mixing [8, 9], but does not exclude an admixture of subdominant $\nu_\mu \to \nu_s$ mixing with the dominant $\nu_\mu \to \nu_\tau$ mixing. MINOS has recently carried out the first dedicated search at fixed long-baseline for $\nu_\mu$ oscillating to both $\nu_\tau$ and $\nu_s$ [17]. The analysis presented here uses a larger exposure and extends the earlier analysis by considering specific models in which a sterile neutrino state is incorporated into the neutrino mixing matrix.

The possibility that a neutrino may decay into a sterile state [18] is also explored in this work. In this scenario, the mass eigenstate $\nu_3$ is unstable and allows active neutrinos to decay into undetectable final states. The decays would give rise to an anomalous depletion of the neutral-current event rate observed at the far-detector. The occurrence of pure neutrino decay, without oscillation, has already been shown by MINOS and Super-Kamiokande to be highly disfavored [10, 19]. The analysis reported here represents the first direct test of the neutrino-decay-with-oscillations scenario in a long-baseline experiment.

## II. NUMI BEAM AND MINOS DETECTORS

Neutrinos from the NuMI (Neutrinos from the Main Injector) beam [20] originate from decays of pions and kaons produced in the beamline target; a significantly smaller contribution arises from subsequent muon decays. The secondary mesons are created using 120 GeV protons extracted from the Fermilab Main Injector incident on a graphite target. The proton extraction occurs in $10\,\mu$s spills with a 2.2 s cycle. Positioned downstream of the target are two parabolic magnetic horns which focus $\pi^+$ and $K^+$ secondary particles. The focused mesons proceed into a 675 m long evacuated decay pipe, where they may decay into muons and neutrinos. The remnant hadrons are stopped by a beam absorber placed at the end of the decay pipe. The tertiary muons are stopped by 240 m of rock between the end of the decay volume and the near-detector cavern so that only neutrinos reach the near-detector. The neutrino energy spectrum can be changed by adjusting either the horn current or the position of the target relative to the horns. The data employed in this analysis were obtained using the low-energy beam configuration, in which the peak neutrino energy is 3.3 GeV [4], and correspond to a far-detector exposure of $3.18 \times 10^{20}$ protons on target, collected during the period of May 2005 to July 2007. In this configuration, according to Monte Carlo simulations, the neutrino flavor composition of the beam is 91.8% $\nu_\mu$, 6.9% $\overline{\nu}_\mu$, and 1.3% $\nu_e + \overline{\nu}_e$. For this analysis the neutrinos and antineutrinos are assumed to oscillate with the same parameters.

The MINOS detectors are planar steel/scintillator tracking calorimeters [20]. The vertically oriented detector planes are composed of 2.54 cm thick steel and 1 cm thick plastic scintillator. A scintillator layer is composed of 4.1 cm wide strips. Each strip is coupled via a wavelength-shifting fiber to one pixel of a multianode photomultiplier tube (PMT) [21, 22].

The MINOS near-detector is located 1.04 km downstream of the target, has a total mass of 980 metric tonnes, and lies 103 m underground at Fermilab. The detector consists of two sections, a calorimeter encompassing the upstream 121 planes and a spectrometer containing the downstream 161 planes. In both sections, one out of every five planes is fully covered with 96 scintillator strips attached to the steel plates. In the calorimeter section, the other four out of five planes are partially covered with 64 scintillator strips, whereas in the spectrometer section no scintillator is attached to the steel. The far-detector is 734 km downstream of the near-detector, has a total mass of 5400 metric tonnes, and is located in the Soudan Underground Laboratory, 705 m below the surface. It is composed of 484 fully instrumented planes organized in two supermodules [4]. The fiducial masses used for the near and far-detectors are 27 metric tonnes and 3800 metric tonnes respectively. The near-detector steel is magnetized with an average field intensity of 1.3 T whereas the far-detector has an average field of 1.4 T in the steel.

## III. DATA SELECTION

A neutrino interacting in one of the MINOS detectors produces either a charged-current event with a charged lepton plus hadrons emerging from the event vertex or a neutral-current event with hadrons but no charged lepton in the final state. In either case, the particles in the final state deposit energy in the scintillator strips, which is converted to light and collected by optical fibers and converted to electronic signals by PMTs. The MINOS reconstruction algorithms use event topology and the recorded time stamps of the strips where energy was deposited to identify neutrino events inside the detector. Events must have at least four strips with signal to be considered in the analysis. Individual scintillator strips are grouped into either reconstructed tracks or showers, and the tracks and showers are combined into events [4]. The vertex of each event is required to be sufficiently far from any edge of the detector to ensure that the final-state hadronic showers are contained within the instrumented regions of the detectors. On average, each GeV of energy deposition in a neutral-current event induces activity in 12 scintillator strips.

The Monte Carlo simulation of the neutrino beam utilizes FLUKA05 [23] to model hadroproduction in the NuMI target and a GEANT3 [24] simulation of the NuMI beam line to propagate the particles exiting the target. The neutrino interactions in the MINOS detectors are modeled by the NEUGEN-v3 [25] program. The simulated neutrino flux is constrained to agree with the neutrino energy spectra measured in the near-detector for nine different beam configurations [4]. This procedure reduces the uncertainties due to the neutrino flux in the far-detector prediction.