Recent results from Atmospheric ν and K2K

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Super- Kamiokande and K2K experiment

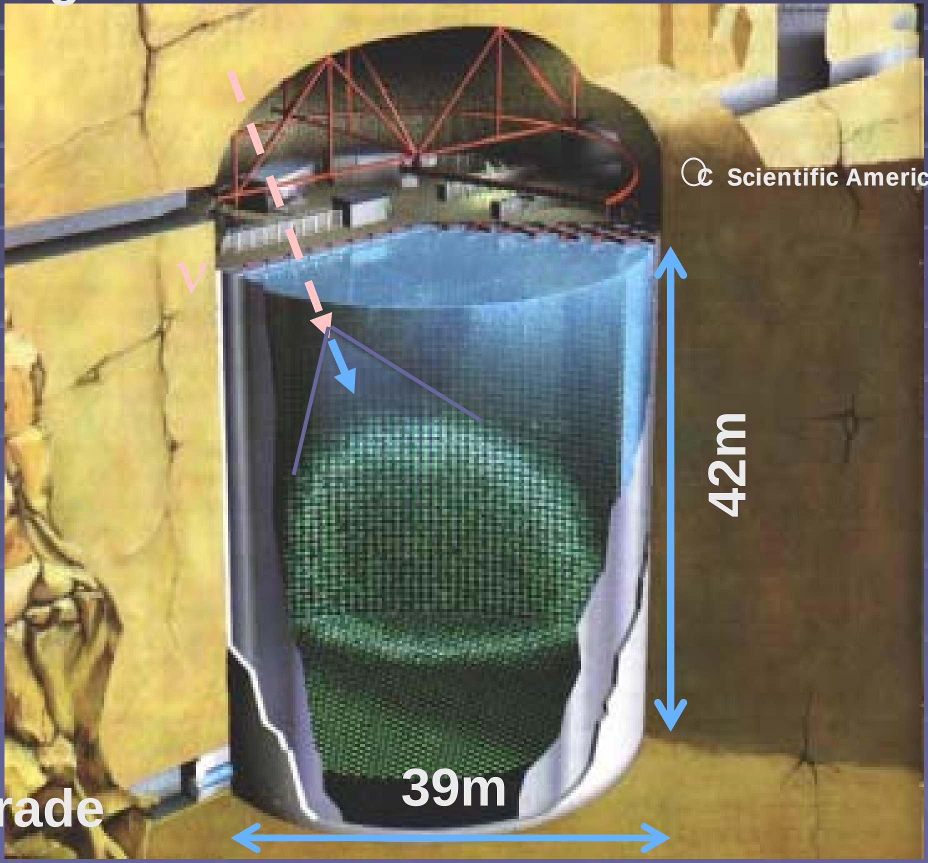
SK- I

K2K-I

- 1996.4 Start data taking

World Largest
Water Cherenkov detector

- 1000 m underground
- 50,000 ton
  (22,500 ton fid.)
- 11,146 20 inch PMTs
- 1,885 anti-counter PMTs



- 1999.3 K2K start
- 2001.7 Detector upgrade
- 2001.11 Accident

  partial reconstruction of the detector

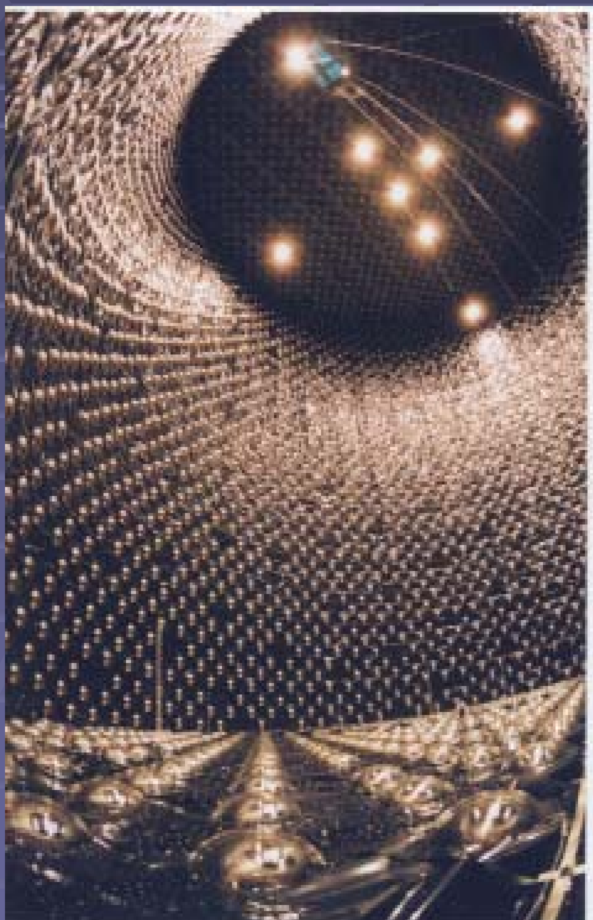
- 2002.10 resume data taking
- 2002.12 resume K2K beam

SK- II

K2K-II

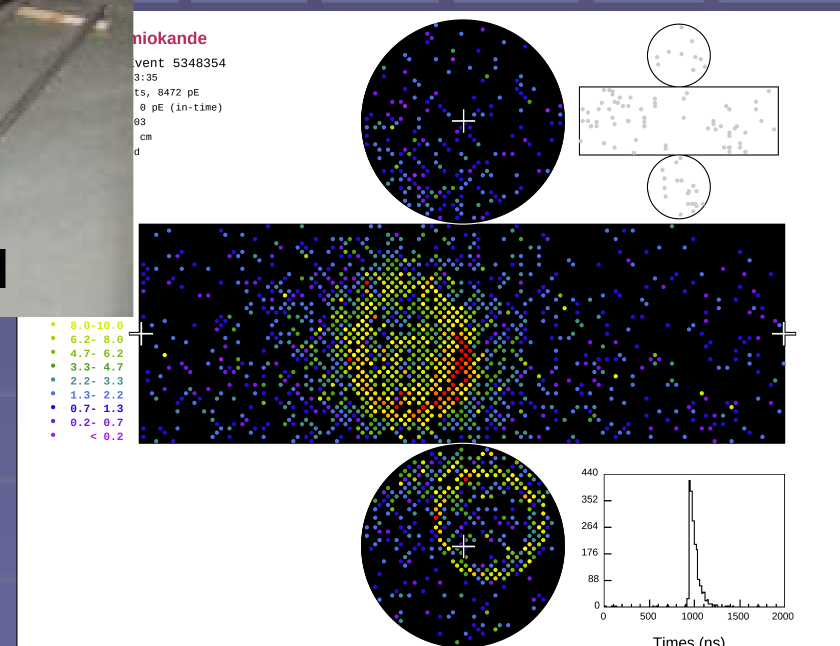
SK is back !

Full water on 10-Dec.-2002



Sep.-2002, before water filling

Jan.-2003, fully contained event



Outline of this talk

- Atmospheric results from SK-I
  - Entire re-analysis with new ν-flux, ν-int model.
- K2K-I results
  - ν_μ disappearance
  - ν_e appearance search
  - Study ν interaction
- Status of SK-II / K2K-II

Neutrino oscillation

Two neutrino case

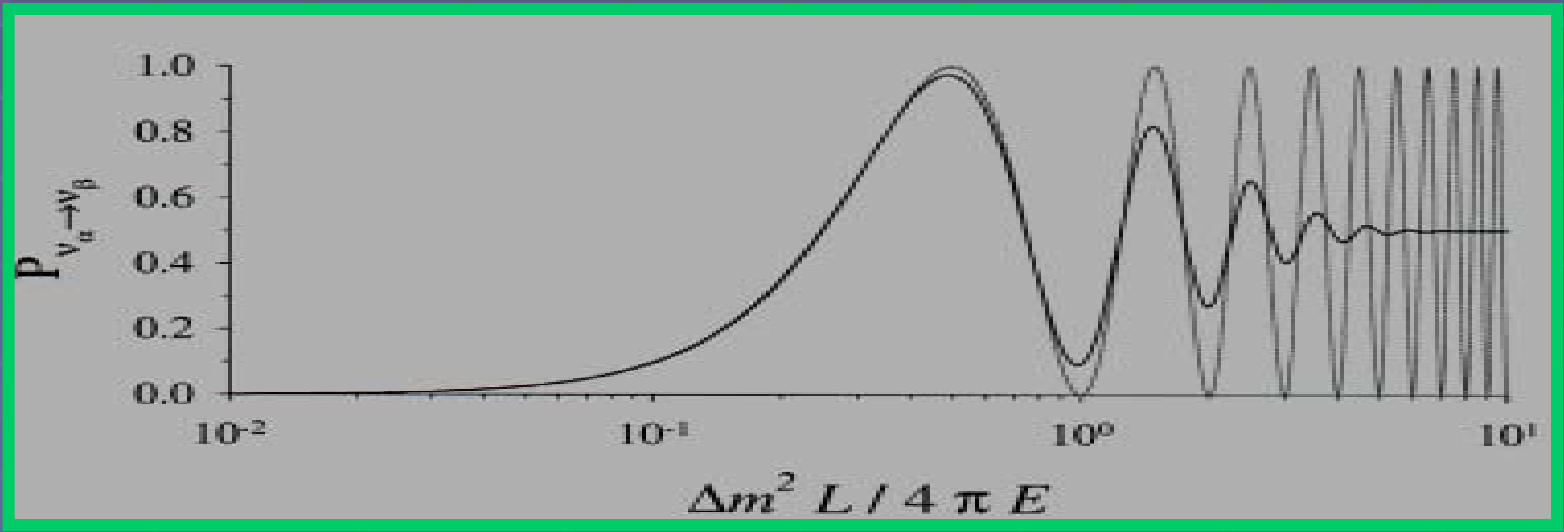
$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 L/E)$$

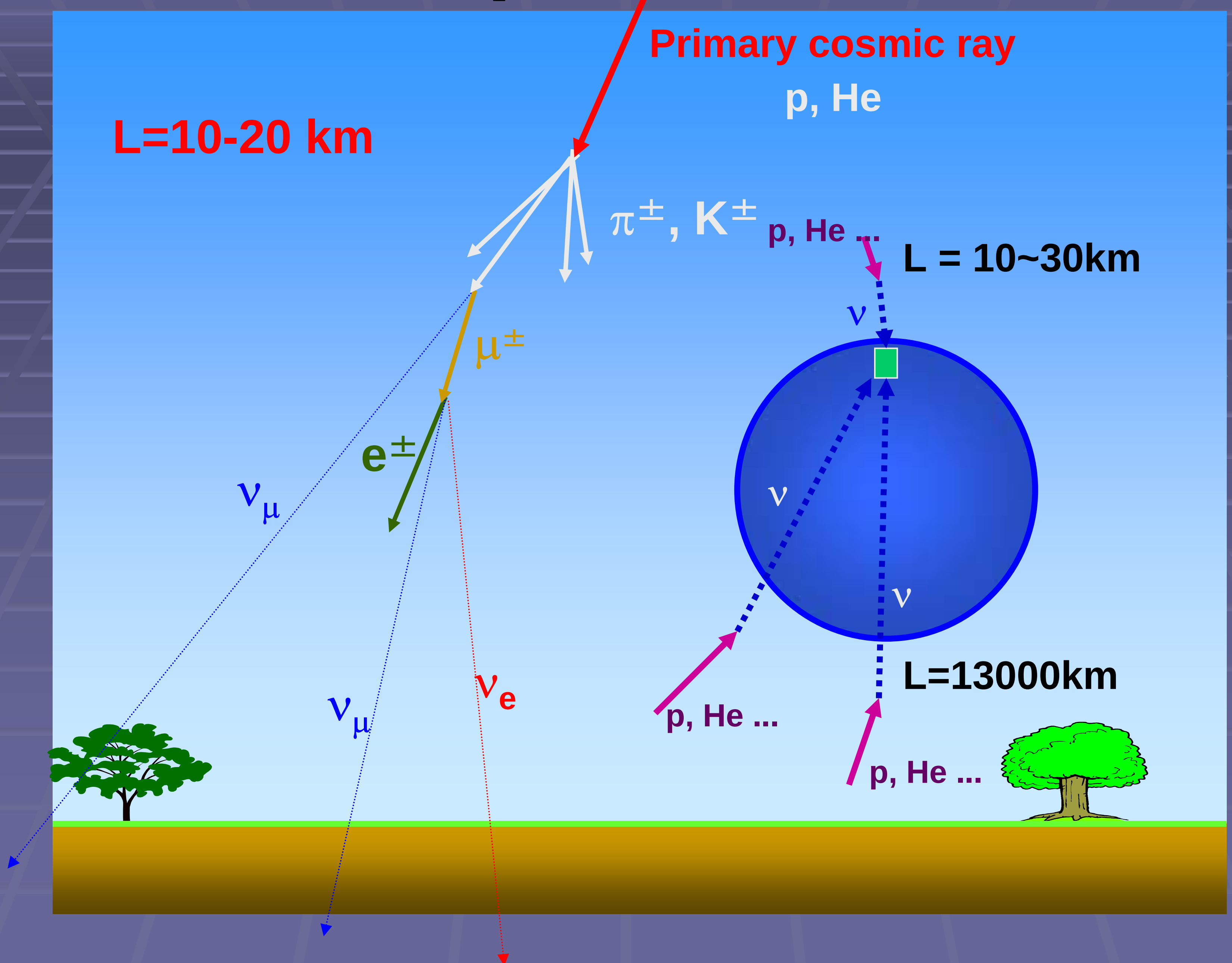
$\Delta m^2 = m_2^2 - m_1^2$ (eV^2)

