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(Present) Accelerator Neutrino Experiments

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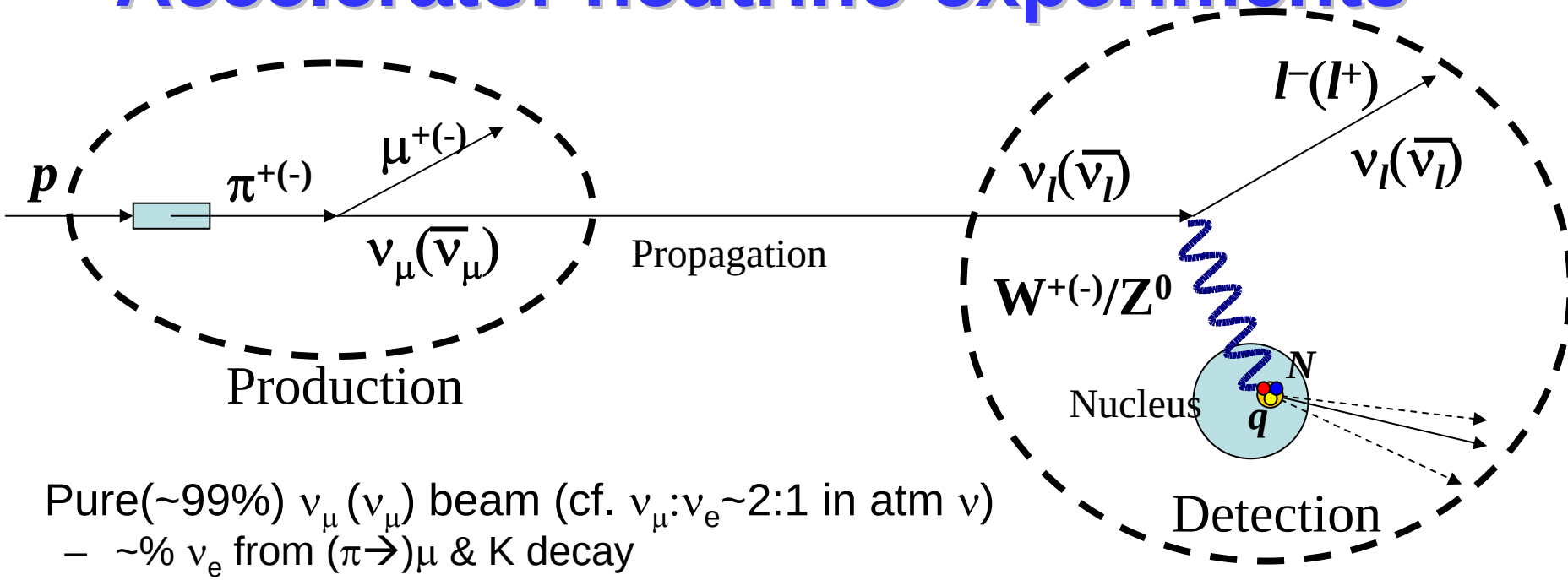
Contents

Accelerator neutrino experiments



- Pure(~99%) ν_μ (ν_μ) beam (cf. ν_μ:ν_e~2:1 in atm ν)
  - ~% ν_e from ($\pi\rightarrow$)μ & K decay
- Oscillation experiments
  - Flavor contents after propagation → mass & mixing in lepton sector
  - Measure ν_μ:disappearance, look for $\nu_{l\neq\mu}$: Appearance
- Non-oscillation experiments/measurements
  - ν_μ+Nucleus interactions in GeV region (resonance, coherent,..)
    - → for future precision oscillation measurements
  - Nucleon structure with weak bosons as probes (DIS)
  - Electroweak couplings of light quarks → $\sin\theta_W$ (DIS)

Neutrino mixing

If neutrino have finite mass, weak and mass eigenstates can differ

$$\left|\nu_l\right\rangle = \Sigma U_{li} \left|\nu_i\right\rangle$$

Weak — Mass eigenstates

m_i: 3 masses, Δm_{ij}: 2 differences

Maki-**N**akagawa-**S**akata **Matrix** $s_{ij}=\sin\theta_{ij}$, $c_{ij}=\cos\theta_{ij}$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

3 mixing angles and 1 CPV phase

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

$\sin^2 2\theta_{12}\sim 0.8$ (Solar)

$\sin^2 2\theta_{23}\sim 1$ (Atm ν)

Reactor

Long baseline experiments

Neutrino oscillation

Oscillation Probability

$$P_{l\to m} = \left|\left\langle \nu_m(t) \middle| \nu_l(0)\right\rangle\right|^2 = \delta_{ml} - 2\sum_{i<j} \mathrm{Re}\left[\left(U^*_{mi}U_{li}\right)\cdot\left(U_{mj}U^*_{lj}\right)\cdot\left\{1-\exp\left(-i\frac{\Delta m^2_{ij}}{2E}L\right)\right\}\right]$$

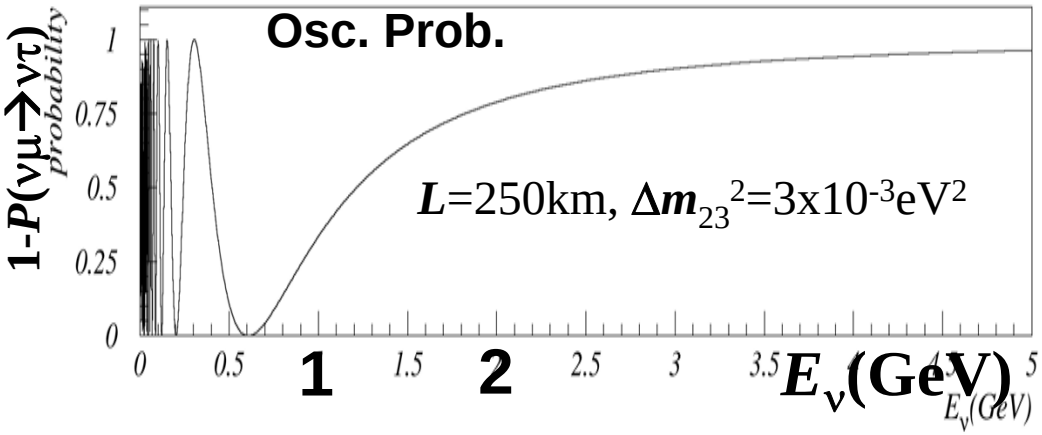
L : flight length, E : neutrino energy, $\Delta m^2_{ij} \equiv m^2_i - m^2_j$ mass eigenvalues

$P_{l\to m} \neq \delta_{ml} \Leftrightarrow \Delta m_{ij} \neq 0$, Non-zero off-diag U

In 2 flavor approximation

L (km), E (GeV)

$$P\left(\nu_\mu \to \nu_\tau\right) = \left|\left\langle \nu_\tau(t) \middle| \nu_\mu(0)\right\rangle\right|^2 = \sin^2 2\theta_{23} \sin^2\left(1.27\frac{L}{E}\Delta m_{23}{}^2\right)$$



Signature:

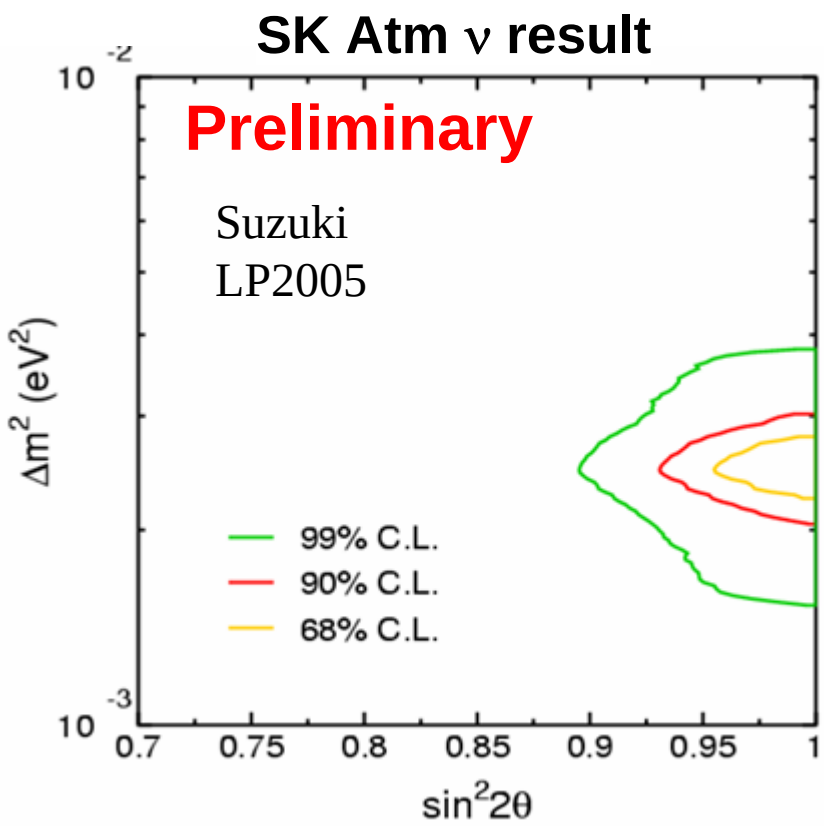
- Decrease of original flavor (appearance of diff flavor)
- Spect. Distortion

Osc. Max

- $1.27\Delta m_{23}{}^2 L/E = \pi/2$
- E=0.6GeV @L=250km,Δm^2=0.003

Long baseline osc. experiments

- Evidence of ν osc in Atm ν at SK (1998)
  - First observation contradictory to SM
  - Small but non-zero mass!!
  - Large mixing!!!
- 1st generation LBL experiments
  - Confirmation of SK atm ν results
  - w/ different, controlled systematics
  - K2K (1999~2004)
  - MINOS (2005~)
  - CNGS(2006~)-OPERA/ICARUS



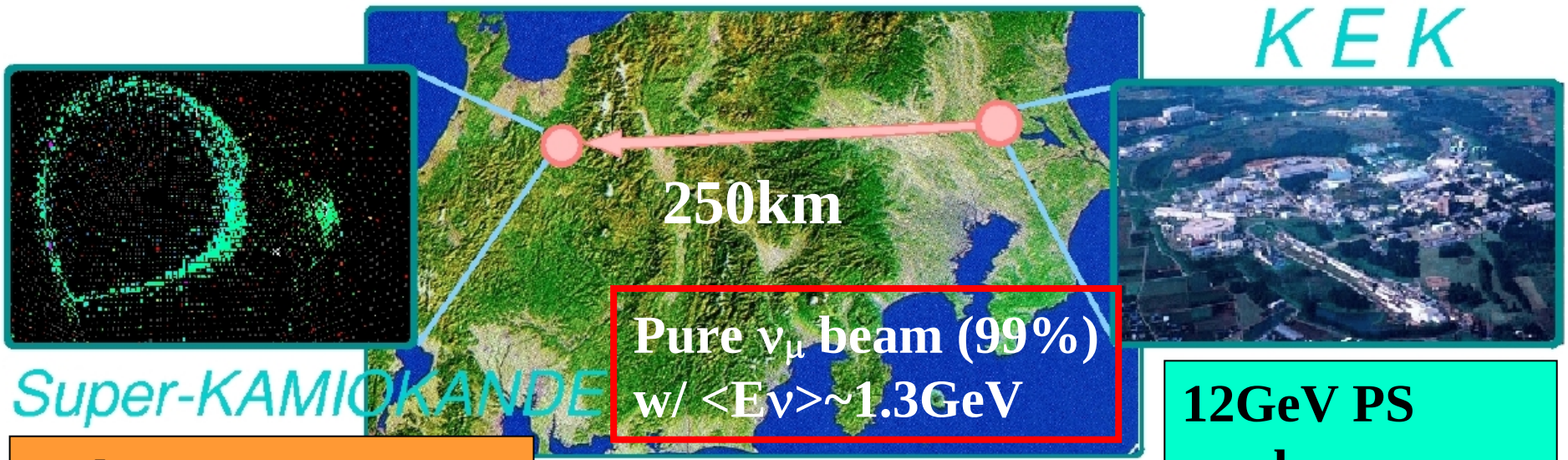
$\Delta m^2 = 2.5 \times 10^{-3}$ eV^2, $\sin^2 2\theta = 1.0$

$2.0 < \Delta m^2 < 3.0 \times 10^{-3}$ eV^2, $\sin^2 2\theta > 0.93$ (90%CL)

K2K experiment

First long baseline (***250*km**) neutrino experiment.

