Study of neutrino oscillations in the long base-line experiment K2K

Yu.G. Kudenko

Institute for Nuclear Research, Moscow

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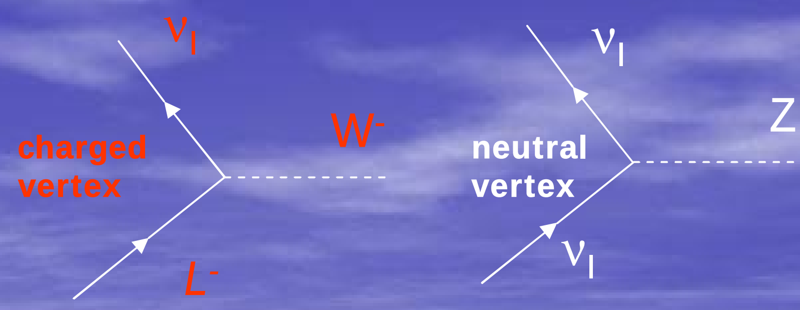
Outline

- Phenomenology of neutrino oscillations
- K2K
  - principles of the experiment
  - detectors
  - performance
  - analysis
  - results
- Neutrino oscillations: status and problems
- T2K
- Near future

Leptons

$\begin{pmatrix} e \\ n_e \end{pmatrix} \begin{pmatrix} m \\ n_m \end{pmatrix} \begin{pmatrix} t \\ n_t \end{pmatrix}$ → **EM, weak** (upper row)
→ **weak** (lower row)



two different neutrino bases

Flavor states	n_e	n_m	n_t
produced via charged currents	L_e=+1	L_μ=+1	L_τ=+1

Mass eigenvalues	m_i
Mass eigenstates	$\vert n_i\rangle$

flavor eigenstates $|n_a\rangle$ 1 mass eigenstates $|n_i\rangle$

Unitary transformation: $|n_a\rangle = U_{ai}|n_i\rangle$

U_{ai} – neutrino(lepton) mixing matrix

Mixing in two families

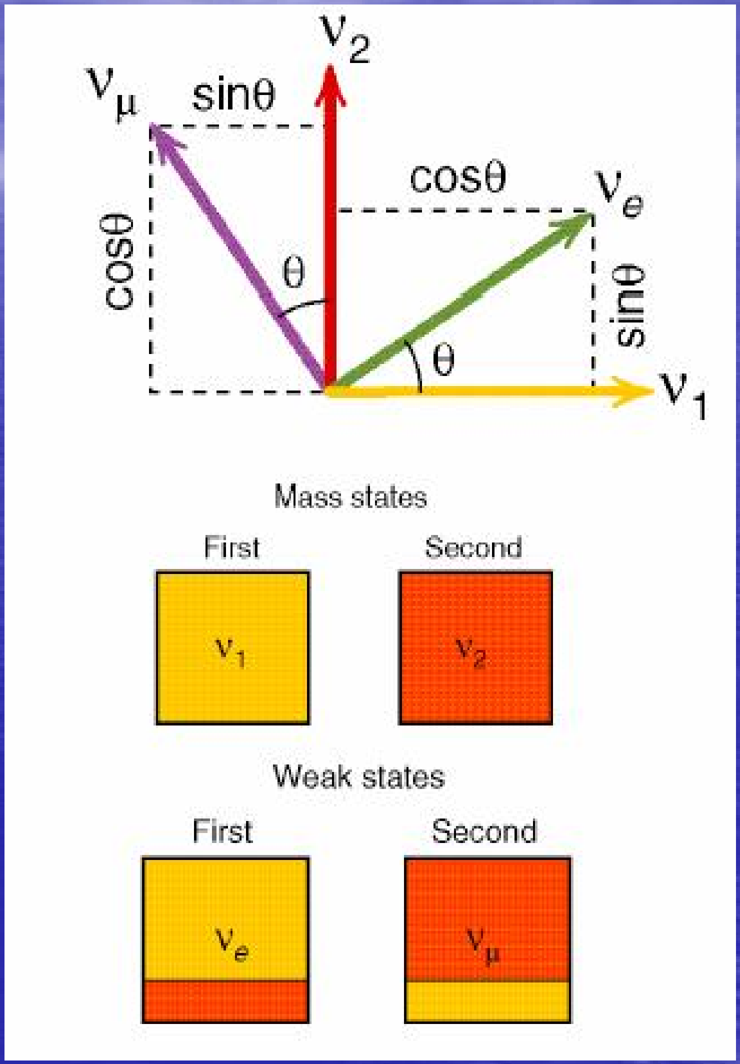
Consider for simplicity two families. Mixing matrix depends of a single parameter, the mixing angle θ

The weak and mass eigenstates are connected by a simple two-dimensional rotation

$$\begin{pmatrix} n_e \\ n_m \end{pmatrix} = \begin{pmatrix} \cos q & \sin q \\ -\sin q & \cos q \end{pmatrix} \begin{pmatrix} n_1 \\ n_2 \end{pmatrix} = U \begin{pmatrix} n_1 \\ n_2 \end{pmatrix}$$

n_e = **cos**q|n_1> + **sin** q|n_2>

n_m = **-sin**q|n_1> + **cos** q|n_2>



Neutrino oscillations

The weak interaction produces neutrinos of a given flavor

Distance $x_0 = 0$ time $t=0$

$$|\nu(x_0)\rangle = |\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

The mass eigenstates propagate at different velocities

Distance x time t

$$|\nu_e\rangle_t = \cos\theta\,\exp(i\pi_1 x)\exp(-iE_1 t)\,|\nu_1\rangle + \sin\theta\,\exp(i\pi_2 x)\exp(-iE_2 t)\,|\nu_2\rangle$$

Detection via weak interactions

$$\nu_\mu N \rightarrow \mu^- X$$

$$\nu_e N \rightarrow e^- X$$

$$P(\nu_e \rightarrow \nu_\mu) = |<\nu_\mu\,|\,\nu(t)>|^2$$

Oscillation formalism

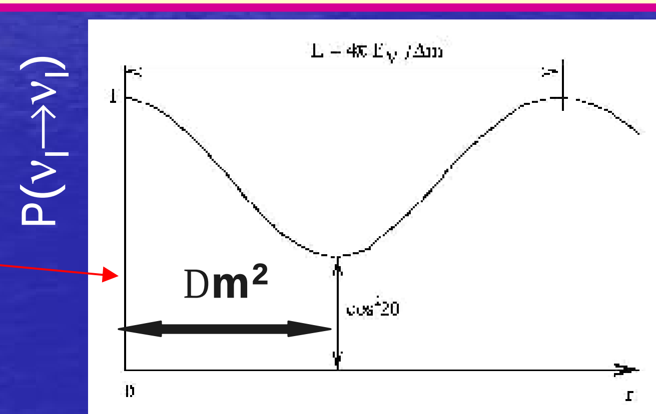
$E^2 = p^2 + m^2$ neutrino: $p >> m$ à E » $p + m^2/2p$ $E_2 - E_1 = $ D$m^2/2E$

D$m^2 = |m_1^2 - m_2^2|$ E » p

$$P(n_e \to n_m) = |< n_m | n(L) >|^2 = \left| -sce^{-i\frac{m_1^2}{2E}L} + cse^{-i\frac{m_2^2}{2E}L} \right|^2$$

$$= 4s^2c^2\left(1 - \cos\frac{m_1^2 - m_2^2}{2E}L\right) = \sin^2(2q)\sin^2\left(\frac{\Delta m_{12}^2}{4E}L\right)$$

$P(\nu_\mu \to \nu_\mu) = 1 - P(\nu_\mu \to \nu_x)$



$P(n_m$ ® $n_x) = \sin^2 2q \sin^2[1.27Dm^2(eV^2)L(km)/E_n(GeV)]$

$P(n_m$ ® $n_m) = 1 - \sin^2 2q \sin^2[1.27Dm^2(eV^2)L(km)/E_n(GeV)]$

PMNS mixing matrix

3 families

$$\begin{pmatrix} n_e \\ n_m \\ n_t \end{pmatrix} = U \begin{pmatrix} n_1 \\ n_2 \\ n_3 \end{pmatrix} \qquad U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{m1} & U_{m2} & U_{m3} \\ U_{t1} & U_{t2} & U_{t3} \end{pmatrix}$$

U parameterization

three mixing angles θ_{12} θ_{13} θ_{23}

complex phase δ

$$\frac{|U_{e2}|^2}{|U_{e1}|^2} = \tan^2 q_{12} \qquad \frac{|U_{m3}|^2}{|U_{t3}|^2} = \tan^2 q_{23} \qquad U_{e3} = \sin q_{13} e^{-id}$$

$$\Delta m_{ij}^2 = m_i^2 - m_j^2 \qquad \Delta m_{12}^2 + \Delta m_{23}^2 + \Delta m_{31}^2 = 0$$

→ two independent Δm^2

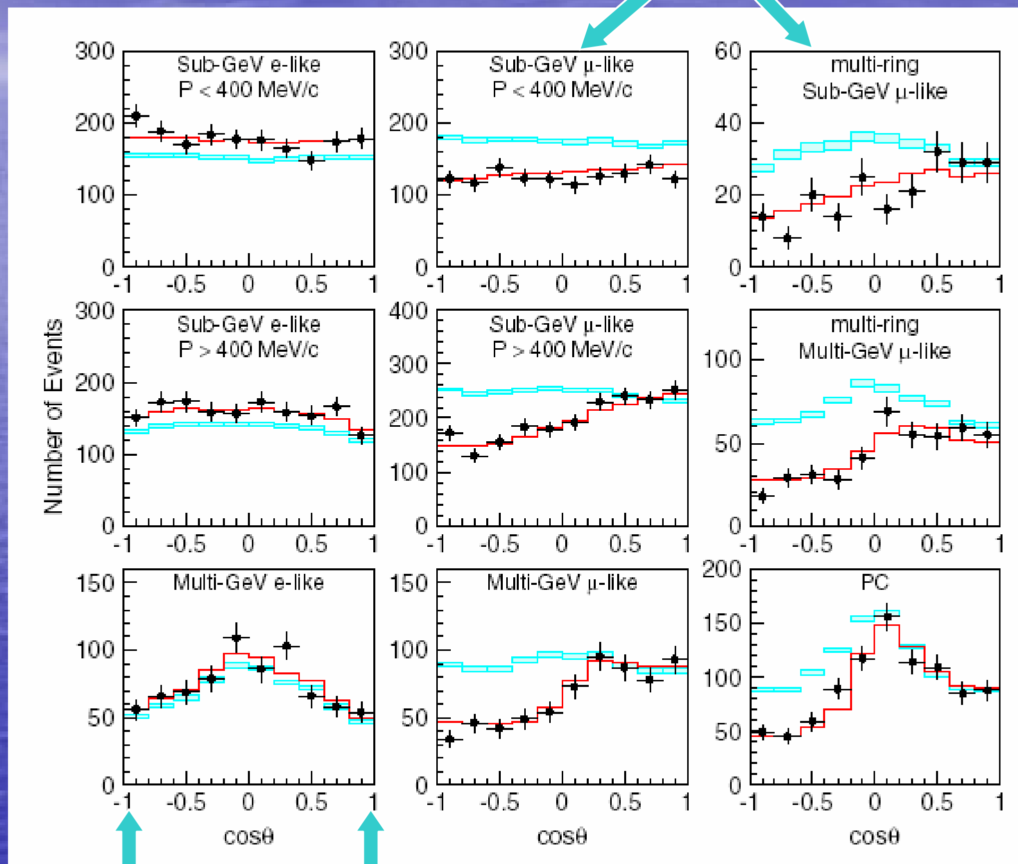
$$\Delta m_{12}^2 = \Delta m_{sol}^2 \qquad \Delta m_{23}^2 \cong \Delta m_{31}^2 = \Delta m_{atm}^2$$

Atmospheric neutrino oscillations

0.2 < cosq <1	**L = 20-500 km**
-1 < cosq <-0.2	**L = 500-13000 km**

n_e n_m

SK



upgoing downgoing

$(U/D)_m$ = 0.54 ±0.04 ±0.01

SK : n_m oscillation with $\Delta m^2 \sim (2\text{-}3)\times 10^{-3}\,eV^2$

Main goal of K2K

First accelerator long base-line neutrino experiment

Measurement of (search for) neutrino oscillations in LBL accelerator experiment to confirm the oscillation observed by the SuperKamiokande

$\Delta m^2 \sim (2\text{-}3)\text{x}10^{-3}\,\text{eV}^2$ $\sin 2\theta \sim 1$

Experiment K2K

Collaboration K2K: Japan-USA-Korea-Canada-Russia-France-Italy-Spain-Switzerland

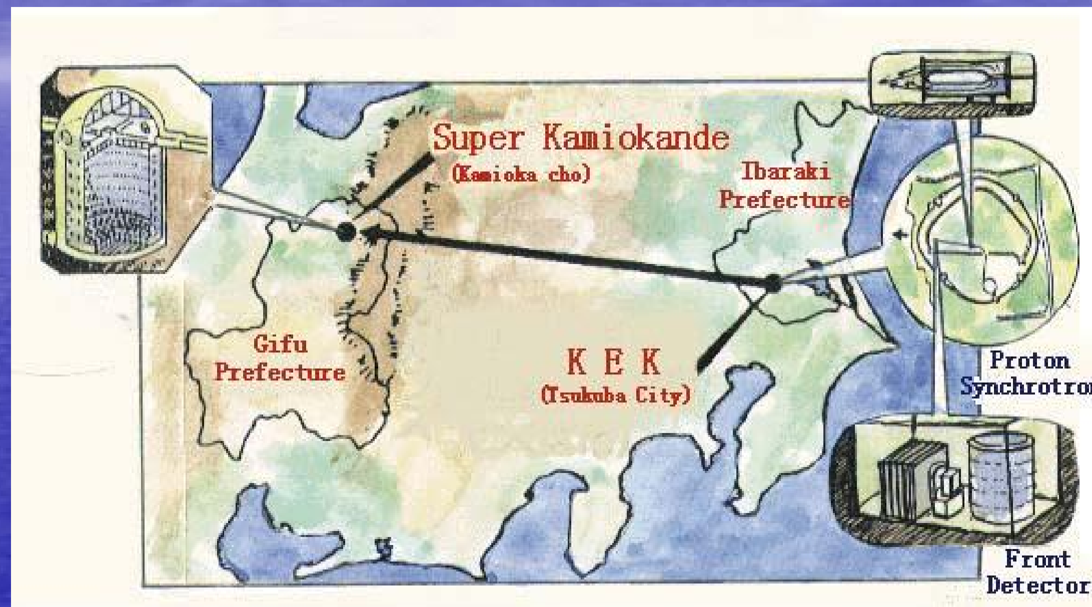
$\nu_\mu \rightarrow \nu_\tau \; (\nu_\mu \rightarrow \nu_x)$

