Present (and near future) Experimental Situation

with emphasis on
Accelerator-based experiments

Villars, Switzerland

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One has to bear in mind

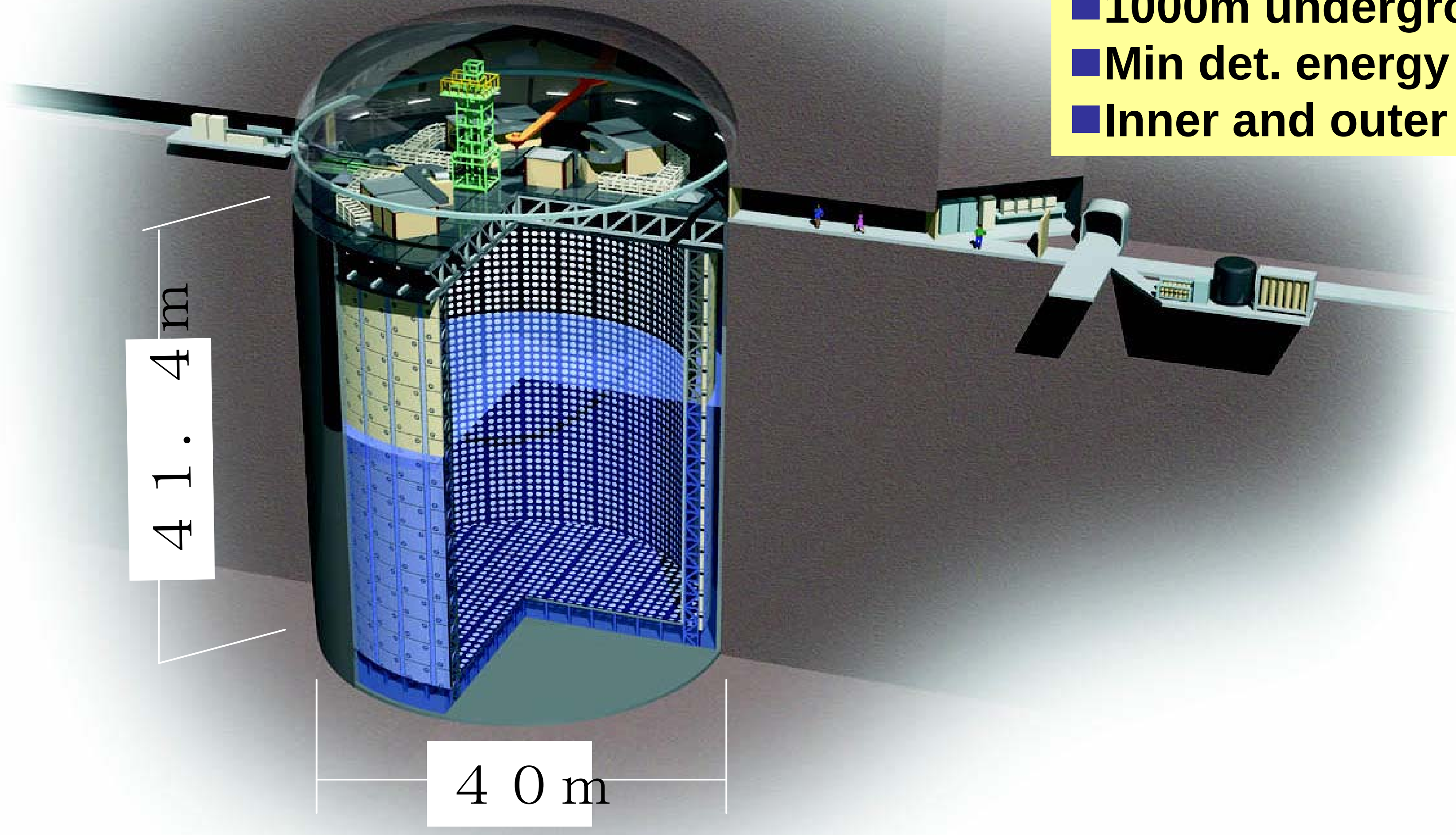
- The solar, atmosphric observations are good at discovering a surprise (if it is a large effect) for which small scale (controlled) experiments do not have enough sensitivity.
  - Long baseline (100 – 10^8 km)
- They are however not good at measuring underlying parameters very precisely.

- High precision accelerator experiments are needed
- Prepare for surprises
- Current plan may have to be changed

- Important works are not covered in this talk

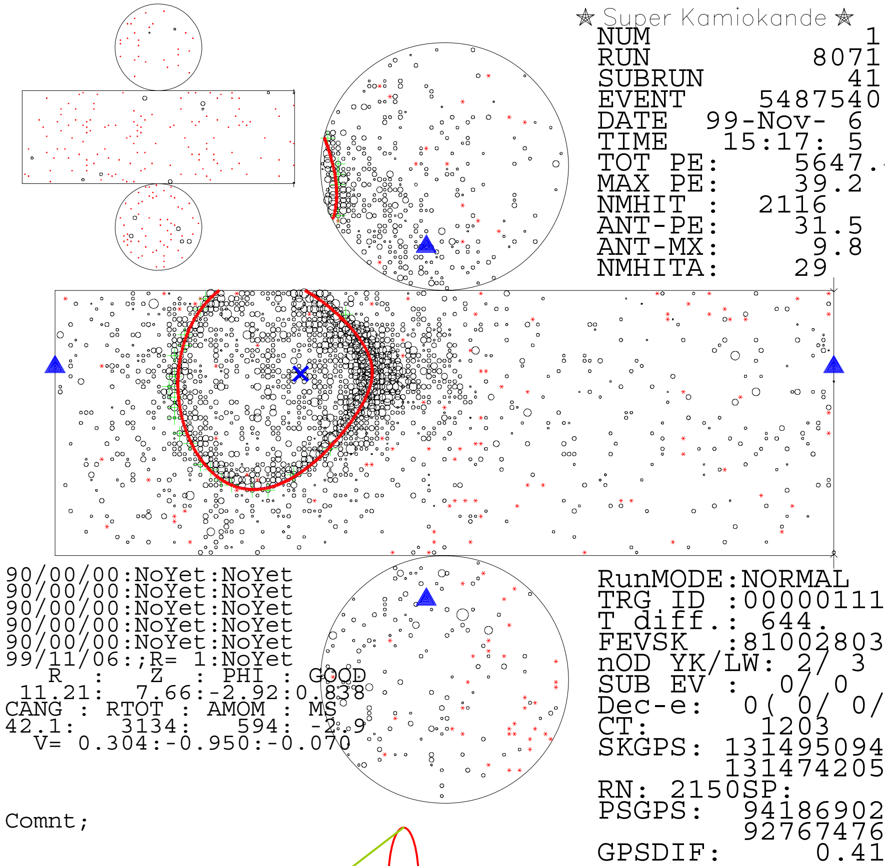
Super-Kamiokande (

- 1996-
- 50000ton water
- 11146 50cmϕ PMT
  (40% photo coverage)
- 1000m underground
- Min det. energy ~ 5 MeV
- Inner and outer

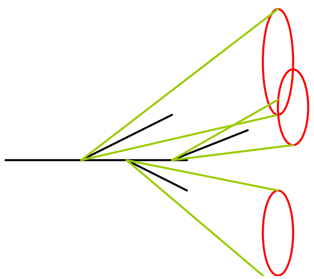


Electron-like and muon-like events

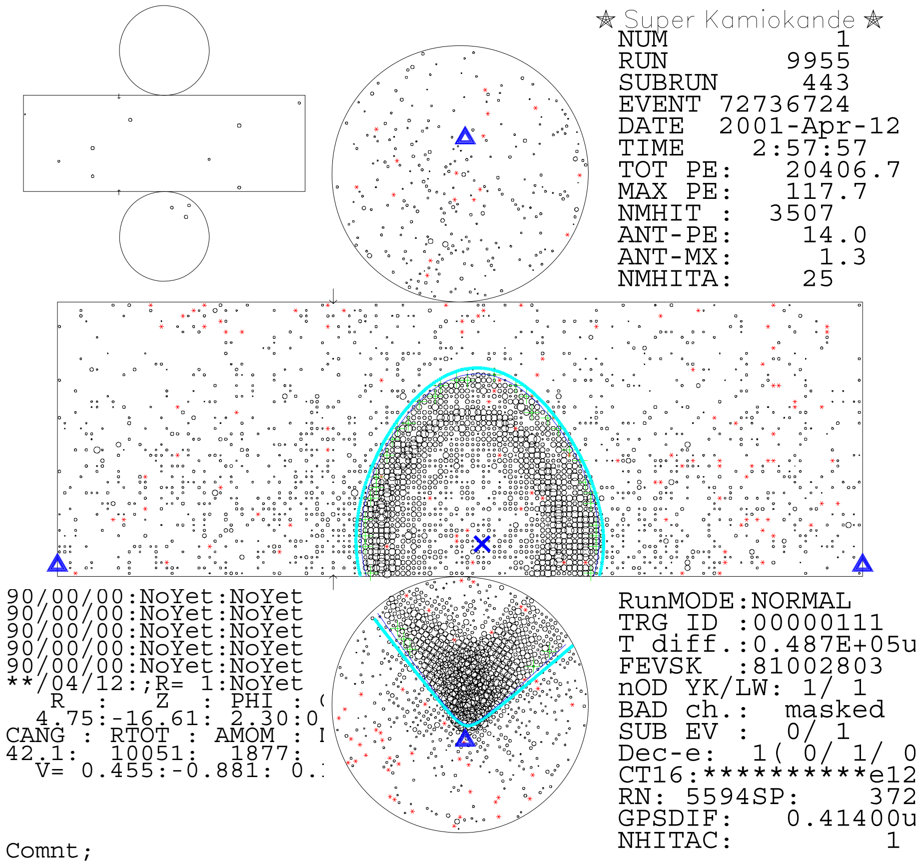
e-like



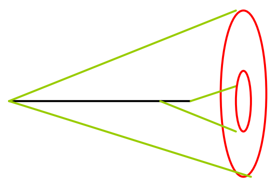
e



μ-like



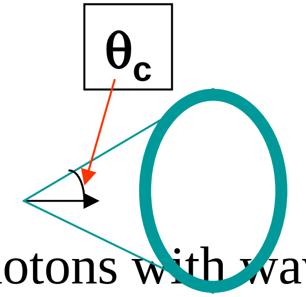
μ



Principle of the technique

- Cherenkov radiation: electromagnetic radiation in a medium with refractive index n if $n\beta>1$ ($\beta=v/c$)
  - $\cos\theta_c = 1/n\beta$,

$$\frac{dN}{dx d\lambda} = \frac{2\pi\alpha \sin^2\theta_c}{\lambda^2}$$

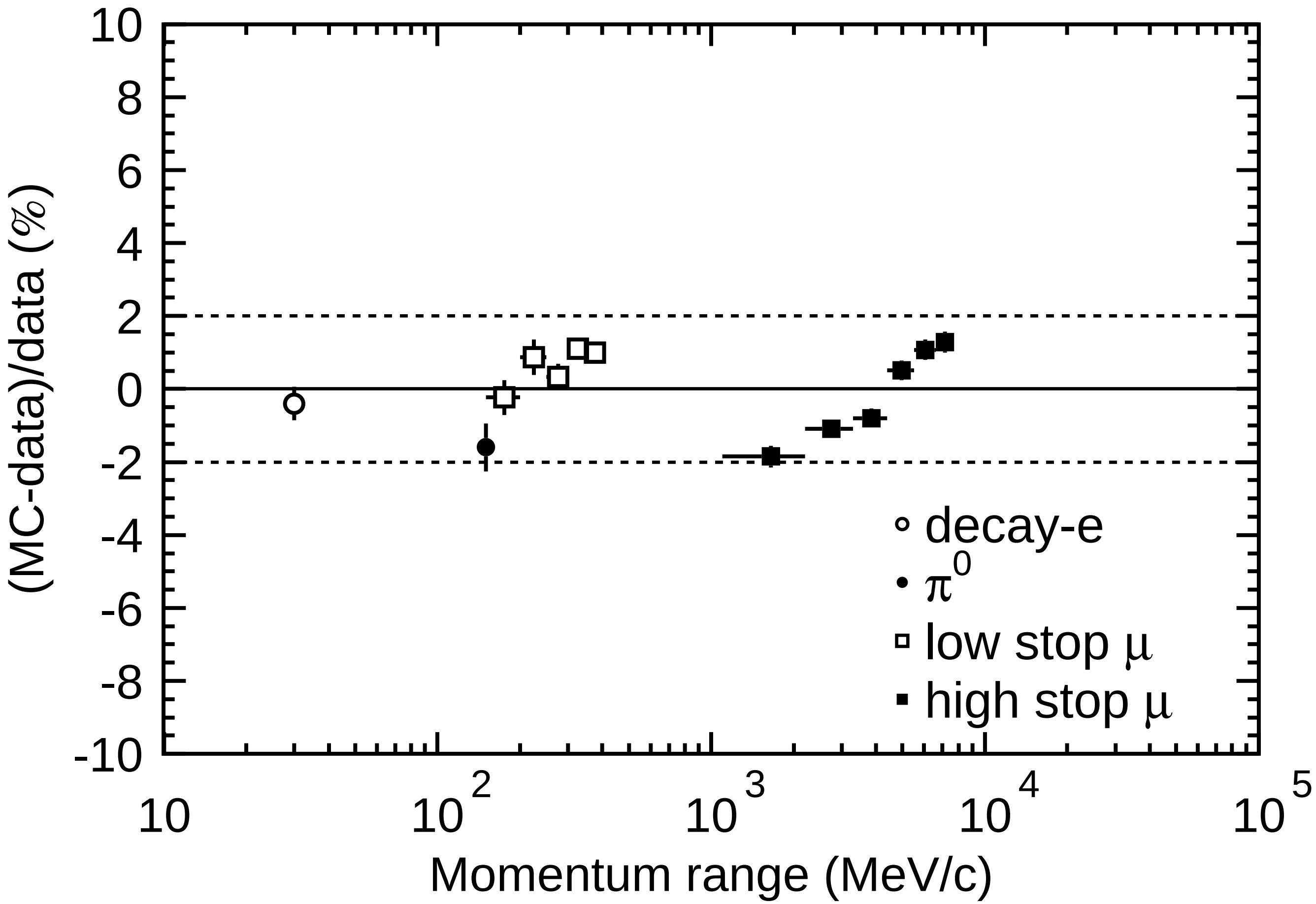


  - where N is the number of emitted Cherenkov photons with wavelength λ, dx is the particle's path length, and α =1/137
  - Cherenkov photons are detected with a large number of photomultiplier tubes (PMT)

- For Super-K (water), θ_C = 42deg (β = 1),
  N(photo e.) ~ 6 P.E./ MeV e^-
- Analysis threshold 208 MeV/c for μ , 30MeV for e

- P(threshold)~1.2 GeV/c for protons
  → blind to nucleons NOT a good hadron calorimeter

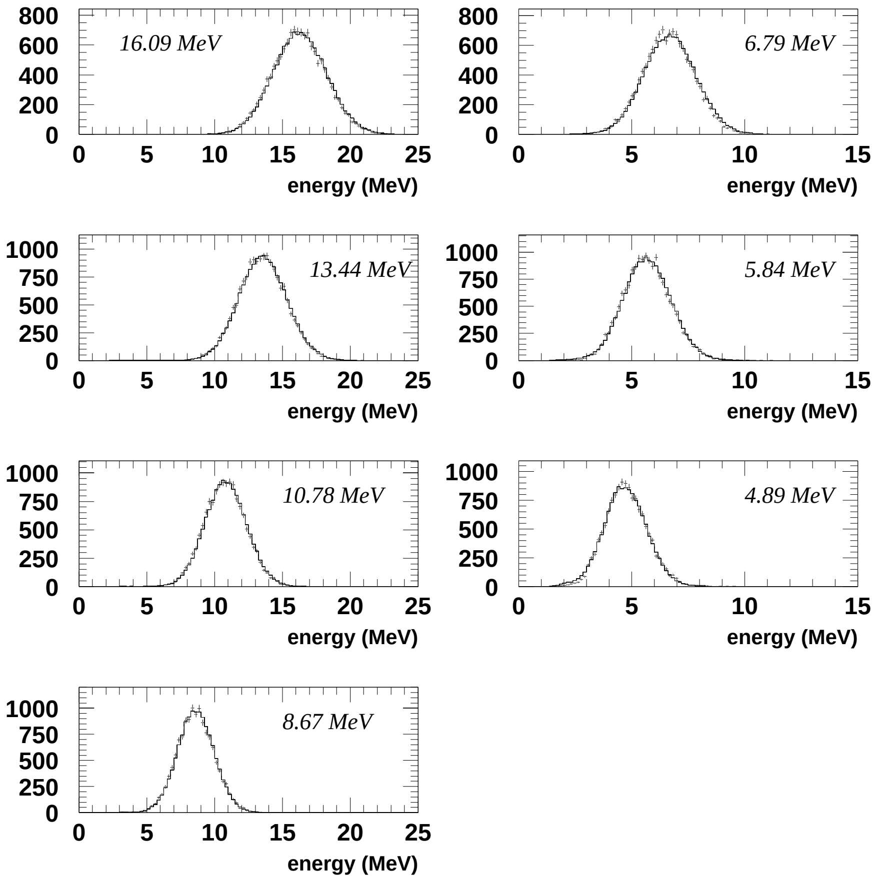
Energy scale uncertainty for SK-1

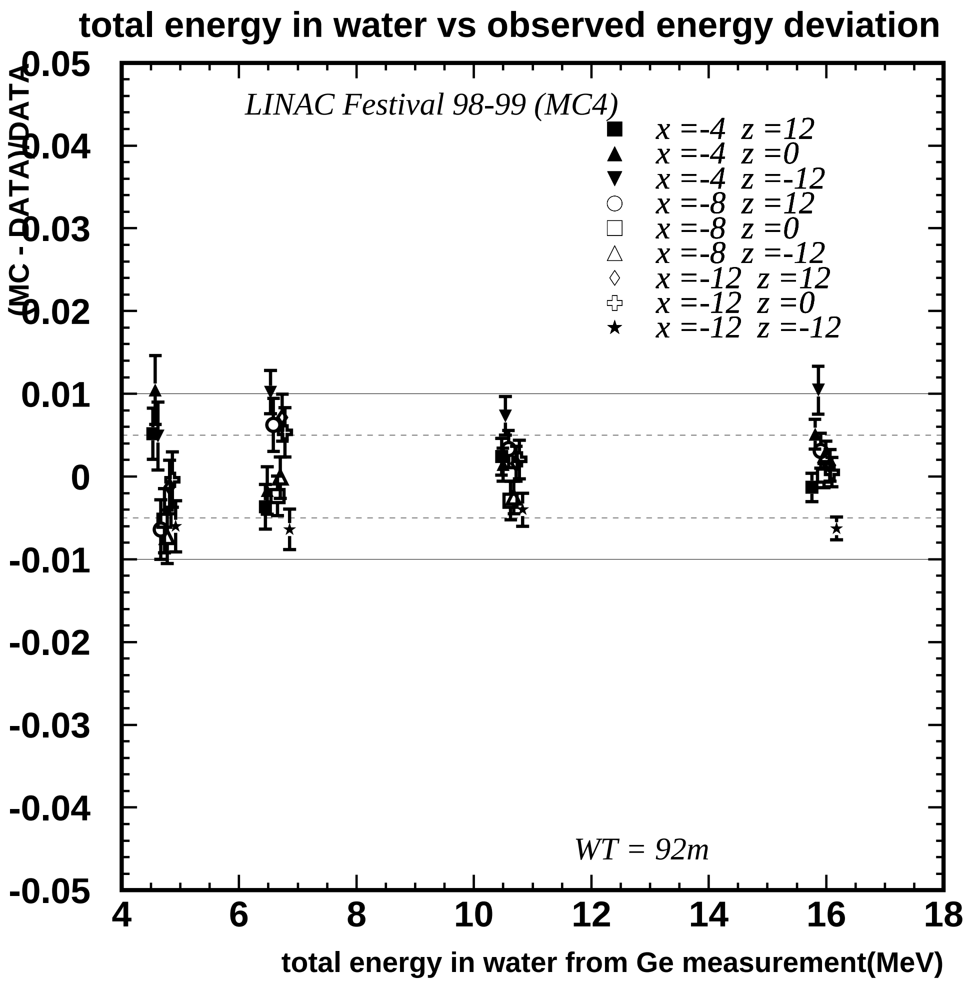


Energy scale calibration : 1.8%
time variation : 0.9%

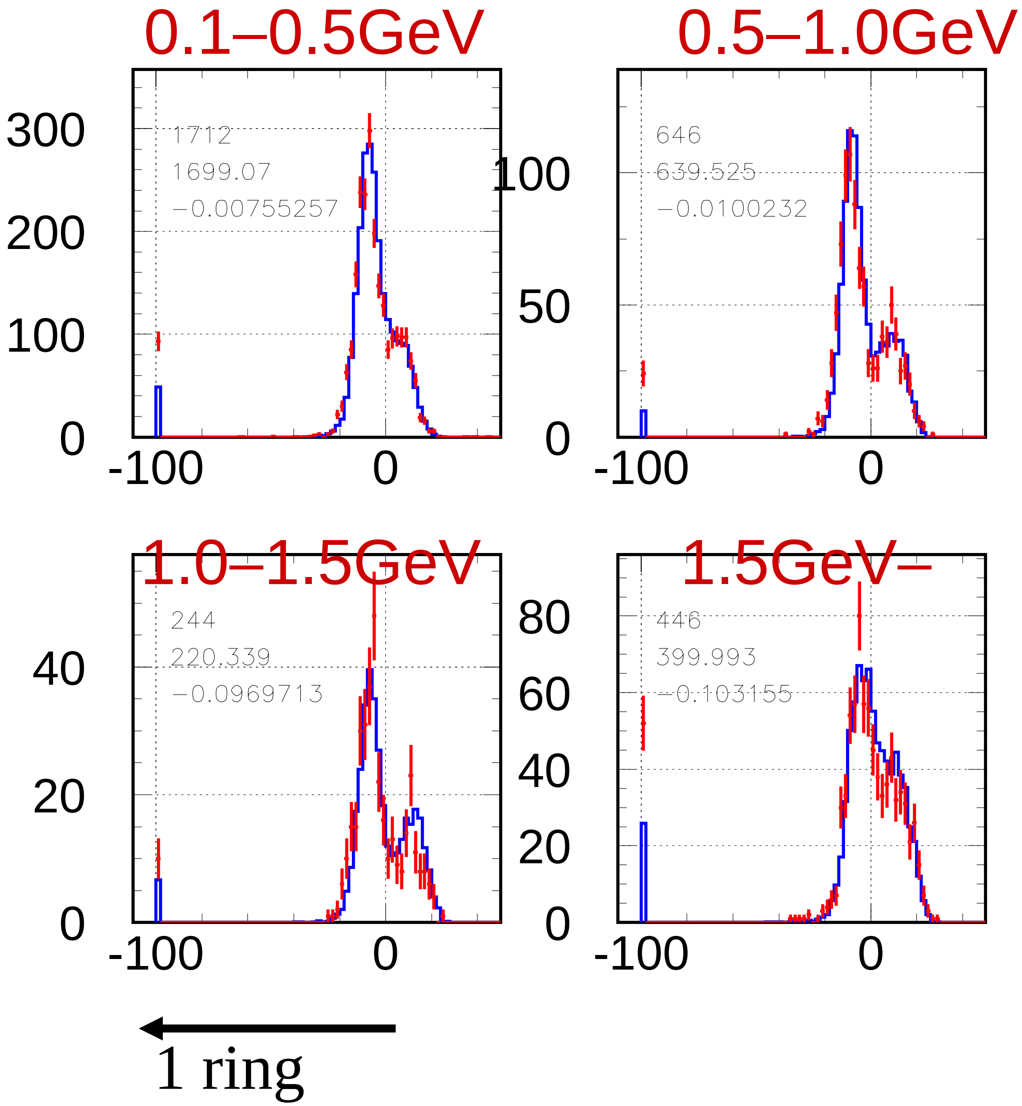
total : 2%

Energy calibration by 16 MeV LINAC

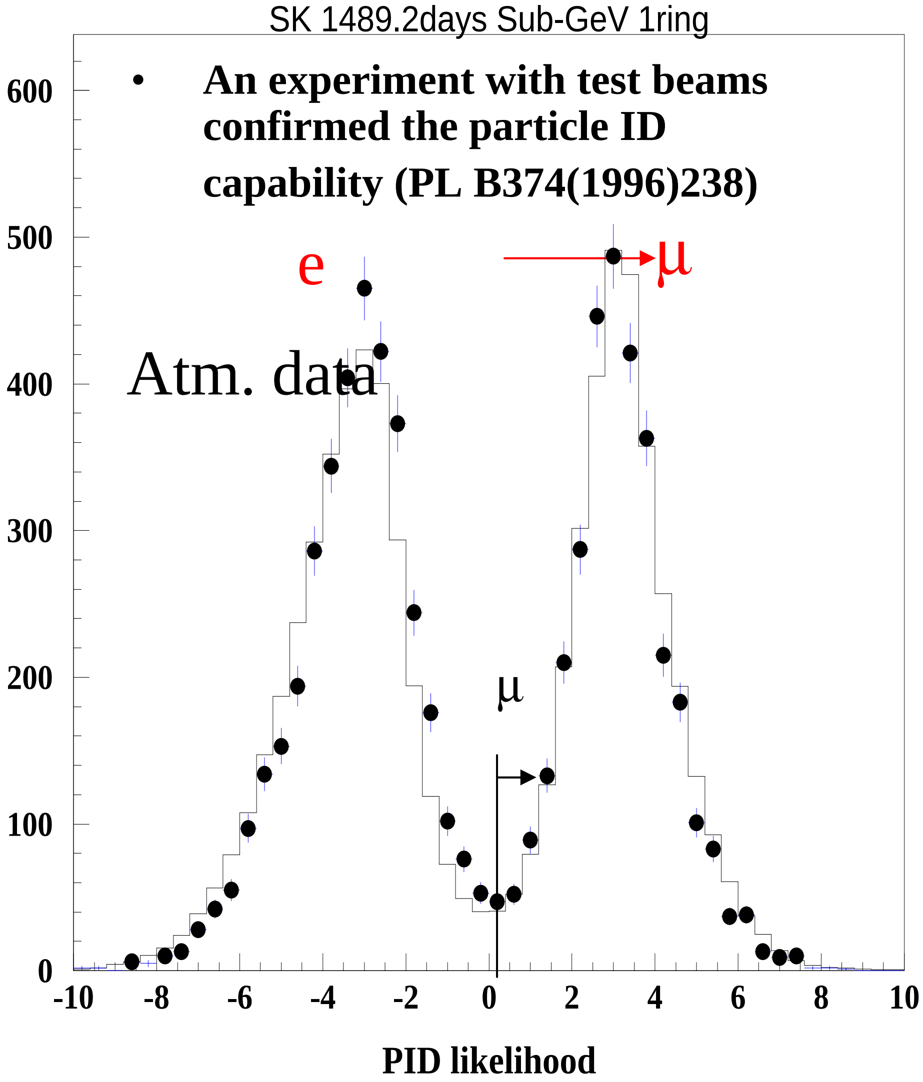


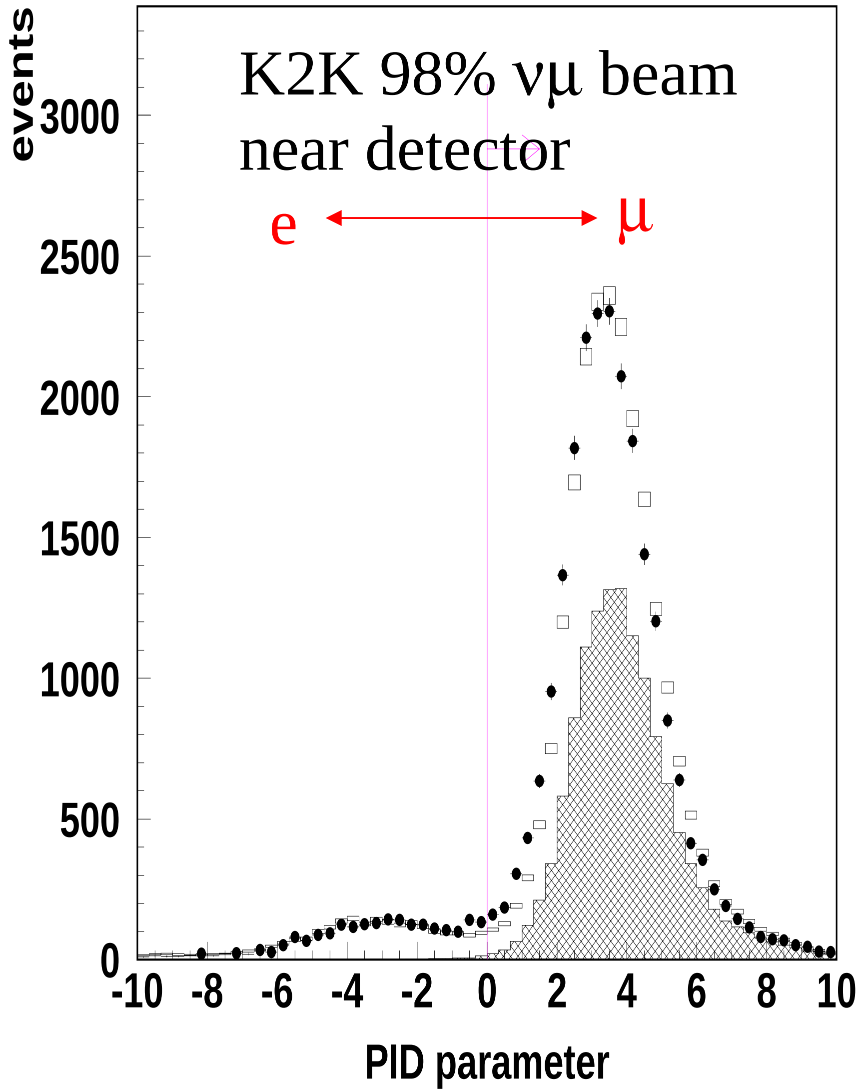


multi-ring likelihood for atm ν

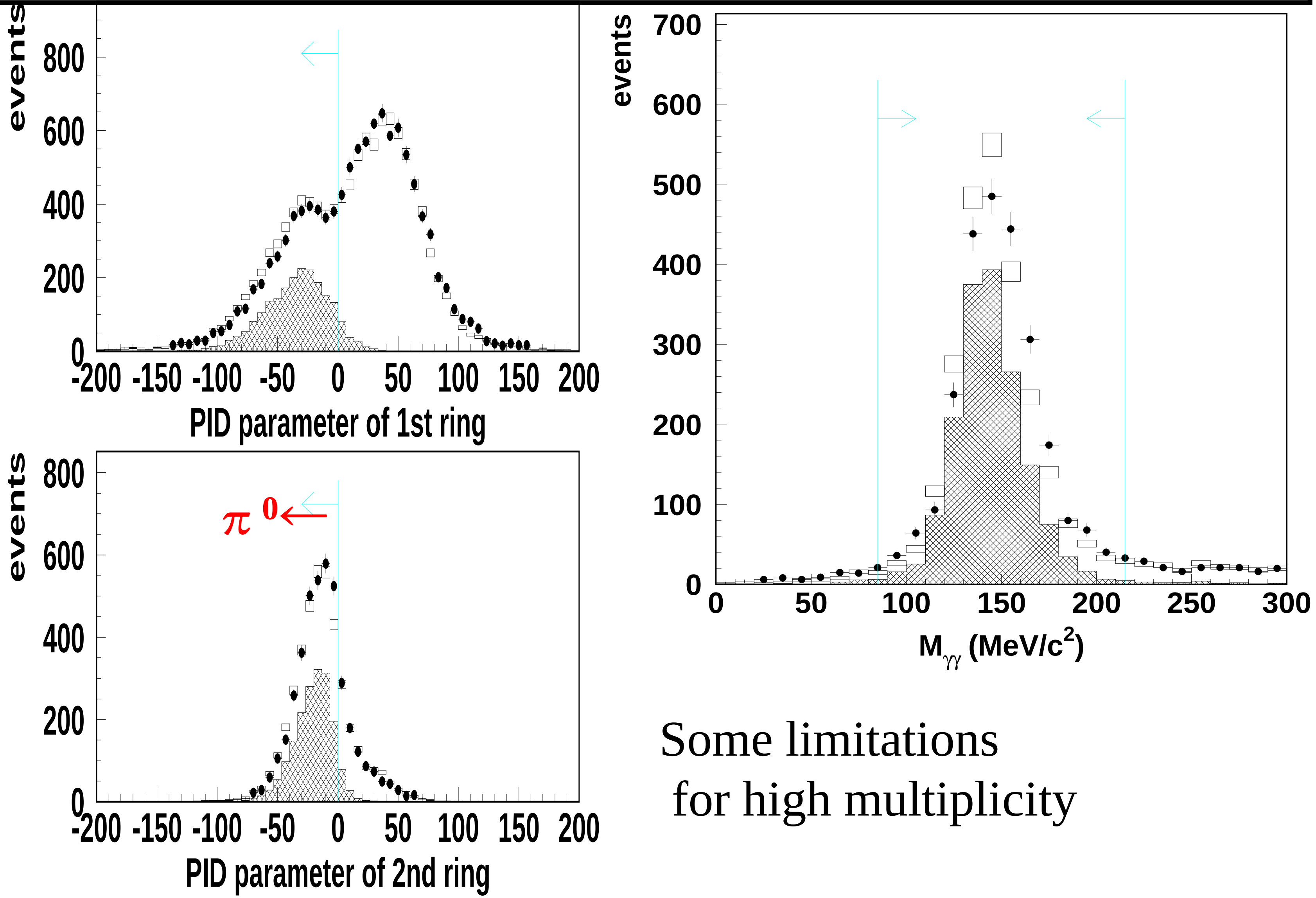


Particle ID (e & μ) (in single ring events)





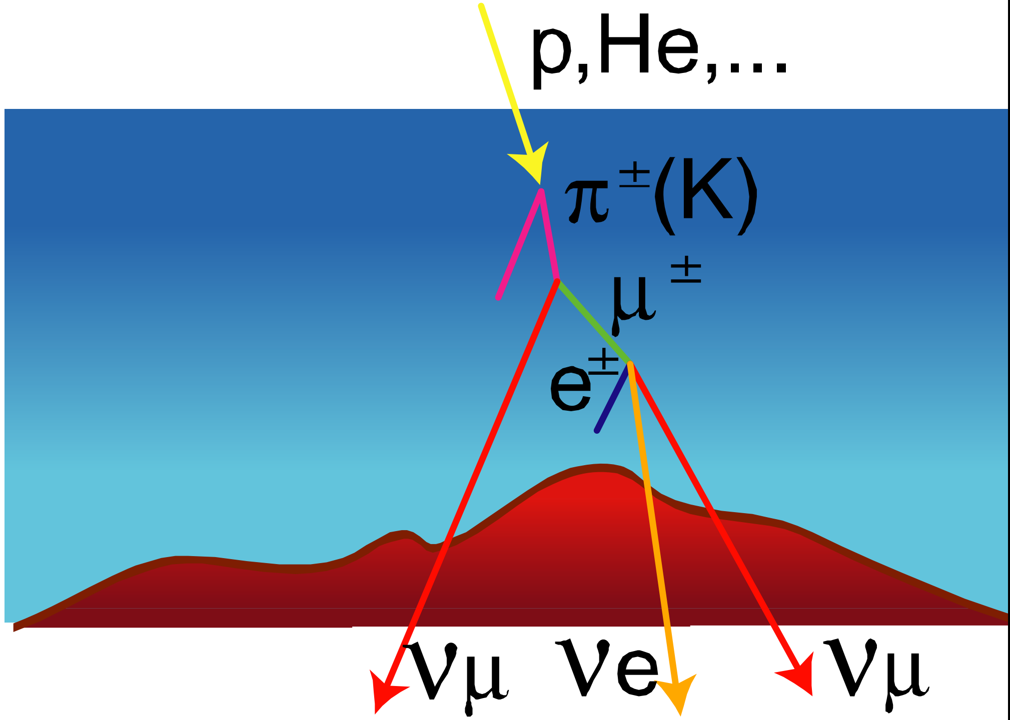
Particle ID in multi ring events (π^0 selection)

