August 10, 1999

ACCELERATOR AND REACTOR NEUTRINO EXPERIMENTS

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CERN

1. PRECISION MEASUREMENTS OF ELECTROWEAK PARAMETERS
2. SEARCHES FOR NEUTRINO OSCILLATIONS
   - Long baseline* reactor experiments
   - $\nu_\mu - \nu_e$ (LSND, KARMEN)
   - $\nu_\mu - \nu_\tau$ (CHORUS, NOMAD)
   - "Single mode" (NUTEV)
3. PROSPECTS
   - Verification of LSND result
   - Long baseline* accelerator experiments
   - Very long baseline* reactor experiment
4. SEARCH FOR NEW PARTICLES
6. CONCLUSIONS

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* Long (Very Long) baseline $\equiv$ sensitivity to $\Delta m^2 < 10^{-2}$ (10^{-5}) eV^2

NUTEV (E-815)
PRECISION MEASUREMENT OF $\sin^2\theta_W$

- Use pure ν_μ, $\bar{\nu}_\mu$ beams from Sign Selected Quadrupole Train at the Tevatron

  ν_μ beam: $\bar{\nu}/\nu \lesssim 10^{-3}$ $\quad \nu_e/\nu_\mu = 1.3\times10^{-2}$

  $\bar{\nu}_\mu$ beam: $\nu/\bar{\nu} \lesssim 2\times10^{-3}$ $\quad \bar{\nu}_e/\bar{\nu}_\mu = 1.1\times10^{-2}$

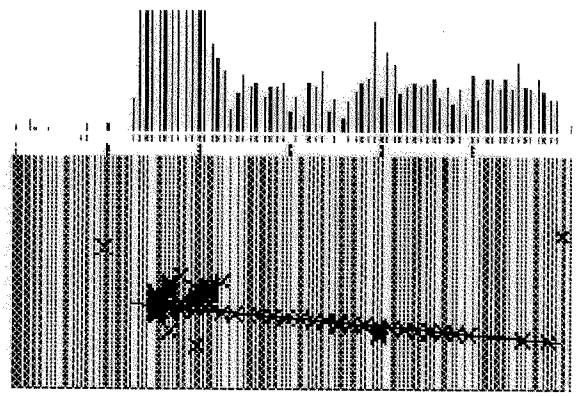
- NUTEV detector: 690 Ton Sampling Calorimeter (Iron-Scintillator — longitudinal granularity 10.2 cm Fe) followed by iron spectrometer

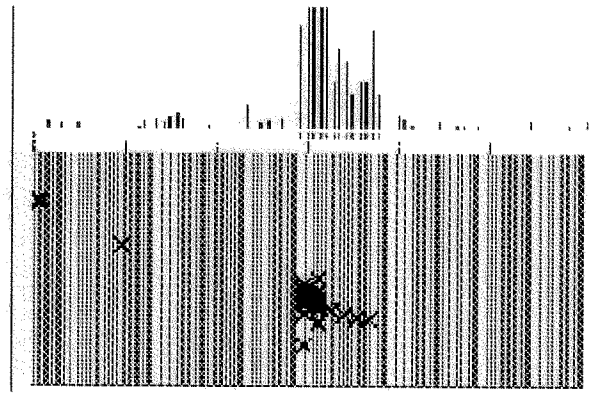
- Measure Paschos-Wolfenstein quantity

$$R^- \equiv \frac{\sigma(\nu_\mu N \to \nu_\mu X) - \sigma(\bar{\nu}_\mu N \to \bar{\nu}_\mu X)}{\sigma(\nu_\mu N \to \mu^- X) - \sigma(\bar{\nu}_\mu N \to \mu^+ X)} = \frac{1}{2} - \sin^2\theta_W$$

This method reduces by a factor ~8 the large systematic error from charm production (uncertainty on m_c) affecting previous experiments based on measurements of the ratio $\sigma(\nu_\mu N \to \nu_\mu X)/\sigma(\nu_\mu N \to \mu^- X)$

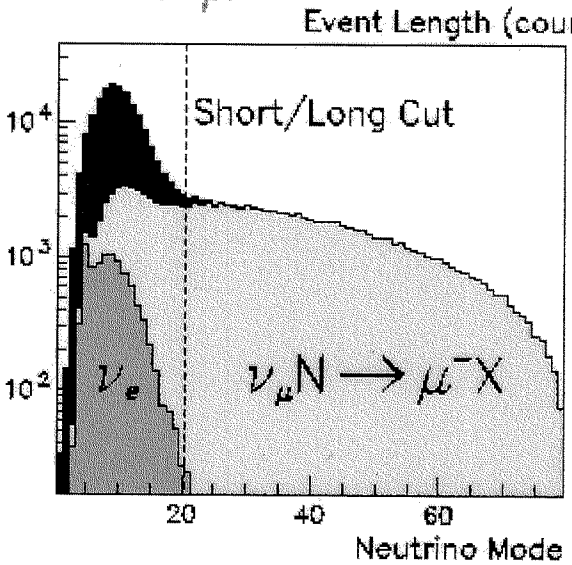
NC/CC Discrimination





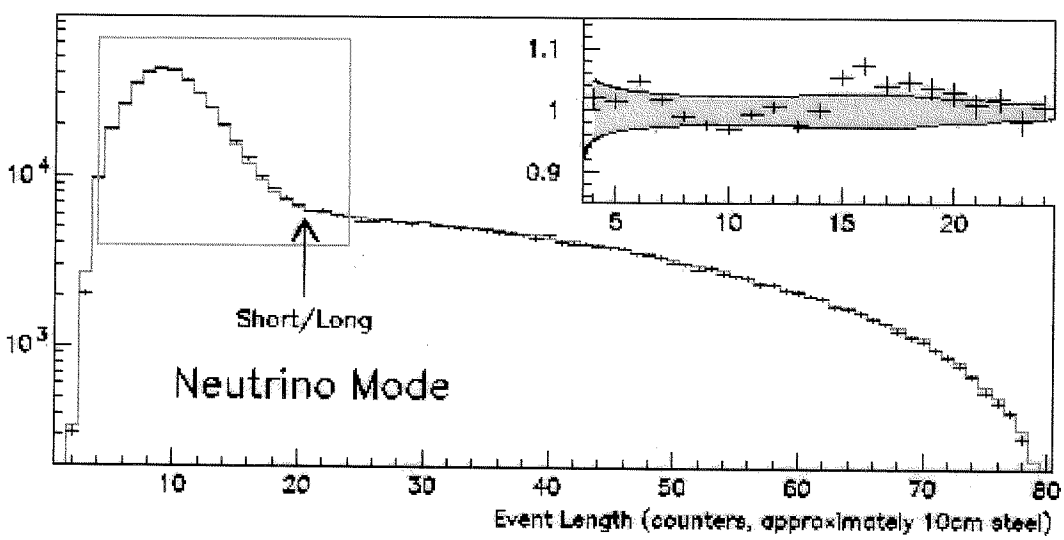
$\nu N \to \mu^+ X$

$\nu N \to \nu X$



Events Ater All Cuts

	Short	Long
ν	386K	919K
$\bar{\nu}$	88.7K	210K



NUTEV data from the 1996-97 Fixed Target Tevatron run

Compare measured R^- with value expected from full simulation using $\sin^2\theta_W$ as free parameter in the simulation

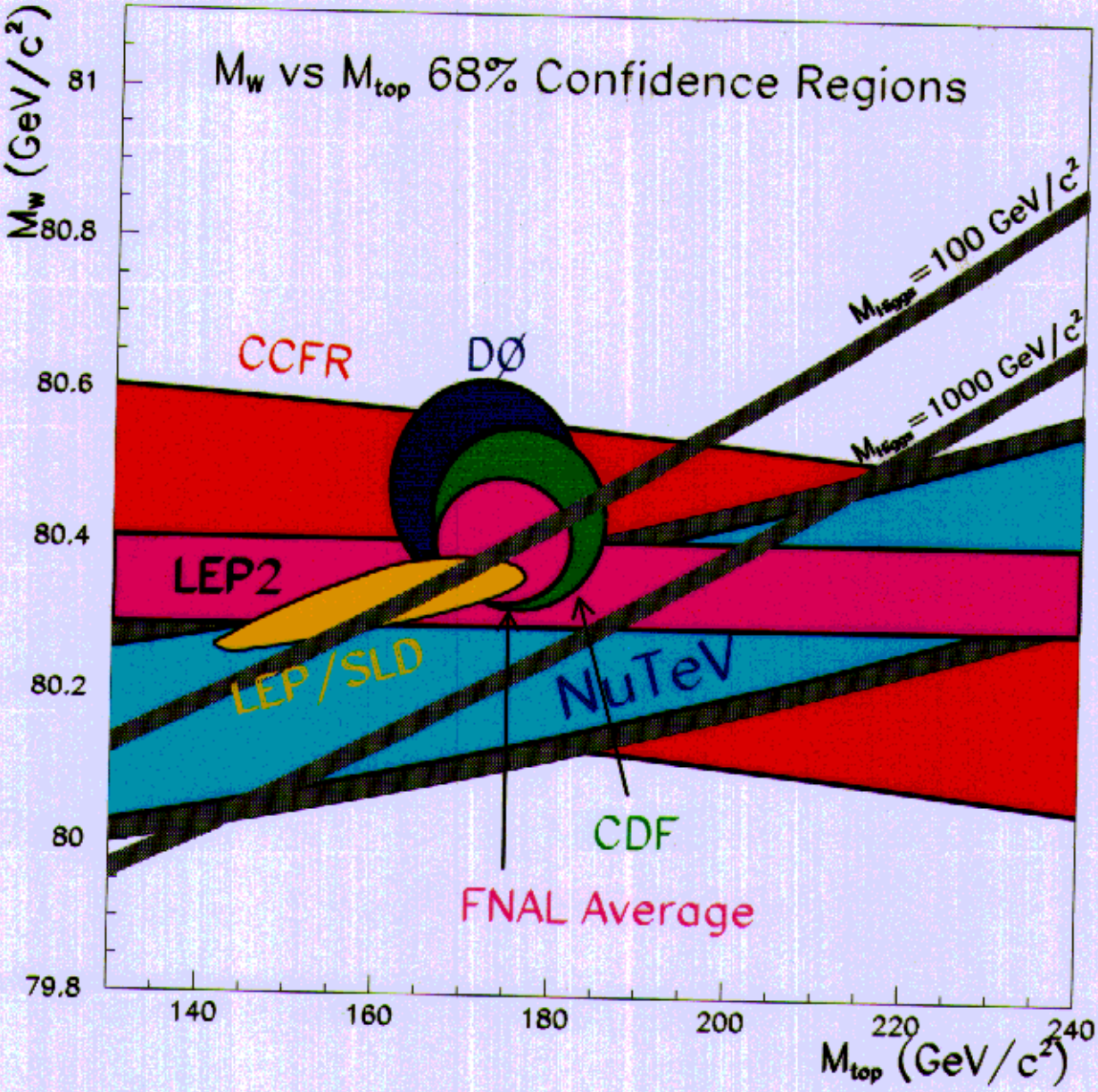
$$\sin^2\theta_W \equiv 1 - \frac{M_W^2}{M_Z^2} = 0.2253 \pm 0.0019 \pm 0.010$$
(stat.) (syst.)

(for $m_{top} = 175$ GeV, $M_H = 150$ GeV)

This result implies

$$M_W = 80.26 \pm 0.10 \pm 0.05 \text{ GeV}$$
stat. syst.

Precision comparable with that of direct measurements of M_W


M_W vs M_{top} 68% Confidence Regions
M_W (GeV/c^2)
81
80.8
80.6
80.4
80.2
80
79.8
140
160
180
200
220
240
M_{top} (GeV/c^2)
M_{Higgs} = 100 GeV/c^2
M_{Higgs} = 1000 GeV/c^2
CCFR
DØ
LEP2
LEP/SLD
NuTeV
CDF
FNAL Average

DETECT $\bar{\nu}_e + p \rightarrow e^+ + n$

IN LIQUID SCINTILLATOR $(CH_2)_n$

- prompt e^+ signal → scintillation light (+ Čerenkov light in LSND ⇒ improved electron/hadron separation)
- delayed signal from neutron capture after thermalization:

LSND, KARMEN: $n + p \rightarrow d + \gamma$ (2.2 MeV)

KARMEN: $n + Gd \rightarrow Gd^* \rightarrow \gamma$'s ($\Sigma E_\gamma \approx 8$ MeV)

	KARMEN-2	LSND
Accelerator	ISIS (RAL)	LANSCE (LANL)
Proton K.E.	800 MeV	800 MeV
Beam current	200 μA	1000 μA
Detector	Segmented liquid scintillator (512 cells)	Liquid scintillator (single tank)
Position determination	cell size	PMT timing
Detector mass	56 tons	180 tons
Distance from proton target	17 m	29 m
Angle to beam axis	90°	17°
DATA TAKING	Feb 97-Feb 99	1993-98
protons on target	2.9×10^{22}	1.8×10^{23}
STATUS	DATA TAKING UNTIL FEB 2001	COMPLETED

OSCILLATION SEARCHES AT NUCLEAR REACTORS

Nuclear Reactors: intense, isotropic sources of $\bar{\nu}_e$

1.9×10^{20} $\bar{\nu}_e$ s^{-1}/GW thermal power

UNCERTAINTY ON EXPECTED $\bar{\nu}_e$ FLUX:

$\pm 2.7\%$

$\langle E(\bar{\nu}_e) \rangle \approx 3$ MeV

DETECTION

$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

e^+: prompt signal, e^+ + annihilation γ's

n: late γ-signal from n capture by Gd (8.1 MeV)

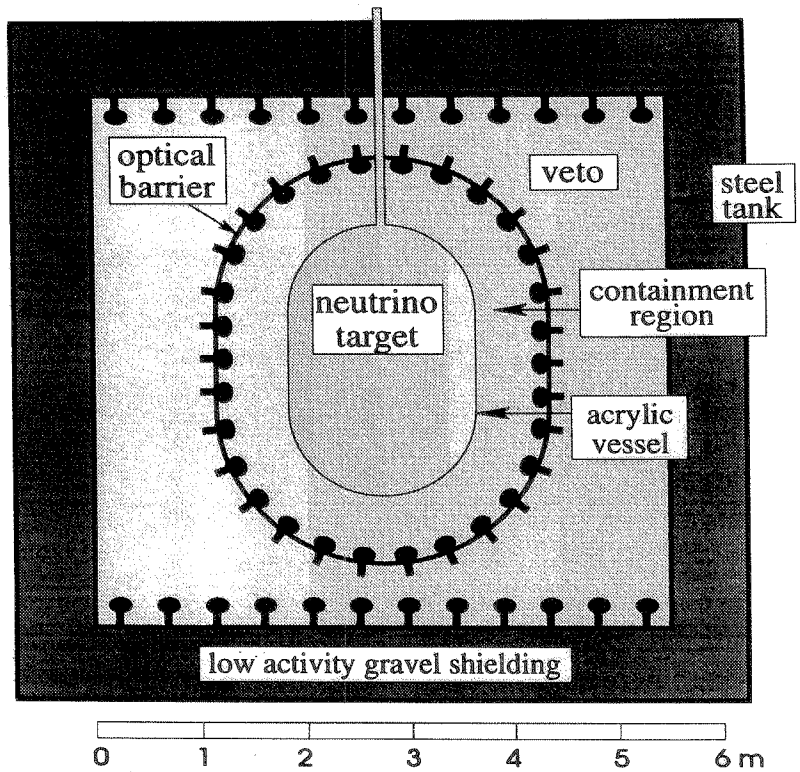
$$E(\bar{\nu}_e) = E(\text{prompt signal}) + 1.8 \text{ MeV}$$

LONG BASELINE REACTOR EXPERIMENTS

		CHOOZ	PALO VERDE
Number of reactors		2	3
Distance (m)		1114 / 998	890/890/750
Total power (GW)		8.5	11.0
Detector type		Gd-doped homogeneous scintillator	Gd-doped segmented scintillator
Detector mass		5 Ton	12 Ton
Rock overburden		300 m.w.e.	32 m.w.e.
Event Rates	FULL POWER	25 d^{-1}	39 d^{-1}
	REACTORS OFF	1.2 d^{-1}	32.6 d^{-1}
STATUS		COMPLETED	TAKING DATA

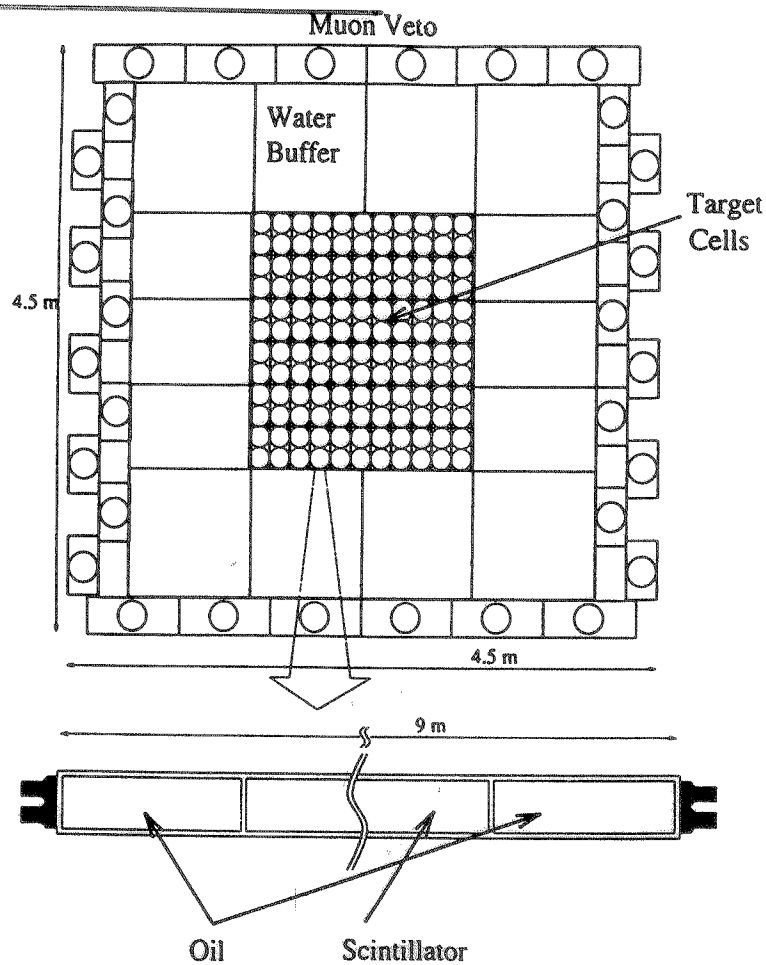
CHOOZ DETECTOR

(Location: Chooz Nuclear Power Plant, France)



PALO VERDE DETECTOR

(located at Palo Verde, AZ)



CHOOZ DATA

REACTOR 1	REACTOR 2	Data taking time (hrs)	Integrated thermal power (GWh)
OFF	OFF	3420.4	—
OFF	ON	1187.8	4136
ON	OFF	2058.0	8295
ON	ON	1543.1	8841

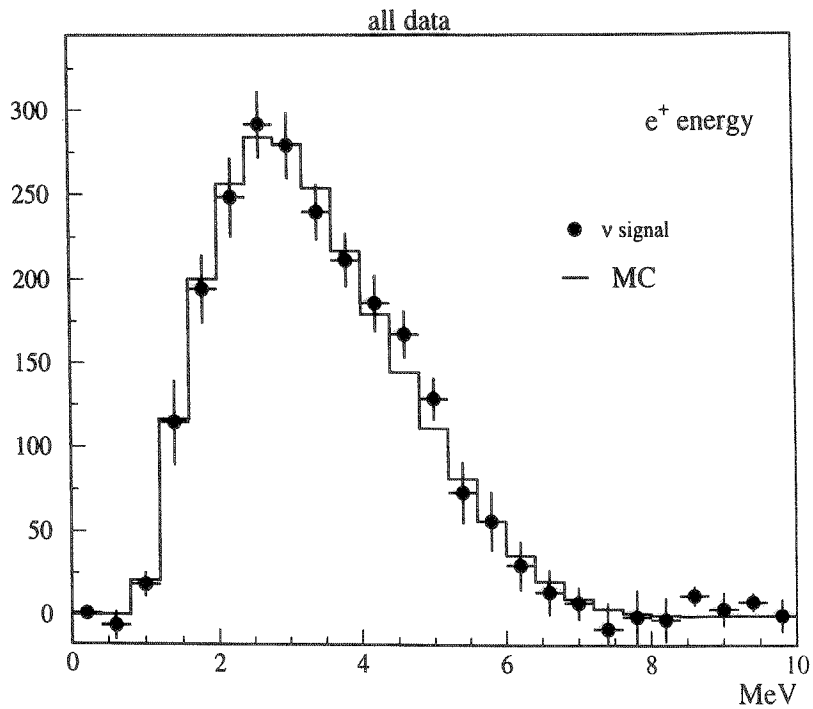
CHOOZ FINAL RESULTS

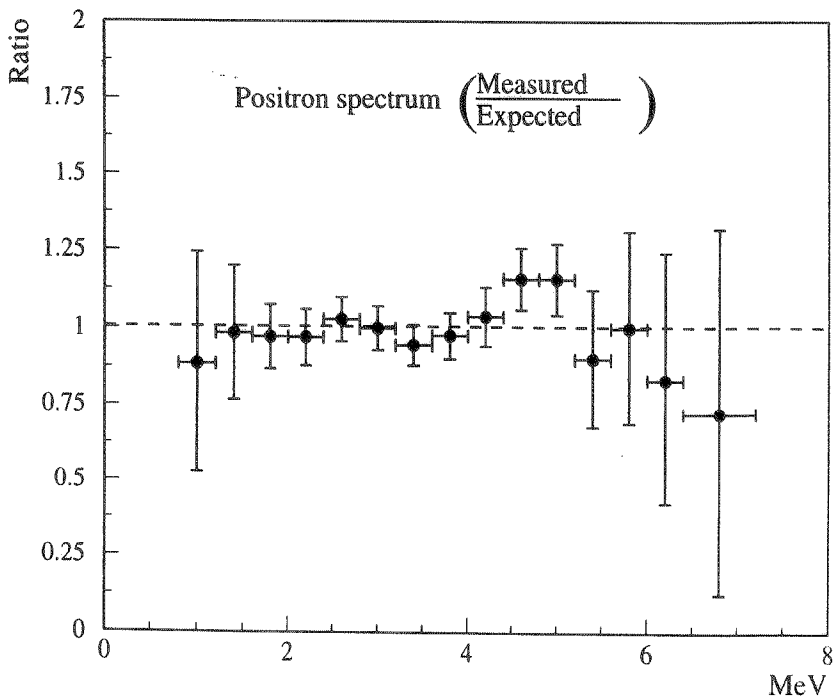
Reactors OFF event rate 1.20 ± 0.03 /day

Event rate at full power 24.6 ± 0.7 /day

$$\left\langle \frac{\text{Measured event rate}}{\text{Expected event rate}} \right\rangle = 1.010 \pm 0.028 \pm 0.027$$

stat. syst.

