May 27, 2002

長基線ニュートリノ振動実験（K2K）実験の現状

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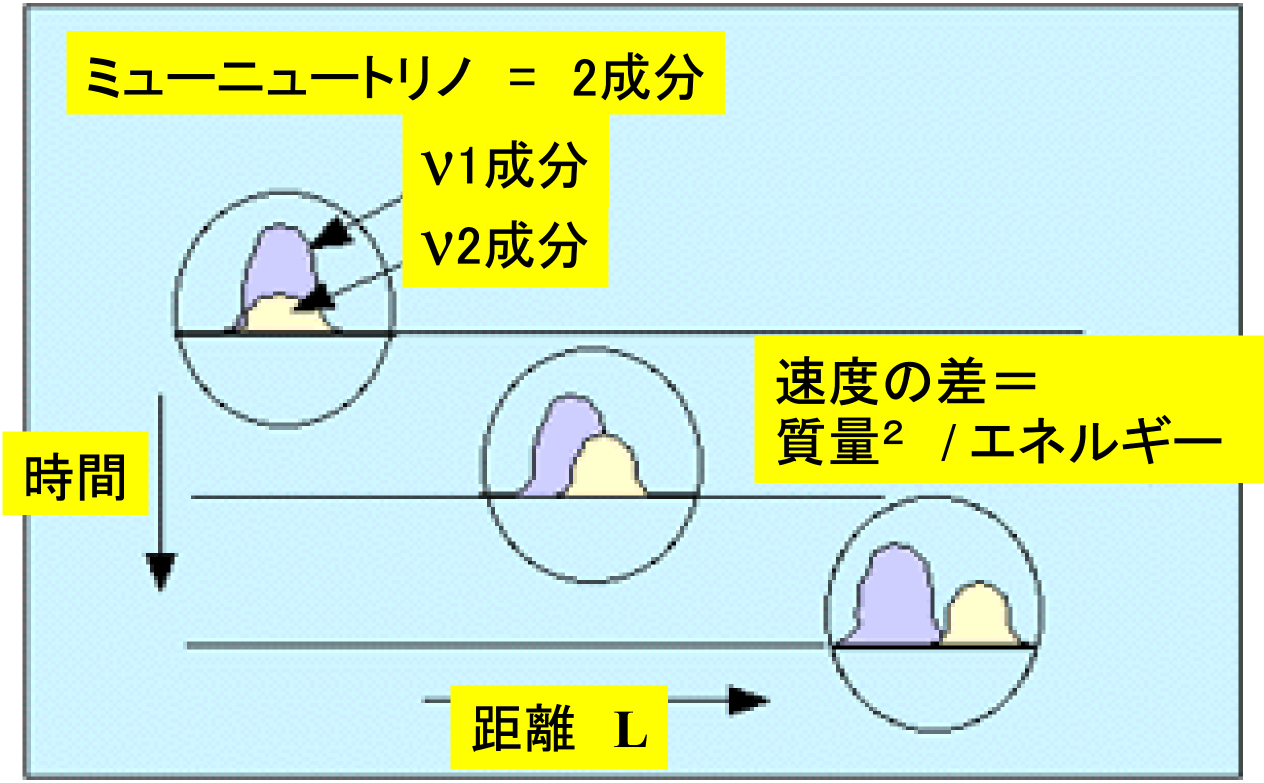
Based on the talk by K.Nishikawa, Neutrino 2002 @ Munich
May 26, 21:50~(JST)

1. Introduction to Introduction
2. Introduction
3. Spectrum measurement at front detector
4. Far/near Extrapolation
5. Oscillation analysis
6. Conclusions

Neutrino oscillation



ミューニュートリノ

μ : τ =1:0

|μ> =-s|1> +c |2>

(|τ> = c |1> +s |2>)

長距離

↓

- |1>=s| μ>−c|τ>
  μ : τ =s² (s²:c²)
- |2>=c|μ>+s|τ>
  μ : τ =c² (c²:s²)

μ : τ =s⁴+c⁴ : 2*s²c²

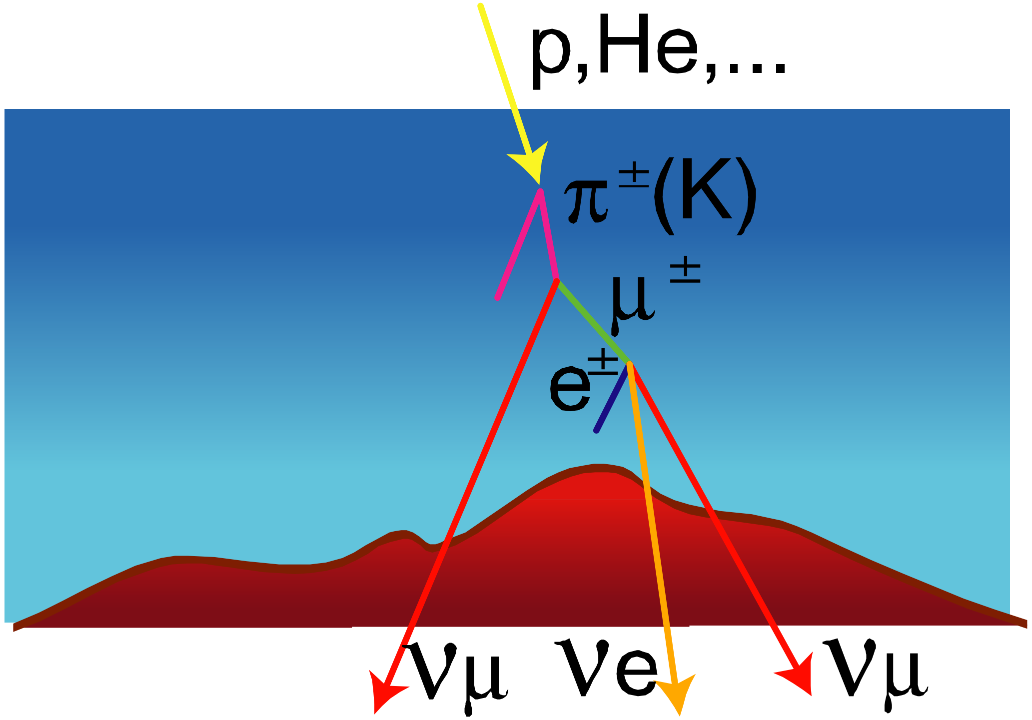
$$時間差＝\frac{L}{速度の差}=\frac{\Delta m^2 \times L}{E}$$

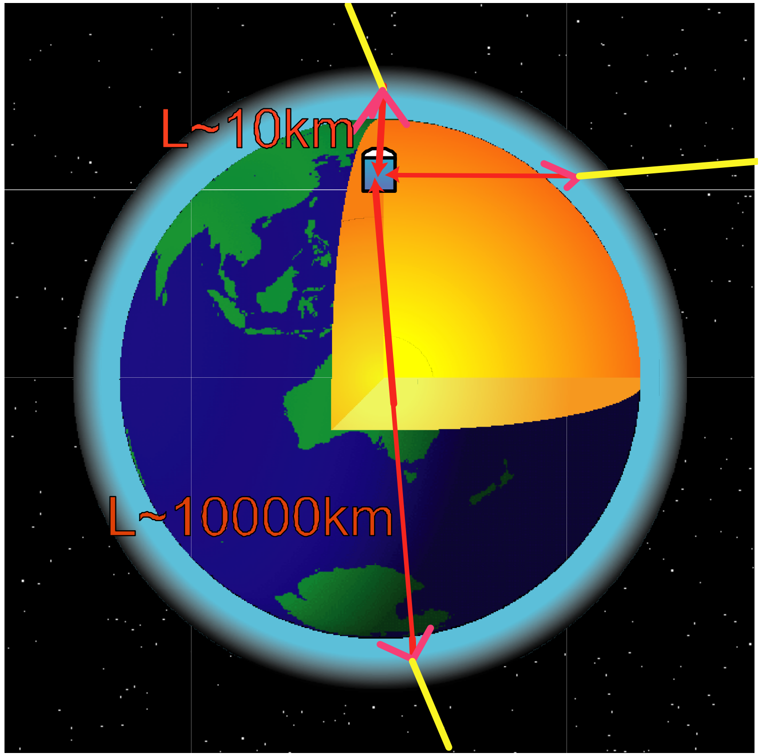
$$P = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2(eV^2)L(km)}{E_\nu(GeV)}\right)$$

有限な質量

スーパーカミオカンデによる
大気ニュートリノの観測(1996～)

大気ニュートリノ





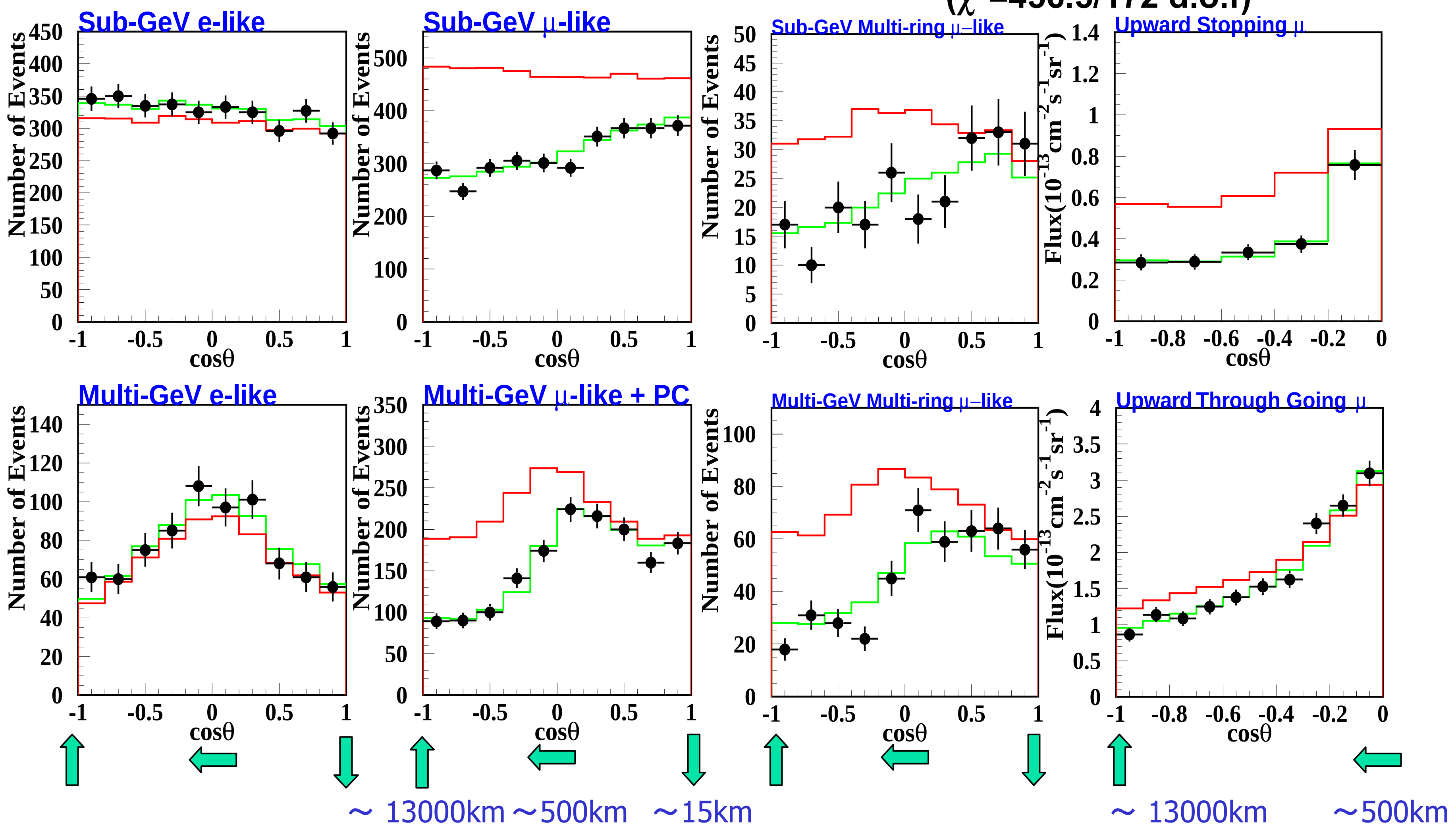
Zenith angle distributions (FC+PC+up-μ)

Neutrino2002
M.Shiozawa

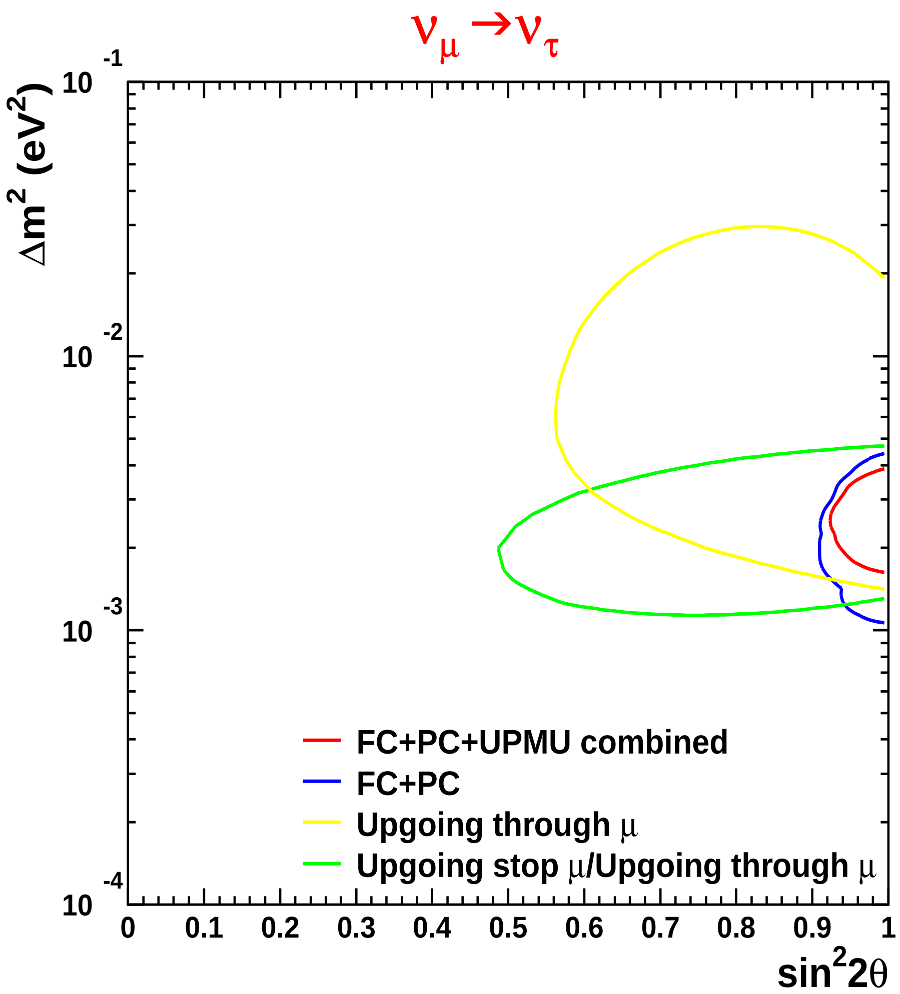
$\nu_\mu \leftrightarrow \nu_\tau$
2-flavor oscillations

Best fit (Δm^2=2.5x10^{-3}eV^2, $\sin^2 2\theta$=1.0
χ^2_{min}=163.2/170 d.o.f)

Null oscillation
(χ^2=456.5/172 d.o.f)



大気ニュートリノの結果 (Neutrino2002, May26,2002, M.Shiozawa)



$\nu_\mu \leftrightarrow \nu_\tau$ oscillations

Best fit($\Delta m^2=2.5\times10^{-3}$,$\sin^2 2\theta=1.0$

χ^2_{min}=163.2/170 d.o.f)

No oscillation

(χ^2 =456.5/172 d.o.f)

$\Delta m^2 = (1.6\sim3.9)\times10^{-3} eV^2$

$\sin^2 2\theta > 0.92$ @ 90%CL

K2K実験(1999年開始)

人工ニュートリノを使って大気ニュートリノの結果を検証

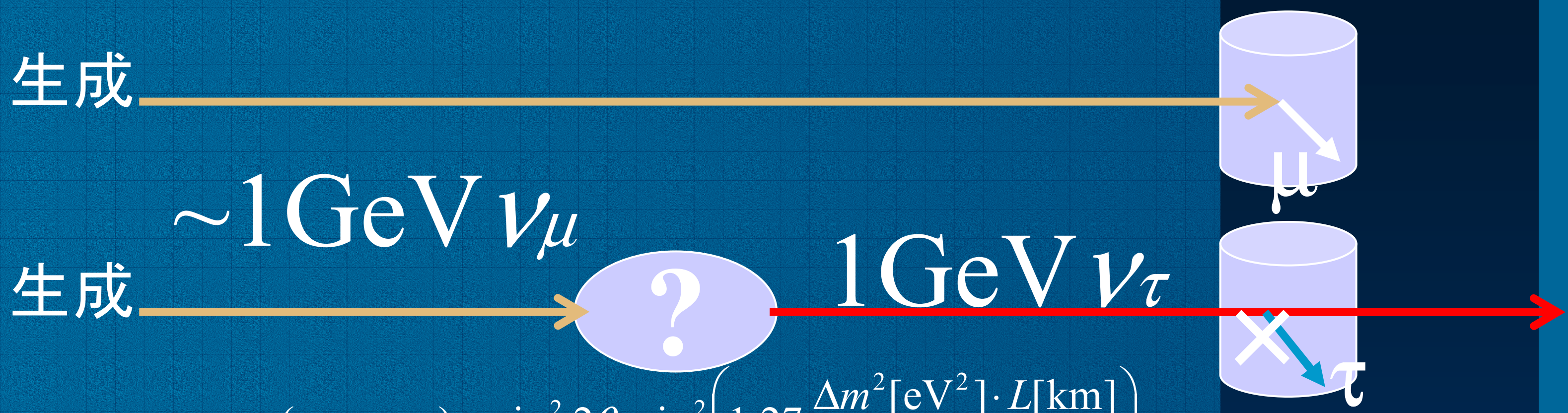
①KEKの12GeV陽子シンクロトロンを用いてν_μビーム(～1GeV)を生成。

