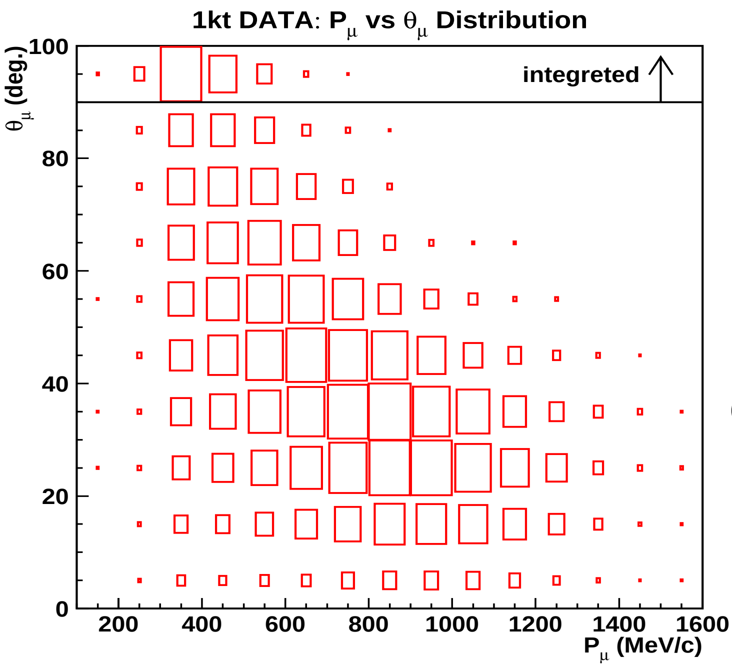
✧ NC

QE and nQE in SciFi 2track events

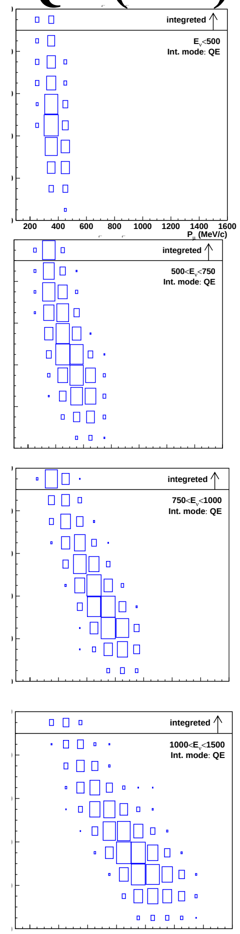


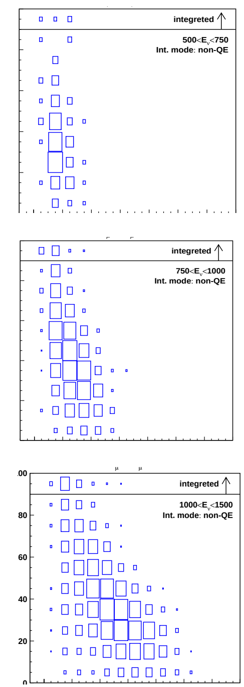


Fitting method
$(p_\mu,\theta_\mu) \rightarrow \phi(E\nu)$, nQE/QE



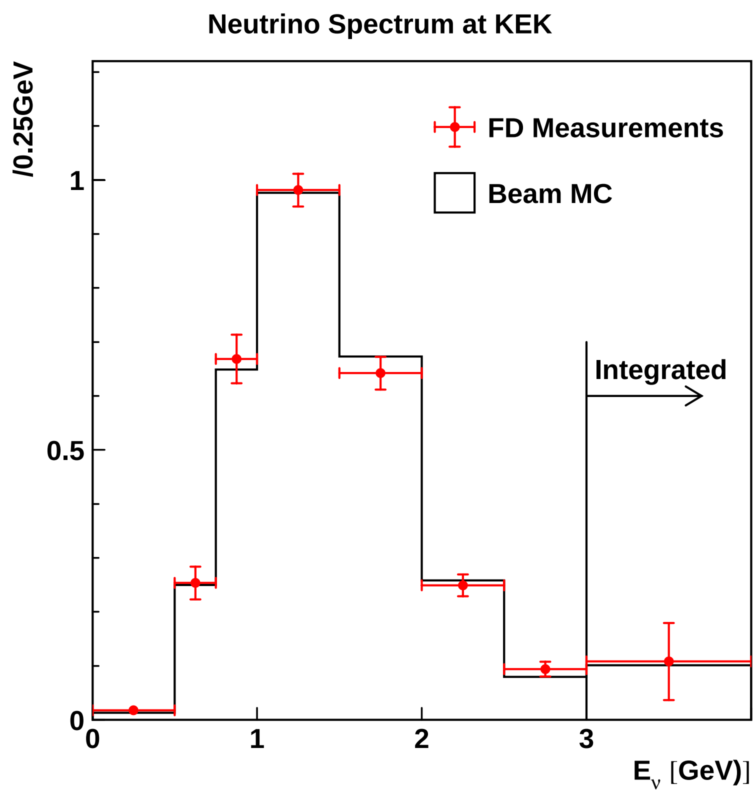
Eν	QE (MC)	nQE(MC)
0-0.5 GeV		MC templates
0.5-0.75GeV		
0.75-1.0GeV		
1.0-1.5GeV		



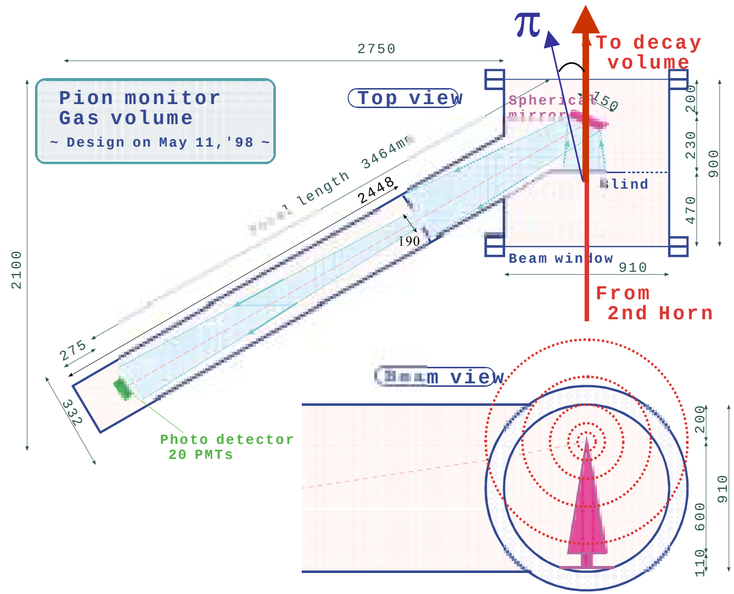


Also (p_μ,θ_μ) dist. in
SciFi 1track, 2track(QE-like), 2track(nQE-like)
$\chi2$=227 for 197 d.o.f.

Fit result of Neutrino Flux at KEK Site



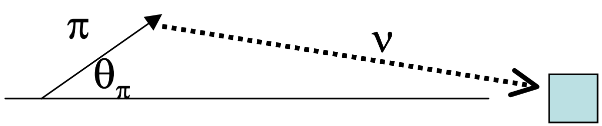
Pion Monitor:
Measure Momentum / Angle Dist. of π's just after Horn/Target



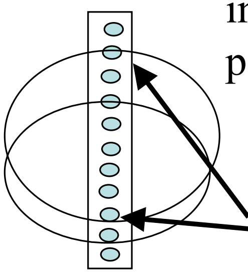
Well known π Decay Kinematics
+Well Defined Decay Volume Geometry

π (p_π ,θ_π) can calcurate
- ν_μ Energy at Near Site and Far Site
- ν_μ Flux Ratio (Far/Near) as a Function of Neutrino Energy

Ring Image Gas Cherenkov Detector
(Index of Refraction is Changeable)



To Avoid Severe Proton Beam Background,
ν_μ Energy Information above 1GeV is Available
(β of 12GeV Proton ~ β of 2GeV π)