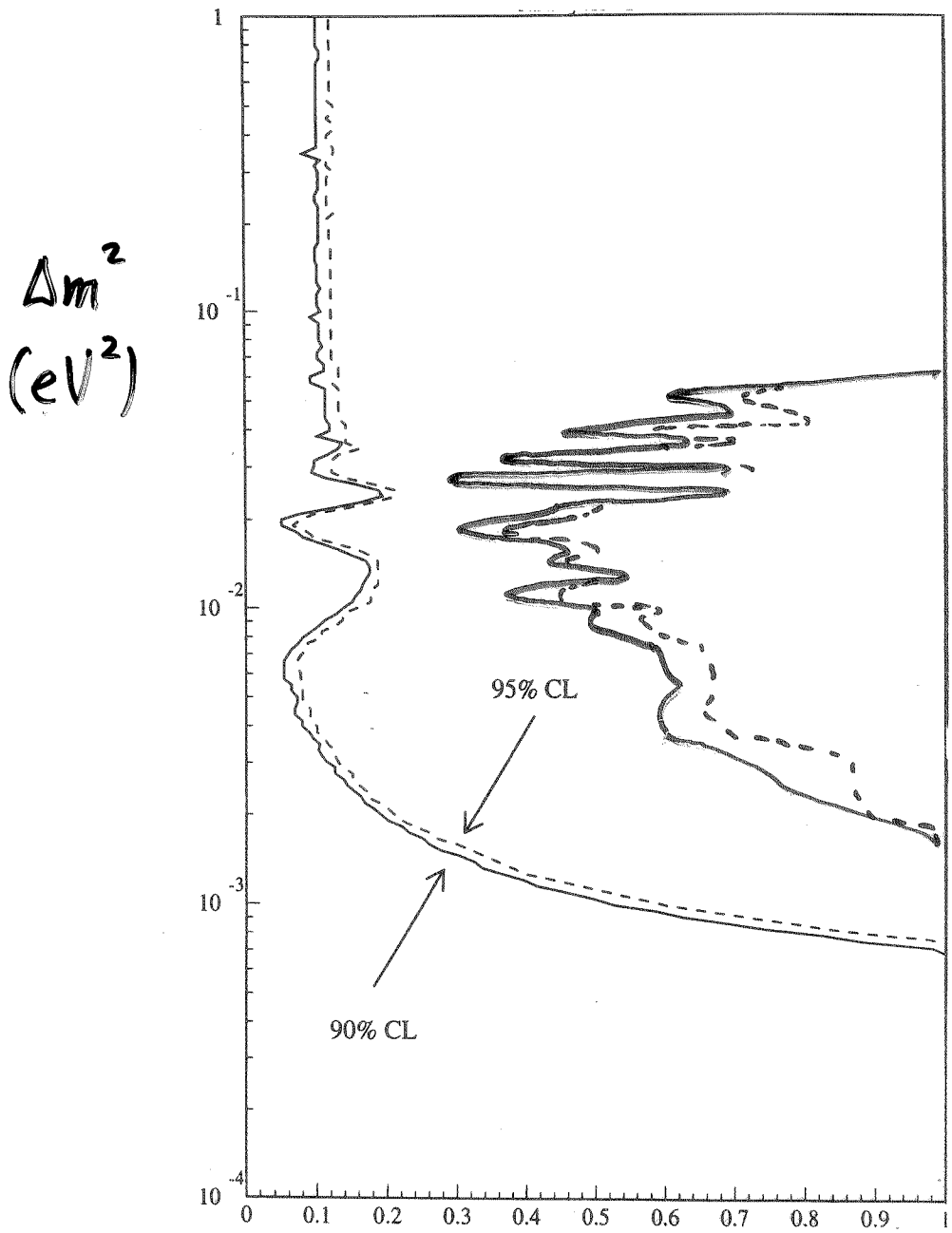




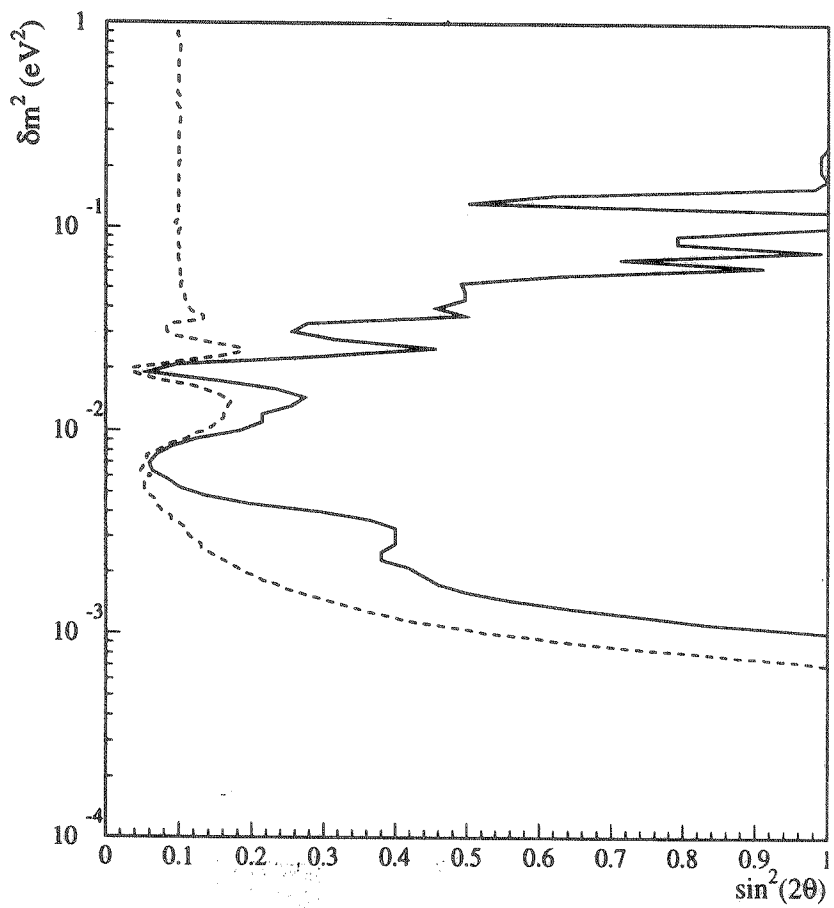
CHOOZ EXCLUSION REGIONS

Comparing measured with expected $E(e^+)$ spectrum

From $E(e^+)$ spectrum ratio Reactor 1 / Reactor 2

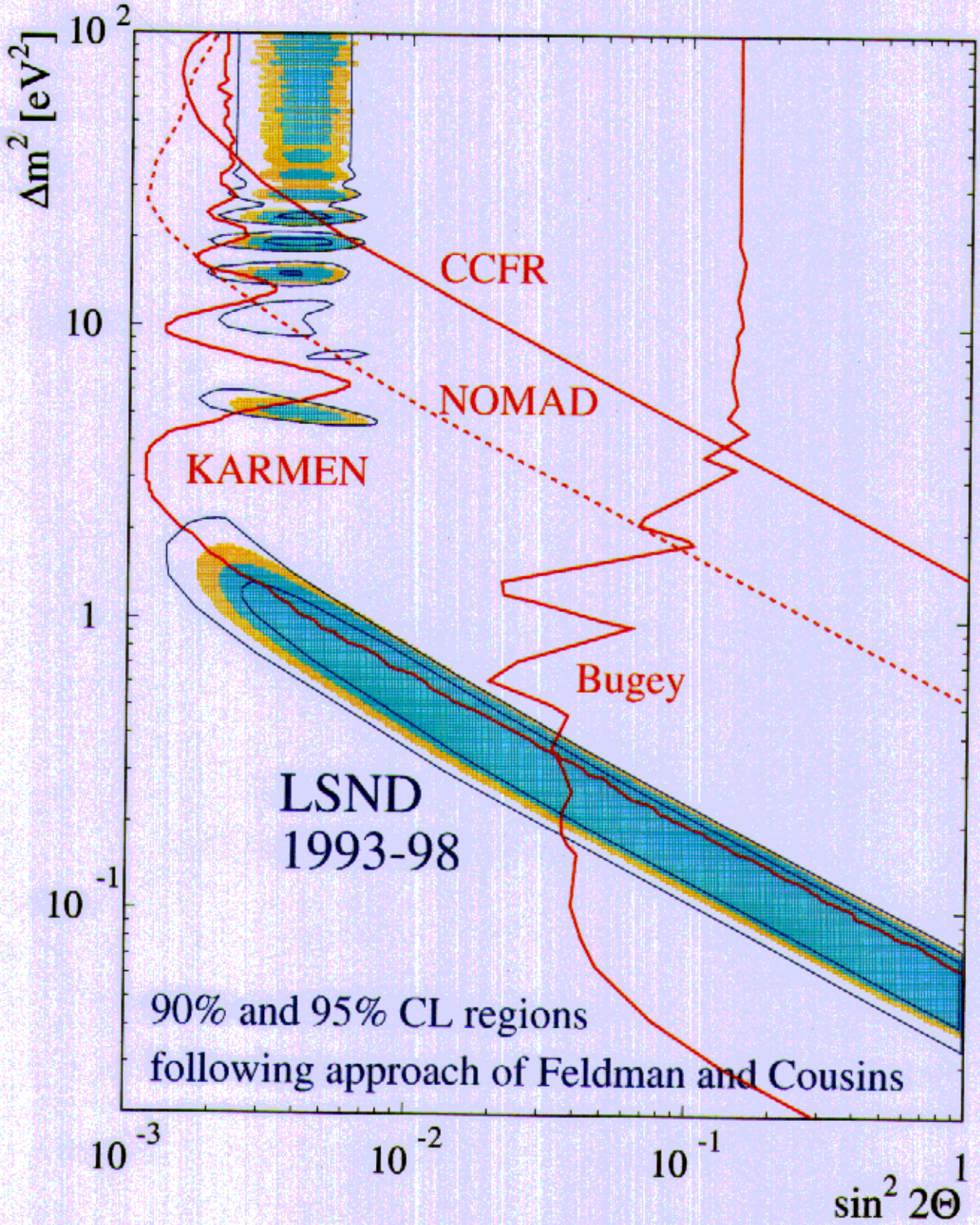


CHOOZ EXCLUSION REGION FROM ANALYSIS OF SPECTRAL SHAPES WITHOUT ABSOLUTE NORMALIZATION CONSTRAINT



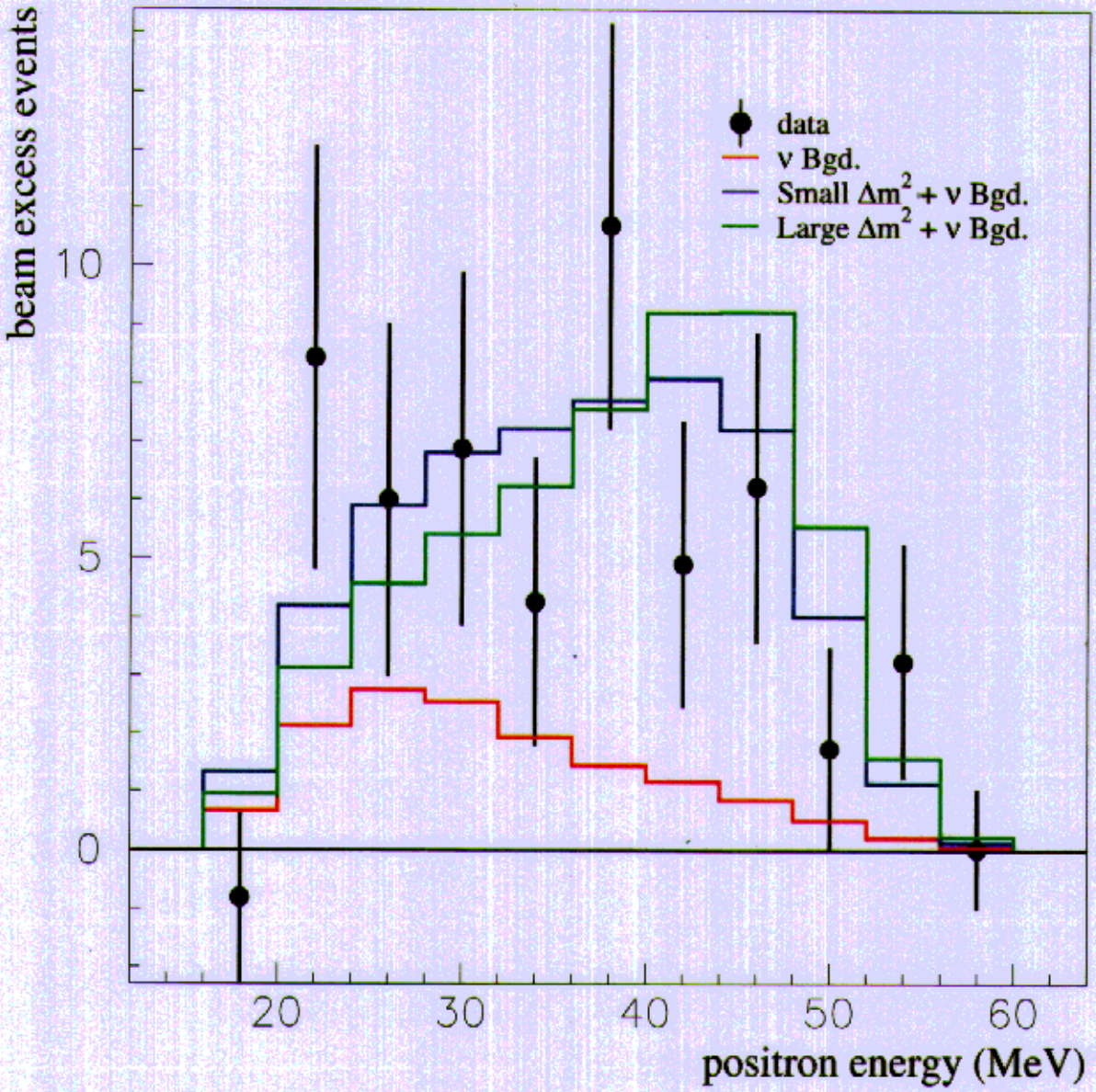
ν_μ-ν_e EXCLUSION REGIONS

LSND D.A.R. CONFIDENCE REGIONS



LSND 1993-98

Preliminary



LSND (1993-98) DAR analysis (Preliminary)

$20 < E(e^+) < 60$ MeV

Prompt e^+ signal correlated in space and time with delayed signal from neutron capture

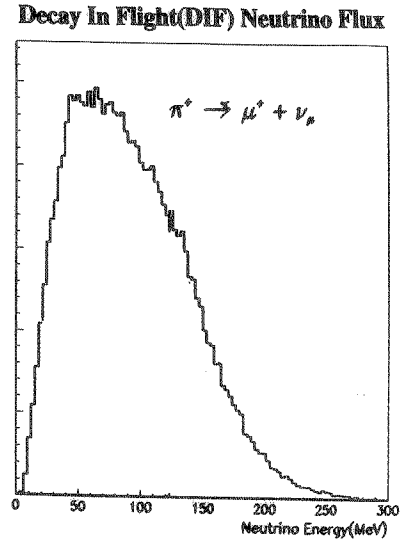
Number of events	70	
Beam-off background	17.7 ± 1.0	
Machine-related background	12.8 ± 1.5	conventional ν interactions
Excess events	39.5 ± 8.8	
$\bar{\nu}_\mu - \bar{\nu}_e$ oscillation probability	$(3.3 \pm 0.9 \pm 0.5) \times 10^{-3}$	

LSND (1993-95) DIF analysis

(published: PRC 58 (1998) 2489)

$\pi^+ \to \mu^+ \nu_\mu$ $\quad \nu_\mu \rightsquigarrow \nu_e$ $\quad C^{12} \to e^- X$

$E(e) > 60$ MeV (prompt signal only)



Number of events	40	
Beam-off background	12.3 ± 0.9	
Conventional ν events	9.6 ± 1.9	
Excess events	18.1 ± 6.6	
$\nu_\mu - \nu_e$ oscillation probability	$(2.6 \pm 1.0) \times 10^{-3}$	

KARMEN (Feb 97 - Feb 99) DAR analysis

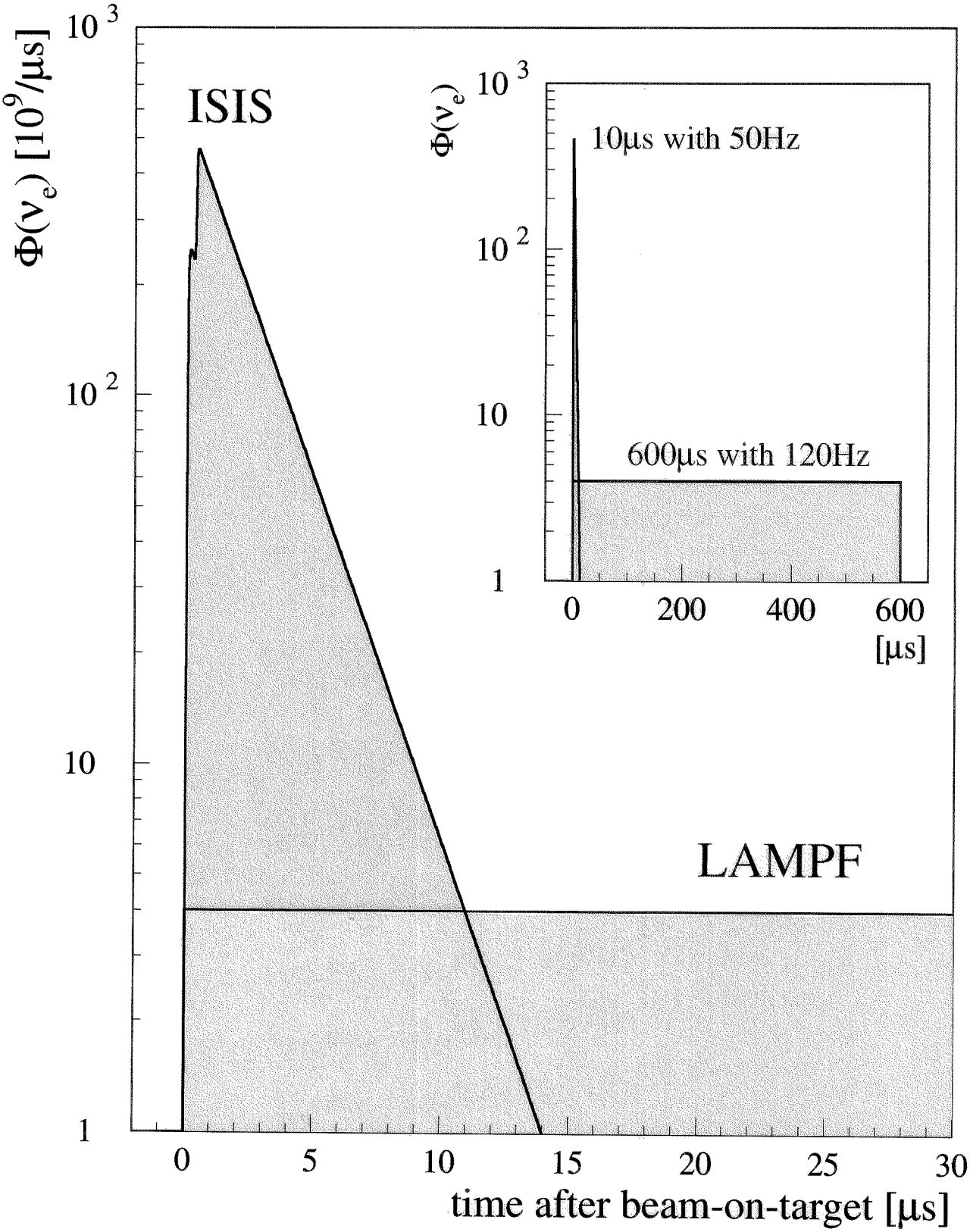
$16 < E(e^+) < 50$ MeV, $t(e^+) < 10\,\mu$s w.r.t. to beam

Prompt e^+ signal correlated in space and time with delayed signal from neutron capture

Number of events	8	
Cosmic background	1.9 ± 0.1	
Total background	7.82 ± 0.74	
$\bar{\nu}_\mu - \bar{\nu}_e$ signal	< 6.2 events	90% C.L.
$\bar{\nu}_\mu - \bar{\nu}_e$ oscillation probability	$< 4.2 \times 10^{-3}$	90% C.L.

(limit calculation uses Feldman & Cousins method)

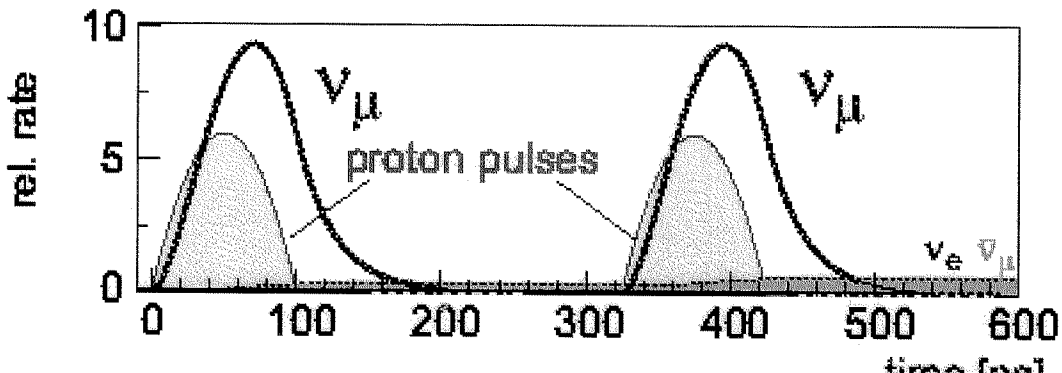
ν production at ISIS and LAMPF

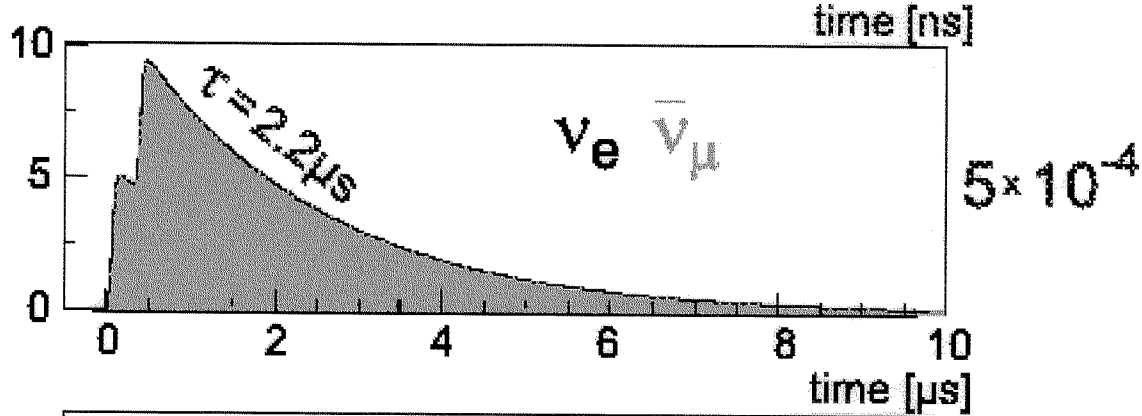


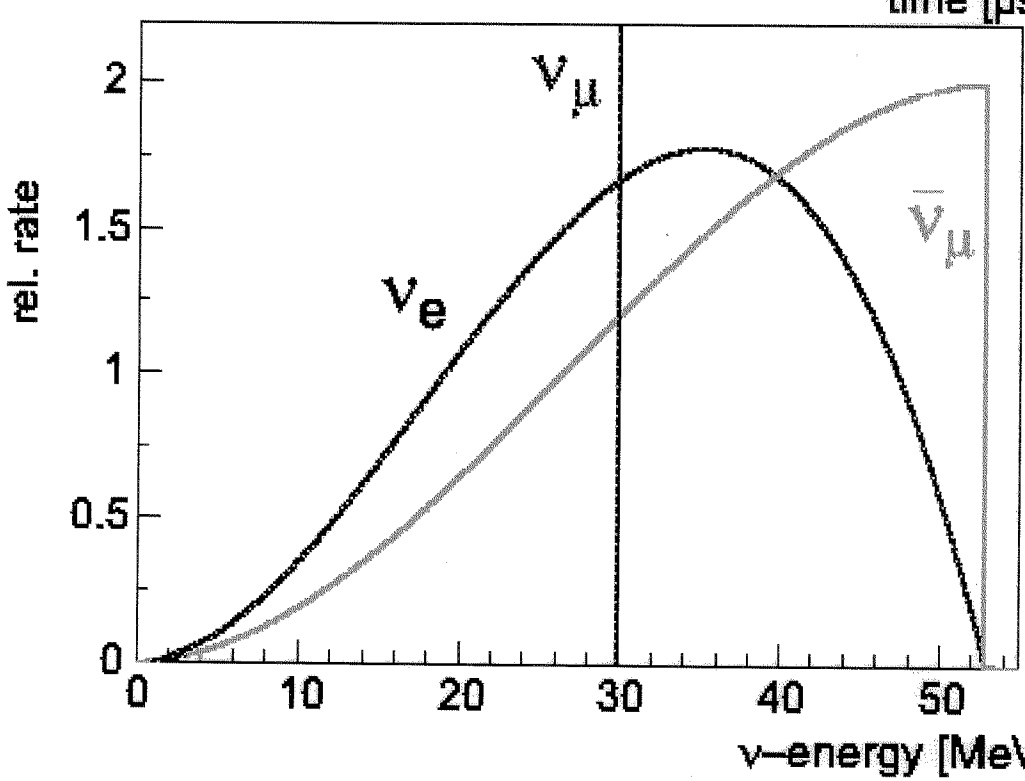
ISIS BEAM TIME STRUCTURE

$\pi^+ \rightarrow \mu^+ + \nu_\mu$ $\qquad \tau_\pi = 26$ ns

$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ $\qquad \tau_\mu = 2.2\ \mu$s







$\pi^+ \rightarrow \mu^+ \nu_\mu$

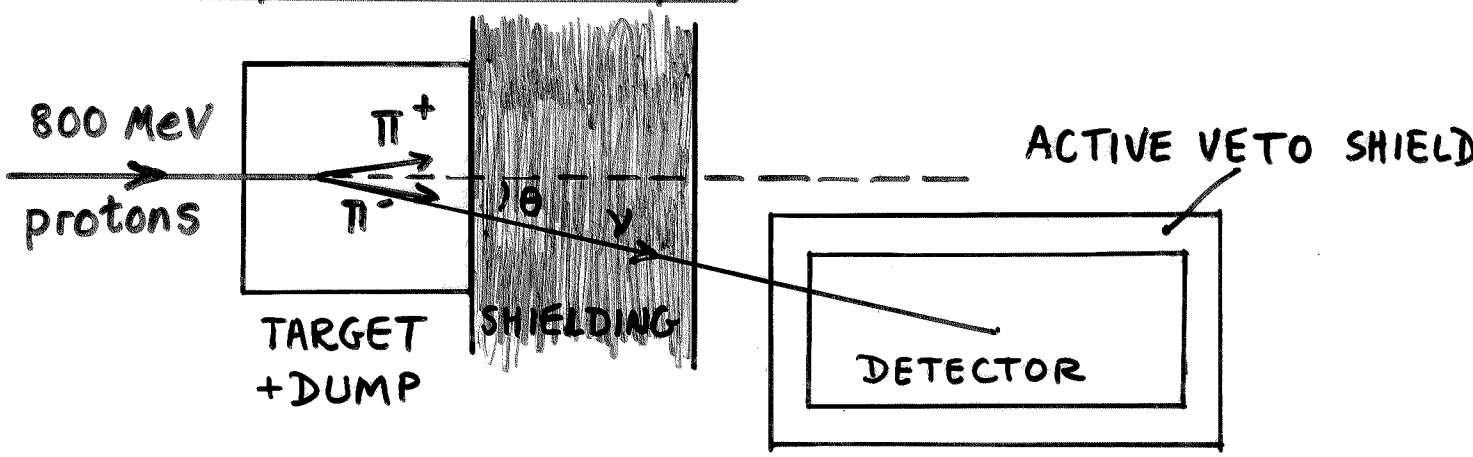
$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$

DECAY AT REST

LSND and KARMEN EXPERIMENTS

SEARCH FOR $\bar{\nu}_\mu - \bar{\nu}_e$ OSCILLATION

Conceptual set-up



NEUTRINO SOURCES

800 MeV (K.E.) proton-nucleus collision

70-90%

30-10%

π^+

~20%

nuclear absorption

few%

DECAY AT REST (DAR)

DECAY IN FLIGHT (DIF)

~75%

$\mu^+ \nu_\mu$

100%

DAR

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

π^-

few%

DIF

$\mu^- \bar{\nu}_\mu$

nuclear absorption

$\lesssim 10\%$

$\gtrsim 90\%$

DAR

$\mu^- \to \nu_\mu e^- \bar{\nu}_e$

capture

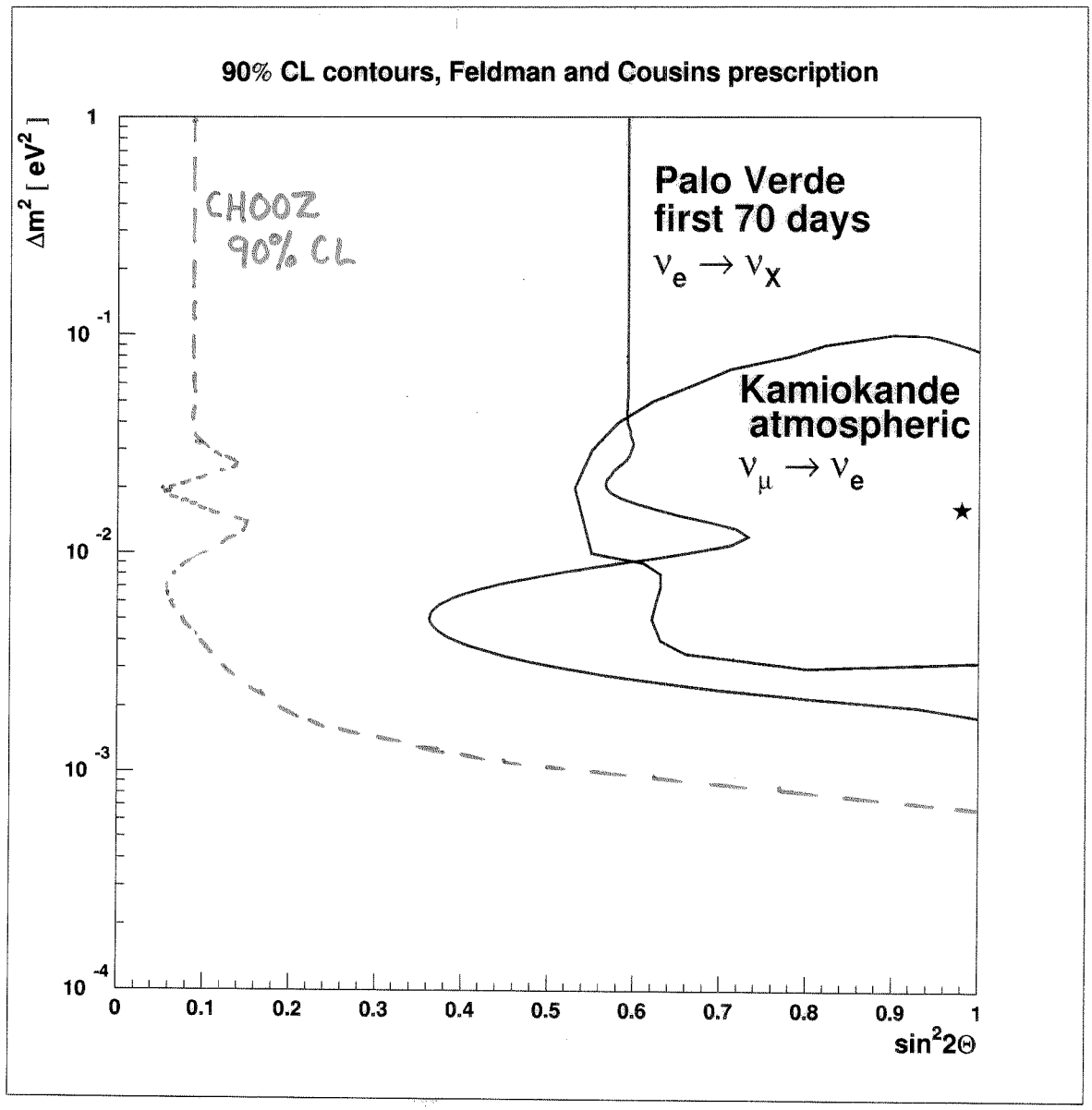
$\mu^- p \to n \nu_\mu$

THE ONLY $\bar{\nu}_e$ SOURCE

$\Rightarrow \quad \bar{\nu}_e / \nu_e \lesssim 10^{-3}$

SEARCHES FOR NEUTRINO OSCILLATIONS AT ACCELERATORS

- LSND, KARMEN $\bar{\nu}_\mu - \bar{\nu}_e$, $\nu_\mu - \nu_e$
- CHORUS, NOMAD $\nu_\mu - \nu_\tau$, $\nu_e - \nu_\tau$
- NUTEV Single Mode: $\bar{\nu}_\mu - \bar{\nu}_e$, $\bar{\nu}_\mu - \bar{\nu}_\tau$ (assuming CP violation)


90% CL contours, Feldman and Cousins prescription
Δm^2 [eV^2]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
CHOOZ
90% CL
Palo Verde
first 70 days
$\nu_e \rightarrow \nu_x$
Kamiokande
atmospheric
$\nu_\mu \rightarrow \nu_e$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
$\sin^2 2\Theta$

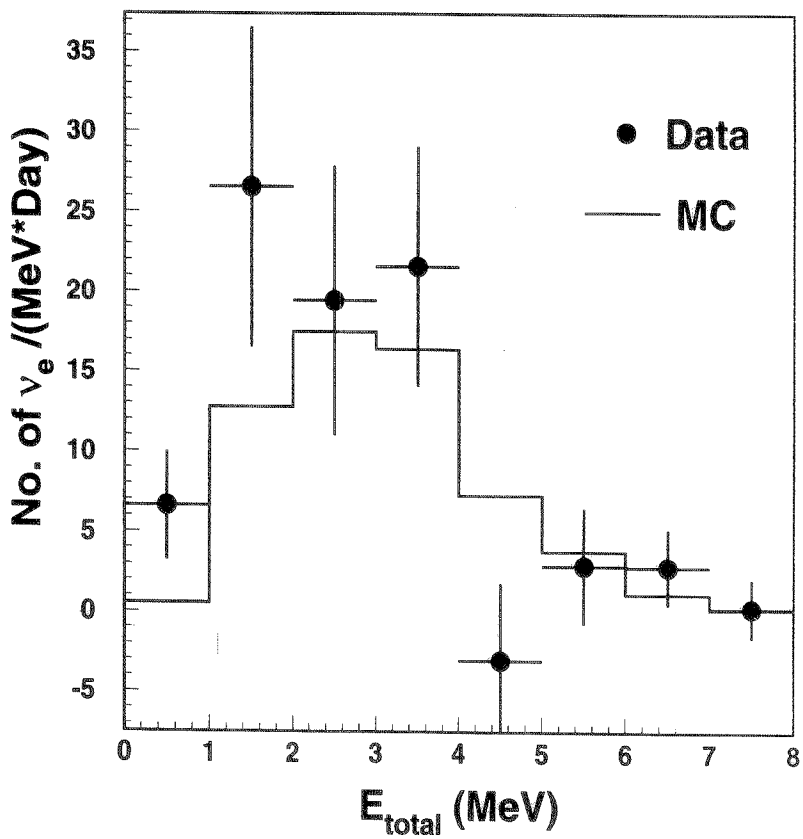
PALO VERDE

1998 RUN (first 70 days)

Reactor ON : 39.06 ± 1.00 events/day

Reactor OFF : 32.62 ± 1.02

SIGNAL : 6.4 ± 1.4 events/day



Efficiency 0.083

$$\left\langle \frac{\text{Measured event rate}}{\text{Expected event rate}} \right\rangle = 1.3 \pm 0.3 \pm 0.2$$

(stat) (syst)

LSND MEASUREMENTS OF CONVENTIONAL NEUTRINO PROCESSES

- $\nu_e + C^{12} \rightarrow e^- + N^{12}_{g.s.}$ $\quad N^{12}_{g.s.} \rightarrow C^{12} e^+ \nu_e$ ($\tau = 15.9$ ms)

  515 events above background

  $\sigma_{measured} = (9.1 \pm 0.4 \pm 0.9) \times 10^{-42}\ cm^2$

  $\sigma_{theory} = 9.3 \times 10^{-42}\ cm^2$

- $\nu_e + C^{12} \rightarrow e^- + (N^{12})^*$

  660 events above background

  $\sigma_{measured} = (5.7 \pm 0.6 \pm 0.6) \times 10^{-42}\ cm^2$

  $\sigma_{theory} = 6.3 \times 10^{-42}\ cm^2$

- $\nu_\mu + C^{12} \rightarrow \mu^- + N^{12}_{g.s.}$ (from π^+ DIF)

  57 events above background

  $\sigma_{measured} = (6.6 \pm 1.0 \pm 1.0) \times 10^{-41}\ cm^2$

  $\sigma_{theory} = 6.4 \times 10^{-41}\ cm^2$

- $\nu_\mu + C^{12} \rightarrow \mu^- + (N^{12})^*$

  1738 events above background

  $\sigma_{measured} = (11.2 \pm 0.3 \pm 1.8) \times 10^{-40}\ cm^2$

  $\sigma_{theory} = 20.5 \times 10^{-40}\ cm^2$

$\Rightarrow$ DISAGREEMENT : $\sigma_{measured} < \sigma_{theory}$

$\nu_\mu - \nu_\tau$ OSCILLATION SEARCHES AT CERN

- Two experiments: CHORUS NOMAD

	CHORUS	NOMAD
Approved in	1991	1992
Data taking completed	1997	1998

- Wide-band neutrino beam from the CERN 450 GeV SPS
  Flux at detector $\sim 5\times10^{10}\ \nu_\mu/m^2 \times$ SPS cycle
  (SPS rep. rate 1/14.4 s, 2.5×10^{13} p.o.t.)