L (km): Distance from source to detector

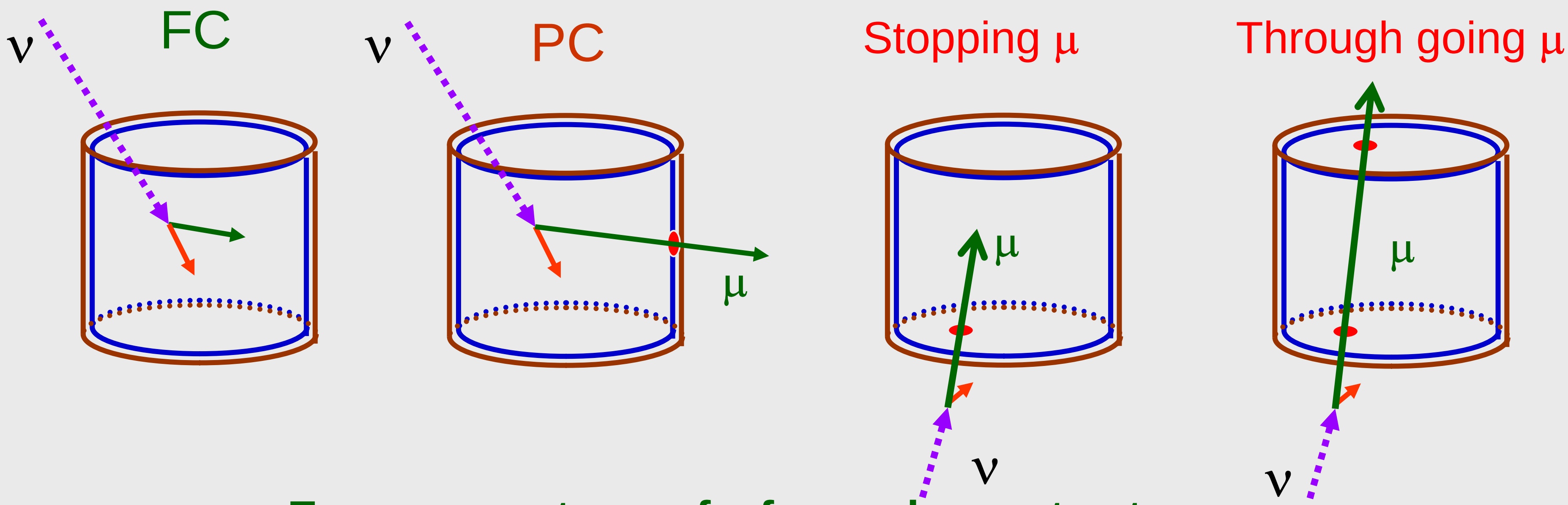
E (GeV): Neutrino energy



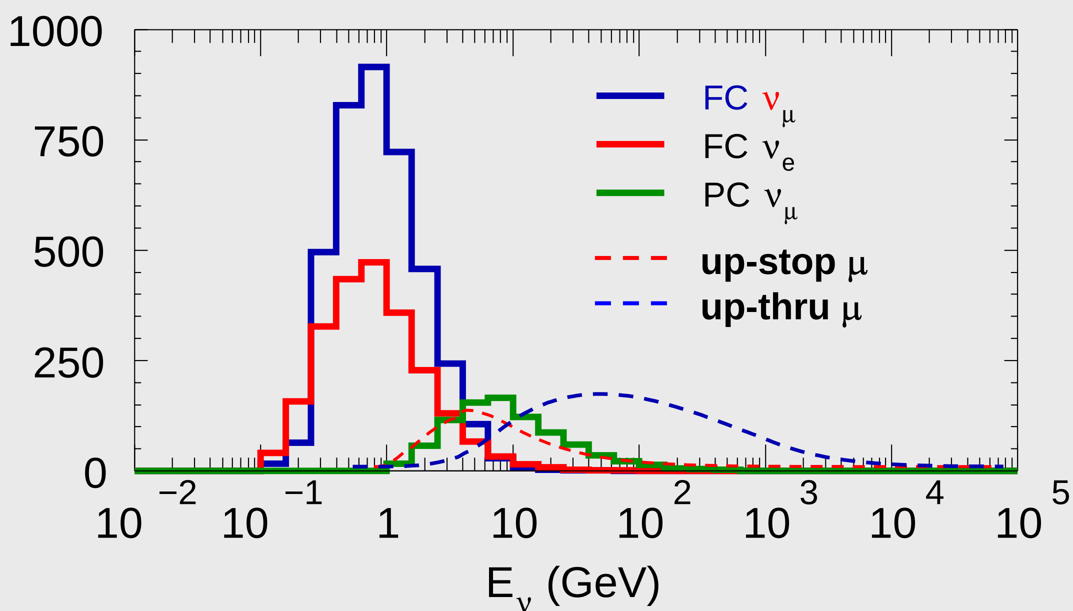
Atmospheric neutrinos



Atmospheric ν categories at SK



Energy spectrum of ν for each event category



Summary of SK-I contained events

Preliminary!

Sub-GeV (Fully Contained)

E_{vis} < 1.33 GeV,
P_e > 100 MeV, P_μ > 200 MeV

		Data	MC(Honda)
1ring	e-like	3353	3013.9
	μ-like	3227	4466.9
Multi ring		2361	2959.0
	(μ-like)	(208)	(346.4)
Total		8941	10439.8

$$\frac{(\mu/e)_{data}}{(\mu/e)_{MC}} = 0.649^{+0.016}_{-0.016} \pm 0.051$$

Multi-GeV

Fully Contained (E_{vis} > 1.3 GeV)

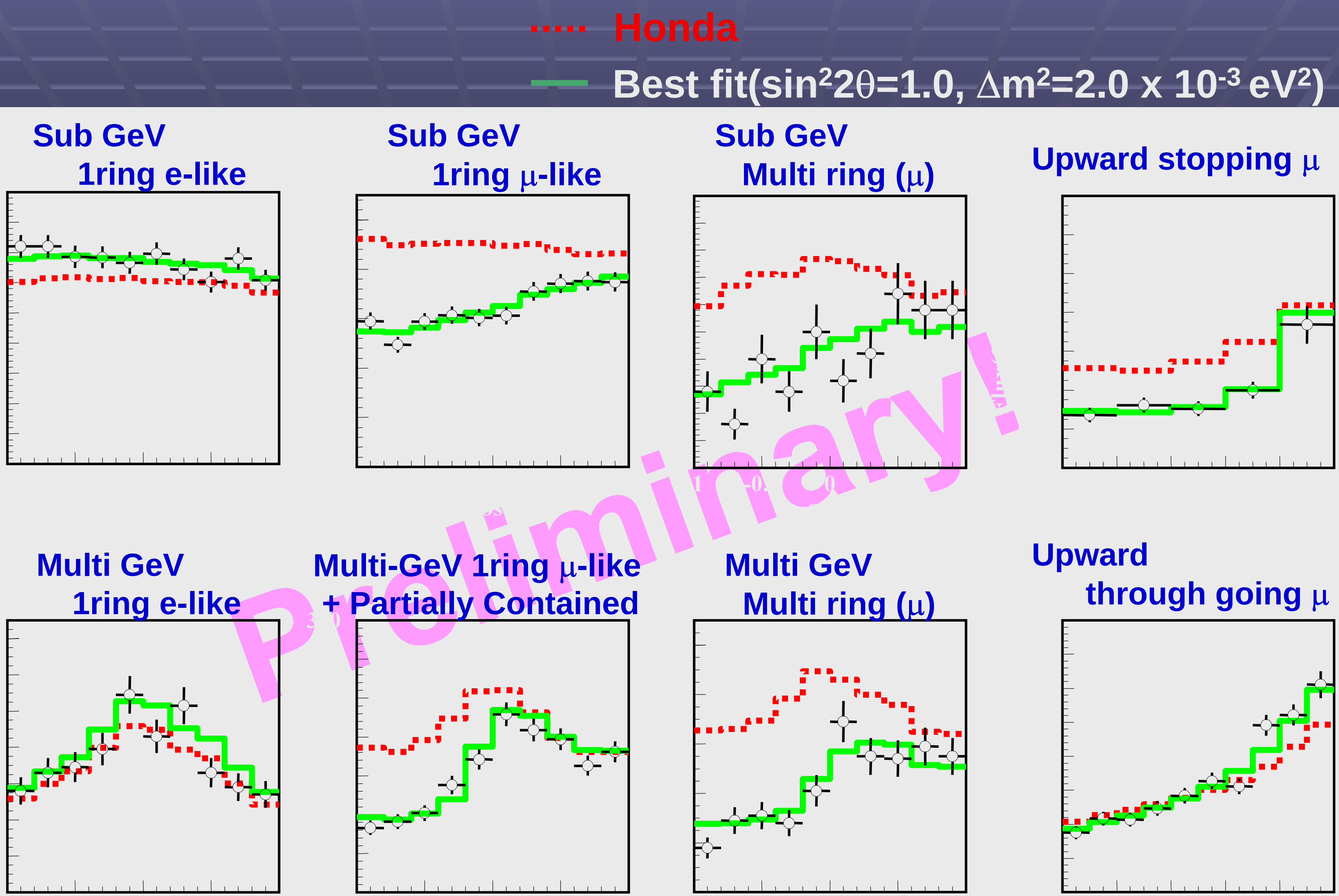
		Data	MC(Honda)
1ring	e-like	746	700.4
	μ-like	651	948.2
Multi ring		1504	1944.6
	(μ-like)	(439)	(739.4)
Total		2901	3593.2

Partially Contained (assigned as μ-like)

	Data	MC(Honda)
Total	913	1149.8

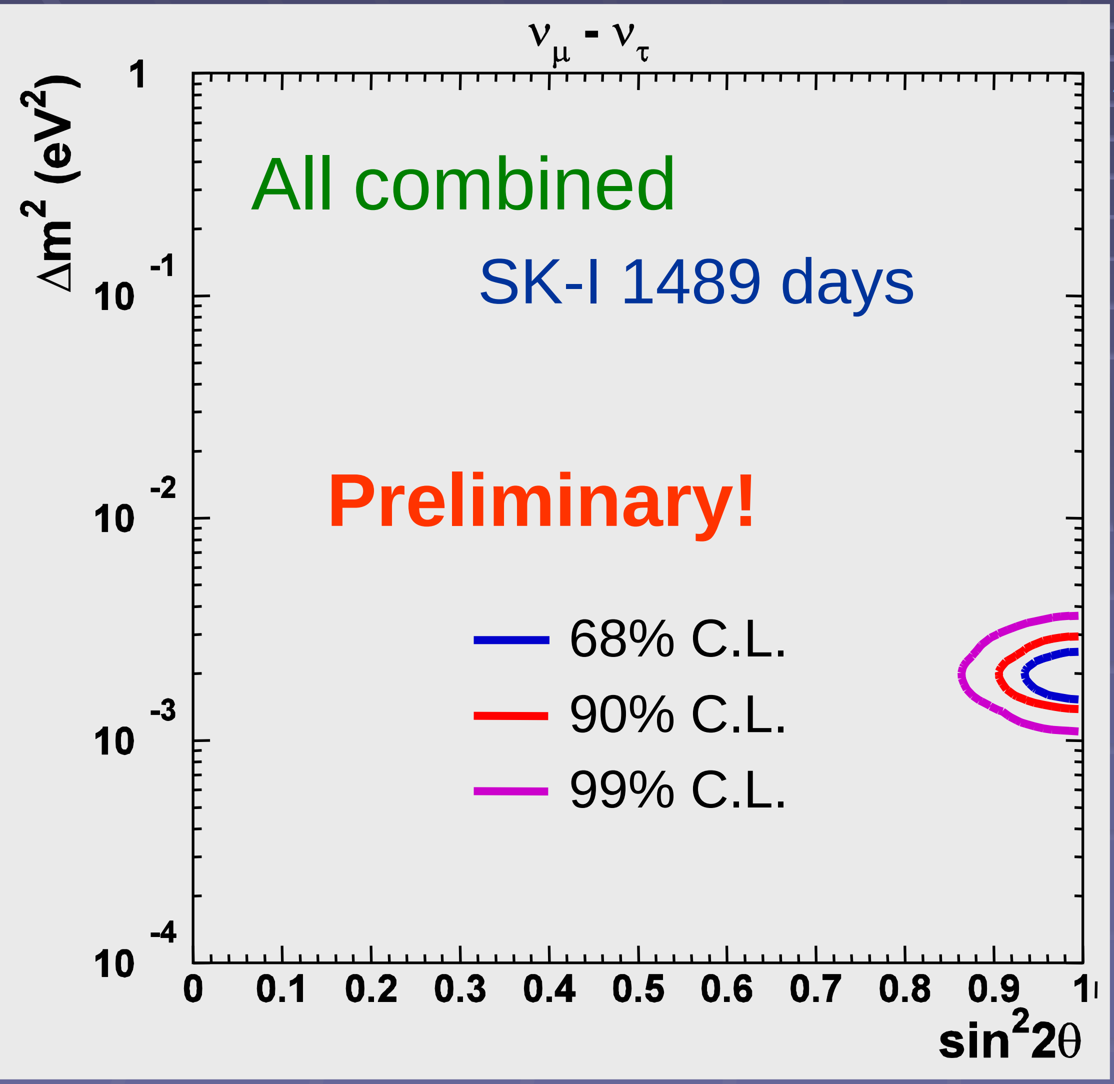
$$\frac{(\mu/e)_{data}}{(\mu/e)_{MC}} = 0.700^{+0.032}_{-0.030} \pm 0.083$$

Atmospheric ν zenith angle distribution



Allowed region of the oscillation parameters (subGeV+multiGeV+PC+MultiRing+Upμ)

(complete SK-I data set)



Assuming $\nu_\mu \leftrightarrow \nu_\tau$ oscillation

Best fit

χ^2_{min} = 170.8/170 d.o.f.

at ($\sin^2 2\theta$, Δm^2)

= (1.0,2.0 x 10^{-3} eV^2)

90% confidence level allowed region

$\sin^2 2\theta > 0.9$

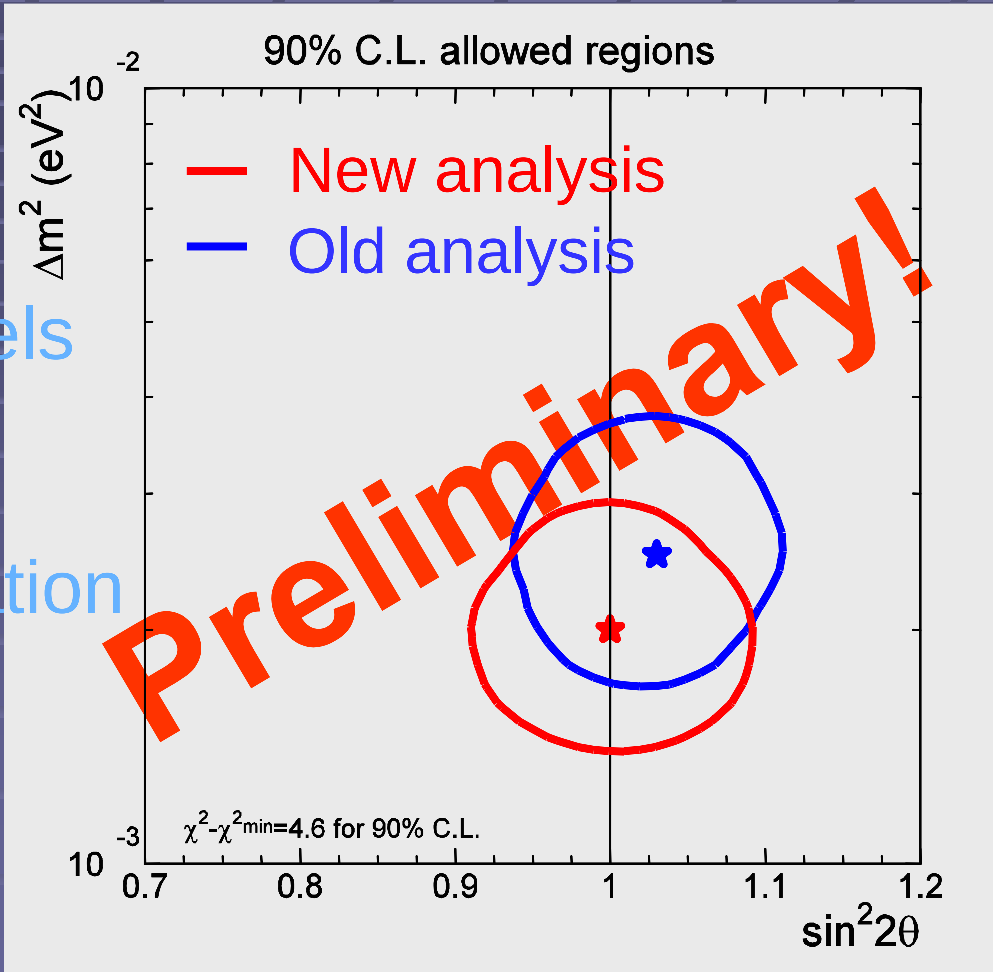
$1.3\times10^{-3} < \Delta m^2 < 3.0\times10^{-3}$ (eV^2)

Assuming null oscillation

χ^2 = 445.2/172 d.o.f.