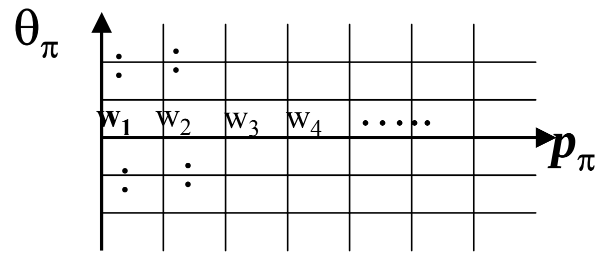


index of refraction : p_π threshold

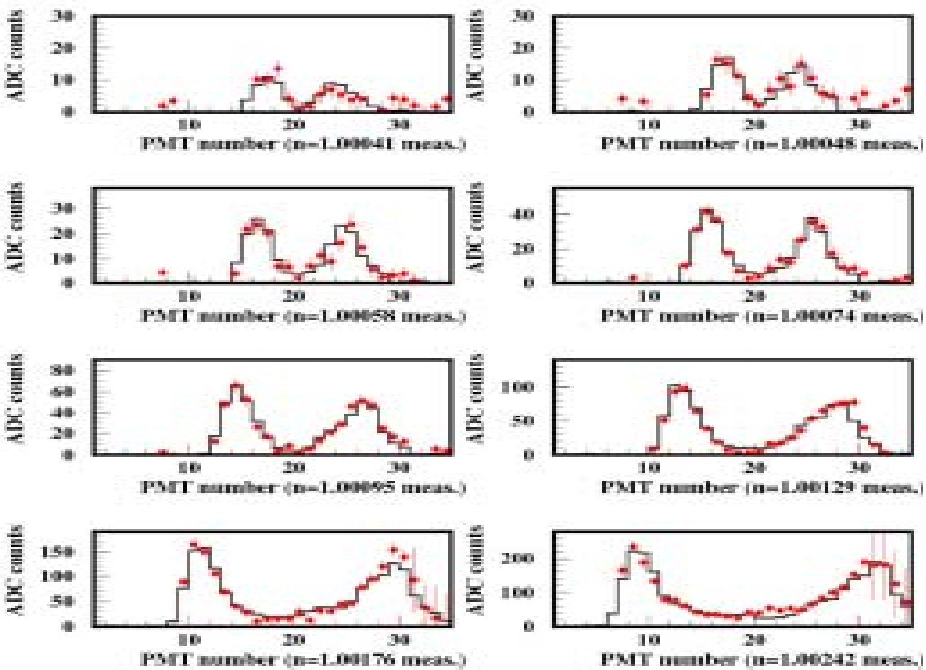
position of ring : θ_π

p_π, θ_π gives two C-light peaks

fit with Σ (wi • C-light)



Pion Monitor Fitting (November)



π production

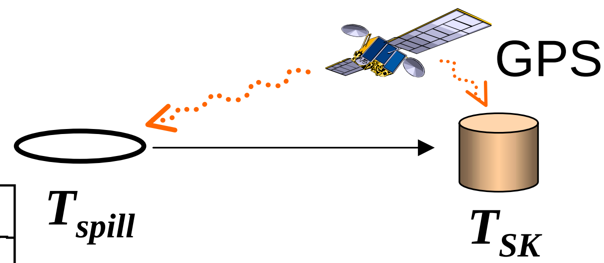
Good agreement with old data. (Cho et.al. in 70')

Beam MC → Far/Near

Error assignment

Super-K Event selection

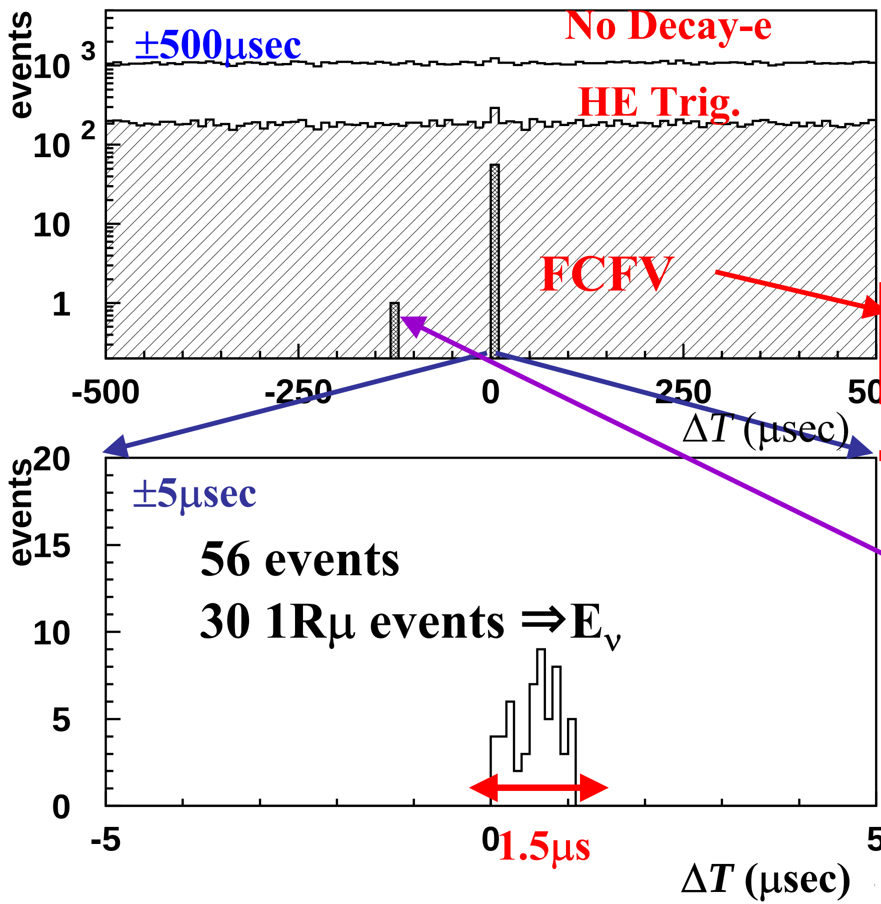
$$-0.2 \leq \Delta T \equiv T_{SK} - T_{Spill} - \mathrm{TOF} \leq 1.3\mu\mathrm{sec}$$



T_{Spill}: Abs. time of spill start

T_{SK}: Abs. time of SK event

TOF: 0.83ms (KEK to Kamioka)



FC: fully contained

(No activity in Outer Detector)

FV: 22.5kt Fiducial Volume

Expected Atm. ν BG

$<10^{-3}$ within 1.5μs.

Flow of Neutrino Oscillation Analysis in K2K

Observed (p_μ, θ_μ) **distributions at Near Detectors**

↓ ν ***Int. Model***

Neutrino Spectrum at Near detector $\phi_{near}(E\nu)$,

↓

Far/Near Extrapolation vs Eν $R_{FN}(E\nu)$

Neutrino Spectrum w/o oscillation at SK $\phi_{SK}(E\nu)$

$\phi_{SK}(E\nu)$ ⊗ **Oscillation** $(\sin^2 2\theta, \Delta m^2)$ ⊗ ***Int. Model***