	Rel. abundance	$\langle E_\nu \rangle$ GeV
ν_μ	1.00	23.5
$\bar{\nu}_\mu$	6.1%	19.2
ν_e	0.94%	37.1
$\bar{\nu}_e$	0.24%	31.3
$\nu_\tau, \bar{\nu}_\tau$	$\sim 5\times10^{-6}$	17, 44

from $D_s^\pm \to \tau^\pm \nu_\tau$, $\tau^\pm \to \bar{\nu}_\tau X$

- $L \approx 0.6$ km $\Rightarrow$ sensitivity to oscillation with $\Delta m^2 \gtrsim$ few eV^2 (region of cosmological interest: ν_τ ($\approx \nu_3$) important component of Dark Matter)

EXPERIMENTAL METHOD

Detect ν_τ + nucleon $\rightarrow \tau^-$ + hadrons

Sensitivity of the experiments (goal):

$$N(\nu_\tau \rightarrow \tau^-)/N(\nu_\mu \rightarrow \mu^-) \approx 10^{-4}$$

$\Rightarrow$ observation of τ^- production at a level higher than sensitivity is evidence for $\nu_\mu - \nu_\tau$ oscillation

- CHORUS

  Observe τ^- decay in photographic emulsion (spatial resolution 1 μm !)

  Typical decay path ~ 1 mm

  DATA TAKING PERIOD : 1994 - 97

  458,601 identified $\nu_\mu \rightarrow \mu^-$ events with vertex in emulsion (search for $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ decay)

  116,049 with no μ — search for $\tau^- \rightarrow \nu_\tau + h^-$

- NOMAD

  Identify τ^- production and decay using kinematical criteria

  DATA TAKING : 1995 - 1998

  $N(\nu_\mu \rightarrow \mu^-$ events$) \approx 1.3 \times 10^6$

STATUS OF CHORUS ANALYSIS

Protons on target		5.06×10^{19}
Emulsion triggers		2.305×10^{6}
$1\mu^-$ events	to be scanned	458,601
	scanned so far	305,643
	vertex localized	126,229
0μ events	to be scanned	116,049
	scanned so far	67,107
	vertex localized	19,436

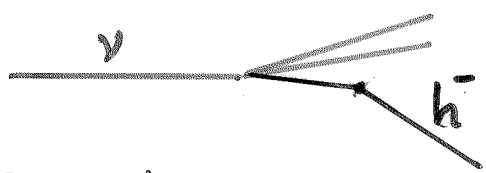
Expected backgrounds

$1\mu^-$ events $\bar{\nu}_\mu(\bar{\nu}_e) + \text{Nucleon} \rightarrow \mu^+(e^+) + \bar{D}^- + X$, $\bar{D}^- \hookrightarrow \mu^-$

with $\mu^+(e^+)$ not identified

Expected background 0.24 ± 0.05

0μ events "white kinks": hadronic interactions with no visible recoil



Expected background 0.73 ± 0.66

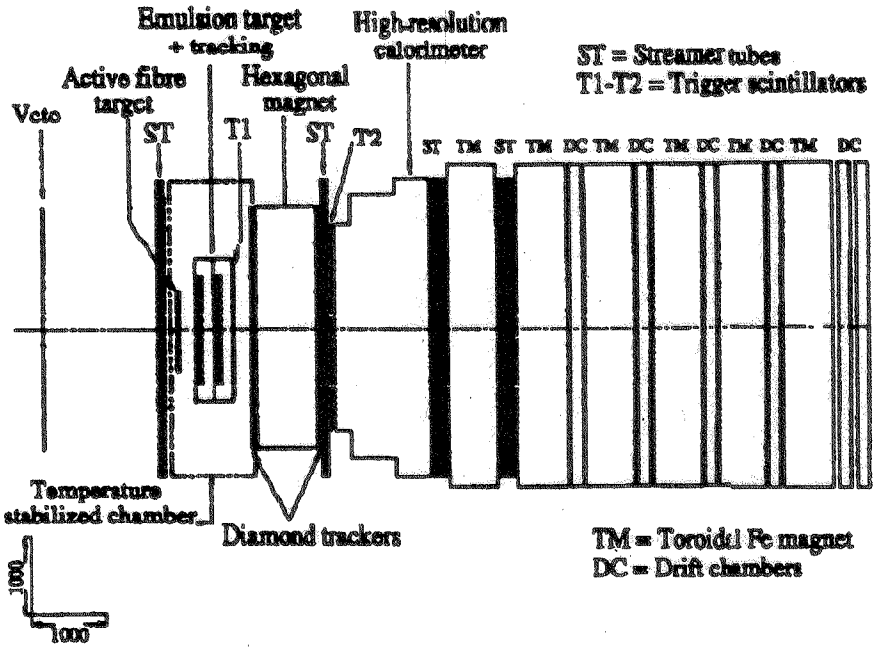
DETECTION EFFICIENCY MEASURED USING NEUTRINO INTERACTIONS WITH CHARM PRODUCTION

NO τ^- CANDIDATE SEEN

$\Rightarrow$ OSCILLATION PROBABILITY $P_{\mu\tau} < 4.0\times10^{-4}$ (90% confidence)

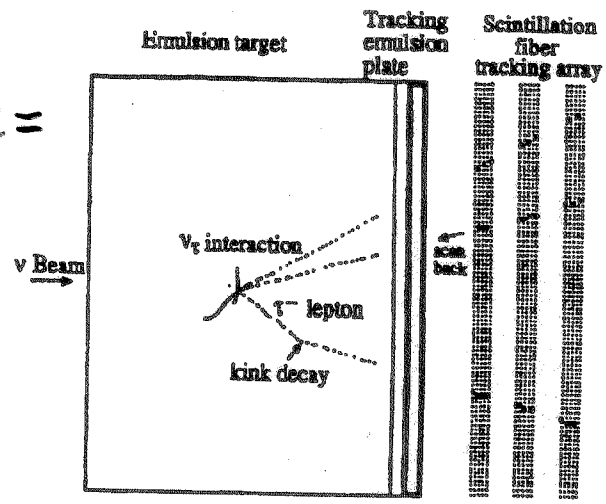
CHORUS

Emulsion target (770 Kg) + precision tracker (scintillating fibres) + calorimeters + magnetic spectrometers



A typical ν_τ interaction in emulsion

τ^- lifetime = 2.91×10^{-13} s



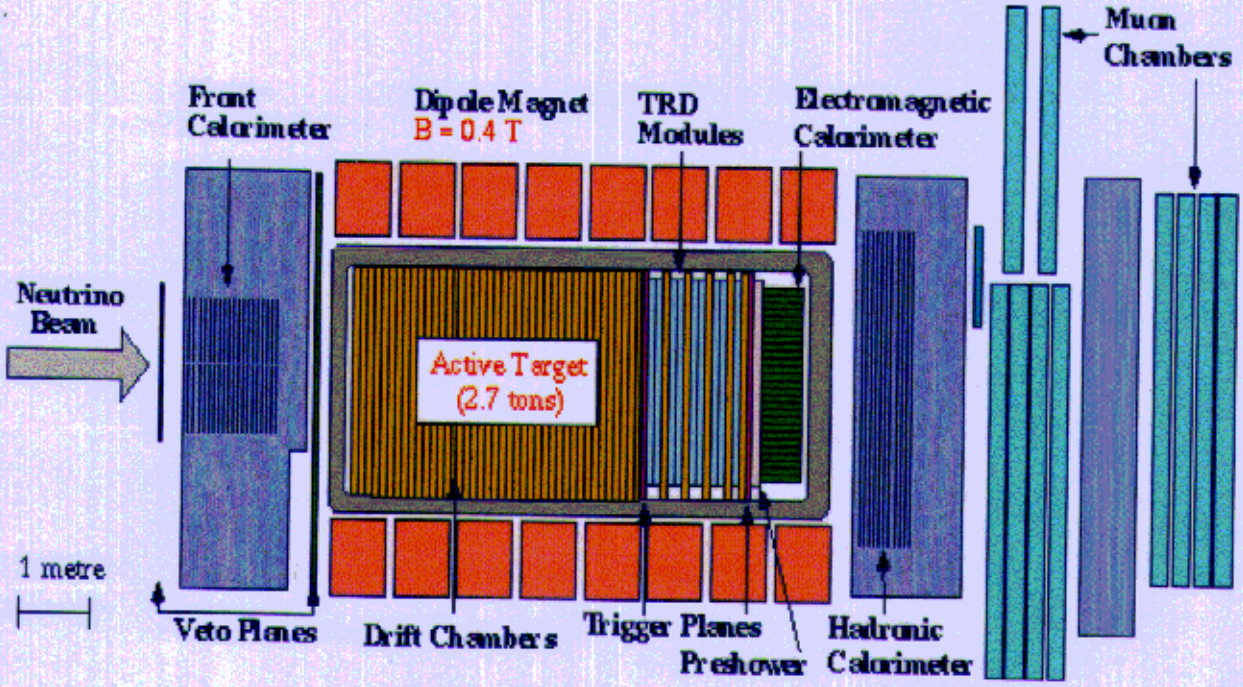
Tracks from a recorded neutrino interaction are used to localize event vertex in emulsion and to search for kink from τ decay ($\tau^- \rightarrow$ one charged particle has BR $\approx$ 86%)

USE AUTOMATIC, COMPUTER-CONTROLLED MICROSCOPES (~ 15 minutes/event)
τ^- DECAY CANDIDATES ARE SCANNED "BY EYE"

NOMAD

- MEASURE PRECISELY ALL SECONDARY PARTICLES FROM ν INTERACTIONS
- USE KINEMATIC VARIABLES CAPABLE OF DISTINGUISHING $\nu_\tau \to \tau^-$ EVENTS FROM $\nu_\mu \to \mu^-$, $\nu \to \nu$ AND $\nu_e \to e^-$ EVENTS
- LOOK FOR EXCESS OF EVENTS CONSISTENT WITH $\nu_\tau \to \tau^-$ OVER PREDICTED BACKGROUNDS FROM CONVENTIONAL ν INTERACTIONS
- USE $\nu_\mu \to \mu^-$ EVENTS FROM DATA THEMSELVES TO PREDICT BACKGROUNDS AND DETECTION EFFICIENCIES:
  - replace μ^- with e^- → simulated $\nu_e \to e^-$ events
  - replace μ^- with ν → simulated neutral-current events
  - replace μ^- with τ^- → simulated $\nu_\tau \to \tau^-$ events
- CHECK PROCEDURE BY SEARCHING FOR τ^+ EVENTS (no oscillation signal expected because $\bar{\nu}_\mu/\nu_\mu \approx 0.06$ and $\sigma(\bar{\nu})/\sigma(\nu) = 0.5$)

NOMAD Detector (NIM A404(1998)96)



- Drift Chambers (target and momentum measurement)

  Light material $< \rho >= 0.1 \mathrm{g/cm^3}$, $L \sim 1X_0$ ($< 1\%X_0$ between successive measurements)

  Spatial resolution $< 200\ \mu$m (small angle tracks)

  Momentum resolution $\sim 3.5\%$ ($p < 10$ GeV/c)

- Transition Radiation Detector (TRD) for $e^{\pm}$ identification

  π rejection $\simeq 10^3$ $\varepsilon(e) \geq 90\%$ for isolated tracks

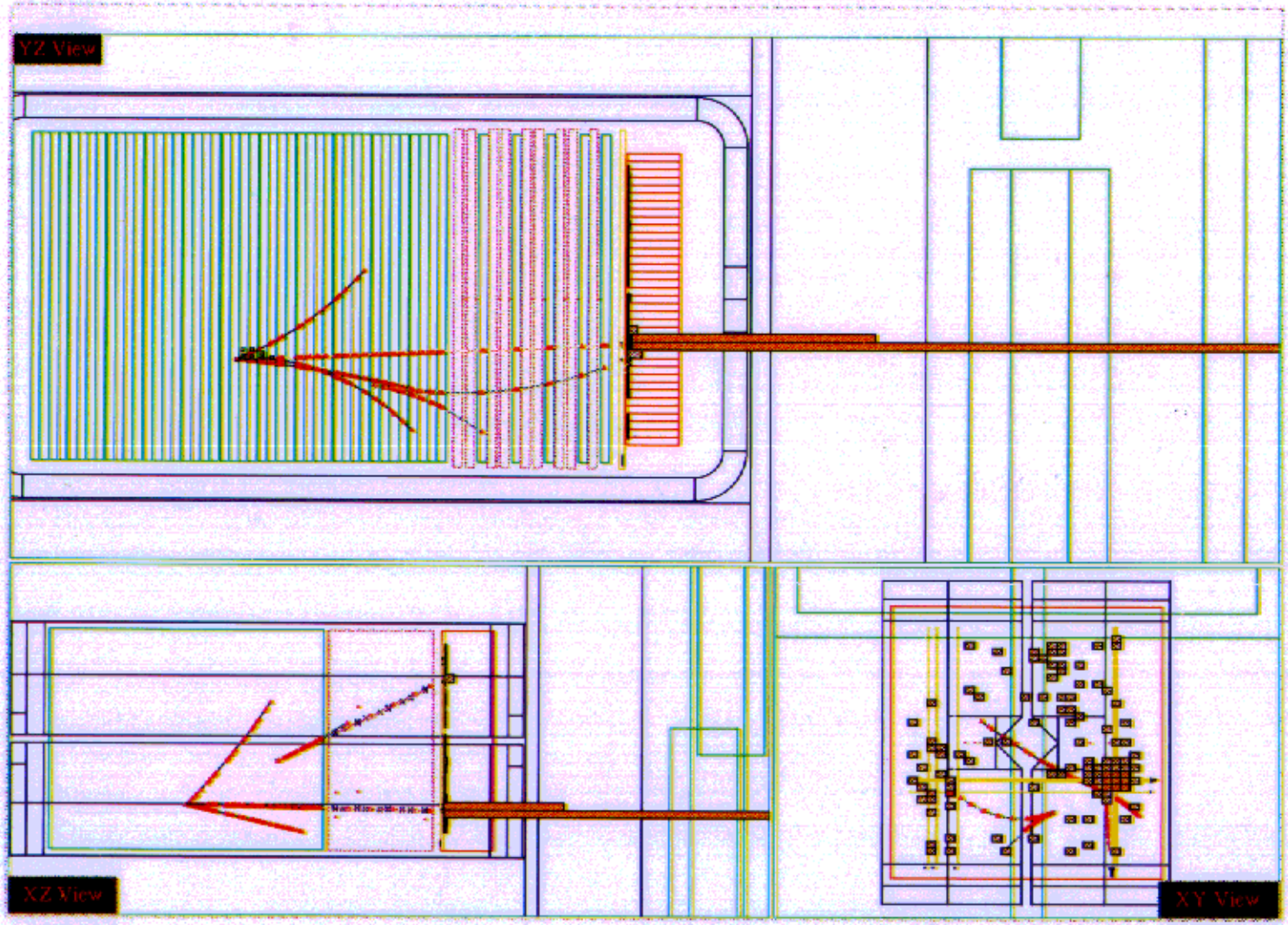
- Lead Glass Electromagnetic Calorimeter

$$\frac{\sigma(E)}{E} = 1.0\% + \frac{3.2\%}{\sqrt{E(GeV)}}$$

- Muon Chambers

  $\varepsilon \approx 97\%$ for $p_\mu > 5$ GeV/c

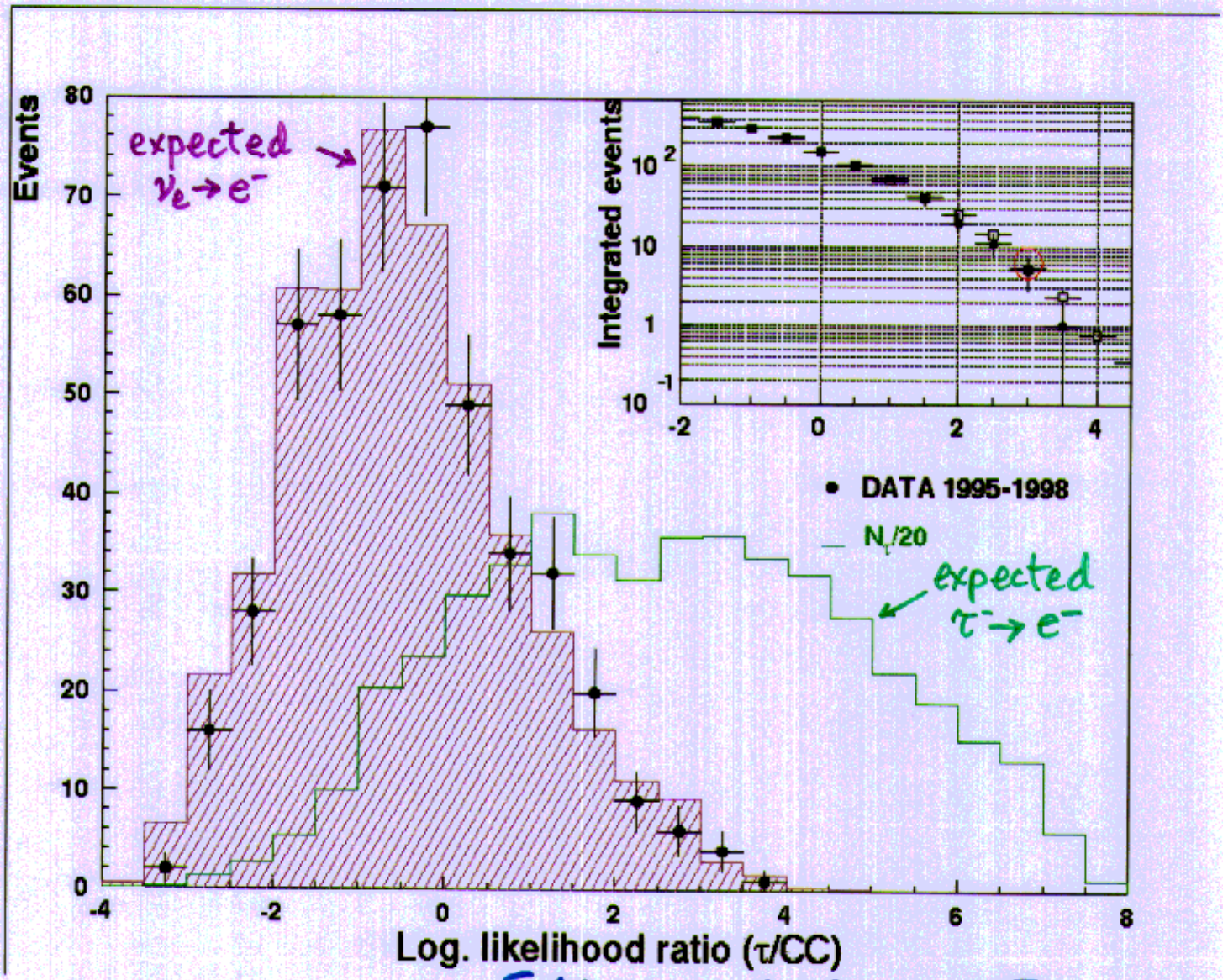
$\nu_e + N \rightarrow e^- + \text{hadrons}$ in NOMAD



NOMAD

Search for $\nu_\tau N \to \tau^- X$
$\hookrightarrow e^- \nu \bar{\nu}$

Main background: $\nu_e N \to e^- X$



$\text{Log}\left[\mathcal{L}(\tau^- \to e^-)/\mathcal{L}(\nu_e \to e^-)\right]$

$\mathcal{L}(\tau^- \to e^-)$, $\mathcal{L}(\nu_e \to e^-)$ are approximate likelihood functions built from multi-dimensional distributions of various discriminating variables for $\tau^- \to e^-$ and $\nu_e \to e^-$ events, respectively

NOMAD - STATUS OF ANALYSIS

Energy of recoil hadrons

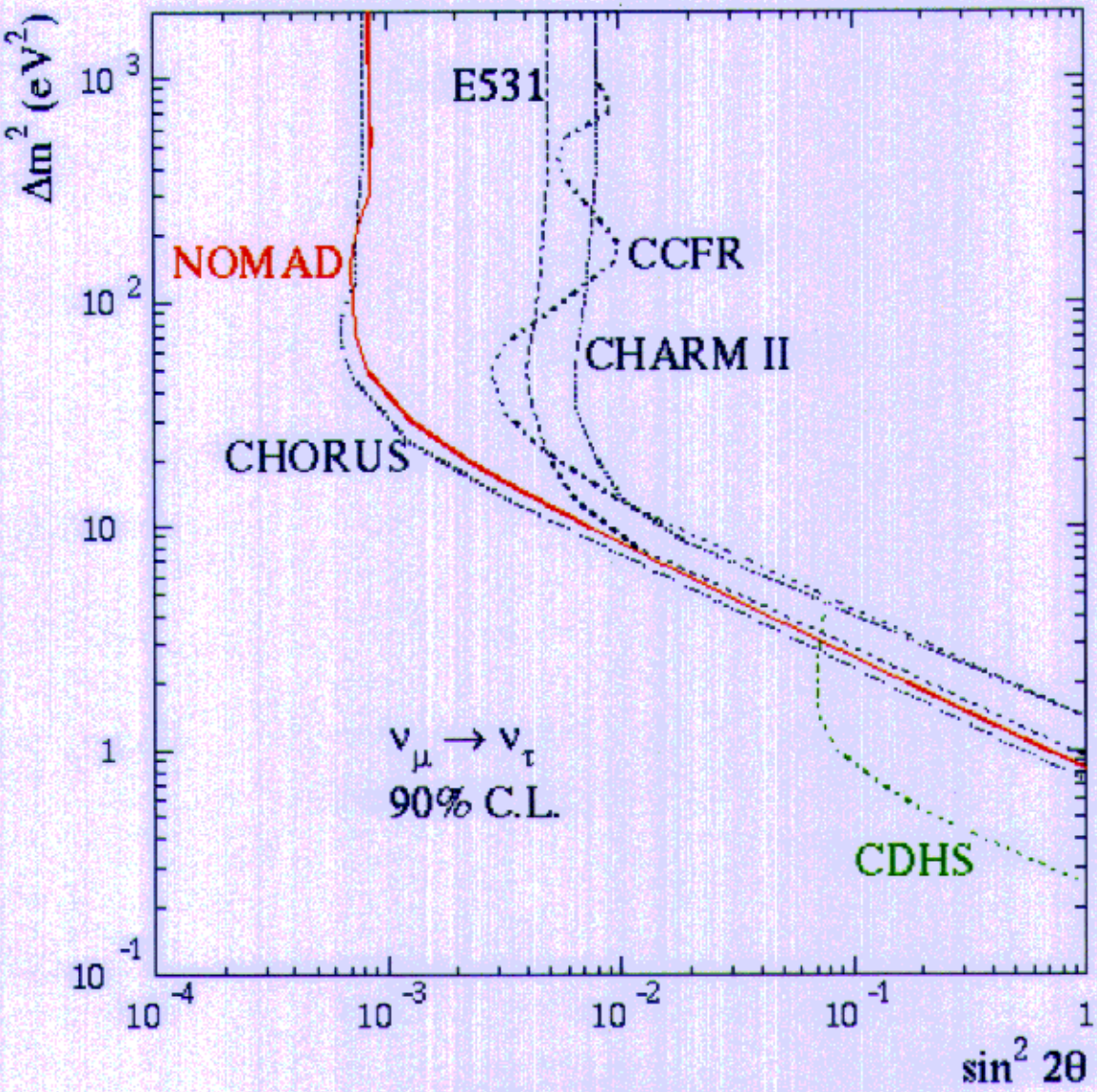
DIS: $E_h > 1.5GeV$, LM: $E_h < 1.5GeV$

analysis	Bin*	N_τ**	Bg	Seen
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$ DIS 95-98	1	178	$1.15^{+0.26}_{-0.17}$	2
	2	208	$0.53^{+0.23}_{-0.12}$	1
	3	903	$0.28^{+0.31}_{-0.09}$	0
	4	654	2.13±0.23	2
	5	473	0.98±0.16	0
	6	1694	0.25±0.09	0
$\tau^- \to h^- (n\pi^0) \nu_\tau$ DIS 95-98	1	918	4.4 ± 1.9	3
	2	1314	2.4 ± 0.8	3
$\tau^- \to \rho^- \nu_\tau$ DIS 95-98		2547	$7.3^{+2.2}_{-1.2}$	9
$\tau^- \to \pi^-\pi^-\pi^+ (n\pi^0) \nu_\tau$ DIS 95-96		1180	6.5± 1.1	5
$\tau^- \to \pi^-\pi^-\pi^+ (n\pi^0) \nu_\tau$ LM 95		108	$.4^{+0.6}_{-0.4}$	0
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$ LM 95-98	1	282	3.08±0.67	3
	2	285	1.49±0.50	2
	3	292	0.82±0.42	1
$\tau^- \to \pi^- \nu_\tau$ LM 95-98		357	6.7±2.3±2.0	5
$\tau^- \to \rho^- \nu_\tau$ LM 95-98		457	5.2±1.8±1.6	7

No excess seen $\Longrightarrow P(\nu_\mu \leftrightarrow \nu_\tau) \leq 4.2 \times 10^{-4}$ at 90% CL

* Bin in likelihood ratio

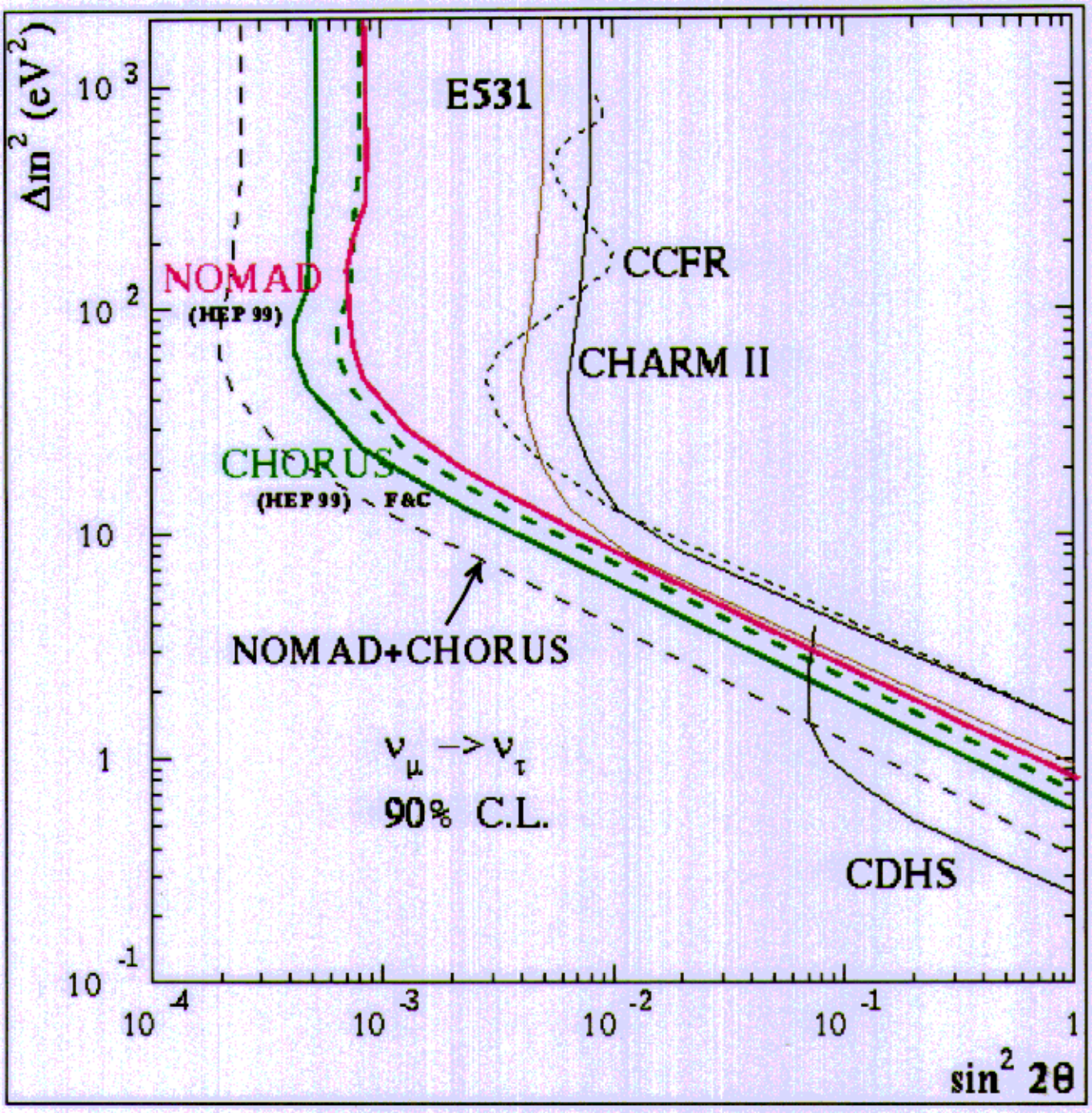
** N_τ : expected number of events for $P(\nu_\mu \leftrightarrow \nu_\tau) = 1$.