②250km離れたスーパーカミオカンデ(SK)に向けて撃ち出す。

③SKでKEKからのニュートリノを検出し、その数、種類、エネルギー分布を測定する。

- **ミューオンニュートリノ消失実験(νμ disappearance)**
- （電子ニュートリノ出現実験: νe appearance）

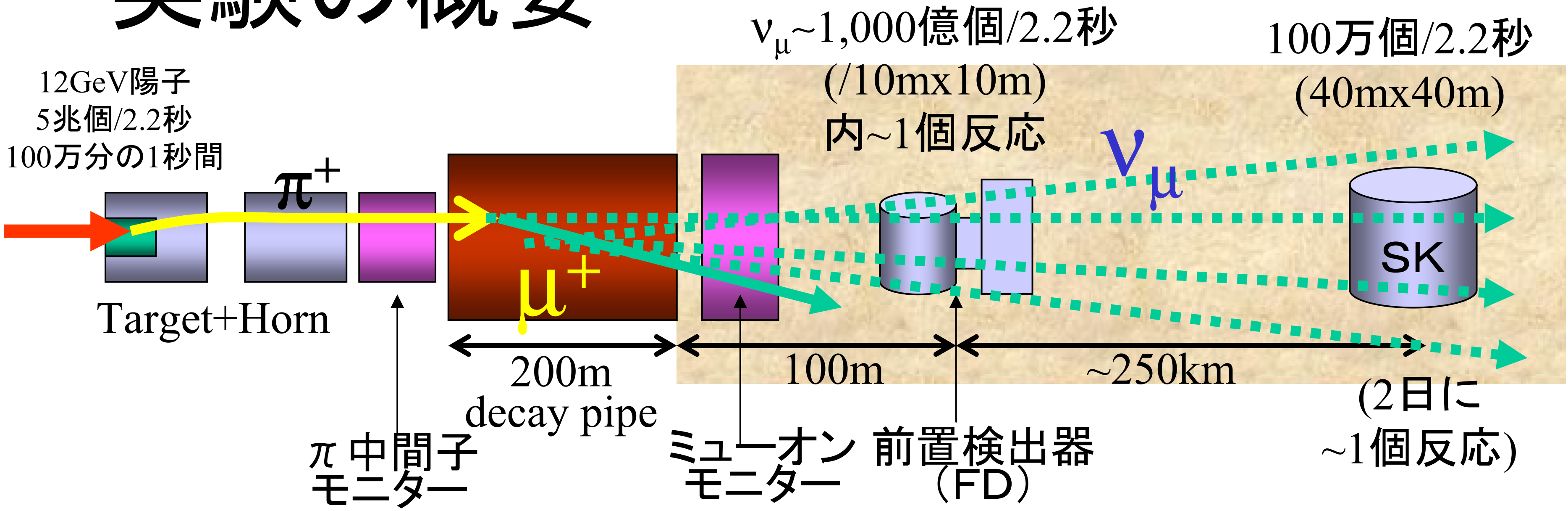
ミューオンニュートリノ消失実験（ν_μ disappearance）



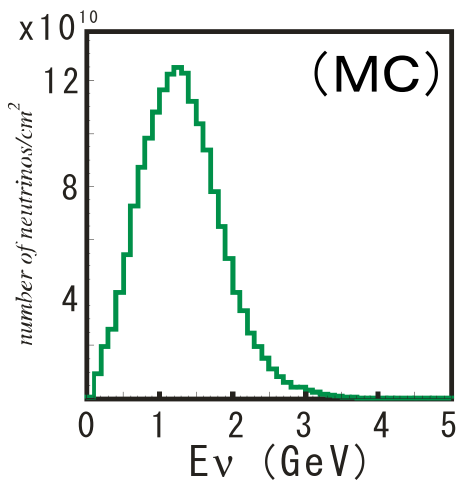
$$p(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \cdot \sin^2\left(1.27\frac{\Delta m^2[\mathrm{eV}^2]\cdot L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)$$

- ニュートリノ反応、識別
  - ν_l+X→l+X'
  - 生成されるレプトンで識別(eならν_e, μならν_μ,..)
- 反応閾値
  - ν_μ→μ:110MeV, ν_τ→τ: 3.5GeV (生成レプトンの質量による)
  - 1GeV ν_μが振動してν_τ (1GeV) : 反応できない
- 信号
  - 振動していない場合に比べ、ニュートリノ反応の数が減る。
  - 残ったν_μのエネルギーはニュートリノ振動に特有の分布を示す

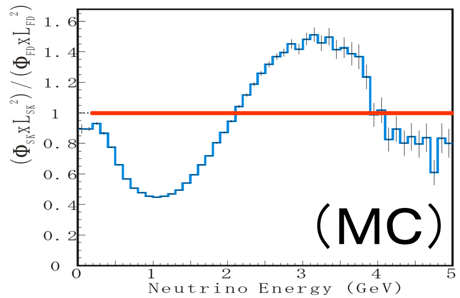
実験の概要



生成時のνμスペクトル



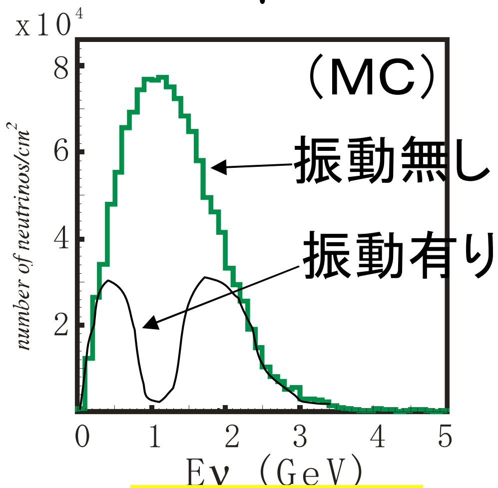
前置検出器で測定



スペクトルの比≠1

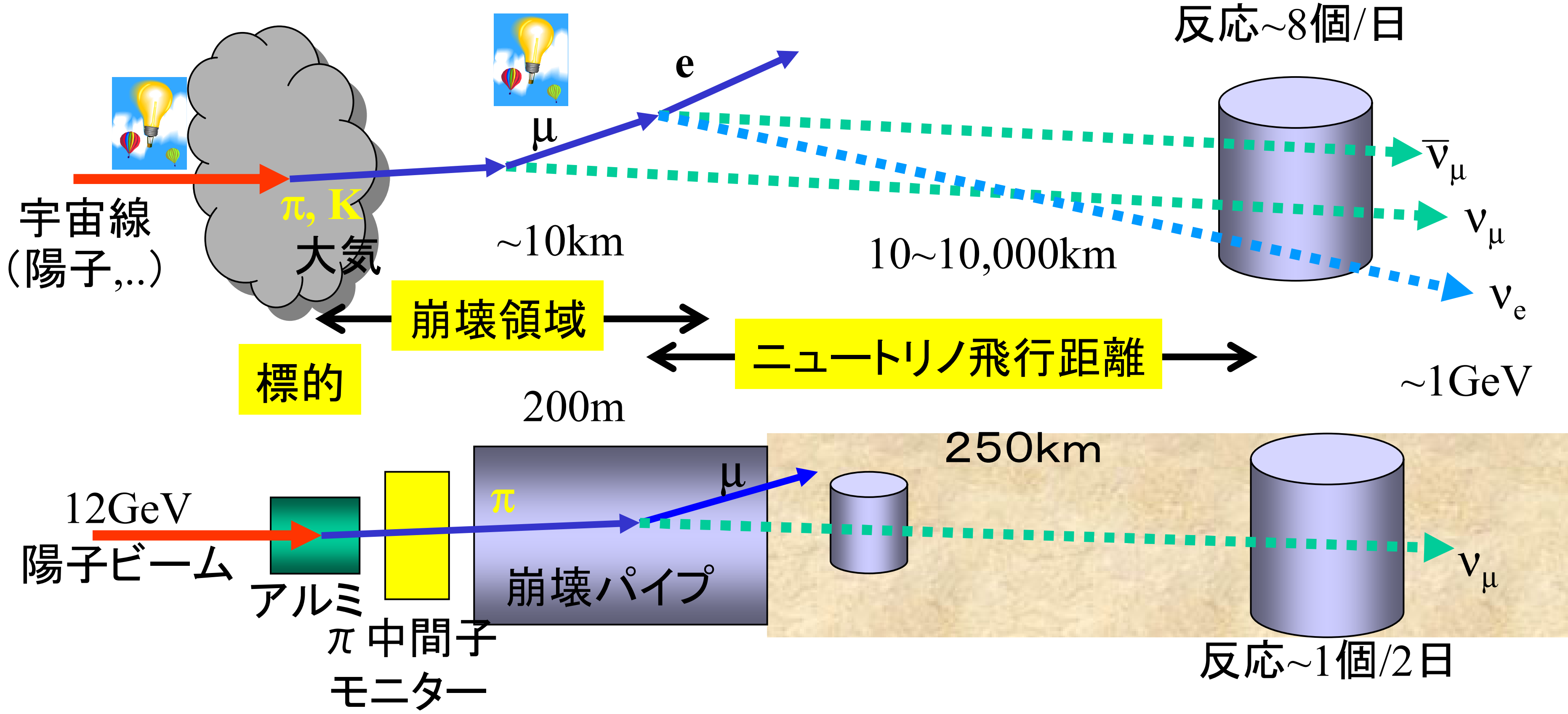
π中間子モニターで測定

SK到達時のνμスペクトル



観測と比較

大気ニュートリノ vs K2K



- K2K: ~100% νμ, Atm: νμ:νe~2:1
- K2K:ニュートリノの飛行距離決まっている。(250km) ➔ 特にΔm^2測定に高感度
- K2K:ニュートリノの方向決まっている。
  →一部の反応生成粒子から親ニュートリノのエネルギー算出可能
- K2K:生成直後のπ中間子、振動前ニュートリノの(数、エネルギー分布)直接測定
- Atm: 反応数大
- Atm:広いΔm^2探索可能"discovery machine", 加速器実験:狙いを絞った"精密実験"

K2K results

Results of
Total Event Rate & Spectrum Shape Analysis

K2K collaboration

K.Nishikawa
Kyoto University
NEUTRINO 2002, May 26,2002
Munich, Germany

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

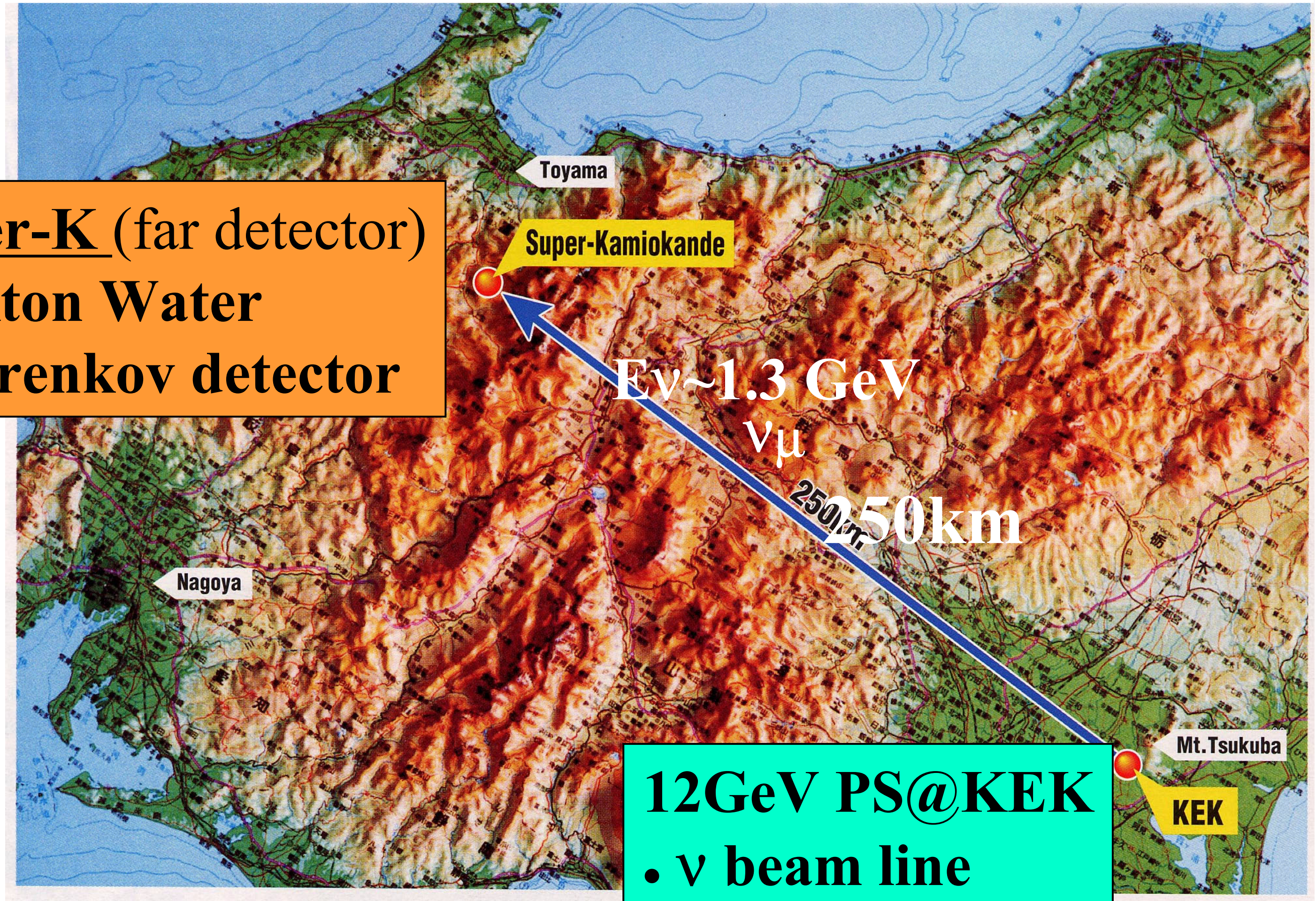
Chonnam National University
Dongshin University
Korea University
Seoul National University

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

<u>K</u>EK to <u>K</u>amioka Neutrino Oscillation Experiment

<u>Super-K</u> (far detector)
50 kton Water Cherenkov detector



12GeV PS@KEK

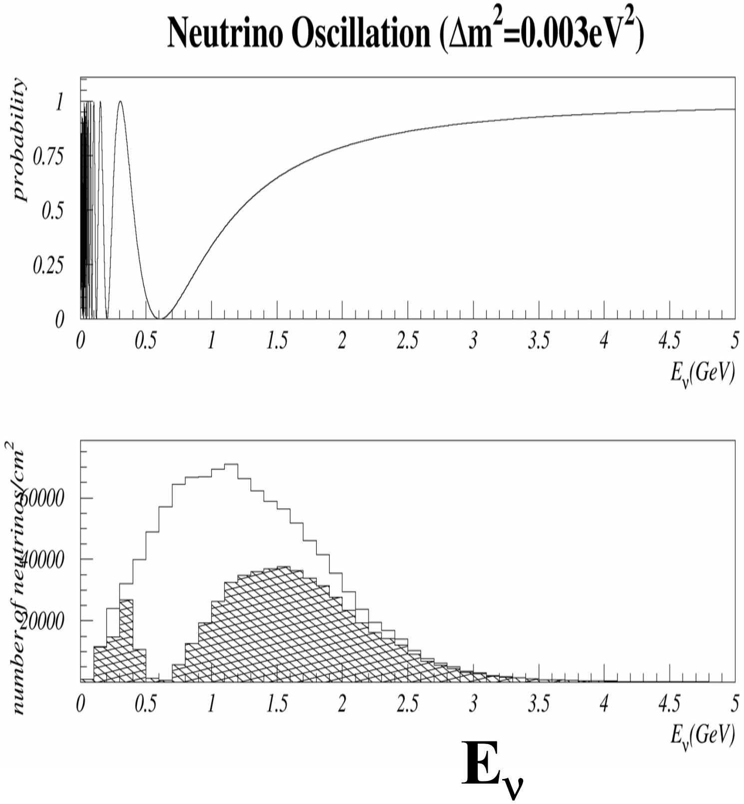
- **ν beam line**
- **Beam monitor**
- **Near detectors**

Principle of K2K

Fixed distance
(E_ν~1.3 GeV, L=250km)
(99% ν_μ, $\sigma_\tau << \sigma_\mu$)

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

Results
- **Reduction of events**
- **Spectrum distortion**



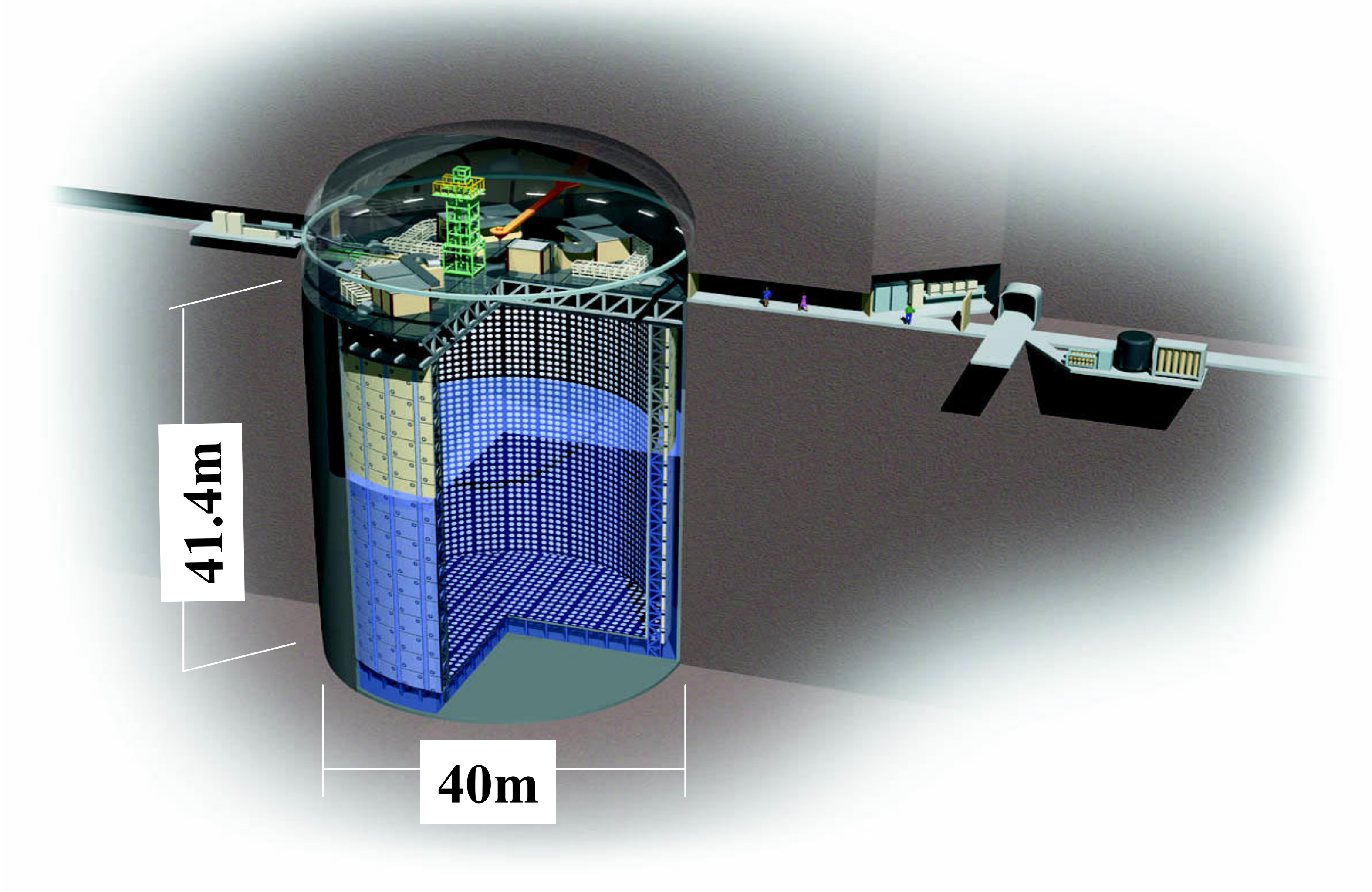
- **Neutrino beam at near site**
- **Near to Far extrapolation**
- **Rate and spectrum shape @ SK**

