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NEUTRINO PROJECT X AT FERMILAB [a]

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ABSTRACT

In this talk I will give a brief description of Project X and an outline of the Neutrino Physics possibilities it provides at Fermilab.

1. Current Neutrino Experiments at Fermilab:

Fermilab is currently running three neutrino experiments: MINOS, MiniBooNE and SciBooNE. MINOS uses 120 GeV protons from the main injector with a nominal beam power of 200kW and currently has the world's best measurement of $|\Delta m^2_{32}|$. Whereas, MiniBooNE and SciBooNE are in the booster neutrino beamline (BNB) which uses 8 GeV protons. Both of these experiments are measuring neutrino cross sections relevant for future neutrino experiments. Whereas, MiniBooNE is also looking for deviations from the three active neutrino Standard Model that has been assembled in the last ten years and in particular confirming or refuting the LSND anomaly.

2. Project X and Neutrinos

Project X is the generic name given to a new intense proton source at Fermilab. This source would produce more than 2 MW of proton power at 50 to 120 GeV, using the main injector, which could be used for a variety of long baseline neutrino experiments. A new 8 GeV linac would be required with many components aligned with a possible future ILC. In addition to the beam power from the main injector there is an additional 200 kW of 8 GeV protons that could be used for kaon, muon, ... experiments.

2.1. Phase I

The first phase of Project X is to increase the beam power in NuMI (Neutrinos from the Main Injector) from 200 kW to 700 kW and to build the 15 kton liquid scintillator NOνA detector in Ash River, 810 km from Fermilab, so as to explore

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both $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ at the sub 1% level. This will put a limit of $\sin^2 2\theta_{13}$ at the 0.01 level, see Fig. 1. This experiment will also give us the first glimpse of the neutrino mass hierarchy and/or the first restrictions of the range of the CP violating phase δ_{CP}.

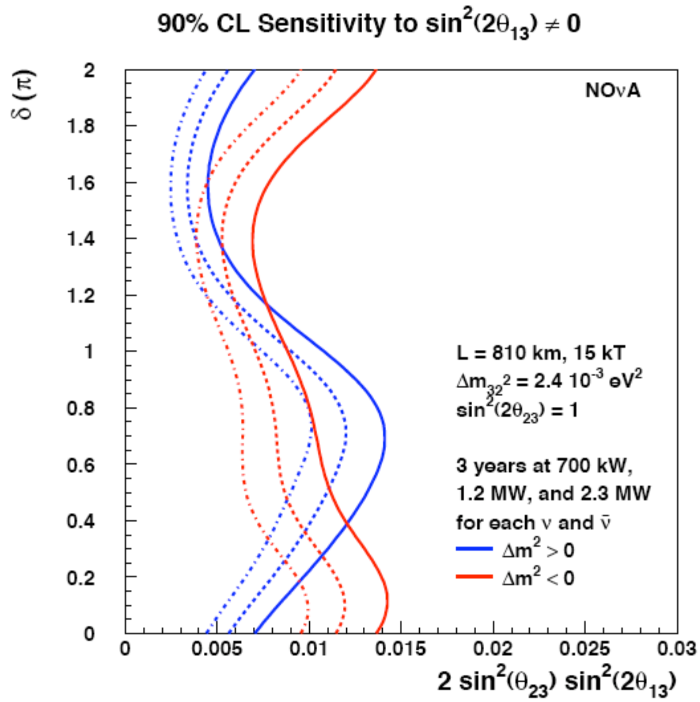

Figure 1: The 90% sensitivity to $\sin^2 2\theta_{13}$ for NOνA [1] assuming equal running time for neutrinos and anti-neutrinos. The blue (red) curves is for the normal (inverted) hierarchy. The three lines from right to left are for 0.7, 1,2 and 2.3 MW of protons on target respectively. These curves correspond to $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ at the sub 1% level.

Also the MINERvA experiment operating in the NuMI near detector hall will perform precision measurements of neutrino cross sections above 1 GeV on various nuclear targets. The information obtained from this experiment will be invaluable for future very long baseline neutrino oscillations.

