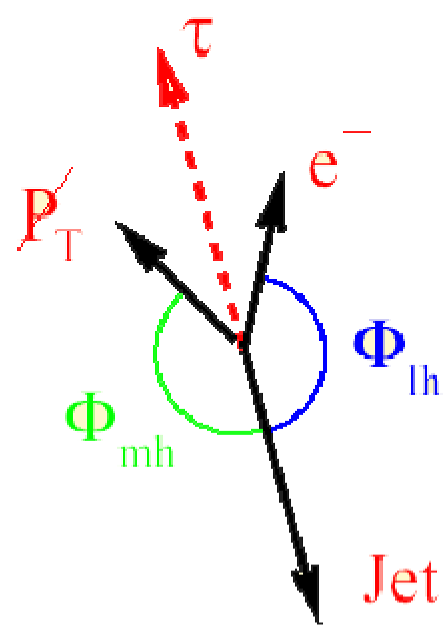
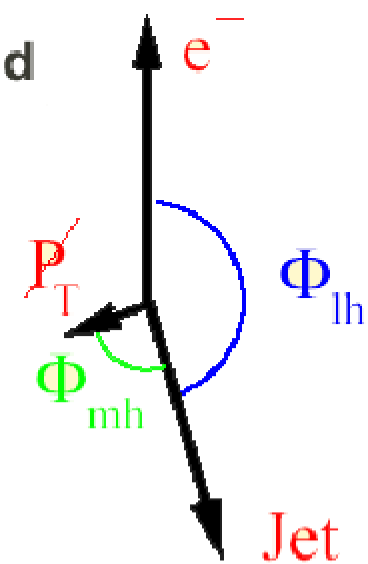
NOMAD:
τ Detection by Kinematics

- Detection of the $\tau \rightarrow e\,\bar{\nu}\nu$ mode:

Signal
ν_τ CC

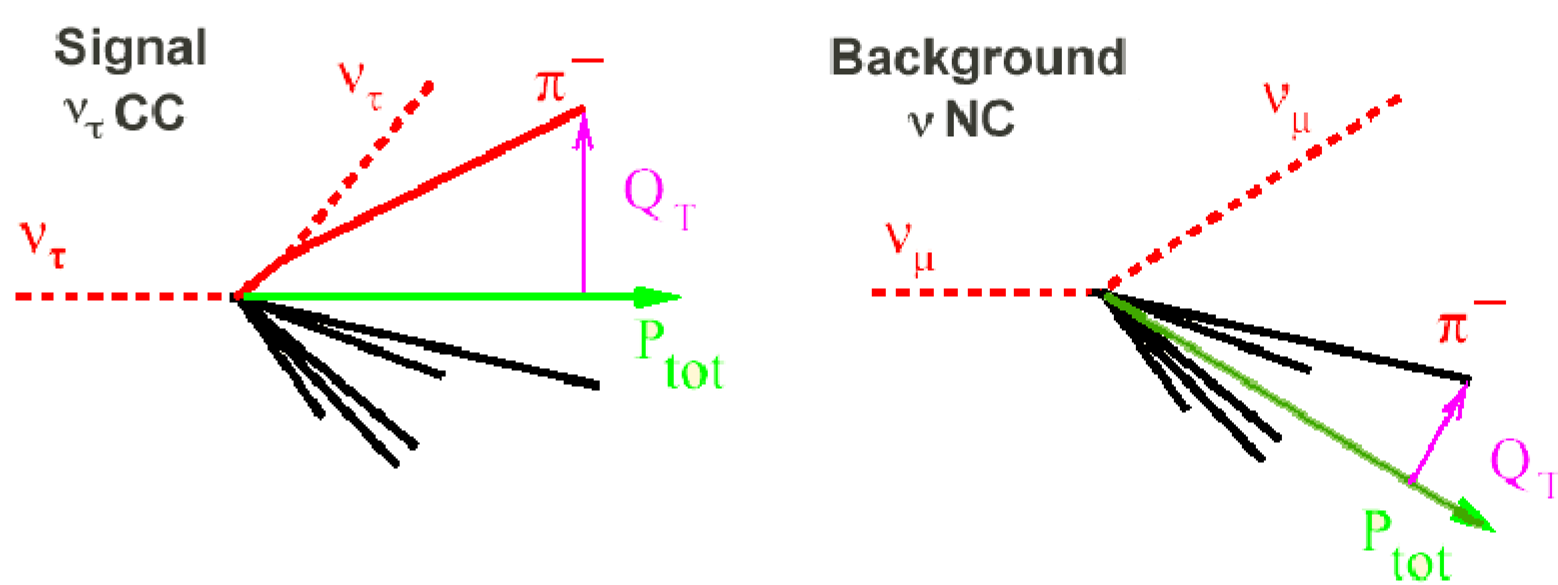


Background
ν_e CC



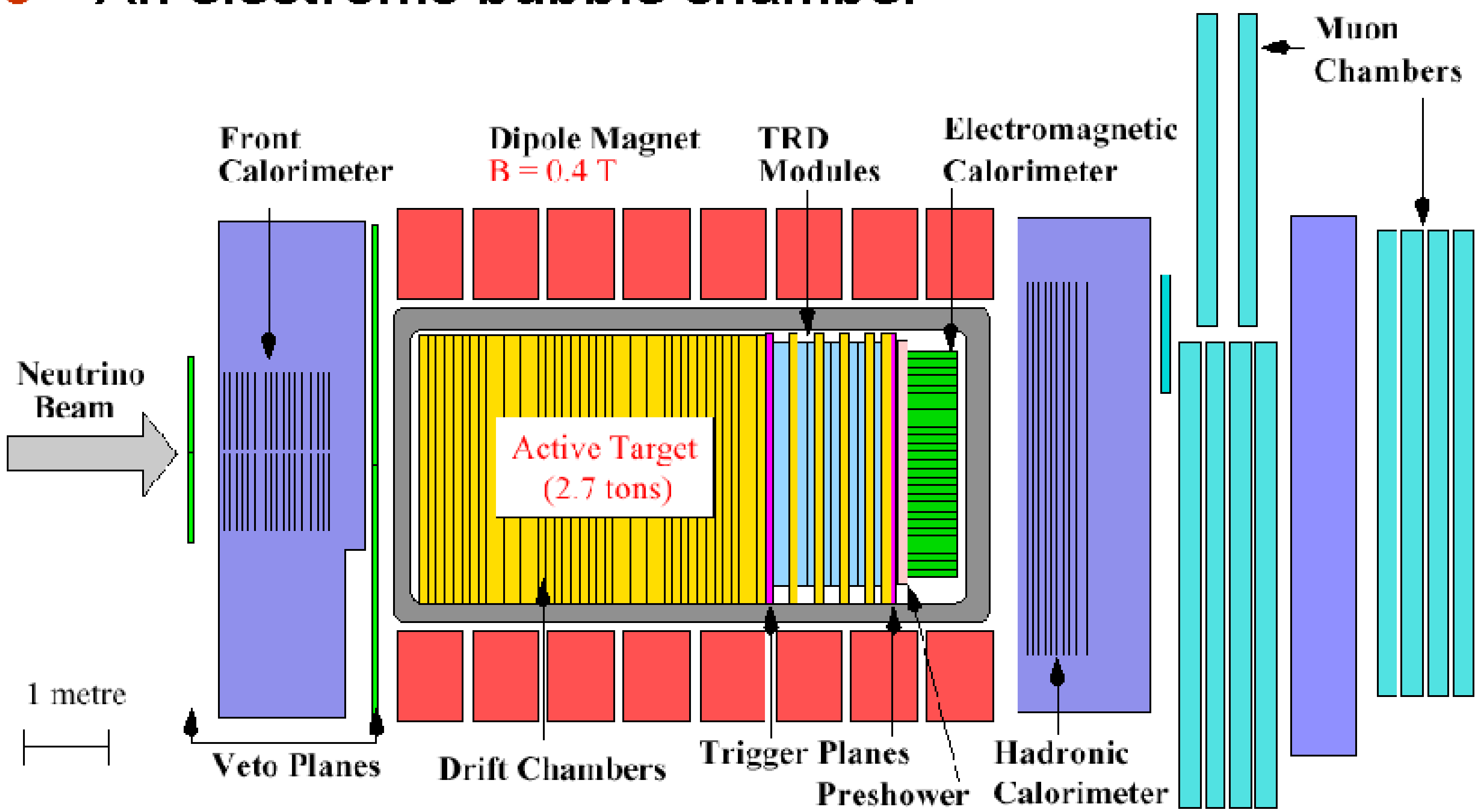
NOMAD: τ Detection by Kinematics

- Detection of the $\tau \to h\, \nu + n\, (\pi^0)$ modes:



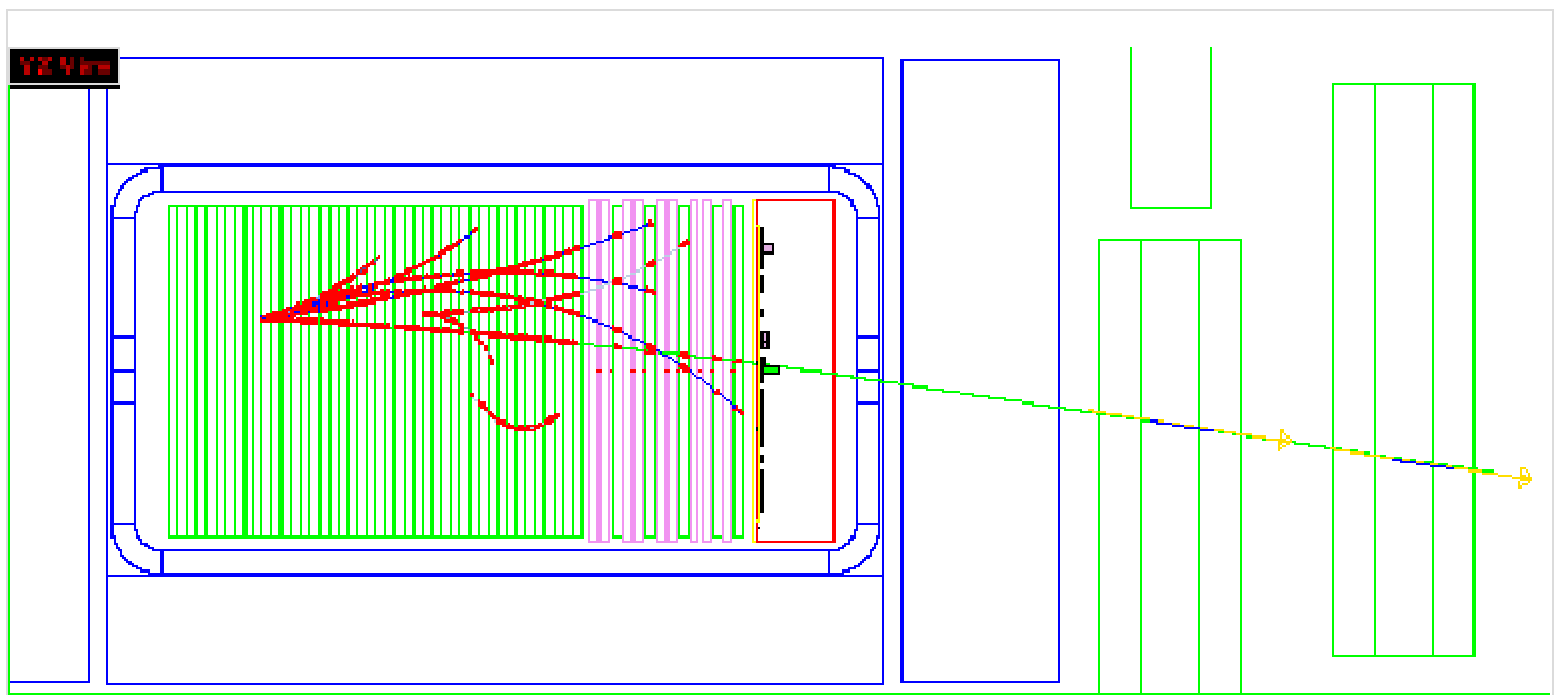
NOMAD: Detector

- "An electronic bubble chamber"



