NEUTRINO OSCILLATIONS EXPERIMENTS AT FERMILAB *

Adam Para

Fermilab, Pine St., Batavia IL 60510, USA

(Received May 1, 2000)

Neutrino oscillations provide an unique opportunity to probe physics beyond the Standard Model. Fermilab is constructing two new neutrino beams to provide a decisive test of two of the recent positive indications for neutrino oscillations: MiniBOONE experiment will settle the LSND controversy, MINOS will provide detailed studies of the region indicated by the SuperKamiokande results.

PACS numbers: 14.60.Pq, 14.60.Lm

1. Introduction

Neutrinos are special. They are the only elementary fermions which are neutral, thus they can be their own antiparticles. Their masses (if non-zero) are several orders of magnitude smaller than those of charged leptons or quarks. These two facts may be, in fact, related: with both Dirac and Majorana, masses present, the neutrino mass eigenstates will naturally split, with the light mass eigenstate being

$$m_\nu \sim \frac{m_{\rm D}^2}{m_{\rm R}}\,. \tag{1}$$

If the Dirac mass m_D is of the order of a typical quark or charged lepton mass and the right-handed Majorana mass is of the order of the GUT scale, the left-handed neutrinos would then have a mass well below 1 eV.

Direct measurements of the neutrino masses are very difficult; experiments so far have been able to yield only upper limits. The best limit can be set for the $\overline{\nu}_e$ from tritium β decay, which is of the order of 1 eV [1]. A very similar limit, although dependent on the assumed Majorana nature of

* Presented at the Cracow Epiphany Conference on Neutrinos in Physics and Astrophysics, Cracow, Poland, January 6–9, 2000.

the neutrino, is derived from the measured rates of the neutrino-less double beta decays. Mass limits for other neutrino species are considerably worse: $m_{\nu_\mu} < 170$ keV from the decay of charged pions and $m_{\nu_\tau} < 24$ MeV from the decay $\tau \to 5\pi^{\pm} + \nu_\tau$. Neutrino oscillations offer the only practical means to unravel details of the neutrino mass spectrum.

2. Neutrino oscillations

If neutrinos have masses, we may expect in analogy with the quark sector, that the weak interaction eigenstates are mixtures of the mass eigenstates ν_1, ν_2, ν_3, with the CKM-like mixing matrix U [3]

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \tag{2}$$

usually parametrized as

$$\begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}, \tag{3}$$

where $s_{ij} = \sin\vartheta_{ij}$ and $c_{ij} = \cos\vartheta_{ij}$ and ϑ_{ij} is the mixing angle of ν_i and ν_j.

Differences of mass eigenvalues will lead, through differences in time evolution of the components of the wave function, to the phenomenon of neutrino oscillations: [2] the beam of neutrinos of a given flavor, say ν_μ, will be observed as a mixture of all three neutrino flavors after a certain distance L. Frequency of these oscillation is governed by $\Delta m^2_{ij} = m^2_i - m^2_j$.

For example, starting with a pure ν_μ beam and assuming $|\Delta m^2_{12}| \ll |\Delta m^2_{23}|$, we would expect probabilities of detecting of ν_μ, ν_e and ν_τ to be

$$\begin{aligned} P\left(\nu_\mu \to \nu_\mu\right) &= 1 - 4U^2_{\mu 3}\left(1 - U^2_{\mu 3}\right)\sin^2\left(\tfrac{\Delta m^2_{23}L}{4E}\right), \\ P\left(\nu_\mu \to \nu_e\right) &= \sin^2\theta_{23}\,\sin^2 2\theta_{13}\,\sin^2\left(\tfrac{\Delta m^2_{23}L}{4E}\right), \\ P\left(\nu_\mu \to \nu_\tau\right) &= \cos^4\theta_{13}\,\sin^2 2\theta_{23}\,\sin^2\left(\tfrac{\Delta m^2_{23}L}{4E}\right), \end{aligned} \tag{4}$$

where E is the neutrino beam energy and L is the distance of the detector from the neutrino source.

At present, there are three experimental indications, shown in Fig. 1, that the neutrino oscillations might, in fact, occur in nature:

