

Accelerator Neutrino Programme at Fermilab *

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The accelerator neutrino programme in the USA consists primarily of the Fermilab neutrino programme. Currently, Fermilab operates two neutrino beamlines, the Booster neutrino beamline and the NuMI neutrino beamline and is in the planning stages for a third neutrino beam to send neutrinos to DUSEL. The experiments in the Booster neutrino beamline are miniBooNE, SciBooNE and in the future microBooNE, whereas in the NuMI beamline we have MINOS, ArgoNut, MINERVA and coming soon NO ν A. The major experiment in the beamline to DUSEL will be LBNE.

1. Neutrino Standard Model

The flavor content of the three neutrino mass eigenstates is given in Fig. 1. The current questions in this model are what is the size of

$$\sin^2 \theta_{13}, \quad (\sin^2 \theta_{23} - \frac{1}{2}), \quad (\sin^2 \theta_{12} - \frac{1}{3}), \quad \text{sign}(\delta m_{31}^2) \quad \text{and} \quad \sin \delta_{CP} \quad (1)$$

It is possible that the first three of these are related to some small parameter like $\delta m_{21}^2/\delta m_{31}^2 \approx 0.03$ raised to some power, n . From current experiments the size of this power is constrained to be larger than one, $n > 1$, except for $(\sin^2 \theta_{23} - \frac{1}{2})$ where the lower bound is weaker, approximately $n > 1/2$.

This could be due to some broken Tri-Bi-Maximal symmetry which would be very interesting and exciting. Another possibility is that it is coincidental which would be much less interesting from a theorists perspective.

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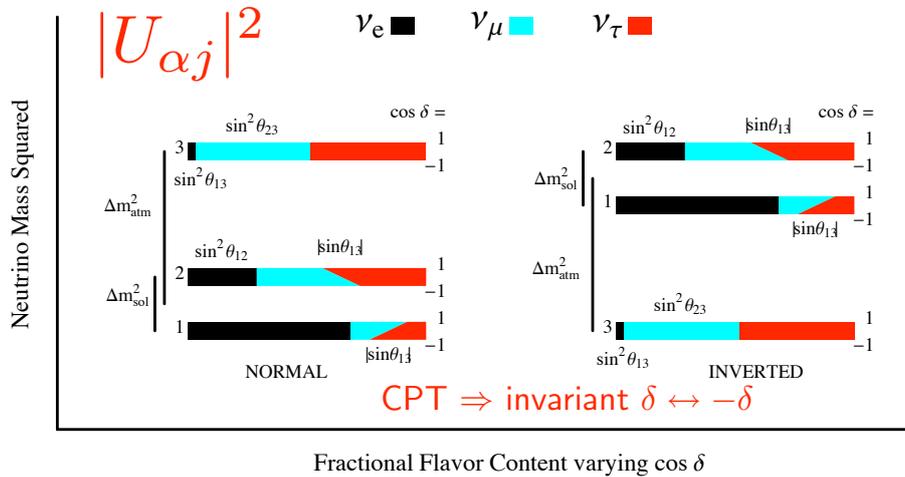


Fig. 1. The flavor content of the neutrino mass eigenstates[1]. The width of the lines is used to show how these fractions change as $\cos \delta_{CP}$ varies from -1 to +1. Of course, this figure must be the same for neutrinos and anti-neutrinos if CPT is conserved.

2. Current Neutrino Program at Fermilab

Currently there are two operating neutrino beamlines at Fermilab with another being proposed. These are

- The Booster Neutrino Beamline which uses 8 GeV protons from the Booster. Currently only miniBooNE is taking data in this beamline since SciBooNE has completed it's data taking and mircoBooNE is still in the approval process.
- NuMI (Neutrinos from the Main Injector) which uses 120 GeV protons from the main injector. This beamline sends neutrinos to the MINOS near and far detectors. Also in the near detector hall is ArgoNut and MINERVA. ArgoNut is taking data and MINERVA will start data taking in 2010. The NO ν A near and far detectors will also use neutrinos from this beamline.
- In addition there is a proposal to build a third neutrino beamline to send a neutrino beam from Fermilab to DUSEL in the Homestake mine. This beamline will initially be powered by protons from the main injector but will eventually be powered by a very high intensity proton beam (>2MW) from Project X.