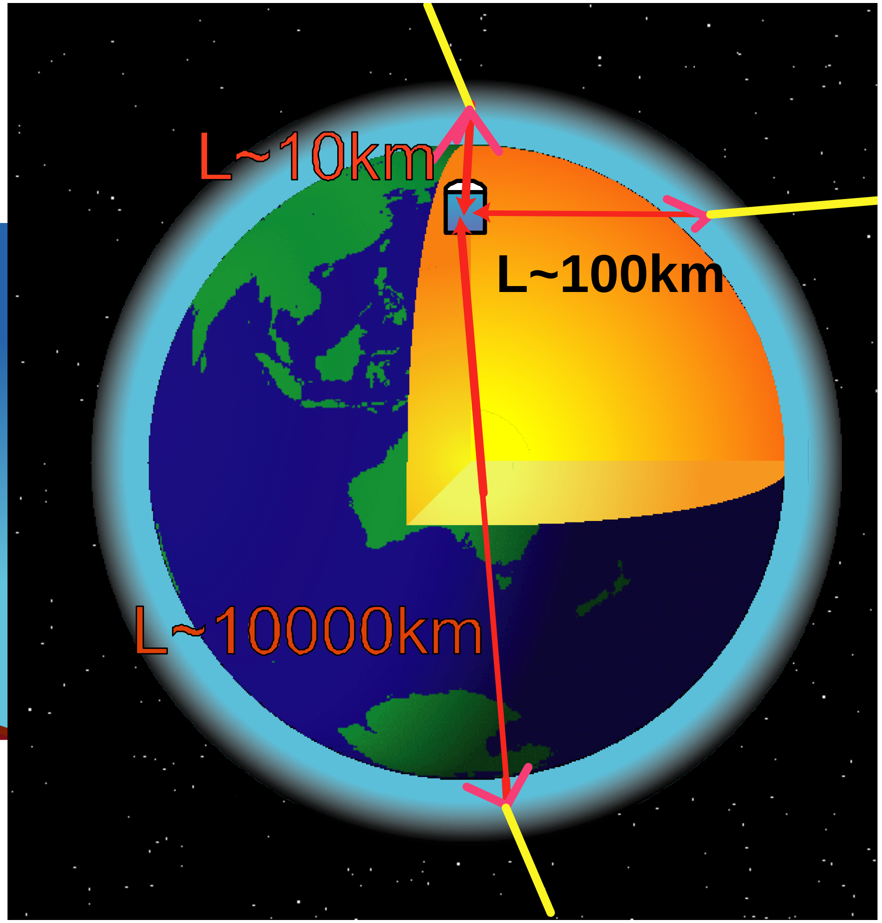


Some limitations
for high multiplicity

Updates of atmospheric neutrinos results

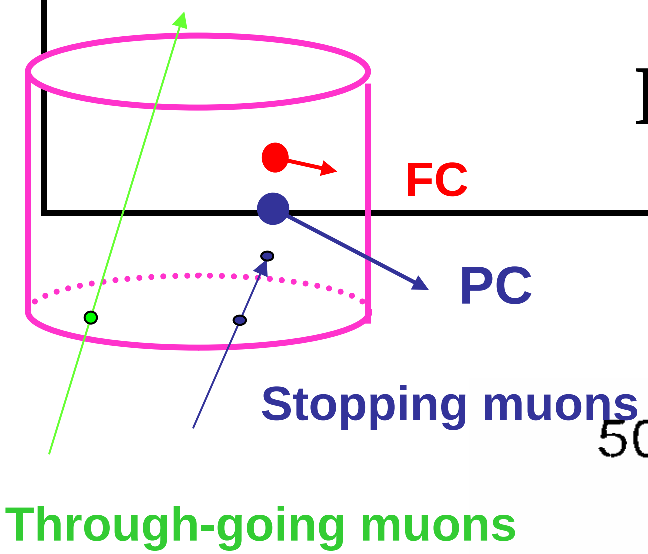
Atmospheric ν



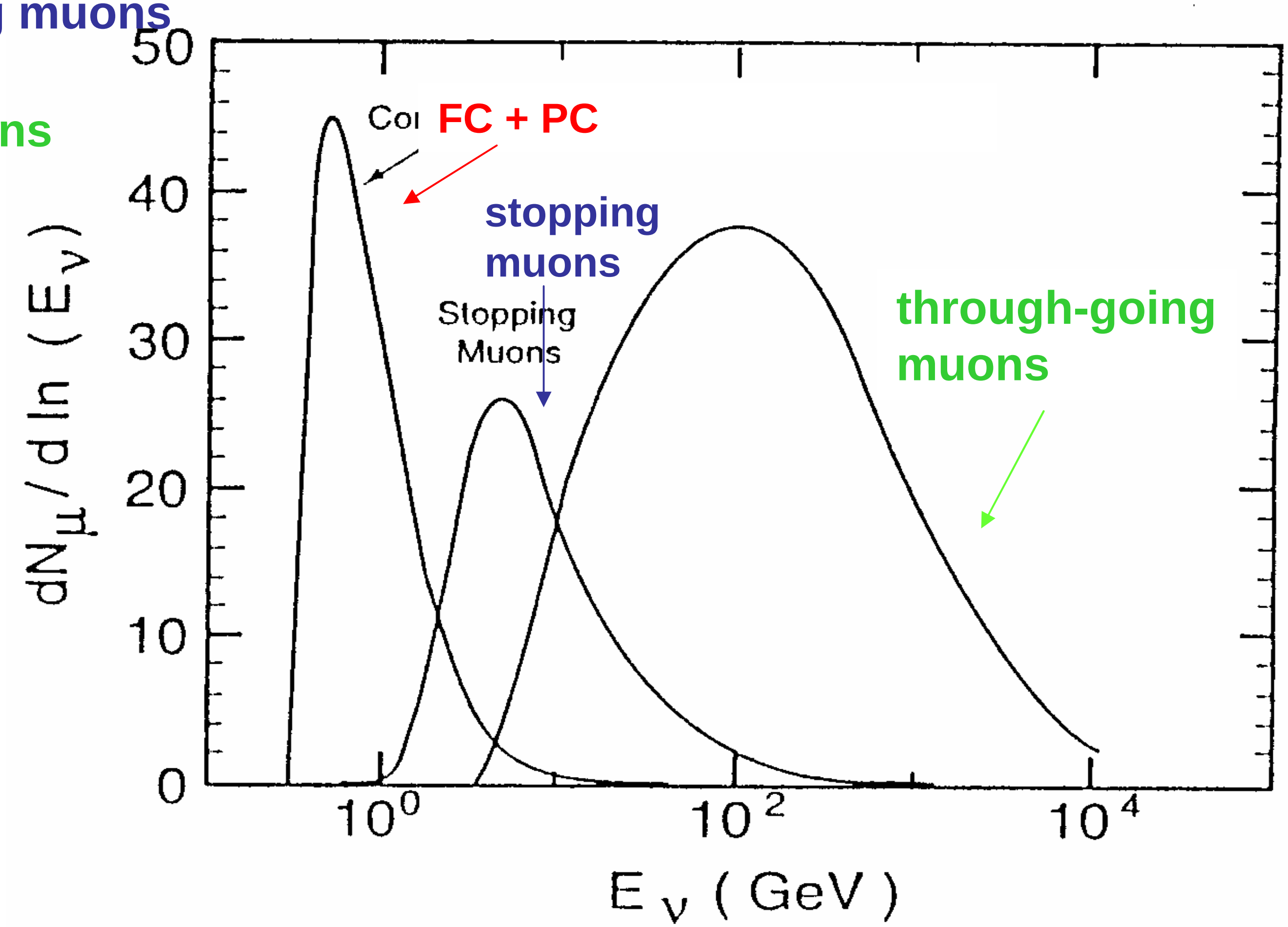


Event topology

$\nu_e + N \rightarrow e + X$
$\nu_\mu + N \rightarrow \mu + X$
~~$\nu_\tau + N \rightarrow \tau + X$~~



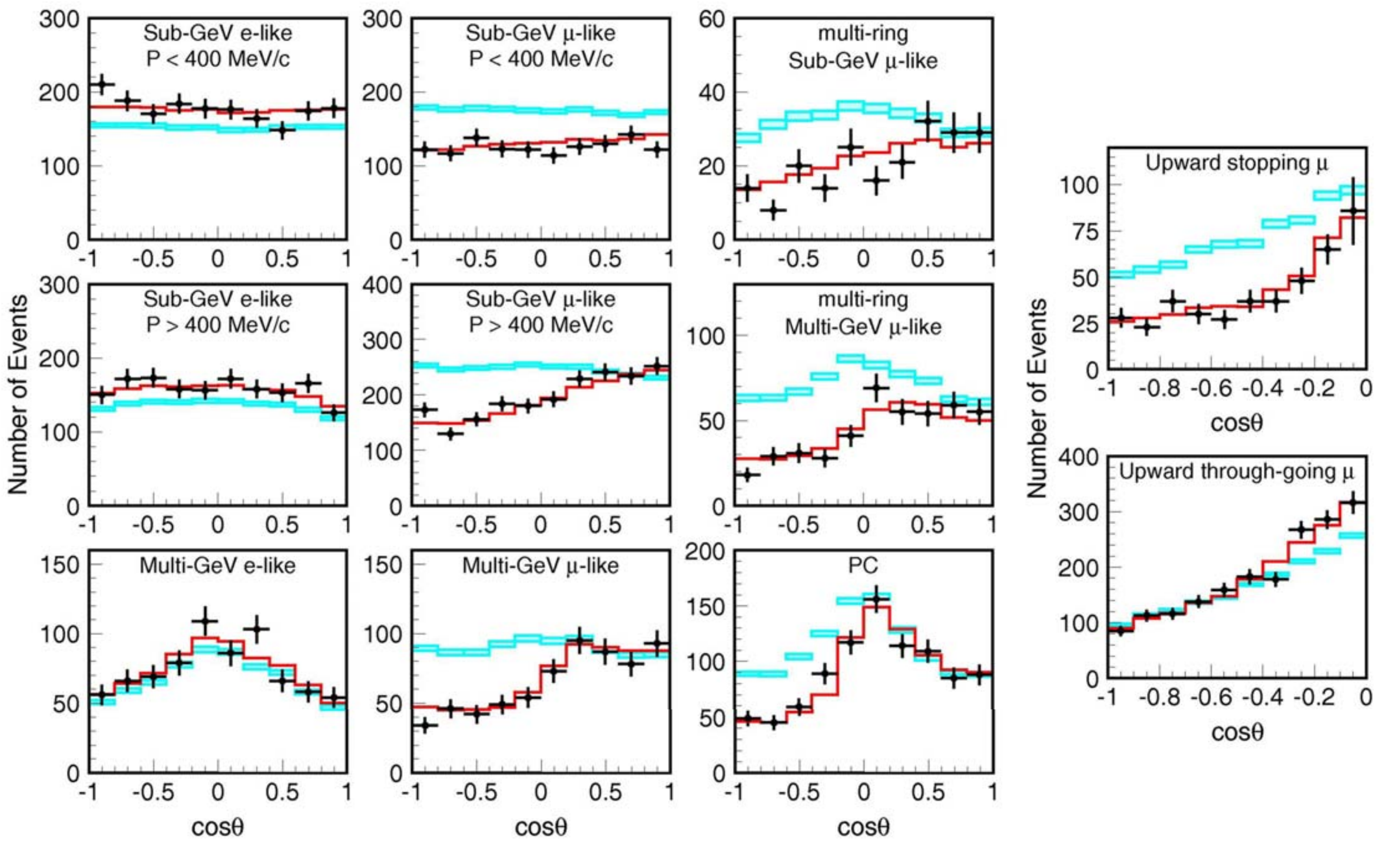
Initial neutrino energy spectrum



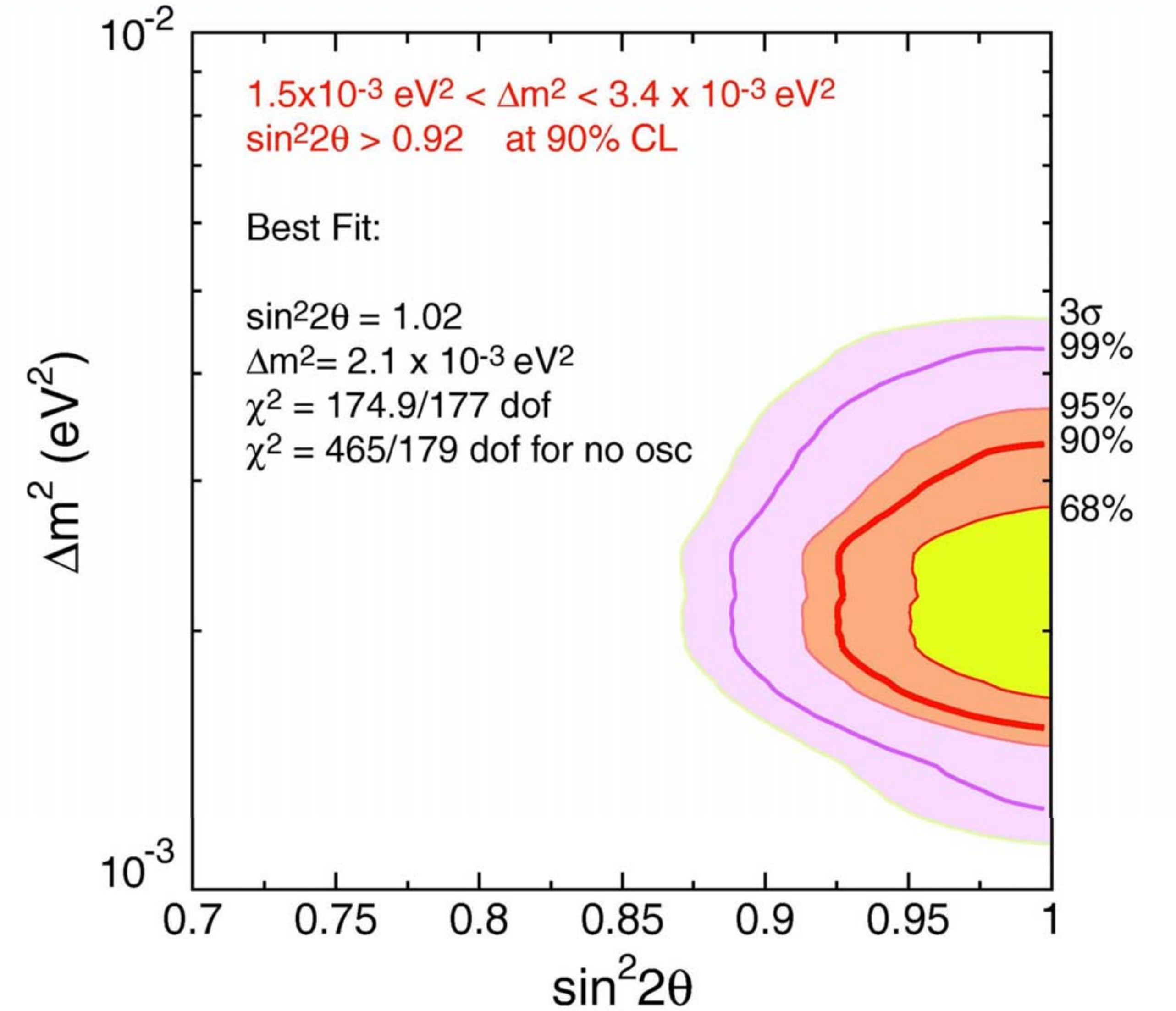
10^4 in L
10^5 in E

Up-Down
μ/e ratio

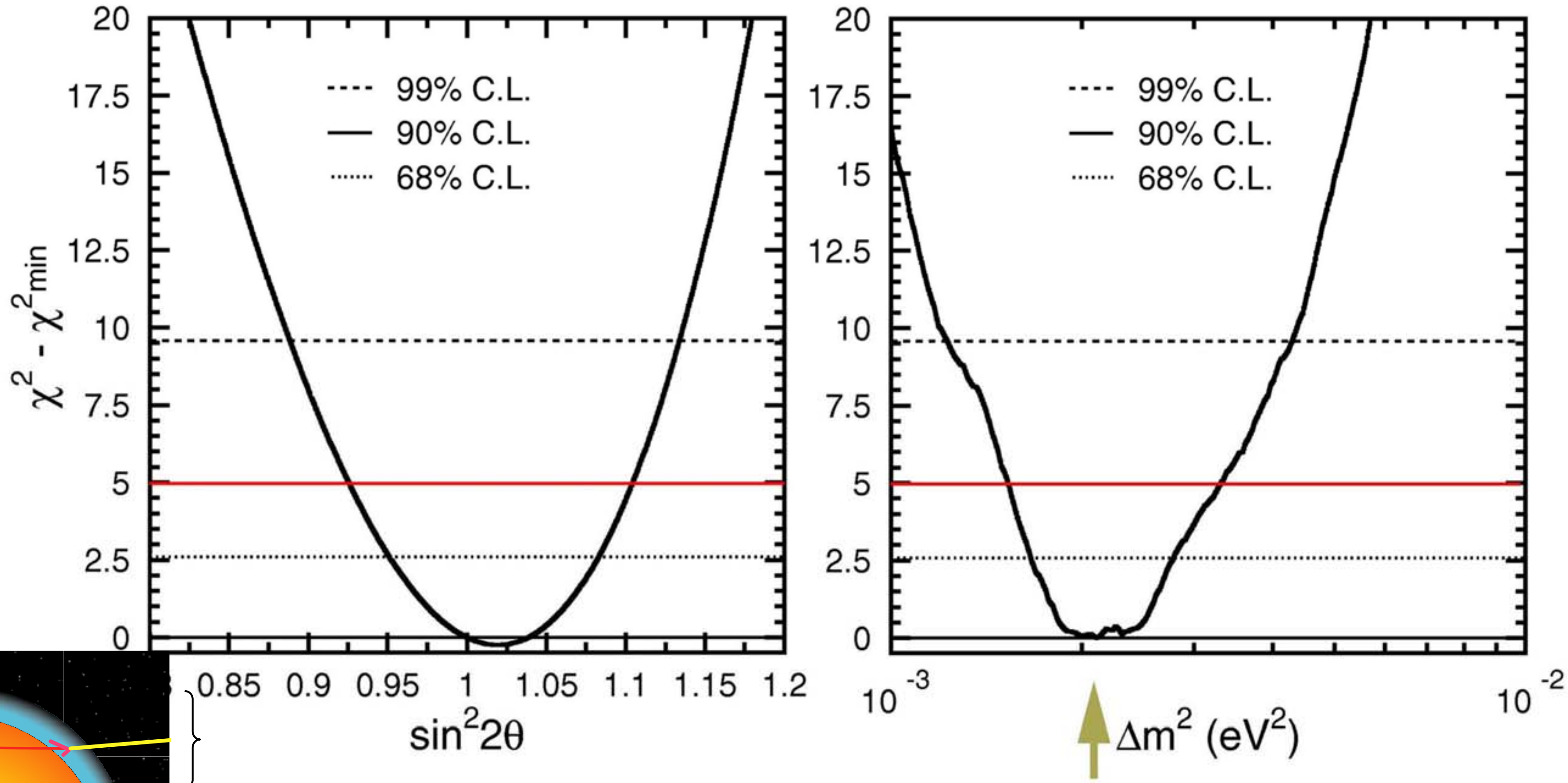
Zenith angle distribution from SK-1

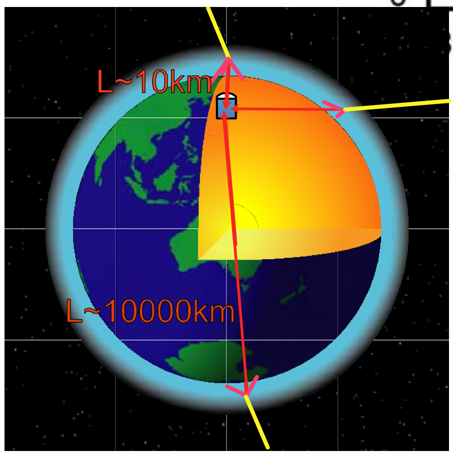


Contour of allowed region SK-1



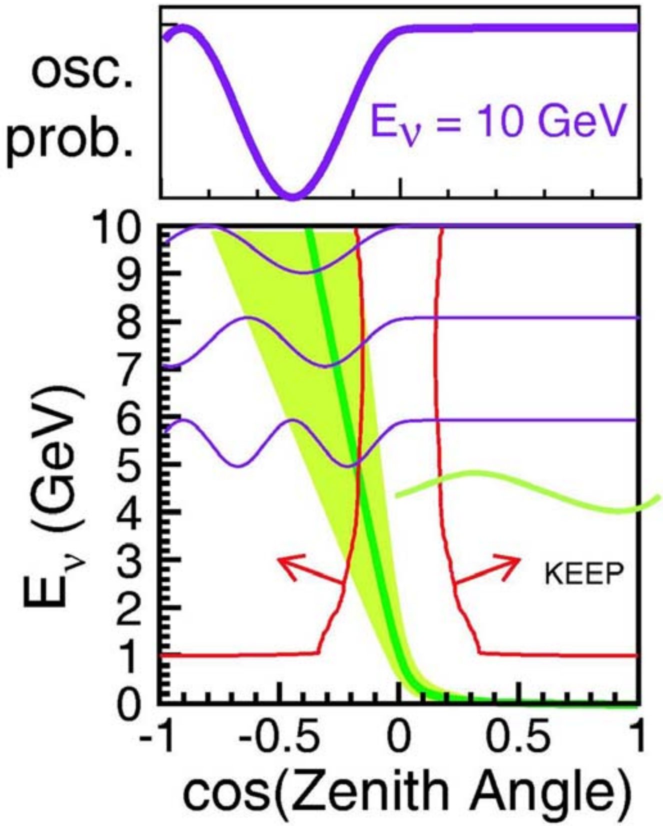
χ^2 in $\sin^2 2\theta$ and Δm^2 determination

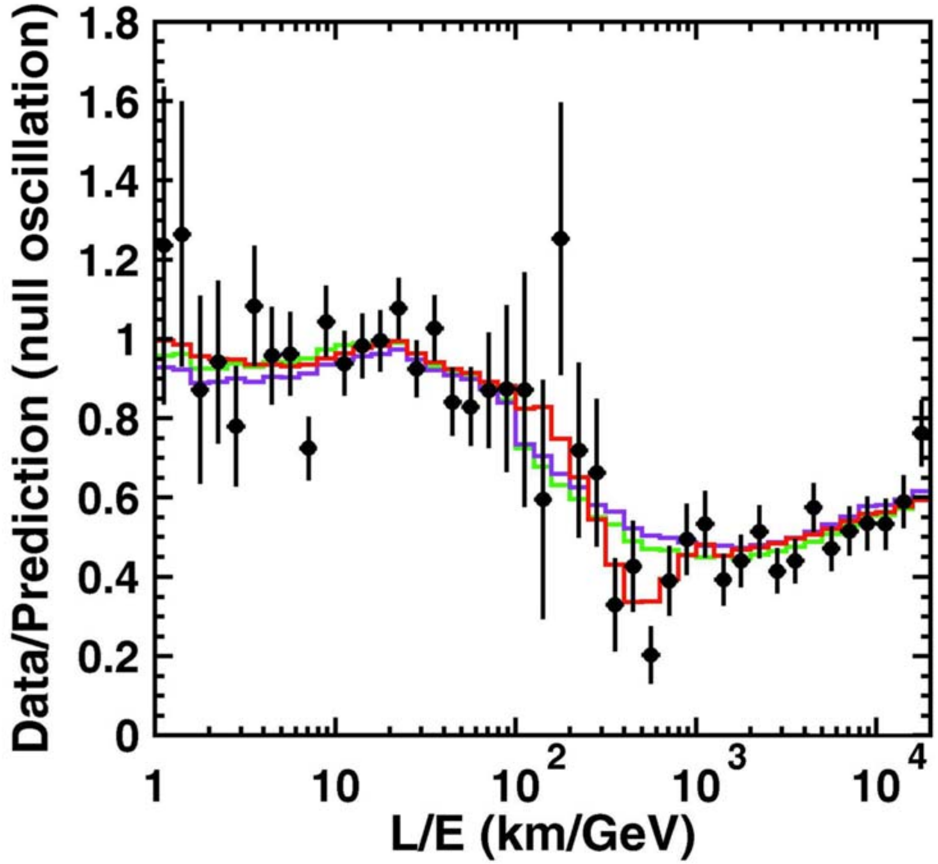




rather flat distribution

L/E analysis



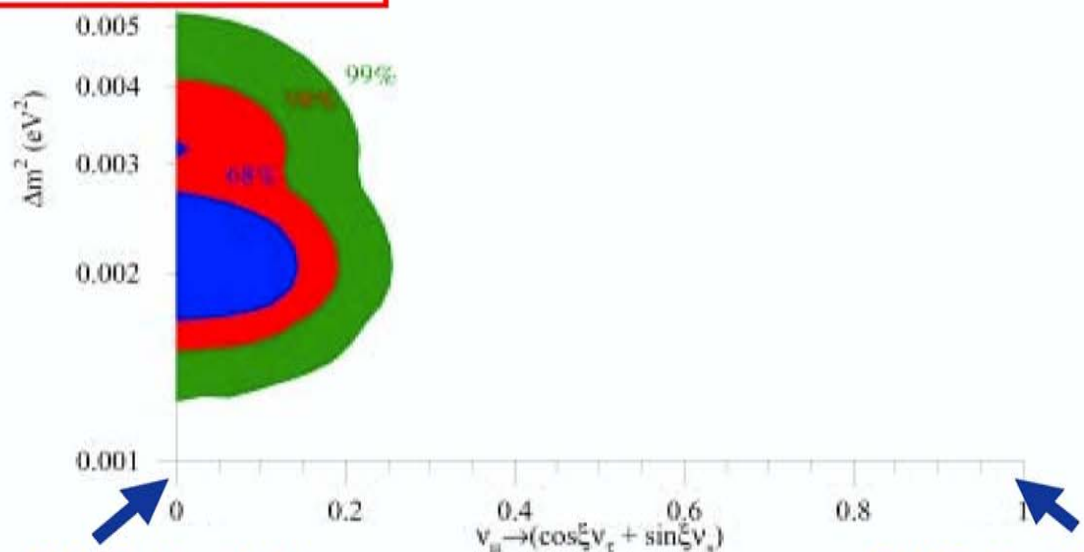


- rapid change of L near horizontal
- $\mu-\nu$ direction vs. $E\nu$
- $E\nu$ dist.

Oscillation to sterile neutrinos?

- Use NC deficit or Matter effect to discriminate
- Use all the SK data
  (including NC, up-through-going-muons and High-E PC j
  ➔
- 100% transition to the sterile state have been rejected
  (>99%C.L.)

$\nu_\mu \rightarrow \cos\xi\nu_\tau + \sin\xi\nu_s$



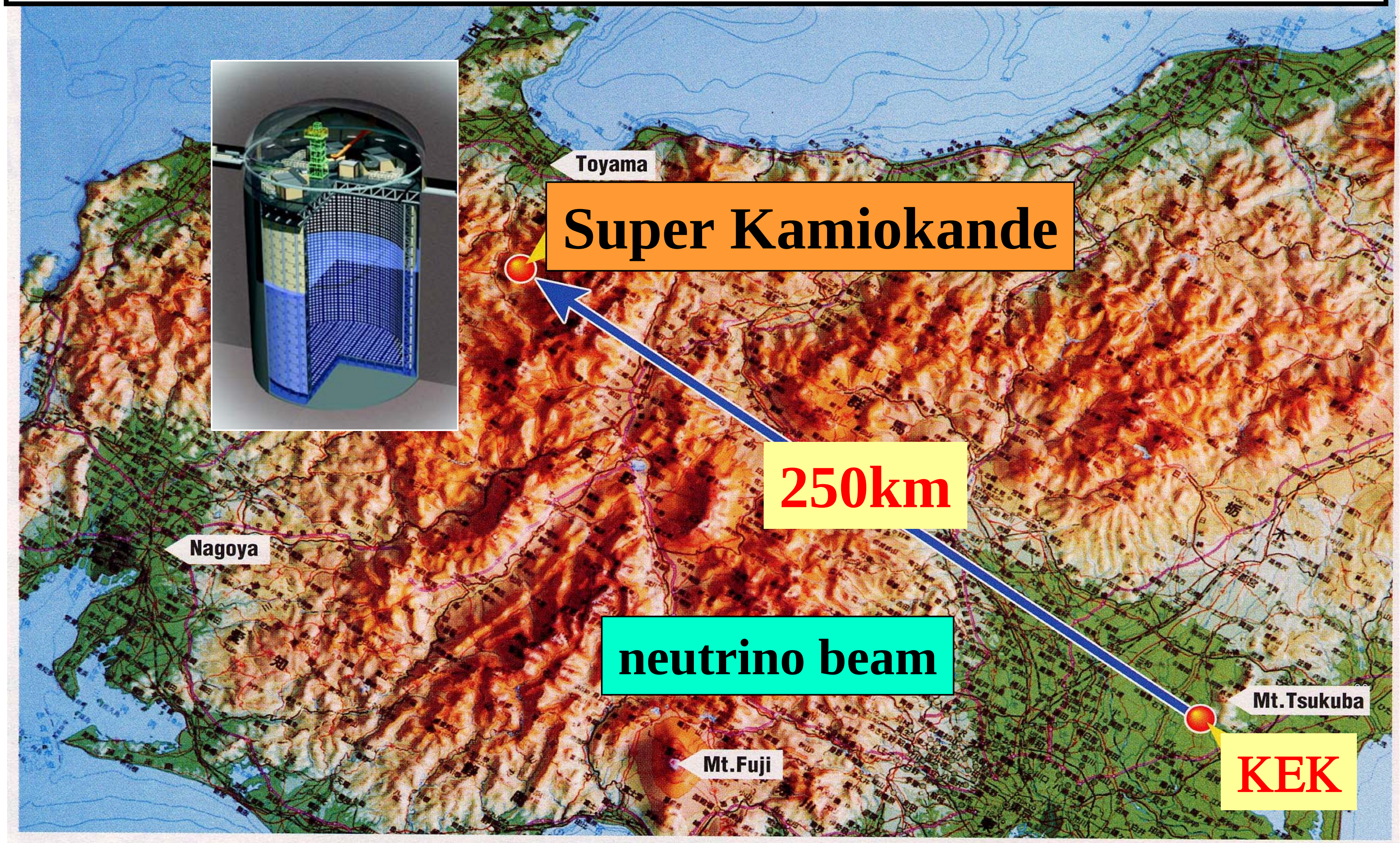
pure $\nu_\mu \rightarrow \nu_\tau$ $\sin^2\xi$ pure $\nu_\mu \rightarrow \nu_s$

Summary of Atmospheric Neutrino

- $1.5\ 10^{-3}\ eV^2 < \Delta m^2 < 3.4\ 10^{-3}\ eV^2$
- $\sin^2 2\theta > 0.92$ 90%CL
- Hint of dip of oscillation pattern
- 100% transition to sterile neutrinos is rejected
- Consistent with CHOOZ limit in $\nu\mu \rightarrow \nu e$

K2K as a working example for improvements to be done

K2K（*KEK* to *Kamioka*） experiment

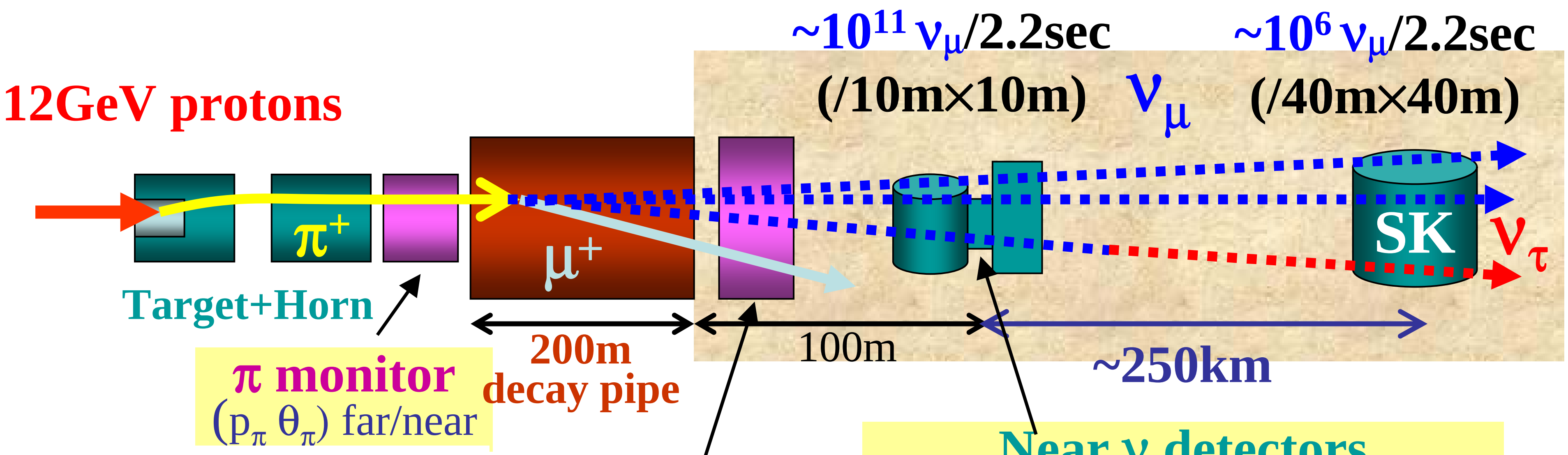


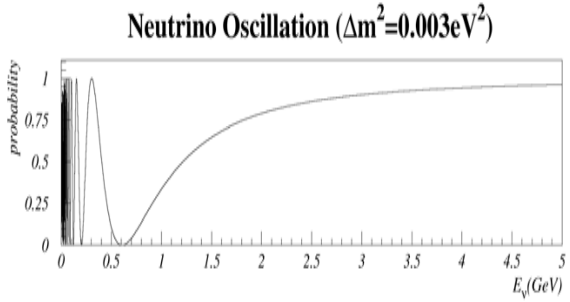
Key issues of the experiment

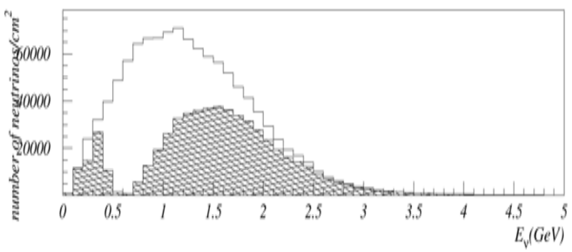
- Directionality and stability of beam
  - required 3-4 mrad. attained 1mrad through-out the run
  - spill-by-spill (limited to HE muons) >5GeV
  - GeV neutrinos
- Flux normalization (total number of events)
  - detector response for various type of interactions (particles)
- $\nu\mu$ spectrum shape at near detector
  - different kinematics for various type of interactions
- 300m $\rightarrow$ 250km extrapolation
  - hadron (p,θ) distribution
- Event selection $\Leftrightarrow$ atm. Backgrounds

K2K experiment

~1 event/2days







Signal of ν oscillation at K2K

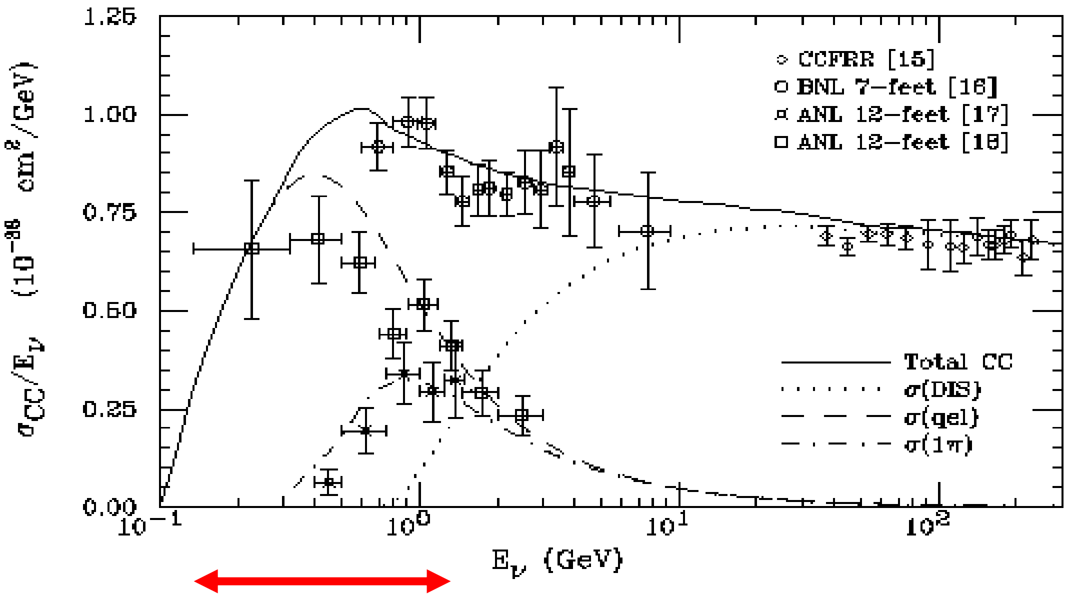
- Reduction of ν_μ events
- Distortion of ν_μ energy spectrum

Neutrino Oscillation - Spectrum change

- Only Flux(Eν) x σ(Eν) will be measured
  - Eν, L must be known event-by event to get Δm^2
  - Measurement at two distances

$$N_{obs}(E_\nu) = F(E_\nu) \cdot P(\nu_\alpha \to \nu_\beta) \cdot \sigma(E_\nu)$$

$$P(\nu_\alpha \to \nu_\beta) = \frac{N_{obs}^{far}(E_\nu) / \sigma(E_\nu)}{N_{obs}^{near}(E_\nu) / \sigma(E_\nu)}$$

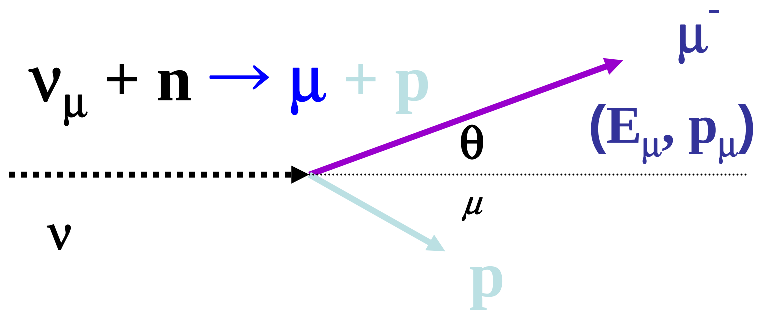


Neutrino Interactions

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

p,n no signal in W-C
E_{had} measurement!

