DUNE - Atmospheric Neutrinos

1. Introduction

Atmospheric neutrinos are a unique tool to study neutrino oscillations: they contain all flavors of neutrinos and anti-neutrinos, are very sensitive to matter effects and to both Δm^2, and cover a wide range of L/E. In principle, all oscillation parameters could be measured, with high complementarity to measurements performed with a neutrino beam. In addition, atmospheric neutrinos are available all the time, in particular before the beam becomes operational. Atmospheric neutrinos also provide a laboratory in which to search for exotic phenomena where the dependence of the flavor-transition and survival probabilities on energy and path length can be defined. The DUNE far detector, with its large mass and the overburden to protect it from backgrounds, is an ideal tool for these studies. In the following, we will focus on the measurement of the oscillation parameters where the role of atmospheric neutrinos is most important.

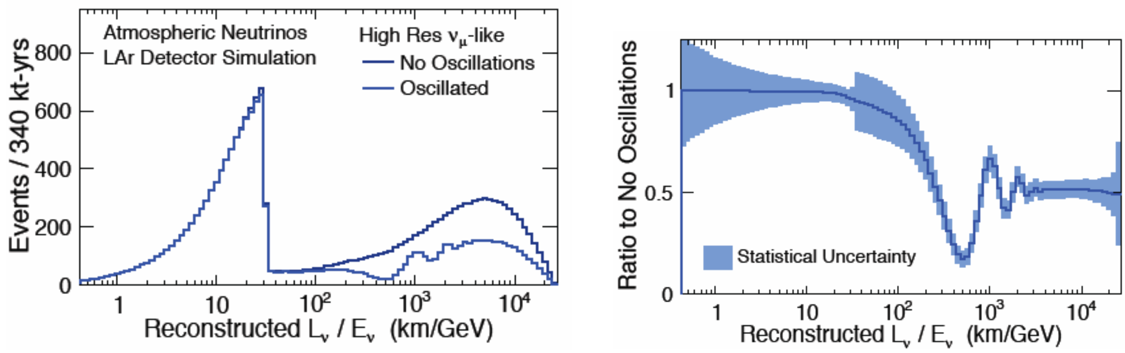
2. Sensitivity to oscillation parameters

The sensitivity to oscillation parameters has been evaluated [ref,ref] with a dedicated simulation, reconstruction and analysis chain. The fluxes, after oscillation, of each neutrino species at the far detector location were computed. Interactions in the LAr medium were simulated with the GENIE event generator. Detection thresholds and energy resolutions based on full simulations were applied to the outgoing particles, to take into account detector effects. Events were classified as Fully Contained (FC) or Partially Contained (PC) by placing the vertex at a random position inside the detector and tracking the lepton until its edges. The number of events expected for each flavor and category is summarized in table 4.13 *[we can rescale to 350 kt*y].*

Table 4.13: Atmospheric-neutrino event rates including oscillations in 100 kt · year with a LArTPC, fully or partially contained in the detector fiducial volume.

Sample	Event rate
fully contained electron-like sample	4,015
fully contained muon-like sample	5,958
partially contained muon-like sample	1,963

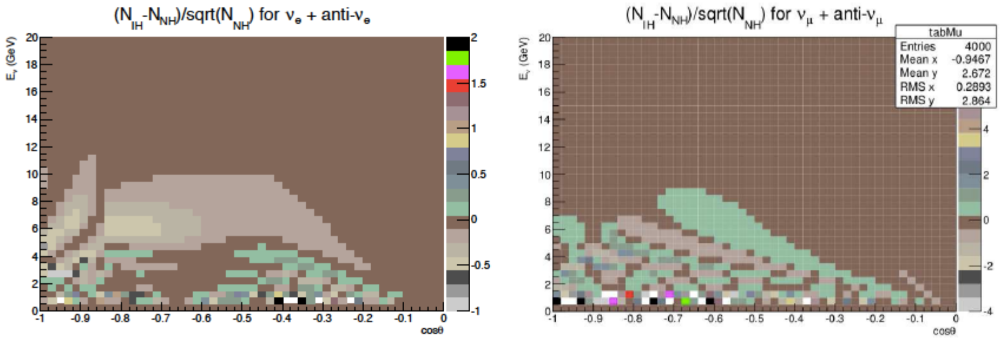
Figure 4.22 shows the expected L/E distribution for high-resolution muon-like events from a 350 kt · year exposure. The data provide excellent resolution of the first two oscillation nodes, even when taking into account the expected statistical uncertainty.