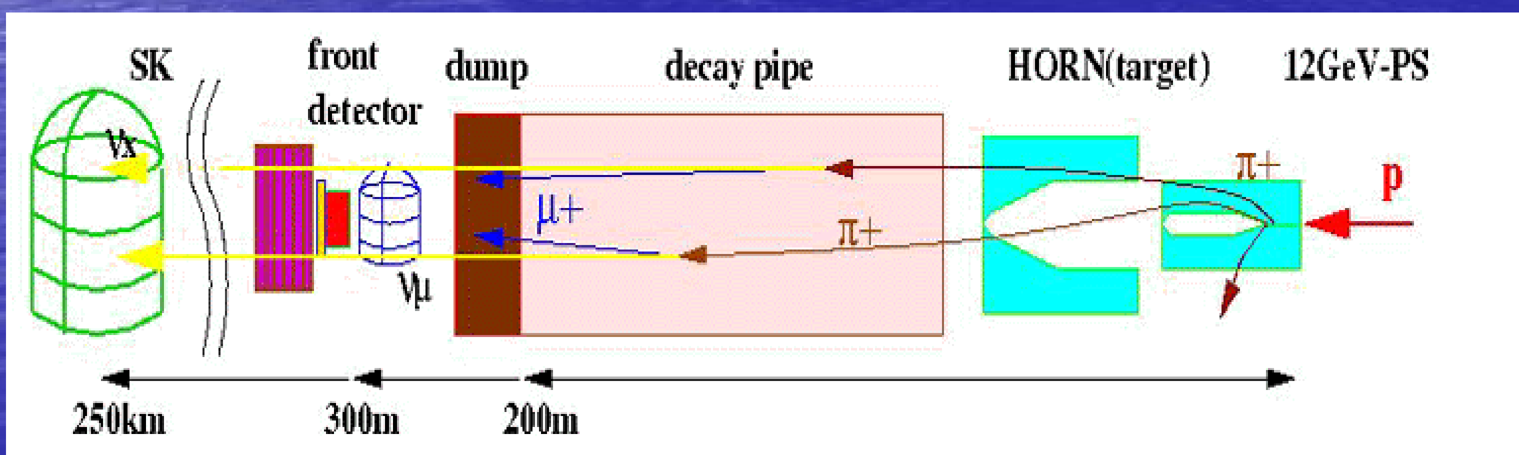
$L/E_\nu \approx 200$

$L = 250$ km $\langle E_\nu \rangle \approx 1.3$ GeV

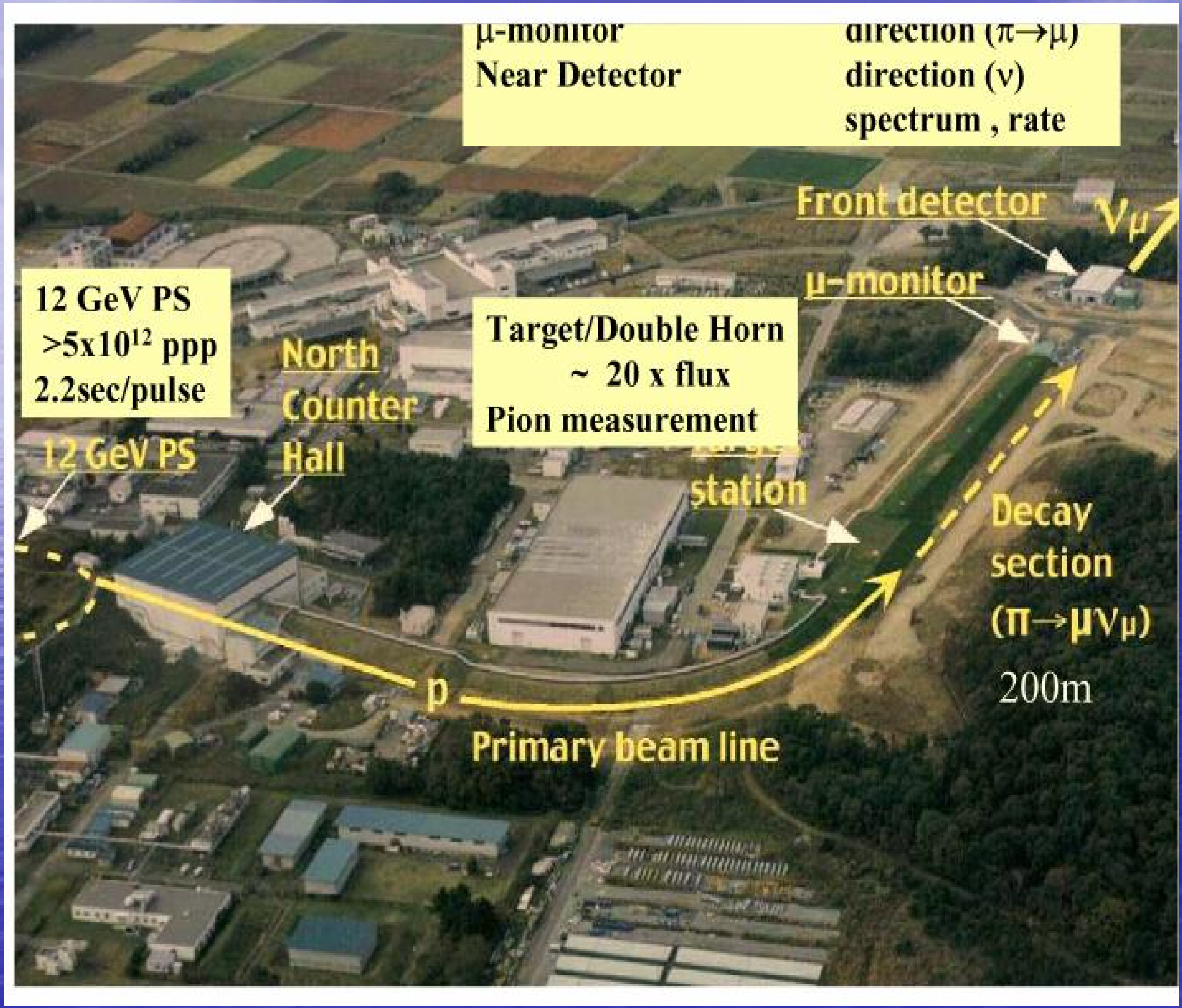
ν_μ	98.2%
ν_e	1.3%

$\Delta m^2 \geq 2 \times 10^{-3} eV^2$

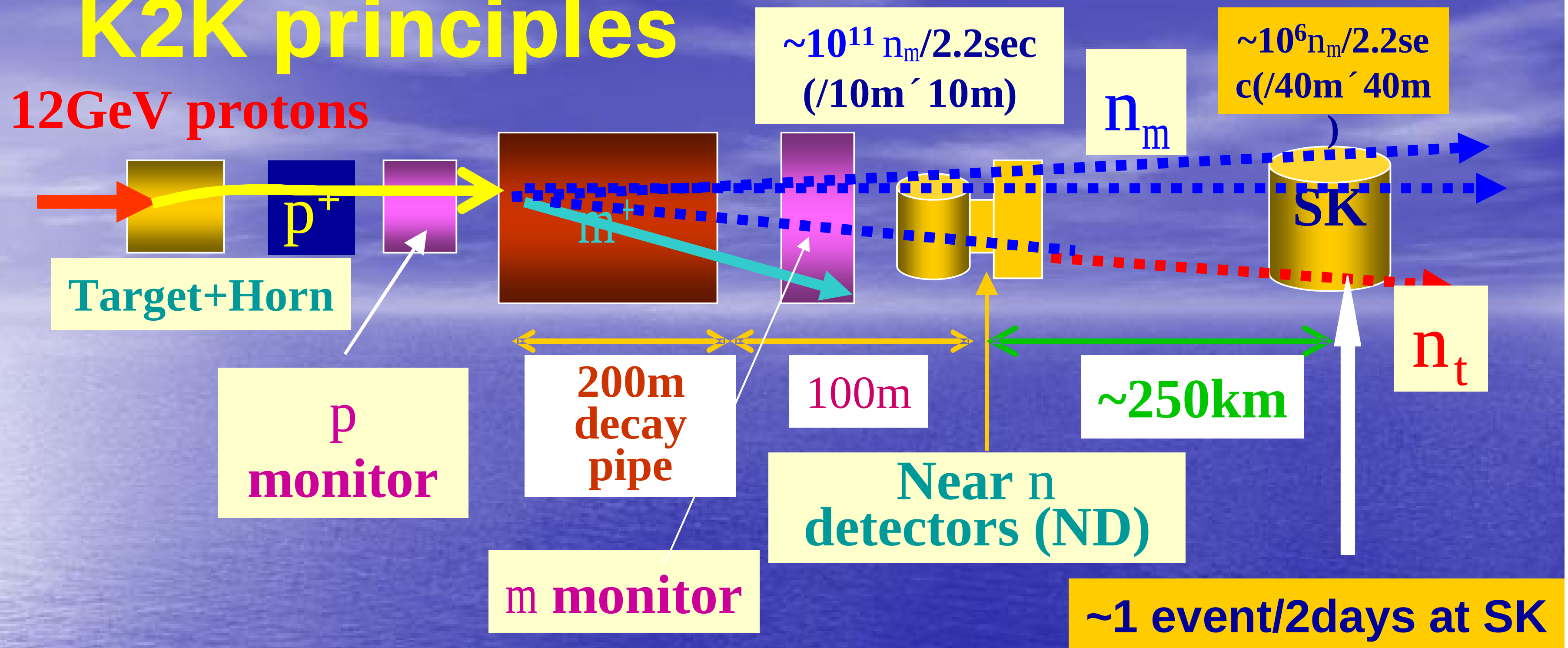




K2K Beam Line



K2K principles



n_m flux at SK = n_m(flux at ND) x (Far / Near)

Far / Near ratio (by MC) ~ 10^{-6}

Signal of n oscillation

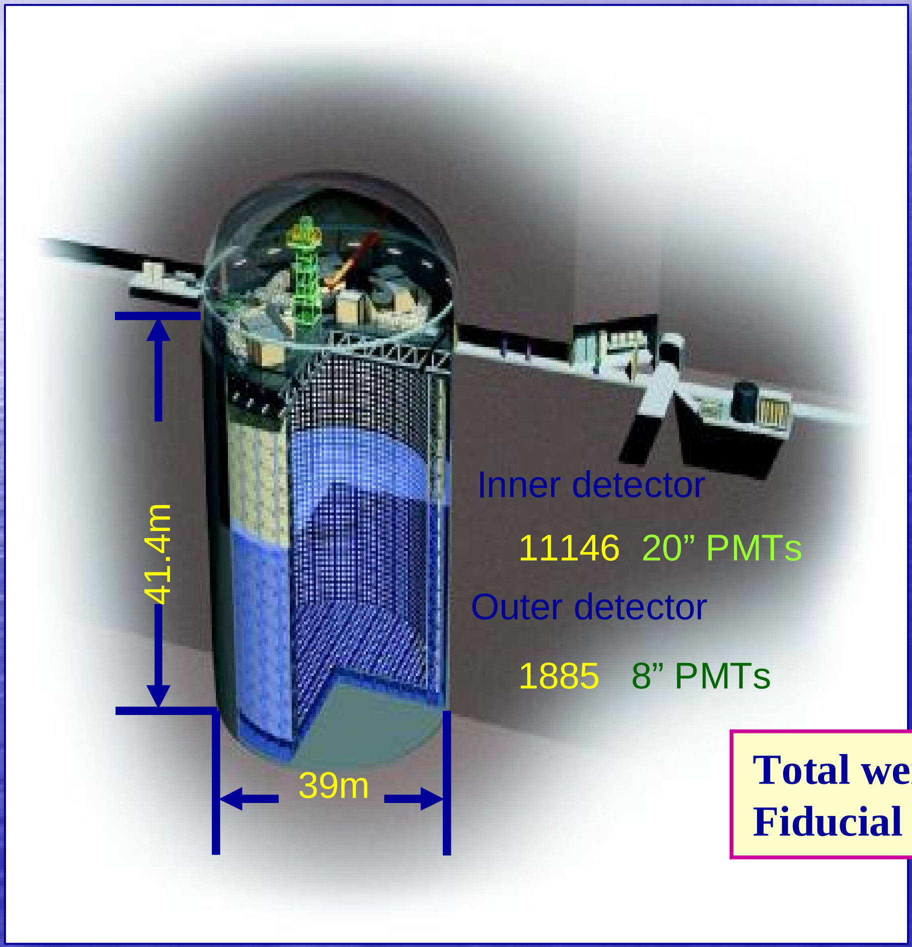
- **Reduction of n_m events**
- **Distortion of n_m energy spectrum**