WARNING:

NOMAD uses Feldman & Cousins statistics

CHORUS uses Bayesian limit

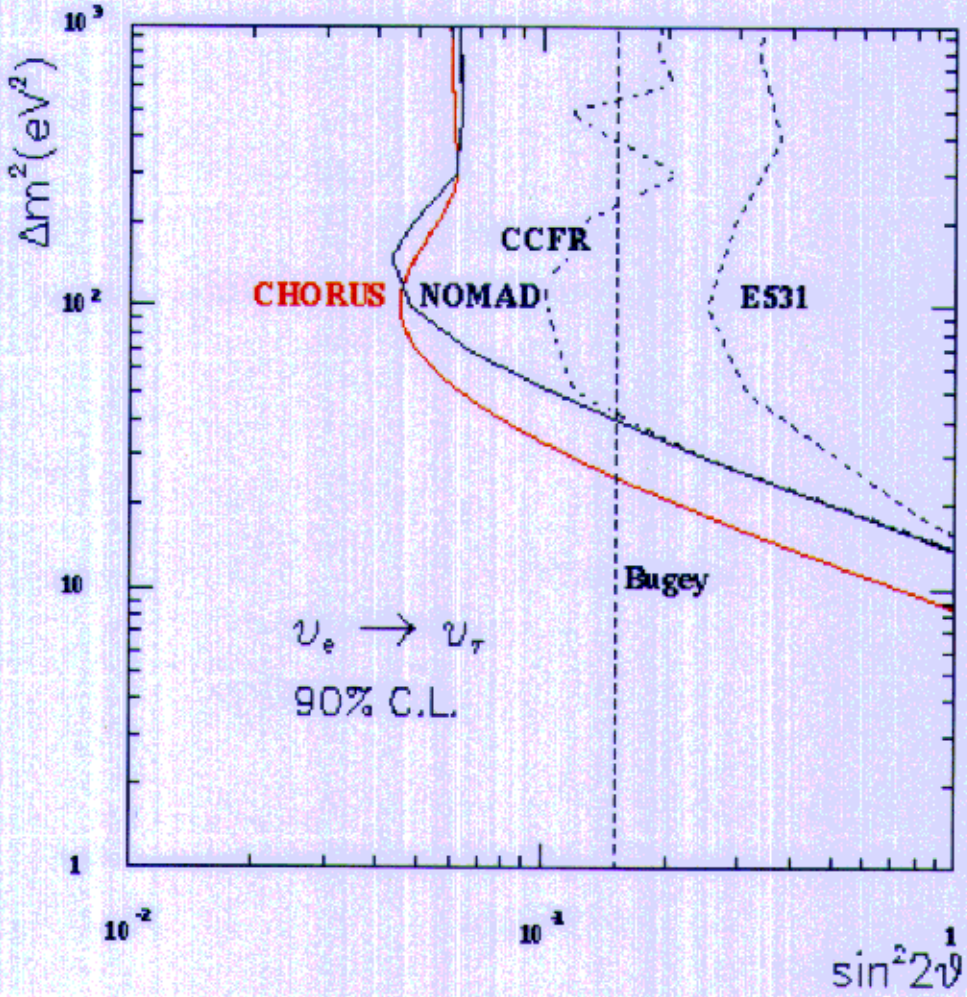


- - - - - CHORUS Bayesian Limit

MY EVALUATION { ——— CHORUS Feldman-Cousins method

- - - - - combined CHORUS-NOMAD limit (Feldman-Cousins method)

CHORUS, NOMAD $\nu_e - \nu_\tau$ EXCLUSION REGION



NUTEV

SEARCH FOR SINGLE MODE OSCILLATIONS ASSUMING CP VIOLATION

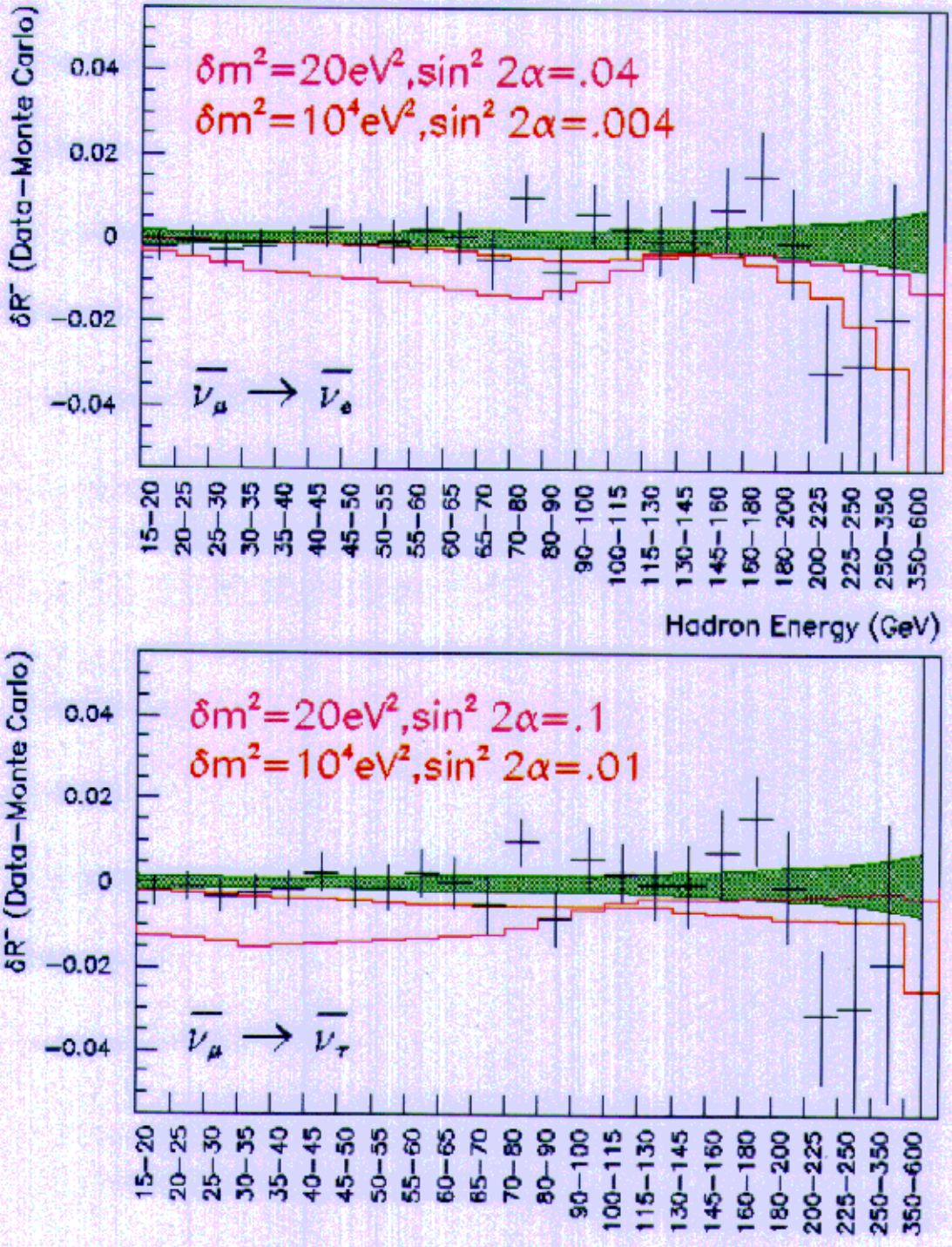
- $\nu_\mu - \nu_e$, $\nu_\mu - \nu_\tau$ oscillations change NC/CC ratio vs. visible energy (increase number of short events, distort energy spectrum)
- Effect cancels in $R^- = \frac{\sigma_{NC}(\nu_\mu) - \sigma_{NC}(\bar{\nu}_\mu)}{\sigma_{CC}(\nu_\mu) - \sigma_{CC}(\bar{\nu}_\mu)}$ if $P_{osc}(\nu_\mu \to \nu_e, \nu_\tau) = P_{osc}(\bar{\nu}_\mu \to \bar{\nu}_e, \bar{\nu}_\tau)$

  ⇒ assume no oscillation for one mode, search for oscillation effects in charge-conjugate mode
- To predict R^- must use $\sin^2\theta_W$ value from experiments not using ν beams

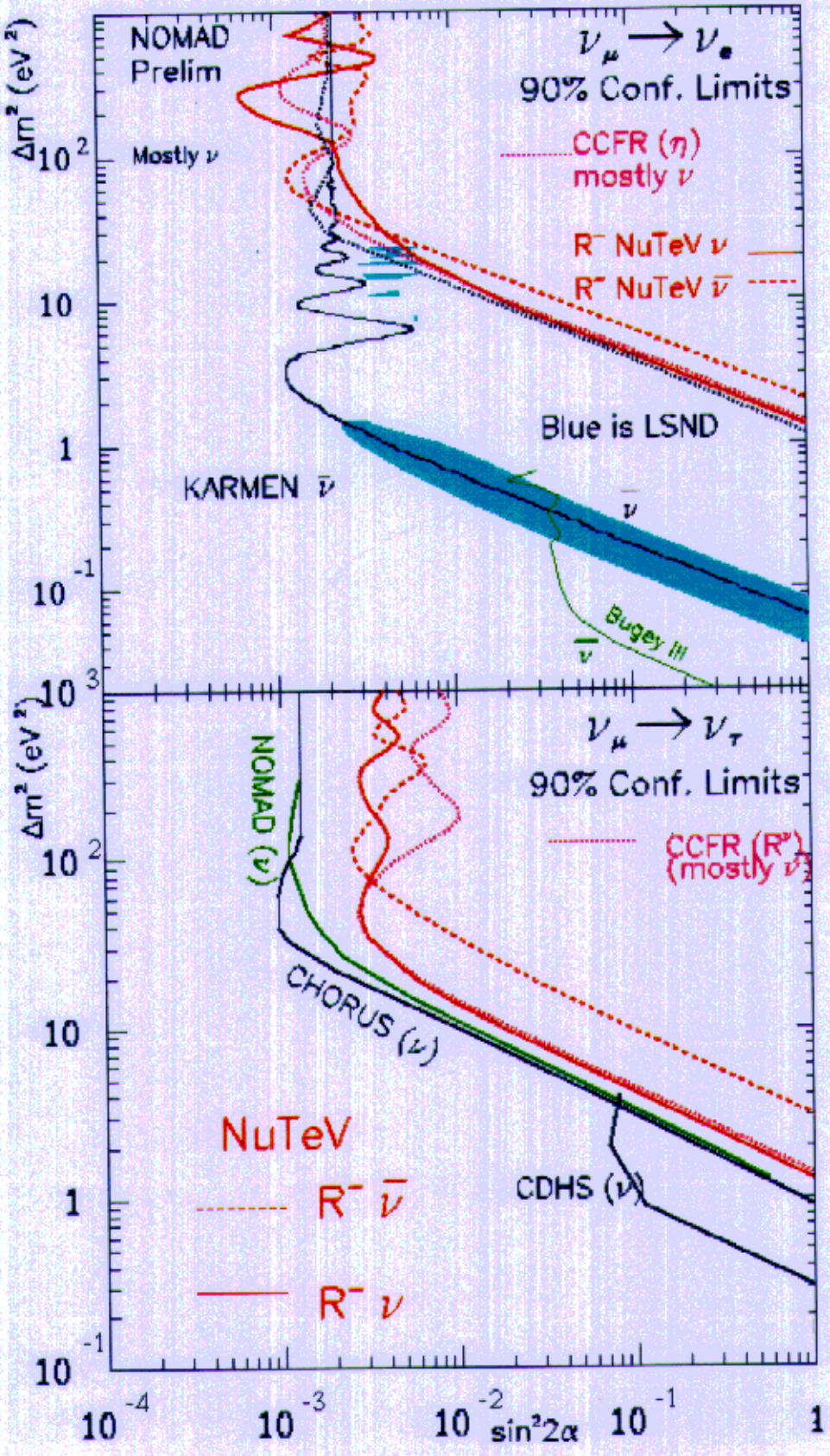
NOTE

Effects of CP violation are expected to be very small if the two independent Δm^2 values $(\Delta m^2, \delta m^2)$ are such that $\Delta m^2 >> \delta m^2$

What would oscillations look like?



PRELIMINARY NuTeV Single Mode Limits



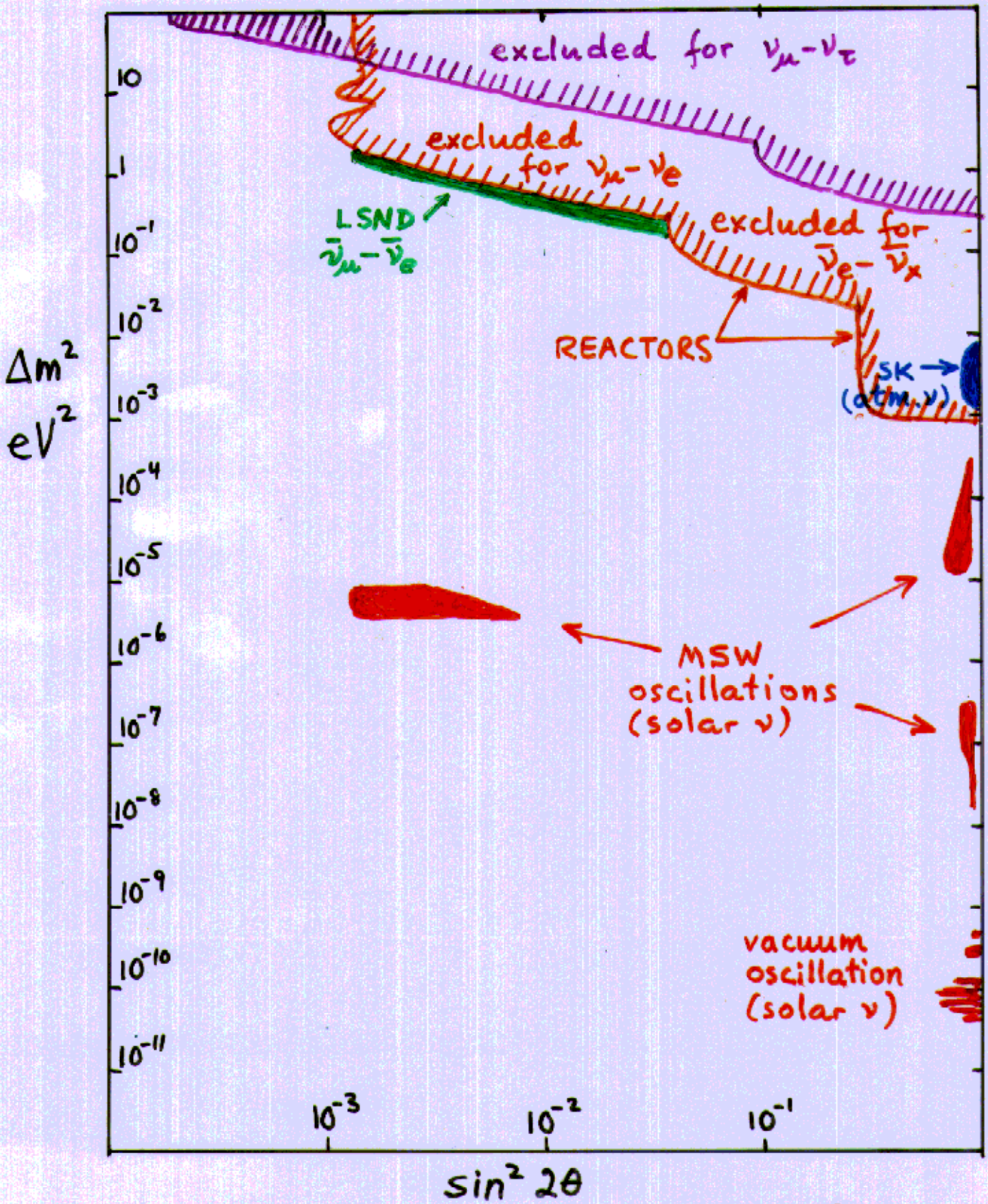
SHORT AND MEDIUM-TERM PROSPECTS

1.- EXPERIMENTS TO VERIFY LSND RESULT

2.- LONG BASELINE EXPERIMENTS AT ACCELERATORS

3.- KAMLAND: VERY LONG BASELINE EXPERIMENT USING $\bar{\nu}_e$ FROM REACTORS

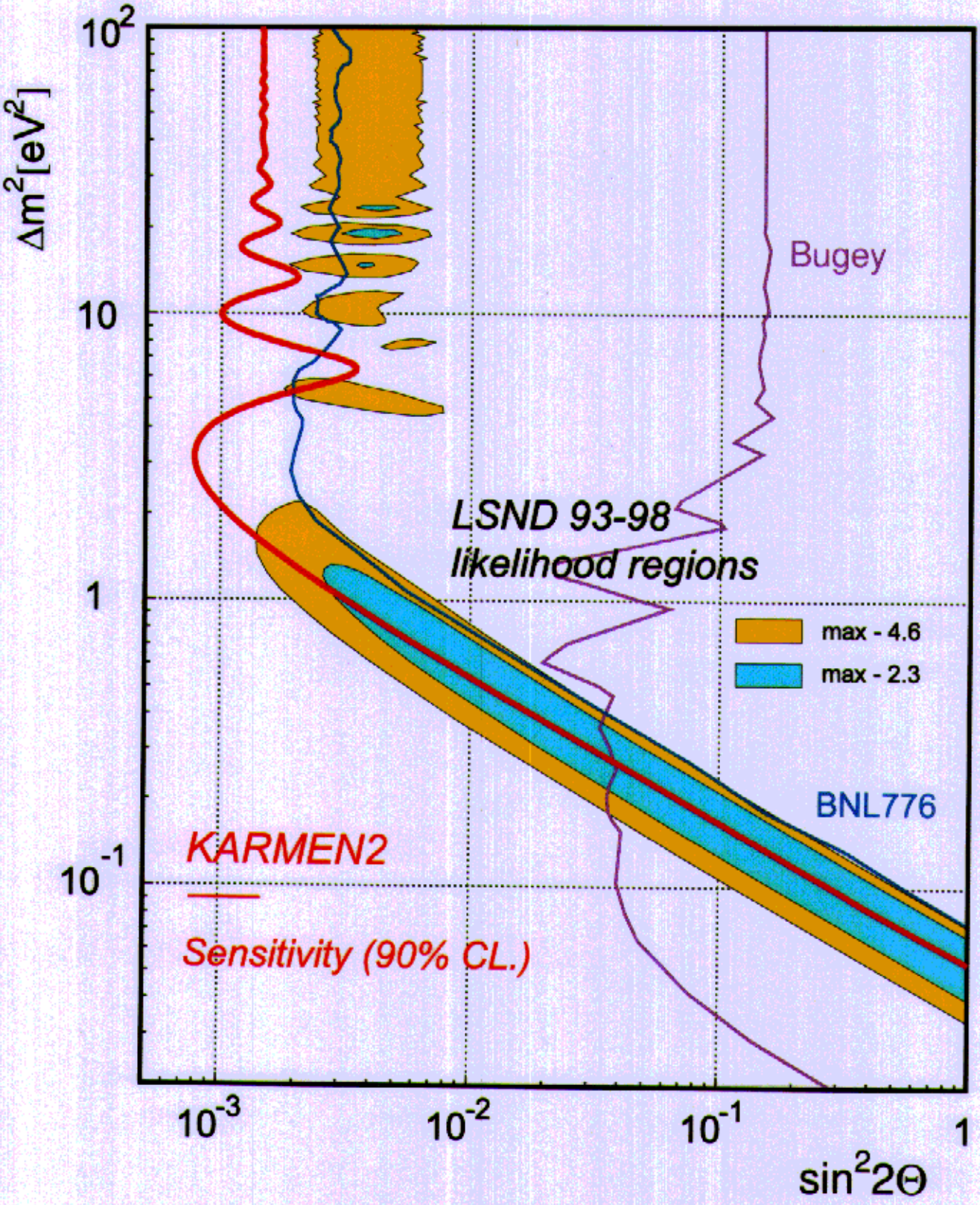
SUMMARY OF EXPERIMENTAL EVIDENCE/HINTS FOR NEUTRINO OSCILLATIONS ASSUMING TWO-NEUTRINO MIXING



3 NEUTRINOS → 2 INDEPENDENT Δm^2 VALUES

$\Delta m^2_{12} + \Delta m^2_{23} + \Delta m^2_{31} = 0 \qquad \Delta m^2_{iK} \equiv m^2_i - m^2_K$

4 years of data taking 2/97-2/01



$\sin^2 2\theta < 1.4 \times 10^{-3}$ (90% CL.)

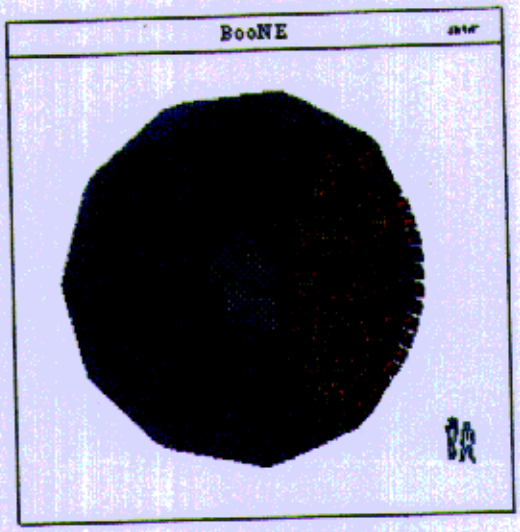
Sensitivity = 'average' oscillation-limit (MC Basis)

MiniBOONE at Fermilab

The Detector

- Pure mineral oil throughout
- 807 tons total, 445 tons fiducial
- 1280 phototubes in detector region
- 240 phototubes in veto region

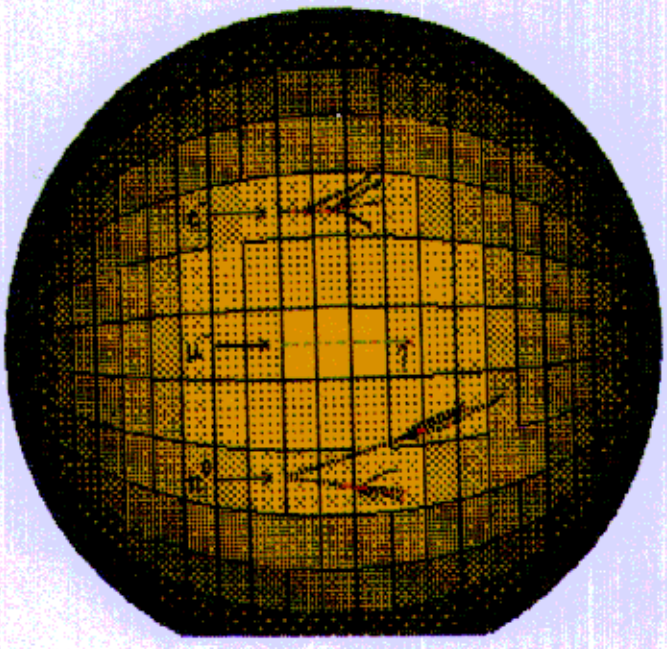
L = 500 m



Detect Čerenkov rings in oil

$\mu/e/\pi^0$ separation from light pattern

(Examples at 500 MeV)

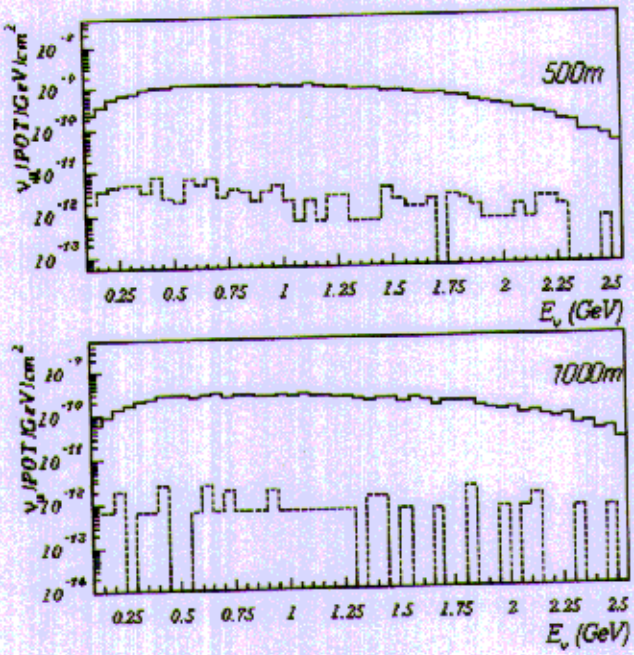


Expected ν fluxes

ν source

8 GeV protons from Fermilab Booster

$\nu_e/\nu_\mu \approx 0.3\%$



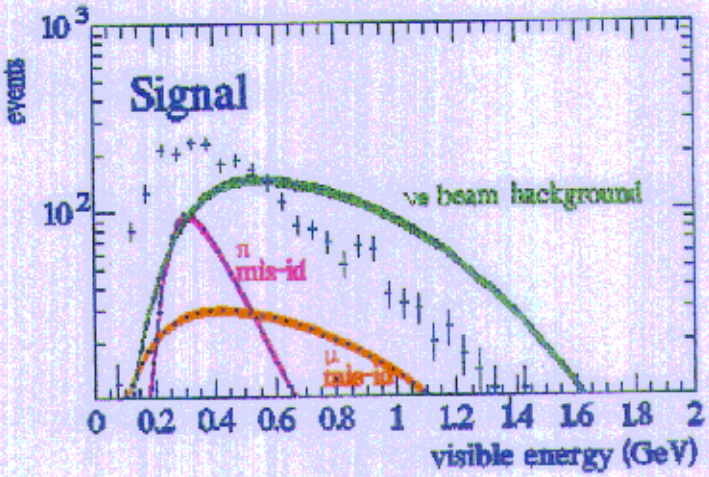
Event rate/year (at 500 m)

