K2K results

Results of
Total Event Rate &
Spectrum Shape Analysis

K2K collaboration

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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

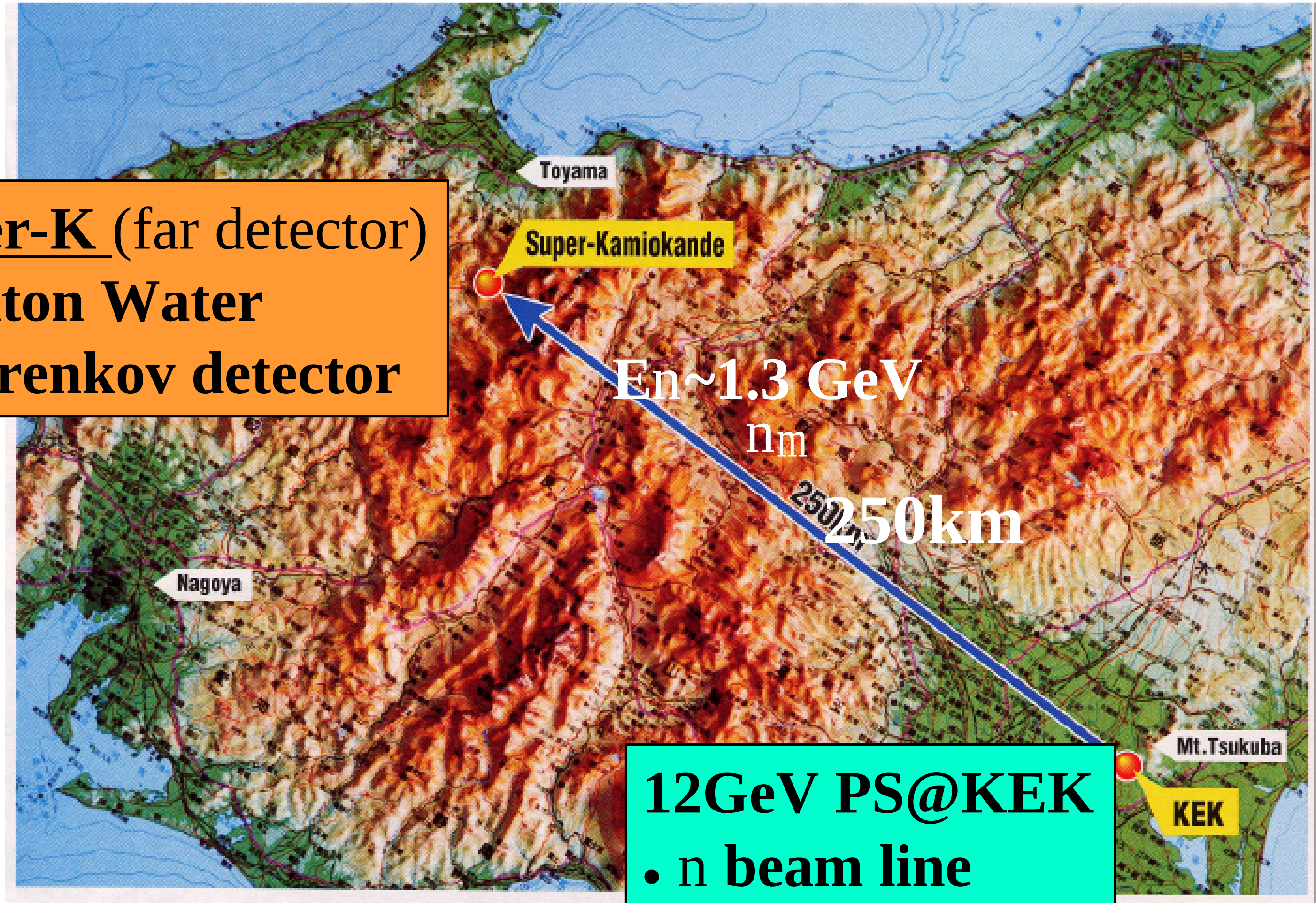
Chonnam National University
Dongshin University
Korea University
Seoul National University

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 forNnuclear Study

KEK to Kamioka Neutrino Oscillation Experiment

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

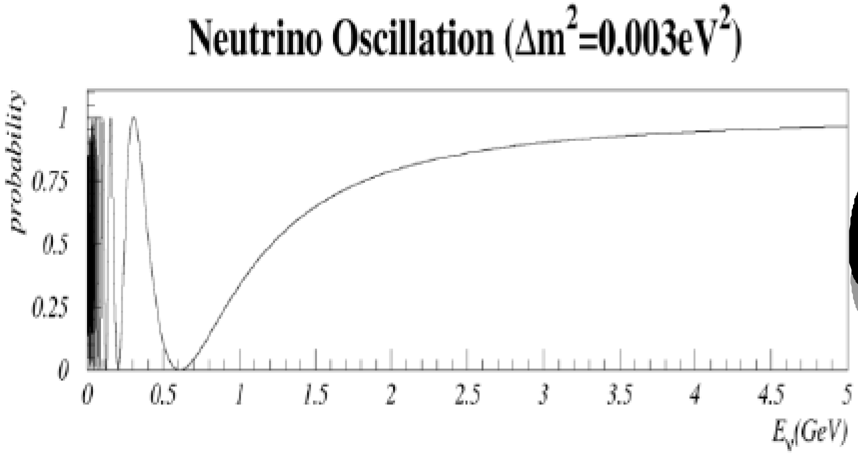


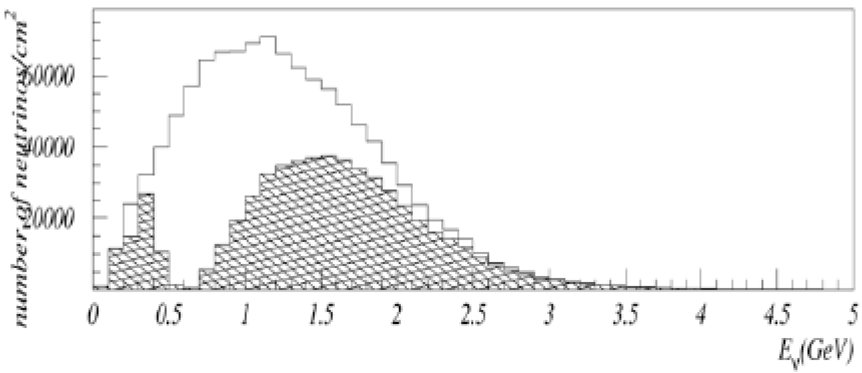
12GeV PS@KEK
- n **beam line**
- **Beam monitor**
- **Near detectors**

Principle of K2K

Fixed distance, direction
(E_n~1.3 GeV, L=250km)
(99% n_m, s_t<<s_m)

$$\text{prob.} = \sin^2 2q \cdot \sin^2\left(\frac{1.27Dm^2\ L}{E_n}\right)$$

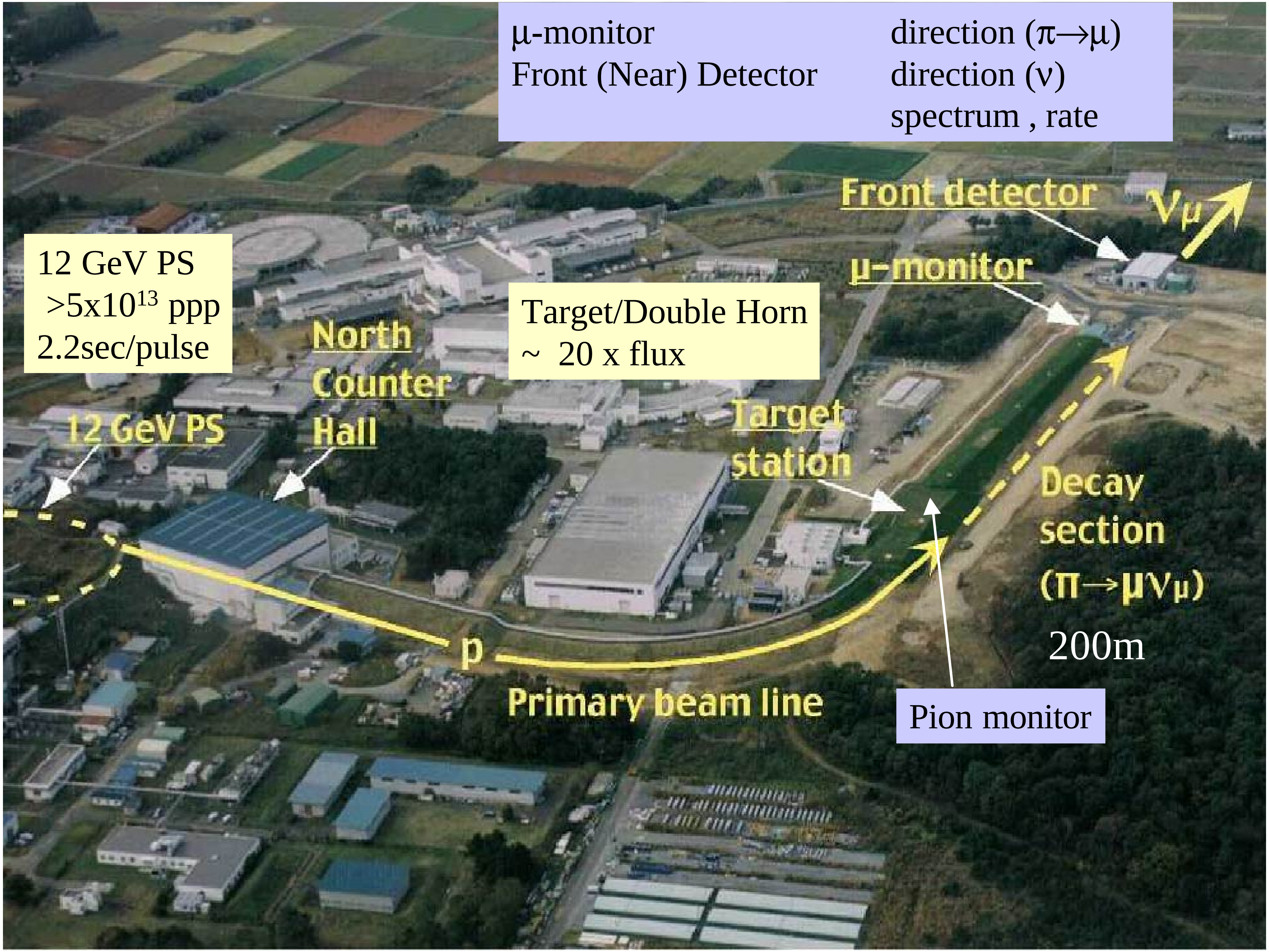




E_n

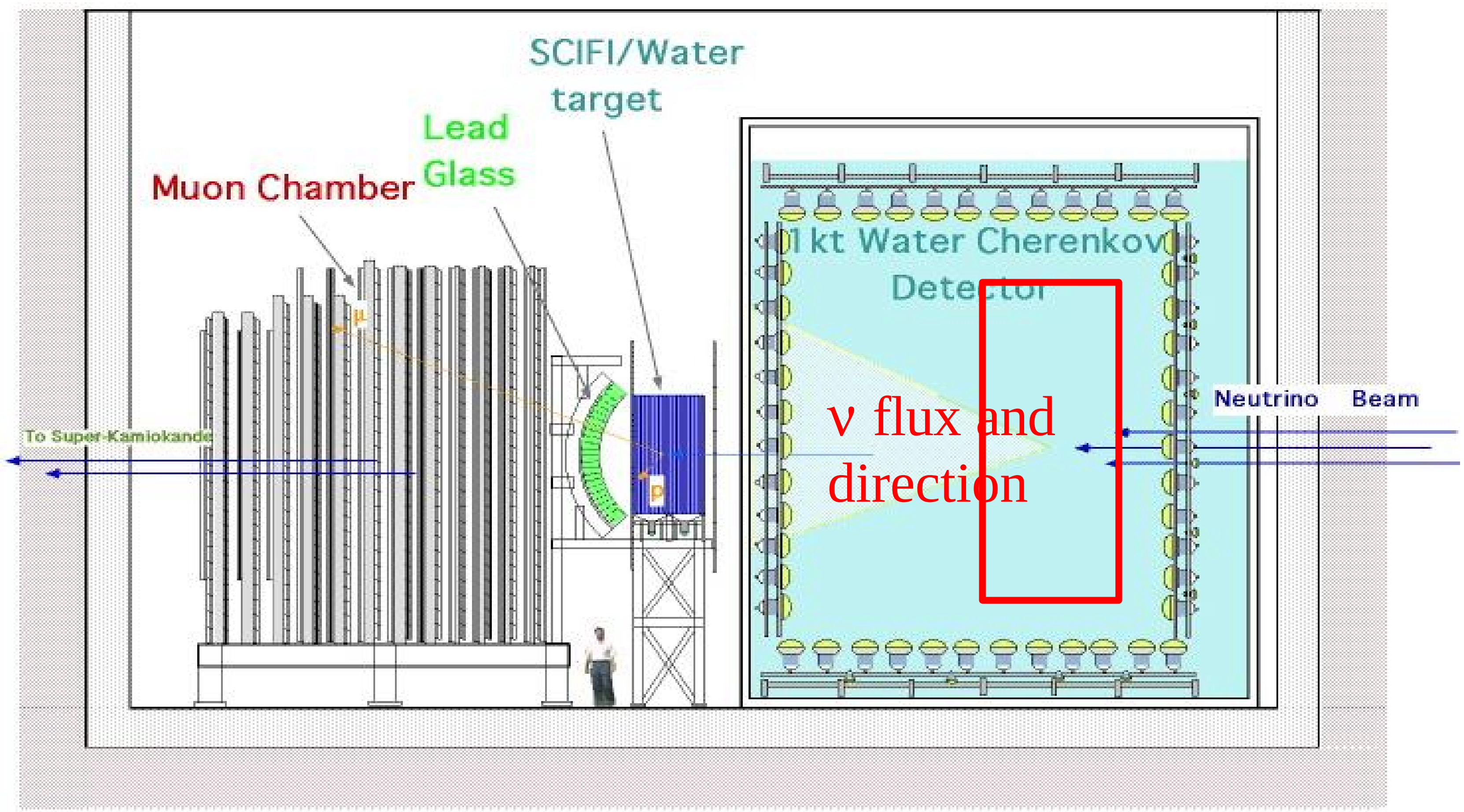
<u>Observations</u>
- **Reduction of events**
- **Spectrum distortion**

