Experiments at Fermilab after Minos

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The recent Superkamiokande [1] results for the ν_μ deficit in the atmospheric neutrino flux have opened an exciting era in neutrino physics. Fermilab has started to investigate the physics potential of a new generation of neutrino experiments based either on muon storage ring neutrino factories or on conventional neutrino beams which use a "super" intense proton source (superbeams). A summary of the status and results from these studies are presented in this note.

One of the options recently considered for the next generation high energy accelerator is that of an intense muon source. Although the ultimate goal is the development of a muon collider [2], a neutrino source using neutrinos from the decays of the large number of muons produced by such a source, is an appealing first step towards this goal [3]. Building such a source is strongly motivated by the recent evidence for neutrino oscillations from SuperK [1], and also the LSND [4] result. If both observations and the solar neutrino problem are due to oscillations, then a comprehensive measurement of all neutrino oscillation parameters provides great opportunities to probe new physics.

The results of a feasibility study for the design of a neutrino factory based on a muon storage ring and its physics potential can be found in ref. [5] and ref. [6]. In this note, I will summarize the results of this physics study and discuss the alternative possibility to pursue such a program with a conventional neutrino source using an intense proton source, similar to the one needed for the muon storage ring. This second option could, in principle, minimize both the cost and complexity of the new machine.

In the next 10 years the measurement prospects for currently operating, planned, or proposed experiments are summarized below: (i) $\nu_\mu \to \nu_\tau, \nu_s$. If the δm^2 associated with the atmospheric deficit exceeds $\sim 2 \times 10^{-3}$ eV^2, δm^2 and $\sin^2 2\theta$ will be measured with precisions $\mathcal{O}(10\%)$; (ii) $\nu_\mu \leftrightarrow \nu_e$. If BooNE confirms LSND, the associated δm^2 and $\sin^2 2\theta$ would be measured with precisions $\mathcal{O}(10\%)$, and the oscillation framework could be more complicated. If not, then a first measurement of $\sin^2 2\theta_{13}$ could be obtained from $\nu_\mu \to \nu_e$ at long baseline experiments, if $\sin^2 2\theta_{13} > 10^{-2}$; (iii) $\nu_e \to \nu_\mu$, ν_τ, ν_s. Either one or none of the current solar neutrino deficit solutions will be remaining. If the $\nu_e \to \nu_\mu, \nu_\tau$ mode is favored then $\nu_e \to \nu_\tau$ will not have been observed at long baseline accelerator experiments.

Based on the above expectations, oscillation measurements in the era beyond the next generation of long baseline experiments would be most likely required to follow the following program: (i) establish the oscillation framework, by measuring both muon and electron neutrino transitions as a function of L/E (ii) make precise measurements or place stringent limits on all of the mixing–matrix elements (especially θ_{13}), (iii) determine the pattern of neutrino masses using matter effects, (iv) measure matter effects to confirm the MSW phenomenon, and (v) observe or place stringent limits on CP violation in the lepton sector.

Conventional neutrino beams are produced from the 2-body decay of charged pions (mainly) and kaons, which are secondary beams produced from the interaction of a proton beam with a target. The resulting flux is an almost pure muon flavor beam, with a small $\mathcal{O}(1\%)$ electron flavor component either from 3-body kaon decays or from the decays of the secondary muons produced from the 2-body decays. This ν_e flux constitutes a background source in searches for μ to e flavor transitions. Both the flavor composition and the energy spectrum of the flux depend heavily on the production model used to describe the secondary beam. In contrast, neutrino beams from 3-body muon decays in a storage ring have a composition of 50% muon and 50% electron flavor, $\mu^+ \to e^+\nu_e\overline{\nu_\mu}$ or $\mu^- \to e^-\nu_\mu\overline{\nu_e}$, and a spectrum which is very well constrained from the known decay kinematics and the storage ring parameters.

Clearly the ν_e beam from the muon storage ring is an asset for pursuing a program like the one outlined above. Assuming that LSND is not confirmed, $\nu_e \to \nu_\mu$ transitions give directly θ_{13}, and its value will determine if a search for CP violations is possible or not. Also, to establish the oscillation framework, more than one flavor beams are required. The $\nu_e \to \nu_\mu$ search allows for a "golden" appearance measurement; that of a "wrong-sign" muon observation, from the charged current (CC) interactions of the $\nu_m u$ flux from the oscillated ν_e's. "Wrong-sign" muon here refers to muons with the opposite sign of the one expected from the CC interactions of the muon flavor already present in the flux generated from muon decay (for example, if the beam is generated from μ^- decay, the $\overline{\nu_e} \to \overline{\nu_\mu}$ produces a μ^+ in CC interactions at the detector, while the ν_μ produces a μ^-). This calls for detectors with good muon identification and charge determination. The simplest case for such a detector is a magnetized iron-scintillator calorimeter, a detector well studied with current generation experiments. The backgrounds in such a measurement are initiated from (i) π or K decay events producing a "wrong-sign" muon in neutral current interactions (NC), (ii) charm production and π or K decay in CC interactions with the "right-sign" muon lost, and (iii) π punch-through in NC interactions. A combination of energy and transverse momentum cuts on the muon can reduce such backgrounds to the $2-4\times10^{-4}$ level (with respect to the total CC interaction rate), maintaining a signal acceptance on the order of 50% (depending on oscillation scenario). Other detector technologies, based on a liquid argon TPC (ICANOE type detector with added muon spectrometer) and water Cerenkov detectors, are discussed in ref. [6].