$\sim 5 \times 10^5$ $\nu_\mu C \to \mu^- X$

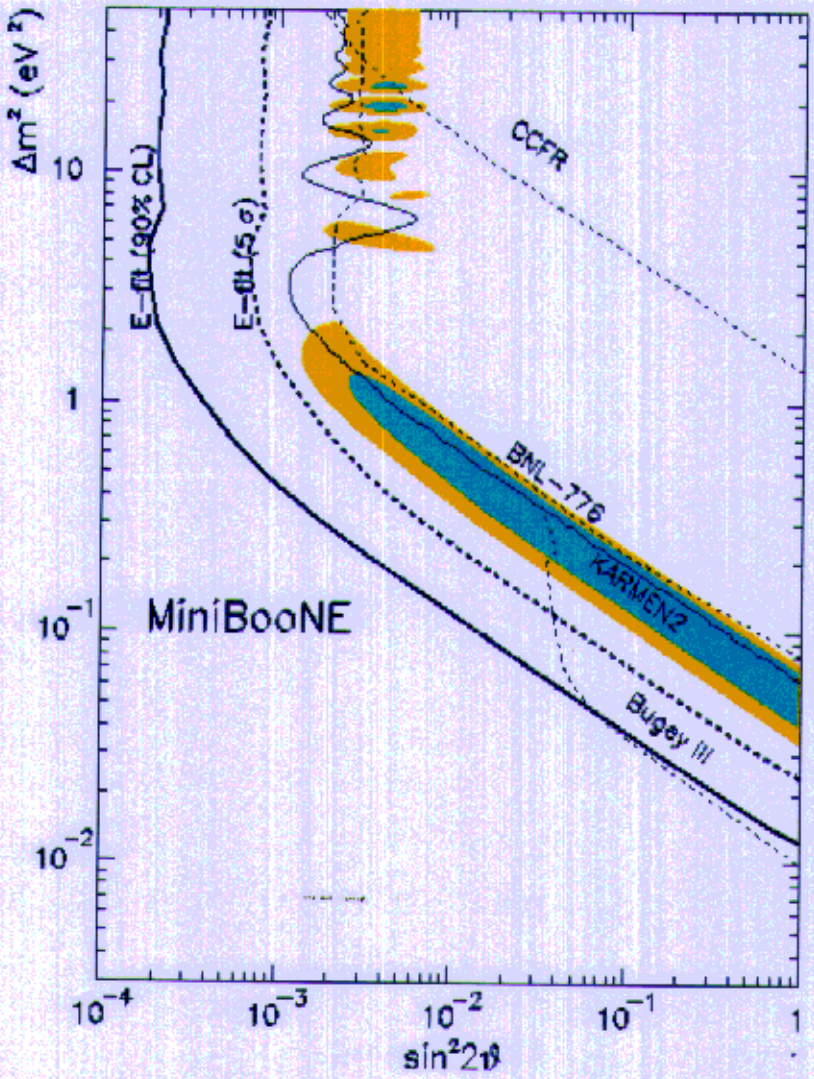
~ 1700 $\nu_e C \to e^- X$

+ 1500 additional $\nu_e C \to e^- X$ events if LSND result is correct

OSCILLATION SIGNAL HAS DIFFERENT ENERGY SPECTRUM WITH RESPECT TO BACKGROUND



MiniBOONE EXCLUDED REGION
IF NO SIGNAL IS OBSERVED AFTER
ONE YEAR OF DATA



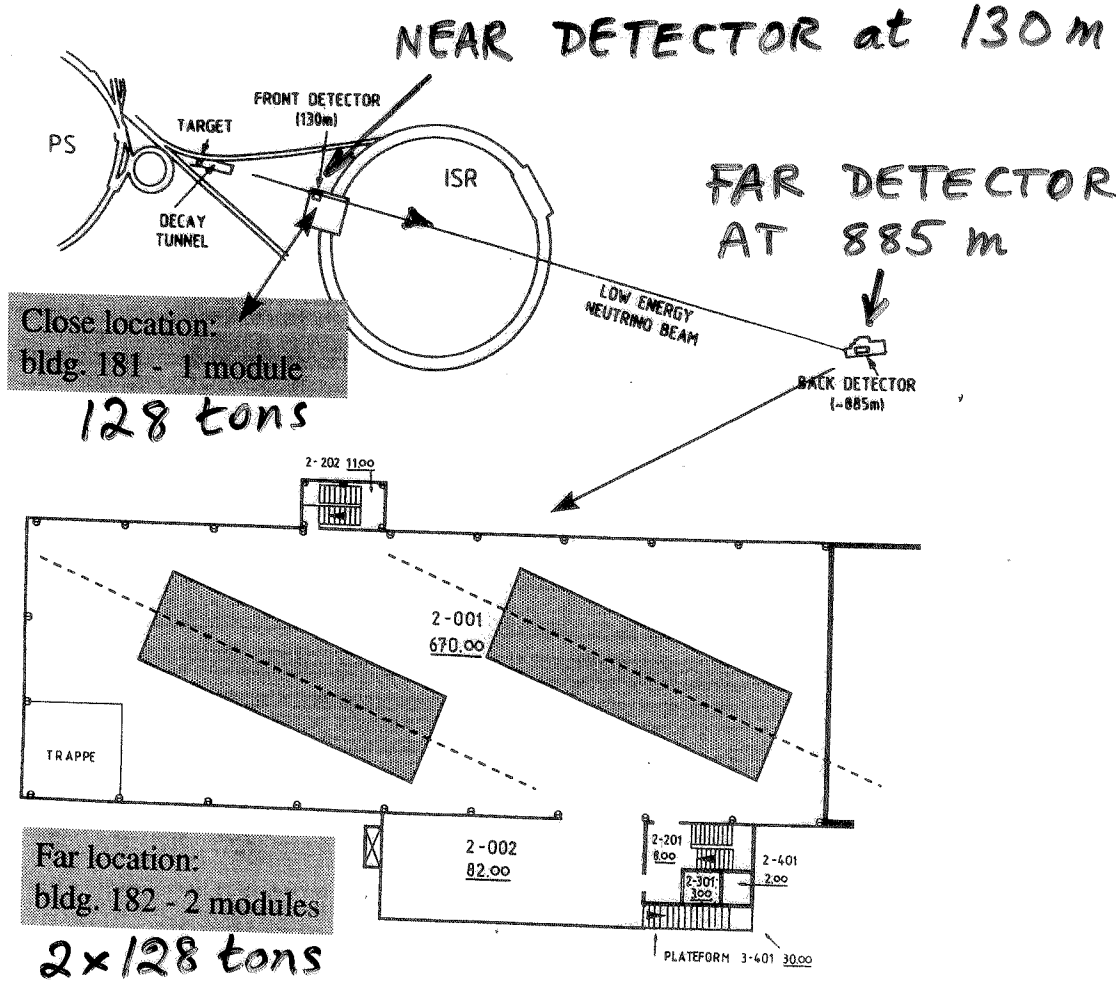
START DATA TAKING : Beginning 2002
First results ~ 2003

IF OSCILLATION SIGNAL IS OBSERVED,
BUILD AND INSTALL A SECOND DETECTOR
AT DIFFERENT DISTANCE

I-216

"Letter of Intent" for a two-detector experiment to study $\nu_\mu - \nu_e$ oscillations at the CERN PS

(Proposal in preparation)

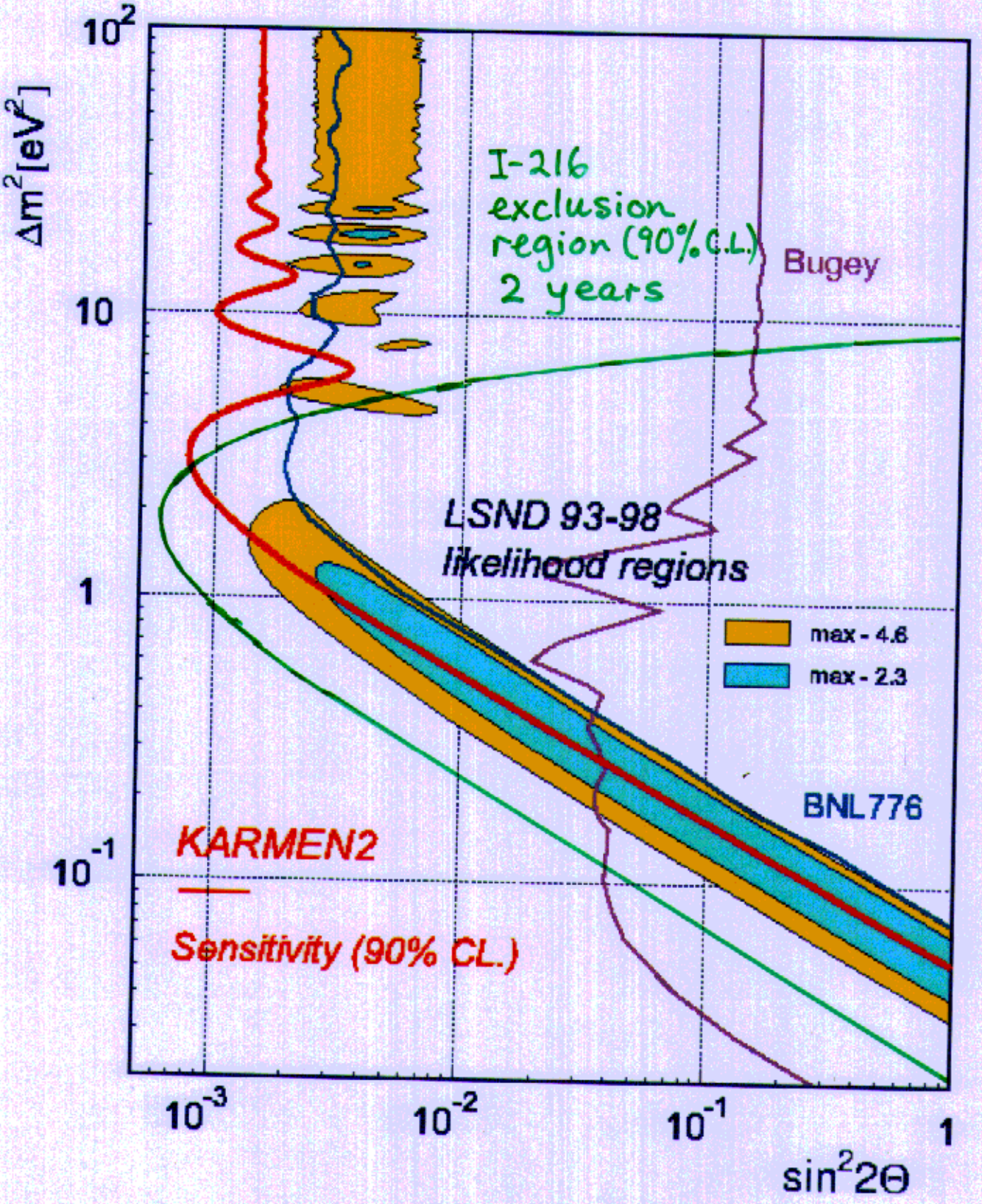


- All three modules are identical (planes of orthogonal bars of extruded scintillator with w/s fiber readout - dimension of a bar 3×3×400 cm)
- $\langle E_{\nu_\mu} \rangle \approx 1.5$ GeV, $\nu_e/\nu_\mu \approx 0.3\%$

Expected numbers of events (2-year run, 2×10^{20} p.o.t.)

	NEAR	FAR
$N(\nu_\mu N \to \mu^- X)$	1.87×10^6	0.85×10^5
$N(\nu_e N \to e^- X)$ no oscill.	6813	309

COMPARE $(\nu_e/\nu_\mu)_{FAR}$ WITH $(\nu_e/\nu_\mu)_{NEAR}$
(systematic uncertainty FAR/NEAR ~3%)



LONG BASELINE ACCELERATOR EXPERIMENTS

PURPOSE :

- VERIFY THE NATURE OF THE OSCILLATION RESPONSIBLE FOR THE ATMOSPHERIC NEUTRINO RESULTS

  $\nu_\mu - \nu_\tau$ versus $\nu_\mu - \nu_s$

- MEASURE $\sin^2 2\theta$ AND Δm^2

BASELINE	L(Km)	$\langle E_\nu \rangle$ GeV	STATUS
KEK → KAMIOKA	250	1.4	TAKING DATA
Fermilab → Soudan	730	few → 16 GeV	Start 2002
CERN → Gran Sasso	732	few → 30 GeV	Start 2005 (if approved by end 1999)

To observe $\nu_\tau N \to \tau^- X$ need $E_\nu > 5$ GeV
(threshold is at 3.5 GeV)

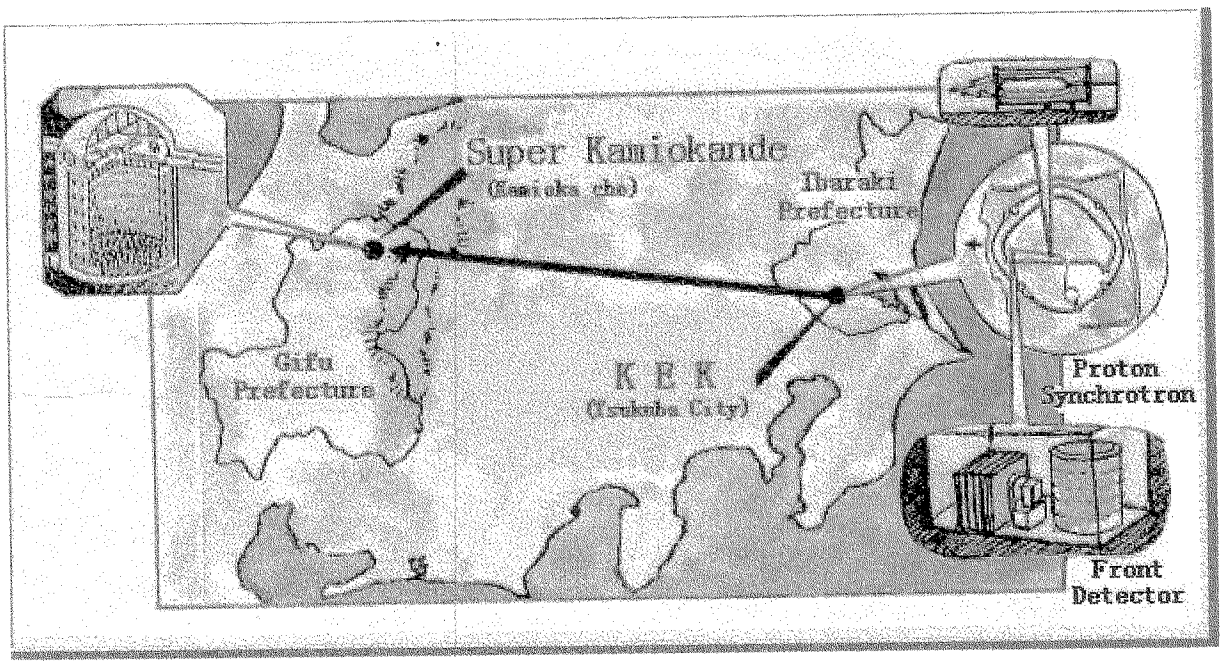
Very low event rates

Typically $\lesssim 1$ $\nu_\mu \to \mu^-$ event/year per ton of detector mass

$\Rightarrow$ need several Kton detectors

K2K EXPERIMENT

TAKING DATA!



January 27 : protons in ν line

February 14 : start of ν run

March → May : runs at various horn currents

June 4 → 27 : run at horn current = 200 kA

SUMMER SHUTDOWN

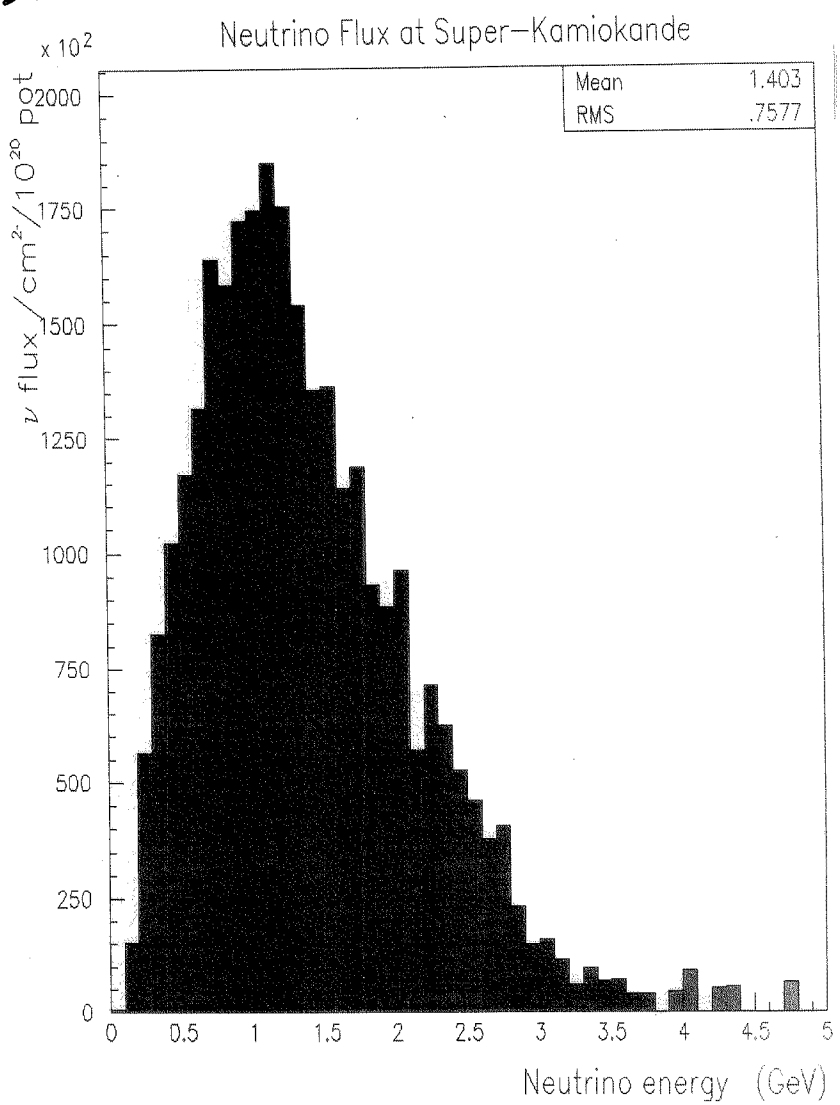
November : run at nominal horn current (250 kA)

K2K (KEK to KAMIOKA)

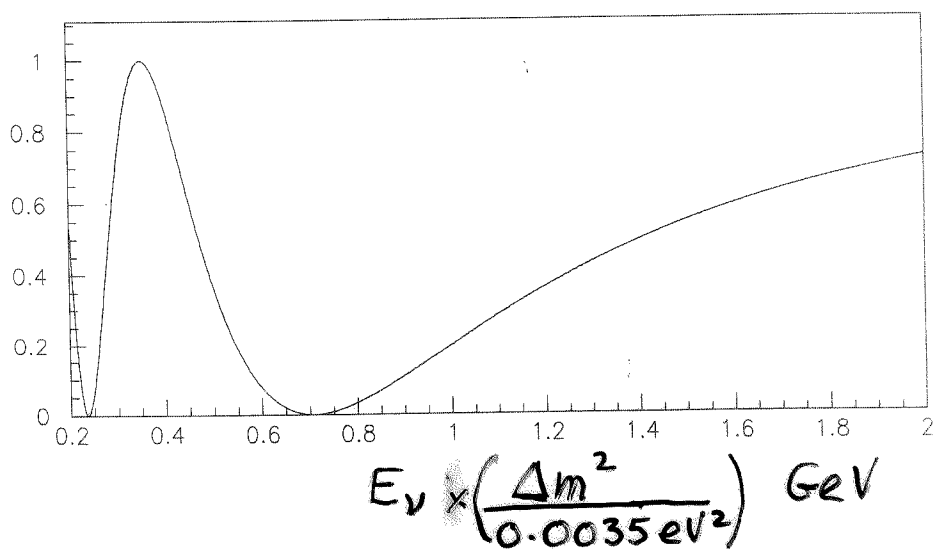
12 GeV proton synchrotron $\rightarrow \pi^+, K^+$
$\rightarrow \nu_\mu$ (+ 2% $\bar{\nu}_\mu$ + 0.7% ν_e)

EXPECTED
ν_μ SPECTRUM
AT Super-K

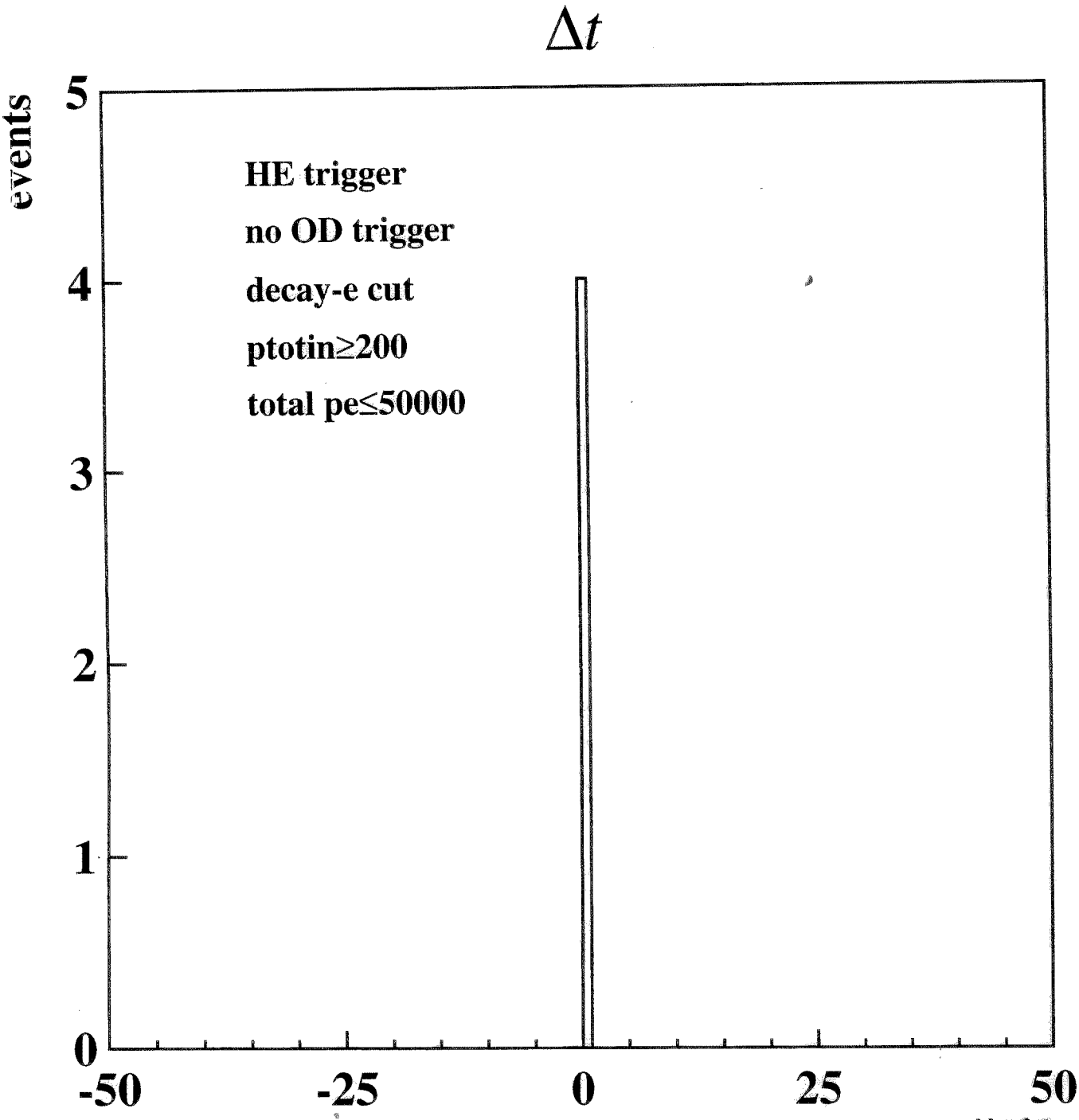
10^{20} protons on target (3 years)
$\rightarrow$ 345 $\nu_\mu \rightarrow \mu^-$
12C $\nu \rightarrow \nu$
4 $\nu_e \rightarrow e^-$



$P(\nu_\mu - \nu_\mu)$
for full mixing



Event time distribution at Super-K in ± 50 μsec window centered on expected arrival time of neutrino beam pulse (based on GPS time)

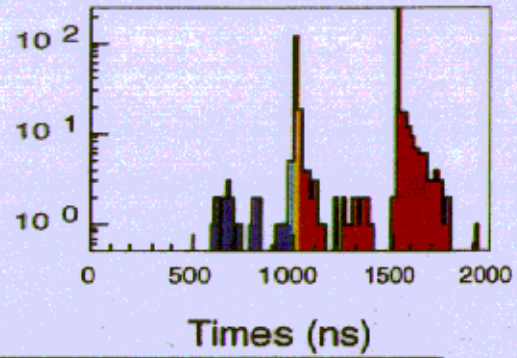


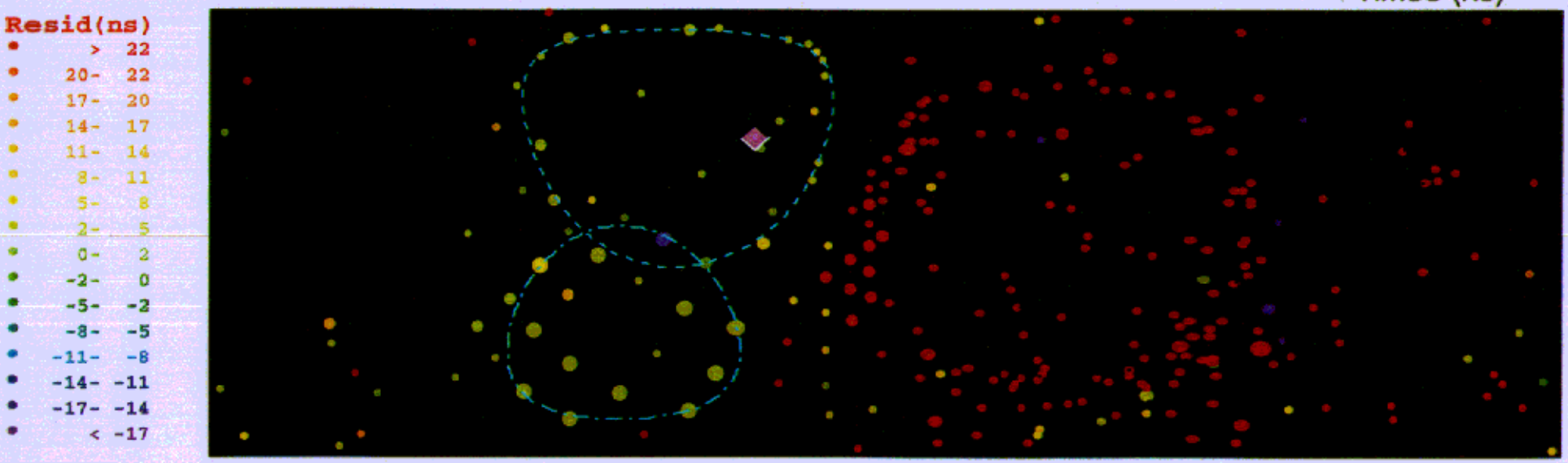
beam pulse length 1.1 μs, rep. rate 1/2.2 s^{-1}