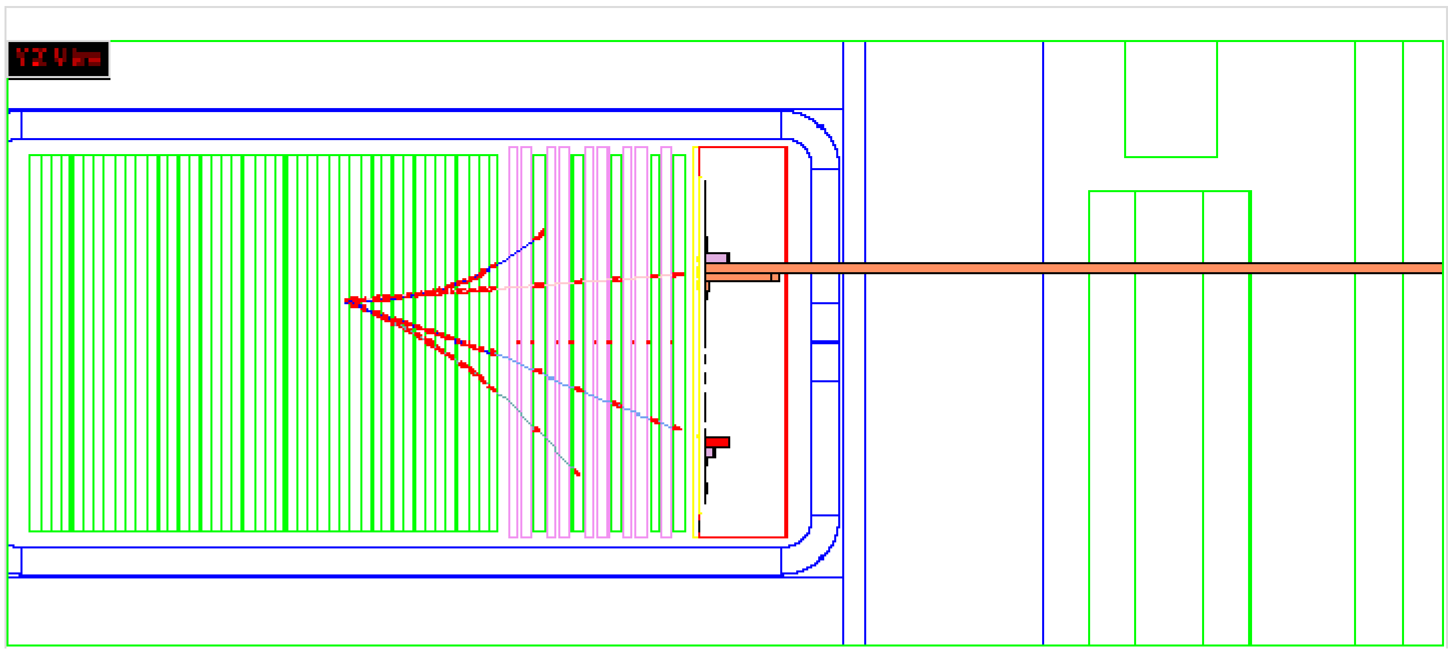
NOMAD: ν_μ CC Event

run 9771, event 2227: $\nu_\mu \; CC$



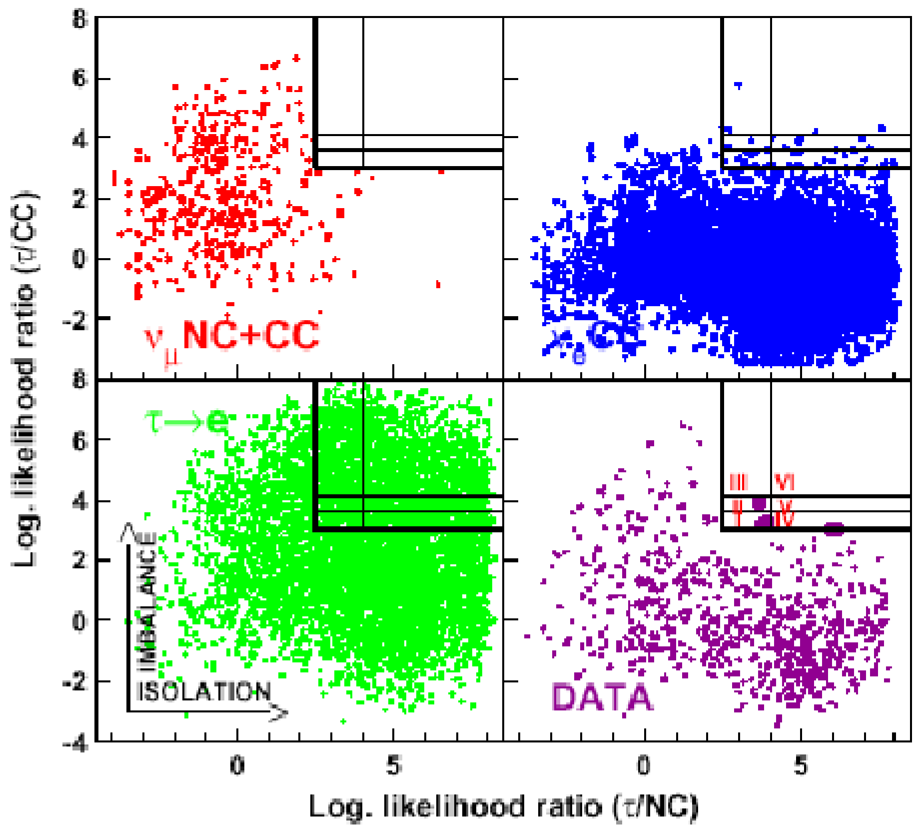
NOMAD: ν_e CC Event

run 8754, event 396: $\overline{\nu}_e\ CC$



NOMAD: Analysis

- **Extensive use of likelihood functions**

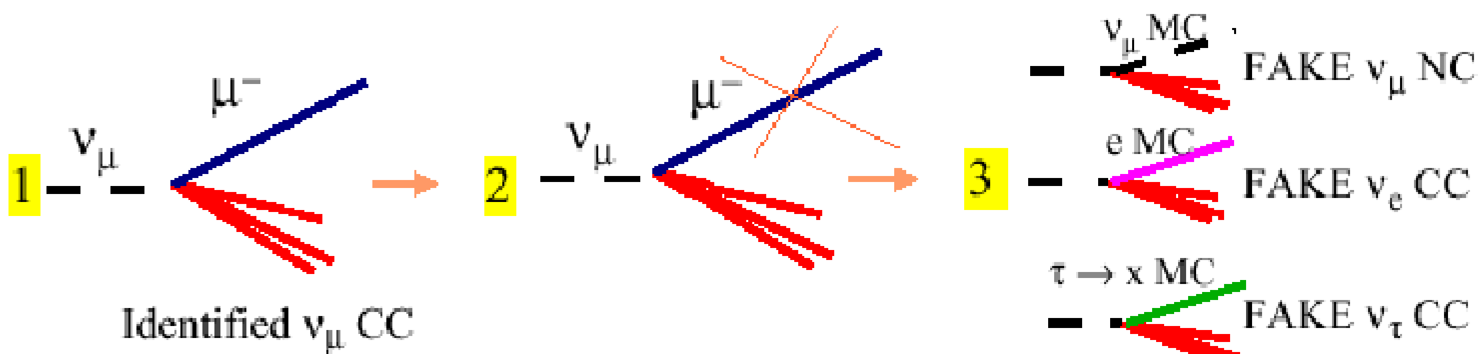


Example from the $\tau \rightarrow e\ \bar{\nu}\nu$ analysis

5+ independent kinematic variables. Using likelihood functions yields optimum signal to background ratios.

NOMAD: Analysis

- Data simulators
  - The Monte Carlo simulations did not simulate either the details of the reconstruction or the physics precisely.
  - Therefore, whenever possible, we used data simulators: The muon from observed ν_μ CC events was eliminated and replaced by a simulated particle to form a fake NC event , ν_e CC event, or ν_τ CC event.



NOMAD: Analysis

- Data simulators (continued)
  - The data simulator is itself simulated by a Monte Carlo to produce a "Monte Carlo simulator" (MCS).
  - Efficiencies and backgrounds are then calculated from the following formula:

$$\varepsilon = \frac{\varepsilon_{MC}\,\varepsilon_{DS}}{\varepsilon_{MCS}}$$

  - To first order, all the deficiencies of both the data simulator and the Monte Carlo cancel in this ratio.
  - No data simulator was possible for the $\tau \to \mu\nu\bar{\nu}$ mode, so it was not used to avoid uncontrolled systematic errors.

NOMAD: Analysis

- Elimination of self-reference bias
  - An independent set of data or simulations must be used to set cuts and form likelihood functions from those used to evaluate efficiencies and backgrounds.
  - This can be done in such a way that statistics are not lost.
  - The bias from not eliminating self-reference can be easily evaluated.

NOMAD: Analysis

- Blind analyses
  - Early results with non-blind analyses indicated biases, so blind analyses were instituted:
  - A “signal box” was defined near the start of the analysis and it was not permitted to examine data in the box.
  - Analyses had to come to their final form and show consistency with data outside the box and “wrong sign” data within the box before permission to open the box was given.
  - Everyone in NOMAD became convinced that this was the only way to do reliable analysis. Most collaborations now use blind analyses for sensitive results.


Science Times

The New York Times

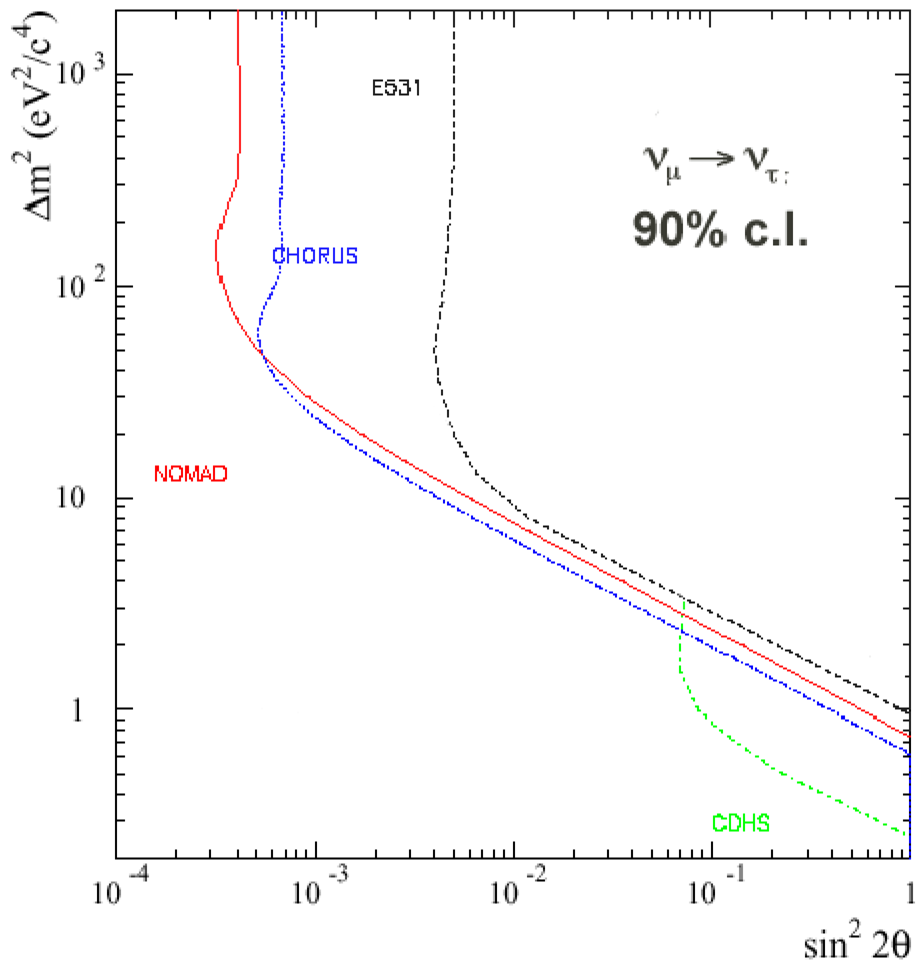
New Tactic in Physics: Hiding the Answer

Theorists fool themselves to thwart errors of enthusiasm

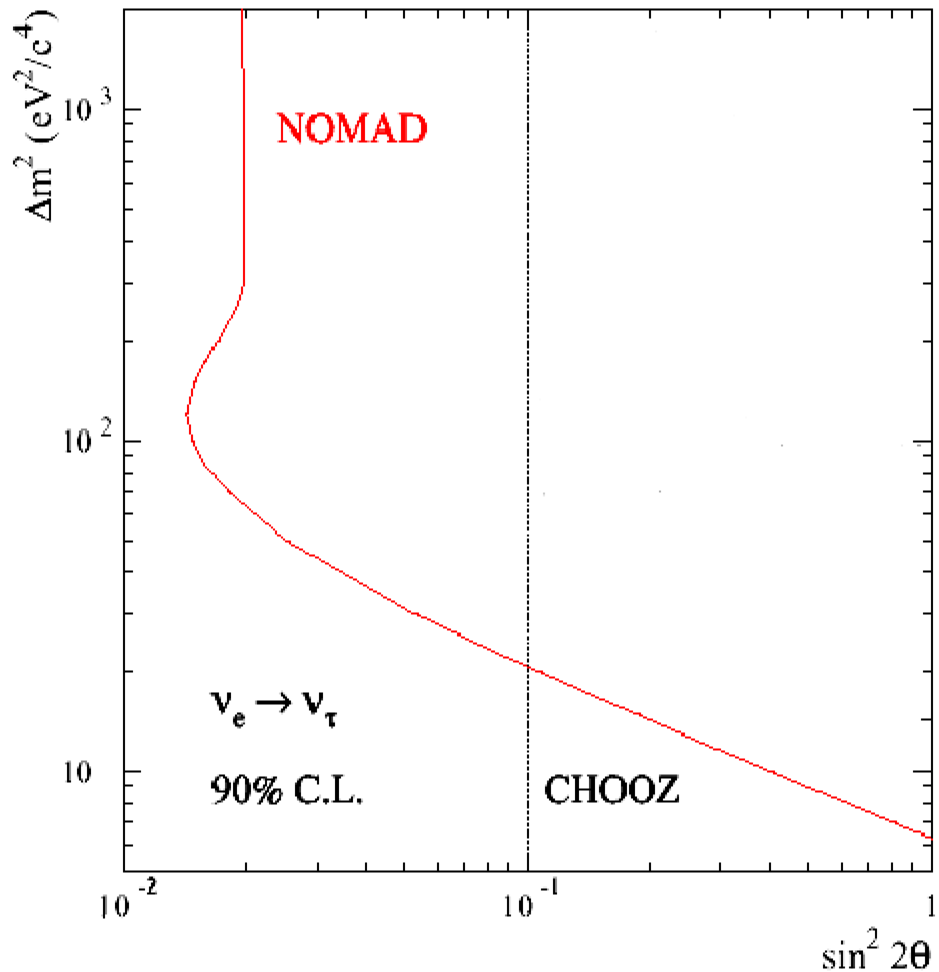
NOMAD: Results

- The analysis was done by combining 31 modes and bins.
- If every ν_μ had oscillated to a ν_τ, we would have observed 14,900 signal events ($+N_\tau$).
- We actually saw 58 signal events with 55 ± 5 events expected from backgrounds.
- However, 75% of the sensitivity came from low background bins: N_τ = 7,600; 1 signal event observed with $1.3_{-0.2}$ [illegible] events expected from backgrounds.
- At 90% c.l., $\sin^2(2\theta) < 4.1\ 10^{-4}$ (sensitivity $< 5.2\ 10^{-4}$).

