Search for Electron Neutrino Appearance in a 250km Long-Baseline Neutrino Experiment

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2004/03/16
KEK seminar

K2K Collaboration

~100 collaborators from;

- JAPAN: High Energy Accelerator Research Organization (KEK)
  Institute for Cosmic Ray Research (ICRR), Univ. of Tokyo
  Kobe Univ. / Kyoto Univ.
  Niigata Univ. / Okayama Univ. / Osaka Univ.
  Tokyo Univ. of Science / Tohoku Univ.
- KOREA: Chonnam National Univ. / Dongshin Univ. / Korea Univ.
  Seoul National Univ.
- U.S.A.: Boston Univ. / Univ. of California, Irvine / Univ. of Hawaii
  Massachusetts Institute of Technology
  State Univ. of New York / Univ. of Washington
- POLAND: Warsaw Univ. / Solton Institute for Nuclear Studies

Since 2002 (K2K-II);

- JAPAN: Hiroshima Univ.
- CANADA: TRIUMF / Univ. of British Columbia
- EUROPE: Rome / Saclay / Barcelona / Valencia / Geneva
- RUSSIA: INR-Moscow

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- Introduction to K2K
- Strategy for νe appearance search
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K2K Long Baseline Neutrino Oscillation Experiment

Kamioka
•Super-K

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

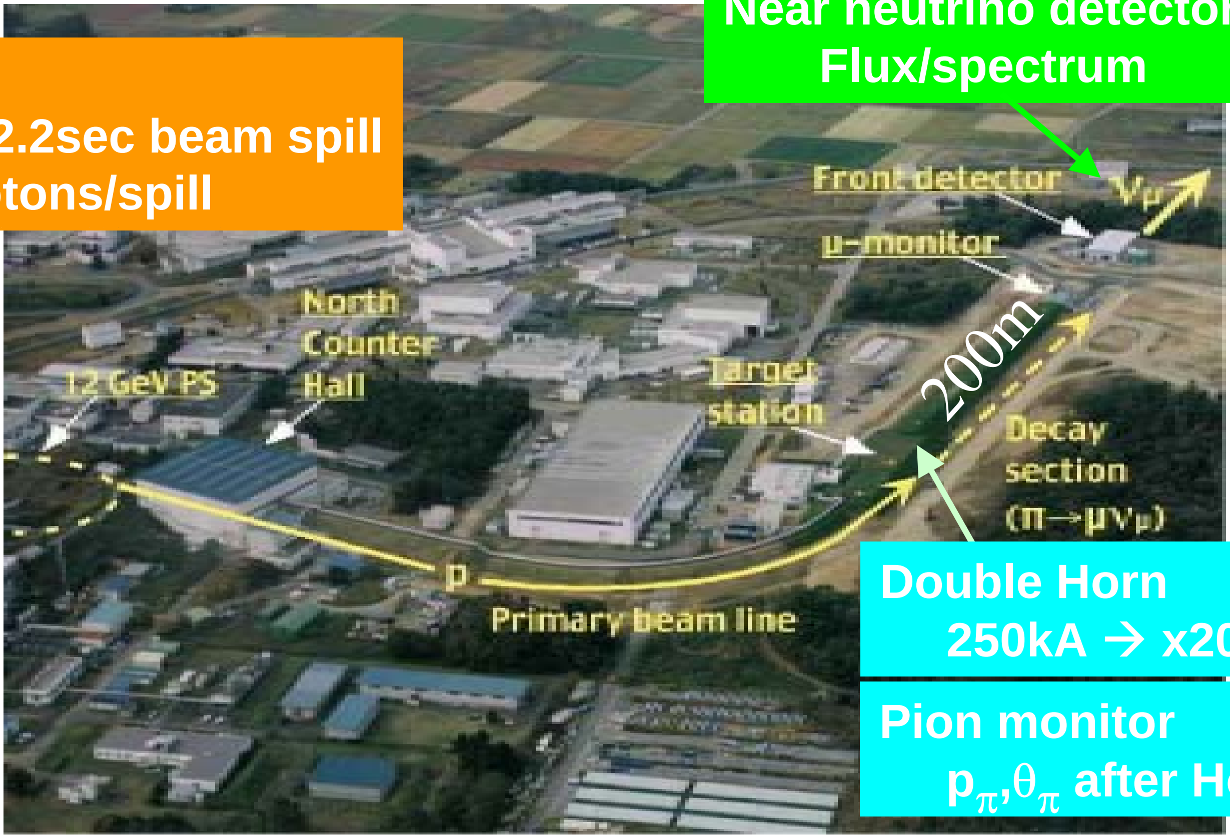
- Neutrino beam
  almost pure ν_μ (98%)
  $<E_\nu>\sim 1.3$GeV
- Near detectors
  Measure ν_μ flux/spectrum
- Far detector
  Super-Kamiokande (SK)
  250 km far from KEK
- Probe to ν_μ disappearance and ν_e appearance

Neutrino Beam Line @KEK

$$p + \mathrm{Al} \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\rightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

12GeV PS
1.1μsec / 2.2sec beam spill
6×10^{12} protons/spill

Near neutrino detectors
Flux/spectrum

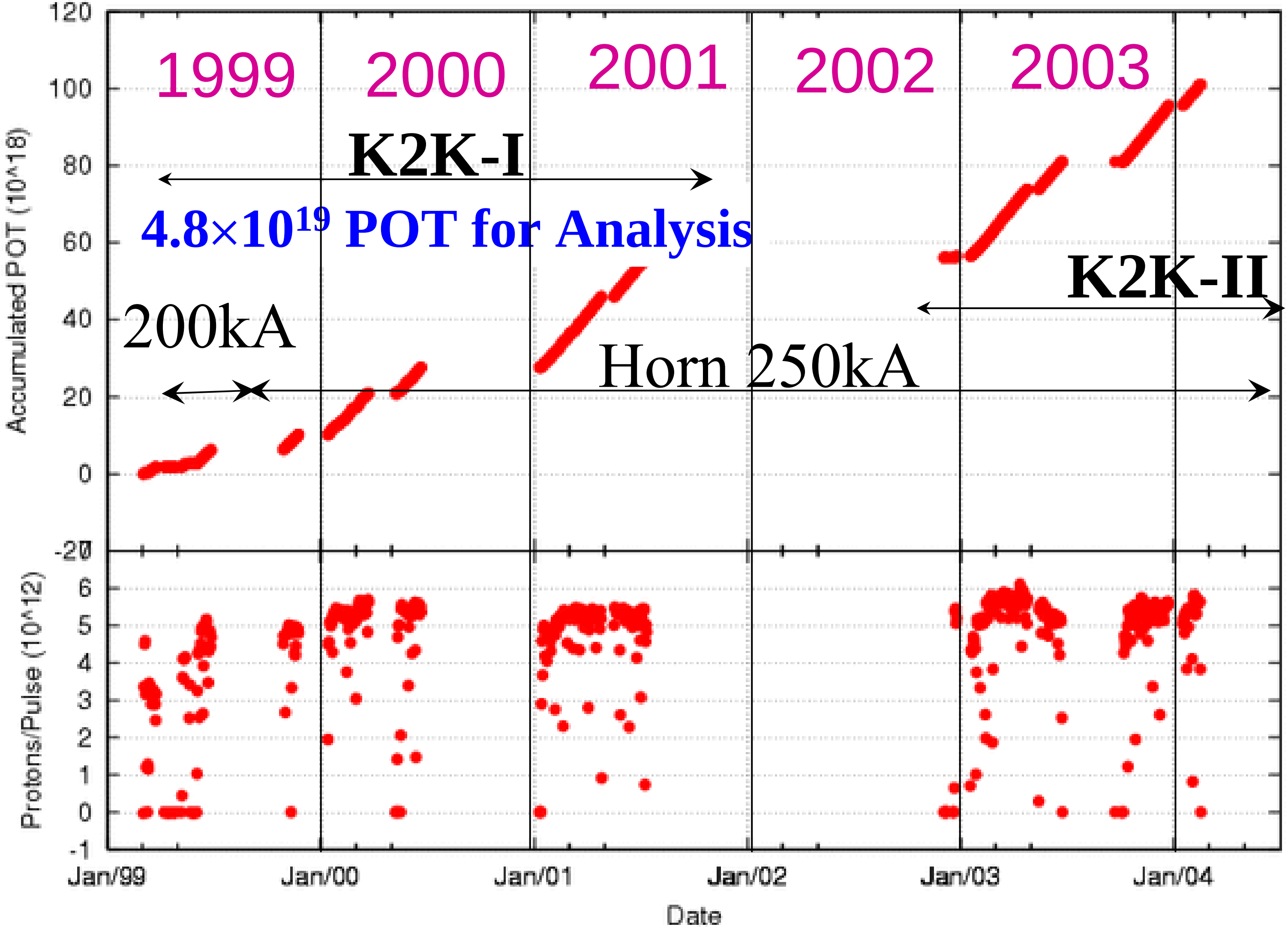


Double Horn
250kA → x20 ν_μ

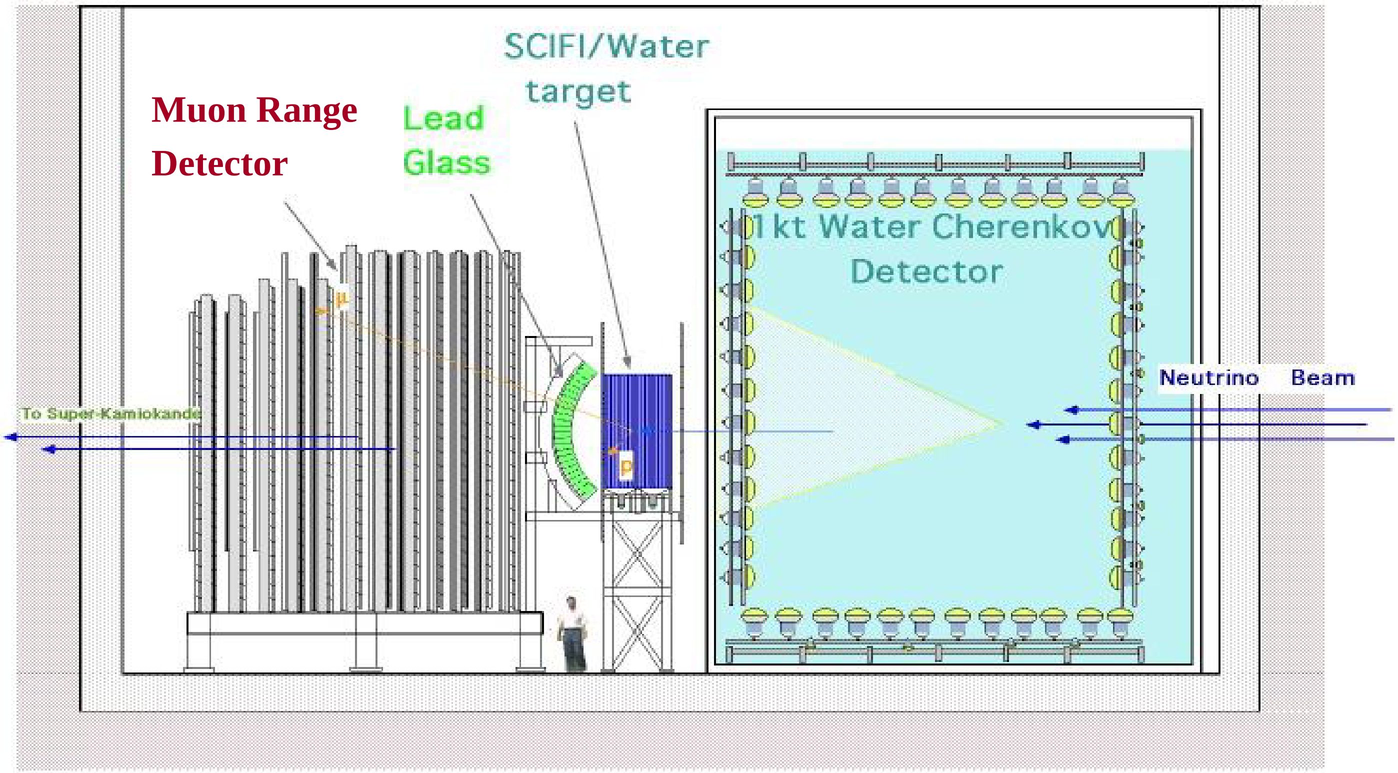
Pion monitor
p_π, θ_π after Horn

Near to Far flux ratio
R_{FN}

Delivered Protons on Target



Near Neutrino Detectors



- 1kton water Cherenkov detector (1KT) same type as SK (25ton fiducial)
- Fine Grained Detectors (FGD)
  - Scintillation fiber tracker (SciFi) w/ water target (6ton fiducial) CCQE identification
  - Scintillator wall stamp event time
  - Lead glass calorimeter (LG) detect electrons from SciFi
  - Muon range detector (MRD) measure muon momentum ν beam monitor (Fe, 330ton fiducial)