In performing oscillation fits, the data in each flavor/containment category are binned in energy and zenith angle. *[... add a few lines on the chi2, nuisance parameters, systematics* *etc...]*

2.1 Sensitivity to Mass Hierarchy (MH)

When neutrinos travel through the Earth, the MSW resonance influences electron neutrinos in the few-GeV energy range. More precisely, the resonance occurs for ν_e in the case of normal mass hierarchy (NH, $\Delta m^2_{23} > 0$), and for anti-ν_e in the case of inverted mass hierarchy (IH, $\Delta m^2_{23}<0$). This is illustrated in Fig.40.



The MH sensitivity can be greatly enhanced if neutrino and antineutrino events can be separated. The DUNE detector will not be magnetized; however, its high-resolution imaging offers possibilities for tagging features of events that provide statistical discrimination between neutrinos and antineutrinos. For the sensitivity calculations that follow, two such tags were included: a proton tag and a decay electron tag. The reconstructed zenith angle distribution for different event categories is shown in Figure 4.24.

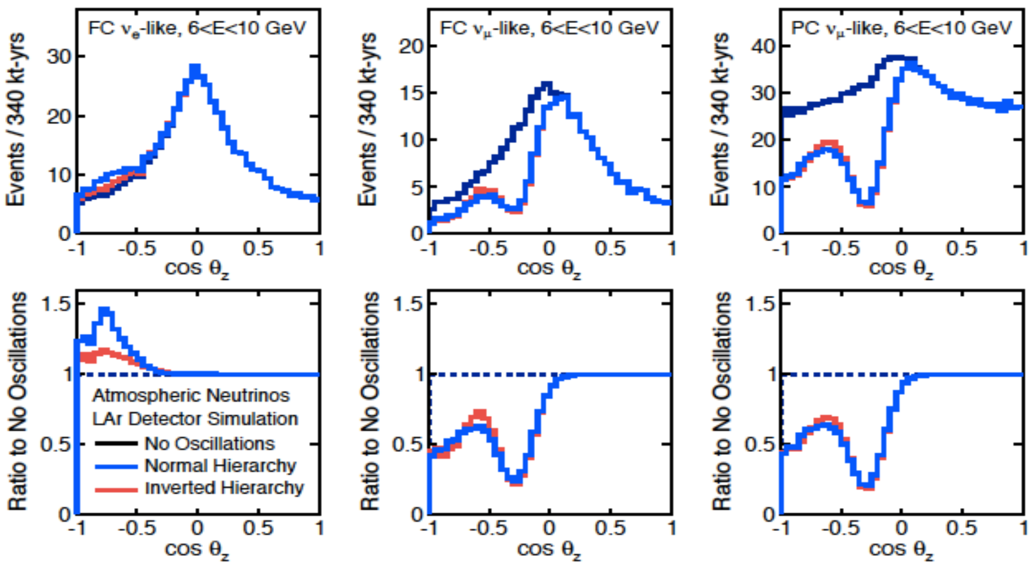


Figure 4.24: Reconstructed zenith angle distributions for 6 to 10-GeV events in the different FC and PC samples. Top plots show the expected distributions for no oscillations (black), oscillations with normal (blue), and inverted (red) hierarchy. Bottom plots show the ratio of the normal and inverted expectations to the no-oscillation distributions for each category.

Figure 4.26 shows the MH sensitivity as a function of the fiducial exposure. Over this range of fiducial exposures, the sensitivity goes essentially as the square root of the exposure, indicating that the measurement is not systematics-limited.

