

Wide and narrow bands

Getting neutrino beams is all about getting enough parent particles. The pioneer neutrino experiments at Brookhaven in 1962 used no focusing tricks, however the invention of the magnetic horn by Simon van der Meer at CERN enabled a wide range of parent kaon or pion momenta to be concentrated into a cone, boosting the subsequent neutrino yield in a 'wide band beam'. The focusing horn also selects the electric charge of the pions and kaons, thereby determining whether neutrinos or anti-neutrinos are obtained. However there is little indication of what the energies of these neutrinos (or antineutrinos) are.

Another approach is the 'narrow band beam', where a limited range of parent pion or kaon momenta is selected, giving a forward peak. Here the offset of the neutrinos from the forward direction gives an indication of their energy. However as pions and kaons decay in different ways, the resultant neutrino beam covers two (narrow) momentum bands, and is 'dichromatic'. The first such beams were used at Fermilab in the early 1970s.

The Fermilab 'flagship' E1A neutrino experiment pioneered the use of large neutrino calorimeters. In this 1973 photo are, left to right, standing, Alfred Mann, Richard Imley, David Cline, T.Y. Ling, Don Reeder, Jim Pilcher and Bernard Aubert; seated, Carlo Rubbia, Karen Mattison and Fred Messing.

FERMILAB

Neutrino experimentation at higher energies was among the justifications for the construction of Fermilab and the earliest studies utilized these new beams produced with 350-400 GeV protons. This pre-Tevatron period used both electronic counters and the new 15-foot cryogenic bubble chamber.

The counter experimental programme was basically divided into two generations. The first covered the discovery of new phenomena and confirmation of the parton model using high rate wide-band and the first dichromatic narrow-band neutrino beams. The second concentrated on precision measurements with dichromatic beams.

One flagship experiment, designated "E1A", was originally a collaboration of Harvard, Pennsylvania and Wisconsin, and was the prototype of large neutrino calorimeters: a target/calorimeter followed by a large set of iron toroidal magnets. E1A and its successor, E310 (which included

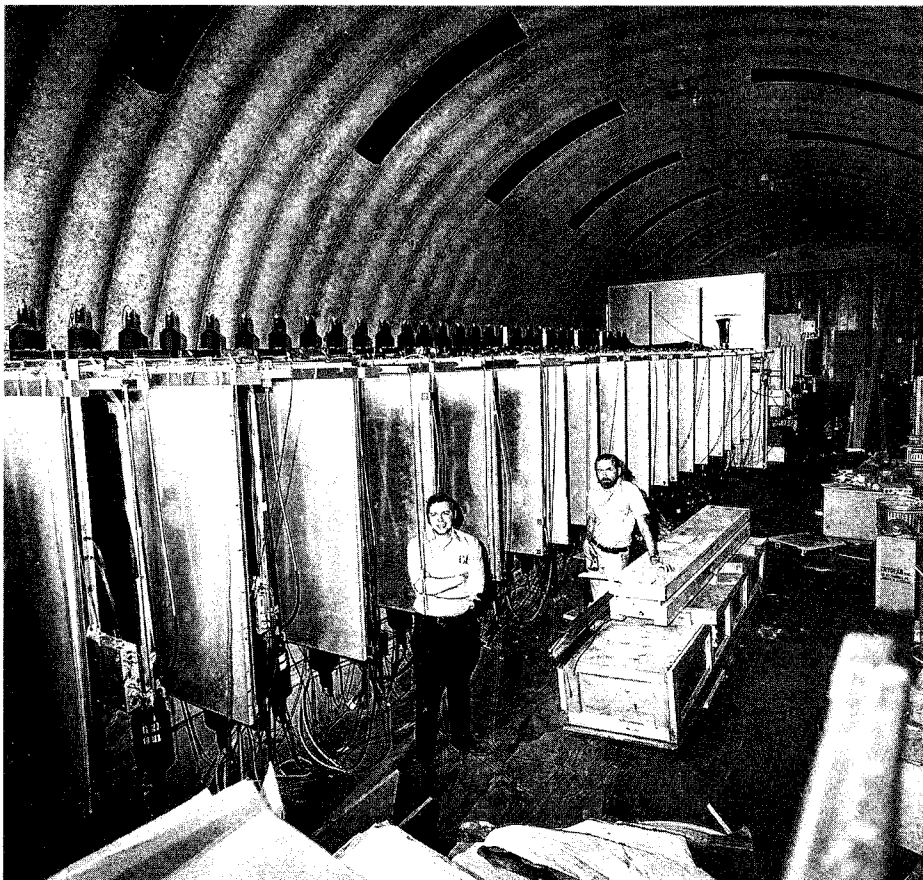
Rutgers), ran for a total of 6,650 hours from 1972 through 1978. Contemporary with these experiments was another large counter experiment by CalTech and Fermilab, designated originally as E21A. Along with its successors, E262, E320, and E356 (which collected data over some 4,600h) it took part in the first generation programme, and subsequently spearheaded the second generation with precision measurements of both charged current structure functions and the weak mixing angle. Finally, this latter collaboration extended its participation into the early Tevatron era, and will continue through the 1990s.