（April 1996 commissioned）

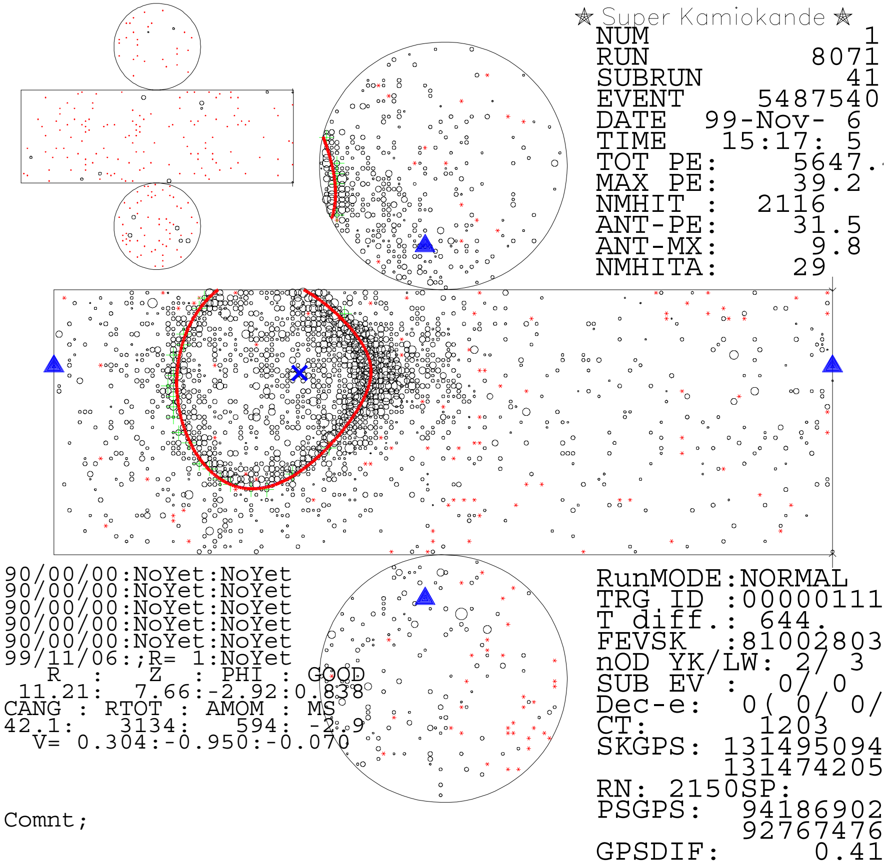
Super-Kamiokande

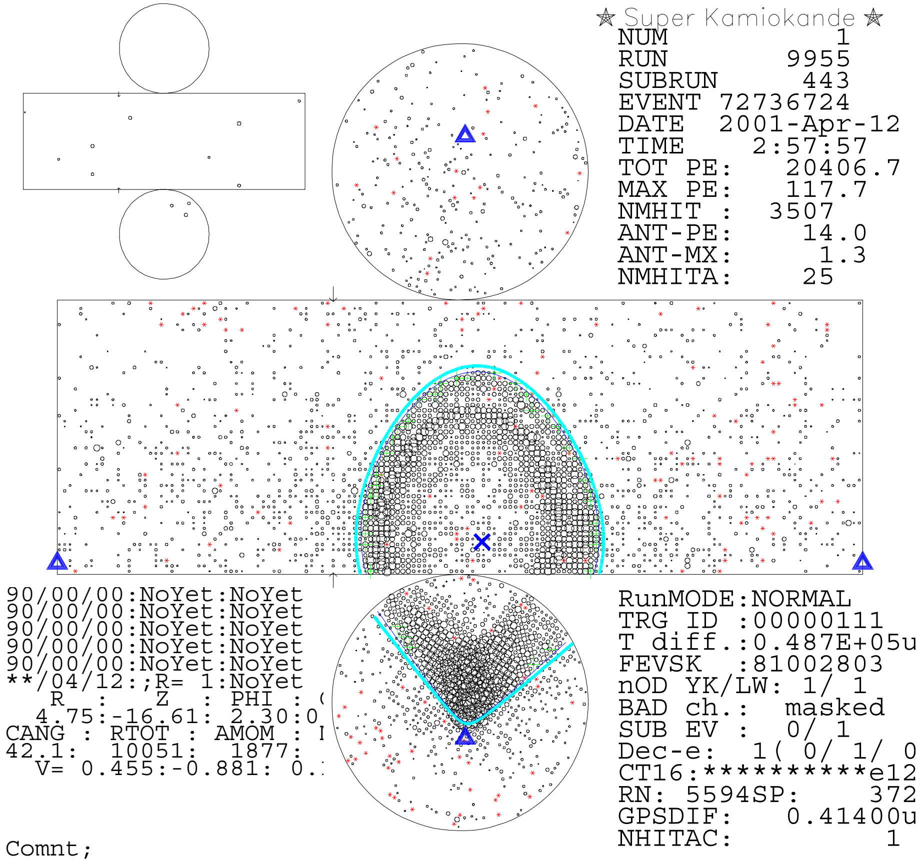
50,000 ton water Cherenkov detector (22.5 kton fiducial volume)

Optically separated INNER and OUTER detector



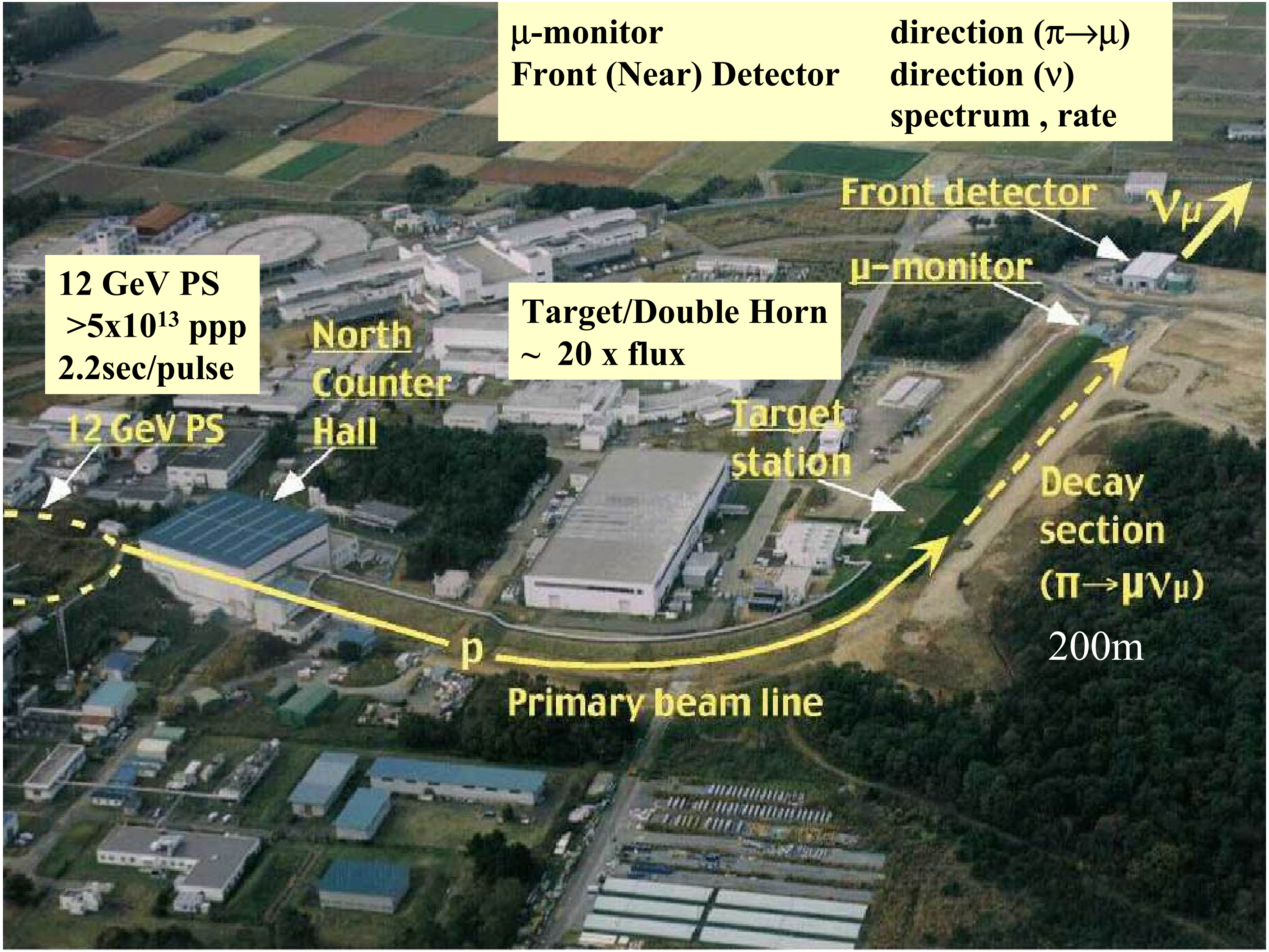
e-like and μ-like events in Super-Kamiokande



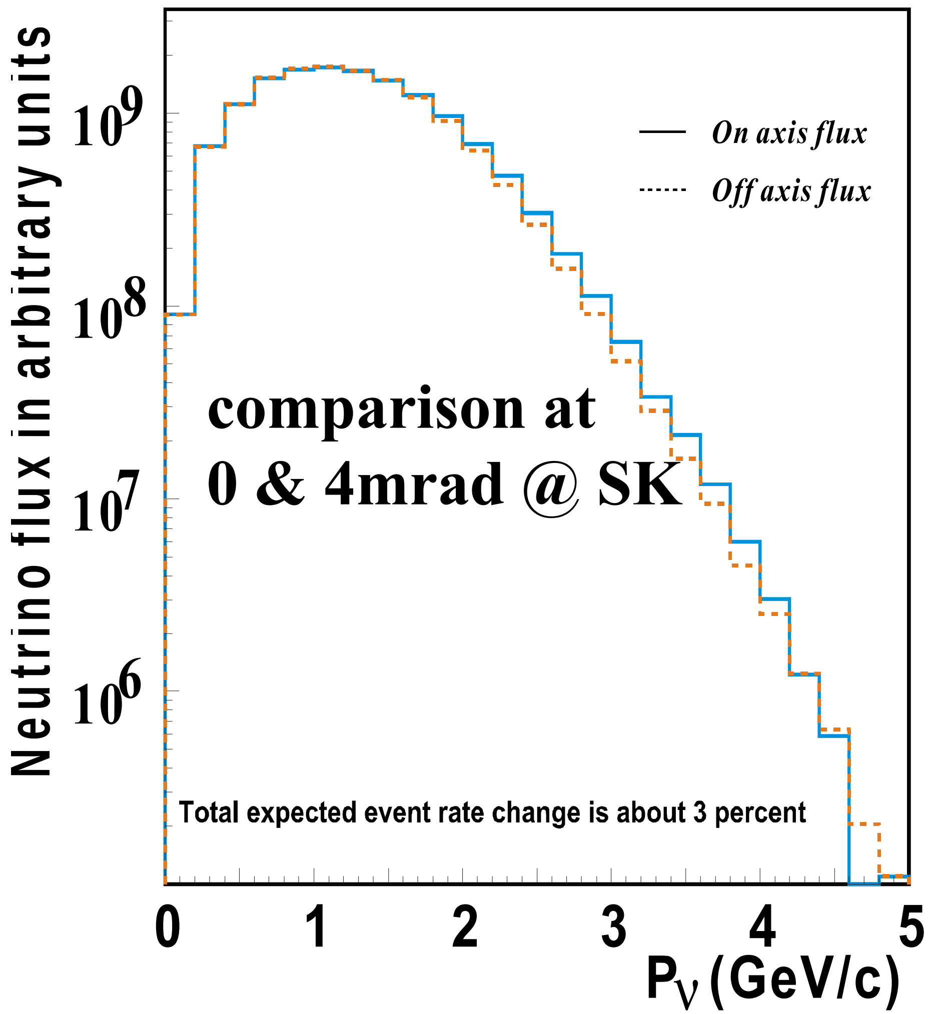


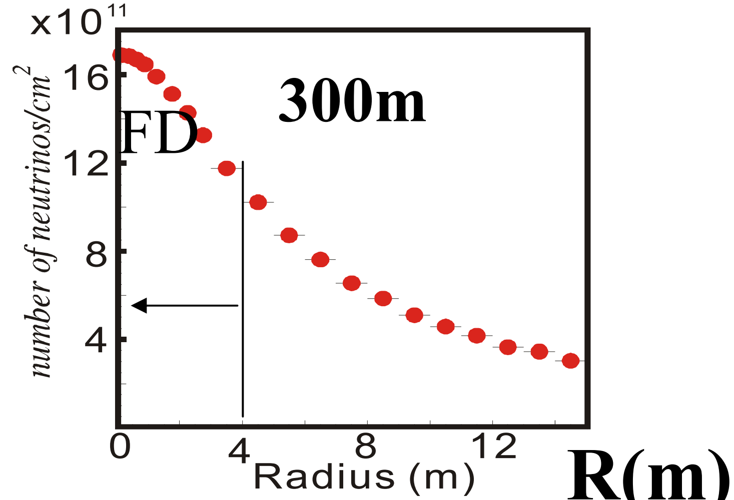
Total rate with low threshold (>30MeV)

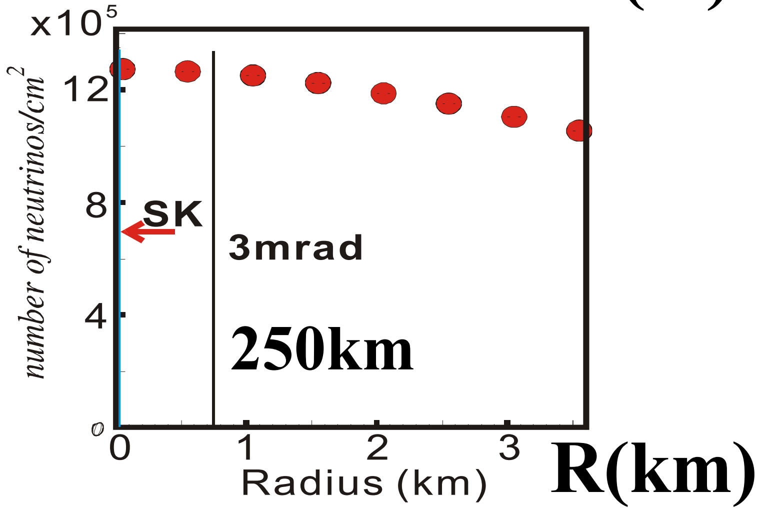
Identification of μ (1Rμ) , e (1Re)


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

Expected (MC) Neutrino Spectra and Radial Distributions at 300m/250km





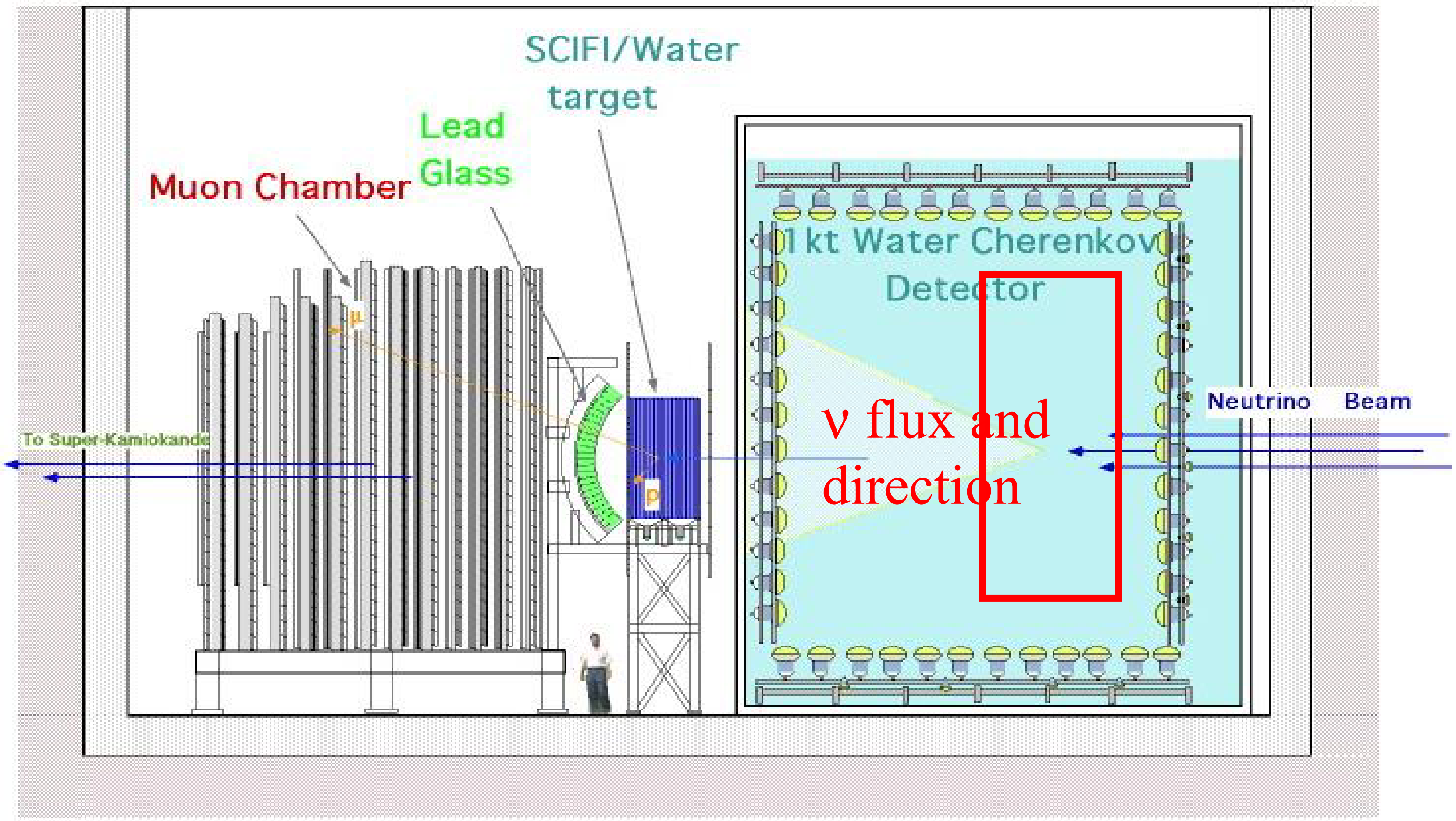


1km(4mr) off axis @ SK no change in rate and spectrum

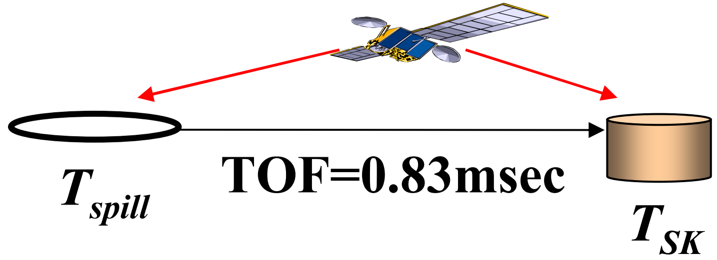
Near Detectors

At KEK: **1kt Water Cherenkov detector (KT) 25 ton fiducial**

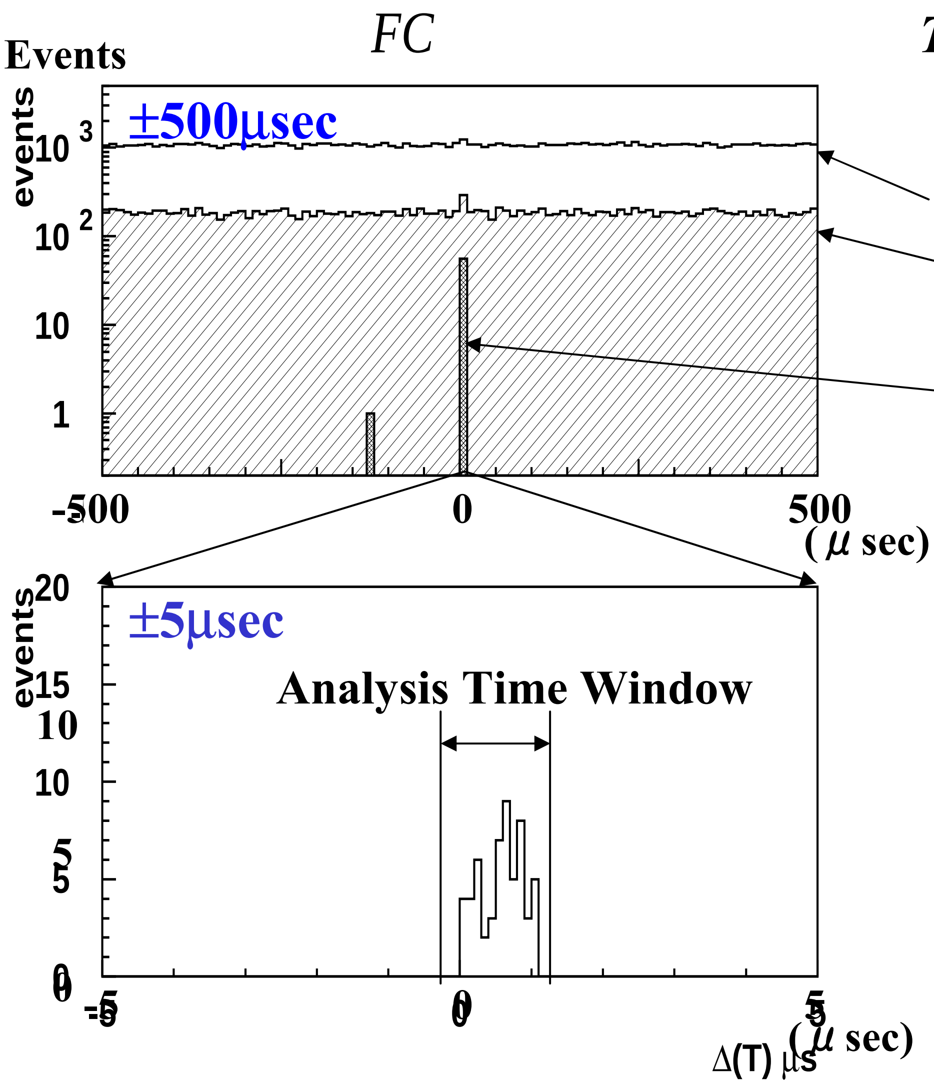
+ **Water tube sandwitched Scintillation fiber detector (SciFi) 6 ton**
+ **Muon range detector(MRD) 700 ton direction by ν & stability**
+ **Lead glass detector (LG)**