Prediction

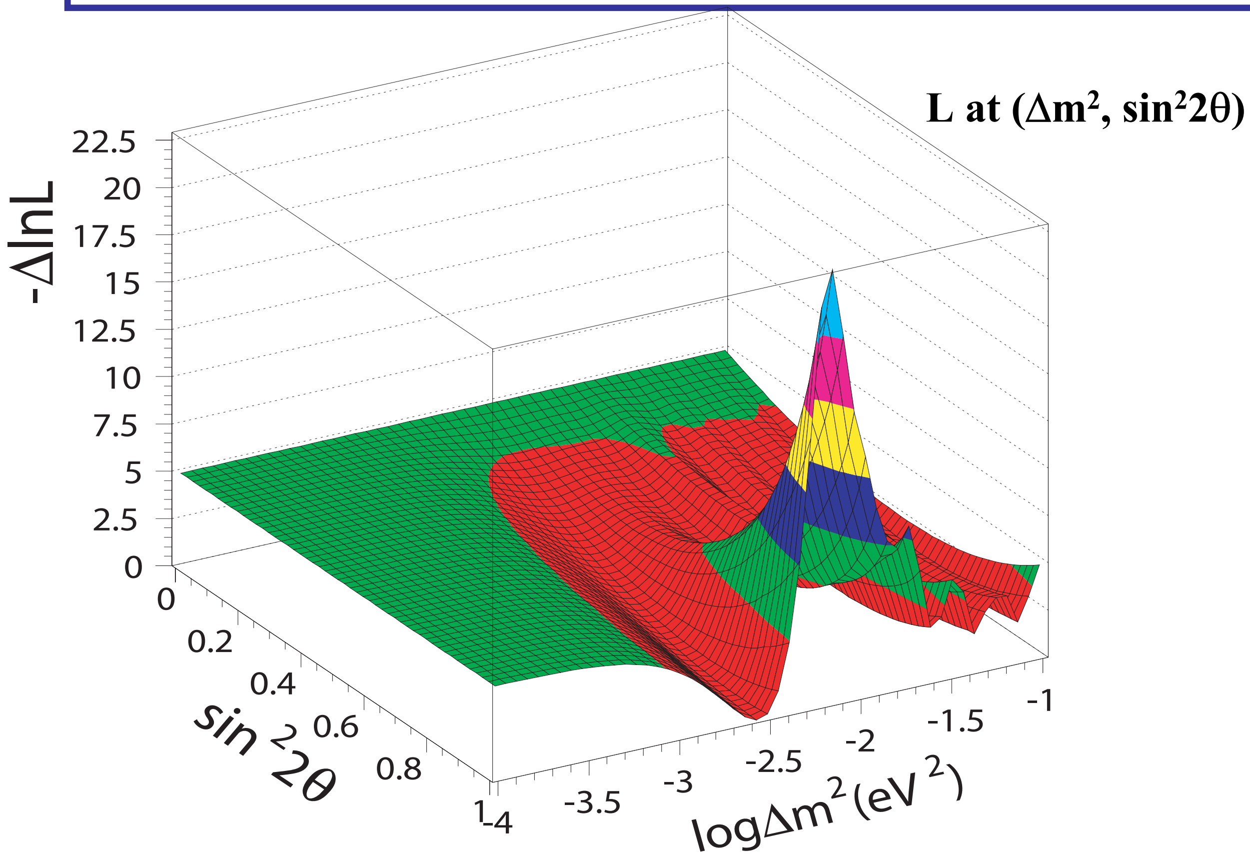
- N_{SK}**(exp't) : Expected no. of SK events**
- $S_{SK}(E_\nu^{rec})$ **:1R**μ E_{rec}**distribution(shape)**

SK observation

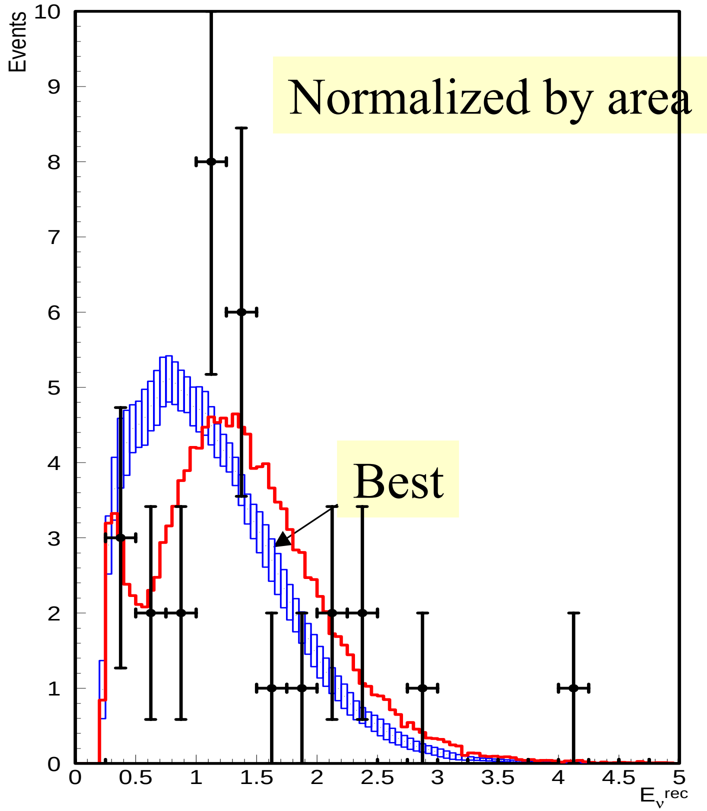
- N_{SK}**(obs)**
- **1R**μ E_{rec} **distribution**

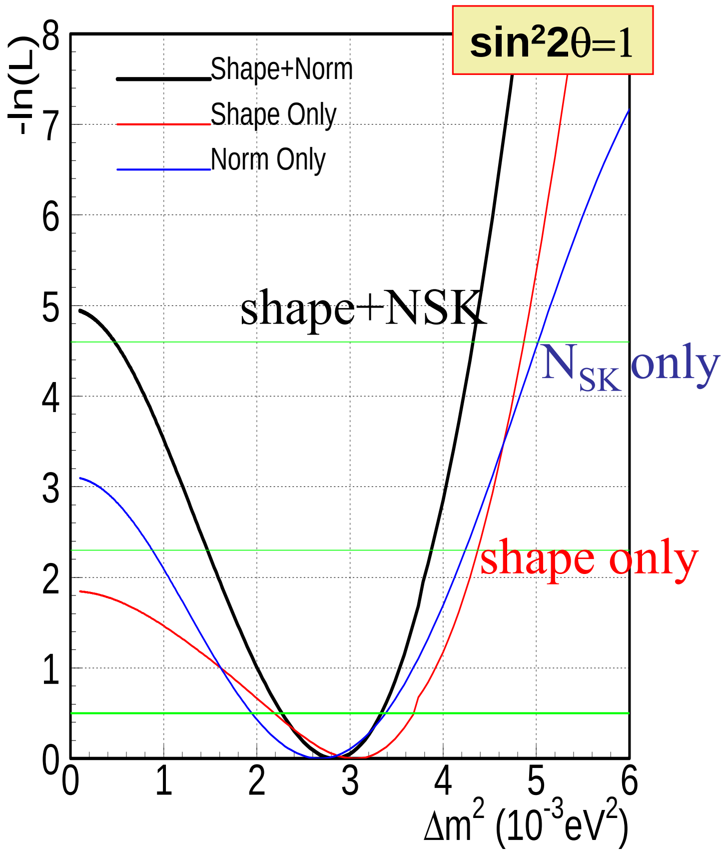
Maximum Likelihood Fit in $(\sin^2 2\theta, \Delta m^2)$

3d plots of ΔlnL for shape+norm

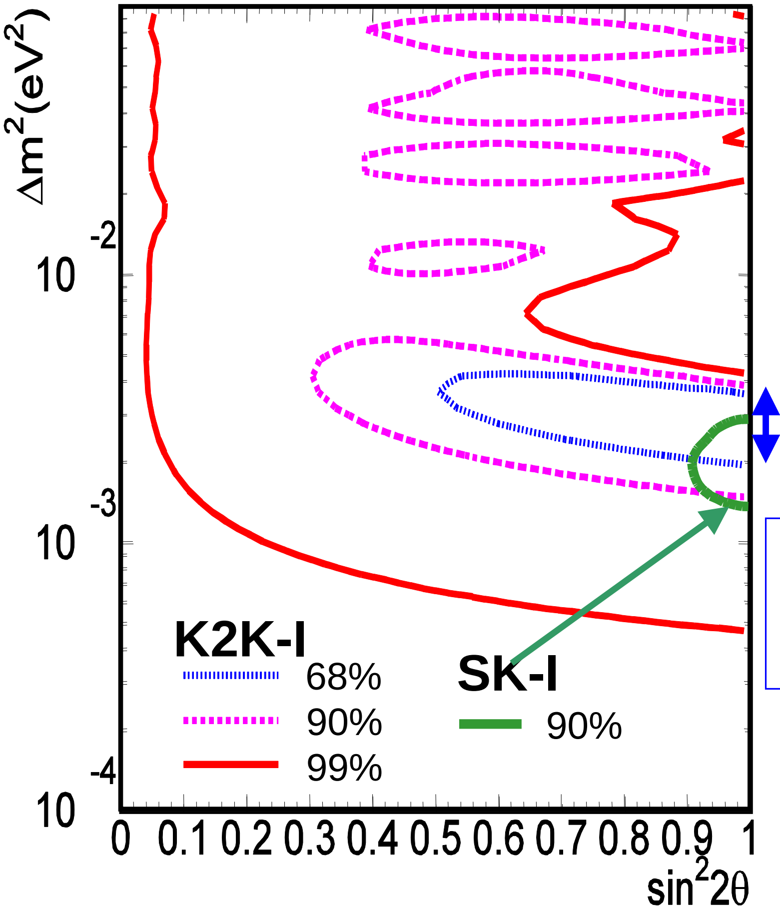


1Rμ shape & Nsk





Comparison of K2K-I result and new result of atmospheric neutrinos in SK-I



K2K-II data being analyzed

K2K 90%CL
$1.5 \sim 3.9 \times 10^{-3} eV^2$
@ $\sin^2 2\theta = 1$

Atm. 90% CL
$\sin^2 2\theta > 0.9$
$1.3 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3} eV^2$

