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Status and Prospects of Long Baseline ν Oscillation Experiments

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We will start with a brief overview of neutrino oscillation physics with emphasis on the remaining unanswered questions. Next we will discuss results and status of long baseline accelerator neutrino oscillation experiments that are in a mature data taking mode, have just started or are about to start data taking. Then, we will present the next generation of long baseline experiments with a primary goal to search for the yet to be measured third neutrino mixing angle. Finally we will introduce the plans for future long baseline accelerator neutrino oscillation experiments of which the primary goals are the search for CP violation in the neutrino sector, and the determination of the neutrino mass hierarchy. We will focus on experiments utilizing powerful (0.7 - 4.0 MW) neutrino beams, either existing or in the design phase.

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1. Introduction

Non-zero neutrino masses are perhaps the only experimental evidence we have so far, for the existence of physics beyond the Standard Model. In the past ten years tremendous (experimental) progress has been made towards precisely measuring and better understanding neutrino mass differences and mixings ([1]-[8]). However, there are still many open questions:
1) What is the value of the third neutrino mixing angle, θ_{13}, for which only a limit exists from the CHOOZ [9] experiment ?
2) Do neutrinos violate CP symmetry and if so by how much?
3) What is the hierarchy of neutrino masses?
4) What are the absolute values of neutrino masses? Neutrino oscillation experiments provide information only on the mass differences between the different eigenstates.
5) Are neutrinos Majorana or Dirac particles?
6) Are there still more "surprises" to come in neutrino physics ? Namely, is there new physics involving neutrinos that will result in entirely "unexpected" experimental observations? Perhaps, for some of us, this is the most exciting scenario

The first three of the five questions we can address with experiments using reactor and/or accelerator neutrinos, and the remaining two with natural neutrinos.

2. MINOS-OPERA-ICARUS

• **MINOS** is a two detector long baseline neutrino oscillation experiment (baseline $L = 735$ km) with its near detector located at Fermilab and its far detector at SOUDAN Underground Laboratory. It utilizes an almost pure (98%) ν_μ beam produced by the Fermilab Main Injector (NUMI beam) with a mean energy $< E >\sim 3$. MINOS near and far detectors are magnetized segmented (steel/scintillator) tracking calorimeters. Muon neutrino charged current (CC) interactions are primarily identified by the presence of a muon-like track and neutral current (NC) interactions by the absence of it. There is a small contamination, $\sim 2\%$, of ν_e's in the beam whose CC interactions are distinguished from ν_μ CC and NC using the different characteristics of hadronic and electromagnetic showers. MINOS primary physics goals using accelerator neutrinos are the precise measurement of the dominant $P(\nu_\mu \to \nu_\tau)$ oscillation parameters, the comparison between neutrino oscillations and alternative disappearance hypotheses [10],[11], the existence of sterile neutrinos ν_s, as well as the study of the subdominant $P(\nu_\mu \to \nu_e)$ oscillations. The first ν_μ disappearance results were published [6] in 2006. In Figure 1 we show the recent [12] MINOS ν_μ disappearance results, obtained with a factor of three higher statistics compared to the sample used in the first analysis, which present the most precise measurement of $|\Delta m^2_{32}|$. In addition, fitting the energy distribution shown in Figure 1 under the pure neutrino decay and pure neutrino decoherence hypotheses and comparing it to the fit under the neutrino oscillation hypothesis, MINOS is able to disfavor them with a significance of 3.7σ and 5.7σ respectively.

