Studying Neutrino Oscillations with Atmospheric Neutrinos and Searches for BSM Physics in DUNE

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On behalf of the DUNE Collaboration

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Outlook

- Deep Underground Neutrino Experiment
- Atmospheric Neutrinos
- Studying Neutrino Oscillation with Atmospheric Neutrinos
- Searches for BSM Physics
- Summary
Deep Underground Neutrino Experiment

An international mega-science project

- CP-violation
- Mass hierarchy
- No-beam physics

\{ Atmospheric neutrinos, Nucleon decay, Neutrinos from supernova \}
Deep Underground Neutrino Experiment

- The use of Liquid Argon TPC detector technology will provide excellent energy resolution, angular resolution and particle ID capabilities
- Photon detector system
- 40-kt of fiducial mass
Deep Underground Neutrino Experiment

- **2015** New collaboration DUNE
- **2017** Start excavation at the far site (SURF)
- **2018** Two ProtoDUNE Detectors (SP & DP) operational at CERN
- **2021** Start of FD installation: 1st module
- **2023** Continue FD installation: 2nd module
- **2024** 20 kt operational (start non-beam physics)
- **2026** Beam operations begin at nominal power and proton energy
Atmospheric Neutrinos

- High-energy cosmic-ray interactions at the top of the atmosphere produce an intense flux of neutrinos
- Provide a unique tool to study neutrino oscillations
- The unoscillated flux contains all flavors of neutrino and antineutrinos
- Atmospheric neutrinos also provide a wide-band coverage of energies and baselines
DUNE and Atmospheric Neutrinos

- Preliminary studies of a 350 kt-year exposure were performed
- Neutrino interactions on argon were simulated using Bartol 3D flux model and GENIE

![Graph showing atmospheric neutrinos and reconstructed L/E ratio](image)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Event Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>fully contained electron-like sample</td>
<td>14,053</td>
</tr>
<tr>
<td>fully contained muon-like sample</td>
<td>20,853</td>
</tr>
<tr>
<td>partially contained muon-like sample</td>
<td>6,871</td>
</tr>
</tbody>
</table>
Neutrino Oscillation Sensitivities with Atmospheric Neutrinos

- Oscillation sensitivities are calculated using a joint fit to $\nu_\mu$-like and $\nu_e$-like sample
- MSW resonance enables determination of mass hierarchy
- Resonance occurs for neutrinos in case of normal hierarchy, and for antineutrinos in case of inverted hierarchy

arXiv:1512.06148
Neutrino Oscillation Sensitivities with Atmospheric Neutrinos

- The octant and CPV sensitivity from a 340 kt-year exposure of atmospheric neutrino data alone was calculated.
- For the determination of the octant of $\theta_{23}$, the $\Delta\chi^2$ value is calculated between the best-fit points in the lower ($\theta_{23} < 45^\circ$) and higher ($\theta_{23} > 45^\circ$) octants.

arXiv:1307.7335
DUNE and Atmospheric Neutrinos
Work in Progress

- Implementing Bartol 3D flux, GENIE and LArSoft
- We have developed an end-to-end simulation and reconstruction chain
- Enabling track reconstruction and PID for atmospheric neutrinos

- The use of LAr TPC gives an advantage over water Cherenkov detectors, better angular resolution, lower tracking thresholds
DUNE and Atmospheric Neutrinos
Work in Progress

- One person’s signal is another person’s background
- Atmospheric neutrinos are a potential background for proton decay events when the proton is misID as kaon
- PIDA based on dE/dx and residual range

(JINST 8 P08005 (2013))
Search for BSM Physics in DUNE

Proton Decay

Simulation of proton decay at DUNE LArTPC

\[ p \rightarrow K^+ \bar{\nu} \]

- This channel represents a challenge for water Cherenkov detectors because the kaon is below threshold.

See also Inés Gil-Botella talk in the astroparticle physics session.
Search for BSM Physics in DUNE

Neutron — Antineutron Oscillation

- Baryon number violation process: neutron spontaneously oscillates into antineutron
- Search for subsequent annihilation with bound nucleon inside nucleus
- MC truth n-\bar{n} topology in 40Ar
Search for BSM Physics in DUNE

Neutron — Antineutron Oscillation

- LArTPC is an image-based technology
- Investigate CNN’s ability to distinguish n-\(\bar{n}\) from atmospheric neutrino events
- High-level difference in shape of signal and background events

- Network performs convolutions on input images to pick out complex features, and learns to associate these features with the event type
Searches for BSM Physics

Atmospheric neutrinos cover a wide range of L and E

- **Search Lorentz Invariance and CPT violation**: The Standard Model Extension (SME) is an effective field theory that contains the SM, GR, and all possible operators that break Lorentz invariance, such effects introduce additional effects in neutrino oscillation that are \( \sim \) to L

- **Search for Nonstandard Interactions (NSI)**: to quantify NSI it is useful to define the difference between oscillation probability with and without NSI, Atmospheric neutrinos are the best candidates for the study of NSIs due to propagation

- **Search for Mass Varying Neutrinos (MaVaNs)**: Neutrino mass can vary depending on the matter density along the of the neutrino. A way to search for for mass varying effects is using atmospheric neutrinos looking at \( \nu_\mu \rightarrow \nu_\tau \) oscillations