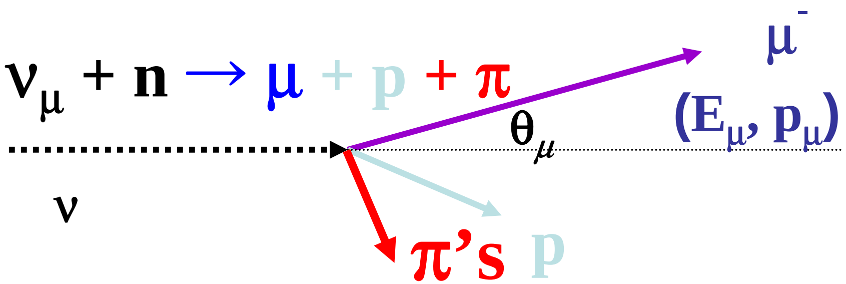
$\nu_\mu + n \rightarrow \mu + p$



- ✧ <u>CC QE</u> (1Rμ in W-Cherenkov)
  - ✧ can reconstruct Eν ←(θ_μ,p_μ)

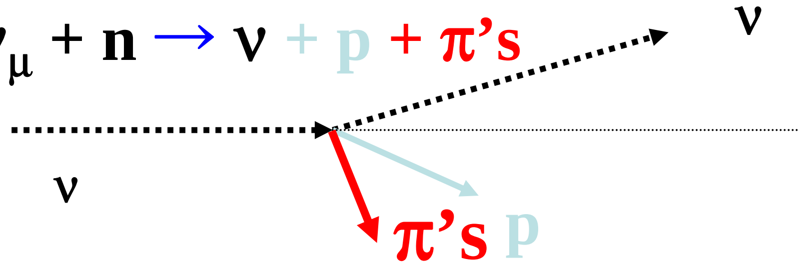
$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

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



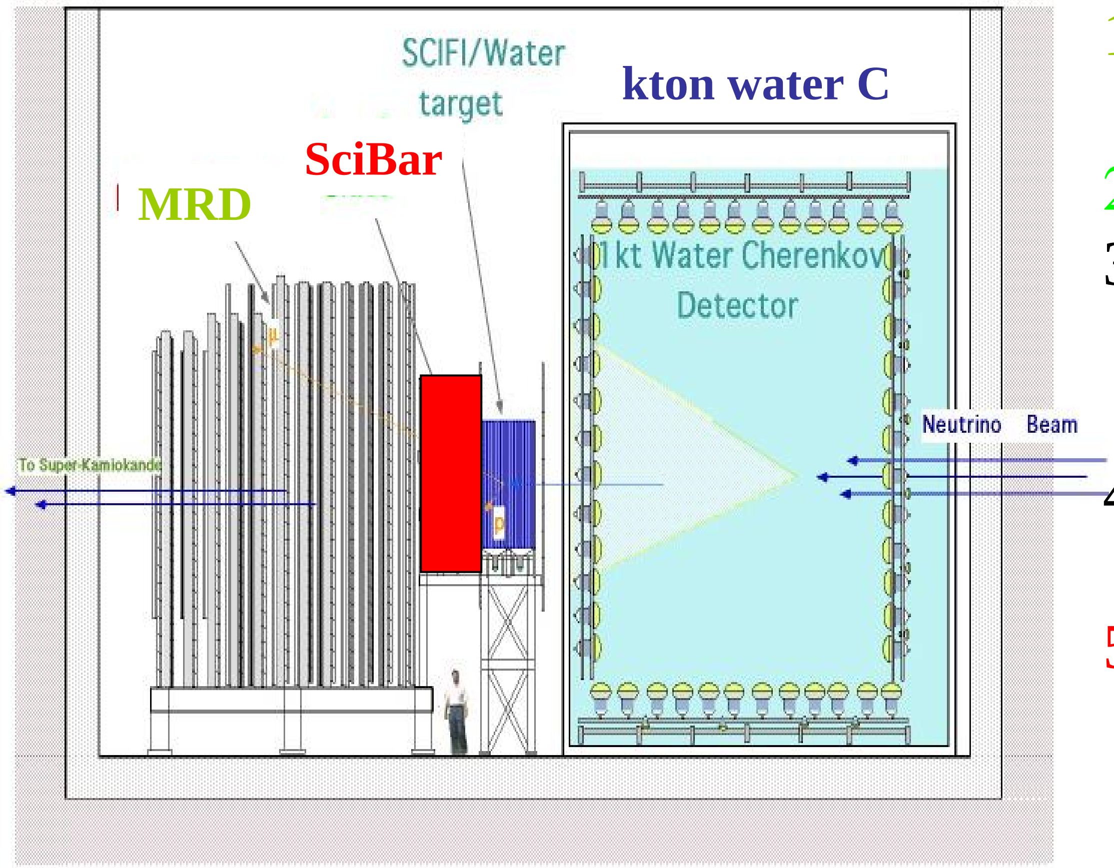
- ✧ <u>CC nonQE</u>
  - ✧ $E_\nu^{rec} < E_\nu$
  - ✧ different (θ_μ,p_μ) distribution for given E_ν

$\nu_\mu + n \rightarrow \nu + p + \pi\text{'s}$



- ✧ <u>NC</u>
  - ✧ small E_ν^{rec}

Near Detectors at KEK

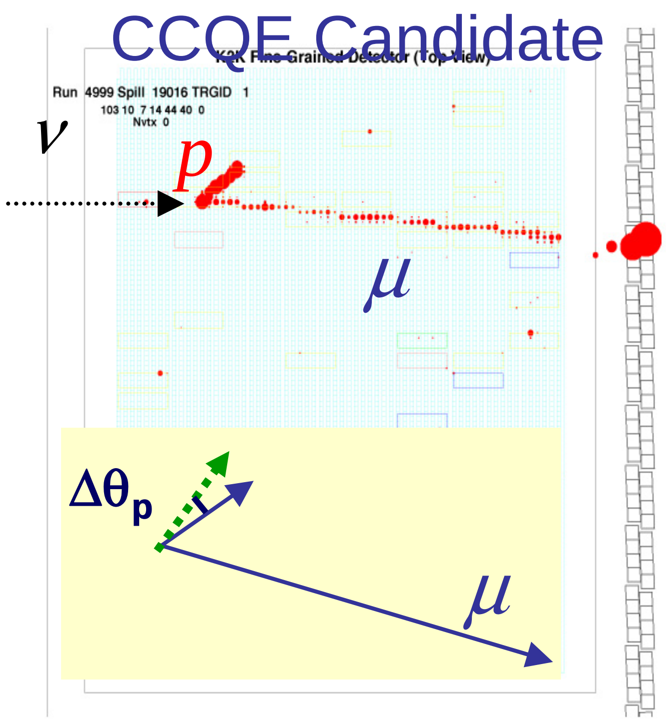


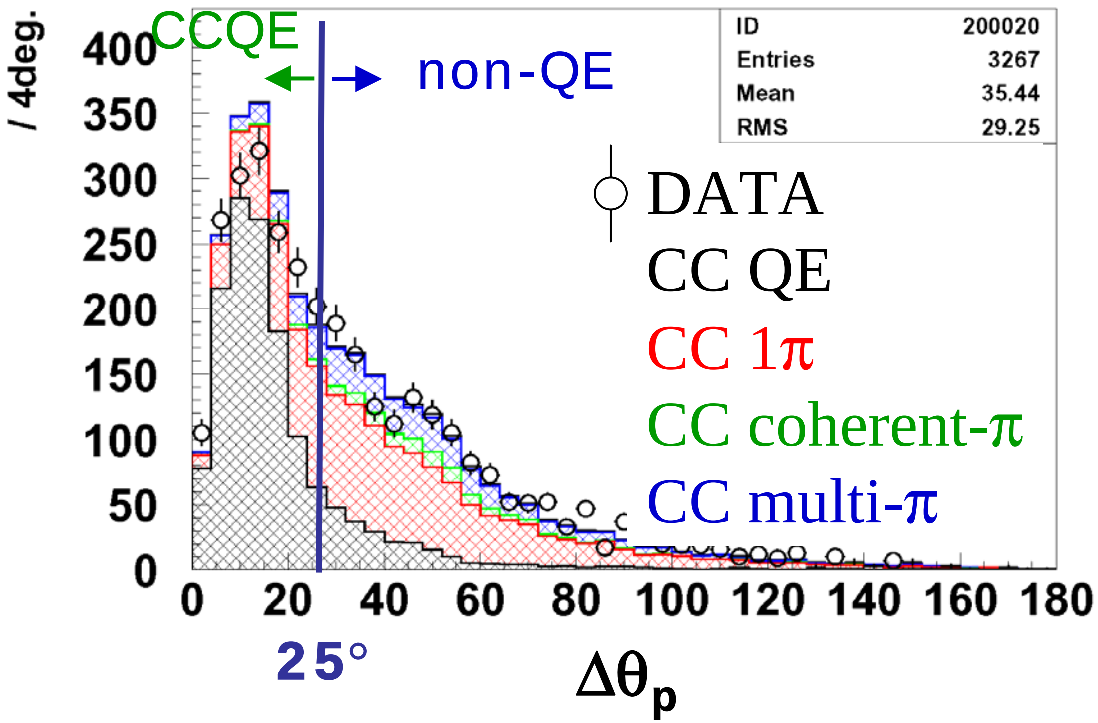
At 300 m from target

1. neutrino beam profile
   - massive MRD
2. νe contamination
3. rate in KT
   - same response as SK for each int. mode
4. spectrum
   - distinction of int modes
5. CCQE nonQE NC
   - PID (p ↔ π,μ)
   - Low energy particles
   - νe measurement

CCQE and nonQE
SciBar neutrino interaction study.

- Full Active Fine-Grained detector.
  - Sensitive to a low momentum track.
  - Identify CCQE events and other interactions (non-QE) separately.





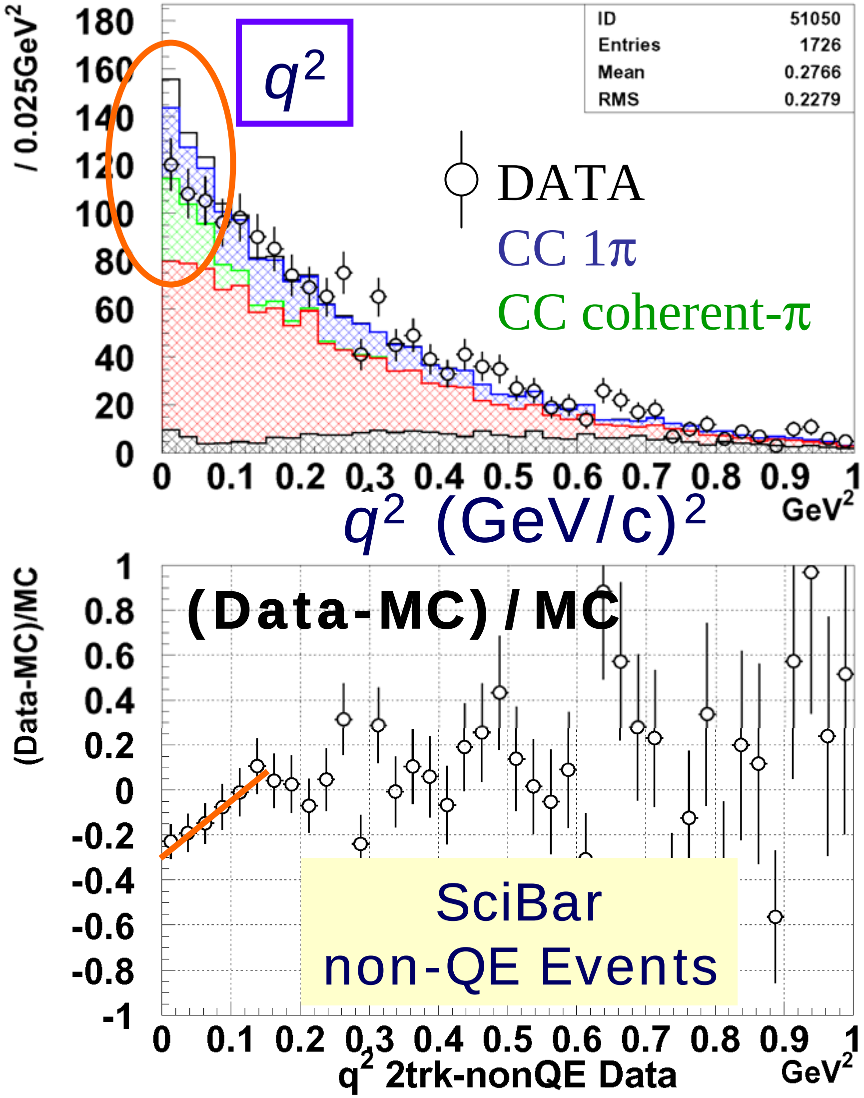
A hint of K2K forward μ deficit.

K2K observed forward μ deficit.

- A source is non-QE events.
- For CC-1π,
  - Suppression of ~q^2/0.1[GeV^2] at q^2<0.1[GeV^2] may exist.
- For CC-coherent π,
  - The coherent π may not exist.

We do not identify which process causes the effect. The MC CC-1π (coherent π) model is corrected phenomelogically.

Oscillation analysis is insensitive to the choice.



Flow of Neutrino Oscillation Analysis

Observed (p_μ,θ_μ) distributions at Near Detectors

$\downarrow$ ν ***Int. Model***

Neutrino Spectrum at Near detector $\phi_{near}(E\nu)$,

$\downarrow$

Far/Near Extrapolation vs Eν $R_{FN}(E\nu)$

Neutrino Spectrum w/o oscillation at SK $\phi_{SK}(E\nu)$

$\phi_{SK}(E\nu)$ $\otimes$ Oscillation $(\sin^2 2\theta, \Delta m^2)$ $\otimes$ *Int. Model*

Prediction

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

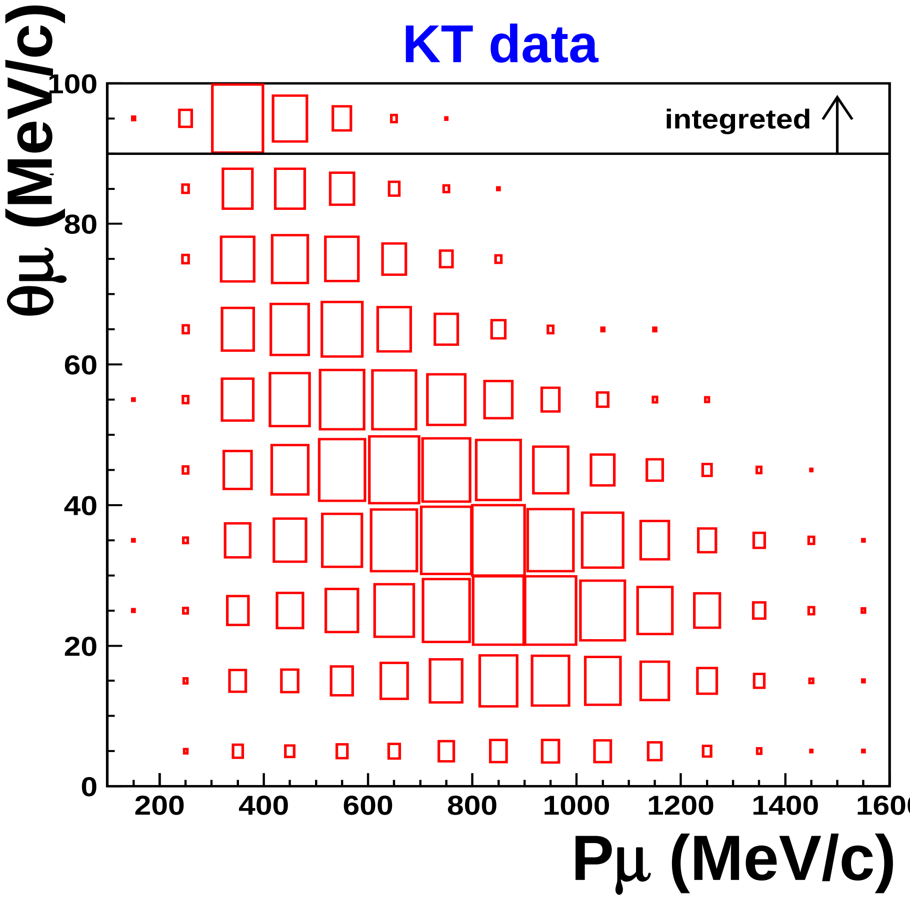
SK observation

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

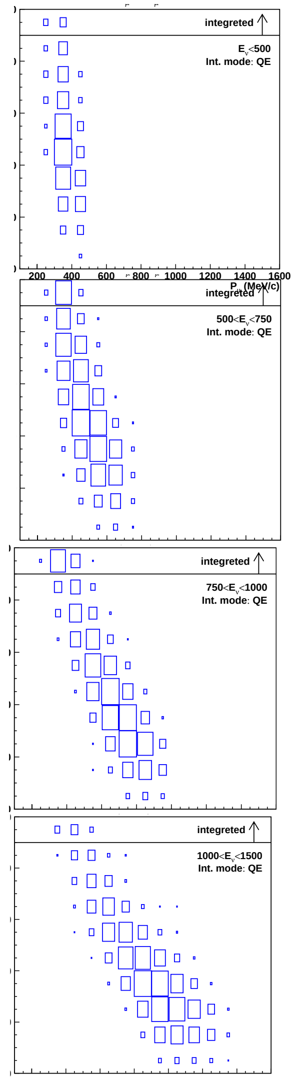
Maximum Likelihood Fit in $(\sin^2 2\theta, \Delta m^2)$

Neutrino Spectrum at Near

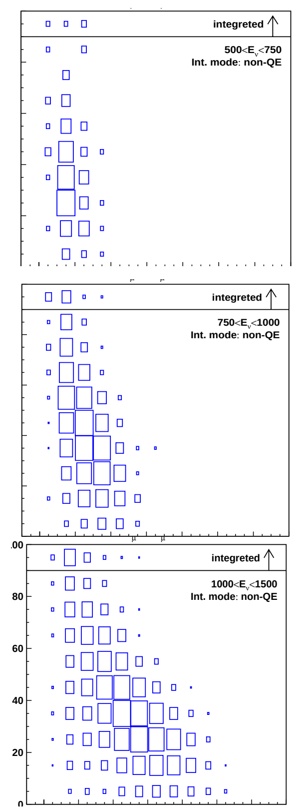
KT data



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



MC templates



:

:

- ν flux $\Phi_{KEK}(E_\nu)$ (8 bins)
- ν interaction (nQE/QE)

1 track and two track events for $\phi_{near}(E\nu)$

KT

Fully Contained Fiducial Volume (FCFV) events

- **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 nonQE-like events

SciBar

(5) 1-track m events
(6) 2-track QE-like events
(7) 2-track nonQE-like events

norm. (N_{SK}) from KT & 7 sets of (p_μ, θ_μ) distributions

- **ν flux $\phi_{near}(E\nu)$ (8 bins)**
- **ν interaction model (nQE/QE ratio as parameter)**

Flux measurements

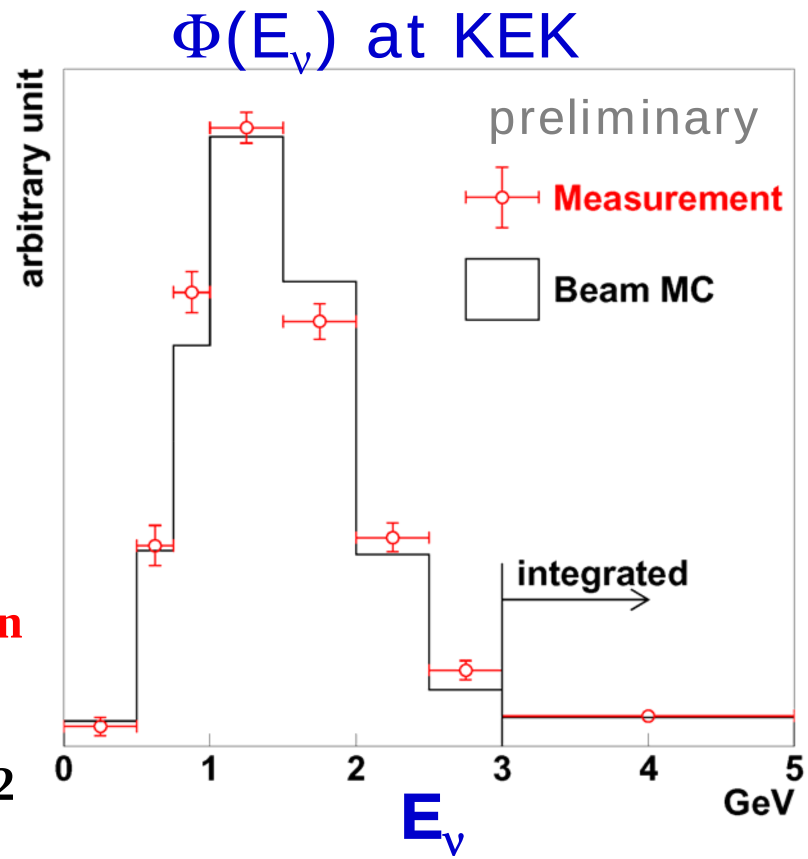
χ^2=638.1 for 609 *d.o.f*

- **Φ1 (Eν < 500) = 0.78 ± 0.36**
- **Φ2 (500≤ Eν < 750) = 1.01 ± 0.09**
- **Φ3 (750≤ Eν <1000) = 1.12 ± 0.07**
- **Φ4 (1500≤ Eν <2000) = 0.90 ± 0.04**
- **Φ5 (2000≤ Eν <2500) = 1.07 ± 0.06**
- **Φ5 (2500≤ Eν <3000) = 1.33 ± 0.17**
- **Φ6 (3000≤ Eν   ) = 1.04 ± 0.18**
- **nQE/QE   = 1.02 ± 0.10**

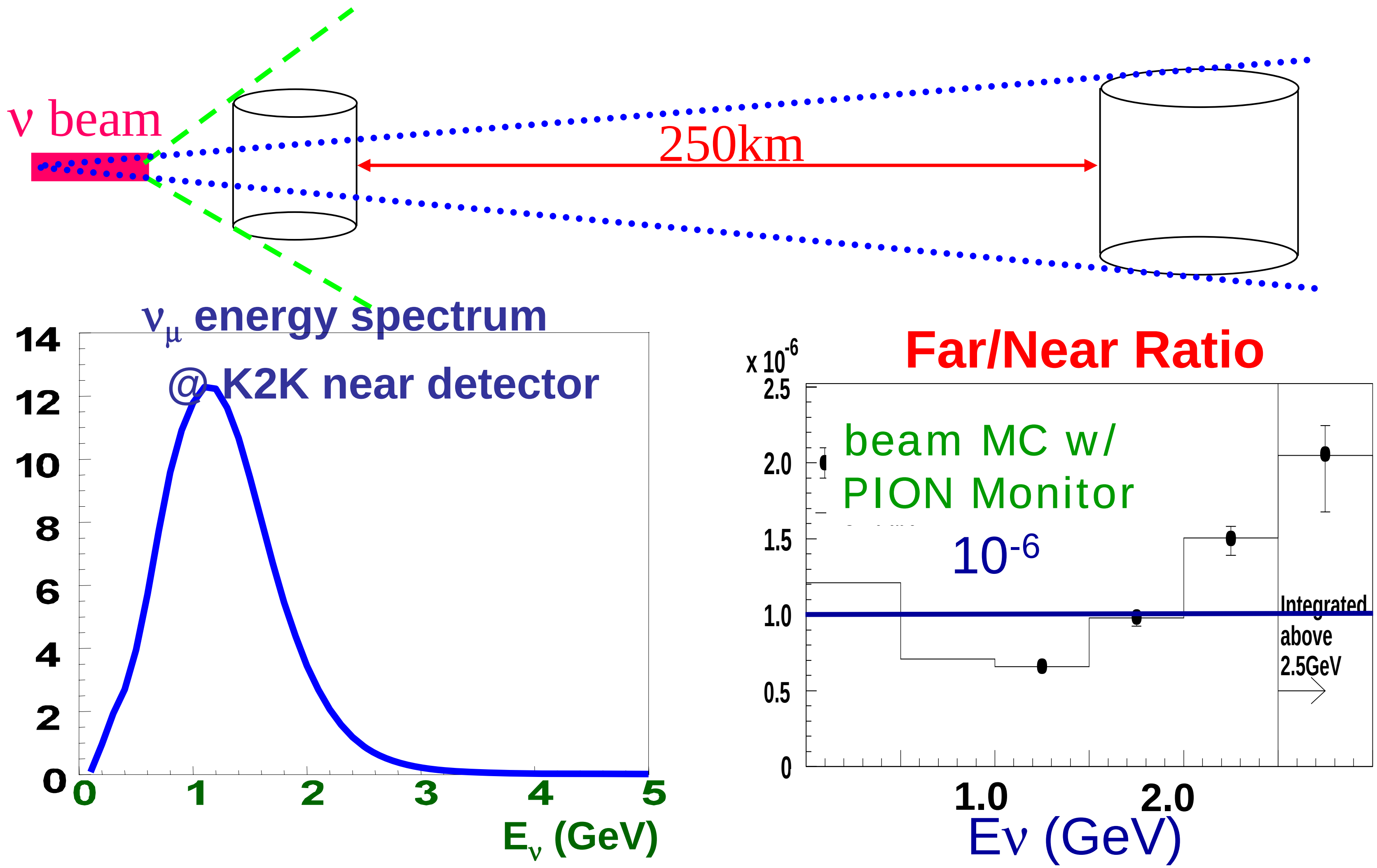
The nQE/QE error of 10% is assigned based on the variation by the fit condition.

θ>10°(20 °) cut: nQE/QE=0.95 ±0.04

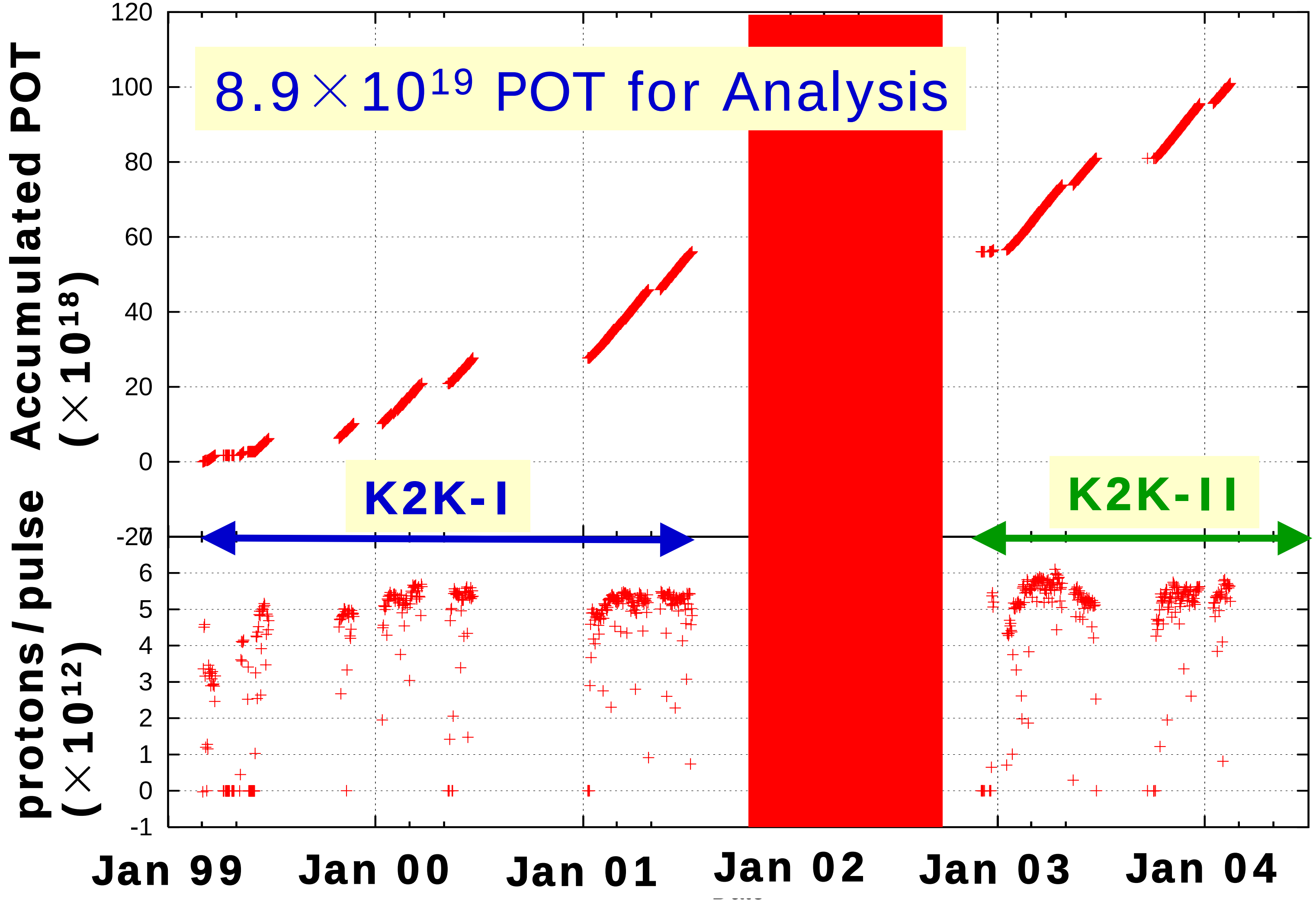
- **standard(CC-1π low q^2 corr.): nQE/QE=1.02 ±0.03**
- **No coherent: π=nQE/QE=1.06 ±0.03**



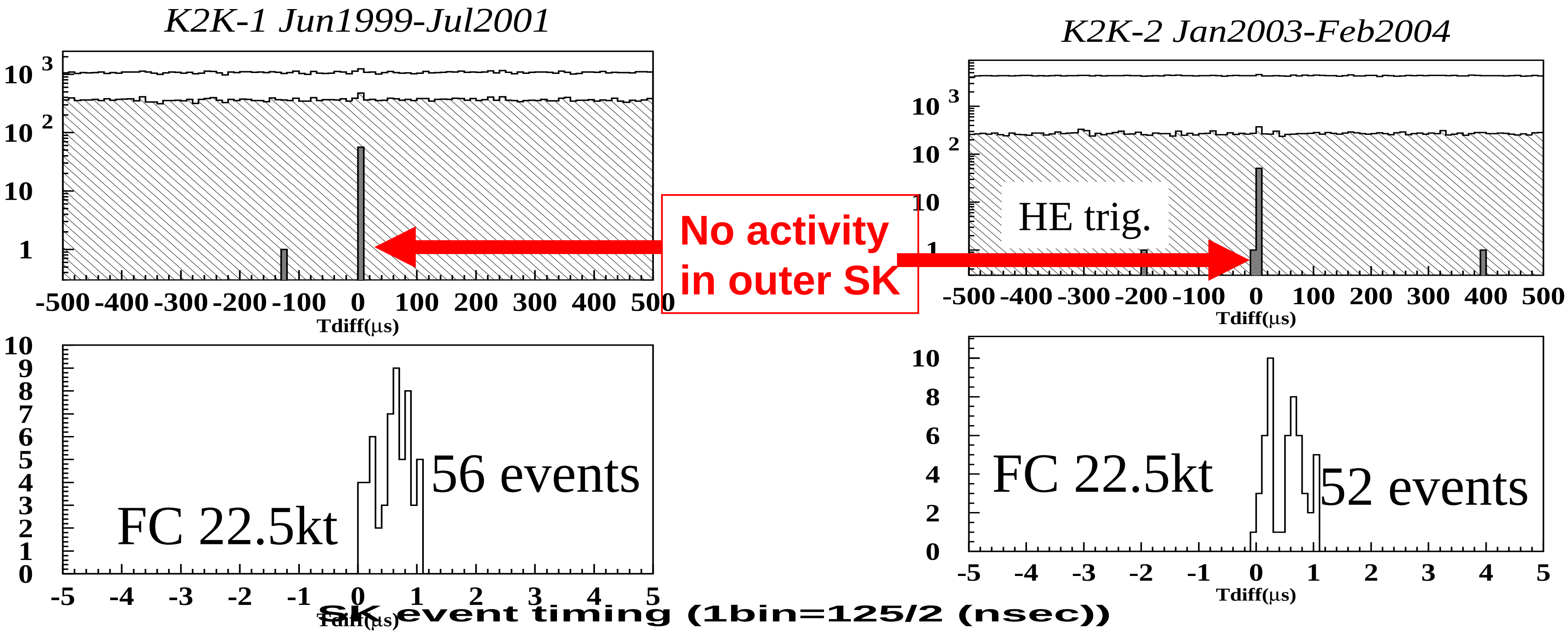
Neutrino spectrum and the far/near ratio

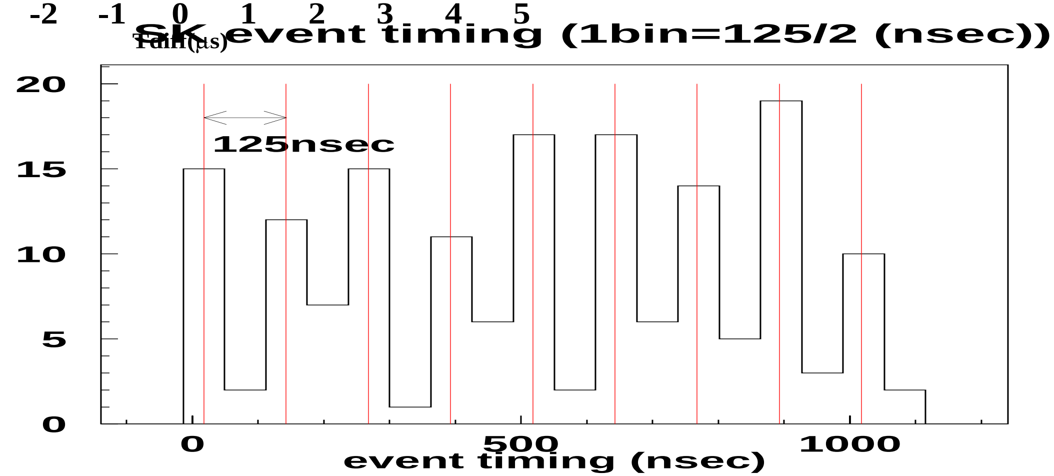


Accumulated POT (Protons On Target)



Selection of SK events : $T_{SK}^{GPS} - T_{acc}^{GPS}$ -TOF





No atm bkg.

$\sigma_t \sim 30$ nsec

1KT Flux measurement

- **The same detector technology as Super-K.**
  (same response for each interaction)

Sensitive to low energy neutrinos.

$$N_{SK}^{exp} = N_{KT}^{obs} \bullet \frac{\int \Phi_{SK}(E_\nu)\sigma(E_\nu)dE_\nu}{\int \Phi_{KT}(E_\nu)\sigma(E_\nu)dE_\nu} \bullet \frac{M_{SK}}{M_{KT}} \bullet \frac{\varepsilon_{SK}}{\varepsilon_{KT}}$$

≡Far/Near Ratio (by MC)~1×10^{-6}

M: Fiducial mass M_{SK}=22,500ton, M_{KT}=25ton

ε: efficiency $\varepsilon_{SK-I(II)}$=77.0(78.2)%, ε_{KT}=74.5%

$N_{SK}^{expect}=150.9\,^{+11}_{-10}$ ⟺ $N_{SK}^{obs}=107$

K2K-SK events

K2K-all (K2K-I, K2K-II)	DATA (K2K-I, K2K-II)	MC (K2K-I, K2K-II)
FC 22.5kt	**107** (55, 52)	**150.3** (78.5, 71.8)
1ring	**66** (32, 34)	**93.7** (48.6, 45.1)
μ-like for E_ν^{rec}	**57** (30, 27)	**84.8** (44.3, 40.5)
e-like	**9** (2, 7)	**8.8** (4.3, 4.5)
Multi Ring	**42** (24, 18)	**57.2** (30.5, 26.7)

Ref; K2K-I(47.9×10^{18}POT), K2K-II(41.2×10^{18}POT)

Super-K oscillation analysis

- Total Number of events
- E_ν^{rec} spectrum shape of FC-1ring-μ events
- Systematic error term

$$L(\Delta m^2, \sin 2\theta, f^x)$$

$$= \underline{L_{norm}(\Delta m^2, \sin 2\theta, f^x)} \cdot \underline{L_{shape}(\Delta m^2, \sin 2\theta, f^x)} \cdot \underline{L_{syst}(f^x)}$$

f^x : Systematic error parameters

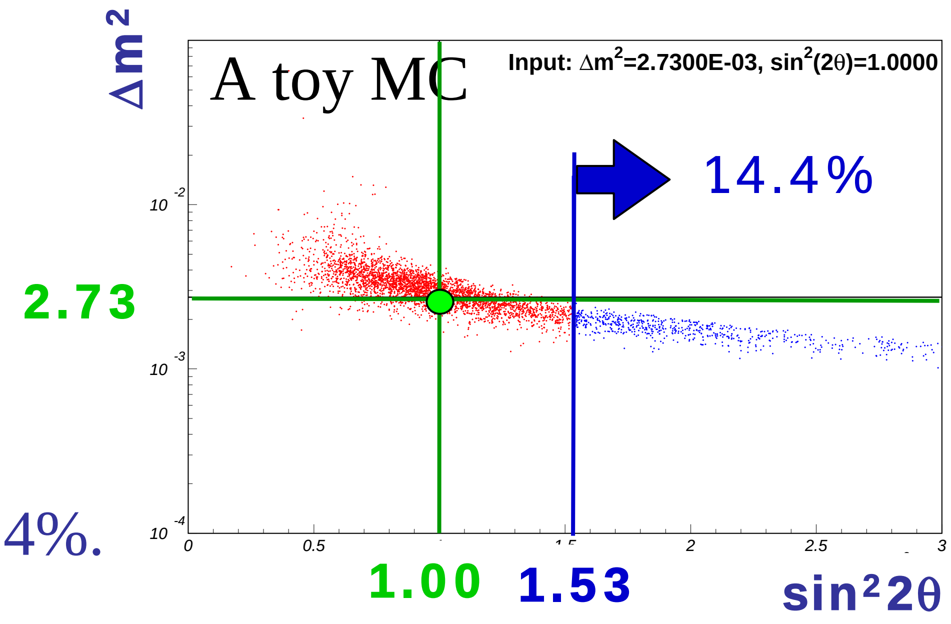
Normalization, Flux, and nQE/QE ratio are in f^x

Near Detector measurements, Pion Monitor constraint, beam MC estimation, and Super-K systematic uncertainties.

Results

- Best fit values.
  - $\sin^2 2\theta = 1.53$
    Δm^2 [eV^2] = 2.12×10^{-3}
- Best fit values in the physical region.
  - $\sin^2 2\theta =$ **1.00**
    Δm^2 [eV^2] = **2.7910^{-3}**

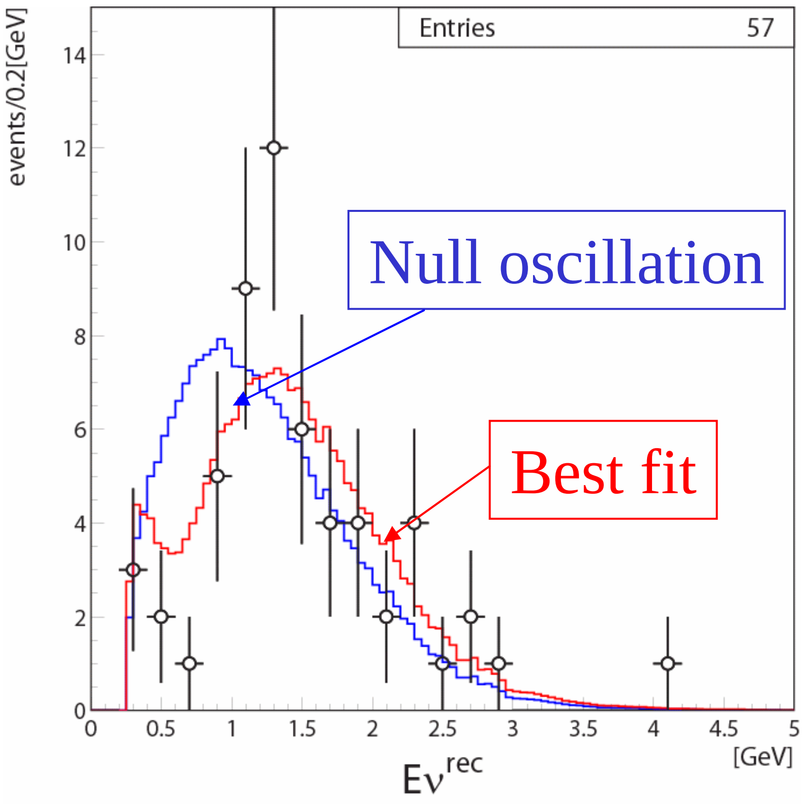
$\Delta\log\boldsymbol{L}$=0.64



$\sin^2 2\theta$=1.53 can be occurred
by statistical fluctuation with 14.4%.

