NOMAD: \( \tau \) Detection by Kinematics

- Detection of the \( \tau \rightarrow e\nu\bar{\nu} \) mode:
NOMAD:
\( \tau \) Detection by Kinematics

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

```
\begin{align*}
\text{Signal} & : \nu_\tau \text{ CC} \\
\text{Background} & : \nu NC
\end{align*}
```
“An electronic bubble chamber”

- Front Calorimeter
- Dipole Magnet $B = 0.4 \text{ T}$
- TRD Modules
- Electromagnetic Calorimeter

Neutrino Beam

1 metre

Veto Planes
Drift Chambers
Trigger Planes Preshower
Hadronic Calorimeter

Active Target (2.7 tons)

Muon Chambers
NOMAD: $\nu_\mu$ CC Event

run 9771, event 2227: $\nu_\mu CC$
NOMAD: $\nu_e$ CC Event

run 8754, event 396: $\bar{\nu}_e CC$
Extensive use of likelihood functions

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

5+ independent kinematic variables. Using likelihood functions yields optimum signal to background ratios.
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 $\nu_\mu$ CC events was eliminated and replaced by a simulated particle to form a fake NC event, $\nu_e$ CC event, or $\nu_\tau$ CC event.

![Diagram showing the simulation process](image)
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 \( \tau \rightarrow \mu \nu \bar{\nu} \) mode, so it was not used to avoid uncontrolled systematic errors.
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.
● 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.
The analysis was done by combining 31 modes and bins. If every $\nu_\mu$ had oscillated to a $\nu_\tau$, we would have observed 14,900 signal events ($\equiv N_\tau$).

We actually saw 58 signal events with 55 ± 5 events expected from backgrounds.

However, 75% of the sensitivity came from low background bins: $N_\tau = 7,600$; 1 signal event observed with $1.3^{+1.6}_{-0.2}$ events expected from backgrounds.

At 90% c.l., $\sin^2(2\theta) < 4.1 \times 10^{-4}$ (sensitivity < 5.2 \times 10^{-4}).
NOMAD: $\nu_\mu \rightarrow \nu_\tau$

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

Exclusion Plot

$\Delta m^2 (\text{eV}^2/c^4)$ vs $\sin^2 2\theta$

- NOMAD
- $\nu_e \rightarrow \nu_\tau$
- 90% C.L.
- CHOOZ
LSND Beam
LSND Detector
LSND Technique

- $\pi^+$ produced in the target come to rest in the beam dump and decay to muons, which also decay:

\[
\pi^+ \rightarrow \mu^+ \nu_\mu \\
\rightarrow e^+ \bar{\nu}_\mu \nu_e
\]

- This produces $\nu_\mu, \bar{\nu}_\mu, \nu_e$, but not $\bar{\nu}_e$. Thus, one can look for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations.
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 μ⁻ get captured from atomic orbits producing a nm, but not a \( \bar{\nu}_e \).

Thus the total suppression is \( (0.125)(0.05)(0.12) = 7.5 \times 10^{-4} \).
But how does one detect a few $\bar{\nu}_e$s in an intense beam of $\nu_e$s?

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 $\gamma$ to the $e^+$ in position and time.
LSND: $R$ Distribution

![Graph showing $R$ distribution with different event categories: DAR, Fit, All Accidentals, and All Correlated.](image-url)
Neutrino Energy Spectrum
LSND $E$ Distribution

83 events total
-33.7 beam off
-16.6 beam on
= $32.7 \pm 9.2$ signal
LSND Allowed Region
3.4% of $\pi^+$ decay in flight between the target and the beam dump, yielding high-energy $\nu_\mu$s.

Signal is a single electron with $60 < E < 200$ MeV.

40 events observed with 21.9 background expected $\Rightarrow$ 18.1 excess events.
LSND DIF Allowed Region

Decay in flight allowed 95% c.l.

Δm^2 [eV^2]

10

10

1

10^{-3}

10^{-2}

10^{-1}

sin^2 2θ
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$_2$O$_3$ for neutron capture
KARMEN Event Distributions

11 events observed for 12.3 ± 0.6 background events expected
KARMEN Exclusion Plot

\[ \sin^2(2\Theta) < 1.3 \times 10^{-3} \text{ for large } \Delta m^2 \]

- BUGEY
- BNL E776
- LSND 1993-98
- CHOOZ
**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 $\nu_\mu \rightarrow \nu_e$ oscillations.
- Technique and backgrounds different from LSND.
MiniBooNE Energy Spectrum

relative flux

$\nu_e$

$\nu_\mu$

Energy (GeV)
MiniBooNE Detector

800 T mineral oil
445 T fiducial

1280 PMTs signal
240 PMTs veto

Detect Cerenkov rings

μ

e

Gary Feldman
SLAC Summer Institute
14 - 25 August 2000
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 \times 10^{-3}:
  - $\nu_e$ contamination from muons \quad 2.3 \times 10^{-3}
  - $\nu_e$ contamination from kaons \quad 0.7 \times 10^{-3}
  - misidentified $\nu_\mu$ CC events \quad 1.0 \times 10^{-3}
  - misidentified NC events \quad 1.0 \times 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

$\nu_e$ q.e. interaction
m.i.p. $\rightarrow$ shower
(recoil proton)

$\nu_\mu$ q.e. interaction
m.i.p.
(recoil proton)
CERN I-216 Sensitivity

Proposed sensitivity after two years
This proposal was rejected by CERN

Why?

- Apparently CERN is betting that LSND is wrong
- “LSND is an American problem”
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

- Vertex in rock
- Vertex in OD
- Vertex in ID

- FC (Fully Contained; Light in ID only)
- OD contained (Light in OD only)
- Crossing (Light in both ID and OD)

- Vertex inside the 22.5 kton fiducial volume
- Vertex outside the fiducial volume
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 $\sigma$ level.
Unauthorized K2K Allowed Region

90% c.l. for $\sin^2(2\theta) = 1$

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

However, almost an exact overlap with SK allowed region

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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?