<u>Goal</u>
- **Does n_m decrease ?**
- **Does it depend on E_n ?**
- **Is it consistent to $\sin^2(1/En)$?**
- **What is Dm^2?**


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
Pion monitor

Near Detectors at KEK

	fiducial	
1kt Water Cherenkov detector (KT)	**25 ton**	**~ SK**
Water tube + Scintillation fiber detector (SciFi)	**6 ton**	**1, 2, >2 tracks**
Muon range detector(MRD)	**~700 ton**	n **beam monitor**
Lead glass detector (LG)		

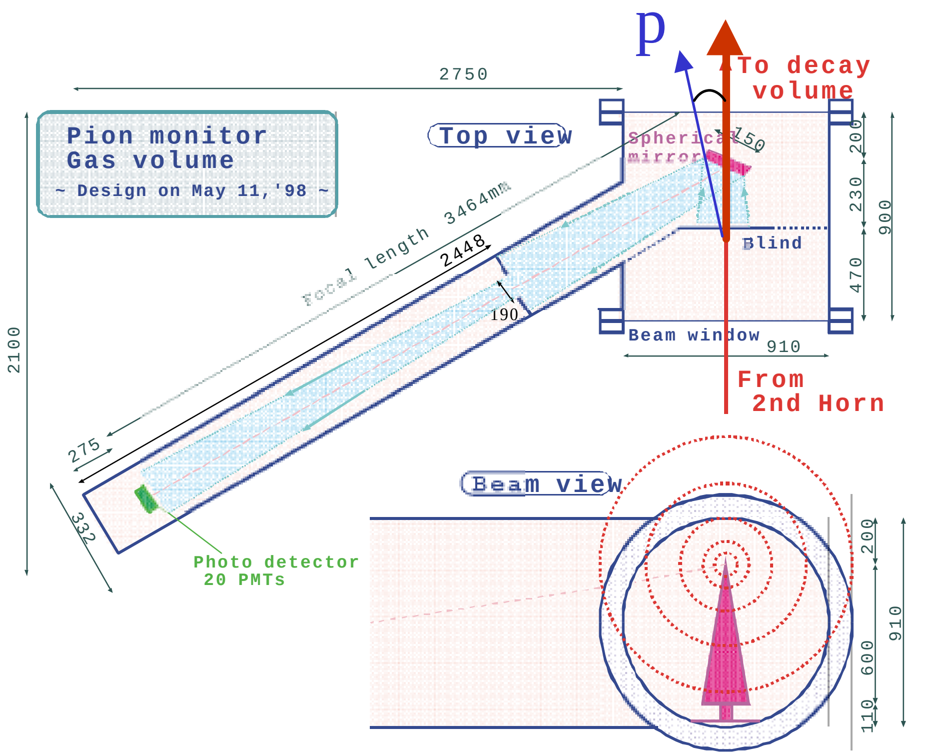


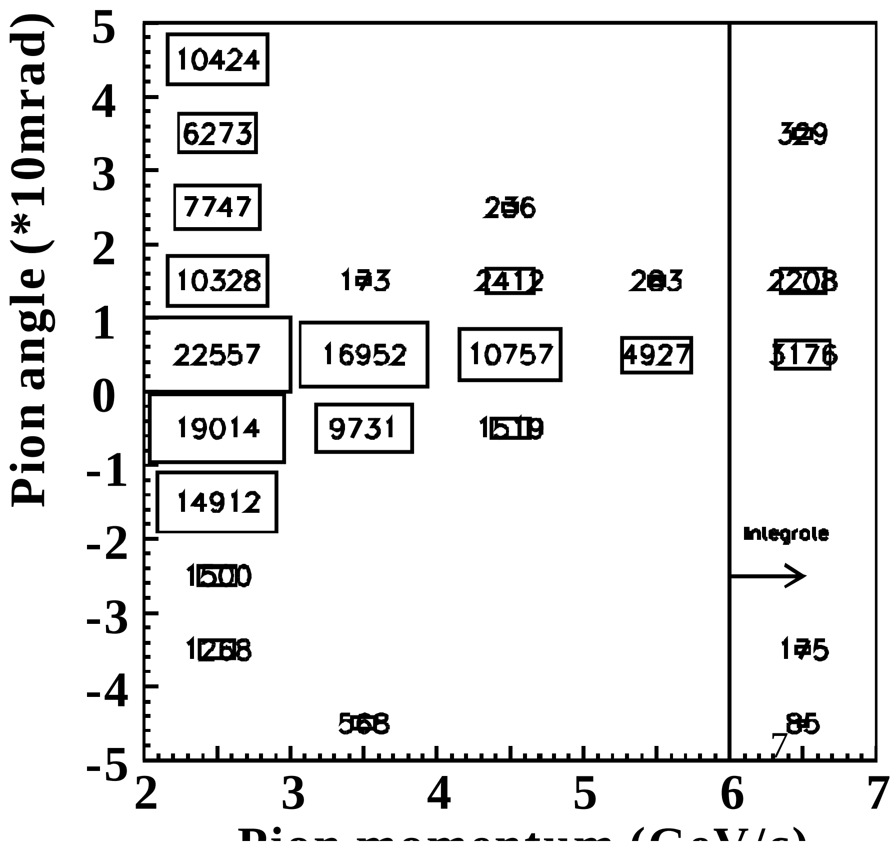
Pion Monitor : measure (p_p, q_p) distribution

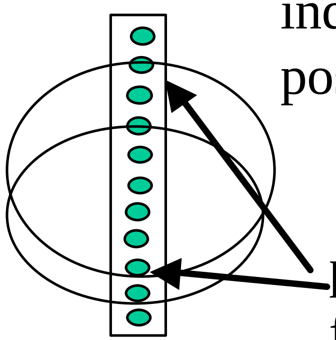
Gas Cherenkov detector: (insensitive to primary protons)

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

Choice of p Production model and error estimate

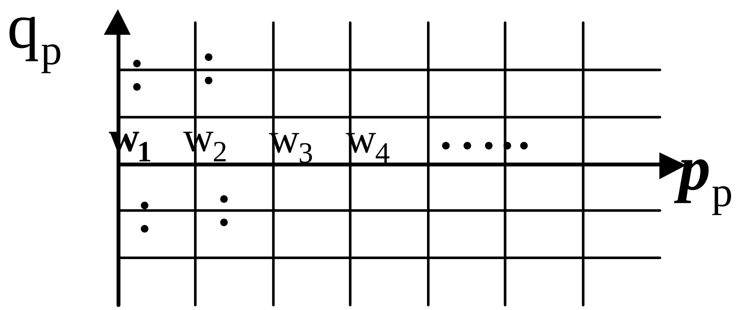


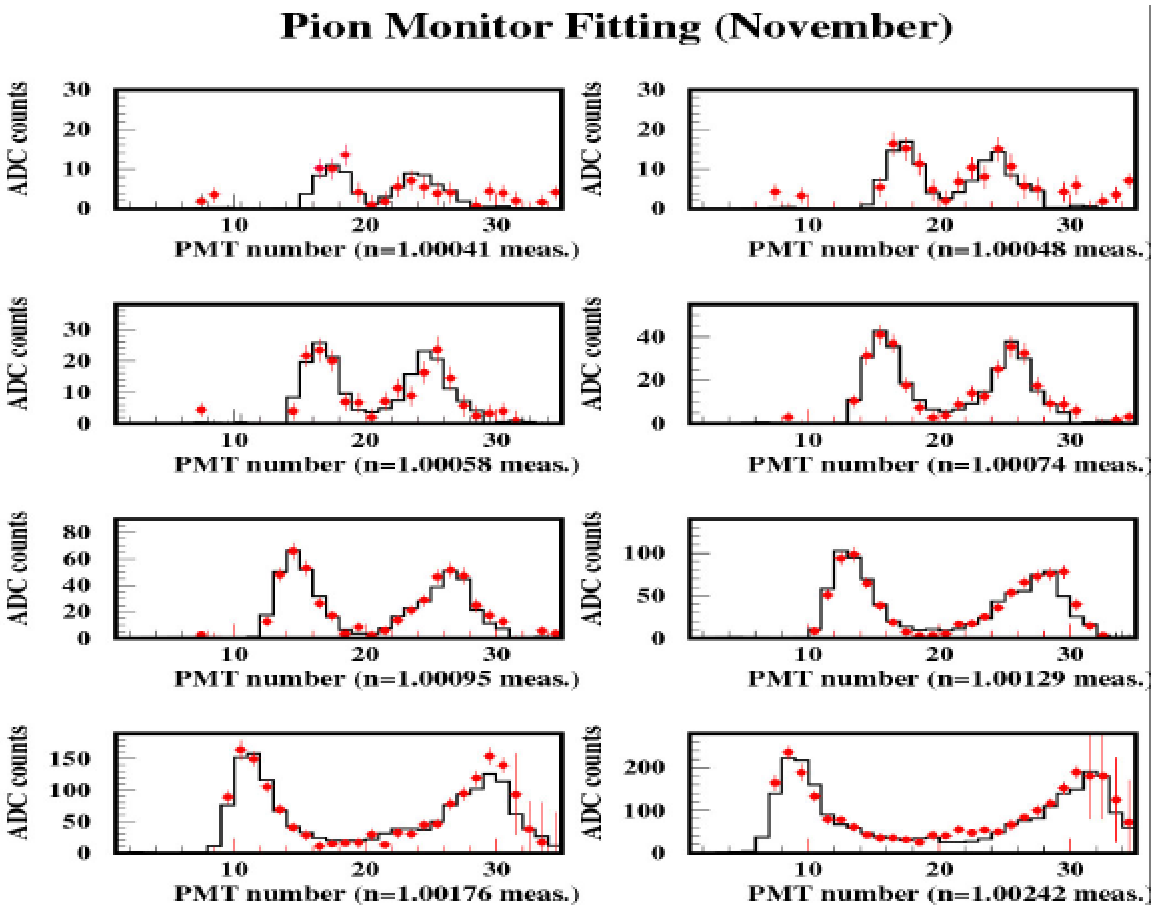




index of refraction : p_π threshold
position of ring : θ_π

p_π, θ_π gives two C-light peaks
fit with Σ (wi • C-light)





π production

Good agreement with old data. (Cho et.al.)