2.2. Phase I · V

Phase I.V consists of the possibility of putting a 5 kton Liquid Argon TPC, LAr5, in the MINOS cavern at Soudan. This assumes a successful R&D program on smaller LAr TPC's. Fermilab together with various university groups are involved in such an R&D program and have constructed a small detector (0.3 ton active volume), call ArgoNeuT, which is nearly operational in the MINOS near detector hall. Following ArgoNeut will be a 200 ton detector in the BNB, call microBooNE, which will also

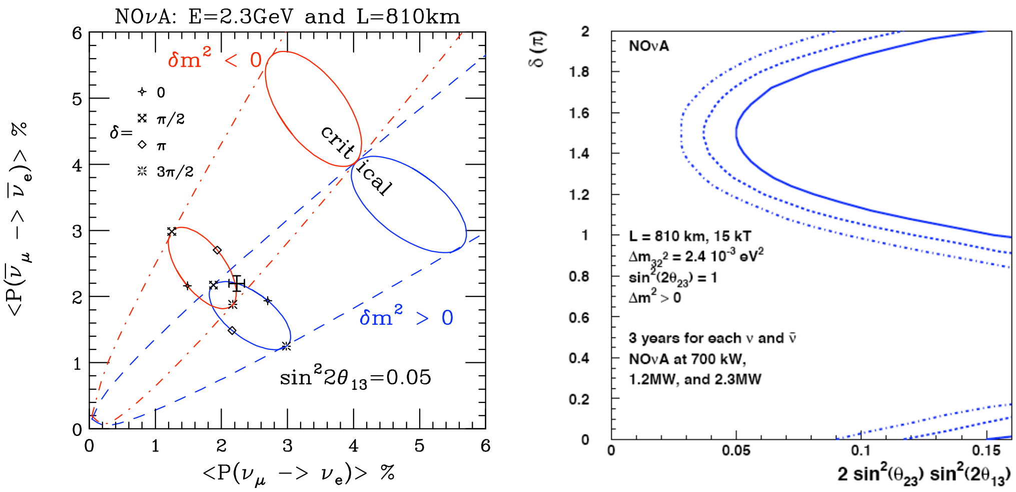

Figure 2: The left panel is the bi-probability plot, $\nu_\mu \to \nu_e$ verses $\bar{\nu}_\mu \to \bar{\nu}_e$ for the NOνA experiment showing the critical value of θ_{13} ($\sin^2 2\theta_{13} = 0.11$) as well as two (out of four) of the ellipses which pass through the data point (large cross) with $\sin^2 2\theta_{13} = 0.05$ [2]. The right panel shows the parameters in $\sin^2 2\theta_{13}$ v δ plane that NOνA [1] determines the hierarchy assuming it is normal.

push the LAr technology as well as explore neutrino interactions in LAr at lower energies and address the miniBooNE lower energy "electron" excess. The LAr5 detector at Soudan will significantly enhance the sensitivity of NOvA as well as demonstrate a new detector technology which could be scaleable to 100 kton detector. See Fig.3.

2.3. Phase II

Phase II is the replacement of the current Fermilab booster with a new 8 GeV linac cable of delievering 150 kW of beam power to the main injector. Thus the beam from the main injector at 120 GeV would be 2.3 MW. This would significantly enhance the reach of NOνA plus LAr5 since these two experiments are statistics limited.

The Project X linac is based on an 8 GeV superconducting H^- linac and would be aligned as much as possible with the ILC. The beginning of the linac would be specially designed for H^- but the downstream 7 GeV would use the ILC cryomodules and RF distribution system.

2.4. Phase III

Phase III would consist of building a new neutrino beamline to DUSEL at Homestake, 1300 km from Fermilab as well as new 0.1 to 1 megaton detector at DUSEL. The beamline would be powered by 50 to 120 GeV protons at a power greater than 2 MW. Whether this is an on axis beam or a slightly off axis beam (say 0.5 degrees) depends on the optimization of the number of events near the first and second os-