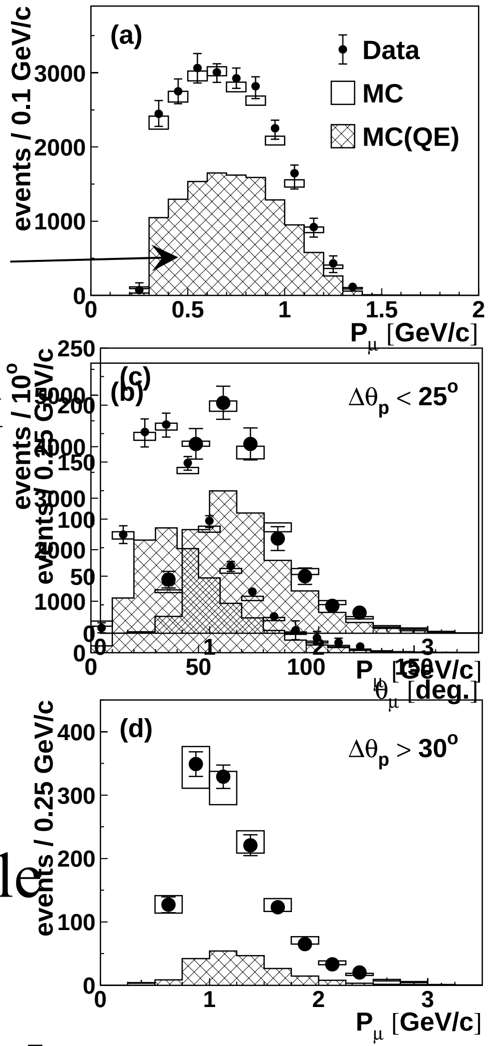
ν_μ Energy Spectrum Measurement at Near Site (Horn250kA)

1KT: 1Rμ

CCQE

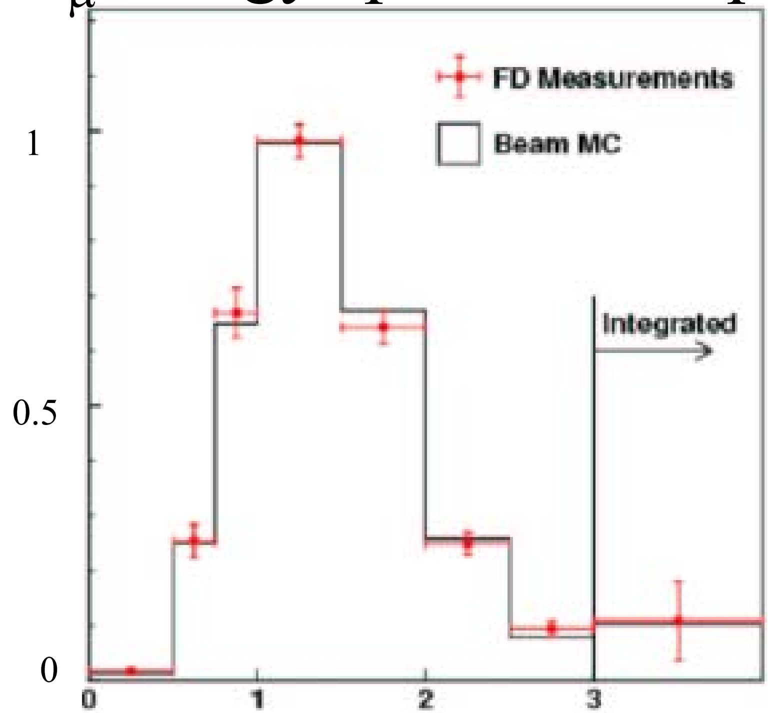
SciFi: 2-Track QE sample

SciFi: 2-Track Non-QE sample



Muon momentum

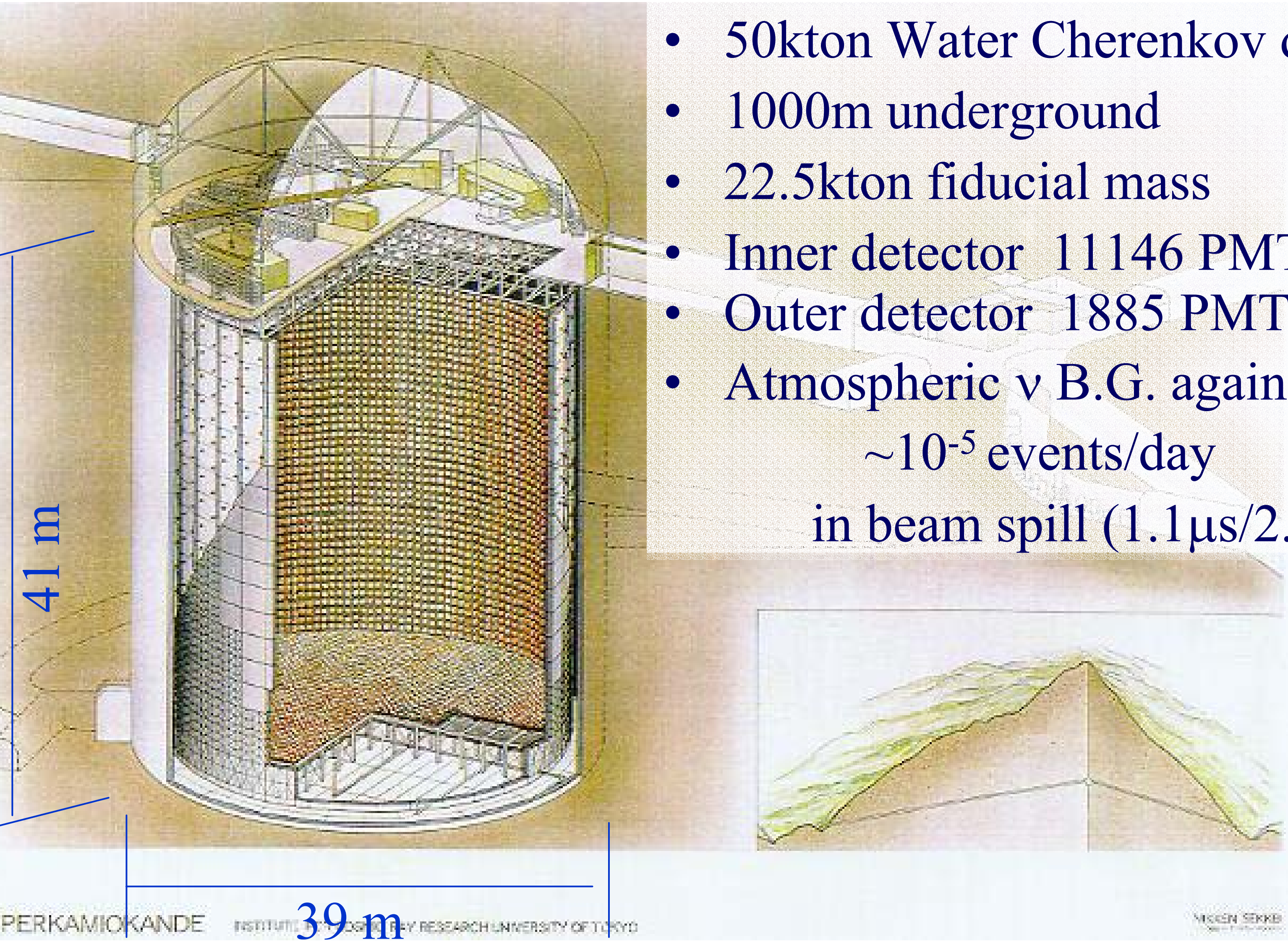
ν_μ energy spectrum shape



E_ν (GeV)

→ Extrapolate to SK with Far/Near rati

Super-Kamiokande



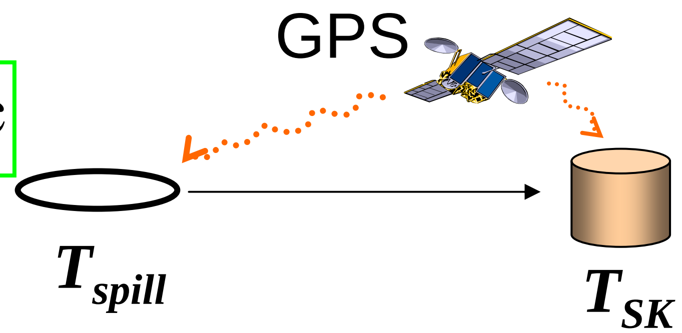
- 50kton Water Cherenkov detector
- 1000m underground
- 22.5kton fiducial mass
- Inner detector 11146 PMTs(20’’)
- Outer detector 1885 PMTs(8’’)
- Atmospheric ν B.G. against K2K