The E1A-inspired programme ended with E310 and a dedicated low-mass, highly visible counter neutrino experiment, E594 took its place. E616 plus E594 constituted the second generation of pre-Tevatron Fermilab experiments.

The Fermilab "15-foot" bubble chamber (actually, a 12 foot diameter sphere with a 3 foot upstream nose), began operation in 1973, with a neon-hydrogen mixture exposed to



The E21A counter neutrino experiment by CalTech and Fermilab, here tended by Frank Sciulli (left) and Barry Barish.



the wide-band beam in conjunction with E28, a collaboration of CERN, Hawaii, LBL, and Wisconsin. This was followed by a series of 15 other experiments using wide- and narrow-band beams focused for both neutrinos and antineutrinos.

The 15-foot chamber was later modified to include an external muon identifier and an internal "picket fence".

The first generation experiments at Fermilab were responsible for measuring the ratio of neutral to charged current interactions with high statistics, although the priority on the actual discovery of neutral currents was somewhat controversial. The first observation of opposite sign dilepton final states and their determination occurred at Fermilab in E1A

(dimuon final states) while precision measurements of the accompanying strange particle content of those events were carried out by the bubble chamber experiments (muon-electron final states). Observation of trileptons and same-sign dimuons led to a decade of further experimentation and subsequent verification of the Standard Model.

The nucleon structure functions were determined through both charged current and neutral current scattering during this period. By the early 1980s, the total neutrino experimental programme at Fermilab had contributed greatly to our understanding of the parton model and particle production in charged current events.

There were three "other" experiments of note during the pre-Tevatron era which deserve mention. The first was E253, a 1978 experiment designed to observe and measure neutrino-electron scattering, with an early determination of the weak mixing angle.

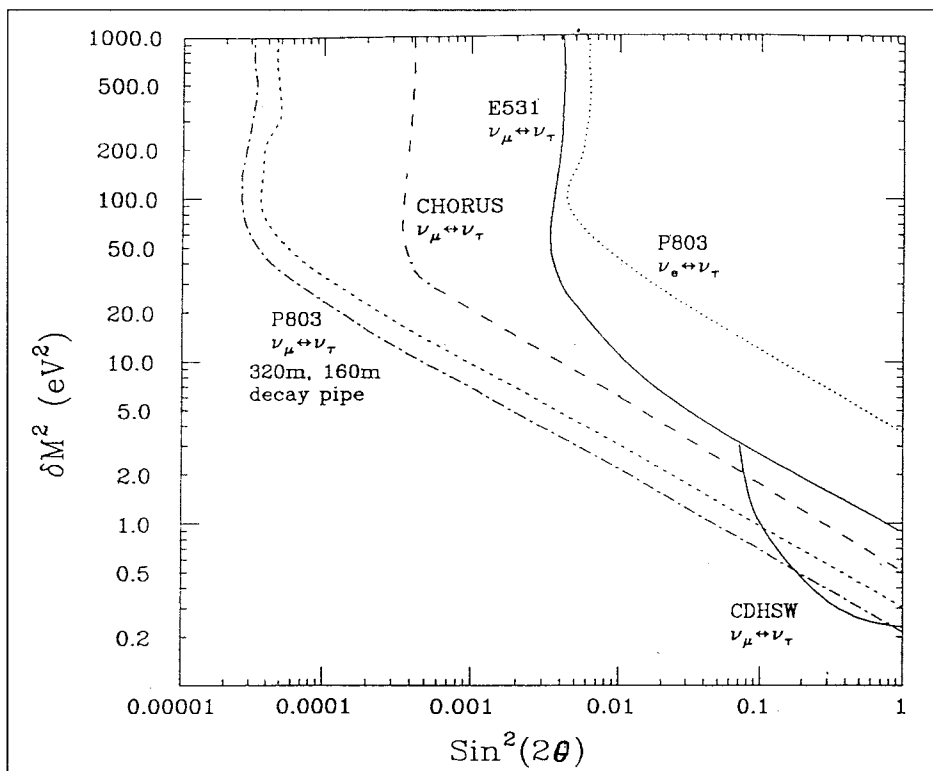
The second was the first major emulsion neutrino experiment, E531. This was highly successful, establishing a detailed understanding of charmed particle production and the properties of charmed particles. Interestingly the limits set on the oscillation of muon to tau neutrinos through a search for the appearance of the latter still stand today. Also of note was E701 (the original E616 apparatus with an upstream detector) - a true 'disappearance' oscillation experiment in the dichromatic beam in 1982.

