Recent results from the K2K experiment

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for the K2K collaboration

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  (Number of events + Spectrum)
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K2K Collaboration

High Energy Accelerator Research Organization(KEK)
Institute for Cosmic Ray Research(ICRR), University of Tokyo
Kobe University
Kyoto University
Niigata University
Okayama University
Tokyo University of Science
Tohoku University

Chonnam National University
Dongshin University
Korea University
Seoul National University

Boston University
University of California, Irvine
University of Hawaii, Manoa
Massachusetts Institute of Technology
State University of New York at Stony Brook
University of Washington at Seattle

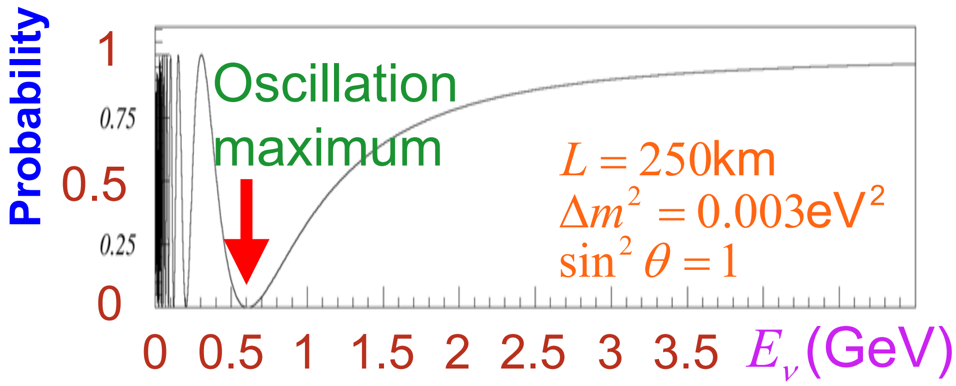
Warsaw University
Solton Institute

Introduction

Principle of the long baseline experiment

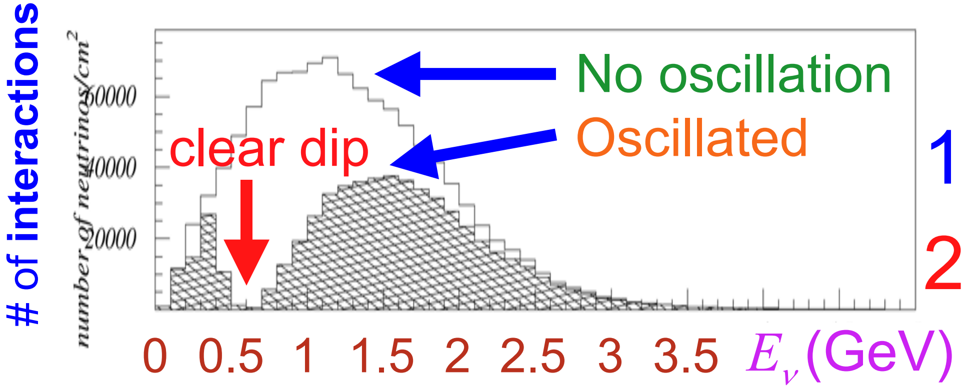
Oscillation Probability= $\sin^2 2\theta \cdot \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$

(2 flavor)



long baseline experiment

→ **Fixed distance**



Compared to
the NULL oscillation case,

1)Reduced number of events

2)Distorted energy spectrum
dip around 0.6 ~ 0.7 GeV

The K2K experiment

Super Kamiokande
(far detector)
50kt water Cherenkov detector

12GeV PS@KEK
ν beamline
beam monitors
near detectors

Neutrino beam

$<E_\nu> \sim 1.3$GeV

almost pure $\nu_\mu (\sim 98\%)$

Beam monitors & near detectors

- beam direction
- π monitor
- ν_μ flux & spectrum

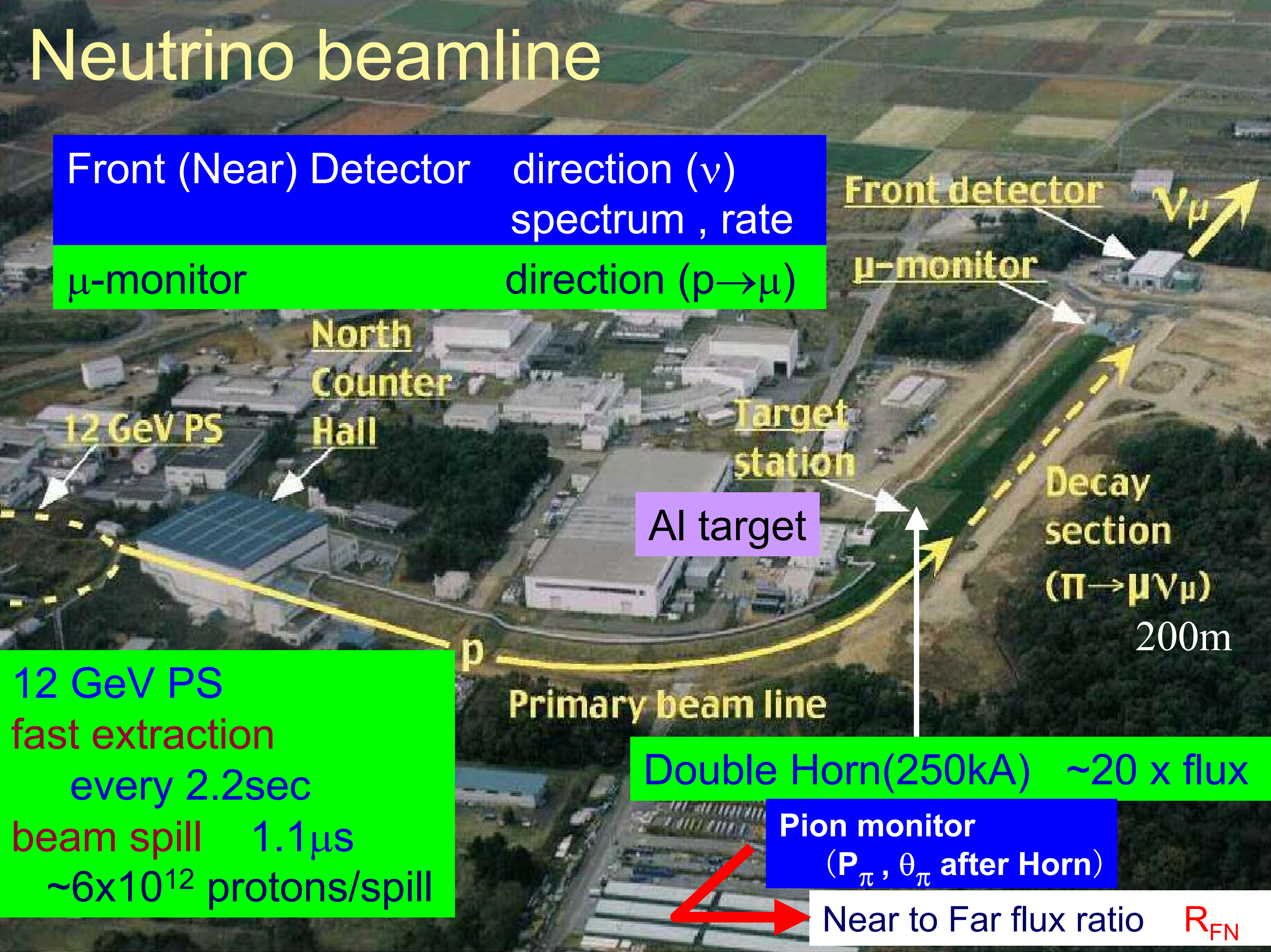
Far detector

- ν_μ flux & spectrum

ν_μ disappearance
spectrum distortion

Neutrino beamline

Front (Near) Detector	direction (ν)	spectrum , rate
μ-monitor	direction ($p \rightarrow \mu$)	