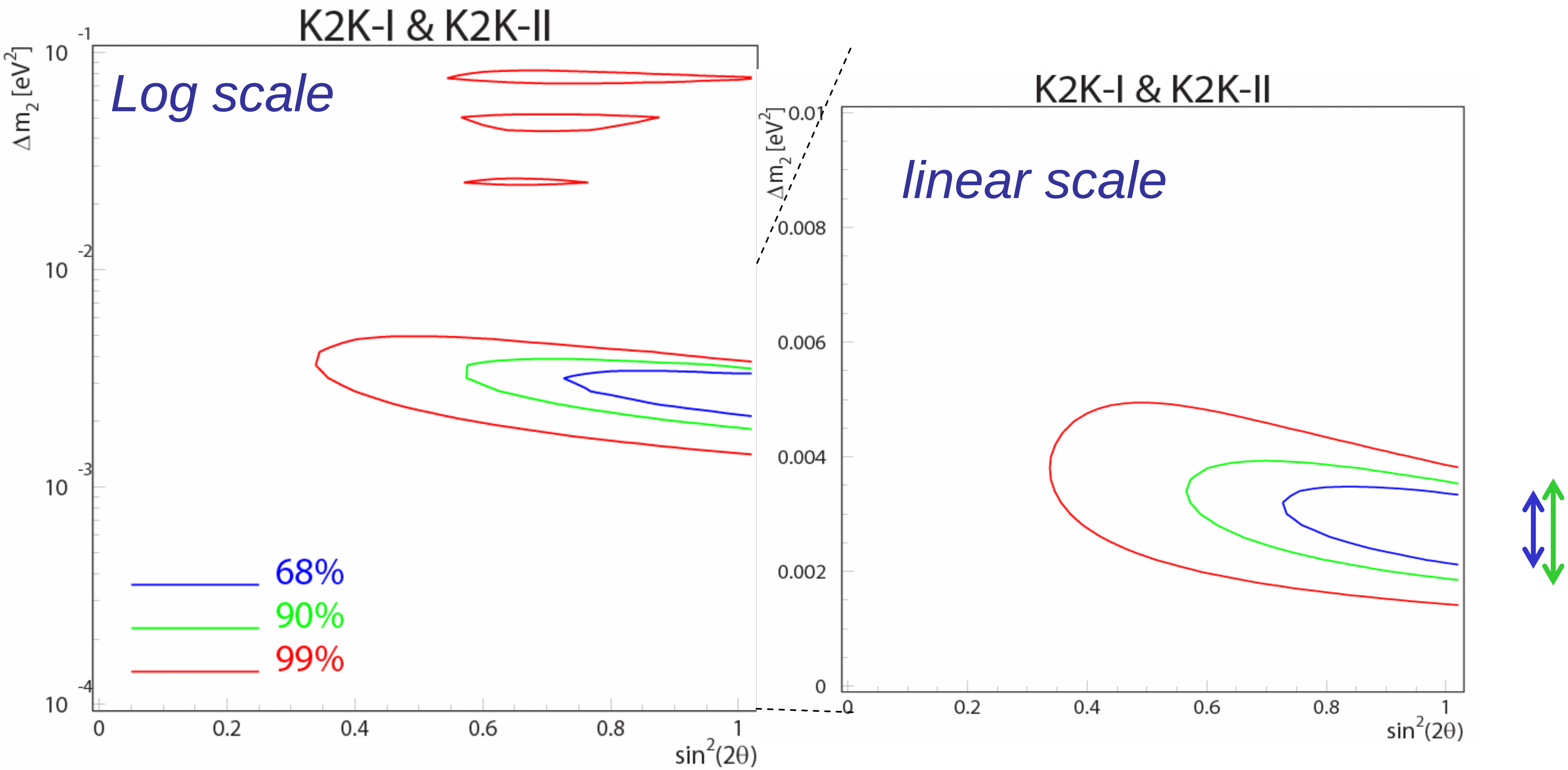
Best fit in Physical region

K2K-I+ K2K-II



- Best fit value
  - $\sin^2 2\theta = 1.00$
    $\Delta m^2\,[eV^2] = (2.79 \pm 0.36)\times 10^{-3}$
- # of FCFV events
  - Nexp = 103.8
    ←→ Nobs(Jun,99)=107
- KS-test probability: data & fit result: 36%

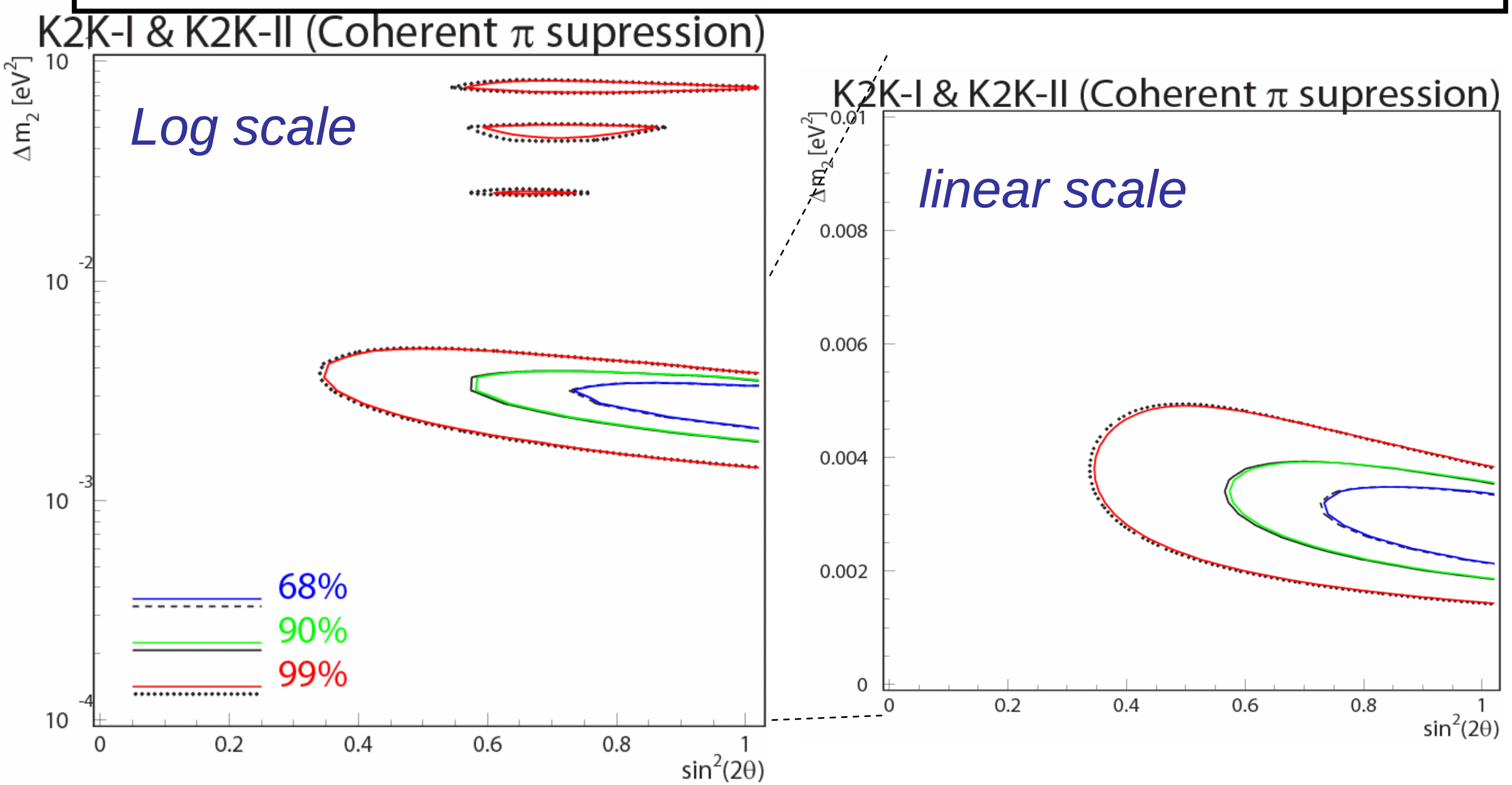
Allowed region



Δm^2 @ $\sin^2 2\theta=1$: 68% … $2.14\times10^{-3} \leq \Delta m^2 \leq 3.37\times10^{-3}$ [eV²]

90% … $1.87\times10^{-3} \leq \Delta m^2 \leq 3.58\times10^{-3}$ [eV²]

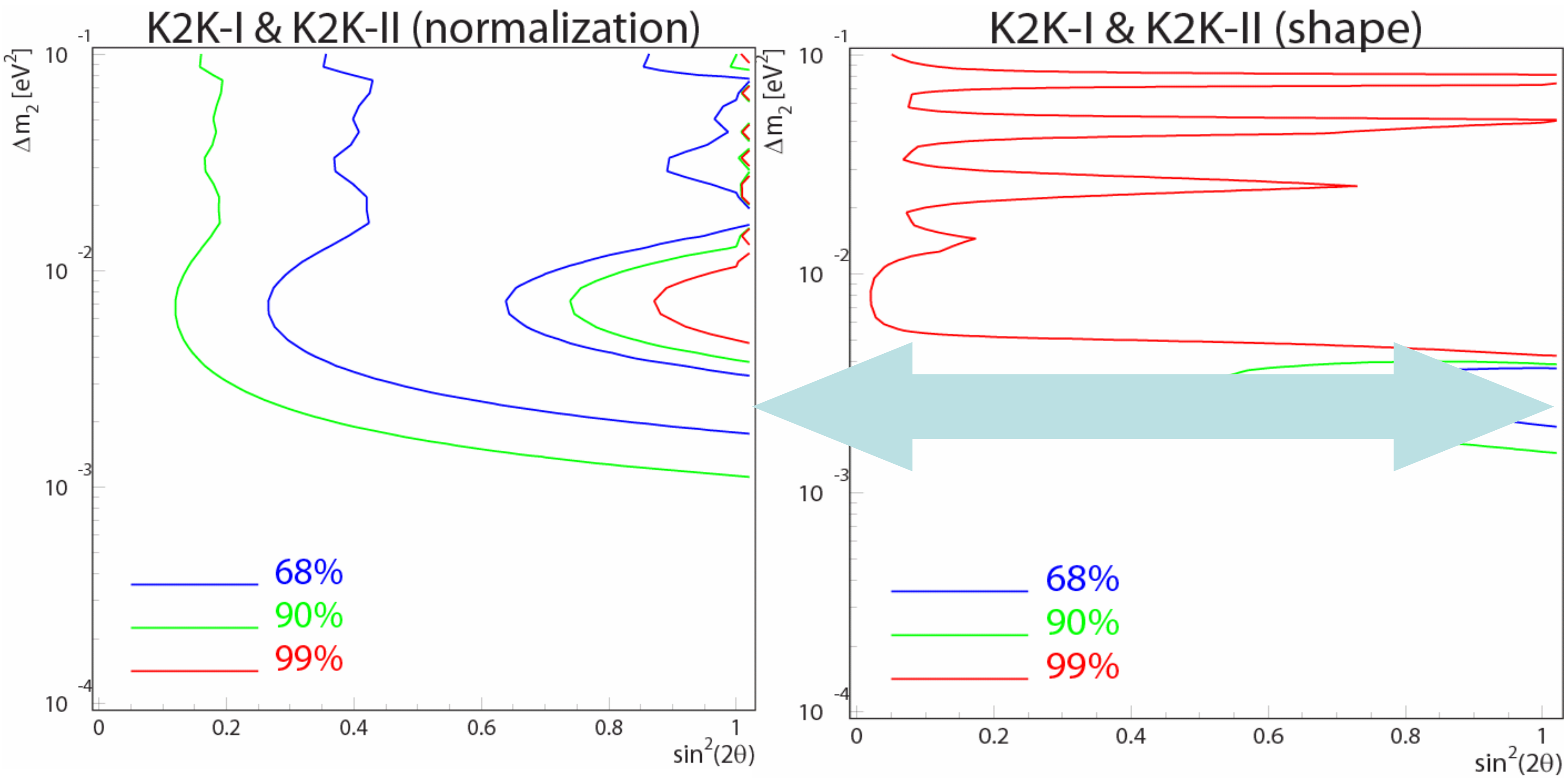
Model dependence (if Coherent-π suppression)



Color: Coherent-π suppression → Null Osci. prob. = 0.0044%(4.08σ)

Mono: CC-1π suppression (Official method) [0.0050%(4.06σ)]

Allowed regions



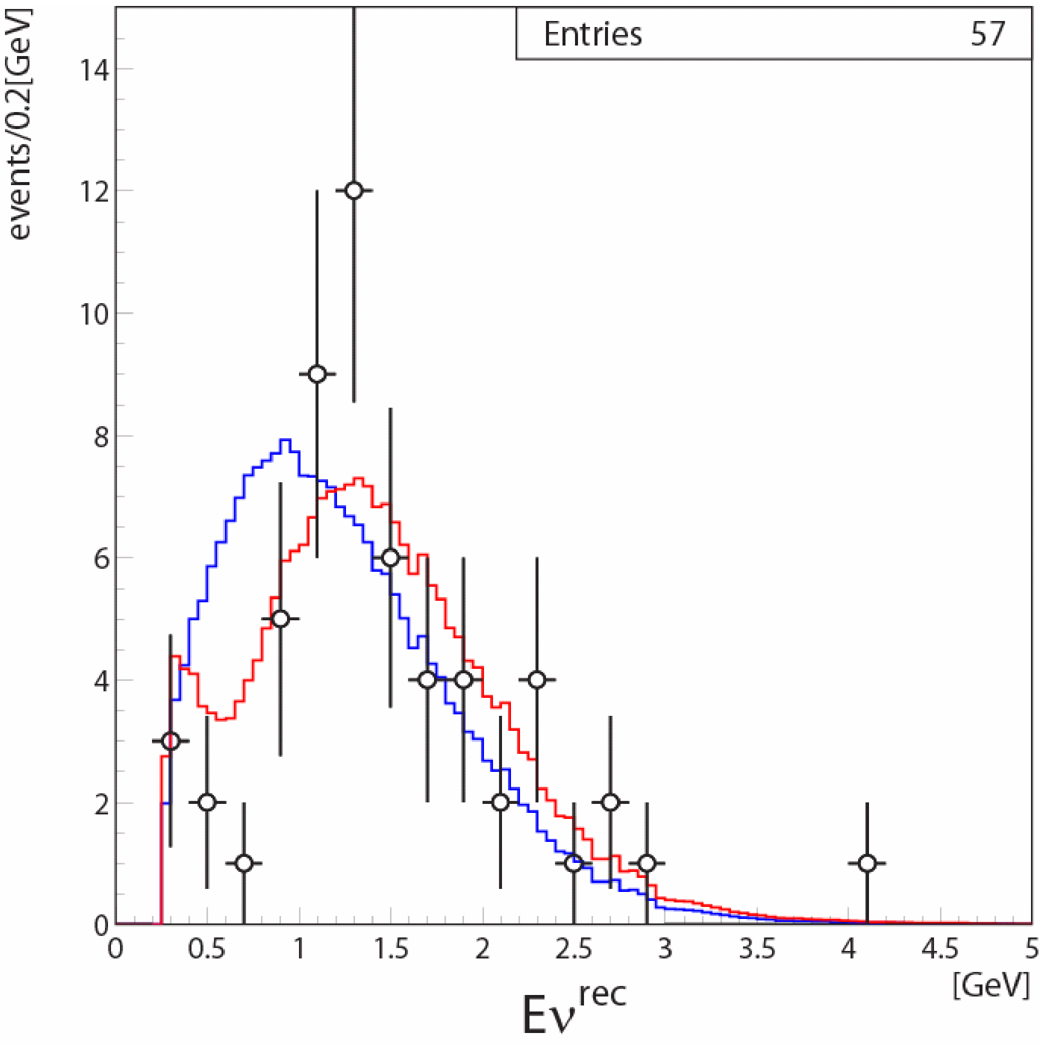
Null oscillation probability

	K2K-I	K2K-II	K2K-I+II
number of events	1.4%	3.7%	0.26%(3.0σ)
E_ν spectrum distortion	12.0%	5.8%	0.74% (2.6σ)
Combined	0.58% (2.7σ)	0.56% (2.7σ)	**0.005%** (4.0σ)

K2K confirmed ***neutrino oscillation*** *discovered in Super-K atmospheric neutrinos.*

The νμ deficiency is consistent with oscillation

But, for future



Far/Near (E_ν)

Cross sections
  Near spectrum
  Spill over to LE

Need improvements for higher statistics and higher precision exp.

Kamland L/E

Contribution of each systematic errors

- N_{SK}^{exp} (Null Oscillation)…150.9 $^{+11.5}_{-10.1}$
  - K2K-I … 79.1 $^{+6.1}_{-5.4}$
  - K2K-II … 71.8 $^{+5.9}_{-5.1}$

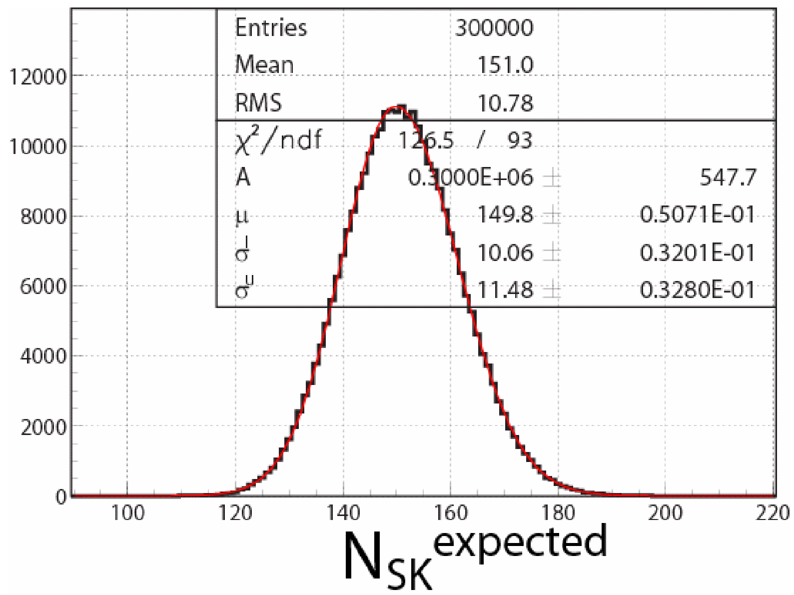
HARP results !

Studies of interaction in SciBar

	Error	(relative error)
Far/Near	+7.7	(+5.1%)
	-7.5	(-5.0%)
Normalization	+7.6	(+5.0%)
(1KT fid.)	-7.7	(-5.1%)
NC/CC-QE,	+0.7	(+0.5%)
CC-nQE/QE	-0.8	(-0.5%)
ND spectrum	+1.0	(+0.7%)
	-0.9	(-0.6%)

Toy MC (NULL oscillation)

All systematic error included



Activities before T2K

Fiscal yr	2004	2005	2006	2007	2008
K2K data taking					
Full paper on oscillation incl. νe					
Analysis of neutrino interactions					
SK full rebuild					
SK3 analysis tool					
T2K construction and commissioning					
?					

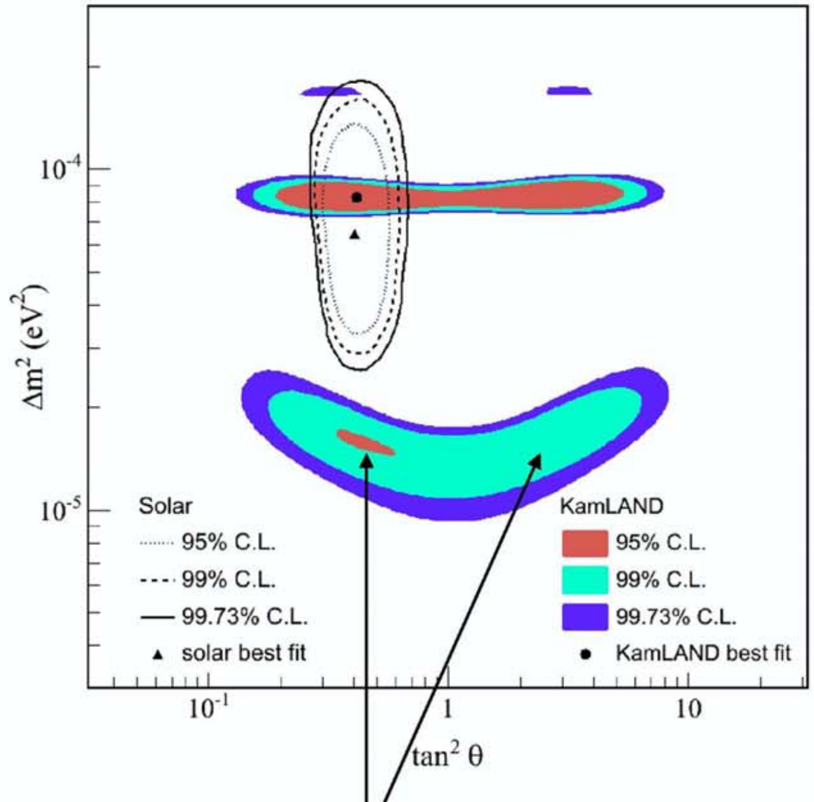
Solar Neutrinos

- Using Deuterium (SNO) allowed separate measurements of νe CC, NC ($\nu e+\nu\mu+\nu\tau$), ν +e ($\nu\varepsilon+1/6(\nu\mu+\nu\tau)$)
  - Total ν flux agree with SSM
  - $\nu\mu$, $\nu\tau$ component in solar ν
- Energy dependence of deficiency
  - No observation of ^{8}B spectrum distortion （SK, SNO)
    - Asumming ^{8}B β–decay spectrum
  - No observation of Day/Night effect
    - earth matter effect (regeneration of νe)
  - overall fit with Ga (E>0.3 MeV), Cl (E>0.7 MeV) and SK, SNO (E>5MeV)
    - Asumming Solar model

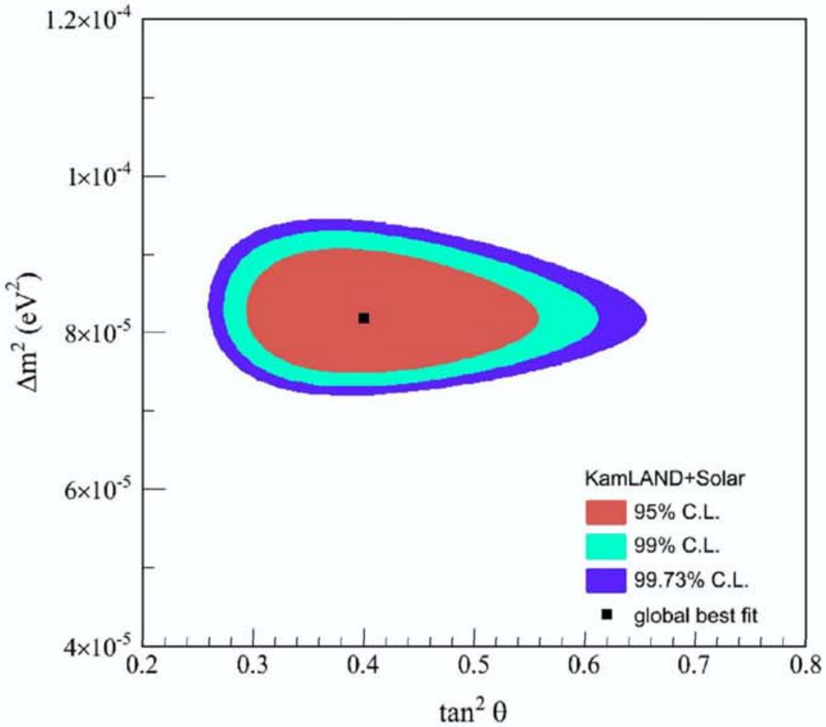
Combined solar ν – KamLAND 2-flavor analysis

$$\Delta m^2_{12} = 8.2^{+0.6}_{-0.5} \times 10^{-5}\, eV^2$$

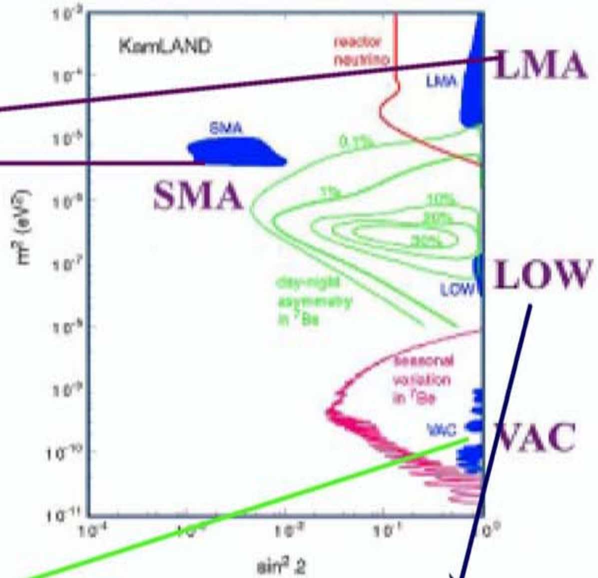
$$\tan^2\theta_{12} = 0.40^{+0.09}_{-0.07}$$



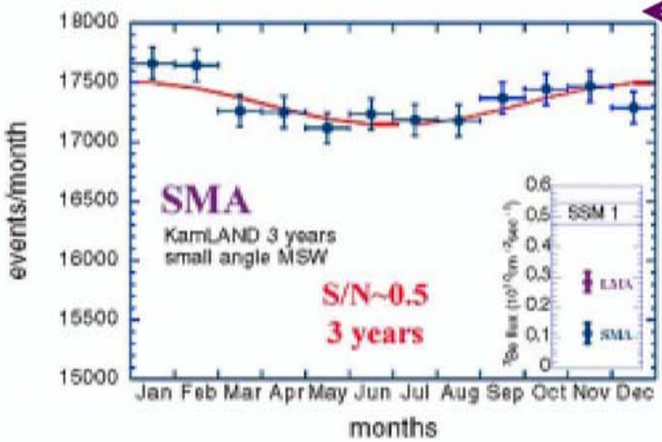
Includes (small) matter effects



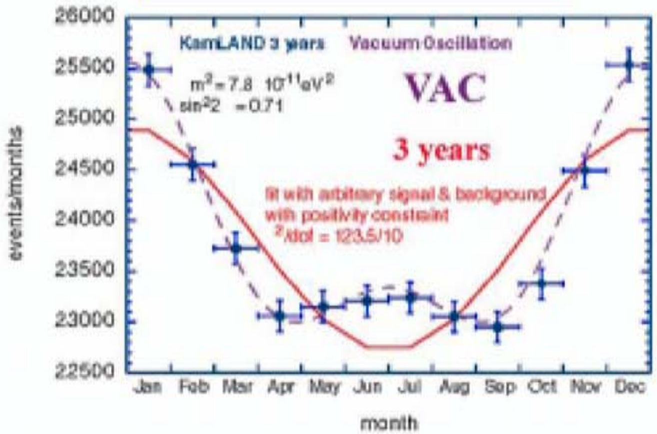
Physics 1 : Reconfirmation of Oscillation Solution



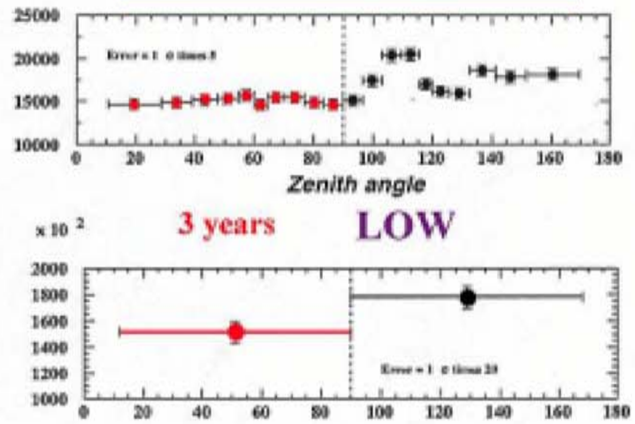
Seasonal Variation



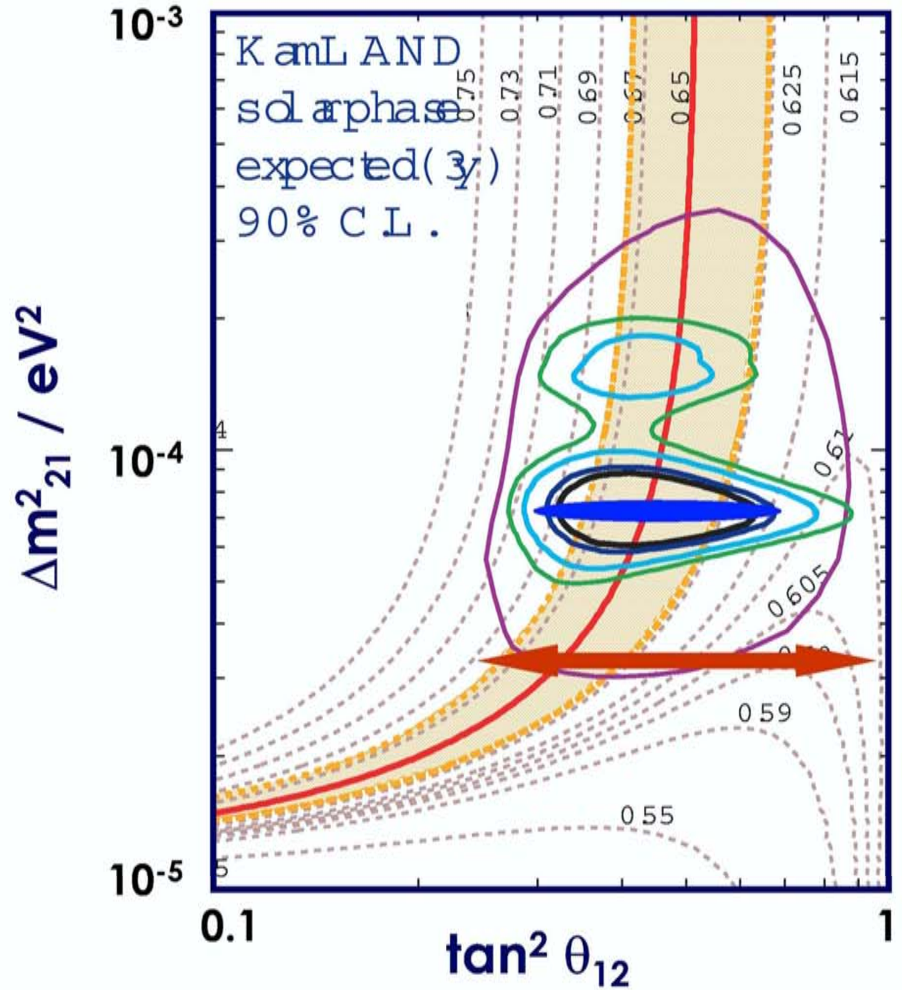
Just So Resonance



Day / Night Variation



Physics 2 : Determination of Θ_{12} ?



A.Bandyopadhyay et al., hep-ph/0302243 (2003)

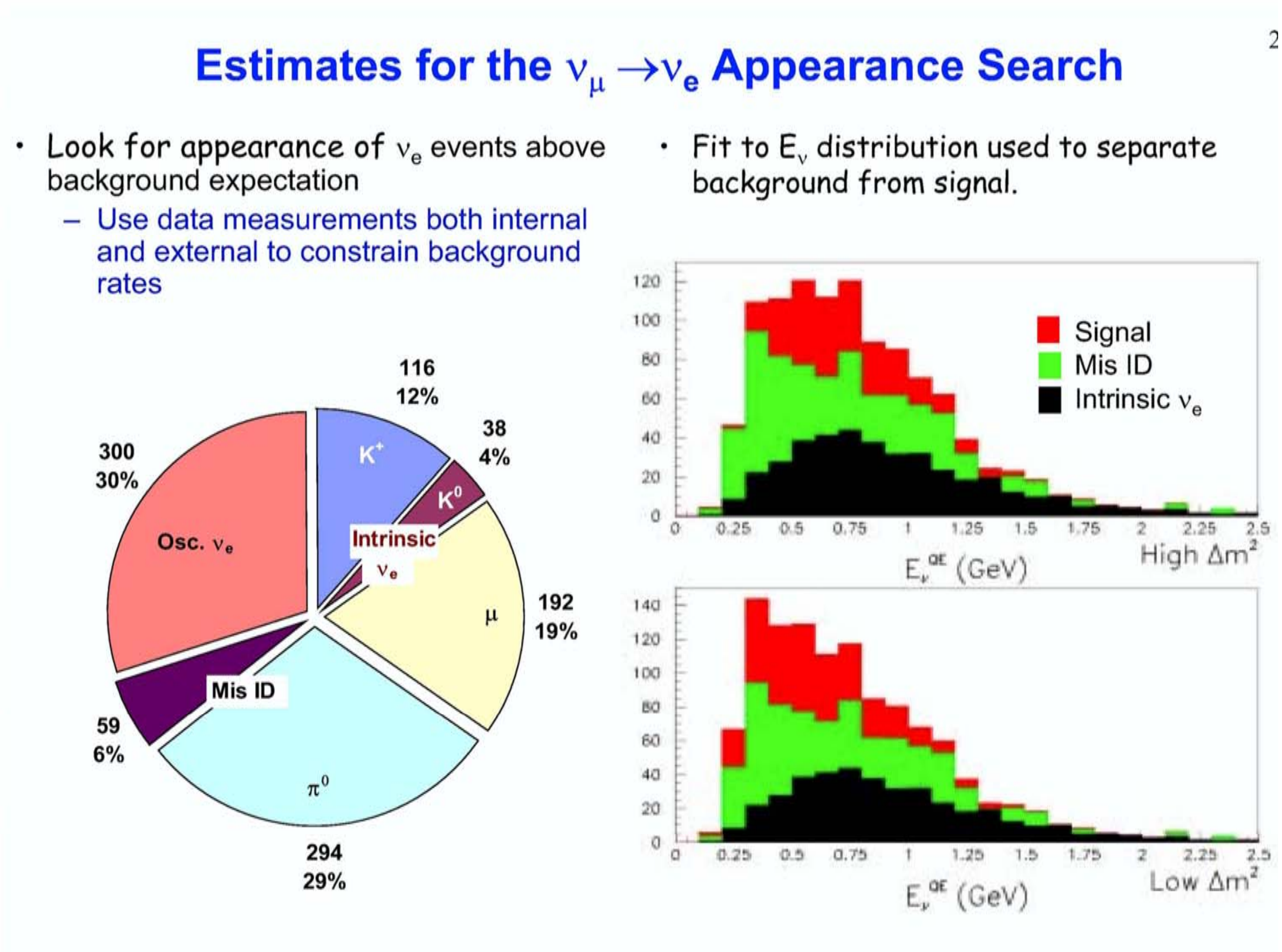
KamLAND reactor

flux uncertainties ± 10 %

Critical path for future oscillation experiment

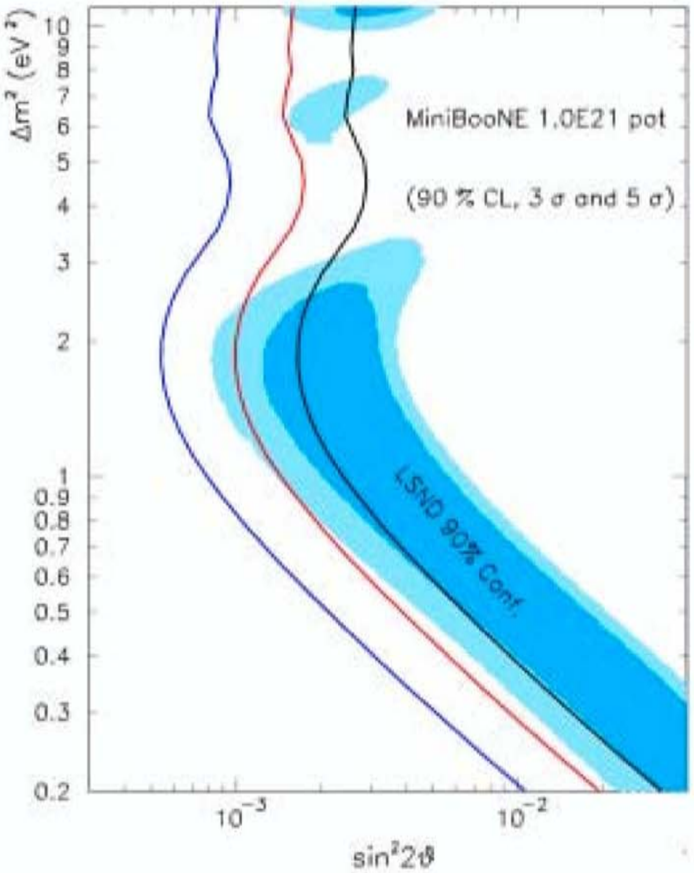
- Confirmations
  - Atmospheric ν K2K
  - Solar ν (Kamland)
  - νμ →ντ confirmation
- Surprises ?
  - Sterile ν 3 neutrinos cannot accommodate LSND
  - Oscillation pattern(decay, de-coherence, ……)
- Use oscillation as a tool to study lepton sector
  - Precision measurements of θ23 ~π/4?
  - θ13 →CP violation
  - Solar sector θ12, Δm^2_{12}
  - Sign of Δm^2

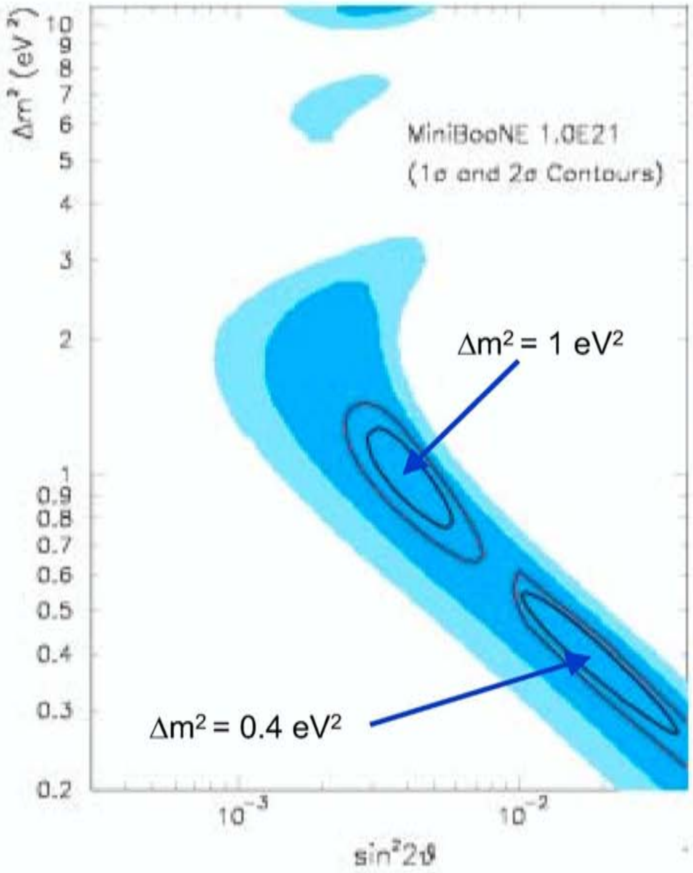
MiniBooNE (will open box in 2005)