- **Search for Sterile Neutrinos**: Search for oscillation into sterile neutrino instead of tau neutrinos at the atmospheric mass splitting

- **Decoherence**: Search for effects which arise from the wave packet treatment of neutrino oscillation
Summary

- 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 neutrinos.
- Atmospheric neutrinos provide a complementary analysis approach to beam neutrinos, and can help resolve ambiguities in beam-only analyses.
- DUNE has a rich program from neutrino oscillation physics to BSM physics.
The End

Thanks for listening

DUNE Collaboration, CERN, January 2017
Atmospheric Neutrino
Atmospheric Neutrino Interactions

- Atmospheric neutrino model:
  - Use Bartol 3D flux calculation for Soudan mine.
- Neutrino interactions simulated using GENIE event generator.
- Interaction rates (per 100 kt-yr):

<table>
<thead>
<tr>
<th></th>
<th>CC</th>
<th>NC</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$</td>
<td>10069</td>
<td>4240</td>
<td>14309</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>2701</td>
<td>1895</td>
<td>4596</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>5754</td>
<td>2098</td>
<td>7852</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>1230</td>
<td>782</td>
<td>2012</td>
</tr>
<tr>
<td>Total</td>
<td>19754</td>
<td>9015</td>
<td>28769</td>
</tr>
</tbody>
</table>

NOTE: Have not considered either neutrino-induced rock-muons or cosmic-ray muon background.

Andy Blake / Hugh Gallagher ISOUPS
Pseudo-Reconstruction

<table>
<thead>
<tr>
<th>Angular Resolution</th>
<th>Electron</th>
<th>1°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Muon</td>
<td>1°</td>
</tr>
<tr>
<td></td>
<td>Hadronic system</td>
<td>10°</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>Stopping muon</td>
<td>3%</td>
</tr>
<tr>
<td></td>
<td>Exiting muon</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td>Electron</td>
<td>1%/√E + 1%</td>
</tr>
<tr>
<td></td>
<td>Hadronic system</td>
<td>30%/√E</td>
</tr>
<tr>
<td>Signal Acceptance</td>
<td>Electrons</td>
<td>90%</td>
</tr>
<tr>
<td></td>
<td>Muons</td>
<td>100%</td>
</tr>
<tr>
<td>Background Rejection</td>
<td>e-like (π^0, γ)</td>
<td>95%</td>
</tr>
<tr>
<td></td>
<td>μ-like (π^+, π^-)</td>
<td>99%</td>
</tr>
</tbody>
</table>

Previous studies have demonstrated that MH sensitivity, and susceptibility to systematic uncertainties, is strongly driven by resolutions. Petcov and Schwetz, Nucl.Phys. B740 (2006) 1-22

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Fitting Framework

- Joint oscillation analysis of e-like and $\mu$-like event samples.
  - Start by calculating sensitivities for atmospheric neutrinos only. Then, perform combined analysis of beam and atmospheric data.
  - Events are separated by flavour and containment.
    - e-like FC, $\mu$-like FC, $\mu$-like PC, (discard NC-like events).
  - Atmospheric neutrinos are separated according to proton and electron tags (provides some $\nu$/anti-$\nu$ enhancement)
    - Binning:
      - Beam events binned by energy.
      - Atmospheric events binned by energy and angle.

- Simulate the following experiment:
  - '35kton' LAr detector:
    - Two modules, each 14.0m high, 23.3m wide, 45.4m long
  - 350 kton-yr exposure.
    - Assume equal amounts of $\nu$ and anti-$\nu$ running
      (assume $6.5\times10^{20}$ POT/year, taken from LBNE CDR).

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## Systematic Errors

<table>
<thead>
<tr>
<th></th>
<th>Atmospheric</th>
<th>Beam (Assume ND)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalisations</td>
<td>Overall (15%)</td>
<td>μ-like (1%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>e-like (1%)</td>
</tr>
<tr>
<td>NC Backgrounds</td>
<td>(No ND decomposition for atmos ν)</td>
<td>μ-like (10%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>e-like (5%)</td>
</tr>
<tr>
<td>Spectrum Ratios</td>
<td>up/down (2%)</td>
<td>Flux ratios cancel strongly, so these are estimated detector uncertainties</td>
</tr>
<tr>
<td></td>
<td>νₑ/νₑ (2%)</td>
<td>f(E &lt; E₀) = 1 + α(E - E₀)/E₀</td>
</tr>
<tr>
<td></td>
<td>anti-νₑ/νₑ &amp; anti-νₑ/νₑ (5%)</td>
<td>f(E &gt; E₀) = 1 + α log(E/E₀)</td>
</tr>
<tr>
<td>Spectrum Shape</td>
<td>Apply separate functions for</td>
<td></td>
</tr>
<tr>
<td></td>
<td>νₑ, νₑ, anti-νₑ, anti-νₑ</td>
<td></td>
</tr>
<tr>
<td>Energy Scales</td>
<td>Muons (stopping 1%, exiting 5%)</td>
<td></td>
</tr>
<tr>
<td>(Correlated)</td>
<td>Electrons (1%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hadronic system (5%)</td>
<td></td>
</tr>
</tbody>
</table>

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