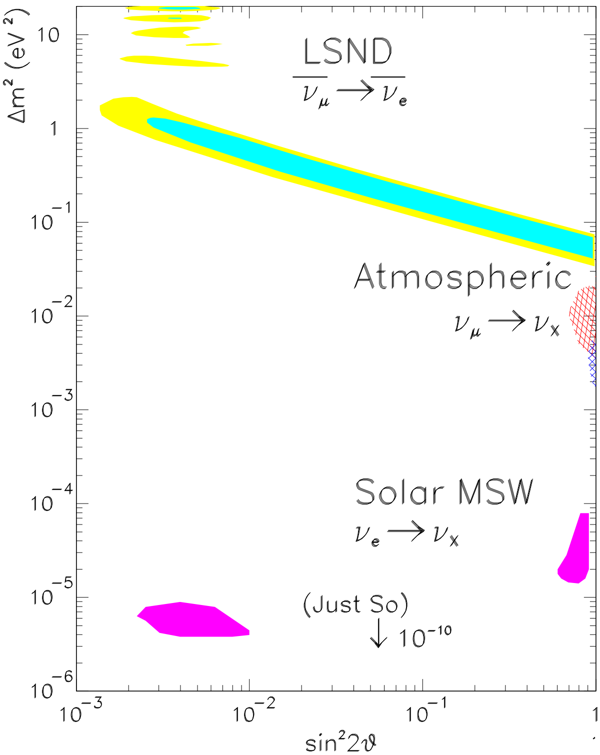

Fig. 1. Summary of possible indications for neutrino oscillations

1. Solar neutrino deficit

   The flux of solar ν_e measured in several experiments is about 50% of the flux expected in the Standard Solar Model. This large discrepancy is unlikely to be caused by our ignorance of the physics of the Sun; it can be interpreted as a result of $\nu_e \rightarrow \nu_x$ oscillations. The Δm^2 responsible for these oscillations would be of the order of 10^{-10} eV^2 if the oscillations occur in a vacuum, or $10^{-5} - 10^{-4}$ eV^2 if the oscillation occur in matter via the MSW effect.

2. Atmospheric neutrinos

   The SuperKamiokande detector [4] has been used to detect interactions of atmospheric neutrinos. The results show depletion of the ν_μ interaction rate as a function of the zenith angle, while the ν_e interaction rate is consistent with the expectations [4], as shown in Fig. 2. The observed depletion is consistent with the hypothesis of neutrino oscillations and strongly suggests $\nu_\mu \rightarrow \nu_\tau$ oscillations with a very large mixing angle and a Δm^2 in the range 0.003–0.01 eV^2 [5].

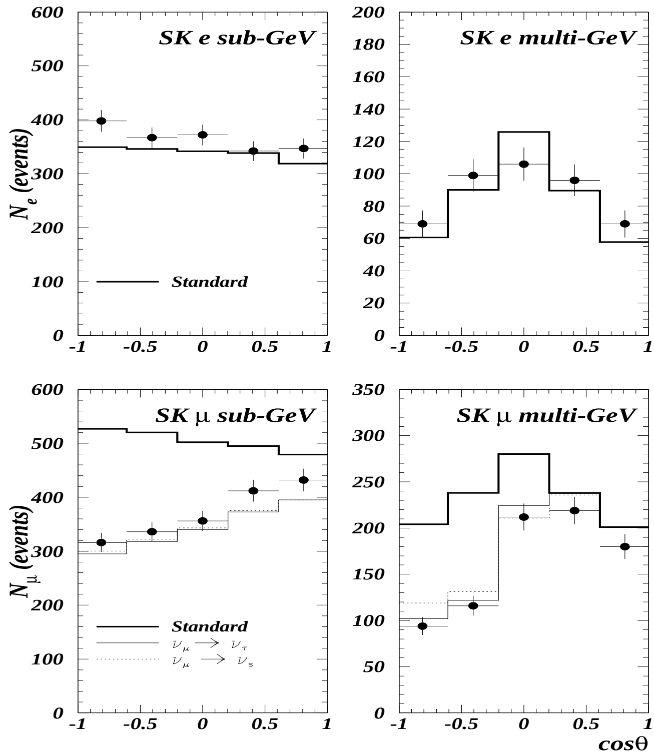

Fig. 2. Zenith angle distribution of atmospheric ν_e and ν_μ events observed in SuperKamiokande experiment.

3. LSND experiment

   An 800 MeV proton beam at LAMPF was used to produce pions, which were subsequently stopped in the absorber. A liquid scintillator detector recorded an excess of 82.8 ± 23.7 $\overline{\nu}_e$ interactions above the expected background of 17.3 ± 4 events. These interactions are consistent with the hypothesis of $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations (Fig. 3), if the oscillation parameters are in the region shown in Fig. 1. Neutrino oscillations in the large mixing angle region are excluded by the reactor experiments. The large Δm^2 region is excluded by CCFR and NOMAD experiments, but the possibility of the neutrino oscillations in the region $0.3 < \Delta m^2 < 2$ eV^2 remains open.

Developing a consistent interpretation of the data shown in Fig. 1 is difficult. Three different massive neutrinos allow for only two independent Δm_{ij}. Most of the proposed scenarios invoke a new, hitherto unknown, sterile neutrino or postulate that some of the experimental results are not, in fact, manifestations of the neutrino oscillations.