Far detector

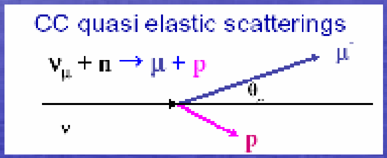
Super-Kamiokande II

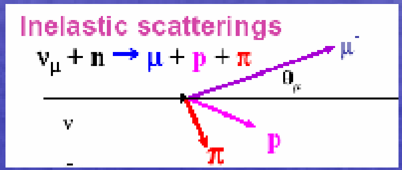
~5200 PMTs
with FRP+Acrylic cover

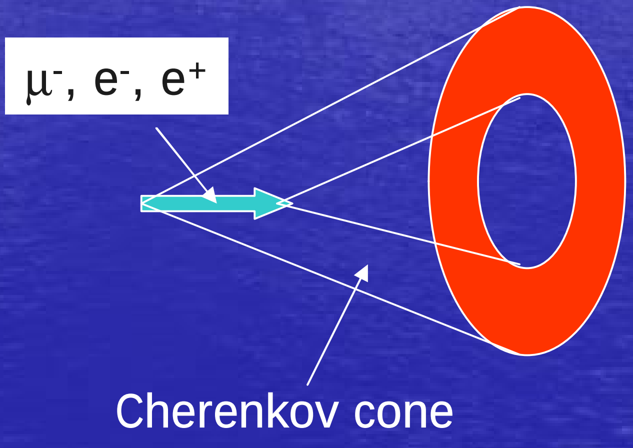
Super-Kamiokande I



Total weight 50 kt
Fiducial 22.5 kt

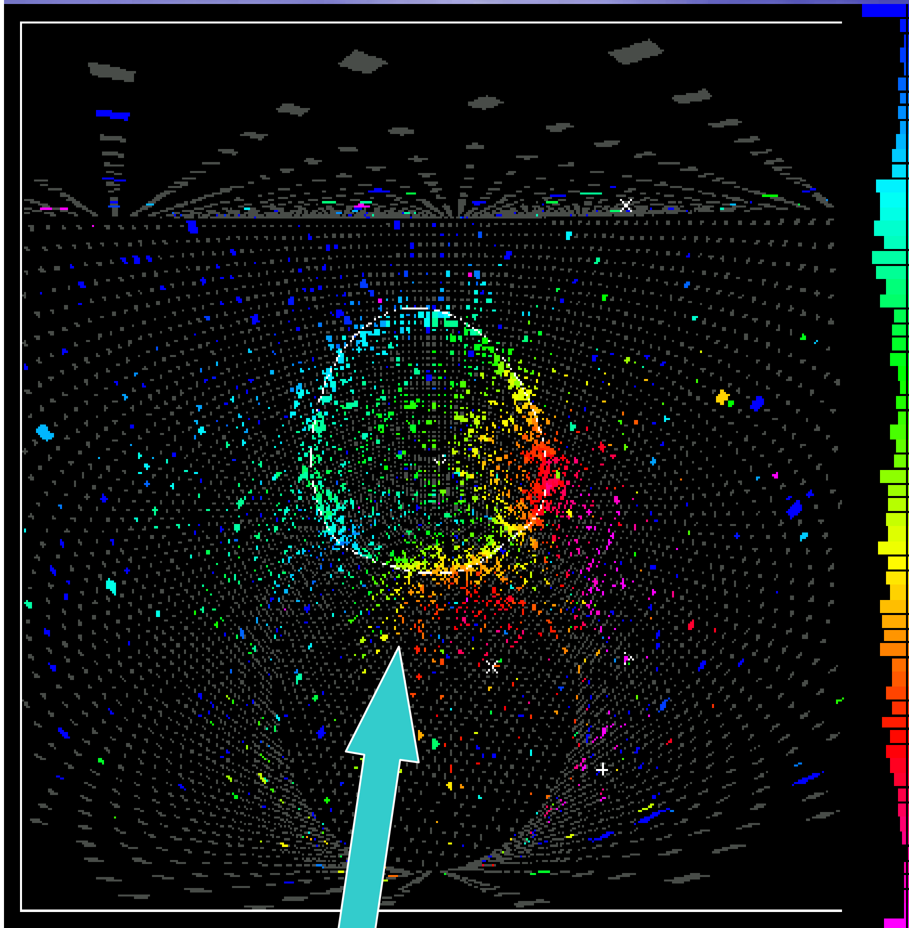


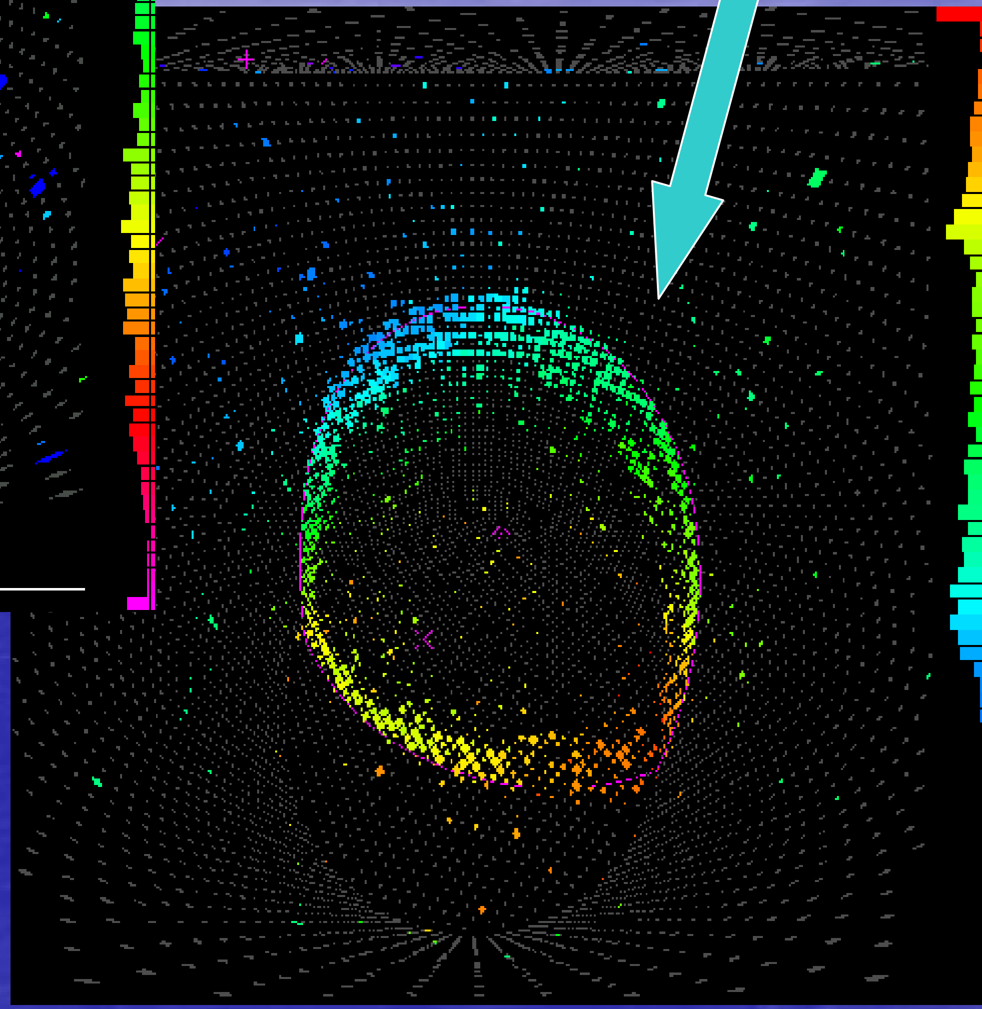




SK events

m - like

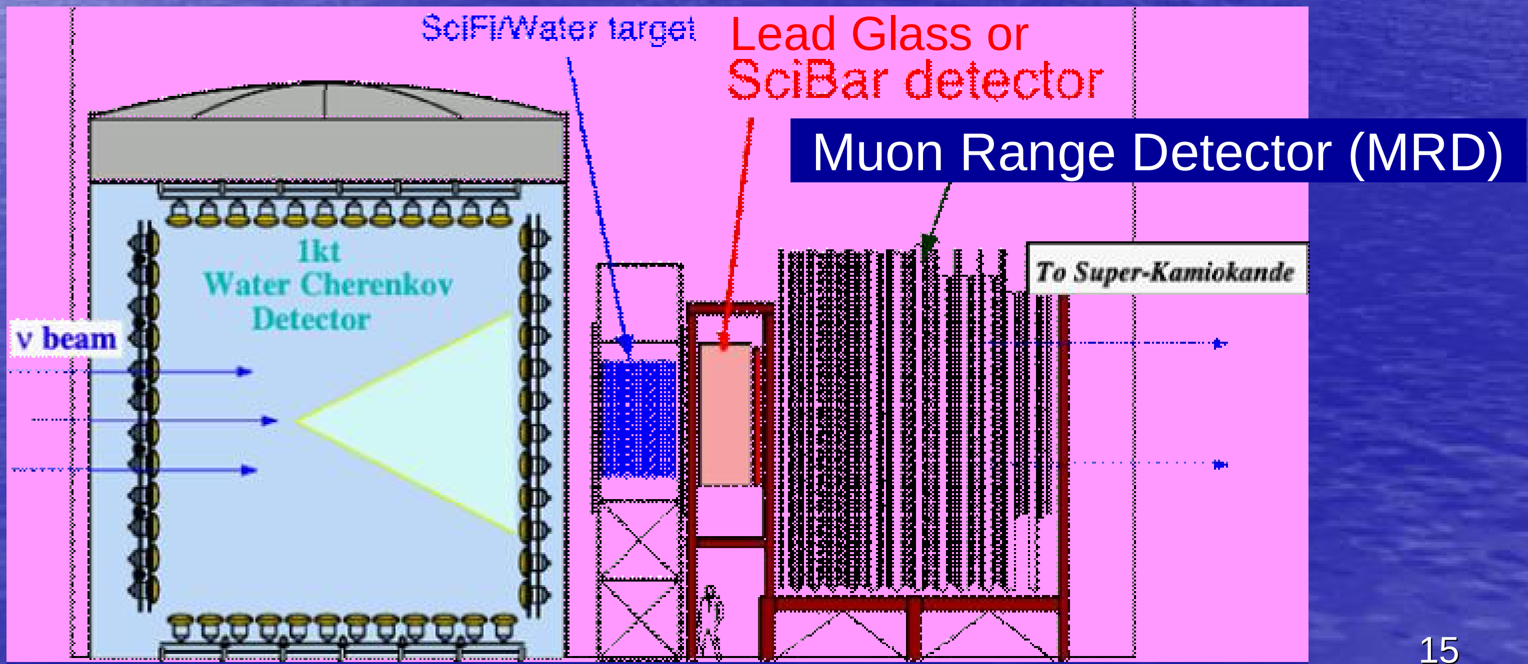




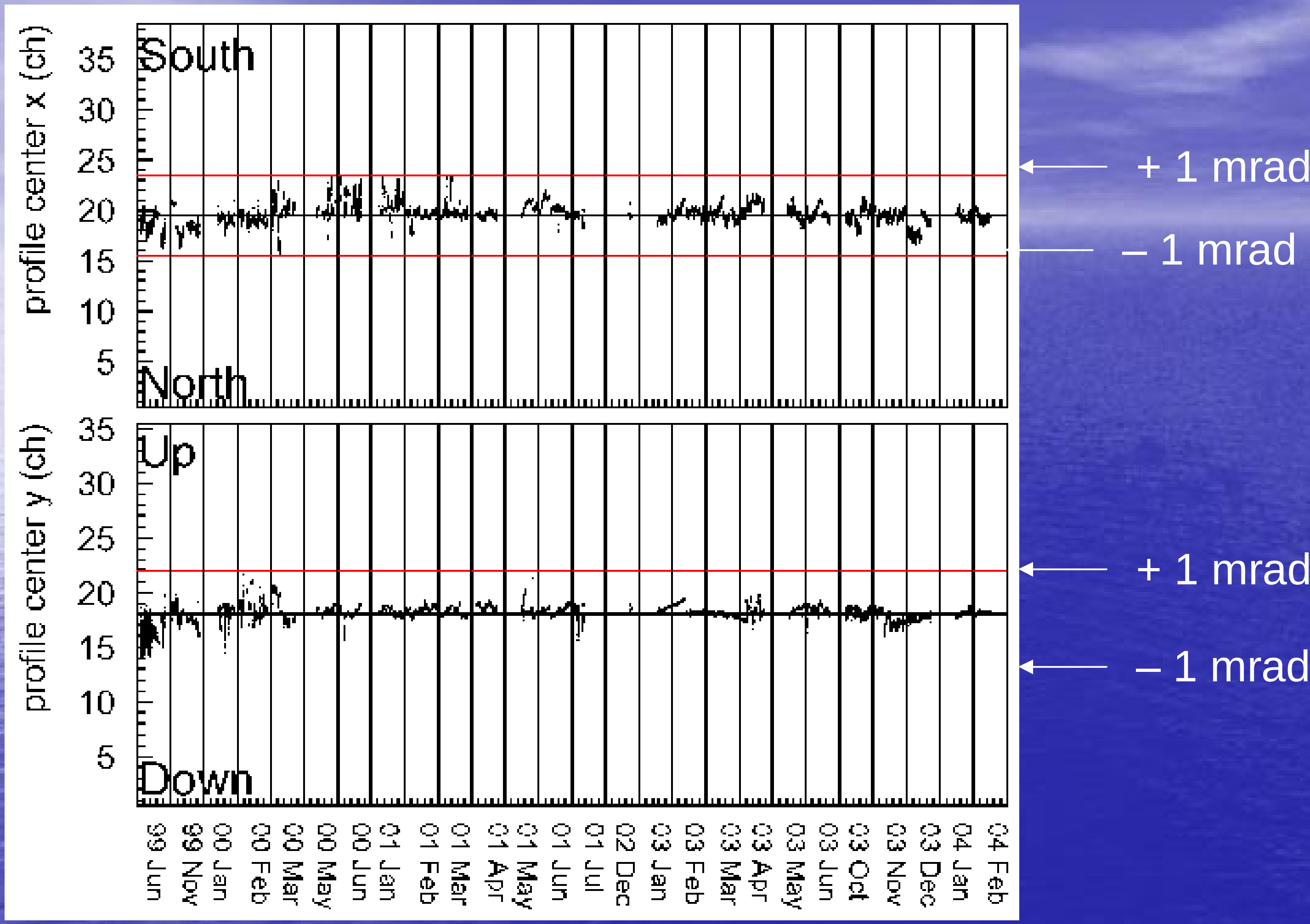
e - like

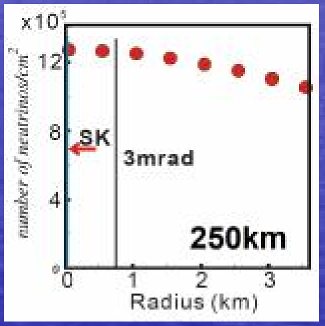
Near Detectors

- 1KT: water Cherenkov detector [25t fiducial]
- SciFi: scintillating fiber and water target [6t fiducial]
- LG: Lead glass calorimeter (removed in 2002)
- SciBar: fully-active scintillator detector [10t fiducial] (installed in 2003)
- MRD: muon range detector