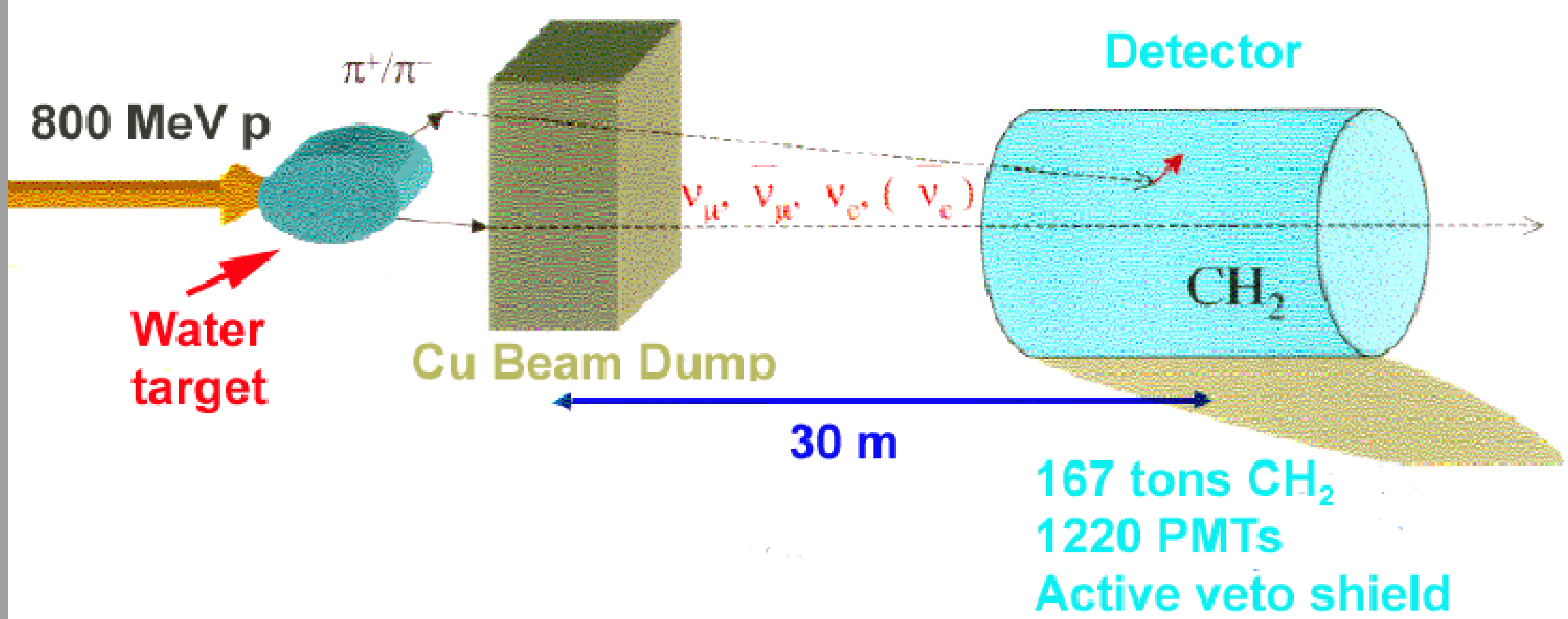
NOMAD: $\nu_\mu \to \nu_\tau$ Exclusion Plot



NOMAD: $\nu_e \to \nu_\tau$ Exclusion Plot

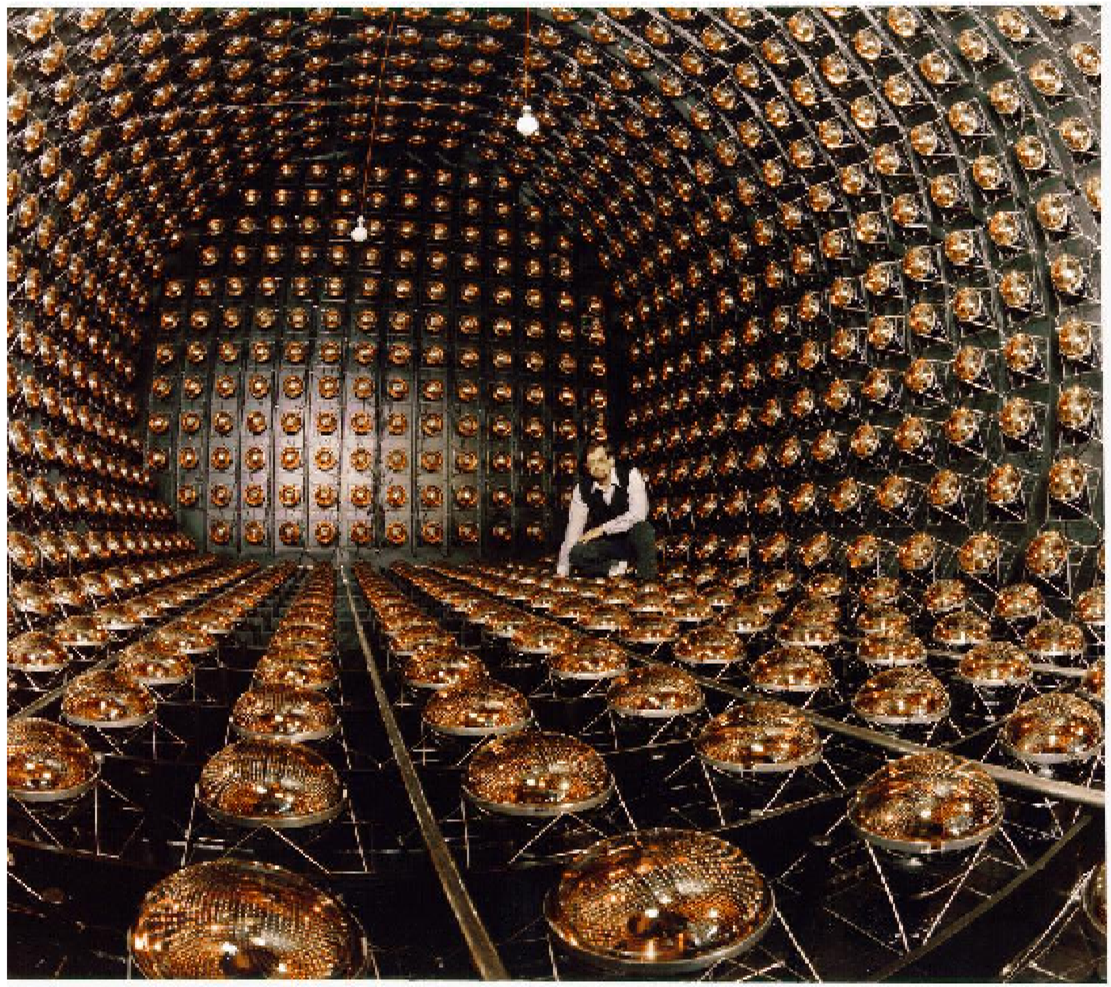


LSND Beam



800 MeV p
π^+/π^-
Water target
Cu Beam Dump
ν_μ, $\bar{\nu}_\mu$, ν_e, ($\bar{\nu}_e$)
Detector
CH_2
30 m
167 tons CH_2
1220 PMTs
Active veto shield

LSND Detector

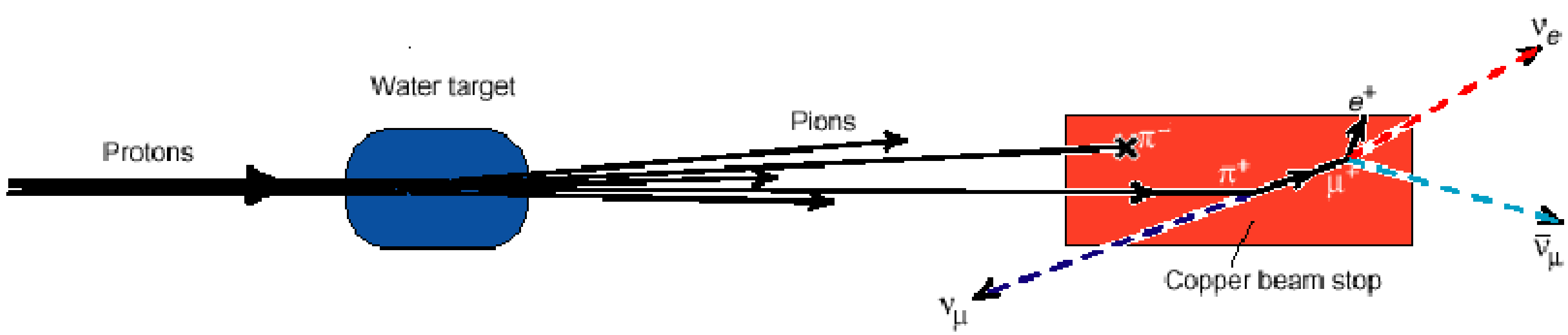


LSND Technique

- π+ produced in the target come to rest in the beam dump and decay to muons, which also decay:

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

- This produces ν_μ, $\bar{\nu}_\mu$, ν_e, but not $\bar{\nu}_e$. Thus, one can look for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations.



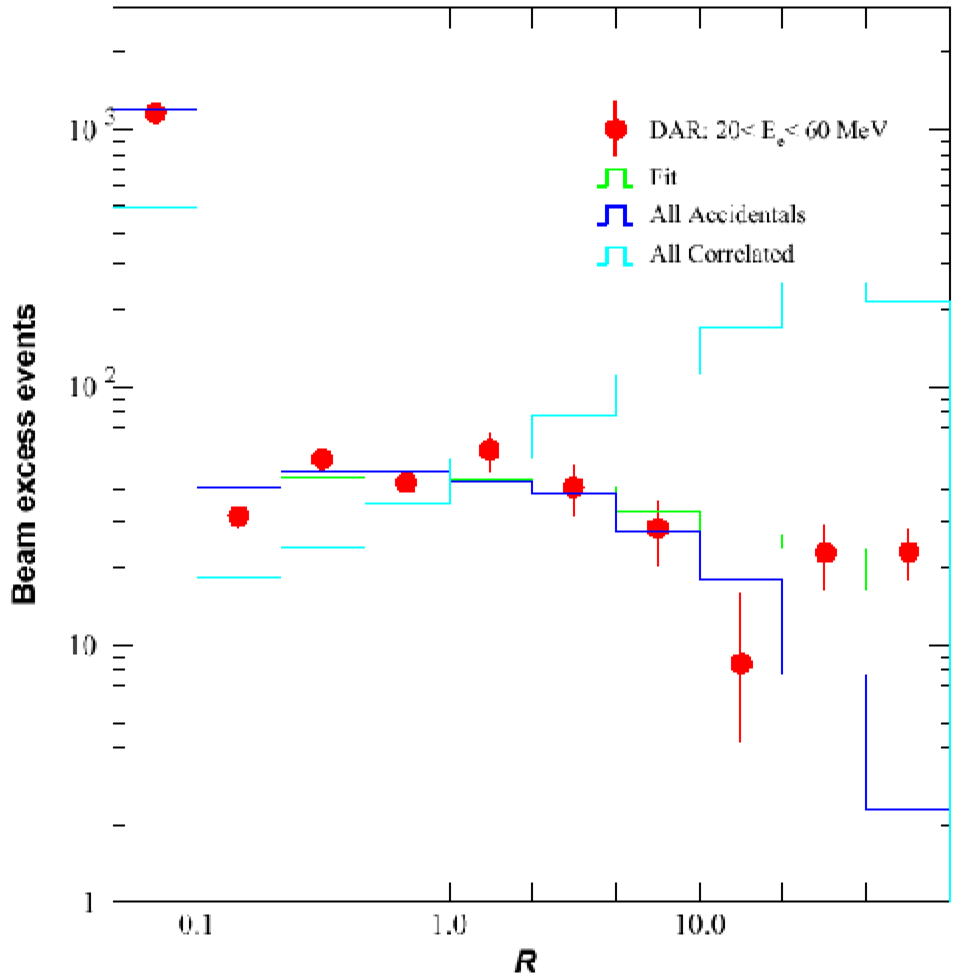
LSND Technique

- But what about the π^-s? Don't they produce $\bar{\nu}_e$s ?
- Yes, but they are highly suppressed:
  - 8 times more π^+ produced than π^-.
  - Only 5% of π^- decay (in flight). The rest are captured by the strong interactions and do not produce neutrinos.
  - 88% of m- get captured from atomic orbits producing a nm, but not a $\bar{\nu}_e$.
- Thus the total suppression is (0.125)(0.05)(0.12) = 7.5 10^{-4}.

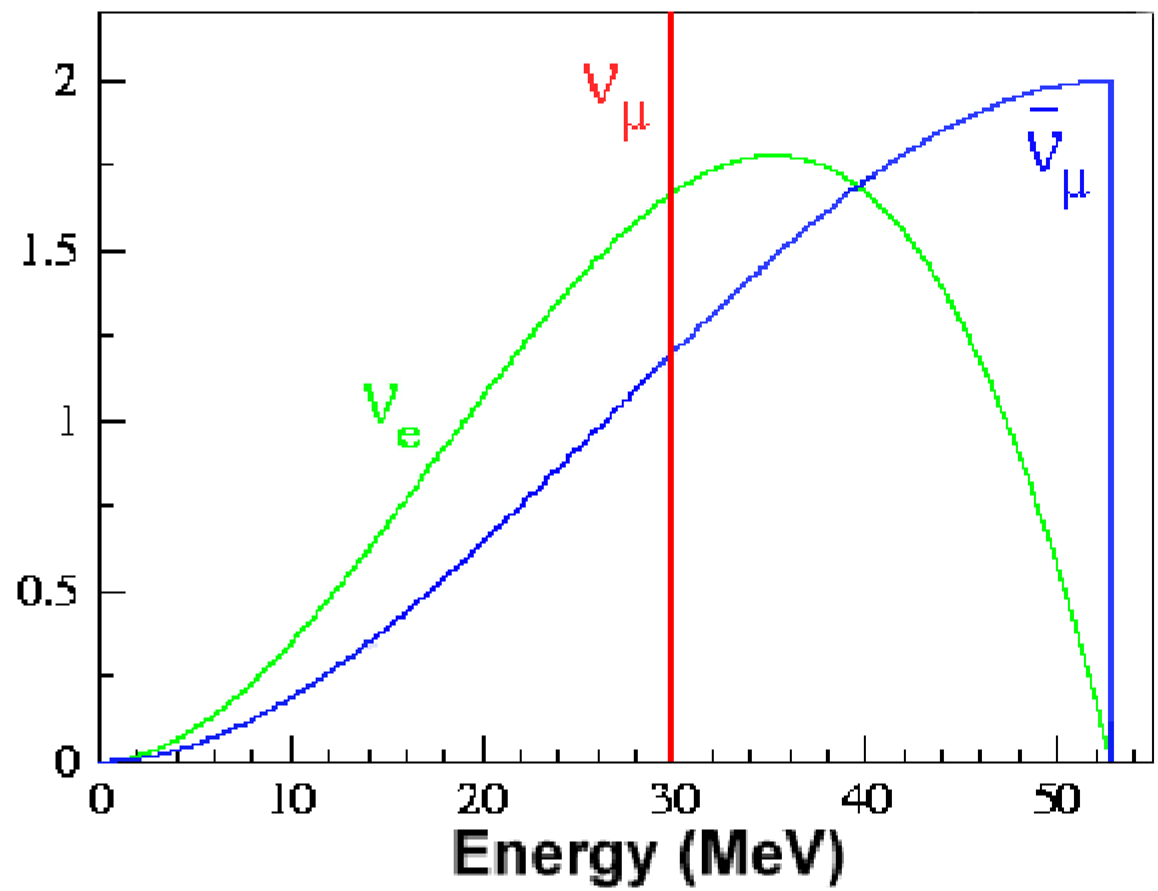
LSND Technique

- But how does one detect a few $\bar{\nu}_e$s in an intense beam of ν_es?
- The technique relies on the fact that only $\bar{\nu}_e$s can interact with protons to produce both a neutron and an electron with energy > 20 MeV.
- The signal is a coincidence between an electron (positron) with E > 20 MeV followed by a photon from the neutron capture reaction $n + p \rightarrow d + \gamma$.
- Define a likelihood ratio R which measures the coincidence of the γ to the e^+ in position and time.

