A Gaseous Argon-Based Near Detector to Enhance the Physics Capabilities of DUNE

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Snowmass Community Summer Study Workshop
DUNE and Neutrino Interactions Session
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why a gaseous-argon based ND

**DUNE’s gaseous-argon based ND, ND-GAr (Phase II, ND Upgrade)** measures ν-Ar interactions with low threshold and high resolution to enable **5σ sensitivity to CP violation** and provides the basis for a comprehensive and a strong BSM program in DUNE.

DUNE Near Detector, ND Complex

In the early running, a simpler downstream detector can reconstruct muon tracks exiting ND-LAr (Phase I).

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DUNE’s highly capable **ND complex** includes **ND-LAr** (see Z. Vallari’s talk [here](#)), **ND-GAr**, **SAND** (see Z. Ghorbanimoghaddam’s talk [here](#)), & **DUNE-PRISM**:

- Precisely measure the ν-energy spectrum and ν-flavor composition of the 1.2 MW (upgradable to 2.4 MW) high-intensity, wide-band ν-beam
- Precisely measure ν-Argon cross-sections (see K. Mahn’s talk [here](#))
A magnetized High Pressure Gas Argon TPC (HPgTPC) surrounded by ECAL and \( \mu \)-tagger:
- Reference design repurposes ALICE multi-wire chambers
- Other designs under consideration, e.g. GEMs
- Main design capabilities:
  - Low threshold
  - Excellent PID, tracking efficiency, momentum resolution
  - \(4\pi\) coverage
  - Minimal secondary interactions
Nucleus is a complicated environment (e.g. specially problematic when using heavy nuclei as target):

- Nuclear effects, e.g. final state interactions not yet fully understood
- Introduces uncertainties in neutrino energy reconstruction and neutrino event rate estimation which need to be constrained
Examples from Existing Experiments

- Cross sections/neutrino interaction model uncertainties from existing experiments (all using high threshold detectors) are too large for DUNE.
- We need to do better – low threshold ND-GAr can help.

<table>
<thead>
<tr>
<th>T2K</th>
<th><a href="https://doi.org/10.1038/s41586-020-2177-0">https://doi.org/10.1038/s41586-020-2177-0</a></th>
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<tbody>
<tr>
<td><strong>Type of Uncertainty</strong></td>
<td>$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)</td>
</tr>
<tr>
<td>Super-K Detector Model</td>
<td>1.5</td>
</tr>
<tr>
<td>Pion Final State Interaction and Rescattering Model</td>
<td>1.6</td>
</tr>
<tr>
<td>Neutrino Production and Interaction Model Constrained by ND280 Data</td>
<td>2.7</td>
</tr>
<tr>
<td>Electron Neutrino and Antineutrino Interaction Model</td>
<td>3.0</td>
</tr>
<tr>
<td>Nucleon Removal Energy in Interaction Model</td>
<td>3.7</td>
</tr>
<tr>
<td>Modeling of Neutral Current Interactions with Single $\gamma$ Production</td>
<td>1.5</td>
</tr>
<tr>
<td>Modeling of Other Neutral Current Interactions</td>
<td>0.2</td>
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<tr>
<td>Total Systematic Uncertainty</td>
<td>6.0</td>
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<table>
<thead>
<tr>
<th>NOvA</th>
<th><a href="https://doi.org/10.1103/PhysRevLett.123.151803">https://doi.org/10.1103/PhysRevLett.123.151803</a></th>
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<tbody>
<tr>
<td><strong>Source</strong></td>
<td>$\nu_e$ Signal (%)</td>
</tr>
<tr>
<td>Cross-sections</td>
<td>$+4.7/-5.8$</td>
</tr>
<tr>
<td>Detector model</td>
<td>$+3.7/-3.9$</td>
</tr>
<tr>
<td>ND/FD diffs.</td>
<td>$+3.4/-3.4$</td>
</tr>
<tr>
<td>Calibration</td>
<td>$+2.1/-3.2$</td>
</tr>
<tr>
<td>Others</td>
<td>$+1.6/-1.6$</td>
</tr>
<tr>
<td>Total</td>
<td>$+7.4/-8.5$</td>
</tr>
</tbody>
</table>
The Need for the Low Threshold ND-GAr