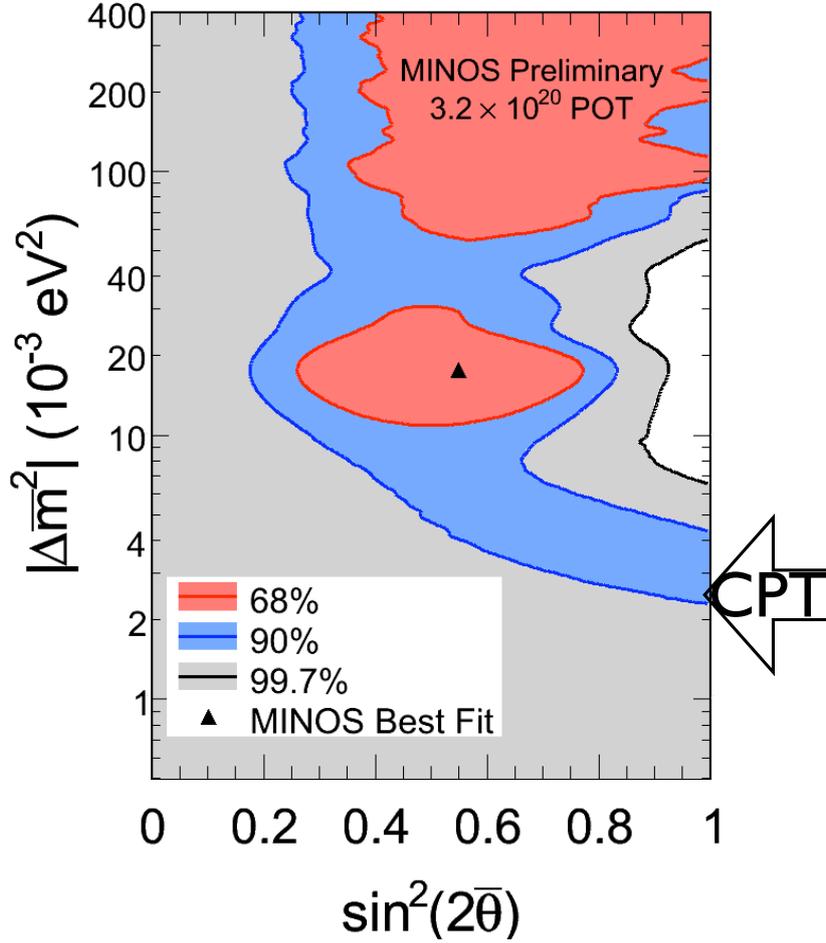


Fig. 2. The δm_{32}^2 v $\sin^2 2\theta_{23}$ allowed region obtained using the anti-neutrinos in the neutrino beam. The CPT conserving point is within the 90% contour. MINOS has now finished a dedicated run with anti-neutrinos to tighten the contours on this plot.

MINOS uses 120 GeV protons from the main injector with a nominal beam power of 300kW and currently has the world's best measurement of $|\Delta m_{32}^2|$ using the neutrino beam [2],

$$|\Delta m_{32}^2| = 2.43 \pm 0.13 \times 10^{-3} \text{ eV}^2, \quad (2)$$

and is currently running in anti-neutrino mode to check whether or not CPT is violated in the neutrino sector, see Fig.2.

MiniBooNE and SciBooNE are measuring neutrino cross sections relevant for future neutrino experiments. Also, 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 to confirming or refuting the LSND anomaly. No evidence in support of LSND has been found but a unexplained low energy excess in the 200 to 475 MeV was observed [3],

$$\text{Excess Events (200 to 475 MeV)} = 128.8 \pm 20.4 \pm 38.3. \quad (3)$$

While in the anti-neutrino channel the evidence for an excess is inconclusive.

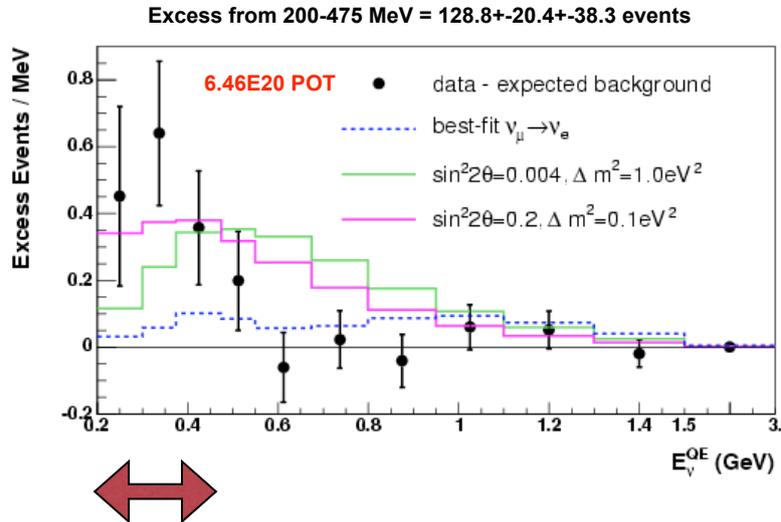


Fig. 3. The excess events as seen in neutrino running at MiniBooNE. Between 200 and 475 MeV, a clear excess is seen.