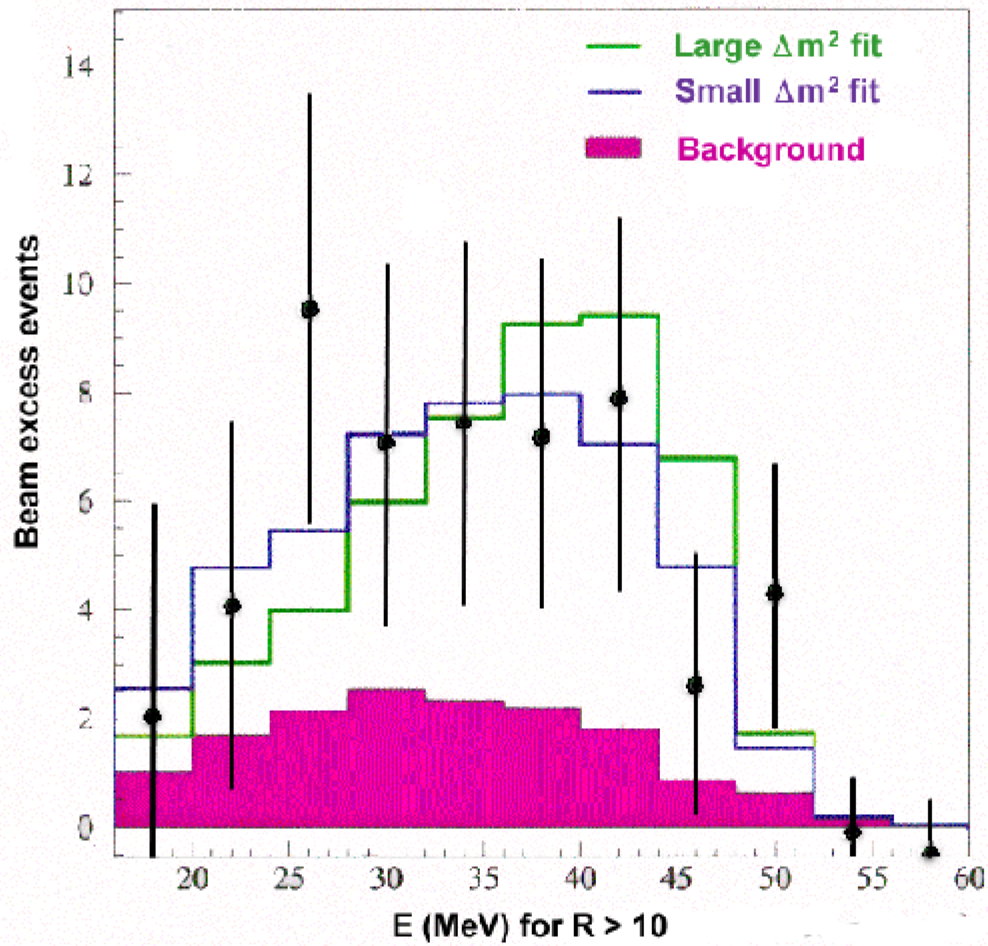
LSND: *R* Distribution



Neutrino Energy Spectrum



LSND *E* Distribution



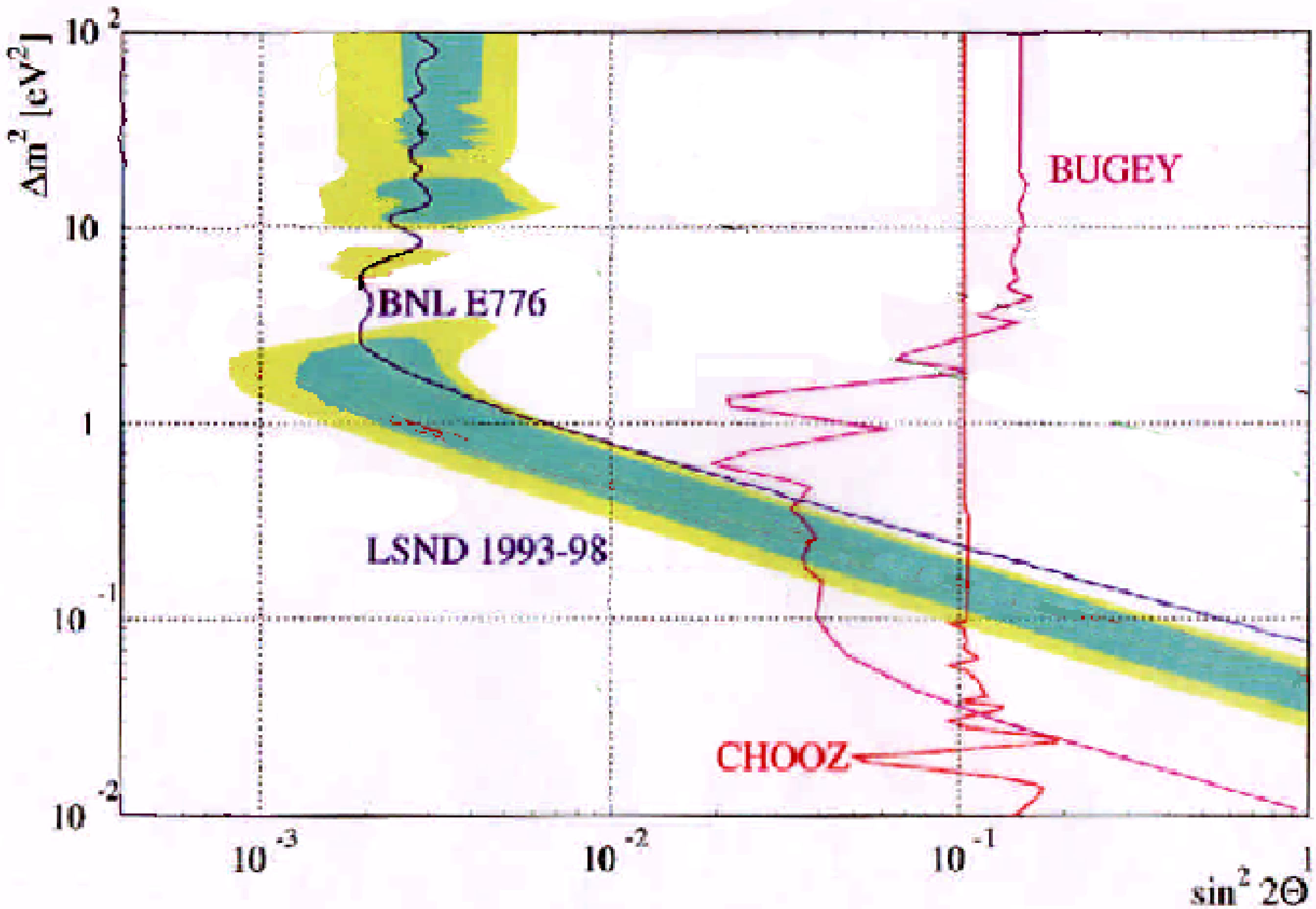
83 events total

-33.7 beam off

-16.6 beam on

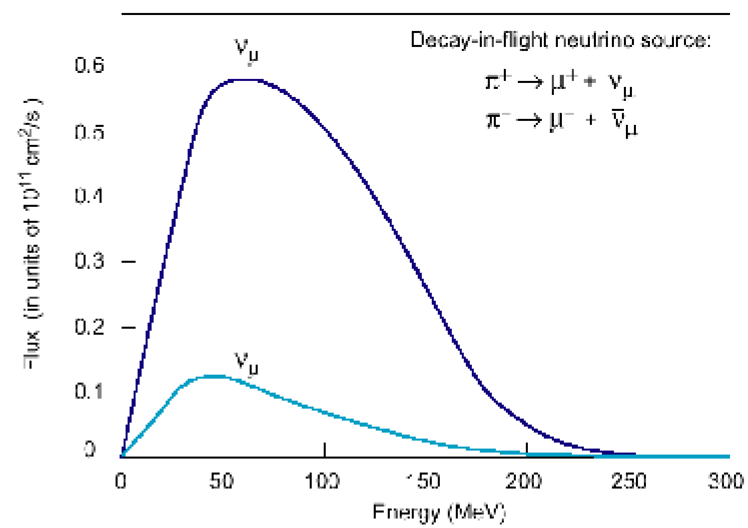
= 32.7 ± 9.2 signal

LSND Allowed Region

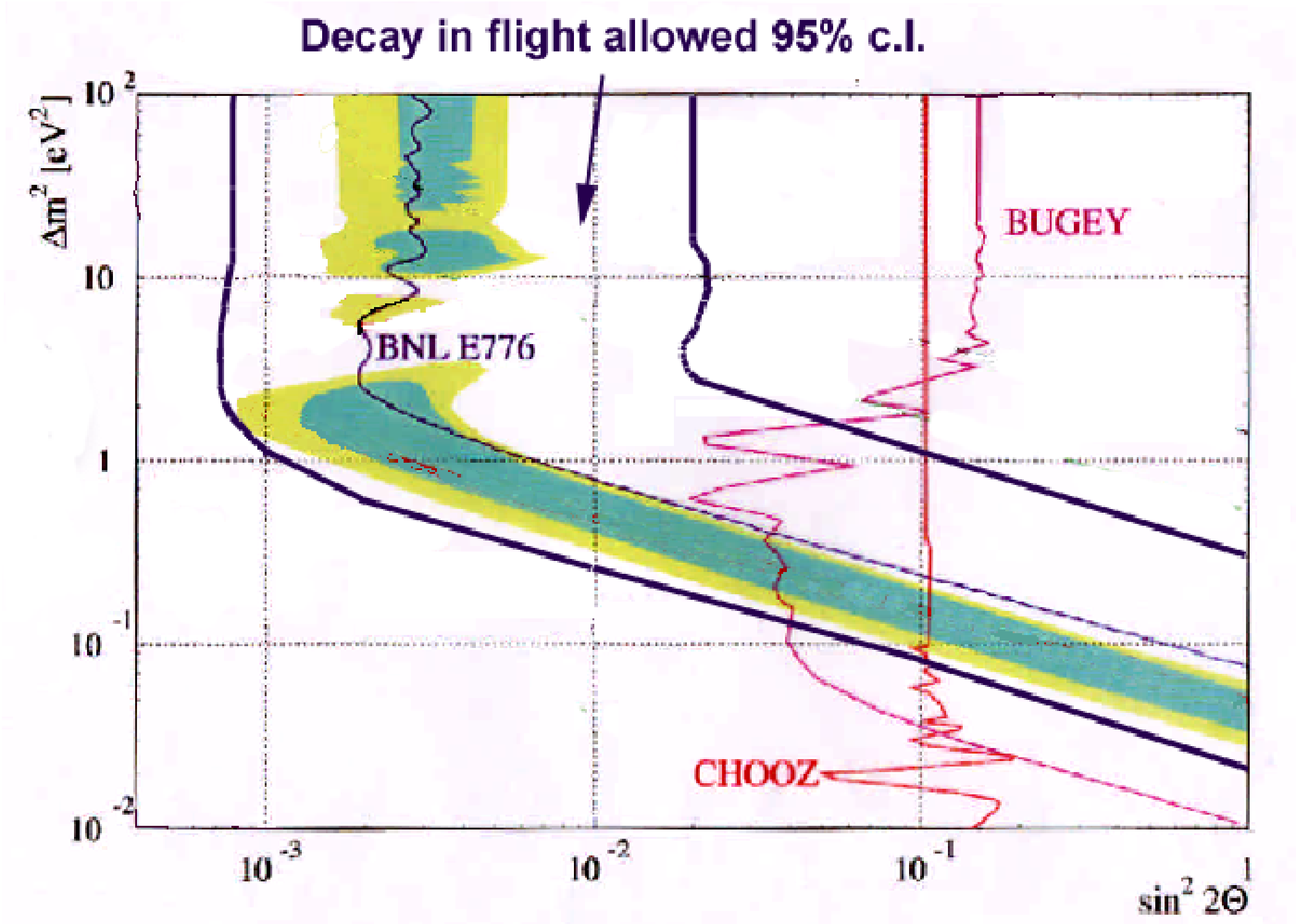


LSND Decay in Flight Analysis

- 3.4% of π^+ decay in flight between the target and the beam dump, yielding high-energy ν_μs.
- Signal is a single electron with 60 < E < 200 MeV.
- 40 events observed with 21.9 background expected ⇒ 18.1 excess events.