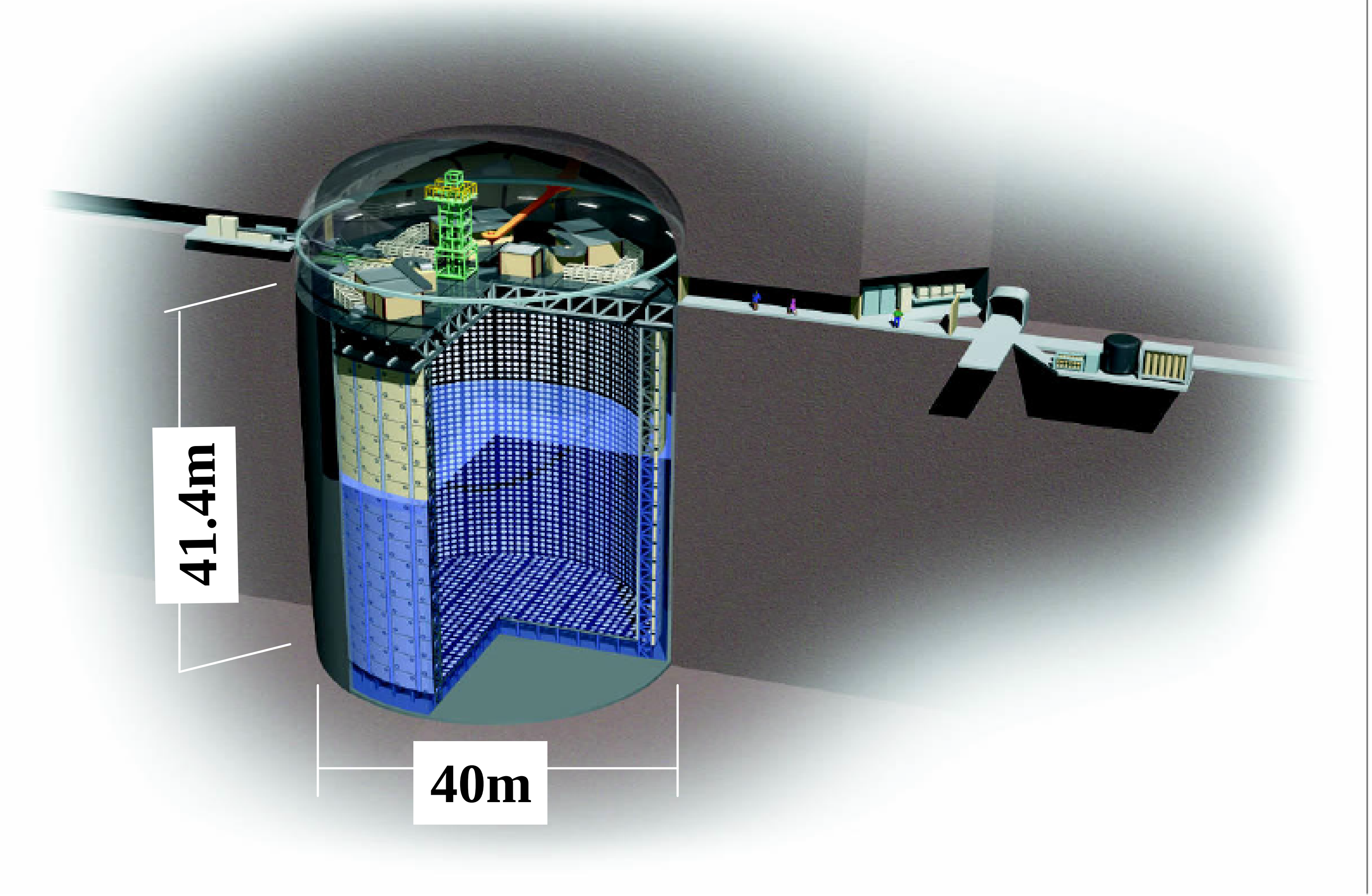
- **Beam MC**
- **Error asignment**

（ April 1996 commissioned）

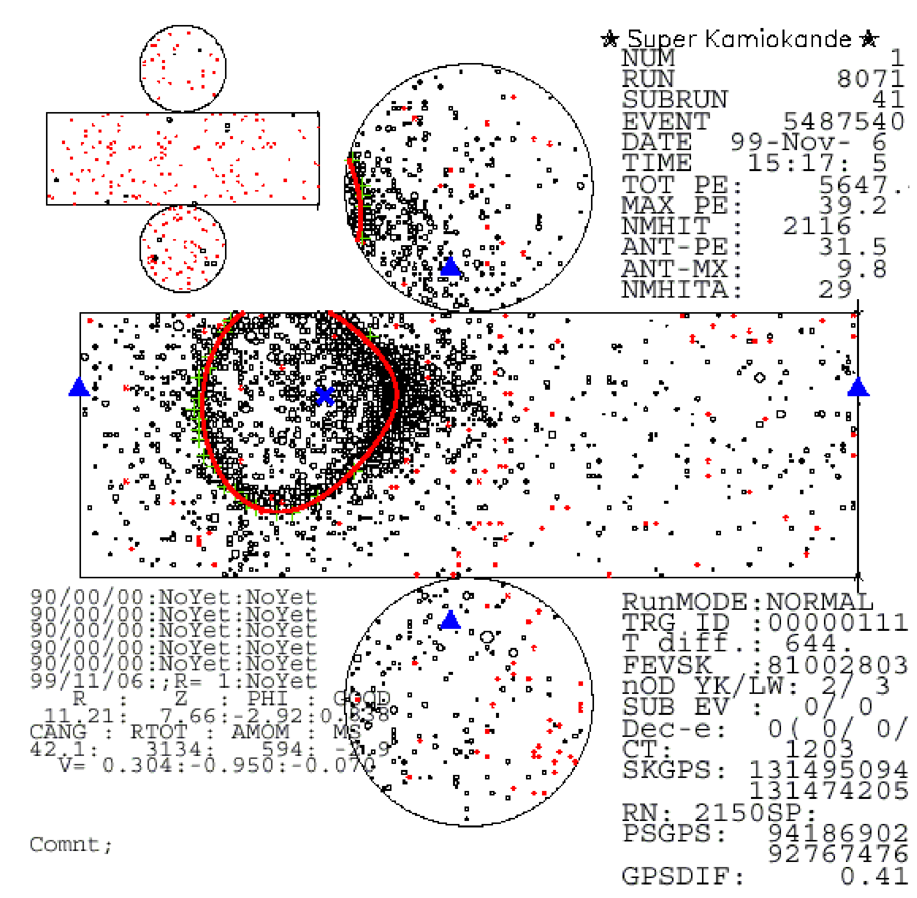
Super-Kamiokande

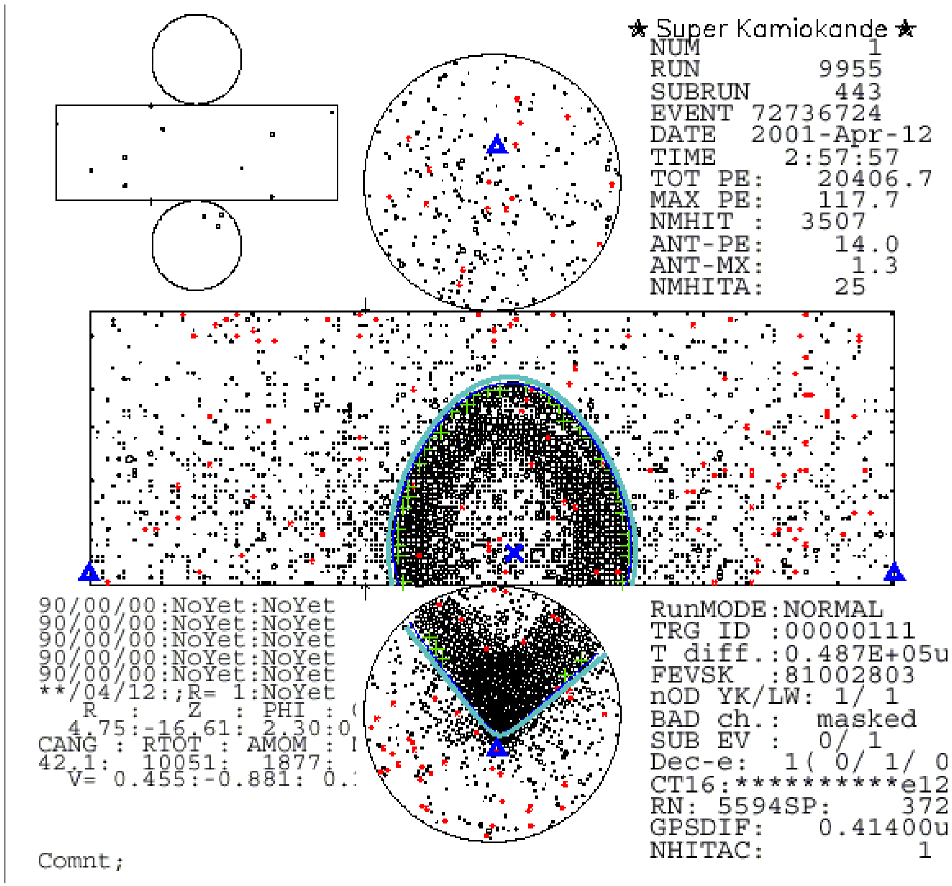
50,000 ton water Cherenkov detector (22.5 kton fiducial volume)

Optically separated INNER and OUTER detector



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

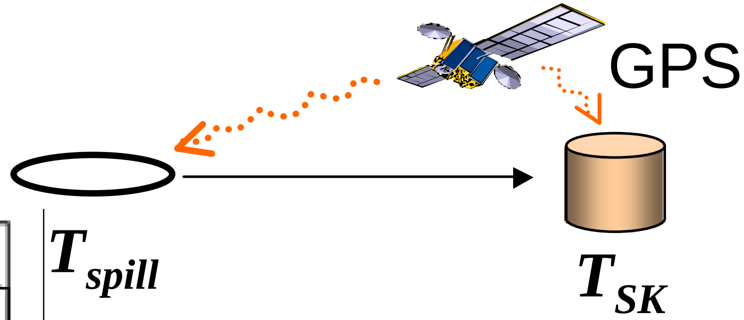




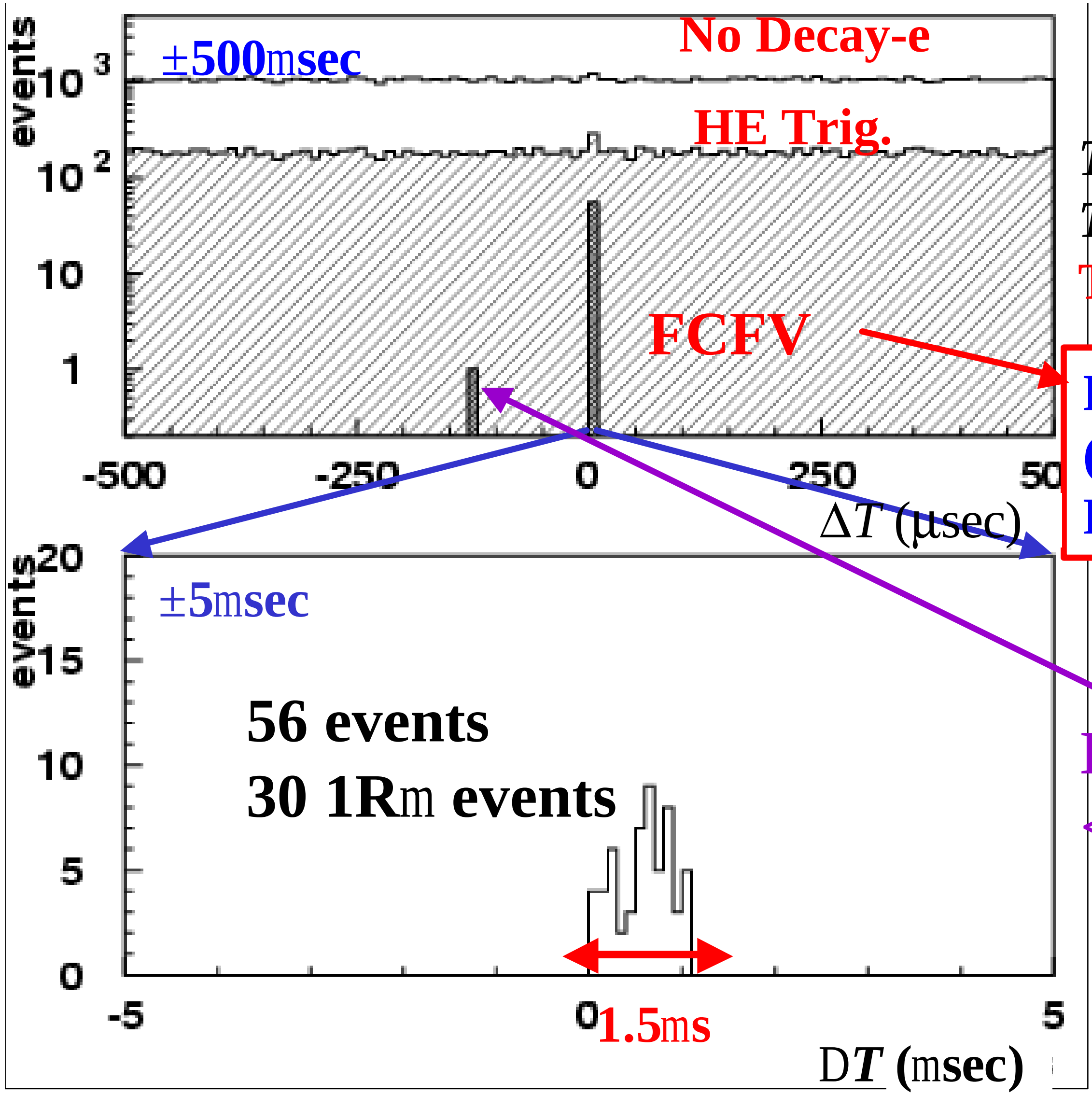
Total rate with low threshold (>30MeV) ~100% efficient for CC
Identification of μ (1Rμ) , e (1Re)

Super-K Event selection

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



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. n BG
$<10^{-3}$ within 1.5ms.

last year

Summary of K2K results 2001

- **Neutrino beam is well under control**
  - **Beam direction<1mrad. Û 3~4 mrad required**
  - **Stable Em spectrum from n interactions**
- **Accumulated 4.8x10^{19}POT @ SK from Jun ’99 to July ’01.**
  - **No change (obvious reason !)**
- **# 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% **(F/N, KT fid)**

This year

Full error treatment (correlation, etc.)