ν_μ disappearance and ν_e appearance



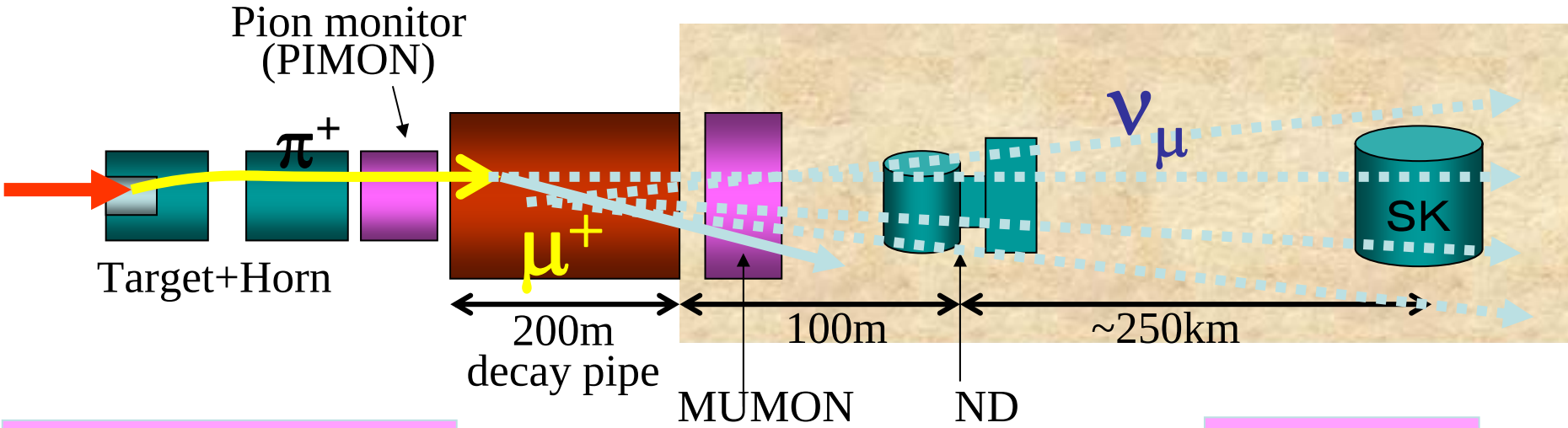
Pure ν_μ beam (99%)
w/ <Eν>~1.3GeV

50 kton Water Cherenkov detector

12GeV PS
- **ν_μ beam**
- **Beam monitor**
- **Near detector**

Experiment started in April, 1999
Terminated in November, 2004

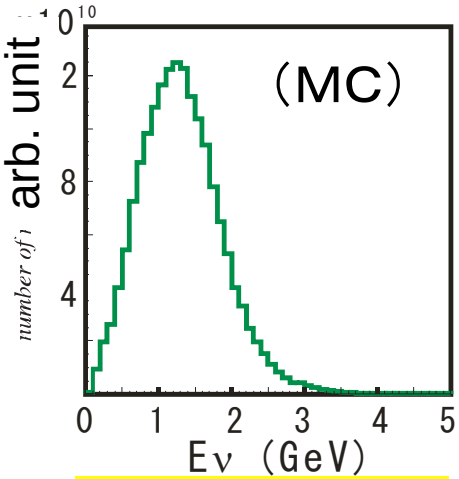
Strategy of K2K

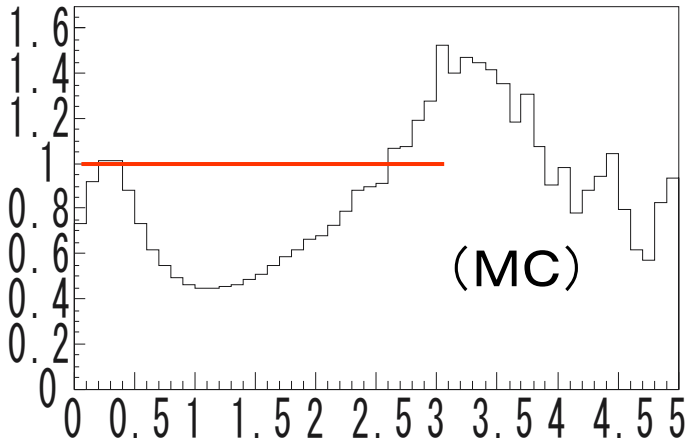


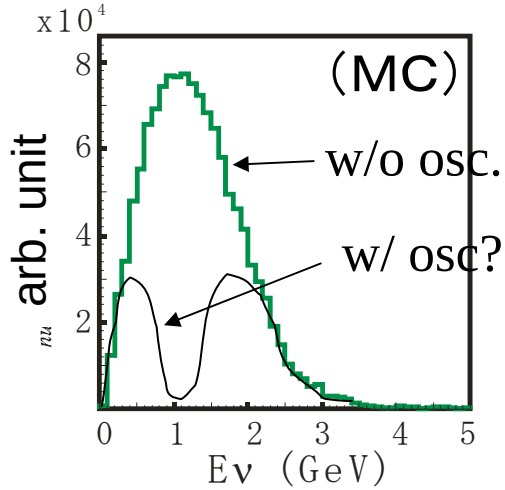
ν_μ @ production
- Abs. norm: 1KT
- spectrum:1KT&FGD

Extrapolate using
Far/Near spect. ratio (MC)

Predict
- # of events
- ν_μ spectrum







measure w/ ND

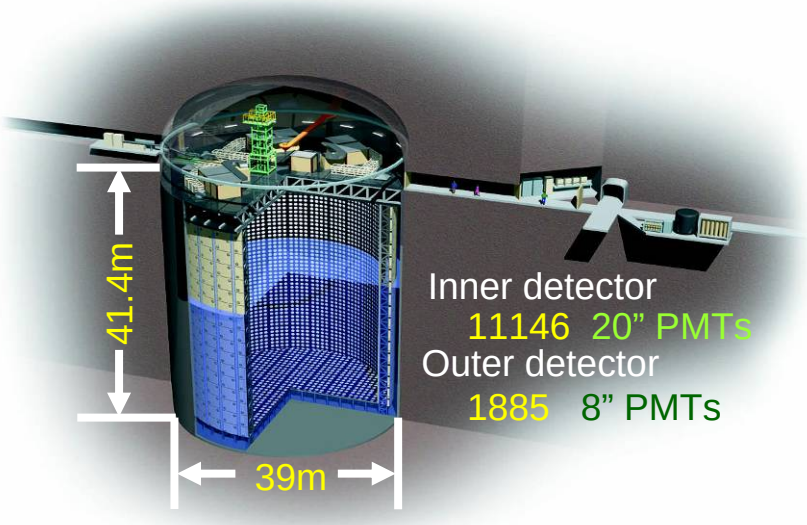
Confirmed by PIMON/HARP

Neutrino Detectors

K2K-I

From Mar.1999 ~ Jul.2001

Super-Kamiokande I



K2K-II

From Dec.2002 ~ Nov. 2004

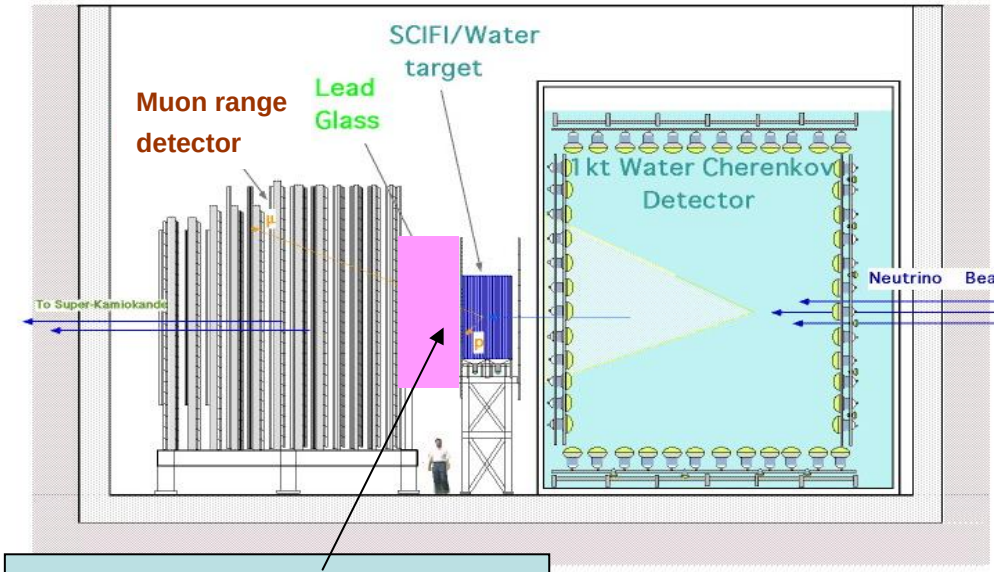
Super-Kamiokande II

Inner detector

➔ ~5200 PMTs with covers

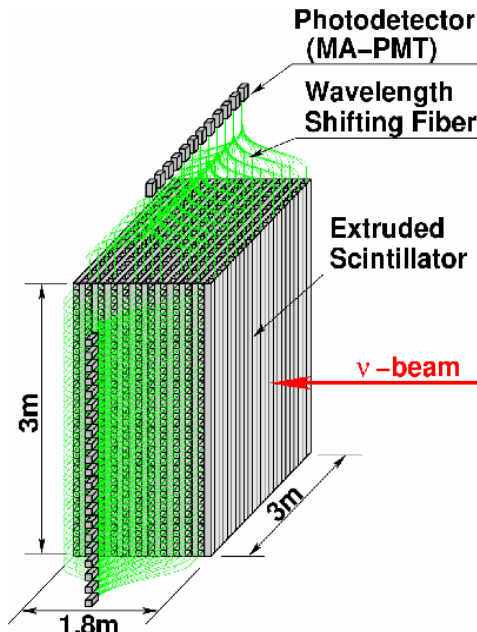
Outer detector :1885 PMTs

Near neutrino detectors

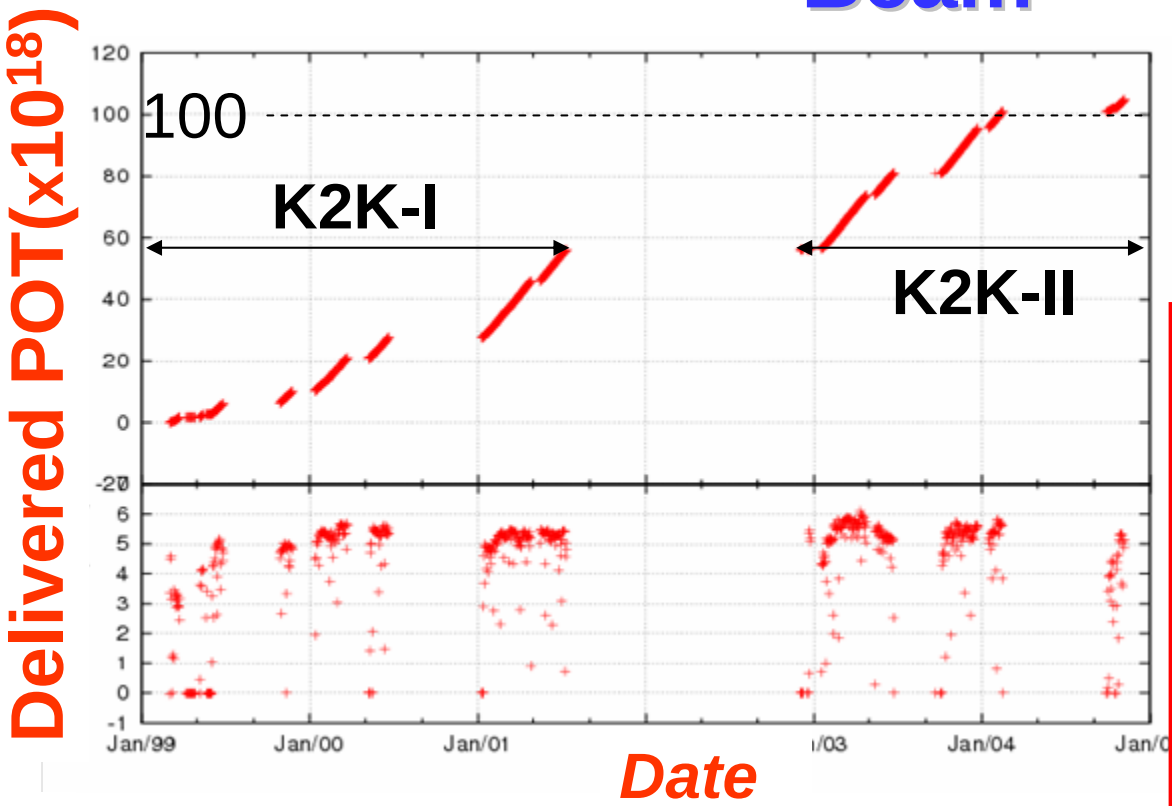


SciBar detector

- Oct. 2003~
- Fully active fine grained scintillation tracker
- Good for multi track, low E thresh.
- ➔ high stat ν int studies



Beam



POT delivered

K2K-I : 0.561×10^{20} POT

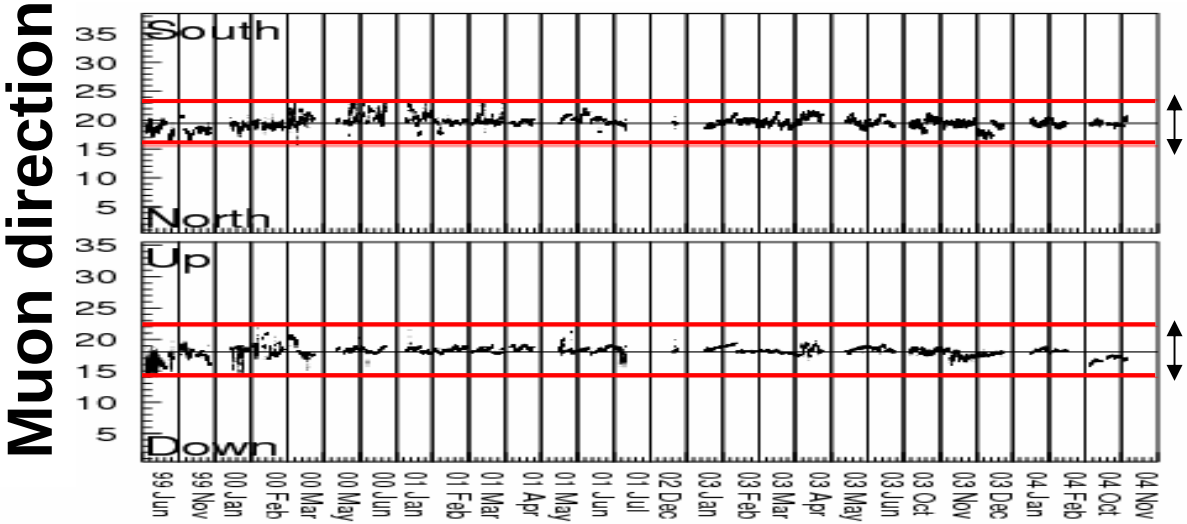
K2K-II: 0.488×10^{20} POT

Total POT delivered
Jun.1999 – Nov.2004

1.049×10^{20} POT

Used for analysis

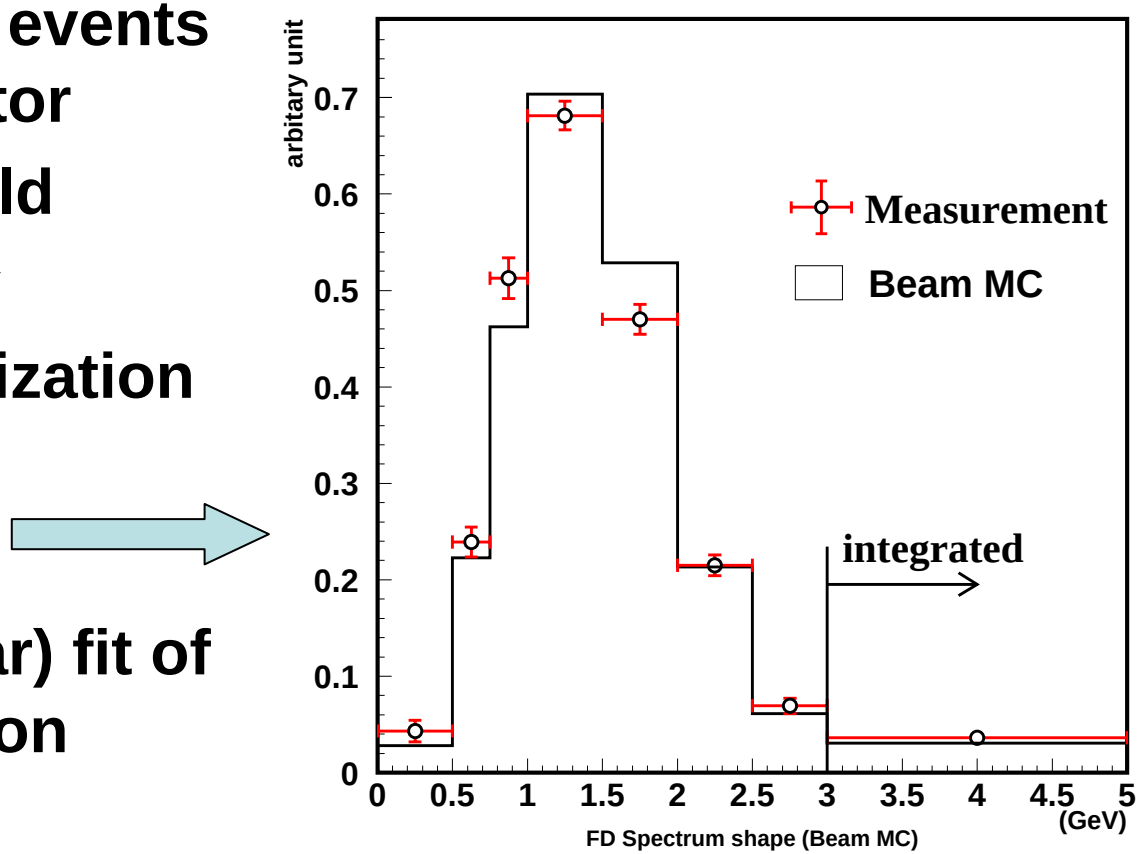
0.922×10^{20} POT



Near detector measurements

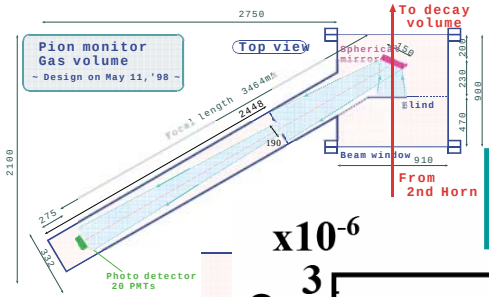
- **Normalization**
  - **Total number of events in 1kt-WC detector**
  - **100MeV threshold**
  - **74.9% efficiency**