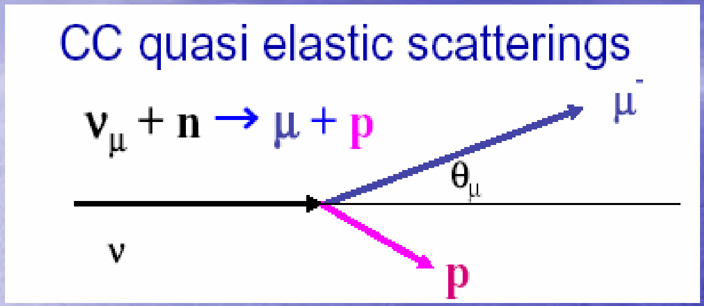
Beam stability (muon monitor)

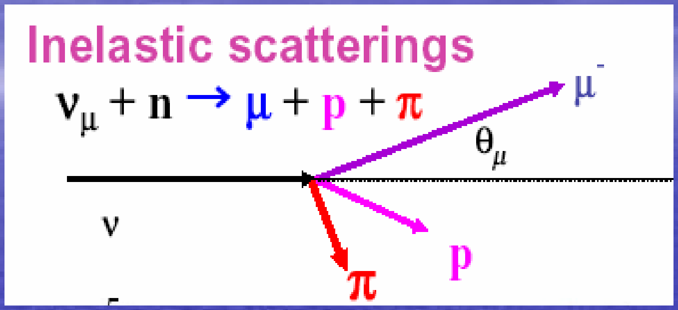


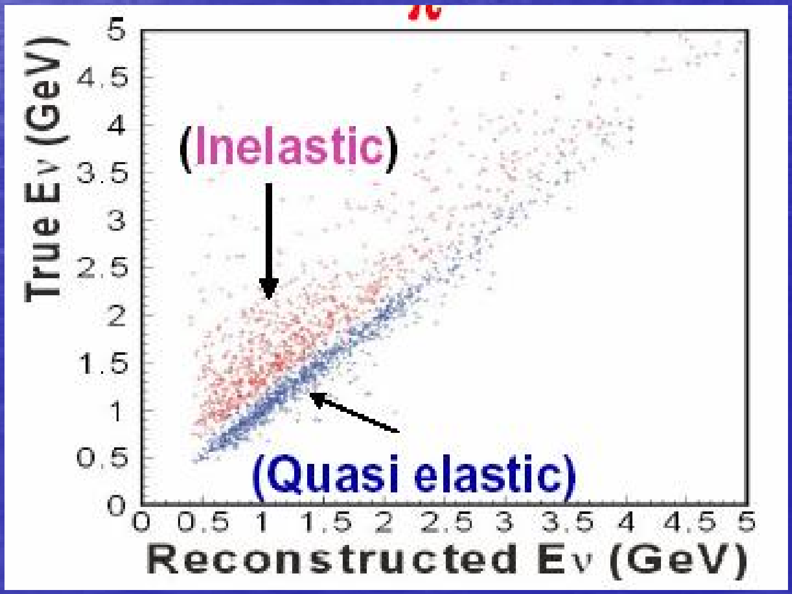


- muon profile is monitored spill-by-spill
- muon center is stable within 1mrad.

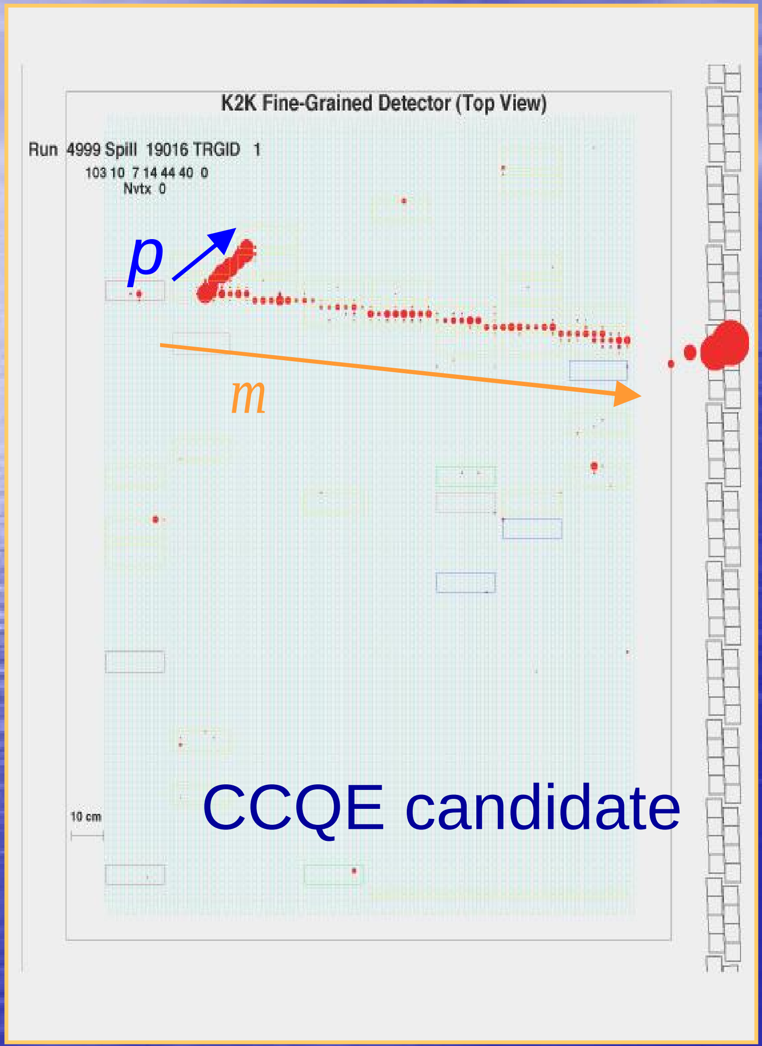
Neutrino energy reconstruction

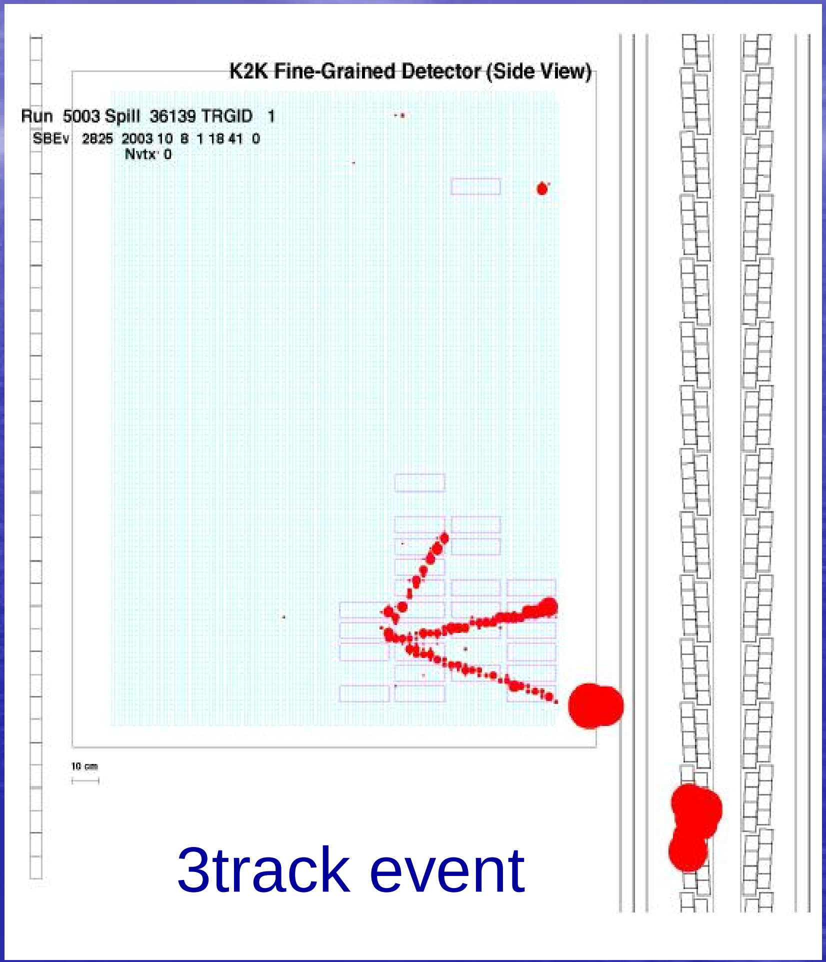




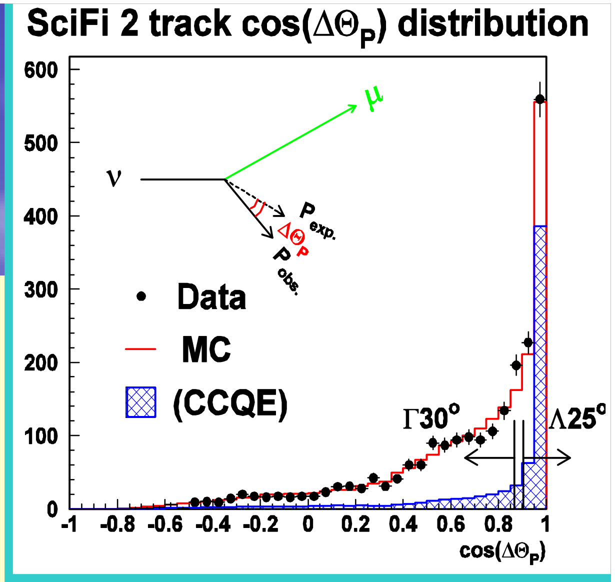


SciBar Event Display





Measurements at ND



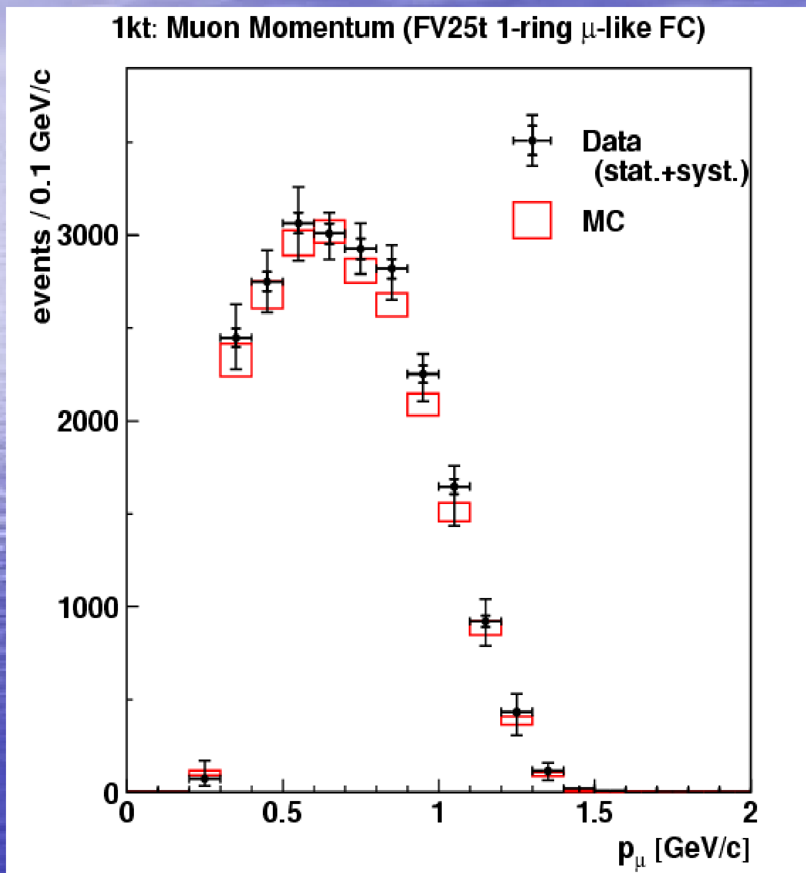
- 1KT : P_μ<1.5GeV/c, 4π acceptance
  - 1-ring μ-like(1Rμ) fully contained in Fiducial volume 25 ton (FC)
- SciFi : P_μ>0.55GeV/c, θ_μ<60deg. Fid volume 5.6 t
  - 1-track μ-like QE-like ($\Delta\theta_p$<25deg)
    nonQE-like ($\Delta\theta_p$>30deg)
- Scibar : P_μ>0.45GeV/c Fid. volume 9.4 t
- PIMON