Comparison between old and new results

- Neutrino flux
  (Honda 1995 → Honda 2001)
- Neutrino interaction models
  (several improvements, agree with K2K near data)
- Improved detector simulation
- Improved event reconstruction tools



Each change slightly shifted the allowed region to lower Δm^2

Evidence for ν_μ-ν_τ

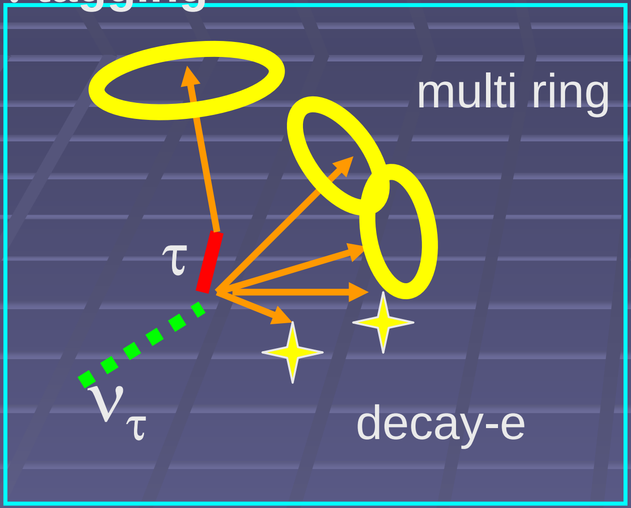
- Search for ν_τ-cc like events
  - Multi-GeV e-like multi ring events
  - τ-likelihood
- Search for mixing supression by Matter effect

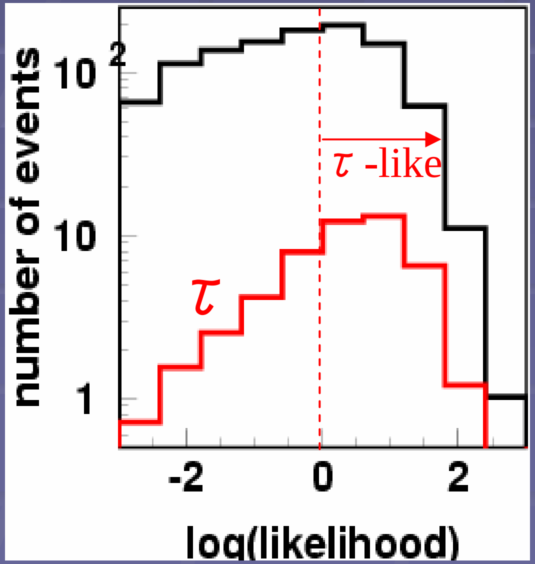
- Absolute NC rate by NC1π^0
  - Use π^0 rate measurement at K2K 1kt detector

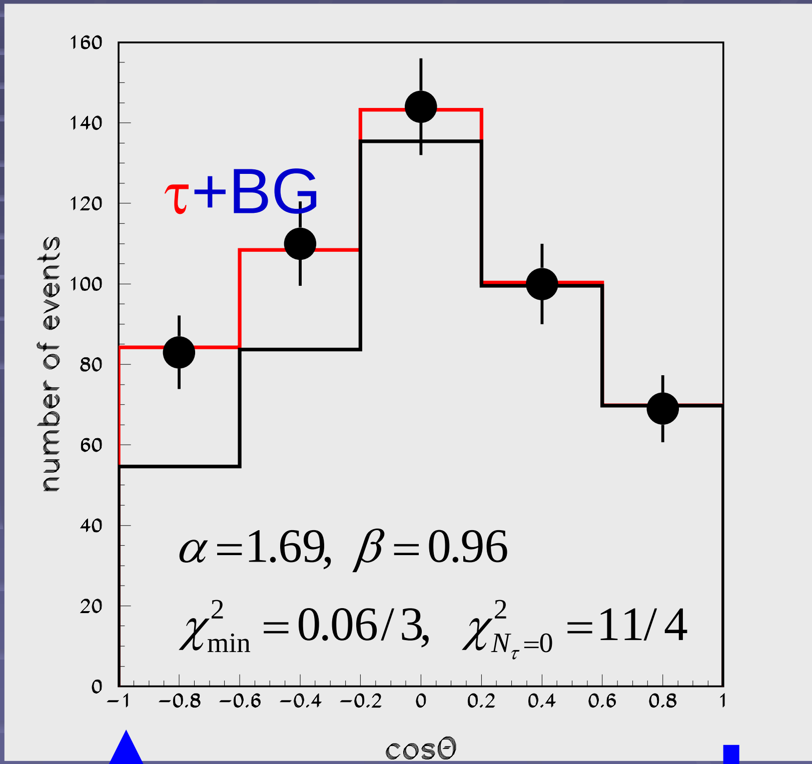
zenith angle dist. of cc τ-enhanced sample

τ–like selection; effτ=44%, S/N=8%

cc-τ tagging







Consistent with $\nu_\mu \leftrightarrow \nu_\tau$

$$N\tau = 145 \pm 44(stat)^{+11}_{-16}(sys)$$

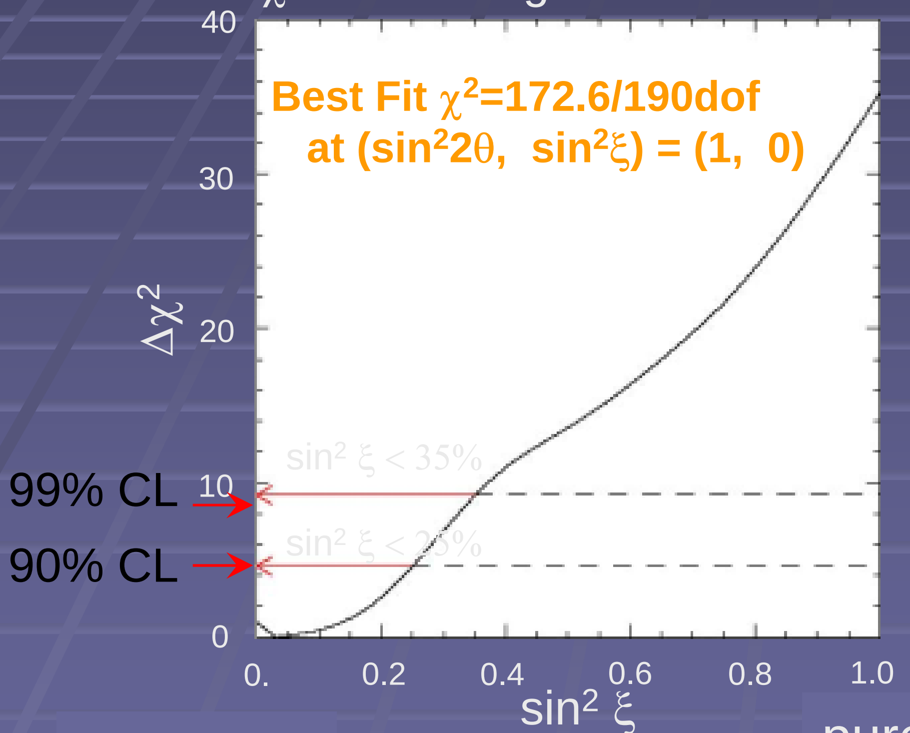
(86 expected)

limit on $\nu_\mu \Leftrightarrow \nu_s$ admixture (4-flavor mixing)

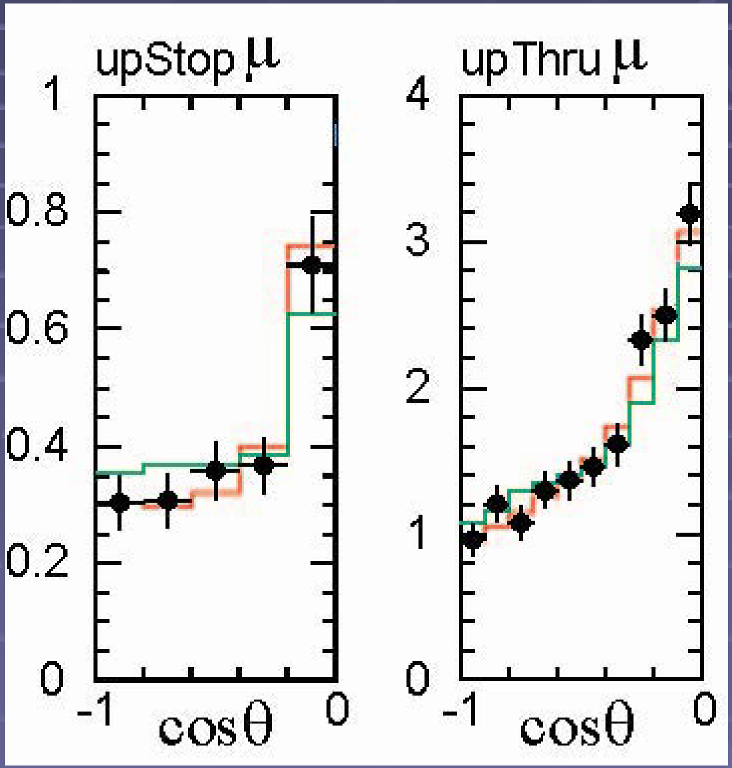
(Following Fogli,Lisi, and Morrone, hep-ph/000299)

$$\nu_\mu \rightarrow (\cos\xi\, \nu_\tau + \sin\xi\, \nu_s)$$

χ^2 scan along Δm^2=3.2x10^{-3}eV^2



pure $\nu_\mu - \nu_\tau$ ⟷ pure $\nu_\mu - \nu_s$



pure $\nu_\mu - \nu_\tau$ (red)

pure $\nu_\mu - \nu_s$ (green)

pure $\nu_\mu - \nu_s$ is excluded by $\Delta\chi^2 > 30$!

π^0 in atm-ν sample at Super-K

Check
$\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_s$ hypotheses
by a NC rate measurement

	$\nu_\mu \rightarrow \nu_\tau$	$\nu_\mu \rightarrow \nu_s$
π^0	⇨	⇩
μ	⇩	⇩

SK Data set : 1489 days (*) normalized by livetime

SK-atmν	Data	MC(*)
π^0	475	483.8
1-R FC μ	3878	5415.1
π^0/μ	**0.122** ±5% (stat) ± 7% (sys)	0.089 ± ~30% **0.087 ± ~13%** (sys)

Use K2K results

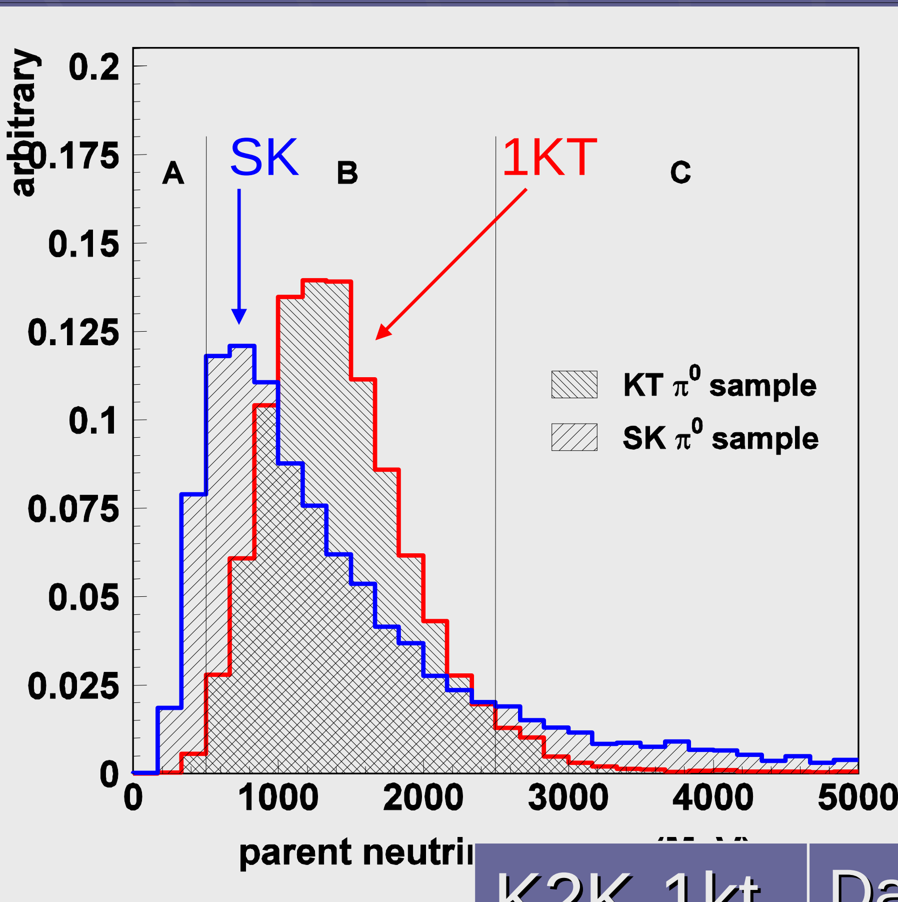
Detector systematics
Particle ID
Ring counting, etc..