MINOS has recently completed the first analysis of NC interactions in the near and far detectors [13]. Oscillations of ν_μ to ν_s would result in a depletion of the far detector NC-like data with respect to expectation. The magnitude of such a depletion would depend on the fraction, f_s, of active neutrinos that oscillate to sterile neutrino species with $f_s = \frac{P(\nu_\mu \to \nu_s)}{1-P(\nu_\mu \to \nu_\mu)}$. Fitting the NC-like

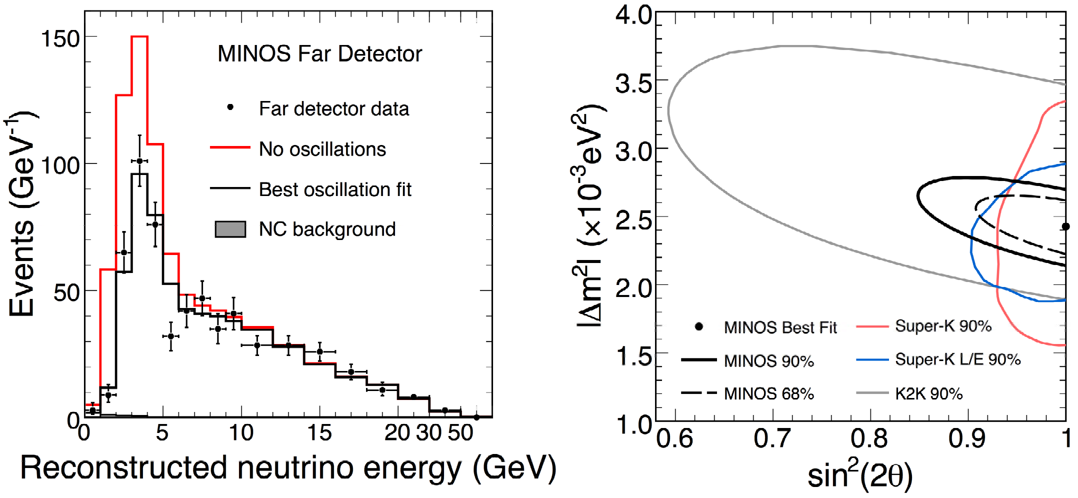


Figure 1: Left Figure: MINOS Far detector reconstructed energy (GeV) spectrum for charged current-like events. Black points are the data, black solid line the unoscillated expectation and red solid line the best fit under the neutrino oscillation hypothesis. Right Figure: MINOS two dimensional 68%$C.L.$ (black dotted line) and 90%$C.L.$ (black continuous line) contours along with Super-Kamiokande 90%$C.L.$ contours from both the zenith angle (red line) and the L/E (blue line) analyses and the K2K 90%$C.L.$ contours (gray line).

far detector spectrum, shown in Figure 2 (left plot), under the assumption that ν_μ oscillate to ν_τ and ν_s with the same mass-squared difference, MINOS obtains an f_s limit of $f_s < 0.68$ at 90%$C.L.$.

MINOS analysis on ν_e appearance is on-going and results are expected soon (end of 2008, beginning of 2009). The potential of this analysis, for the current statistics as well as for the full statistics at the end of data taking, is shown n Figure 2 (right plot). If θ_{13} is at the current CHOOZ [9] limit MINOS has the potential of being the first experiment to observe it. If not, MINOS will further improve the current CHOOZ limit.

• **OPERA** is a long baseline neutrino oscillation experiment ($L = 730$ km) located at the Gran Sasso Underground Laboratory (LNGS). It utilizes an almost pure (98%) ν_μ beam from the CERN SPS accelerator with a mean energy $< E >\sim 17$ GeV, such that ν_τ's would have energies above the τ production threshold. The OPERA detector is a hybrid lead-emulsion spectrometer [14] with target mass of 1.25KTons. The emulsion target provides the very high spatial resolution needed, $< 1\mu$, in order to observe and identify τ decays through the so called "kink decay topology".

The primary goal of the OPERA experiment is the direct, unambiguous, verification of ν_μ to ν_τ oscillations by the observation of ν_τ CC interactions originating in a pure ν_μ beam. OPERA is complementary to the MINOS experiment : MINOS has studied in detail ν_μ (to ν_τ) disappearance and OPERA will study in detail ν_μ to ν_τ appearance. OPERA will also study subdominant ν_μ to ν_e oscillations, the existence of sterile neutrinos, and alternative hypothesis to neutrino oscillations like neutrino decay and decoherence.