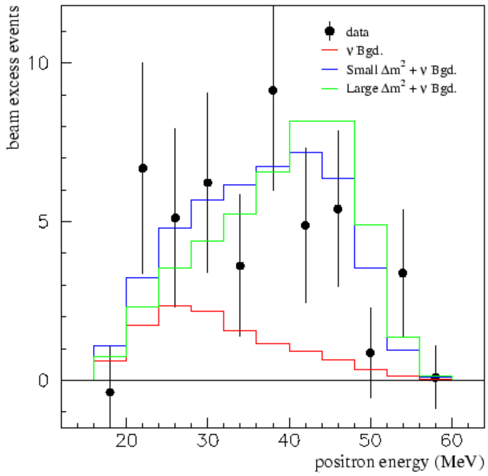

Fig. 3. Energy distribution of the excess $\overline{\nu}_e$ interactions observed in the LSND detector.

Given the potential importance of the neutrino mass sector, the following questions pose an experimental challenge in the near future:

- Are all three indications really examples of neutrino oscillations?
  Observation of oscillatory behavior as a function of distance and/or neutrino energy, would be particularly convincing proof. Seasonal or day–night variation of the solar neutrino flux could serve as a proof of the solar neutrino oscillation hypothesis. Observation of energy dependence of the disappearance of the ν_μ flux is also possibility in the atmospheric or LSND regions.

- What are the oscillation modes?
  The LSND result implies $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations. What are the oscillation modes responsible for the solar neutrino effect? The atmospheric neutrino deficit? Are there sterile neutrinos? Preliminary results from the SuperKamiokande experiment shown in Fig. 2 disfavor such a possibility as the dominant oscillation mode, because matter induced effects would lead to a small reduction of the observed deficit.

- What are the oscillation parameters?
  What are the patterns of the Δm^2_{ij}? The mixing angles? What are the elements of the lepton mixing matrix? Are there dominant and subdominant oscillation modes corresponding to each oscillation frequency (Δm^2)?

- The presence of the phase factor $e^{-i\delta}$ in the mixing matrix U implies a possibility of CP-violating effects in neutrino oscillations. How large are they? What is the value of δ ?

Studies of oscillations in the solar neutrino region require extra-terrestrial distances and/or very low energy neutrino sources, such as nuclear reactors. Oscillations in the atmospheric neutrinos region or the region indicated by the LSND experiment lend themselves to studies with neutrino beams produced in the laboratory. Such investigations of the neutrino oscillations are an important part of the scientific program at Fermilab.

3. Fermilab accelerators and neutrino beams

The flagship of the Fermilab high energy physics program is the Tevatron Collider. Recent upgrades of the accelerator infrastructure were specifically designed to boost the luminosity of the Collider and at the same time to enable a fixed-target program, like neutrino experiments, to be carried simultaneously with the Collider experiments. Two of the existing Fermilab's accelerators are being used to produce neutrino beams: the 8 GeV Booster and the newly constructed Main Injector.

3.1. 8 GeV booster neutrino beam (MiniBOONE)

The Booster is the oldest part of the of the accelerator complex at Fermilab. Upgraded to 400 MeV injection in 1993, it is capable of delivering up to 5×10^{12} protons per pulse. In the past, it was operated at 2.5 Hz, but after improvements of its pulsed magnets, its repetition rate can be as high as 7.5 Hz.

A Booster [7] neutrino beam is under construction. An 8 GeV proton beam is extracted onto a titanium or nickel target. Two magnetic horns focus secondary pions and kaons, their focusing power being optimized for 3 GeV secondaries. The secondary beam has a relatively short decay path which can be varied from 25 to 50 m. A variable decay path will provide additional information on the ν_e component of the beam.

Combining the high proton flux with a high efficiency horn focusing will provide a high flux neutrino beam, yielding over 2,000,000 ν_μ interactions per kton-year at a distance 500 m from the source. The neutrino flux will have a maximum around $E_\nu = 1$ GeV and an exponential high energy tail falling to the 10% level at $E_\nu = 3$ GeV.

3.2. NuMI: neutrino beams from the Main Injector

The Main Injector accelerator is a 150 GeV proton synchrotron constructed to replace the original Fermilab Main Ring. It is expected to serve as a high intensity, fast-cycling accelerator for antiproton production, as an injector into the Tevatron and simultaneously to support fixed target experiments using 120 GeV protons.

It is expected that after the completion of the NuMI construction project, the Main Injector will be able to deliver 3.6×10^{20} protons per year onto the NuMI target, in parallel with the simultaneous support for the antiproton production for the Tevatron Collider experiments.

The high intensity and high repetition rate of the Main Injector offers an opportunity for neutrino beams of unprecedented intensity, thus creating an opportunity for long baseline neutrino oscillation experiments. The Main Injector will accelerate 6 batches of 8×10^{12} protons each with a repetition rate of 1.9 secs. One of these batches will be used for antiproton production, while the remaining five batches will be extracted onto the neutrino target.