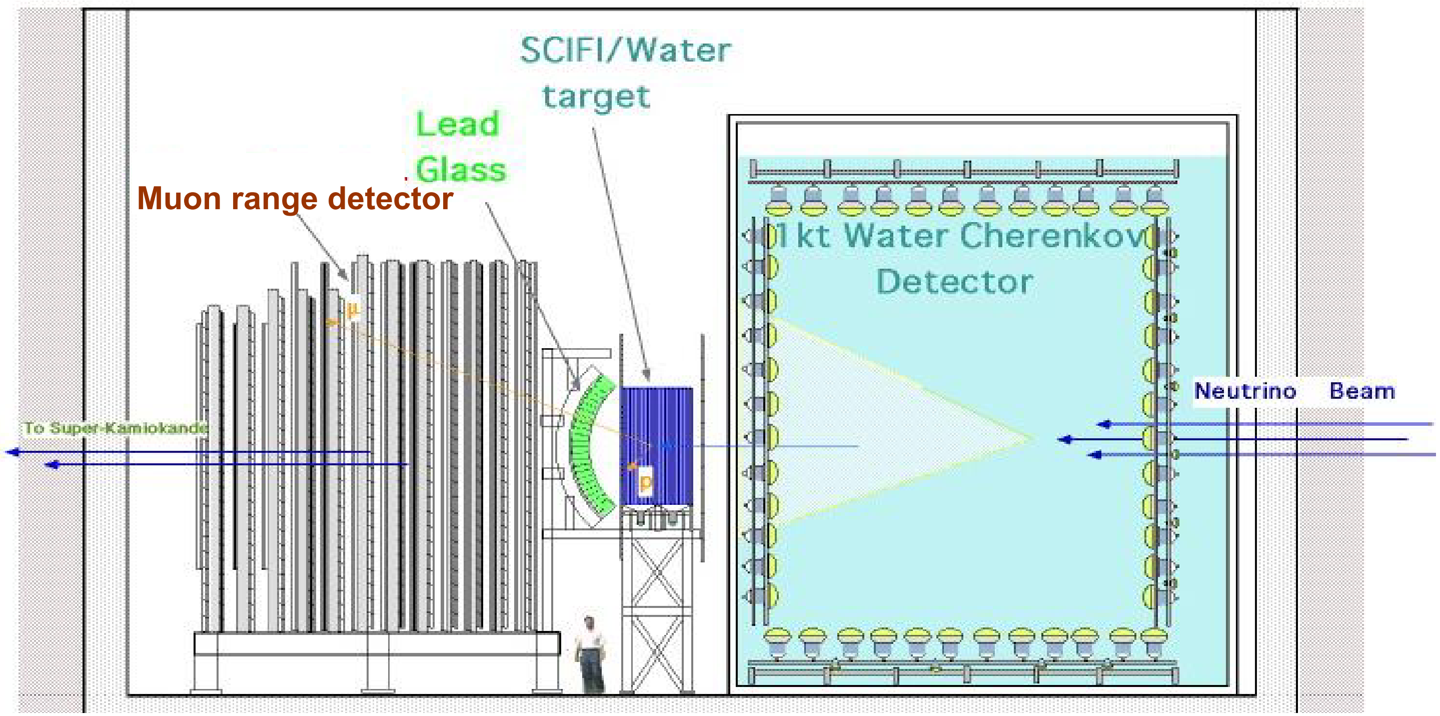
12 GeV PS
fast extraction
every 2.2sec
beam spill 1.1μs
~6×10^{12} protons/spill

Double Horn(250kA) ~20 x flux

Pion monitor
(P_π , θ_π after Horn)

Near to Far flux ratio R_{FN}

Near neutrino detectors



1kt water Cherenkov detector (1kt) — water target (25t fid. vol.)
same type as SK

Fine grained detectors

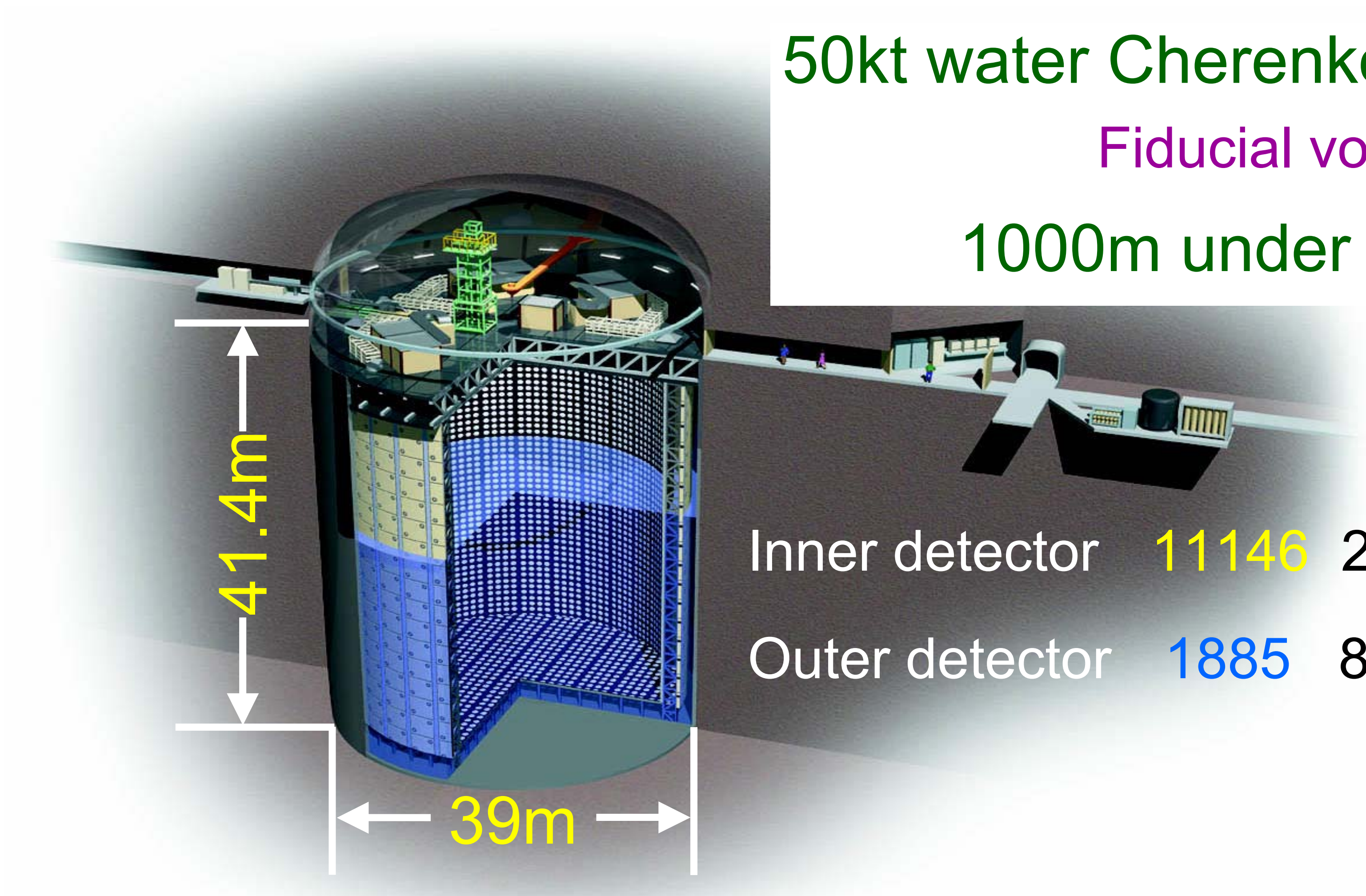
- **Scintillating fiber tracker** (SciFi) — water target (6t fid. vol.)
  CCQE identification
- **Muon range detector** (MRD) — Iron target (330t fid. vol.)
  ν beam monitor (mom. & dir.)