Super-Kamiokande Event Selection



GPS



Not a Decay Electron Event

More than 20MeV Deposited Energy

No Activity in Outer Detector
Event Vertex is in Fiducial Volume
More than 30MeV Deposited Energy

56 Events

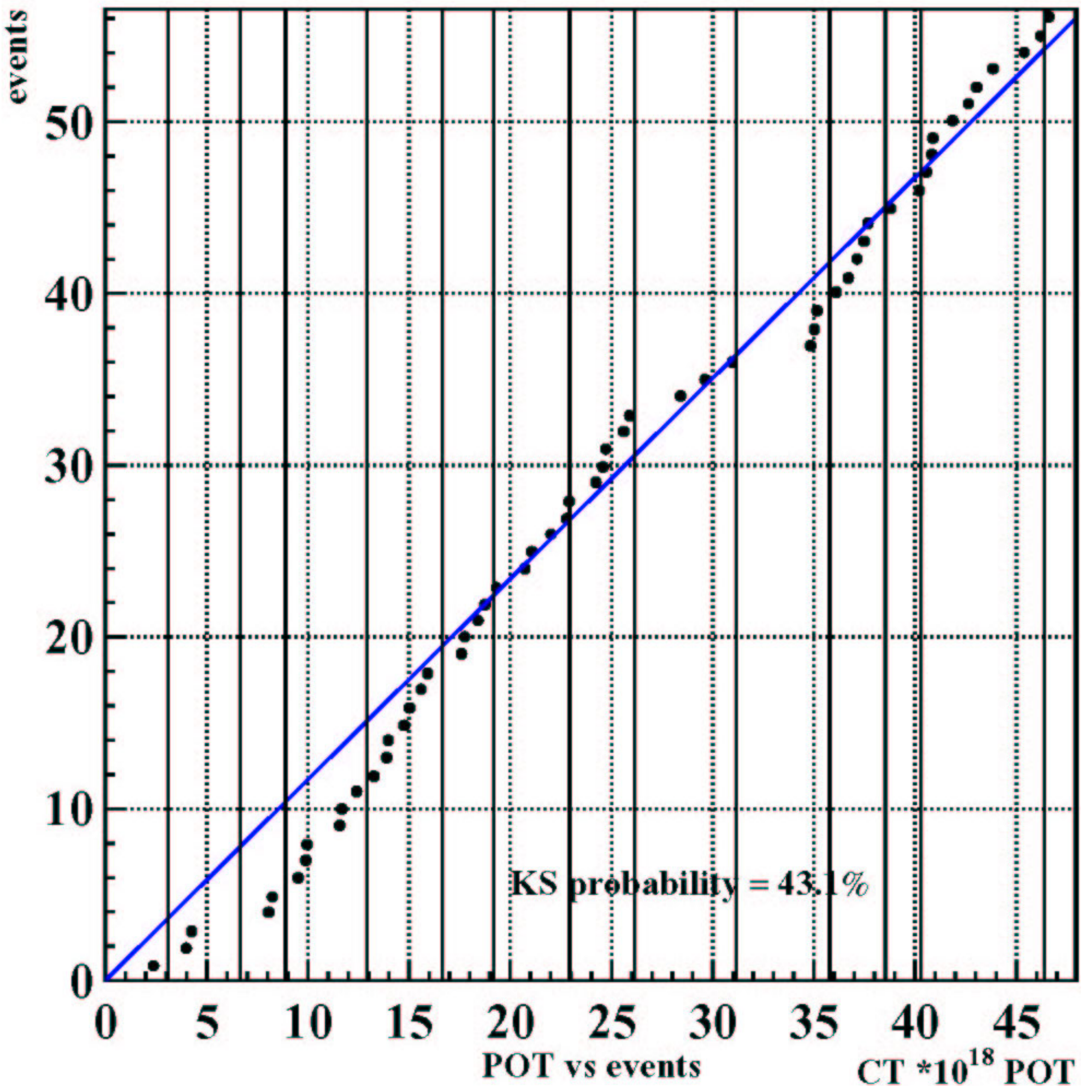
in

$$-0.2 < T_{SK} - T_{spill} - \mathrm{TOF} < 1.3\mu\mathrm{sec}$$

Analysis Time Window

(B.G. ~10^{-3} in 1.5μs Window)

Event POT distribution



KS test probability

43%

Summary of K2K results in last year

- **Accumulated 4.8×10^{19}POT @ SK from Jun '99 to July '01.**
- **Neutrino beam is well under control**
  - **direction<1mrad. (pulse by pulse $\pi\rightarrow\mu$, ν interaction vertex profile)**
  - **Stability of $E\mu$ spectrum from ν interaction**
- **# of fully contained events in fiducial volume (FCFV)@ SK**

  Observed: 56, Expected with null oscillation $80^{+7.3}_{-8.0}$

  Probability of null oscillation < 3%

•Full & improved error estimates

•Spectrum shape analysis

Flow of Neutrino Oscillation Analysis

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
- $S_{SK}(E_\nu^{rec})$:1Rμ E_{rec}distribution(shape)

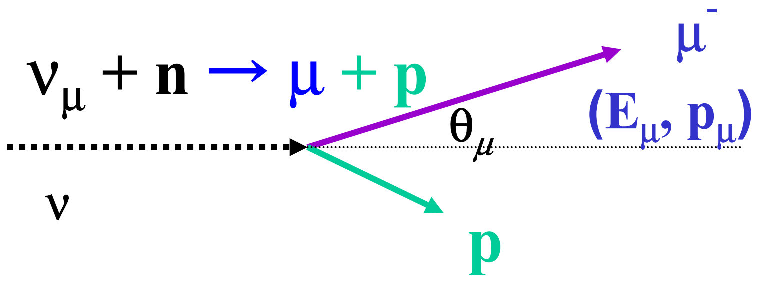
SK observation

- N_{SK}(obs)
- 1Rμ E_{rec} distribution

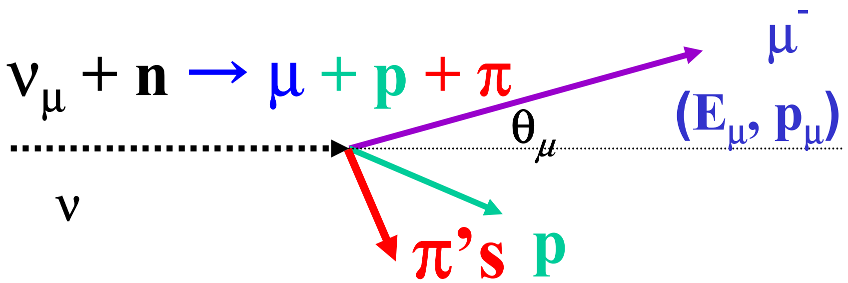
Maximum Likelihood Fit in $(\sin^2 2\theta, \Delta m^2)$

ν_μ spectrum measurement at front detector

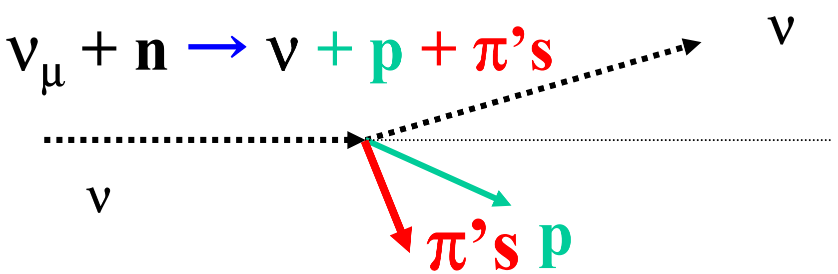
1Rμ events in water Cherenkov detector



- ✧ CC QE
  - ✧~100% efficiency for N_{SK}
  - ✧can reconstruct Eν



- ✧ CC nQE
  - ✧~100% efficiency for N_{SK}
  - ✧Bkg. for E_ν measurement

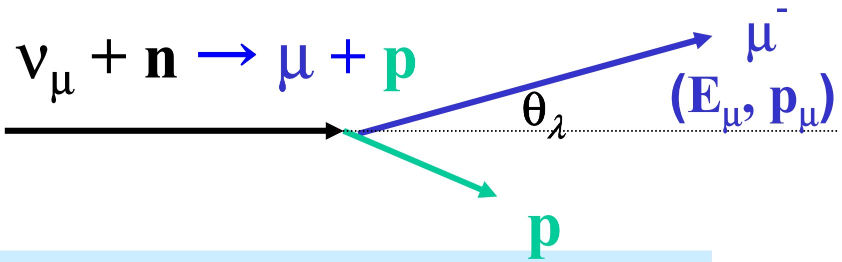


- ✧ NC
  - ✧~40% efficiency for N_{SK}

Neutrino Energy E_ν Reconstruction

CC quasi elastic (QE)

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



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

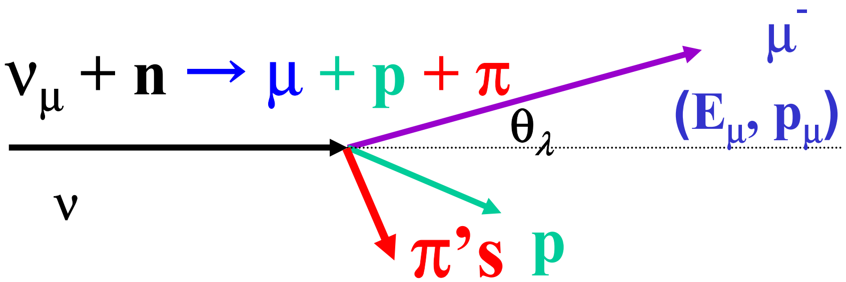
Rate(Eν,Near) → <u>φ(Eν,Near)</u>

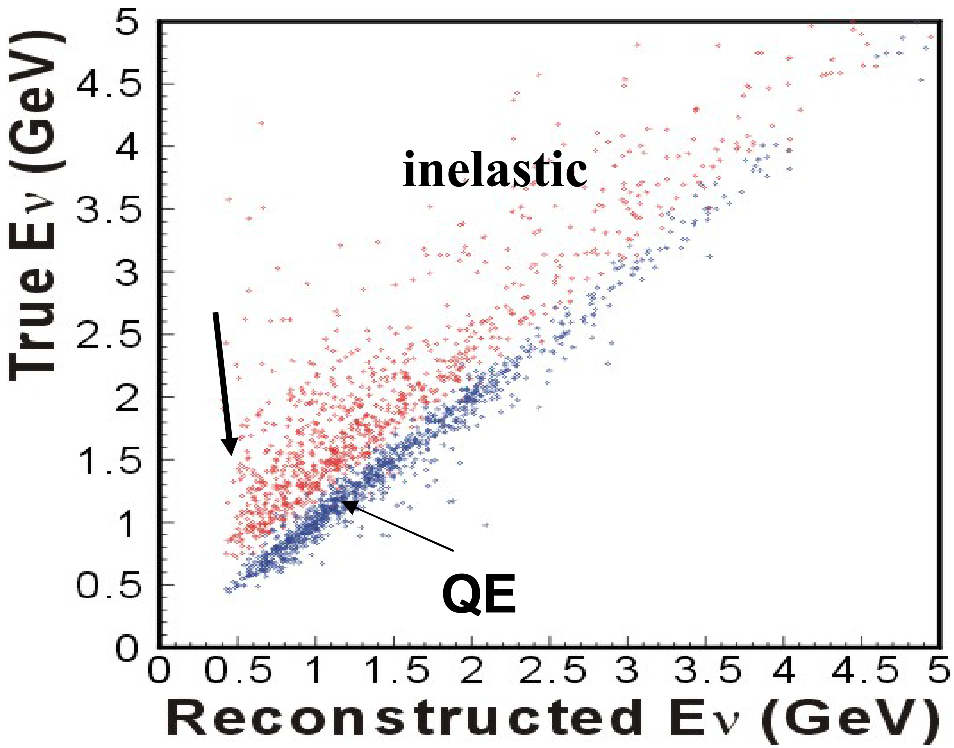
↑

σ(QE), σ(nonQE)

CC inelastic

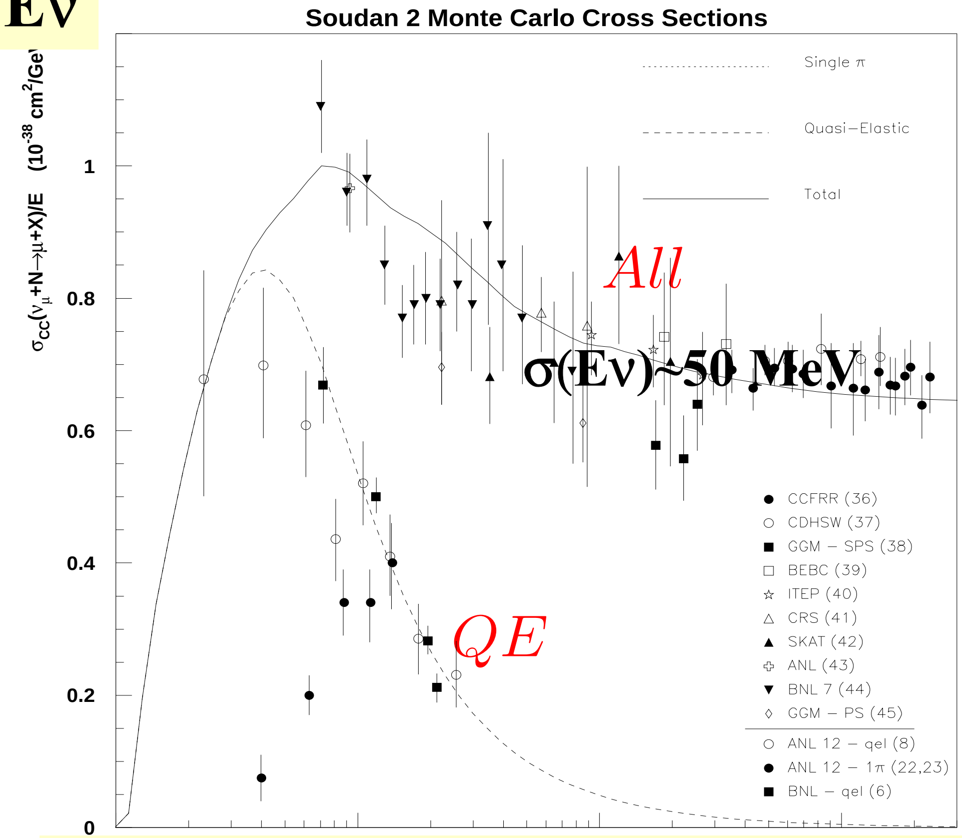
$\nu_\mu + n \rightarrow \mu + p + \pi$





CC Quasi Elastic(QE) and Other Processes(nQE)

σ/Eν



0.1 1 10

Eν(GeV)

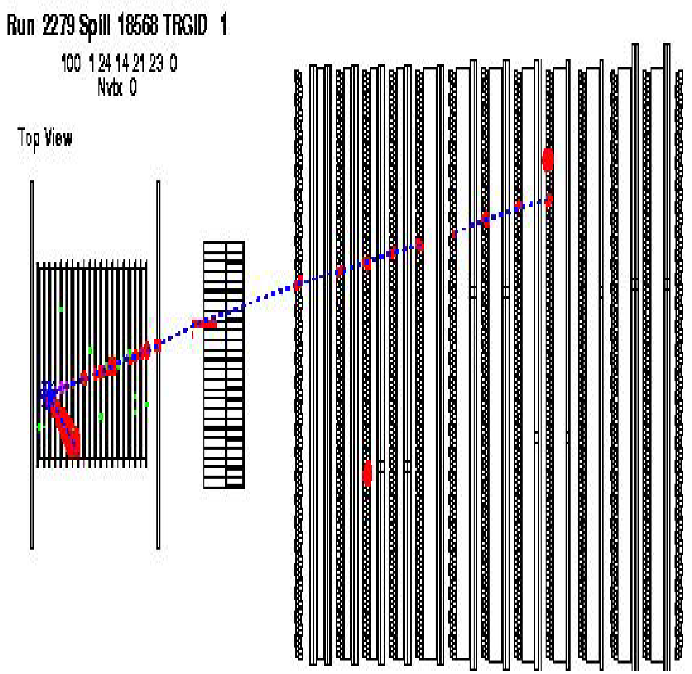
Not well known

Used Parameters
MA(QE)=1.11GeV
MA(1π)=1.21 GeV
Coherent π : Marteau et.al.
Multi-π: use hep-ex/0203009

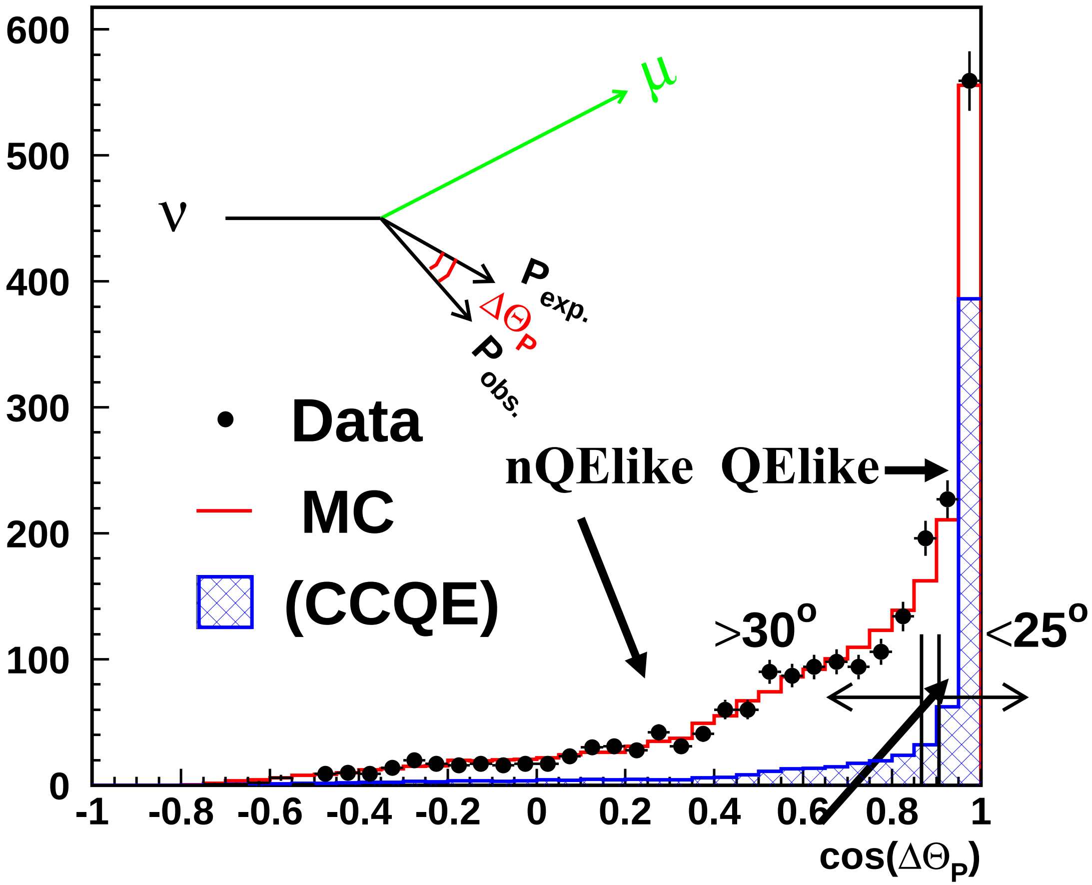
Checked
MA(QE)=1.01-1.11
MA(1p)=1.01-1.51
GRV94-Mod.GRV94