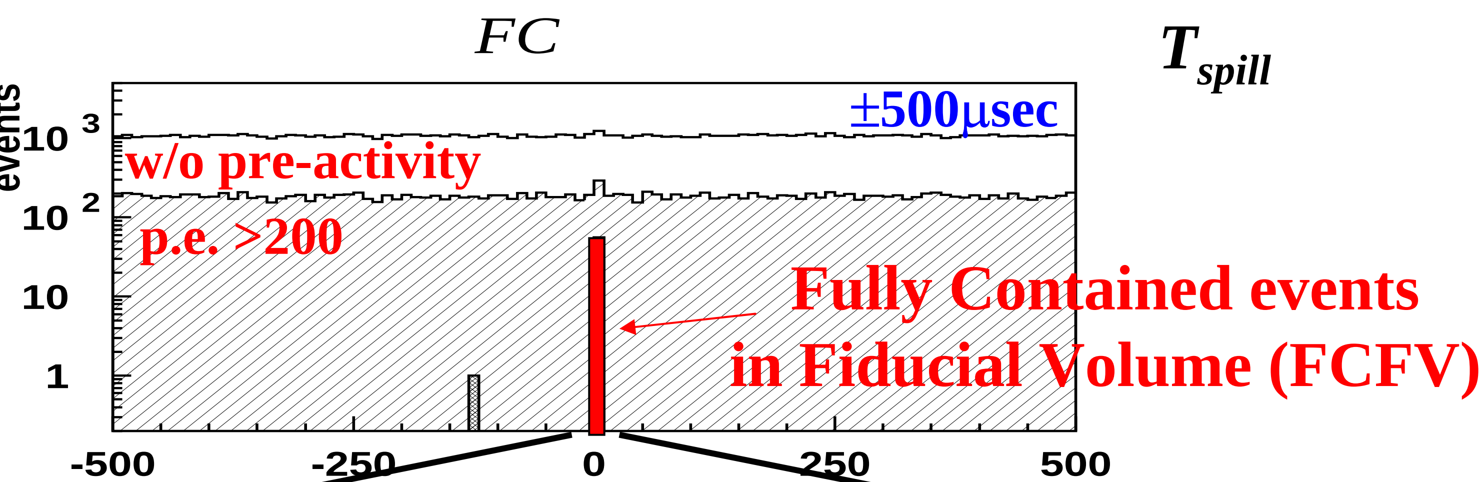
  ~10^{-5} events/day

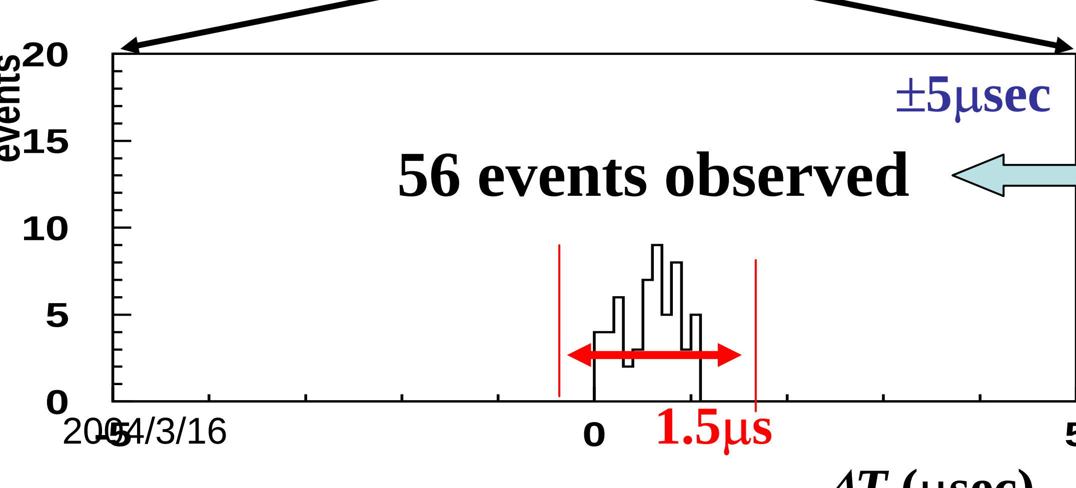
  in beam spill (1.1μs/2.2s)

Neutrino Event Selection in SK

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







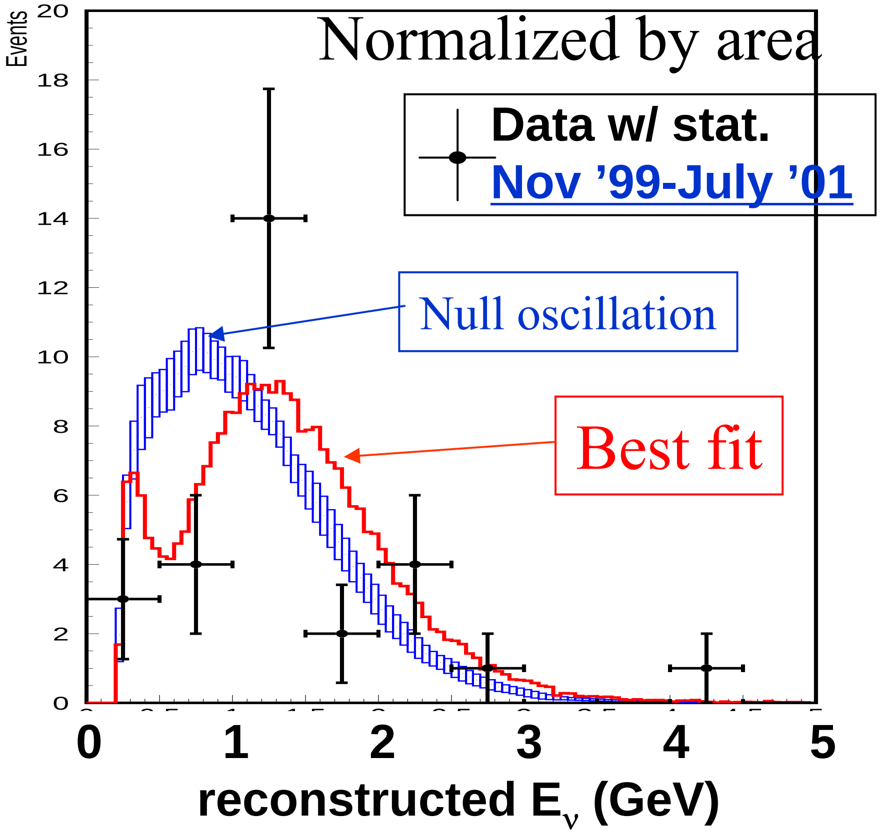
Number of FCFV events (N_{SK})

$80^{+7.3}_{-8.0}$ expected
in null oscillation case

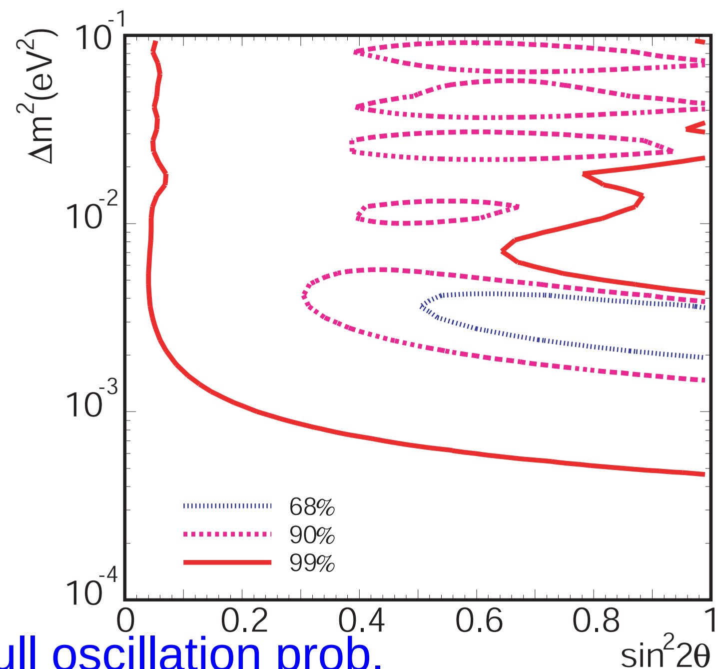
Probability < 3%

K2K result on $\nu\mu \rightarrow \nu_x$ oscillation

($\nu\mu$ disappearance)



June '99-July '01



null oscillation prob. (shape+norm) = 0.7%

null oscillation prob. (shape) = 16%

KS test prob.(shape) at best fit = 79%

$1.5\sim3.9\times10^{-3}$eV^2

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

Consistent with atm. ν result

Motivation of this analysis

- K2K and atmospheric neutrino experiments have indicated neutrino oscillations from ν_μ to ν_x.
- How much fraction of ν_μ oscillates to ν_e?
  - The first search for ν_e appearance sensitive down to Δm^2_{atm}
- ν_e appearance is expected at Δm^2_{atm} in 3 flavor mixing framework

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{\mu\mu})\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta_{\mu e})\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

$$\sin^2(2\theta_{\mu e}) = 1/2\sin^2(2\theta_{13})$$

Strategy for ν_e appearance search

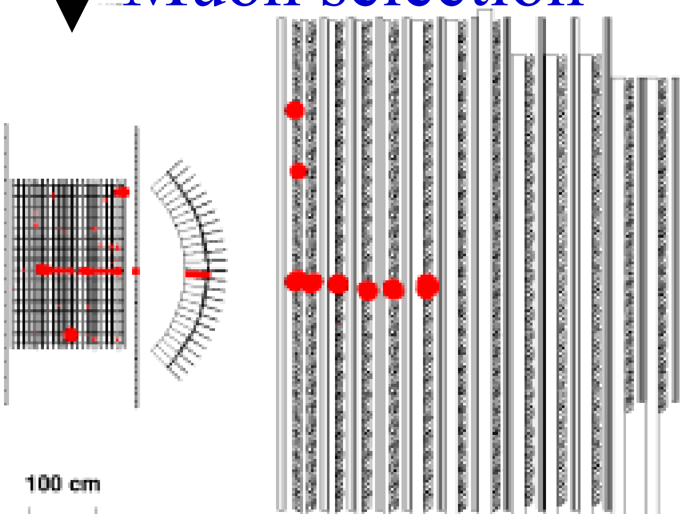
- Compare
  - $N_{exp} = N_{sig}(\theta_{\mu e},\Delta m^2) + N_{BG}^{\nu\mu} + N_{BG}^{\nu e}$
  - N_{obs}
  - Significance calc'ed based Feldman&Cousins
- Norm. for 3 N_{exp} terms determined by extrapolating N_{KT}^{obs}
- $N_{BG}^{\nu e}$
  - Expected $\nu e/\nu\mu$ ratio calculated with beam MC
  - contamination is measured at near site
- $N_{BG}^{\nu\mu}(\theta_{\mu\mu},\Delta m^2)$
  - Dominant BG in K2K
  - Dominated by NC int. (87%)
  - NC/QE cross section ratio constraint by 1KT π^0/μ measurement.
  - $\nu\mu$ energy spectrum is measured at near site.

