Studying Neutrino Oscillations with Atmospheric Neutrinos in DUNE

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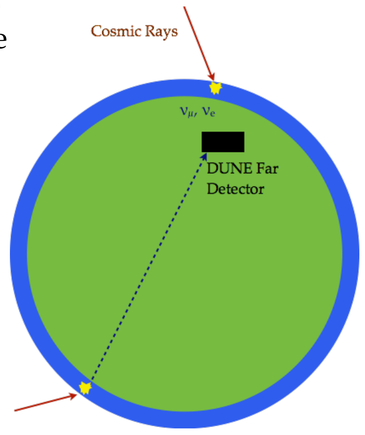
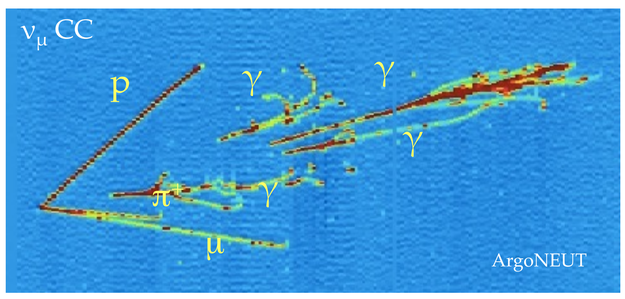
Atmospheric Neutrinos

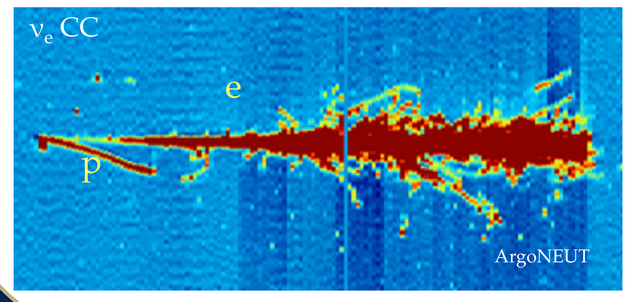
- High-energy cosmic ray interactions at the top of the atmosphere produce an intense flux of neutrinos.
- Atmospheric neutrinos provide a rich source of oscillation physics
  - Baseline: from 10-13000 km
  - Energy spans 4 orders of magnitude.
- The 40 kton DUNE Far Detector [1], to be built at the Sanford Underground Research Facility in South Dakota will offer unique capabilities for studying atmospheric neutrinos.
- The 4850 ft rock overburden will shield against cosmic ray backgrounds.
- The use of Liquid Argon TPC detector technology will provide excellent energy resolution, angular resolution and particle ID capabilities.
- The large mass of the DUNE detector will deliver high event yields, enabling precision measurements of atmospheric neutrino oscillations.

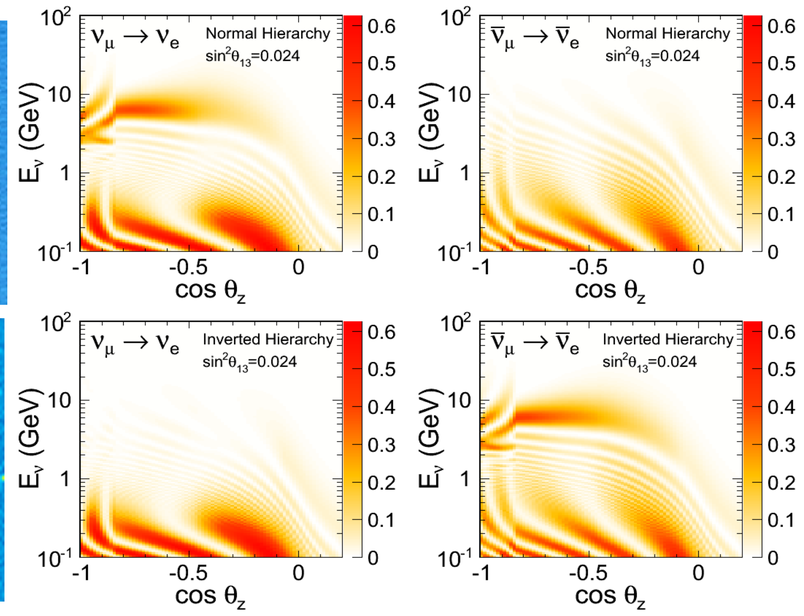


Atmospheric Neutrino Oscillation Physics

- Atmospheric neutrions offer aunique probe of oscillations:
  - All flavors of neutrinos and antineutrinos.
  - Upward-going multi-GeV neutrinos are sensitive to matter effects via MSW resonance.
  - Can probe neutrino mass hierarchy, θ_{23} octant and δ_{CP} phase.
- Test standard oscillation model over multiple oscillation wavelengths.
- Search for exotic phenomena.
- Atmospheric neutrino data can help resolve the ambiguities that arise in beam-only oscillation analyses.