  → Over all normalization
- **Spectrum**
  - **Combined (1kt+Scifi+SciBar) fit of (p_μ, θ_μ) distribution**

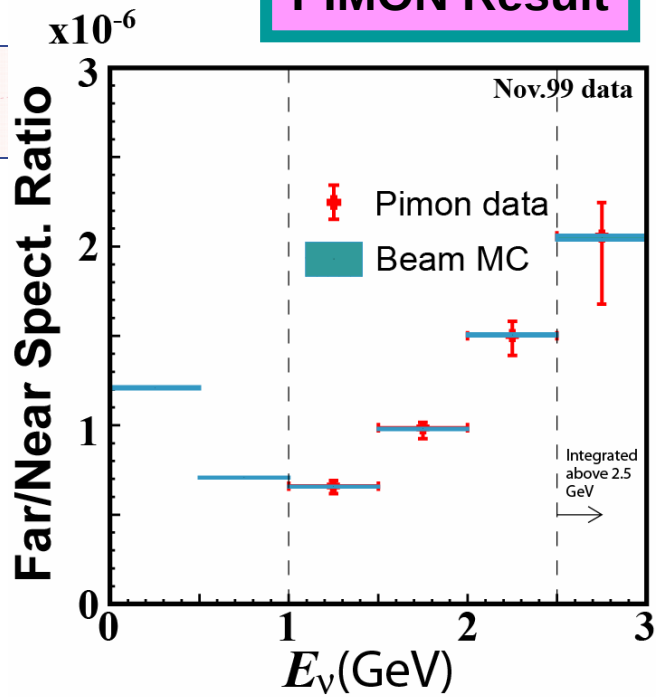


F/N spectrum ratio for extrapolation

- Use beam MC for F/N ratio central value
  - Sanford-Wang model w/ Cho(CERN) data
  - Confirmed by in-situ PIMON & HARP measurements
- Error
  - >1GeV: PIMON measurement error
  - <1GeV: Model parameter uncertainty

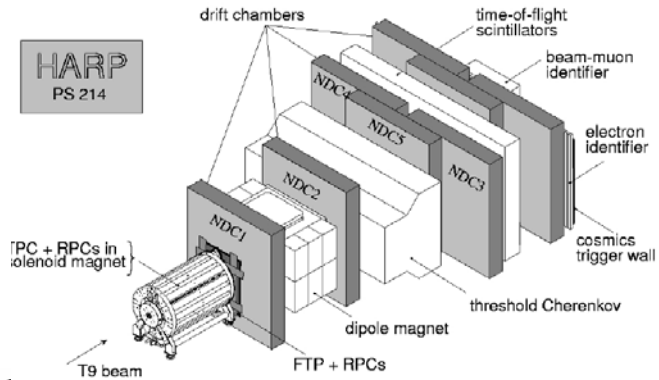


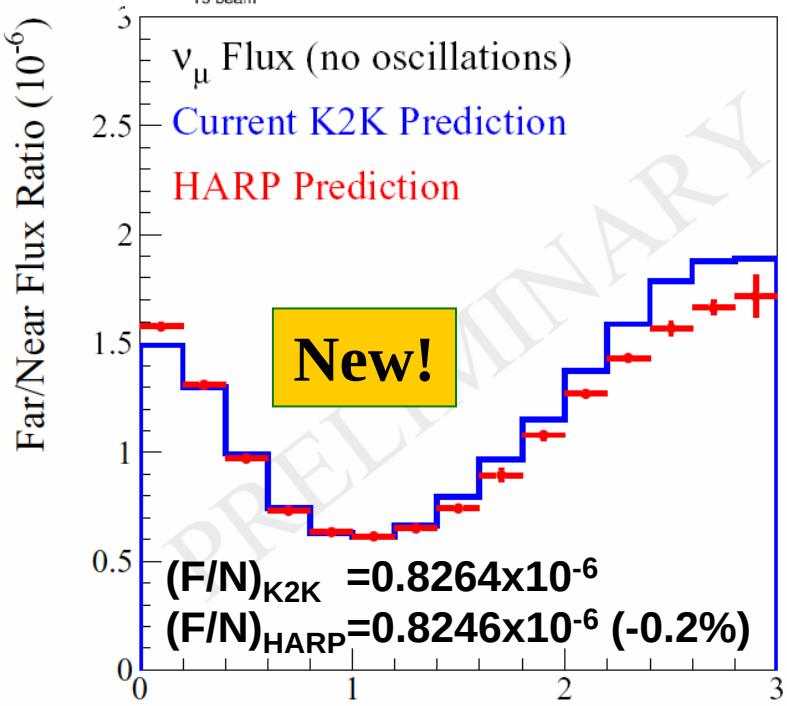
PIMON Result



HARP Result

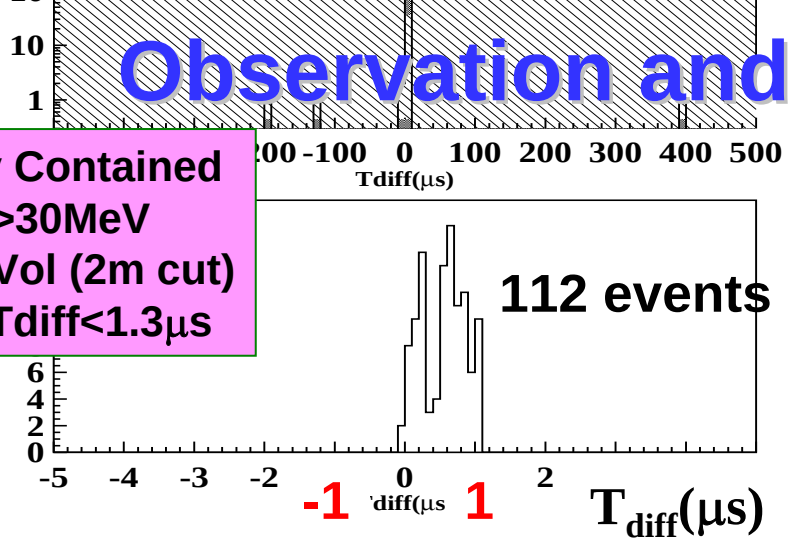
Hadron prod meas. at CERN-PS 12.9GeV/c ***p*** on Al





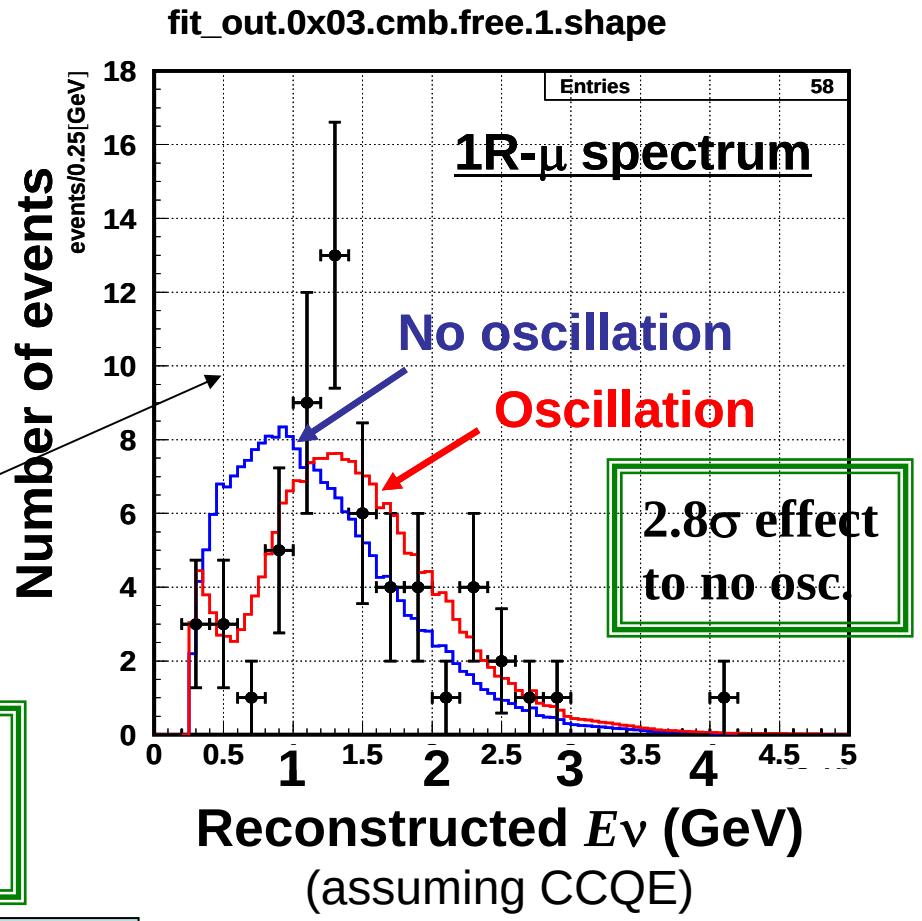
Observation and Expectation at SK

- Fully Contained
- Evis>30MeV
- Fid. Vol (2m cut)
- 0.2<Tdiff<1.3μs



	N_{sk}^{obs}	N_{sk}^{pred}
All	**112**	**155.9**
1 ring	67	99.0
μ-like	58	90.8
e-like	9	8.2
multi-ring	45	56.8

Deficit 3.1σ



Sys. err on # of evts

155.9 +11.5(7.4%) - 10.2(6.5%)

Dominant error

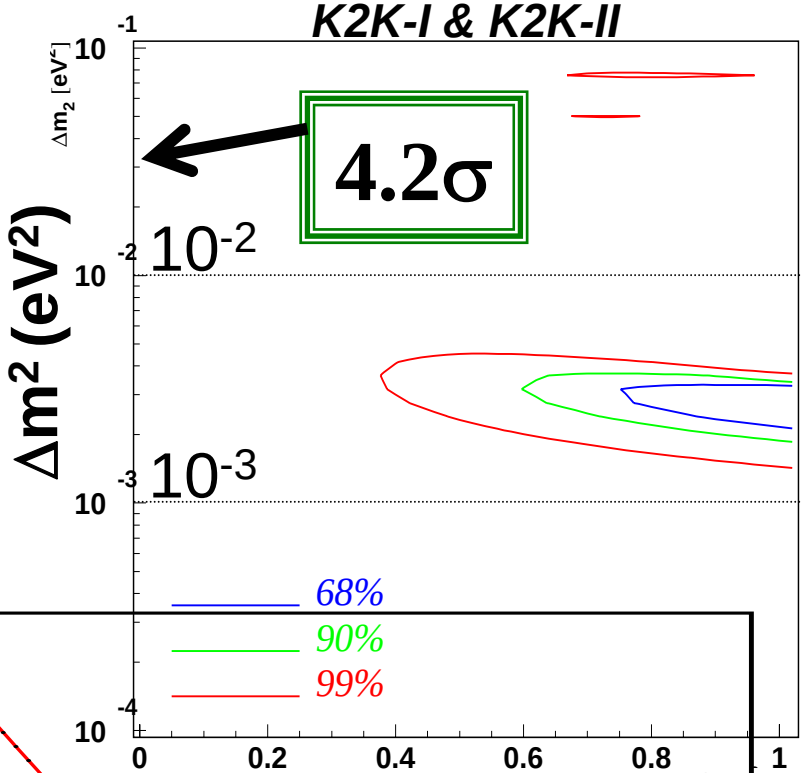
Far/Near +7.9evt - 7.7evt

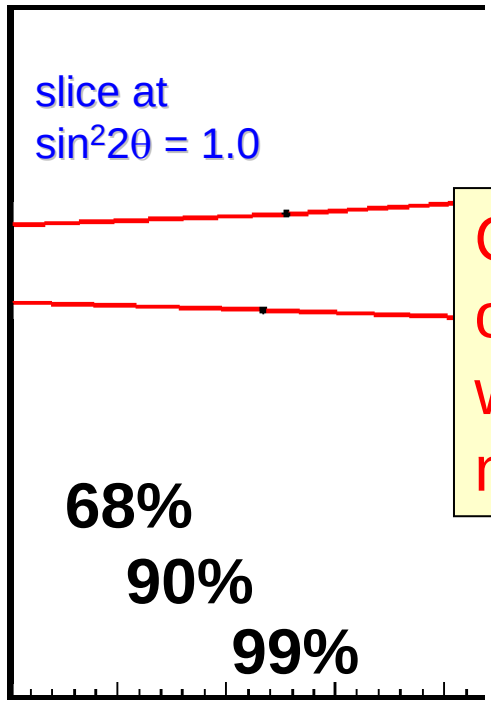
Norm. +7.5evt - 7.6evt

Spectrum syst. (1 ring μ) (depend on the energy bin)

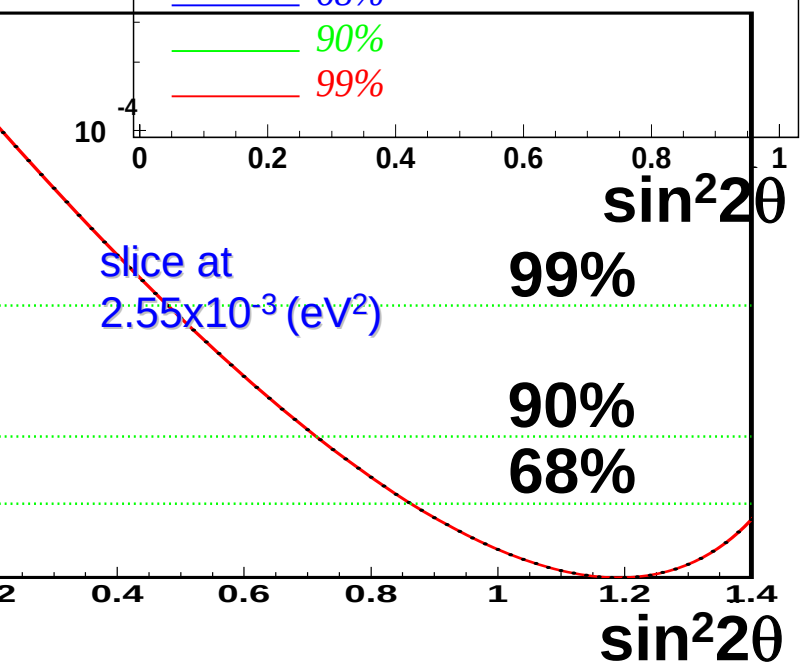
Ring count	~3~5%
Fiducial volume	2%
Particle Id	<1%
Energy scale	~2%