K2K measurement (8%)
SK- K2K ν–flux difference (4%), etc..

$(\pi^0/\mu)_{MC}$
- **No osc** **0.087**
- **Pure $\nu\mu-\nu\tau$** **0.124**
- **Pure $\nu\mu-\nu s$** **0.103**

@ $\sin^2 2\theta$=1.0
Δm^2=2.0x10^{-3} eV^2

NCπ^0 measurement at K2K



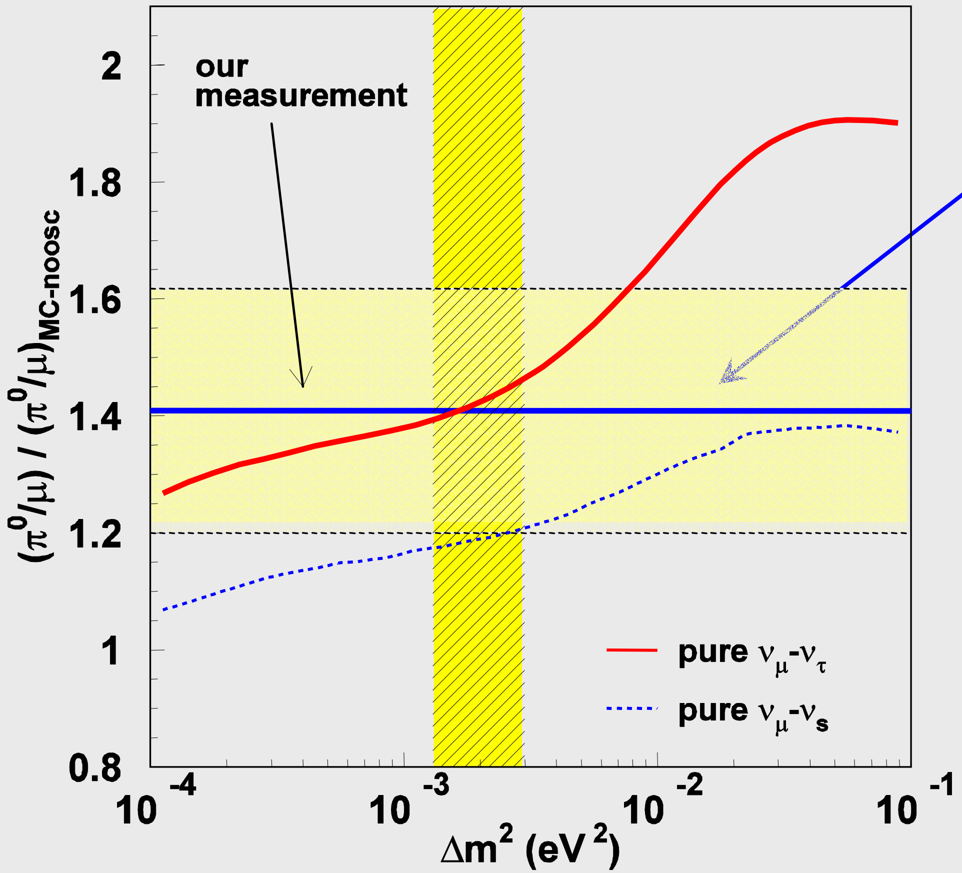
	1kt	SK
NC frac.	86%	85%
Eff.for π^0	47%	46%

Eν producing π^0 for 1kt and SK

K2K-1kt	Data	MC(*)
π^0	2496	2582.3
1-R FC μ	22612	22545.2
π^0/μ	**0.110** $\pm$ 2% $\pm$ 8% (stat) (sys)	**0.115** $\pm$ ~30% (sys)

Atm-ν π^0/μ for data, $\nu\mu-\nu\tau$ and $\nu\mu-\nu s$ hypothesis @ $\sin^2 2\theta=1.0$ $\Delta m^2=2.0\times10^{-3}$ eV^2

$\nu\mu-\nu\tau$ is consistent



$(\pi^0/\mu) / (\pi^0/\mu)_{noosc}$

- Data 1.41
- Pure $\nu\mu-\nu\tau$ 1.42
- Pure $\nu\mu-\nu s$ 1.19

3 Flavor Mixing

⋆ If neutrinos are massive particles, then it is possible that the **mass eigenstates** and the **weak eigenstates** are not the same:

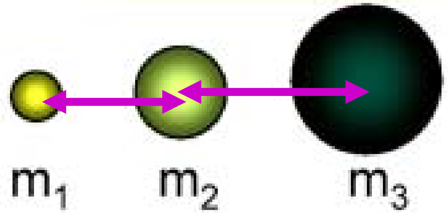
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Weak eigenstates „flavor eigenstates"

3 independent parameters + 1 complex phase

Mass eigenstates

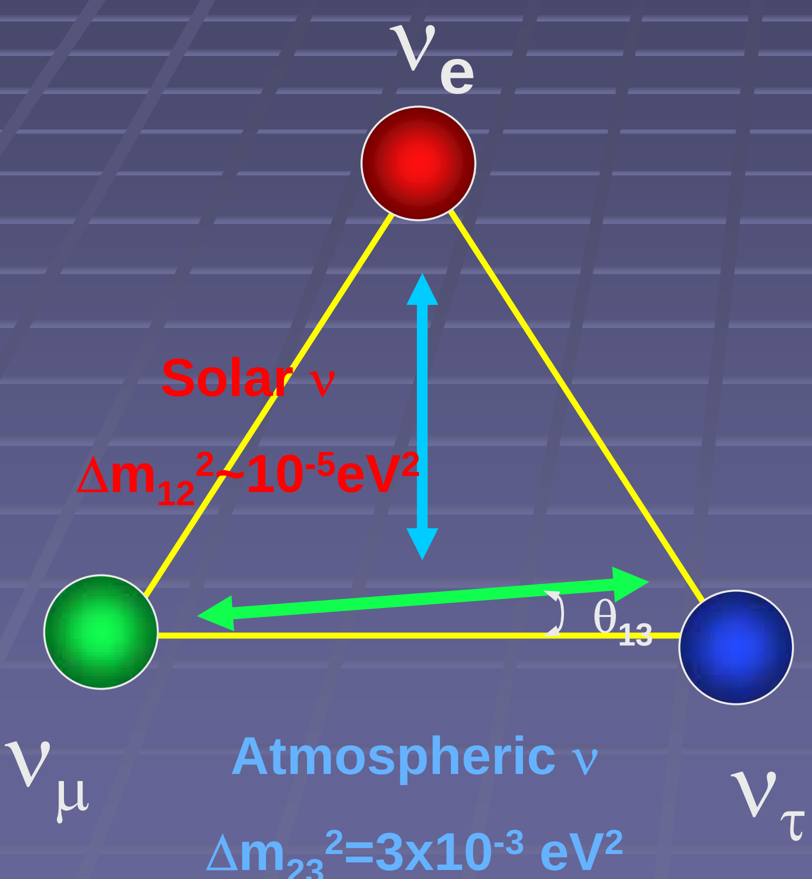
$\theta_{12}, \theta_{23}, \theta_{13}$
$+ \delta$