Table 1
Comparison of neutrino event rates in the absence of oscillations between conventional and muon-derived beams of comparable energies, and a 1.6MW proton source (at a baseline of 732km).

	$<E_\nu>$	Events/kt-yr		E_μ
Beam	(GeV)	π	μ	(GeV)
MINOS-LE	3.5	1800	120	4.5
MINOS-ME	7	5760	1120	9.1
MINOS-HE	15	12800	9430	18.2
	20		21770	30

The details needed to describe the results of the study are numerous and depend on the type of detector and the physics assumptions, so only a summary of the conclusions is presented. A 20 GeV storage ring providing 10^{19} muon decays per year would be the "entry–level" facility allowing either (i) the first observation of $\nu_e \to \nu_\mu$ oscillations, the first direct measurement of matter effects, and a determination of the pattern of neutrino masses from the sign of δm^2_{32}, or (ii) a very stringent limit on $\sin^2 2\theta_{13}$ and a first comparison of the sum of all appearance modes with the disappearance measurements. The optimum baseline for this physics program is on the order of 3000 km or greater, for which matter effects are substantial. A 20 GeV neutrino factory providing 10^{20} muon decays per year would be the next step (or alternatively a higher energy facility providing a few $\times10^{19}$ decays per year). This would enable the first observation of, or meaningful limits on, $\nu_e \to \nu_\tau$ oscillations, and precision measurements of the leading oscillation parameters. Finally, a facility which provides $O(10^{21})$ decays per year would enable the measurement of, or stringent limits on, CP violation in the lepton sector.

In the case of the absolutely minimal future scenario, the study of the physics reach of conventional "superbeams" focuses on the muon to electron flavor transitions. As shown in Table 1, a conventional beam (two-horn NUMI configuration), has higher rates per Watt of proton power than a beam from a storage ring, below neutrino energies of 15 GeV. In the conventional beam case, the signal extraction is harder, since the detection of electrons is more challenging than the detection of “wrong-sign” muons. In addition, a “near” detector appears to be necessary, since the beam spectrum is not very well constrained. The backgrounds which affect the measurement in the conventional case are: (i) intrinsic ν_e, (ii) misidentification of NC interactions for electron interactions, and (iii) $\nu_\mu \to \nu_\tau, \tau \to e$ events, which will occur at a significant level for $\sin^2 2\theta_{23} \sim 1$. To deal with (i) and bring the ν_e/ν_μ fraction in the beam to acceptable levels (0.1%) a low energy primary proton beam and a narrow-band beamline for the secondaries are preferred. Both requirements cut down the signal reach since they reduce the overall event rate and restrict the energy spectrum of the neutrino beam. The techniques to deal with (ii) and (iii) depend both on the detector technology used and the beamline configuration. For example, for neutrino energies below 1GeV and with a Water Cerenkov detector, it has been shown that the NC background fraction can be reduced to 1% of the total expected rate. A discussion of the performance obtained by different types of detectors can be found in ref. [7]. One of the conclusions of this study is that the sum of the backgrounds with neutrino beams of a few GeV and above does not get below the 10^{-3} level. The θ_{13} reach expected from upgraded conventional beams from this study is plotted together with the summary of the expectations for a muon storage ring neutrino factory (as a function of muon energy) in figure 1.

In summary, the possible scenarios considered for a future Fermilab Long Baseline program are based either on a multi-GeV muon storage ring neutrino factory or a conventional neutrino source, most probably in the few to sub-GeV range. Both options require an upgrade of FNAL’s proton source, about 4 times the power of the MINOS source, and share some of the requirements in detector development. Which option would be optimal depends on many factors: (i) the results of the next generation neutrino experiments, and most importantly the magnitude of θ_{13} and the confirmation (or not) of the LSND result (ii) feasibility and cost of a high energy and intensity storage ring (iii) detector technology. After completing a feasibility study on both

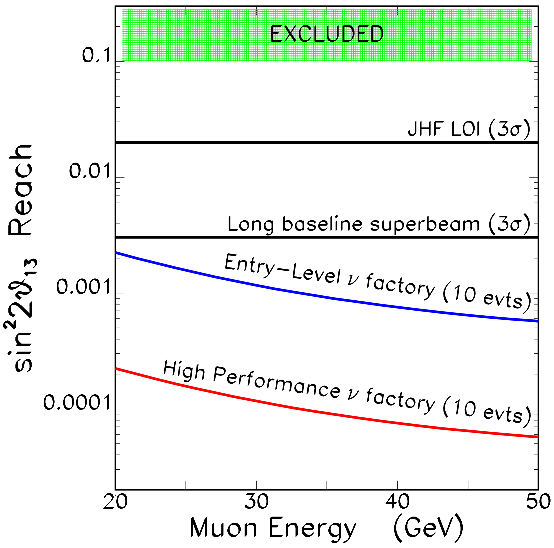

Figure 1. Summary of the θ_{13} reach (at the 3σ level) of the next planned set of experiments [8], along with the reach of an upgraded conventional beam, assuming a much upgraded detector in all cases. Other assumptions for these experiments can be found in ref. [6].

the machine and the physics reach of neutrino factory, Fermilab is supporting a study on the physics reach and detector requirements of conventional beams and is participating in the R&D and design efforts needed for a neutrino factory.

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