The direct observation of ν_τ in a hybrid emulsion spectrometer via the detection of the produced τ lepton in the ν_τ CC interactions has been successfully demonstrated by the DONUT experiment [15]. OPERA, during the October 2007 GNGS run, has accumulated 369 neutrino interactions, 38 of which were recorded and reconstructed in the emulsion target. In Figure 3 we

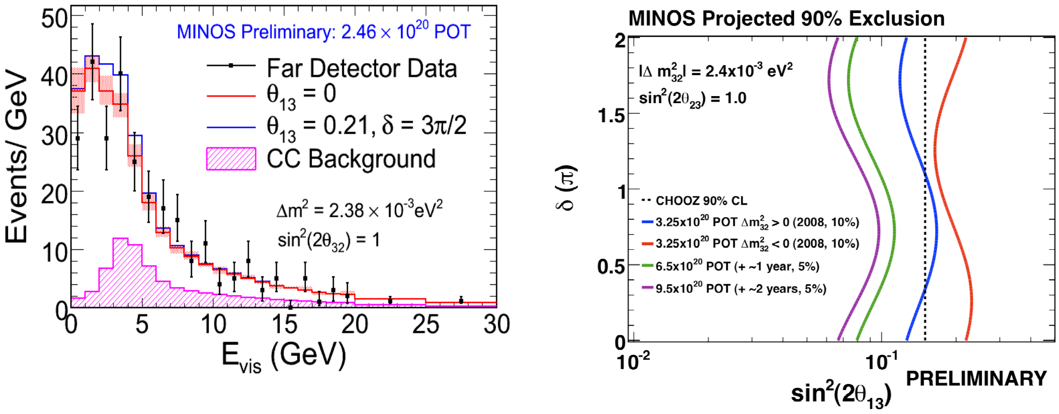


Figure 2: Left Plot: MINOS Far detector reconstructed visible energy (GeV) spectrum for neutral current-like events. Black points are the data. Red solid line is the expectation under the hypothesis that ν_μ oscillate exclusively to ν_τ ($P(\nu_\mu \rightarrow \nu_s) = 0$ and $P(\nu_\mu \rightarrow \nu_e) = 0$). Blue solid line is the expectation under the hypothesis that ν_μ oscillate to ν_τ and ν_e with the latter allowed to have its maximal possible value (θ_{13} at the current CHOOZ limit, normal neutrino mass hierarchy and maximal CP violation with $\delta = 3\pi/2$). **Right Plot**: MINOS projections (Monte Carlo) of the $90\% C.L.$ exclusion limit on $\sin^2(2\theta_{13})$ as a function of the CP violating phase $delta$ for the current and total foreseen integrated statistics (Protons on Target).

show an event with a "kink" topology classified as a charm candidate having two electromagnetic showers originating from the neutrino interaction vertex. In the 2008 GNGS run OPERA expects to see $\sim 1.2\nu_\tau$ CC interactions, and with the the full statistics sample, corresponding to 2.25×10^{20} protons on target, 10.4 ± 0.76 ν_τ CC events assuming maximal mixing with a $|\Delta m^2_{32}| = 2.5 \times 10^{-3}$ eV^2.

Due to the excellent spatial resolution of the emulsion target one can distinguish e from π^0 and also reconstruct kinematic variables (momentum imbalance in the transverse plane) that can help to separate ν_e CC from NC interactions. These capabilities enable OPERA to perform a ν_e appearance study [16] with a sensitivity as shown in Figure 4.

- **ICARUS** [17] is a 600 Ton Liquid Argon (LAr) Time Projection Chamber (TPC) now located in the LNGS. The installation is well under way and start of operation is anticipated this calendar year (2008). This detector has excellent three dimensional imaging capabilities with spatial resolution similar to those of bubble chambers, but with electronic readout and continuous sensitivity. In Figure 5 we show cosmic ray and neutrino events in the detector which clearly illustrate how powerful this detector technology is.

Perhaps one of the most important goals of the ICARUS experiment is to prove that this detector technology can function as expected, in an underground laboratory, and for sizable periods of time, performing a variety of physics measurements using atmospheric, accelerator, supernova and solar neutrinos.