Super-Kamiokande (Far detector)

50kt water Cherenkov detector

Fiducial volume 22.5kt

1000m under the ground



Inner detector 11146 20” PMTs

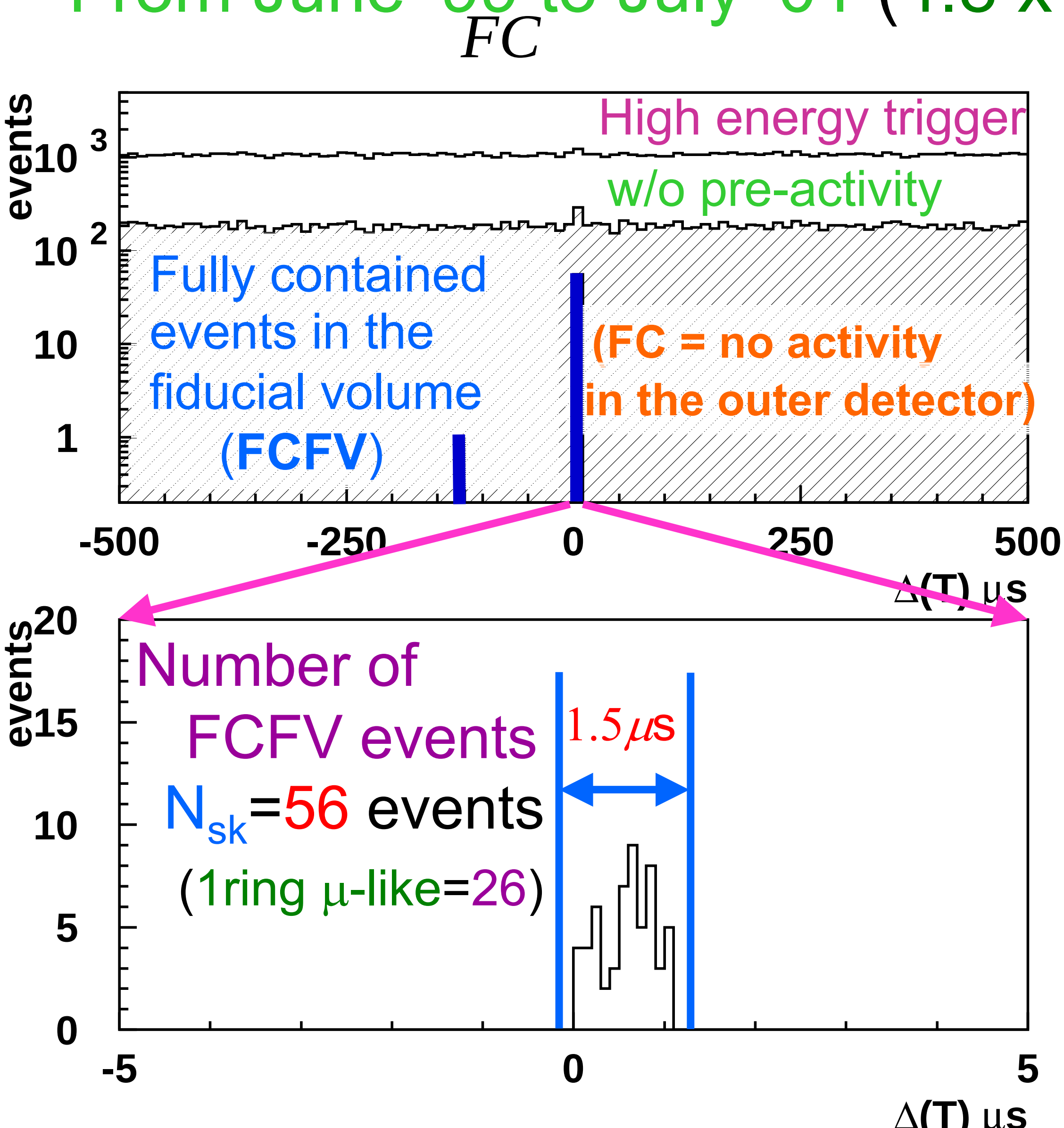
Outer detector 1885 8” PMTs

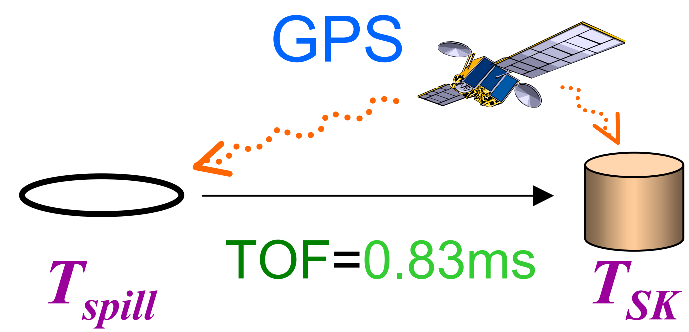
Atmospheric ν ~8 events/day (FCFV)

→ accidental coincidence ~10^{-5} events/day

Event selection at Super-Kamiokande

From June '99 to July '01 (4.8 x 10^{19} protons on target)





$$\Delta T \equiv T_{SK} - T_{spill} - \mathrm{TOF}$$

requiring

$$-0.2 \le \Delta T \le 1.3\mu s$$

Expected number of atmospheric ν BG

$<10^{-3}$ events

Summary of K2K results in 2001

From June '99 to July '01

accumulated number of protons

4.8×10^{19} POT for the analysis

Neutrino beam was very stable

- **direction of the beam** : controlled less than 1mrad.

  confirmed by μ profile monitor ($\pi \to \mu$ decay)

  muon range detector (MRD)

  (ν interaction vertex)