Re-calibration KT, SciFi, MRD

Rate + Shape

- **Null oscillation prob.**
- **Allowed region**

Flow of Neutrino Oscillation Analysis

Observed **(p_{m},q_{m})** **distributions at Near Detectors**

¯ n ***Int. Model***

Neutrino Spectrum at Near detector *f_{near}(En),*

–

Far/Near Extrapolation vs En **R_{FN}(En)**

Neutrino Spectrum w/o oscillation at SK *f_{SK}(En)*

f_{SK}(En) Ä **Oscillation** **($sin^{2}2q$,Dm^{2})** Ä ***Int. Model***

Prediction

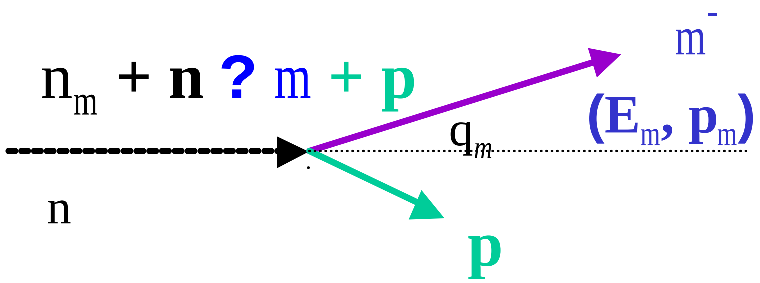
- ➢ **N_{SK}(exp’t) : Expected no. of SK events**
- ➢ **$S_{SK}(E_{n}^{rec})$:1Rm E_{rec}distribution(shape)**

SK observation

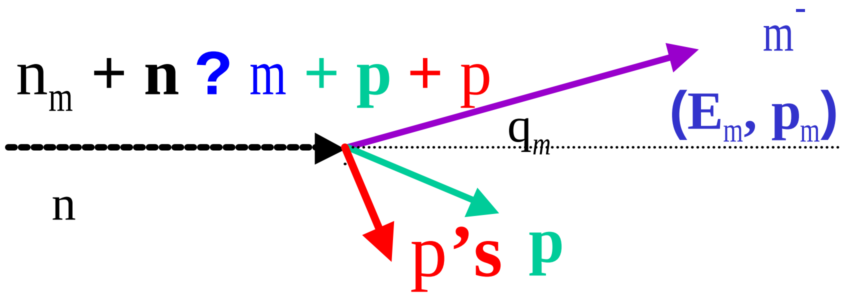
- **N_{SK}(obs)**
- **1Rm E_{rec} distribution**

Maximum Likelihood Fit in **($sin^{2}2q$, Dm^{2})**

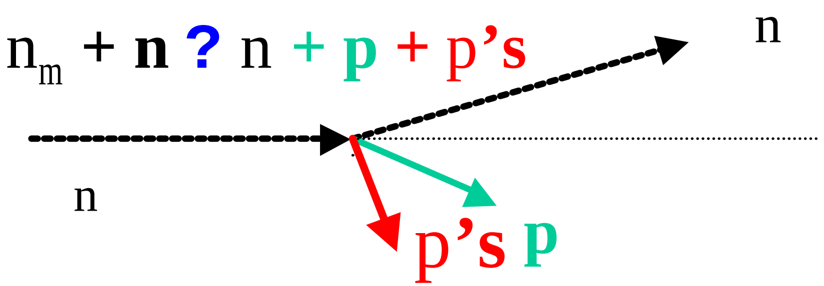
1Rm events in water Cherenkov detector
QE-like events in SciFi



- ✧ **CC QE**
  - ✧ **~100% efficiency for N$_{SK}$**
  - ✧ **can reconstruct En ¬ (q$_{m}$,p$_{m}$)**

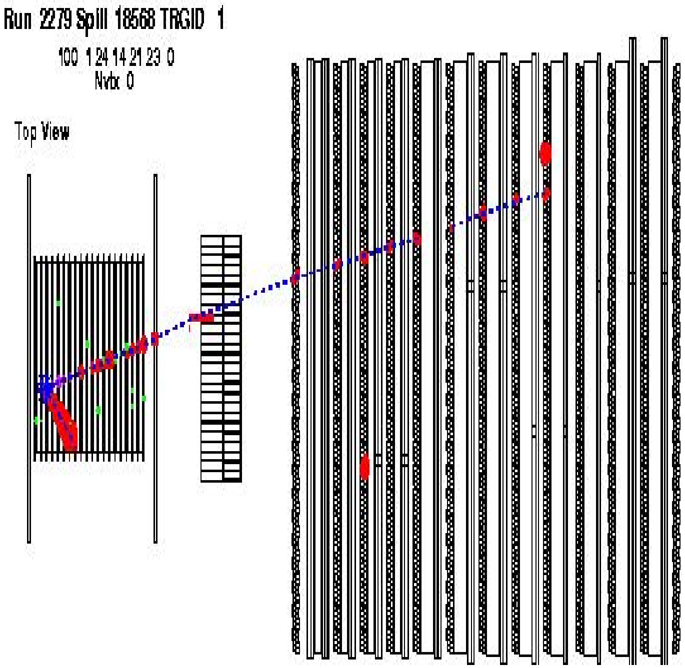


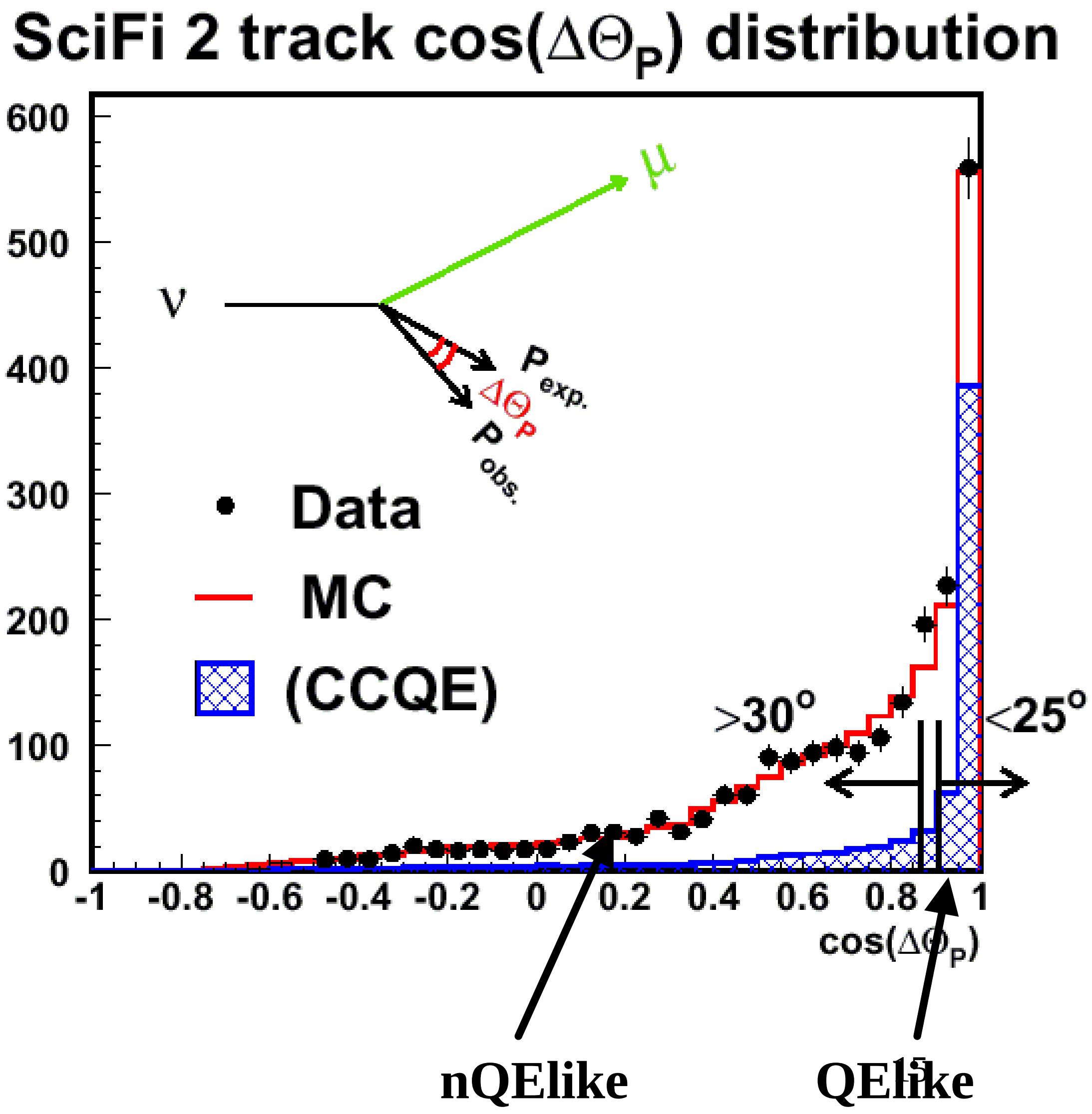
- ✧ **CC nQE**
  - ✧ **~100% efficiency for N$_{SK}$**
  - ✧ **Bkg. for E$_{n}$ measurement**



- ✧ **NC**
  - ✧ **~40% efficiency for N$_{SK}$**

QE and nQE in SciFi 2track events





Used data for f_{near}(En)

KT

Fully Contained Fiducial Volume (FCFV) events

•No. of events (Evis>100MeV)

(1) Single m-l ke events

SciFi

(2) 1-track m events

(3) 2-track QE-like events

(4) 2-track nonQE-like events

4 sets of (p_m, q_m) distributions

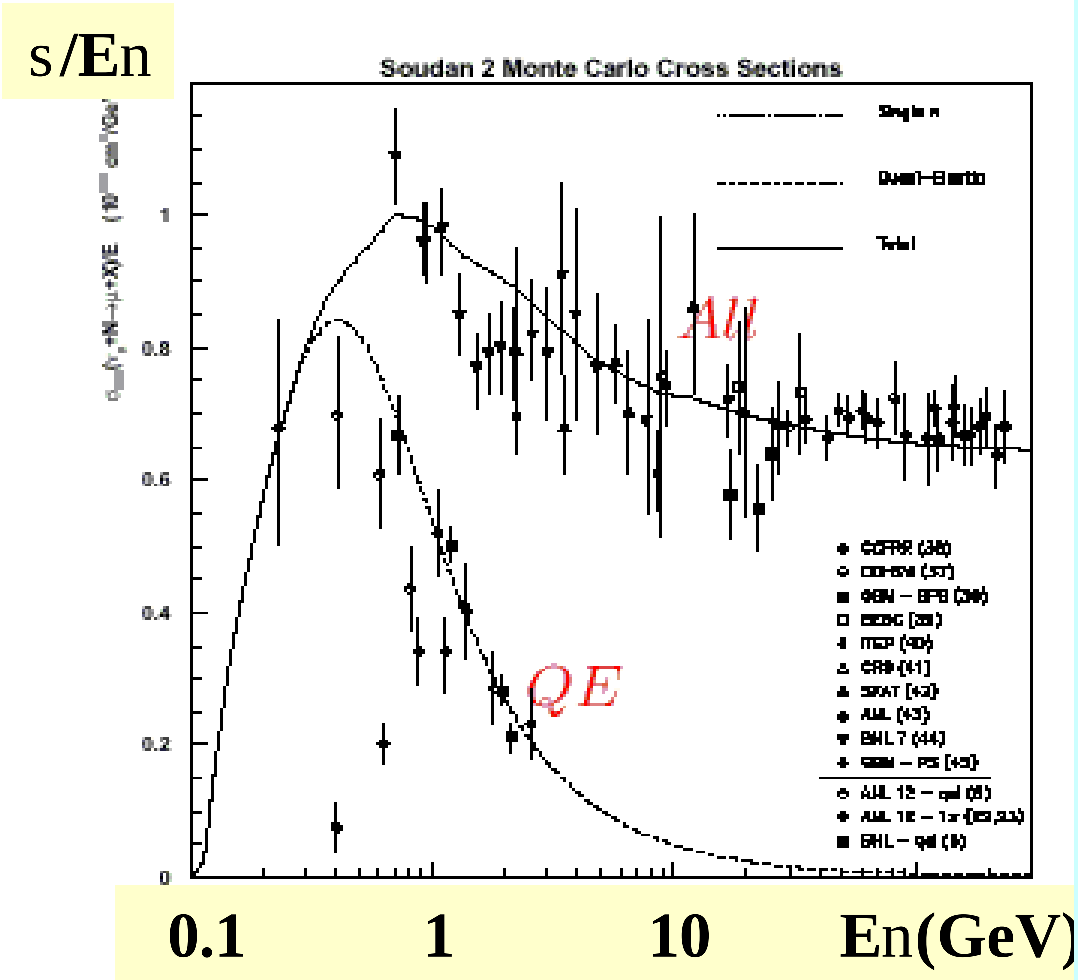
Pion monitor & Beam simulation

p **distribution in (p_p,q_p) ® flux estimate f_{near}(En) w. error**

n **flux f_{near}(En) (8 bins)**

n **interaction model (param. as nQE/QE ratio)**

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



Not well known

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

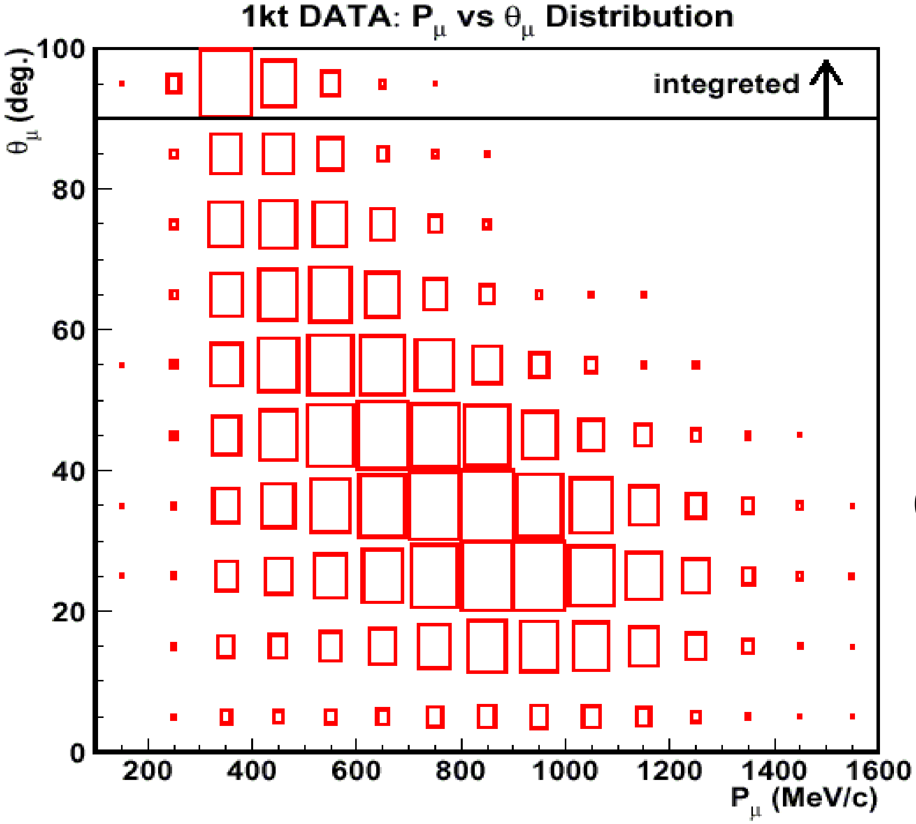
Checked

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

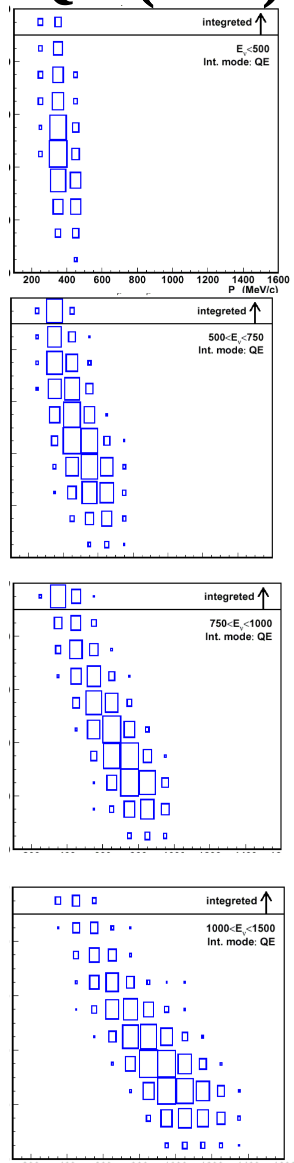
Very small effect on oscilllation anlysis