The advent of the Tevatron with its higher energies boosted Fermilab's programme, with neutrinos produced (indirectly) from 800 GeV protons. This era saw the continuation of the CalTech/Fermilab programme, augmented by Columbia, Chicago, Rochester, Rockefeller, and subsequently Wisconsin (CCFRW), the continuation of the flash-chamber programme (E733), and the introduction of holography in bubble chambers with the 15-foot (E632) and hybrid (E745) chambers. These studies have extended the precision of many Standard Model tests and form the basis for the second generation of Tevatron neutrino experiments scheduled for 1995.

Future neutrino experiments

As Fermilab moves into its third decade of operation, much of the experimental programme, particularly in the fixed target area, emphasizes

Limits on neutrino oscillation parameters expected from several future experiments, compared with the historical results from CDHSW (WA1) at CERN.



precision experiments to probe deep inside the Standard Model and hopefully get a glimpse of what lies beyond it.

Neutrinos are penetrating probes and will make up an important part of this ongoing programme.

After more than a five-year hiatus, the detector used for the CCFRW (Chicago/Columbia/Fermilab/Rochester/Wisconsin) collaboration's experiments (E770/774) will be reincarnated as E815, an experiment designed to make precision measurements of the basic electroweak parameters.

One of these - the electroweak mixing parameter (Weinberg angle, linking the two neutral carriers of the theory with the physical photon and Z boson) - can be obtained in a number of ways: direct measurement of the W and Z masses, left/right asymmetry in Z decays, neutrino-nucleon scattering, and atomic parity

violation. Measuring this parameter in several processes provides insight into small effects due to higher order corrections to the Standard Model as well as possible deviations from it.

The other parameter - Greek rho - dictates the strength of the neutral current interaction, and in the basic Standard Model is equal to 1. Small effects can creep in due to various electroweak corrections, such as those depending on the mass of the long-awaited sixth ('top') quark. Present values of the Standard Model parameters predict rho to be 1.0026 ± 0.0038 , along with a top heavier than 113 GeV, and a higgs particle somewhere in the range 60 to 1000 GeV.

Experiment 815 will measure rho to a precision of ± 0.005 , and the mixing parameter to ± 0.003 . The key feature will be the operation of a new charge selected beam to provide neutrinos or antineutrinos. Separate

running in each beam will open up the two vital parameters.

To date such an analysis has not been worthwhile due to the paucity of antineutrino data. E815 anticipates normal operation of 10^{13} protons per cycle, for a total of 2×10^{18} integrated protons after an eight-month run. This should yield approximately 1.2 million neutrino charged current, 400,000 neutrino neutral current, 220,000 antineutrino charged current and 84,000 antineutrino neutral current events.

As the end of the decade approaches, Fermilab's new Main Injector (May, page 10) will provide new opportunities for fixed target experiments using either the increased intensity Tevatron beam, or the high intensity 120 GeV beam extracted directly from the Main Injector, and available during collider operation.

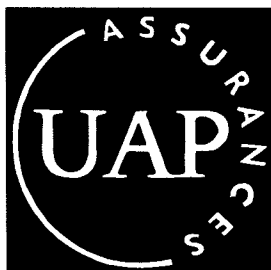
One of the most exciting of these opportunities is a search for neutrino oscillations and the concomitant evidence for neutrino mass.