2.1. $NO\nu A$

The $NO\nu A$ project consists of increasing the beam power in NuMI (Neutrinos from the Main Injector) from 300 kW to 700 kW and to build the 15 kton liquid scintillator $NO\nu A$ detector in Ash River, 810 km from Fermilab, so as to explore 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 on $\sin^2 2\theta_{13}$ at the 0.01 level, see Fig. 4. 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} , see Fig. 5.

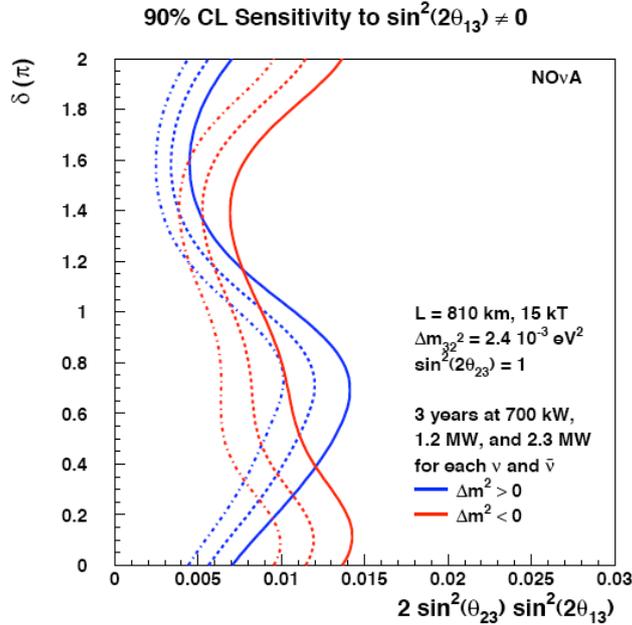


Fig. 4. The 90% sensitivity to $\sin^2 2\theta_{13}$ for NO ν A [4] assuming equal running time for neutrinos and anti-neutrinos. The blue (red) curves is for the normal (inverted) hierarchy. The three lines from right to left are for 0.7, 1.2 and 2.3 MW of protons on target respectively. These curves 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. The Physics of Long Baseline: $\nu_\mu \rightarrow \nu_e$

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

$$U_{\mu 1}^* e^{-im_1^2 L/2E} U_{e1} + U_{\mu 2}^* e^{-im_2^2 L/2E} U_{e2} + U_{\mu 3}^* e^{-im_3^2 L/2E} U_{e3}.$$

The first term can be eliminated using the unitarity of the MNS matrix and thus the appearance probability can be written as follows[6]

$$P(\nu_\mu \rightarrow \nu_e) \approx \left| \sqrt{P_{atm}} e^{-i(\Delta_{32} + \delta)} + \sqrt{P_{sol}} \right|^2. \quad (4)$$

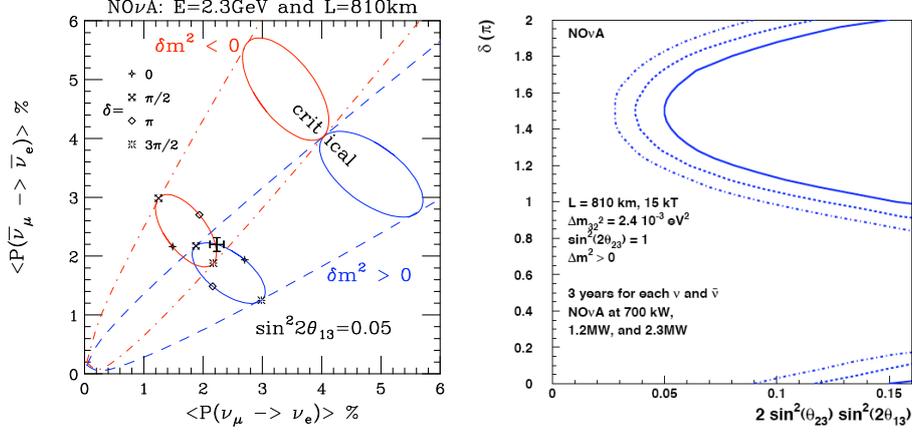


Fig. 5. The left panel is the bi-probability plot, $\nu_\mu \rightarrow \nu_e$ versus $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ for the NO ν A experiment showing the critical value of θ_{13} ($\sin^2 2\theta_{13} = 0.11$) as well as two (out of four) of the ellipses which pass through the data point (large cross) with $\sin^2 2\theta_{13} = 0.05$ [1]. The right panel shows the parameters in $\sin^2 2\theta_{13}$ v δ plane that NO ν A [4] determines the hierarchy assuming it is normal.