Allowed parameter region (#evts/spect combined)





Confirmation of the oscillation consistent with the atmospheric neutrino oscillation



Best fit value

(all region)

$\sin^2 2\theta = 1.19 \pm 0.23$

$\Delta m^2 = (2.55 \pm 0.40) \times 10^{-3}$ eV^2

(in physical region)

$\sin^2 2\theta = 1.0$

$\Delta m^2 = (2.76 \pm 0.36) \times 10^{-3}$ eV^2

$1.88 \times 10^{-3} \leq \Delta m^2 \leq 3.48 \times 10^{-3}$ eV^2 (90%CL) @ $\sin^2 2\theta = 1$

Electron appearance

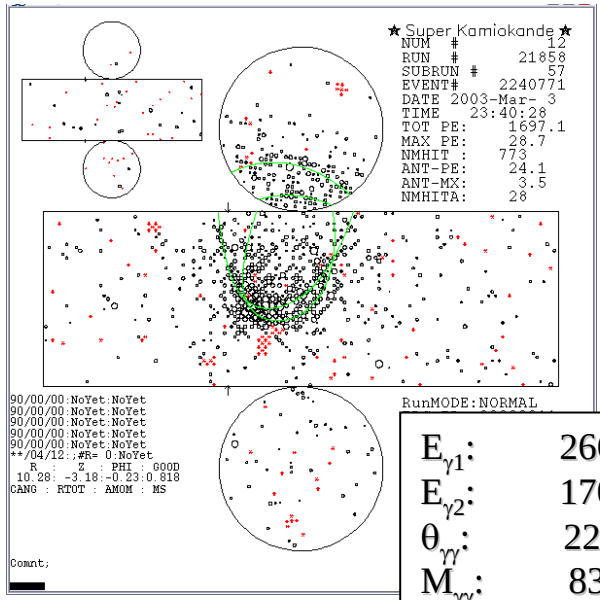
For K2KI+II

FCFV	112 ev
Single Ring	67
e-like	9
Further Reduction	
tight e –ID	8
Evis>100 MeV	7
No e from $\mu \rightarrow e$	5
Pi0 cut	1

Efficiency 35.7% for K2K-I

40.9% for K2K-II

Candidate



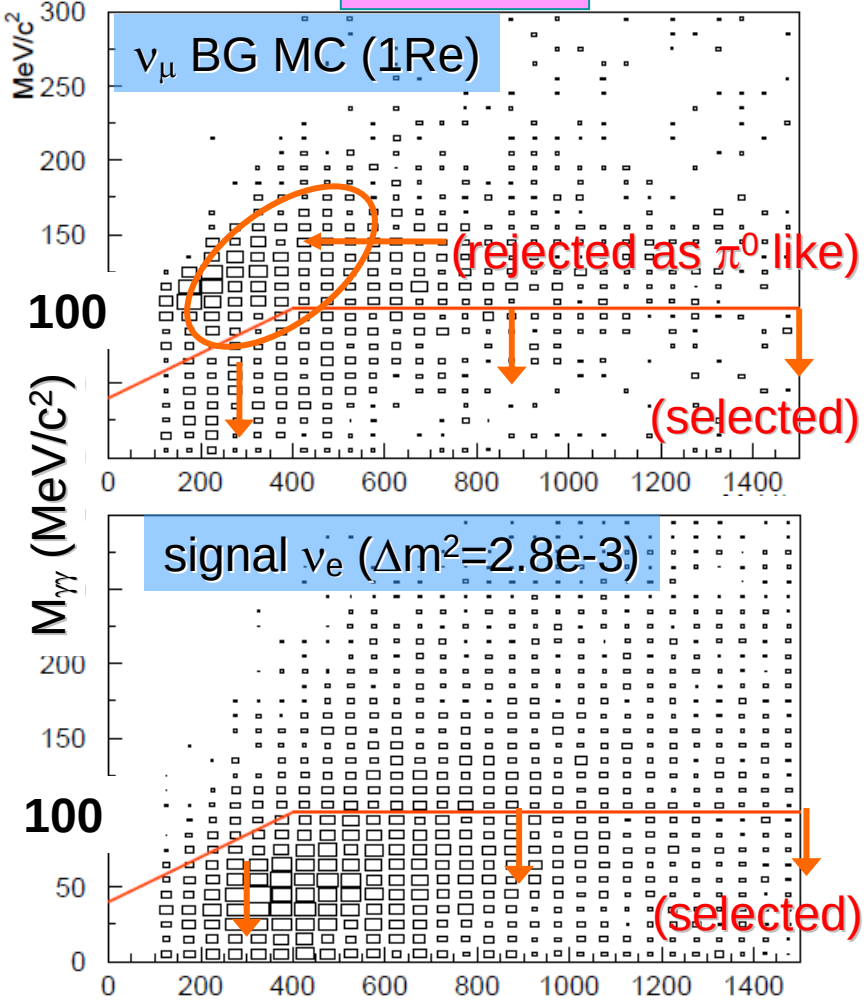
$E_{\gamma 1}$: 266.7MeV
$E_{\gamma 2}$: 170.8MeV
$\theta_{\gamma\gamma}$: 22.5 deg.
$M_{\gamma\gamma}$: 83.1MeV/c^2

BG	ν_μ int.	beam ν_e
1.63 ev	1.25	0.38
K2K-I	0.60%	17.1%
K2K-II	0.80%	20.4%

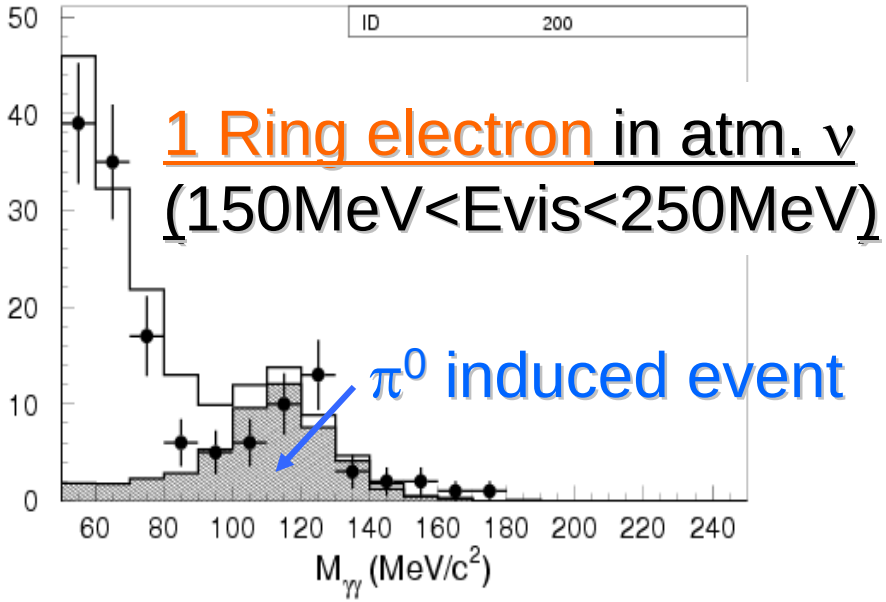
Neutral pion rejection

- Pi0 cut: Forced to find 2nd e/γ-ring

K2K-MC



SK Atm ν DATA/MC



- **Reject 70% of neutral pions**
  (efficiency loss 30%)

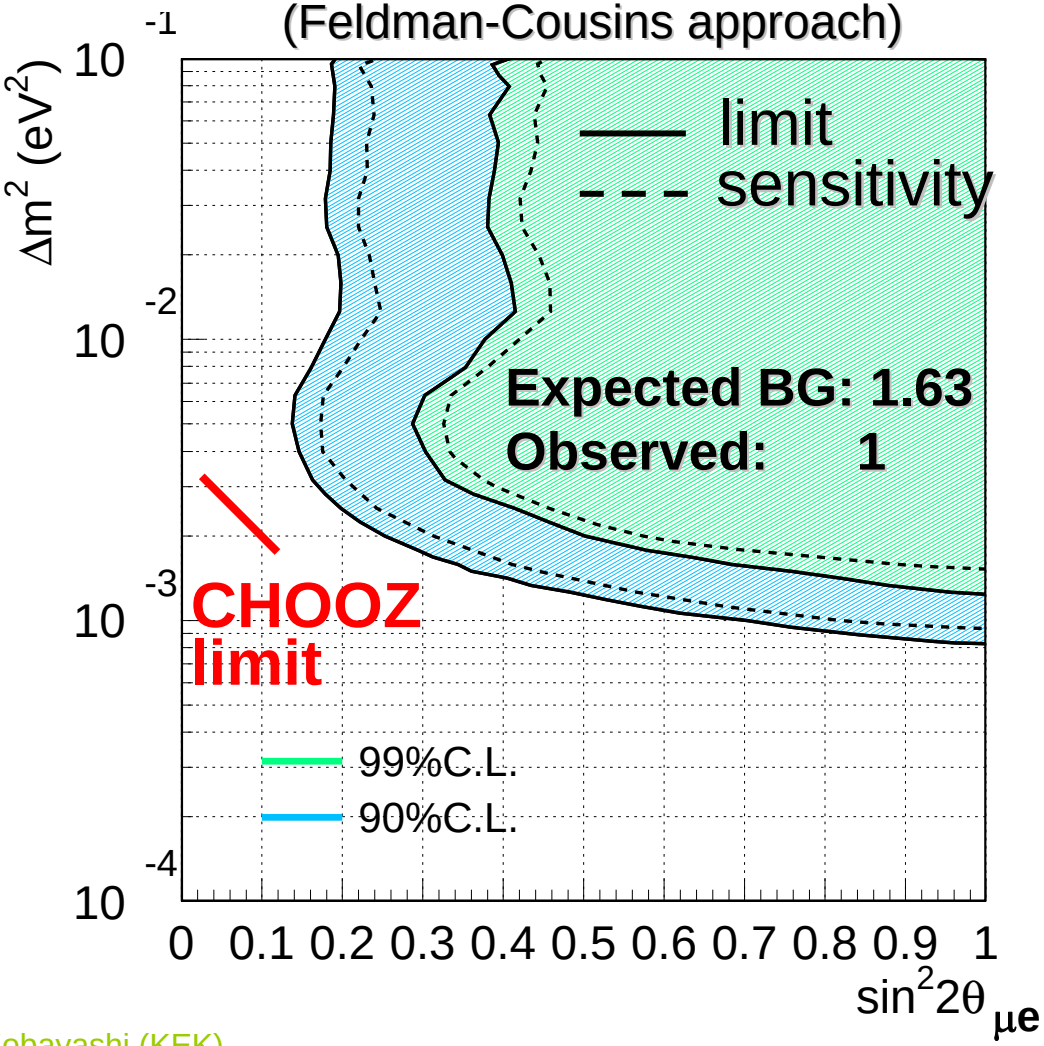
Limit on the oscillation parameters

Expected # of electron cand.

$$N^{SK} = N^{BG}_{\nu_\mu}(\Delta m^2) + N^{BG}_{BEAM\,\nu_e} + N^{SIG}_{OSC\,\nu_e}(\sin^2 2\theta, \Delta m^2)$$

K2K-1+K2K-2

(Feldman-Cousins approach)

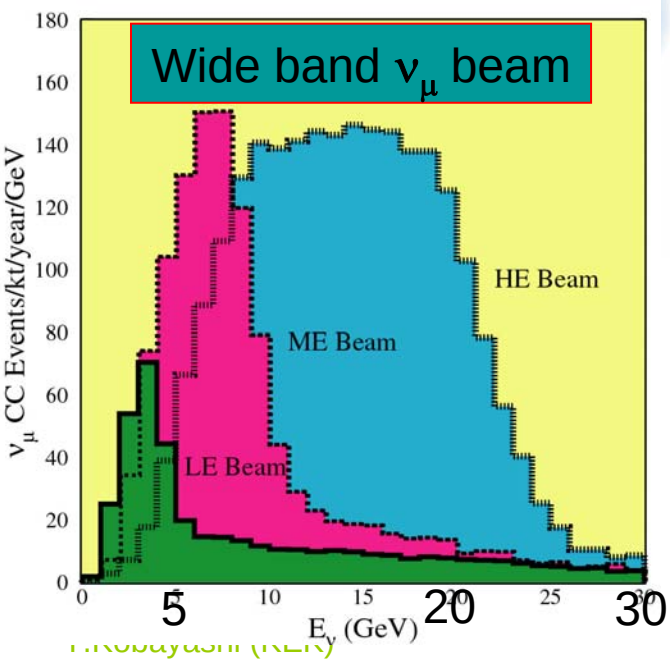


$\sin^2 2\theta_{\mu e}$ <0.18 @2.8x10^{-3}eV^2

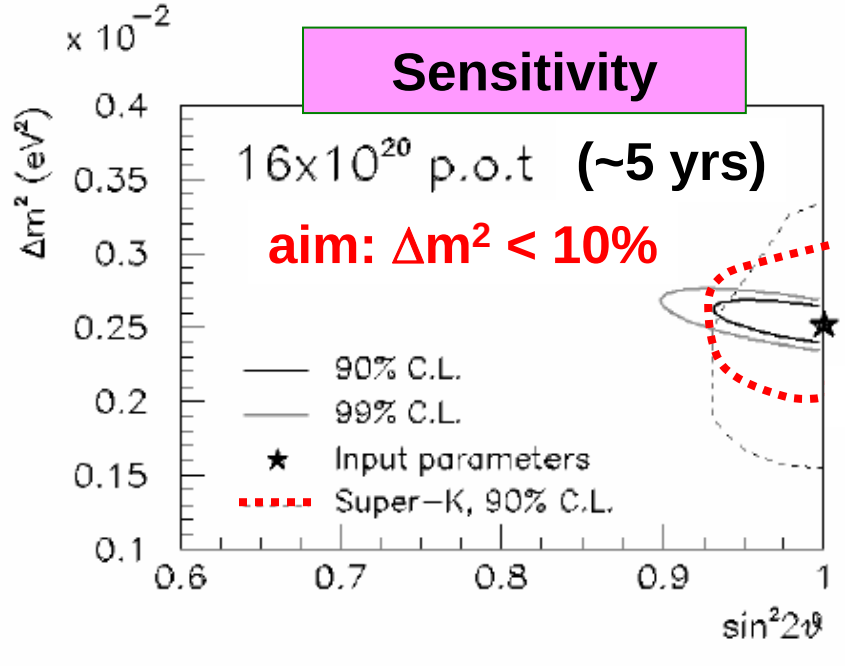
<0.16 @3x10^{-3} eV^2
<0.25 @2x10^{-3} eV^2