Very small effect on oscilllation anlysis

QE and nQE in SciFi 2track events



SciFi 2 track cos($\Delta\Theta_P$) distribution



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

KT

Fully contained in fiducial volume (FCFV)

•No. of events (Evis>100MeV)

(1) Single ring μ–like events

SciFi

(2) 1-track μ events

(3) 2-track QE-like events

(4) 2-track nonQE-like events

4 sets of (p_μ, θ_μ) distributions

Pion monitor

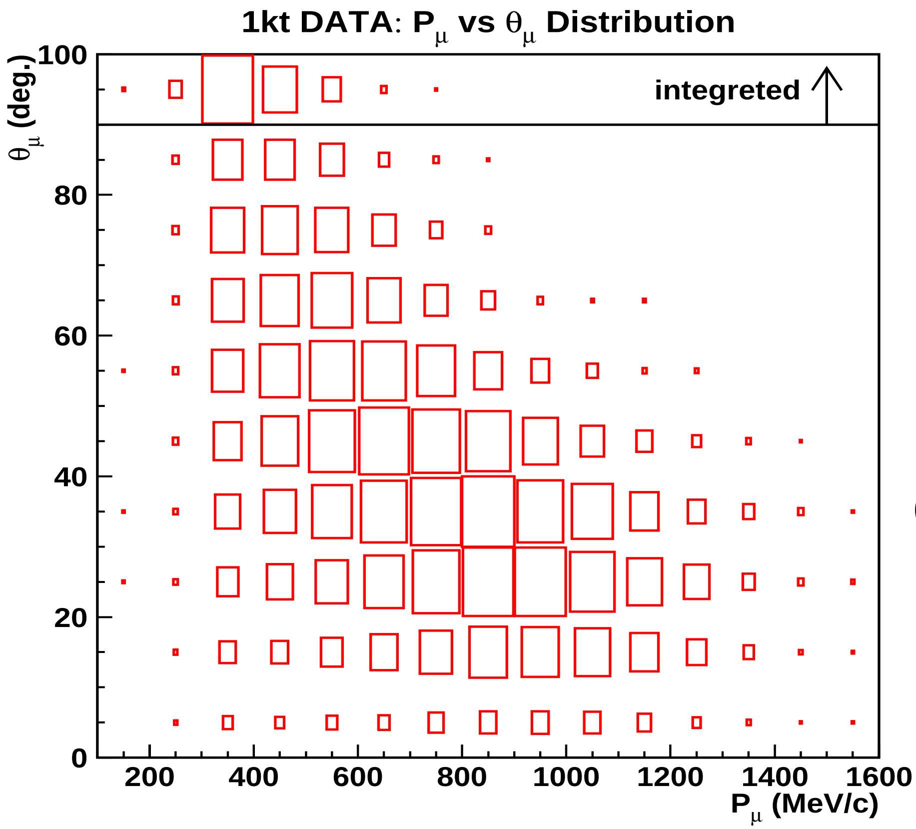
π distribution in (p_π,θ_π) $\rightarrow$flux estimate $\phi_{near}(E\nu)$

ν flux $\phi_{near}(E\nu)$ (8 bins)

ν interaction model (parameterized as nQE/QE ratio)

Fitting method

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



Also (p_μ,θ_μ) dist. in SciFi

1track, 2track(QE-like), 2track(nQE-like)

$\chi 2$=227 for 197 d.o.f.

Eν	QE (MC)	nQE(MC)