Secondary pions and kaons will be collected and focused using a system of two parabolic magnetic horns, and subsequently they will produce a neutrino beam by decaying inside a 675 m long decay pipe. The beam optics is designed to allow tuning of the neutrino beam energy by moving the focusing elements (horns) in a manner similar to a zoom lens. The energy spectra of three possible beam configurations are shown in Fig. 4, together with a

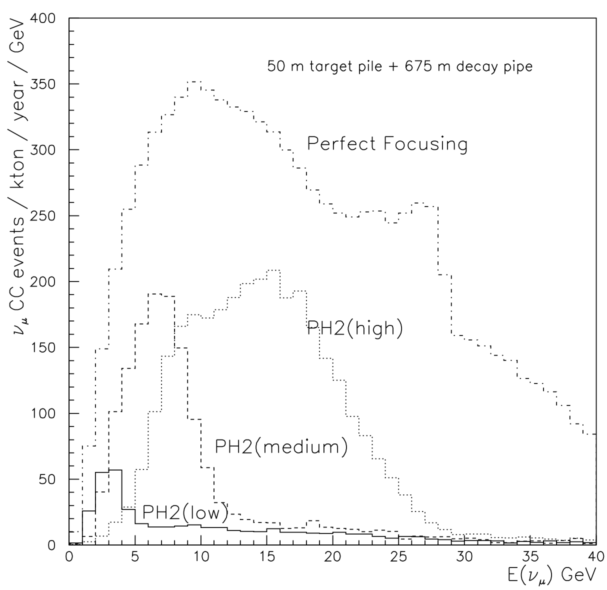

Fig. 4. Neutrino beam spectra for different NuMI beam configurations

spectrum of a hypothetical beam, where all of the secondary particles were collected and allowed to decay. The NuMI beam design provides overall efficiency of the order of 50%, in all three beam configurations.

4. MiniBOONE experiment: checking the LSND result

The primary goals of this experiment are:

- Unambiguously confirm or disprove the existence of the neutrino oscillation signal suggested by the LSND experiment.
- Provide precise measurements of the oscillation parameters, should the existence of the effect be established, or improve the existing limits if the effect is not confirmed.

The detector will consist of a 12 m diameter spherical tank filled with 769 tons of mineral oil, located at the distance of 500 m from the neutrino source. Cerenkov light emitted by particles produced in the neutrino interactions will be detected by 1220 eight-inch phototubes. The pattern of the detected Cerenkov rings will be used as a primary tool of the particle ID, as shown in Fig. 5. The outer 50 cm volume, optically isolated from the main detector volume and viewed 292 outward-pointing photomultipliers, will serve as a veto against cosmic rays.

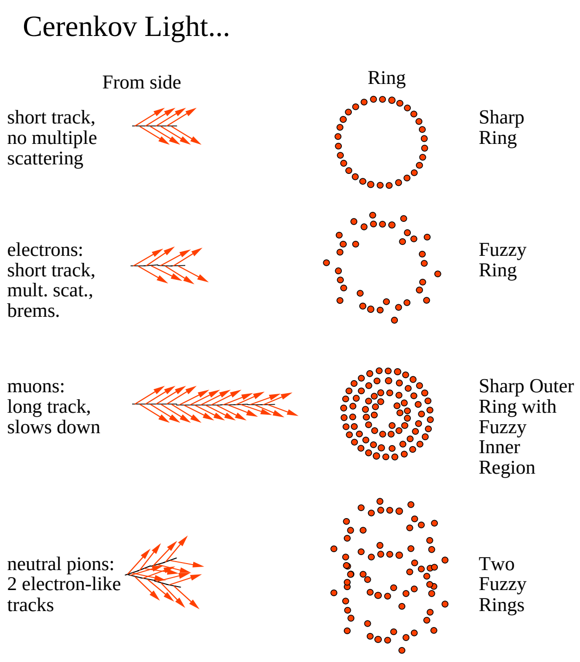

Fig. 5. Particle identification in the MiniBOONE experiment

The Booster neutrino beam is expected to yield 500,000 ν_μ quasi-elastic CC interaction per year in the MiniBOONE fiducial volume. The expected signal of the neutrino oscillations, predicted from the LSND results, will consist of a sample of 1000 identified ν_e CC interactions. The main background will be due to the intrinsic ν_e component of the beam: it is expected that there will be 1275 events of ν_e from muons decays and 425 events of ν_e from K decays. The background calculations can be experimentally verified by changing the length of the decay volume. An additional handle will be provided by the fact, that the sample of ν_e interactions due to $\nu_\mu \rightarrow \nu_e$ oscillations will have an energy distribution different from that expected ν_e component of the beam (see Fig. 6).