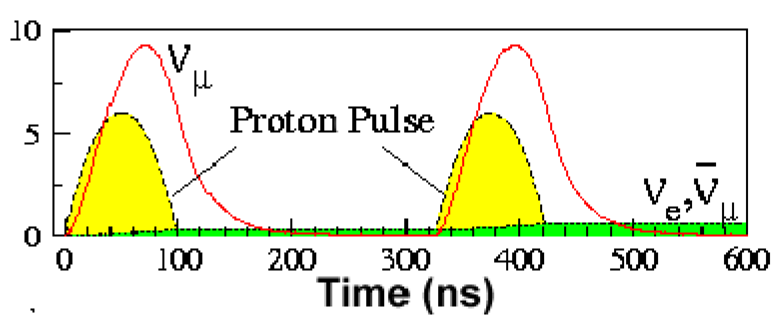


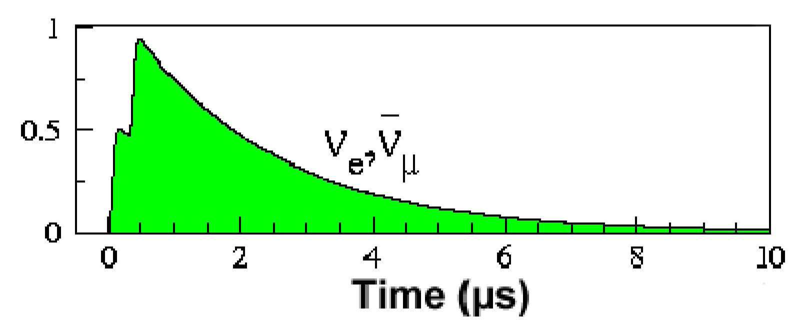
LSND DIF Allowed Region



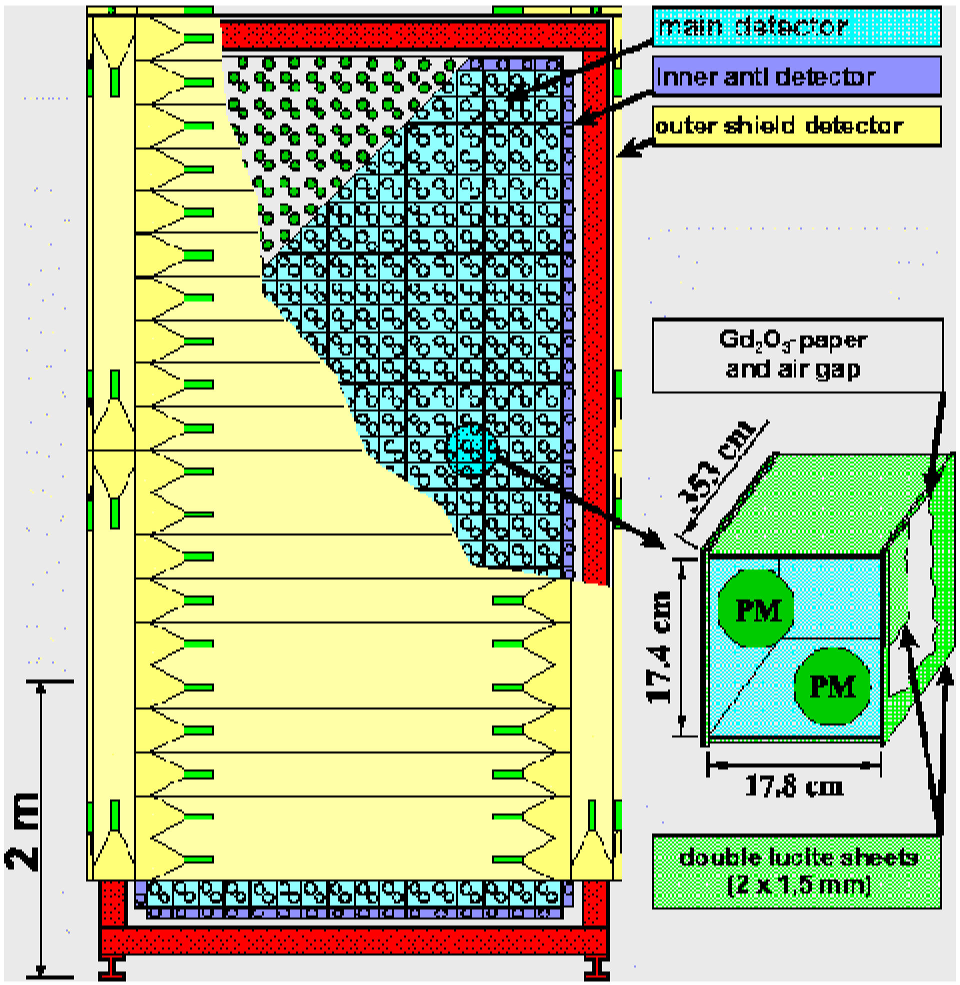
KARMEN Experiment

- The KARMEN experiment, located at the ISIS neutron spallation source at the Rutherford laboratory, is similar to LSND, except that the detector is only 18 m from the beam stop and the beam is pulsed at 50 Hz:



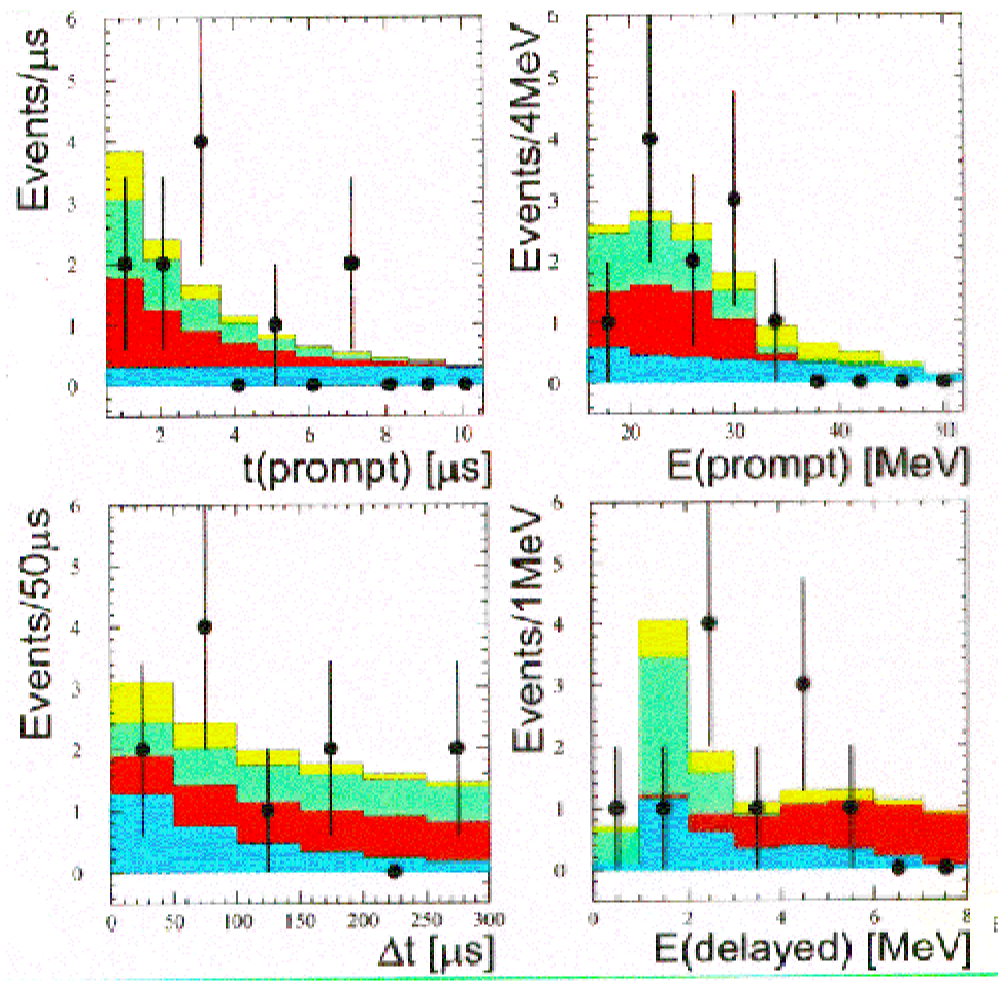


KARMEN Detector



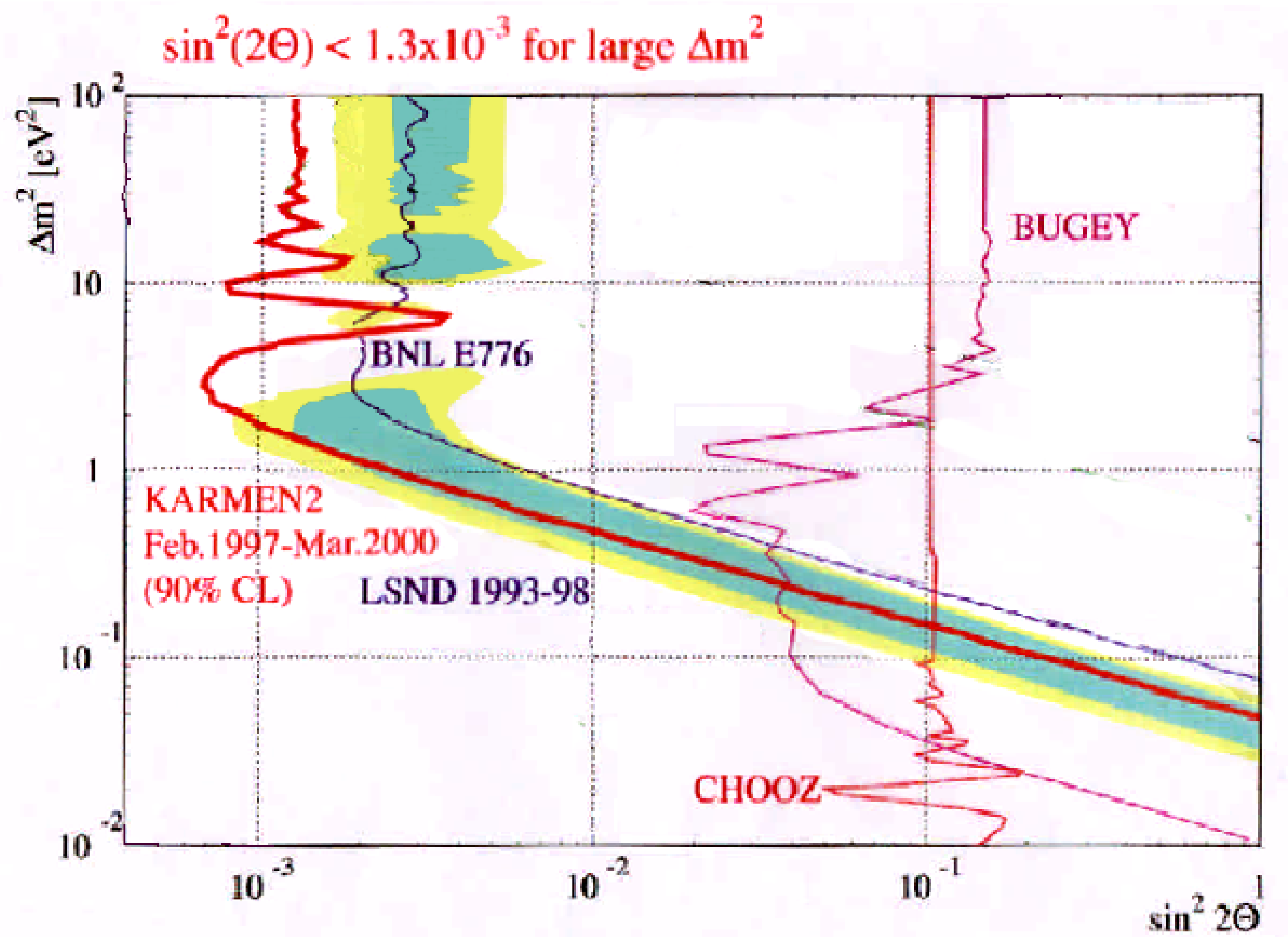
512 modules of liquid scintillator with Gd_2O_3 for neutron capture