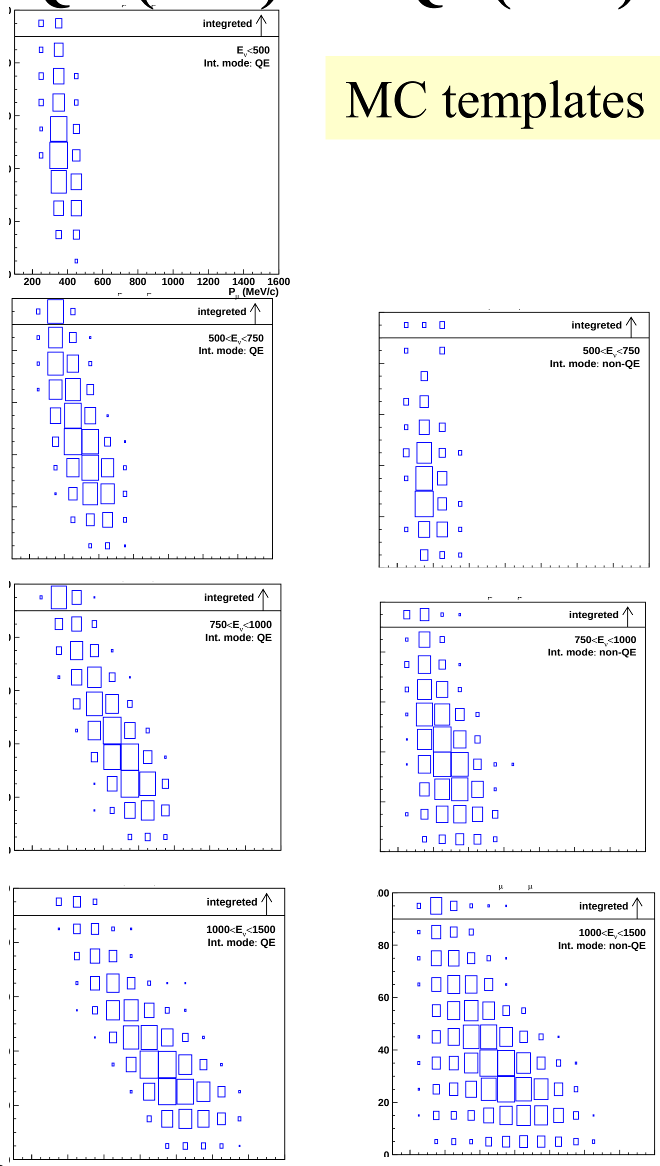
MC templates

0-0.5 GeV

0.5-0.75GeV

0.75-1.0GeV

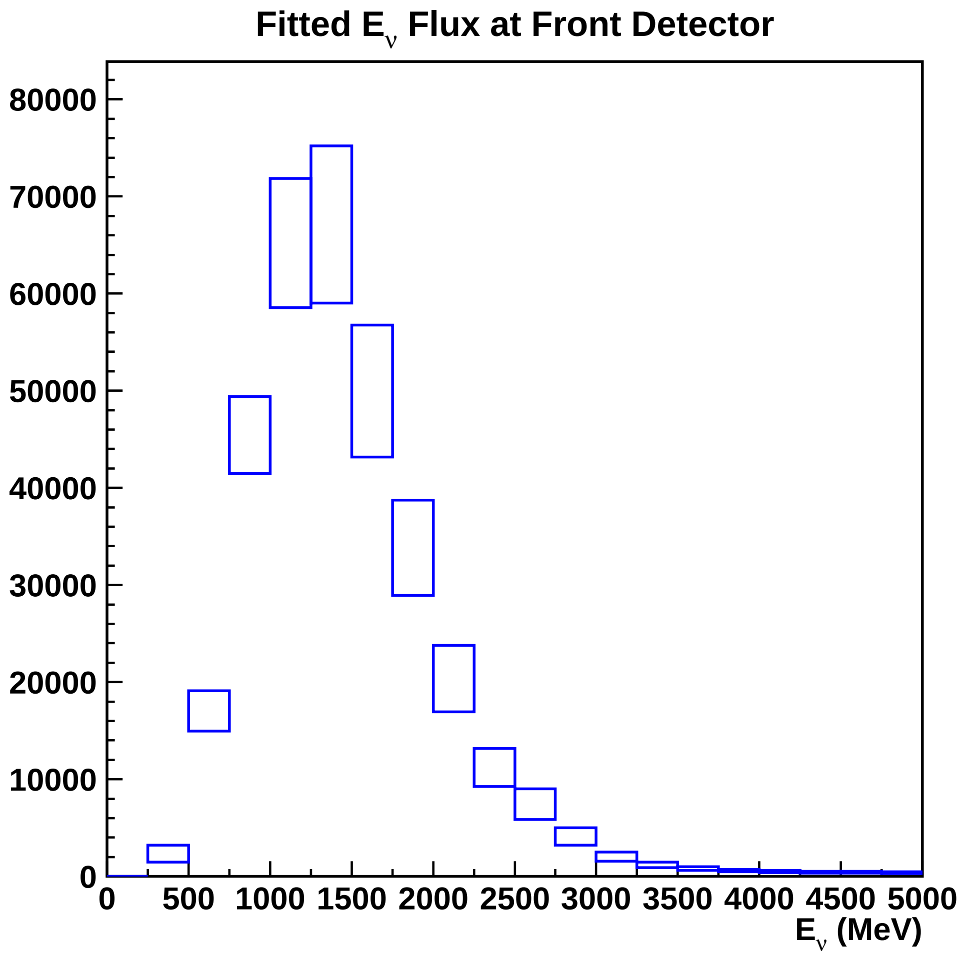
1.0-1.5GeV



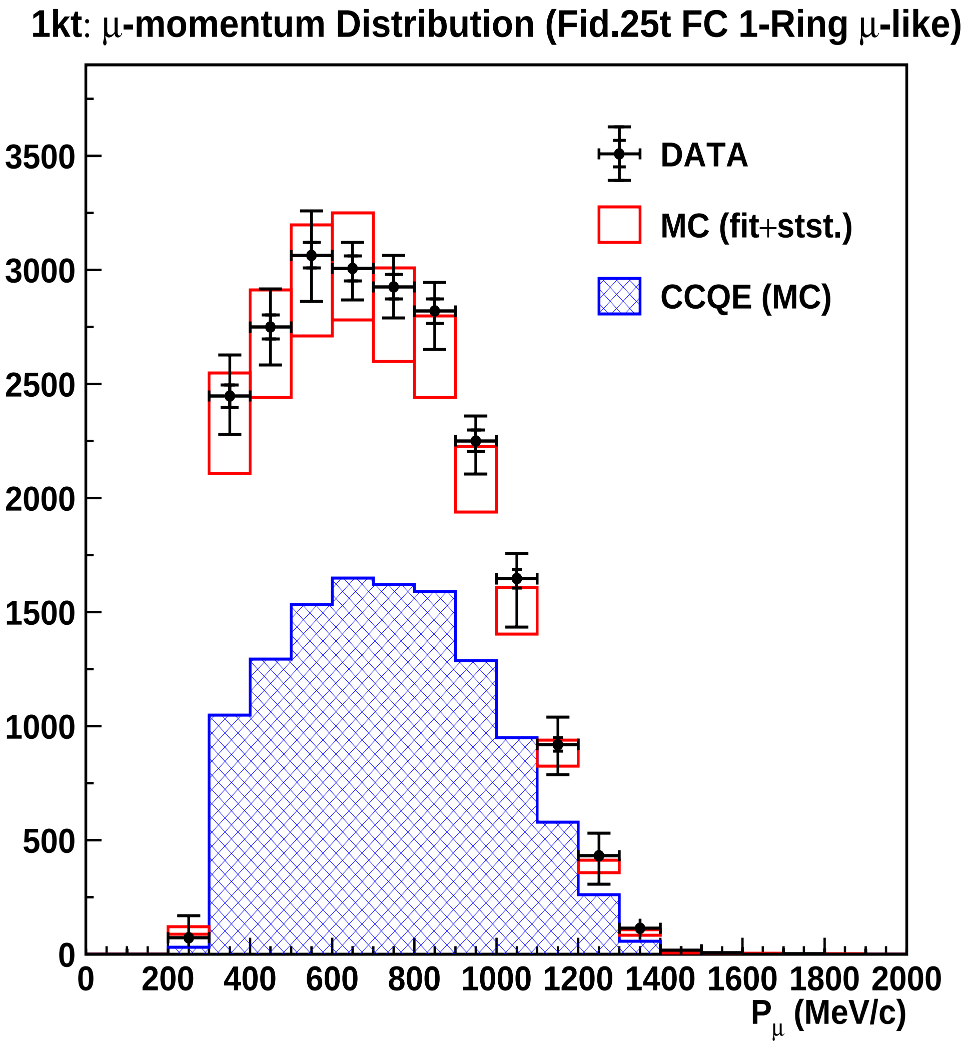
⋮

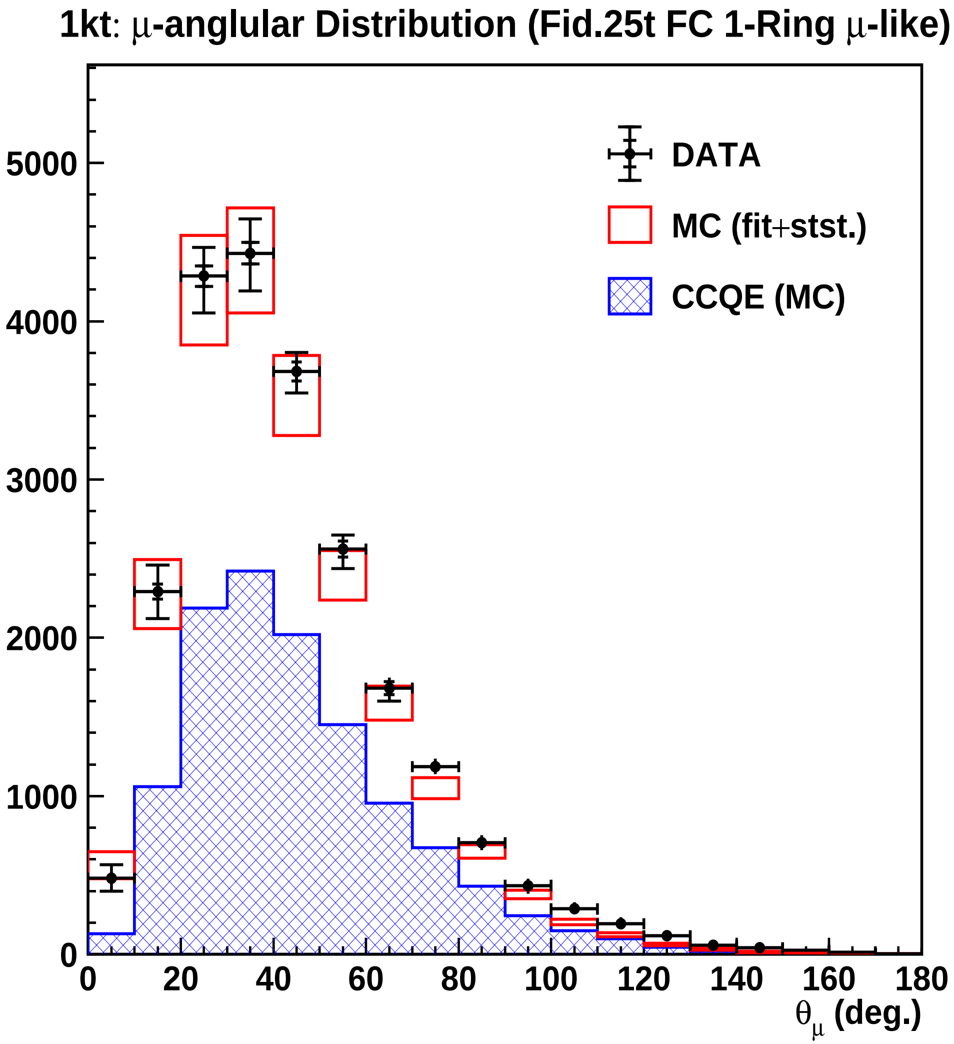
⋮

Fit result of Neutrino Flux at KEK Site

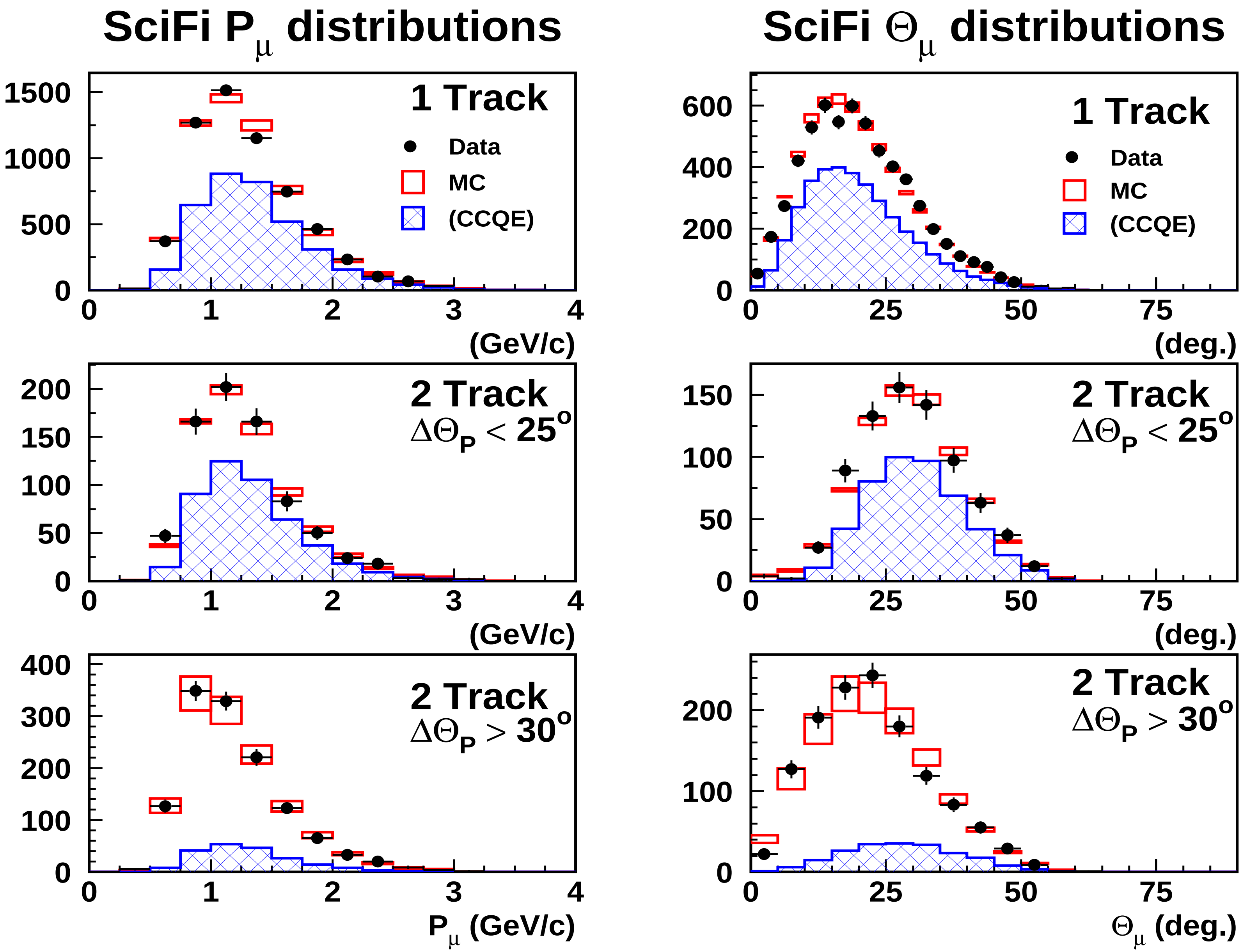


KT (p_μ, θ_μ) distribution using ϕ_{fit}, QE/nQE$_{fit}$

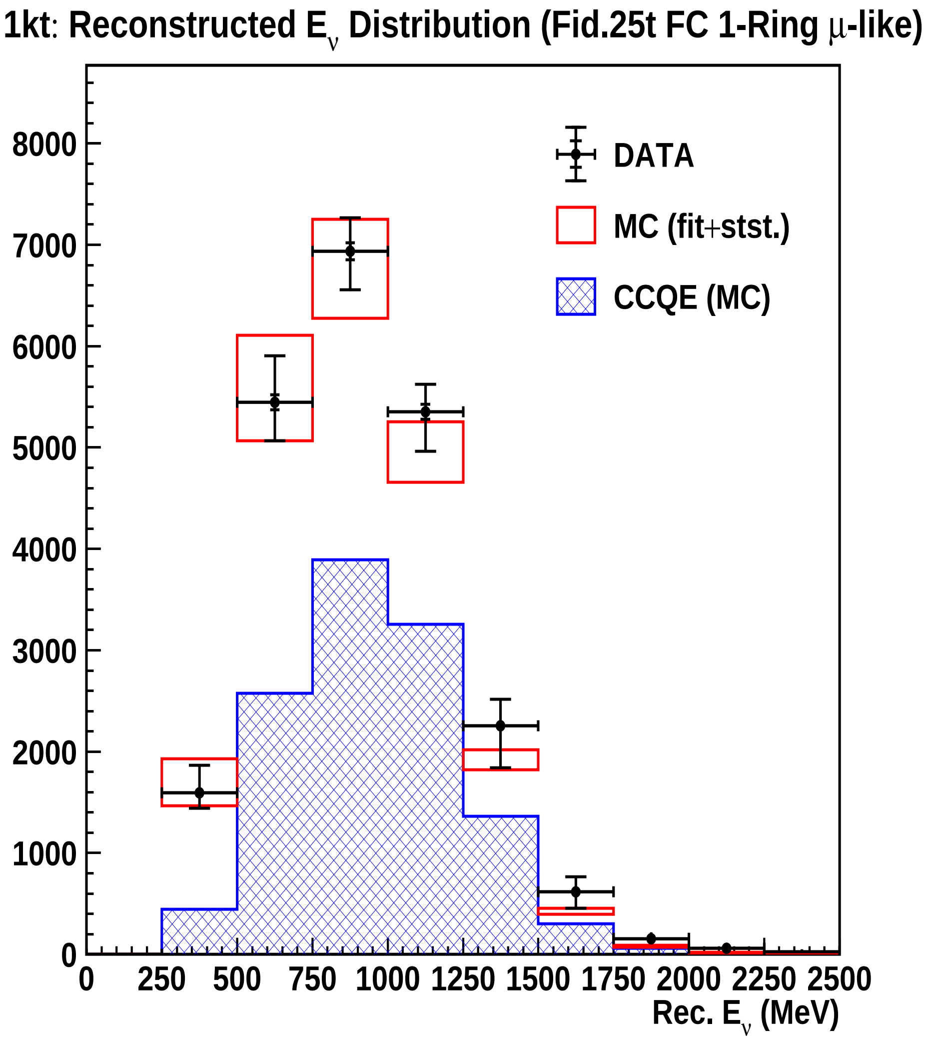




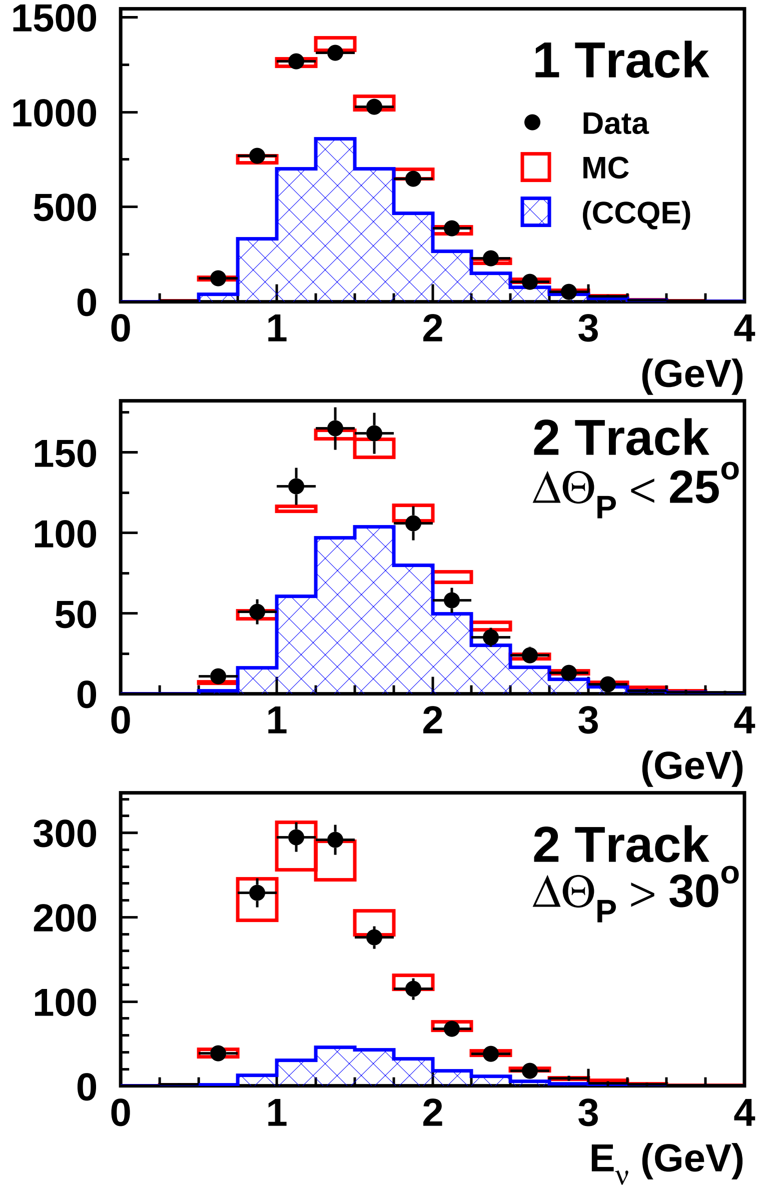
Scifi p_μ,θ_μ distributions using ϕ_{fit}, QE/nQE$_{fit}$



Reconstructed Eν using ϕ_{fit}, QE/nQE$_{fit}$



SciFi E$_\nu$ distributions

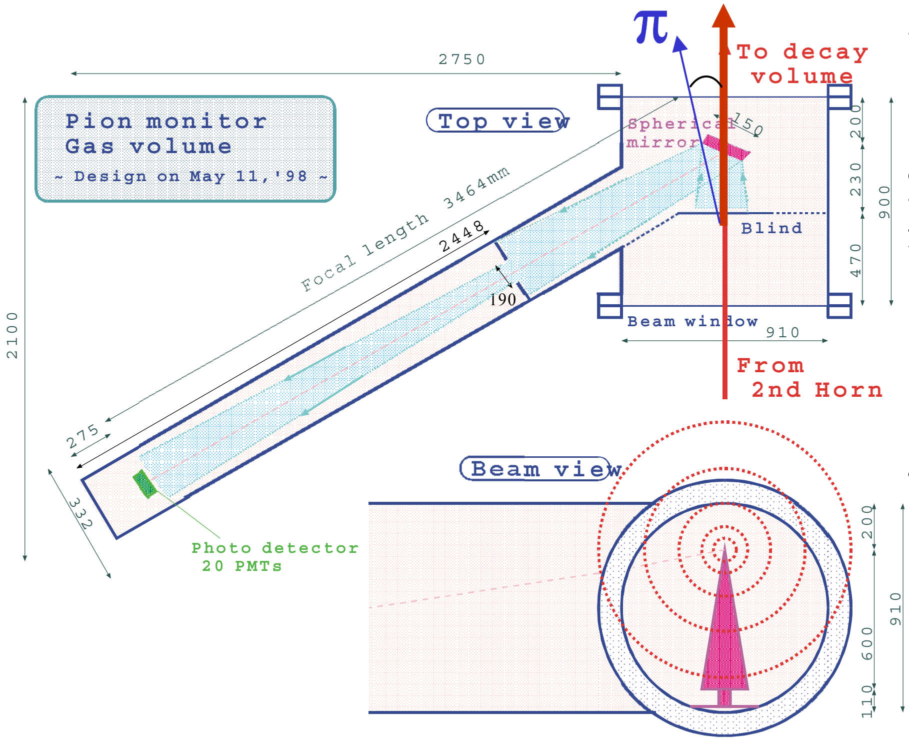


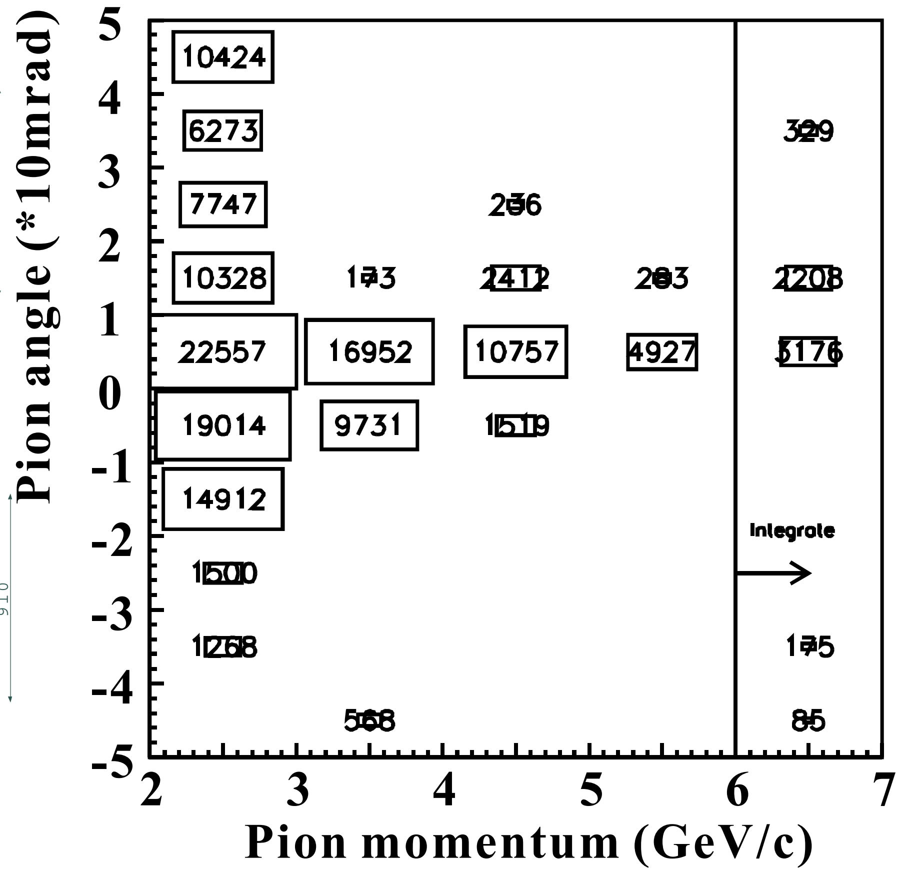
Far/Near Extrapolation

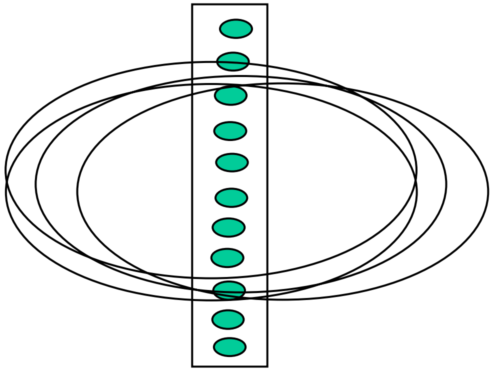
Pion Monitor
Far/Near Extrapolation F/N(Eν)

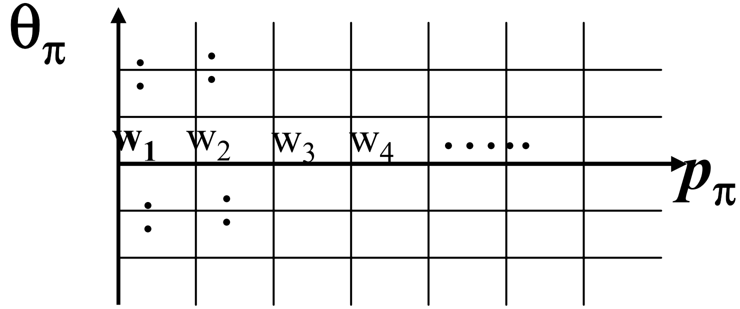
Gas Cherenkov detector: (insensitive to primary protons)

Measure momentum and angular distribution of pions, N(p_π, θ_π) just after the horns. p_π>2GeV/c

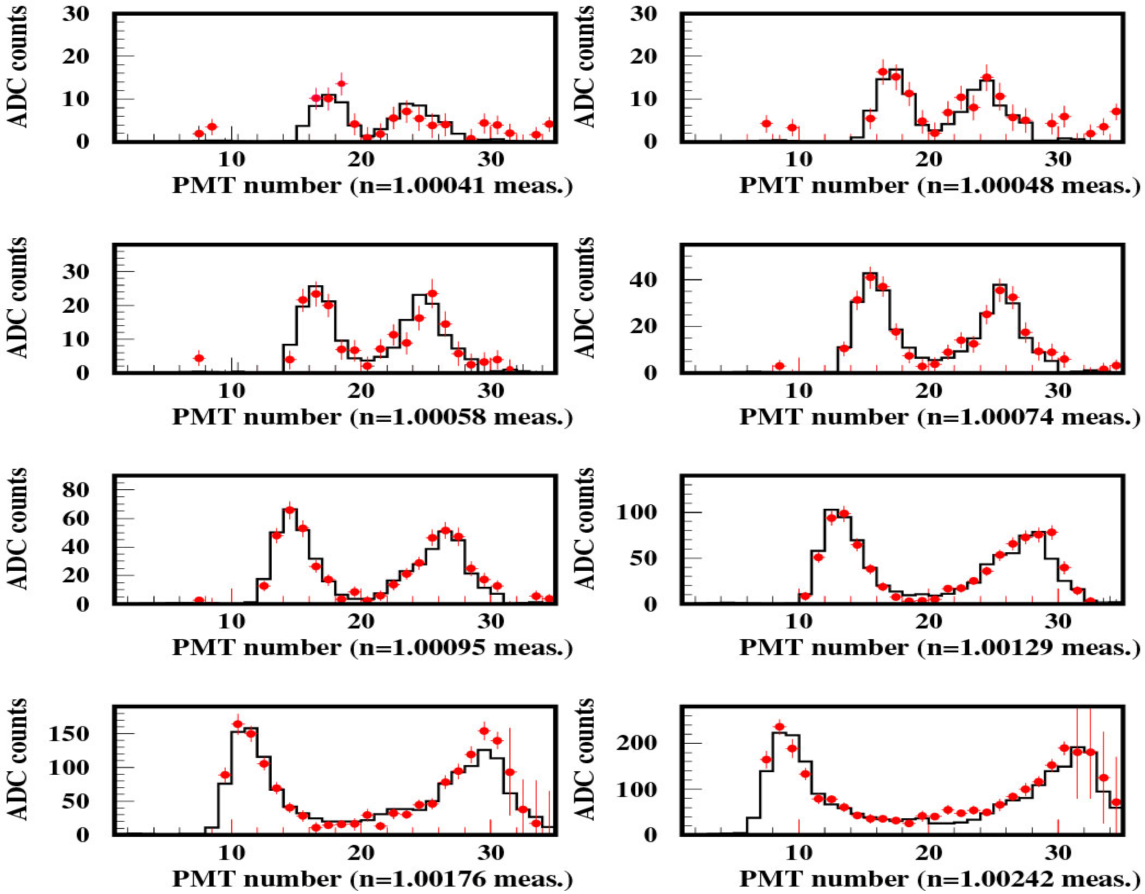








Pion Monitor Fitting (November)



Fit with Cherenkov light distribution by populations in (p_π,θ_π)

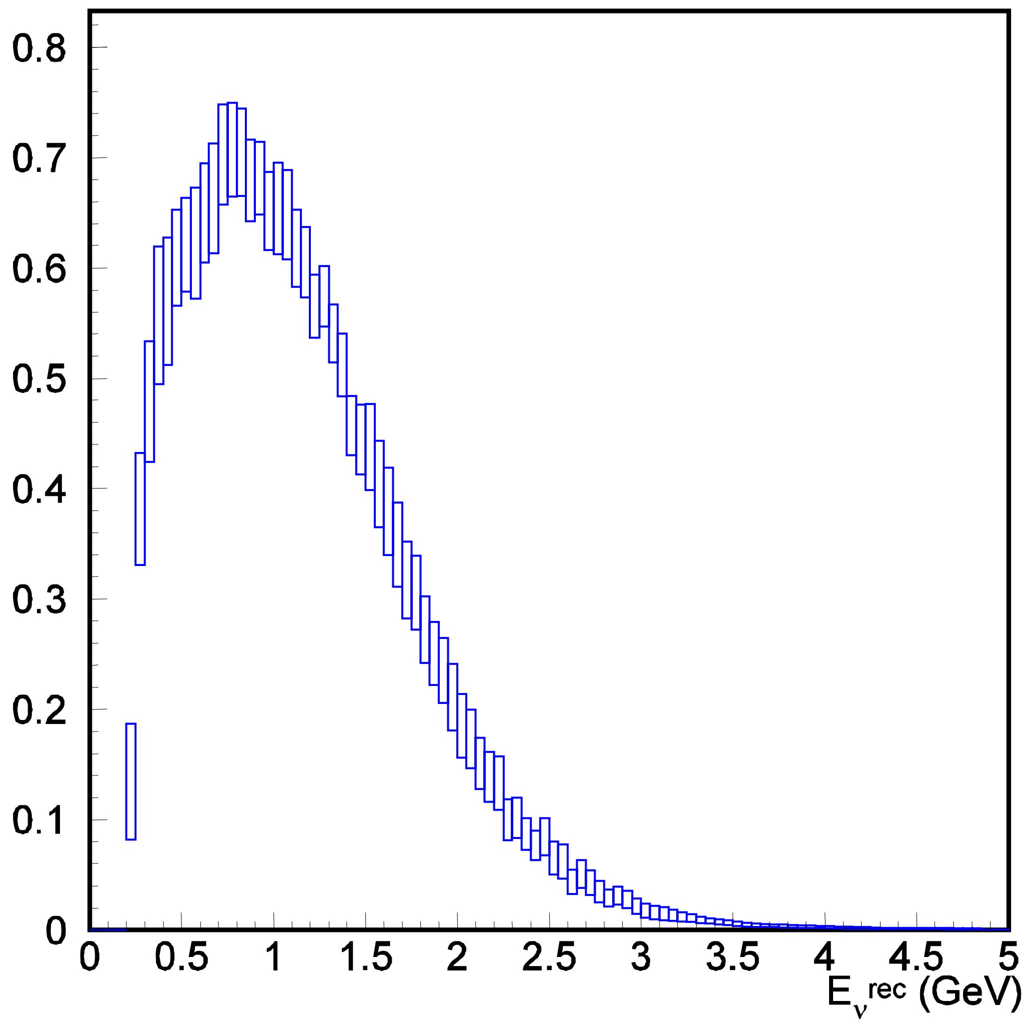
Error on F/N(Eν)