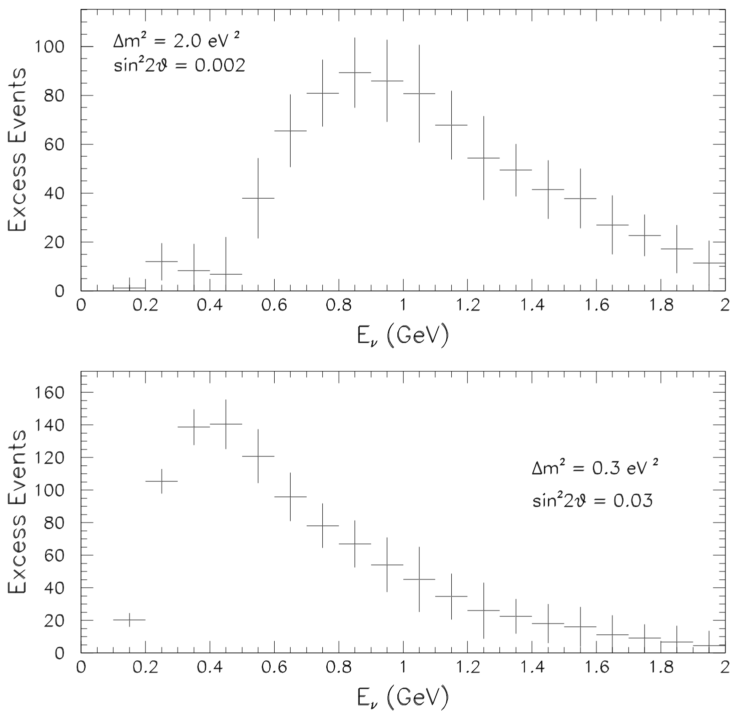

Fig. 6. Expected spectra of the excess ν_e interactions for two possible oscillation scenarios.

The large size of the expected LSND-inspired oscillation signal will enable a precise measurement of the underlying oscillation parameters whereas an absence of the signal will lead to greatly improved limits on possible $\nu_\mu \rightarrow \nu_e$ oscillations, shown in Fig. 7.

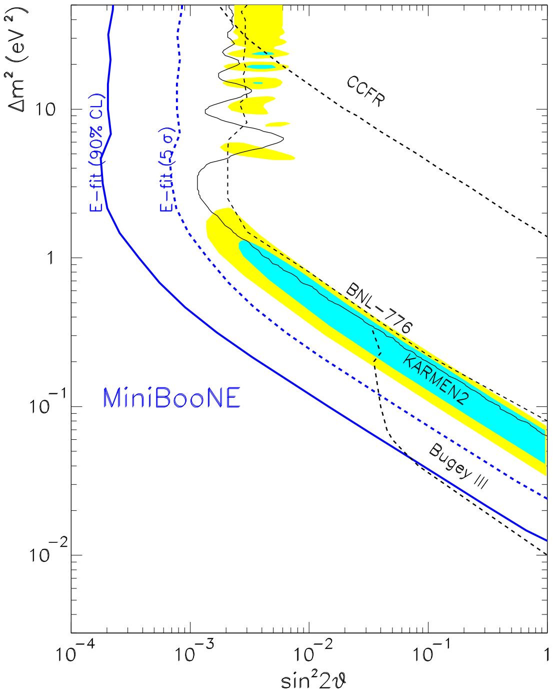

Fig. 7. Sensitivity of the MiniBOONE experiment

5. MINOS experiment: measuring oscillation parameters in the SuperKamiokande region

MINOS [8] experiment is designed to investigate neutrino oscillations in the region indicated by the atmospheric neutrino experiments. Two detectors, functionally identical, will be placed in the NuMI neutrino beam: one at Fermilab and the second one in Soudan iron mine, 732 km away.

5.1. Two detectors neutrino oscillation experiment

Two identical detectors placed in the same neutrino beam make the oscillation experiment relatively easy. Observed interactions of ν_μ can be divided into two classes: "CC"-like, with an identified μ track, and "NC"-like, muonless. The ratio of the observed numbers of the CC and NC-like events in the two detectors must be the same, provided that the same classification algorithm is used. This remains quite true, even if the beam spectra at the two detector locations differ slightly, as the ratio $\sigma^{\rm NC}/\sigma^{\rm CC}$ is energy independent.

If ν_μ undergoes oscillations, then some fraction of the original ν_μ beam will arrive at the far detector in an 'oscillated' form. The CC interaction of the oscillated neutrino (with the interaction cross section potentially reduced by a factor η with respect to the $\sigma_{\nu_\mu}^{\rm CC}$) will not, in general, produce a μ in a the final state and they will be classified as "NC"-like interactions. We will have, therefore:

$$\text{Near}\left\{\begin{array}{l} \mathrm{NC}_{\rm near} = \Phi_{\rm near}\left(\sigma^{\rm NC}+\varepsilon\sigma^{\rm CC}\right) \\ \mathrm{CC}_{\rm near} = \Phi_{\rm near}\left(1-\varepsilon\right)\sigma^{\rm CC} \end{array}\right. \tag{5}$$