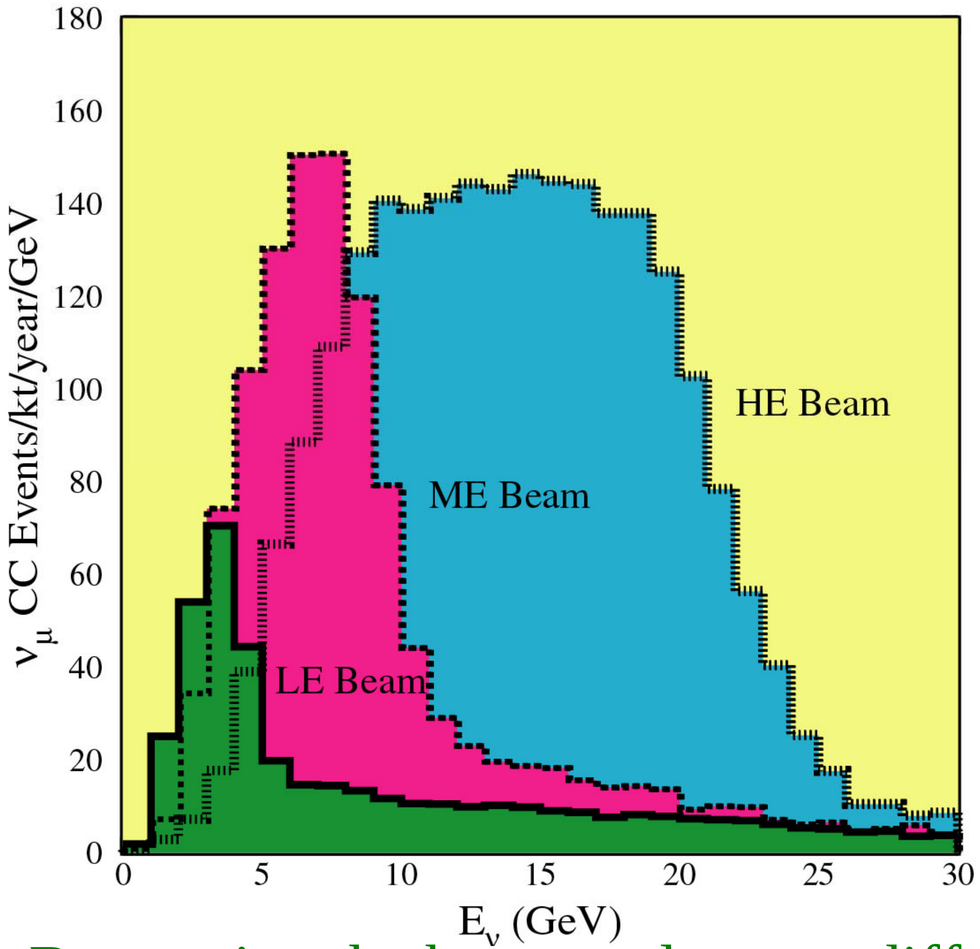
MiniBooNE Oscillation Sensitivity

- Oscillation sensitivity and measurement capability
  - Data sample corresponding to 1×10^{21} pot
  - Systematic errors on the backgrounds average ~5%





The NuMI Neutrino Energy Spectra



ν_μ CC Events/kt/year

Low	Medium	High
470	1270	2740

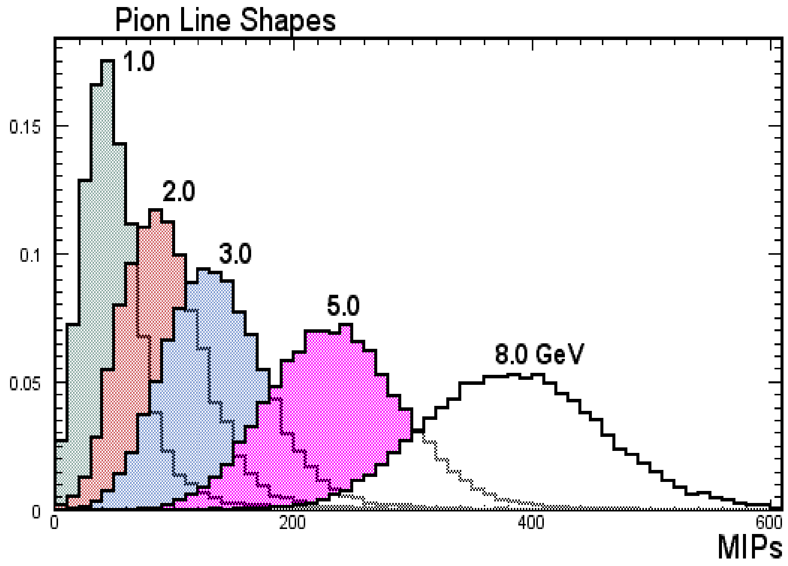
ν_μ CC Events/MINOS/2 year

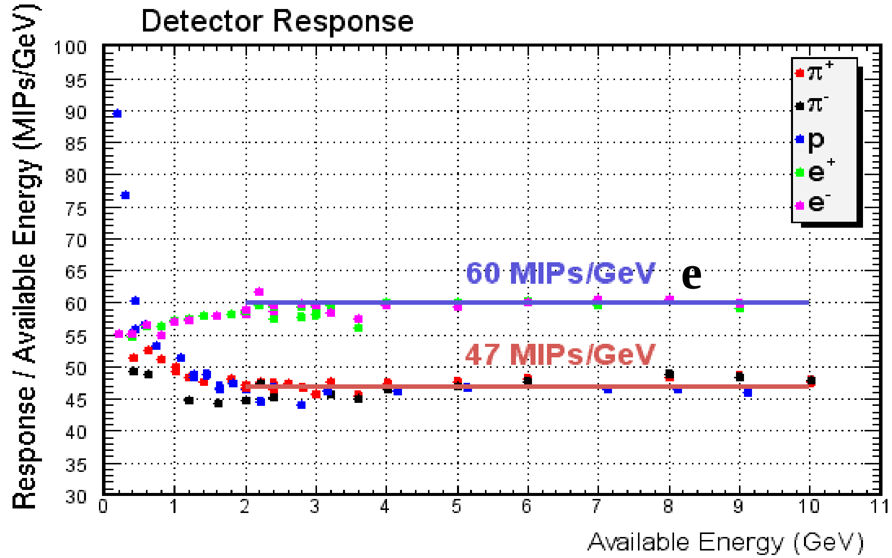
Low	Medium	High
5080	13800	29600

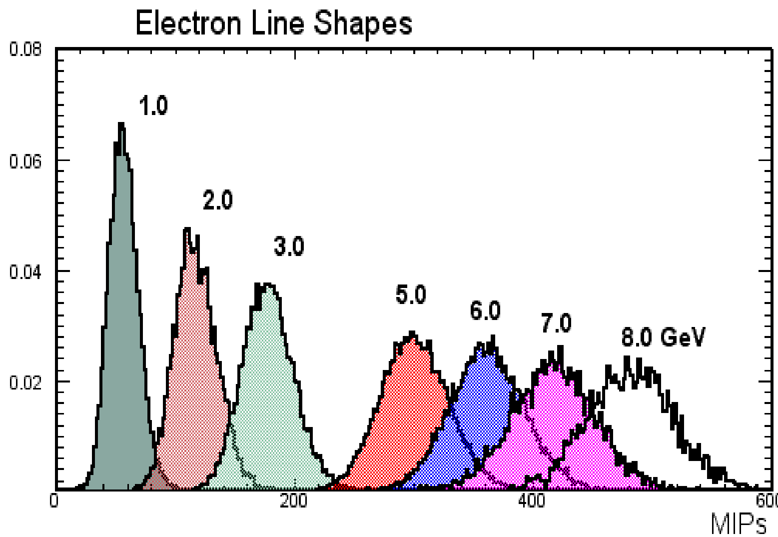
4×10^{20} protons on target/year
4×10^{13} protons/2.0 seconds

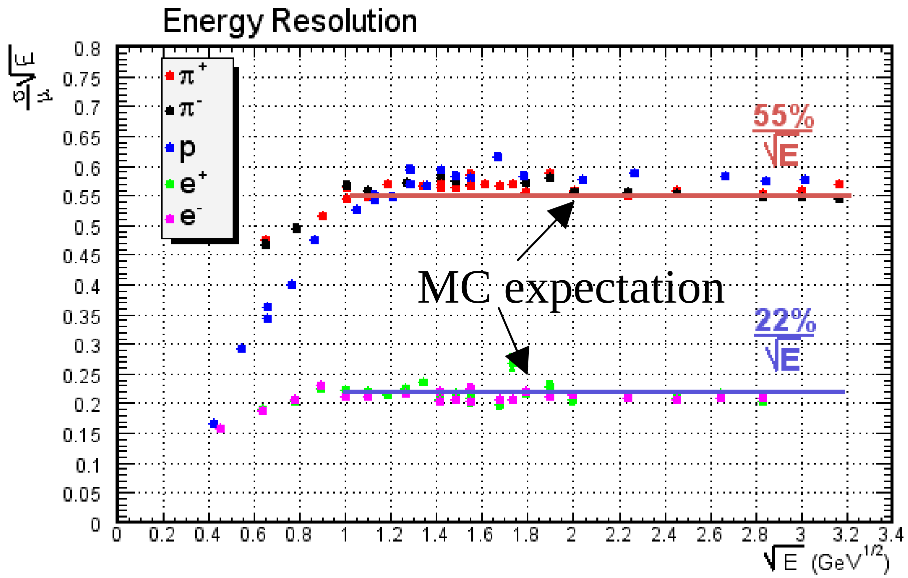
By moving the horns and target, different energy spectra are available using the NuMI beamline. The energy can be tuned depending on the specific oscillation parameters expected/observed.

Particle Response (preliminary)

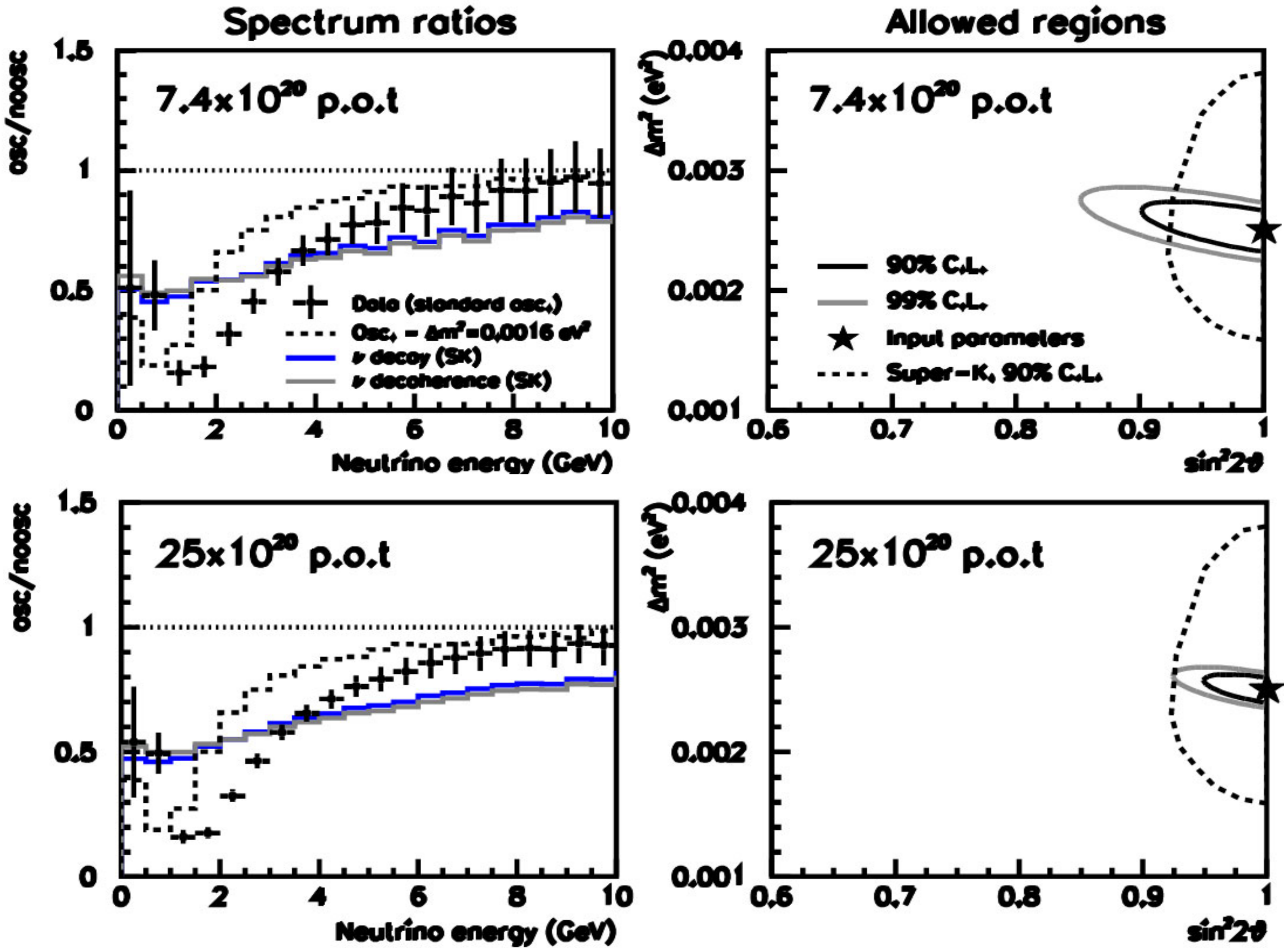








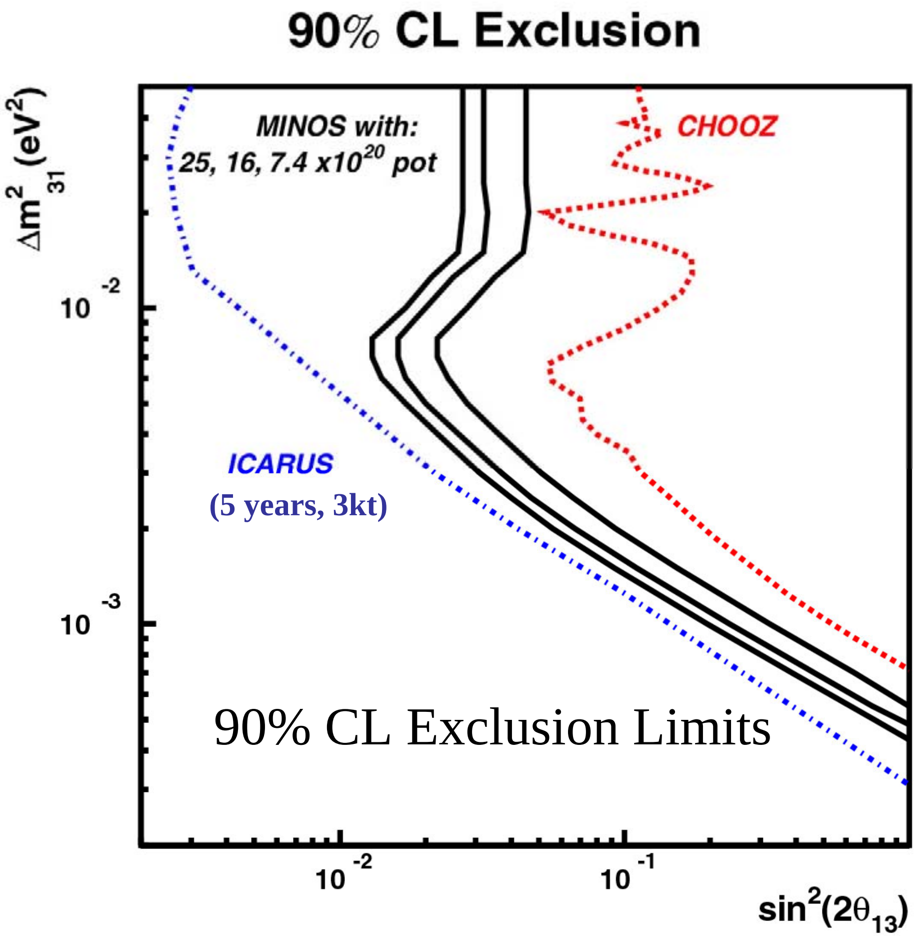
Measurement of Oscillations in MINOS

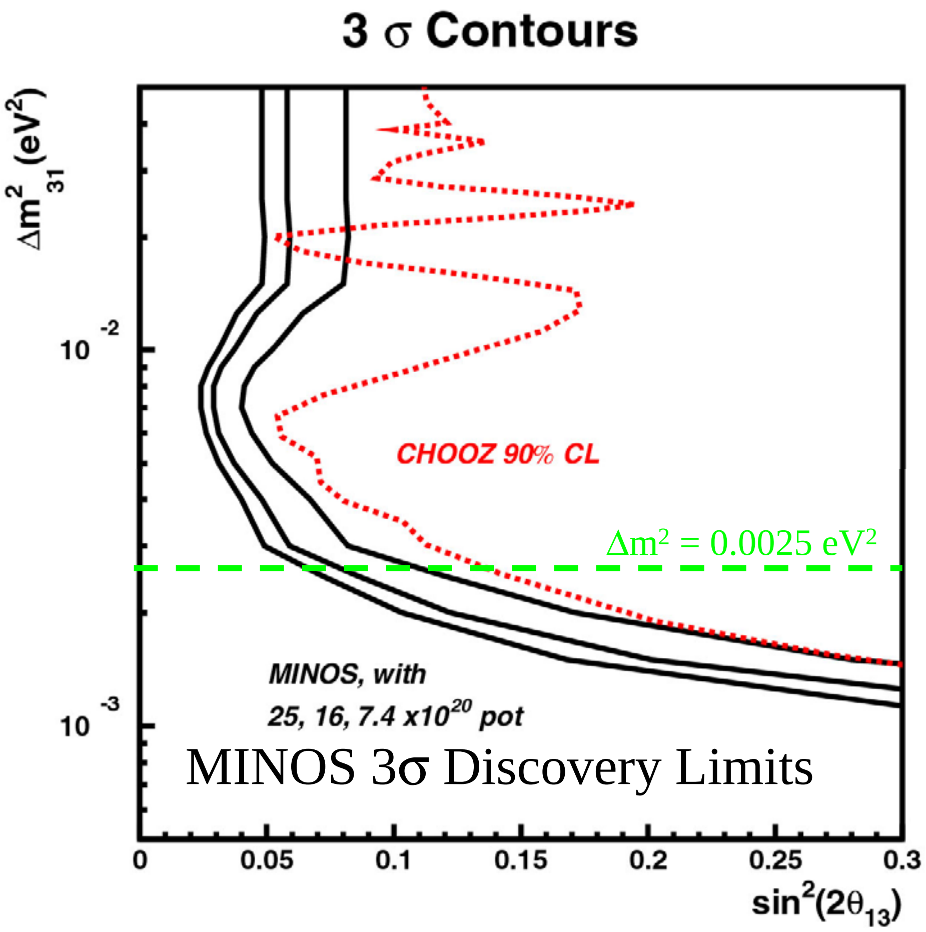


For $\Delta m^2 = 0.0025\ eV^2$, $\sin^2 2\theta = 1.0$

Essential to understand detector response
E resolution   Mis reconstruction to LE

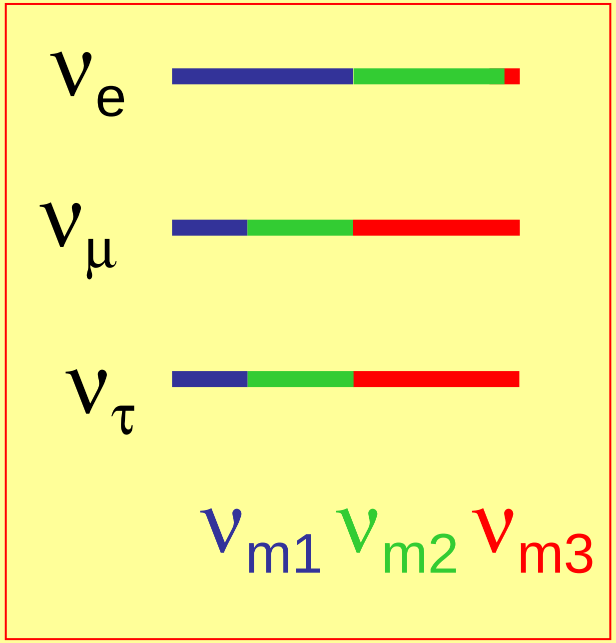
Appearance of Electrons in MINOS





- MINOS sensitivities based on varying numbers of protons on target

- The mixing angles θ_{12}, θ_{23}, θ_{31}, δ ?
  - How small the mixing of 1st and 3rd generation?
    - Does ν_e contain ν_3?
  - Symmetry of 2nd and 3rd generation?
    - How close θ_{23} to $\pi/4$? 3 flavor analysis
  - Is sterile neutrino exist?
    - Fraction in disappearance of ν_μ
  - How large is the phase δ?
    - CP violation in lepton?



- Prepare for un-expected
  - precision measurement of physics quantities

δ : CP Violation in Pure Leptonic process
(Why $\nu_\mu \to \nu_e$)

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{j>i} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2 \frac{(m_j^2 - m_i^2)L}{4E_\nu}$$

$$\mp 2\sum_{j>i} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin \frac{(m_j^2 - m_i^2)L}{2E_\nu}$$

=0 for α=β → appearance exp!

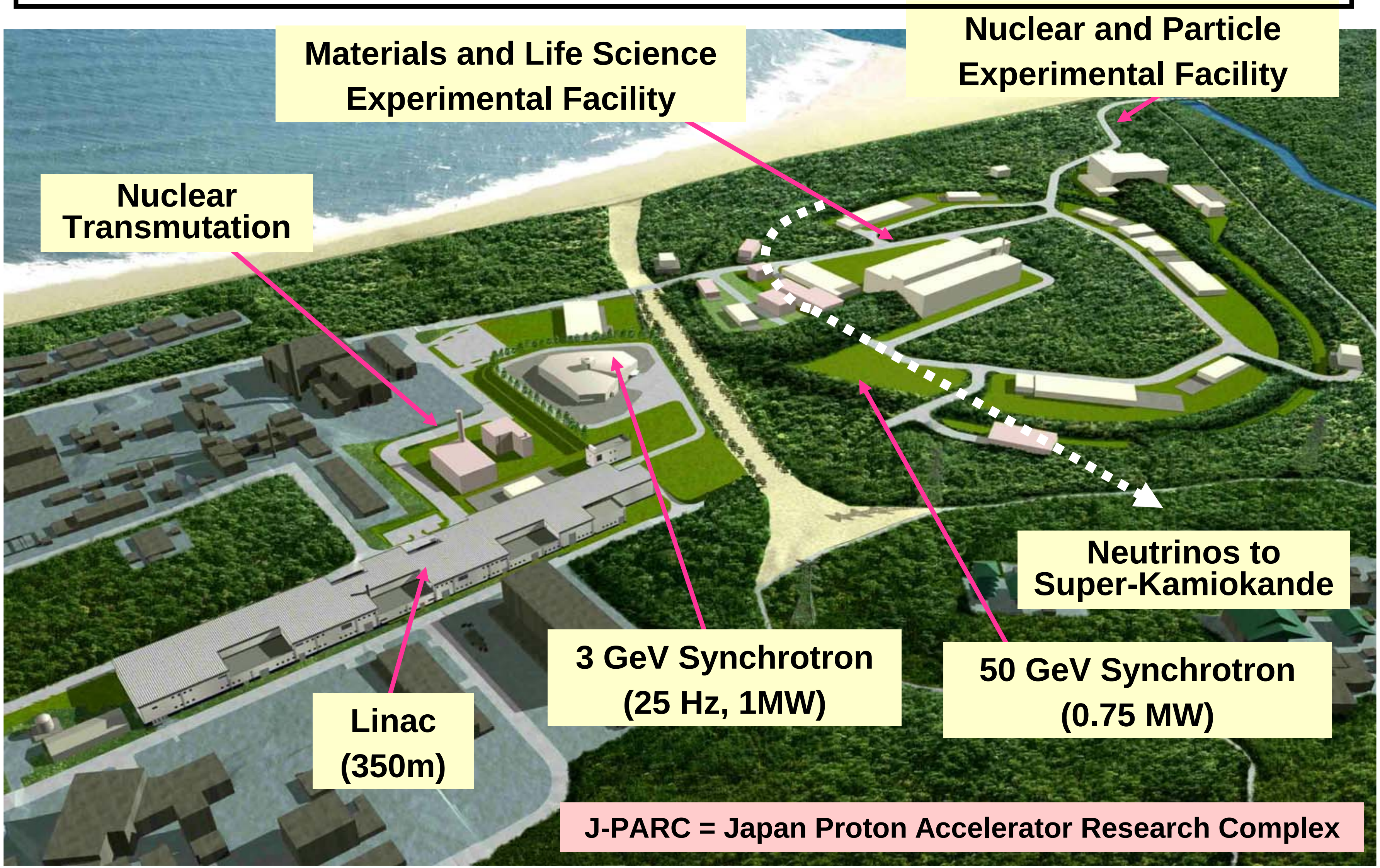
- $\nu_\mu \to \nu_e$

- Recent developments toward CPV search

- CPV ∝ $\sin\theta_{12} \sin\theta_{23} \sin\theta_{13} \Delta m^2_{12}$ (L/E) $\sin\delta$

- Solar LMA solution (large Δm^2_{12}, large θ_{12})
  - Near max. mixing in atmospheric ($\theta_{23} \sim \pi/4$)

J-PARC Facility



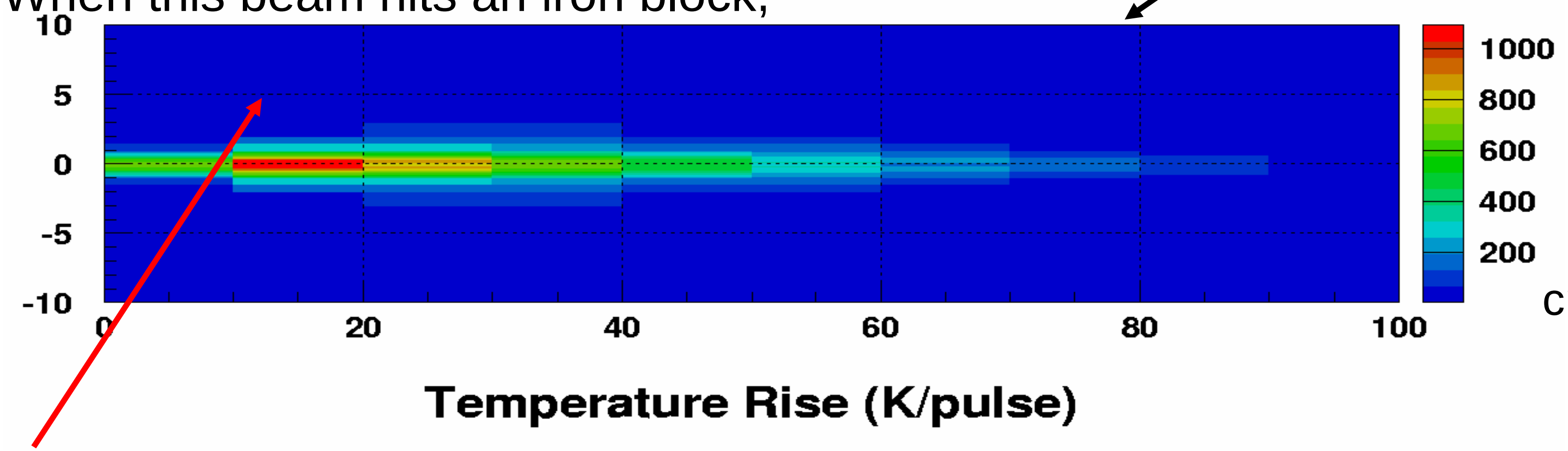
Technological step for high intensity

3.3E14 ppp w/ 5μs pulse

radio activity

> 1000Sv/h

When this beam hits an iron block,



1100^{o}

(cf. melting point 1536^{o})

✓ Material heavier than iron would melt.

✓ Thermal shock stress $\approx E\alpha\Delta T \approx 3GPa$

(cf. stress limit ~300 MPa)

Material heavier than Ti might be destroyed.

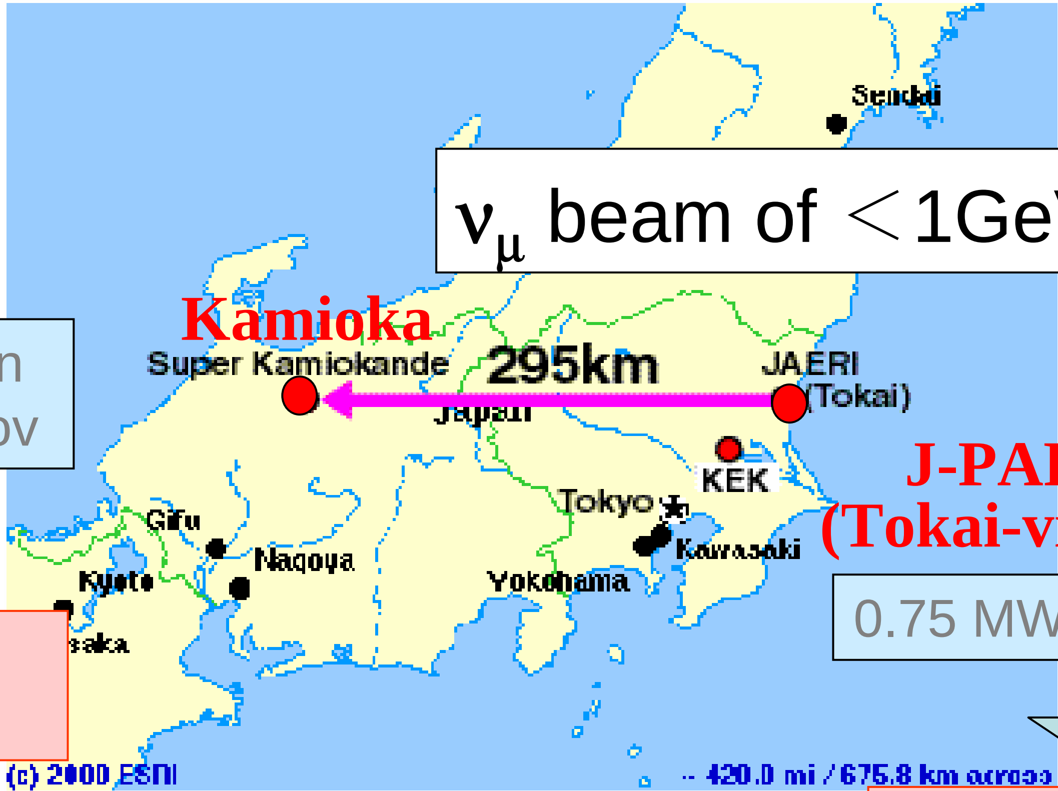
✓ Cooling power and radiation shield

"T2K" (Tokai-to-Kamioka) neutrino experiment

LOI: hep-ex/0106019

Super-K: 50 kton Water Cherenkov

~Mt "Hyper Kamiokande"



ν_μ beam of ＜1GeV

J-PARC (Tokai-village)

0.75 MW 50 (40) GeV PS

4MW 50GeV PS

Approved exp (x10^2 of K2K)

- $\nu_\mu \rightarrow \nu_x$ disappearance
- $\nu_\mu \rightarrow \nu_e$ appearance
- NC measurement

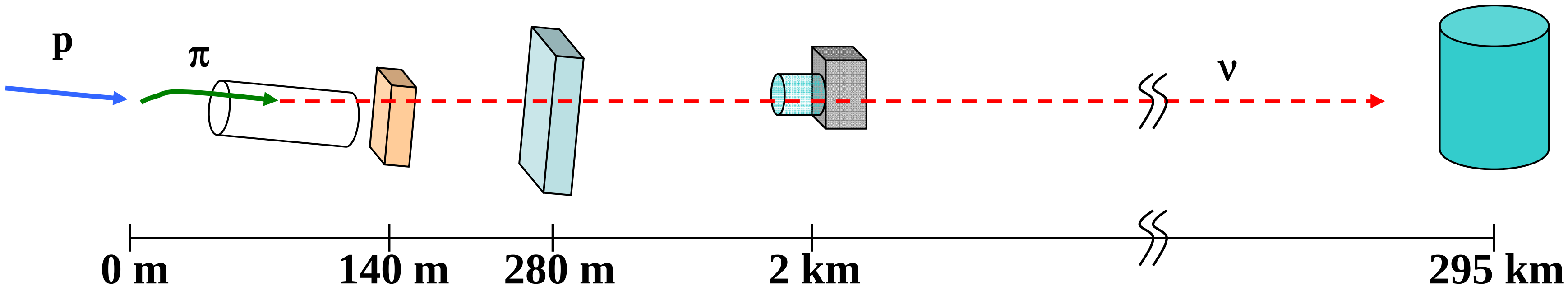
Future Extension

- CP violation
- proton decay

Collaboration

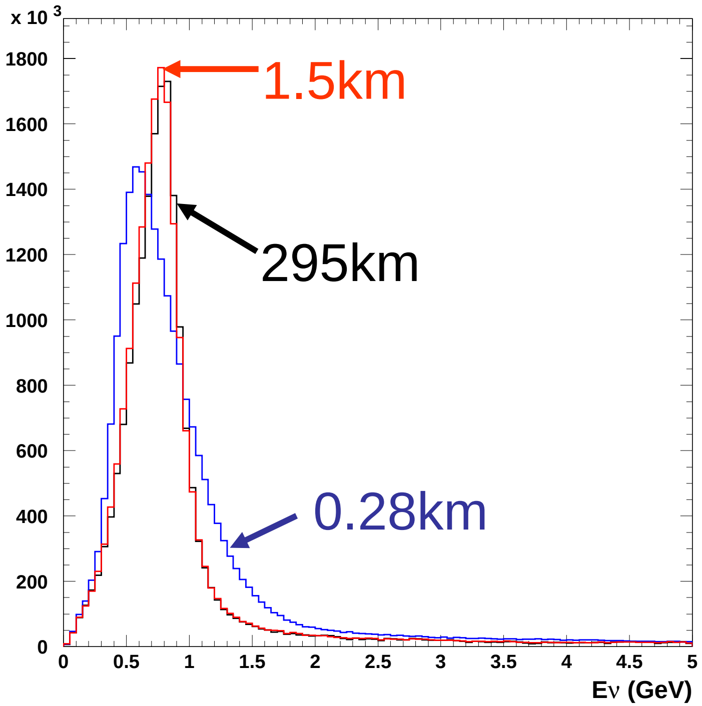
- Formed in May 2003
- 12 countries, 52 institutions
- 148 collaborators (w/o students)


T2K
Tokai-to-Kamioka Neutrino Project
at J-PARC



- Muon monitors @ ~140m
  - spill-by-spill monitoring of π–beam direction/intensity
- First Front detector @280m
  - 0 degree definition
  - High stat. neutrino inter. studies
- (Second Front Detector @ ~2km for future addition)
- Far detector @ 295km
  - Super-Kamiokande (50kt)

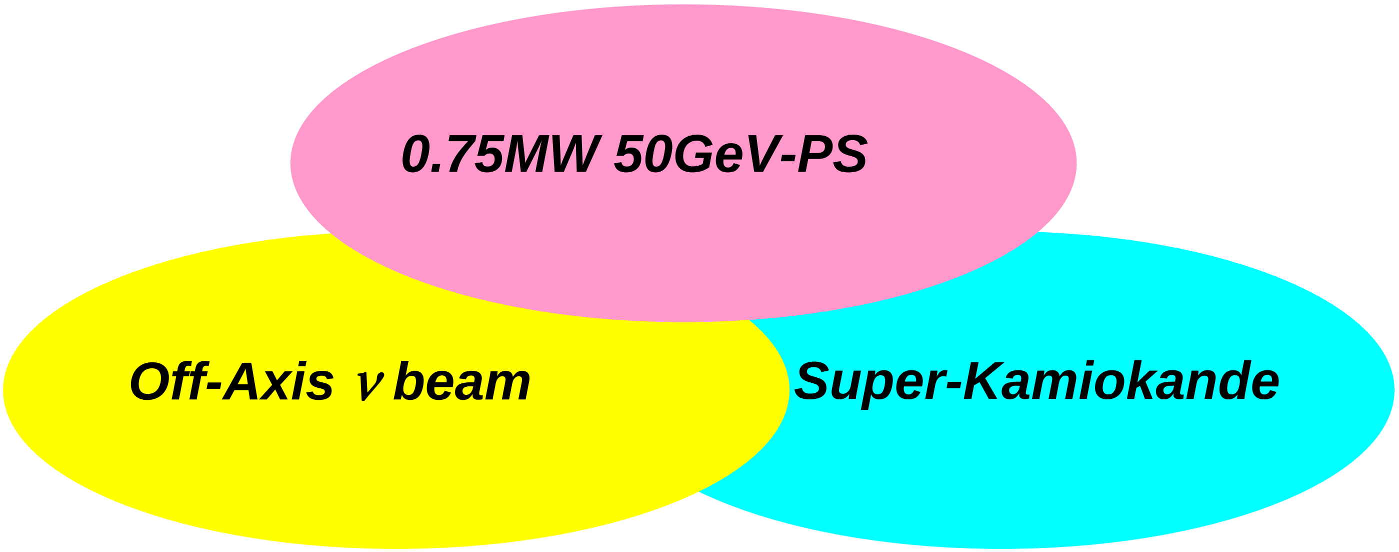
Neutrino spectra at diff. dist



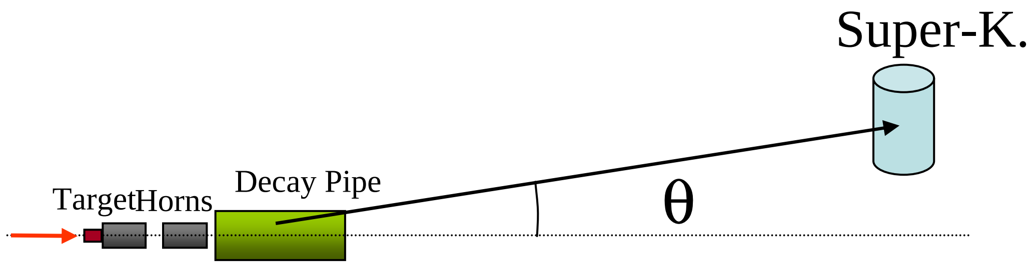
dominant syst. in K2K

Strategy

- High statistics by high intensity ν beam
- Tune Eν at oscillation maximum
- Sub-GeV ν beam
  - Low particle multiplicity suited for Water Cherenkov
  - Good Eν resolution : dominated by $\nu_\mu + n \rightarrow \mu + p$
- Narrow band beam to reduce BG