- **energy spectrum of ν**

  confirmed by 1kt water Cherenkov detector (1kt) & MRD

Summary of K2K results in 2001

Neutrino flux @ SK

estimated by Monte-Carlo

confirmed by π monitor

normalization was done by 1kt water Cherenkov detector

[number of protons was measured by Current Transformer (CT)]

of FCFV events in Super-K

Observed : **56** ⟷ **Expected** : $\mathbf{80^{+7.3}_{-8.0}}$

→ Probability of null oscillation < 3%

→ **Next step**

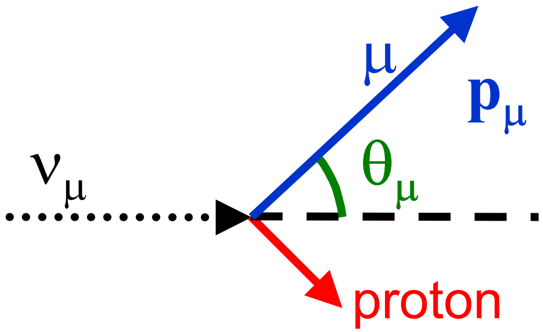
Full and Improved error estimations

and **spectrum shape analysis**

Neutrino interactions around 1GeV

Charged current quasi-elastic scattering (QE)

E_ν can be reconstructed from P_μ and θ_μ.



p_μ : muon momentum

θ_μ : muon angle

1kt : **single ring μ-like FCFV** events

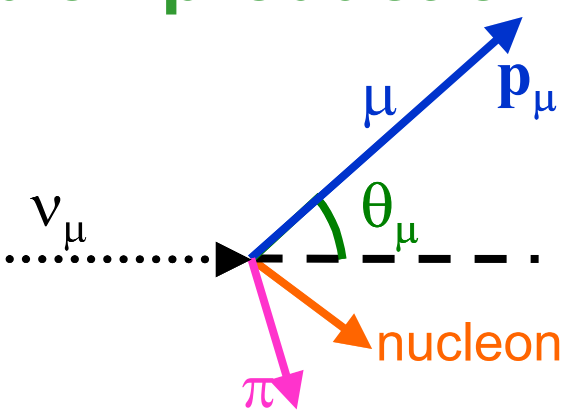
SciFi : **QE-like 2track** events

(when protons are identified)

or single track events

(when protons are not observed)

pion productions



1kt : FCFV events

(single-ring or multi-rings)

SciFi : **non-QE-like** events

Flow of the oscillation analysis

Observed quantities at the near detectors

(P_μ , θ_μ) for each event category

↓ Neutrino interaction models

Obtain neutrino spectrum at near detectors

↓ Near to Far extrapolation ($R_{FN}(E_\nu)$)

Predict neutrino spectrum without oscillation ($\phi_{SK}(E_\nu)$)

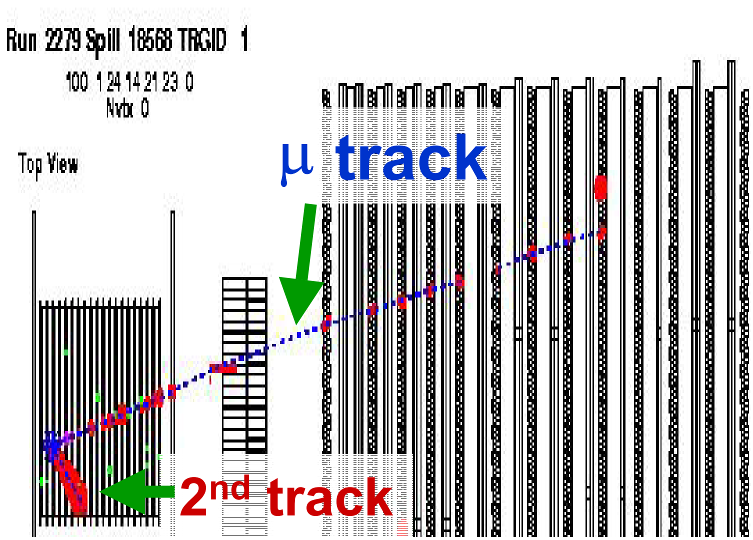
Observables at SK

- number of events (N_{SK})
- Reconstructed energy of ν (E_ν^{rec})

→ Fit the observed results at SK with ($\sin^2 2\theta, \Delta m^2$)

Use maximum likelihood fit

QE and non-QE events in SciFi 2track events

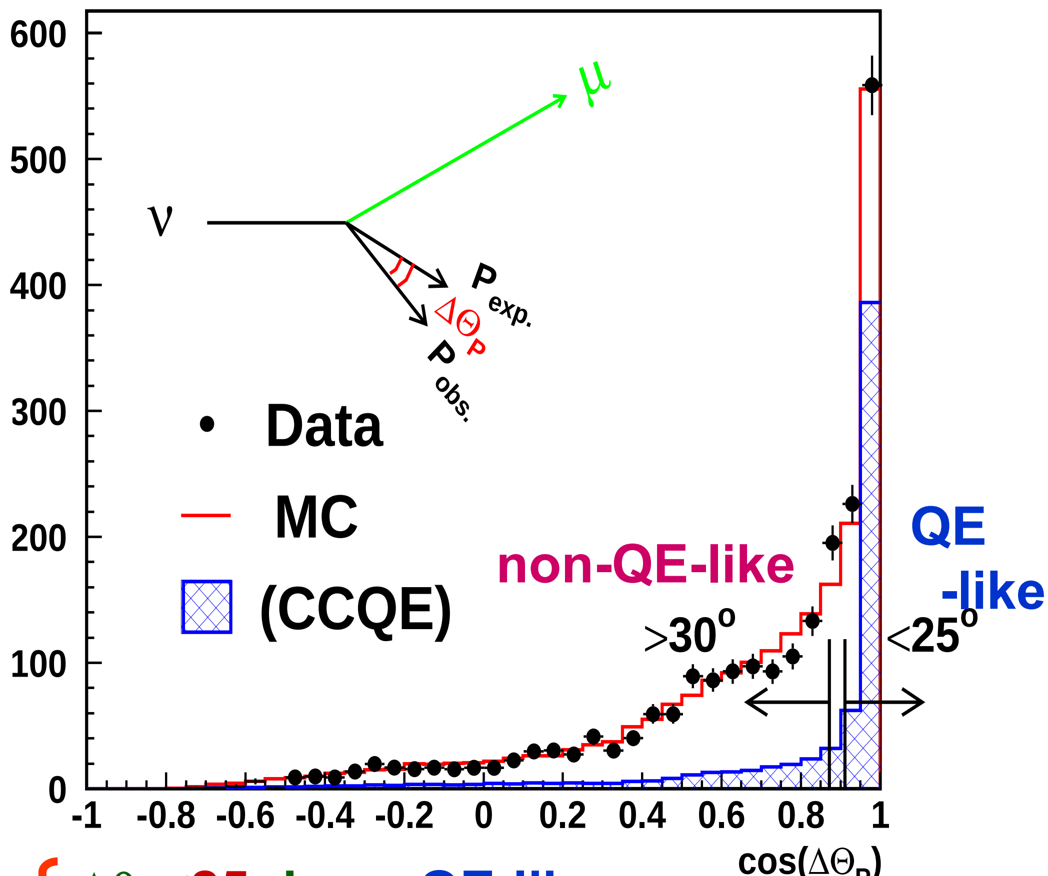


QE/non-QE selection

1. Select **2track** events
2. Select **muon track**
3. Calculate expected direction of proton θ_{exp} (assuming **QE** interaction)
4. **Compare** with the observed direction of 2nd track θ_{obs}