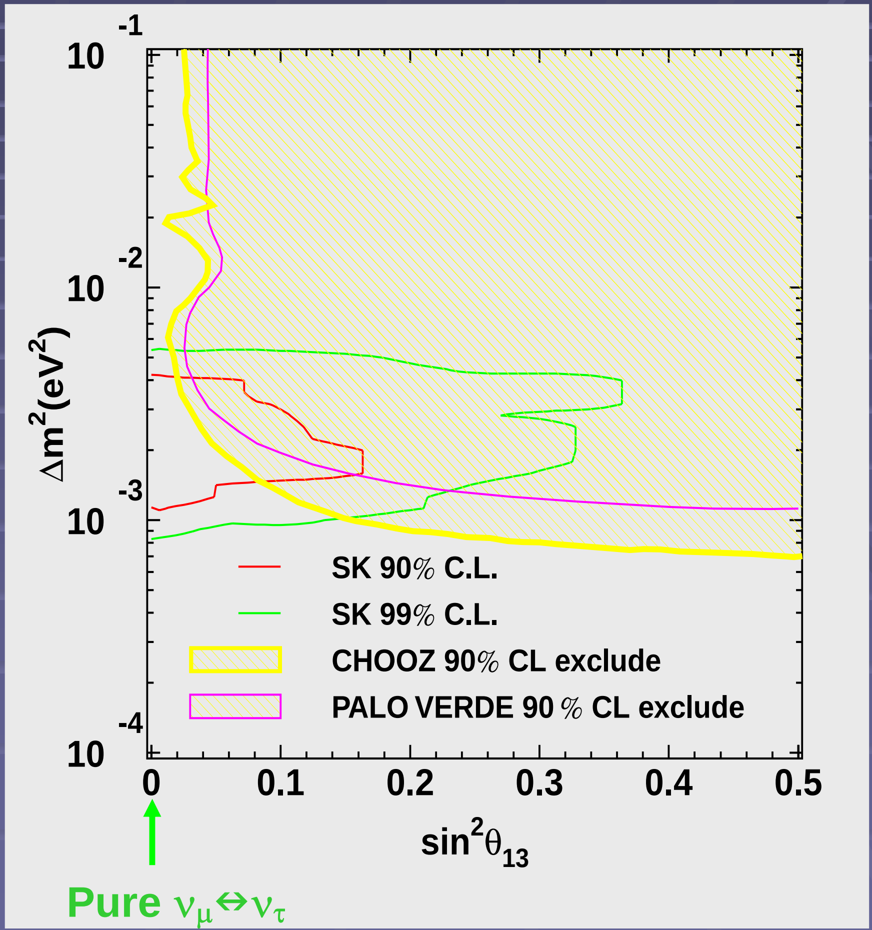


$\Delta m^2_{12}, \Delta m^2_{23}$

MNS (Maki-Nakagawa-Sakata) matrix

Allowed region for active 3-flavor oscillations

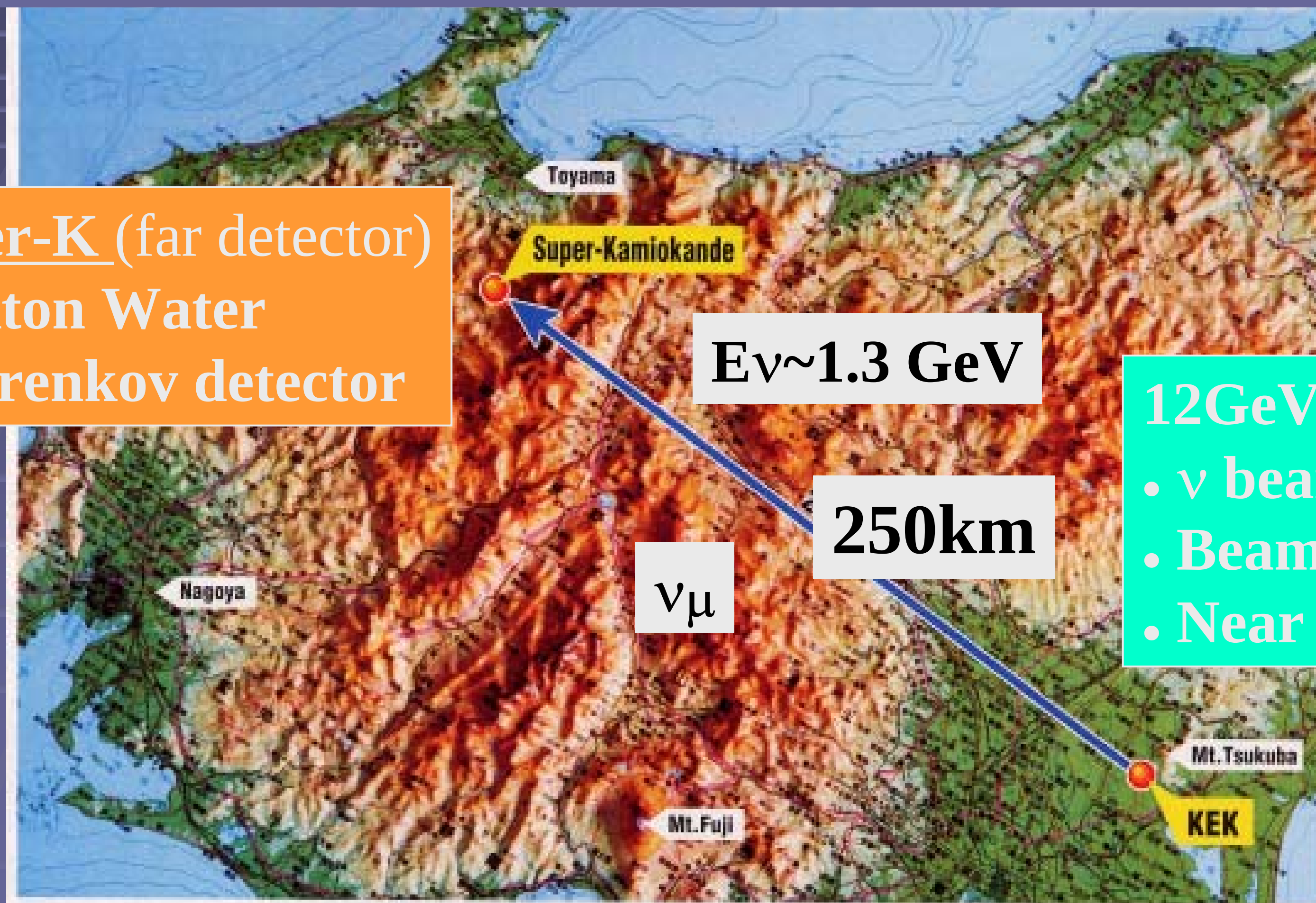




consistent with CHOOZ's excluded region

K2K experiment

KEK to Kamioka Neutrino Oscillation Experiment



Super-K (far detector)
50 kton Water Cherenkov detector

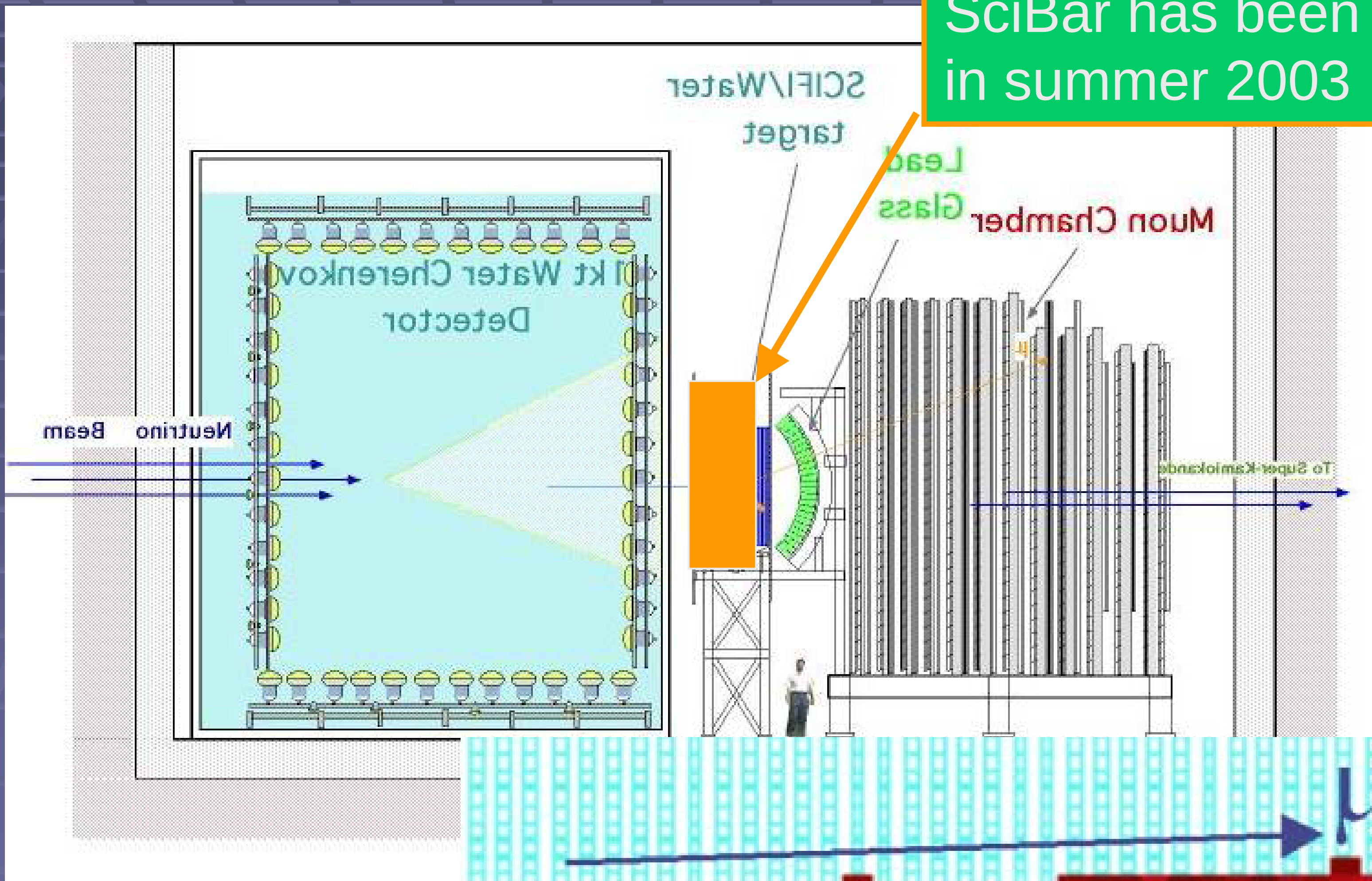
12GeV PS@KEK
- **ν beam line**
- **Beam monitor**
- **Near detectors**

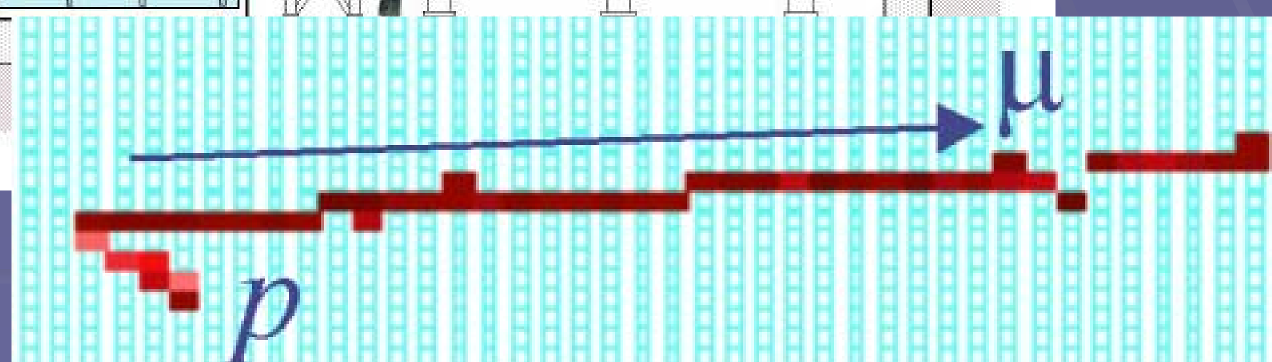
K2K collaboration

- University of Barcelona
- Boston University
- Chonnam National University
- Dongshin University
- University of Geneva
- Hiroshima University
- ICRR
- Inst. for Nuclear Research, Moscow
- KEK
- Kobe University
- Korea University
- Kyoto University
- Massachusetts Institute of Technology
- Niigata University
- Okayama University
- University of Rome
- "La Sapienza"Saclay (DSM-DAPNIA)
- Seoul National University
- SUNY at Stony Brook
- Tokyo University of Science
- Tohoku University
- University of California, Irvine
- University of Hawaii
- University of Tokyo
- University of Washington
- University of Valencia
- Warsaw University

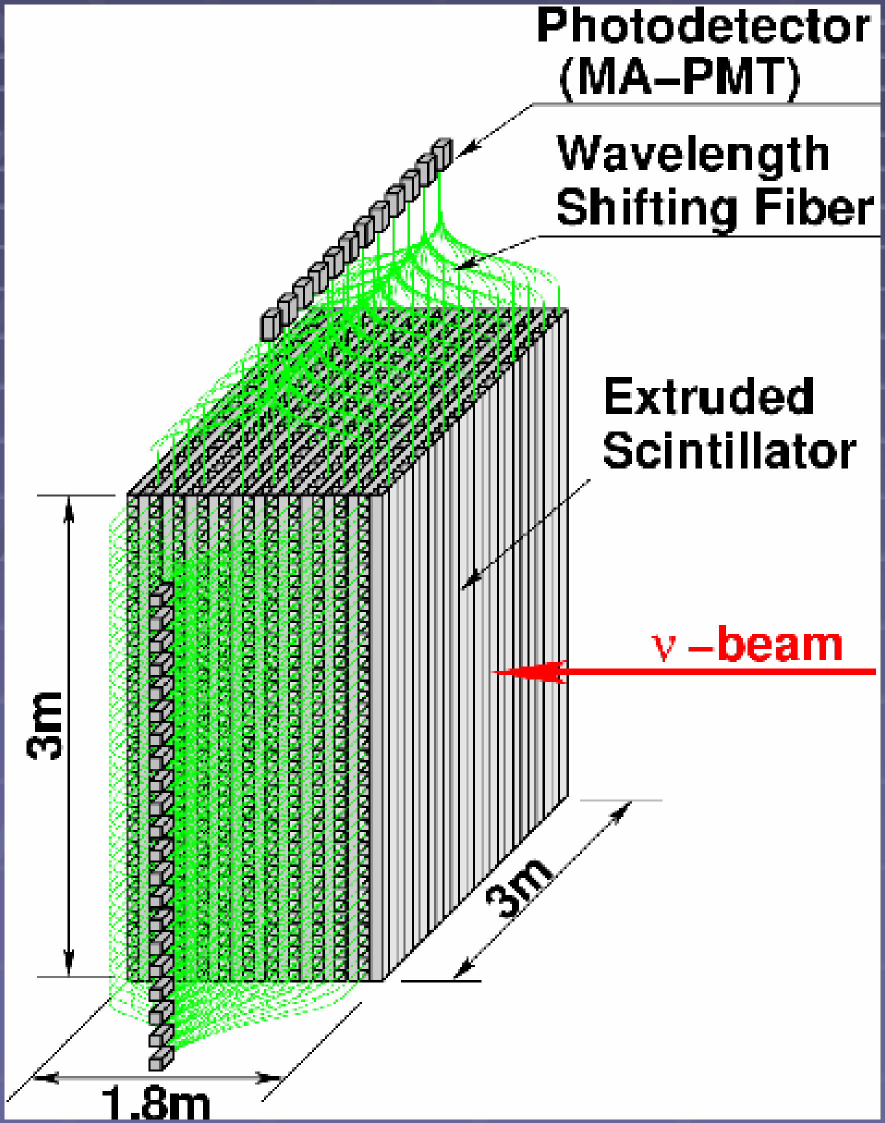
K2K near detector

SciBar has been installed in summer 2003





SciBar detector



Full active

Large Volume:

(300 × 300 × 166) cm^3 ~15tons

Fine segment: 2.5 × 1.3 × 300 cm^3

Large Light Yield:
7~20 photo-electrons/cm for MIP
the factor 3 of 7~20 comes from the fiber attenuation.