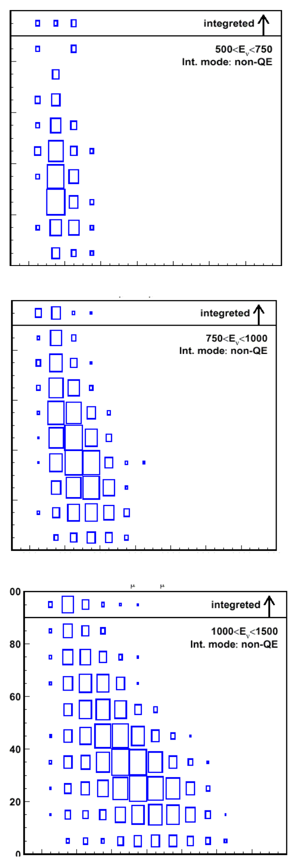
Fitting method

(p_m,q_m) ® f(En), nQE/QE



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



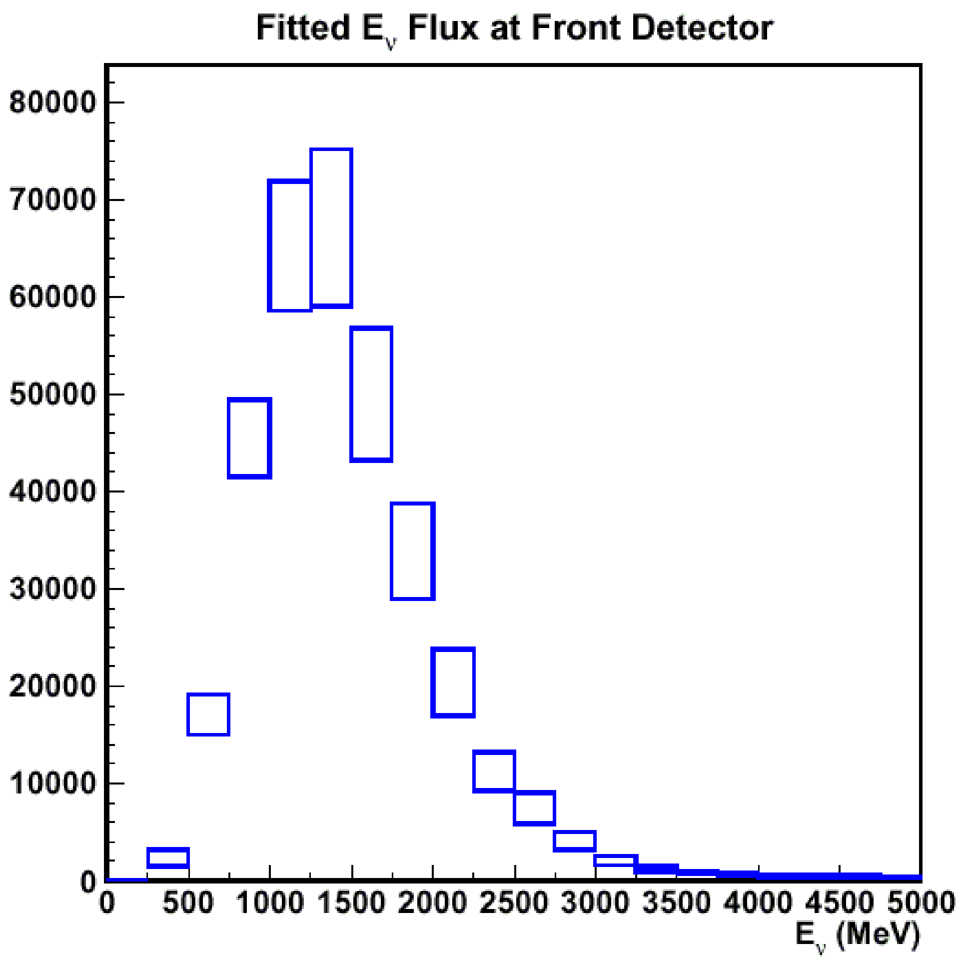


Also (p_m,q_m) dist. in SciFi

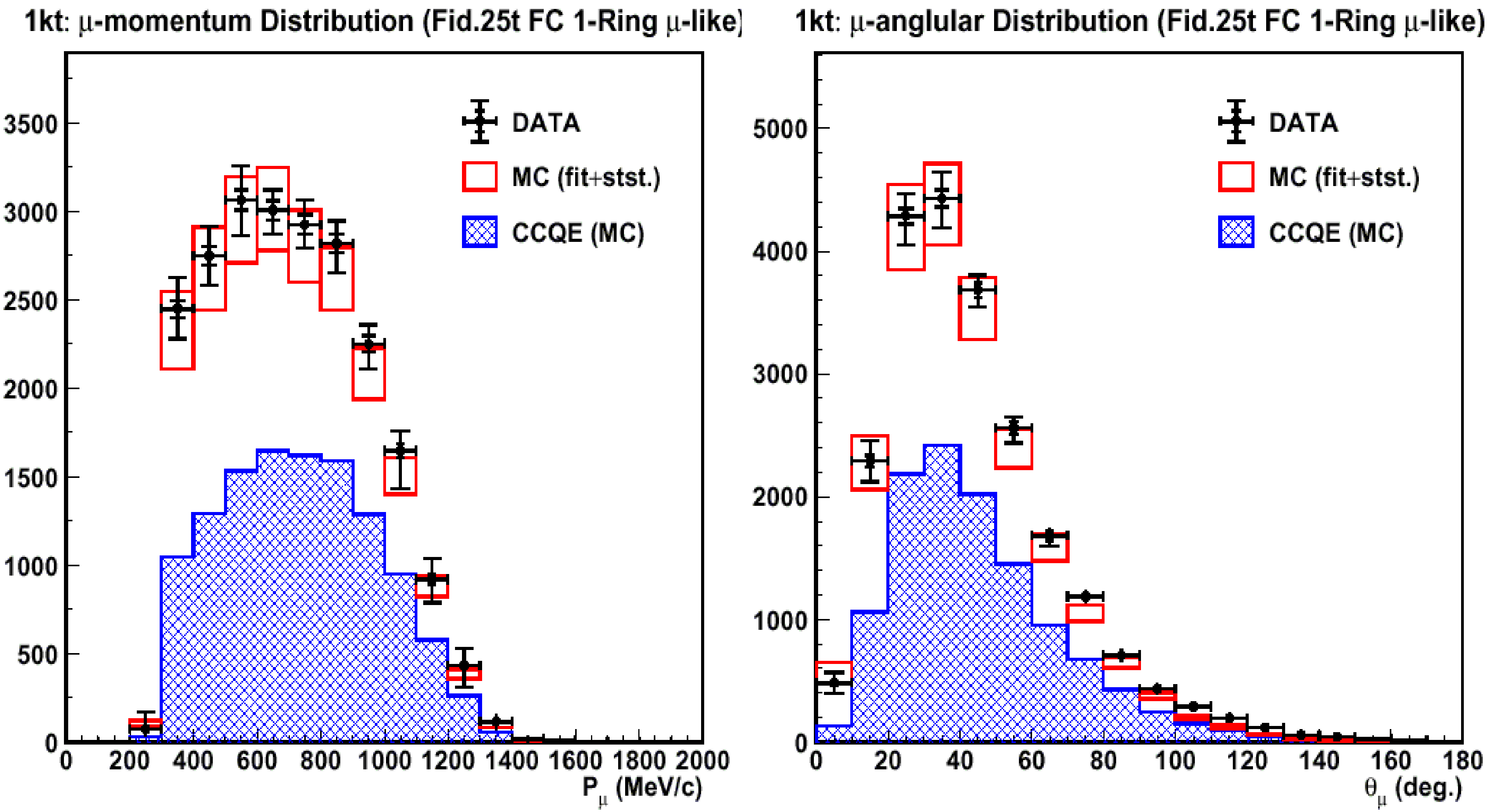
1track, 2track(QE-like), 2track(nQE-like)

c2=227 for 197 d.o.f.

