Results and Status of Current Accelerator Neutrino Experiments

XXI Lepton Photon Symposium
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Batavia, Illinois

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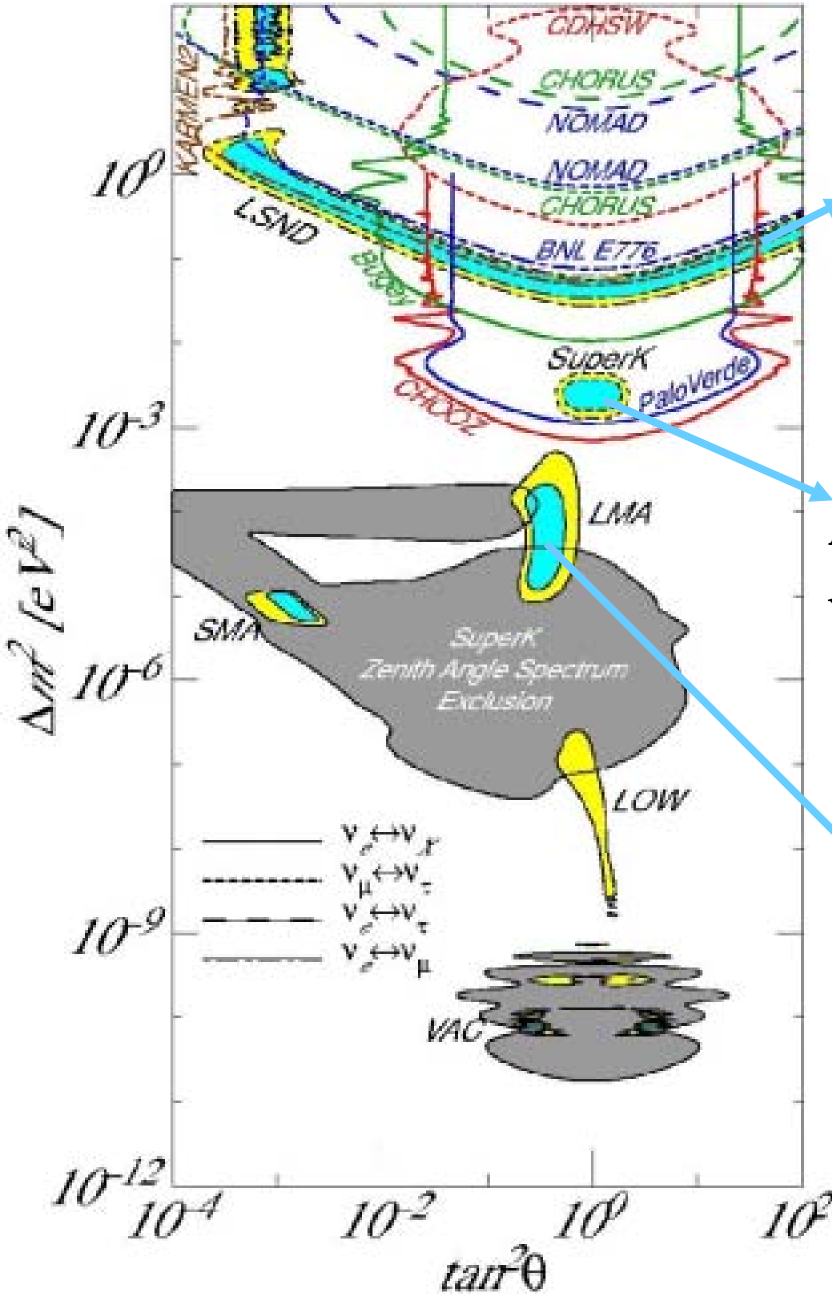
- **Number of ‘ ν ’**
  - –DONUTS, NOMAD, CHORUS results
  - –Mini-BooNE status
- **Results and status of on-going oscillation experiments**
  - –SK-I latest Δm^2 in atmospheric neutrinos observation
  - –Status of K2K-II
  - – π^0 and upper limit of e appearance in K2K-I
- **Expected results in the near future**
  - –NUMI/MINOS
  - –CNGS/OPERA,ICARUS
- **Summary**

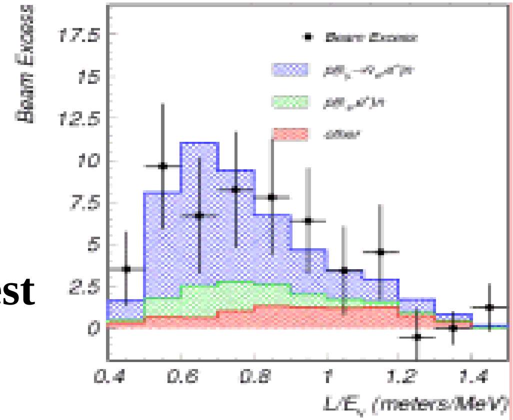


LSND

$\overline{\nu_\mu} \rightarrow \overline{\nu_e}$

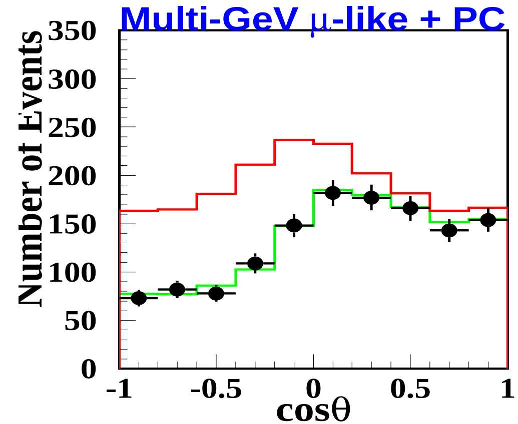
π decay at rest

P ~ 2 x 10^{-3}



Atmospheric

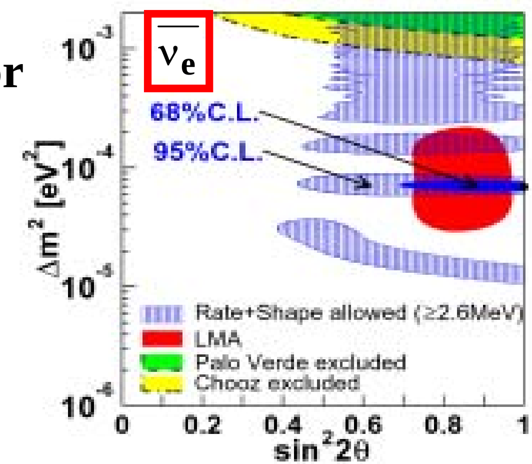
$\nu_\mu \rightarrow \nu_\tau$



Solar, Reactor

$\nu_e \rightarrow \nu_\mu, \nu_\tau$

$\overline{\nu_e} \rightarrow \overline{\nu_\mu}, \overline{\nu_\tau}$



Maki-Nakagawa-Sakata Matrix and Oscillation probability

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

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

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

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

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

$$P_{\alpha\to\beta} = \sin^2 2\theta \cdot \sin(1.27 \cdot \Delta m^2 \cdot L / E_\nu)$$

$$\Delta m_{ij}^2 \equiv m_j{}^2 - m_i{}^2, \Delta m_{31}^2 + \Delta m_{23}^2 + \Delta m_{12}^2 = 0$$

3 ν's → 2 indep. Δm^2

Aim of accelerator neutrino oscillation experiments

1. Number of 'ν' : Establish or refute the LSND effect
2. Confirm that atmospheric ν results are due to ν oscillation
   - Oscillatory behavior of ν_μ's
   - Explicit detection of ν_τ in $\nu_\mu \rightarrow \nu_\tau$
3. Measure oscillation parameters
4. Any unexpected

Ultimately

- Make precise measurement of oscillation parameters
  - Measurement of $\nu_\mu \rightarrow \nu_e$ subdominant oscillation mode
  - Search for CP violation in lepton sector
    - Jahlskog factor : $\sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \sin\delta$
    - N-$\overline{\mathrm{N}}$ in the universe
  - Determine mass hierarchy

DONUT Status

FNAL E872 Beam dump beam

Status :

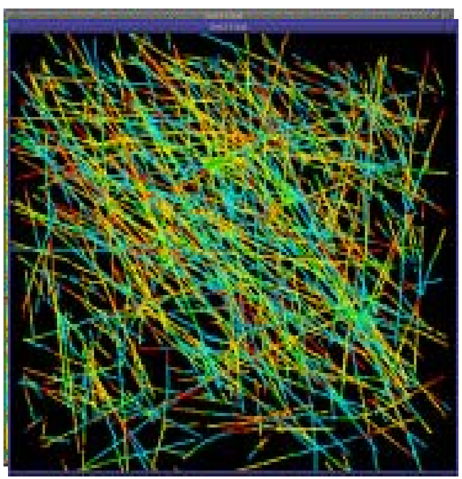
406 neutrino interaction analyzed.

7 ν_τ CCevent detected

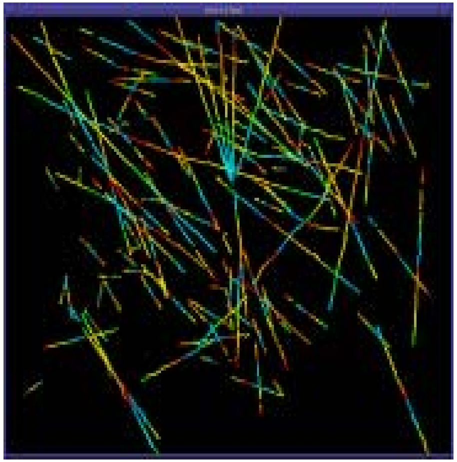
On-going :

Component analysis of the prompt neutrino beam

$\nu_e : \nu_\mu : \nu_\tau$



All tracks in the Scanning region (4179 tracks)

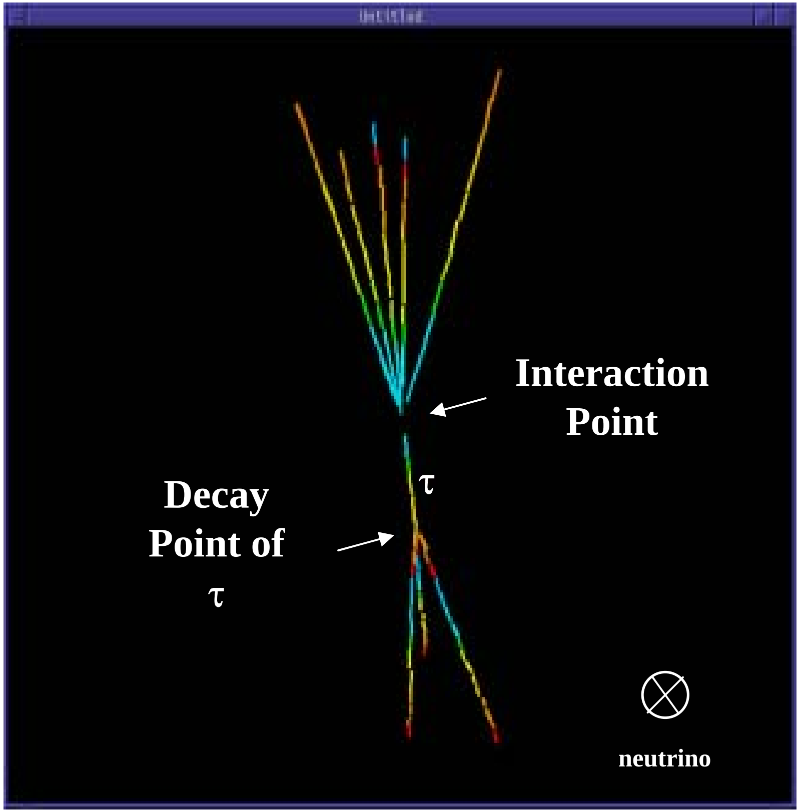


Reject passing through tracks

(420 tracks remained)

Reject Low momentum tracks

(114 tracks remained)

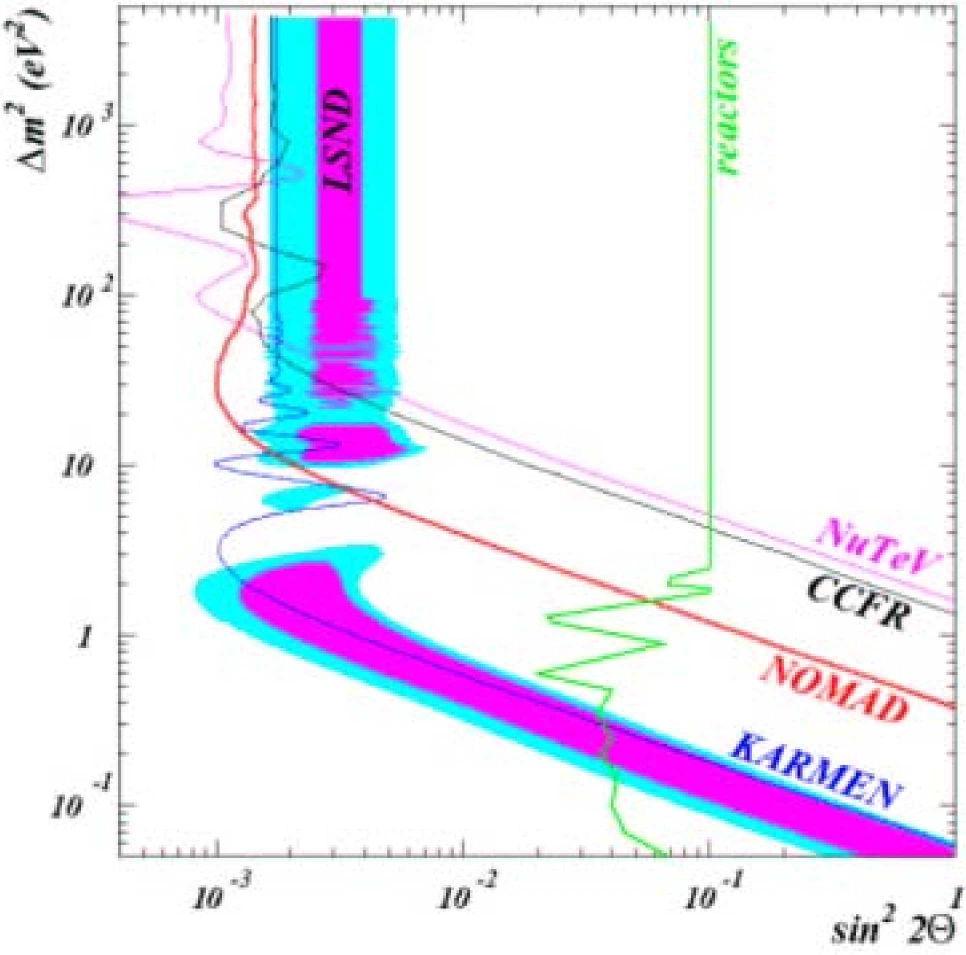


Vertex detection :