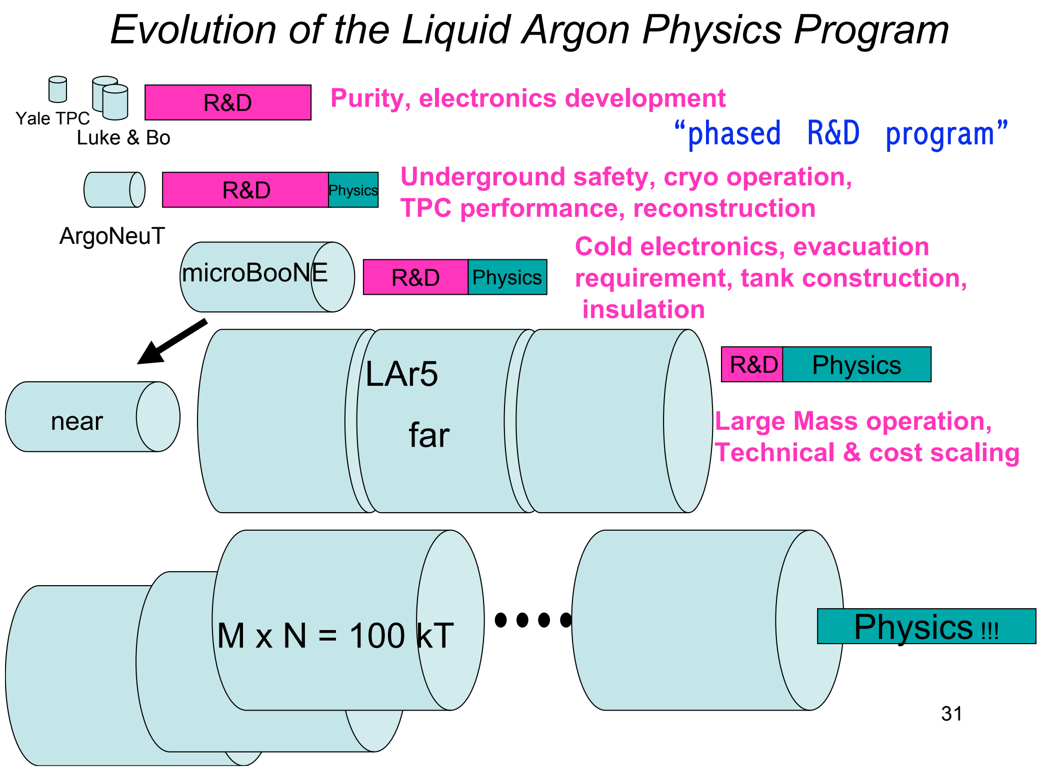

Figure 3: Possible evolution of a Liquid Argon detector program[3)] in North America.

cillation maxima compared to the neutral current π^0's coming from higher energy neutrinos. These π^0 events can mimic ν_e events in the detector and are the principle background and need to be reduced to the level of the intrinsic ν_e background. These higher energy neutrinos are suppressed in the off axis option.

The detector technology would be either water cerenkov similar to SuperK or a LAr TPC or a combination of both. The water cerenkov detector could be built with little R&D but would have to be larger than LAr due to it's lower efficiency. Whereas substantial R&D is required for a large LAr TPC but this technology has a higher efficiency than water cervenkov due to it's better discrimination of electron and gamma (π^0) events. LAr also has a enhanced sensitivity to proton decay in the $K^+\nu$ channel over water Cerenkov which also makes it an attractive alternative assuming a successful R&D program. For both detector technology a modular design is probably necessary to get the very large fiducial volumes required. If affordable, a combination of both detectors would be very powerful.

2.4.1. Long Baseline: $\boldsymbol{\nu_\mu \longrightarrow \nu_e}$

The amplitude for $\nu_\mu \rightarrow \nu_e$ can be simple written a sum of three amplitudes, one associated with each neutrino mass eigenstate,

$$U^*_{\mu 1} e^{-i m_1^2 L/2E} U_{e1} + U^*_{\mu 2} e^{-i m_2^2 L/2E} U_{e2} + U^*_{\mu 3} e^{-i m_3^2 L/2E} U_{e3}.$$

The first term can be eliminated using the unitarity of the MNS matrix and thus the appearance probability can be written as follows[4)]

$$P(\nu_\mu \rightarrow \nu_e) \quad \approx \quad \left| \sqrt{P_{atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}} \right|^2 . \tag{1}$$