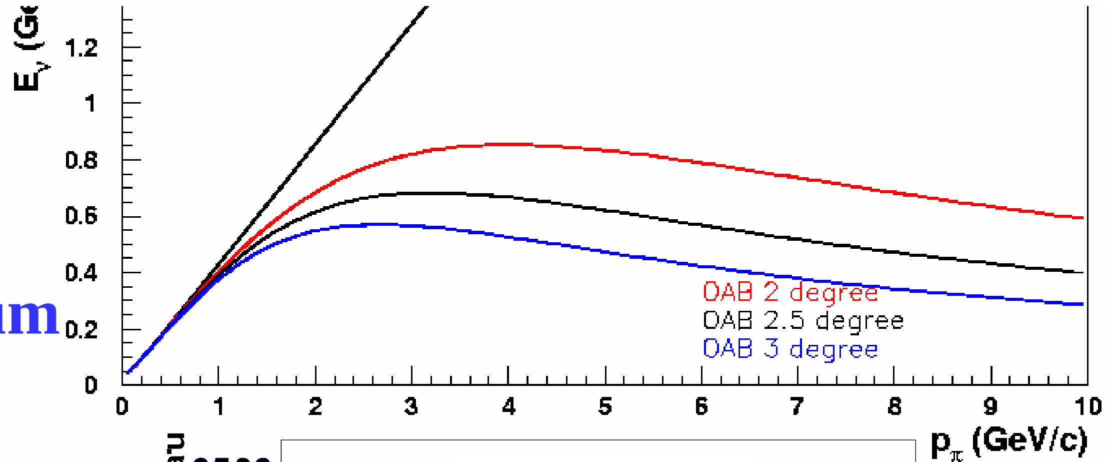
Off Axis Beam



(ref.: BNL-E889 Proposal)

- **Quasi Monochromatic Beam**
- **x 2~3 intense than NBB**

Tuned at oscillation maximum



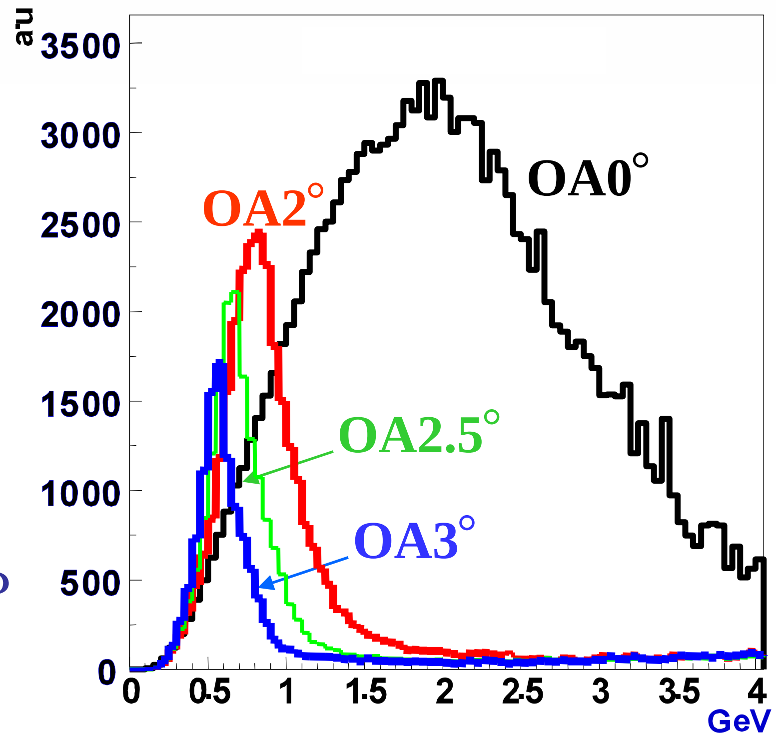
Statistics at SK

(OAB 2.5 deg,1 yr,22.5 kt)

~ 2200 ν_μ tot

~ 1600 ν_μ CC

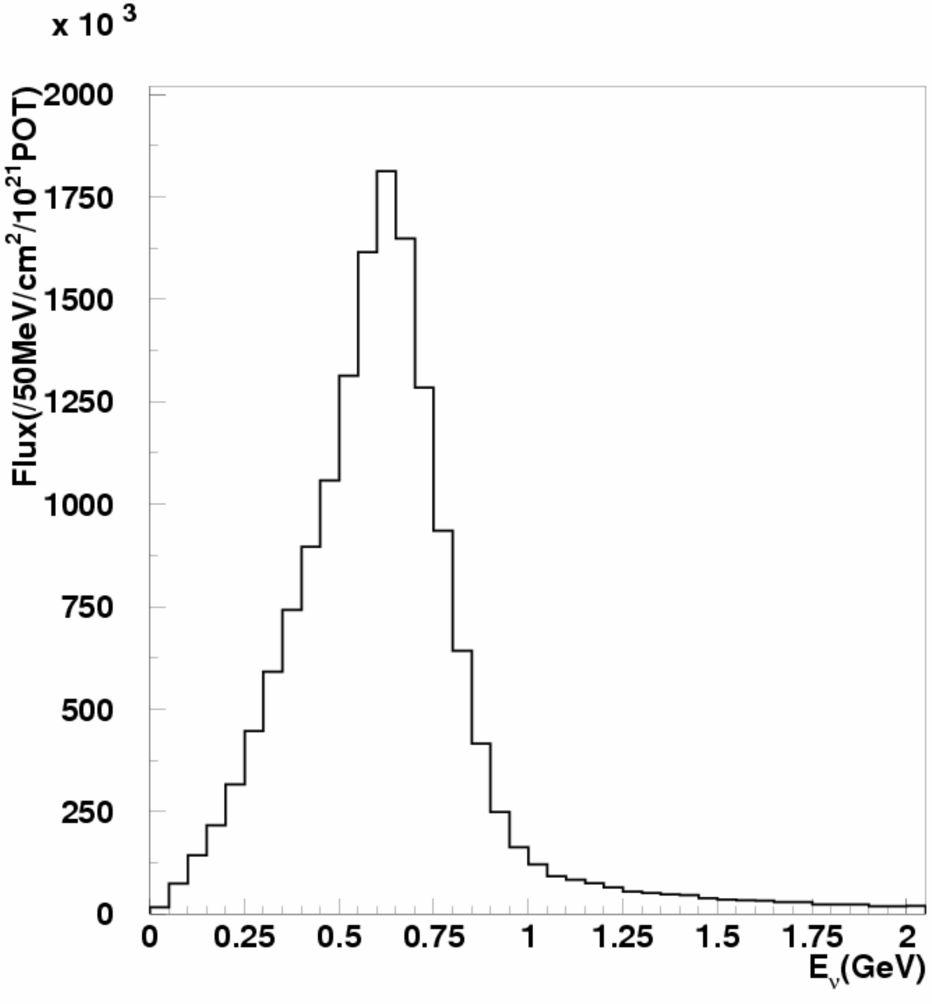
ν_e ~0.4% at ν_μ peak

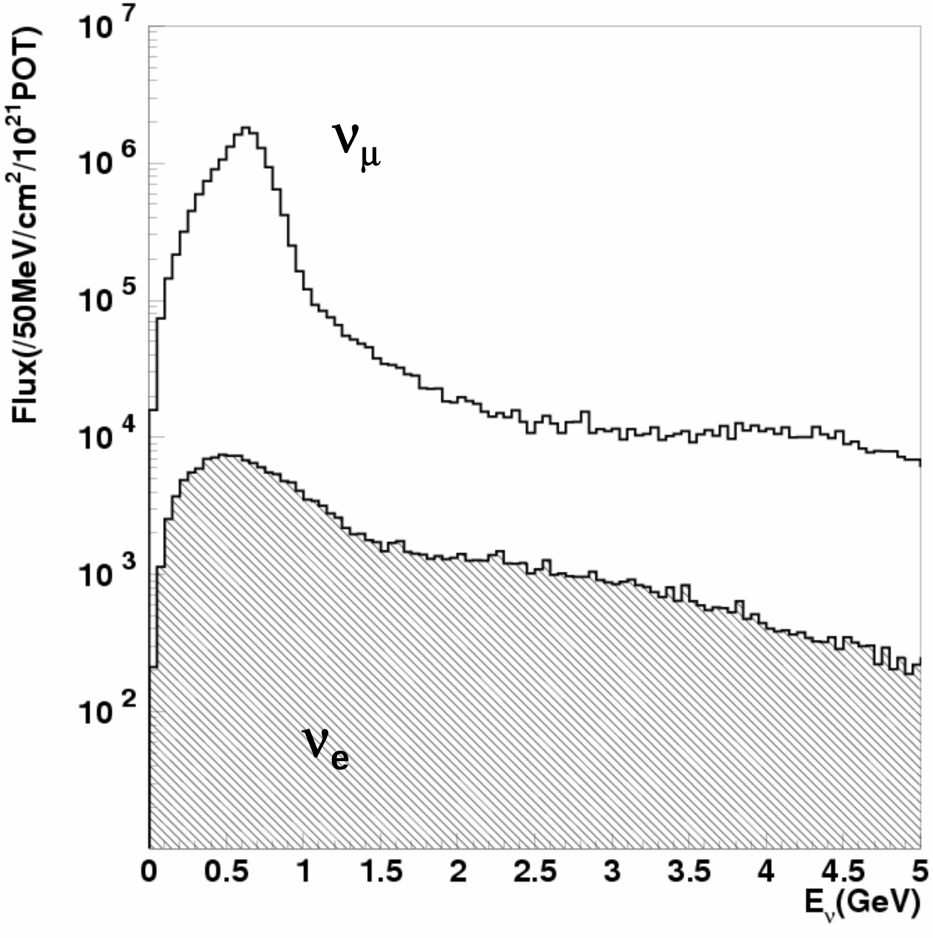


Neutrino energy spectrum σxΦ

(Note $\sigma \propto E$)

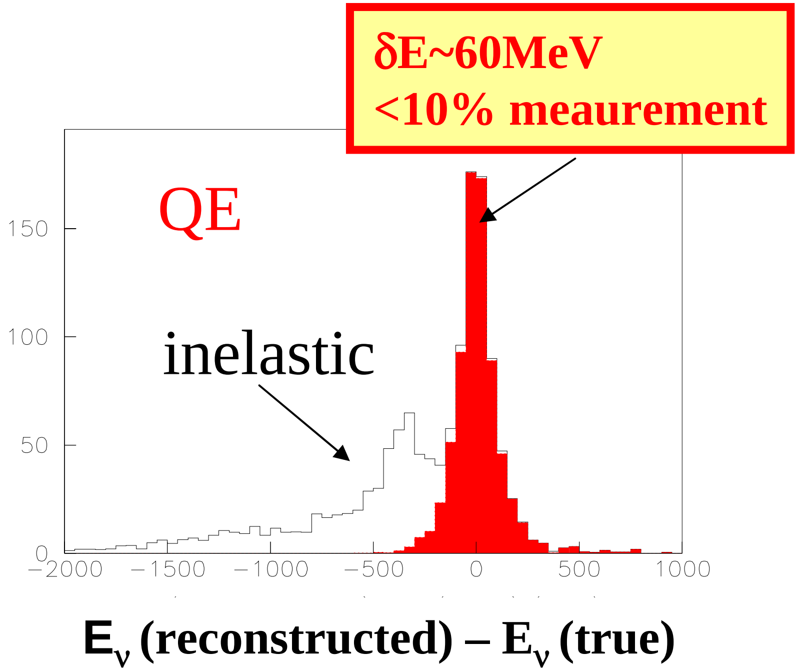
Flux
OAB2.5deg, E_p=40GeV

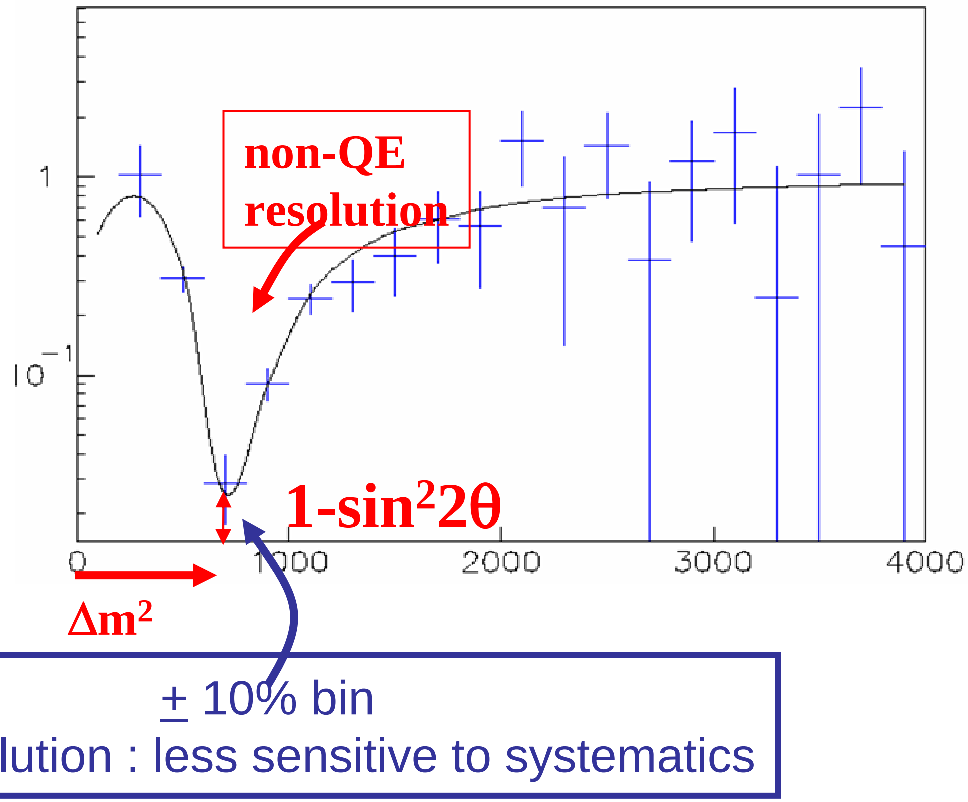




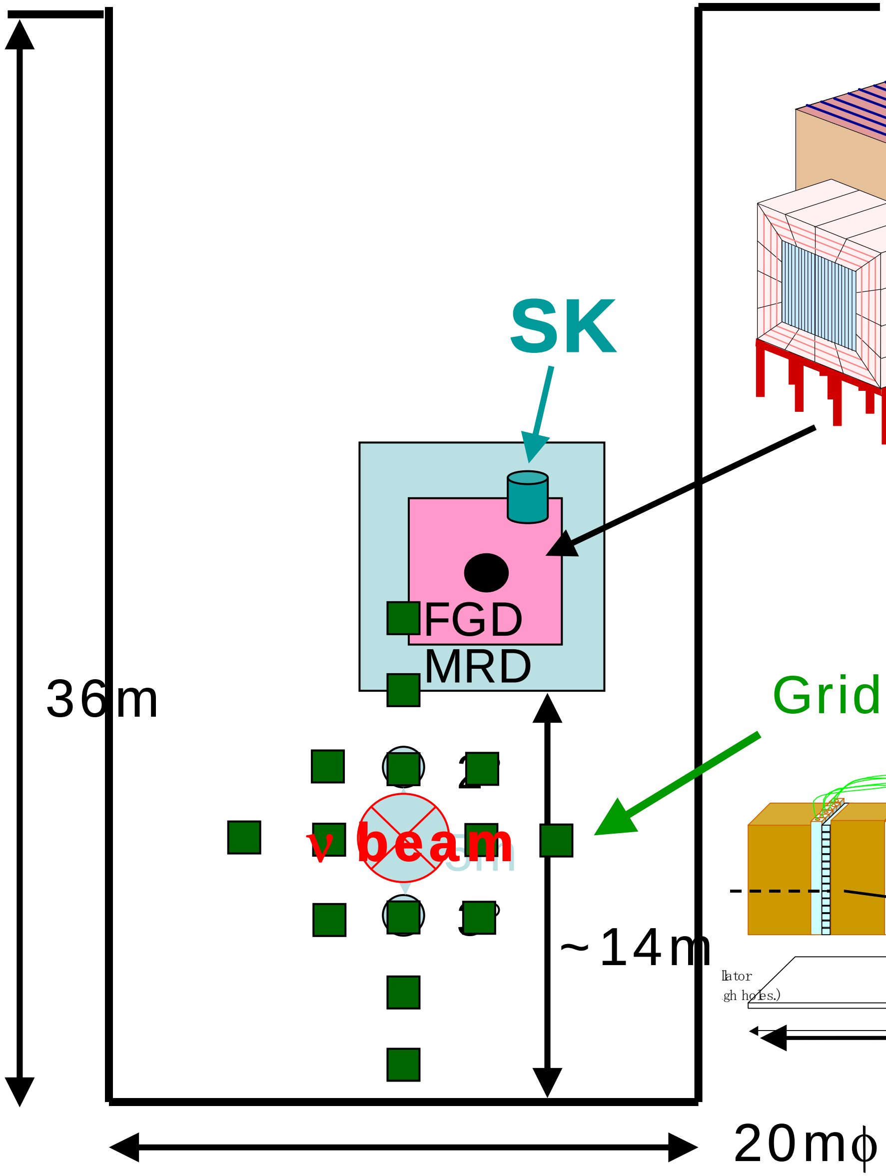
E_ν reconstruction resolution

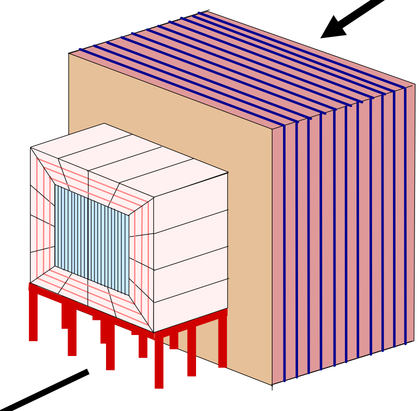
- Large QE fraction for <1 GeV
- Knowledge of QE cross sections
- Beam with small high energy tail



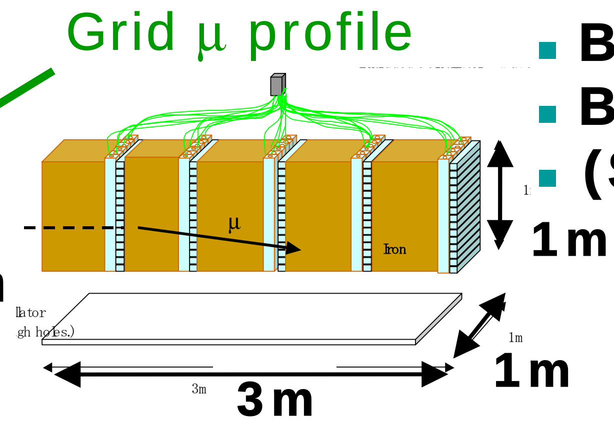


Near Detector @280m



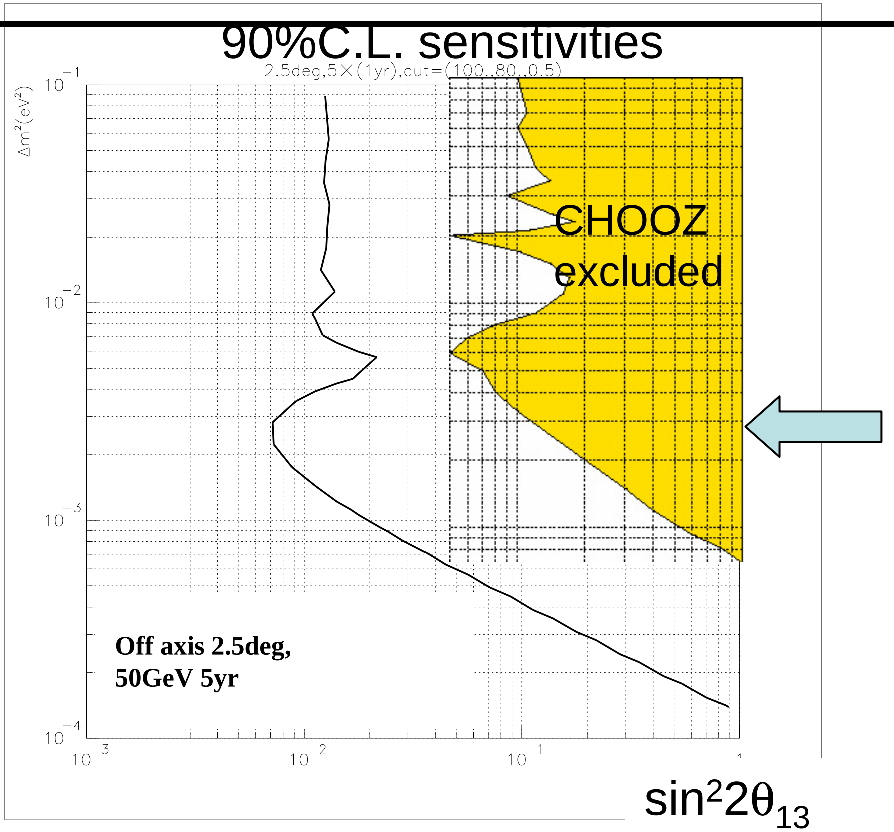


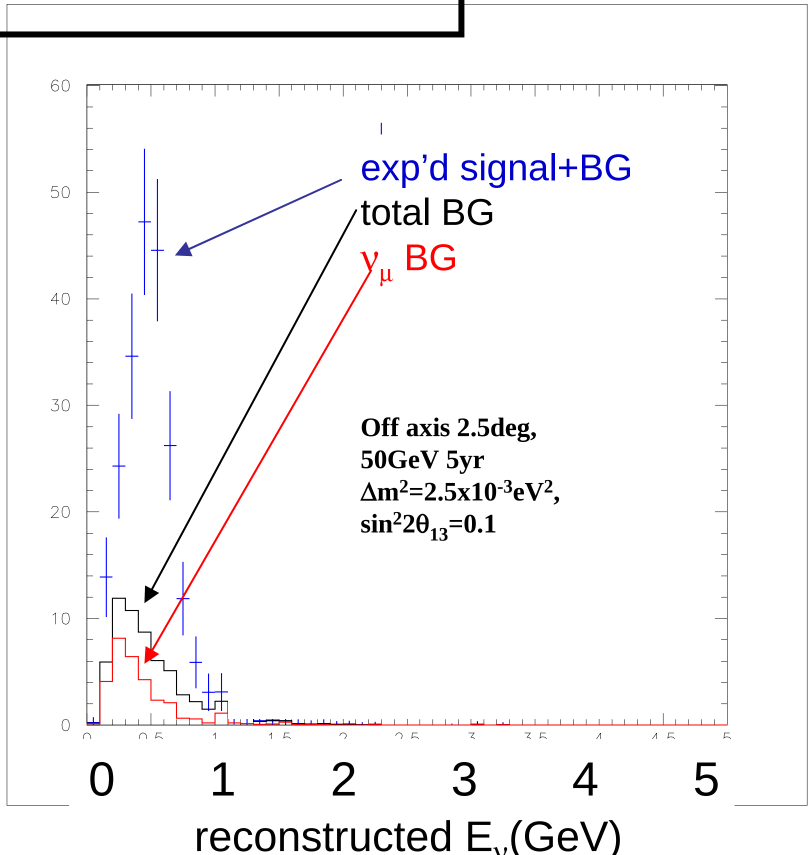
- Off-axis (~2°)
- With Magnet
  - ν_μ and ν_e fluxes and spectra
  - ν interaction study (CC-QE,non-QE,π^0,)
  - Kaon contributions
- On-axis (0°)
  - Beam direction
  - Beam stability
  - (Spectrum)?



The detector design is just started.

sensitivities for $\sin^2 2\theta_{13}$





$\sin^2 2\theta_{13}$	ν_μ (CC+NC)	Bean ν_e	Osc'd ν_e	Signal+BG
0.1	12	16	122	150
0.01	12	16	12	40

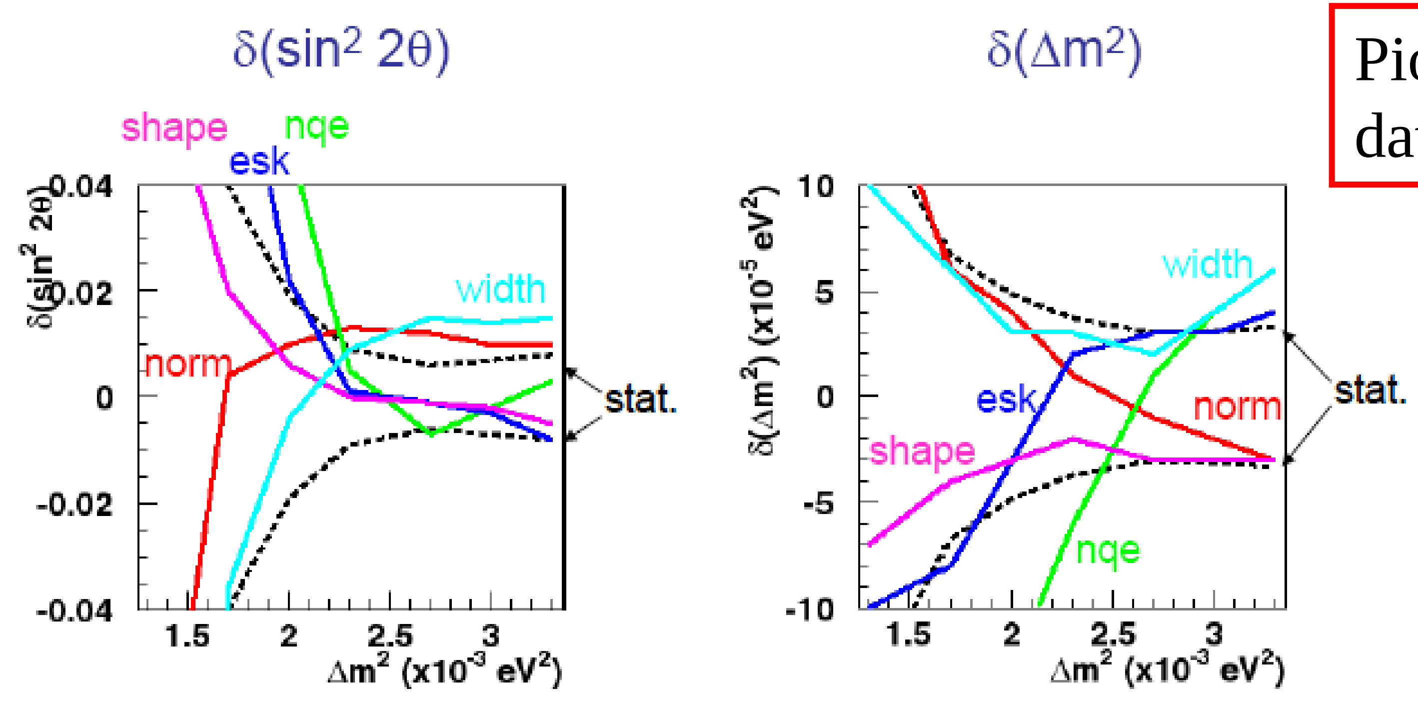
(OA 2.5deg, 50GeV 5yr)

Precision measurement of θ_{23} , Δm^2_{23} possible systematic errors and phase-1 stat.

•Systematic errors
- **normalization (10% （→5%(K2K))**
- **non-qe/qe ratio (20% (to be measured))**
- **E scale (4% (K2K 2%))**
- **Spectrum shape (Fluka/MARS →(Near D.))**
- **Spectrum width (10%)**

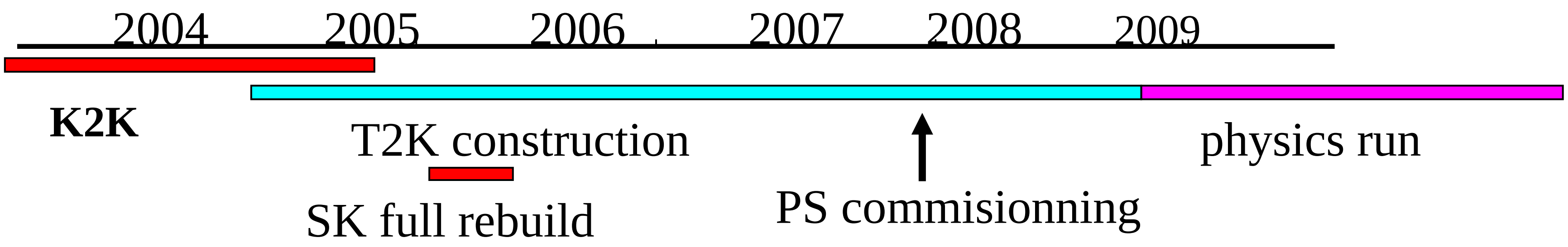
OA2.5°

$\delta(\sin^2 2\theta_{23})\sim 0.01$
$\delta(\Delta m^2_{23})$ $<1\times 10^{-4}$ eV^2



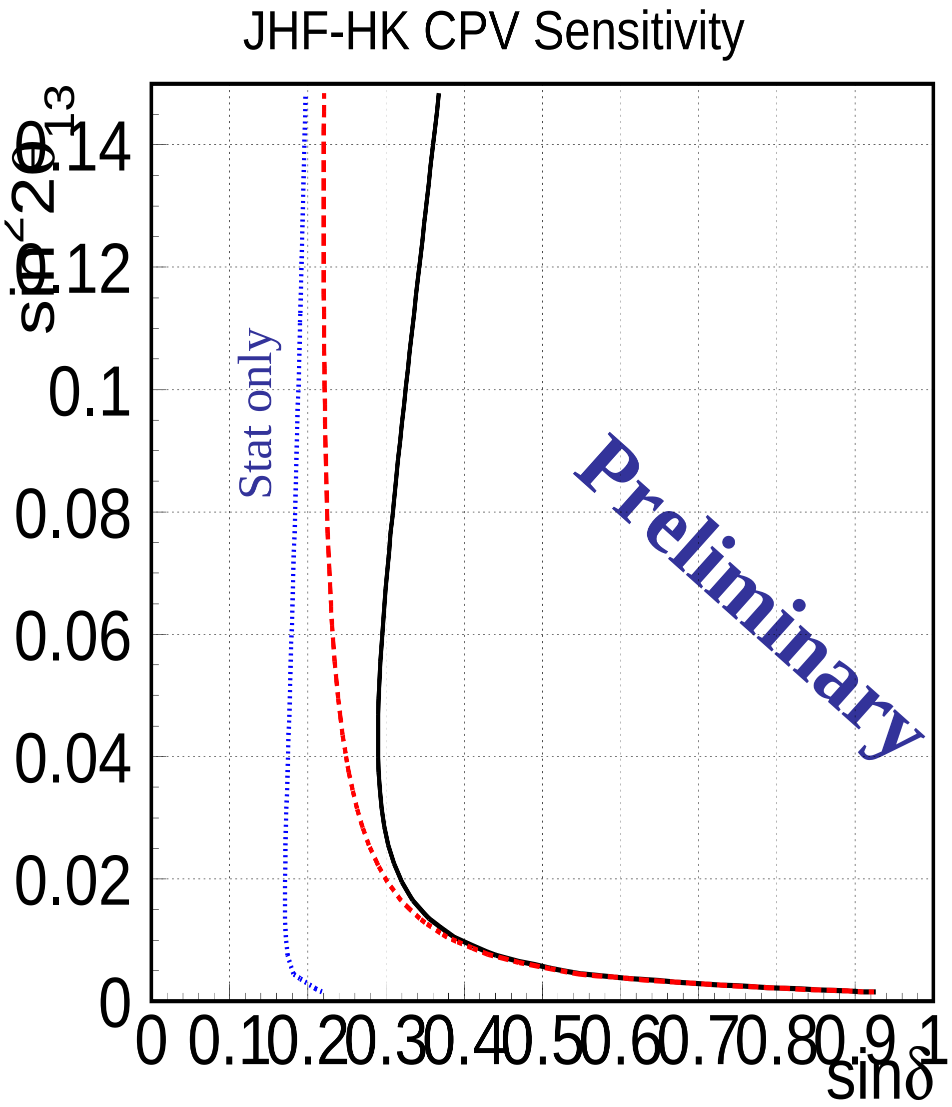
Pion production data is important

Schedule of T2K



- Possible upgrade in future
  - 4MW Super-J-PARC + Hyper-K (1Mt water Cherenkov)
  - CP violation in lepton sector
  - Proton Decay

Sensitivity (3σ) to CP Violation Phase δ with Mega-ton detector



- Bkg. subtraction with 2% accuracy (red),
- bkg(2%)+selection(2%) (black) errors
- Operation of
  2 yr for ν_μ and 6.8 yr for ν_μ
  $\delta \geqq 33$deg at $\sin^2 2\theta_{13}=0.01$
  $\delta \geqq 14$deg for large $\sin^2 2\theta_{13}$
- Understanding of background and systematics is essential

Summary

- **The neutrino oscillation in two Δm^2 regions**
- Sterile ?
- $\nu\mu \rightarrow \nu\tau$ confirmation
- Oscillation pattern
- $\theta_{13} << \theta_{12}$, θ_{23} or just below CHOOZ?
- $\theta_{23} \rightarrow \pi/4$?
- Reactor θ_{13} measurement

- $0\nu\beta\beta$ by Dr. Klapdor may turn out to be right
  - Degenerate mass of ~ 0.4 eV KATRIN and $0\nu\beta\beta$ exp't、cosmology

- Mass hierarchy
- Smaller θ13
- CPV

December, 2003

2) Construction Status

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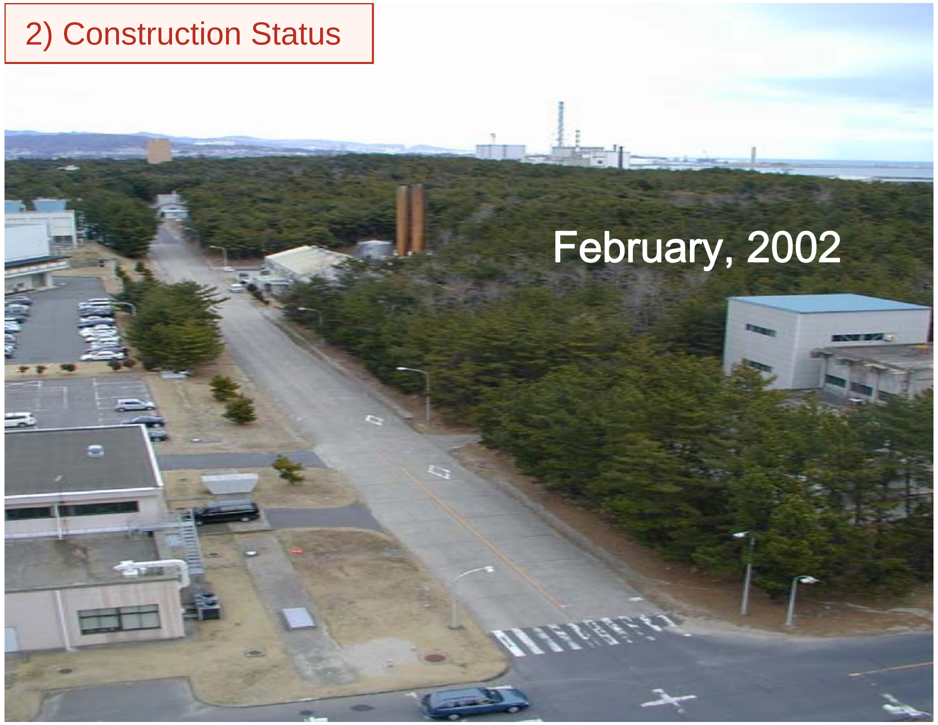
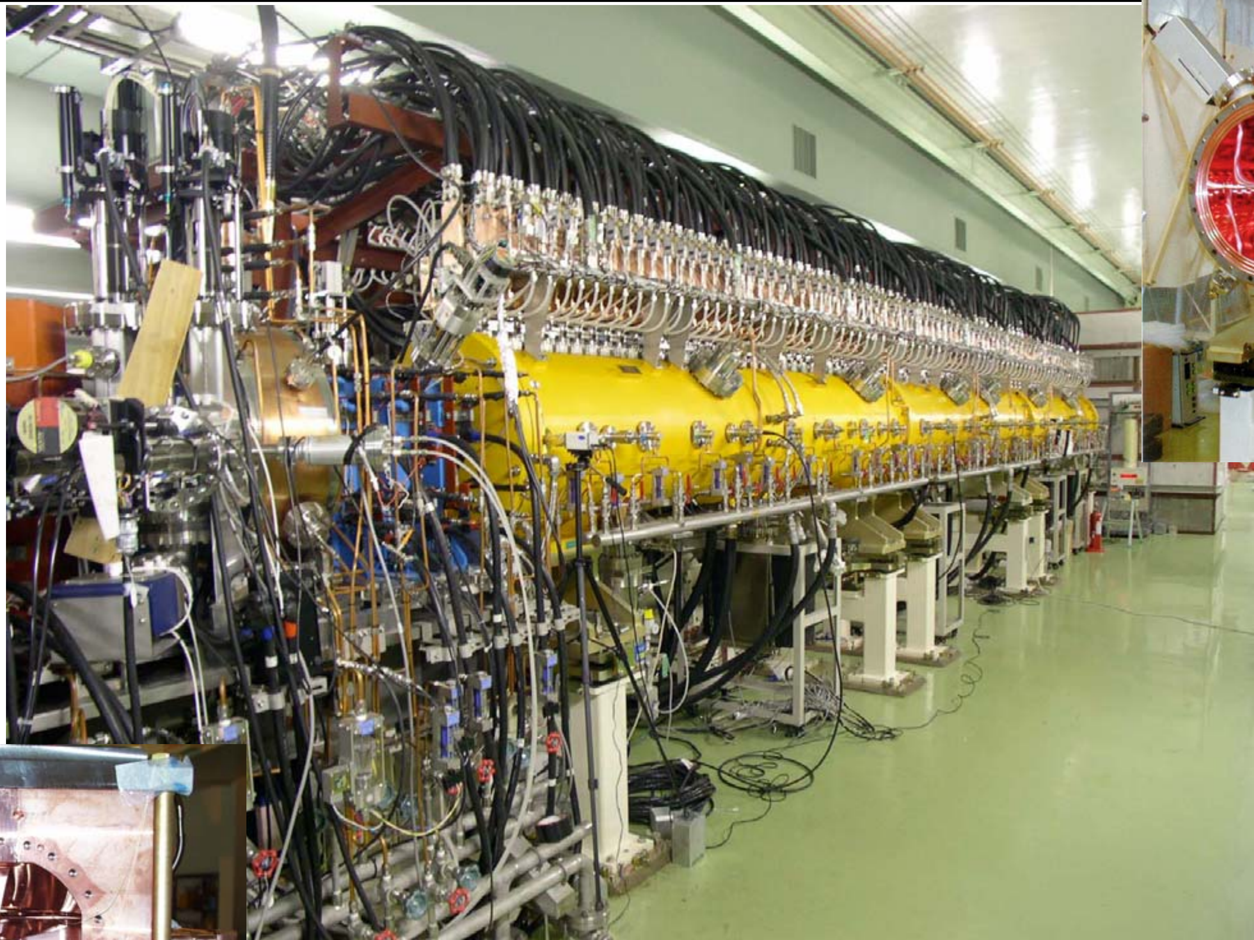


2) Construction Status

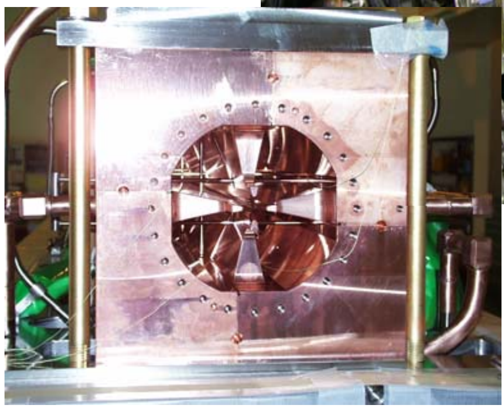
Linac



Inside of Drift Tube Linac

Beam test for chopper was also done.