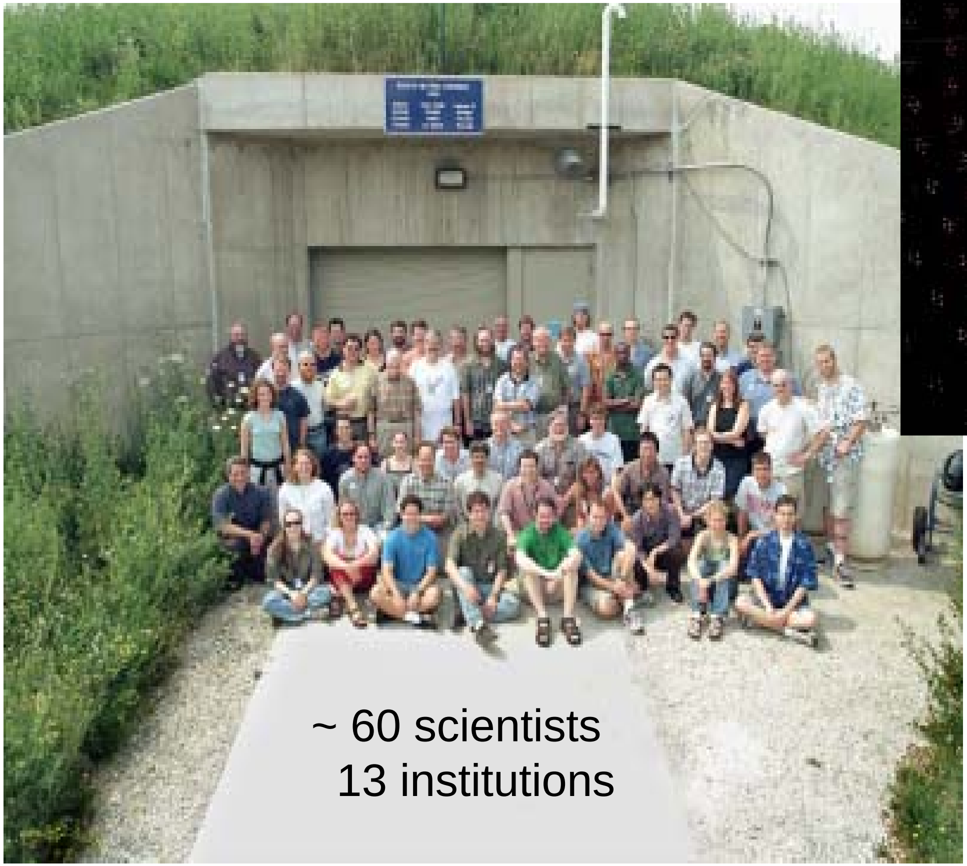
Neutrino interaction and decay of short lived particles

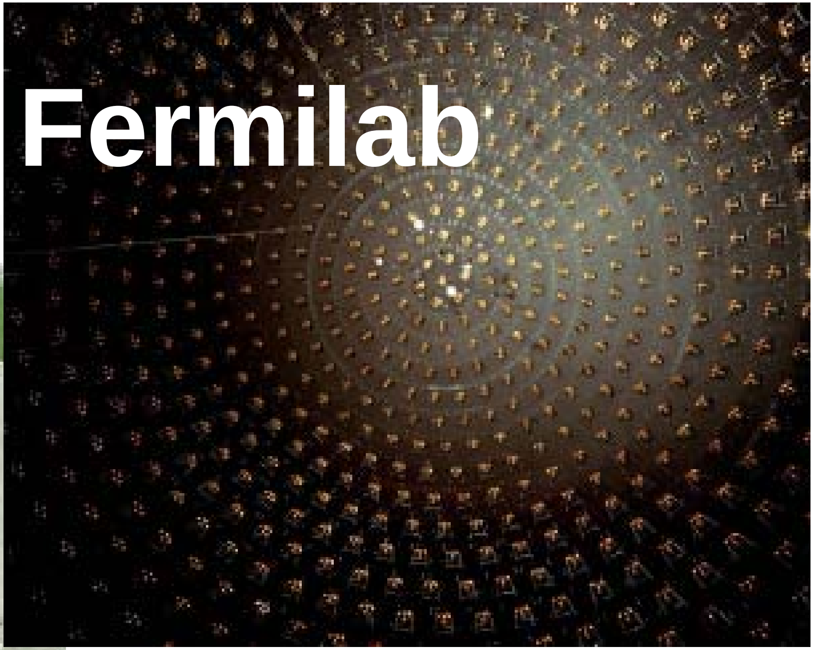
Detection of ν_τ^{CC} in DONUT

Final Results from NOMAD on $\nu_\mu \rightarrow \nu_e$



MiniBooNE at Fermilab





Status of the Experiment

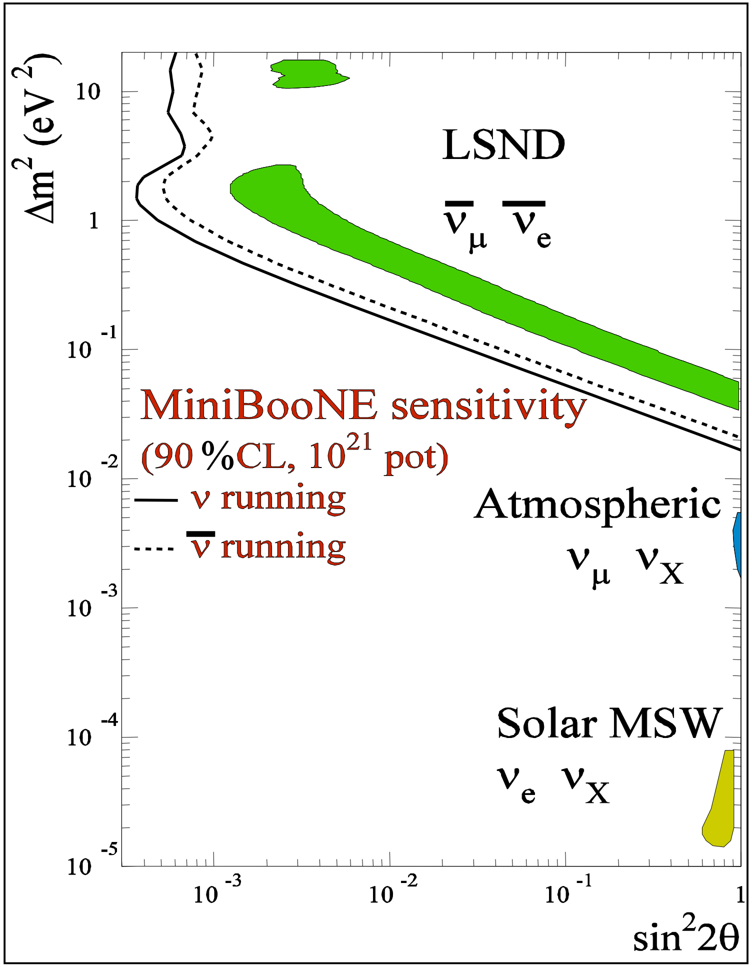
MiniBooNE Goal: Investigate LSND

Taking atmospheric, solar, reactor, and LSND results together … either …

- One or more of the experiments are not seeing oscillations
- or there are >3 neutrinos
  (gives you 3 independent Δm^2 scales)
- or CPT is not a good symmetry
  (gives you different mass scales for $\nu, \bar{\nu}$)

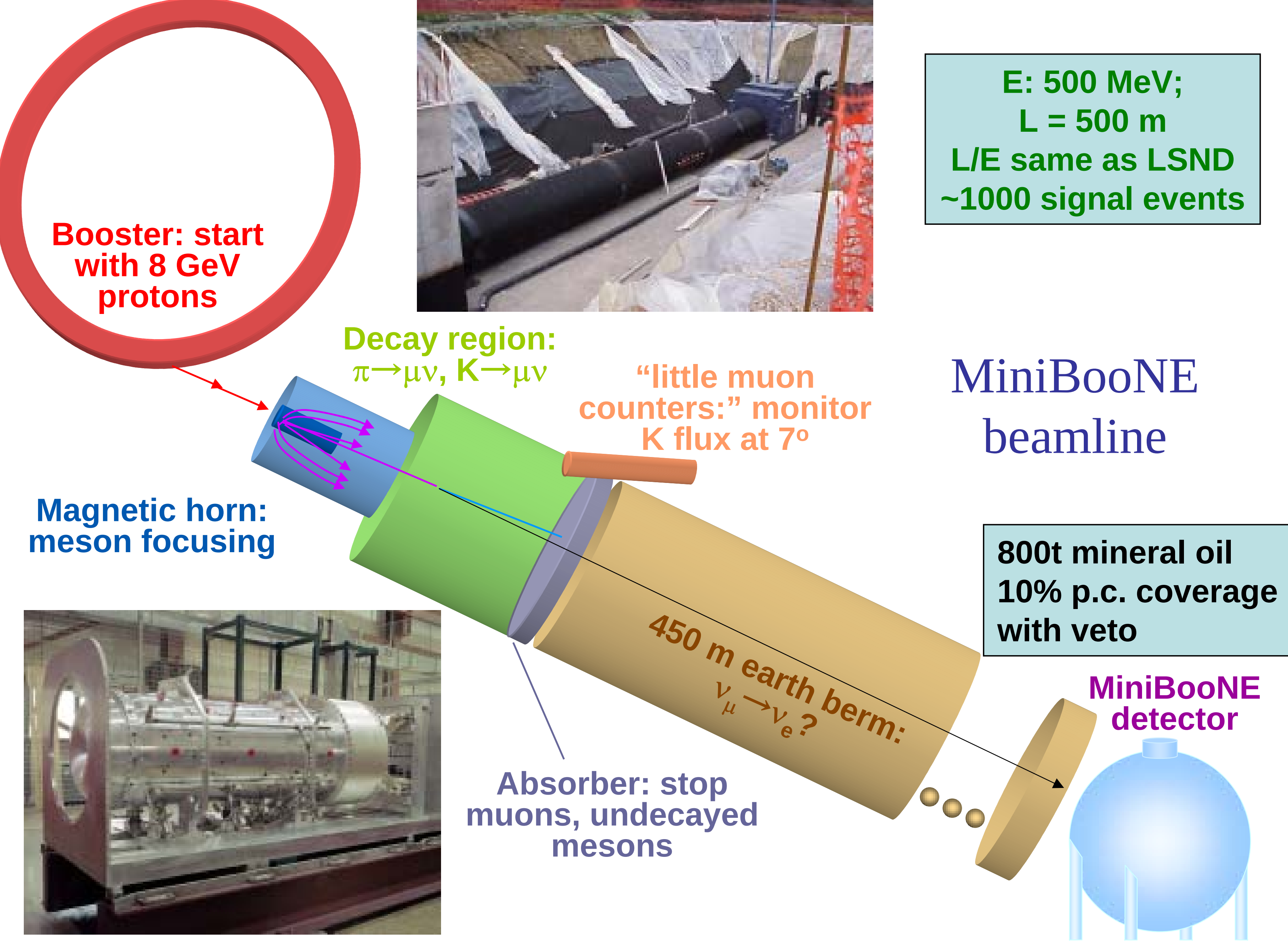
Barenboim, Borissov, Lykken, hep-ph/0212116

- or ???

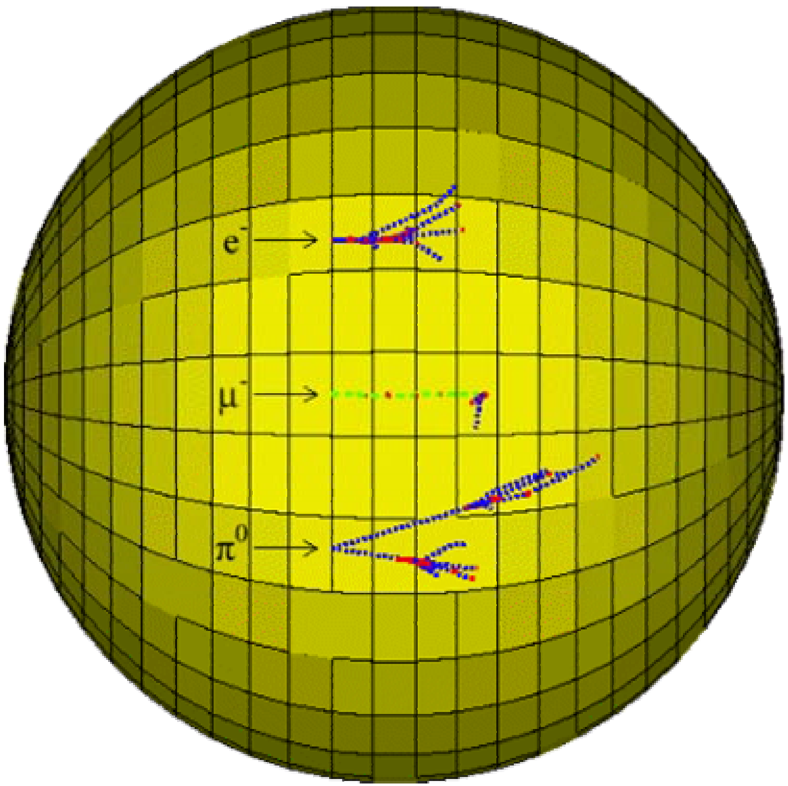


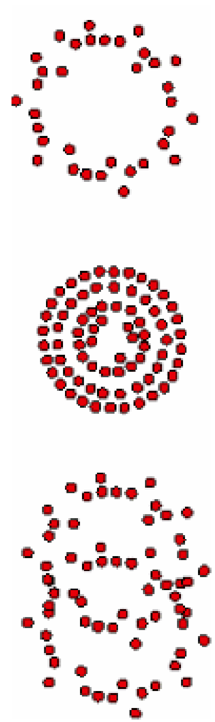
To check LSND want:
- similar L/E
- different systematics
- higher statistics

→ MiniBooNE!


MiniBooNE
beamline
E: 500 MeV;
L = 500 m
L/E same as LSND
~1000 signal events
Booster: start
with 8 GeV
protons
Decay region:
π→μν, K→μν
"little muon
counters:" monitor
K flux at 7º
Magnetic horn:
meson focusing
800t mineral oil
10% p.c. coverage
with veto
450 m earth berm:
ν_μ→ν_e?
MiniBooNE
detector
Absorber: stop
muons, undecayed
mesons

MiniBooNE Particle ID

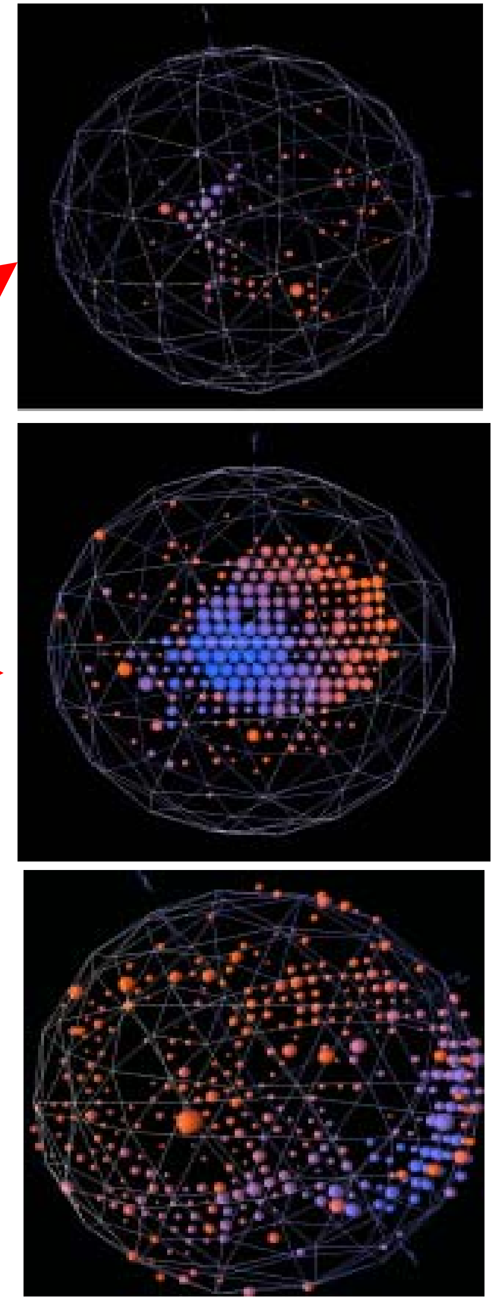




Michel e⁻ candidate

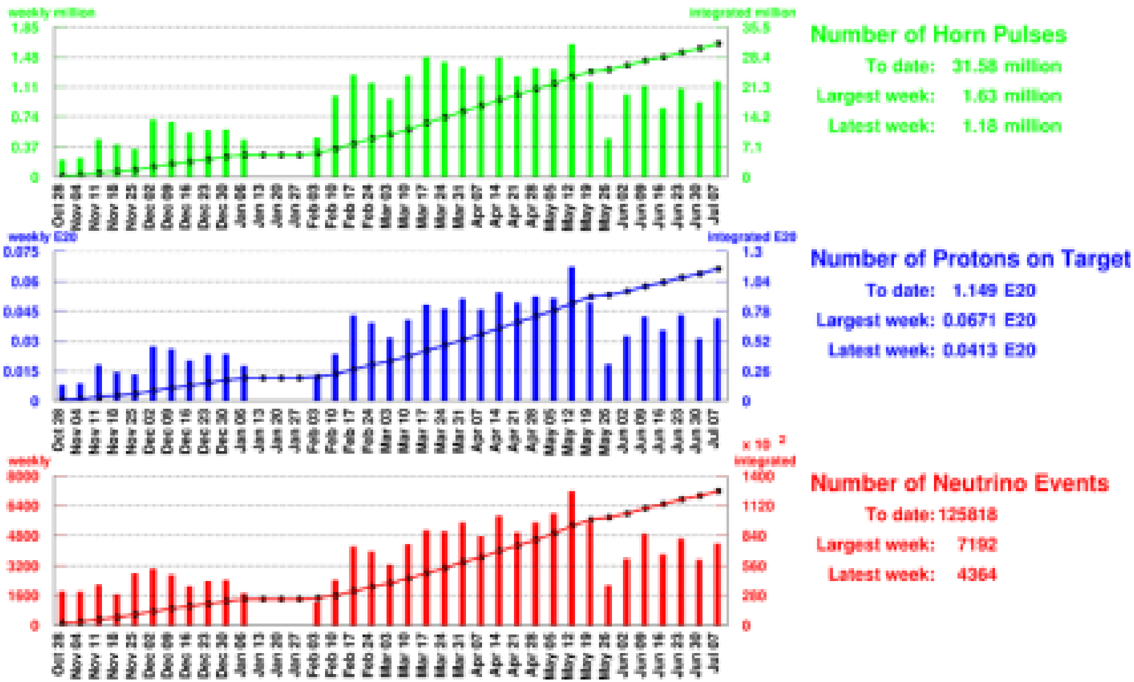
Beam μ candidate

Beam π^0 candidate



Identify electrons (and thus candidate ν_e events) from characteristic hit topology of mineral oil Cherenkov light