and

$$\text{Far}\left\{\begin{array}{l} \mathrm{NC}_{\rm far} = \Phi_{\rm far}\left(\sigma^{\rm NC}+\varepsilon\sigma^{\rm CC}+\eta\xi\sigma^{\rm CC}\right) \\ \mathrm{CC}_{\rm far} = \Phi_{\rm far}\left(1-\varepsilon\right)\left(1-\xi\right)\sigma^{\rm CC} \end{array}\right. , \tag{6}$$

where ε is the fraction CC interactions misclassified as the "NC" events, ξ is the fraction of the beam "oscillated" and $\Phi_{\rm near}$, far is the total neutrino flux at the near/far detectors.

The double ratio $R = \left(\frac{\rm NC}{\rm CC}\right)_{\rm near} / \left(\frac{\rm NC}{\rm CC}\right)_{\rm far}$ is a particularly sensitive measure of the oscillations:

$$R \;=\; \frac{1}{1-\xi}\,\frac{1+(\varepsilon+\eta\xi)\,\frac{\sigma^{\rm CC}}{\sigma_{\rm NC}}}{1+\varepsilon\frac{\sigma^{\rm CC}}{\sigma_{\rm NC}}}\,. \tag{7}$$

R combines the sensitivities of the disappearance experiment, $\frac{1}{1-\xi}$ term, and the appearance experiment, $\eta\xi\frac{\sigma^{\rm CC}}{\sigma_{\rm NC}}$ term. In addition R has very small systematic uncertainty, as most of the neutrino flux uncertainties cancel. The value of R will provide additional information about the oscillation mode through the value of η:

$$\eta = \left\{\begin{array}{ll} 1 & \nu_\mu \to \nu_e \\ 0.2-0.3 & \nu_\mu \to \nu_\tau \\ 0 & \nu_\mu \to \nu_{\rm sterile} \end{array}\right. . \tag{8}$$

5.2. MINOS detectors

The MINOS experiment will consist of two, nearly identical detectors: one located at the Fermilab site, some 500 meters behind the decay pipe, and the second one, in northern Minnesota, at the distance of 732 km from Fermilab. The far detector will be located in a new cavern, which is under construction in the Soudan mine, close to the existing Soudan II detector.

The far MINOS detector will consist of two supermodules, 2.7 kton each. They will be constructed as magnetized steel octagons, 8 m in diameter, with a toroidal magnetic field about 1.5 T. Steel plates, 2.5 cm thick, will be interspersed with planes of scintillator strips, to provide calorimetric measurement of the deposited energy, with energy resolution $\Delta E/E \sim 0.6/\sqrt{E}$. The active detector elements will consist of strips of extruded scintillator, 1 cm thick and 4 cm wide. Scintillation light will be collected by waveshifting fibres and read out by Hamamatsu M16 photomultipliers. The fine granularity of the scintillator strips will allow them to be used as a tracking detector to measure muon trajectories and determine the muon momentum from the curvature in the magnetic field.

The near detector, on the Fermilab site, will be as similar as possible to the far detector, except for its size.

The neutrino beam line and the MINOS detectors are under construction and the data taking is expected to commence in 2003. The choice of the initial beam energy is currently under discussion and it may depend on the forthcoming results of the K2K experiment.

5.3. MINOS physics measurements

Two massive detectors and an intense neutrino beam constitute a powerful tool to investigate neutrino oscillations, especially when the beam energy can be chosen to maximize the oscillation signal. MINOS will perform several independent measurements, which will provide a clear and complete picture of the neutrino oscillations in the SuperKamiokande region. These measurements fall into three different categories:

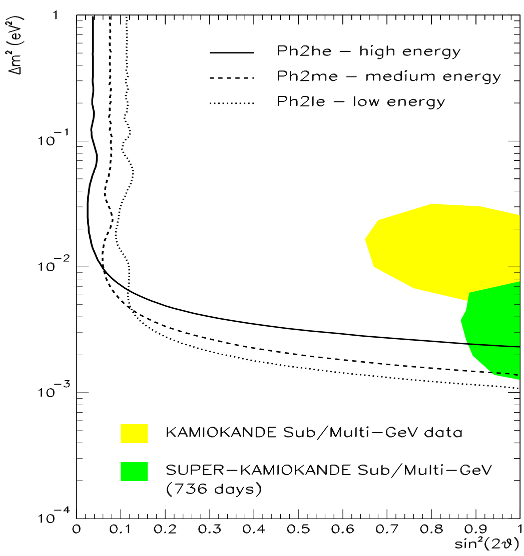

Fig. 8. 90% C.L. limits on the $\nu_\mu \to \nu_\tau$ oscillations parameters for 2 years exposure