Measurement of ν_e Contamination at Near Site

5,512,094 spill
('99Nov.-'01Apr) → Incoming muon cut

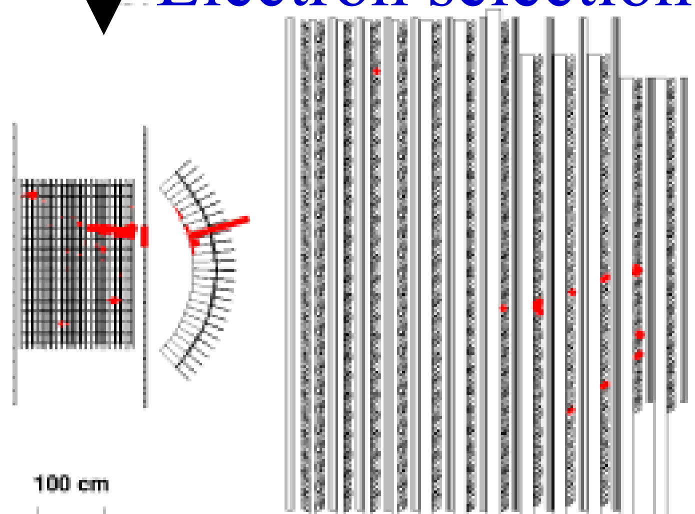
- TOF cut
- Acceptance cut

Muon selection



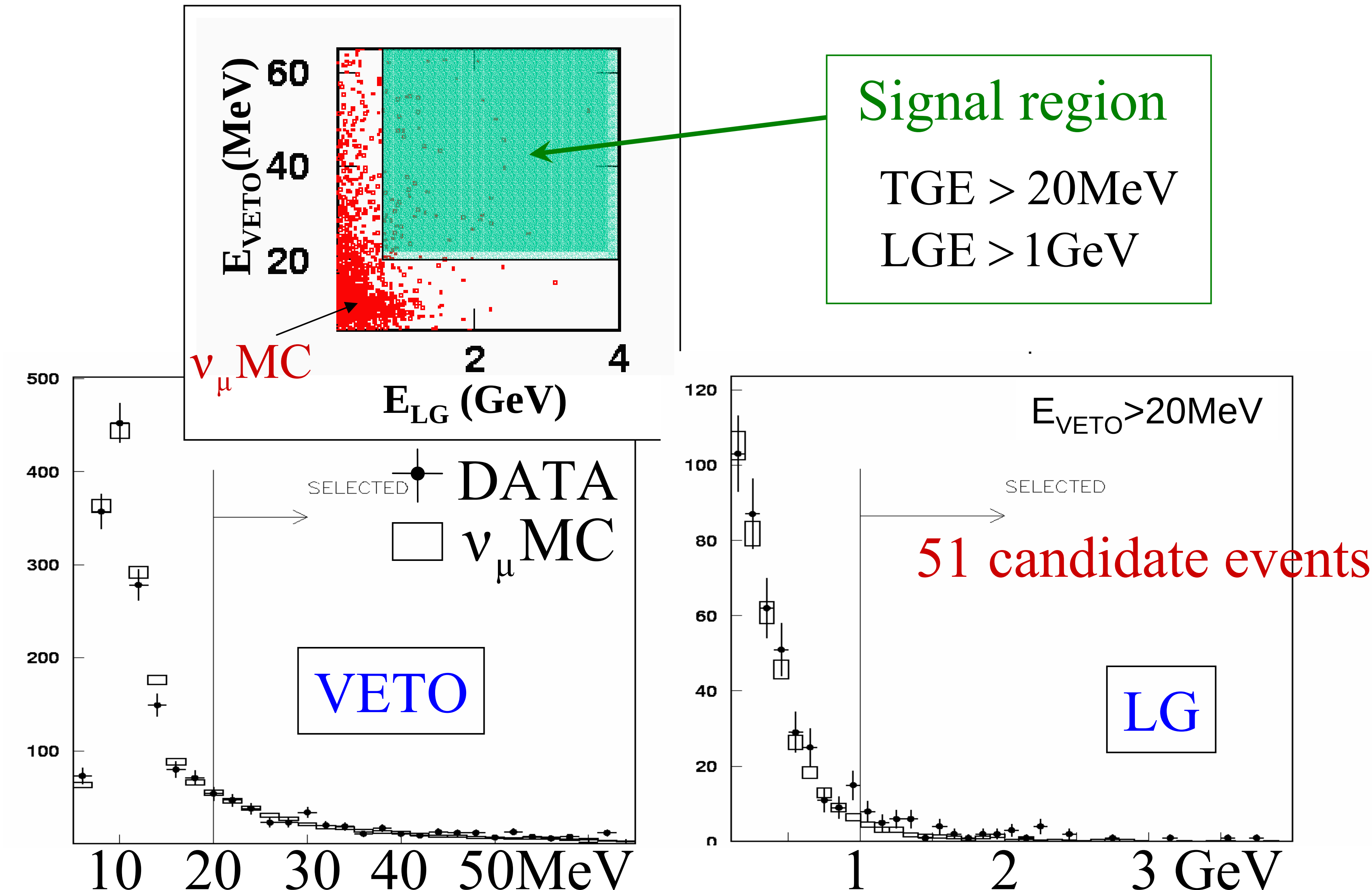
→ event normalization

Electron selection



→ energy cut

Deposit Energy Dist. for Electron Candidates



Electron Neutrino Contamination at Near Site

2.9×10^{19} pot

	DATA	BG	ε	#interaction
Muon candidate	3229	35.4	9.0 %	$3.5 \times 10^4 \nu_\mu$
Electron candidate	51	23.8	4.7 %	$5.8 \times 10^2 \nu_e$

$$R(\nu_e/\nu_\mu) = 1.6 \pm 0.4(\text{stat.})^{+0.8}_{-0.6}(\text{sys.}) \quad (\%)$$

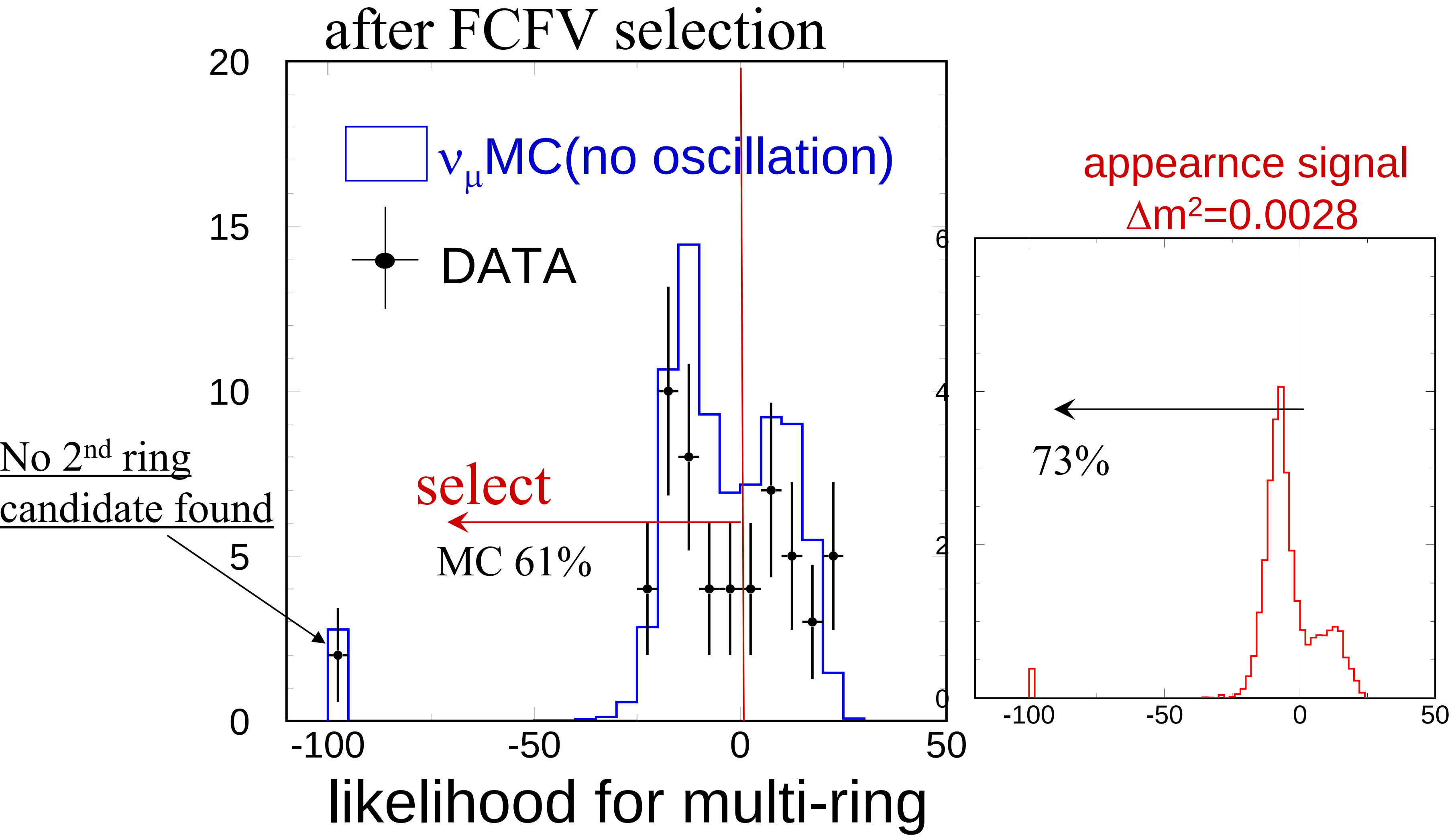
Consistent with beam MC prediction; 1.3%

Enough low level to perform νe appearance search

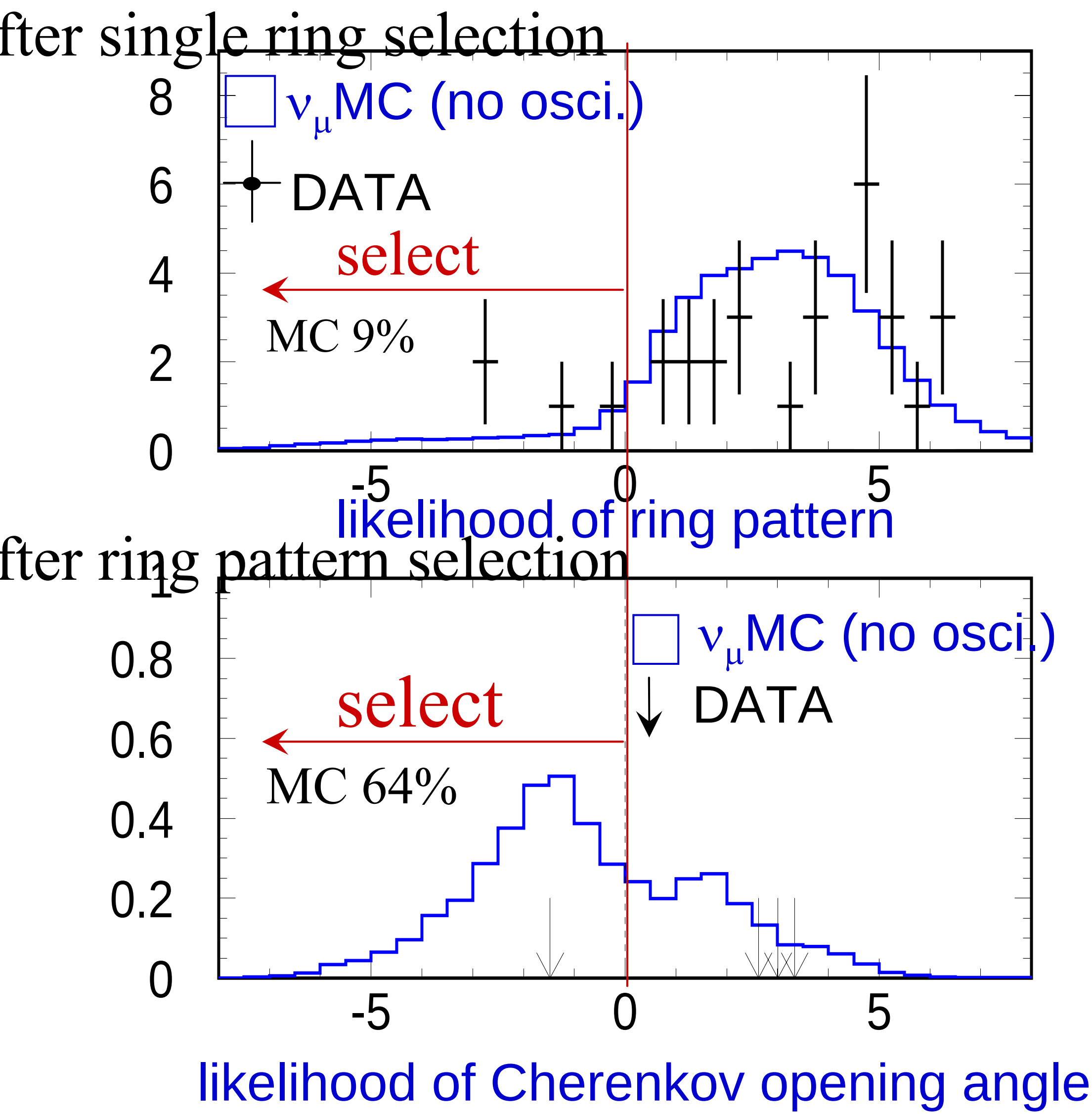
Selection for ν_e events in SK

- Fully Contained events in Fiducial Volume
- Single Ring events
  - reject $\nu\mu$ pion productions
- PID : Ring pattern and opening angle consistent with electron
  - reject $\nu\mu$ CC
- Visible Energy > 100MeV
  - reject low-momentum charged pions and decay-electron
- Without decay electrons
  - reject invisible muons, pions from $\nu\mu$ CC