(p,θ) distribution ⇒ Neutrino Spectrum (>1GeV) Fitting Parameters

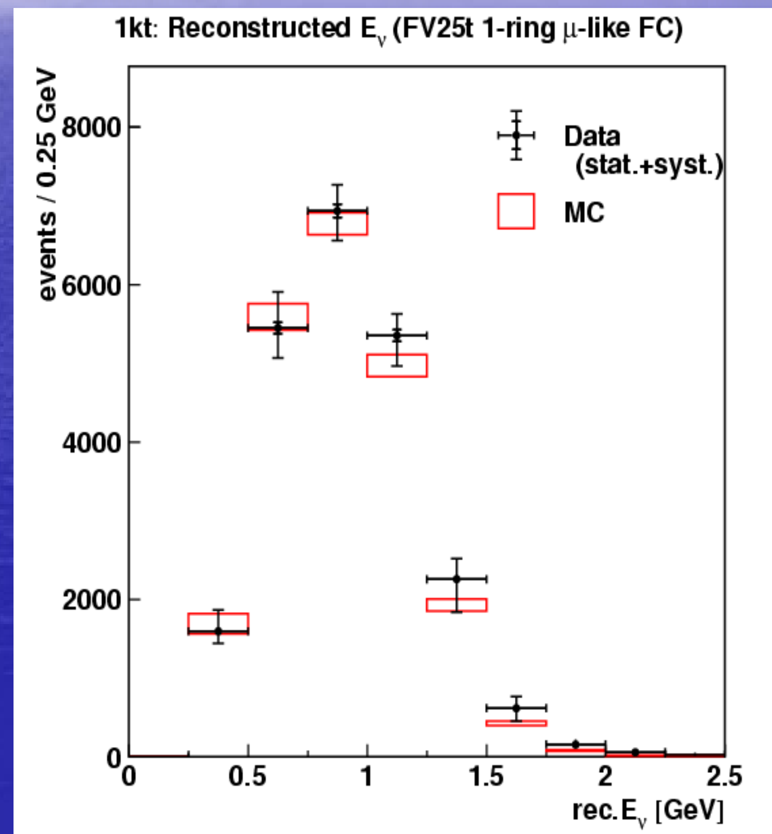
E_ν : 8 bins, nonQE/QE ratio : 1

1kT spectra

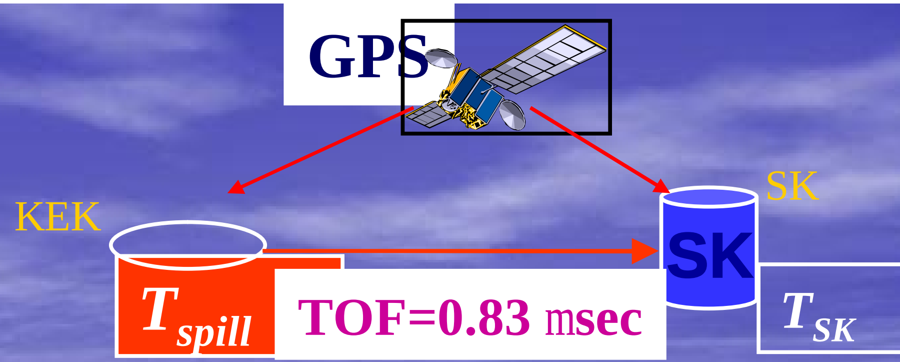
1 ring m-like

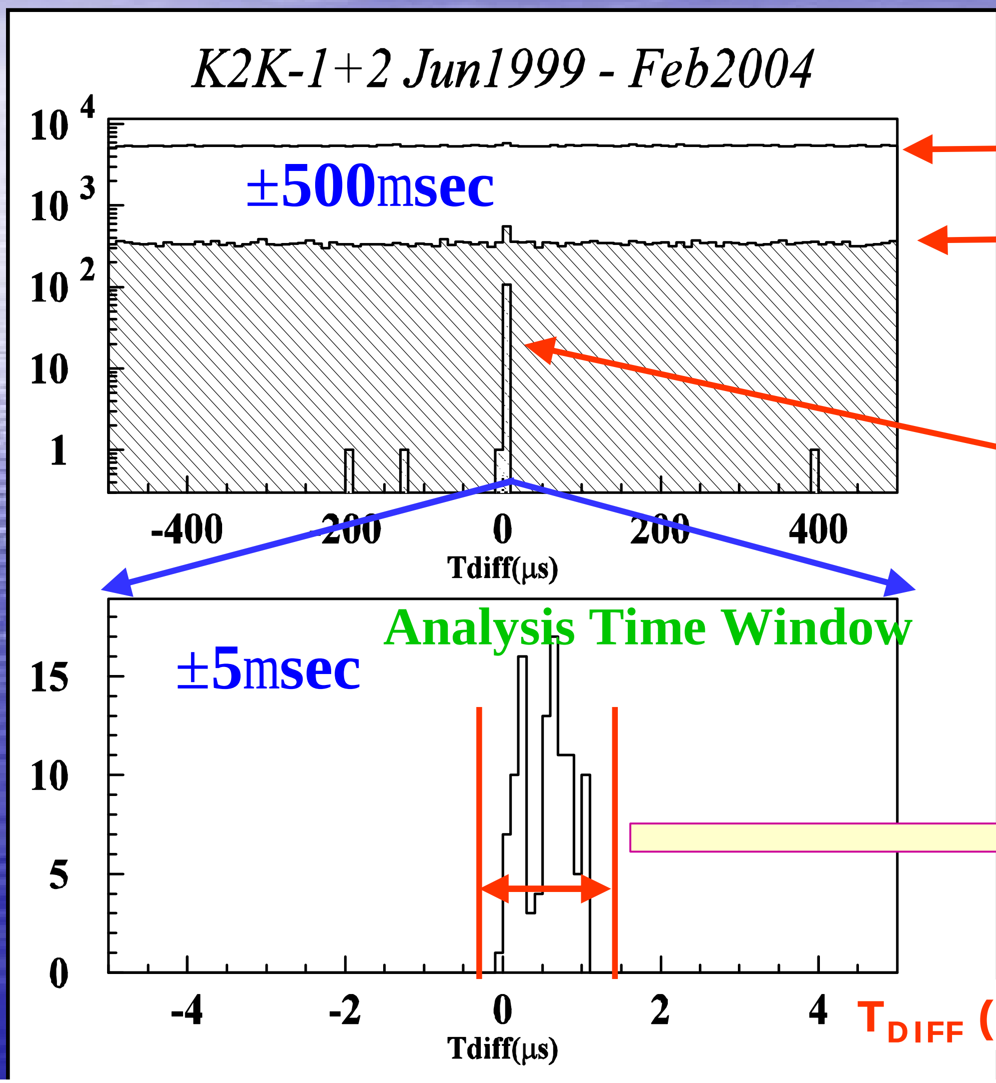


reconstructed neutrino energy



n’s from KEK





Decay electron cut

³20MeV Deposited Energy

No activity in Outer Detector (FV)
Event vertex in fiducial volume (FC)
More than 30MeV deposited energy

$-0.2 < T_{SK} - T_{spill} - TOF < 1.3$msec

(BG: 1.6 events within ±500ms
2.4×10^{-3} events in 1.5ms)

Oscillation analysis

- Total number of FCFV events
- E_n spectrum shape of FCFV 1-ring muon events
- Systematic error term

$$L\,(Dm^2, sin2q\,, f^{\,x}) \;=$$

$$L_{norm}\,(Dm^2, sin2q\,, f^{\,x}) \times L_{shape}\,(Dm^2, sin2q\,, f^{\,x}) \times L_{syst}\,(f^{\,x})$$

Poisson probability for # FCFV events

Shape of E_n spectrum of 1-ring m events

Systematic error

$f^{\,x}$ - systematic error parameters

Normalization, Flux, and nQE/QE ratio are in *f^x*

Events at SK

$$L_{norm}(\Delta m^2, \sin 2\theta, f^x)$$

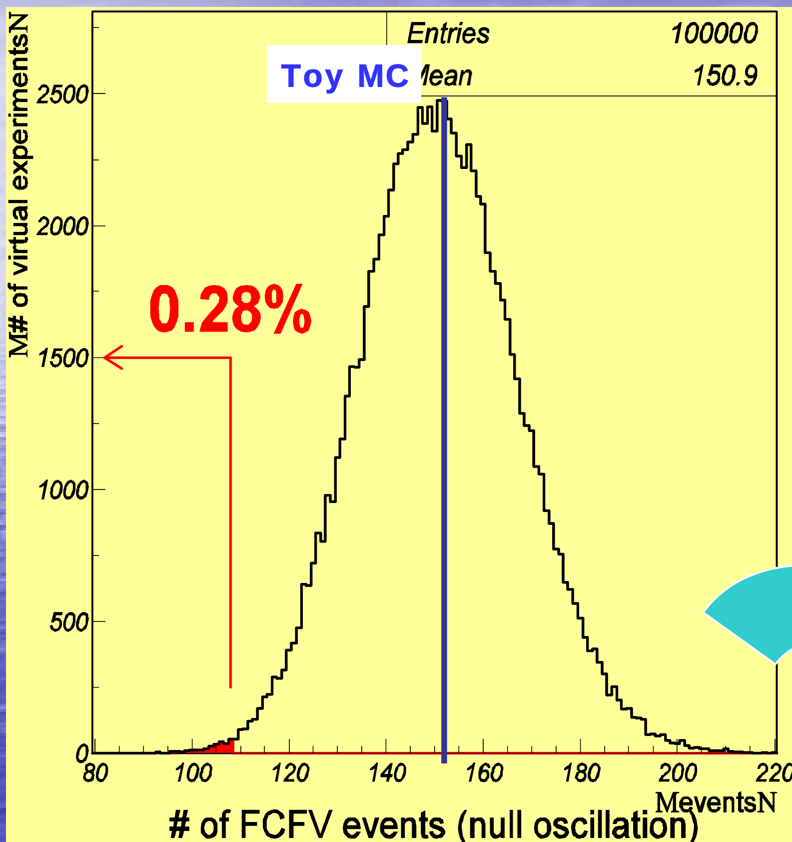
$$L_{norm} = \frac{(N^{exp})^{N^{obs}}}{N^{obs}!} \cdot \exp(-N^{exp})$$

Fully contained events in 22.5 kt fiducial volume of SK

↓

107

#SK Events



107 **150.9**

$N_{SK}^{obs} = 107^{+12}_{-10}$ $N_{SK}^{exp} = 151$

SK Event summary

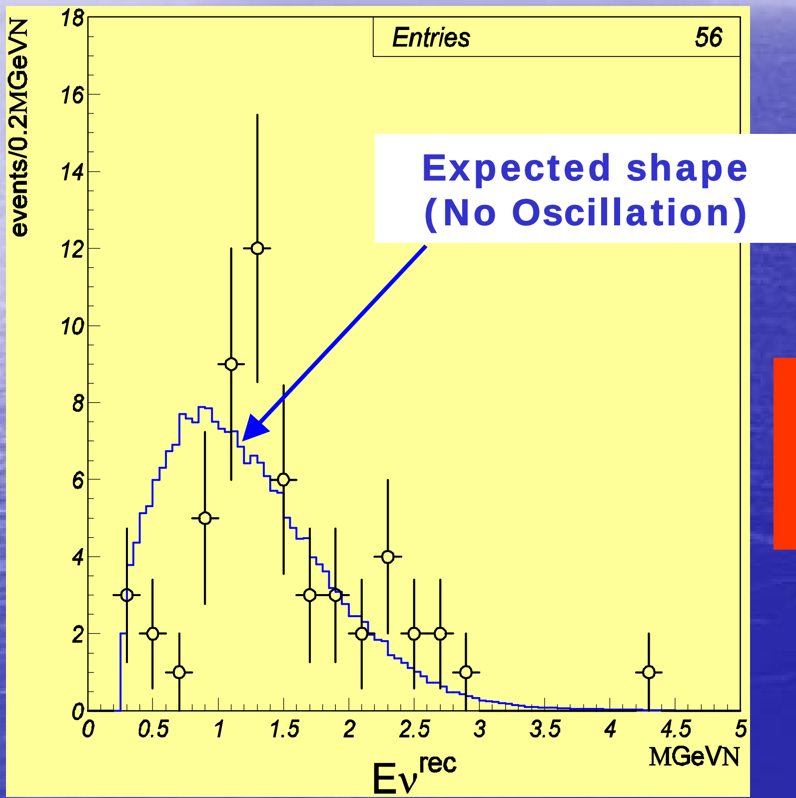
	Data	MC
1-ring μ-like	57	85.5
1-ring e-like	9	8.7
Multi-ring	40	56.7
Total	**107**	**150.9**