MINOS

- FNAL 120GeV Main Injector → Soudan mine (735km)
- Horn-focused wide band ν_μ beam
  - Tunable
  - ν_μ CC int./MINOS/yr ~ 2,500 (LE beam)
- (magnetized)Iron-scintillator sampling calorimeter
  - 5,400tons @ far, 980tons @ near
- ν_μ disappearance
  - Oscillatory behavior
  - Precise determination of Δm_{23}^2, θ_{23}

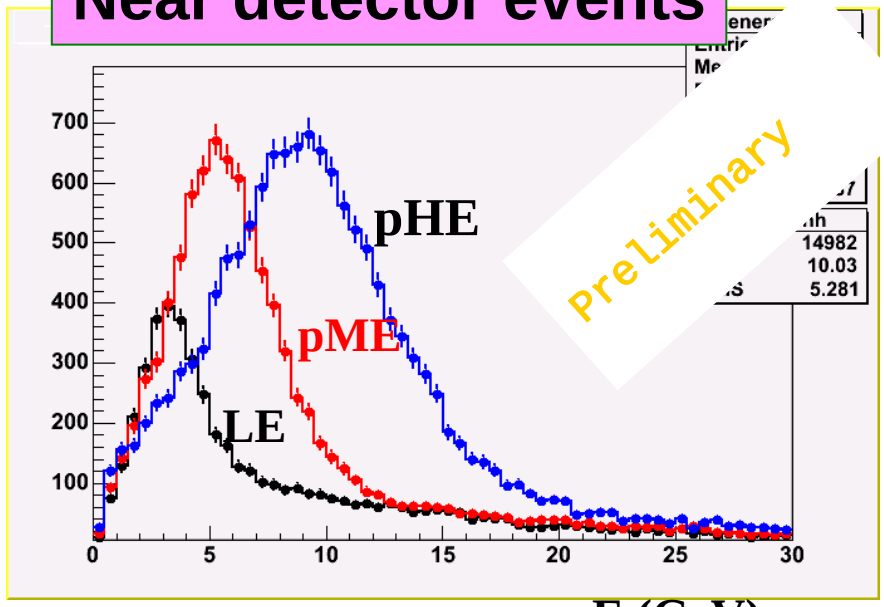


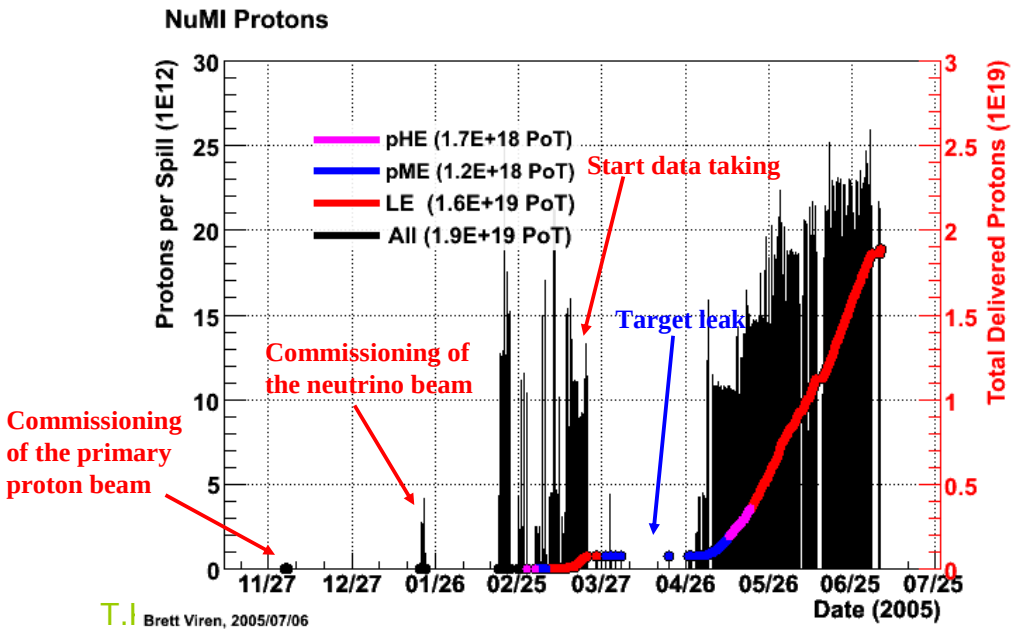
Sensitivity



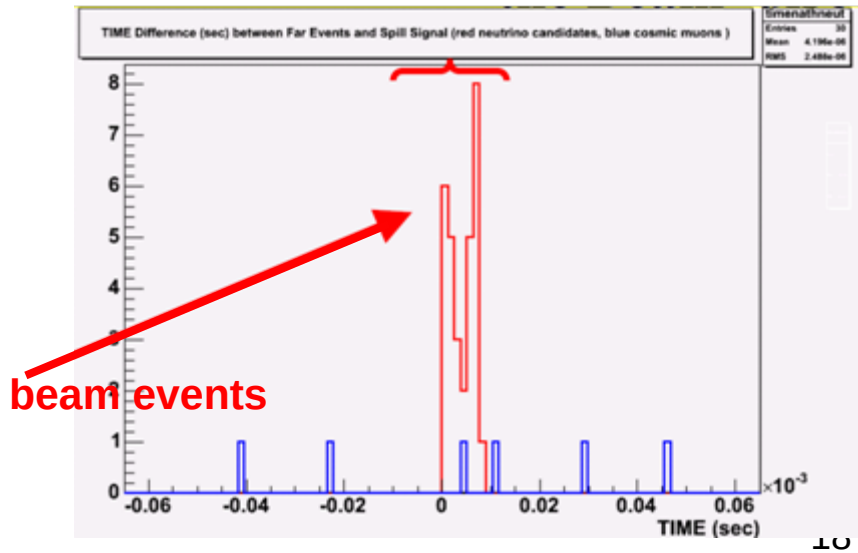
If θ_{13} is close to the CHOOZ limt, MINOS will see >3σ effect in ~3 years of running

Near detector events

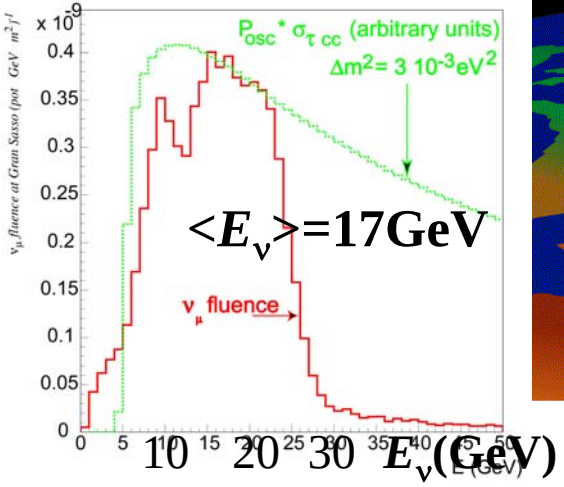


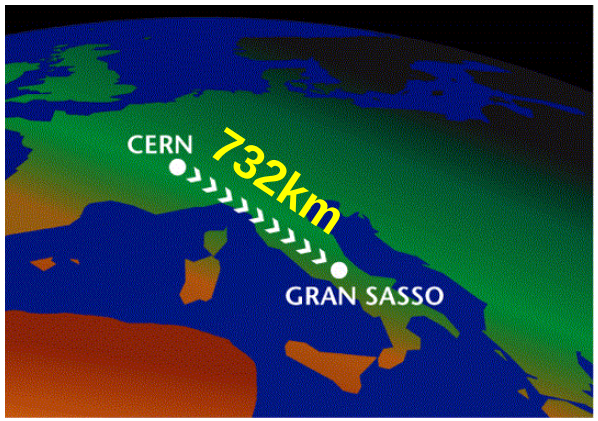


Far detector events



CERN neutrino to Gran Sasso (CNGS)





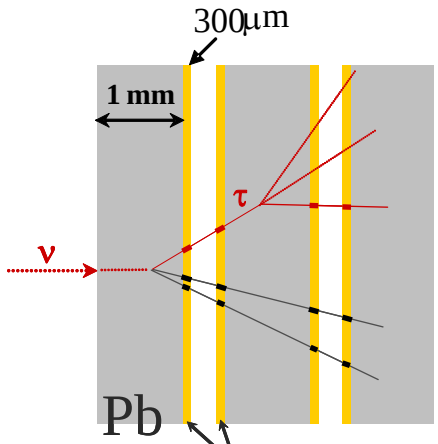
- CERN 400GeV SPS → Gran Sasso
- **ν_τ appearance** (+ ν_e appearance)
- 4.5x10^{19}POT/yr
- Wide band ν_μ beam
- ~2900ν_μ CC events/kt/yr
- **First beam to GS May 2006**
  - Underground civil const. finished Jun.20,2003
  - Beam line instrumentation being installed

OPERA (next next talk for detail!)

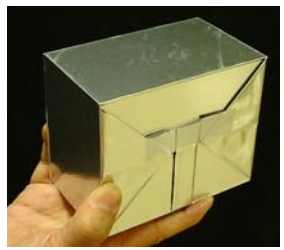
- τ ID by decay topology (kink)
- Emulsion-Counter Hybrid
- Total mass 1700 ton
- For 5yrs @4.5x1019POT/yr(200d)
- 12.8 $\nu\tau$ (0.8BG) for 2.4x10^{-3} eV^2
- Start in June, 2006 with 850 tons emulsion film

ICARUS: Liq. Ar TPC

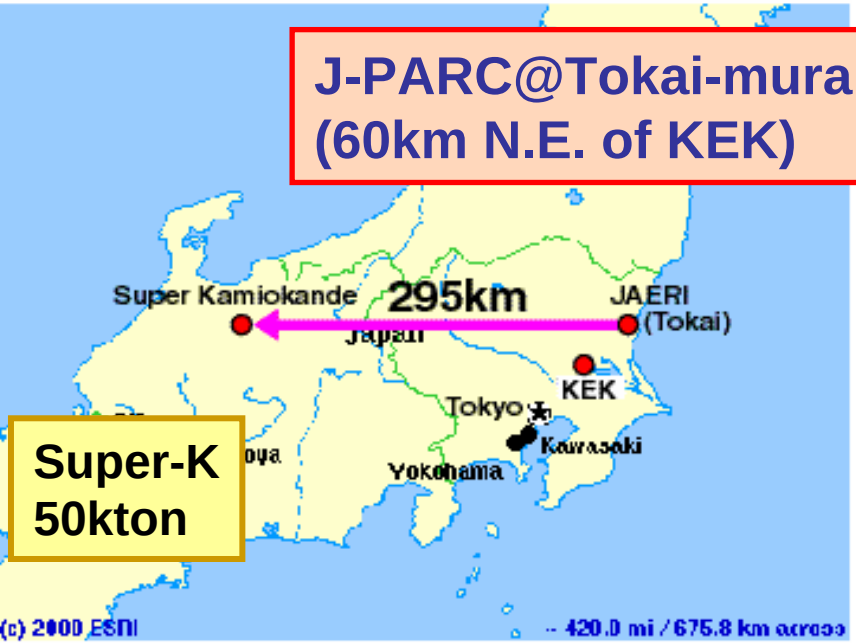
- 600ton in mine (T600).
- T1200 "abandoned" by INFN



OPERA ECC

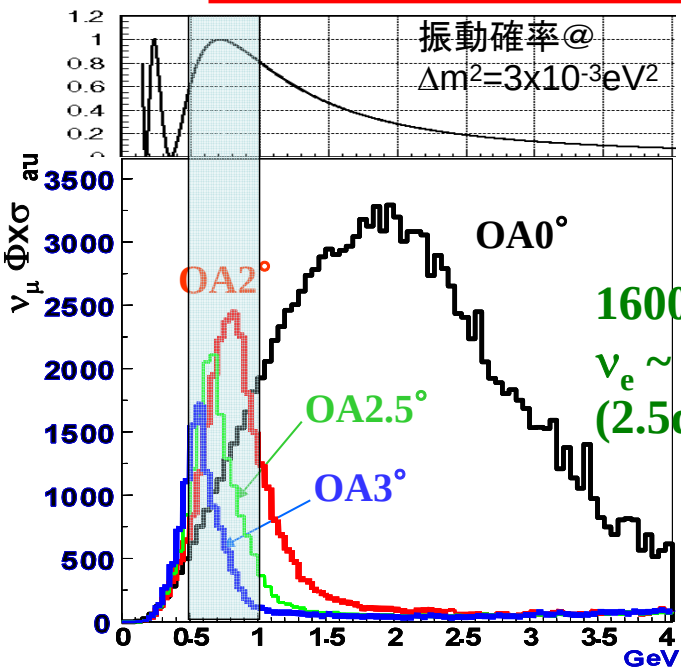


Tokai-to-Kamioka (T2K) (~100xK2K)



- J-PARC (50 GeV/750kW PS)
  - Construction: 2001~2007
  - Operation: 2008~
- T2K (Approved in Dec-03)
  - Construction: 2004~2008
  - Experiment: 2009 ~

Off-axis beam: Narrow intense



1600ν_μCC/yr/22.5kt
ν_e ~ 0.4% at peak (2.5deg)

Phase 1 (0.75MW + SK)

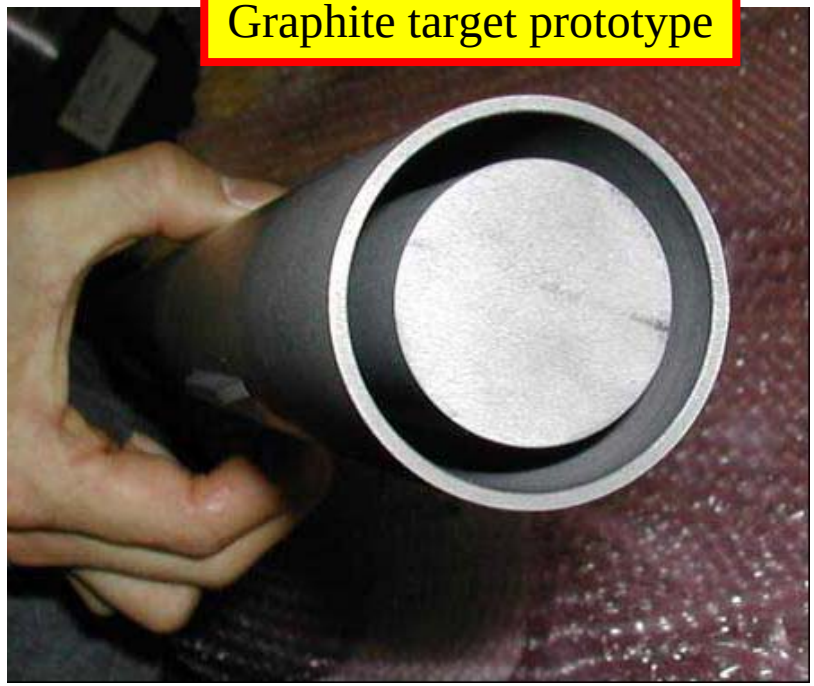
- $\nu_\mu \rightarrow \nu_x$ disappearance
  - Precise Δm^2, $\sin^2 2\theta$
- $\nu_\mu \rightarrow \nu_e$ appearance
  - Finite θ_{13} ?