Pion production model

Beam MC

Expected E_ν^{rec} spectrum for 1Rμ

Initial 1Rμ spectrum w/ all syst. err. incl. Escale



Oscillation Analysis

Oscillation analysis

Neutrino flux @SK ⊗ *Int. Model* ⊗ Oscillation ($\sin^2 2\theta, \Delta m^2$)

Prediction

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

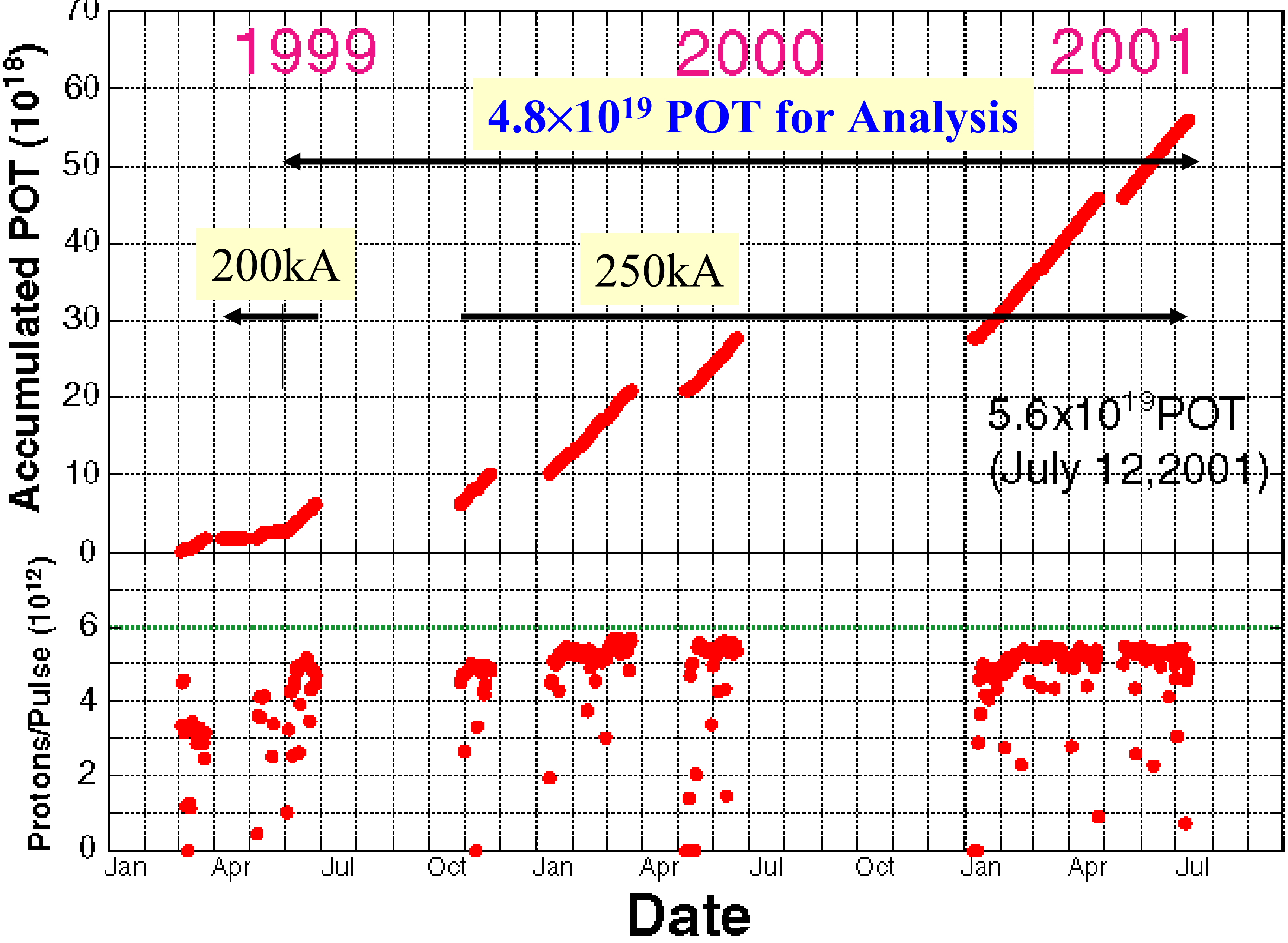
SK observation

- **Observed no. of events in FCFV N_{SK}(obs,>30MeV)**
- **1Rμ events E_ν^{rec} spectrum shape**

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

1. **Rejection of Null oscillation hypothesis**
2. **Contour of allowed region**
   - **Number of events observed/expected**
   - **Obs./exp. neutrino energy spectrum shape**

Delivered Protons on Target (POT)



Data set

- **Data sets**
  - **June 99-July 01 FCFV , Evis>30 MeV**
    - **total number of events**
    - **56 events observed**
  - **Nov 99-July 01 1Rμ events**
    - **E_ν^{rec} shape**
    - **29 events observed**

- **Running condition**
  - **June 99**
    - **Target=2 cmϕ Horn current=200kA (~6.5% of POT)**
    - **Larger systematic errors in 'near' measurements**
  - **Nov 99~July 01**
    - **Target=3cmϕ Horn current=250kA**
    - **Full analysis of systematic errors**

Systematic parameters

$$f = (f_{\Phi}, f_{nQE}, f_{\mathrm{F/N}}, f_{\varepsilon sk}, f_{Esk}, f_{n6}, f_{n11})$$

f_{ϕ} : Flux (8 energy bins)

f_{nQE} : QE/nQE ratio

$f_{F/N}$: Far/Near ratio

$f_{\varepsilon SK}$: SK reconstruction (Fid, PID, Nring)

f_{ESK} : SK energy scale

f_{n6} : Norm. for June 99

f_{n11} : Norm. Nov 99 ~ Jul 01

Likelihood

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

Normalization term

$$L_{norm} = Poisson(N_{obs}, N_{\exp}(f))$$

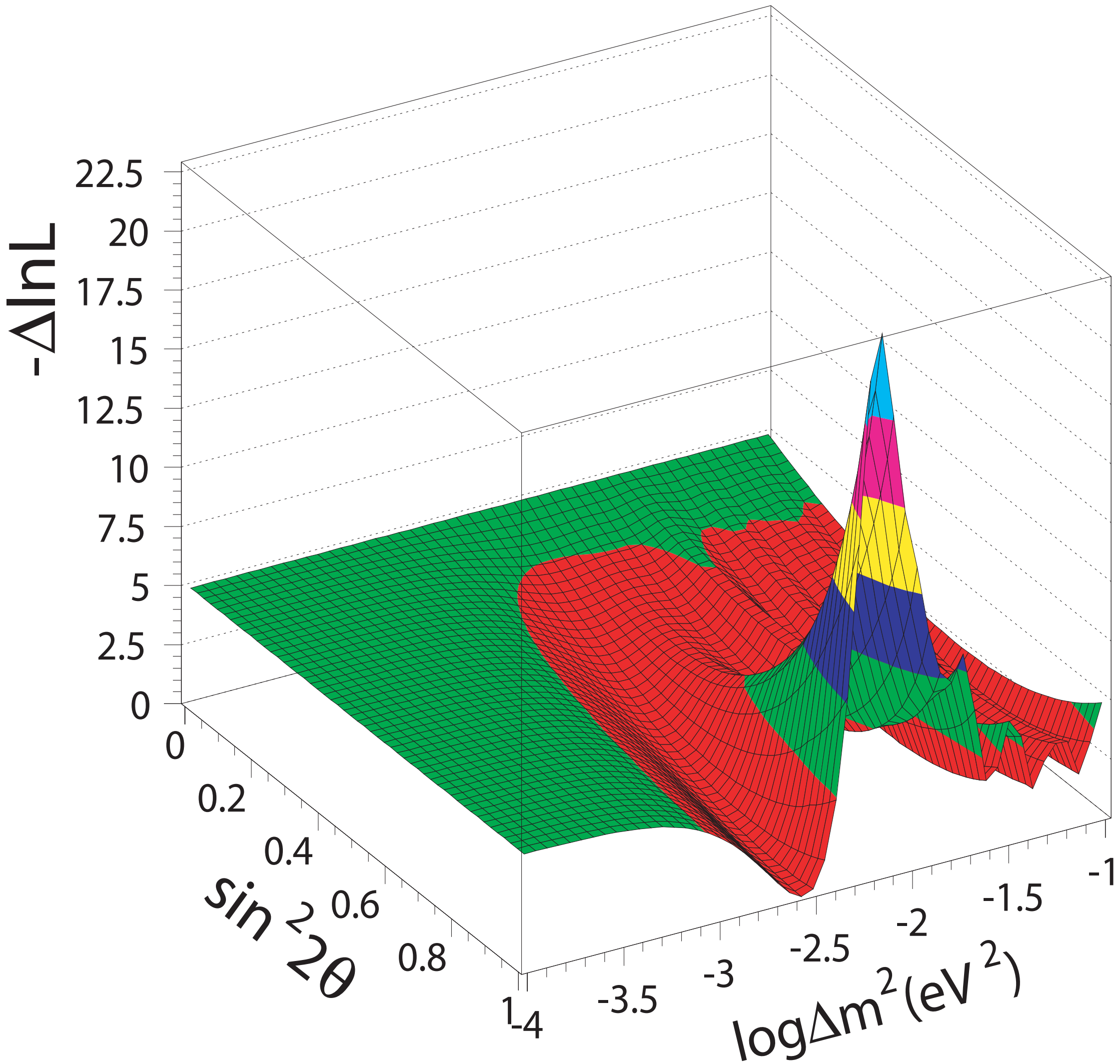
Shape term for FCFV 1Rμ

$$L_{shape} \equiv \prod_{i=1}^{29} P((f_{Esk} \cdot E_i), \Delta m^2, \sin^2 2\theta, f)$$

Systematic parameter constraint term

$$L_{syst} \equiv \exp\left(-\Delta f_{\Phi,nQE}^{T} \cdot M_{FD}^{-1} \cdot \Delta f_{\Phi,nQE} / 2\right) \bullet\bullet\bullet\bullet\bullet \\ \times \exp\left(-f_{n6}^{2} / 2\sigma_{n6}^{2}\right) \exp\left(-f_{n11}^{2} / 2\sigma_{n11}^{2}\right) exp\left(-\Delta f_{Esk}^{2} / 2\sigma_{Esk}^{2}\right)$$

3d plots of ΔlnL for shape+norm



L at (Δm^2, $\sin^2 2\theta$)

- **analysis-1**

  Maximize L by adjusting systematic parameters.

- **analysis-2**

  The MC generation of the systematic parameters & L=the mean values.

Null Oscillation Probability

Null Oscillation Probability

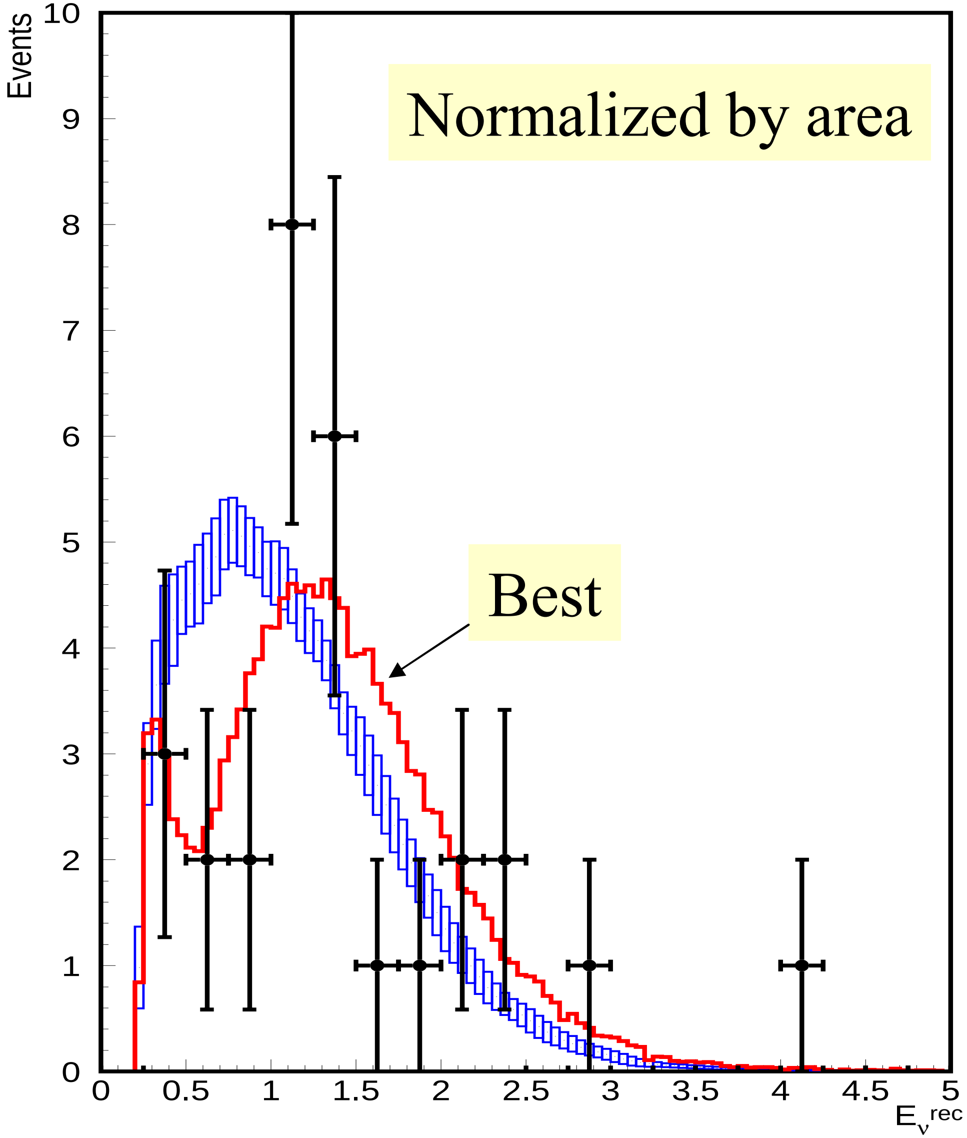
	analysis-1	analysis-2
N_{SK}only	1.3%	0.7%
Shape only	15.7%	14.3%
N_{SK}+Shape	0.7%	0.4%

Best fit ($\sin^2 2\theta$, Δm^2)

Shape only	(1.0, $3.0\times10^{-3}eV^2$)	(1.0, $3.2\times10^{-3}eV^2$)
(Allowing unphys.)	(1.09, $3.0\times10^{-3}eV^2$)	(1.05, $3.2\times10^{-3}eV^2$)
N_{SK} +Shape	(1.0, $2.8\times10^{-3}eV^2$)	(1.0, $2.7\times10^{-3}eV^2$)
(Allowing unphys.)	(1.03, $2.8\times10^{-3}eV^2$)	(1.05, $2.7\times10^{-3}eV^2$)

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

Best fit 1Rμ spectrum & Nsk



Best fit point ($\sin^2 2\theta$, Δm^2) = (1.0, $2.8 \times 10^{-3} eV^2$)

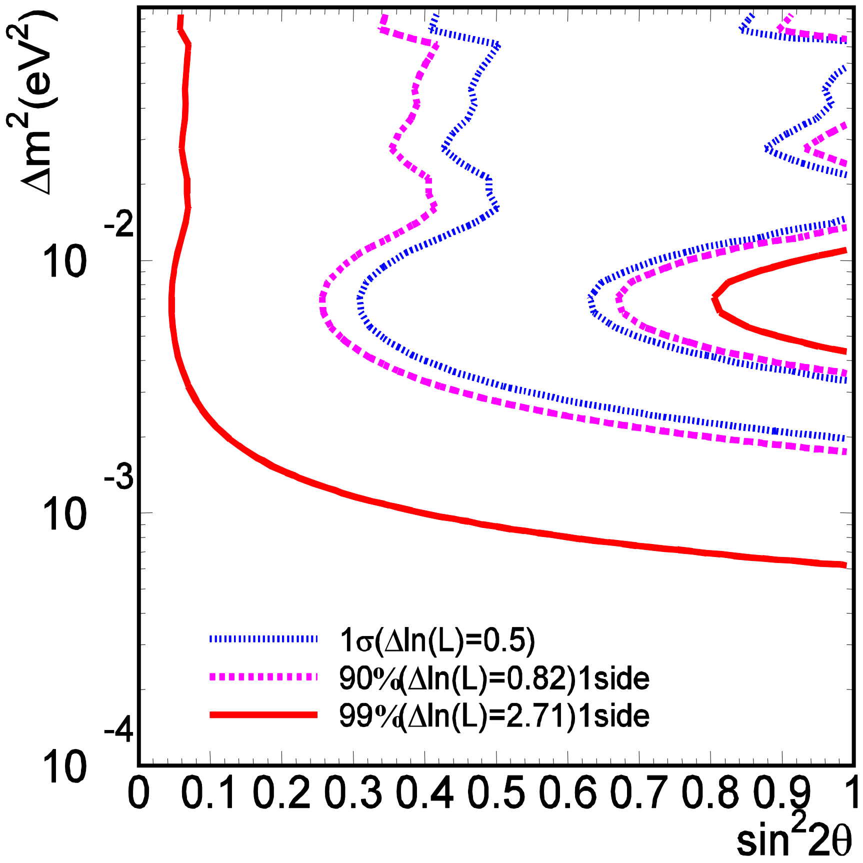
KS test prob.(shape): 79%

N_{SK}=54 (Obs.=56)