Lower threshold of **ND-GAr's HPgTPC** than **ND-LAr**:

- Leads to high sensitivity to low energy protons or pions:
- Reveals discrepancies between neutrino event generators, getting us closer to choosing more accurate neutrino-nucleus interaction models and constraining uncertainties in neutrino oscillation measurements

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**neutrino generator discrepancies at low proton KE, accessible with a GAr-based detector**

[Graph showing neutrino generator discrepancies]

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**credit: J. Raaf**
A Wealth of ν-Argon Interaction Data

- Using high-pressure gas-argon as detecting medium allows for an independent sample of ν-interactions on argon and constrains the cross-section systematic uncertainties to the level needed by the oscillation analysis.
  - e.g. high statistics sample of exclusive neutrino interactions without a pion or with some number of pions in final state.

1 ton fiducial mass for 1 year of ν-mode running with a 1.2MW Beam Power

<table>
<thead>
<tr>
<th>Event class</th>
<th>Number of events per ton-year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ CC</td>
<td>$1.6 \times 10^6$</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$ CC</td>
<td>$7.1 \times 10^4$</td>
</tr>
<tr>
<td>$\nu_e + \bar{\nu}_e$ CC</td>
<td>$2.9 \times 10^4$</td>
</tr>
<tr>
<td>NC total</td>
<td>$5.5 \times 10^5$</td>
</tr>
<tr>
<td>$\nu_\mu$ CC0π</td>
<td>$5.9 \times 10^5$</td>
</tr>
<tr>
<td>$\nu_\mu$ CC1π±</td>
<td>$4.1 \times 10^5$</td>
</tr>
<tr>
<td>$\nu_\mu$ CC1π0</td>
<td>$1.6 \times 10^5$</td>
</tr>
<tr>
<td>$\nu_\mu$ CC2π</td>
<td>$2.1 \times 10^5$</td>
</tr>
<tr>
<td>$\nu_\mu$ CC3π</td>
<td>$9.2 \times 10^4$</td>
</tr>
<tr>
<td>$\nu_\mu$ CC other</td>
<td>$1.8 \times 10^5$</td>
</tr>
</tbody>
</table>

A detailed view of the ν-interaction vertex.

DUNE ND HPGTPC
Run: 1/0
Event: 1
UTC: Wed Jun 17 1981
12:40:26.287119056

Pion stops outside TPC. Decays at rest to a muon.
Superb PID for $\gamma$-Ar Interaction Measurements

- dE/dx resolution: 0.8 keV/cm
- Excellent PID combined with low threshold feature allows ND-GAr to help with correctly identifying the different final state topologies e.g. pion multiplicities very well

BSM Reach

- In addition to precise measurements of neutrino-argon cross sections, ND-GAr also enables a rich BSM physics program in DUNE, e.g. rare events such as:
  ★ Neutrino tridents
  ★ Heavy neutral leptons, HNL
  ★ Anomalous Tau neutrinos
  ★ Light dark matter
  ★ Heavy axions

M. Breitbach, L. Buonocore, C. Frugiuele, J. Kopp and L. Mittnacht, Searching for physics beyond the standard model in an off-axis dune near detector, 2102.03383
Projected Performance

- A full end-to-end simulation and reconstruction already exists (GArSoft)!
- Momentum resolution and tracking efficiency from a sample of muon neutrino events: 2.7% & >90% for tracks with >40 MeV/c momenta, respectively
- Proton tracking efficiency from a sample of isotropic protons at the vertex: >80% for proton tracks with >10 MeV energies

ECAL can efficiently tag/reject $\pi^0$s, $\gamma$s (background to electron-neutrinos), neutrons – without ECAL, sensitivity to neutral particles is almost non-existent.