$\Delta\theta_p = |\theta_{exp} - \theta_{obs}|$

SciFi 2 track cos(ΔΘ$_P$) distribution



$\Delta\theta_p$**<25 deg.** : **QE-like**
$\Delta\theta_p$**>30 deg.** : **non-QE-like**

Used data for $\phi_{near}(E_\nu)$

KT

Fully Contained Fiducial Volume (FCFV) events

(0) No. of events (Evis >100MeV)

(1) Single μ-like events

SciFi

(2) 1-track μ events

(3) 2-track QE-like events

(4) 2-track non QE-like events

→ 4 sets of (p_μ, θ_μ) distributions

Pion monitor & Beam simulation

π distribution in (p_π, θ_π)

→ flux estimation $\phi_{near}(E_\nu)$ w. error

ν flux $\phi_{near}(E_\nu)$ (8 bins)

ν interaction model

(parameterized as QE/non-QE ratio)

Fitting method (ν flux at KEK)

Prepare MC templates

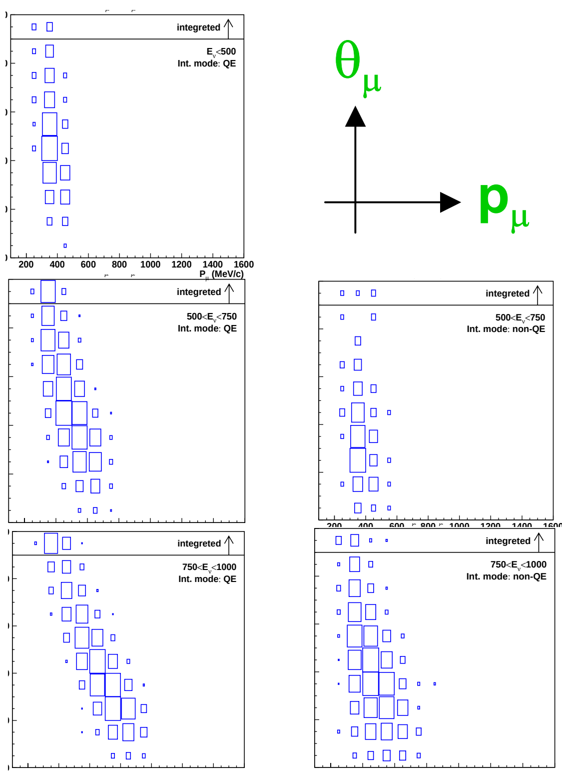
neutrino spectrum $\phi(E_\nu)$
and ν interaction model
(QE/non-QE ratio).

E_ν QE(MC) non-QE(MC)

0 ~0.5 GeV

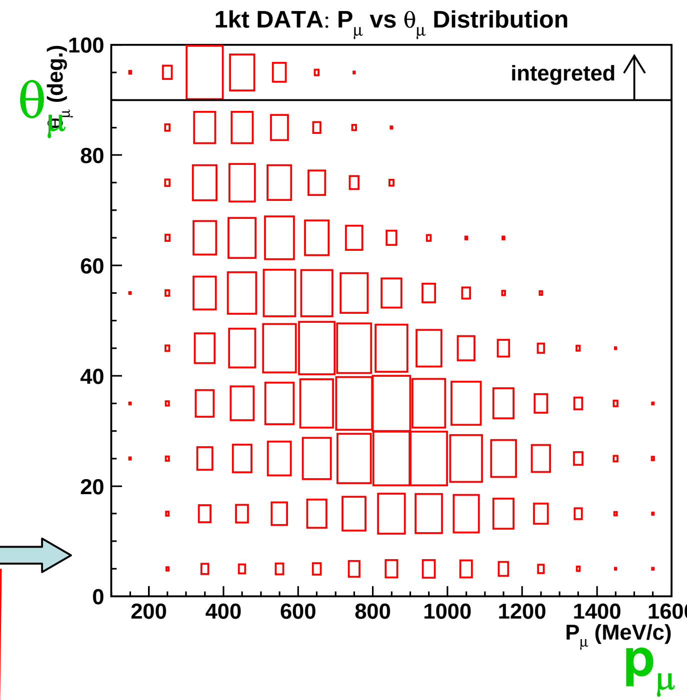
0.5 ~0.75GeV

0.75 ~1.0GeV



8bins 7bins

Measured (p_μ, θ_μ)



Fit the parameters.

$\phi(E\nu)$, QE/non-QE ratio …

χ^2=227 for 197 d.o.f.

(90 from 1kt, 137 from FGD)

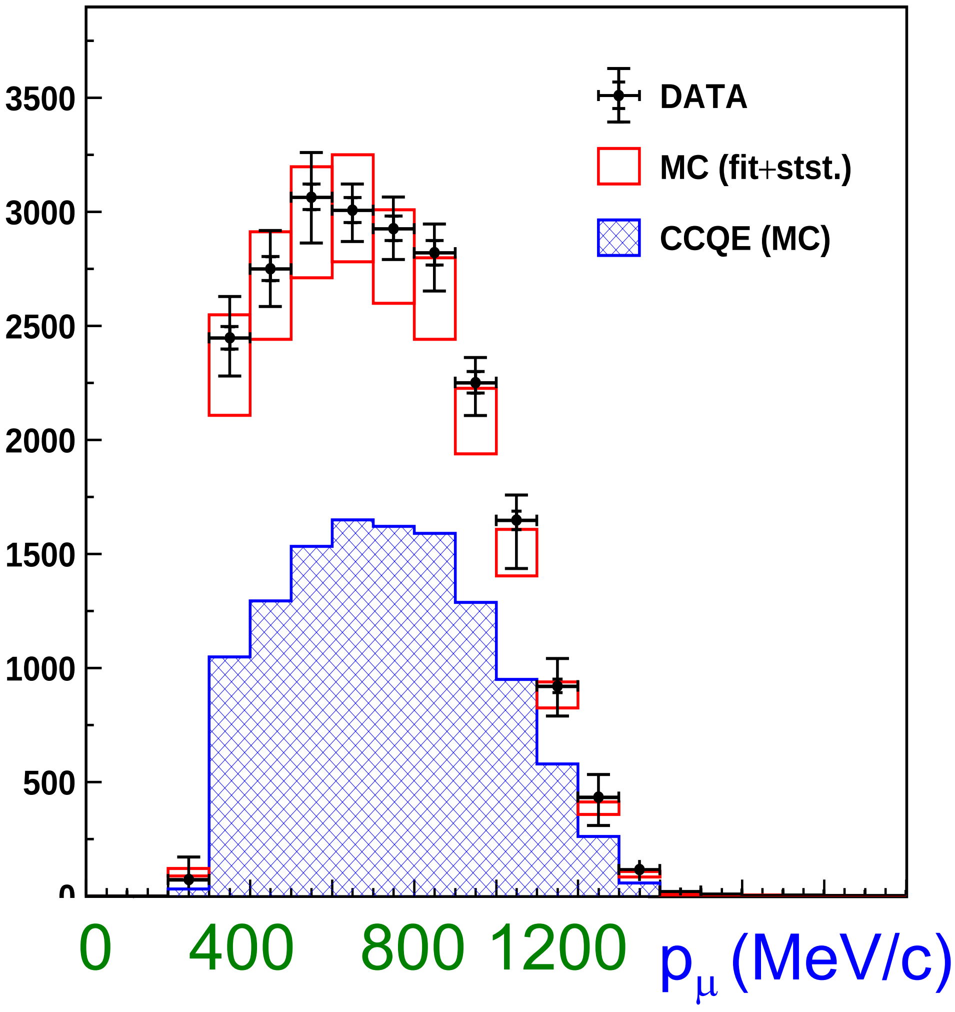
for fitted (p_μ, θ_μ) dist. of 1KT and FGD (124 data points)