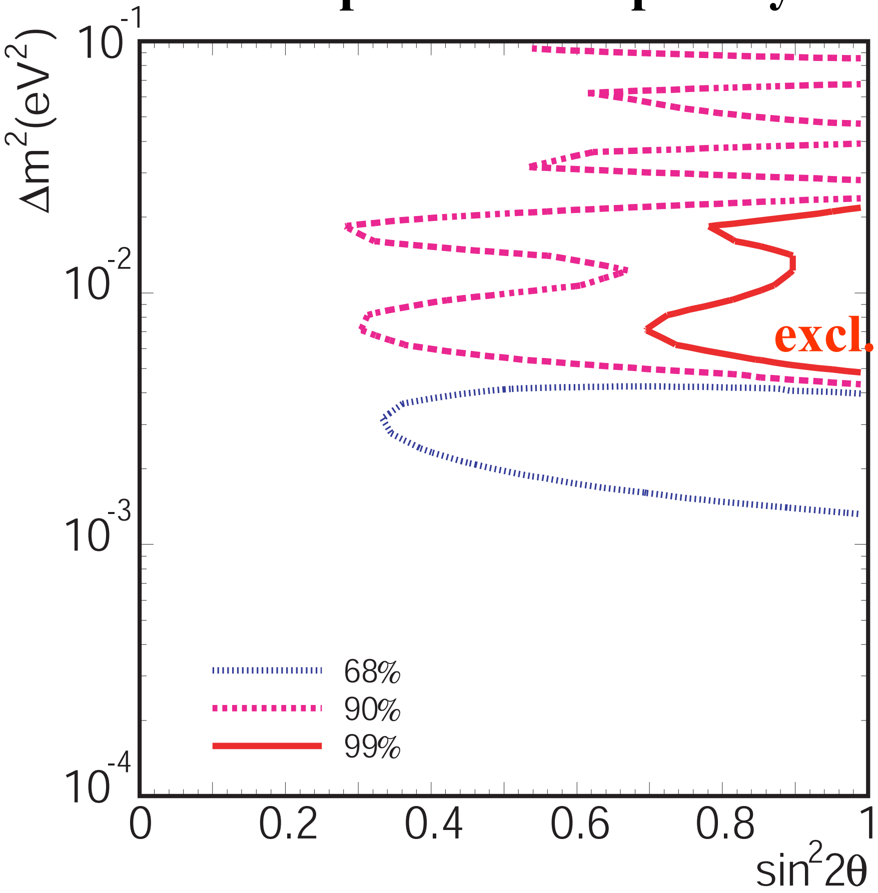
Very good agreement
Shape & N_{SK}

Allowed regions

Total no. of Events only

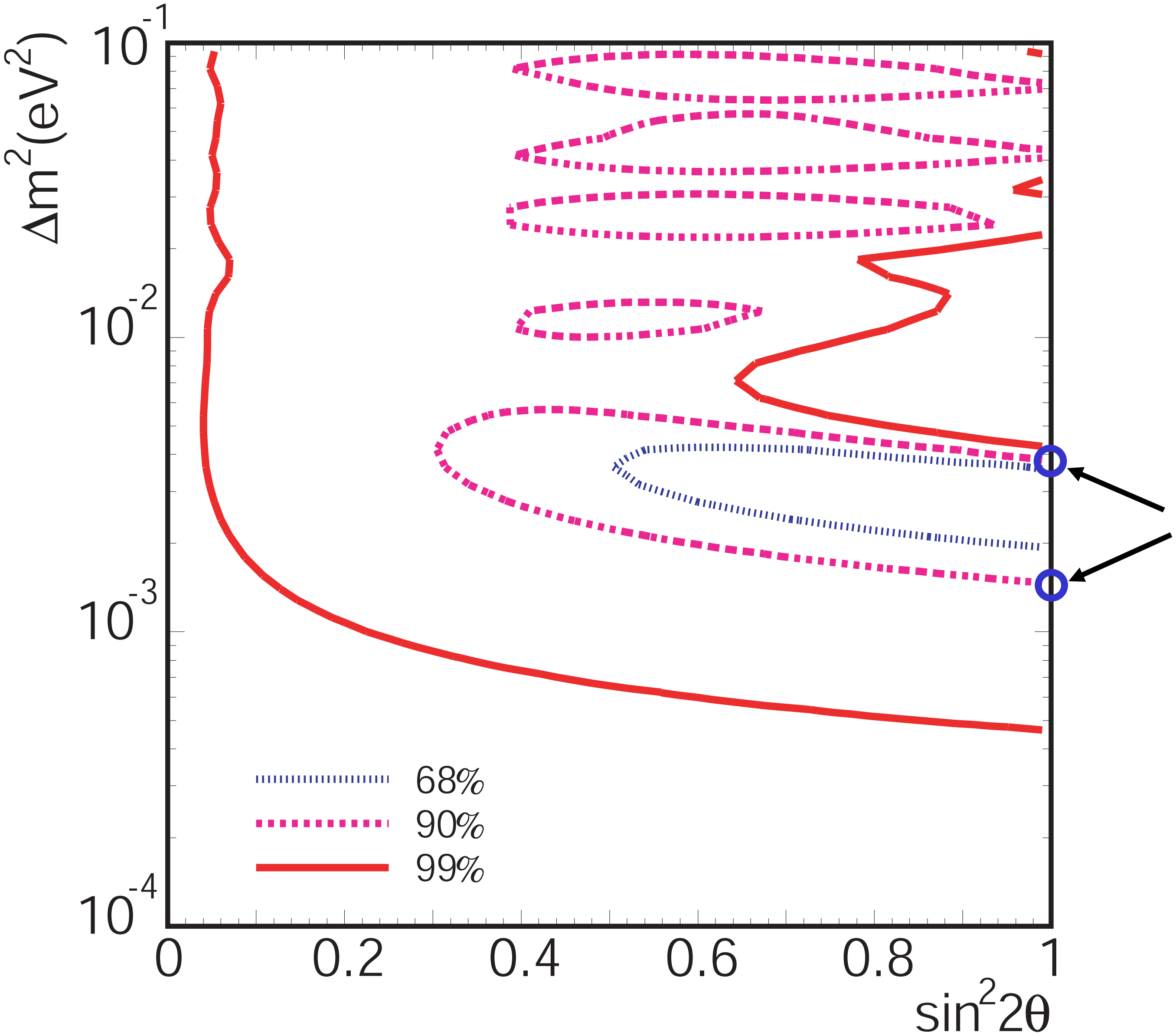


Spectrum Shape only



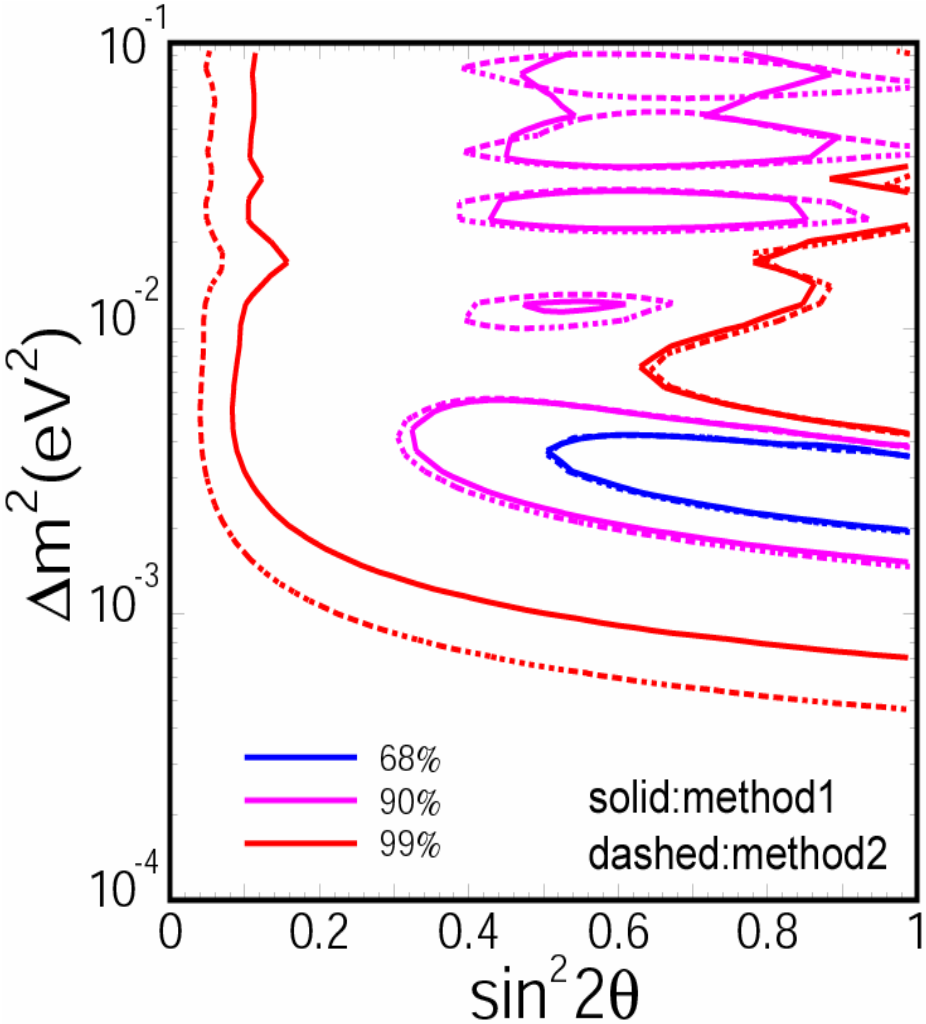
Both indicate consistent Δm^2 region

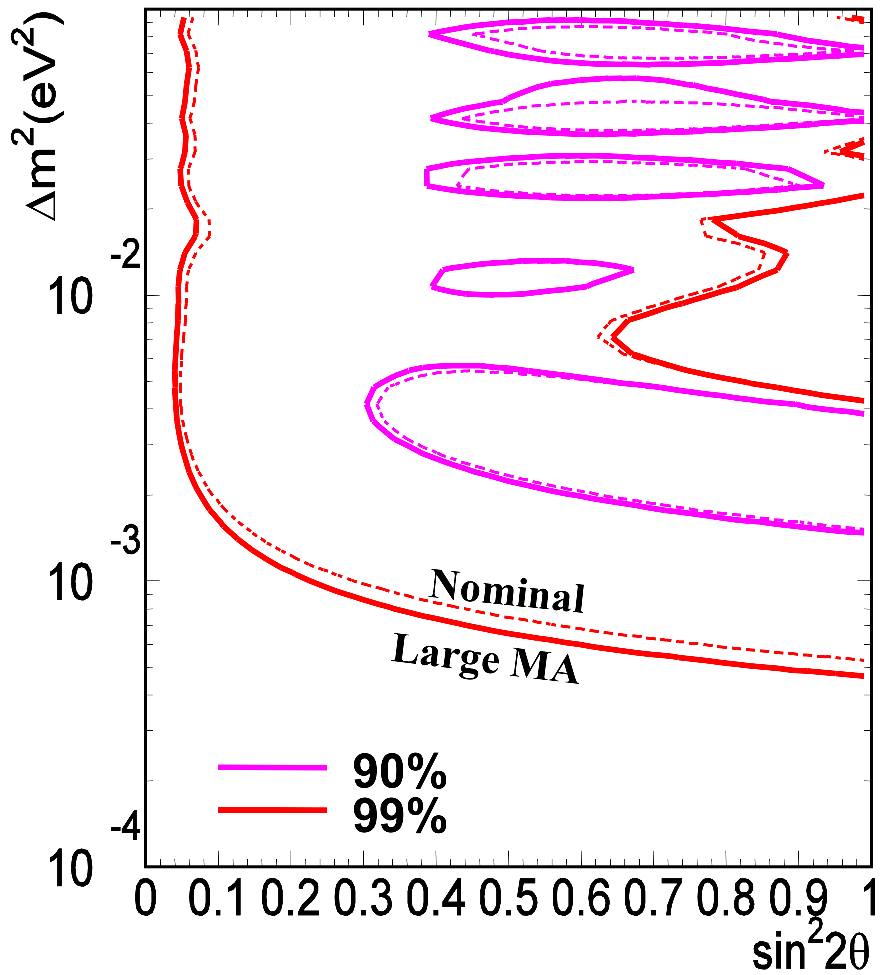
Allowed region (Shape+Norm)



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

Comparison with diff. L & form factor MA

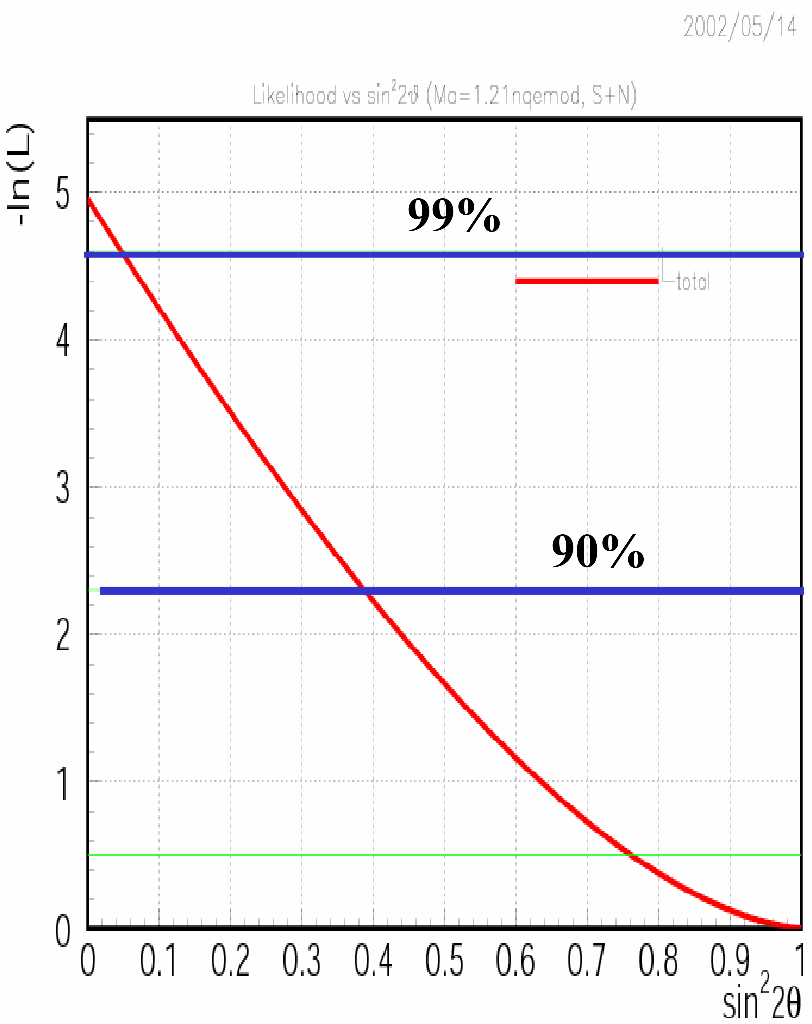




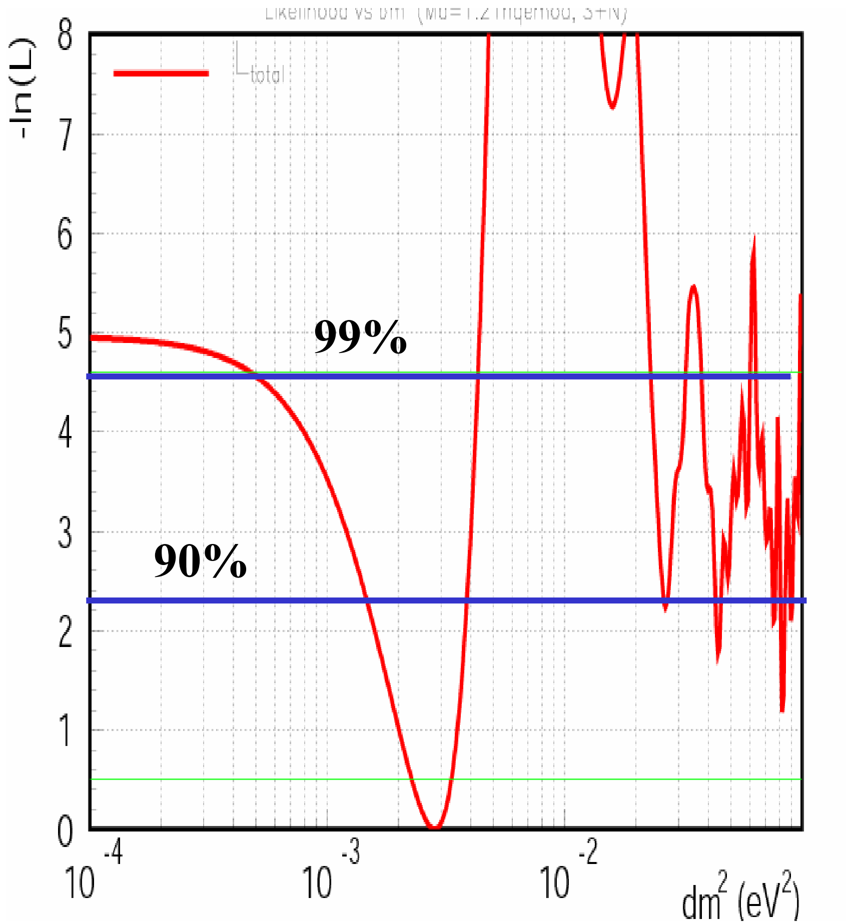
Reasonable agreement btw definition of L

Change of ν interaction model has small effect

$\sin^2 2\theta$ and Δm^2

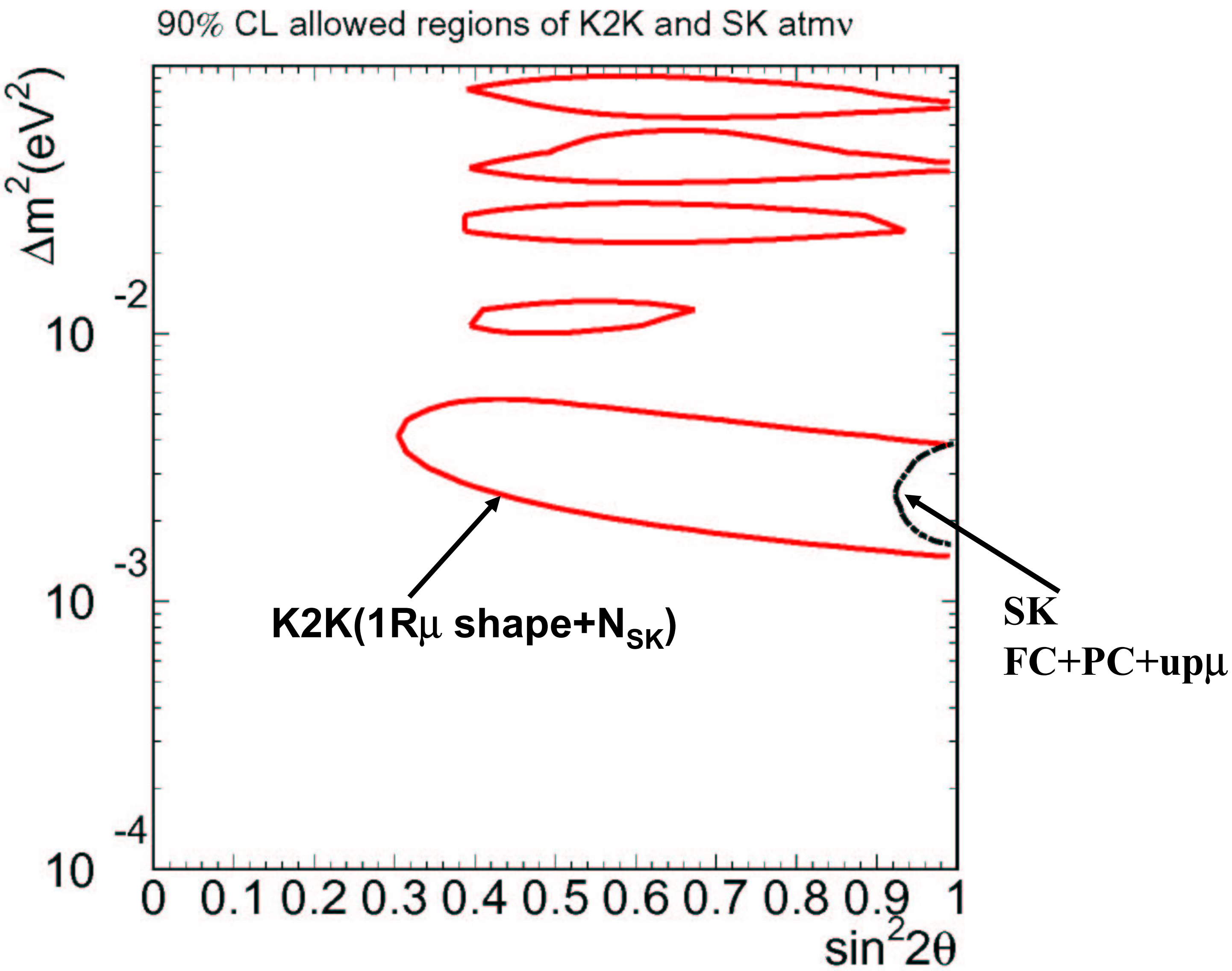


$\sin^2 2\theta$



Δm^2

Comparison with SK atm ν observation
90% allowed region



Conclusion

- **K2K Oscillation analysis on June99 ~July01 data**
  - **Full error analysis**

1. **Null oscillation probability is less than 1%**
2. **Both SK rate reduction and E_ν^{rec} shape indicate consistent oscillation parameters region**
3. **Δm^2=1.5~3.9x10^{-3}eV^2 for $\sin^2 2\theta$=1 @ 90%CL**
4. **$\sin^2 2\theta$, Δm^2 are consistent with atmospheric neutrino results**

   - **The best fit point ($\sin^2 2\theta$=1.0, Δm^2=2.8x10^{-3} eV^2)**

cf. Atmospheric neutrino results

Δm^2=(1.6~3.9)x10^{-3} eV^2 for $\sin^2 2\theta$=1.0

best fit ($\sin^2 2\theta$=1.0, Δm^2=2.5x10^{-3} eV^2)

- **Data taking will resume within this year**