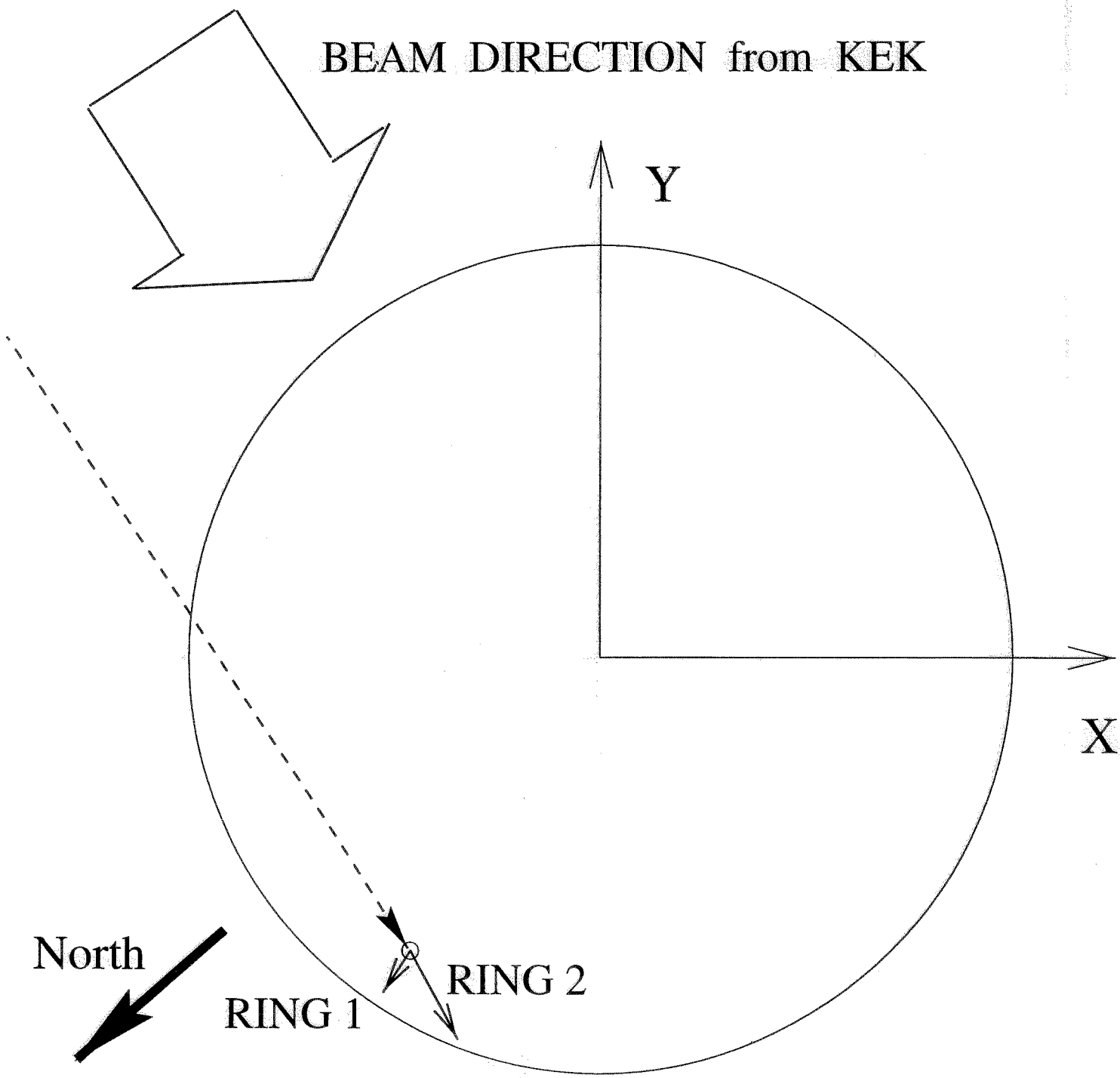
One event in fiducial volume (22.5 Kton)

Super-Kamiokande

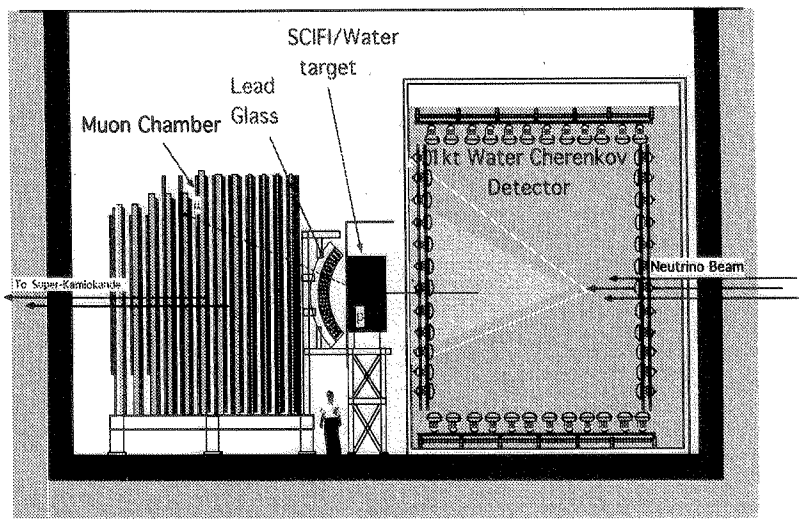
Run 7436 Event 14054126
99-06-19:18:42:49
D wall: 240.4 cm
Inner: 516 hits, 1018 pE
Outer: 2 hits, 2 pE (in-time)
Trigger ID: 0x07






BEAM DIRECTION from KEK
Y
X
North
RING 1
RING 2

Near detector at L = 0.3 Km will measure:



fine-grained detector

- ν_μ flux
- $\bar{\nu}_\mu$ flux
- ν_e flux
- Cross-section for π^0-like events in NC events (will greatly reduce present uncertainty)

EVENT RATES FOR 10^{20} PROTONS ON TARGET
(12 months equivalent to 3 calendar years)

	Fine-grained	1Kton H_2O	Super-K
Fiducial mass	4 tons	21 tons	22.5 Ktons
ν_μ CC events	126,700	408,000	345
ν_μ NC events	44,900	144,000	120
π^0-like events	9,200	29,500	25
ν_e CC events	1,250	4,000	4

Cross-section for π^0-like events in 1Kton H_2O detector will be precisely measured within one year

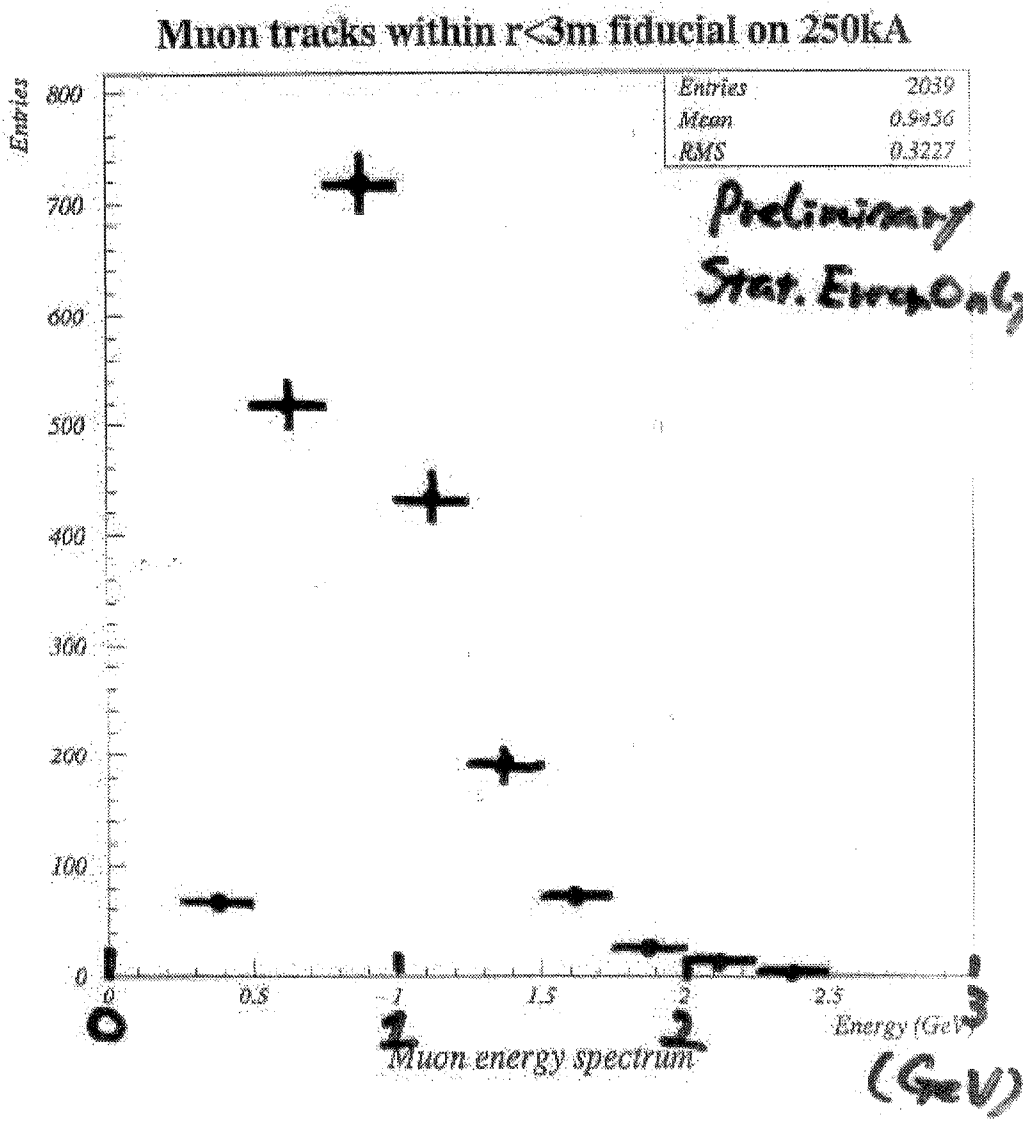
This information + measured rate of π^0-like events from atmospheric neutrinos in SuperK will distinguish ν_μ-ν_τ from ν_μ-ν_s

K2K

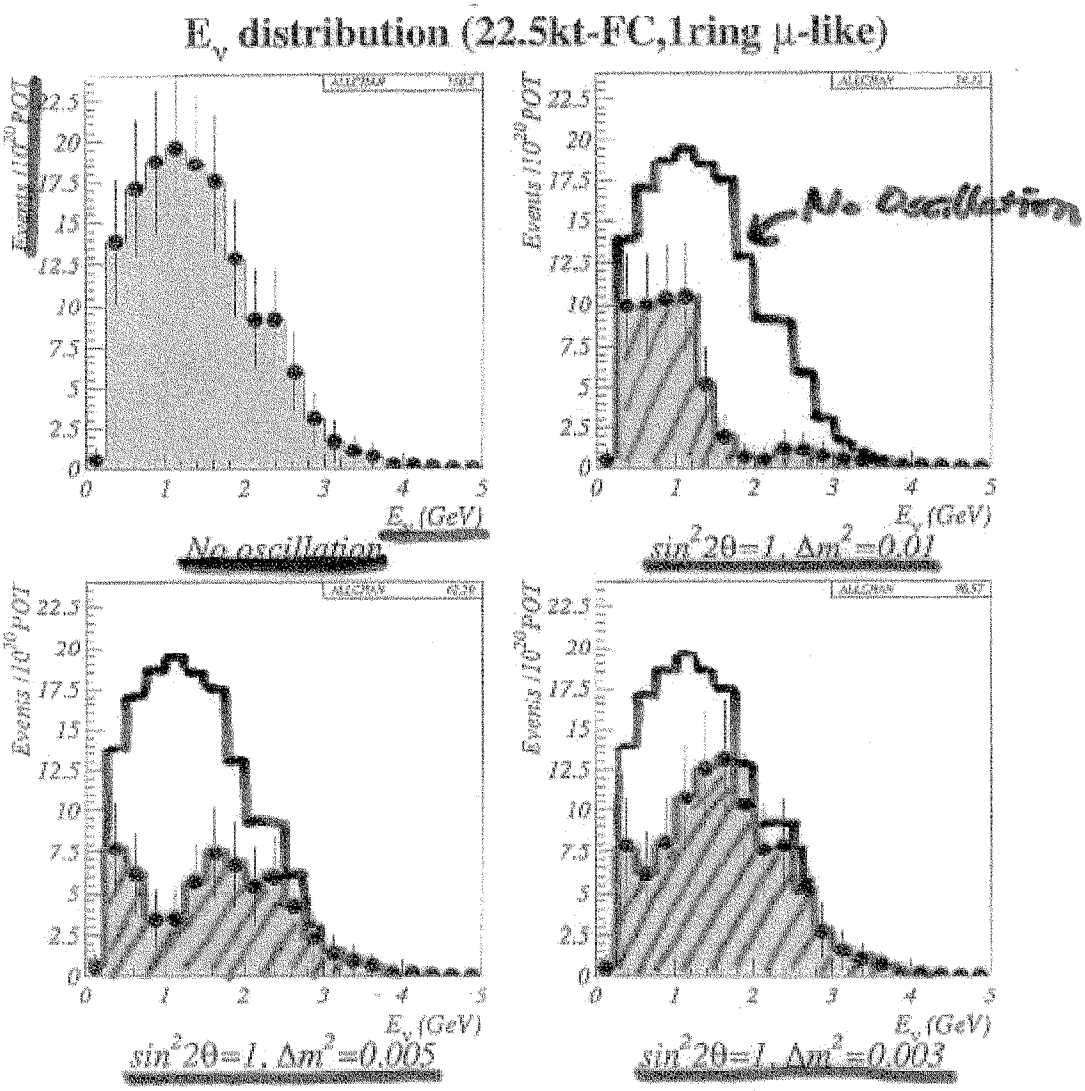
CLOSE DETECTOR

ν_μ-Fe interactions

MUON ENERGY SPECTRUM



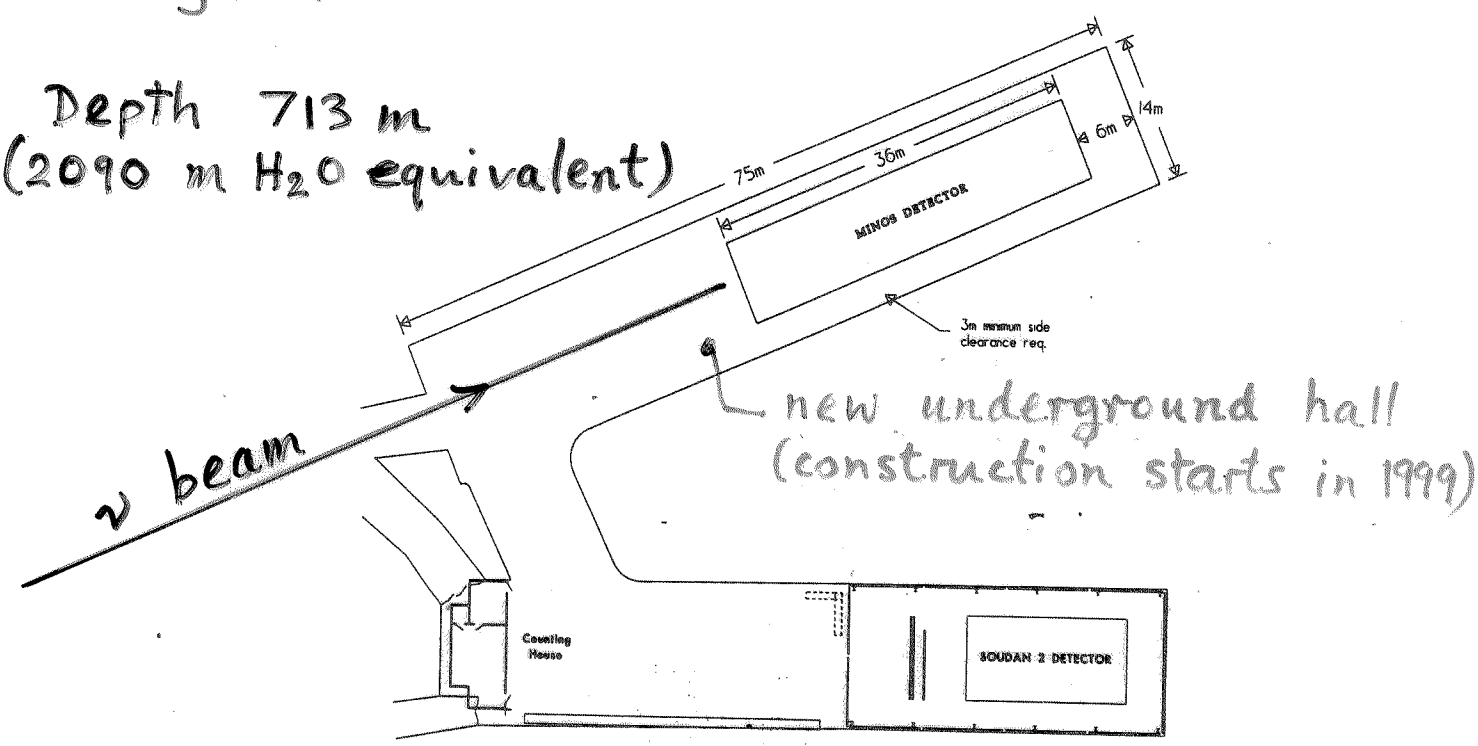
K2K EXPECTED $E(\nu_\mu)$ DISTRIBUTIONS AT SUPER-K DETECTOR



FERMILAB LONG BASELINE EXPERIMENT MINOS (E-785)

ν beam from 120 GeV high-intensity proton synchrotron (Main Injector) now being built

Depth 713 m
(2090 m H_2O equivalent)

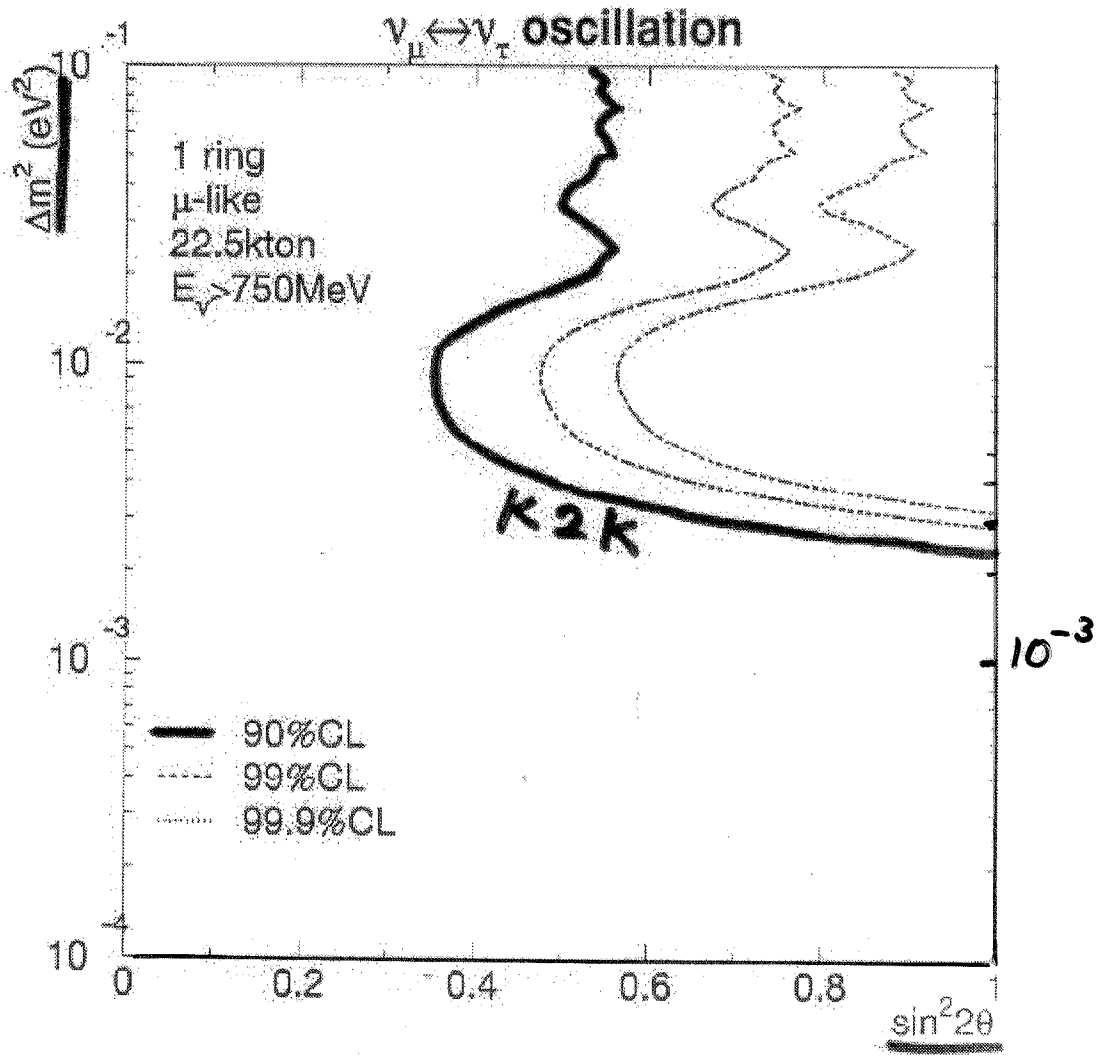


START DATA TAKING ~ 2002

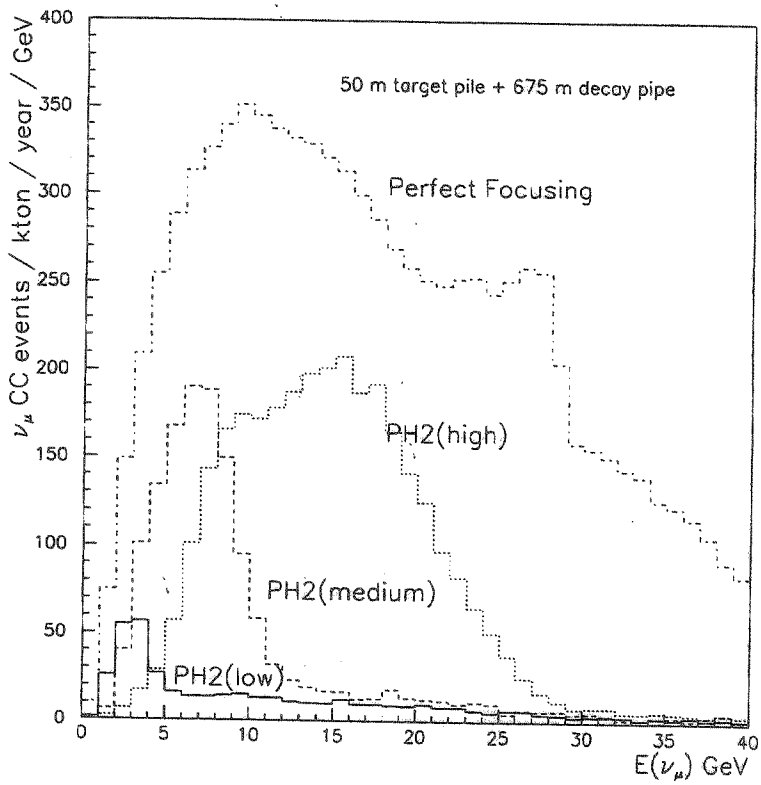
K2K EXCLUDED REGION

IF NO OSCILLATION SIGNAL IS OBSERVED

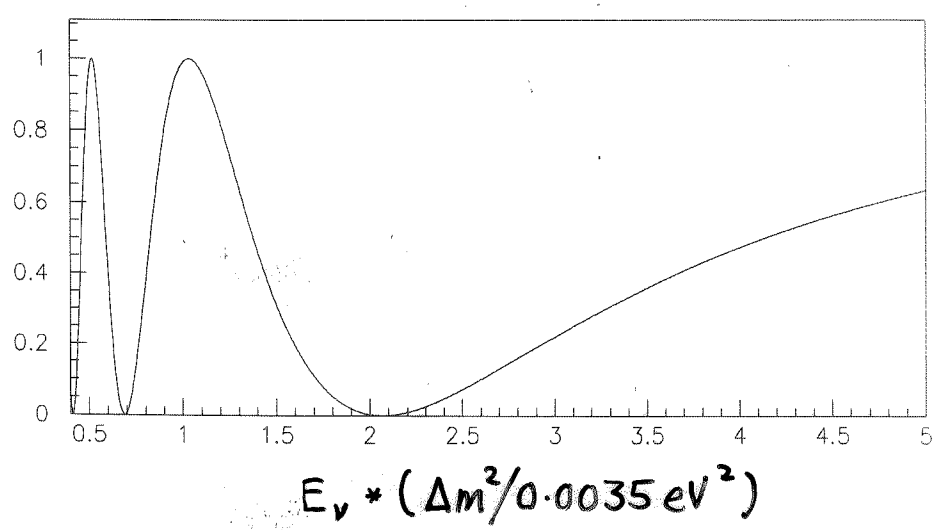
IN 3 YEARS



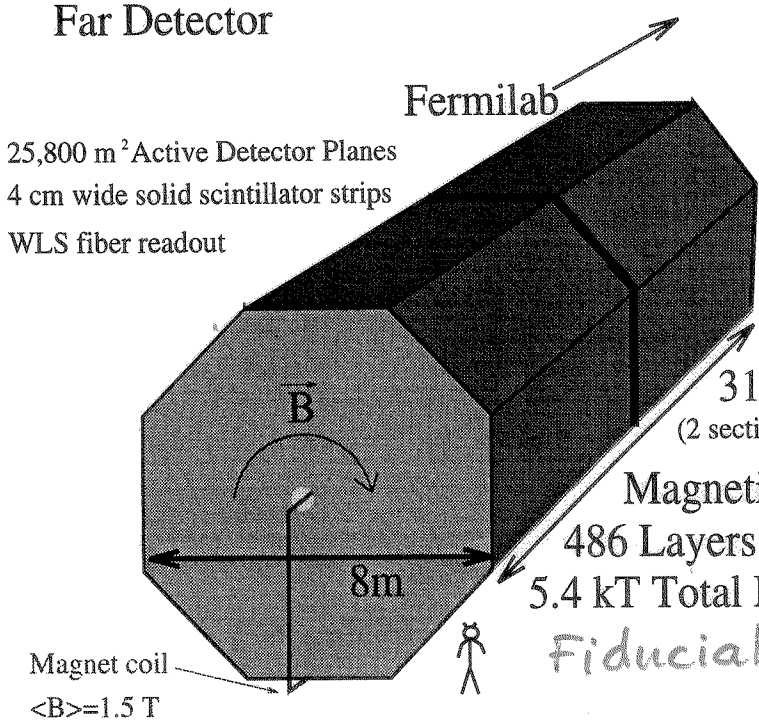
Event energy spectra in far detector



$P(\nu_\mu - \nu_\mu)$ for full mixing



MINOS (Main Injector Neutrino Oscillation Search)
Far Detector



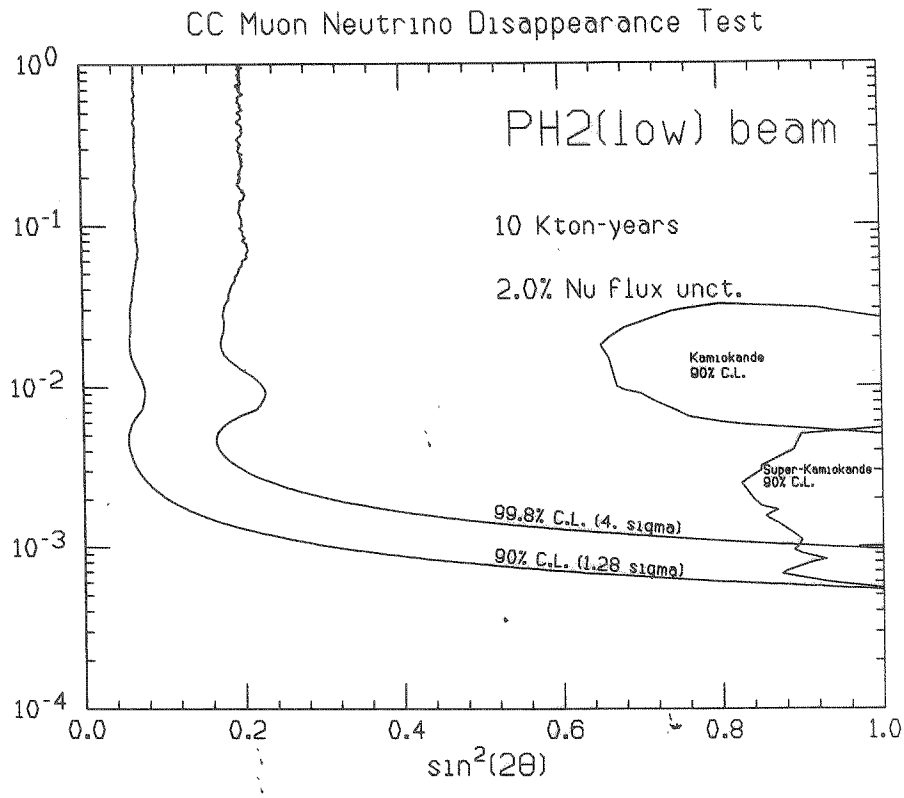
+ near detector of similar design
(920 tons, fiducial mass 100 tons)
250 m downstream from decay pipe end

EVENT RATES / KILOTON
TWO-YEAR RUN, 3.6×10^{20} protons on target/year

	Beam Energy Configuration		
	High	Medium	low
$N(\nu_\mu N \to \mu^- X)$	6241	2500	891

MINOS SENSITIVITY TO OSCILLATION

From comparison of Far and Near ν_μ spectra as measured from $\nu_\mu N \to \mu^- X$ events