Only number of events

No oscillation probability = 0.28%

Shape analysis

$$L_{shape}(\Delta m^2, \sin 2q, f^x)$$

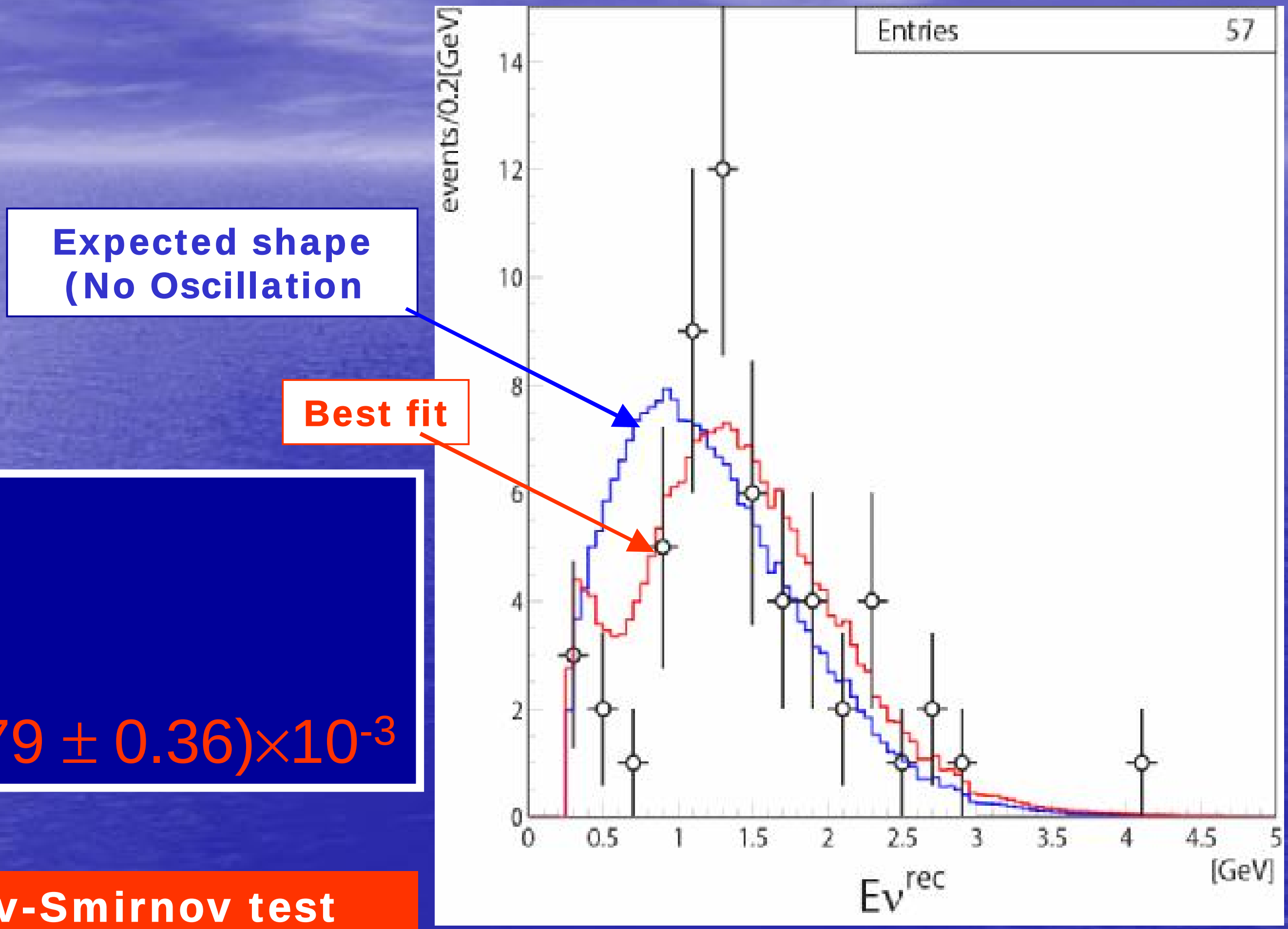


CC-QE assumption

$$E_n^{rec} = \frac{(m_N - V)E_m - m_m^2/2 + m_N V - V^2/2}{(m_N - V) - E_m + p_m \cos q_m}$$

Only shape
Kolmogorov-Smirnov test
No oscillation probability = 0.74%

Shape distortion



Best fit value

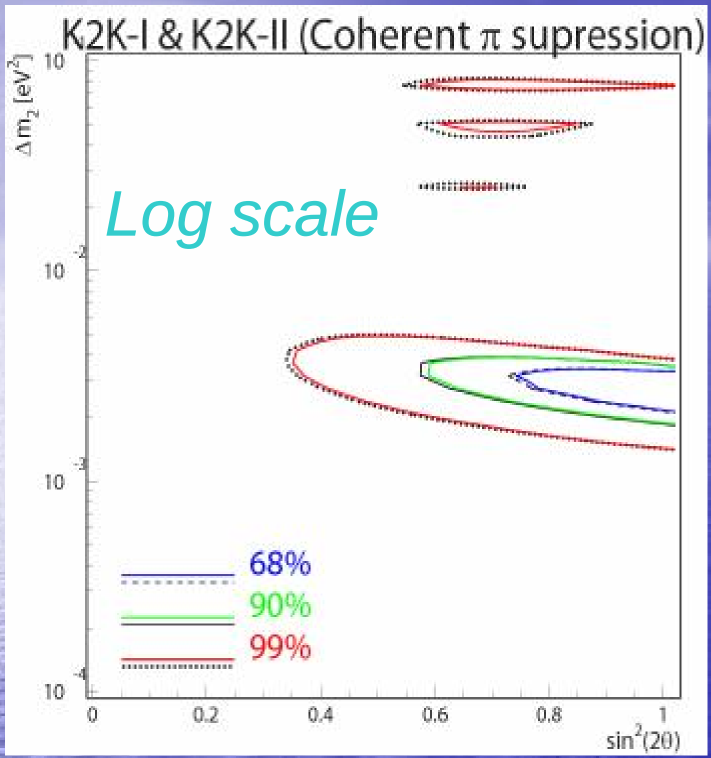
$\sin^2 2\theta = 1.00$

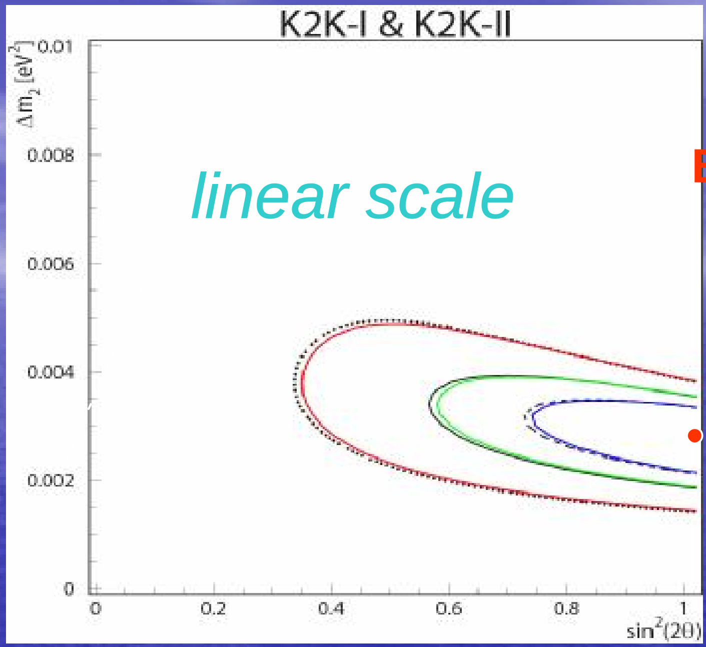
$\Delta m^2\,[\mathrm{eV}^2] = (2.79 \pm 0.36)\times 10^{-3}$

Kolmogorov-Smirnov test

Best fit probability = 36%

Allowed region of oscillating parameters



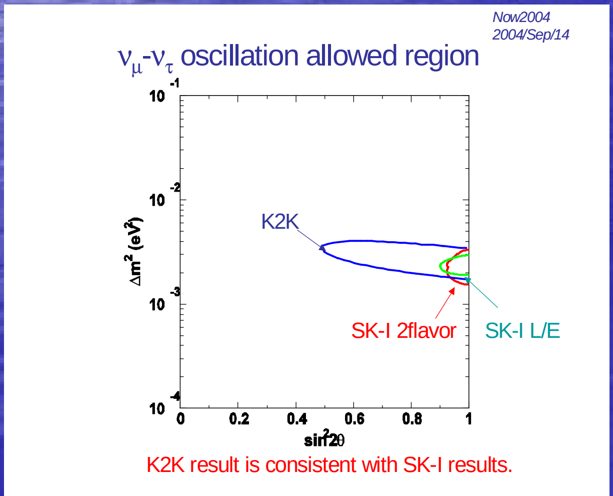


Best fit point
2.8×10^{-3}

Allowed region of Δm^2 @ $\sin^2 2\theta = 1$

1.99 ~ 3.33 [eV^2] (68%)

1.9 ~ 3.6 [eV^2] (90%)



Null Oscillation probability
0.0050%(4.06σ)

Evidence of ν_μ oscillation in K2K experiment

Search for n_m ® n_e oscillation

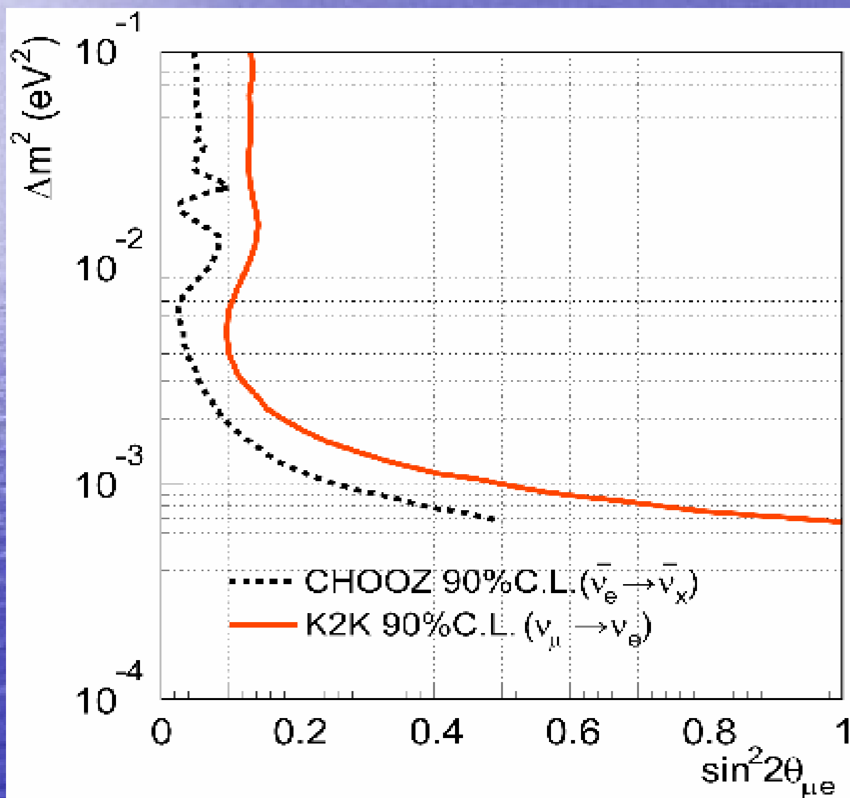
–K2K-1–	ν_μ MC	beam ν_e	Data
FCFV	81.1	0.81	55
Single ring	50.92	0.47	33
Electron like	2.66	0.40	3
Evis > 100 MeV	2.47	0.40	2
No decay-e	1.90	0.35	1
Pi0 cut	0.58	0.17	0

–K2K-2–	ν_μ MC	beam ν	Data
FCFV	77.4	0.86	57
Single ring	49.41	0.52	34
Electron like	3.21	0.44	5
Evis > 100 MeV	2.93	0.44	5
No decay-e	2.17	0.39	4
Pi0 cut	0.74	0.21	1

In total,
#expected BG = 1.70
#observed = 1

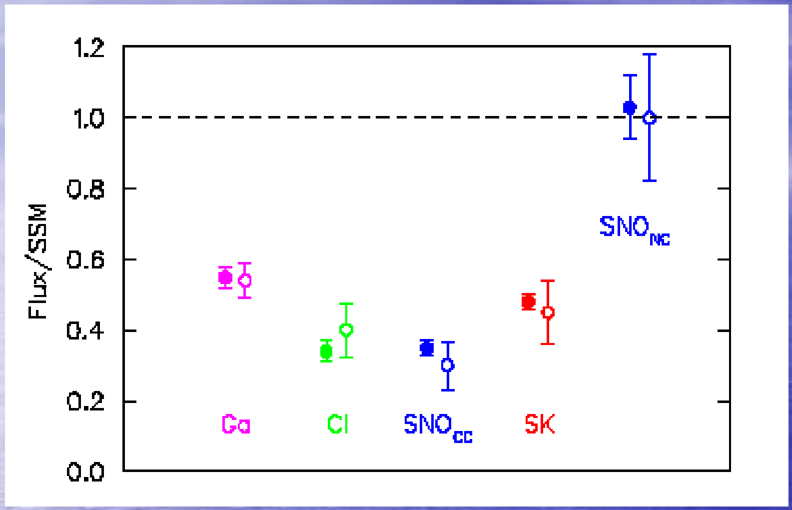
n_m --> n_e

Δm^2 vs. $\sin^2 2\theta_{\mu e}$



Assumption: $2\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{13}$

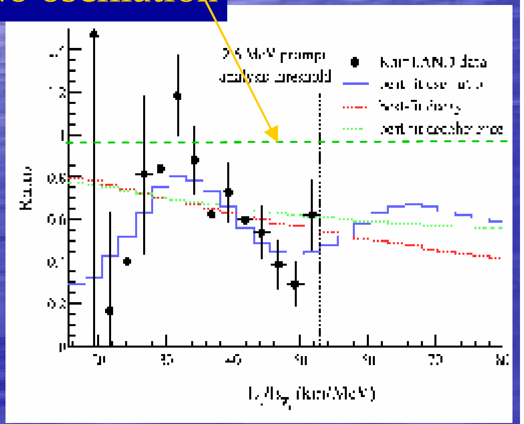
Evidence of neutrino oscillations

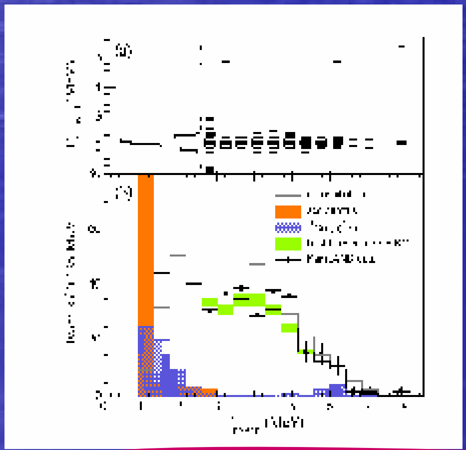


solar

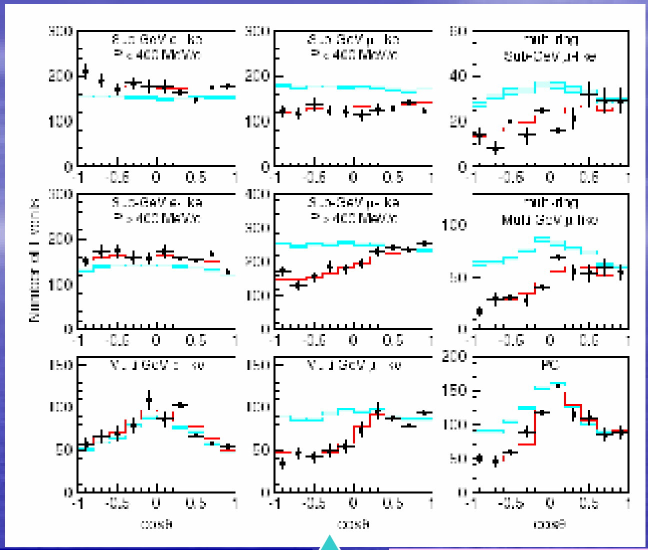
$\Delta m^2 \sim (7\text{-}8) \times 10^{-5}\ eV^2$