Unlike for beam measurements, he sensitivity to MH with atmospheric neutrinos is nearly independent of the CP violating phase.

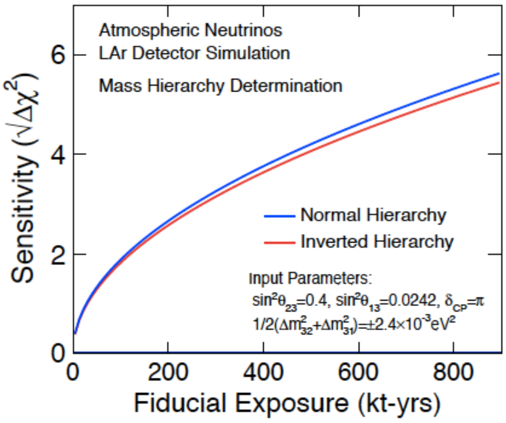


Figure 4.26: Sensitivity to mass hierarchy using atmospheric neutrinos as a function of fiducial exposure in a liquid argon detector.

2.2 Sensitivity to the θ_{23} octant and to CP violation

In the two-flavour approximation, neutrino oscillation probabilities depend on $\sin^2(2\theta)$, which is invariant when changing θ to π/2-θ. The octant degeneracy remains for θ_{23} in the leading order terms of the full three-flavor oscillation probability, making it impossible to determine whether $\theta_{23}<\pi/4$ or $\theta_{23}>\pi/4$. Accessing full three-flavor oscillation with atmospheric neutrinos will give a handle to solve the ambiguity.
The sensitivity to the θ_{23} octant is shown in Figure 4.27. With the nominal exposure of 340 kt*y, DUNE will be able to distinguish between octants at 3σ significance, based on atmospheric data alone, for true values of | θ_{23}-π/4|>*XXXX deg. [quantify],* for any value of δ_{CP}.

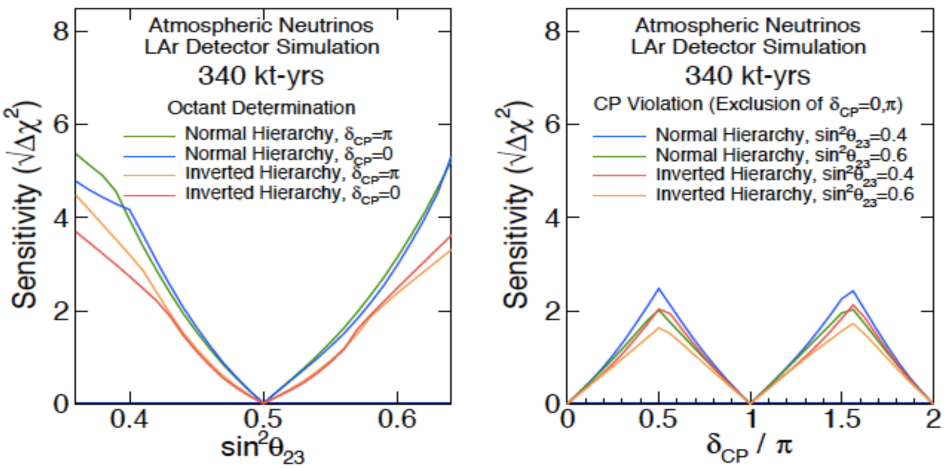


Figure 4.27: Sensitivity to θ_{23} octant (left) and CPV (right) using atmospheric neutrinos.

The sensitivity of atmospheric neutrinos to CPV is quite limited and will not reach 3σ with the nominal exposure, as shown in Fig. 4.27.

Conclude with a summary and a general comment on complementarity to beam ....

3. Other physics opportunities

No detailed studies have ben done by either LBNE or LAGUNA-LBNO.
We should have a few lines only, reference variety of measurements done by SuperK (decoherence, NSI, etc..), and tau appearance capabilities?