Phase 2 → 4MW, Mton, CPV

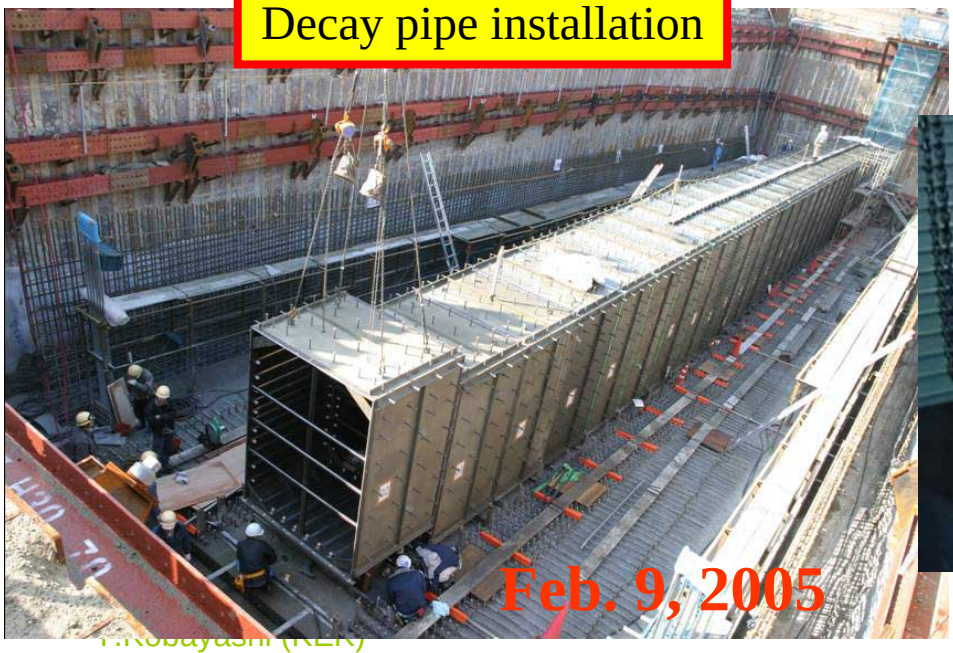
Construction status

Superconducting combined function magnet

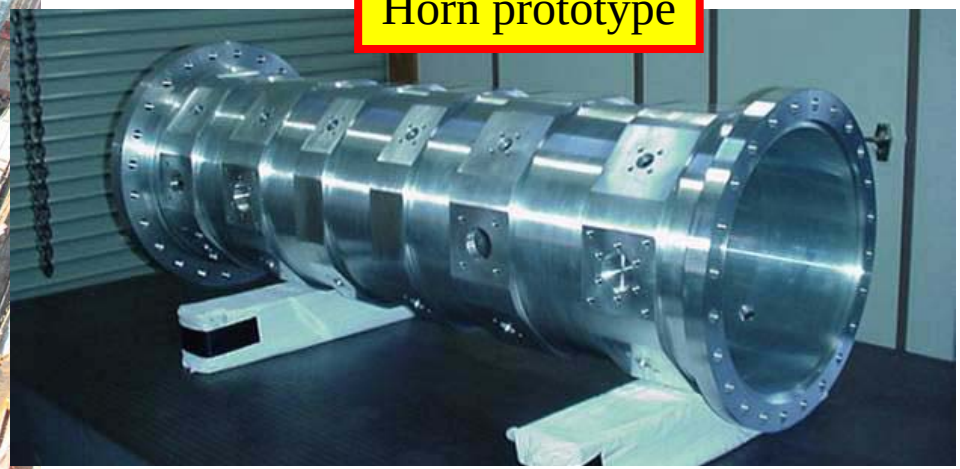
Graphite target prototype



Decay pipe installation

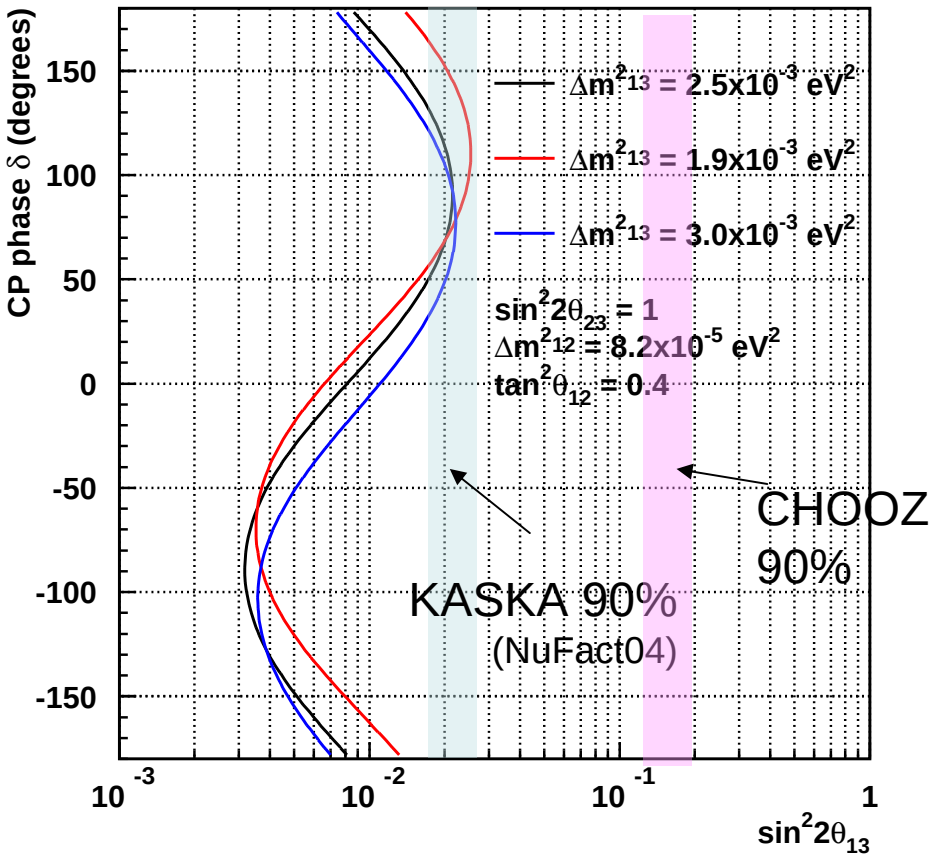


Horn prototype



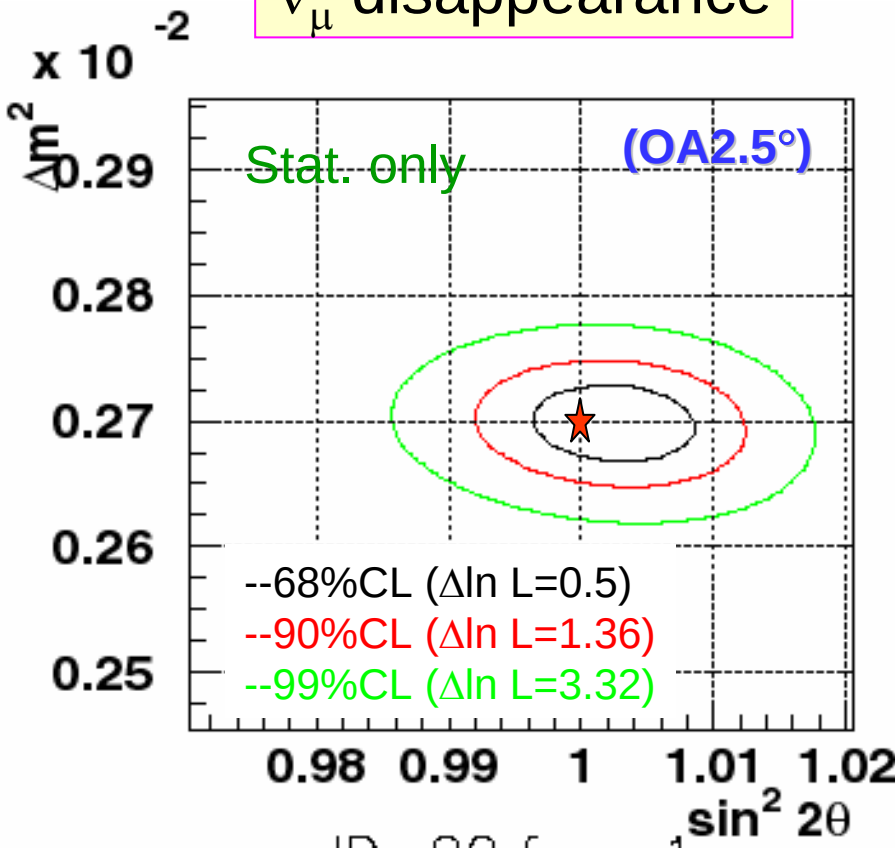
Sensitivities

ν_e disappearance



>10 times improvement from CHOOZ

ν_μ disappearance



Goal

$\delta(\sin^2 2\theta_{23}) \sim 0.01$

$\delta(\Delta m_{23}^2) \sim < 1 \times 10^{-4}$

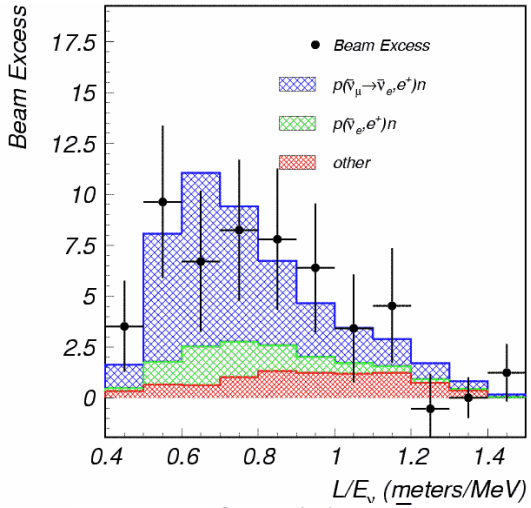
Short baseline experiment

- LSND observe osc signal
  - LANL 800MeV/1mA ***p*** beam
  - μ^+ decay at rest in beam stop
  - E_ν<53MeV, L~30m

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \xrightarrow{?} \bar{\nu}_e$$

  - $\Delta m^2 \sim 1 eV^2$, $\sin^2 2\theta \sim 10^{-(2\sim3)}$
- If true
  - 3 mass diff. (sol/atm/LSND)
  - **>3 ν's?**
    - Sterile? (LEP says # of light ν=3)
  - **CPV?**
    - Mass spect different for ν/anti-ν?
- Definite confirmation necessary
  - w/ different systematics

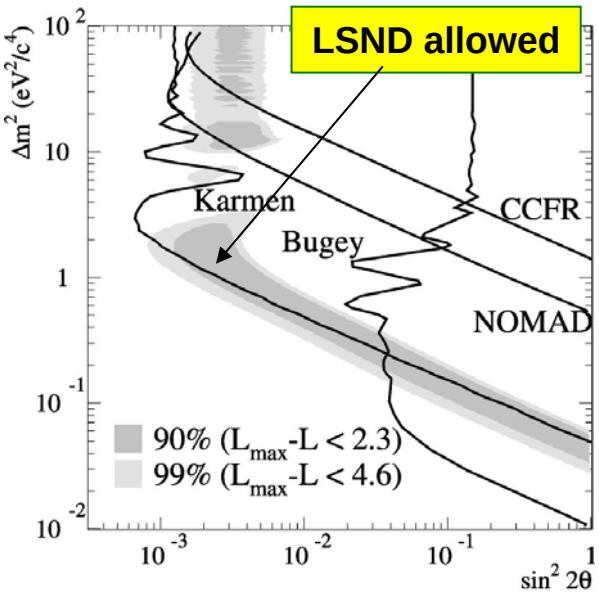
➔ **MiniBooNE**



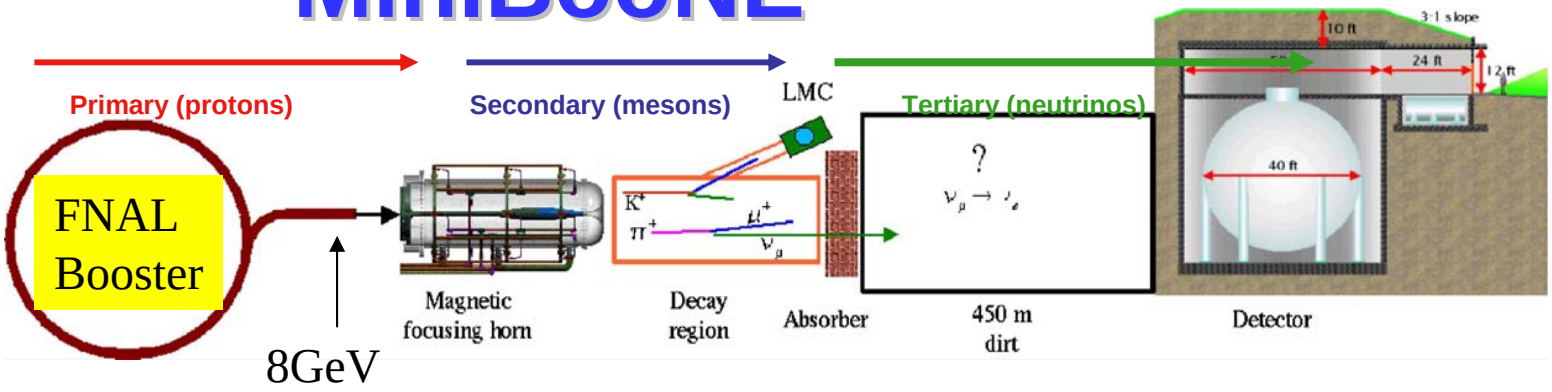
Excess of candidate $\bar{\nu}_e$ events

87.9 ± 22.4 ± 6.0 events (3.8σ)

$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ = 0.264 ± 0.081 %



MiniBooNE



Look for ν_e in ν_μ beam at ~ GeV

Beam

- 8 GeV proton beam on Be target
- Horn-focused wide-band beam

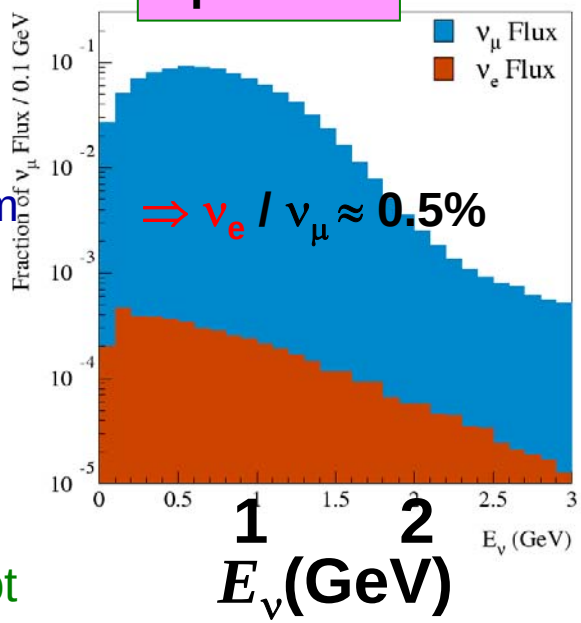
Detector @ L~541m

- 800ton of pure mineral oil
- 1280 (240) PMT's in inner(outer) region
- Cherenkov and scintillation light