- Firm evidence for the oscillations
  Near/far detector comparison will reduce the systematic uncertainties. The neutrino beam spectrum measurement with the near detector will constrain the predicted neutrino flux at the far detector. In the presence of the SuperKamiokande-indicated effect we expect at least two evidences for the oscillations:
  - A double ratio $R = \left(\frac{\mathrm{NC}}{\mathrm{CC}}\right)_{\mathrm{near}} / \left(\frac{\mathrm{NC}}{\mathrm{CC}}\right)_{\mathrm{far}}$ (see Eq. 7) different from one. The sensitivity of this measurement for different possible Δm^2 depends on the selected beam energy, as shown in Fig. 8
  - The ν_μ charged current interaction rate and the observed energy distribution. Presence of neutrino oscillations will lead to a characteristic oscillatory modification of the spectrum observed at the far detector, as shown in Fig. 9

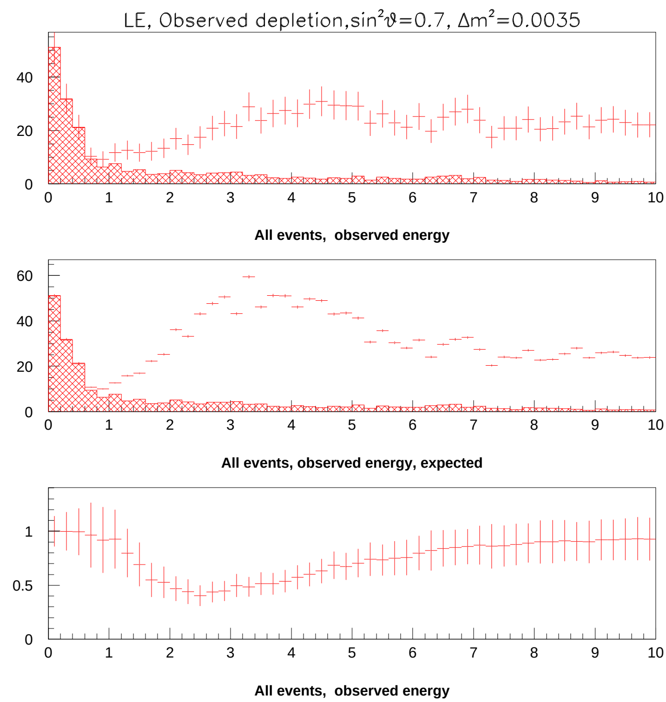

Fig. 9. Observed spectrum of the identified ν_μ CC events in the presence (top) or absence (middle) of oscillations. Shaded histogram represents contribution of misidentified NC events. Ratio of the observed and the expected distributions is shown at the bottom for 2 years exposure.

- Measurement of the oscillation parameters: Δm^2 and $\sin^2 2\theta$
  Fits of the observed depletion of the CC energy spectrum in Fig. 9 will provide a precise estimate of the oscillation parameters. The expected precision of this determination depends somewhat on the oscillation scenario and on the choice of the beam. Two years exposure of the MINOS detectors will yield measurements with the precision illustrated in Fig. 10.

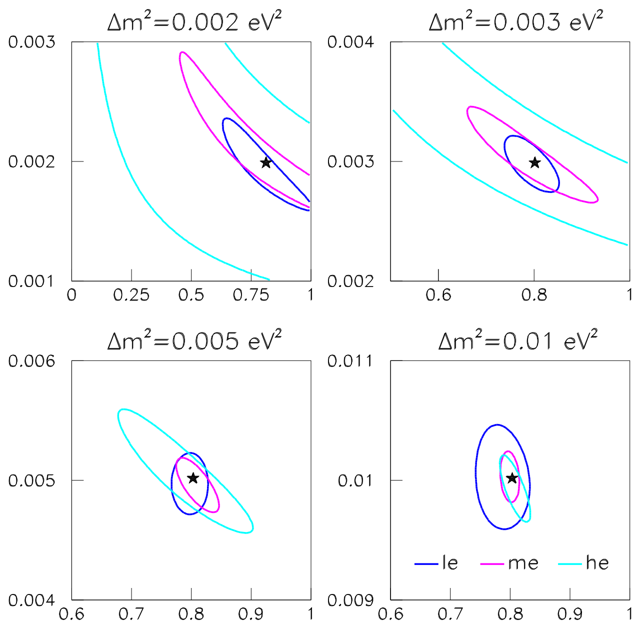

Fig. 10. The 68% C.L. error contours for the expected oscillation signal with $\sin^2 2\theta = 0.8$ and different Δm^2. Different contours represent measurements with different beams: low (le), medium (me) and high (he) energy and two years exposure.

- Determination of the oscillation mode(s)
  - $\nu_\mu \to \nu_{\text{sterile}}$?
    The large mixing angle indicated by the SuperKamiokande results leads to a significant contribution of the appearance term to R in Eq. (7). The measurement of R will provide a decisive demonstration for or against sterile neutrinos as a dominant oscillation mode over the entire region of SuperKamiokande.