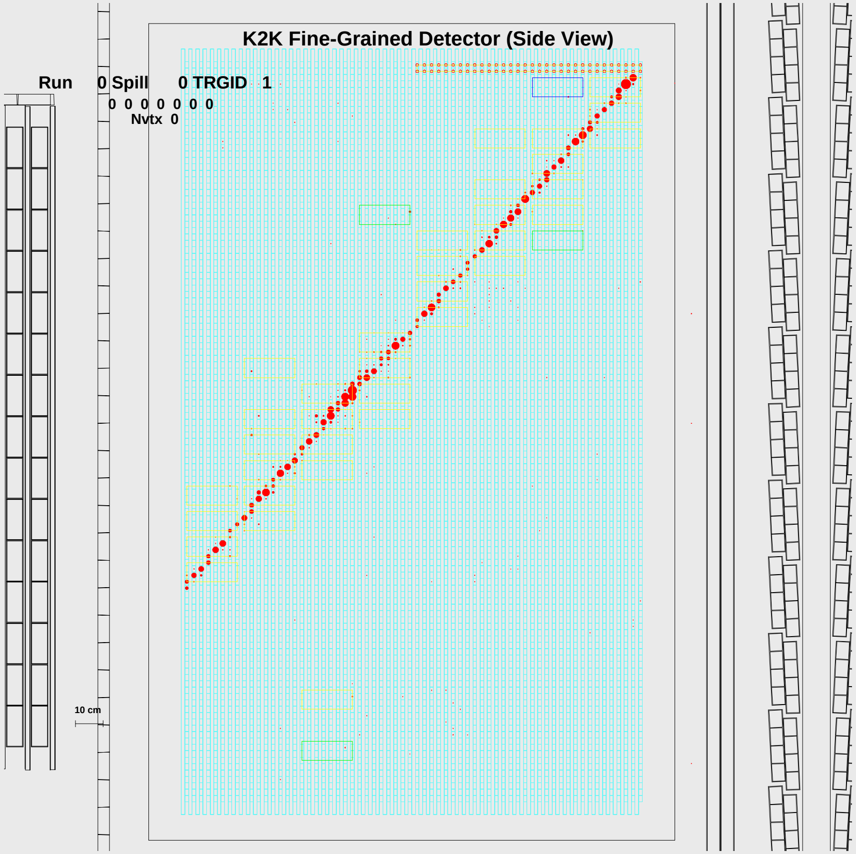
Particle ID:
p/π : dE/dx
μ/π : range

Proton Momentum:
by dE/dx and the range

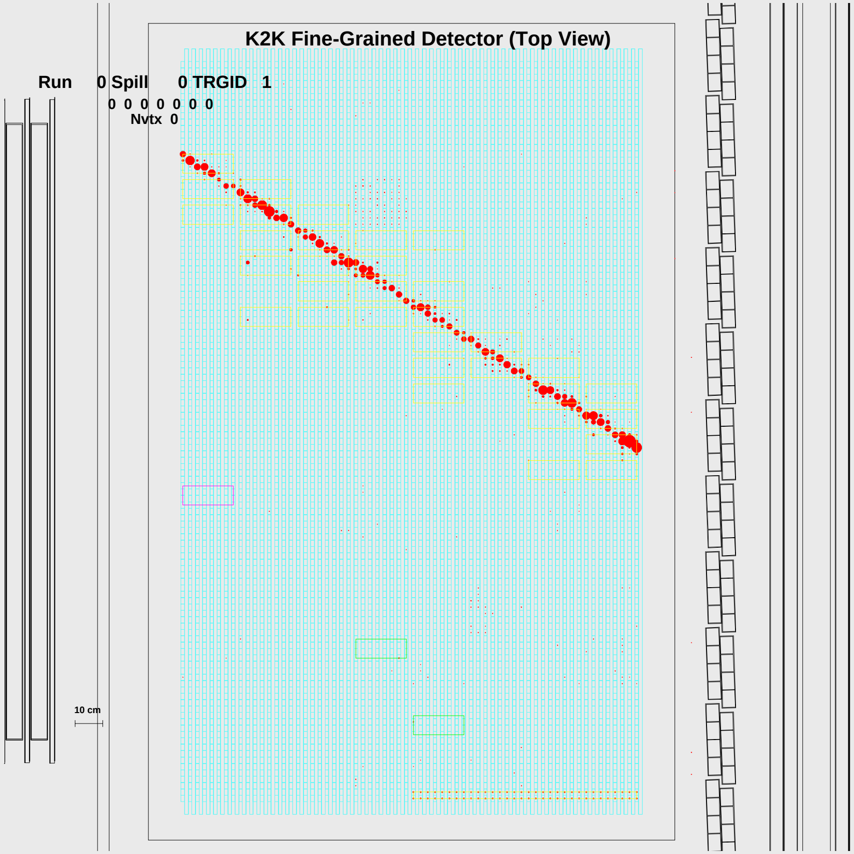
#channels : ~15,000

Cosmic Ray muon at SCIBAR

SIDE View



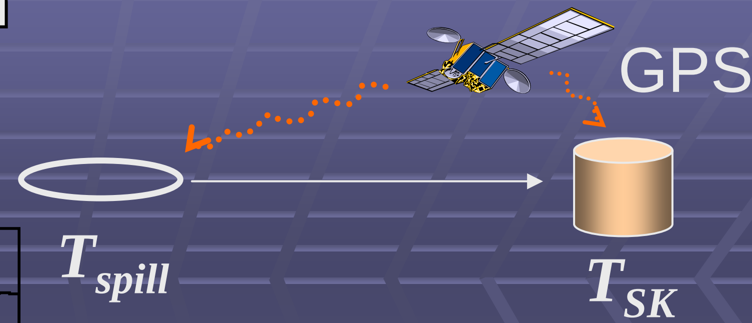
TOP View



Results of K2K-I

Super-K Event selection

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



T_{Spill}: Abs. time of spill start

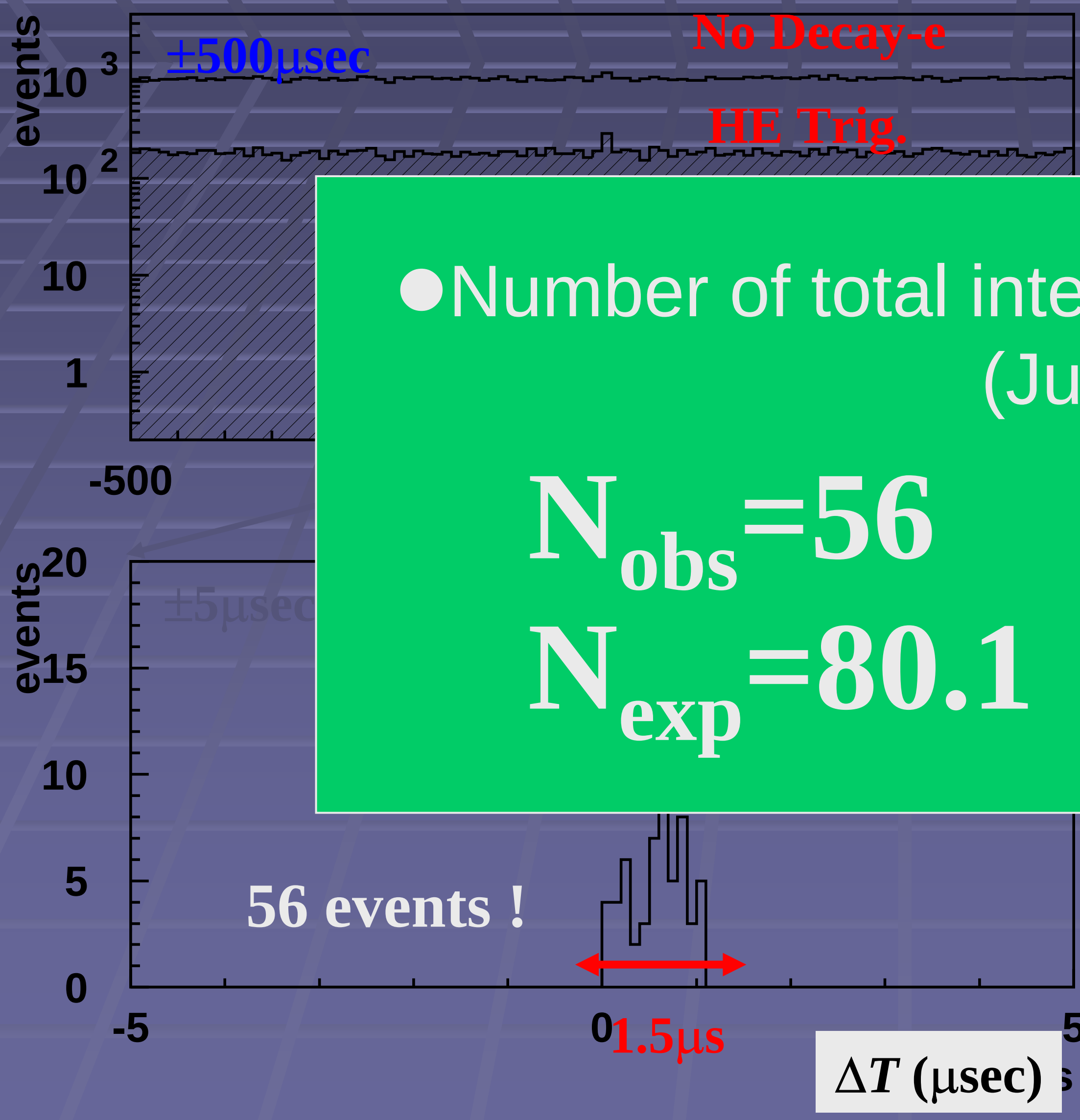
SK event

K to Kamioka)

ed

ter Detector)

ial Volume



- Number of total interactions (Jun99-Jul01)

$$N_{obs} = 56$$

$$N_{exp} = 80.1 \; {}^{+6.2}_{-5.4}$$

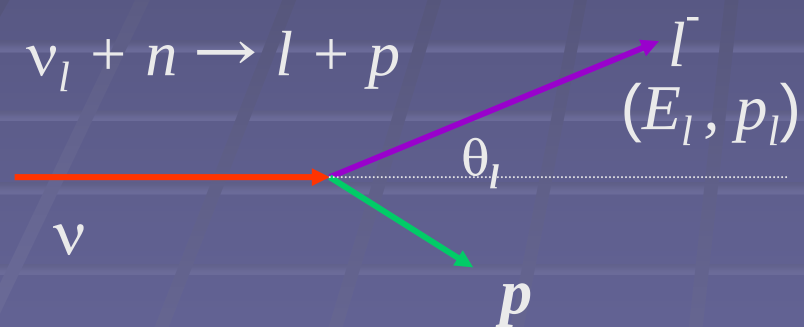
tm. ν BG $<10^{-3}$ within 1.5μs.

Eν spectrum analysis

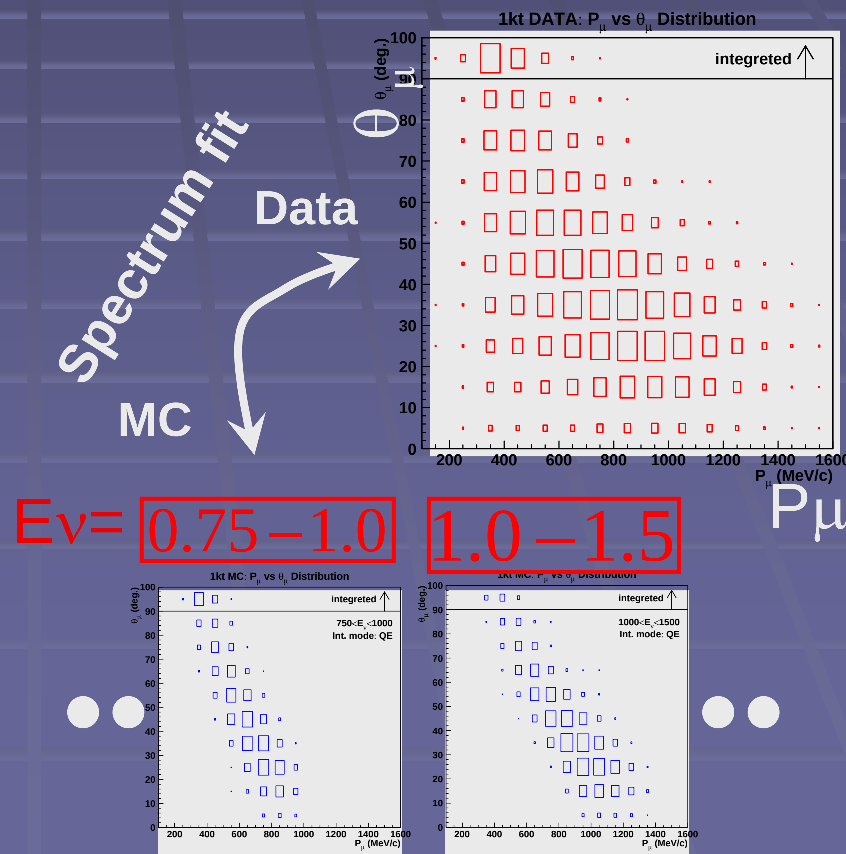
- Determination of expected Φ(Eν) spectrum
  - Beam Monte Carlo
  - π-monitor
  - Measurement of CC spectrum by near detector

CCQE interaction (2 body)

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

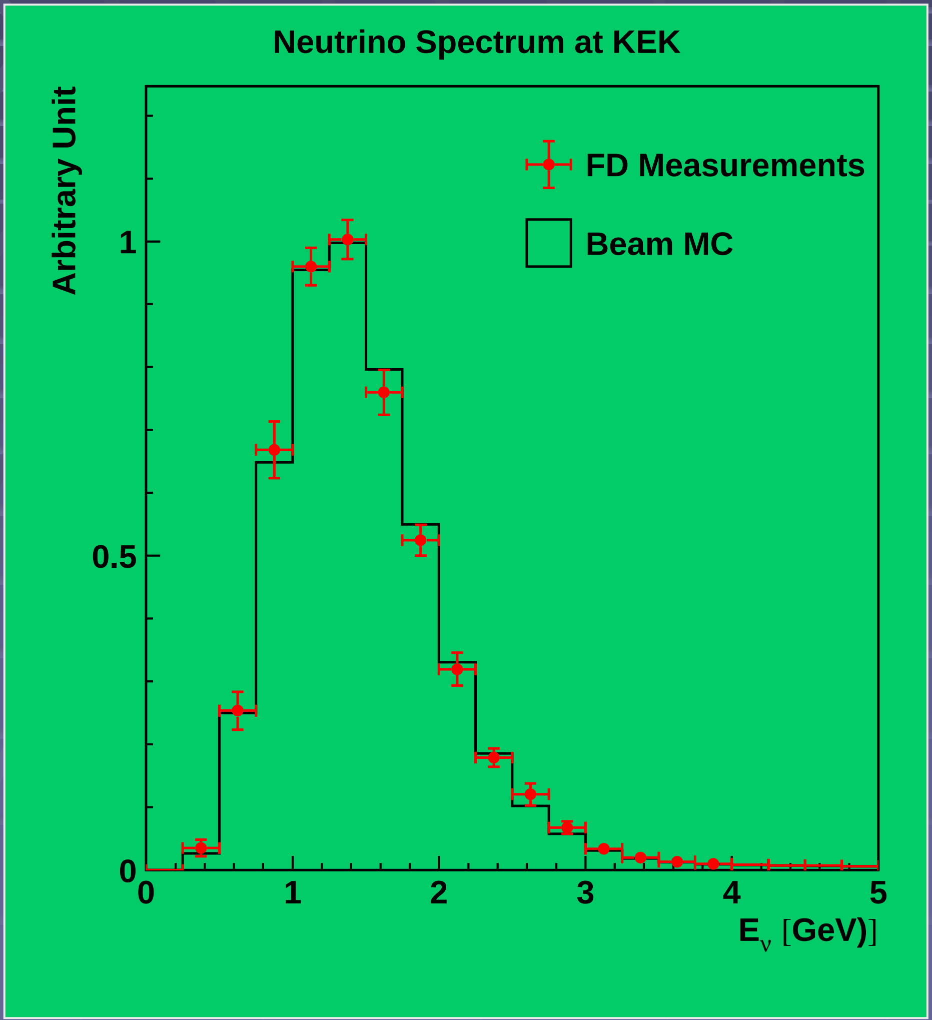


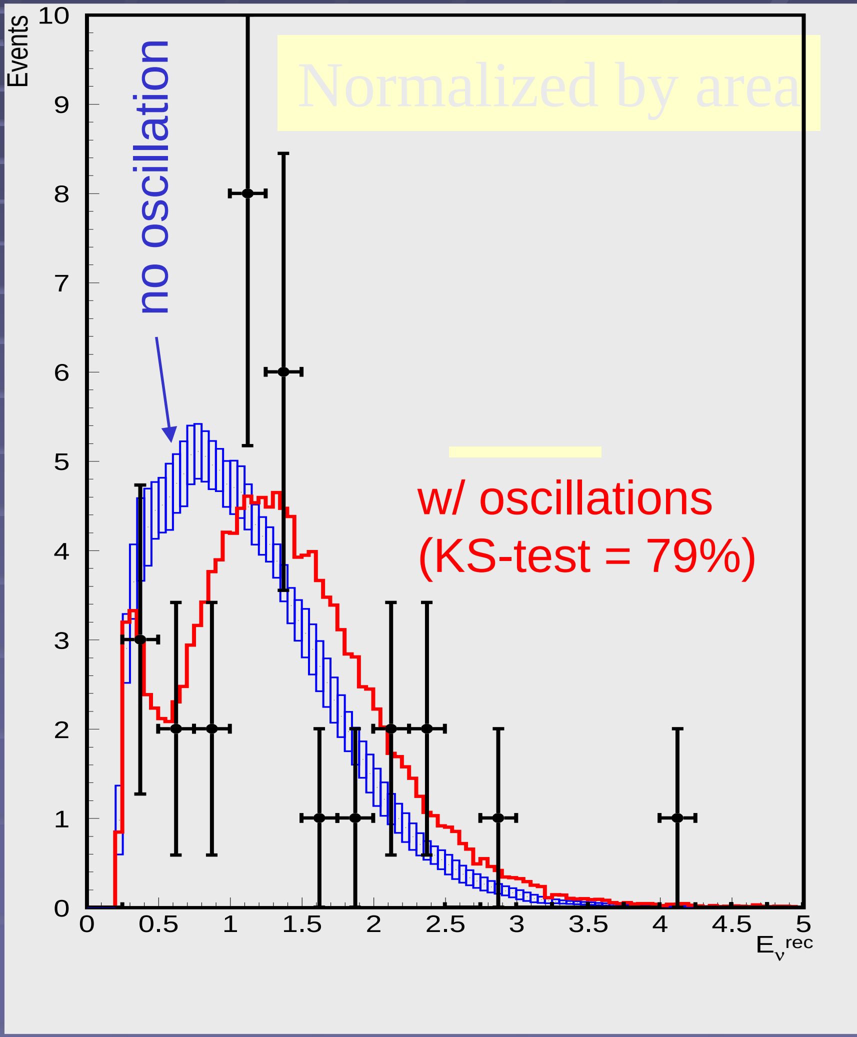
$$E_\nu = \frac{m_N E_l - m_l^2/2}{m_N - E_l + p_l \cos\theta_l}$$



Eν spectrum results in K2K-I

● Reconstructed Eν shape of 1-RFCμ at SK
(29 1-R events in Nov99-Jul01)