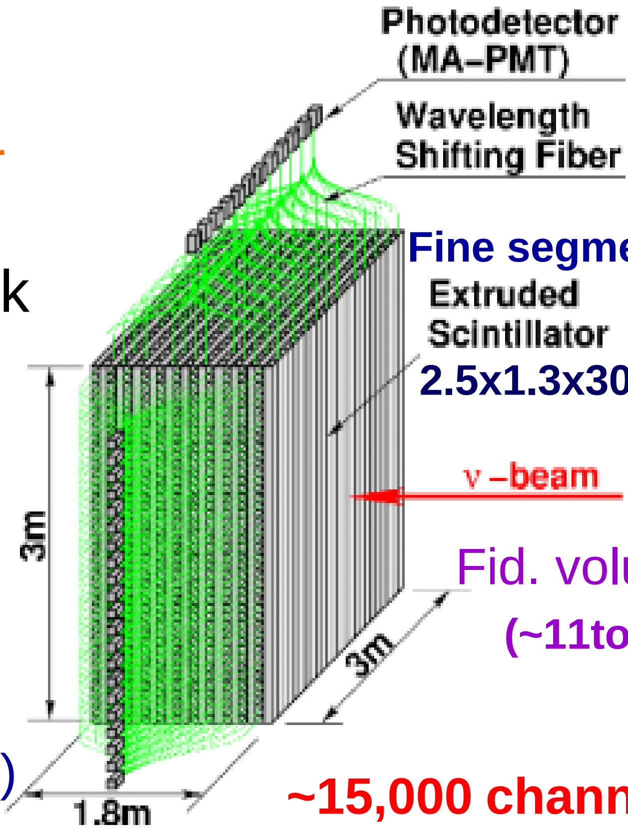
New SciBar detector at K2K

improve spectrum measurement at LE

Full Active tracking detector

High efficiency for short track

- Can detect and ID low momentum protons down to 350 MeV/c.



64ch

Fine segmented

2.5x1.3x300cm^3

Fid. volume

(~11ton)

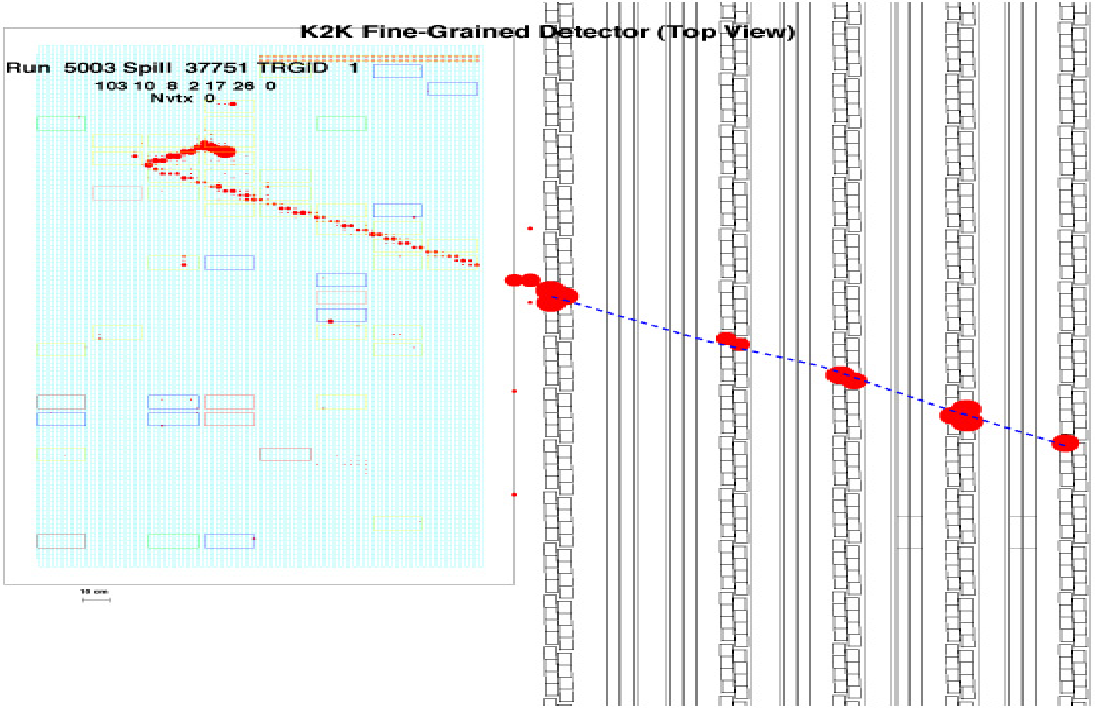
- Expected # of ν int.

~45,000 (Quasi Elastic:~**12,000**)

(3×10^{19} POT)

~15,000 channels

SciBar detector in K2K



Barcelona, CNU, Hiroshima, INR, KEK, Kobe, Kyoto, Osaka, Rome-INFN, Saclary, SNU, SUNY, UCI, Washington

- **The mixing angles θ_{12}, θ_{23}, θ_{31}, δ ?**
  - **Symmetry of 2^{nd} and 3^{rd} generation?**
    - How close θ_{23} to $\pi/4$? - extra symmetry?
  - **How small the mixing of 1^{st} and 3^{rd} generation?**
    - $\nu_\mu \rightarrow \nu_e$ exist – Does ν_e contain ν_3?
  - **How large is the phase δ?**
    - CP violation in lepton?
  - **Is sterile neutrino exist?**
    - Fraction in disappearance of ν_μ

- **Look for un-expected with good resolution**

- **Neutrino beam**
  - **Suited for water Cherenkov**
  - **Energy spectrum measurements**
  - **Good pion production data**