From comparison of NC/CC event ratio in Far and Near detector

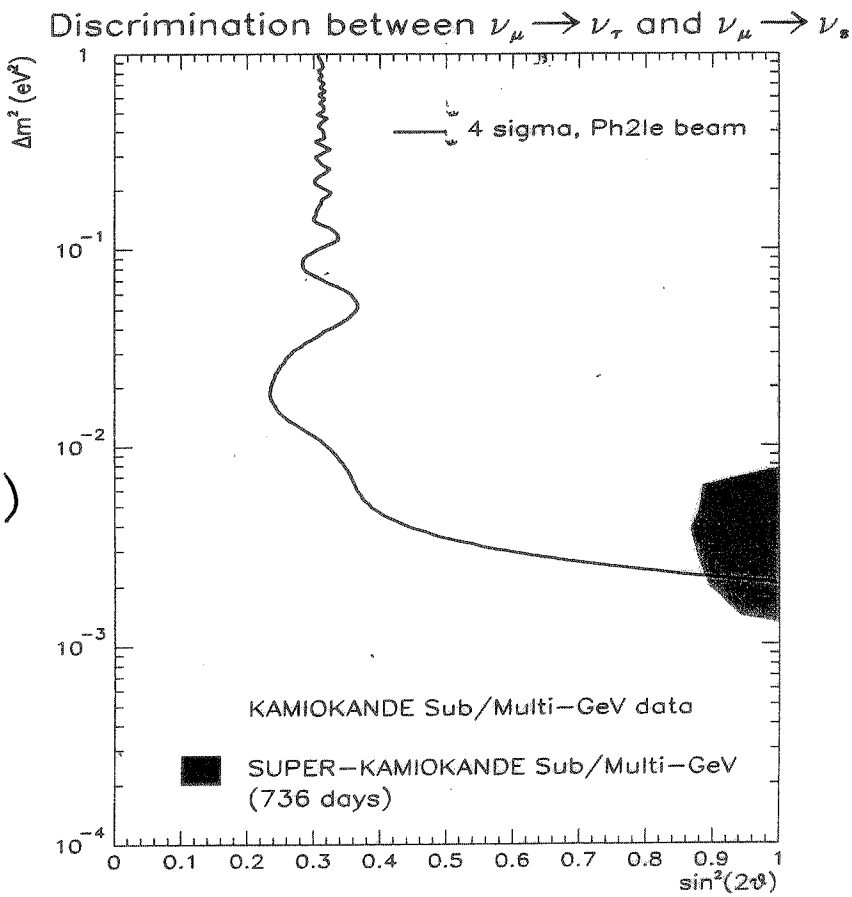
(NC ≡ muonless event)

ν_μ-ν_τ :

$$\left(\frac{NC}{CC}\right)_{far} > \left(\frac{NC}{CC}\right)_{near}$$

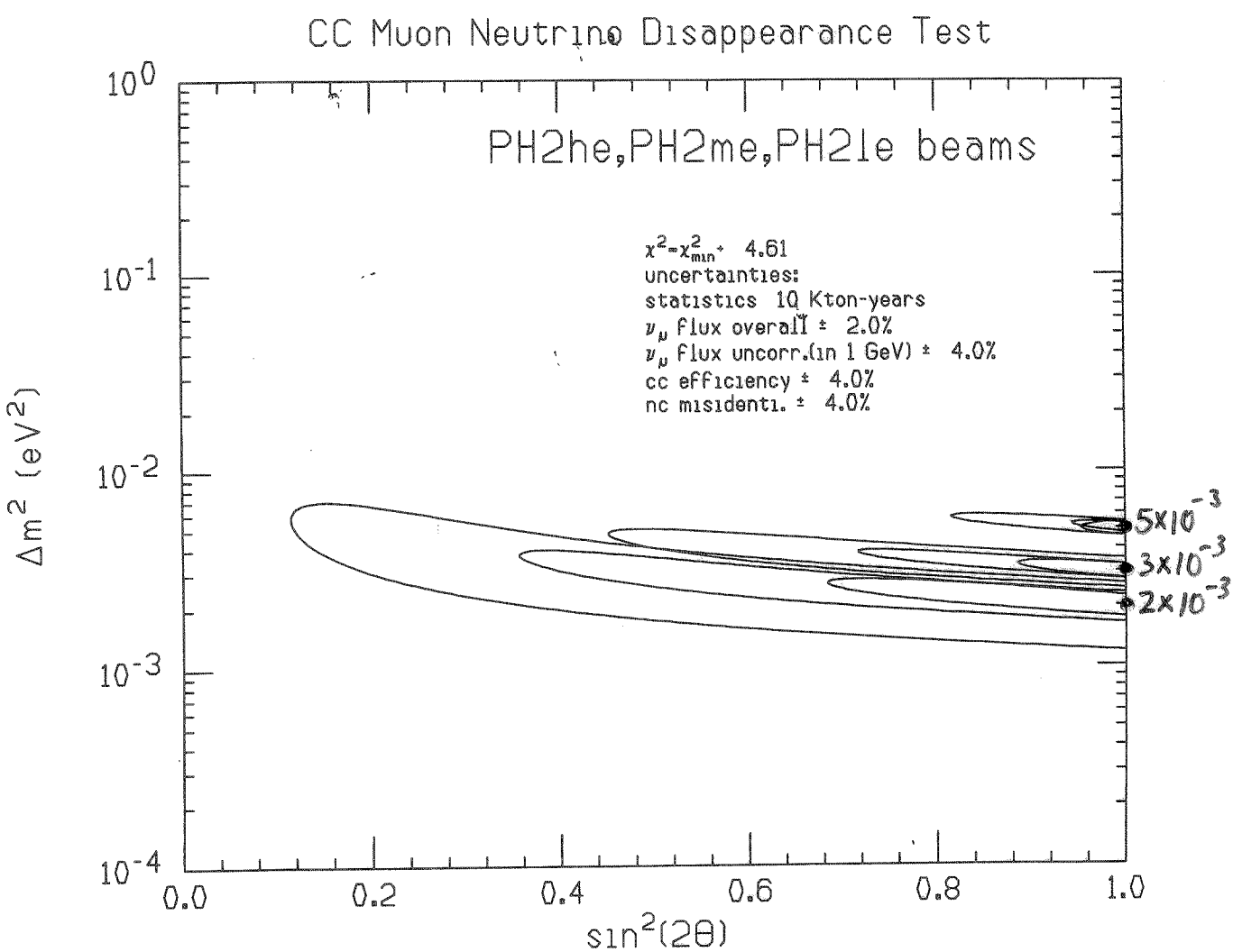
ν_μ-ν_s :

$$\left(\frac{NC}{CC}\right)_{far} = \left(\frac{NC}{CC}\right)_{near}$$



MINOS CAPABILITY TO MEASURE OSCILLATION PARAMETERS

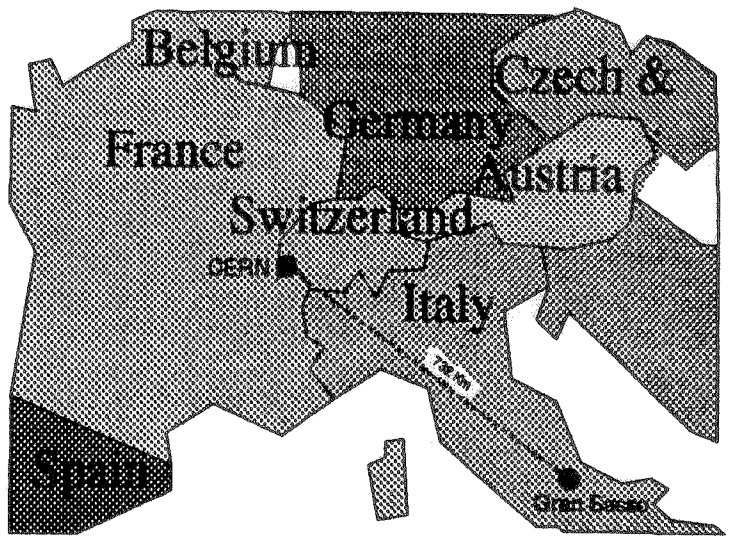
(from fit to spectral distortion of $\nu_\mu N \to \mu^- X$ events in far detector)



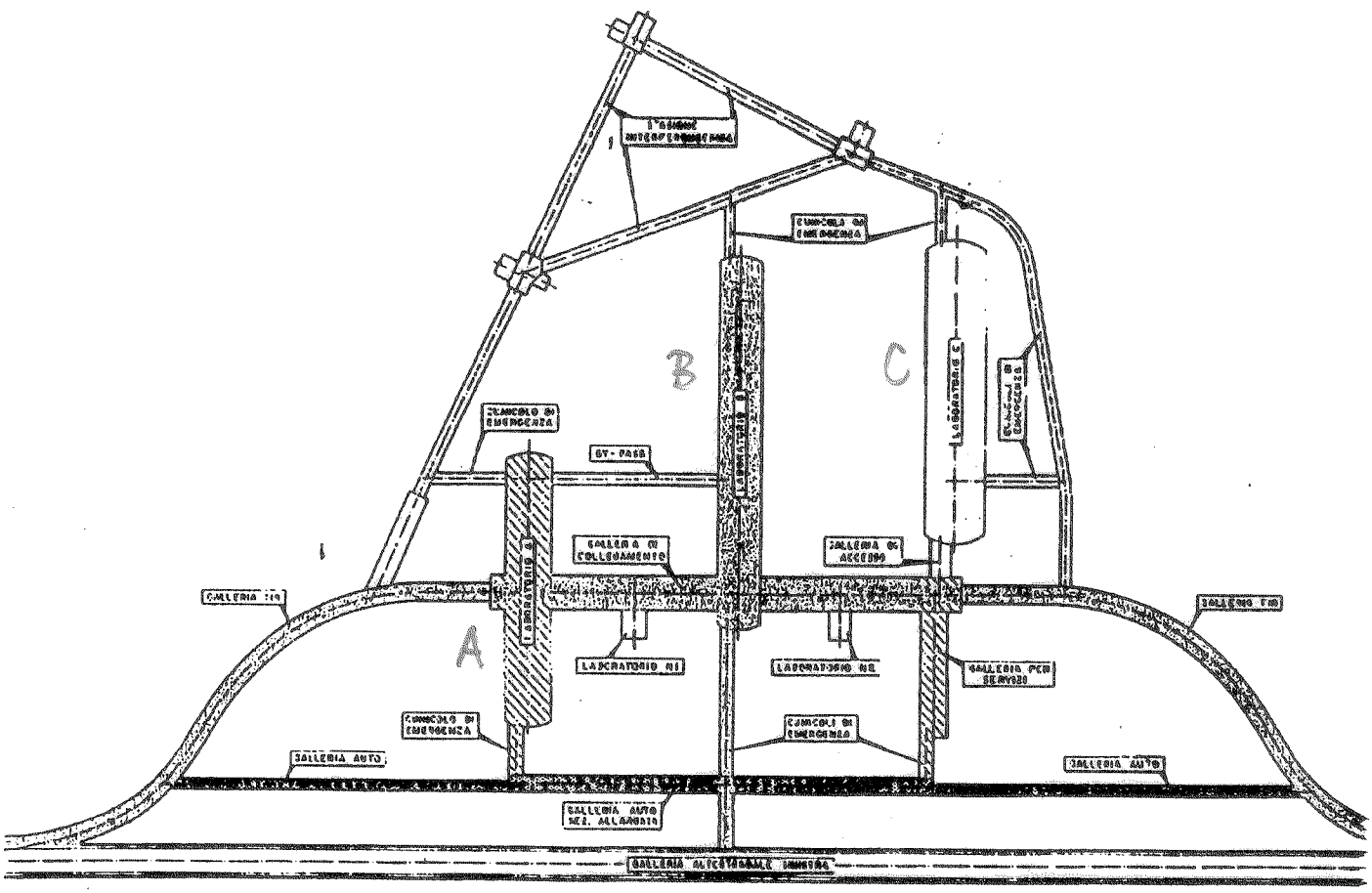
NGS PROJECT

Neutrinos to Gran Sasso

L=732 km



↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ν beam direction



ASSERGI

NGS project earliest start: 2005
WILL FOCUS ON ν_τ APPEARANCE SEARCH
FOR WHICH NO NEAR DETECTOR IS BELIEVED
TO BE NEEDED

SCALING LAWS

FOR ν_τ APPEARANCE EXPERIMENTS

Number of $\nu_\tau + N \to \tau^- + \text{hadrons}$ events:

$$N_\tau = A \int \Phi(E)\, P_{osc}(E)\, \sigma_\tau(E)\, dE$$

A proportional to detector mass

$\Phi(E)$ ν_μ flux at detector

$$P_{osc}(E) = \sin^2(2\theta) \sin^2\left(1.27 \Delta m^2 \frac{L}{E}\right)$$

(two-family mixing) Δm^2 [eV^2] L [km] E [GeV]

$\sigma_\tau(E)$ cross-section for $\nu_\tau + N \to \tau^- + \text{hadrons}$

Threshold $E_0 \approx 3.5$ GeV

$\frac{\Delta m^2 L}{E} << 1$ (true for $\Delta m^2 \lesssim 6 \times 10^{-3}$ eV^2, $L = 730$ Km)

$$P_{osc}(E) \approx 1.6 \sin^2(2\theta) (\Delta m^2)^2 \frac{L^2}{E^2}$$

$$\Rightarrow N_\tau \approx 1.6\, A \sin^2(2\theta) (\Delta m^2)^2 L^2 \int \Phi(E) \sigma_\tau(E) \frac{dE}{E^2}$$

$\Phi(E)$ proportional to L^{-2}

$\Rightarrow$ N_τ does not depend on L

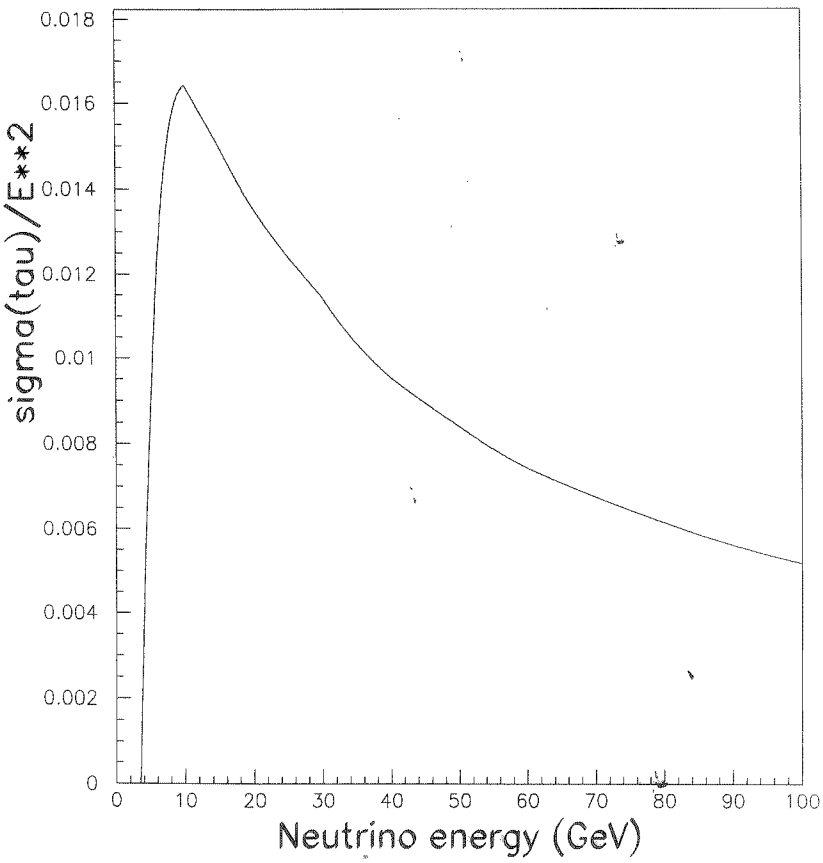
N_τ proportional to $(\Delta m^2)^2$

Standard ν event rate proportional to L^{-2}

$\Rightarrow$ τ signal/background improves as L^2

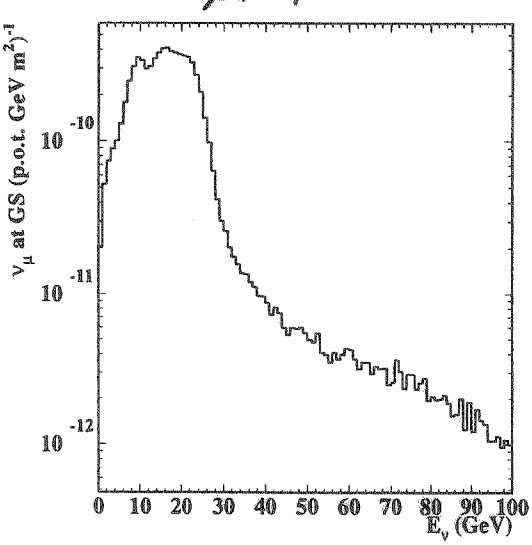
N_τ prop. to $\sin^2(2\theta)(\Delta m^2)^2 \int \phi(E) \dfrac{\sigma_\tau(E)}{E^2} dE$

➡ BEAM OPTIMIZATION DOES NOT DEPEND ON Δm^2

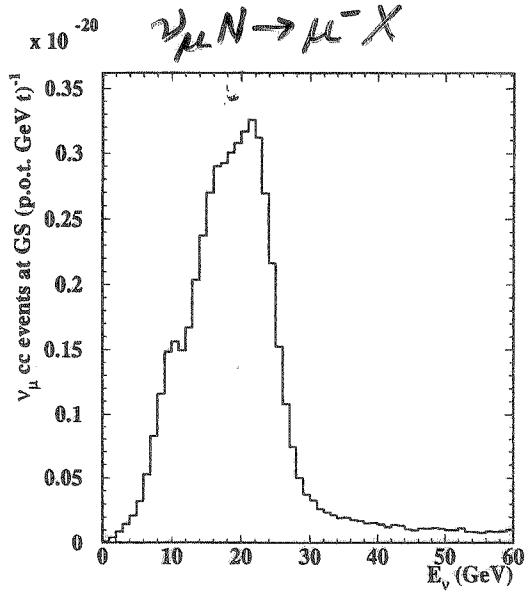


NGS update (CERN-SL report, May 17)
(see also full report CERN 98-02)

ν_μ flux



$\nu_\mu N \to \mu^- X$



$\langle E_\nu \rangle = 17$ GeV

NGS EVENT RATES/YEAR PER KTON

1 YEAR = 4.5×10^{19} protons on target
(a realistic figure after LEP shut-down)

		E_ν range (GeV) 1–30	1–100
$\nu_\mu N \to \mu^- X$		2115	2448
$\nu_\tau N \to \tau^- X$ *	$\Delta m^2 = 10^{-3}$	2.34	2.48
	$\Delta m^2 = 0.003$	20.7	21.7
	$\Delta m^2 = 0.005$	56.2	58.5

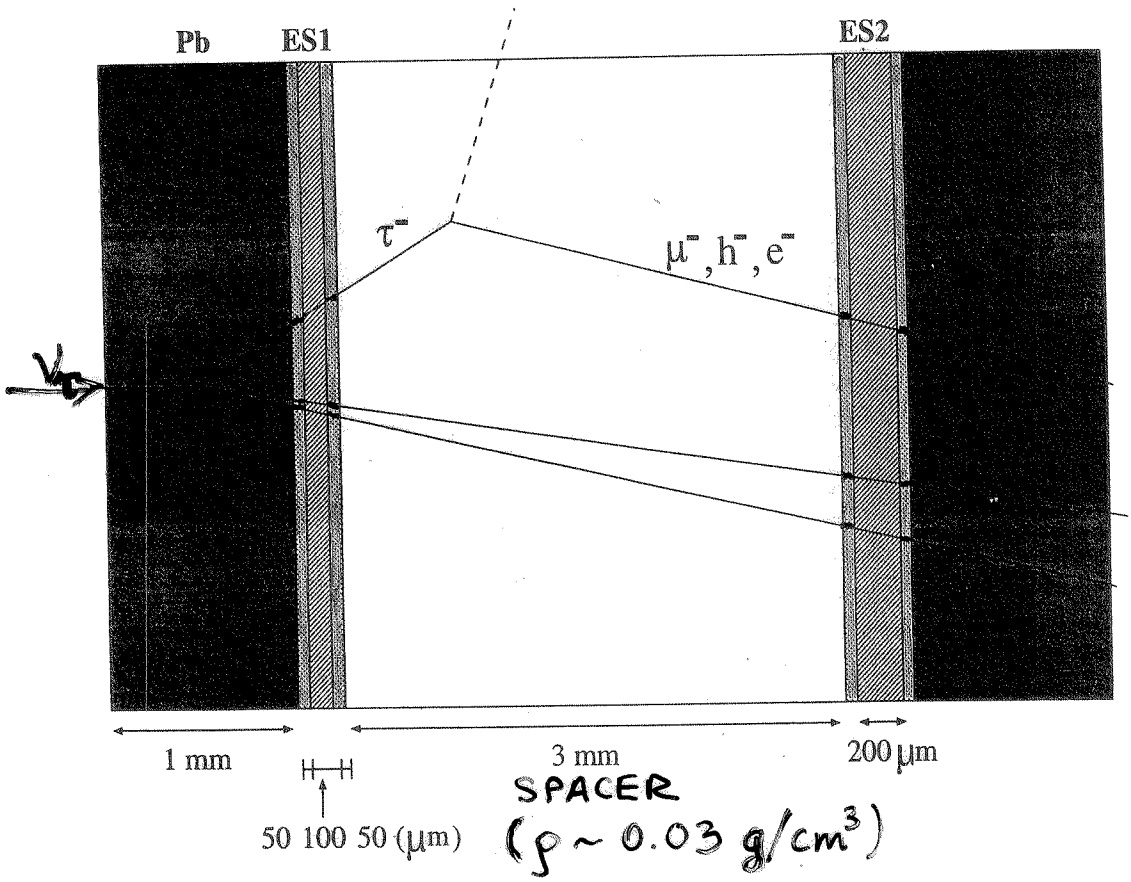
* all decay modes
detection efficiency = 100%

OPERA

- Detect $\nu_\tau + N \rightarrow \tau^- + X$ by observing the τ^- decay "kink"
  (τ decay mean free path ~ 1 mm)
- Neutrino target : thin (1 mm) Pb plates
- Precise tracking using thin emulsion plates ($\sigma \sim 1\,\mu m$) to reconstruct the decay kink
- Total target mass (mainly Pb) ~ 800 Tons
- Expected number of neutrino events in 4 years ($\Rightarrow 18 \times 10^{19}$ p.o.t.) ~ 1.3×10^4
- Target and emulsion tracker are subdivided into ~ 10^5 small "bricks"
- Brick where neutrino event occurred is identified using conventional Trackers and removed from detector for scanning and measurement of emulsion plates
- Scanning time using presently available automatic microscopes ~ few hours/cm^2 – R&D in progress to improve scanning time

Decay kink reconstruction method

ES1, ES2 Emulsion - plastic - emulsion sandwich



STRUCTURE OF A BRICK:

Transverse dimensions 15×15 cm²

30 × (Pb plate + emulsion tracker)

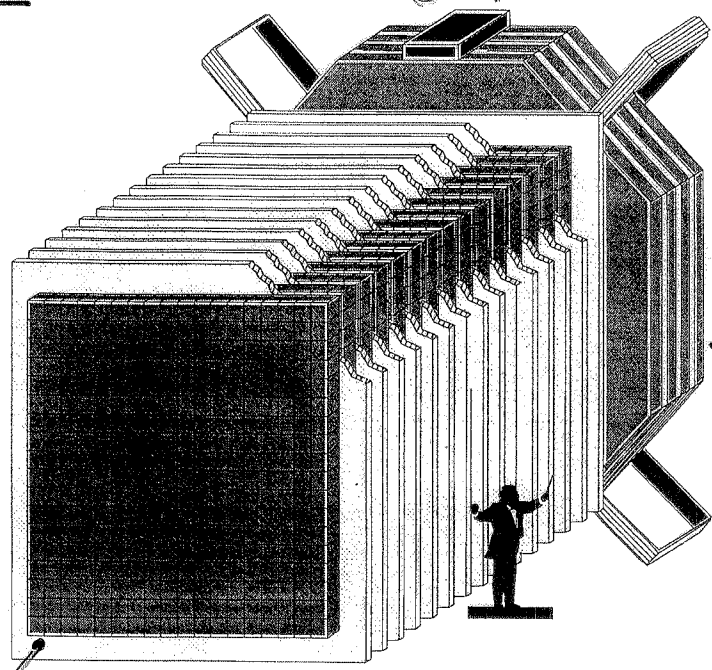
Mass ~ 8 kg

"Gold-plated" events have kink in the gap between ES1 and ES2 (very low density spacer)

τ^- decays in Pb plate can be identified by impact parameter but are contaminated by secondary interactions in Pb

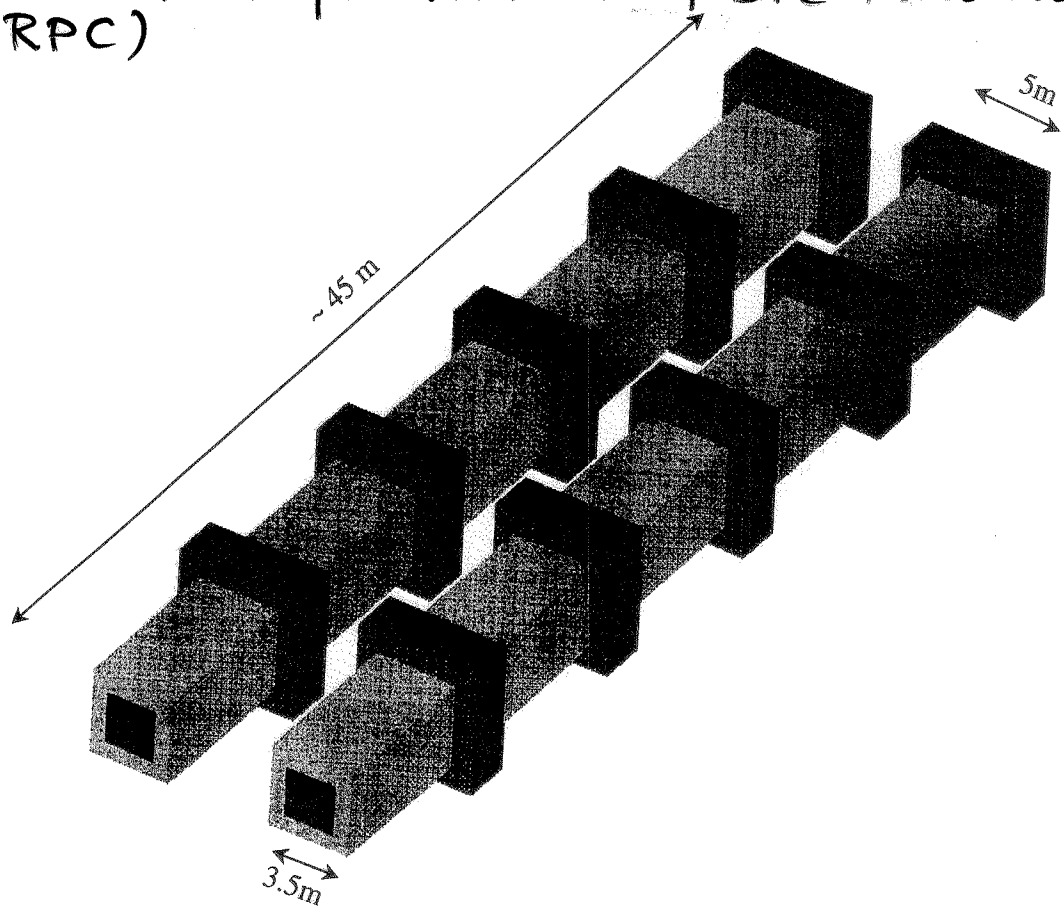
Bricks are arranged in SuperModules

Example (one of many possible configurations)



← magnetized iron toroid identifies μ and reduces background from charm decay

conventional tracker ($\sigma \sim 1$ cm) to identify brick where ν event occurred
(scintillator strips with WLS fibre read out or RPC)



OPERA : EVENT RATE AND BACKGROUND

τ^- detection efficiency ~ 0.30
(τ^- decay in gap, kink angle, geometry)

Useful decay fraction 85% (1-prong)

$\Delta m^2 (eV^2)$	# of events/4 years
1.0×10^{-3}	2.0
3.0×10^{-3}	17.7
5.0×10^{-3}	47.8

Backgrounds (events/10^3 $\nu_\mu N \to \mu^- X$)

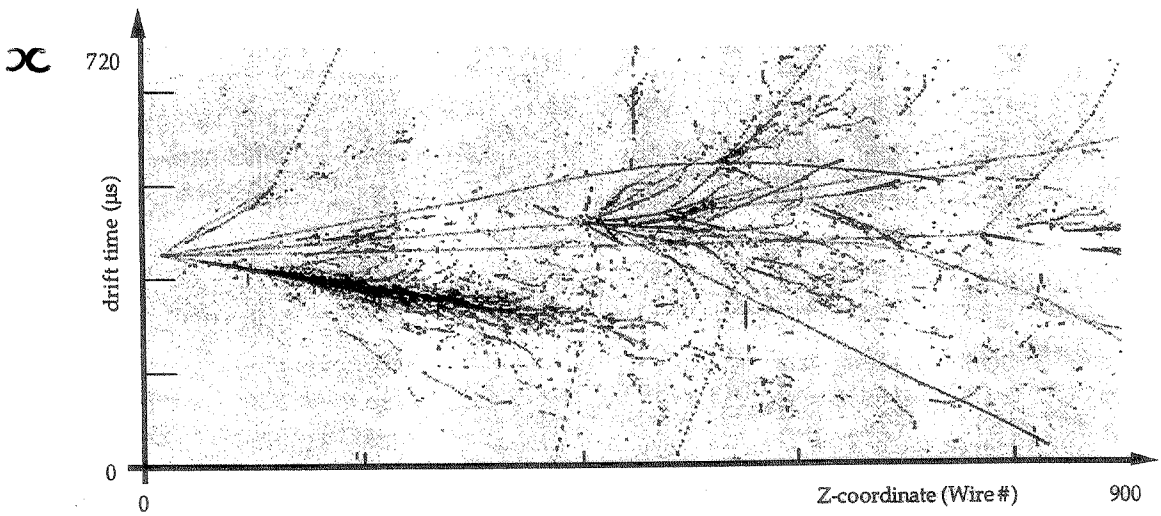
SOURCE	# events
π, K decay in gap	0.03
hadronic interactions in gap	< 0.01
charm decay, $\mu^\pm$ not identified	0.13
TOTAL	0.16

Total background in 4 years (9792 $\nu_\mu N \to \mu^- X$ events) 1.6 events could be further reduced by kinematic cuts at the expense of efficiency.