The 120 GeV Fermilab Main Injector beam will deliver more than 4×10^{13} protons per two-second cycle, producing an unprecedented flux of high intensity, high energy neutrinos.

A preliminary beam design foresees a muon-neutrino beam with an average energy of 15 GeV.

One proposal wants to use this beam with a hybrid emulsion spectrometer for a short baseline experiment to search for muon/tau-neutrino oscillations. This follows the philosophy of the Fermilab E531 experiment and CERN's CHORUS experiment currently under construction.

A compelling feature of this idea is the possibility to actually detect the interaction of a tau neutrino via the tau-neutrino/tau charged current interaction. With the tau neutrino yet to be directly observed, this group



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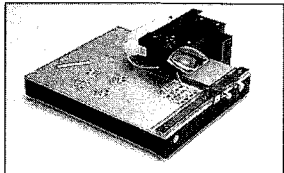
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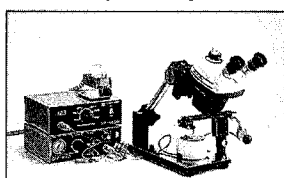
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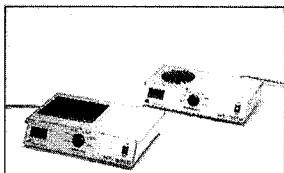
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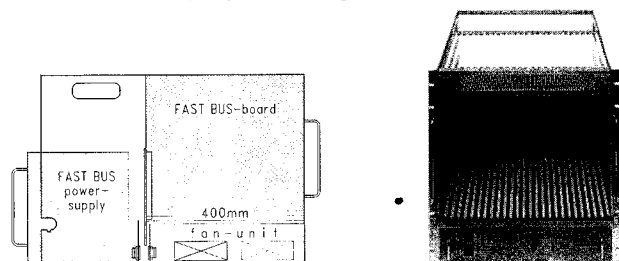
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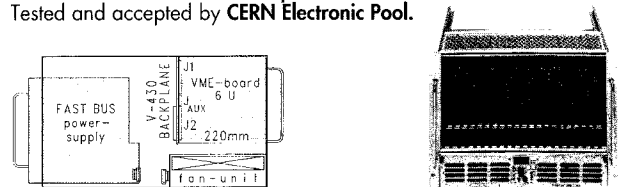
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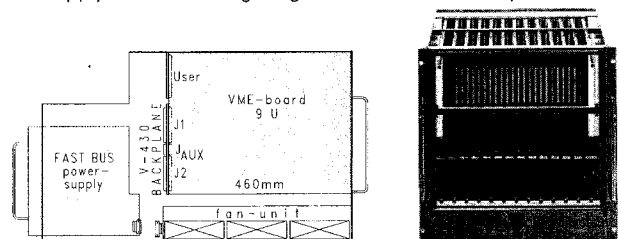
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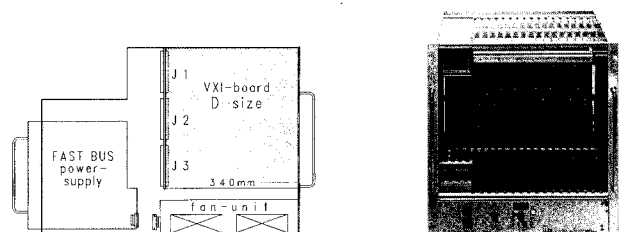
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An aerial photograph of the LAMPF facility with the experimental areas in the foreground. The tunnel housing the LSND neutrino experiment is visible in the lower centre of the photo behind a service building. LSND is about 11 metres downstream of the LAMPF beam stop.

proposes a tau-neutrino beam dump which could use the 800 GeV proton beam prior to the completion of the Main Injector. This proposal will soon be submitted for formal consideration.