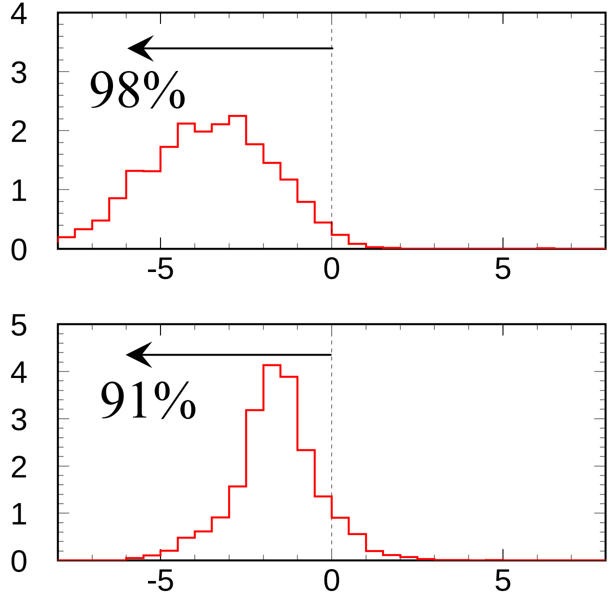
Single-Ring Event Selection



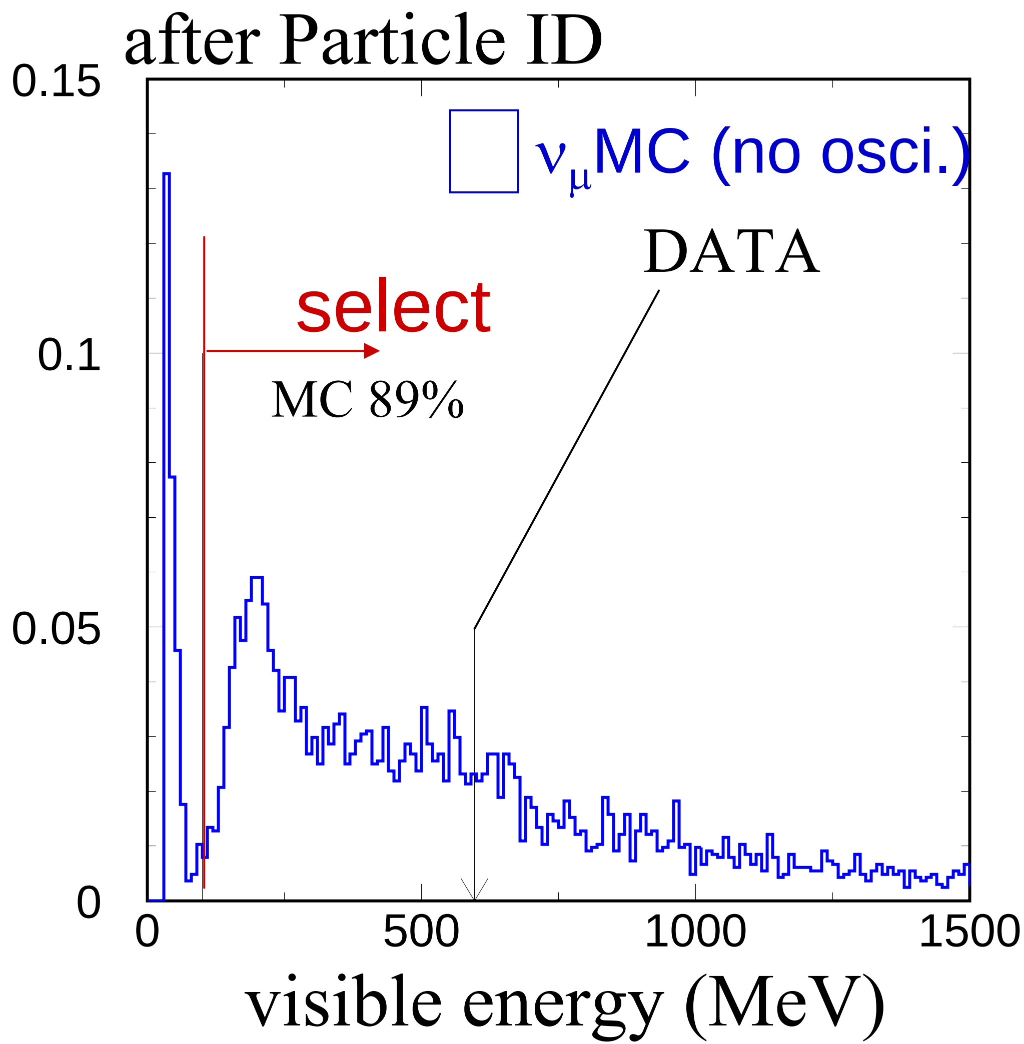
Particle ID

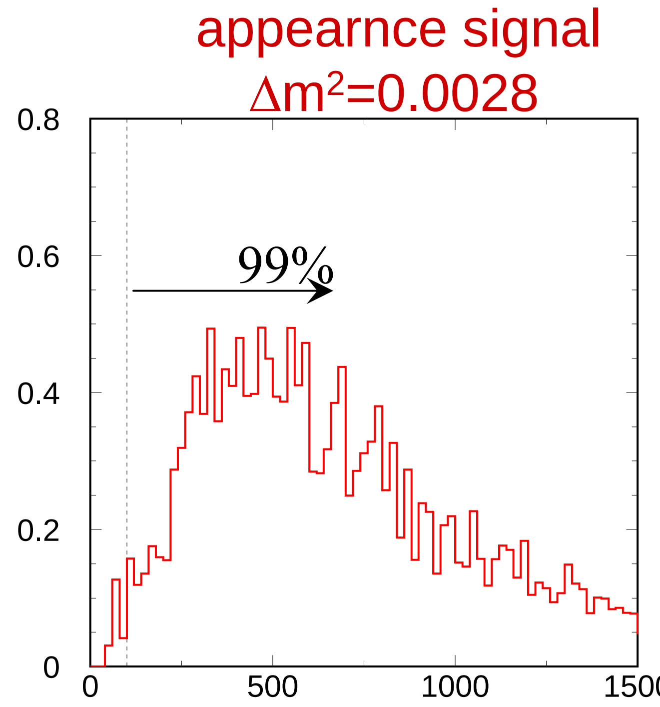


appearnce signal
Δm^2=0.0028

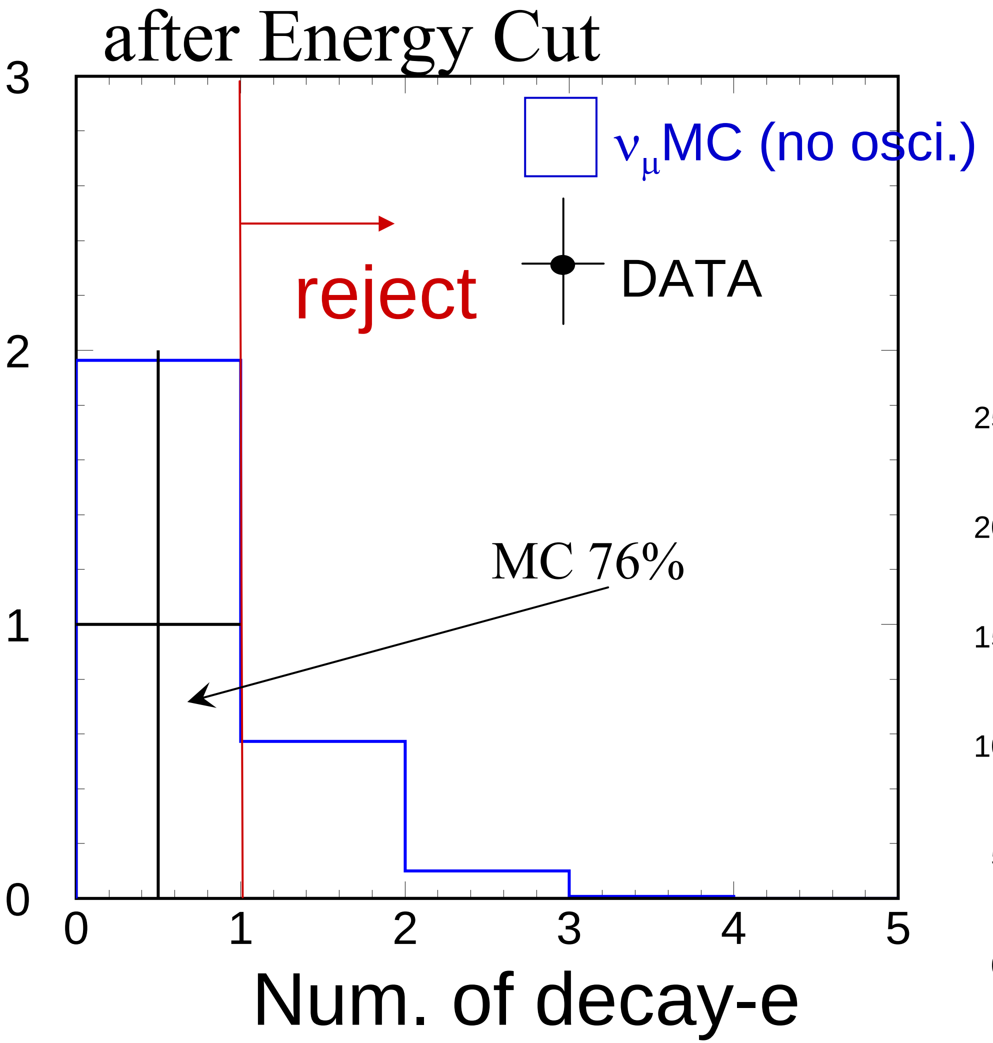


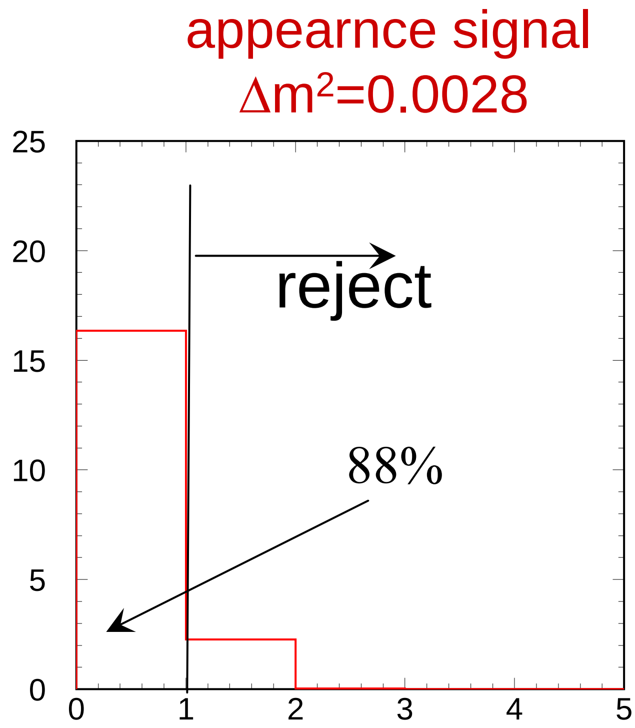
Energy Cut


after Particle ID
0.15
0.1
0.05
0
ν_μMC (no osci.)
DATA
select
MC 89%
0
500
1000
1500
visible energy (MeV)


appearnce signal
Δm^2=0.0028
0.8
0.6
0.4
0.2
0
99%
0
500
1000
150

Invisible muon/pion cut





Reduction Summary

DATA SET

June'99 – July'01 (4.8×10^{19}POT)