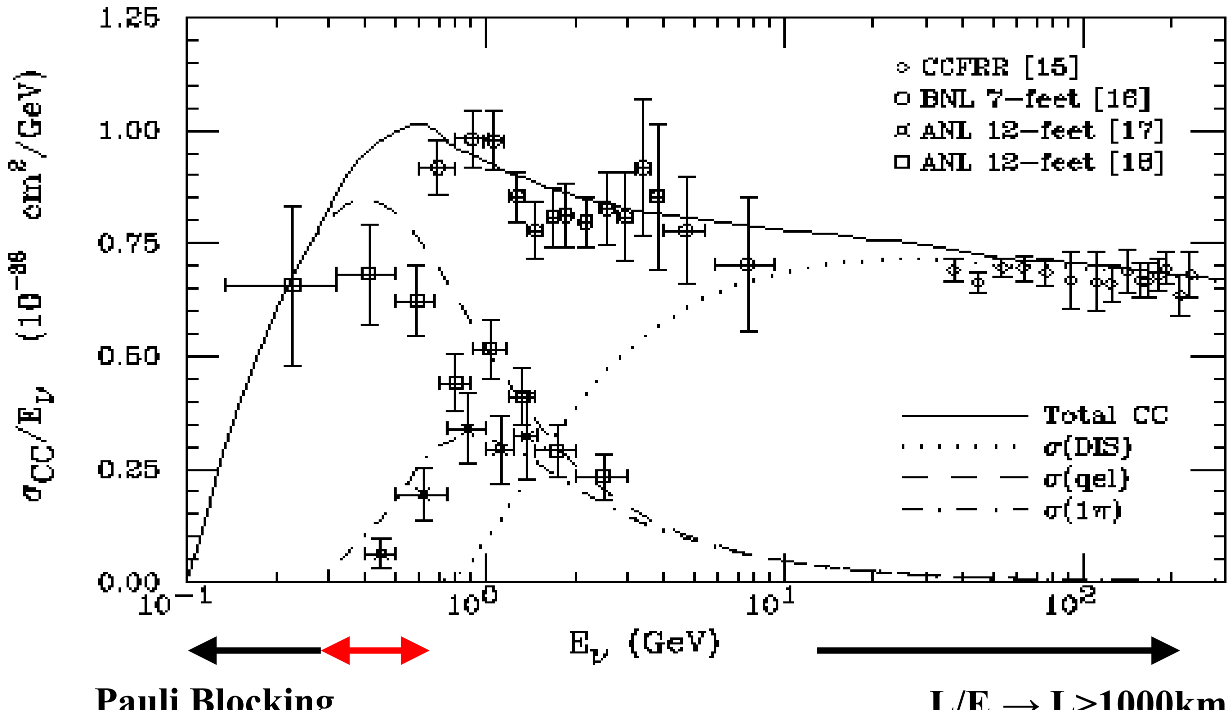
JPARC-Kamioka Project

Phase-I (0.75MW + Fully reconstructed Super-K)~K2K x 100

Phase-II (4MW+Hyper-K) ~ Phase-I × 100

Energy region

non CCQE backgrounds
high E reconstruction resolution with CCQE



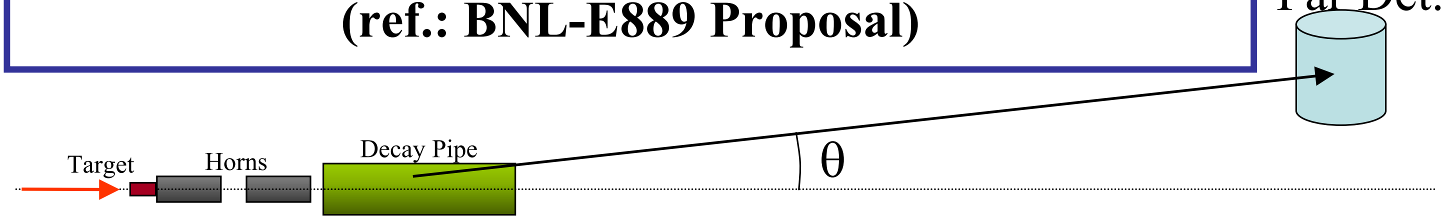
Pauli Blocking

L/E → L>1000km

Off-axis neutrino beam

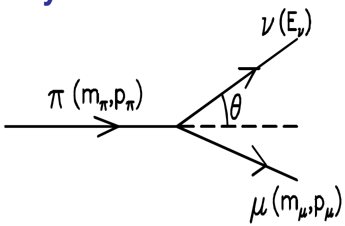
- Highest possible intensity at relevant energy region
  - oscillation maximum at sub-GeV
- ν beam suitable for water Cherenkov detector
  - good PID with single particle final state
  - μ–e decay rejection (ν_e + n → e + p)
- Narrow band beam to reduce BG
  - Small high energy tail : small nonQE contribution
  - CCQE cross section to obtain neutrino spectrum
  - Neutrinos from main part of π

Off Axis Beam
(ref.: BNL-E889 Proposal)

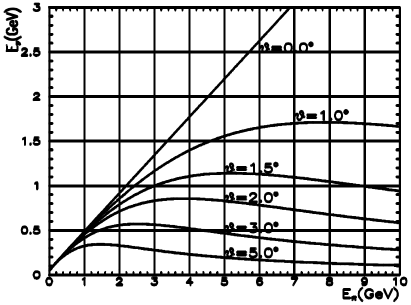


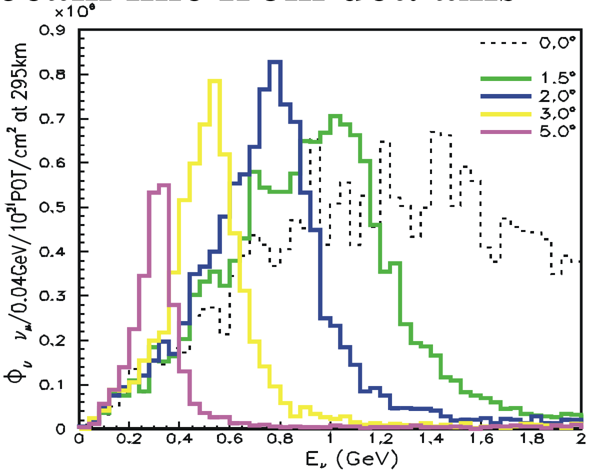
WBB w/ intentionally misaligned beam line from det. axis

Decay Kinematics



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

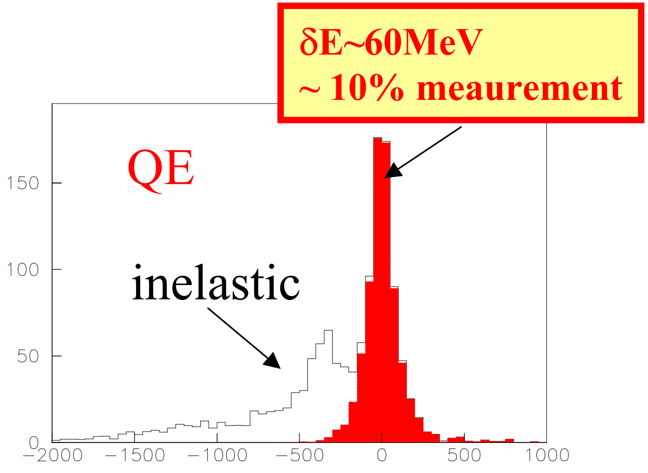




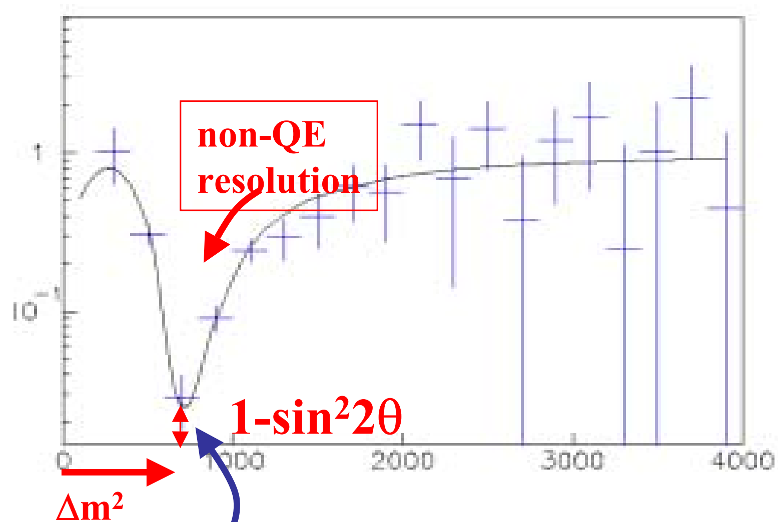
- Highest intensity at low energy ~4000 int./22.5kt/year (10^7 sec.)
- Contamination ν_e:0.8%(0.2% @ peak)
- Low Eν from main part of pion production

E_ν reconstruction resolution

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



E_ν (reconstructed) – E_ν (true)



+ 10% bin
High resolution : less sensitive to systematics

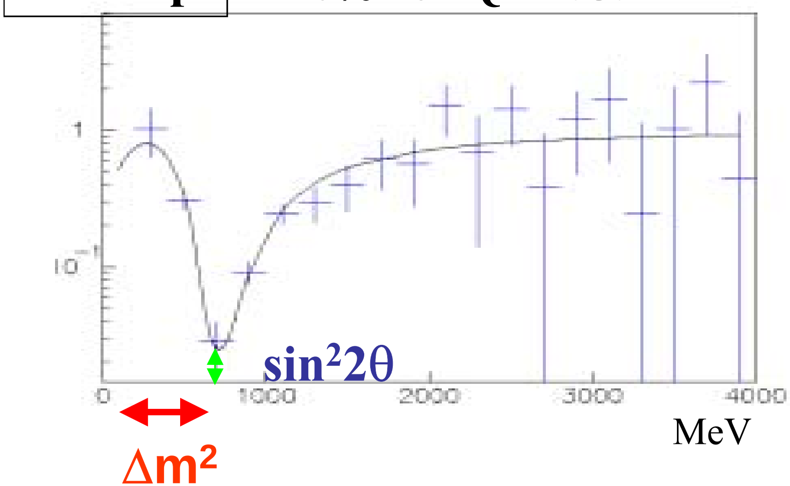
Measurement of $\sin^2 2\theta_{23}$, Δm^2_{23}

ν_μ disappearance: How close to the maximal mixing?