Overall MiniBooNE Status



- **Steadily taking data**
- **Currently at ~10% of 1×10^{21} POT goal**
- **Have collected >125,000 ν events**
- **Detector performing well**
- **Still need more beam!**

- Proton rate delivered by Booster has dramatically improved over time

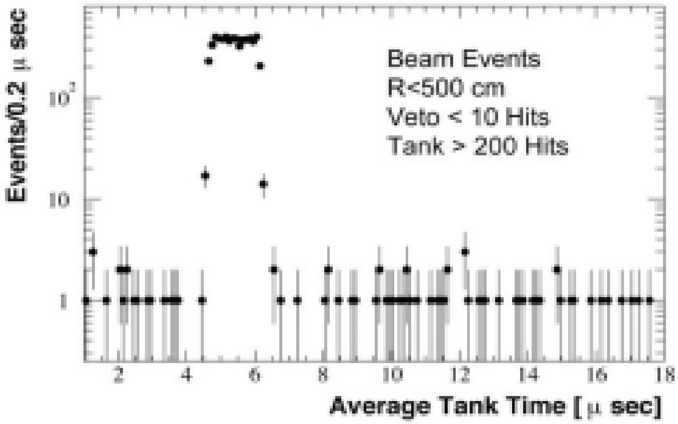
- Further Booster upgrades in the works to reach intended rate
- Detector works beautifully!
- Expect first physics results in the Fall

π^0 Background

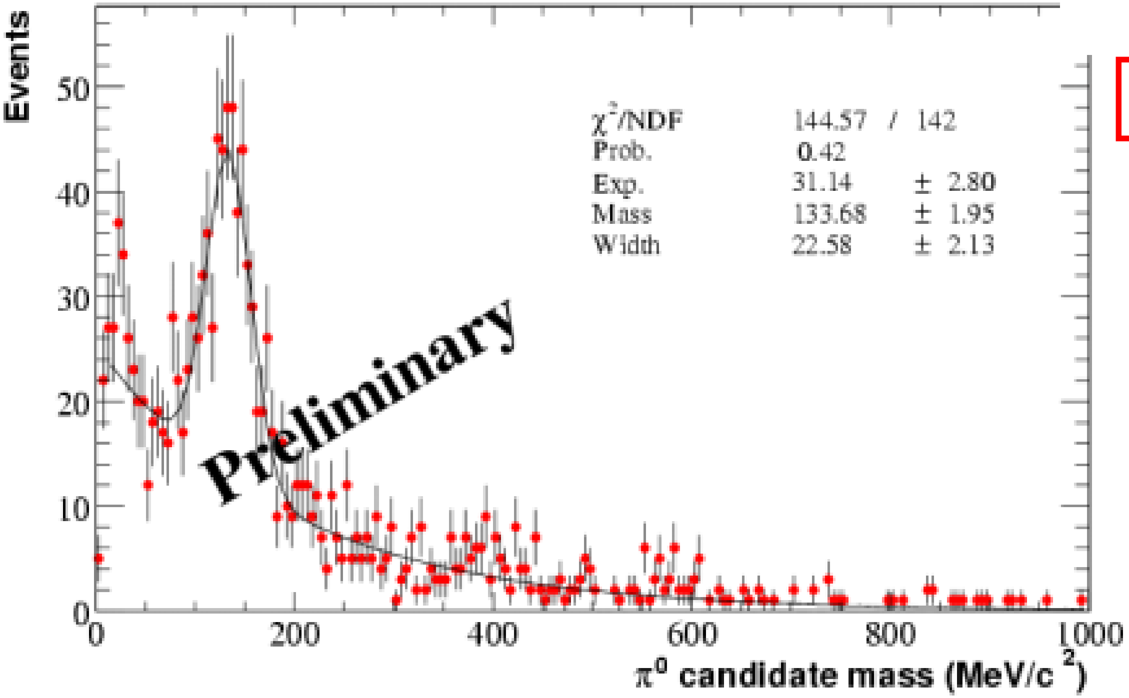
π^0 background to $\nu_\mu \longrightarrow \nu_e$ search

$\pi^0 \longrightarrow \gamma\gamma$ can mimic an electron

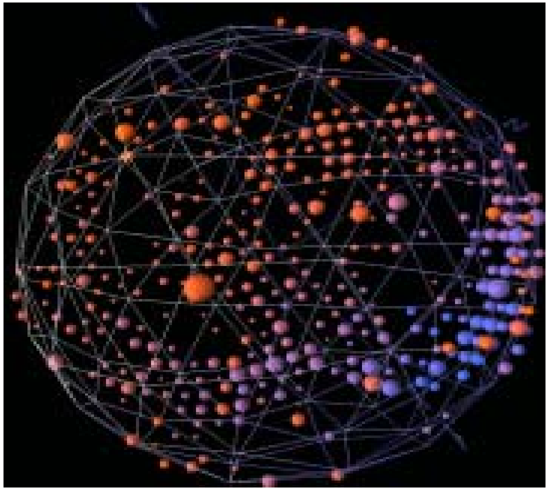
- escaping γ
- asymmetric decays
- ring overlap



non-beam background to ~10^{-3}



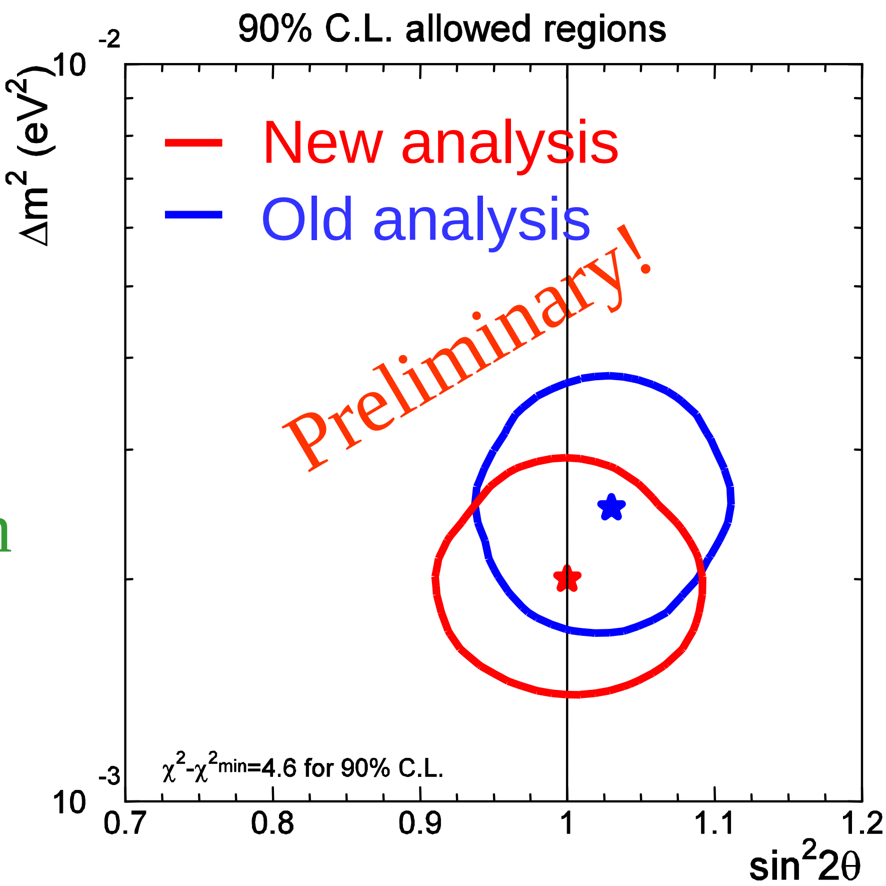
π^0 events are a useful calibration source



New Analysis of Atmospheric Neutrinos in Super-Kamiokande

New analysis results of atmospheric neutrinos in Super-Kamiokande

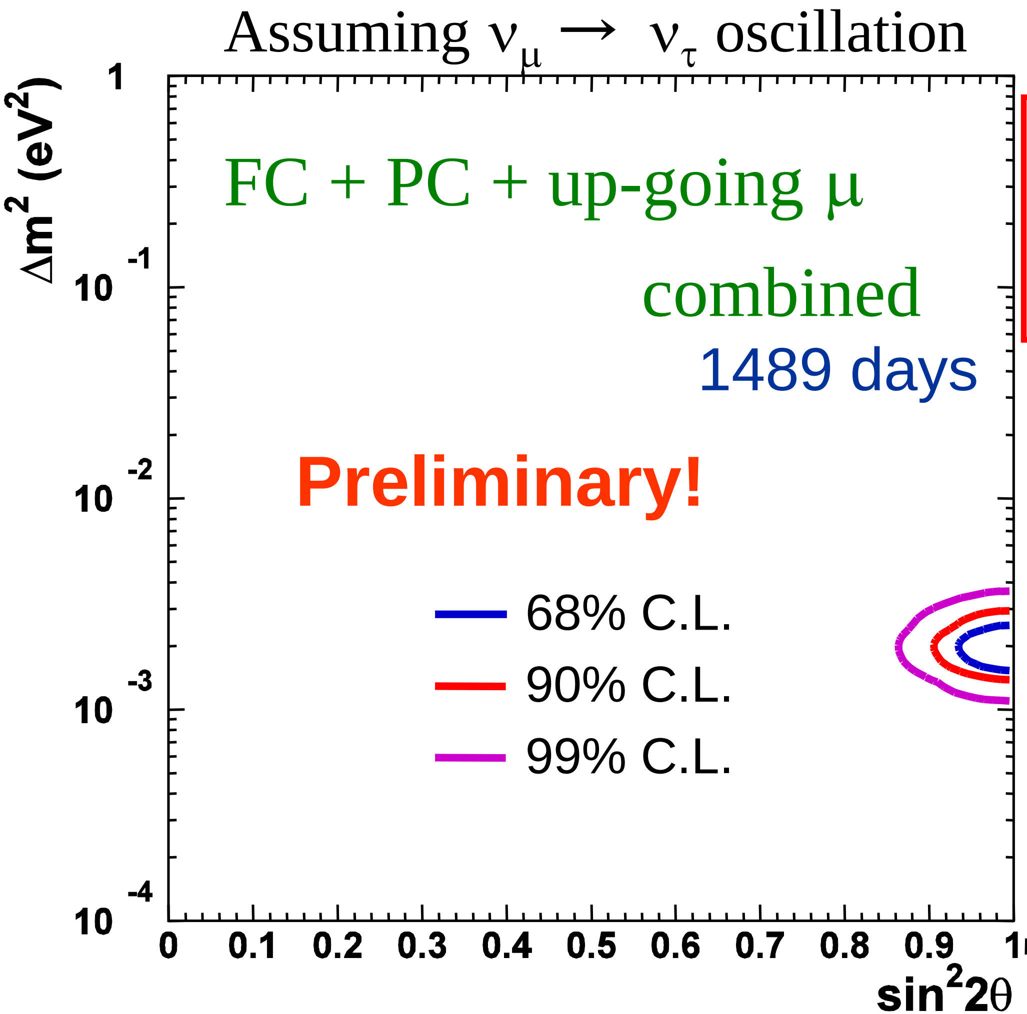
- Neutrino flux (hep-ph/0203272)
  (Honda 1995(1D)   Honda 2001(3D))
- Neutrino interaction model
  (several improvements, agree better with K2K near-detector data)
- Improved detector simulation
- Improved event reconstruction



Each change contributes to the shift in the allowed (Δm^2) region.