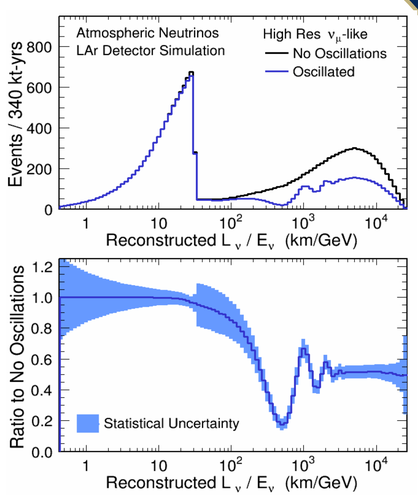


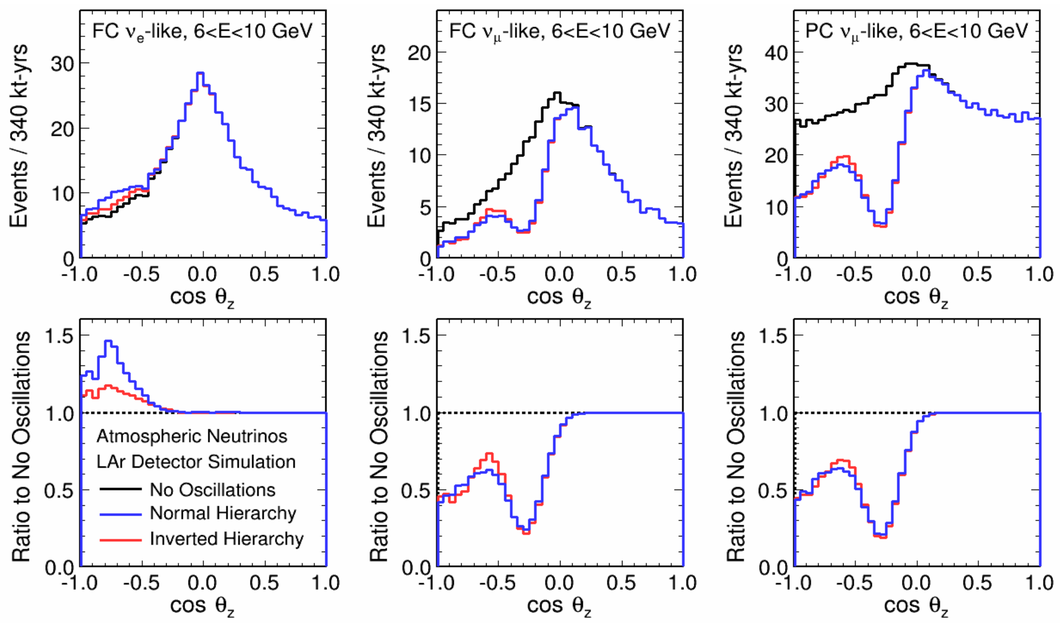




Simulation

- Sensitivity to oscillations evaluated using a 4-vector simulation and pseudo-reconstruction [2].
- Neutrino interactions on argon are simulated using Bartol 3D flux model [3] and GENIE [4].
- Parameterised thresholds, resolutions, and particle ID are applied to the final-state 4-vectors.
- Events are classified as fully contained (FC) or partially contained (PC) based on containment of final-state leptons.
- Final-state protons and decay electrons are also tagged for statistical separation of ν/anti-ν.

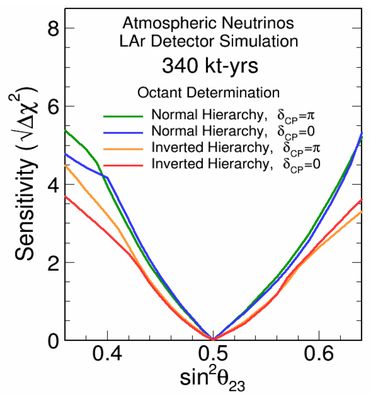


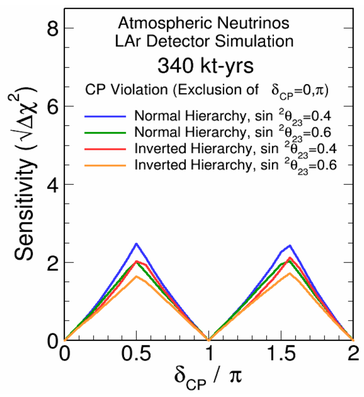


[1] C. Adams et al, arXiv:1512.06148
[2] R. Acciarri et al, arXiv:1307.7335
[3] G. Barr et al, PRD 70, 023006 (2004)
[4] C. Andreopoulos et al, NIM A614, 87 (2010)

Neutrino Oscillation Sensitivities

- Oscillation sensitivities are calculated using a joint fit to ν_μ-like and ν_e-like spectra, with 18 systematic parameters.
- MSW resonance enables determination of mass hierarchy.
  - Resonance occurs for neutrinos in case of normal hierarchy, and for antineutrinos in case of inverted hierarchy.
  - Ability to determine mass hierarchy is nearly independent of δ_{CP} phase, unlike accelerator neutrino experiments.
  - Sensitivity of DUNE comparable to Hyper-K despite smaller detector mass, due to better resolution of energy and angle.
- Moderate sensitivity to both θ_{23} octant and δ_{CP} phase





Sample	Events / 340 kt-yr
FC ν_e-like	13,651
FC ν_μ-like	20,257
PC ν_μ-like	6,675