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

$$\begin{aligned}\sqrt{P_{atm}} &= \sin \theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \\ \sqrt{P_{sol}} &= \cos \theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{(aL)} \Delta_{21}.\end{aligned}\quad (5)$$

The matter potential is given by $a = G_F N_e / \sqrt{2} \approx (4000 \text{ km})^{-1}$ 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.6 [7].

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

$$2\sqrt{P_{atm}}\sqrt{P_{sol}} \cos(\Delta_{32} + \delta) \Rightarrow 2\sqrt{P_{atm}}\sqrt{P_{sol}} \cos(\Delta_{32} - \delta).\quad (6)$$

Expanding $\cos(\Delta_{32} \pm \delta)$, one has a CP conserving part

$$2\sqrt{P_{atm}}\sqrt{P_{sol}} \cos \Delta_{32} \cos \delta\quad (7)$$

and the CP violating part

$$\mp 2\sqrt{P_{atm}}\sqrt{P_{sol}}\sin\Delta_{32}\sin\delta. \quad (8)$$

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 $n\pi$. The first person who emails me having noticed this statement will get a prize. I'm checking to see if anybody reads these things. 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.

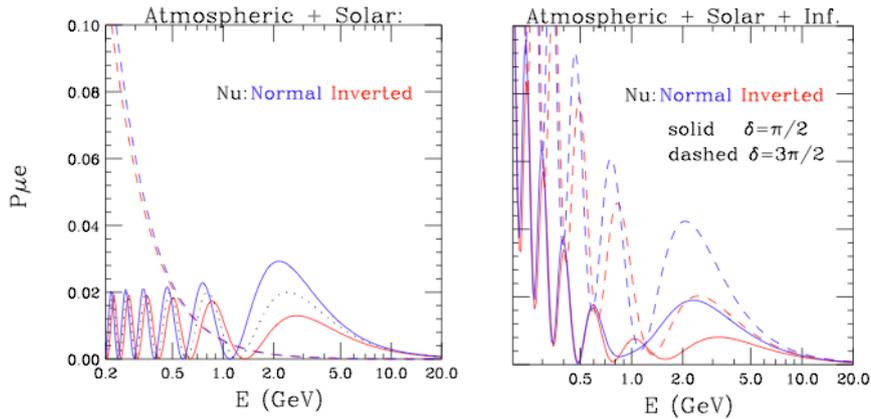


Fig. 6. The left panel shows the two components P_{atm} and P_{sol} in matter for the normal and inverted hierarchies for $\sin^2 2\theta_{13} = 0.04$ and a baseline of 1200 km. The right panel shows the total probability including the interference term between the two components for various values of 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.

2.3. DUSEL and LBNE

Even if $\sin^2 2\theta_{13} > 0.01$, a further experiment will be needed to determine the precise value of the CP violating phase, δ_{CP} . Fermilab has

proposed to build a new neutrino beamline to DUSEL and to build a large neutrino detector there. This experiment is called the Long Baseline Neutrino Experiment (LBNE). The detector would consist of 300 ktons of water Cerenkov detectors or 50 ktons of Liquid Argon detectors or some combination of both.

The new neutrino beamline would be initially powered by the main injector but then by Project X which would deliver 2.2 MW of protons at 50-120 GeV. Project X in addition could provide up to 2 MW of protons at 2-3 GeV for Kaon, Muon and other experiments.