Allowed region in Super-Kamiokande atmospheric ν data

(complete SK-I data-set)

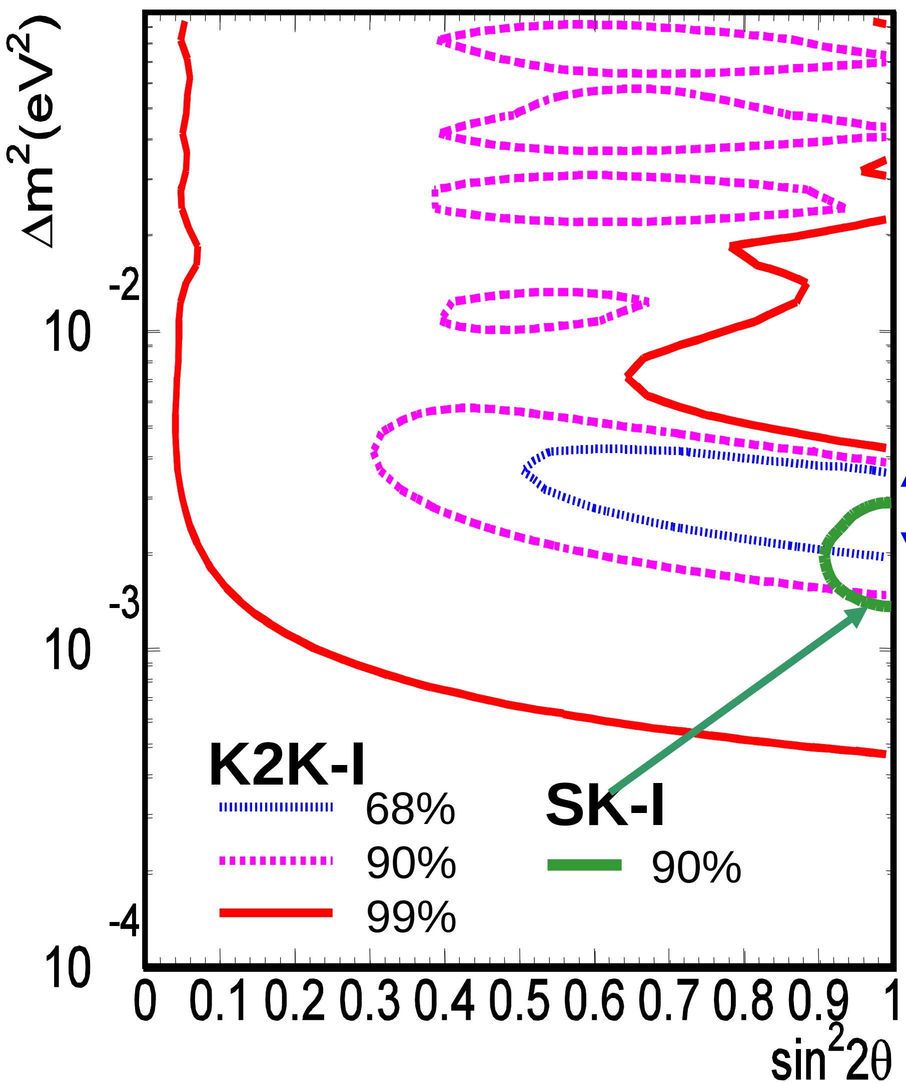


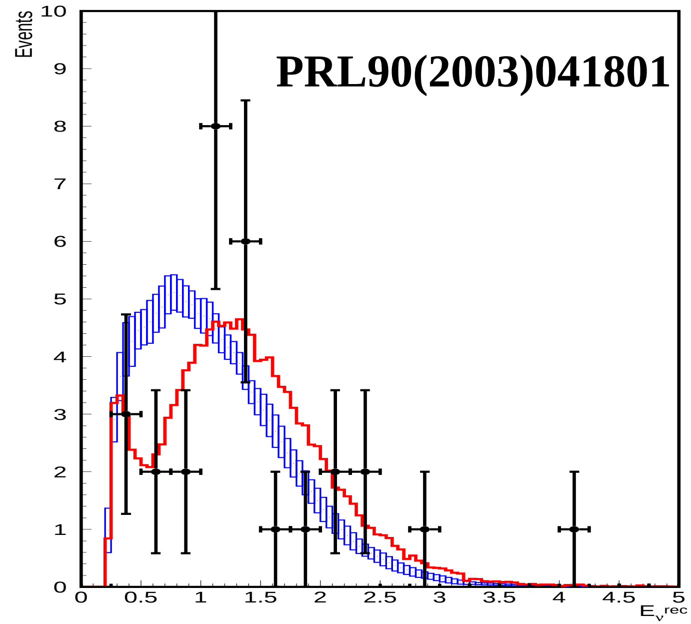
90% CL allowed region
$\sin^2 2\theta > 0.9$
$1.3\times10^{-3} < \Delta m^2 < 3.0\times10^{-3}$ eV^2

Best fit
$(\sin^2 2\theta, \Delta m^2)$
$= (1.0, 2.0 \times 10^{-3}$ eV$^2)$
$\chi^2_{min} = 170.8/170$ d.o.f.

Assuming null oscillation
$\chi^2 = 445.2/172$ d.o.f.

Comparison of K2K-I result and new result of atmospheric neutrinos in SK-I



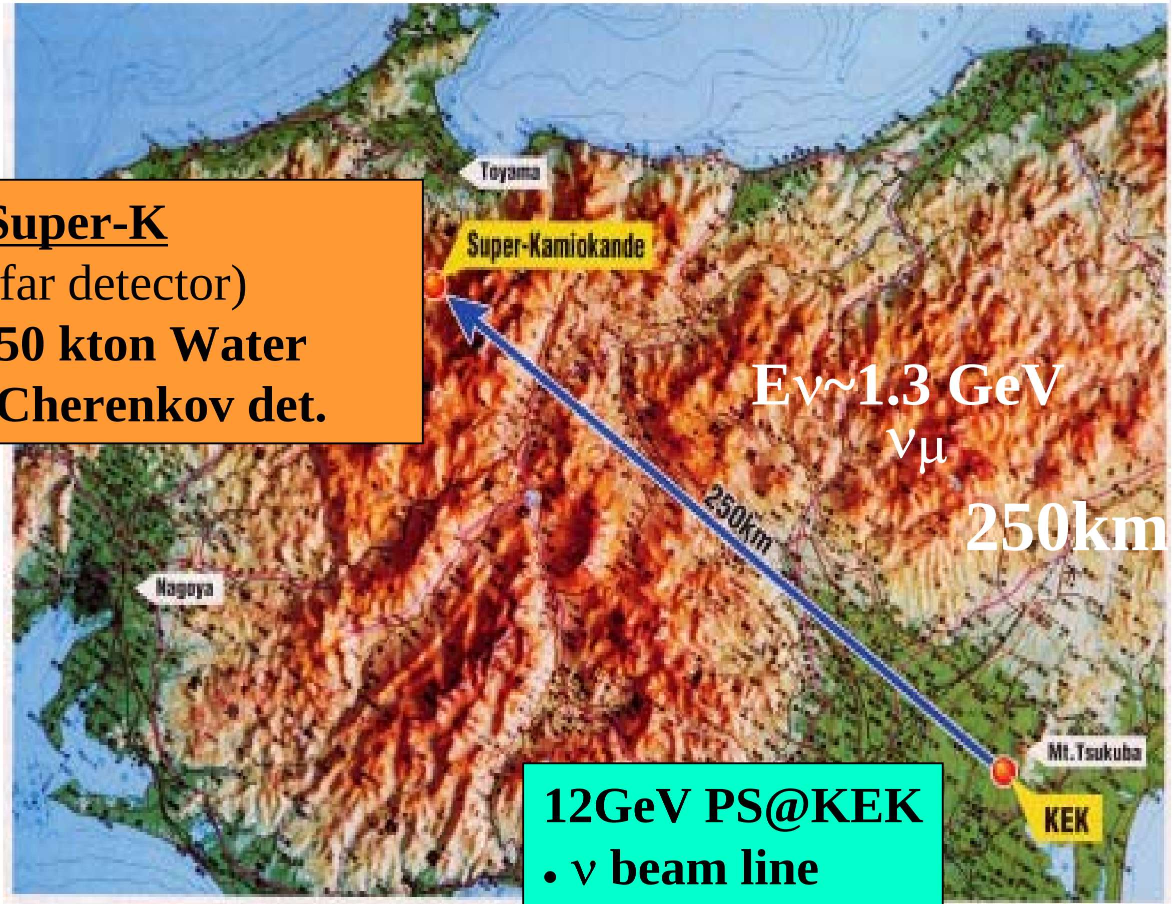


K2K 90%CL
$1.5\sim3.9\times10^{-3}eV^2$
@ $\sin^2 2\theta=1$

Atm. 90% CL
$\sin^2 2\theta > 0.9$
$1.3\times10^{-3} < \Delta m^2 < 3.0\times10^{-3}eV^2$

K2K New Results on π^0 production and $\nu_\mu \to \nu_e$

KEK to Kamioka Neutrino Oscillation Experiment



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

Eν~1.3 GeV
ν_μ
250km

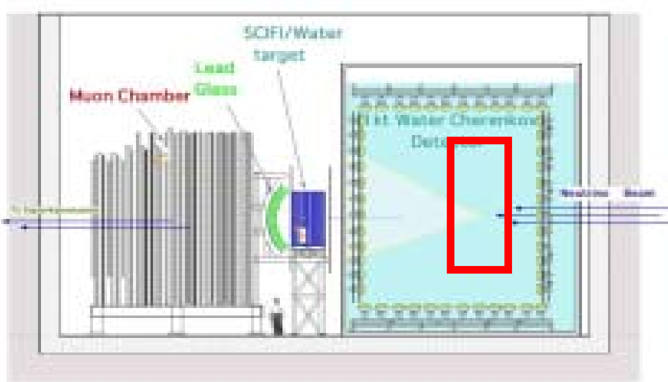
12GeV PS@KEK
- **ν beam line**
- **Beam monitor**
- **Near detectors**

Δm^2 (K2K and Atm.ν)

New K2K-I results
- π^0 measurements
- e appearance

Status of K2K-II

π^0 in K2K 1kt water Cherenkov Detector



Single π^0 sample

(2 ring e-like sample in 25t fiducial)

- **Good NC sample**

  86% from NC interaction

  (54% from NC resonant prod.)

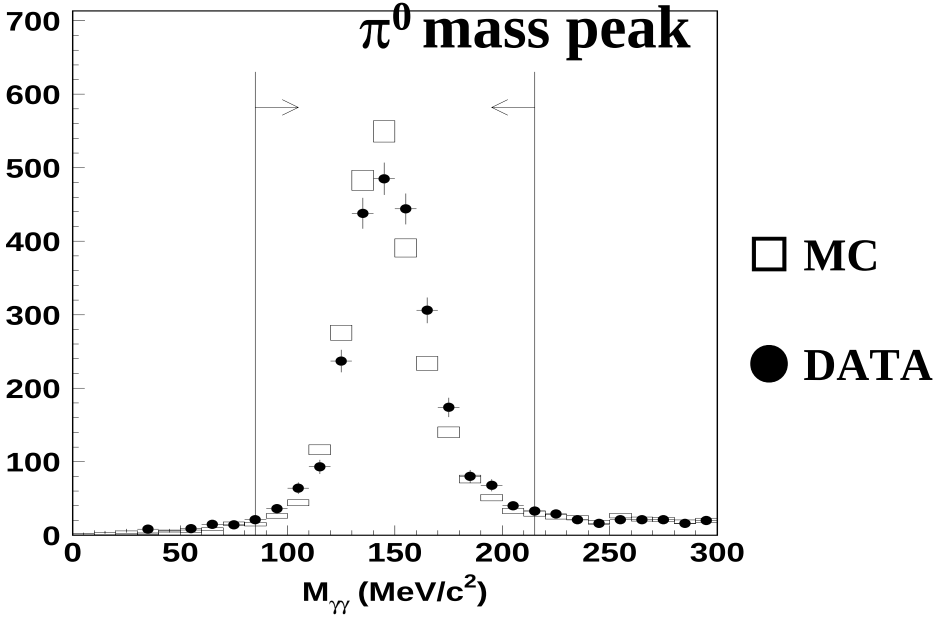
  π^0 efficiency 49%

- **Good measure of NC interaction at low energy**
- **Main background for ν_e search**

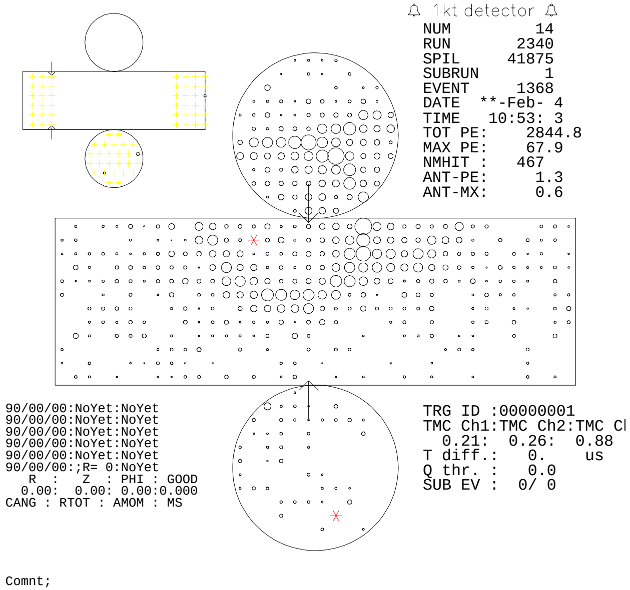
MC

- M_V =0.81GeV
- M_A=1.1 GeV
  for QE and 1π prod.
- Rein-Sehgal model
  for 1π and coherent π prod.
- Fermi Gas
- Final state π absorption
  photo-production data
  π scattering data

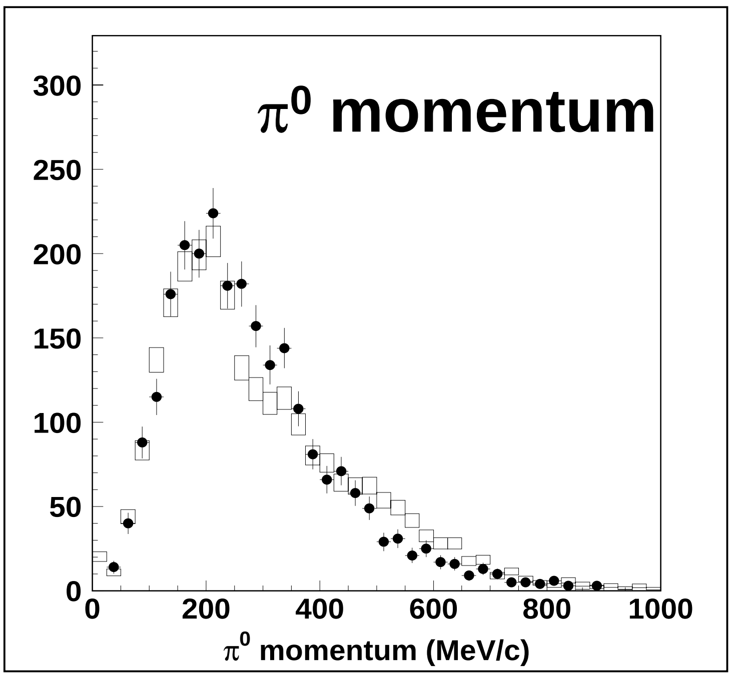
$$\frac{NC}{CC} \Leftarrow \frac{\pi^0}{\mu} \equiv \frac{2\,\text{ring}\ \pi^0\ \text{events}}{1\text{ring}\ \mu\ \text{events}}$$



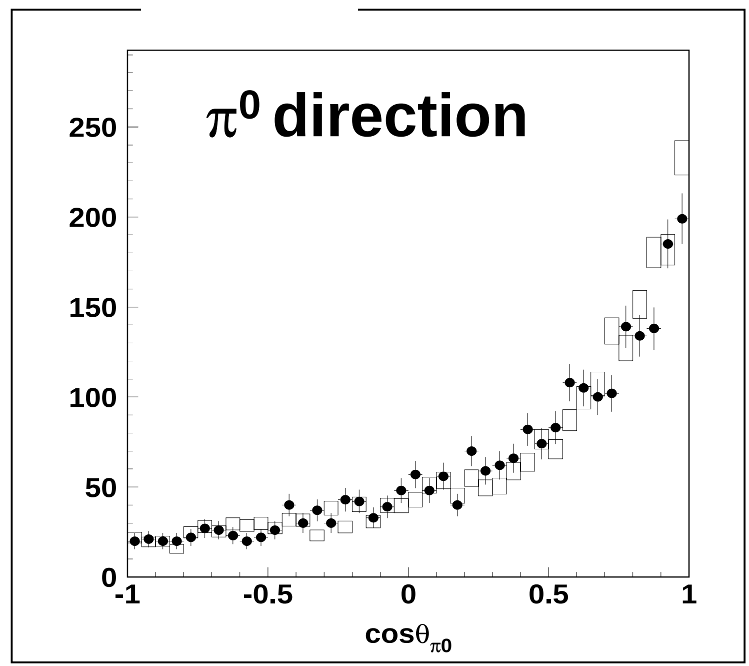
π^0 mass peak
700
600
500
400
300
200
100
0
0
50
100
150
200
250
300
$M_{\gamma\gamma}$ (MeV/c^2)
MC
DATA



1kt detector
NUM 14
RUN 2340
SPIL 41875
SUBRUN 1
EVENT 1368
DATE **-Feb- 4
TIME 10:53: 3
TOT PE: 2844.8
MAX PE: 67.9
NMHIT : 467
ANT-PE: 1.3
ANT-MX: 0.6
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
90/00/00:;R= 0:NoYet
R : Z : PHI : GOOD
0.00: 0.00: 0.00:0.000
CANG : RTOT : AMOM : MS
TRG ID :00000001
TMC Ch1:TMC Ch2:TMC Cl
0.21: 0.26: 0.88
T diff.: 0. us
Q thr. : 0.0
SUB EV : 0/ 0
Comnt;