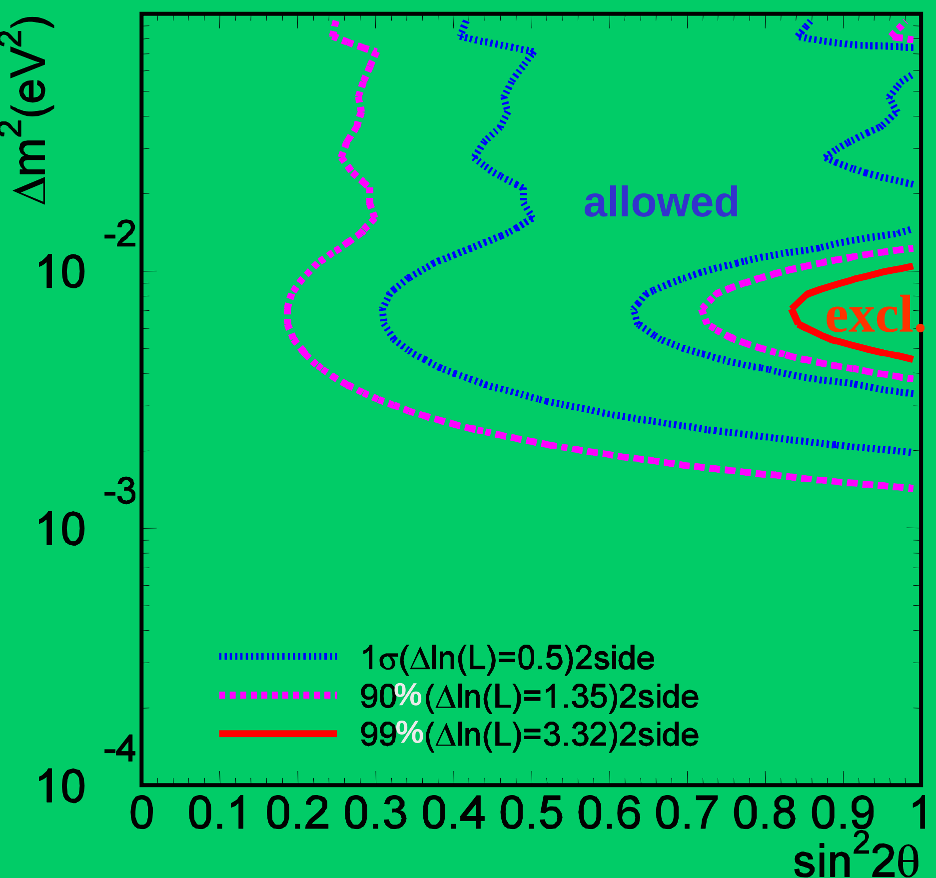


Allowed regions and Null osc. probability

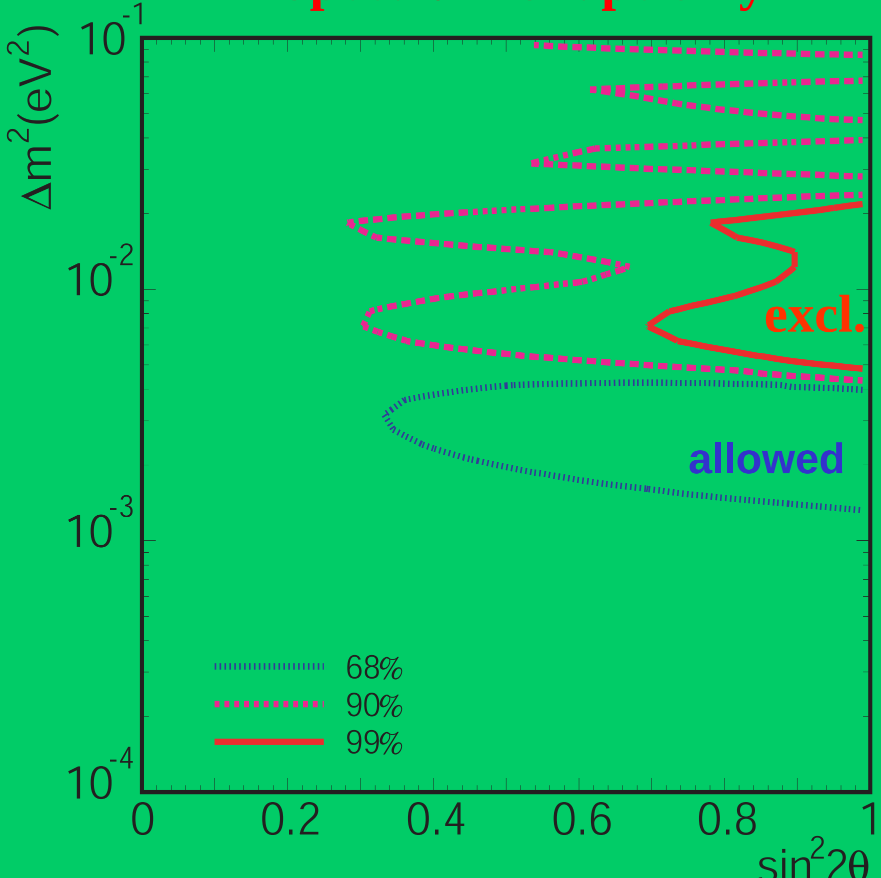
56FC events observed / 80.1 expected (Jun99-Jul01 data)

29 1-R FCμ events shape (Nov99-Jul01 data)

Total no. of Events only

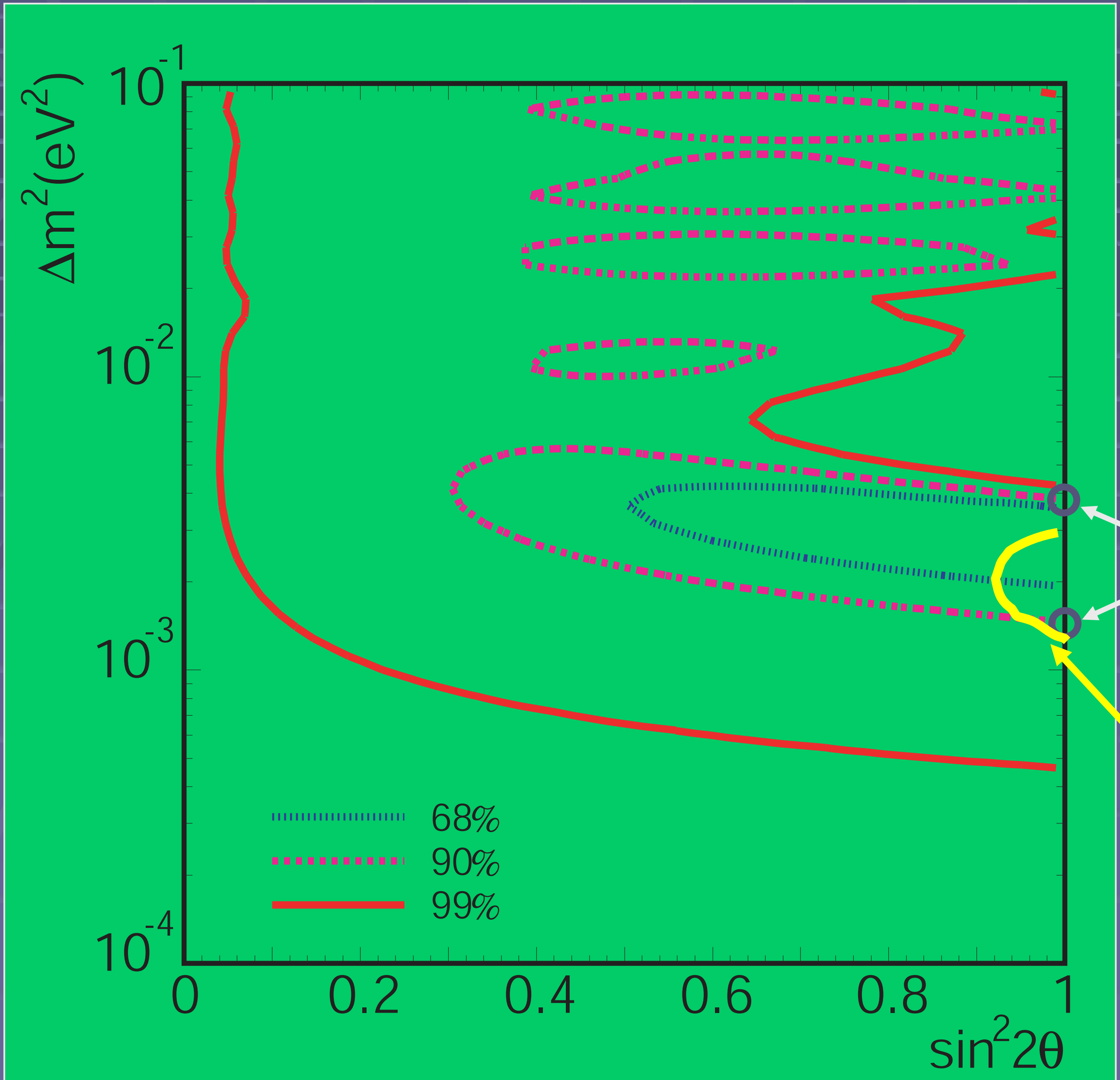


Spectrum Shape only



Shape and N_{SK} +Shape indicate consistent parameter region

Combined Allowed region (Shape+Norm) for K2K-I



- Null oscillation ⇨ < 1%

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

atm-ν results Consistent !

Search for ν_e appearance

DATA SET

June'99 – July'01 (4.8×10^{19} POT)

	DATA	ν_μ MC	beam ν_e MC	signal ν_e MC (CC) $\sin^2 2\theta_{\mu e}=1$, $\Delta m^2=2.8\times10^{-3}\,eV^2$
generated		104 events	0.99 events	28 events
FCFV	56	80 (78%)	0.82 (83%)	28 (98%)
Single ring	32	50 (48%)	0.48 (48%)	20 (71%)
PID (e-like)	1	2.9 (2.7%)	0.42 (42%)	18 (63%)
Evis>100MeV	1	2.6 (2.4%)	0.41 (41%)	18 (63%)
w/o decay-e	1	2.0 (1.9%)	0.35 (35%)	16 (55%)

ν_e e

ν_μ γ π^0

Signal $\nu_\mu \rightarrow \nu_e$

BG beam ν_e

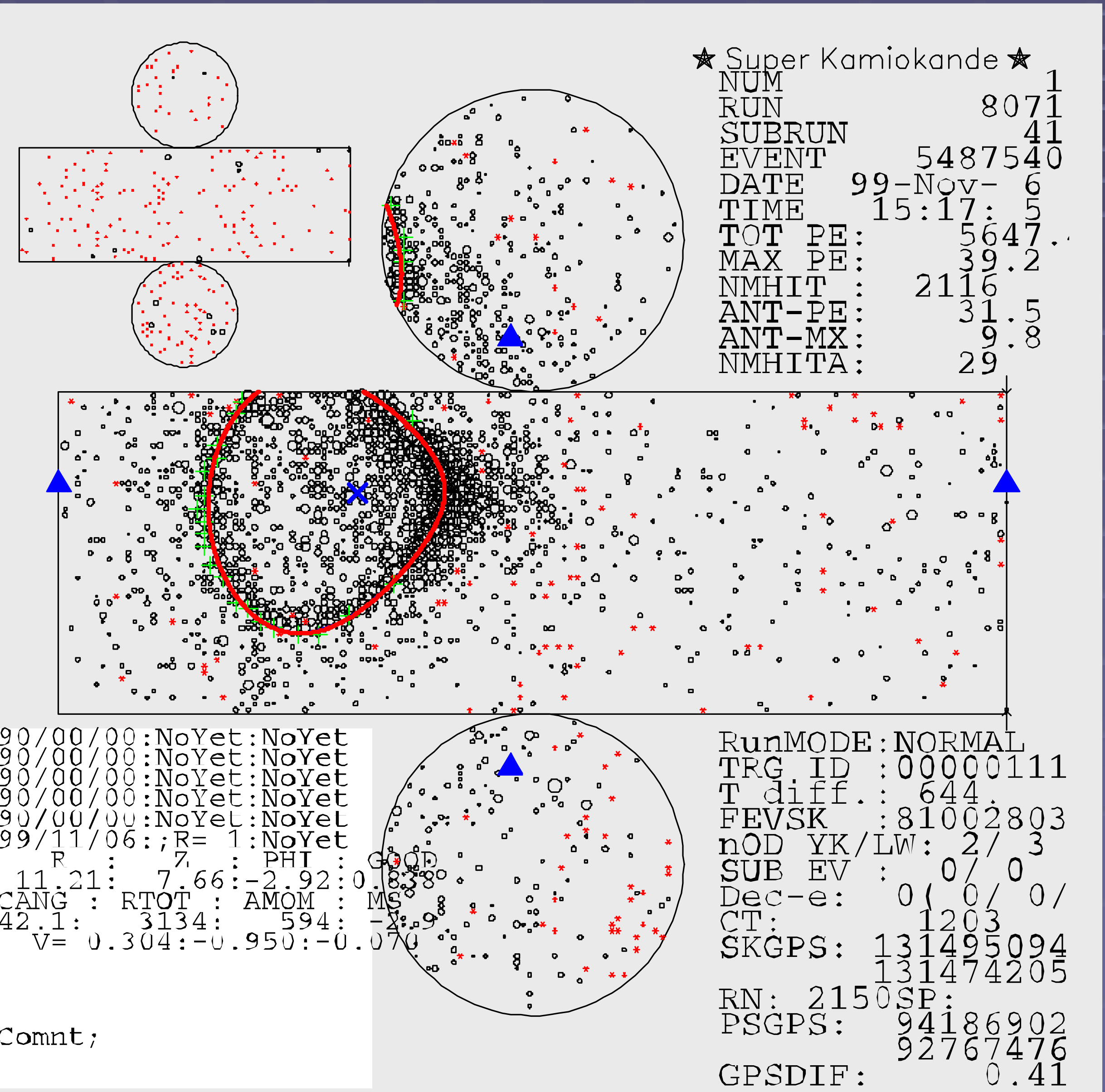
BG π^0 (missing 1 ring)

NC:87% CC1π:7% CCmπ:4% CCQE:2%

electron candidate: 1 event observed

2.4 events expected.