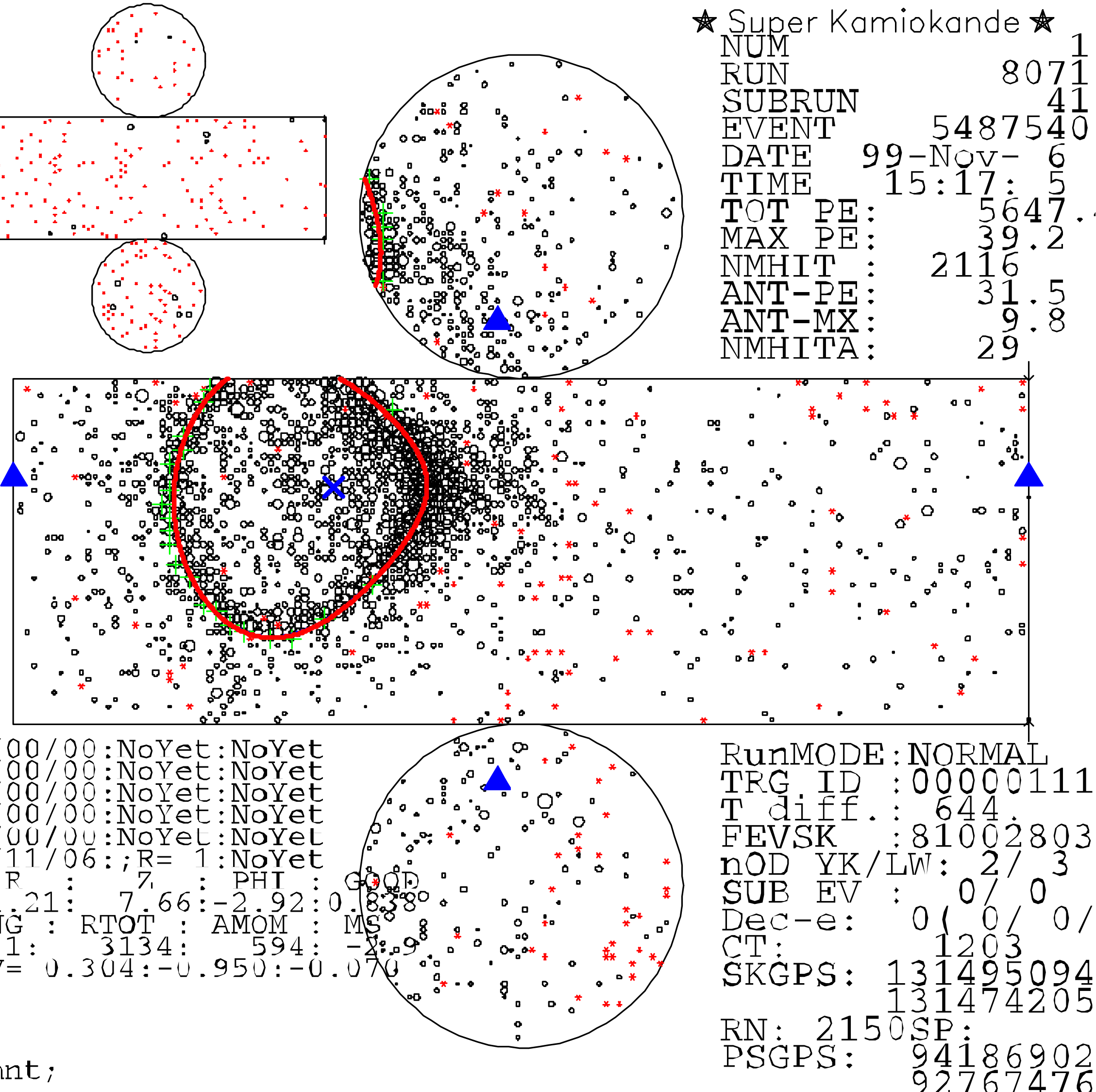
	DATA	ν_μ MC	beam ν_e MC	signal ν_e MC (CC) $\sin^2 2\theta_{\mu e}=1$, $\Delta m^2=2.8\text{x}10^{-3}\text{eV}^2$
generated		104 events	0.99 events	28 events
FCFV	56	80 (78%)	0.82 (83%)	28 (98%)
Single ring	32	50 (48%)	0.48 (48%)	20 (71%)
PID (e-like)	1	2.9 (2.7%)	0.42 (42%)	18 (63%)
Evis>100MeV	1	2.6 (2.4%)	0.41 (41%)	18 (63%)
w/o decay-e	1	2.0 (1.9%)	0.35 (35%)	16 (55%)

NC:87% CC1π:7% CCmπ:4% CCQE:2%

electron candidate: 1 event observed

2.4 events expected.

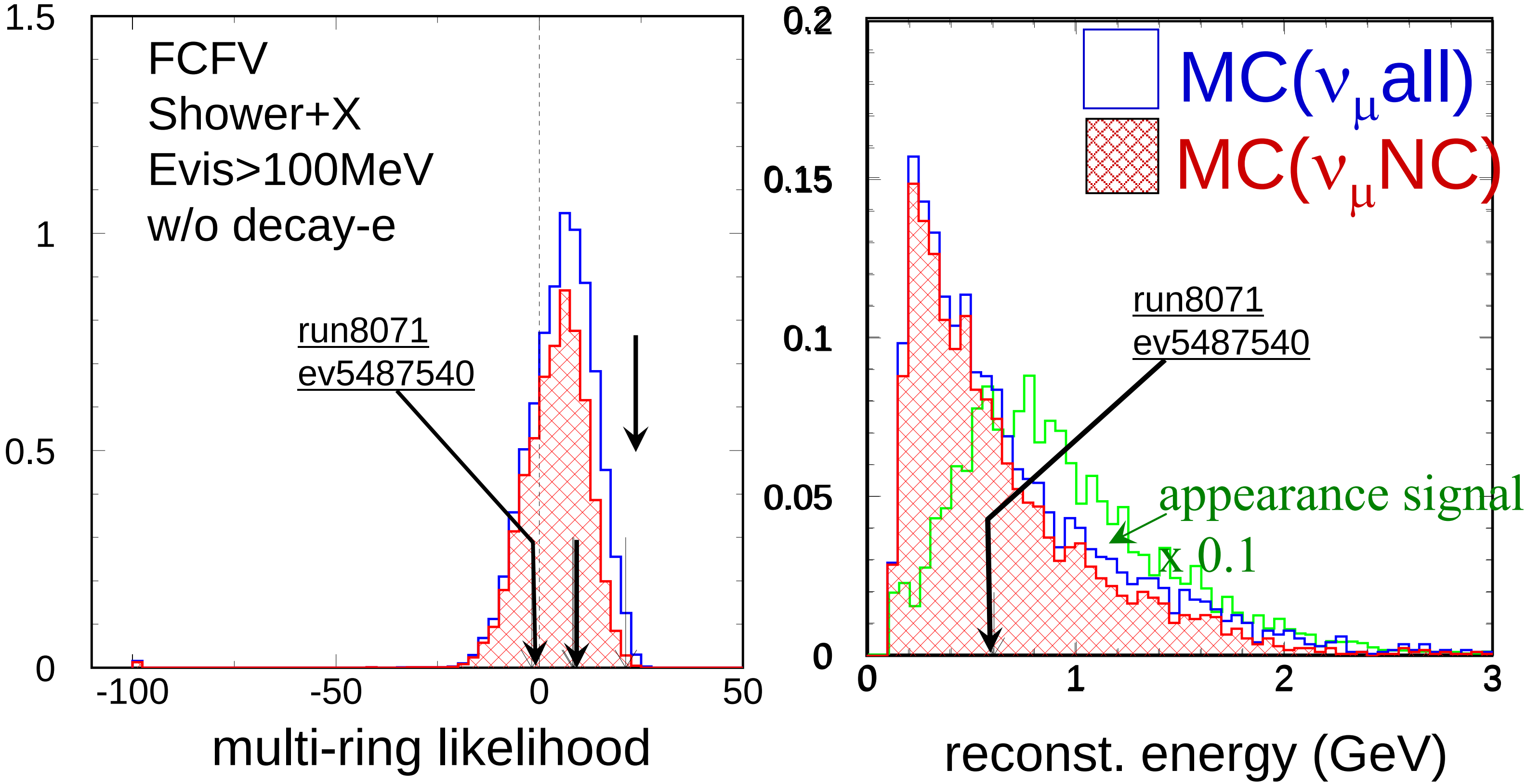
Electron Candidate



reconst. momentum
597 MeV/c

reconst. Eν
assuming νe CCQE
612 MeV

Distributions for observed events and expected background



Observed electron candidate mostly has 2nd ring.

consistent with both BG and Signal

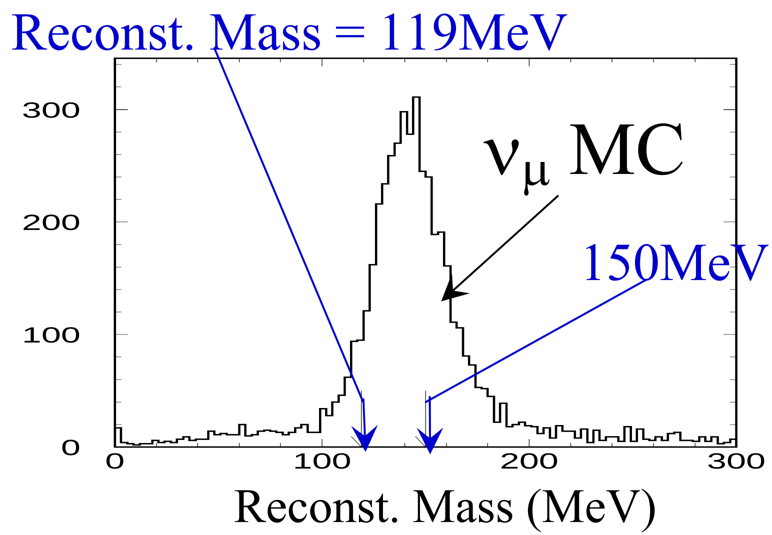
π^0 in K2K-SK

check for amount of π^0 production

$\pi 0$: FCFV & 2 e-like ring & 90<mass<190MeV & Evis>100MeV w/o decay-e
νe : FCFV & 1 e-like(tight) ring & Evis>100MeV w/o decay-e

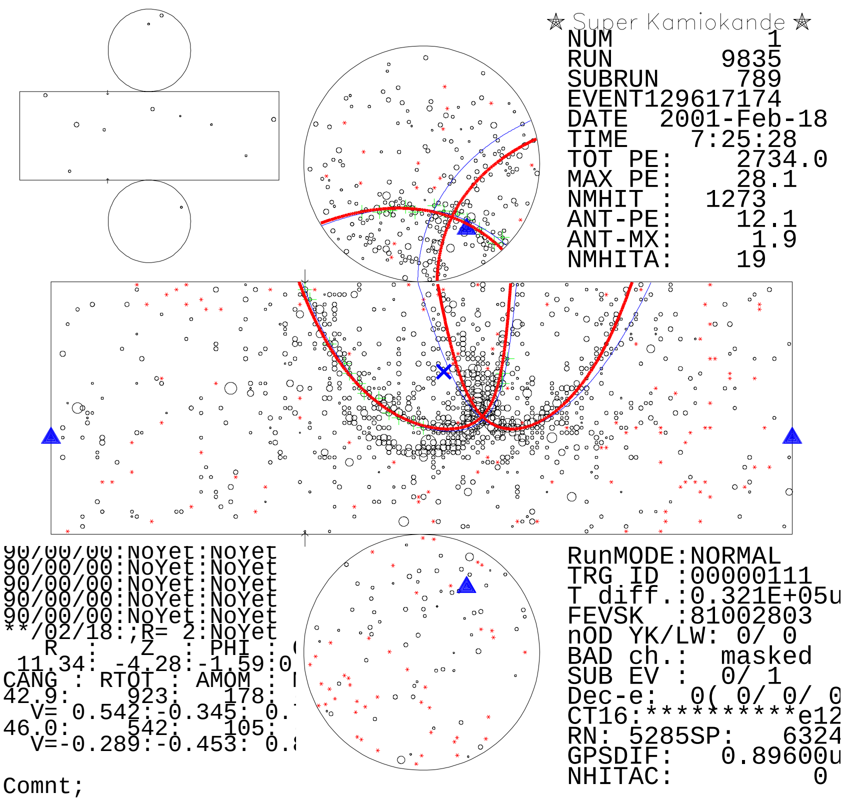
	DATA	$\nu\mu$ MC (NC w/ π^0)
FCFV	56	80.1 (7.7)
$\pi 0$	2	2.6 (2.4)
νe	1	2.0 (1.7)