Fitted results (1kt)

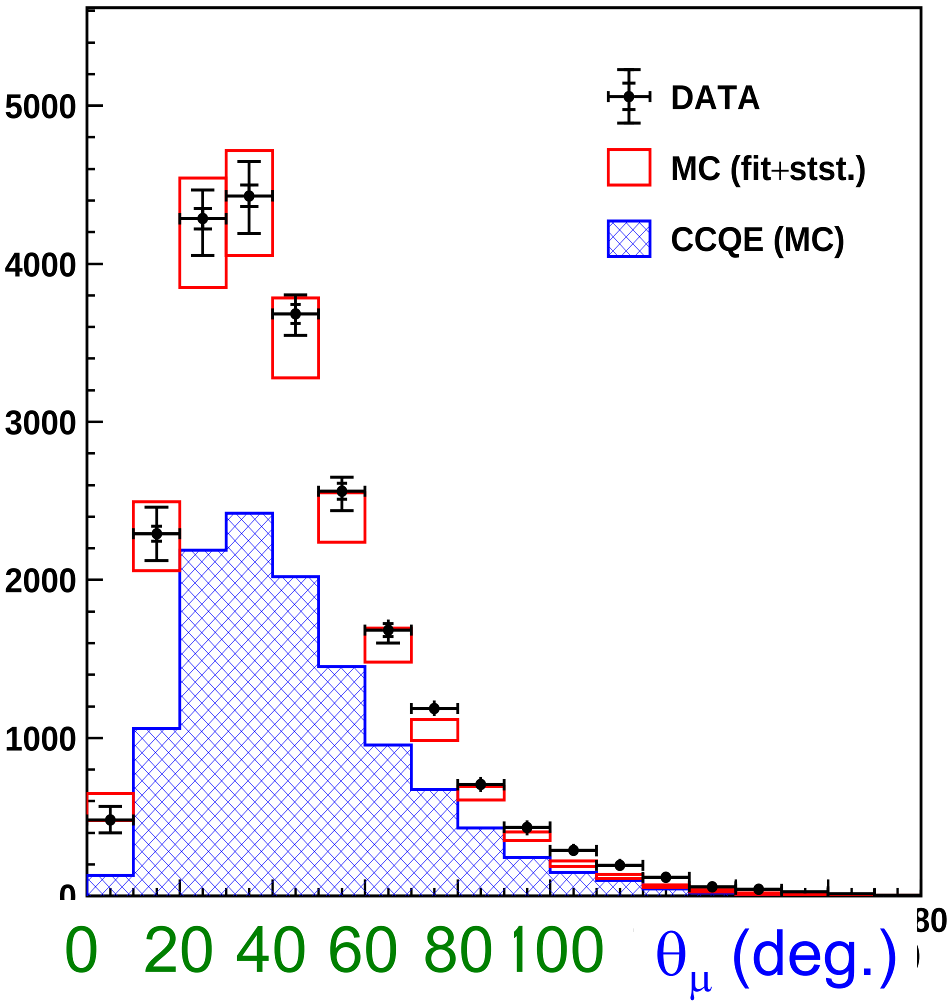
p_μ and θ_μ distributions of 1kt 1ring μ-like FCFV events

Both distributions **agree well** with the fitted MC.

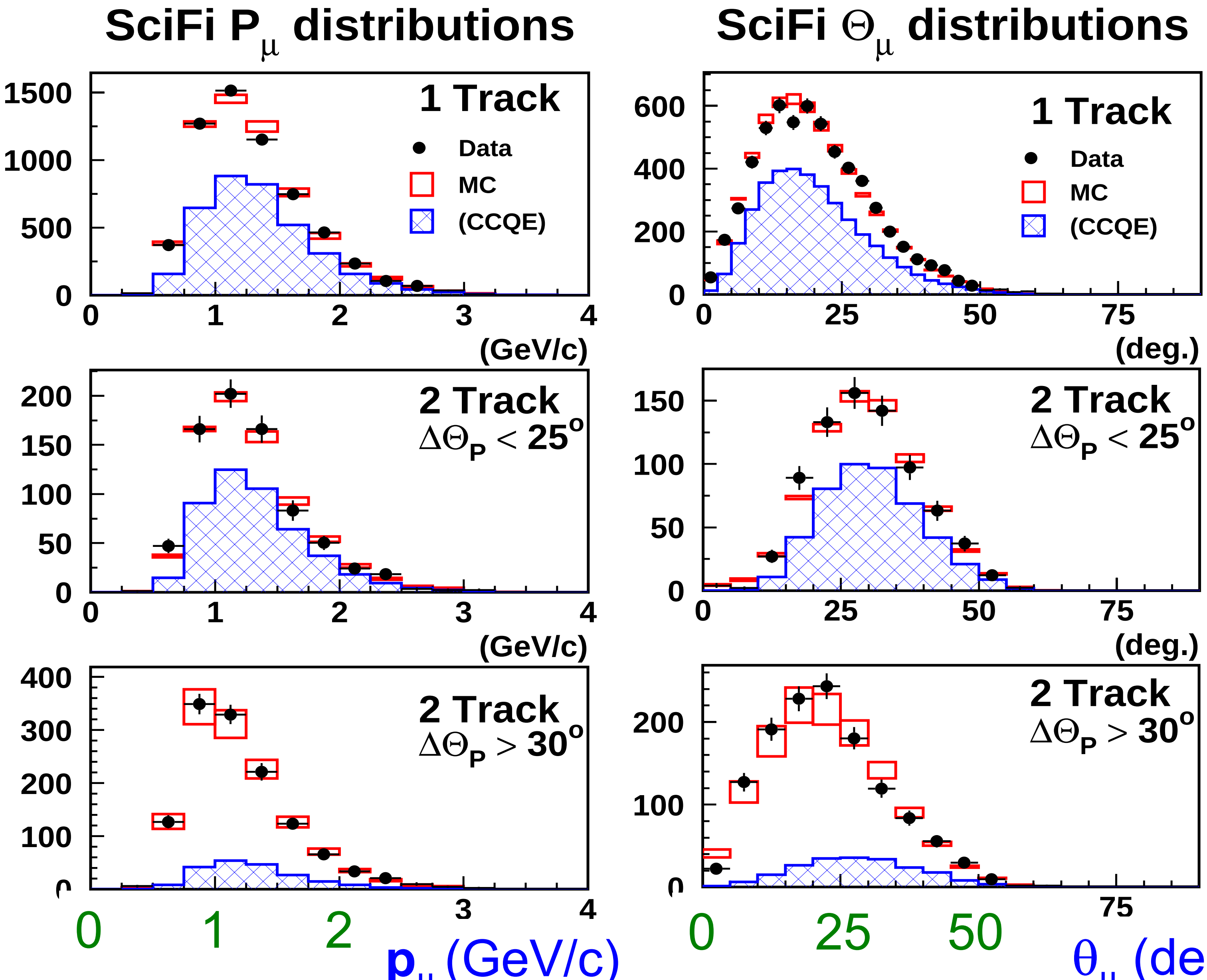
1kt: μ-momentum Distribution (Fid.25t FC 1-Ring μ-like)