Expected observation @ 10^{21}pot

- Signal : 300
- Background 780 (NCπ^0 & beam ν_e dominant)

Spectrum

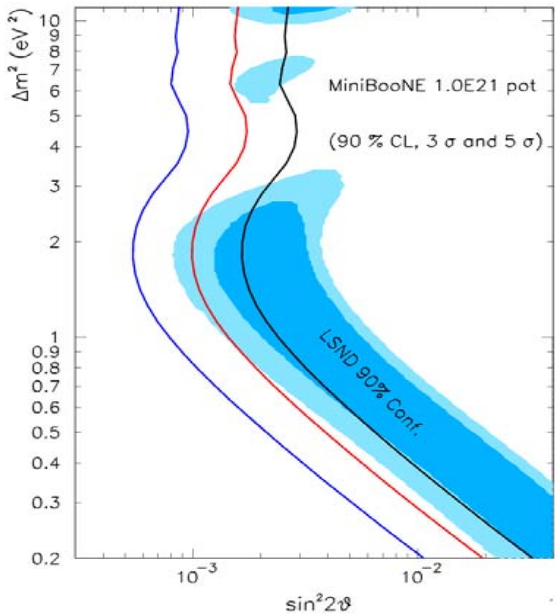


$\Rightarrow \nu_e / \nu_\mu \approx 0.5\%$

1 2

E_ν(GeV)

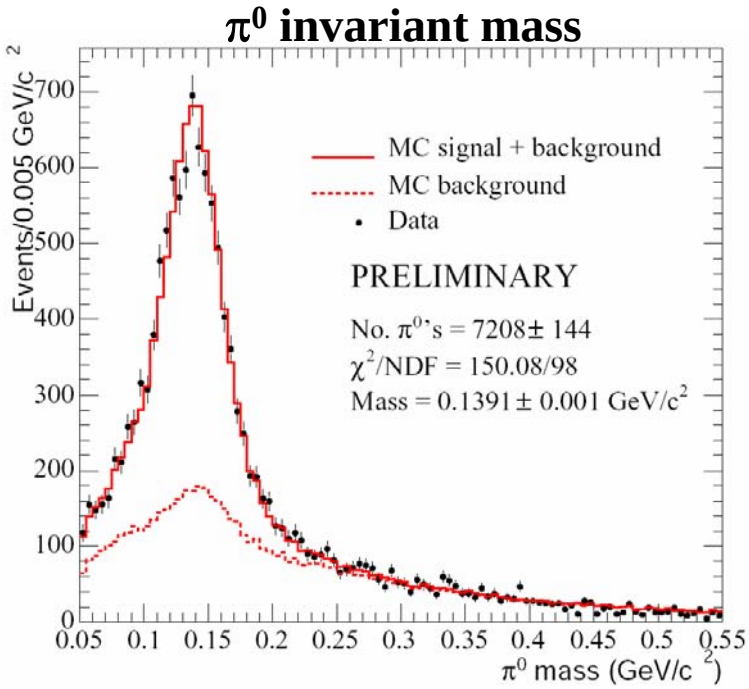
Sensitivity

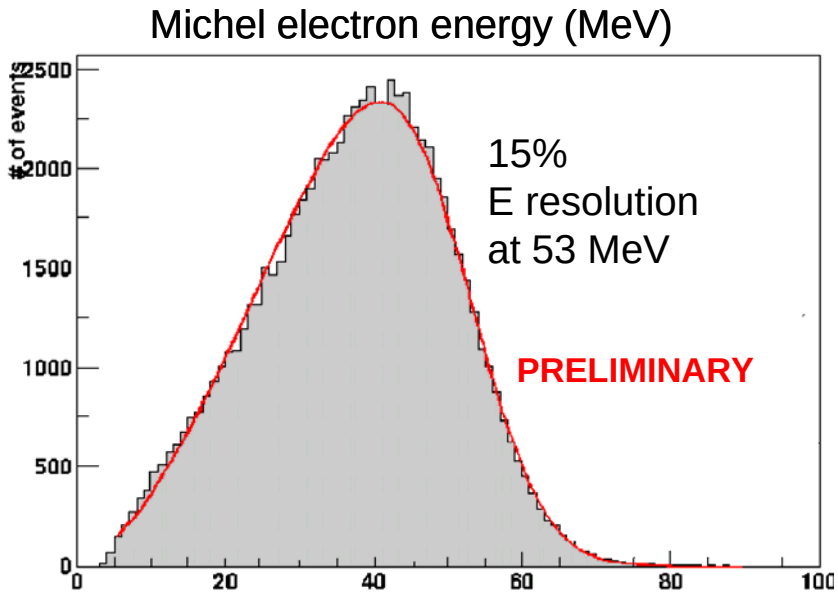


MiniBooNE Status

- Data taking since Aug.2002
- 5.78x10^{20}pot so far (Jun.20,2005)
- >600k ν interaction recorded.
- Detector calibration, studies of ν interactions
- **Signal box will be open in late 2005**

Energy Calibration

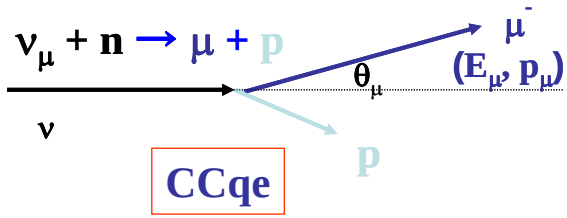


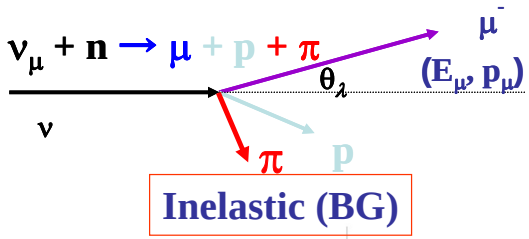


Non-oscillation exp's/measurements

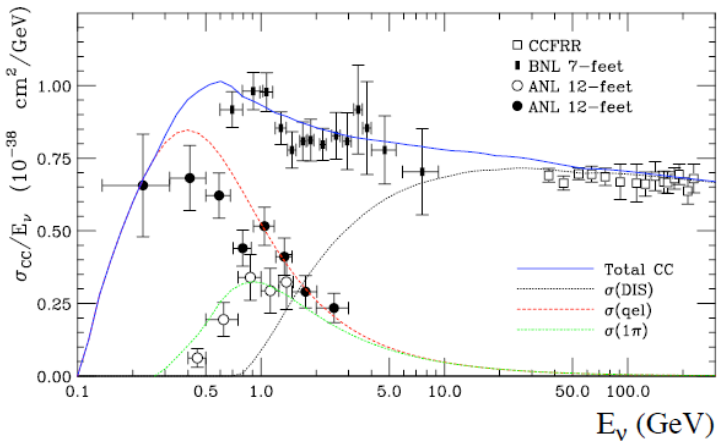
ν interaction @ ~ 1GeV

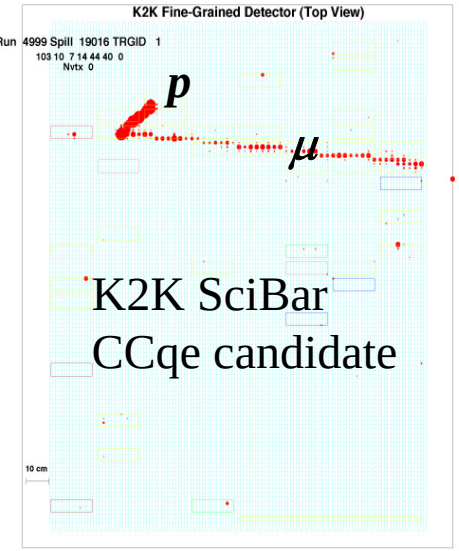
- Future precision oscillation experiments
  - E_ν = Several 100MeV ~ A few GeV
- Neutrino interactions around ~GeV : Complicated!
  - CCQE: 2 body, clean energy reconstruction
  - CC/NC pion productions ➔ Source of syst err/background
    - Deteriorate E_ν reconstruction
    - Serious background from NC π^0 production important for ν_e appearance





- Very limited data
  ➔Let's measure!!
- Players
  - K2K near detector
  - MiniBooNE
  - MINERνA

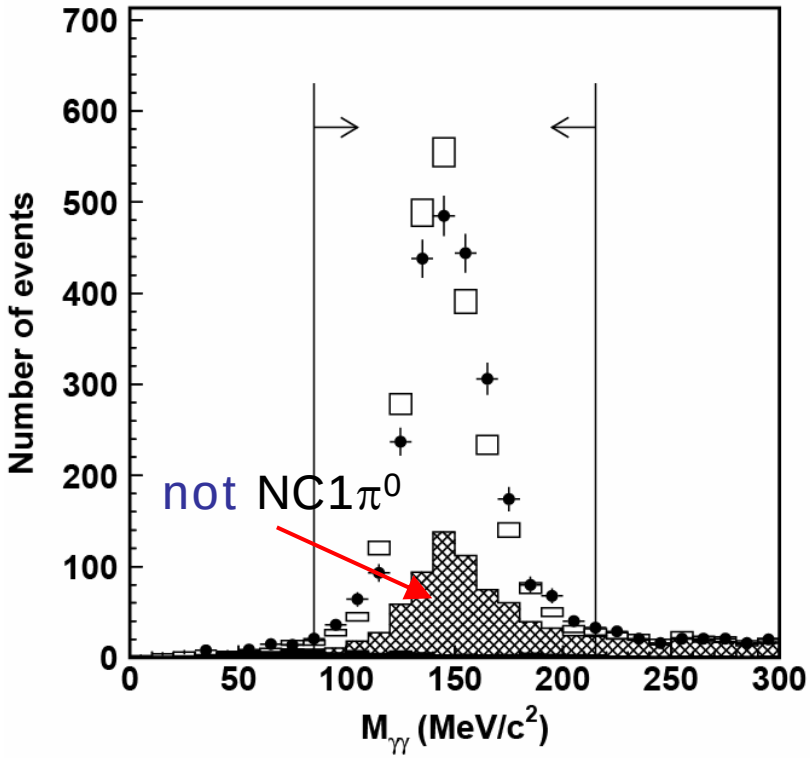




K2K NC π^0 measurement in 1kt det

$\nu_\mu + H_2O \rightarrow NC1\pi^0$

- Important for future ν_e appearance
- Selection
  - Fully contained
  - 2 e-like rings
  - $85 < M_{\gamma\gamma} < 215$MeV



$$\frac{\sigma(\nu_\mu \rightarrow NC1\pi^0)}{\sigma(\nu_\mu \rightarrow CCall)}$$

$= 0.064 \pm 0.001 \pm 0.007$

$= 0.065$ (model prediction)

Phys.Lett.B619:255-262,2005
hep-ex/0408134

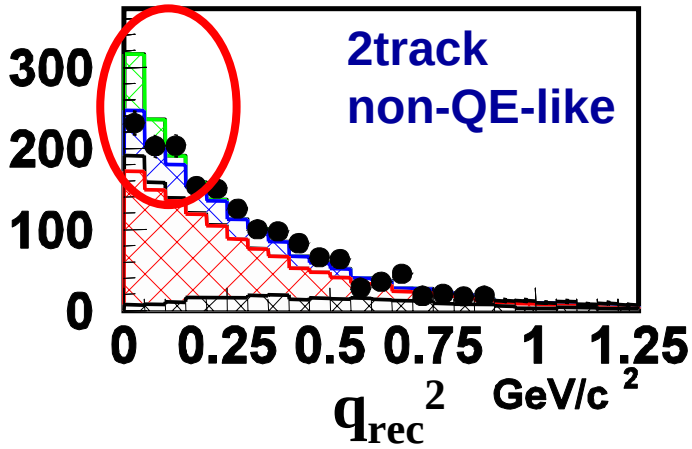
K2K CC Coh. pion measurement

M. Hasegawa et al., hep-ex/0506008

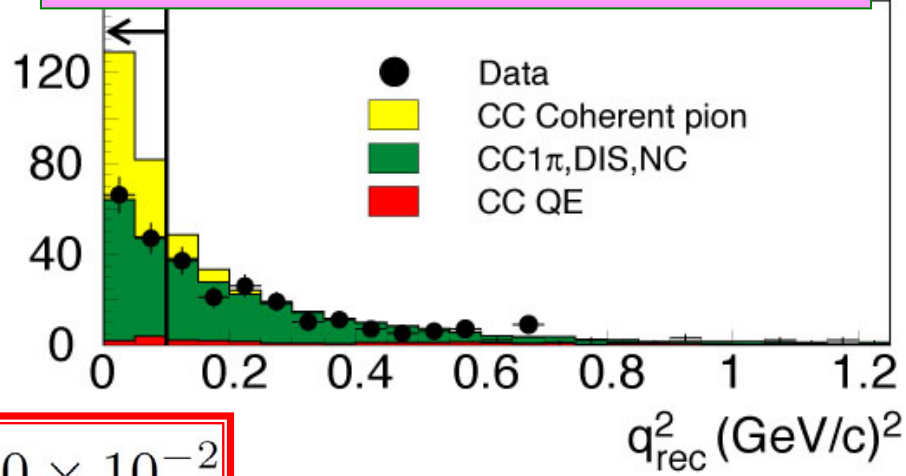
CC Coherent pion production ($\nu_\mu + A \rightarrow \mu^- + \pi^+ + A$) w/ SciBar det.