3. T2K-NOvA

- **T2K** [19] is a next generation long baseline accelerator neutrino oscillation experiment with a baseline $L = 295$ km and a mean neutrino energy $< E > \sim 0.6$ GeV. The far detector is the Super-

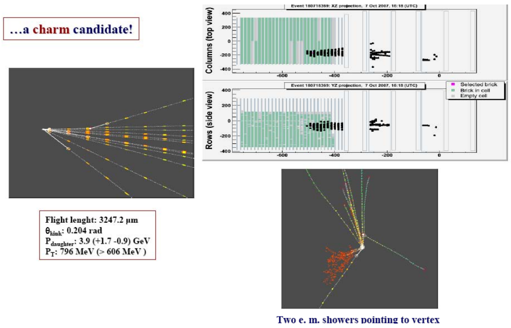


Figure 3: OPERA Charm candidate neutrino interaction. The presence of a clear "kink-topology" in one of the emulsion tracks would classify the interaction as a ν_τ candidate. However there are two electromagnetic showers originating from the interaction vertex, as clearly seen from the reconstructed emulsion information.

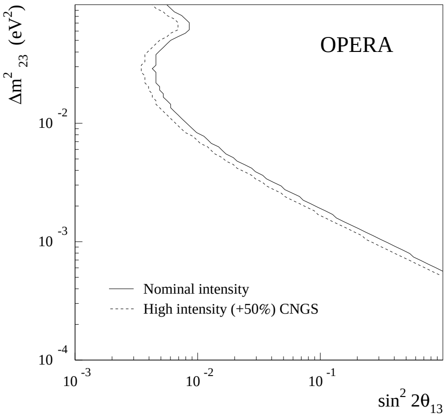


Figure 4: OPERA $90\% C.L.$ sensitivity on $\sin^2(2\theta_{13})$ as a function of Δm^2_{23}.With the full statistics sample OPERA should be able to explore the region well below the CHOOZ limit.

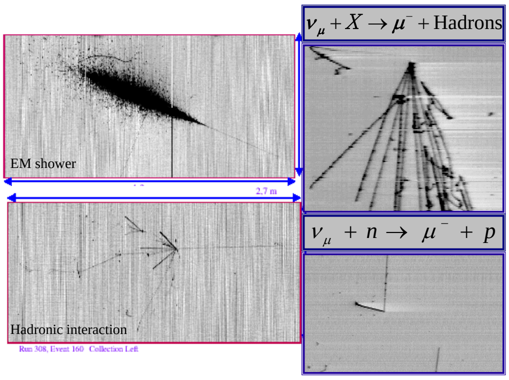


Figure 5: **Left Plots**: ICARUS Cosmic Ray events. **Right Plots**: Neutrino interactions in a small ICARUS Prototype exposed in the CERN neutrino beam. The level of detail on event characteristics, observed even by naked eye, demonstrate how powerful such a detector technology is.

Kamiokande [1] Water Cherenkov (WC) detector. The neutrino beam is an off axis (2.5^o) narrow band beam (NBB) which is currently under construction at JPARC.

The primary goal of the T2K experiment is to search for the subdominant ν_μ to ν_e oscillations with a sensitivity greater by a factor of ~ 20 with respect to the current CHOOZ limit. The off axis idea is used in order to highly suppress NC backgrounds to the ν_e CC signal, especially the ones with a single π^o produced in the final state. In Figure 6 we show the $90\% C.L.$ sensitivity to $\sin^2(2\theta_{13})$ as a function of CP violating phase δ for the full statistics: 5 year of operation at 750 KW of beam power. The T2K experiment is anticipated to start taking data in April of 2009 and have first results possibly by summer of 2010.

• **NOvA** [18] is a next generation long baseline experiment with a much longer baseline than T2K, $L = 810$ km, and a mean energy of $< E > \sim 2$ GeV. The NOvA detector is a fully active 15 KTon liquid scintillator detector and the neutrino beam is the NUMI off axis, at a angle of 14 mrad, NBB.