RFQ

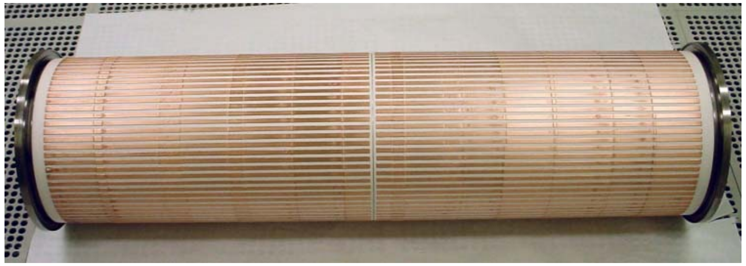


On October 30, 2003, a successful acceleration of 6 mA at 20 MeV. On November 7, 30 mA was achieved.

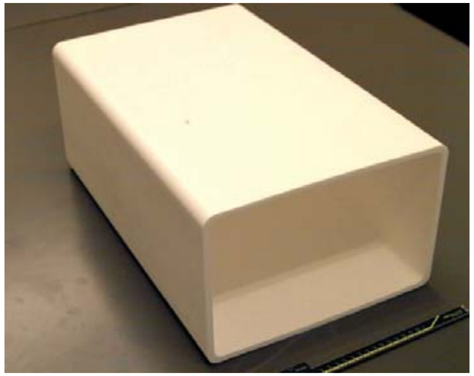
3 GeV Vacuum Pipe and 50 GeV RF Cavity

For dipole

Vacuum Beam Pipe for 3 GeV

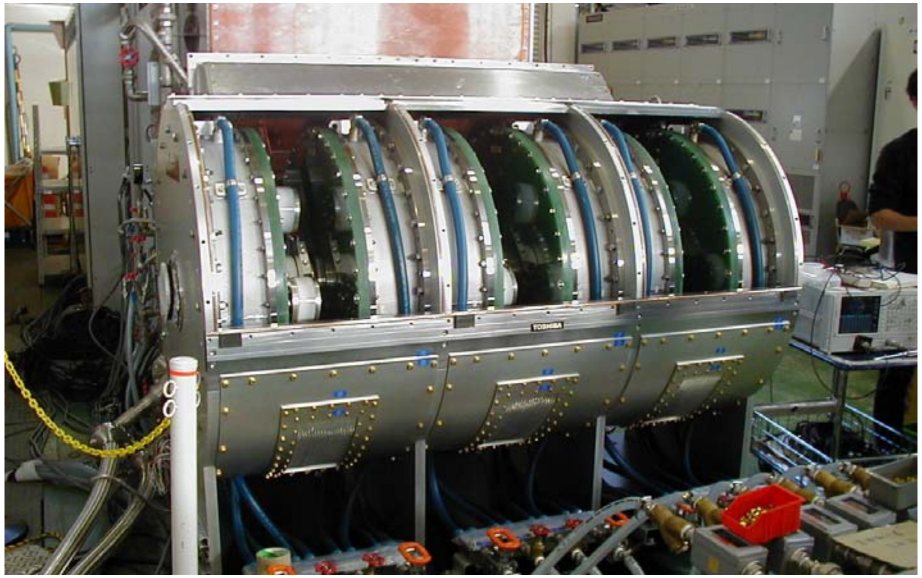


For quadrupole



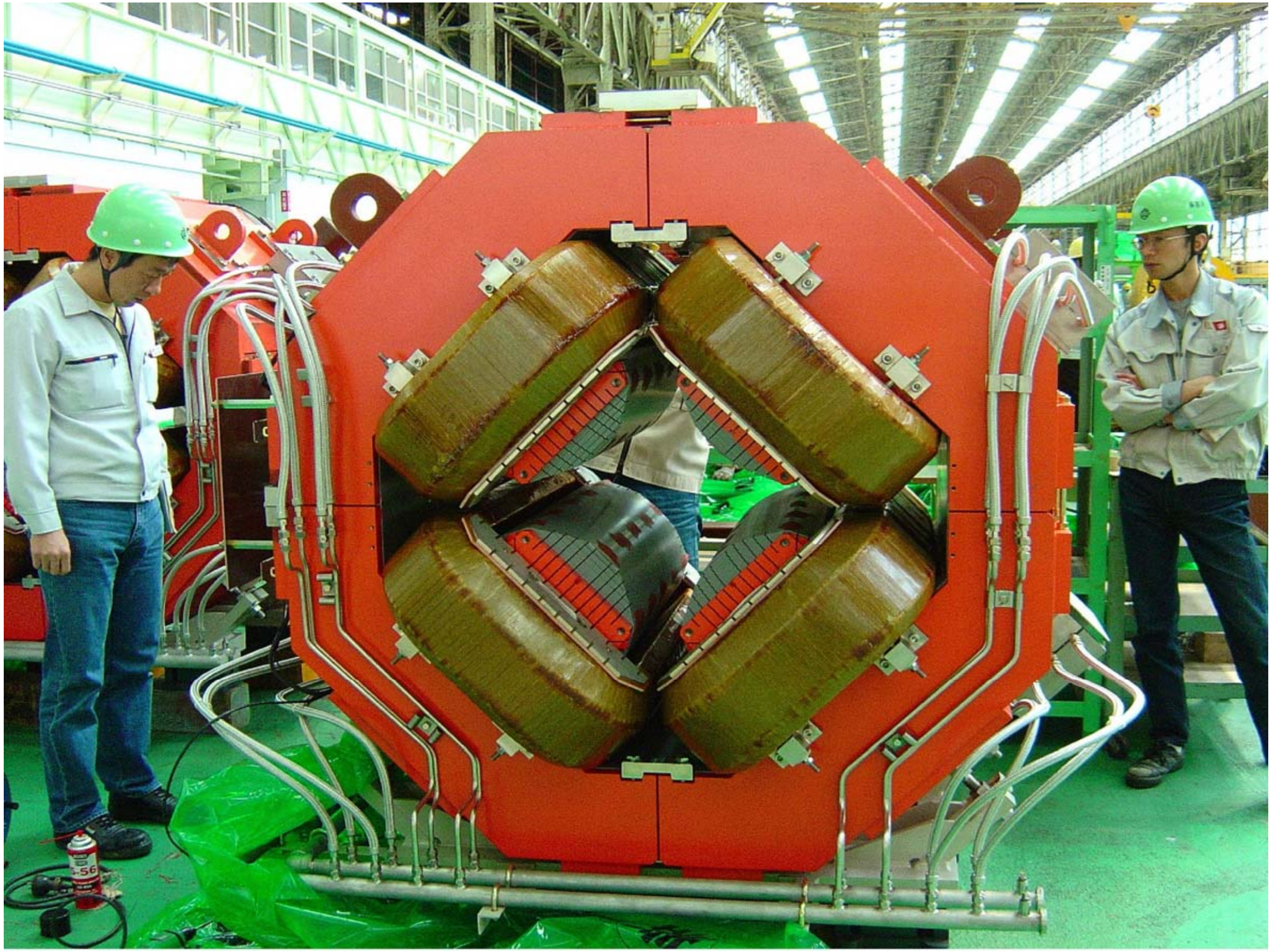
New material (Finemet)

50 kV/m Attained.



RF Cavity for 50 GeV

3 GeV Quadrupole Magnet



50 GeV Magnets

Dipole Magnet

Quadrupole Magnet

Limitations of the observations

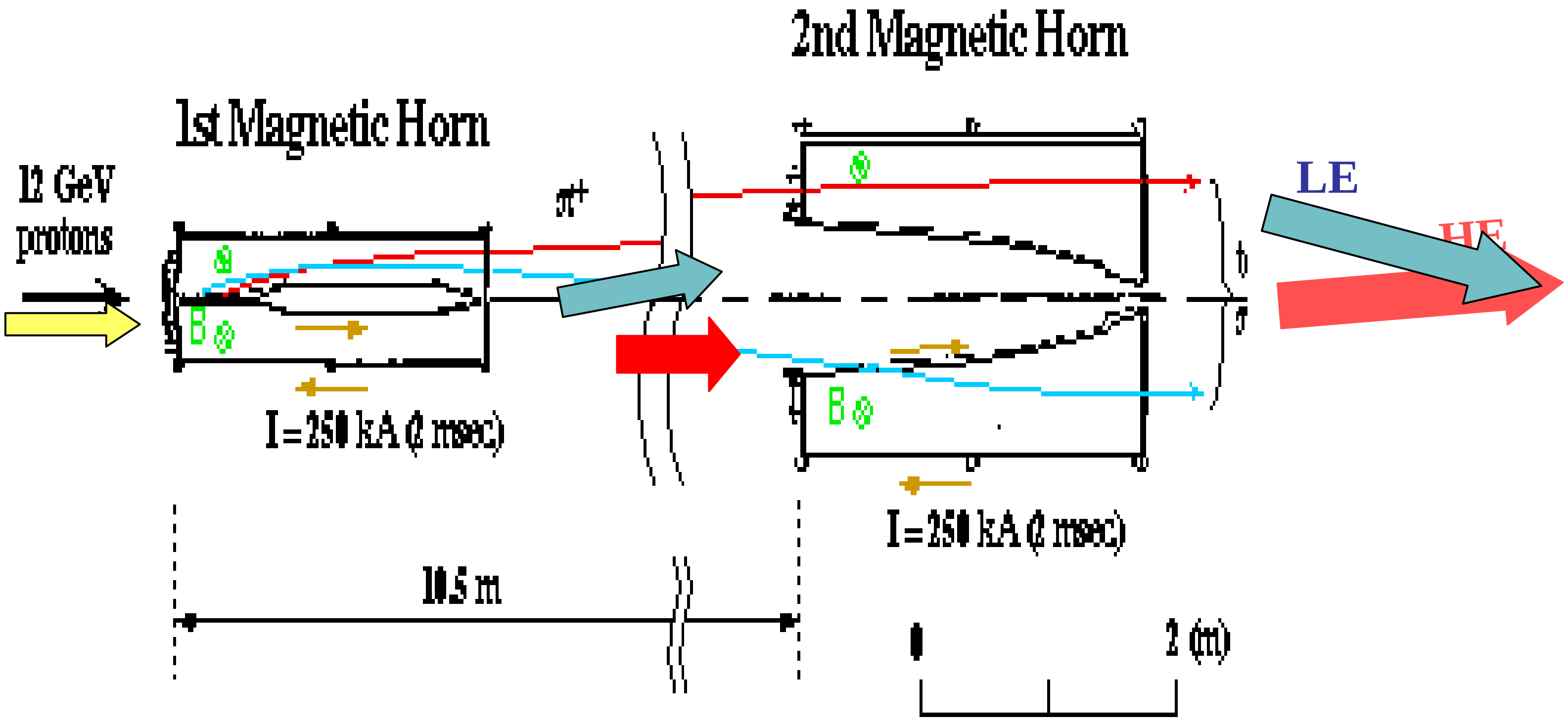
- Nature cannot be artificially controlled.
- Inherent uncertainties exist in calculation of various observables:
  - Fluxes of solar neutrinos on Earth
    - Nuclear reaction cross sections, chemical compositions, opacity, etc.
  - Fluxes of atmospheric neutrinos
    - Primary cosmic ray flux, nuclear interactions, etc.
- Find model-independent observables
  - Solar neutrinos:
    - Comparison of NC and CC interactions
    - Spectral shape, day/night effect, etc
  - Atmospheric neutrinos
    - μ/e ratio
    - Zenith angle distribution

Beam direction in Horn Focused Neutrino Beam

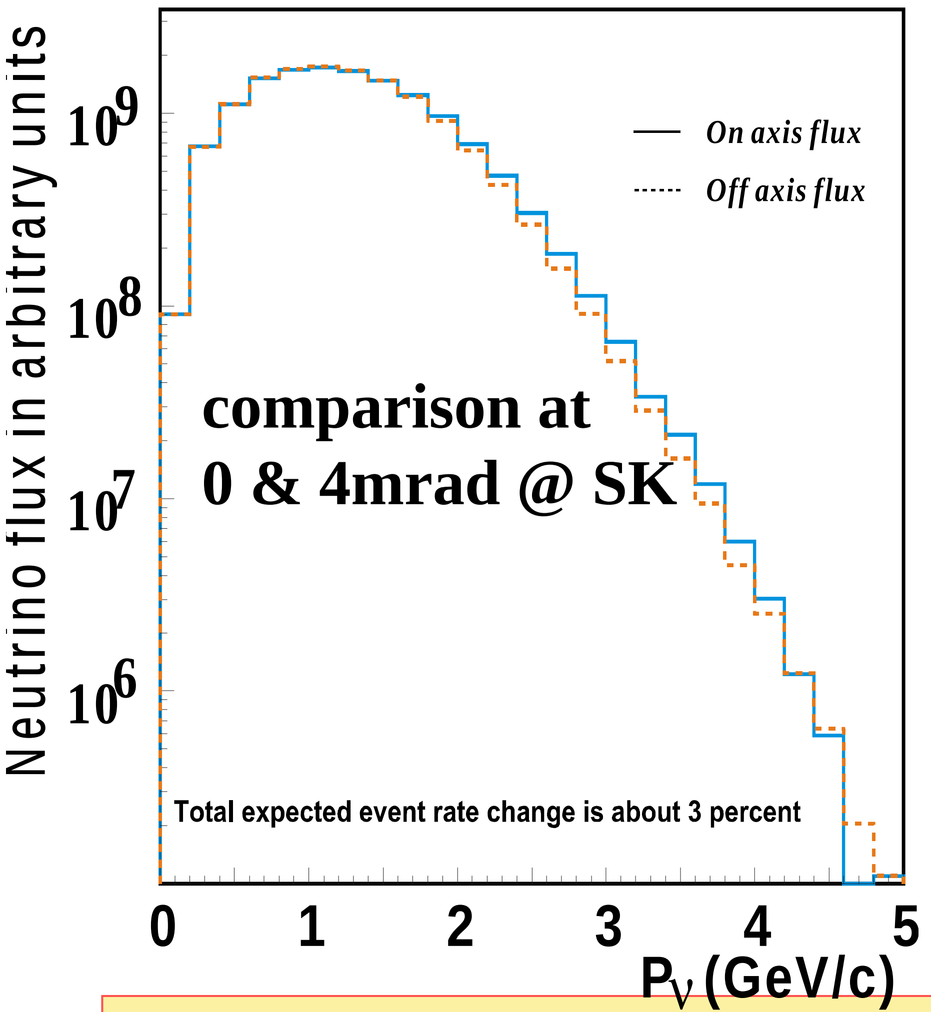
p+Al → π^+ → $\mu^+ + \nu_\mu$

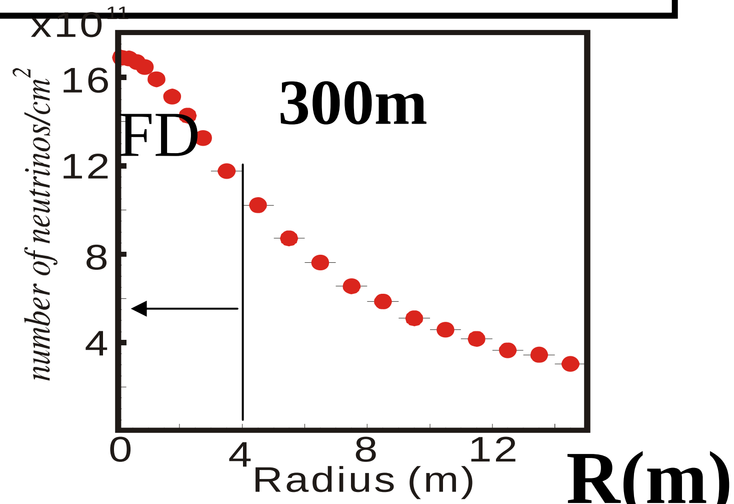
$\rightarrow e^+ + \nu_e + \nu\mu$(1%)

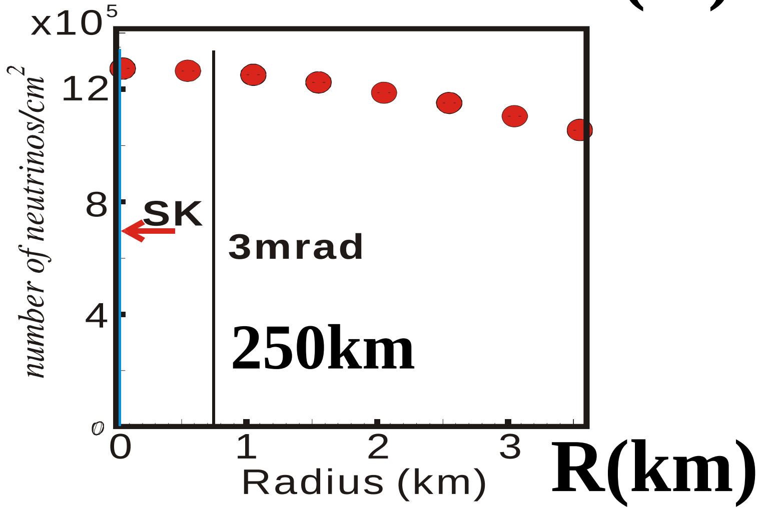
Need measurements for low energy particle direction



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







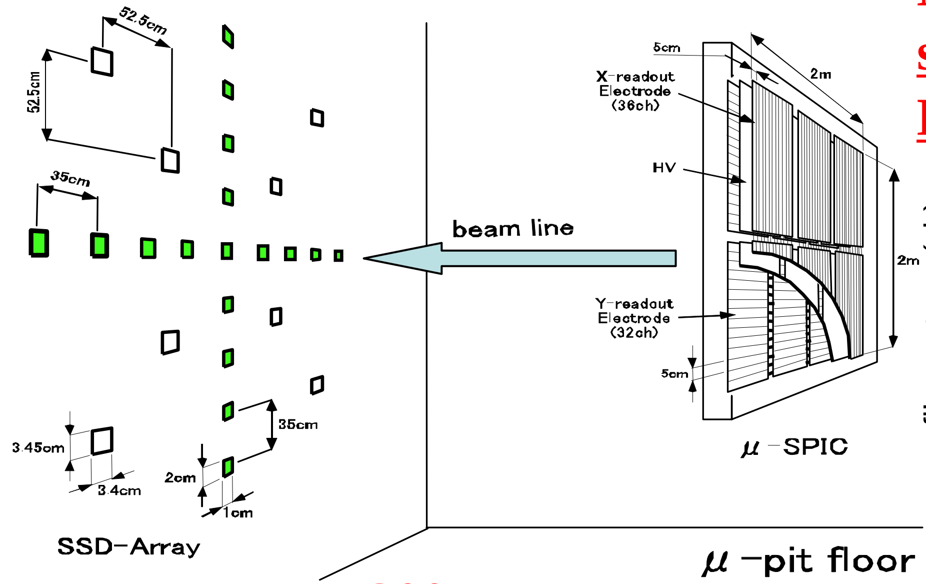
1km(4mr) off axis @ SK no change in rate and spectrum
→ aim for 1 mrad stability monitoring

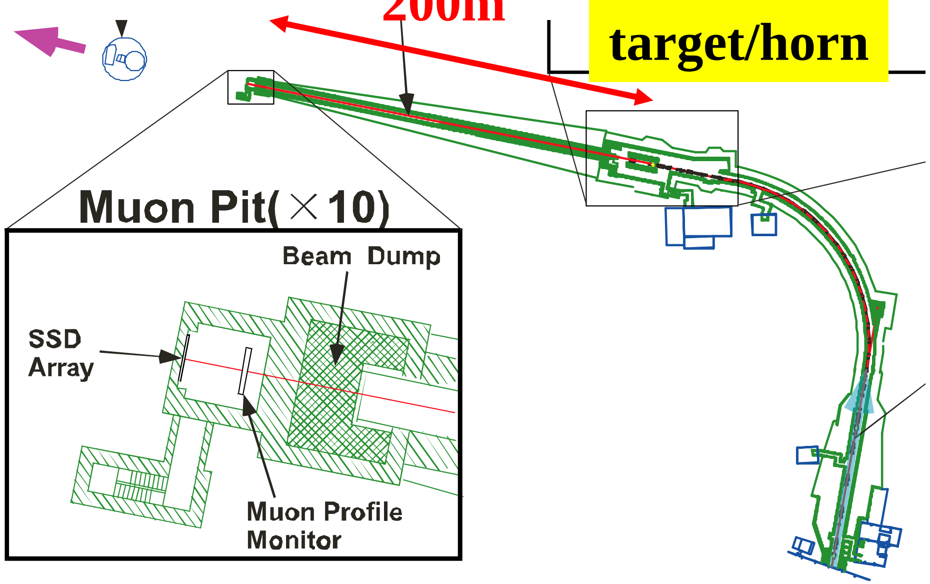
Muon monitor

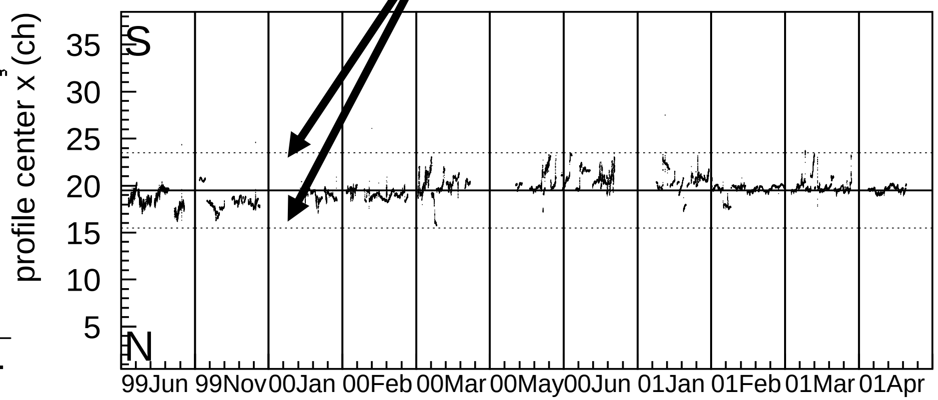
Monitor the profile center of muons spill by spill.

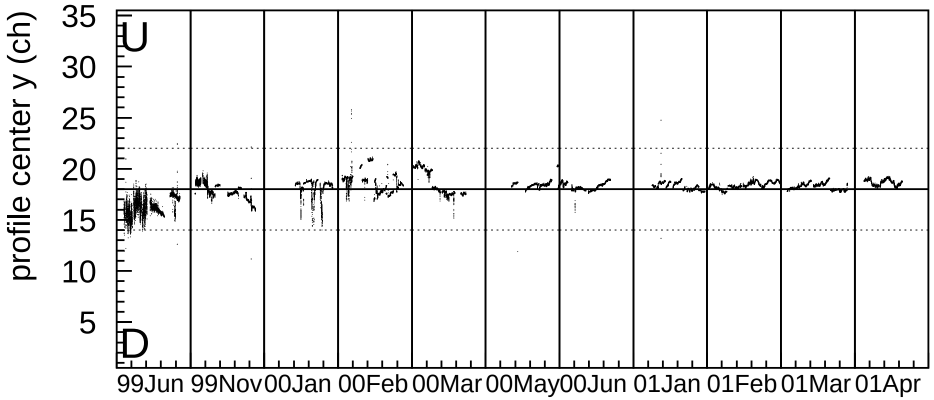
Eμ > 5 GeV

±1 mrad.

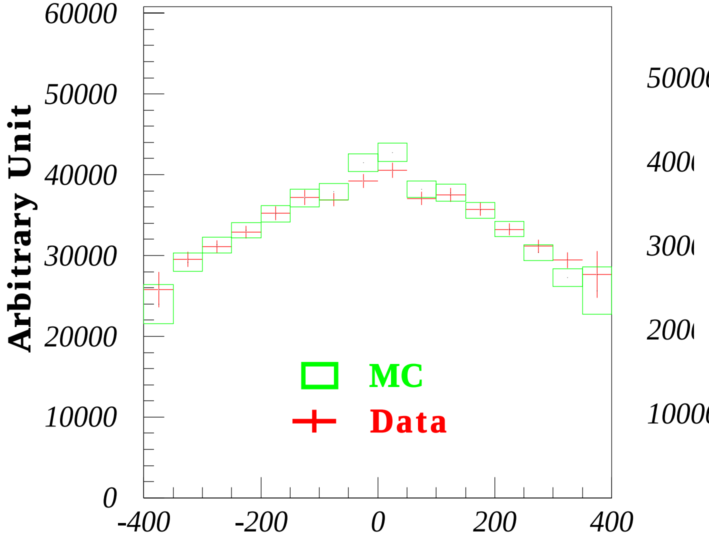




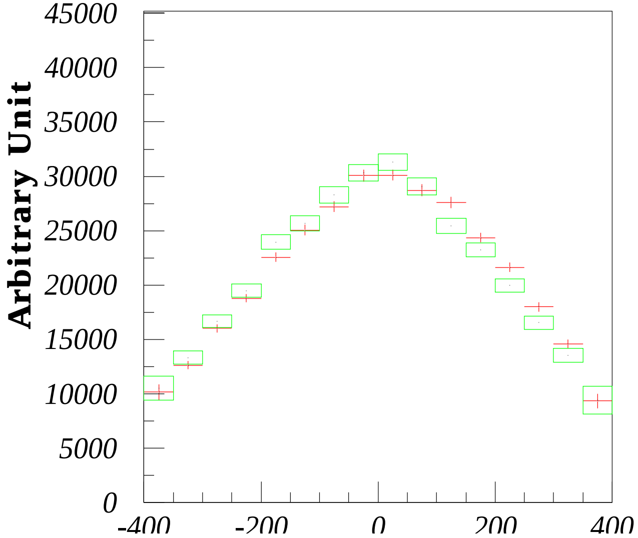




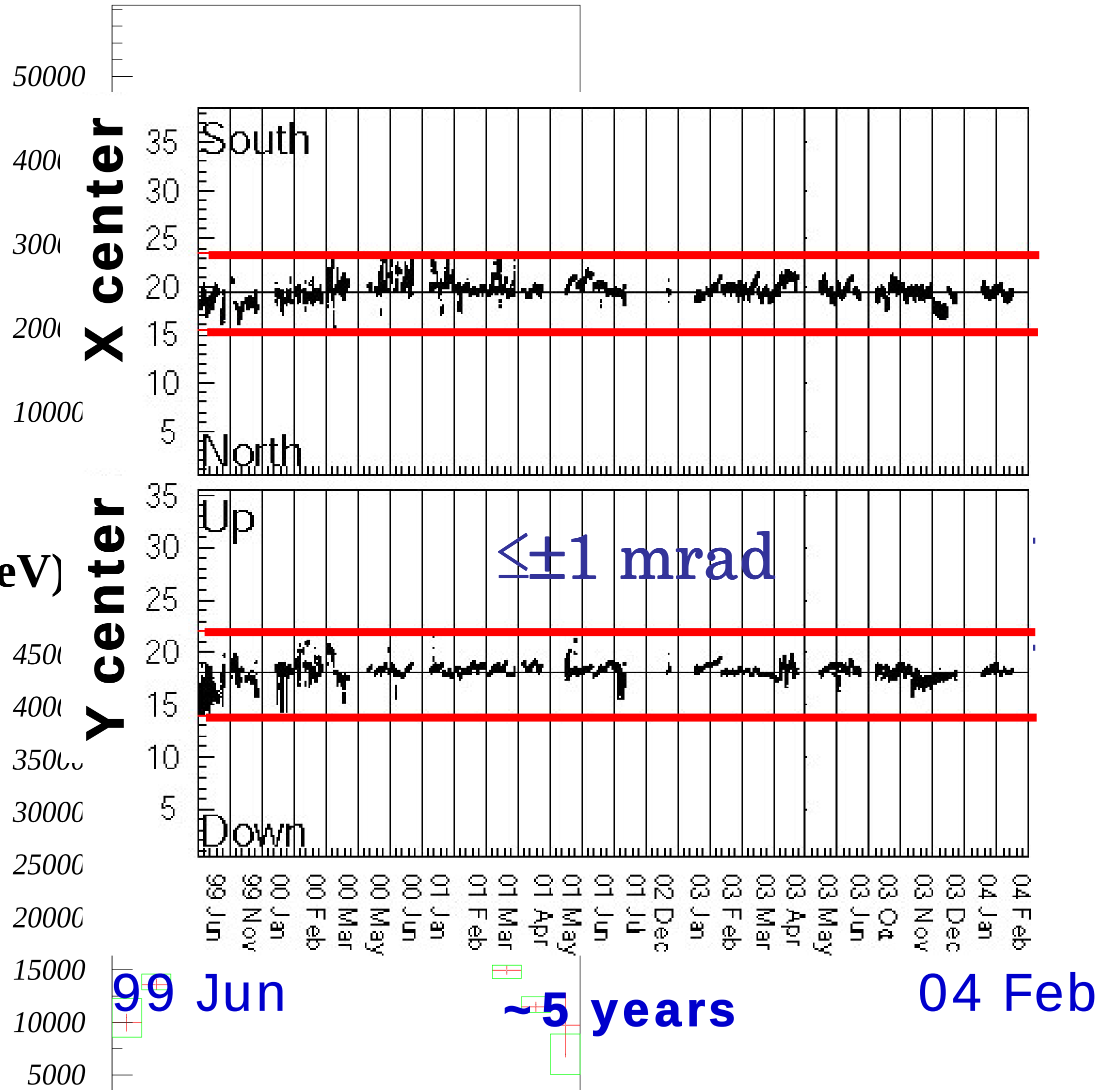
ν beam direction with MRD ν profile



profile x (0.5GeV < E_μ < 1.0GeV)



profile x (1.0GeV < E_μ < 2.5GeV)



Low E neutrinos direction are hard to define

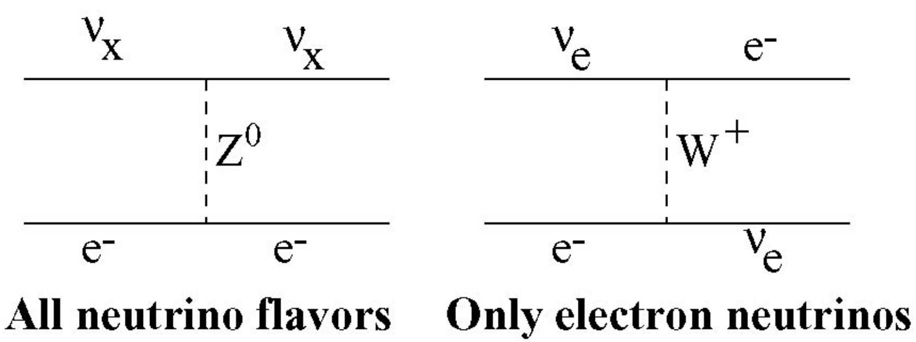
Matter-Enhanced Neutrino Oscillations

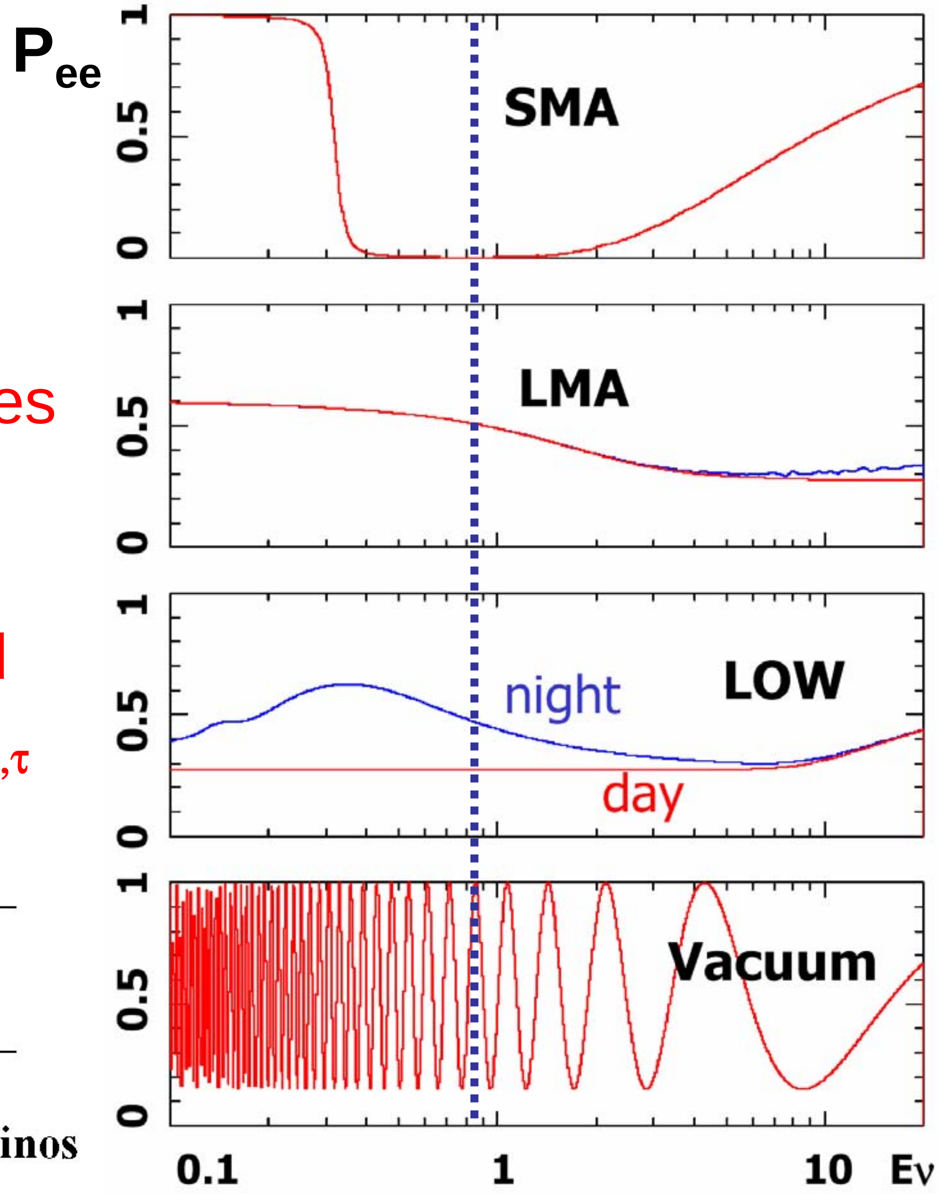
Neutrinos produced in weak state ν_e

⇒ High density of electrons in the Sun

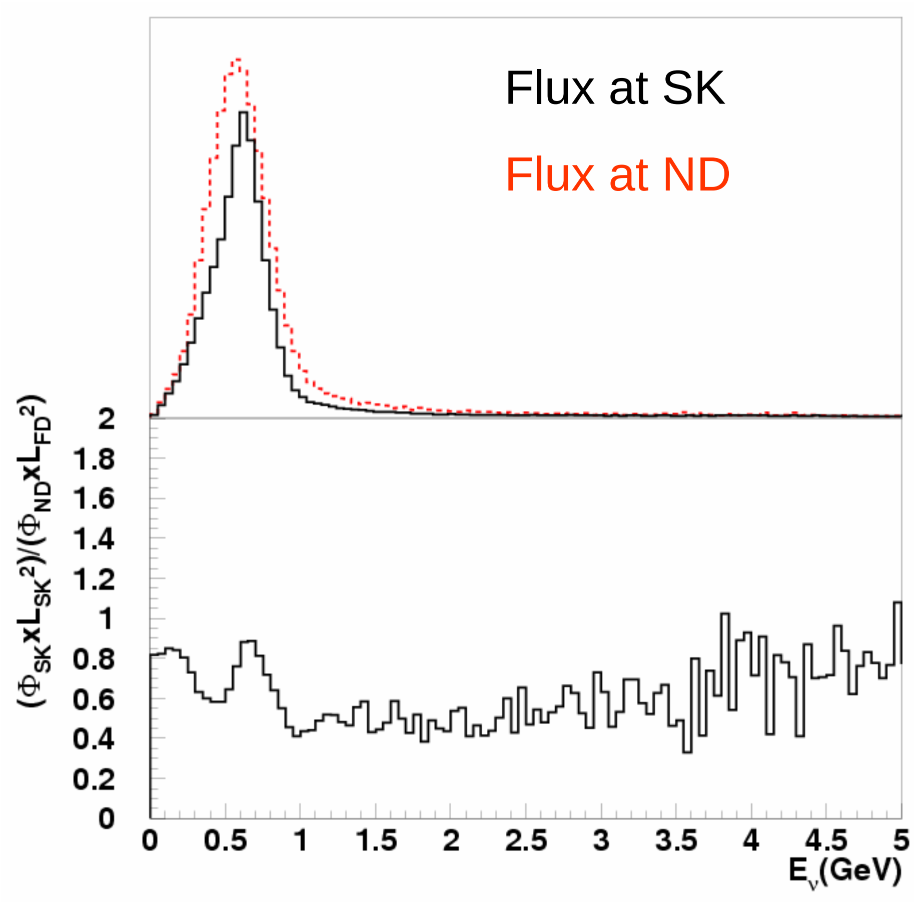
⇒ Superposition of mass states $\nu_{1,2,3}$ changes through the MSW resonance effect