Default NEUT4.3

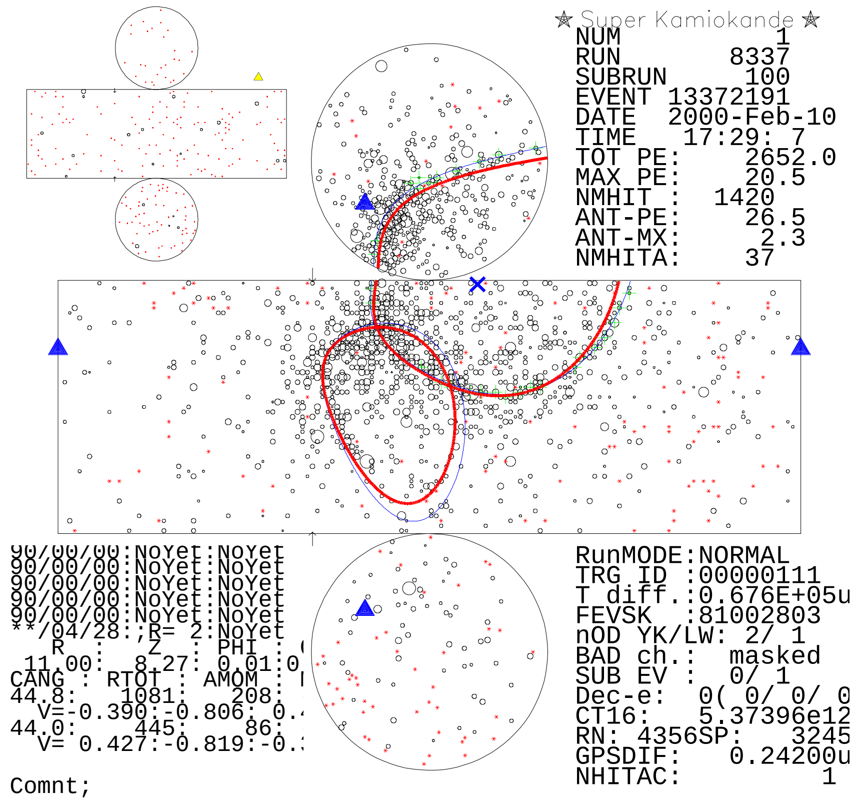


Expectation by $\nu\mu$ MC is consistent with observed 2 events

Observed π^0 candidates



Reconst. Mass = 119MeV



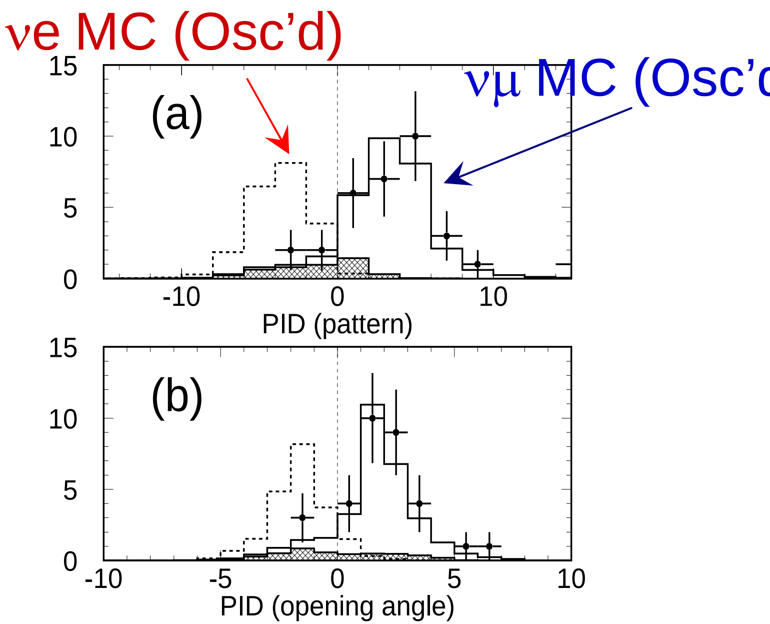
150MeV

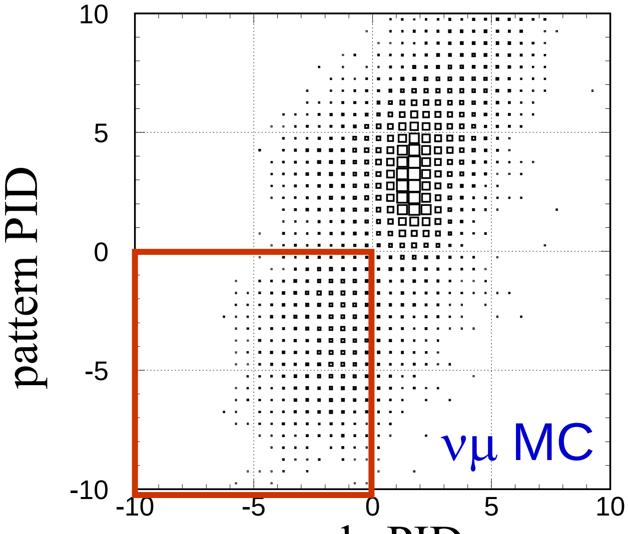
Systematic errors

- $\nu\mu$ background
  - $N_{BG}^{\nu\mu} = 2.0+-0.6$ events w/o oscillations
- νe contamination
  - $N_{BG}^{\nu e} = 0.35+-0.11$ events
- oscillation signal νe
  - $\delta N_{sig}/N_{sig} \sim 15\%$ at $\Delta m^2=2.8\mathrm{x}10^{-3}\mathrm{eV}^2$

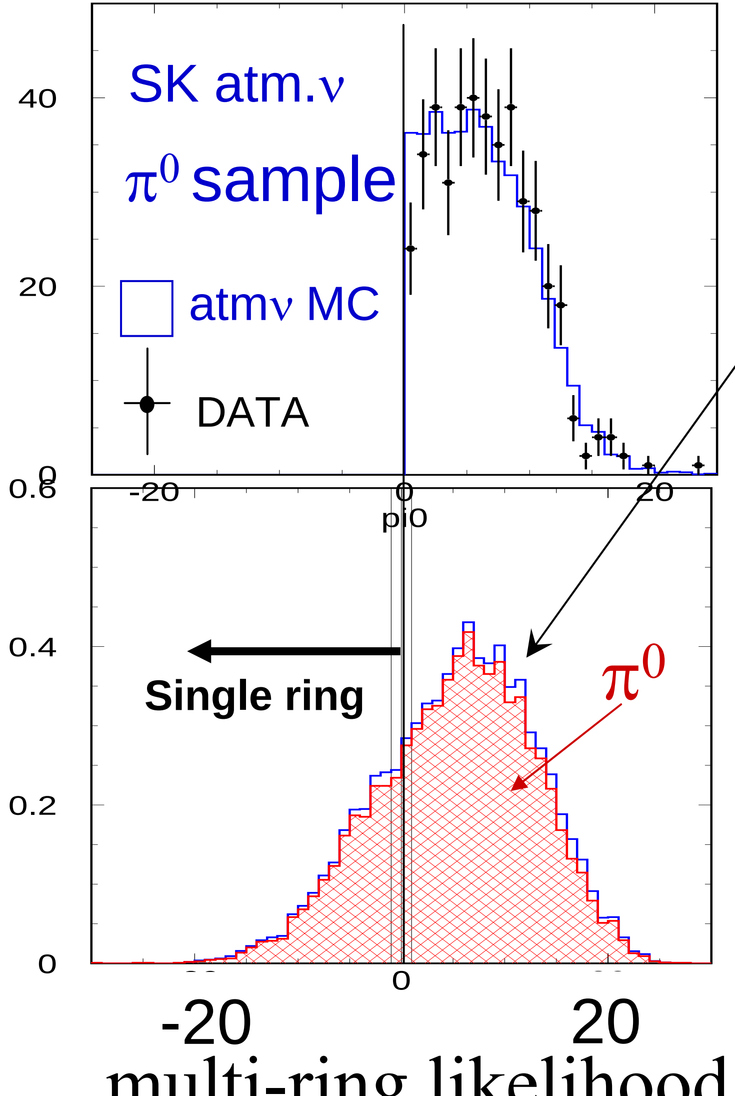
Systematic Error Estimation

- Particle ID
  - shift likelihood distributions in MC
    - ±11% in νμ BG
    - +7%–12% in νe appearance signal
- Ring Counting
  - shift likelihood distributions in MC
    - +15%–13% in νμ BG
  - compare likelihood function distributions for atm.ν DATA and MC
    - ±6% in νe appearance signal
- NC Cross Section
  - change NC cross section within 30%
    - +20%–25% in νμ BG





Systematic error from Ring counting in $\nu\mu$ BG



K2K $\nu\mu$ MC
FCFV elike+X
Evis>100MeV w/o decay-e

If likelihood for multi-ring shifts by ±1 bin…,

$$\frac{\delta N_{1ring}}{N_{1ring}} = {}^{+14.8\%}_{-12.7\%}$$

Constraint on NC/QE cross section ratio (R_{NC})

- $\sigma_{tot} = \sigma_{QE} + R_{nQE} * \sigma_{CCnQE} + R_{NC} * \sigma_{NC}$
- $\pi 0/\mu$ ratio measurement in 1KT
  - DATA/MC= 1.06 +–0.02(stat.)+–0.10(reconst.)+–0.08(int. model)

→ $R_{NC} = 1.07 + 0.20 - 0.15$

- consistent w/ $R_{NC}=1$

→ **use $R_{NC} = 1 \pm 0.3$**

Oscillation Analysis

- calculate confidence interval [1] (upper limit) on $\sin^2 2\theta_{\mu e}$ using the number of electron events with the method suggested in [1].

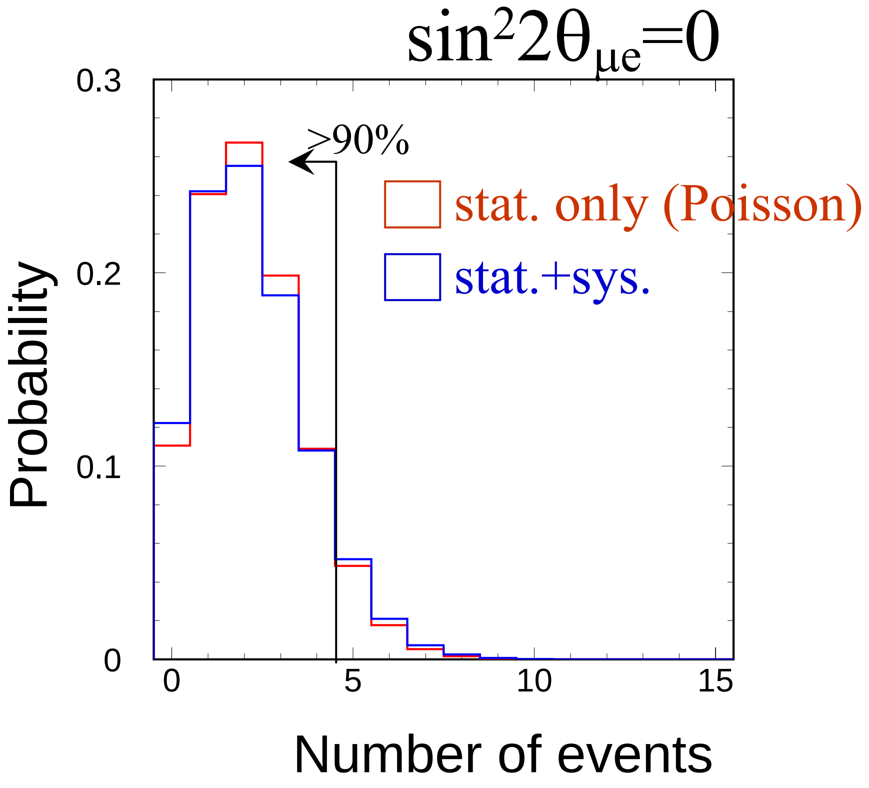
$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta_{\mu e})\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

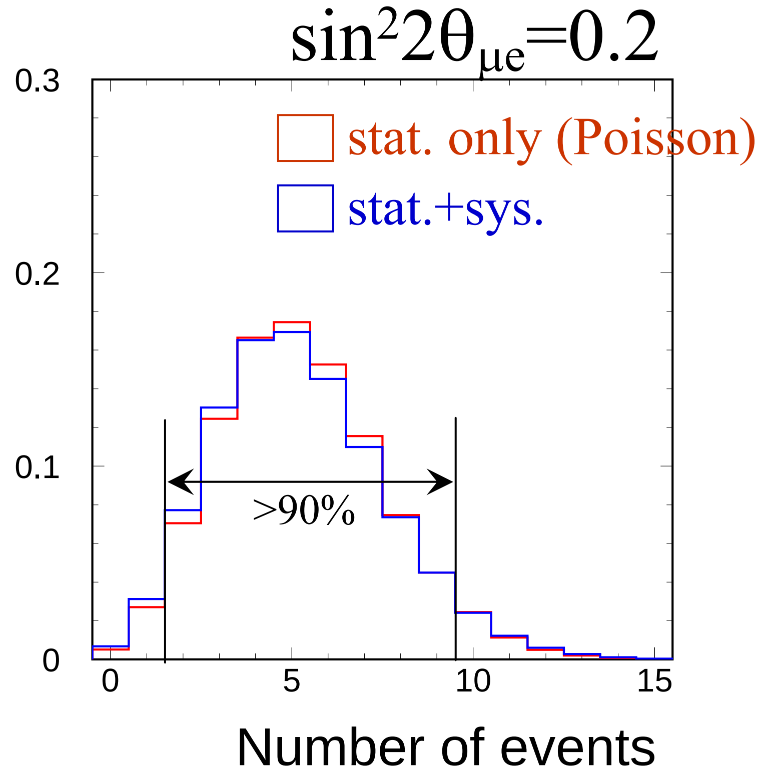
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{\mu\mu})\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

- assumption:
  - one mass scale Δm^2
  - $\sin^2 2\theta_{\mu\mu}=1$
  - $\sin^2 2\theta_{\mu e}$ bound in physical region [0,1]
  - expected number of BG is distributed in Poisson ✕ Gaussian(sys. err.)