— $\nu_\mu \to \nu_e$?

The fine granularity of the MINOS detector will allow for identification of the ν_e interactions by topological criteria with efficiency of the order of 15 – 20%. The background of the misidentified NC interactions as well as the intrinsic ν_e component of the beam (expected to be of the order of 0.6%) will be measured with high accuracy by the near detector. Fig. 11 shows the sensitivity of the MINOS detector to this oscillation mode in comparison with the limits from CHOOZ experiment.

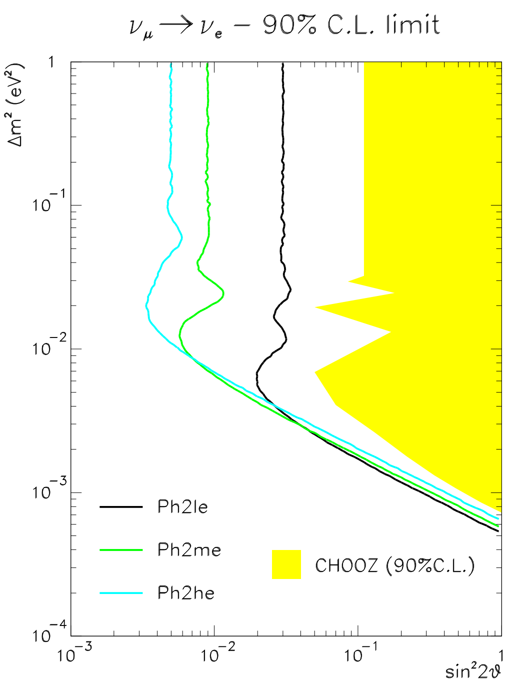

Fig. 11. The 90% C.L. limits for $\nu_\mu \to \nu_e$ oscillation parameters for two years exposure with different beams: low (Ph2le), medium (Ph2me) and high (Ph2he) energy.

— $\nu_\mu \to \nu_\tau$?

Circumstantial evidence for this oscillation mode will be provided by the measurement of R (Eq. (7)). For relatively high Δm^2, above 5×10^{-3} eV^2 a significant sample of CC ν_τ interactions can be identified by exclusive decay modes, like $\tau \to \pi$. The near detector will be again instrumental in reliable determination of the unavoidable background from the NC interactions.

6. Conclusions and outlook

New experiments, under construction at Fermilab, will help to clarify the situation with neutrino oscillations in the $\Delta m^2 > 0.001$ eV^2 region. The MiniBOONE experiment will settle, within coming 2–3 years, the issue of the LSND results by precise determination of the underlying oscillation parameters or by setting limits far outside the LSND-allowed region. MINOS experiment will decisively establish the phenomenon of neutrino oscillations and measure precisely the corresponding mixing angles and Δm^2 values in the region indicated by the SuperKamiokande experiment within next 5–6 years. The question of the dominant oscillation mode: $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_{\rm sterile}$ will be settled. The sub-dominant mode $\nu_\mu \rightarrow \nu_e$ will be established or the existing CHOOZ limit will be significantly improved. The next generation of the oscillation experiments will probably await a new generation of neutrino beams, derived from muon storage rings. The high intensity of such beams will make it possible to detect subtle effects like CP-violation or matter induced effects. By providing ν_e beams along with the ν_μ component, these beams will enable complete measurements of the neutrino mixing matrix elements.

It is a pleasure to thank and to congratulate the organizers, especially Prof. M. Jeżabek, for the flawless organization of such a pleasant and stimulating conference. Many of my colleagues in MINOS collaboration contributed to this presentation, I would like to thank in particular Dr. D. Petyt for his contribution to understanding of the physics potential of this experiment. Profs. J. Conrad and M. Shaevitz helped me to fully appreciate the beauty of the MiniBOONE experiment.

Apologizes go to all those, whom I neglected to quote properly. The number of relevant papers is overwhelming.

REFERENCES

[1] J. Bonn, Ch. Weinheimer, *Acta Phys. Pol.* **B31**, 1209 (2000).

[2] B. Pontecorvo, *Zh. Eksp. Teor. Fiz.* **33**, 549 (1957).

[3] Z. Maki, M. Nakagawa, S. Sakata, *Prog. Theor. Phys.* **28**, 870 (1962).

[4] Y. Fukuda *et al.*, *Phys. Rev. Lett.* **81**, 1562 (1998).

[5] D. Kielczewska, *Acta Phys. Pol.* **B31**, 1181 (2000).

[6] C. Athanassopoulos *et al.*, *Phys. Rev.* **C55**, 2079 (1997); see also: http://www.neutrino.lanl.gov/LSND/pubs/.

[7] http://www-boone.fnal.gov/.

[8] http://www.hep.anl.gov/ndk/hypertext/minos_tdr.html.