No oscillation





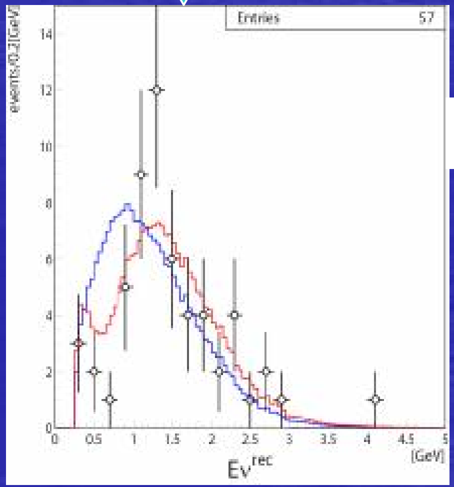
Kamland



SK

atmosferic

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



K2K

LSND à Dm^2 = 0.2 – 10 eV^2 à m$_n$ > 0.4 eV

Neutrino masses and mixings

3 families

Oscillation parameters

	central value	3σ interval
Δm^2_{12} (10^{-5} eV^2)	7.9	7.1 - 8.9
Δm^2_{31} (10^{-3}eV^2)	2.2	1.4 - 3.3
$\sin^2\theta_{12}$	0.31	0.24 - 0.40
$\sin^2\theta_{23}$	0.50	0.34 - 0.68
$\sin^2\theta_{13}$	0.0	<0.047

LSND → $\Delta m^2 = 0.2 - 10$ eV^2 → $m_\nu > 0.4$ eV

Mixing	Quarks	Leptons
1-2 θ_{12}	13º	33º
2-3 θ_{23}	2.3º	45º
1-3 θ_{13}	~ 0.5º	<13º

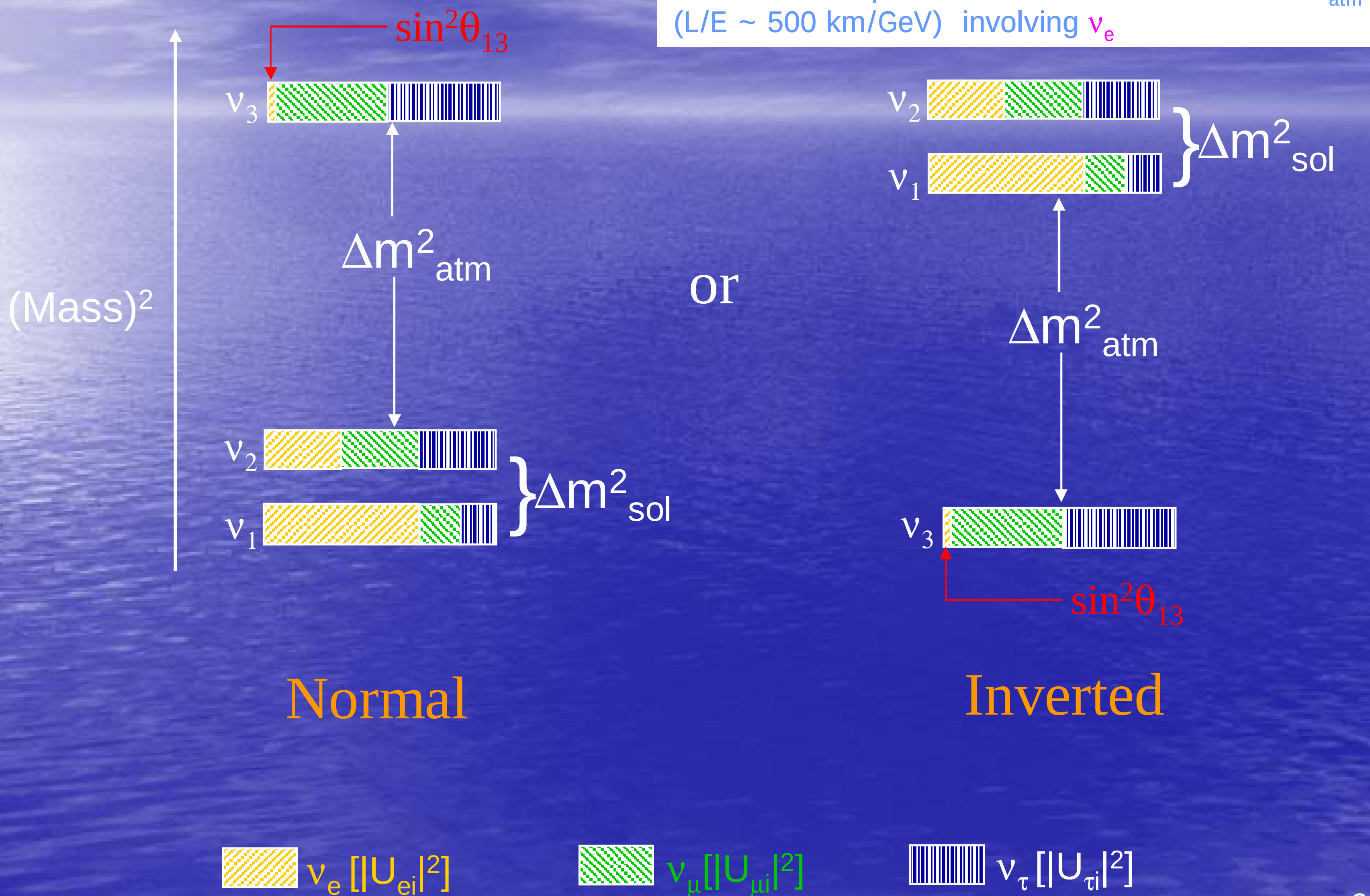
Challenges in neutrino physics

- value of θ_{13} ← reactor
- CP violation in lepton sector
- mass spectrum: normal or inverted
- neutrino mass ← Tritium experiment
- Majorana/Dirac nature ← $0\nu\beta\beta$

LBL accelerator experiments (value of θ_{13}, CP violation in lepton sector, mass spectrum)

Mass spectrum

$\sin^2\theta_{13} = |U_{e3}|^2 \rightarrow$ small ν_e piece of ν_3
ν_3 is at one end of Δm^2_{atm}
We need an experiment with L/E sensitive to Δm^2_{atm}
(L/E ~ 500 km/GeV) involving ν_e



Test of discrete symmetries

$$P(\nu_a \to \nu_b) \neq P(\bar{\nu}_b \to \bar{\nu}_a)$$
$$P(\nu_a \to \nu_a) \neq P(\bar{\nu}_a \to \bar{\nu}_a)$$

CPT violation

$$P(\nu_a \to \nu_b) \neq P(\bar{\nu}_a \to \bar{\nu}_b)$$

CP violation

$$P(\nu_a \to \nu_b) \neq P(\bar{\nu}_b \to \bar{\nu}_a)$$

T violation

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

For $\theta_{12}=\pi/8$ $\Delta m^2_{12}=7\times10^{-5}$ $\sin^2\theta_{12}=0.01$ (1/10 of CHOOZE limit) $\theta = \pi/4$

A_{CP} = 25%

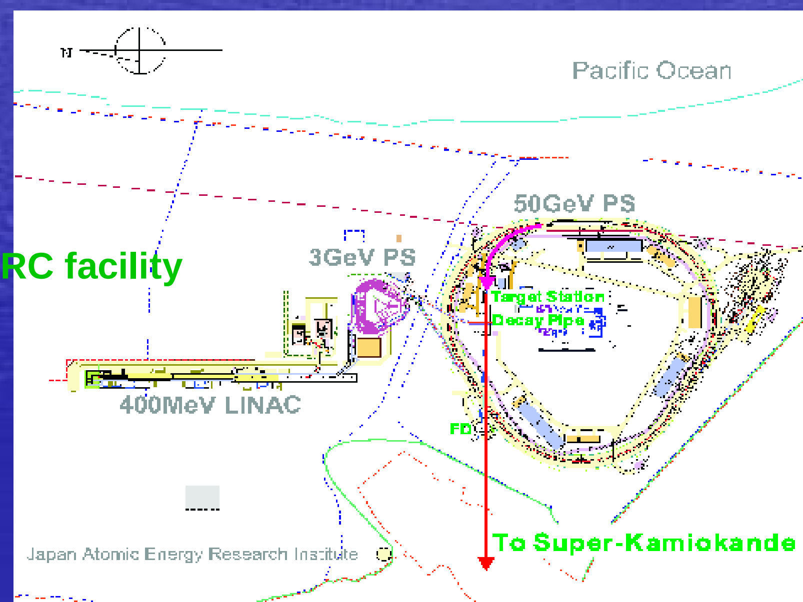
LBL experiment T2K (Tokai to Kamioka)

12 countries, 60 institutions, ~180 collaborators

ν beam off-axis on-axis

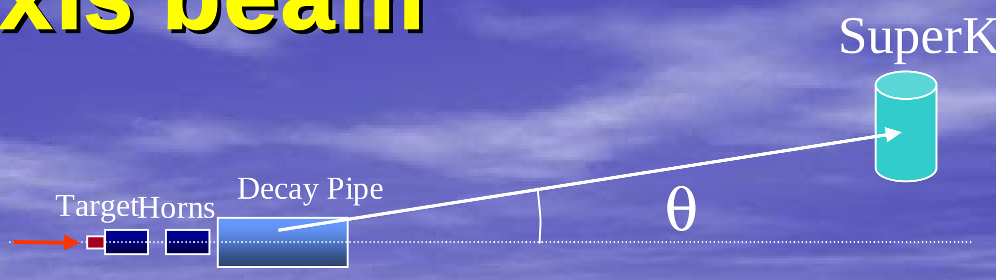
	JPARC	MINOS	K2K
E(GeV)	50	120	12
Int(10^{12}ppp)	330	40	6
Rate (Hz)	0.29	0.53	0.45
Power (MW)	0.77	0.41	0.0052

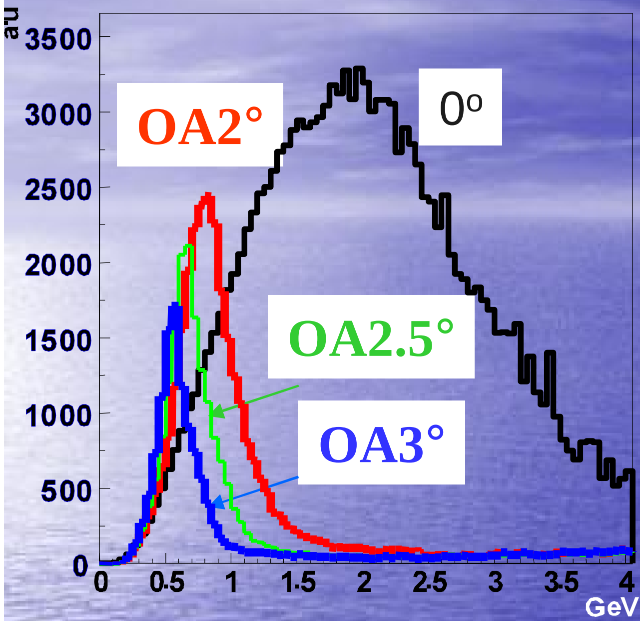
JPARC facility

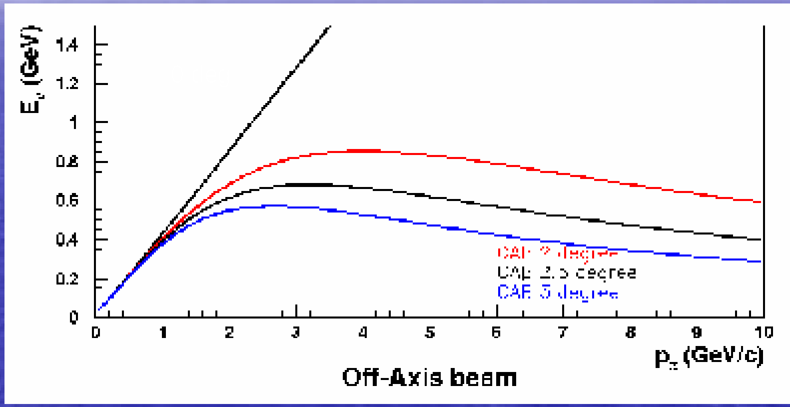


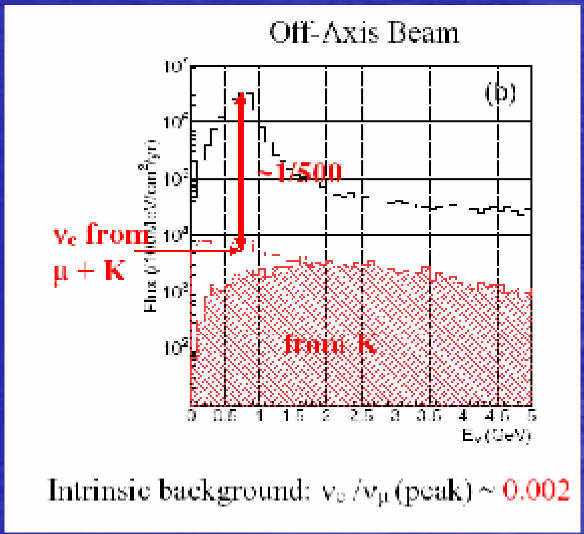
~1GeV ν_μ beam (×100 of K2K)