- K2K & MiniBooNE has been observing forward (low q^2) deficit
- ➔CC Coh doubted
- CC Coh enhanced sample selection
  - 2 track
  - not satisfy QE kinematics (non-QE like)
  - 2nd track pion (not proton)
  - No vertex activity
  - $q_{rec}^2 < 0.1 (GeV/c)^2$
- Result
  - **113 event selected**
  - **BG (non CC Coh)=111.4**
  - Consistent w/ No CC Coh.
- Upper limit (90%CL)

$$\sigma(\text{CC coherent } \pi)/\sigma(\nu_\mu CC) < 0.60 \times 10^{-2}$$



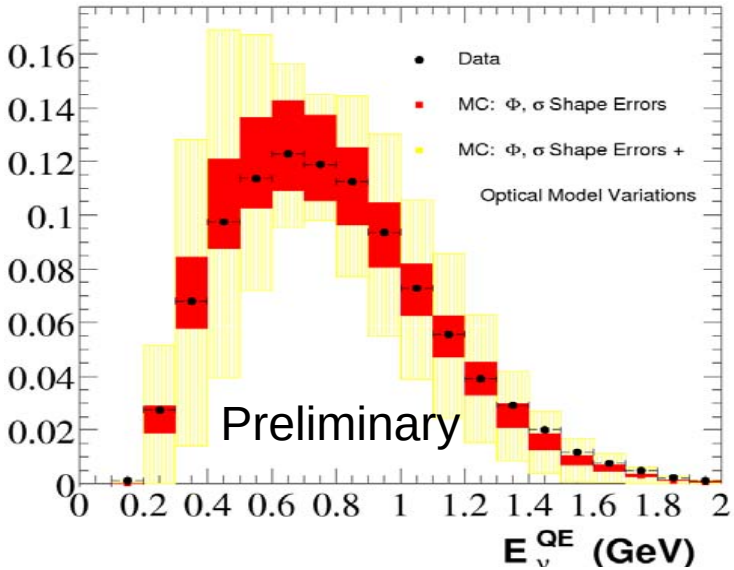
CC Coh enhanced sample

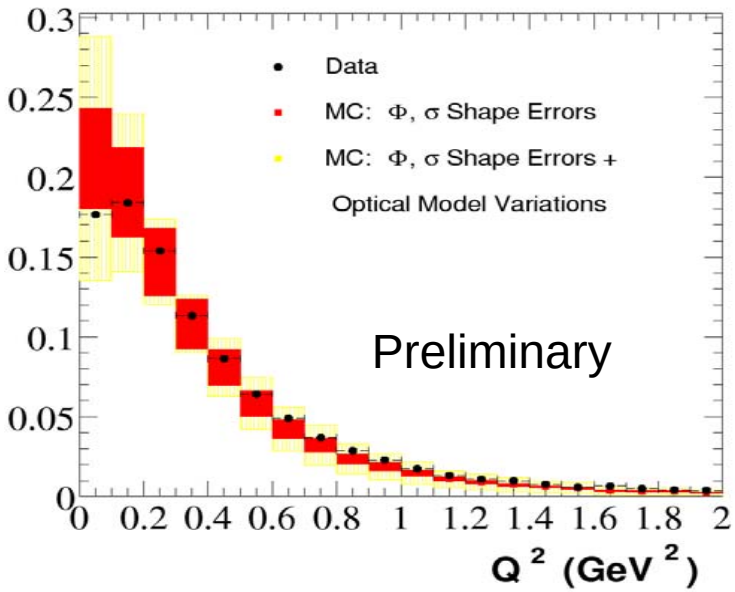


Inconsistent w/ Rein&Sehgal model of 2.67×10^{-2}

MiniBooNE interaction measurements

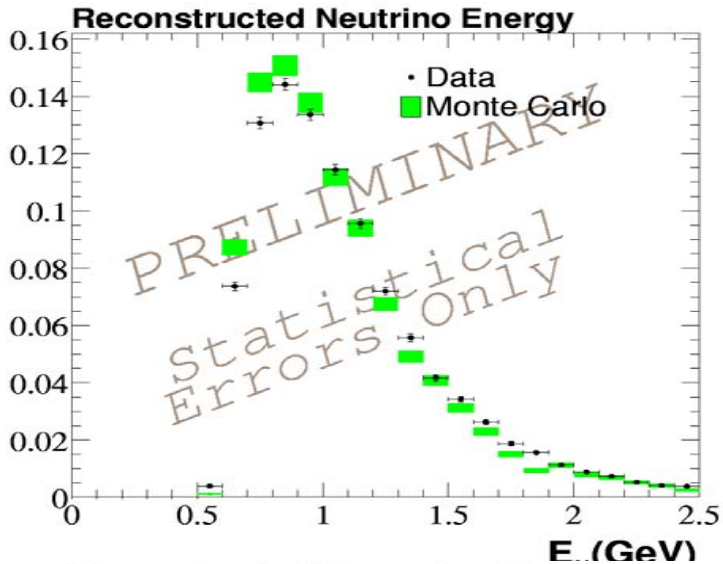
CCqe sample

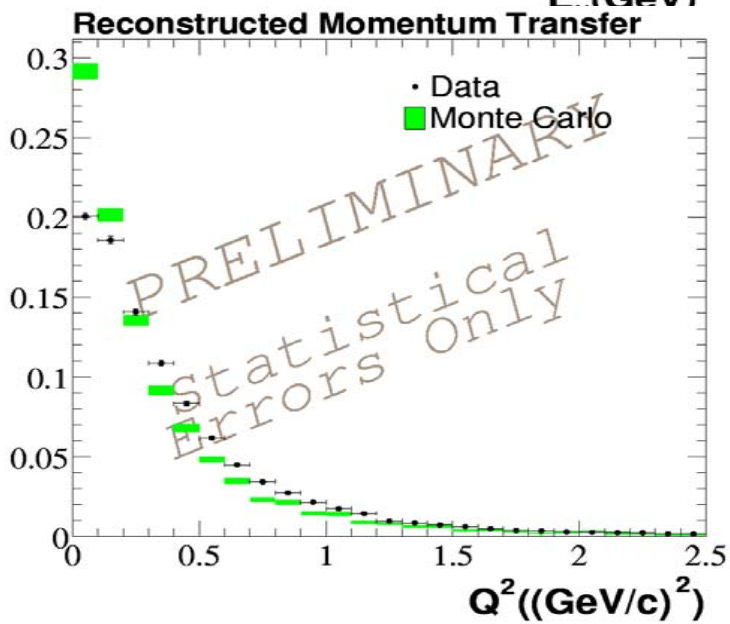




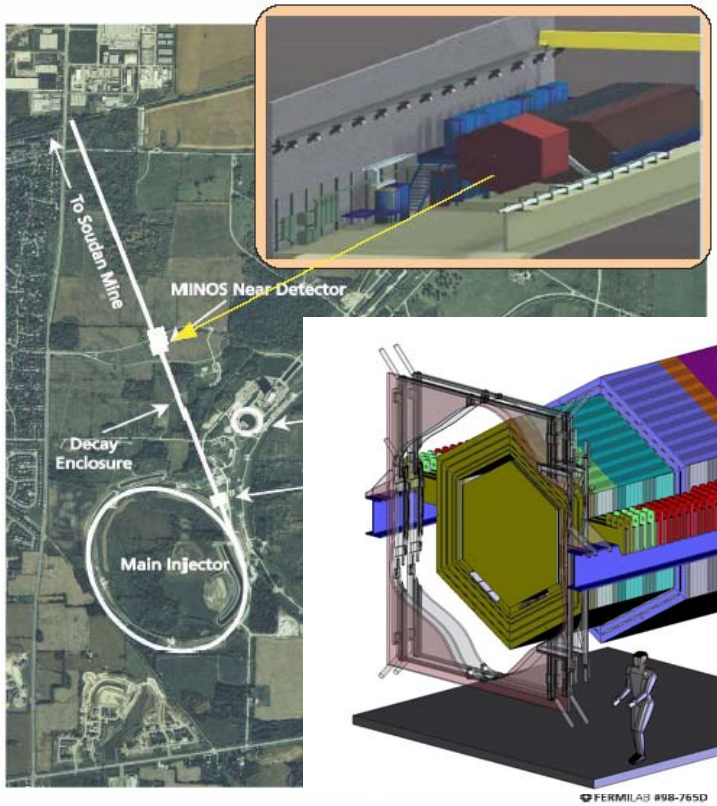
CC1π sample

Require 2 decay-e signal (from μ and π→μ)

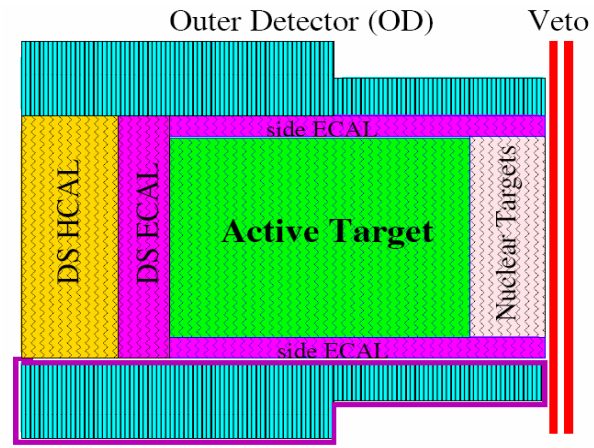




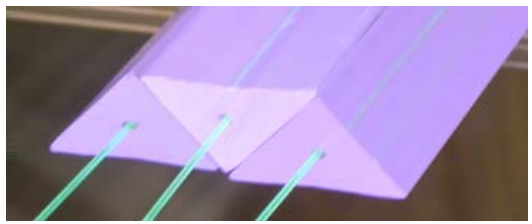
MINERνA



- New experiment for ν int measurements in few GeV region
- Active (scintillator bar) target (5.87ton) fine grained detector
- Placed in front of MINOS near detector
- Expected event rate
  - 16×10^{20} POT **in 4 years**
  - Fiducial Volumes 3 ton (CH), 0.6 ton C, 1 ton Fe & 1 ton Pb
  - **15 Million total CC events**
- Status
  - Stage 1 approval in Apr.2004
  - Fermilab requested DoE funding as part of the laboratory's FY07 program
- Projected schedule
  - 2006 construction start
  - 2008 commissioning start



1.7 × 3.3 cm^2 strips WLS fiber readout in center hole



ν Deep inelastic scattering ➔ $\sin^2\theta_W$

- NuTeV result (2001)
  - Ratio of #events of NC(short) to CC(long) events for ν/νbar

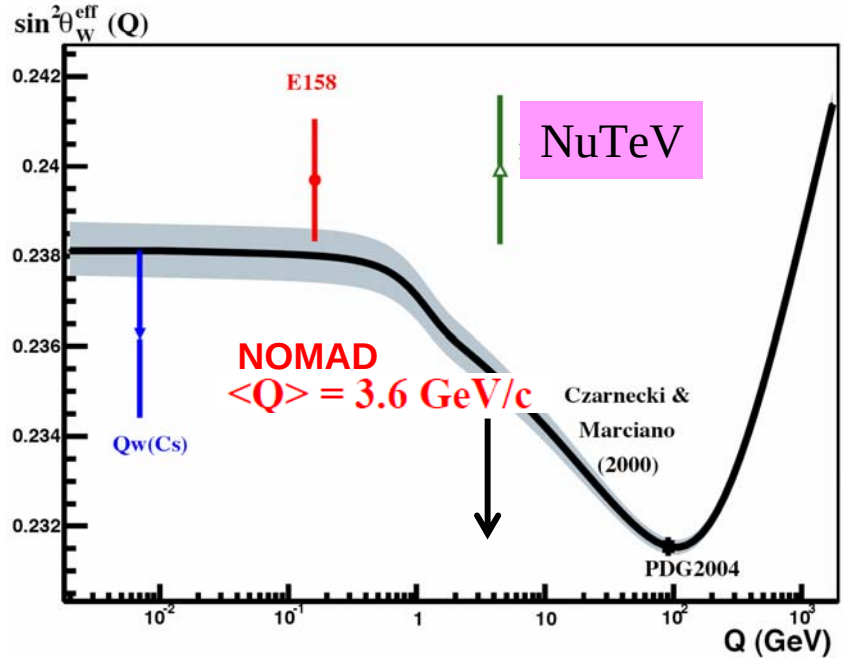
$$\sin^2\theta_W^{\text{on-shell}} \equiv 1.0 - \frac{M_W^2}{M_Z^2} =$$

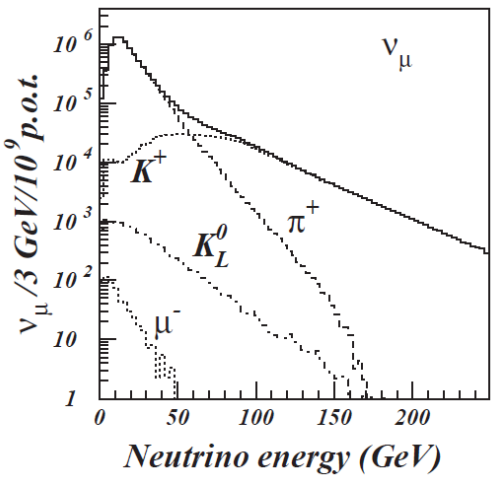
$$0.2277 \pm 0.0013(\text{stat.}) \pm 0.0009(\text{syst.})$$

$$\text{SM from LEPEWWG} \quad = \quad 0.2227 \pm 0.0004$$

  - **3σ away from SM**
- **Still open question**
- NOMAD (1995-1998) is revisiting their data
  - CERN SPS, A few ~ 100GeV νμ
  - Fit to σ_{NC}/σ_{CC} & CC diff σ

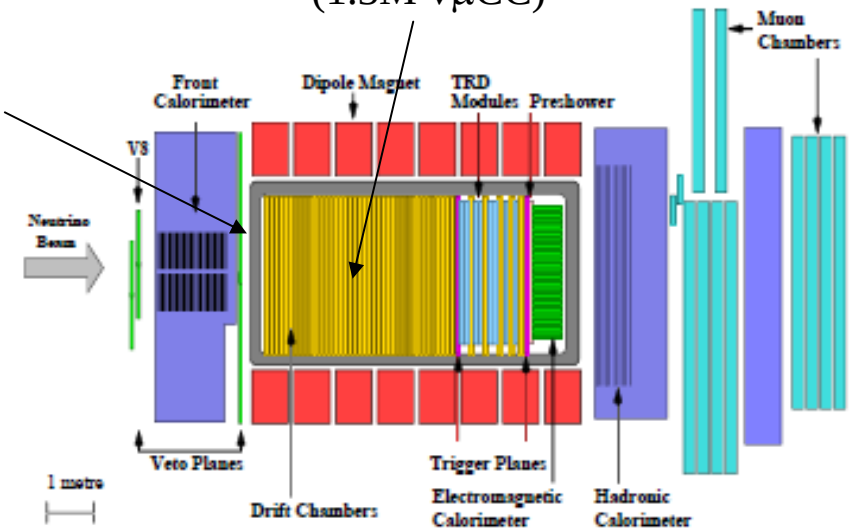
Sensitivity $\delta(\sin^2\theta_W) \sim 1\%$(compara. to NuTeV)
Provide independent check





A few ton Al
(1.5M νμCC)

2.7ton C
(1.3M νμCC)



Summary

- Accelerator neutrino experiments probe/provide
  - Properties of neutrino (mass, mixings) in osc. exp'ts
  - Precision measurements of νN interaction
  - Precision test of standard model
- Oscillation experiments
  - Final results of the first long baseline osc exp K2K
    - **Disapp.:$1.88\times10^{-3} \leq \Delta m^2 \leq 3.48\times10^{-3}$ eV^2 (90%CL) @ $\sin^2 2\theta=1$ → Confirms SK results**
    - **ν_e app.:$\sin^2 2\theta_{\mu e}$ <0.18 @2.8×10^{-3}eV^2 (90%CL)**
  - MINOS/CNGS LBL experiments is (will be) online from 2005 and 2006
  - MiniBooNE result is coming soon
- Non-oscillation measurements/experiments
  - νN interactions are being studied w/ high stat for future precision LBL experiments (K2K, MiniBooNE, NOMAD, MINERνA)
  - NuTeV's 3σ "discrepancy" from SM still remain. NOMAD will provide independent check with comparable uncertainty
- Acc ν experiments have potential to provide breakthrough toward Beyond-the-SM. Many future programs planned. → Next Prof. Lindner's talk.