KARMEN Event Distributions

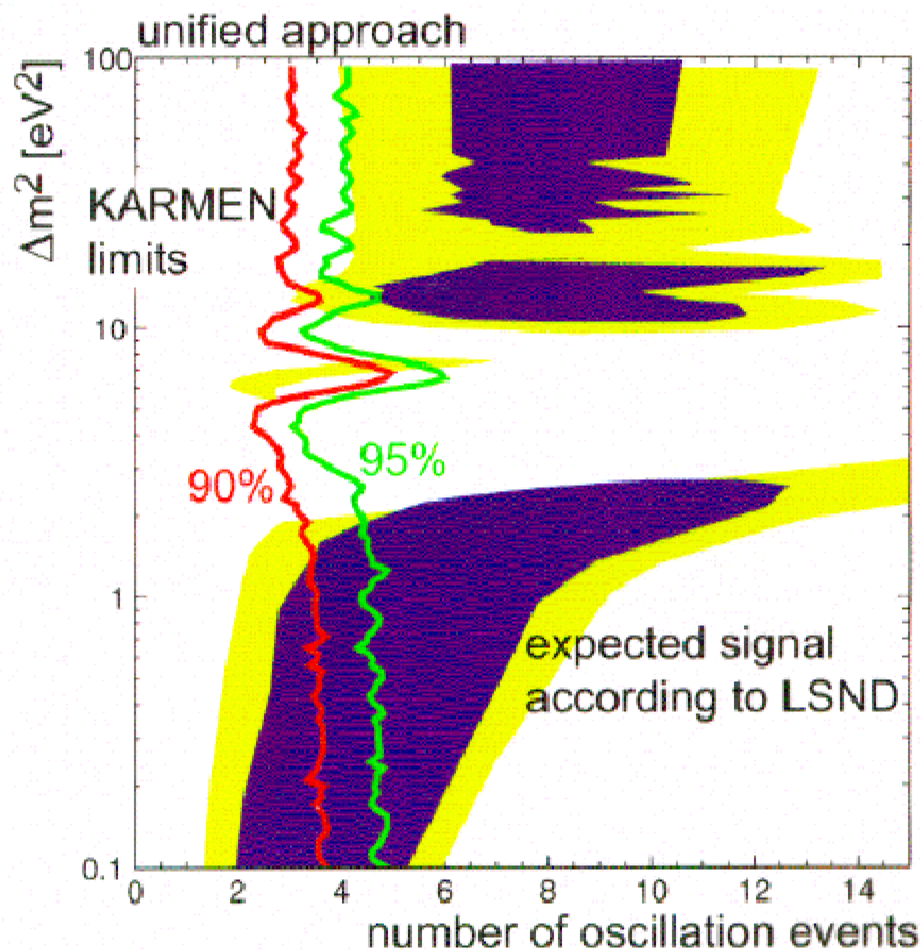


11 events observed for 12.3 ± 0.6 background events expected

KARMEN Exclusion Plot



KARMEN Exclusion Plot



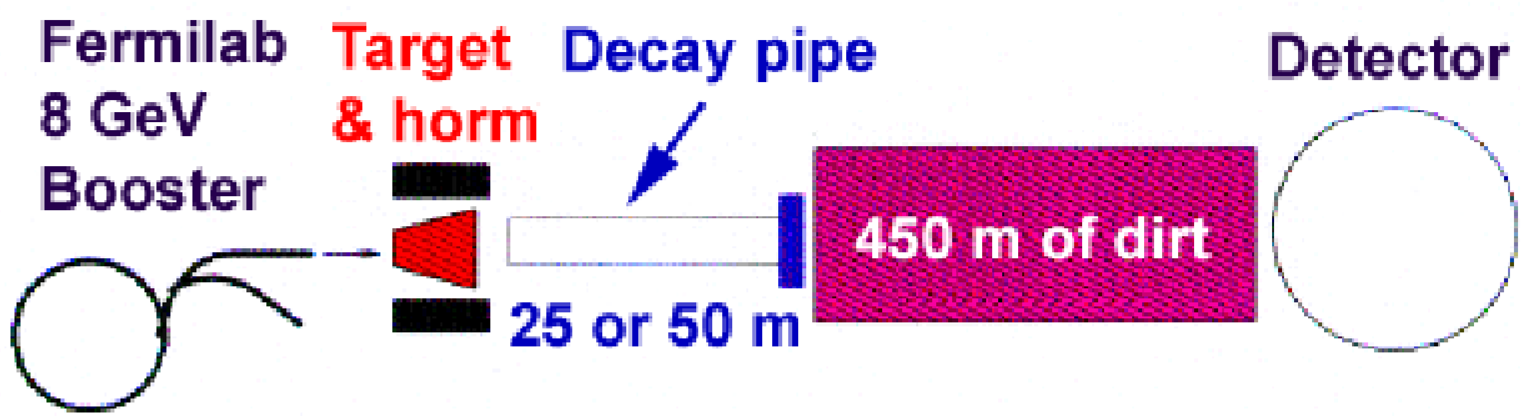
Exclusion based on a maximum likelihood fit

1993-95 LSND signal region completely excluded by KARMEN

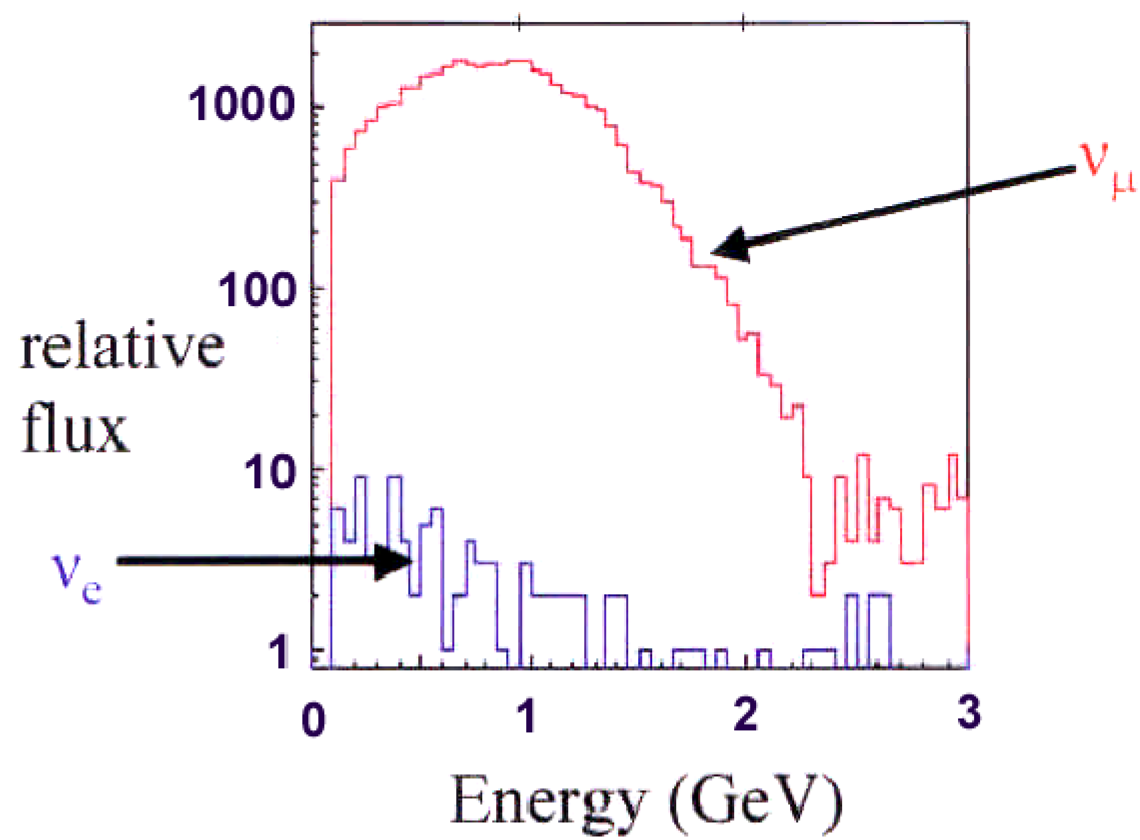
KARMEN will run 1 more year

MiniBooNE Layout

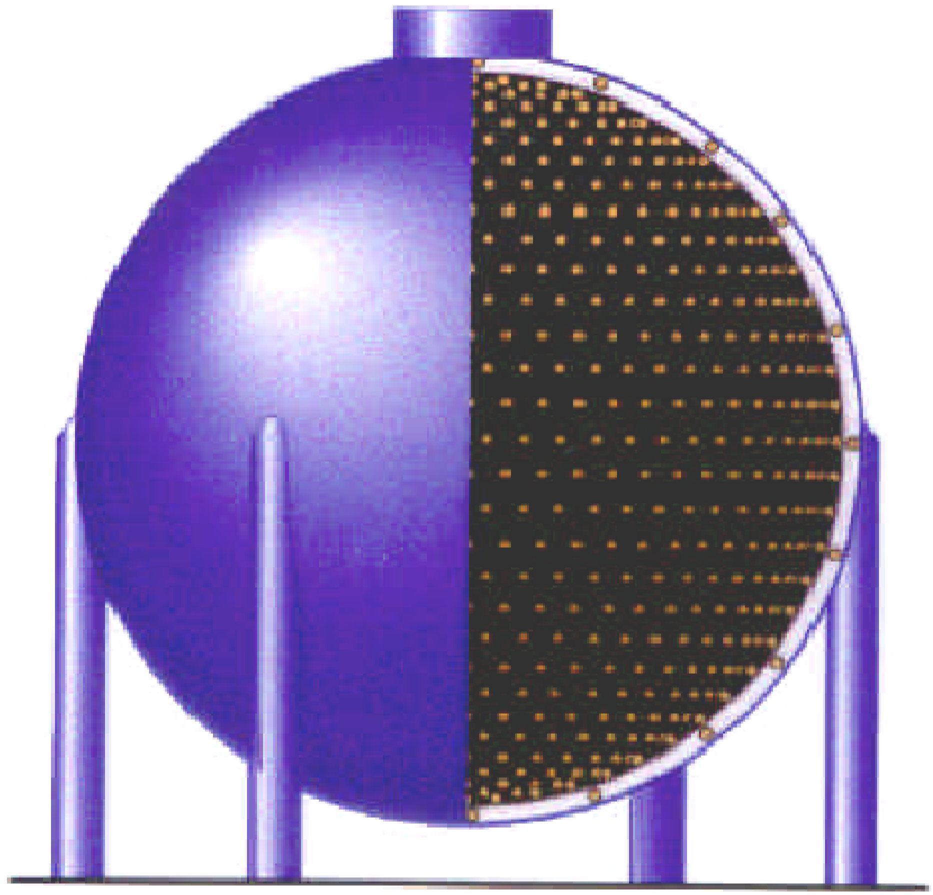
- Experiment to check LSND result by detecting $\nu_\mu \varnothing \nu_e$ oscillations.
- Technique and backgrounds different from LSND.



MiniBooNE Energy Spectrum



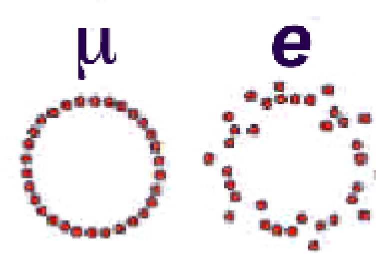
MiniBooNE Detector



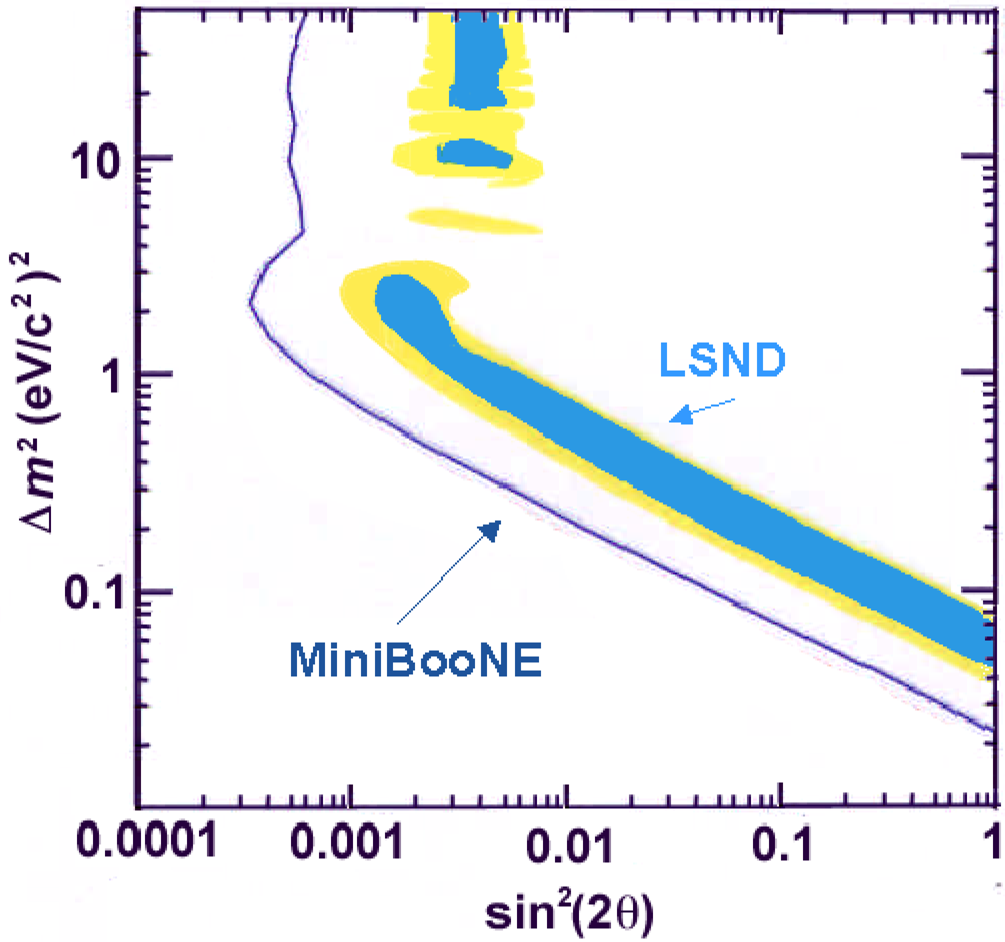
800 T mineral oil
445 T fiducial

1280 PMTs signal
240 PMTs veto

Detect Cerenkov rings



MiniBooNE Sensitivity



MiniBooNE calculated sensitivity after 1 year

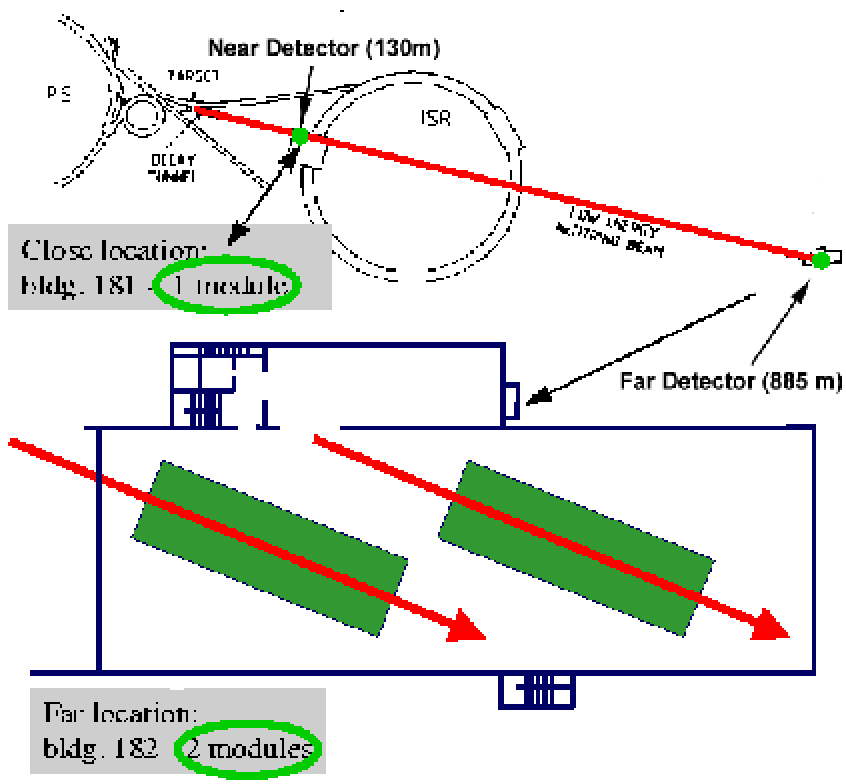
Plan to start running in Dec 2001

MiniBooNE: How Easy Will This Be?