π^0 momentum
300
250
200
150
100
50
0
0
200
400
600
800
1000
π^0 momentum (MeV/c)



π^0 direction
250
200
150
100
50
0
-1
-0.5
0
0.5
1
$\cos\theta_{\pi 0}$

Result of (π^0/μ) in K2K 1kt detector

π^0

25t fiducial (r<2m, -2m<z<0m)
2 ring FC events, both e-like
$M\pi0$ = 85 – 215 MeV

μ

25t fiducial (r<2m, -2m<z<0m)
1 ring FC events, μ-like

K2K Data set : 3.2E19 POT

	Data	**MC(*)**
π^0	**2496**	**2582.3**
1-R FC μ	**22612**	**22545.2**
π^0/μ	0.110 ± 2% (stat) ± 8% (sys)	0.115

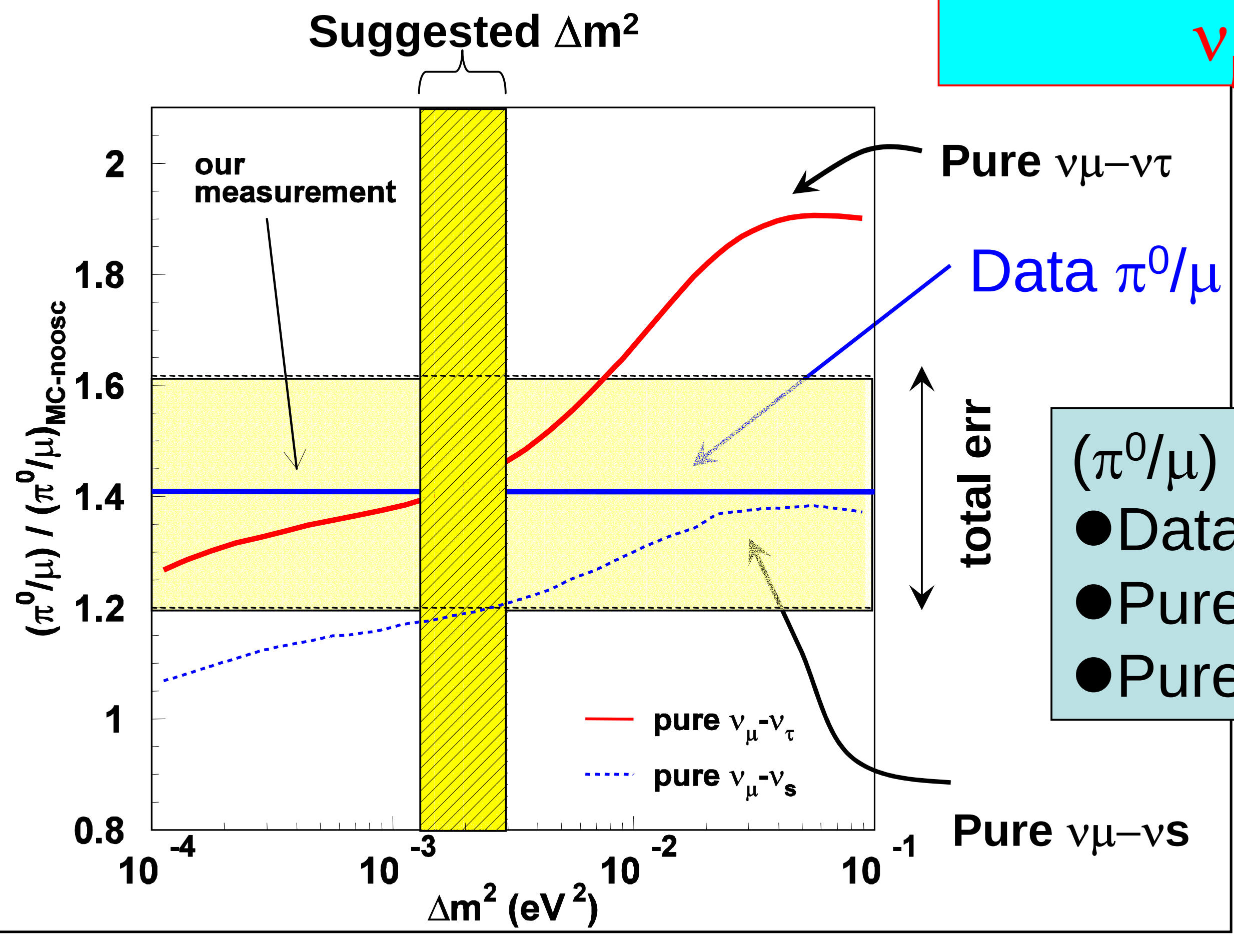
Detector systematics (→ sys)
- **Particle ID**
- **Ring counting, etc..**

(*) normalized by number of total events in 25t fiducial

MC reproduces data in (rate, E_π θ_π)quite well !

Application of π^0/μ to SK atmospheric data
$\nu_\mu-\nu_\tau$ and $\nu_\mu-\nu_s$ hypothesis

consistent with $\nu_\mu-\nu_\tau$

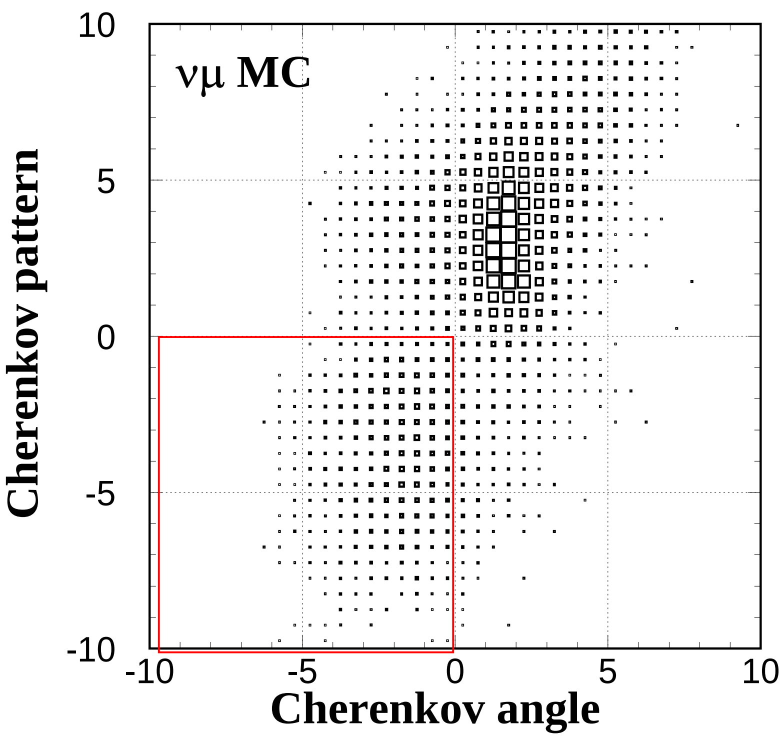


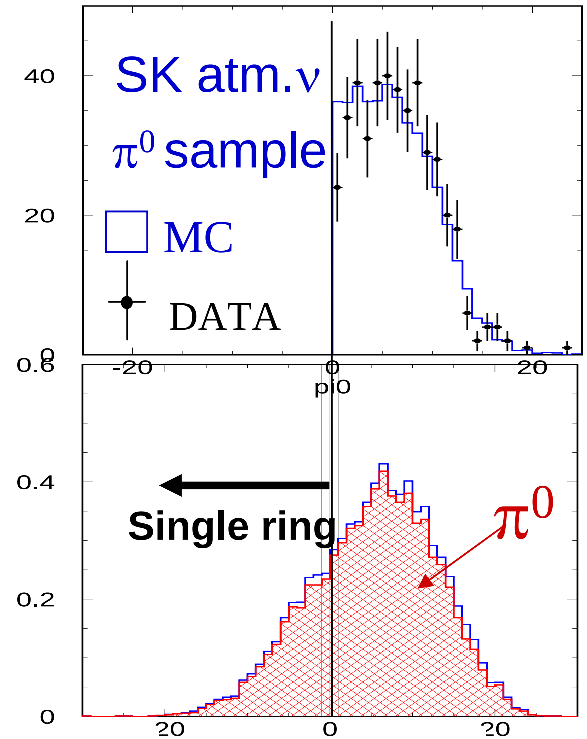
$(\pi^0/\mu) / (\pi^0/\mu)_{noosc}$

- Data 1.41
- Pure $\nu\mu-\nu\tau$ 1.42
- Pure $\nu\mu-\nu s$ 1.19

ν_e appearance search in K2K-I

- Fully Contained - Single Ring – e-like (Ring pattern and opening angle)
- Visible Energy > 100MeV - Without decay electrons





νμ MC ,
FC , e-like+X
Evis>100 MeV
no decay

multi-ring likelihood

Reduction Summary

DATA SET

June'99 – July'01 (4.8×10^{19}POT)

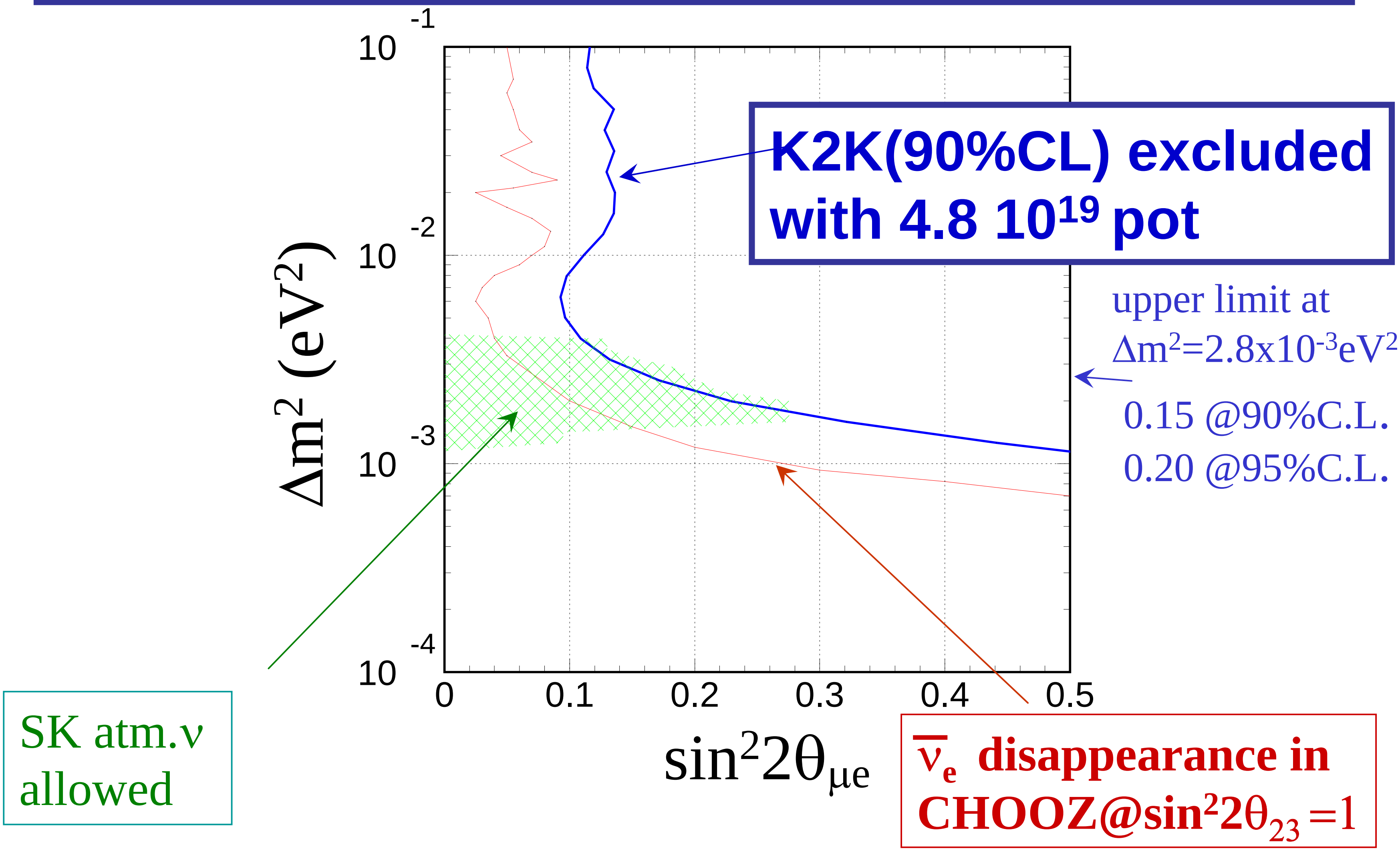
	DATA	ν_μ MC	beam ν_e MC	signal ν_e MC (CC) $\sin^2 2\theta_{\mu e}=1$, $\Delta m^2=2.8\times10^{-3}eV^2$
total exp. events		104 events	0.99 events	28 events
FCFV	56	80 (78%)	0.82 (83%)	28 (98%)
Single ring	32	50 (48%)	0.48 (48%)	20 (71%)
PID (e-like)	1	2.9 (2.7%)	0.42 (42%)	18 (63%)
Evis>100MeV	1	2.6 (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

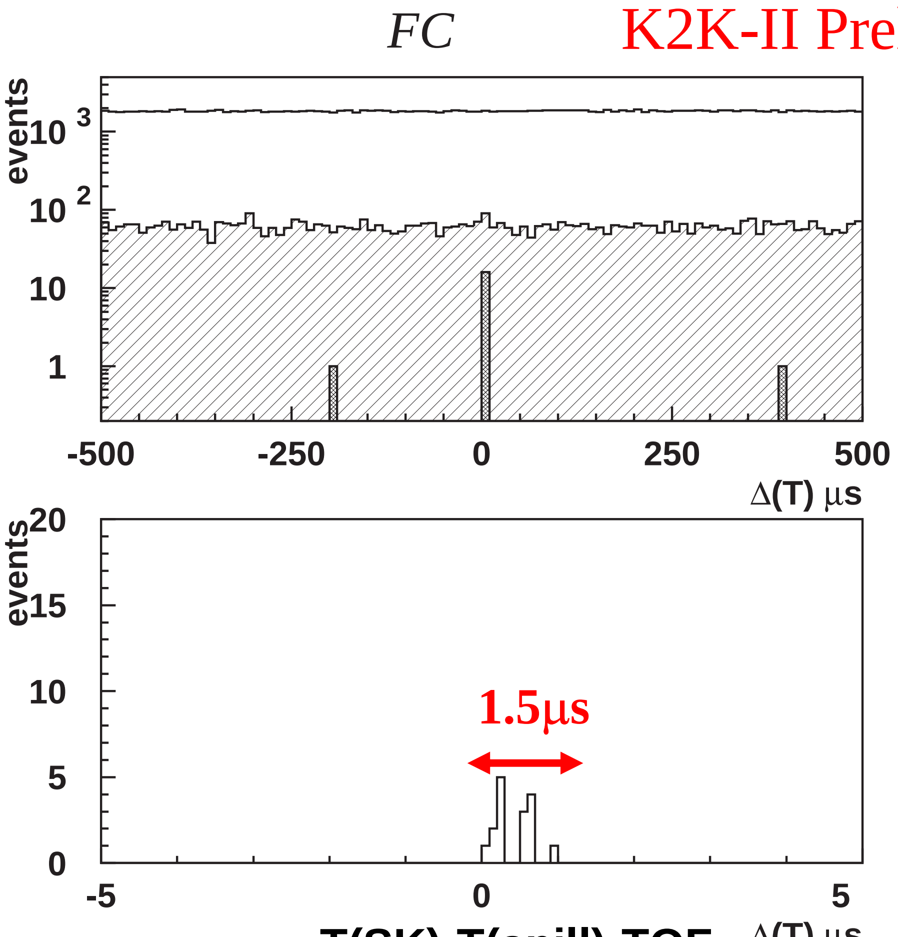
2.4 events expected.