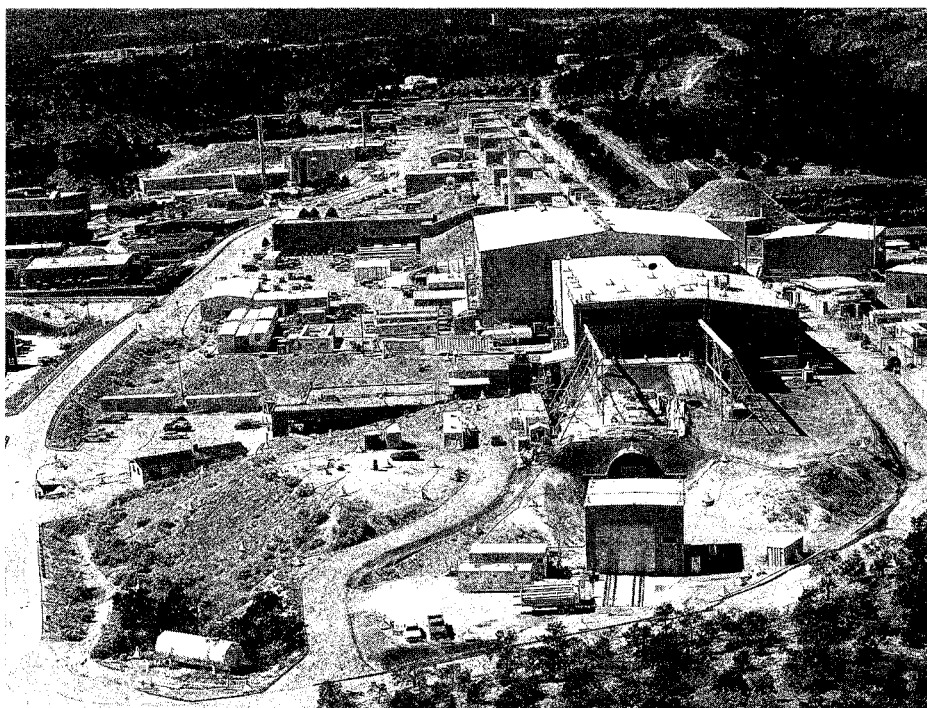
Also being developed are plans for a long baseline experiment. One idea is to extract the Main Injector beam in a direction so that the neutrinos travel toward Soudan, Minnesota, 800 kilometres to the northwest of Fermilab, home of a major underground laboratory. In such a scheme, the near and distant detectors would use the same beam and some common modules.

Other long baseline options being studied involve using protons extracted from the existing 120 GeV Main Ring, the 8 GeV Booster, or the Antiproton Debuncher Ring, the idea being to produce a high intensity neutrino beam, albeit of low energy. This gives good sensitivity to oscillations over a shorter distance, allowing the "far" detector to be much nearer, even on the Laboratory site.

LOS ALAMOS

Following the historic observation of neutrinos in the mid-1950s by two Los Alamos scientists, Fred Reines and Clyde Cowan, Jr, using inverse beta decay, there has been a long and distinguished history of experimental neutrino physics at LAMPF, the Los Alamos Meson Physics Facility. LAMPF is the only meson factory to have had an experimental neutrino programme.

In the late 1970s, the first LAMPF neutrino experiment used a 6-tonne water Cherenkov detector 7 metres from the beam stop. A collaboration of Yale, Los Alamos and several other institutions, this experiment



sought for the forbidden decay of a muon into an electron and two neutrinos, and measured the reaction rate of a neutrino interacting with a deuteron to give two protons and an electron - the inverse of the reaction that drives the sun's primary energy source.

The next LAMPF neutrino experiment, a UC Irvine/Maryland/Los Alamos collaboration, ran from 1982 through 1986 and measured the elastic scattering rate of electron-neutrinos and protons, where both neutral and charged weak currents contribute.

With its precision of about 15%, the experiment provided the first demonstration of (destructive) interference between the charged and neutral currents.

More recent neutrino experiments at LAMPF have searched for neutrino oscillations, especially between muon- and electron-neutrinos.

The newest experiment to pursue

this physics (as well as oscillations in other channels) is LSND (July/August, page 10 and cover). In addition to searching for these oscillations, LSND will measure neutrino-proton elastic scattering at low momentum transfer, providing a sensitive measure of the strange-quark contribution to the proton spin. LSND began taking data in August.

Los Alamos physicists have also been busy in neutrino physics experiments elsewhere.

One such experiment looked at the beta decay of free molecular tritium to obtain an essentially model-independent determination of the electron-neutrino mass. The present result gives an upper limit on the electron-neutrino mass of 9.3 eV, showing that electron neutrinos cannot by themselves 'close' the universe.

Pioneer solar neutrino experiments (see page 21) suggested that the observed flux of high-energy neutri-