1kt: μ-anglular Distribution (Fid.25t FC 1-Ring μ-like)



Fitted results (SciFi) Very good agreements



1track

2track QE like

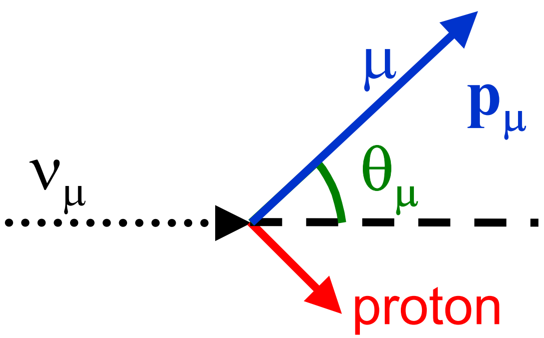
2track non-QE like

Reconstruction of neutrino energy at SK

Use **single-ring μ-like FCFV** (1Rμ) events

Assuming **QE interaction** and **reconstruct E_ν**

(**~50%** of K2K 1Rμ events are **CCQE**)



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

E_μ : muon energy

p_μ : muon momentum

θ_μ : muon angle

Oscillation analysis

1) Used data sets

1. Number of events

June '99 - July '01

FCFV events

(56 events)

2. Spectrum shape

Nov. '99 - July '01

1Rμ events

(29 events)

2) Analysis methods

1.Maximum Likelihood method

$$L_{tot} = L_{norm}(f)\, L_{shape}(f)\, L_{syst}(f)$$

Normalization term ($N_{exp} = 80.1^{+6.2}_{-5.4}$)

Shape term (for 1Rμ)

Constraint term for systematic parameters. (error matrices)

2.different treatment of systematic term.

Generate many MC samples.

(changing systematic parameters within the error.)

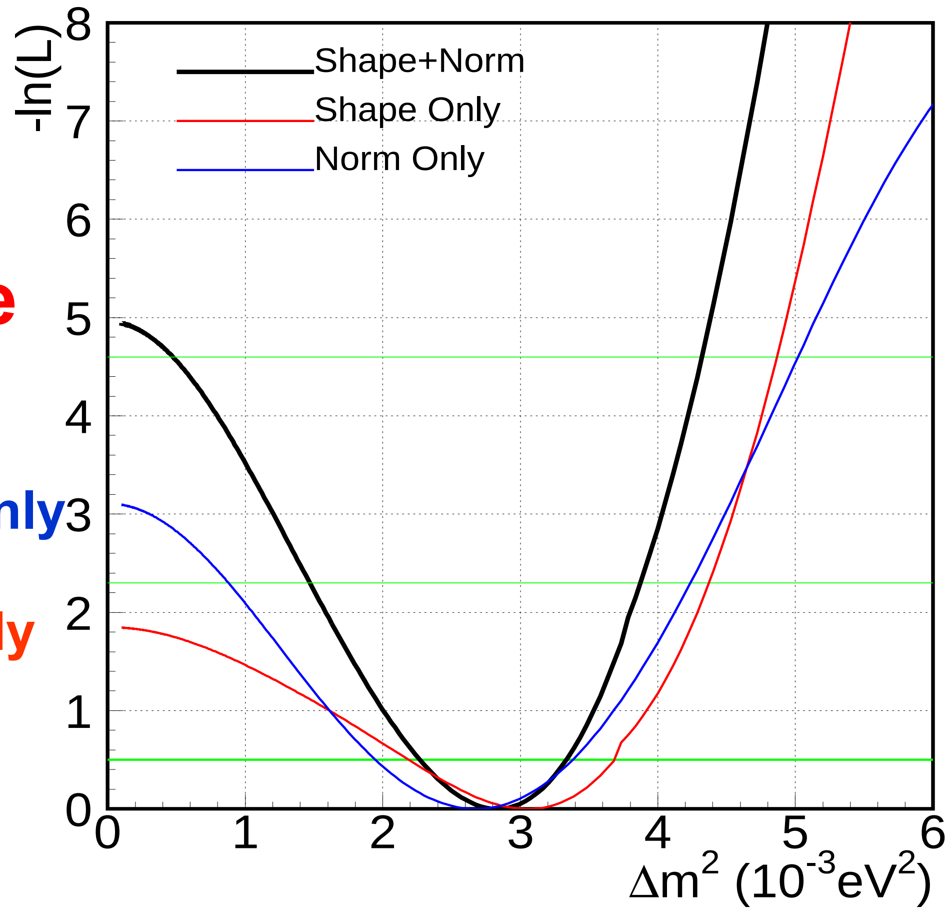
L_{tot} = ***weighted mean of L for the MC samples***