Δ_{jk} is used as a shorthand for the the kinematic phase, $\delta m^2_{jk} L/4E$. As the notation suggests the amplitude $\sqrt{P_{atm}}$ only depends on δm^2_{31} and $\sqrt{P_{sol}}$ only depends on δm^2_{21}. For propagation in the matter, these amplitudes are simple given by

$$\begin{aligned} \sqrt{P_{atm}} &= \sin\theta_{23}\ \sin 2\theta_{13}\ \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)}\ \Delta_{31} \\ \sqrt{P_{sol}} &= \cos\theta_{23}\ \sin 2\theta_{12}\ \frac{\sin(aL)}{(aL)}\ \Delta_{21}. \end{aligned} \tag{2}$$

The matter potential is given by $a = G_F N_e/\sqrt{2} \approx (4000\ km)^{-1}$ and the sign of Δ_{31} (and Δ_{32}) determines the hierarchy; normal $\Delta_{31} > 0$ whereas inverted $\Delta_{31} < 0$. When a is set to zero one recovers the vacuum result. See Fig.4 [5)].

For anti-neutrinos $a \rightarrow -a$ and $\delta \rightarrow -\delta$. Thus the phase between $\sqrt{P_{atm}}$ and $\sqrt{P_{sol}}$ changes from $(\Delta_{32} + \delta)$ to $(\Delta_{32} - \delta)$. This changes the interference term from

$$2\sqrt{P_{atm}}\sqrt{P_{sol}} \cos(\Delta_{32} + \delta) \quad \Rightarrow \quad 2\sqrt{P_{atm}}\sqrt{P_{sol}} \cos(\Delta_{32} - \delta). \tag{3}$$

Expanding $\cos(\Delta_{32} \pm \delta)$, one has a CP conserving part $2\sqrt{P_{atm}}\sqrt{P_{sol}} \cos\Delta_{32} \cos\delta$ and the CP violating part

$$\mp 2\sqrt{P_{atm}}\sqrt{P_{sol}} \sin\Delta_{32} \sin\delta. \tag{4}$$

Therefore CP violation is maximum when $\Delta_{32} = (2n+1)\frac{\pi}{2}$ and grows as n grows. Notice also, that for this term to be non-zero the kinematical phase Δ_{32} cannot be $n\pi$. This is the neutrino counter part to the non-zero strong phase requirement for CP violation in the quark sector.

The asymmetry between $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar\nu_\mu \rightarrow \bar\nu_e)$ is a maximum when $\sqrt{P_{atm}} = \sqrt{P_{sol}}$. At the first oscillation maximum, $\Delta_{31} = \pi/2$, this occurs when $\sin^2 2\theta_{13} = 0.002$ in vacuum. For values of $\sin^2 2\theta_{13} < 0.002$ the oscillation probabilities are dominated by P_{sol} and thus observing the effects of non-zero $\sin^2 2\theta_{13}$ become increasing more challenging.

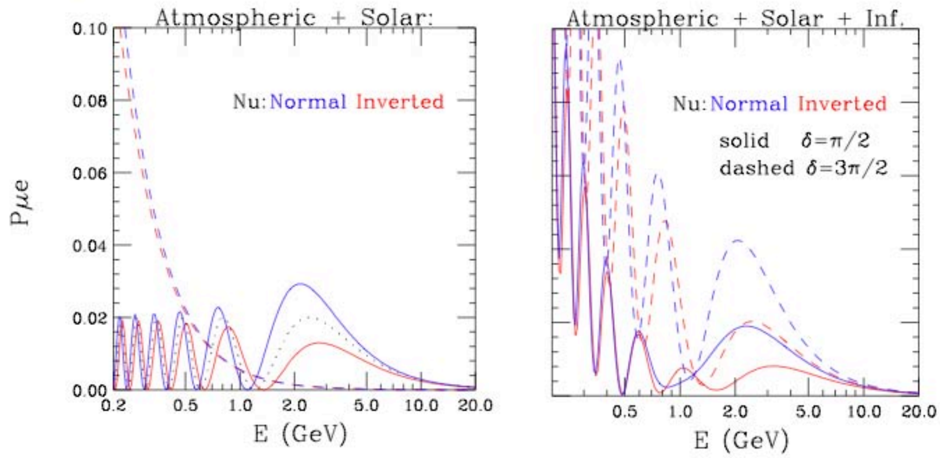

Figure 4: The left panel shows the two components P_{atm} and P_{sol} in matter for the normal and inverted hierarchies for $\sin^2 2\theta_{13} = 0.04$ and a baseline of 1200 km. The right panel shows the total probability including the interference term between the two components for various values of the CP phase δ for the neutrino. Notice that the coherent sum of two amplitudes shows a rich structure depending on the hierarchy and value of CP phase. These curves can also be interpreted as anti-neutrino probabilities if one interchanges the hierarchy AND the values of the CP phase.