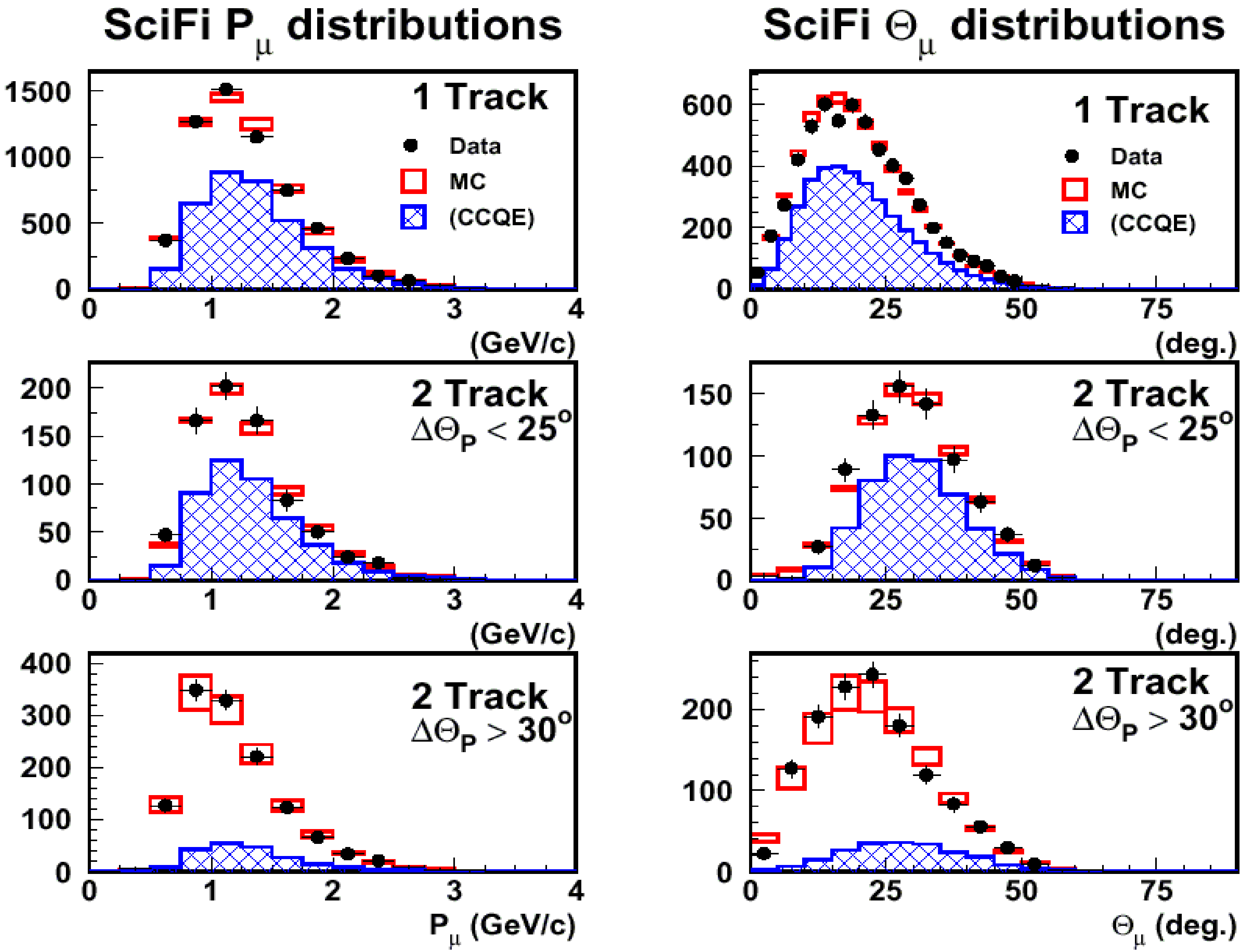
Fit result of Neutrino Flux at KEK Site



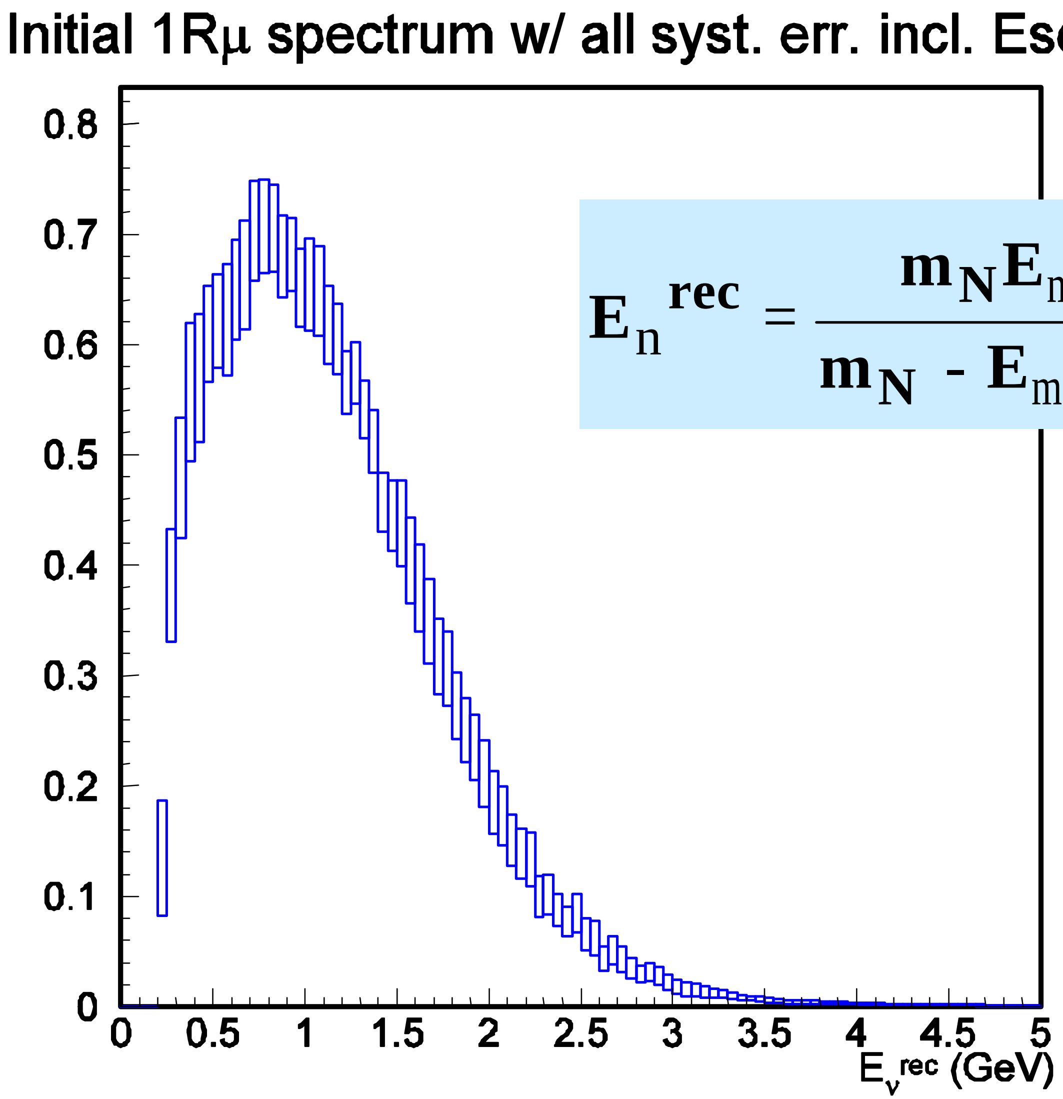
KT (p_m, q_m) distribution using f_{fit}, QE/nQE_{fit}



Scifi p_m, q_m distributions using f_{fit}, QE/nQE_{fit}



Expected E_ν^{rec} spectrum for 1Rμ at SK if no oscillation



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

Oscillation analysis

Neutrino flux @SK Ä *Int. Model* Ä Oscillation (sin^{2}2q,Dm^2)

Separated into No of event & Renormalized E_{rec} shape

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

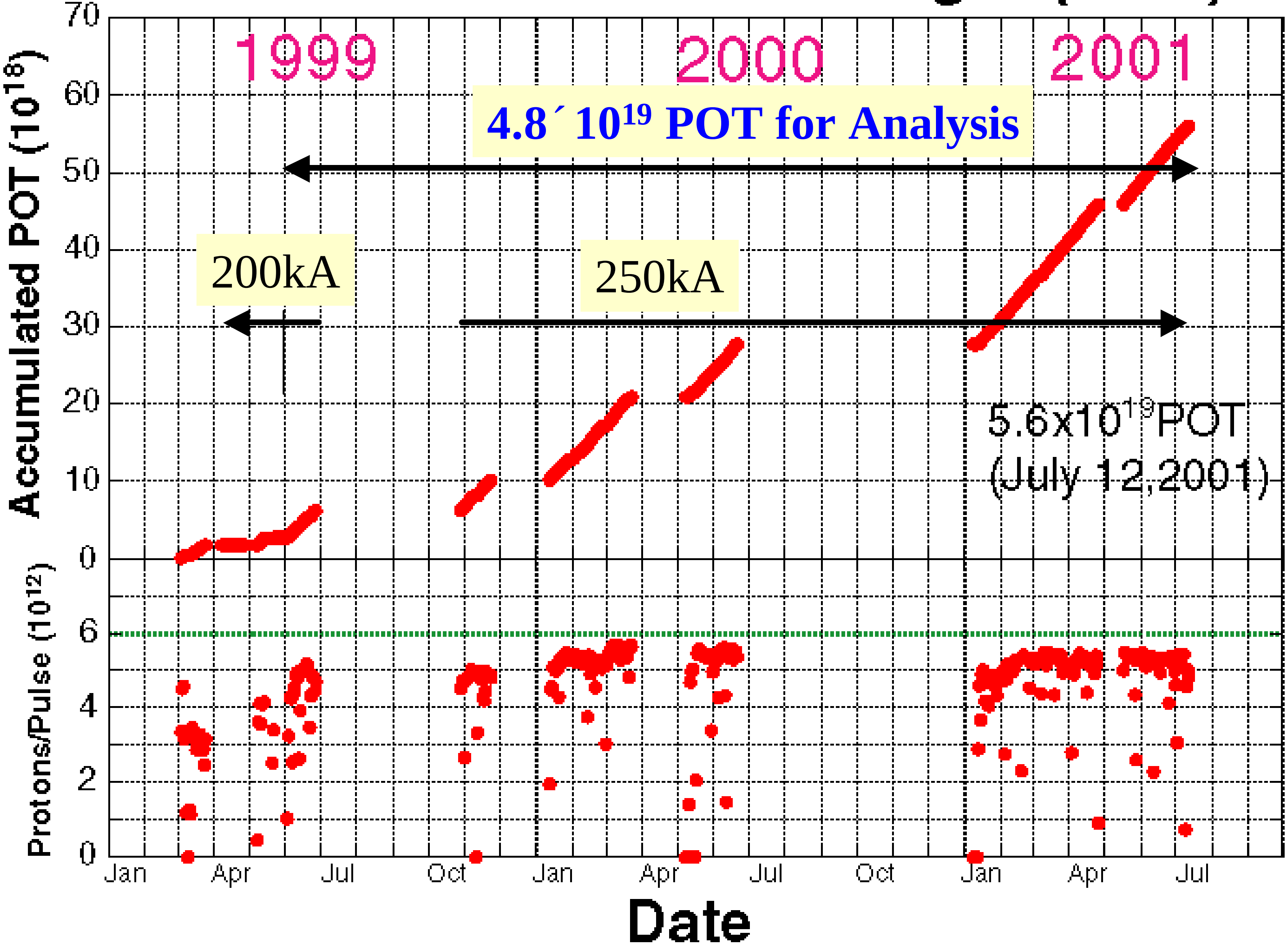
SK observation

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

Maximum Likelihood Fit in (sin^{2}2q,Dm^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**
  - **<u>June 99-July 01</u> FCFV , Evis>30 MeV**
    - **total number of events**
    - **56 events observed**
  - **<u>Nov 99-July 01</u> 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

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

$\mathbf{f}_{\mathrm{f}}$: Flux (8 energy bins)
$\mathbf{f}_{\mathbf{nQE}}$: QE/nQE ratio
$\mathbf{f}_{\mathbf{F/N}}$: Far/Near ratio
$\mathbf{f}_{\mathrm{e}\mathbf{SK}}$: SK reconstruction (Fid, PID, Nring)
$\mathbf{f}_{\mathbf{ESK}}$: SK energy scale
$\mathbf{f}_{\mathbf{n6}}$: Norm. for June 99
$\mathbf{f}_{\mathbf{n11}}$: Norm. Nov 99 ~ Jul 01

Likelihood

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

Normalization term

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

$\mathbf{N_{obs}=56}$

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

Shape term for FCFV 1Rμ

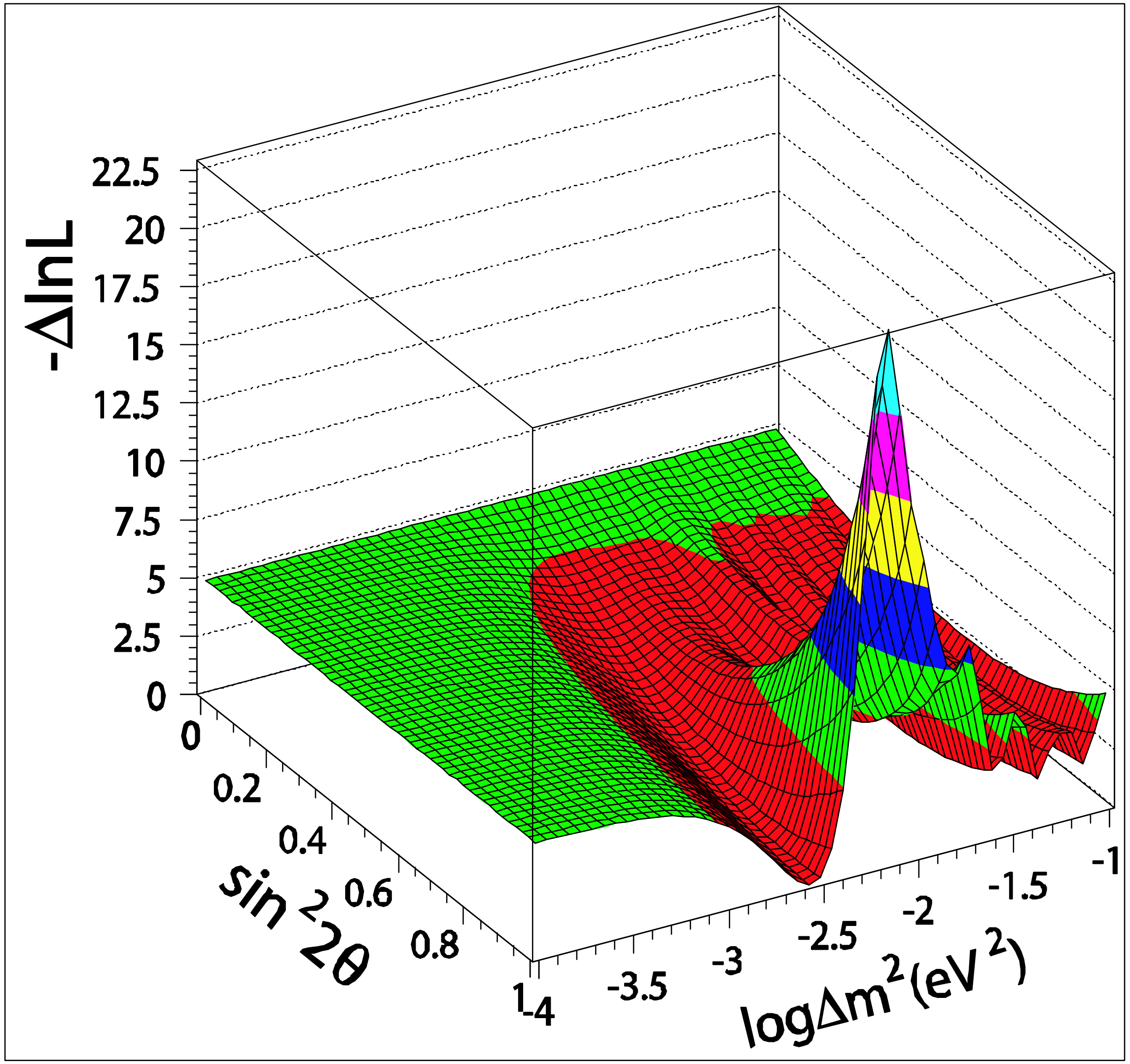
$$L_{shape} \equiv \prod_{i=1}^{29} P((f_{Esk} \cdot E_i), \Delta m^2, \sin^2 2\theta, f)$$

Shape only

Systematic parameter constraint term

$$\mathbf{L_{syst}} \equiv \mathbf{\exp}\left(-\Delta \mathbf{f}^{\mathbf{T}}_{\mathrm{F},\mathbf{nQE}} \cdot \mathbf{M}^{-1}_{\mathbf{FD}} \cdot \Delta \mathbf{f}_{\mathrm{F},\mathbf{nQE}} / 2\right) \cdot \cdot \cdot \cdot \cdot$$
$$\times \mathbf{\exp}\left(-\mathbf{f}^2_{\mathbf{n6}} / 2\sigma^2_{\mathbf{n6}}\right) \mathbf{\exp}\left(-\mathbf{f}^2_{\mathbf{n11}} / 2\sigma^2_{\mathbf{n11}}\right) \mathbf{\exp}\left(-\Delta \mathbf{f}^2_{\mathbf{Esk}} / 2\sigma^2_{\mathbf{Esk}}\right)$$

3d plots of DlnL for shape+norm & definition of L



<u>L at (Dm^2, $\sin^2 2$q)</u>

- method-1

  Maximize L by adjusting systematic parameters.