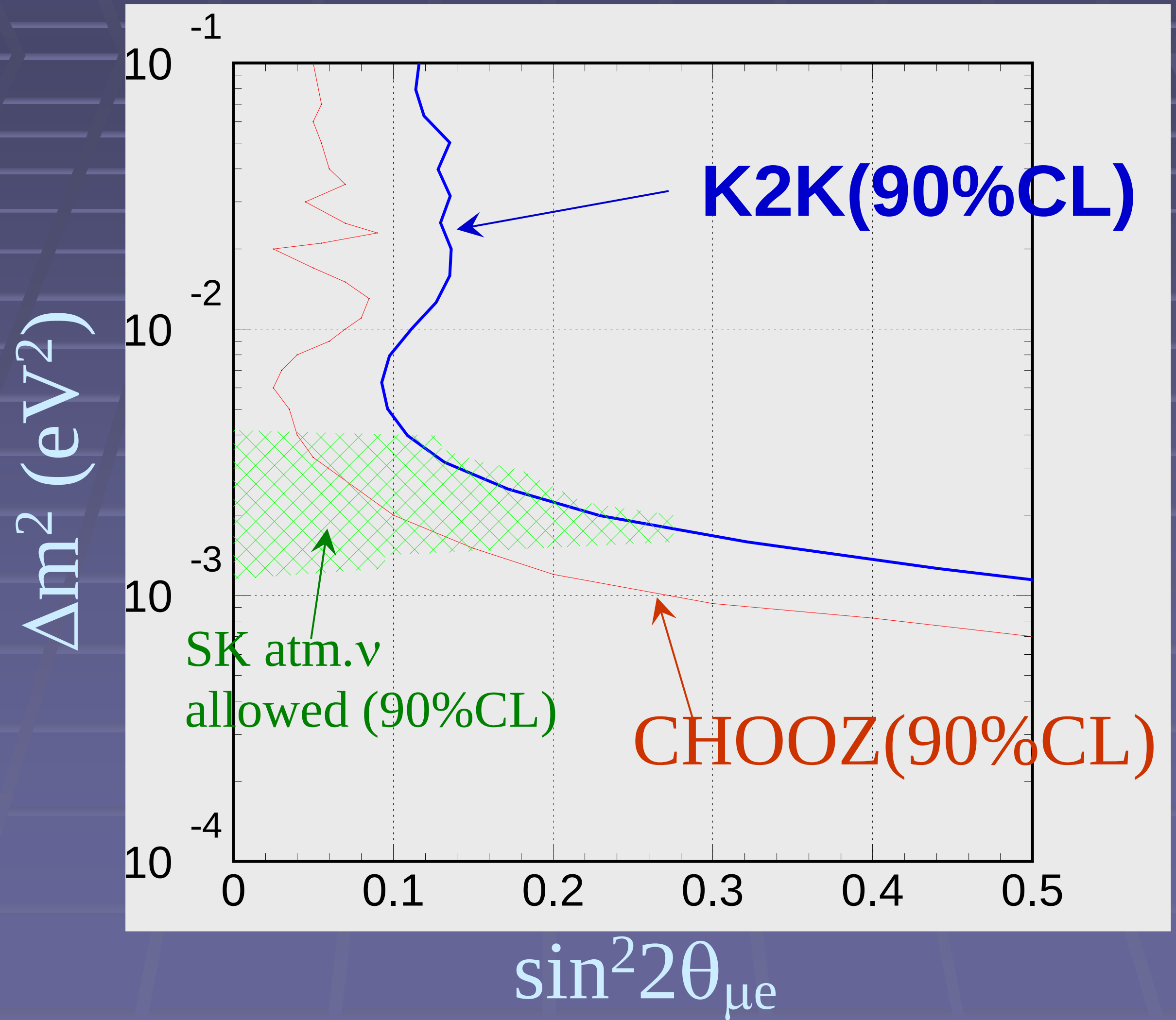
Electron Candidate



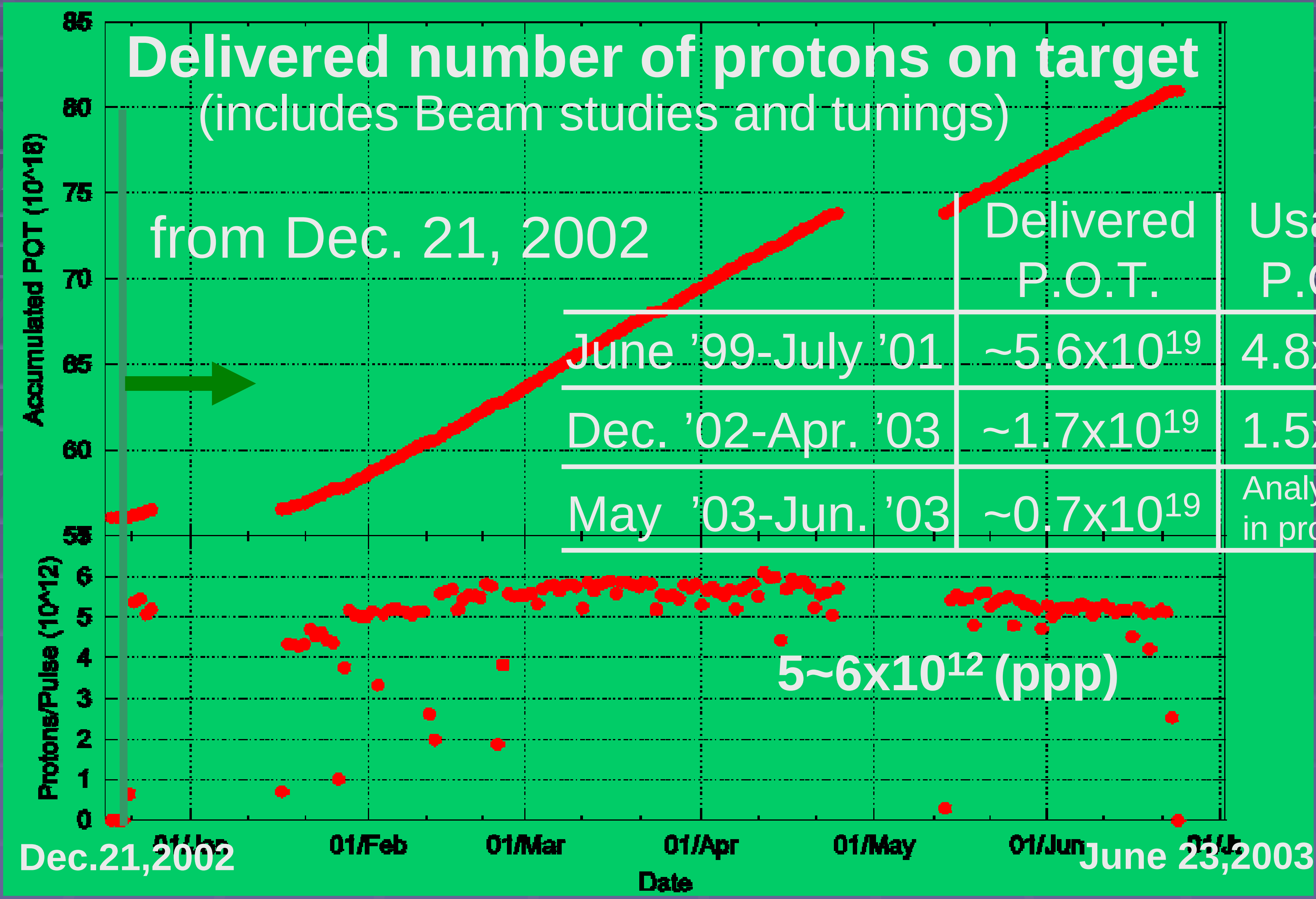
reconst. momentum
597 MeV/c

reconst. Eν
assuming νe CCQE
612 MeV

Allowed region for $\sin^2 2\theta_{\mu e}$



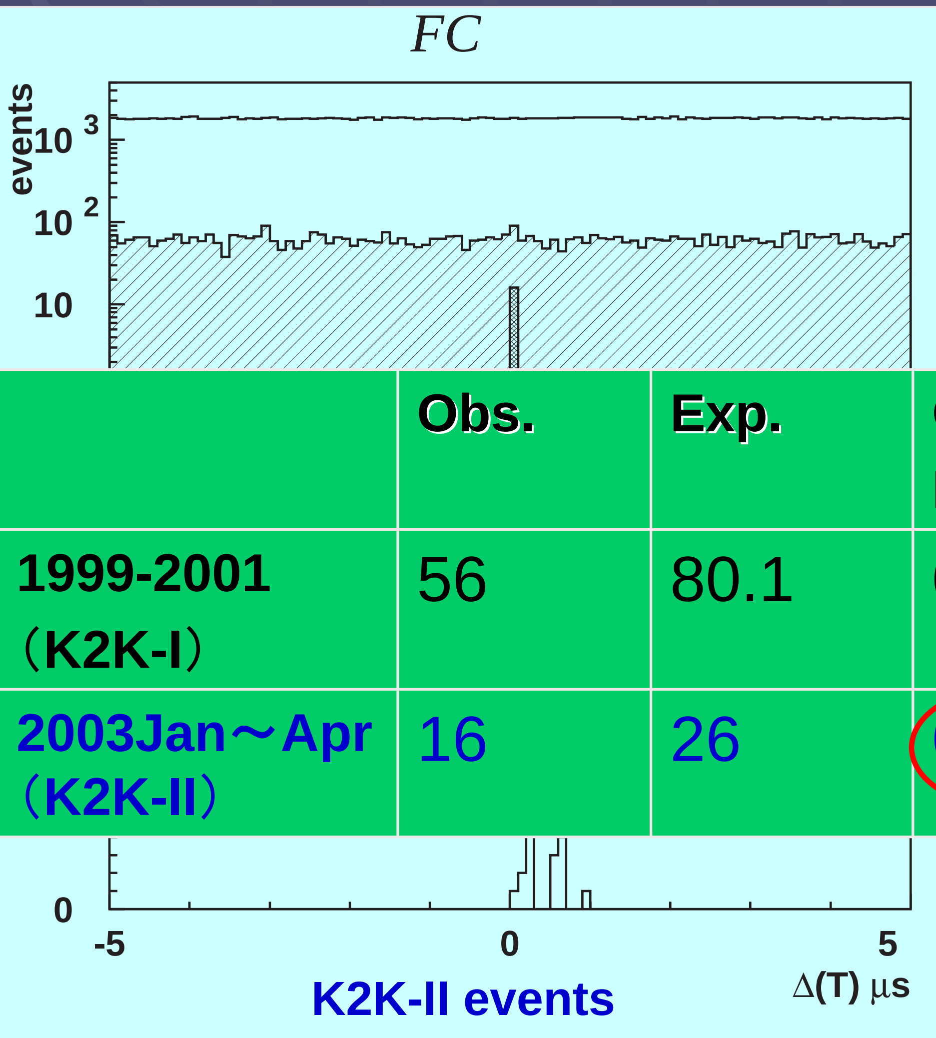
Status of K2K-II

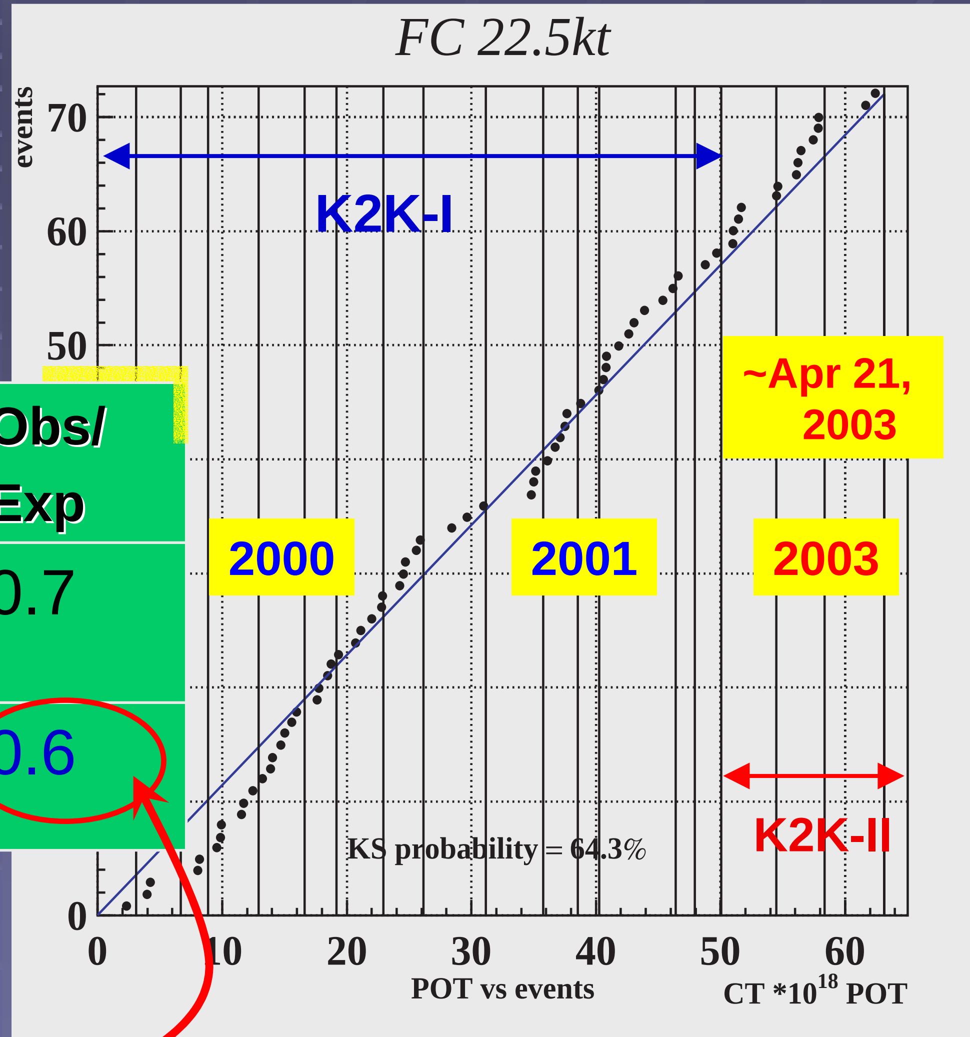


	Delivered P.O.T.	Usable P.O.T.
June '99-July '01	$\sim 5.6\times10^{19}$	4.8×10^{19}
Dec. '02-Apr. '03	$\sim 1.7\times10^{19}$	1.5×10^{19}
May '03-Jun. '03	$\sim 0.7\times10^{19}$	Analysis in progress

Very stable and no serious problems

Status of K2K-II K2K-II Preliminary





	Obs.	Exp.	Obs/Exp
1999-2001 （K2K-I）	56	80.1	0.7
2003Jan～Apr （K2K-II）	16	26	0.6

K2K-II experiment observed consistent reduction rate

Summary

- Atmospheric ν results from SK-I
  - Finalization for SK-I data is going on
  - $\Delta m^2=1.3\sim3.0\times10^{-3}eV^2$, $\sin^2 2\theta>0.92$ @ 90%CL
- K2K results
  - K2K-I results (Total events + $E\nu$ spectrum)
  - Null oscillation probability is less than 1%
  - $\Delta m^2=1.5\sim3.9\times10^{-3}eV^2$ for $\sin^2 2\theta=1$ @ 90%CL
- Sk-II / K2K-II successfully resumed
  - K2K-II observe consistent ν rate with K2K-I