Getting the Most Out of the On-Axis NuMI Beam

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In this white paper we explore how resources already available with the NuMI beam and Soudan Underground Laboratory (735 km baseline) could be leveraged to impact neutrino oscillation measurements in the next decade. On-axis, the NuMI beam has a high flux that covers a wide range in neutrino energy. Soudan has been smoothly operating as an underground high-energy physics laboratory for many years. We considered the physics reach with the current MINOS detector, with modest improvements that might be achieved with new analysis techniques. We also considered an upgraded MINOS detector, in which MINOS is augmented with additional scintillator tracking planes in between the steel target planes. This would improve the event identification capability in MINOS at a relatively low cost. While other proposals discuss the physics reach of new detectors placed off-axis in NuMI, it is worth considering upgrades of the existing MINOS detector, in the event that budget constraints preclude initiatives involving new sites with new detectors. We also considered, as a best-case scenario at Soudan, the physics achievable with a new detector of nearly optimal performance, namely a liquid argon tracking calorimeter. This is of course a more expensive option, but still exploits the existing facilities at Soudan.

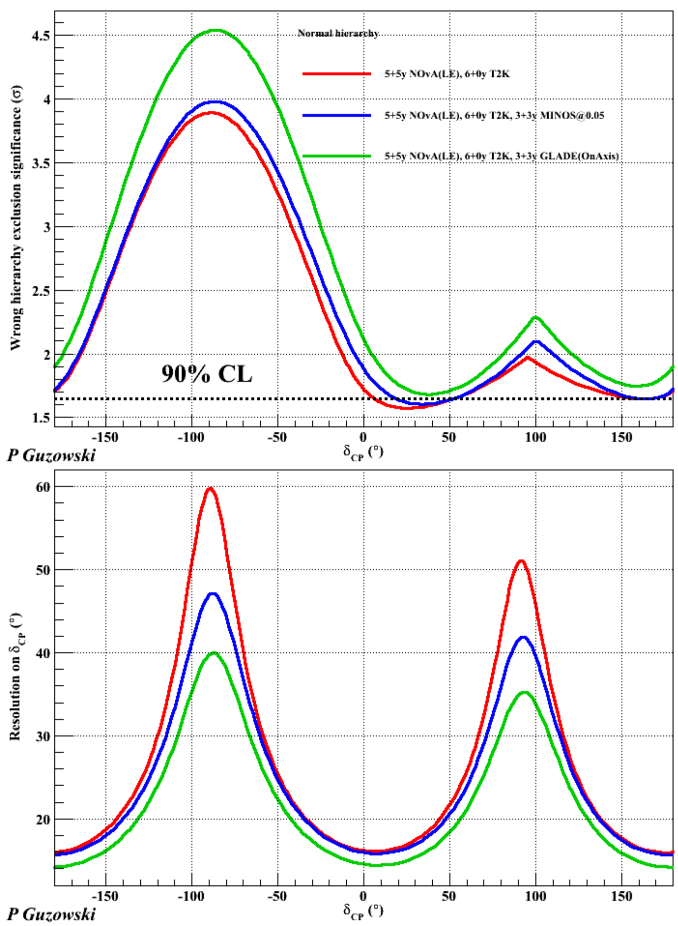

Figure 1: Mass hierarchy sensitivity (top) and resolution in δ_{CP} (bottom) as a function of δ_{CP} for normal hierarchy for NOvA+T2K alone (red), NOvA+T2K combined with an improved MINOS detector that has a NC background acceptance of 5% the current level (blue), and NOvA+T2K combined with an on-axis 5 kton liquid argon detector (green). The MINOS and liquid argon detectors are assumed to accumulate 3 years of data in neutrino mode and 3 years in antineutrino mode in the low-energy NuMI configuration.

Given the relatively large value of θ_{13}, the NuMI beam in the low-energy configuration can provide a large sample of electron neutrinos from muon neutrino oscillations. By itself, this sample cannot significantly constrain δ_{CP} or determine the mass hierarchy, but it can increase the global significance when combined with data from NOvA and T2K. Due to the on-axis location, the MINOS CP sensitivity has a different dependence on δ_{CP} than that of NOvA+T2K, so MINOS can provide complementary information. To simulate the performance of upgraded or new detectors, we adjusted the signal selection efficiency and neutral-current (NC) background rejection capability relative to the current performance in the MINOS electron neutrino appearance analysis.

Figure 1 shows the mass hierarchy sensitivity and δ_{CP} resolution as a function of δ_{CP} for normal hierarchy for NOvA+T2K alone and for NOvA+T2K combined with one of the "improved MINOS" options, where the NC background is greatly reduced (5% of the NC background level in the current MINOS electron neutrino sample). The inclusion of MINOS has a relatively minor impact on the mass hierarchy measurement, but does improve the resolution on δ_{CP} by 10-15° at the values of δ_{CP} where the resolution is worst. The figure also shows NOvA+T2K combined with a 5 kton liquid argon detector at Soudan. This improves the δ_{CP} resolution by about 5° relative to the "improved MINOS" option and has a significant impact on the mass hierarchy sensitivity.

Detector improvements at MINOS would not only help the global δ_{CP} measurements, but could also enhance searches for non-standard interaction (NSI) physics when combined with NOvA. The electron neutrino appearance probability can be enhanced or diminished by a nonzero value of the NSI coupling $\epsilon_{e\tau}$. The on-axis NuMI beam has the advantage of covering a wider range of energy: NSI matter effects distort the neutrino energy spectrum over a broad range of energy, mostly >4 GeV. This neutrino energy range is not accessible to NOvA.

Furthermore, the detector improvements would allow for better identification of tau neutrino candidates, improving the ability of MINOS to search for tau neutrino appearance. In the medium-energy configuration of NuMI that will run for NOvA, we expect roughly 80 charged-current (CC) tau neutrino events in the MINOS detector per year. The challenge in observing these events, similar to the electron neutrino appearance search, is in reducing the large NC background. An upgraded MINOS detector could conduct a more sensitive statistical search for tau neutrino appearance. An event-by-event search in which tau neutrino events are identified by topology could potentially be done with a liquid argon detector at Soudan.