Upper limit of ν_e appearance from K2K-I

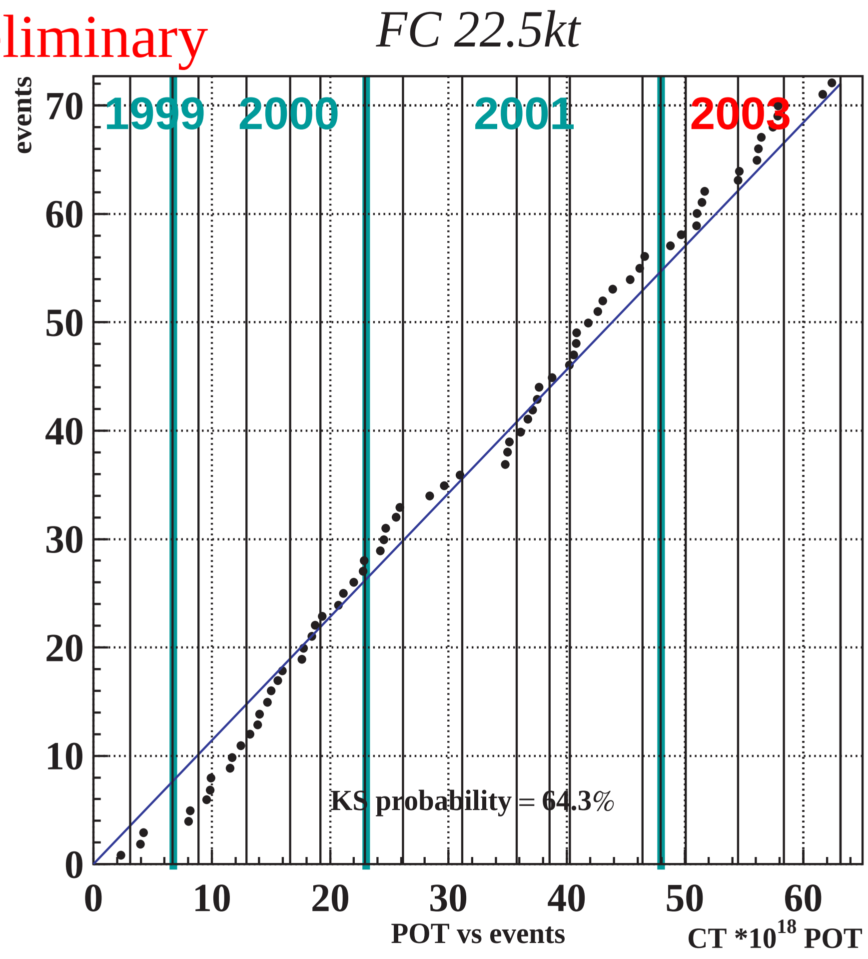


SK is back ! Updated SK events in K2K-II

K2K-II Preliminary



T(SK)-T(spill)-TOF



Full water on 10-Dec.-2002

SK Data Summary K2K-II

	K2K-II (Jan.-Apr. '03)	(K2K-I)
• #spills:	2.8×10^{6}	9.2×10^{6}
• POT:	1.5×10^{19}	4.8×10^{19}
• Observed:	16 (23 incl out of FV)	56 (91)
• Expected:		
– 1kt	$26.4^{+2.3}_{-2.1}$	$80.1^{+6.2}_{-5.4}$

- **Obs/Exp(1kt)** **0.61 ± 0.15(stat)** ↔ **0.70 ± 0.09(stat)**

Consistent rate reduction

Calibration of SK-II (new configuration of PMTs)

Upgrade of near detector with fine segmented scintillator detector

Expected results in the near future NUMI/MINOS and CGNS

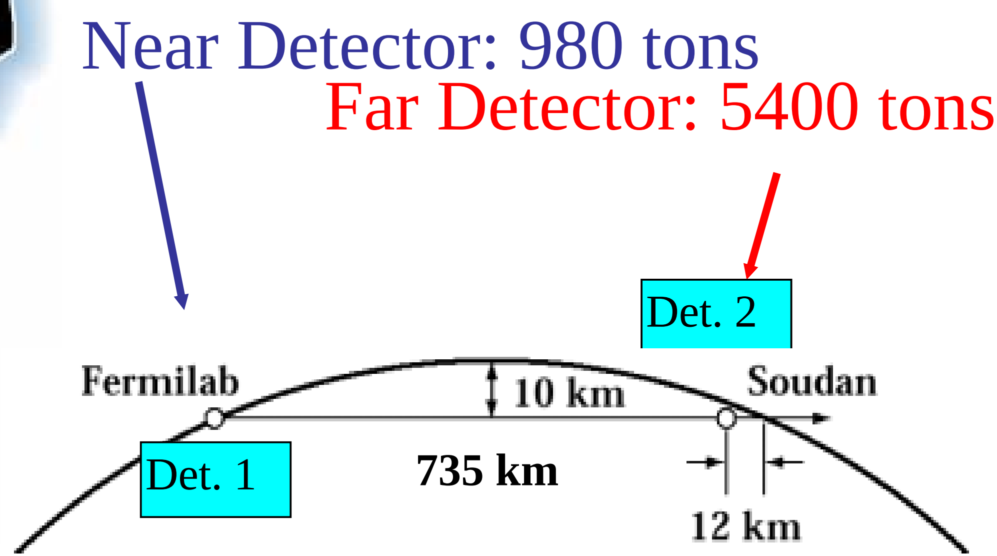
- **Oscillation pattern**
- **Unexpected**
  - **Neutrino decay etc.**
- ν_τ **appearance**

- **Search $\nu_\mu \to \nu_e$ at $\Delta m^2 \sim 3 \times 10^{-3}$ eV^2**
  - **Direct evidence of 3 generations mixing**
  - **lead to CPV in lepton**

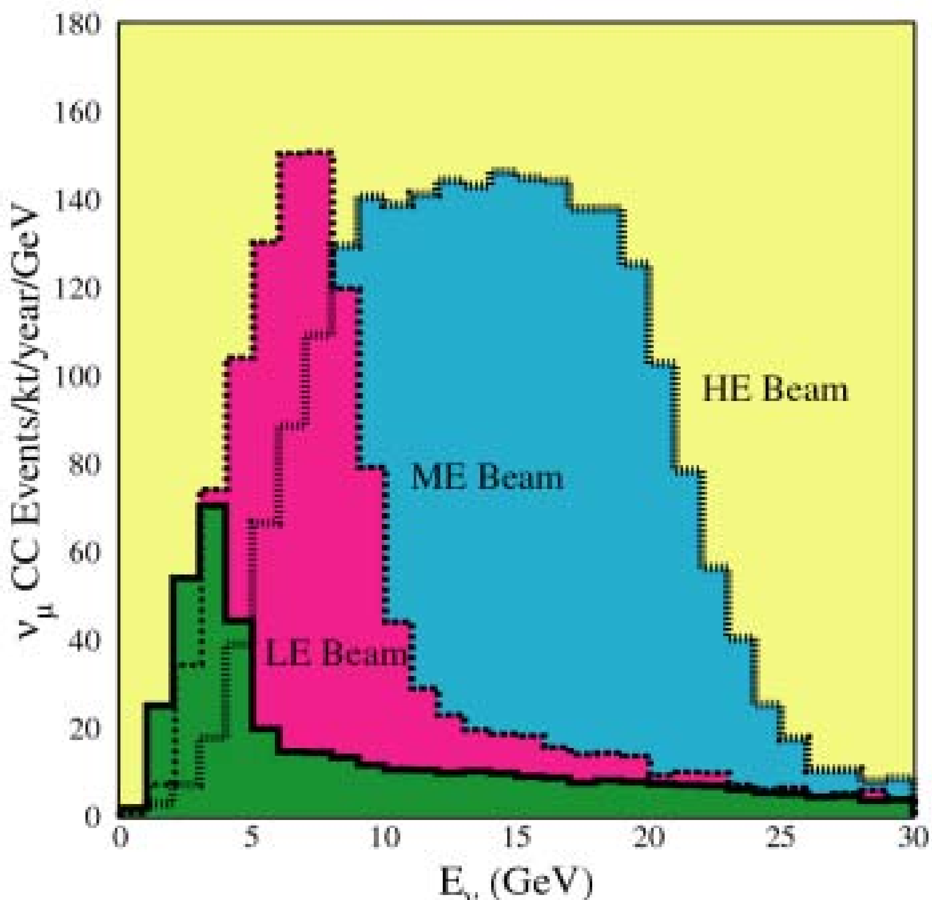
The MINOS Experiment

Status

- The installation in the Target Hall will start in September
- The installation in the Near Detector Hall in December.
- The first beam on target in December '04.
- The Far Detector is now complete, with both coils energized and veto shield also finished.
- Taking good atmospheric $\nu\mu$ and $\bar{\nu}\mu$ data.



The NuMI Neutrino Energy Spectra



ν_μ CC Events/kt/year

Low	Medium	High
470	1270	2740

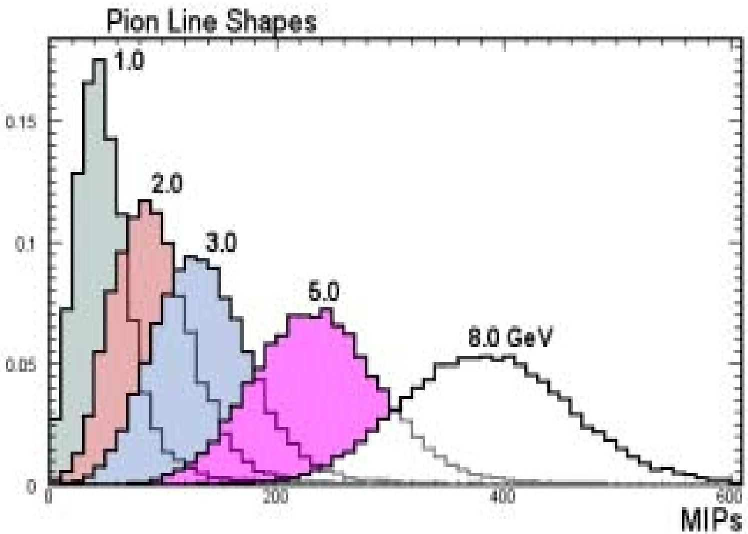
ν_μ CC Events/MINOS/2 year

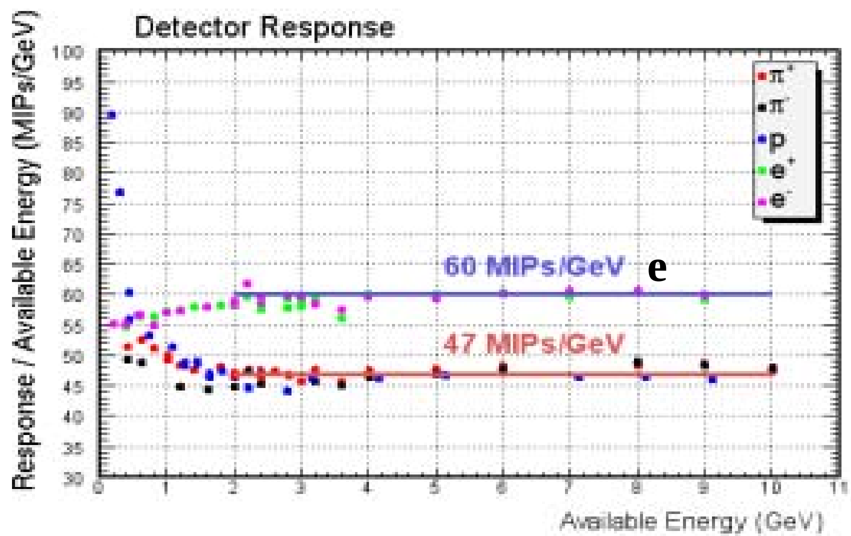
Low	Medium	High
5080	13800	29600

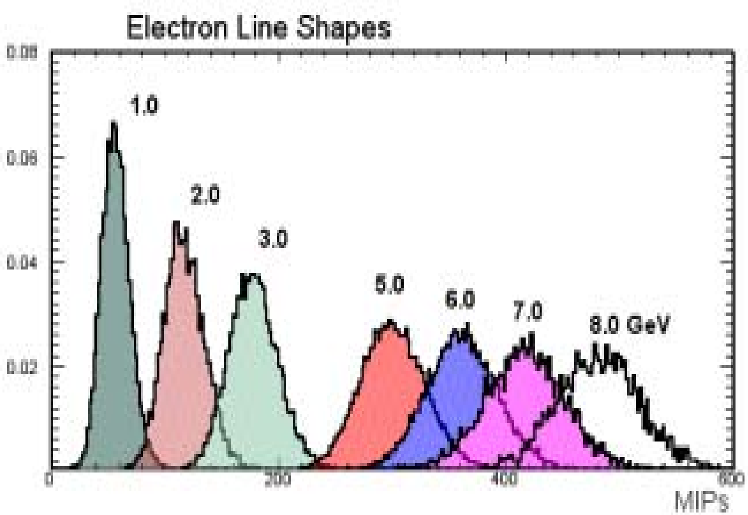
$4\text{x}10^{20}$ protons on target/year
$4\text{x}10^{13}$ protons/2.0 seconds

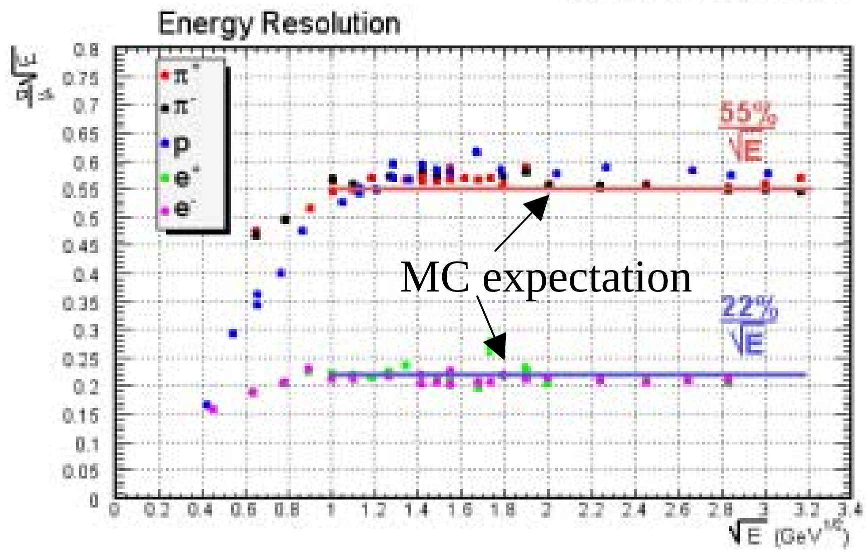
By moving the horns and target, different energy spectra are available using the NuMI beamline. The energy can be tuned depending on the specific oscillation parameters expected/observed.