- To rule out LSND, MiniBooNE needs to have sensitivity << 10^{-3}.
- Backgrounds will be at the level of 5 10^{-3}:
  - ν_e contamination from muons 2.3 10^{-3}
  - ν_e contamination from kaons 0.7 10^{-3}
  - misidentified ν_μ CC events 1.0 10^{-3}
  - misidentified NC events 1.0 10^{-3}
- 2-length decay pipe only helps with the first of these -- the easiest one.
- To be believable, must have a blind analysis.

CERN I-216 Proposal

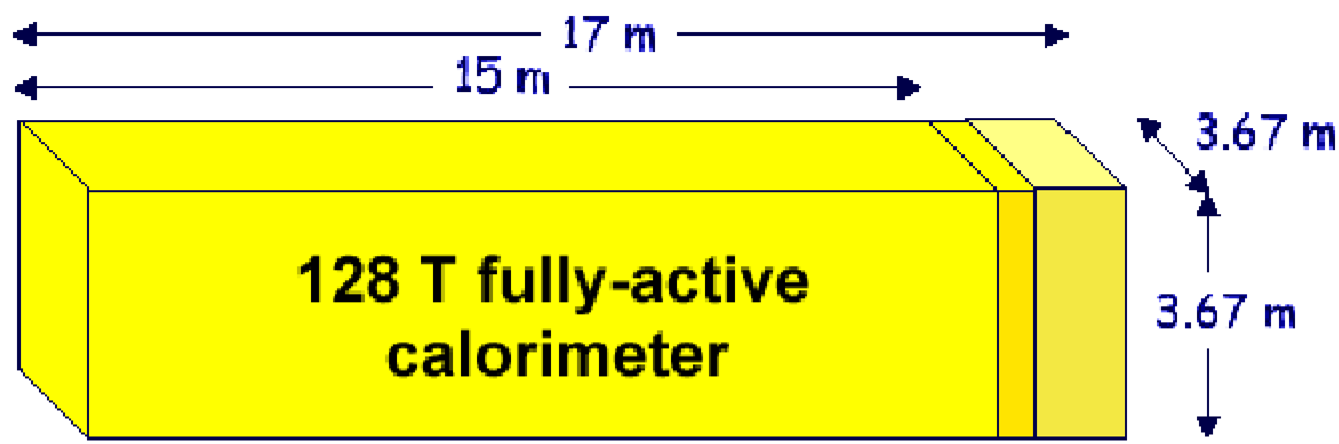
- CERN proposal for a two-detector experiment to check the LSND result



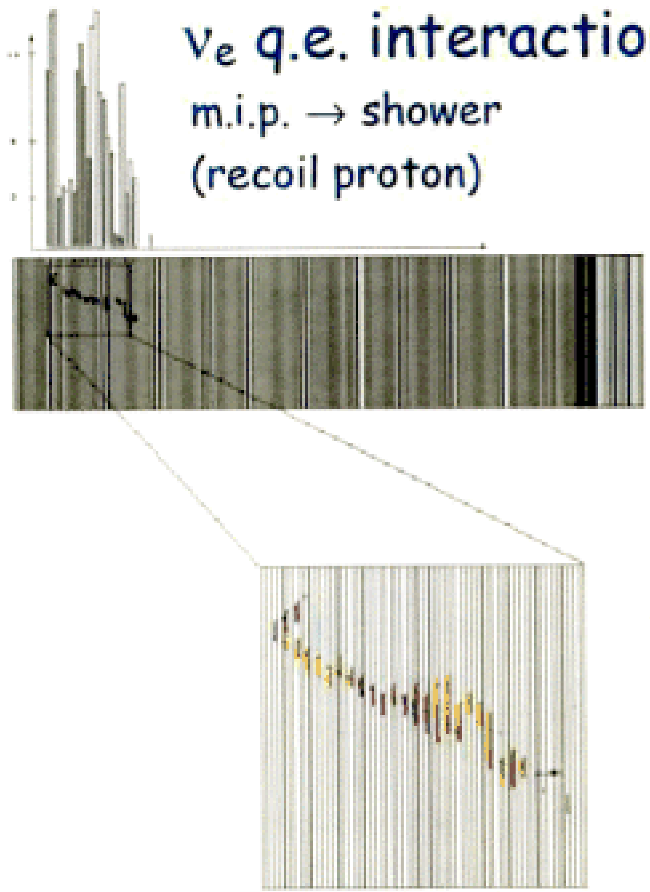
Same beamline as old CDHS/CHARM experiments.

CERN I-216 Detector

- Each module
  - Fine-grained scintillator-streamer-tube calorimeter
  - 20 plate 1-cm Fe tail catcher
  - 10 plate 10-cm Fe muon catcher



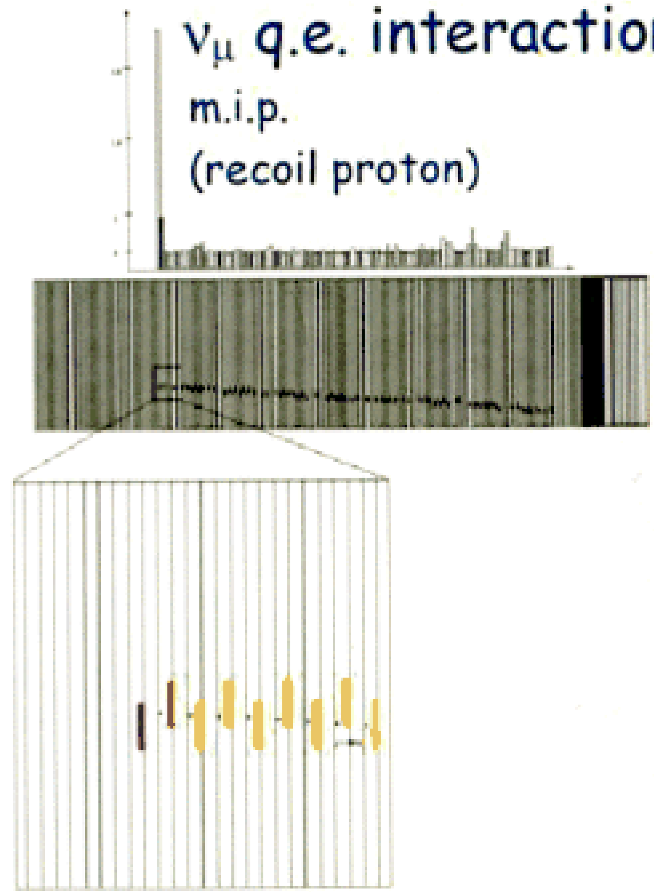
CERN I-216 Detector Simulation



ν_e q.e. interaction

m.i.p. $\rightarrow$ shower

(recoil proton)

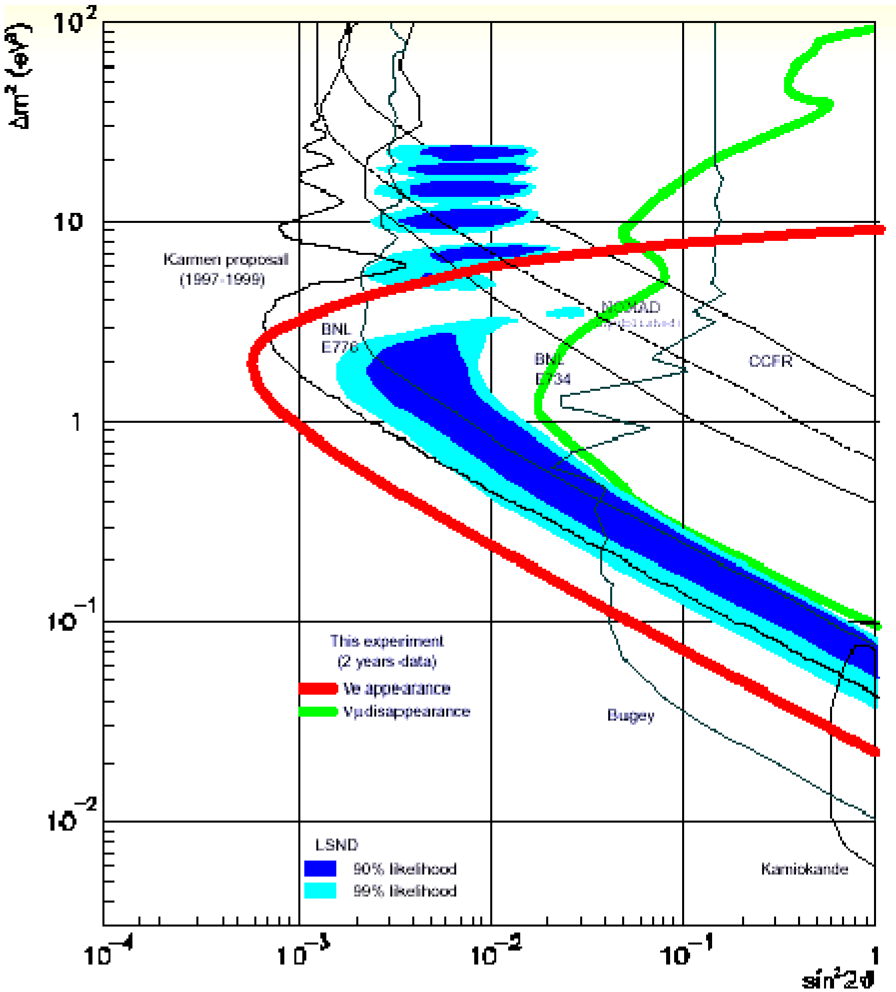


ν_μ q.e. interaction

m.i.p.

(recoil proton)

CERN I-216 Sensitivity



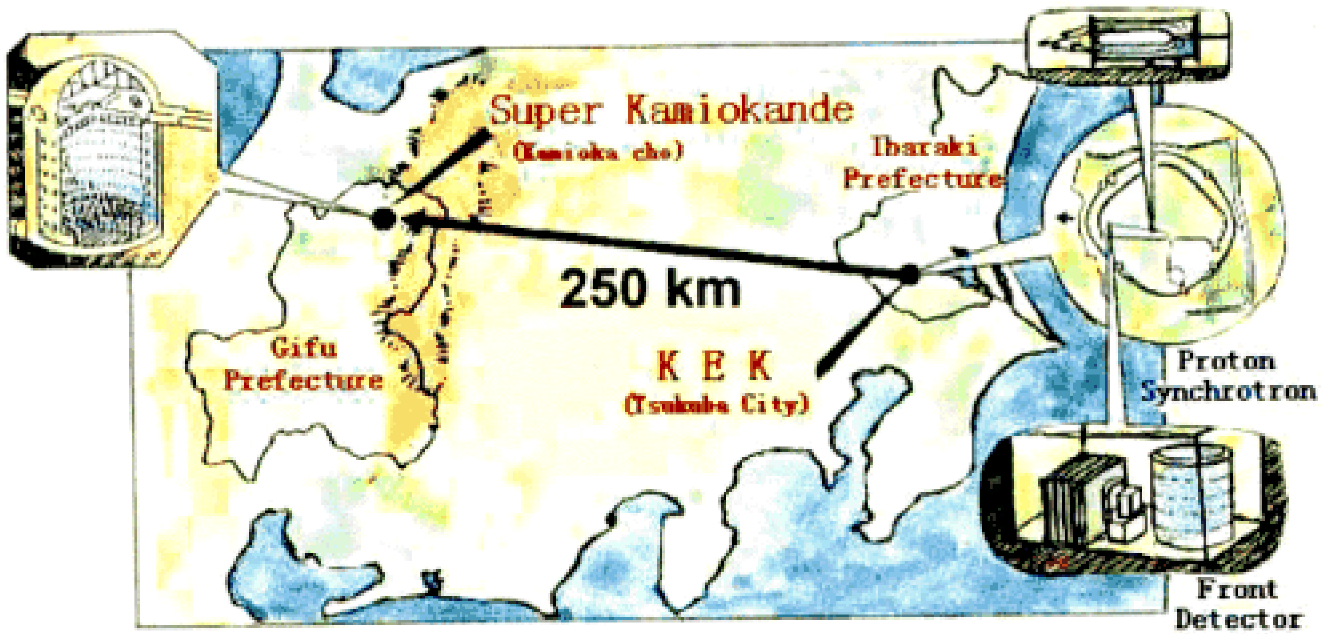
Proposed sensitivity after two years

CERN I-216 Proposal

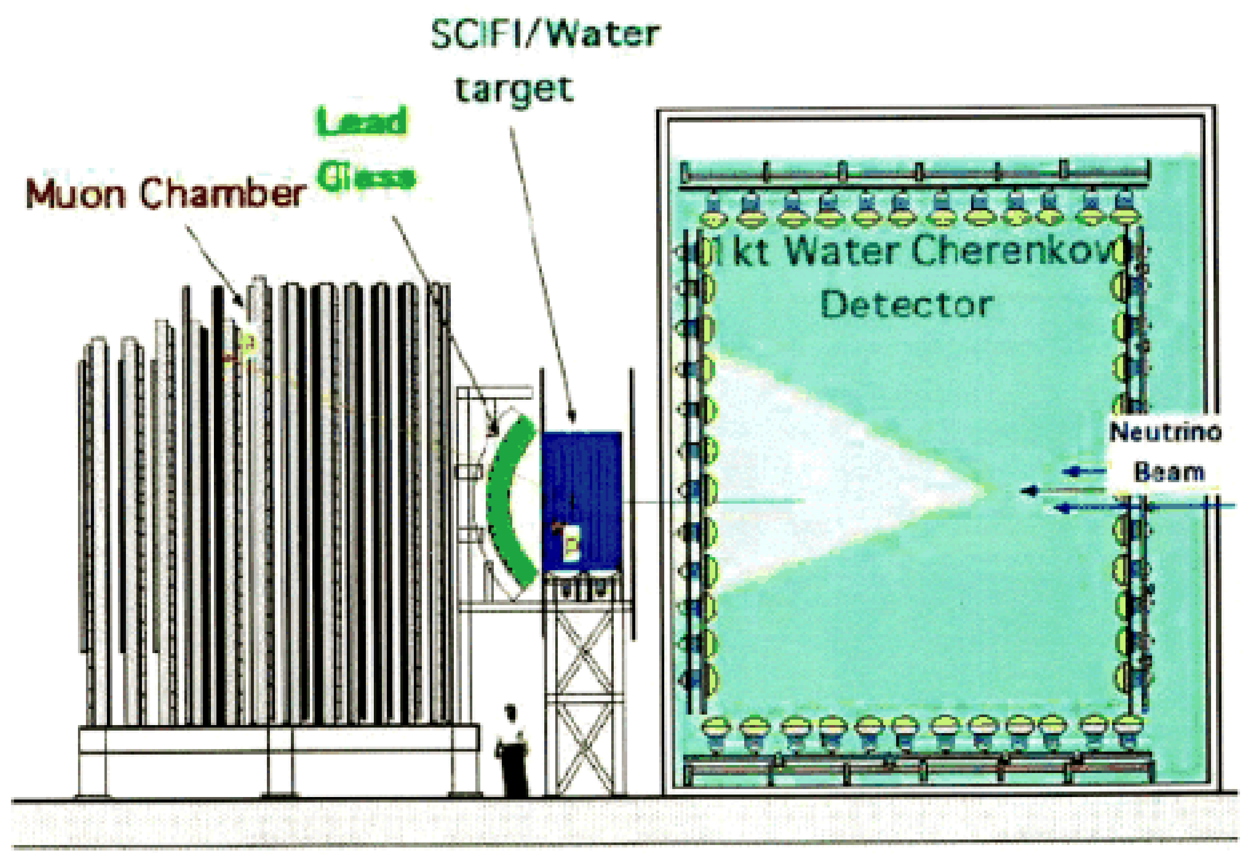
- This proposal was rejected by CERN
- Why?
  - Apparently CERN is betting that LSND is wrong
  - “LSND is an American problem”