Off-axis beam









Statistics at SK

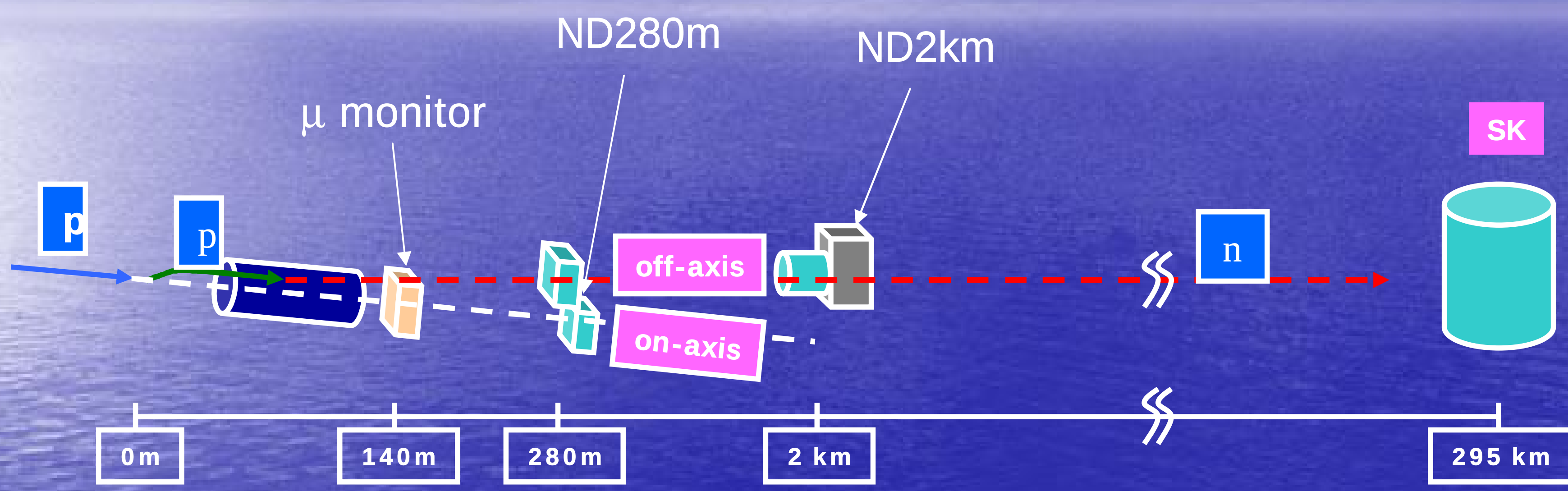
OAB 2.5 deg, 1 yr = 10^{21} POT, 22.5 kt

~ 2200 n_m tot

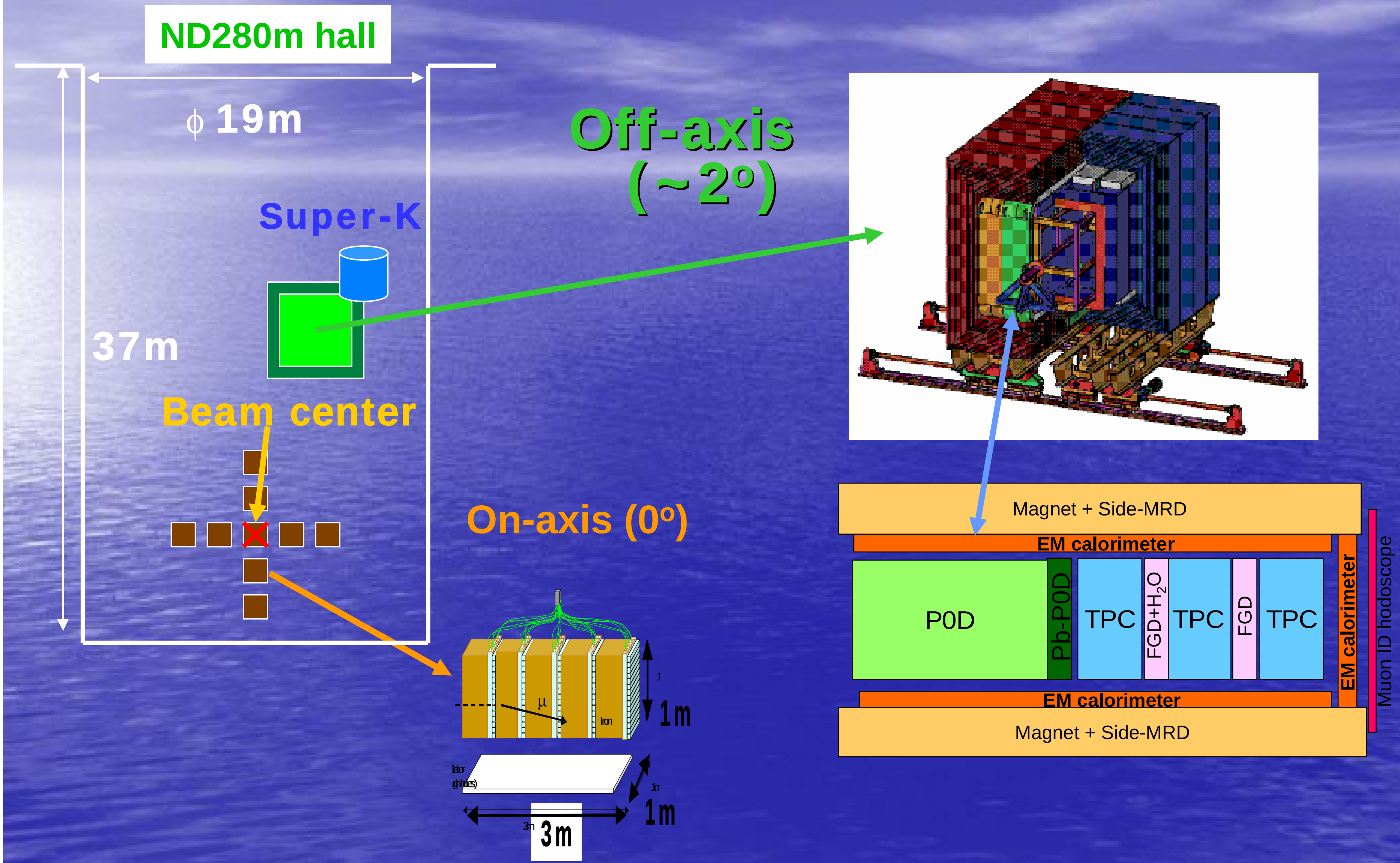
~ 1600 n_m charged current

n_e < 0.5% at n_m peak

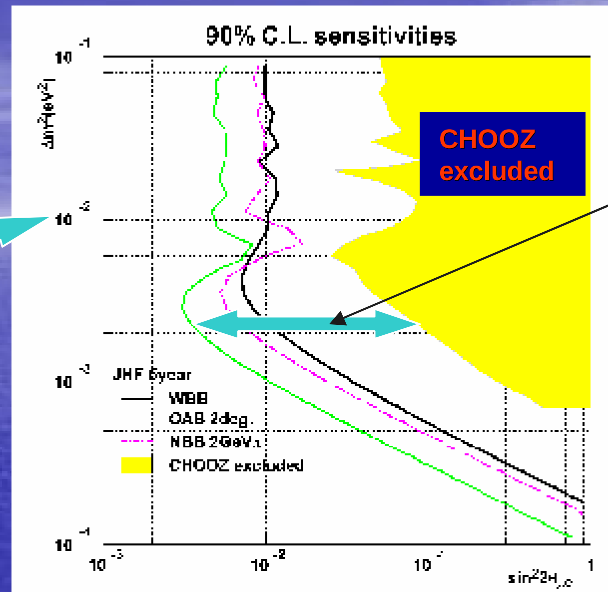
T2K detectors



Near Detectors at 280m

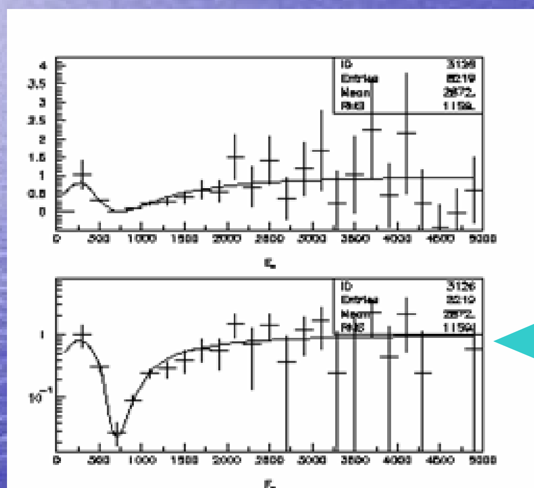


Principle Goals of T2K



Improvement by 20 times

- Search for ν_e appearance
  θ_{13} sensitivity $\leq 1^o$ (90 % c.l.)



- Measurement Δm^2_{23} with accuracy of 1 %
  $\delta(\sin^2 2\theta_{23}) \sim 0.01$
  $\delta(\Delta m^2_{23}) < 1 \times 10^{-4}$ eV^2

- Confirmation of $\nu_\mu \rightarrow \nu_\tau$ oscillation

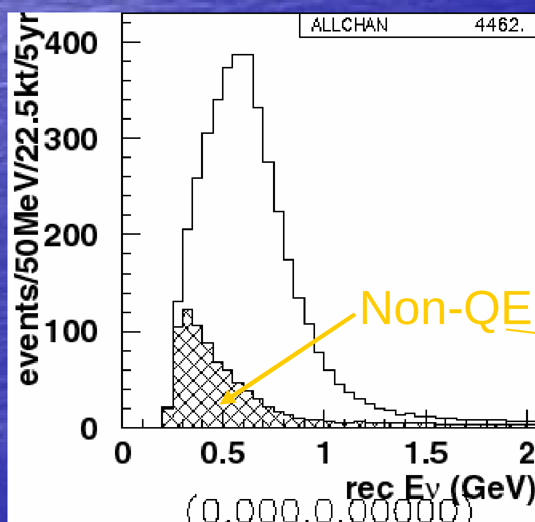
Number of n events at SK for 5 years

Off-axis (deg)	w/o oscillation (events/22.5kt/5yr)	max. deficit (events/22.5kt/5yr)	Δm^2 (eV^2)
2.0	6683	1724	3.22×10^{-3}
2.5	4462	1103	2.70×10^{-3}
3.0	3006	752	2.33×10^{-3}

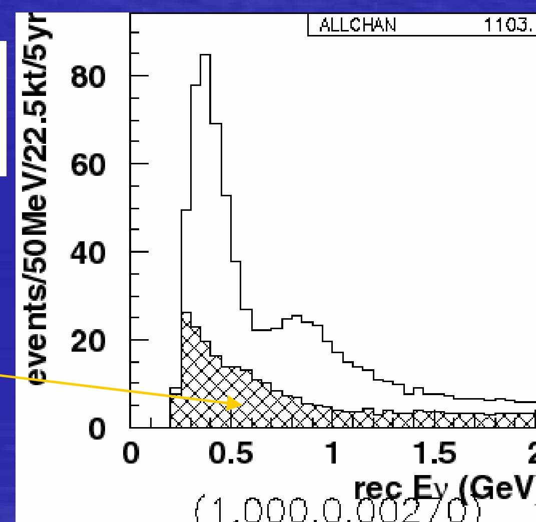
($\sin^2 2\theta=1$)

Reconstructed Eν spectrum at SK (OA2.5deg)

no oscillation



($\sin^2 2\theta$, Δm^2) =(1.0, 0.0027)



LBL experiments

2006 -08

MINOS (FNAL)

n_m ® n_m **search for** n_m ® n_e

OPERA (CERN/Gran Sasso)

search for n_m ® n_t **appearance**

MiniBooNe(FNAL)

LSND anomaly

2009....

T2K Phase I

search for n_m ® n_e **appearance/** q_{13} **measurement**

Phase II depends on q_{13}

CP – violation, if q_{13} ¹ **0**

NOVA (FNAL)

CP – violation, mass hierarchy

Summary

- Neutrinos have masses
- Clear signal of New Physics beyond the Standard Model
(Solar, atmospheric, accelerator experiments)

- Exciting physics from
running and future long base-line experiments

- **search / measurement of q_{13} $|U_{e3}|$ = ?**
- precision measurements of θ_{23} and Δm^2_{23}
- CP violation if θ_{13} is large
- mass hierarchy

- Unexpected or exotic properties?