Allowed Δm^2 by N_{SK} and shape analysis

N_{SK} + Shape

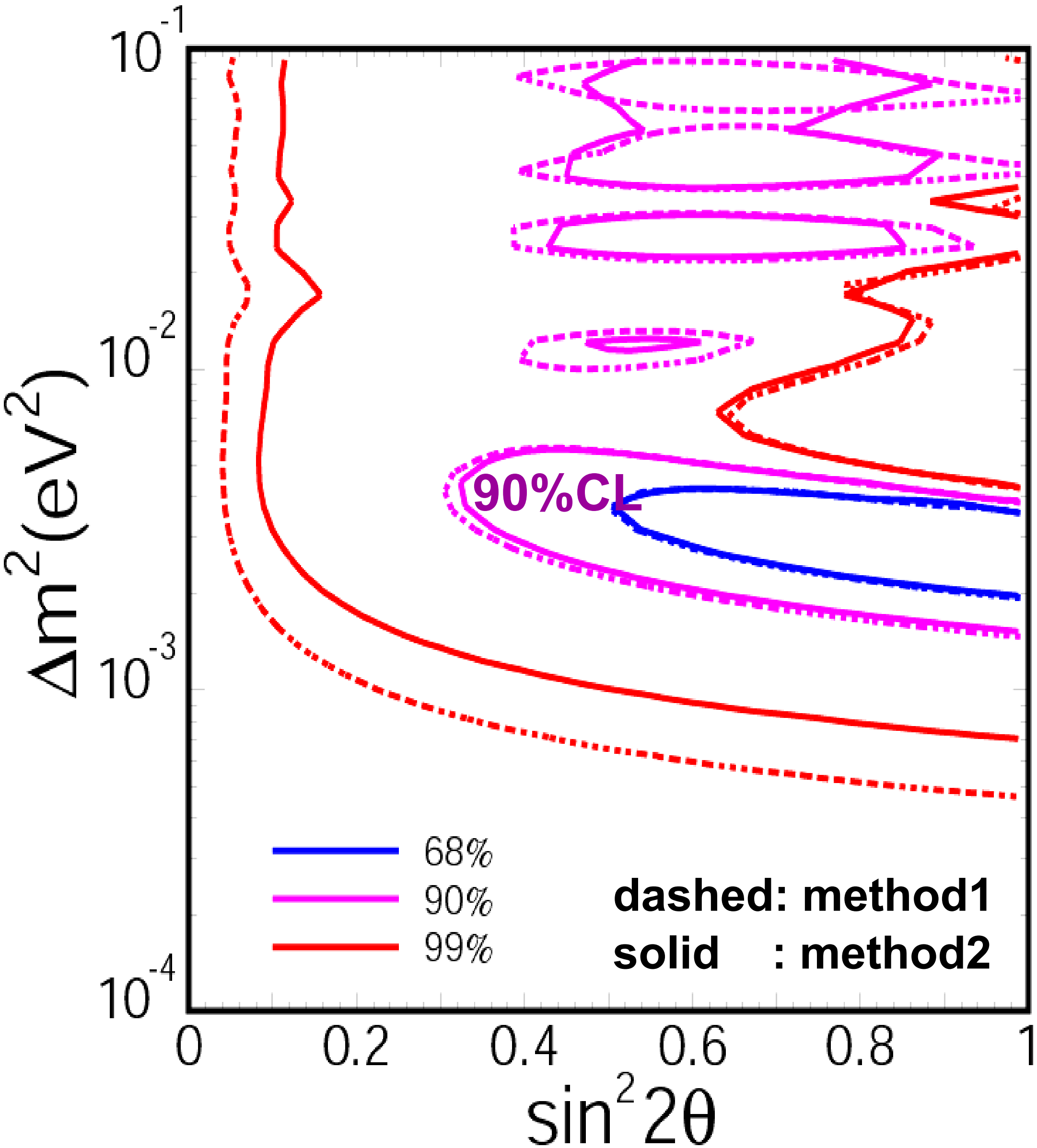
Number of Events only

Spectrum Shape only



N_{SK} and shape analysis indicate the same Δm^2 region for $\sin^2 2\theta=1$

Allowed regions



Δm^2=1.5~3.9 x 10^{-3} eV^2

@$\sin^2 2\theta = 1$(90%CL)

Best fit parameters

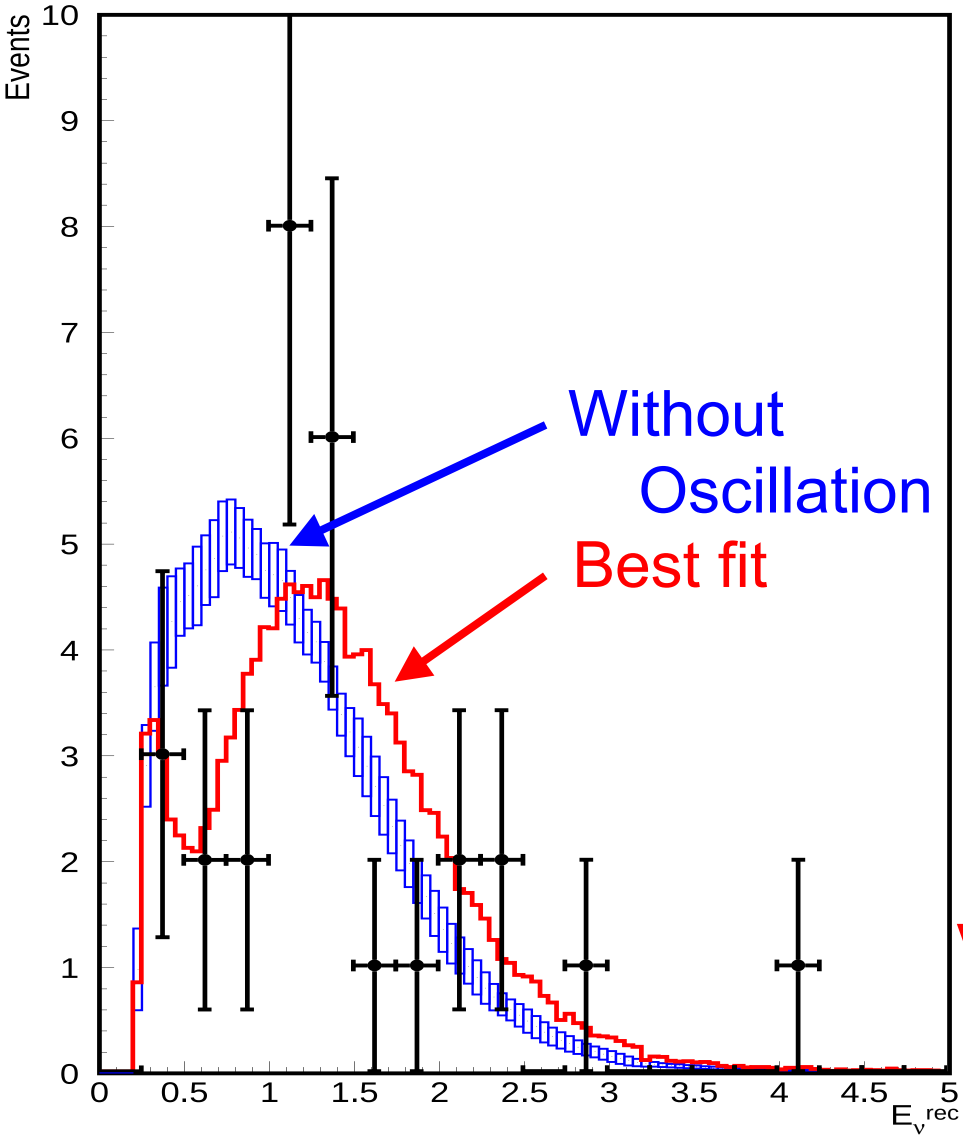
$(\sin^2 2\theta, \Delta m^2)$

=(1.0 , 2.8x10^{-3} eV^2)
[Method-1]

=(1.0 , 2.7x10^{-3} eV^2)
[Method-2]

Best fit results

Reconstructed energy of neutrino for 1Rμ and N_{SK}



Best fit parameters ($\sin^2 2\theta, \Delta m^2$)

$=(1.0\ ,\ 2.8\times10^{-3}\ eV^2)$

- **N_{SK}**

  Expected (W/osc.) **= 54**

  Observed **= 56**

- **Shape**

  KS test **79%**

Very good agreements

Both **shape** and **N_{SK}**

Null oscillation probability

Use Δlog(likelihood) from best fit point in the physical region

	method-1	method-2
N_{SK} only	1.3%	0.7%
Shape only	15.7%	14.3%
N_{SK} + Shape	**0.7%**	**0.4%**

Probability of null oscillation

is **less than 1%.**

Summary

K2K Oscillation analysis on June'99 ~ July '01 data

Full and Improved error estimations
and **spectrum shape analysis**

Use both Number of events + Spectrum shape
(June '99 – July '01) **(Nov. '99 – July '01)**

- Null oscillation probability is less than 1%.
- Spectrum shape distortion
  and observed # of events @SK
  indicates consistent oscillation parameter regions.

- Oscillation parameters ($\sin^2 2\theta$ and Δm^2) are
  consistent with the atmospheric ν results.

Δm^2=**1.5~3.9 x 10^{-3}** eV^2 @$\sin^2 2\theta=1$(90%CL)

(c.f. ATM ν : Δm^2=**1.6~3.9 x 10^{-3} eV^2** @$\sin^2 2\theta=1$(90%CL))