⇒ Solar neutrino flux detected on Earth consists of $\nu_e + \nu_{\mu,\tau}$

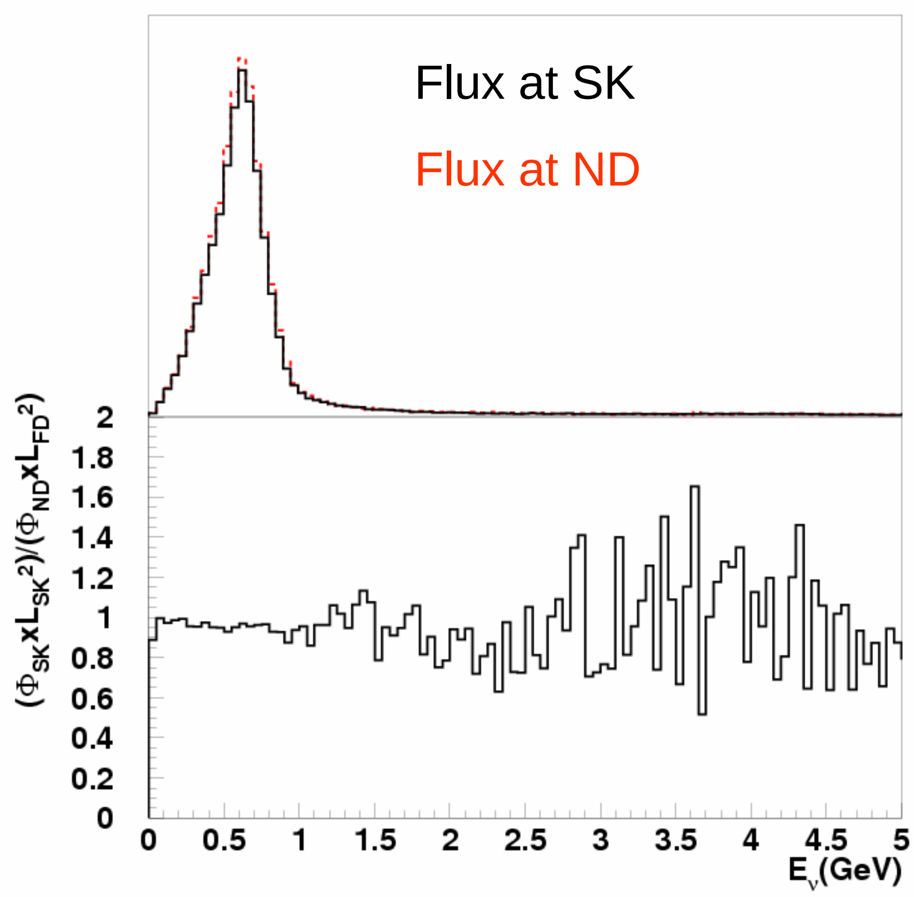




Near/Far ratio



at 280m



at 2km

Oscillation formula

- $P(\nu_\mu \rightarrow \nu_\mu)$ disappearance

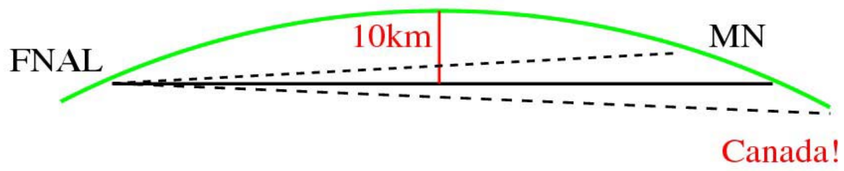
$$1-4(C_{12}^2C_{23}^2+S_{12}^2S_{13}^2S_{23}^2-2C_{12}C_{23}S_{12}S_{13}S_{23}\cos\delta)S_{23}^2C_{13}^2\cdot\sin^2\Delta_{23}$$
$$-4(C_{12}^2C_{23}^2+S_{12}^2S_{13}^2S_{23}^2+2C_{12}C_{23}S_{12}S_{13}S_{23}\cos\delta)S_{23}^2C_{13}^2\cdot\sin^2\Delta_{13}$$
$$-4(C_{12}^2C_{23}^2+S_{12}^2S_{13}^2S_{23}^2-2C_{12}C_{23}S_{12}S_{13}S_{23}\cos\delta)$$
$$\times(C_{12}^2C_{23}^2+S_{12}^2S_{13}^2S_{23}^2+2C_{12}C_{23}S_{12}S_{13}S_{23}\cos\delta)\cdot\sin^2\Delta_{12}$$

- $P(\nu_\mu \rightarrow \nu_e)$ appearance

$$4C_{13}^2S_{13}^2S_{23}^2\cdot\left(1+\frac{2a}{\Delta m_{13}^2}(1-2S_{13}^2)\right)\cdot\sin^2\Delta_{31}$$
$$+8C_{13}^2S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta-S_{12}S_{13}S_{23})\cdot\cos\Delta_{32}\cdot\sin\Delta_{31}\cdot\sin\Delta_{21}$$
$$-8C_{13}^2C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\cdot\sin\Delta_{32}\cdot\sin\Delta_{31}\cdot\sin\Delta_{21}$$
$$+4S_{12}^2C_{13}^2(C_{12}^2C_{23}^2+S_{12}^2S_{23}^2S_{13}^2-2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta)\cdot\sin^2\Delta_{21}$$
$$-8C_{13}^2S_{13}^2S_{23}^2\cdot\frac{aL}{4E_\nu}(1-2S_{13}^2)\cdot\cos\Delta_{32}\cdot\sin\Delta_{31}$$

- With a relation of $\Delta m_{31}^2=\Delta m_{21}^2+\Delta m_{32}^2$

NuMI Geography



NuMI beam off-axis

low energy and ~900 km

Assumption

- Δm^2_{12}, θ_{12} : KamLAND2004 + Solar ν

$$\Delta m^2_{12} = 8.2\times10^{-5}\ \mathrm{eV}^2$$

$$\tan^2\theta_{12} = 0.40$$

- Δm^2_{23}, θ_{23} : Around atmospheric *L*/*E*

- Matter effect (set to be zero in this study)

$$\Delta m^2_{23} = (1.9 \sim 3.0)\times10^{-3}\ \mathrm{eV}^2 \quad (90\%\mathrm{C.L.})$$

$$\sin^2 2\theta_{23} = 0.9 \sim 1$$

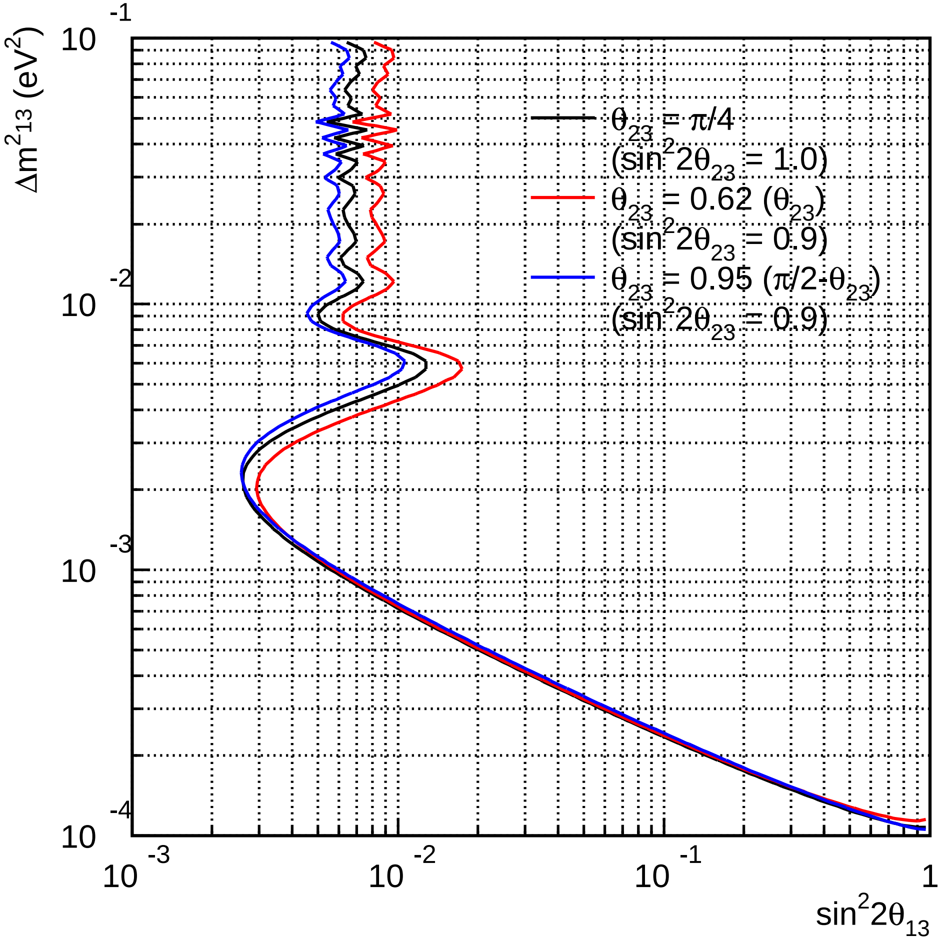
- No CP violation (CP phase δ=0)

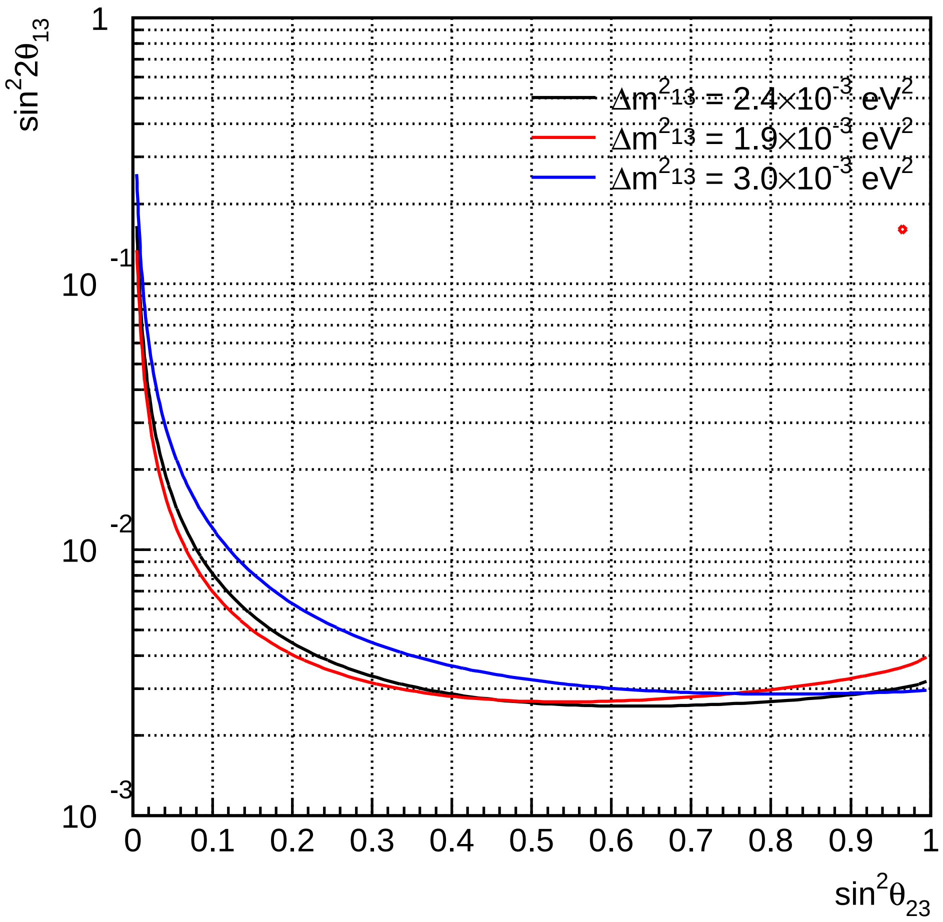
$$a \equiv 2\sqrt{2}G_F n_e E_\nu = 7.56\times10^{-5}[\mathrm{eV}^2]\cdot\frac{\rho}{[\mathrm{g/cm}^3]}\cdot\frac{E_\nu}{[\mathrm{GeV}]}$$

$$\rho = 2.8\ \mathrm{g/cm}^3$$

Sensitivity (exact version)

- Sensitivity to probe ν_e appearance (90%C.L.)



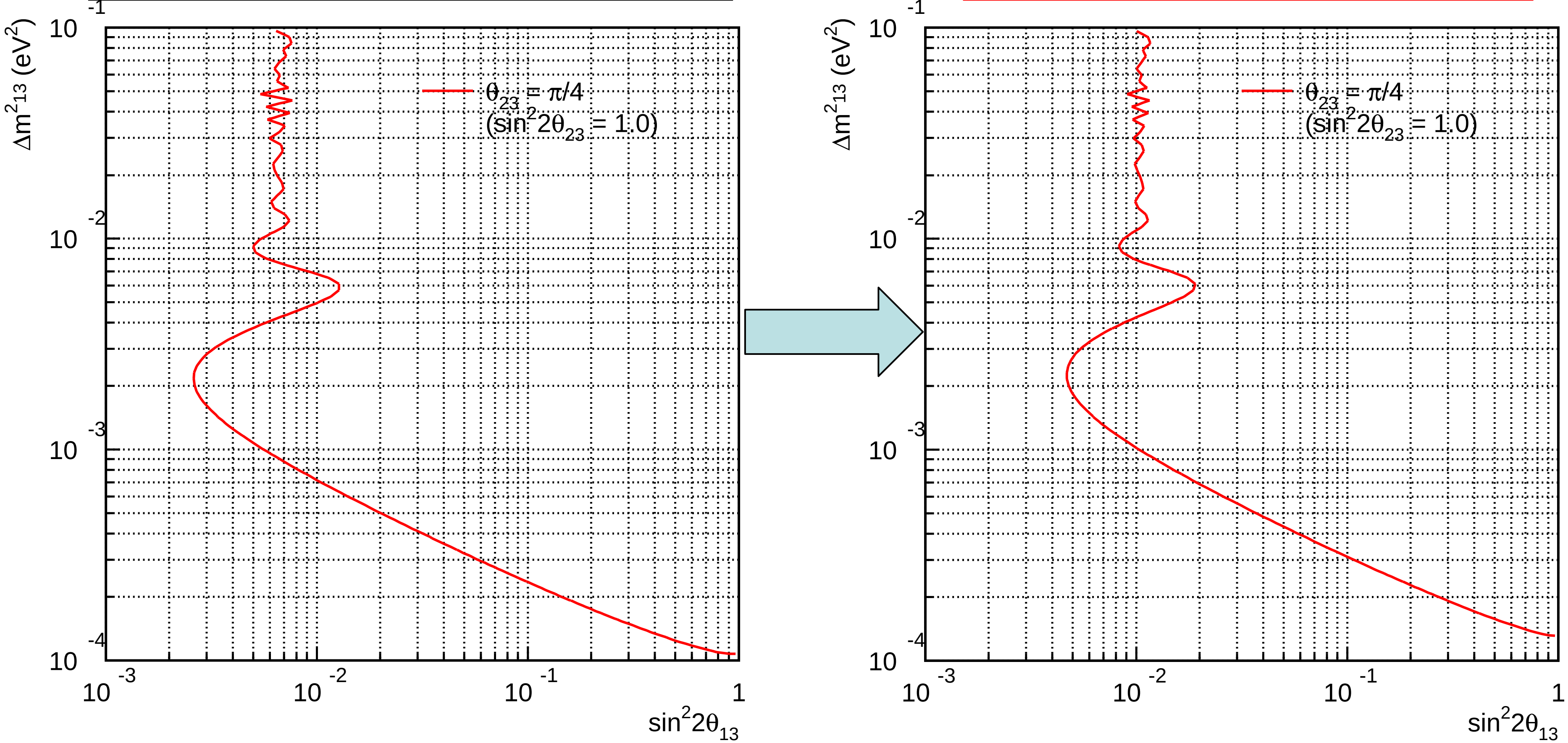


Subtraction of other components

- Additional background : 1.7±0.4 events

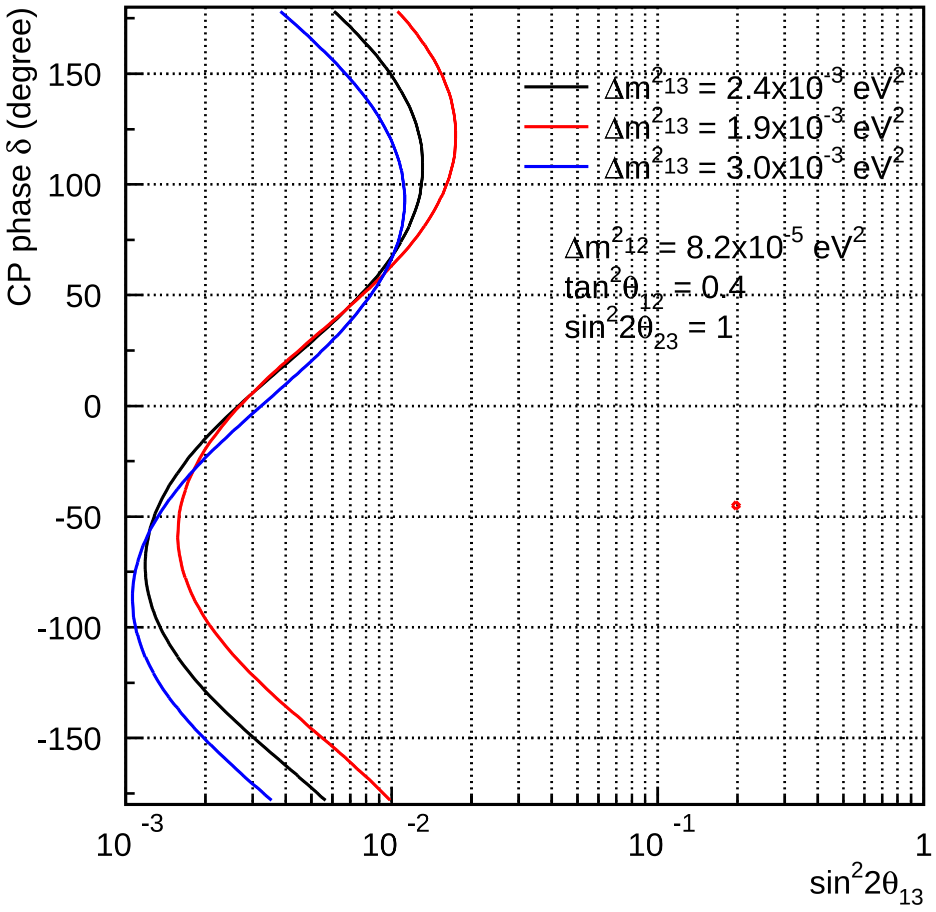
1.7±0.4 events not subtracted

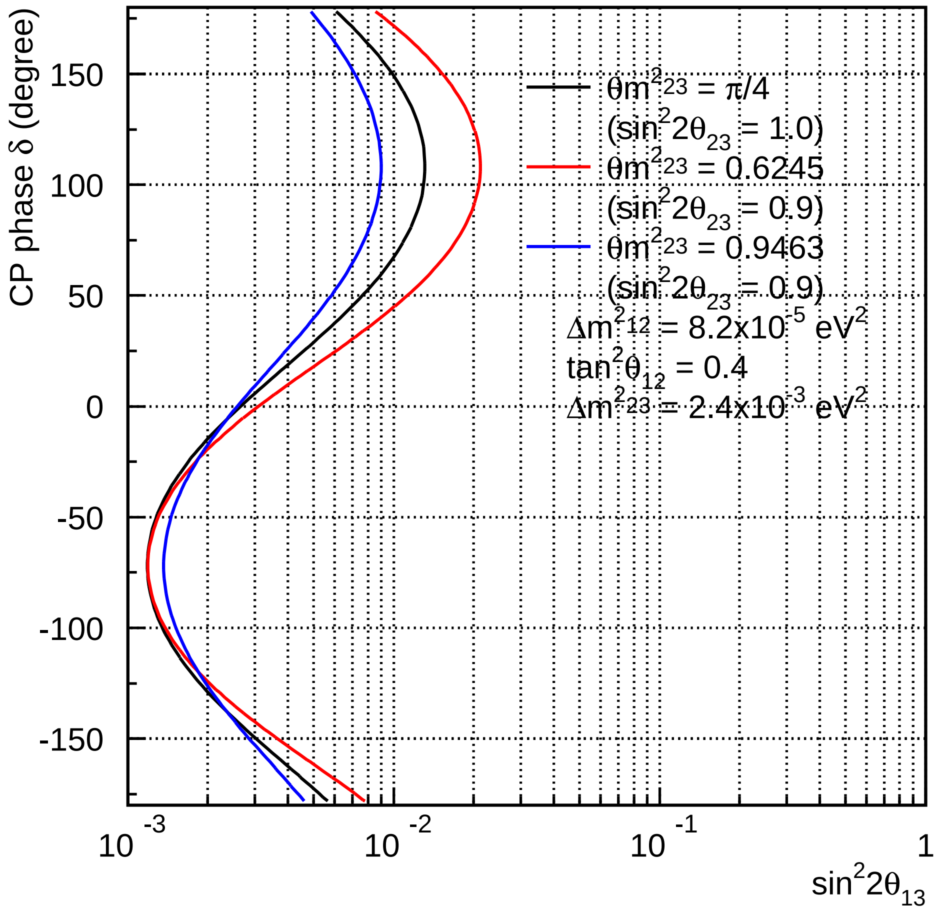
1.7±0.4 events subtracted



$\sin^2 2\theta_{13}$ and CP-δ

- 90% sensitivity to ν_e appearance
- Contribution from Δm^2_{12} is not subtracted





Maki-Nakagawa-Sakata Matrix and Oscillation probability

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{MNS} V_M^{CP} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\left(V_M^{CP} = \begin{bmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \right)$$

$$U_{MNS} = R_1(\theta_{23}) R_2(\theta_{13}) R_3(\theta_{12})$$

$e^{i\delta}$ **Dirac CP Phase**

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

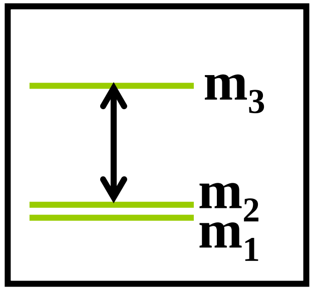
$$P(\nu_\alpha \to \nu_\beta) = -4\,\mathrm{Re} \sum_{j>i} U_{\beta j}^* U_{\alpha j} U_{\beta i} U_{\alpha i}^* \sin^2 \frac{\Delta m_{ij}{}^2 L}{4E} - 2\,\mathrm{Im} \sum_{j>i} U_{\beta j}^* U_{\alpha j} U_{\beta i} U_{\alpha i}^* \sin \frac{\Delta m_{ij}{}^2 L}{2E}$$

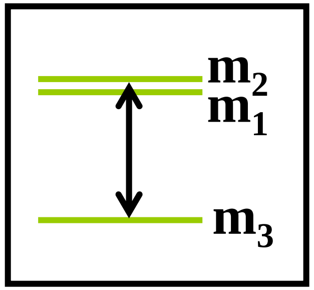
$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4 \sum_{j>i} \left|U_{\alpha i}\right|^2 \left|U_{\alpha j}\right|^2 \sin^2 \frac{\Delta m_{ij}{}^2 L}{4E}$$

Oscillations with two Δm^2's

Oscillation Probabilities

$$\Delta m^2_{12} << \Delta m^2_{23} \approx \Delta m^2_{13}$$
$$\Delta m^2_{ij} = m^2_j - m^2_i$$





$$P(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2(1.27\Delta m^2_{23}L/E_\nu)$$
$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_{13}\sin^2(1.27\Delta m^2_{23}L/E_\nu)$$
$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(1.27\Delta m^2_{23}L/E_\nu)$$
$$P(\nu_e \to \nu_\tau) = \cos^2\theta_{23}\sin^2 2\theta_{13}\sin^2(1.27\Delta m^2_{23}L/E_\nu)$$

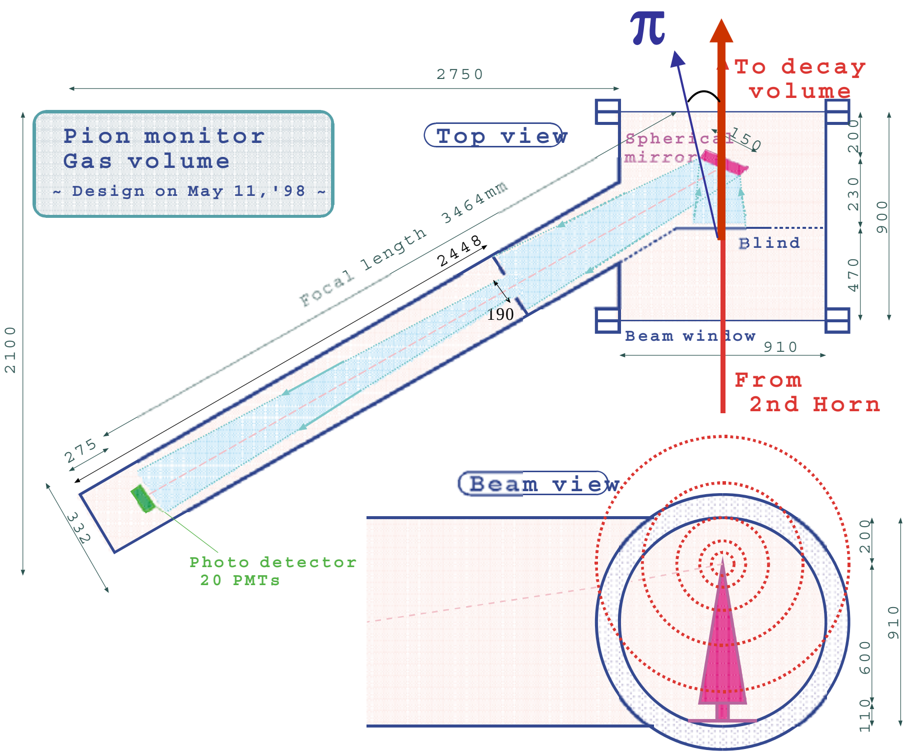
$$P(\nu_e \to \nu_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(1.27\Delta m^2_{12}L/E_\nu)_{MSW}\ (+1/2\sin^2 2\theta_{13})$$

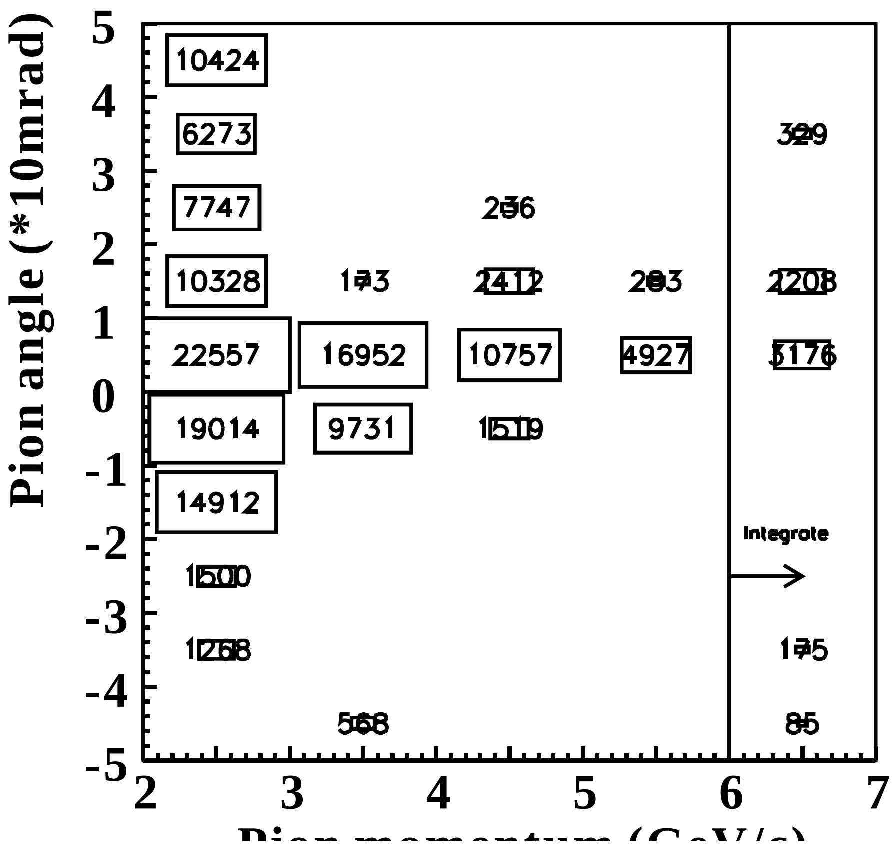
Pion Monitor : measure (p_π, θ_π) distribution

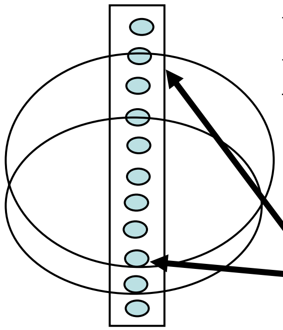
Gas Cherenkov detector: (insensitive to primary protons)

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

Choice of π Production model and error estimate

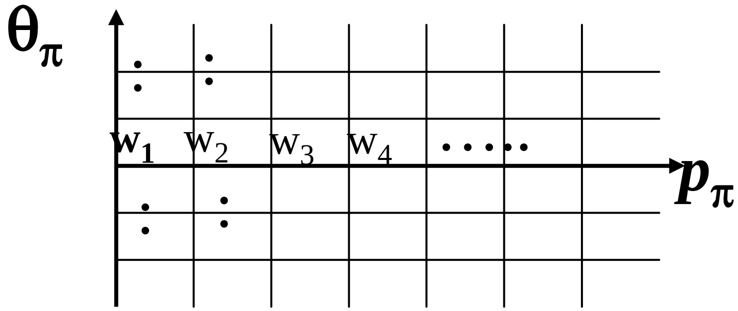


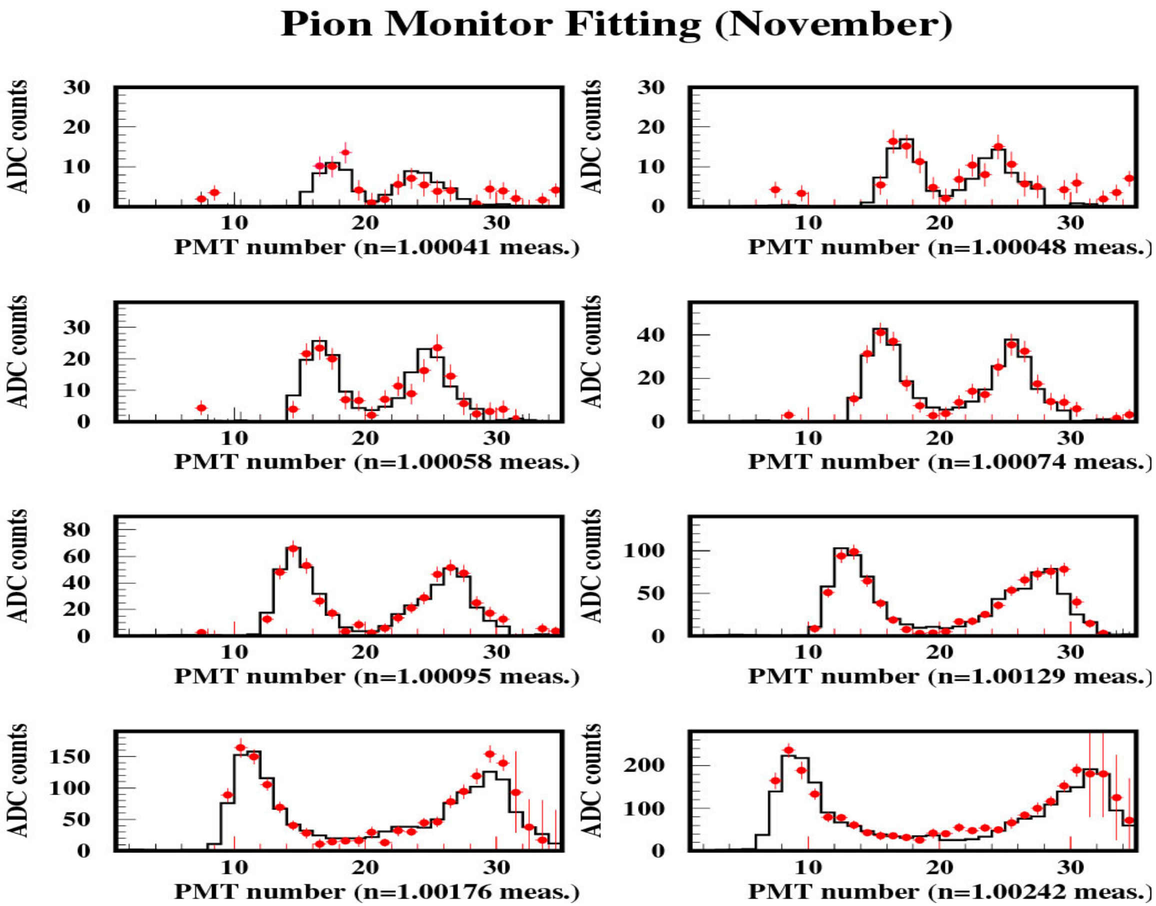




index of refraction : p_π threshold
position of ring : θ_π

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



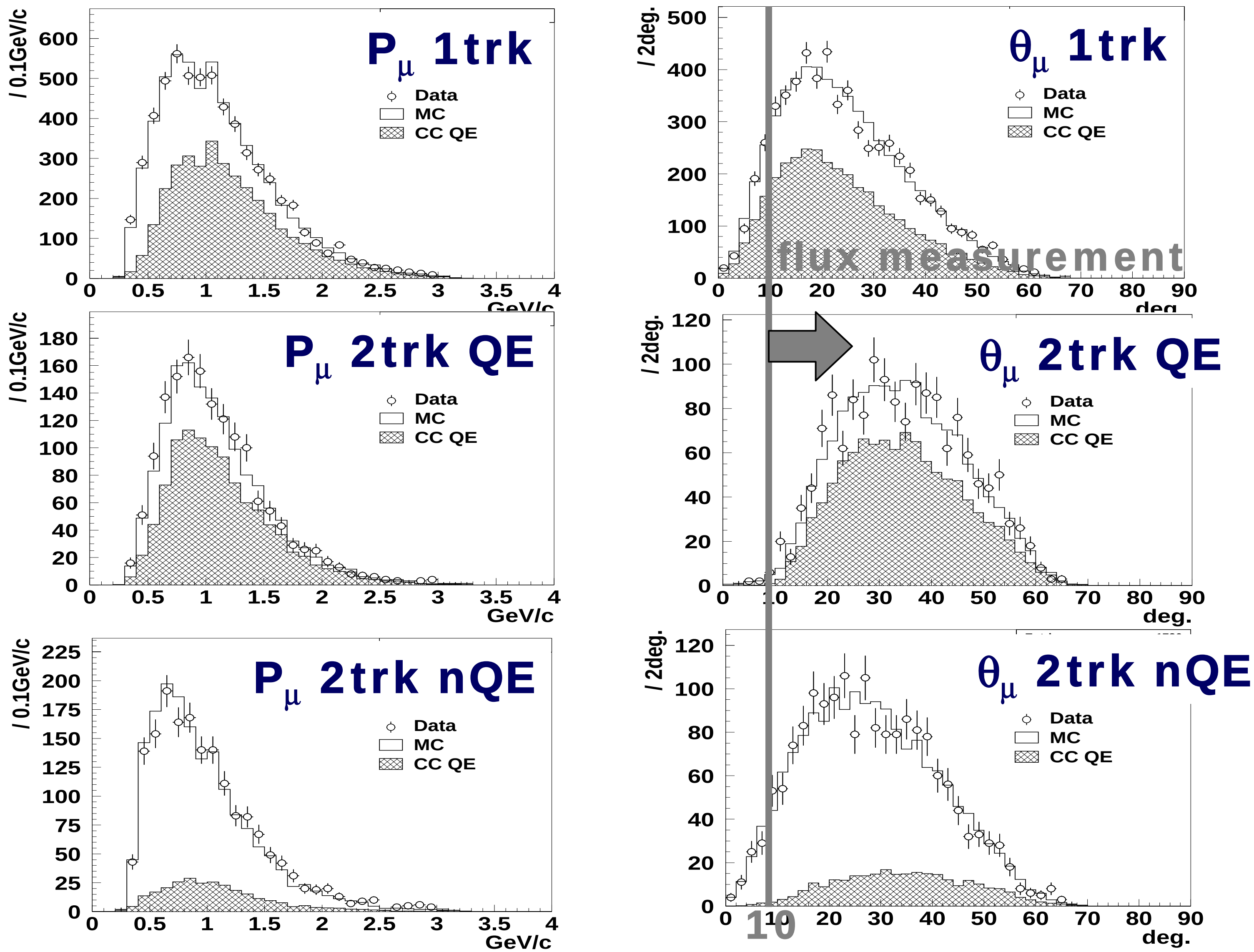


π production

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

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

SciBar (with measured flux)



SK systematic uncertainty

	SK efficiency						SK Energy scale
	<0.5 GeV	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	>2.5	
SK-I	3.7%	3.0%	3.4%	4.9%	4.9%	4.9%	2.0%
SK-II	4.5%	3.2%	8.2%	7.8%	7.4%	7.4%	2.1%

Neutrino mass from Cosmology

Data	Authors	$M_\nu = \Sigma\, m_i$
2dFGRS	Elgaroy et al. 02	< 1.8 eV
WMAP+2dF+…	Spergel et al. 03	< 0.7 eV
WMAP+2dF	Hannestad 03	< 1.0 eV
SDSS+WMAP	Tegmark et al. 04	< 1.7 eV
WMAP+2dF+ SDSS	Crotty et al. 04	< 1.0 eV
Clusters +WMAP	Allen et al. 04	$0.56^{+0.30}_{-0.26}$ eV

All upper limits 95% CL, but different assumed priors !