ICARUS

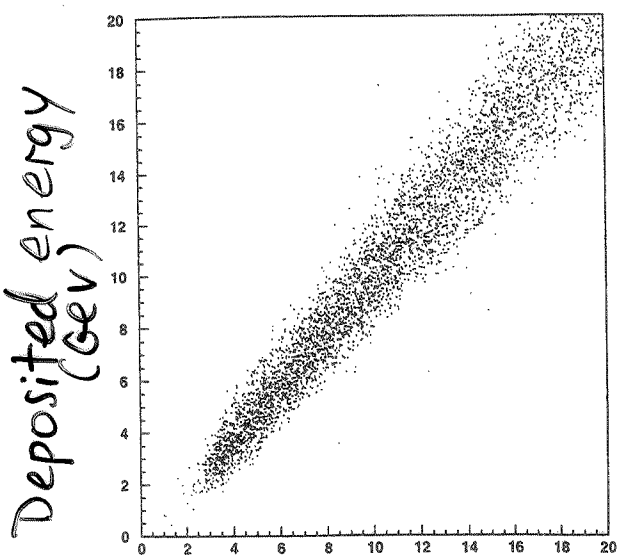
Liquid Argon Time Projection Chamber

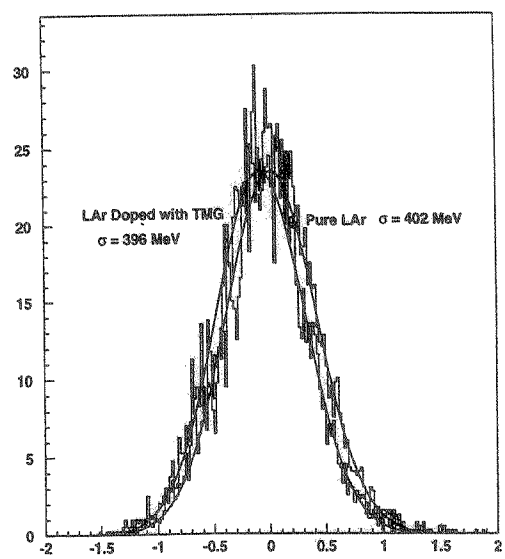
SIMULATED $\nu_e + N \rightarrow e^- + \text{hadrons}$



SIMULATION OF DEEP-INELASTIC ν EVENTS

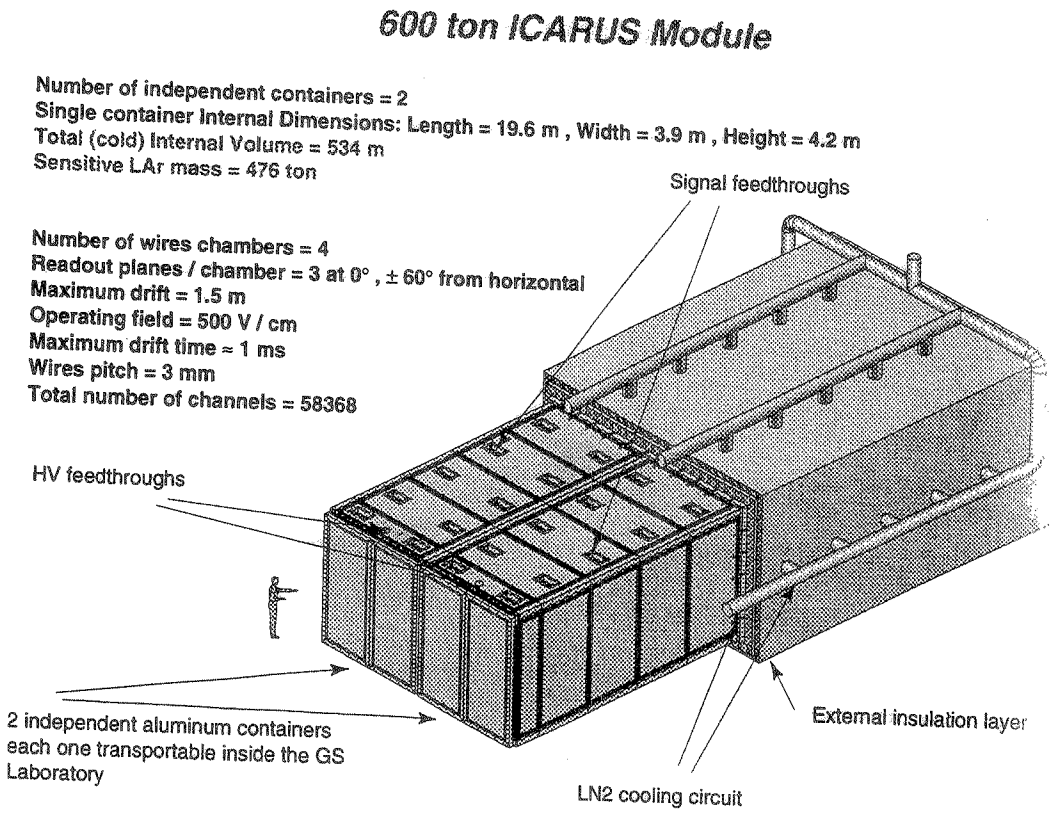
Response to hadronic jet





True - Reconstructed Hadron jet transverse Momentum (GeV)

ALREADY APPROVED :



- BEING CONSTRUCTED BY INDUSTRY
- TO BE ASSEMBLED AND TESTED IN 1999
- TRANSPORT TO LNGS, INSTALLATION IN HALL C FORESEEN FOR ~2000

PLANS TO BUILD 3 ADDITIONAL MODULES → INSTALLATION OF 2400 TON DETECTOR IN HALL B (PENDING SUCCESSFUL OPERATION OF MODULE 1)

ICARUS - SEARCH FOR $\nu_\mu - \nu_\tau$ OSCILLATION

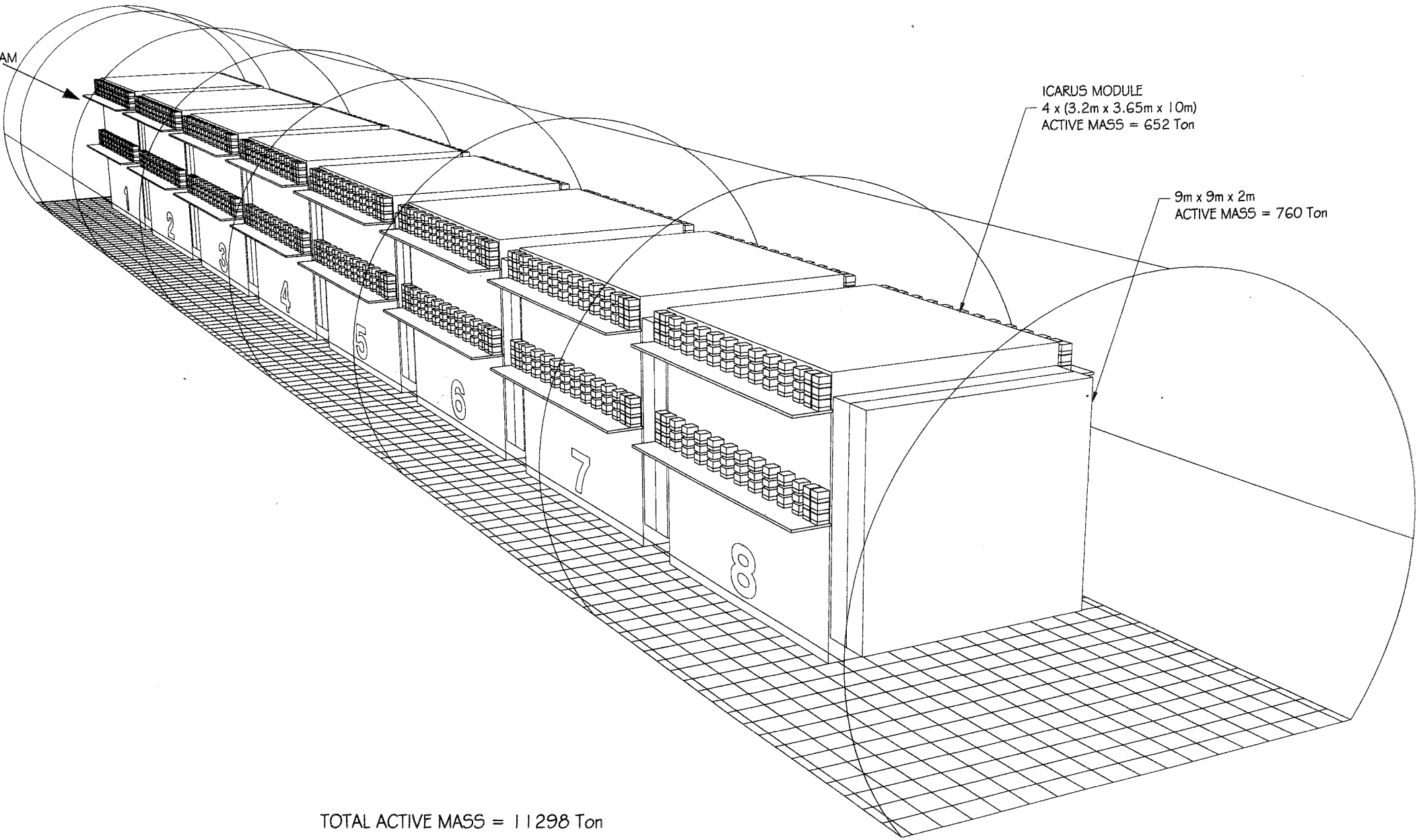
4 MODULES, 2.4 KTON

Detection of $\tau^- \to e^- \nu \bar{\nu}$ using kinematical criteria "à la NOMAD"

Number of events / 4 years (1.8×10^{20} protons on target)

	$\tau \to e$ eff (%)	$\nu_e \to e^-$	SIGNAL Δm^2 (eV^2) 0.0035	0.005
Initial sample	100	222	50.7	101.0
$E_{vis} < 20$ GeV	86	15.4	43.6	87.1
$p_T^e < 1.0$ GeV	71	7.6	36.0	72.0
$p_T^{miss} > 0.5$ GeV	52	4.2	26.4	53.7
$0.05 < \theta_e < 0.9$	46	2.8 ± 0.3	23.3	46.6

		$\tau \to e$	$\tau \to \pi$	$\tau \to \rho$	$\tau \to \pi^- \pi^- \pi^+$	ALL
	Background	2.8 ± 0.3	0.12 ± 0.02	0.19 ± 0.04	0.12 ± 0.04	3.2 ± 0.3
SIGNAL	$\Delta m^2 = 0.0025 eV^2$	12.0	0.7	0.8	0.3	13.8
SIGNAL	$\Delta m^2 = 0.0035 eV^2$	23.3	1.4	1.6	0.6	26.9
SIGNAL	$\Delta m^2 = 0.005 eV^2$	46.6	2.8	3.1	1.2	53.7
SIGNAL	$\Delta m^2 = 0.01 eV^2$	166	10	11	4.0	191



TOTAL ACTIVE MASS = 11298 Ton

LAYOUT IN THE LNGS HALL B

KAMLAND

Long baseline reactor experiment sensitive to $\Delta m^2 \lesssim 10^{-5}\ eV^2$

~1000 ton scintillator detector in deep underground site (2700 m w.e.) (the site of the KAMIOKANDE experiment)

Expected background : 0.3 events/day

Neutrino Flux from different reactors for no oscillations

Reactor Site	Thermal Power (GW)	Distance (km)	Rate (Events/year)
Kashiwazaki	24.5	160	273
Ohi	13.7	190	91
Takahama	10.2	210	60
Hamaoka	10.6	210	64
Tsuruga	4.5	150	52
Total	127.0		700

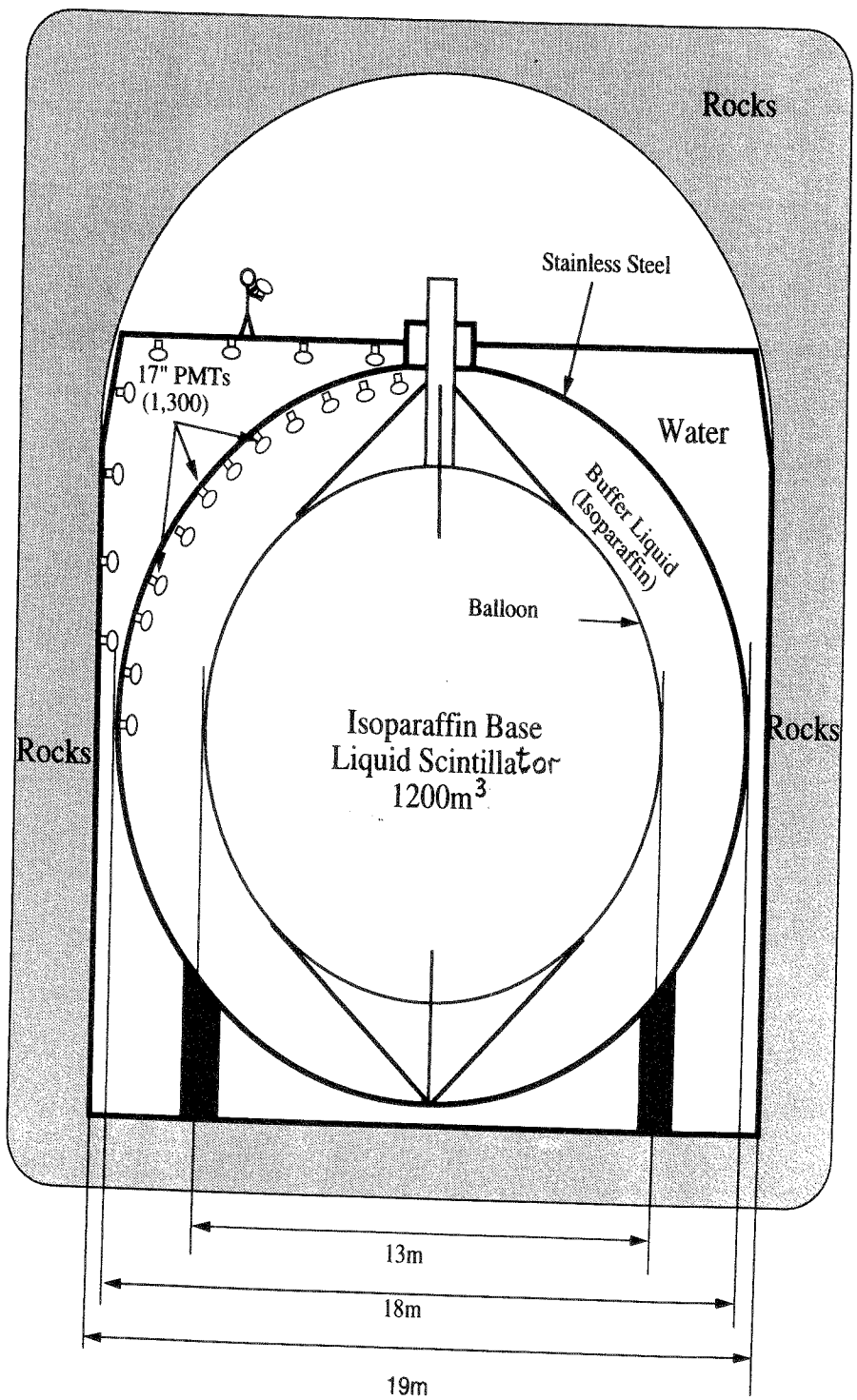
Baseline L ~ 160 Km

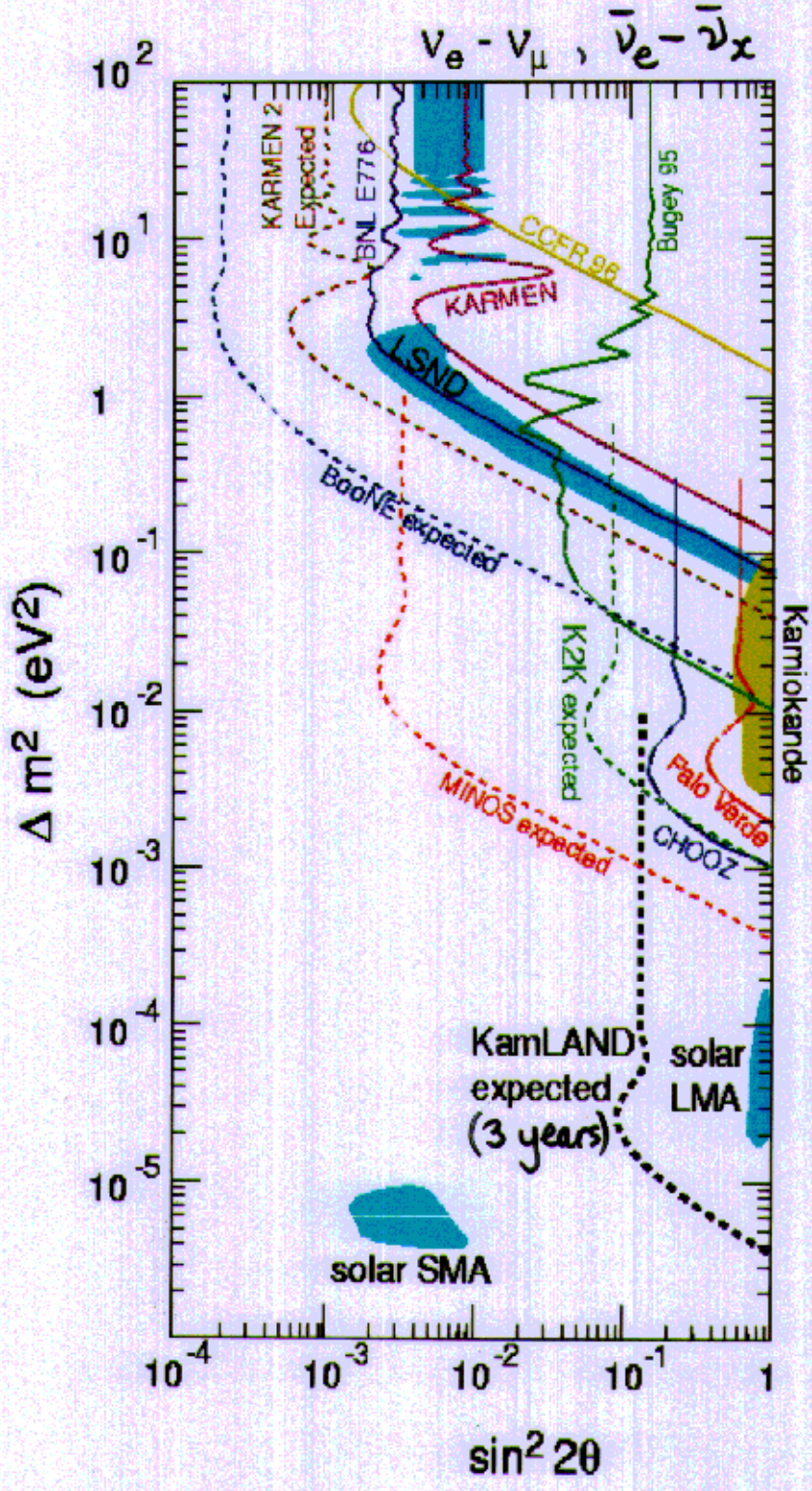
Expected $\bar{\nu}_e + p \rightarrow e^+ + n$ event rate ~2/day

$S/B \approx 7$

START DATA TAKING ~ 2001

KamLAND Detector



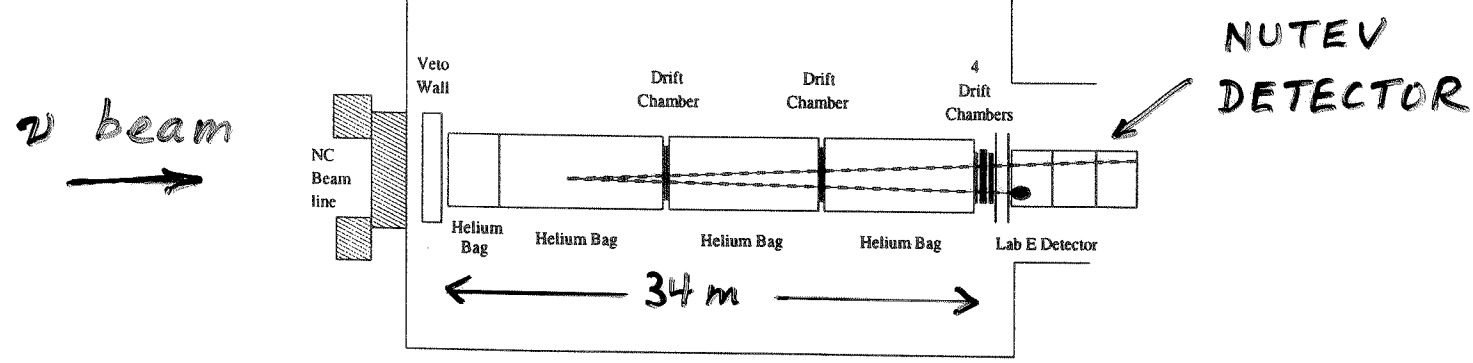

$\nu_e - \nu_\mu$, $\bar{\nu}_e - \bar{\nu}_x$
Δm^2 (eV^2)
$\sin^2 2\theta$
KARMEN 2
Expected
BNL E776
CCFR 96
Bugey 95
KARMEN
LSND
BooNE expected
K2K expected
MINOS expected
Kamiokande
Palo Verde
CHOOZ
KamLAND
expected
(3 years)
solar
LMA
solar SMA

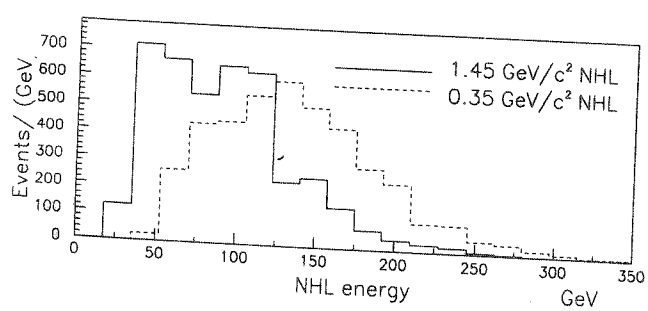
NUTEV : Search for a hypothetical Neutral Heavy Lepton (L_μ) mixing with ν_μ

- Mixing parameter $|U|^2$

- Production mechanism:
  Meson (K^+, D) $\rightarrow \mu L_\mu$
- L_μ decays: $L_\mu \rightarrow \mu^- \mu^+ \nu_\mu$, $\mu^- e^+ \nu_e$, $\mu^- \pi^+$, $\mu^- \rho^+$
- Detection method: search for two-track events originating in decay region in front of NUTEV detector - one track must be μ^-
- Helium bags in decay region reduce ν interaction rate by factor ~7

L_μ DECAY REGION

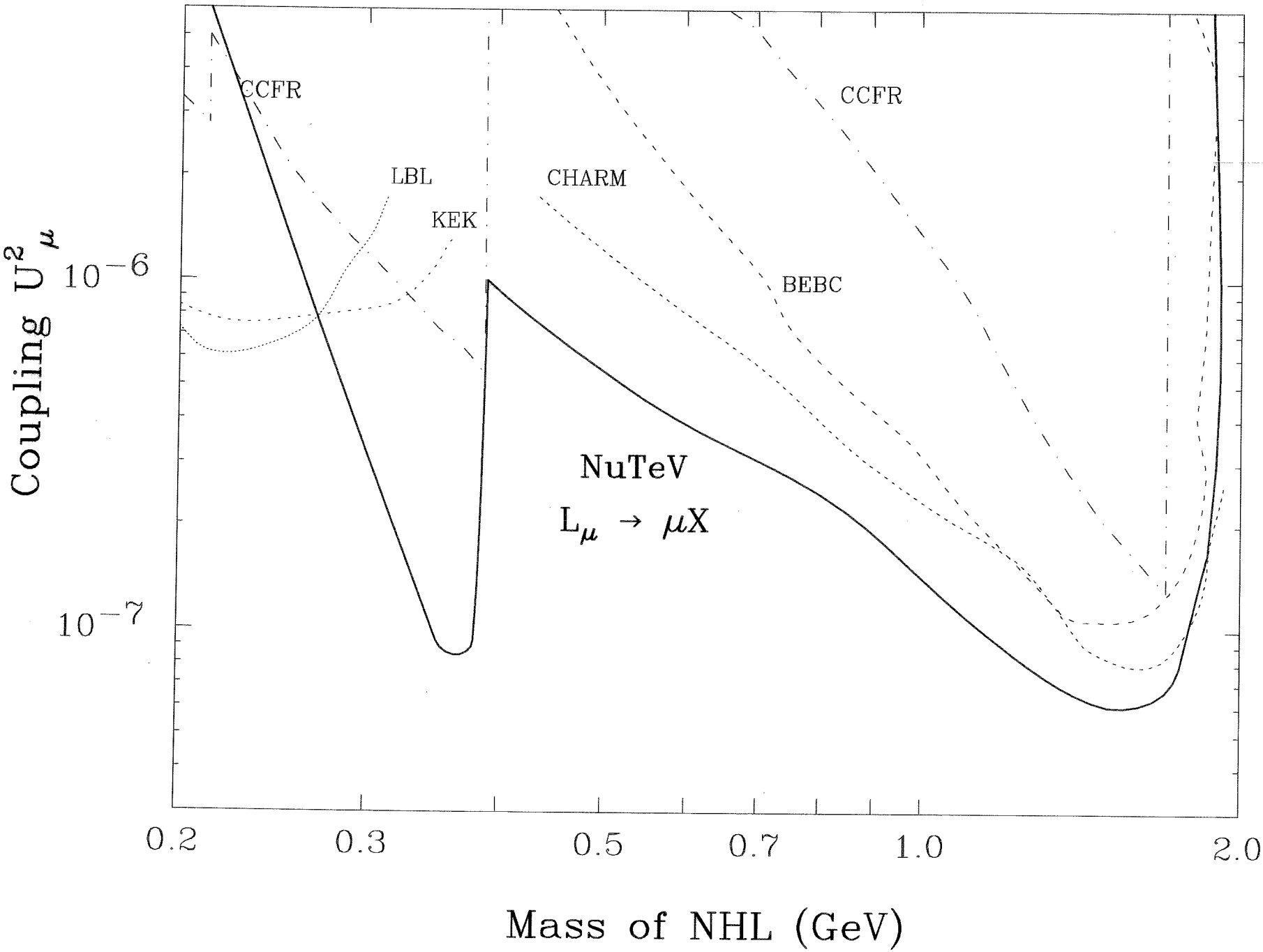




Expected L_μ energy spectra

- NC EVENT CONSISTENT WITH L_μ DECAY SEEN
- EXPECTED BACKGROUND 0.58 ± 0.15 EVENTS (mostly ν_μ CC interactions in decay region)

NUTEV 90% C.L. LIMIT ON $|U|^2$ VS L_μ MASS



CONCLUSIONS

NEUTRINO EXPERIMENTS AT REACTORS AND ACCELERATORS HAVE PROVIDED A WEALTH OF PHYSICS RESULTS IN THE PAST AND WILL CONTINUE TO DO SO IN THE FUTURE

OVER THE NEXT TEN YEARS THEY WILL FOCUS ON OSCILLATION STUDIES. WE EXPECT THAT THEY WILL

- CONFIRM THAT THE ATMOSPHERIC NEUTRINO RESULTS ARE DUE TO OSCILLATIONS
- PROVIDE MORE PRECISE MEASUREMENTS OF THE OSCILLATION PARAMETERS
- PROVIDE CONCLUSIVE EVIDENCE IN FAVOUR/AGAINST A FOURTH, STERILE NEUTRINO
- VERIFY THE LARGE MIXING ANGLE MSW SOLUTION TO THE SOLAR NEUTRINO PROBLEM