The primary goal of the NOvA experiment is to search for a non-zero θ_{13} with a similar sensitivity to that of the T2K experiment, as shown in Figure 7 (left plot). In addition, due to its

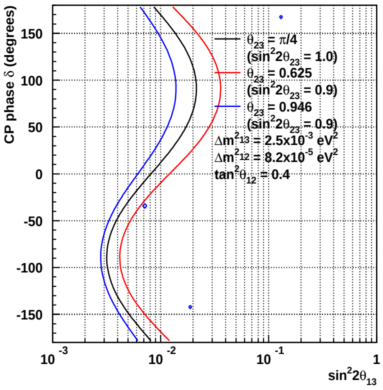
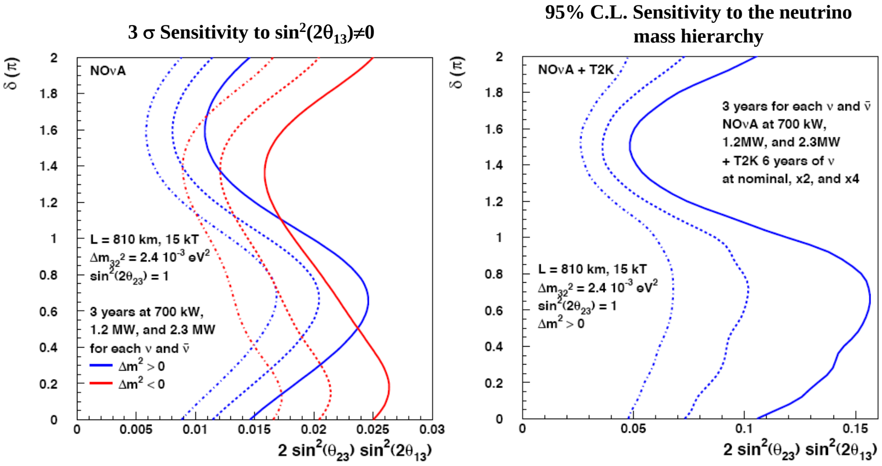


Figure 6: T2K 90%$C.L.$ discovery potential for a non-zero θ_{13} as a function of the CP violating phase δ and for three different values of $\sin^2(2\theta_{23})$. This plots assumes full statistics: 5 years of operation at 750 KW of beam power.

long baseline, NOvA has the unique capability of determining the neutrino mass hierarchy if θ_{13} is close to the current CHOOZ limit. In Figure 7 (right plot) we show the neutrino mass hierarchy discovery potential when NOvA and T2K are combined. NOvA is in the final design/construction phase and is expected to start taking data in 2013.


3 σ Sensitivity to sin²(2θ13)≠0

95% C.L. Sensitivity to the neutrino mass hierarchy

Figure 7: Left Plot: NOvA 3σ discovery potential for a non-zero θ_{13} for normal (blue lines) and inverted (red lines) hierarchy. Running conditions: 3 years of ν and 3 years of $\overline{\nu}$ at 700 KW (continuous line), 1.2 MW (dashed line) and 2.3 MW (doted line). **Right Plot**: NOvA plus T2K 95%$C.L.$ discovery potential for determining the neutrino mass hierarchy assuming normal hierarchy. Running conditions: 3 years of ν and 3 years of $\overline{\nu}$ at 700 KW (continuous line), 1.2 MW (dashed line) and 2.3 MW (doted line) of beam power for the NUMI beam and 6 years of ν running at 750 KW, 1.5 MW and 3 MW of beam power for the JPARC beam.

4. Future Possibilities with JPARC and Fermilab ν beams

The focus of future long baseline accelerator neutrino oscillation experiments is the discovery (if present) of CP violation in the neutrino sector, and the determination of the neutrino mass hierarchy.

The measurement of the neutrino mass hierarchy requires a long baseline in order to enhance matter effects. The measurement of CP violation requires information from both the 1st and 2nd oscillation maxima of $P(\nu_\mu \to \nu_e)$ in order to break the inherent degeneracies between "genuine" CP violating and "fake" CP violation arising from matter effects.