- method-2

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

Null Oscillation Probability

Null Oscillation Probability

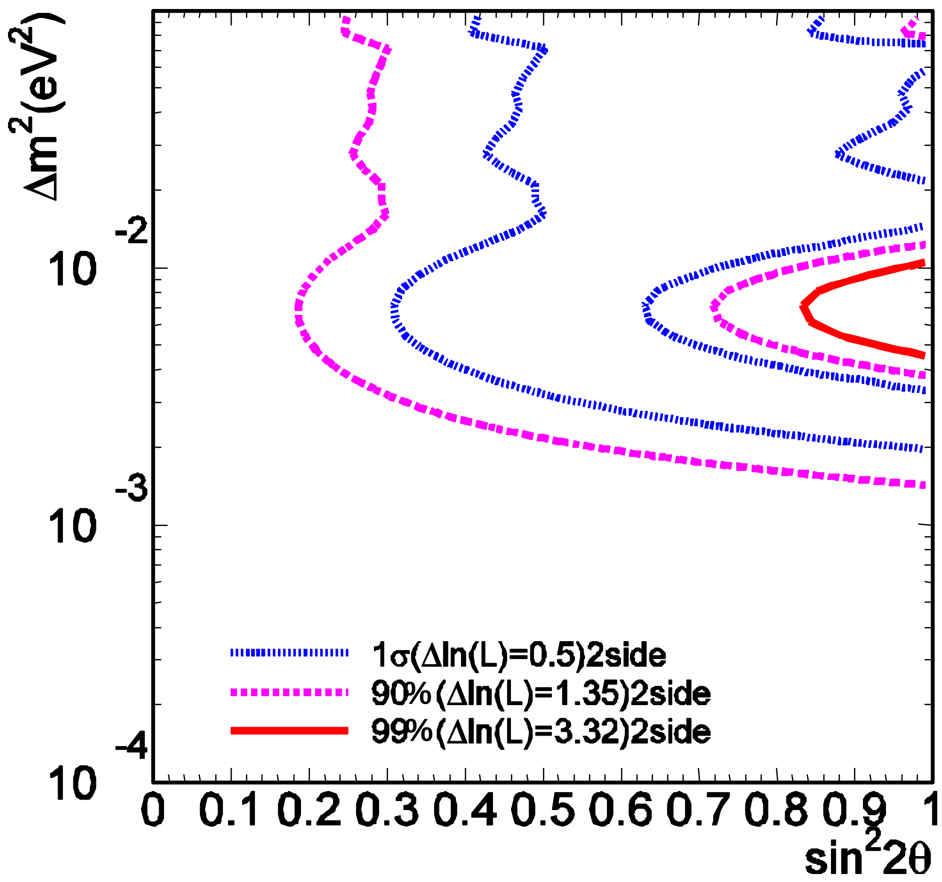
	method-1	method-2
N_{SK}only	1.3%	0.7%
Shape only	15.7%	14.3%
N_{SK}+Shape	0.7%	0.4%

Best fit ($\sin^2 2\theta$, Δm^2)

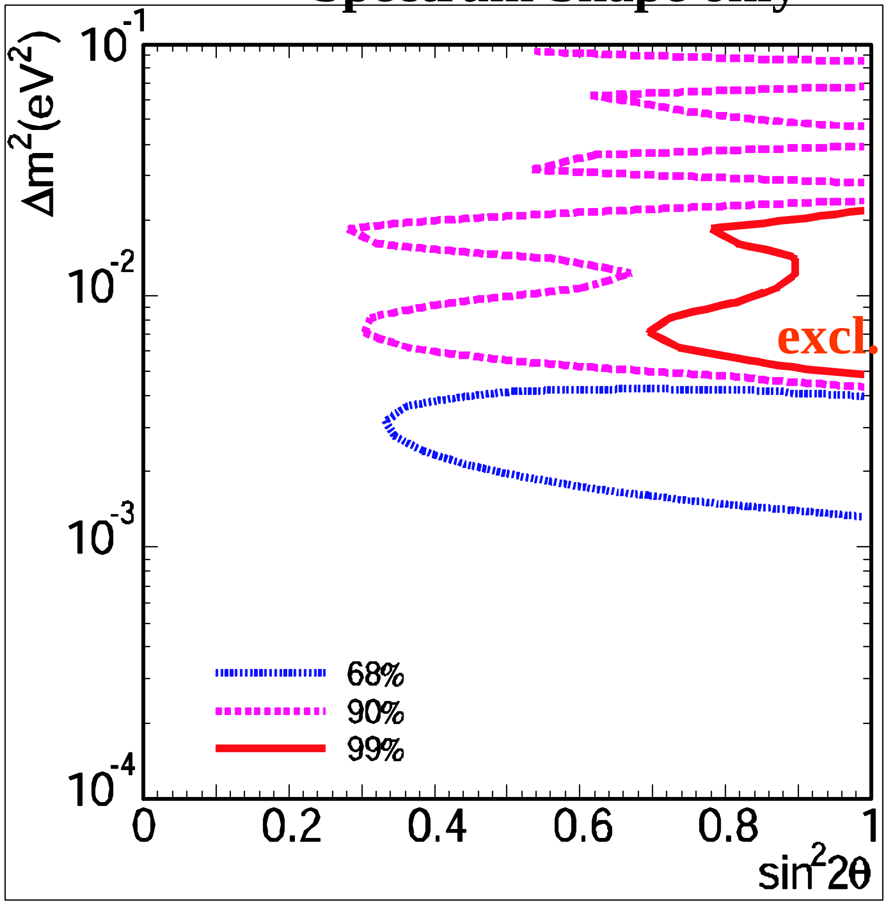
	method-1	method-2
Shape only	(1.0, 3.0×10^{-3}eV^2)	(1.0, 3.2×10^{-3}eV^2)
(Allowing unphys.)	(1.09, 3.0×10^{-3}eV^2)	(1.05, 3.2×10^{-3}eV^2)
N_{SK} +Shape	(1.0, 2.8×10^{-3}eV^2)	(1.0, 2.7×10^{-3}eV^2)
(Allowing unphys.)	(1.03, 2.8×10^{-3}eV^2)	(1.05, 2.7×10^{-3}eV^2)

Allowed regions

Total no. of Events only

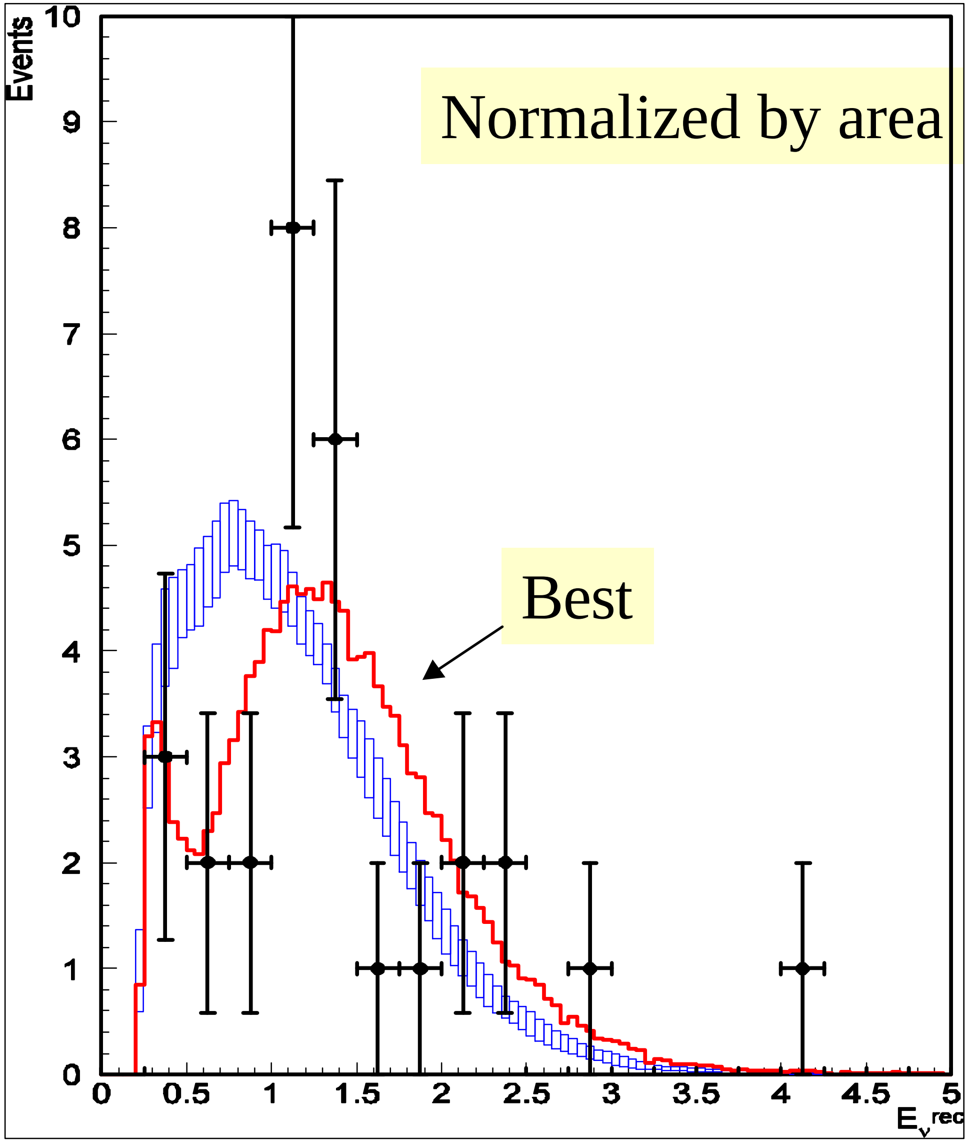


Spectrum Shape only



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

Is best fit point also for 1Rm shape & Nsk ?



Best fit point ($\sin^2 2q$, Dm^2)

method 1

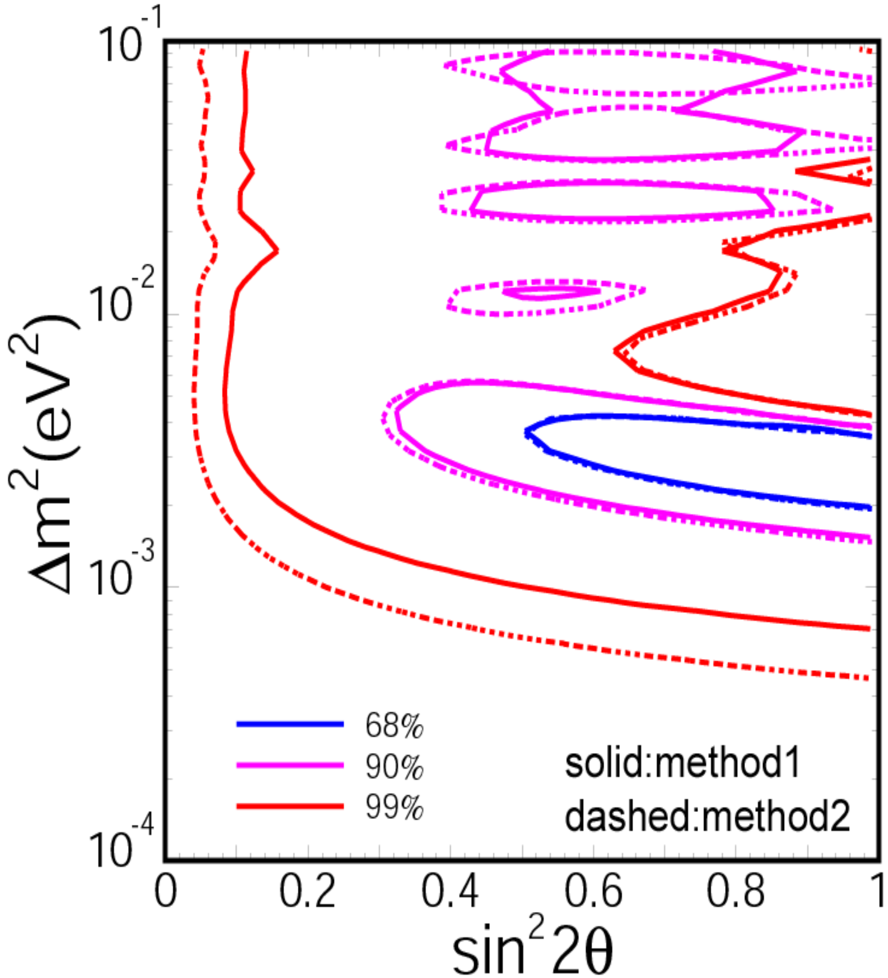
KS test prob.(shape)= 79%

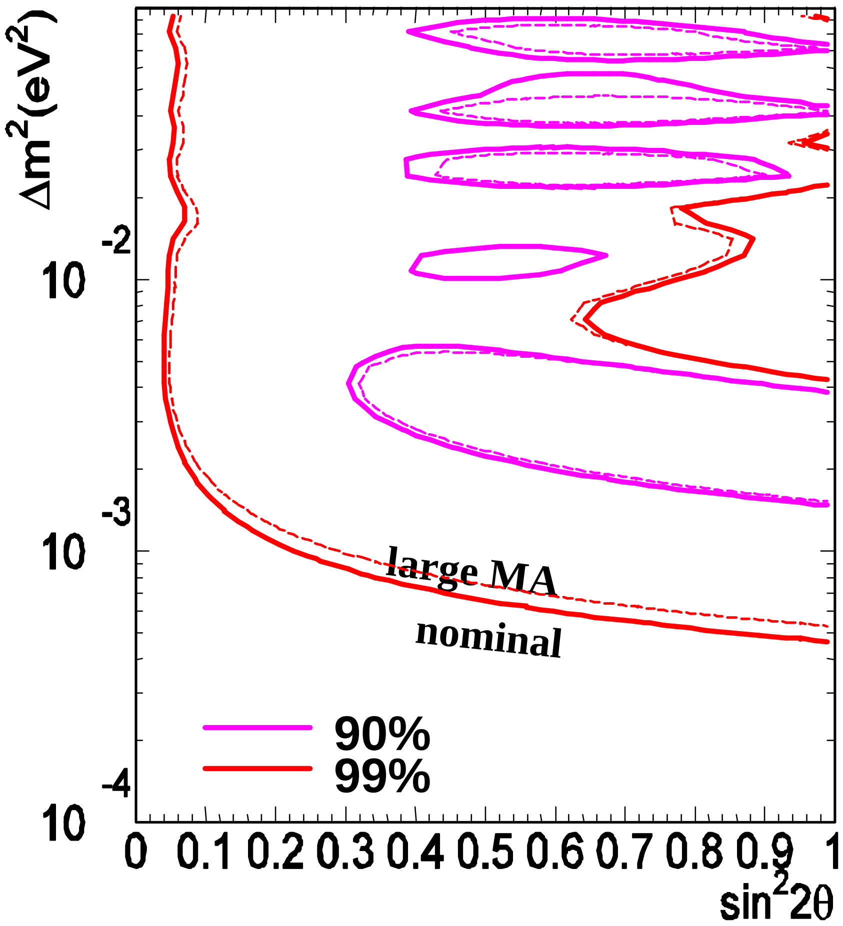
N_{SK} prediction =54 (obs 56)