Can also tag/reject outside of fiducial volume backgrounds using timing.

Projected Performance

Bulk of the charge readout R&D focused on optimizing the ALICE inner (IROC) and outer (OROC) multiwire chambers, CROC's need to be built. But there are opportunities for exploring alternate designs, e.g. Gas-electron multipliers, GEMs (T. Mohayai FNAL New Initiatives R&D award).
**R&D Efforts**

- What is involved in the charge readout optimization studies:
  - Testing the chambers @ various pressures up to 10 atm (e.g. ALICE chambers previously operated at 1 atm)

**IROC Gain T. Mohayai**

![IROC Gain Graph](image1)

- electroncs under development by Pittsburg, Fermilab, & Imperial

**DUNE Work in Progress**

**OROC Gain, A. Ritchie-Yates**

![OROC Gain Graph](image2)

- Royal Holloway Test Stand, housing an OROC, moving to Fermilab Test Beam
What is involved in the charge readout optimization studies:

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  - Control pile up (drift velocity) and improve spatial resolution (diffusion)

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  - Maximize gas gain, while minimizing gas electrical breakdown

![Graph showing the relationship between voltage and pressure-length for Ar/CH₄ (90%/10%) gas mixtures.](image)


<table>
<thead>
<tr>
<th>Projected Breakdown Voltage at 10 bar, 1 cm (kV)</th>
<th>Ar</th>
<th>Xe</th>
<th>Ar-CF₄</th>
<th>Ar-CH₄</th>
<th>Ar-CO₂</th>
<th>CO₂</th>
<th>CF₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>Townsend</td>
<td>52.6</td>
<td>75.4</td>
<td>61.7</td>
<td>63.9</td>
<td>68.6</td>
<td>129.5</td>
<td>179.7</td>
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<tr>
<td>Meek</td>
<td>69.9</td>
<td>98.9</td>
<td>72.1</td>
<td>80.3</td>
<td>87.3</td>
<td>171.2</td>
<td>212.2</td>
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Optical readout & light collection:

- Choose an admixture/dopant that will not quench the scintillation signal
- Benefits: t₀ time-tag, BSM searches, improved track matching with ND-LAr, neutral particle reconstruction via time-of-flight, NC interaction
Summary

- The DUNE ND-GAr unique design includes components that enable:
  - DUNE to reach 5σ sensitivity to CP violation
  - A close-up view of $\nu$-Ar interactions to more precisely identify and resolve the discrepancies in neutrino-nucleus interaction models
  - A comprehensive search for rare decays and symmetries beyond the standard model

- A wide range of detector R&D efforts are underway to build a highly capable ND-GAr:
  - Besides R&D on the acquired ALICE multiwire readout chambers, we are exploring various new detector R&D areas, including GEM development & optical readout

Additional Slides
High-momentum muons and pions will range out of ECAL
A muon tagger can achieve a purity of 100% above 1 GeV/c

Low Threshold ND-GAr

- Lower threshold of ND-GAr's HPgTPC than ND-LAr:
  - Leads to a high sensitivity to low energy protons or pions:

A GAr-based detector sees lower KE protons than a LArTPC

credit: J. Raaf
Gas Multiplication Gain Concept

Ionization

Electron Drift

Drift Volume

Gas Amplification

H.V. (-100 kV)

Drift Field

Field Cage

Charged Particle Track

Gating Plane (-140V)

Cathode Plane (0V)

Anode Plane (+1.3kV)

Pad Plane

Pad Signal

DUNE
DEEP UNDERGROUND
NEUTRINO EXperiment

T. A. Mohayai

Fermilab

IROC/OROC

CATHODE PLANE
ANODE PLANE
GROUND ELECTRODE
PAD PLANE
GATING GRID
COVER ELECTRODE

z = v₀t

[Diagram showing the concepts of ionization, electron drift, and gas amplification in a detector setup.]