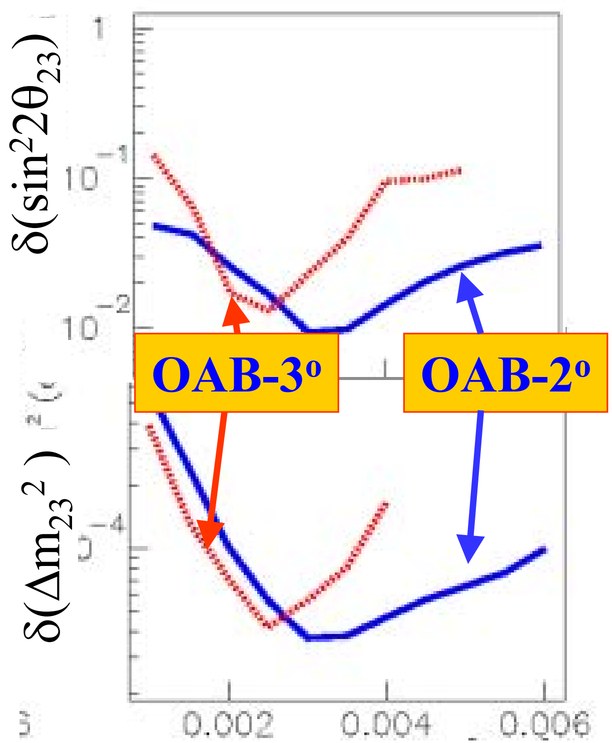
FC, 1-ring, μ-like events

Sys. error 10% for near/far
4% energy scale
20% non-QE B.G.

Attained in K2K



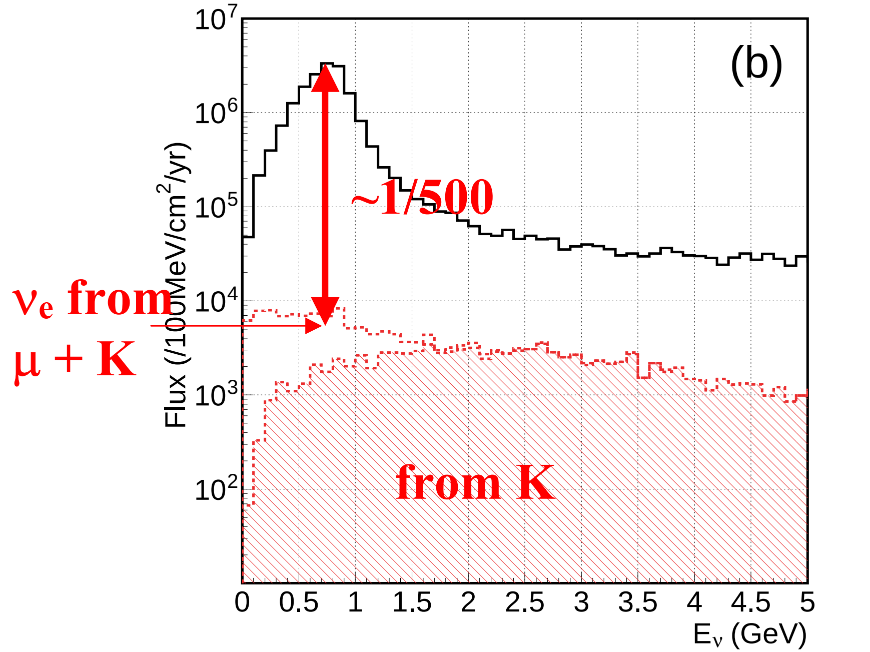
$\delta(\sin^2 2\theta)$~0.01 $\delta(\Delta m^2)$ ~<1 × 10^{-4}



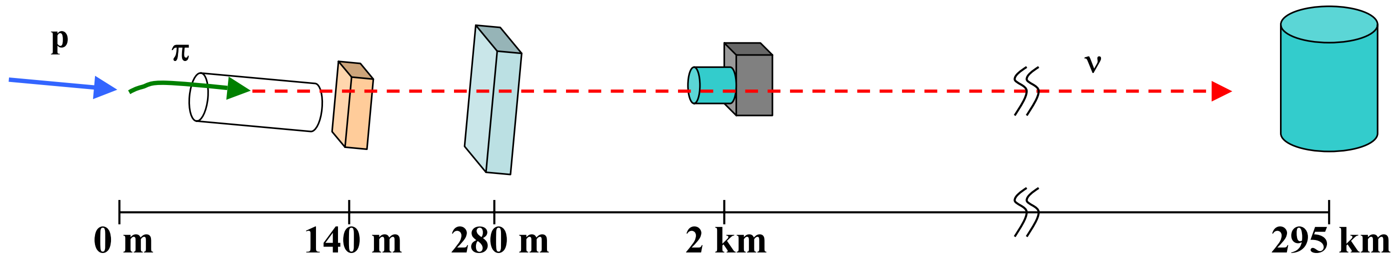
True Δm_{23}^2 (eV²)

Extra handle in ν_e appearance search

Off-Axis Beam

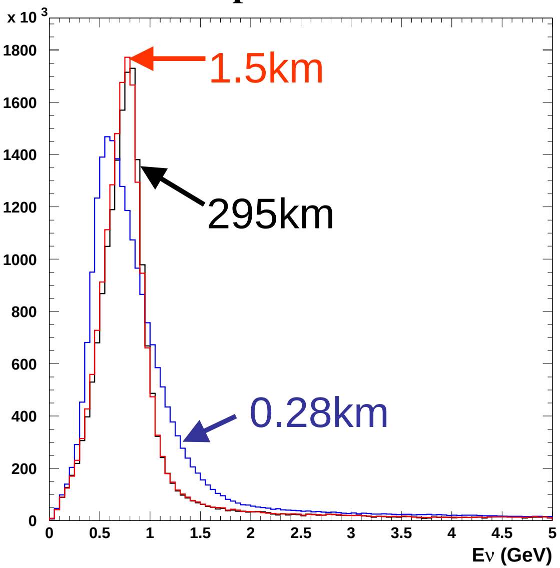


Intrinsic background: ν_e / ν_μ (peak) ~ 0.002



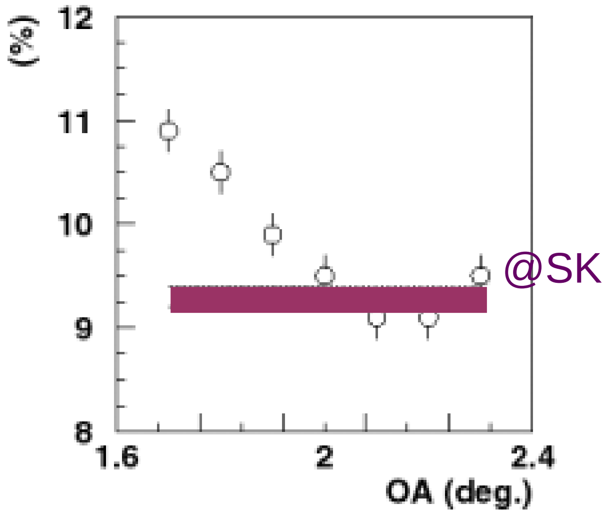
- Muon monitors @ ~140m
  - spill-by-spill monitoring of π–beam direction/intensity
- Near detectors @280m
  - 0 degree definition
  - High stat. neutrino inter. studies
- (Intermediate Detector @ ~2km)
  - Ultimate systematics
- Far detector @ 295km
  - Super-Kamiokande (50kt)