There are two ways one can obtain information from both oscillation maxima:
(1) Create a Wide Band neutrino Beam (WBB) in order to study both of them at a fixed baseline with one detector
(2) Use Narrow Band Beams (NBB) at two different off axis angles, which involve two different baselines, and two detectors to study each one of them separately, combining the information afterwards.

Both JPARC and Fermilab have developed plans for future experiments that fulfill the above requirements.

• **Future Possibilities with JPARC beams**: JPARC will be soon (2009) operating the NBB for the T2K experiment starting from a beam power of 100 KW and gradually increasing to the nominal value 750 KW. There are upgrade plans that could increase the JPARC beam power to 1.7 MW and ultimately to 4 MW.

As far as detector masses and baselines are concerned there are two options examined:
i) One 540 KTon WC detector at Kamioka at the 1^{st} oscillation maximum
ii) Two 270 KTon WC detectors one located in Kamioka at the 1^{st} oscillation maximum and one located in Korea, $L \sim 1000$ km, at the 2^{nd} oscillation maximum.

The physics capabilities of this program, in terms of discovery potentials for the parameters of interest, (CP Violating phase δ, and the neutrino mass hierarchy), are illustrated in Figure 8 where one clearly sees advantage of the two detector configuration covering both oscillation maxima and involving longer baselines.

• **Future Possibilities with Fermilab beams**: Fermilab currently operates the NUMI beam at 250 KW with an approved upgrade plan to 700 KW for the NOvA experiment. Over the course of the previous year Fermilab developed a physics plan for the next decade [21], which includes an upgrade to the accelerator complex, called "Project X". "Project X" could produce ≈ 2 MW of beam power for proton energies ranging from 60-120 GeV and resulting in very high intensity neutrino beams.

The first step of the staged program is the NOvA liquid scintillator experiment described in previous sections.

An intermediate step, with quite interesting physics capabilities, could be an upgraded (technologically) detector consisting of ~5 KT LAr, placed either in the NUMI beam with an $L \sim 700-800$ km, or at the Deep Underground Science and Engineering Laboratory (DUSEL) with an $L = 1300$ km.

The next step would be the construction, using most likely a modular approach, of massive detectors, 300 KT of WC and/or 100KT LAr, at DUSEL in parallel with the construction of new WBB from Fermilab to DUSEL. The initial beam power would be 700 KW.

Finally, the construction of "Project X" would increase the neutrino beam power from 700 KW to 2MW. The physics capabilities of this staged program, in terms of discovery potentials for the parameters of interest, (θ_{13}, CP Violating phase δ, and the neutrino mass hierarchy), are illustrated in Figure 9 where one clearly sees the progressive increase in discovery potential.