2.5. Beyond Phase III

The reach for $\sin^2 2\theta_{13}$, the mass hierarchy and CP violating for the Fermilab Project X program is given in Fig.5. If $\sin^2 2\theta_{13}$ is significantly smaller than 10^{-3} or precision measurements of the oscillation parameters are required then protons from Project X could be used for a neutrino factor with detector(s) at DUSEL. With further technical developments these facilities could also be used for a future multi-TeV muon collider.

3. Summary and Conclusions

A brief outline of Project X is given and a possible neutrino program that could be performed. At this stage many options need to be studied in detail especially with regard to various funding profiles. For example, it the beamline to DUSEL could be constructed earlier than currently envisaged, putting the LAr5 detector at DUSEL may make more sense than at Soudan. However, it is clear that an intense neutrino source combined with very massive detectors is required to explore the size of θ_{13}, the

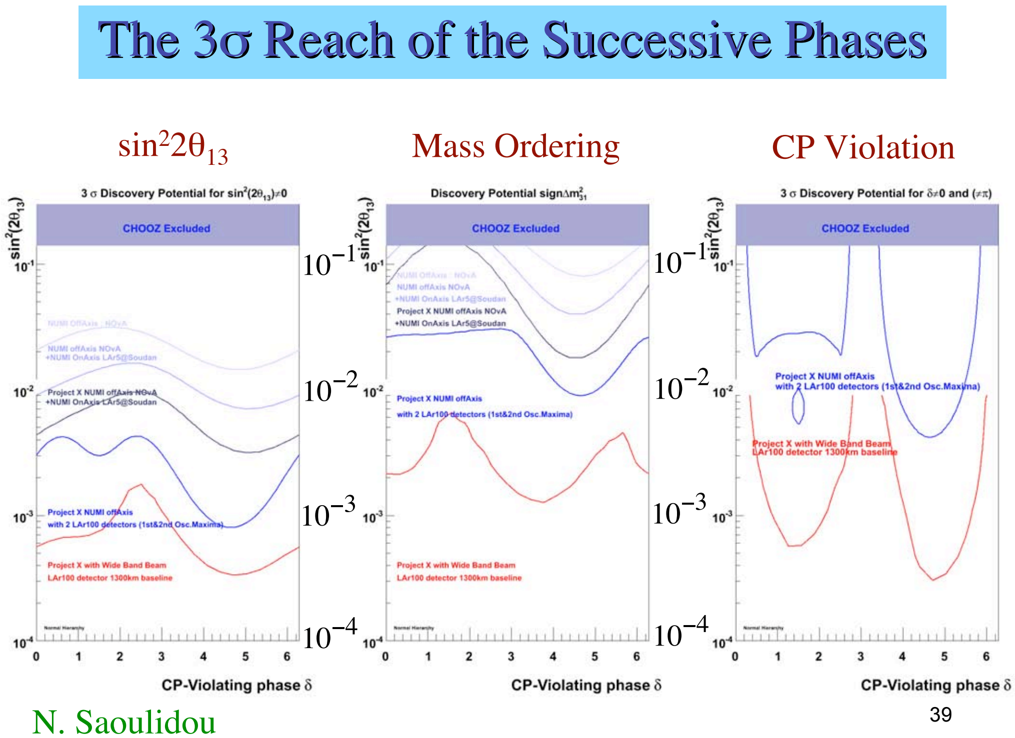

Figure 5: The evolution of the reach for $\sin^2 2\theta_{13}$, the mass hierarchy and CP violating for the Fermilab Project X program [6)].

neutrino mass hierarchy and the CP violation in the neutrino sector.

4. Acknowledgements

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5. References

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