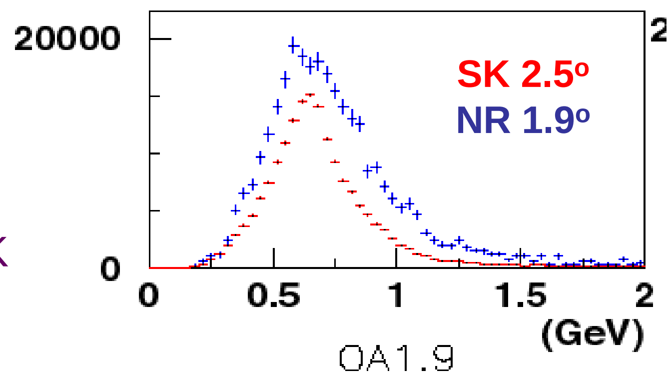
Neutrino spectra at diff. dist

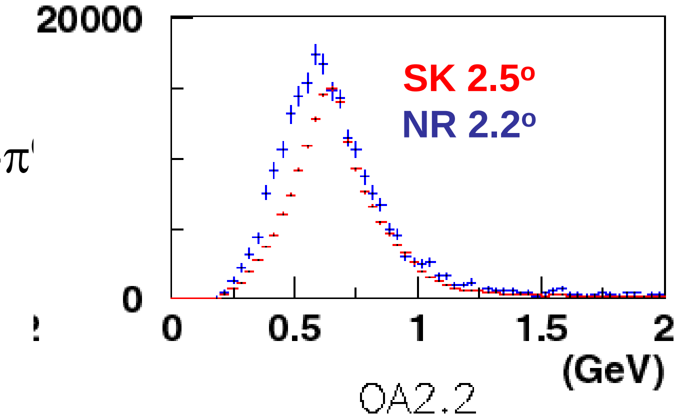


dominant syst. in K2K

NC-π^0 / CC ratio at 280m position



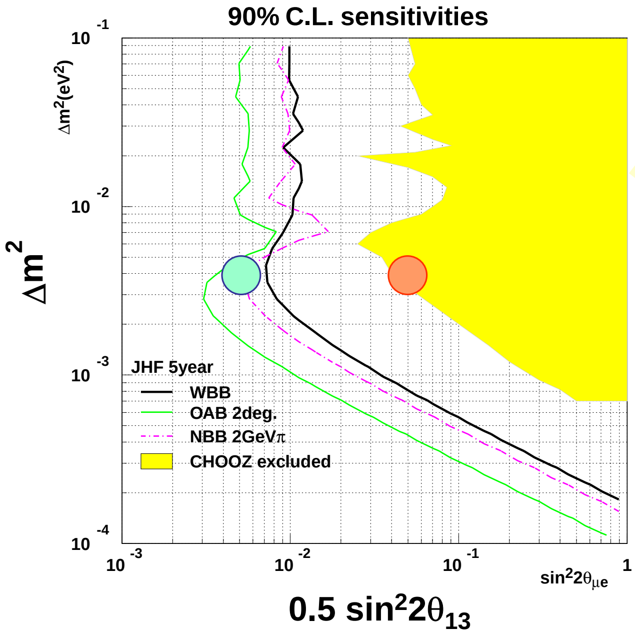




For 10% determination of NC-π background estimation can be measured at close distance

$\sin^2 2\theta_{13}$ from appearance experiment $\nu_e + n \rightarrow e + p$

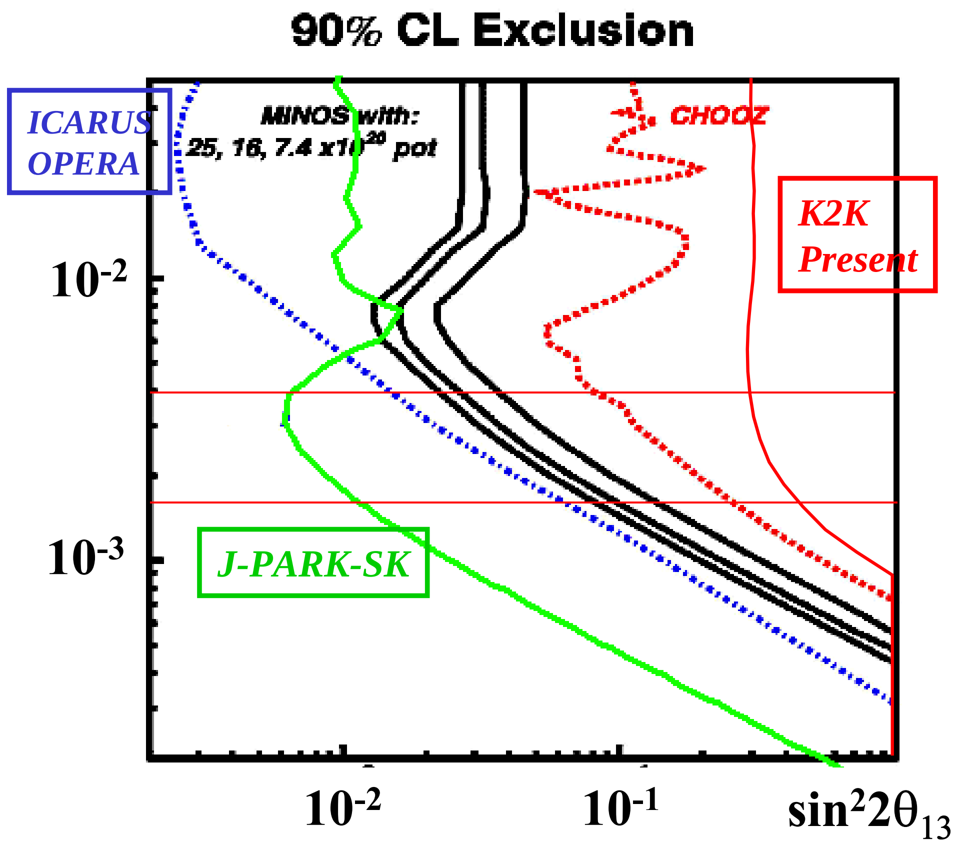
Off axis 2 deg, 5 years



$\sin^2 2\theta_{13}$	Background in Super-K					Signal	Signal + BG
	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$	total		
0.1	12.0	10.7	1.7	0.5	24.9	114.6	139.5
0.01	12.0	10.7	1.7	0.5	24.9	11.5	36.4

Off axis 2 deg, 5 years

Expected 90% CL sensitivity on θ_{13}



δ : CP Violation in Pure Leptonic process (Importance of $\nu_\mu \rightarrow \nu_e$)

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{j>i} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2 \frac{(m_j^2 - m_i^2)L}{4E_\nu}$$

$$\mp 2\sum_{j>i} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin \frac{(m_j^2 - m_i^2)L}{2E_\nu}$$

=0 for $\alpha=\beta$ $\rightarrow$ appearance exp!

- $\nu_\mu \rightarrow \nu_e$

- **Recent developments toward CPV search**

- **CPV $\propto$ $\sin\theta_{12}$ $\sin\theta_{23}$ $\sin\theta_{13}$ Δm^2_{12} (L/E) $\sin\delta$**

- **Solar LMA solution (large Δm^2_{12}, large θ_{12})**
  - **Near max. mixing in atmospheric (θ_{23}~$\pi/4$)**

Summary of Phase-I

★**Precision measurement of neutrino mixing matrix**

$\delta(\sin^2 2\theta_{23})$ ••• 1% (factor 8 improvement)

$\delta(\Delta m^2_{23})$ ••• a few % (factor 10 improvement)

★**Discovery and measurement of non-zero θ_{13}**

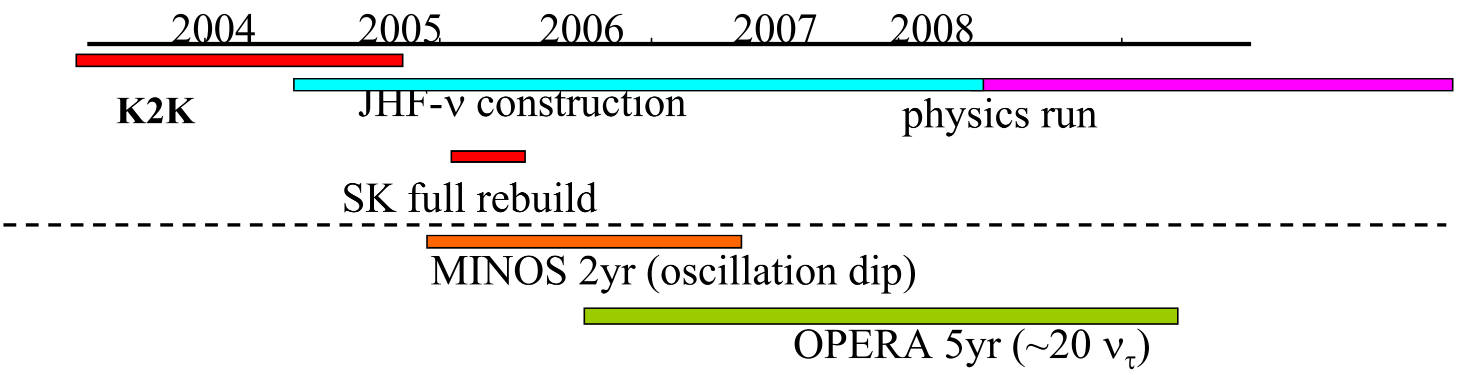
$\sin^2 2\theta_{13}$ ••• > 0.006 (factor 20 improvement)

1st Evidence of 3-flavor mixing !