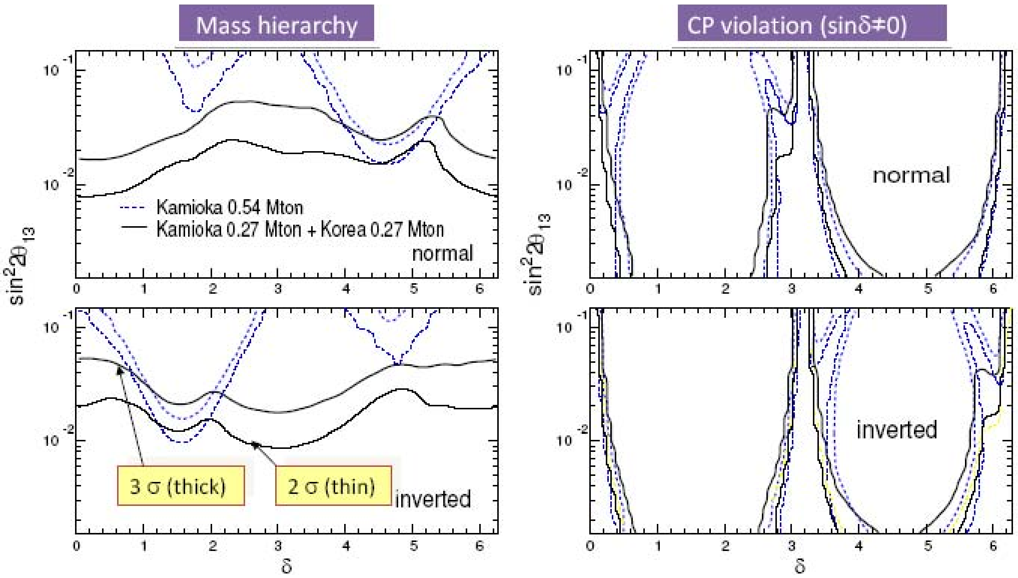


Figure 8: **Left Plot**: 3(blue dashed line) and 2(gray dashed line) σ mass hierarchy discovery potential: 0.54 MTon WC detector in Kamioka with the JPARC off axis beam upgraded to 4 MW. 3(black thick line) and 2(black thin line) σ mass hierarchy discovery potential with two 0.27 MTon WC detectors in Kamioka and Korea with the JPARC off axis beam upgraded to 4 MW. **Right Plot**: 3(blue dashed line) and 2(gray dashed line) σ CP violation discovery potential with 0.54 MTon WC detector in Kamioka with the JPARC off axis beam upgraded to 4 MW. 3(black thick line) and 2(black thin line) σ CP Violation discovery potential with two 0.27 MTon WC detectors in Kamioka and Korea with the JPARC off axis beam upgraded to 4 MW. Running conditions: 4 years of ν and 4 years of $\overline{\nu}$ running.

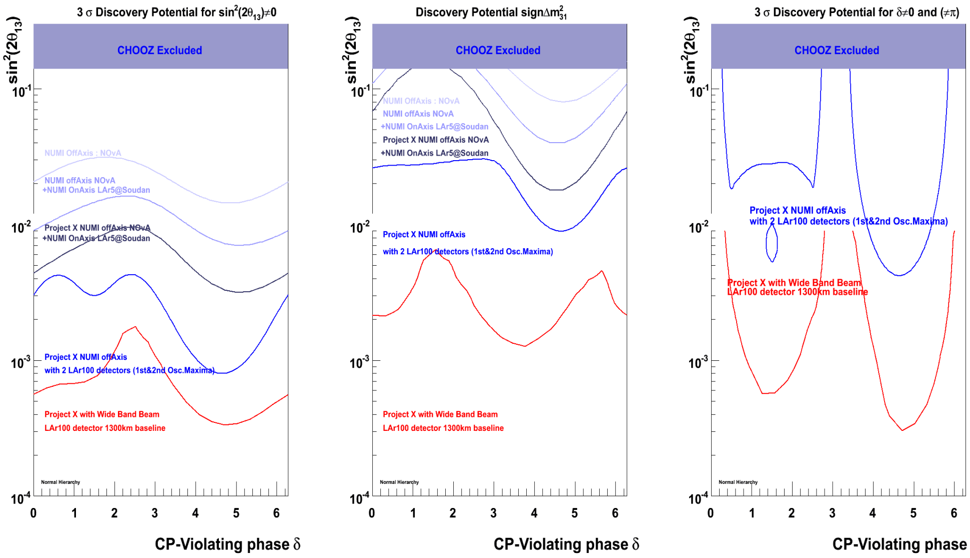


Figure 9: Fermilab Staged Plan: 3σ Discovery potentials for θ_{13}, the neutrino mass hierarchy, and CP violation. From lower to higher discovery potentials: (1) NOvA with NUMI NBB at 700 KW, (2) NOvA+5 KTon LAr with NUMI NBB+WBB at 700 KW, (3) NOvA+5 KTon LAr with NUMI NBB+WBB at 2 MW, (4) 50 KTon LAr at 1st + 50 KTon LAr at 2nd oscillation maxima with NUMI NBB at 2MW, (5) 100 KTon LAr (equivalent with ∼ 500 KTon of WC) at DUSEL with new WBB at 2 MW.

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