[1] "Unified approach to the classical statistical analysis of small signal", Feldman and Cousins, Phys.Rev.D (1998)

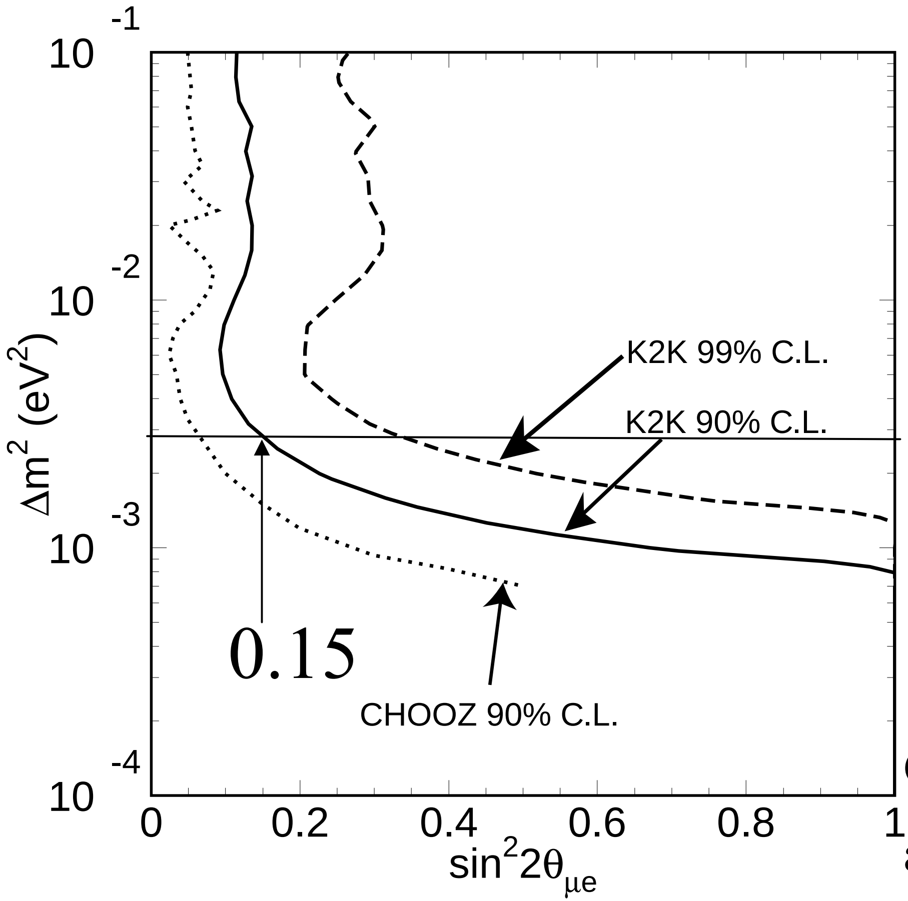
PDF at $\Delta m^2=2.8\times10^{-3}eV^2$





Nobs=1 → $\sin^2 2\theta_{\mu e}=0.2$ is not allowed at 90%C.L.

Result of $\nu_\mu \rightarrow \nu_e$ oscillation analysis



$2.8\text{x}10^{-3}\text{eV}^2$

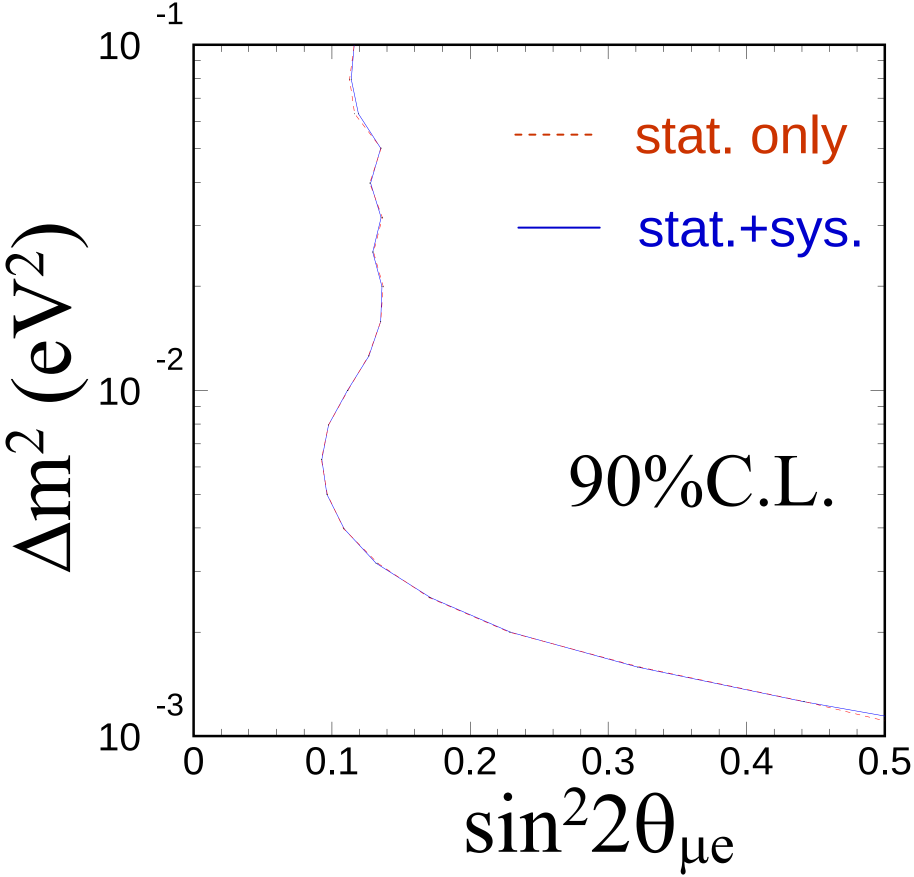
K2K-I νμ disapp. Best-f

CHOOZ result is overlaye
assuming;

$$\sin^2(2\theta_{\mu e}) = 1/2 \sin^2(2\theta_{CHOOZ})$$

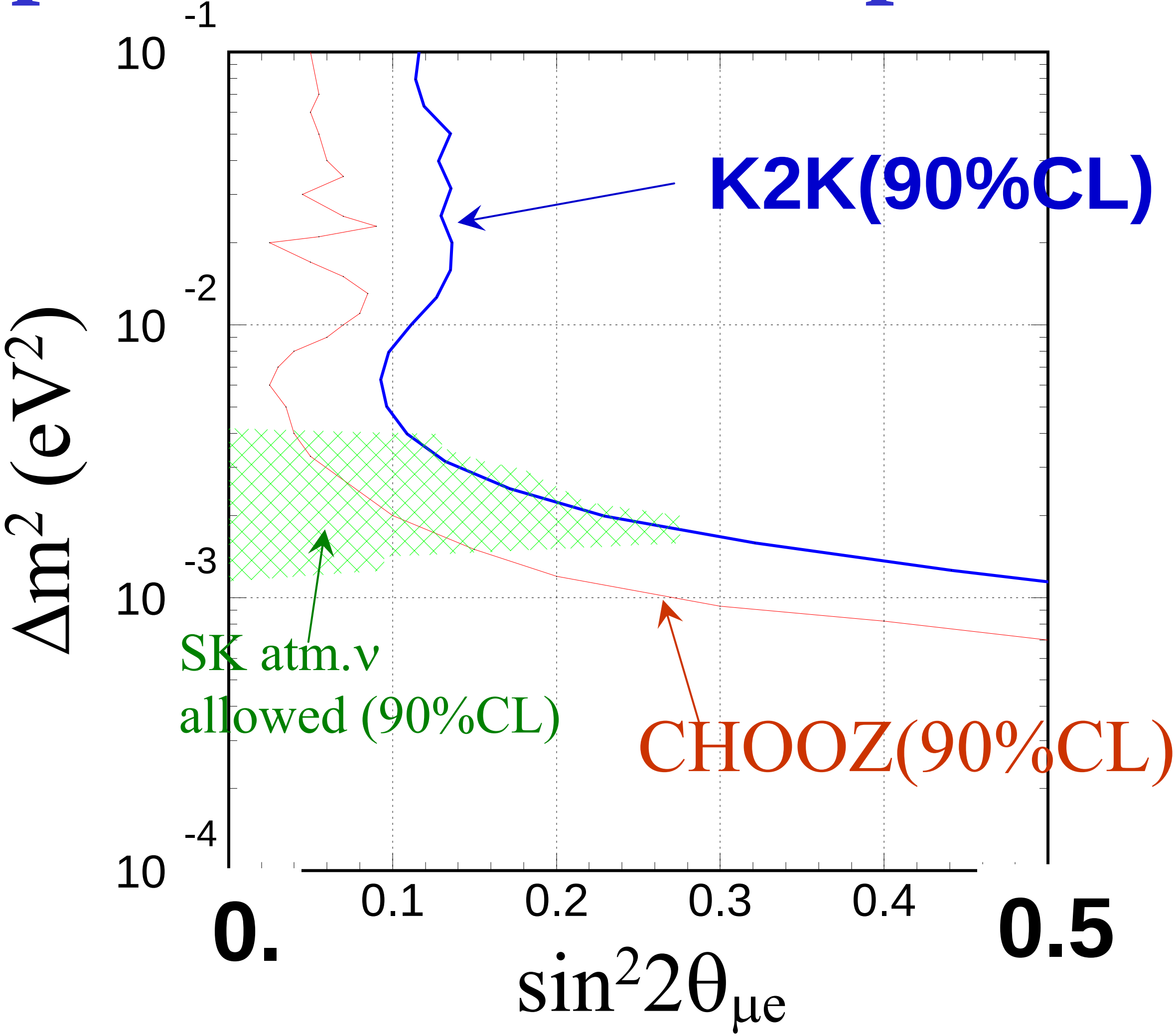
Effect of the systematic errors

$\Delta m^2 = 2.8 \times 10^{-3} eV^2$	90%CL	95%CL
stat. only	0.150	0.201
stat. + sys.	0.150	0.203



Very small effect
of systematic errors
on the limit calculation

Comparison to other experiments



Conclusion

- Electron search in the whole K2K-I data has been performed
  - 1 event observed
- The number of background events has been estimated
  - $(2.0 \pm 0.6$ from $\nu\mu) + (0.4 \pm 0.1$ from $\nu e)$ w/o oscillations
  - In total, BG=2.4 ± 0.6 events (${2.3 \pm 0.6}$ in oscillation case)
- Limit for νe appearance using number of evens only has been obtained.
  - $\sin^2 2\theta_{\mu e} < 0.15$ @ $\Delta m^2 = 2.8\text{x}10^{-3} \mathrm{eV}^2$