1st step to CP measurement


ν

Schedule & Summary

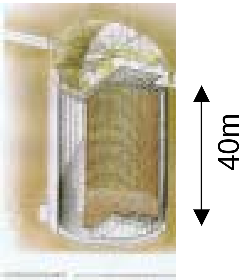


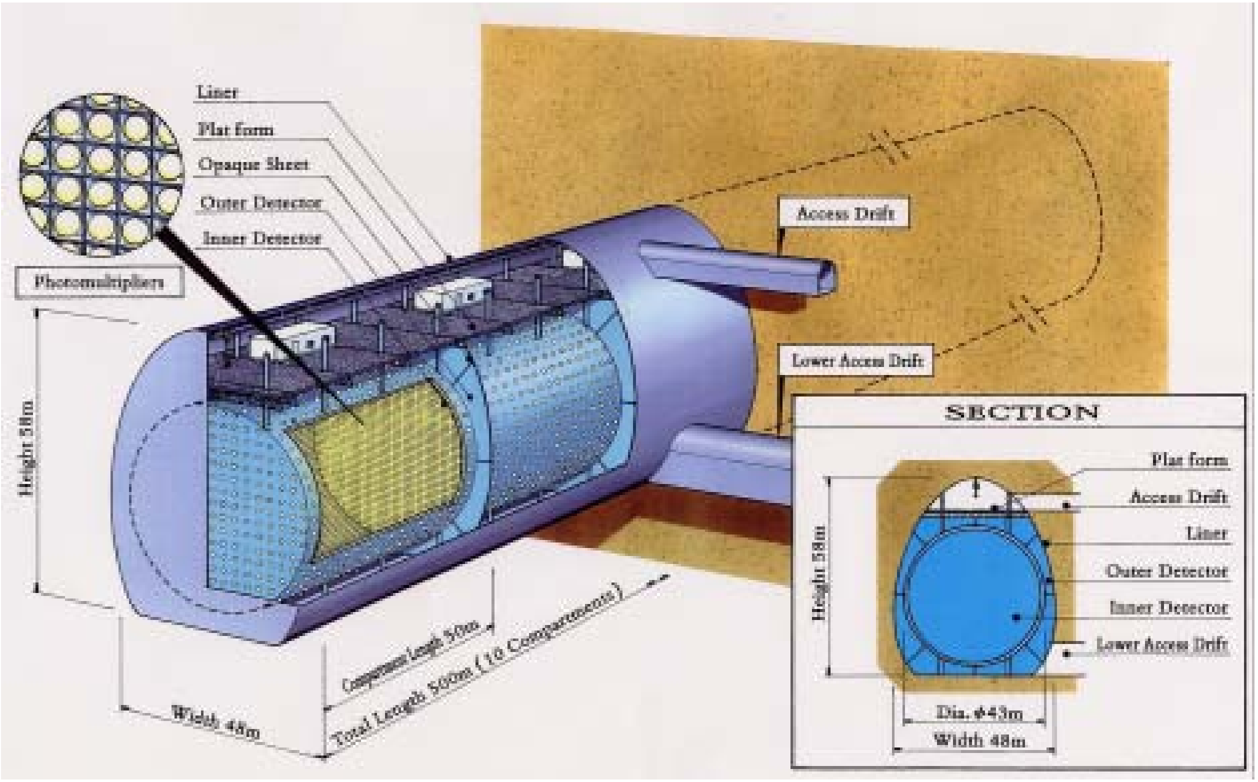
- **Beyond the 'confirmation' of neutrino oscillation**
- **Best possible measurements of neutrino oscillation with present technology**
- **World-wide interests to join the experiment**

- **Possible upgrade in future**
  - **4MW Super-JHF + Hyper-K (1Mt water Cherenkov)**
  - **CP violation in lepton sector**

Schematic drawing of Hyper-Kamiokande

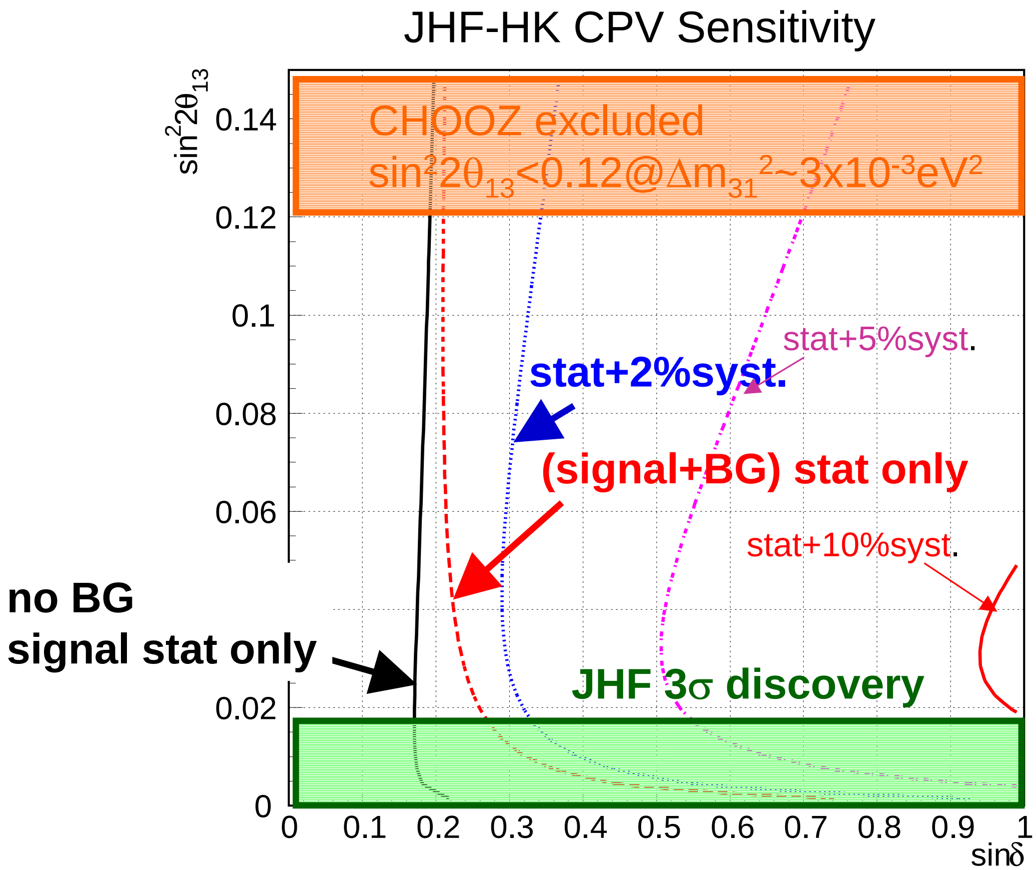
Super-K





1 Mton (fiducial) volume: Total Length 400m (8 Compartments)

~~CP~~ sensitivity (3σ)



3σ CP sensitivity : |δ|>20° for $\sin^2 2\theta_{13}$>0.01 with 2% syst.

Summary

- **Presently, underlying parameters were determined with rather poor accuracies**
- **Hierarchical masses ($m_3>m_2>m_1$):**
  - **$m_3 \sim$ 0.04 – 0.06 eV**
  - **$m_2 \sim$ 0.005 – 0.01 eV**
    - All 90% C.L.

  Degenerate masses ($m_3 \sim m_2 \sim m_1$):

  m_e < 2.2 eV

  Σm_i < 6.6 eV

  (95% CL)
- **Neutrinos**
  - **$\sin^2 2\theta_{12}$ = 0.6 – 0.9**
  - **$\sin^2 2\theta_{23}$ = 0.92 – 1.0**

  Quarks

  $\sin^2 2\theta_{12} = 0.188 \pm 0.007$

  $\sin^2 2\theta_{23} = 0.0064 \pm 0.0010$
- **We are now in the stage of using neutrino oscillation to study leptons with precision measurements**
- **In a decade or two, θ_{23}, θ_{13} and CP phase δ can be determined comparable accuracy as quarks**