Particle Response (preliminary)

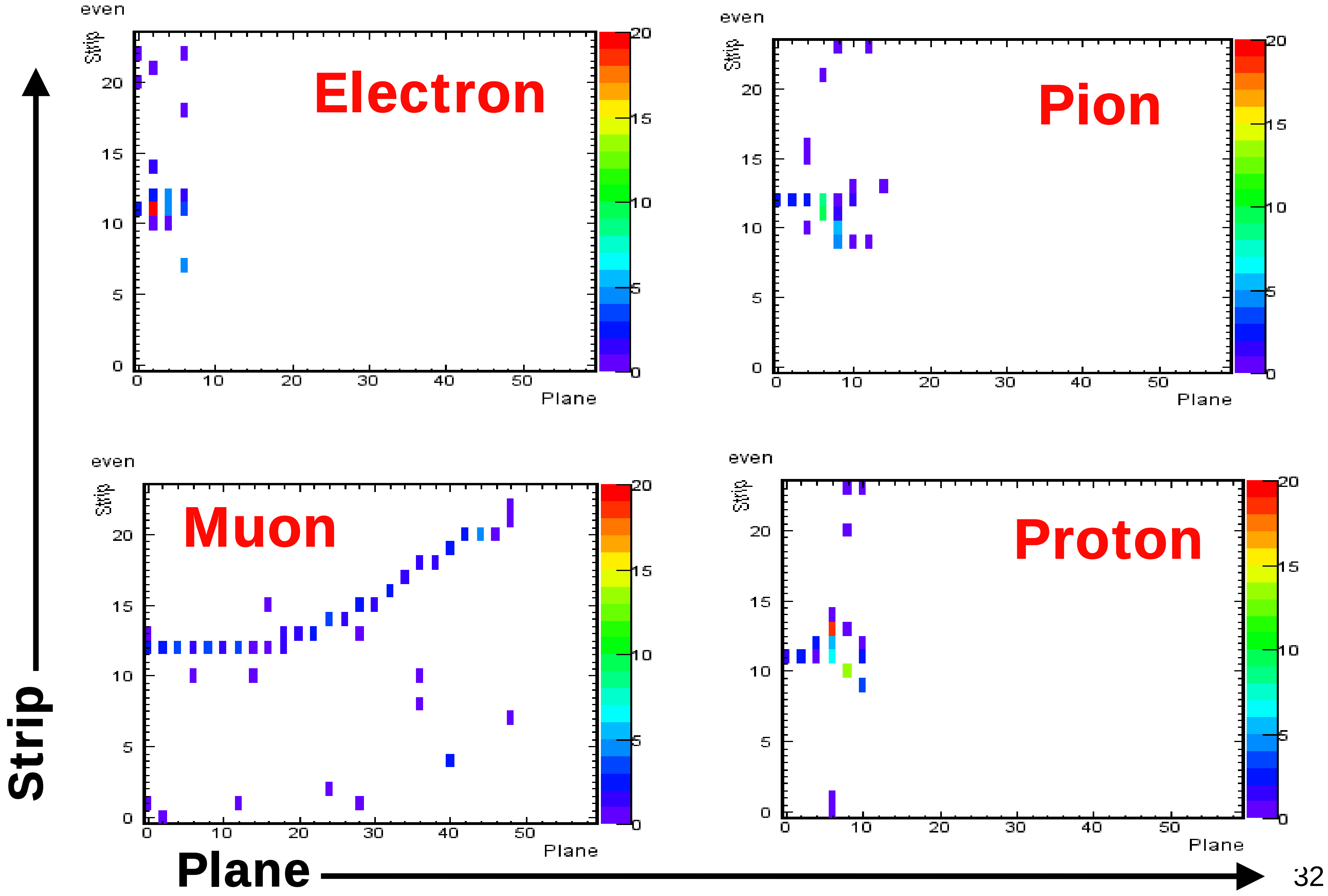




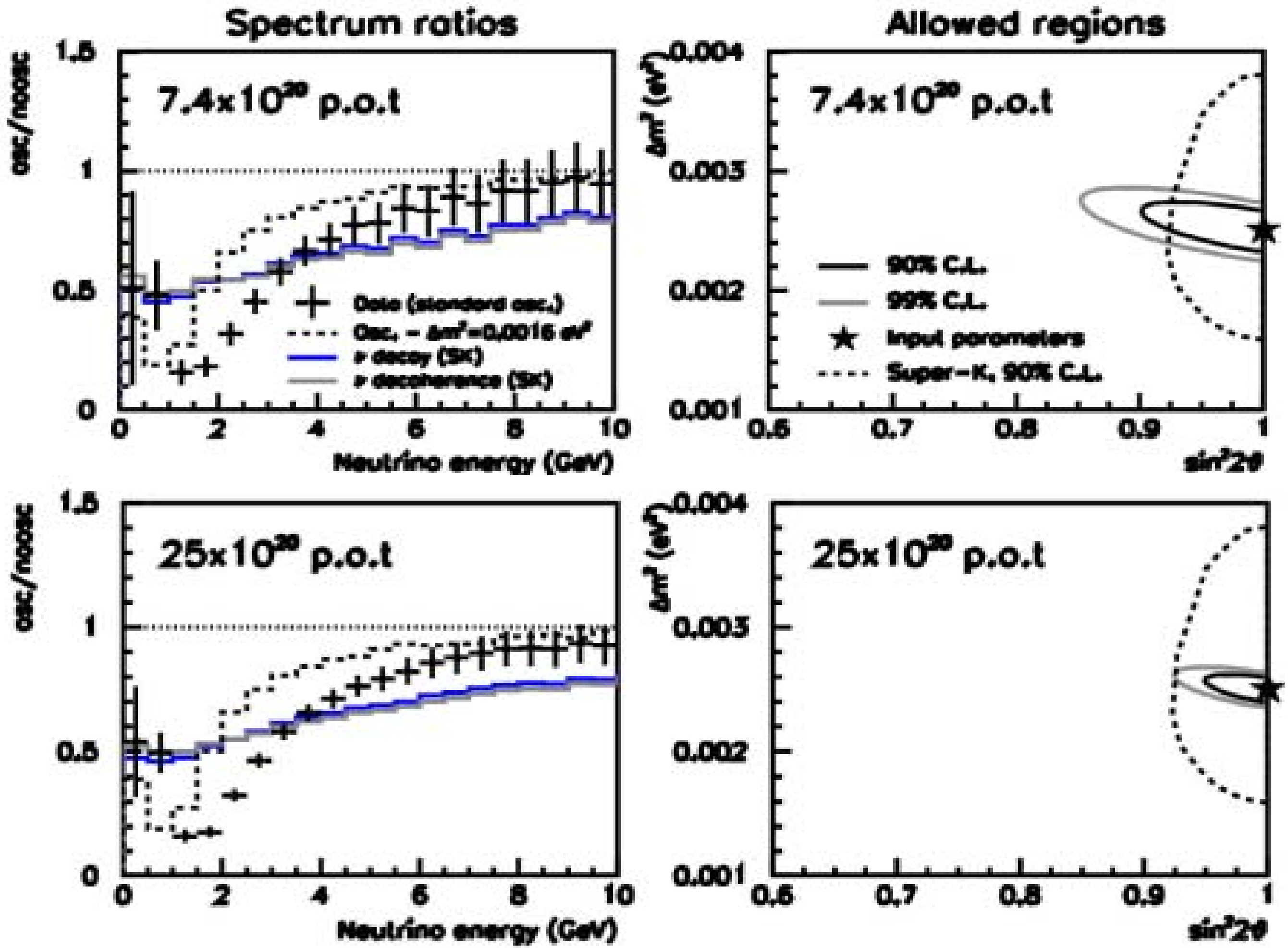




Example Caldet events: 2 GeV



Measurement of Oscillations in MINOS

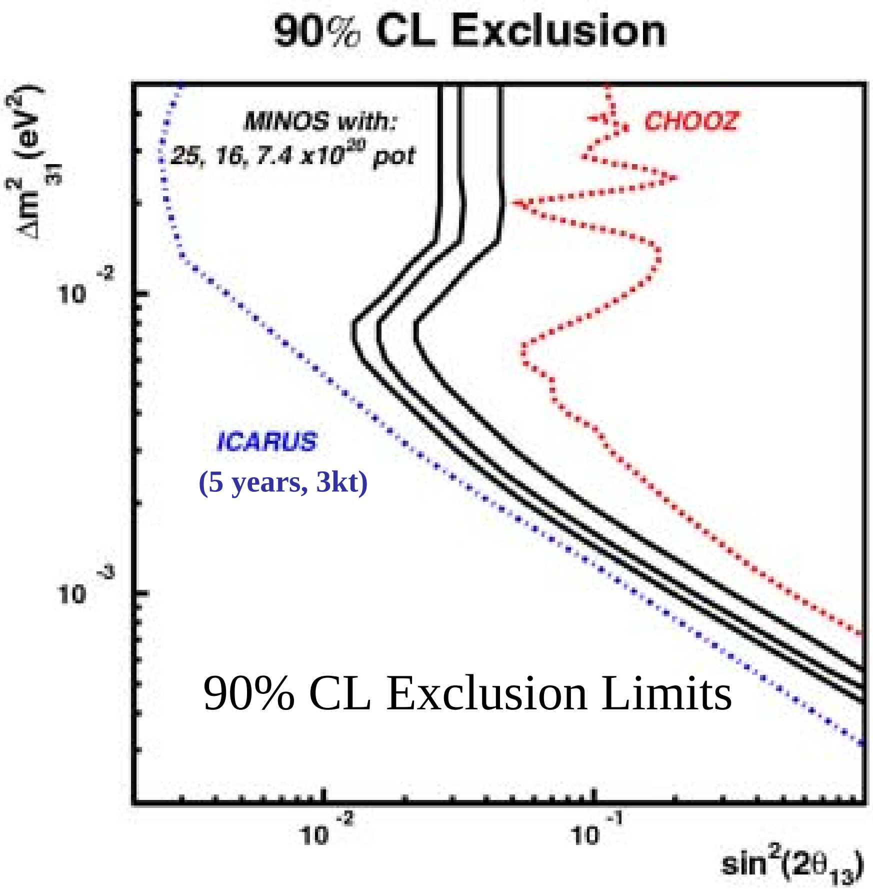


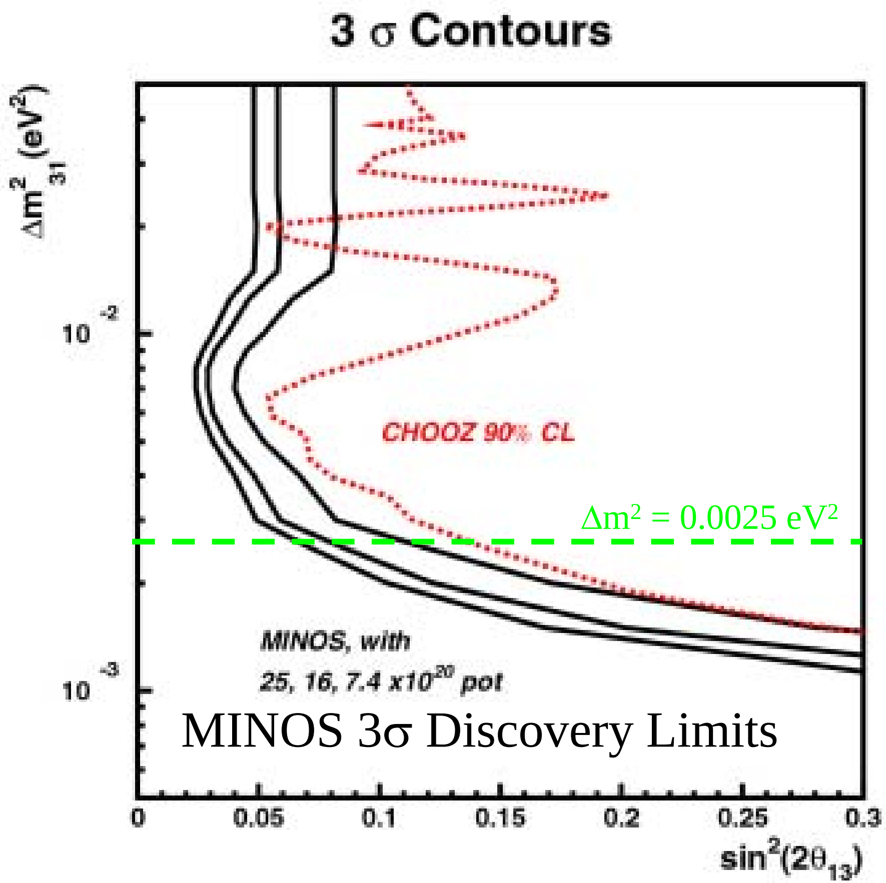
For $\Delta m^2 = 0.0025\ eV^2$, $\sin^2 2\theta = 1.0$

Oscillated/unoscillated ratio of number of ν_μ CC events in the far detector vs $E_{observed}$

MINOS 90% and 99% CL allowed oscillation parameter space.

Appearance of Electrons

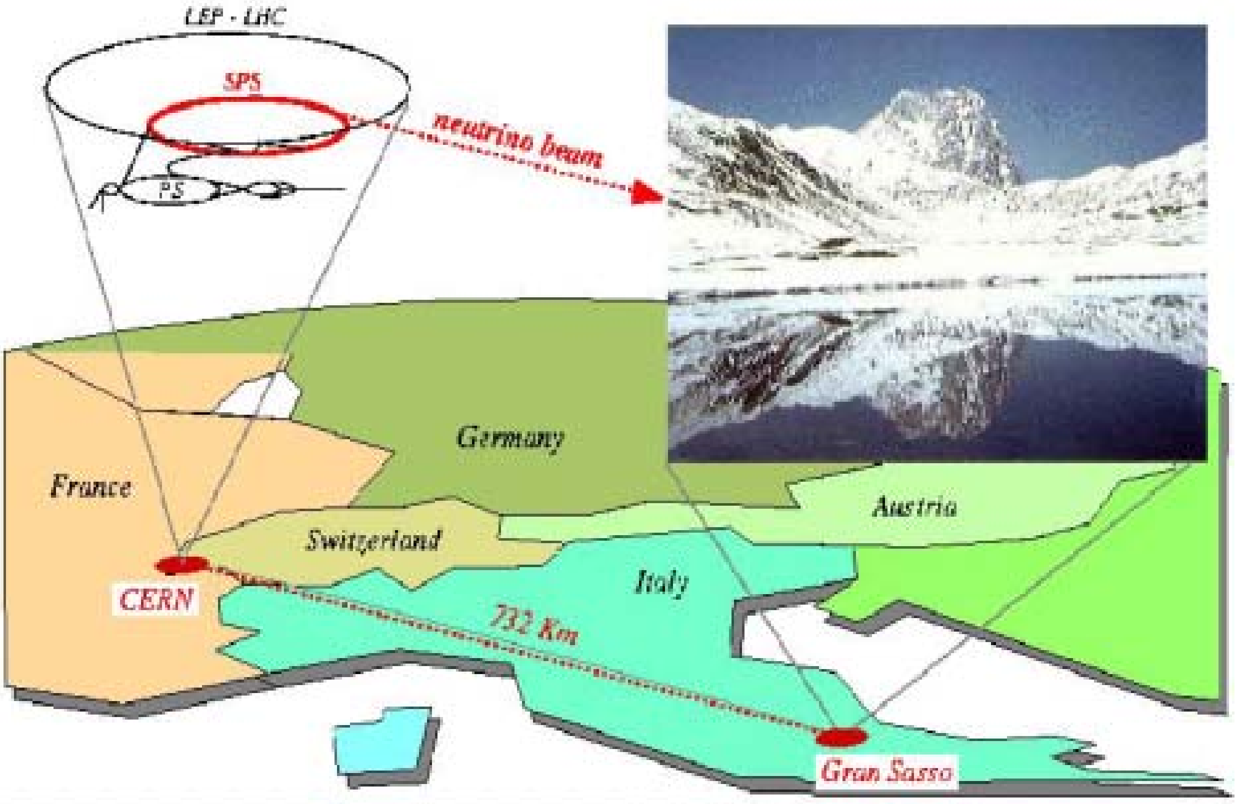




- MINOS sensitivities based on varying numbers of protons on target

Direct ν_τ Detection

CERN to Gran Sasso Neutrino Beam



Status

- Excavation of all the underground structures and concreting was completed on 20 June.
- The installation of the beam dump (2000 tons of material) till September 2003.
- The installation of the decay tube will take 7 months.
- All is going well for the beam to the Gran Sasso experiments to start in May 2006.