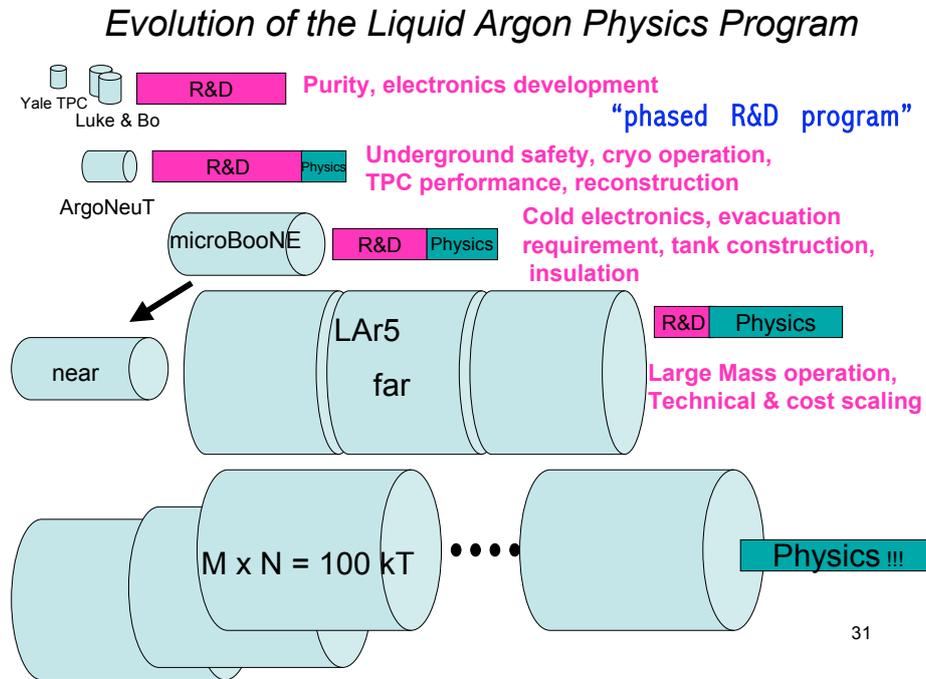
The detector technology would be either water cerenkov similar to SuperK or a LAr TPC or a combination of both. The water cerenkov detector could be built with little R&D but would have to be larger than LAr due to it's lower efficiency. Whereas substantial R&D is required for a large LAr TPC but this 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. For a possible evolution of this R&D see Fig.7.

The reach for $\sin^2 2\theta_{13}$, the mass hierarchy and CP violating for the Fermilab Project X program is given in Fig.8. 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 factory with detector(s) at DUSEL. With further technical developments these facilities could also be used for a future multi-TeV muon collider.

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. However, it is clear that an intense neutrino source combined with very massive detectors is required to explore the size of θ_{13} , the neutrino mass hierarchy and the CP violation in the neutrino sector.

2.4. Project X Summary

Project X with it's multi-megawatt high energy beams for neutrino physics and it's multi-megawatt low energy beams for rare Kaon physics, Muon physics and possibly other projects is a true Intensity Frontier Machine. The neutrino experiments have a clear goal to determine CP violation in the neutrino sector and determine the neutrino mass hierarchy. The Kaon program would look for 1000 events in both $K^+ \rightarrow \pi^+\nu\bar{\nu}$ and $K^0 \rightarrow \pi^0\nu\bar{\nu}$.



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Fig. 7. Possible evolution of a Liquid Argon detector program[5] in North America.

The Muon program would look for $\mu + N \rightarrow e + N$ at unprecedented sensitivity as well as to push for a more precise measurement of $(g-2)_\mu$. Further in time is the possibility to use Project X to power a neutrino factory and then to regain the energy frontier with a multi-TeV muon collider.

3. Acknowledgements

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The 3σ Reach of the Successive Phases

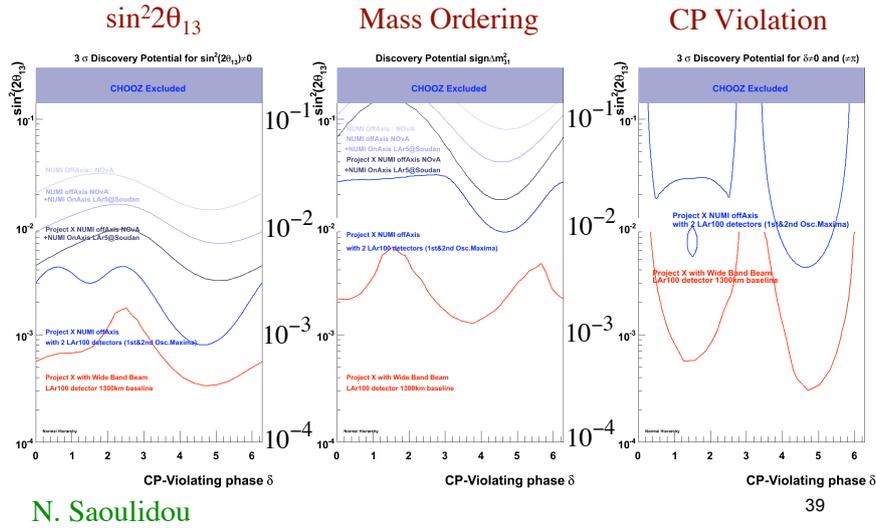


Fig. 8. The evolution of the reach for $\sin^2 2\theta_{13}$, the mass hierarchy and CP violating for the Fermilab Project X program [8].

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