K2K Layout

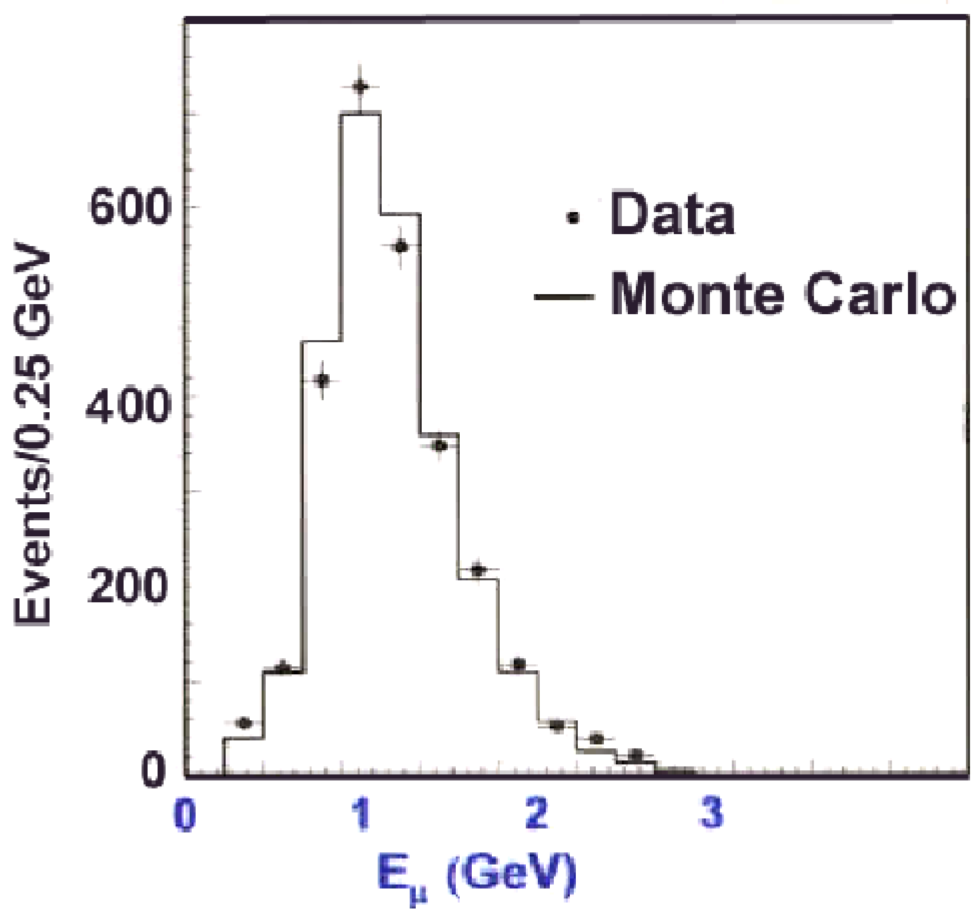
- K2K is the first of the long-baseline experiments to study the region of the atmospheric oscillations
  - KEK is a 12 GeV *p* synchrotron



K2K Near Detector

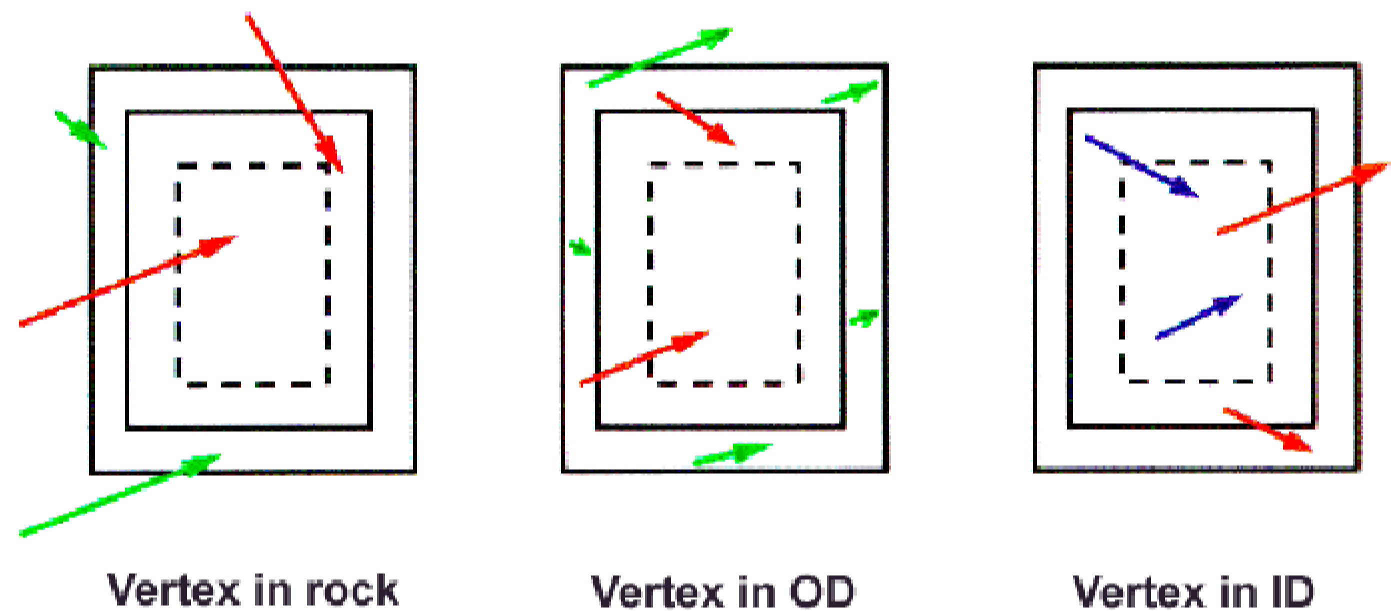


K2K Energy Spectrum



Muon energy measured by the near scintillating fiber detector

K2K Event Classification

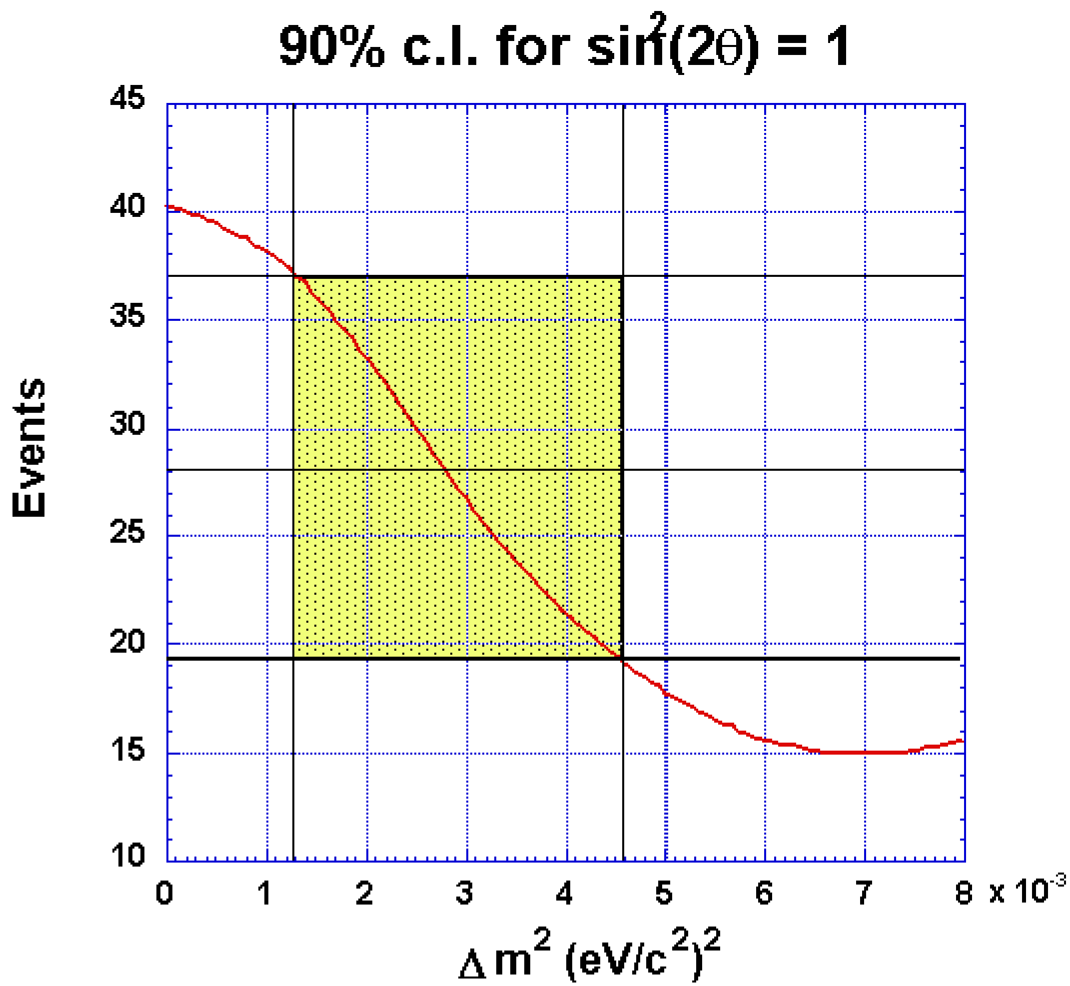


- FC (Fully Contained: Light in ID only)
  - Vertex inside the 22.5 kton fiducial volume
  - Vertex outside the fiducial volume
- OD contained (Light in OD only)
- Crossing (Light in both ID and OD)

K2K Results

- Through June 2000, K2K sees 43 FC events of which 27 are in the fiducial volume, plus 23 OD events.
- Results based only on the 27 FC fiducial events.
- No oscillation expectation is 40.3 ± 4.7 events (error is systematic, due mainly to volume uncertainties and near-far extrapolation error).
- Thus, oscillations observed at 2 σ level.

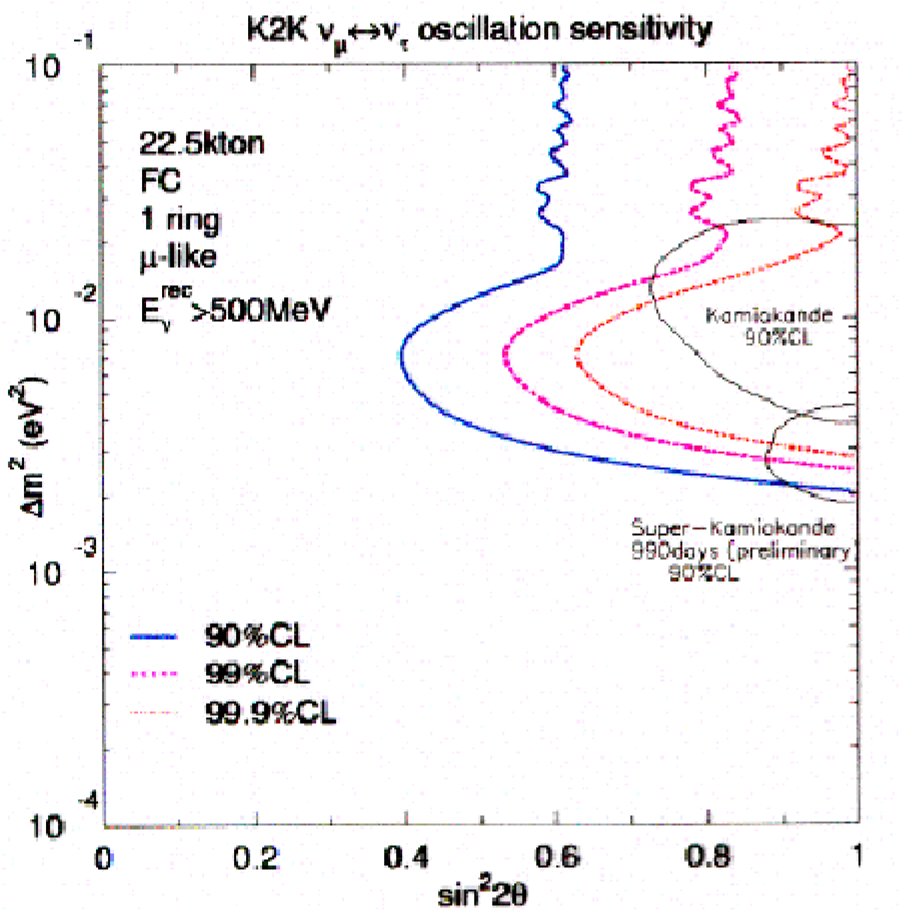
Unauthorized K2K Allowed Region



Don't blame K2K and don't take too seriously

However, almost an exact overlap with SK allowed region

K2K Expected Sensitivity



K2K now has about 1/4 of their total expected data

Therefore, expect about 100 FC events

Expect E spectrum analysis

Enlarged fiducial region?