method 2 KS-test

N_{SK}	**82%**
shape	**93%**
N_{SK}+shape	**50%**

Comparison with diff. L & n interaction model

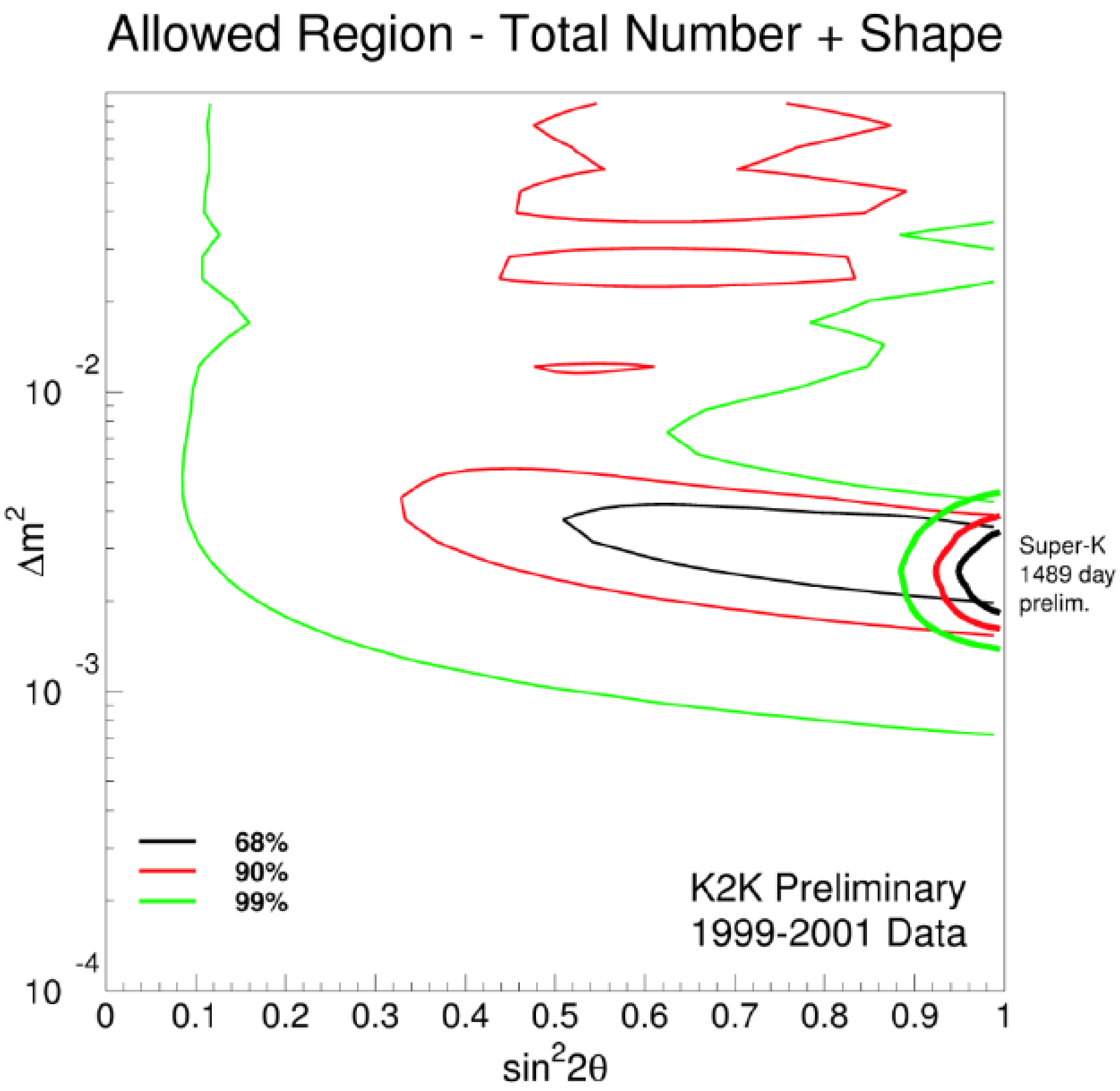




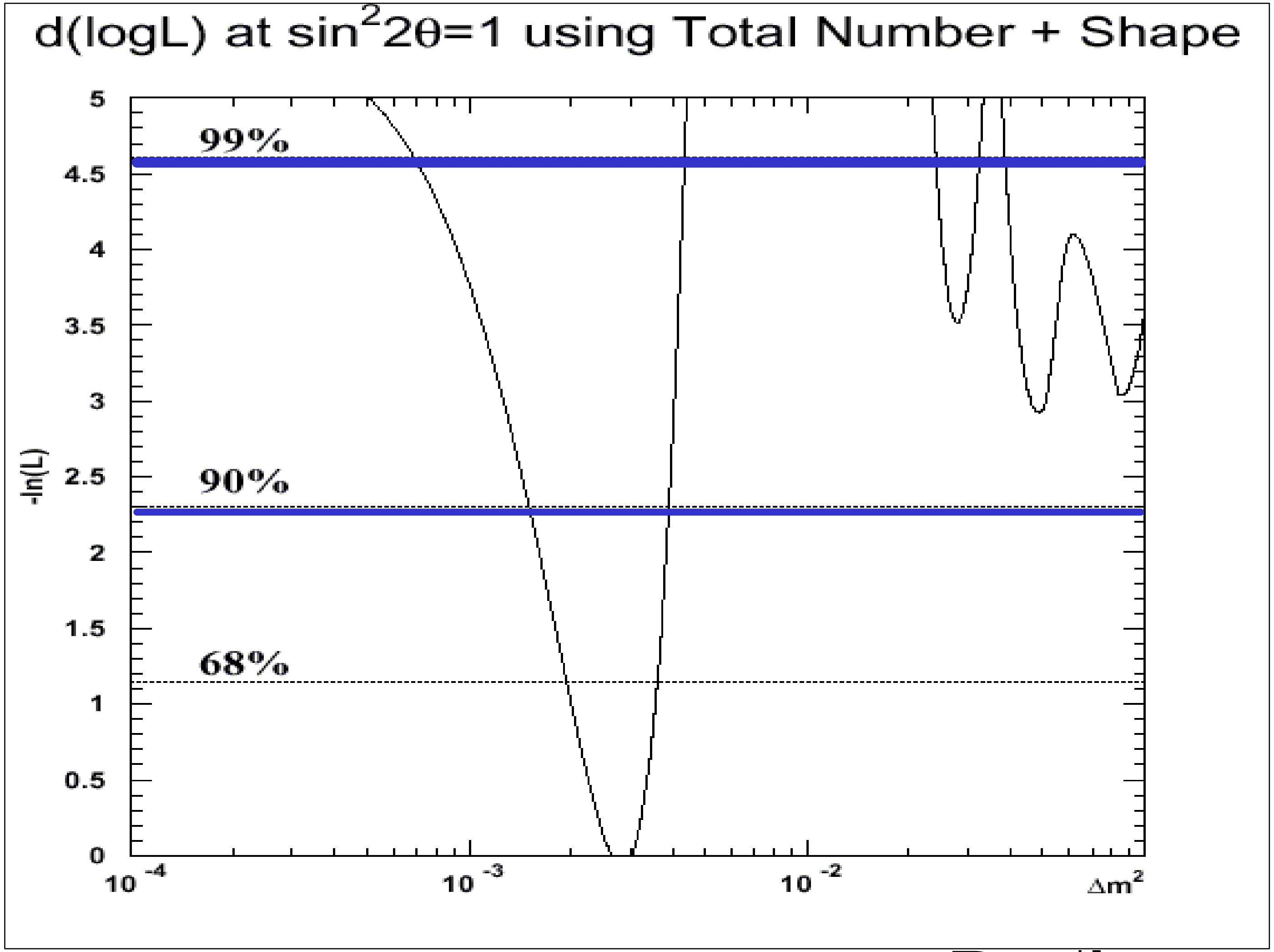
Reasonable agreement btw definition of L

Change of n interaction model has small effect

Comparison with SK atm n observation

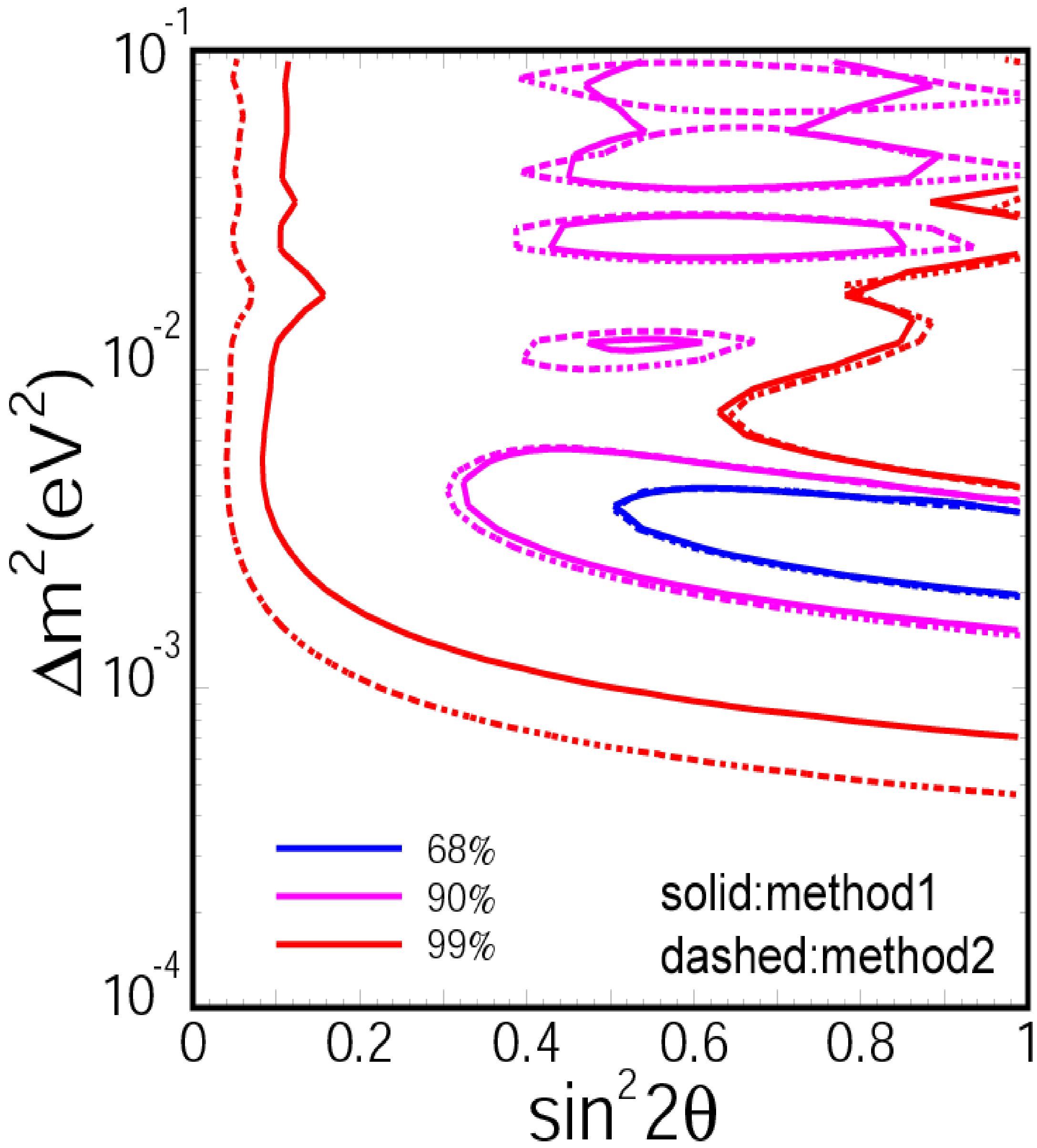


Dm^2 for sin^{2}2q=1



Dm^2

K2K Allowed region (Shape+Norm)



1.5~3.9x10^{-3}eV^2
@ $\sin^2 2$q=1
@90%CL

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_n^{rec} shape indicate consistent oscillation parameters region**
3. Dm^2**=1.5~3.9x10^{-3}eV^2 for sin^{2}2**q**=1 @ 90%CL**
4. **sin^{2}2**q**,** Dm^2 **are consistent with atmospheric neutrino results**

The best fit point (sin^{2}2q**=1.0,** Dm^2**=2.8x10^{-3} eV^2)**

cf. Atmospheric neutrino results

Dm^2**=(1.6~3.8)x10^{-3} eV^2 for sin^{2}2**q**=1.0**

best fit (sin^{2}2q**=1.0,** Dm^2**=2.5x10^{-3} eV^2)**

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