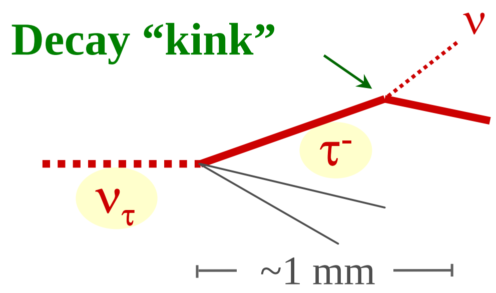
2 ways of detecting τ appearance

ν_μ ….. ν_τ $\rightarrow$ τ^- + X

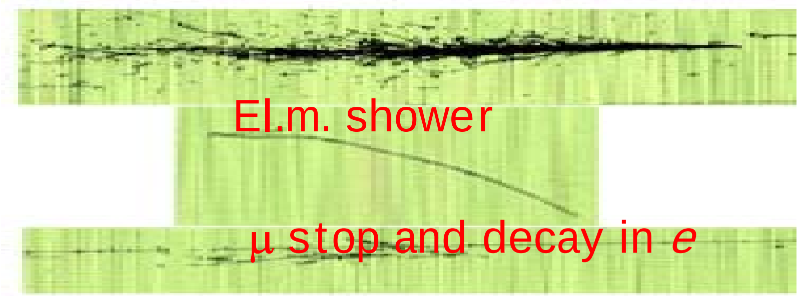
oscillation CC interaction

	BR
$\mu^-\ \nu_\tau\ \bar{\nu}_\mu$	18 %
$h^-\ \nu_\tau\ n\pi^o$	50 %
$e^-\ \nu_\tau\ \bar{\nu}_e$	18 %
$\pi^+\ \pi^-\ \pi^-\ \nu_\tau\ n\pi^o$	14%

OPERA: Observation of the decay topology of τ *(à la CHORUS)*
In photographic emulsion
(~ μm granularity)
A digital Cloud chamber



ICARUS: detailed TPC image in liquid argon and kinematic criteria *(à la NOMAD)*
(~ mm granularity)
A digital Bubble chamber



But also: ν_μ … ν_e $\rightarrow$ e^- + X

Expected number of τ events

- full mixing
- 5 years run @ 6.76×10^{19} pot / year

OPERA

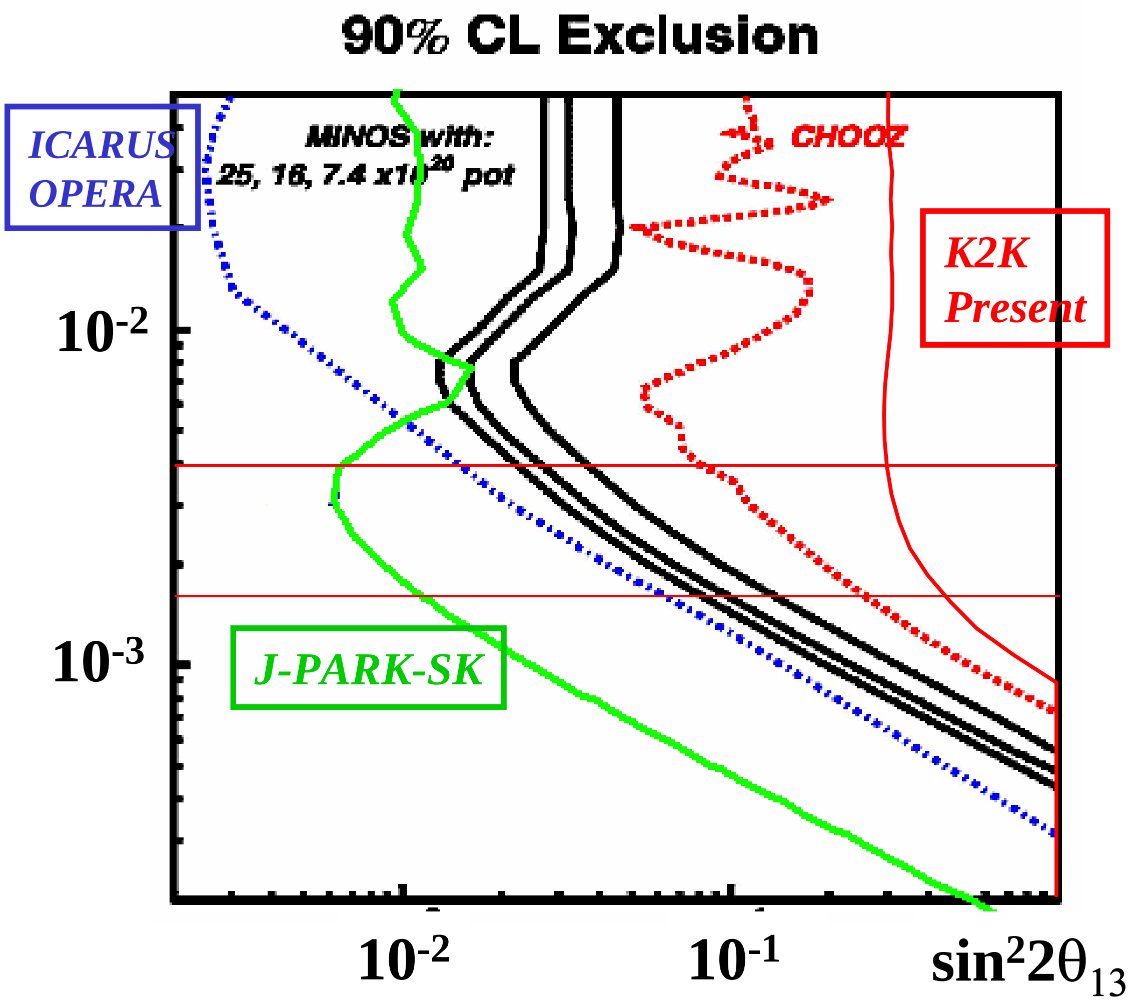
	signal (Δm^2 = 1.8 x 10^{-3} eV^2)	signal (Δm^2 = 2.5 x 10^{-3} eV^2)	signal (Δm^2 = 4.0 x 10^{-3} eV^2)	BKGD
Final Design	9.0	17.2	43.8	1.06
With possible improvements	10.3	19.8	50.4	0.67

ICARUS

τ decay mode	Signal $\Delta m^2 = 1.6 \times 10^{-3}$ eV^2	Signal $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2	Signal $\Delta m^2 = 3.0 \times 10^{-3}$ eV^2	Signal $\Delta m^2 = 4.0 \times 10^{-3}$ eV^2	BG
$\tau \to e$	3.7	9	13	23	0.7
$\tau \to \rho$ DIS	0.6	1.5	2.2	3.9	< 0.1
$\tau \to \rho$ QE	0.6	1.4	2.0	3.6	< 0.1
Total	**4.9**	**11.9**	**17.2**	**30.5**	**0.7**

θ_{13} sensitivity in near future

Expected 90% CL sensitivity on θ_{13} in this decade



Summary

Solar and Atmospheric neutrino observations have (almost) established the existence of neutrino oscillations in two channels

Completed and on-going experiments has reported

1. ν_τ do exist and no evidence of $\nu_\mu \rightarrow \nu_\tau$ nor $\nu_\mu \rightarrow \nu_e$ in large Δm^2
2. New analysis on atmospheric ν data in SK
3. π^0 production in GeV ν_μ beam
4. New limit on ν_e appearance in ν_μ beam

In a few years, accelerator based ν oscillation experiments will:

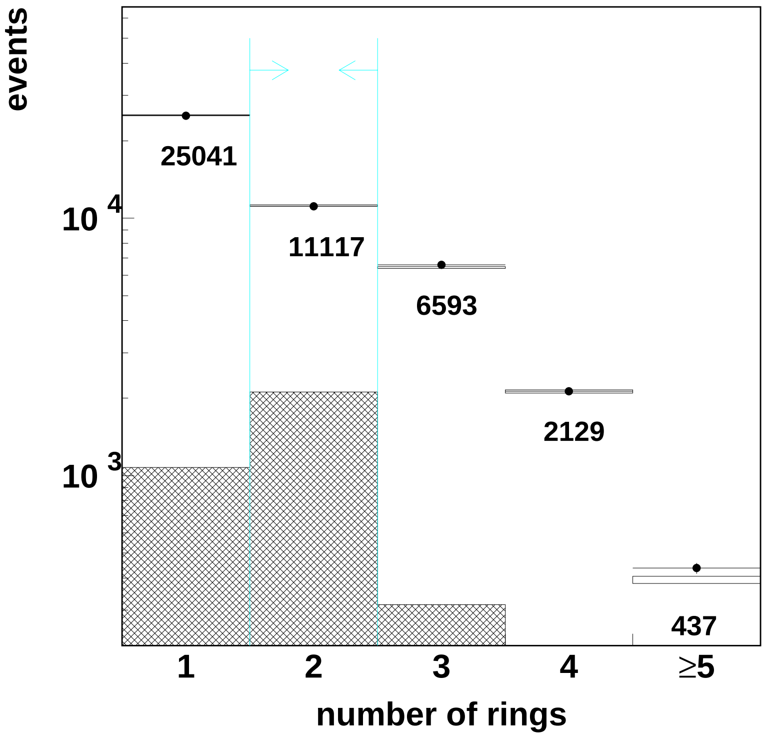
1. Establish or refute the LSND effect (Mini-BooNE)
2. Confirm Atmospheric ν results are due to ν oscillation
   - Oscillatory behavior of ν_μ's (K2K, MINOS)
   - Explicit detection of ν_τ in $\nu_\mu \rightarrow \nu_\tau$ (OPERA, ICARUS)
   - Continued search for $\nu_\mu \rightarrow \nu_e$ appearance
3. Unexpected

Next generation experiments should make precise measurement of oscillation parameters ; esp. $\theta_{13,}$ CP violation in lepton, mass hierarchy

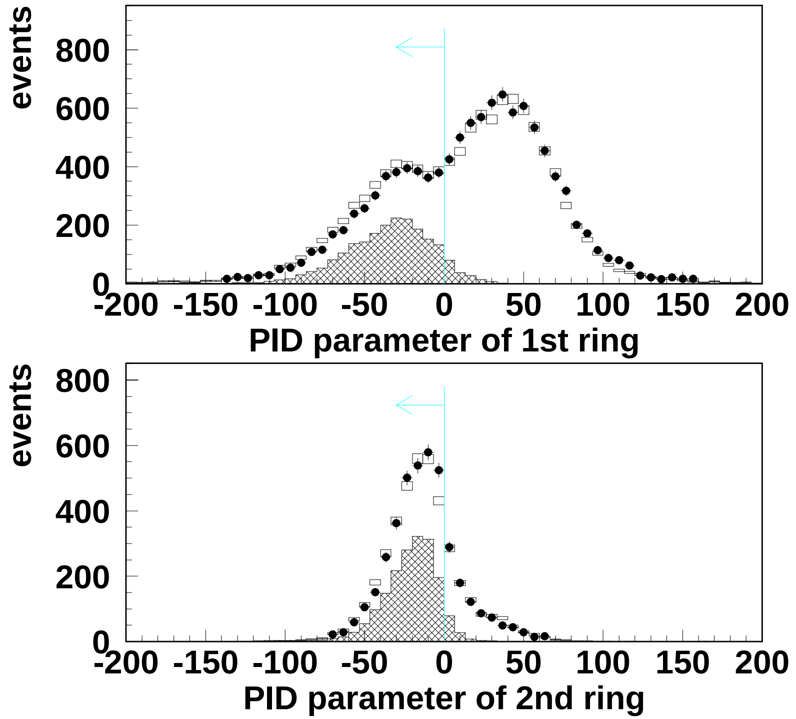
Close in on the question of mass and mixing !

π^0 event selection in K2K 1KT data

Nring

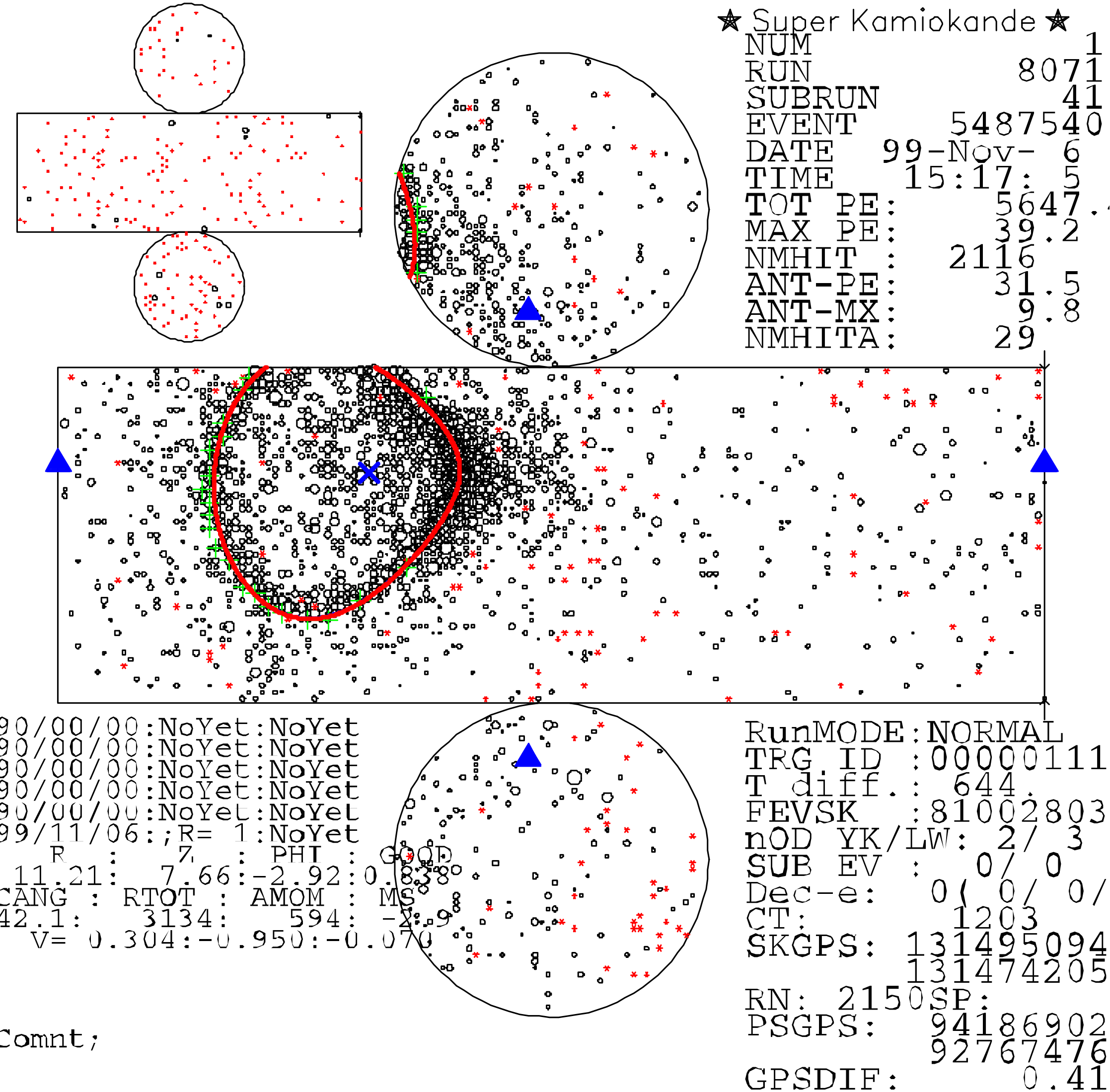


PID cut



(hatch: NC $1\pi^0$ + no other meson in MC)

Electron Candidate



reconst. momentum
597 MeV/c

reconst. Eν
assuming νe CCQE
612 MeV