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

DUNE Collaboration

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Executive Summary

This document presents the concept and physics case for a magnetized gaseous argon-based detector system for the Deep Underground Neutrino Detector (DUNE) Near Detector. A detector system like this is required in order for DUNE to reach its full physics potential.
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1 Introduction

The Deep Underground Neutrino Experiment (DUNE) aims to be a world-class, international particle physics experiment seeking to answer fundamental questions about the elusive neutrino. It will use a new high-intensity neutrino beam that will be generated at the U.S. Department of Energy’s Fermi National Accelerator Laboratory (Fermilab). The experiment will consist of a far detector (FD) located approximately 1.5 km underground at the Sanford Underground Research Facility (SURF) in Lead, South Dakota, at a distance of 1300 km from Fermilab, and a near detector (ND) that will be located on the Fermilab site in Illinois. The FD will consist of a large, modular liquid-argon time projection chamber (LArTPC) with a fiducial mass of roughly 40 kt.

The ND will be located approximately 574 m from DUNE’s neutrino target, which is the starting point for the Long-Baseline Neutrino Facility (LBNF) beam. The conceptual design for the DUNE near detector is described in detail in [1]. The ND will consist of several different components, as shown in Fig. 1: an upstream modular non-magnetized LArTPC (ND-LAr), a magnetized tracker containing a pressurized gaseous-argon time projection chamber (ND-GAr), and a large, magnetized beam monitor (SAND). SAND will remain fixed on the beam axis, while ND-LAr and ND-GAr will move transverse to the beam to collect data at various off-axis positions, providing different spectra by the PRISM concept (GIVE A REFERENCE).

![Figure 1: Profile view of the DUNE ND hall and the DUNE ND detectors. The beam enters from the right.](image)

1.1 Detector Concept

In order to constrain uncertainties in the neutrino interaction models, it is essential that the near detector contain an active argon region to measure neutrino interactions on the same target nucleus...
as the far detector. The non-magnetized ND-LAr can measure neutrino interactions on argon with a similar detection principle as the far detector, but only muons below 0.7 GeV/c will be fully contained in the detector. Thus an additional magnetized detector is required in addition to ND-LAr to measure the momentum and charge-sign of the exiting muons.

![Figure 2: PEP-4/9 TPC (80:20 Ar-CH4, operated at 8.5 Atm) dE/dx-based particle identification.](image)

Incorporating a gaseous argon-based time projection chamber (gaseous-argon TPC), as the primary tracking element in the spectrometer allows for excellent particle momentum resolution and particle identification (PID). An example of the dE/dx-based PID capabilities achieved in the PEP-4 high-pressure gas TPC are shown in Fig. 2. Due to the low detection threshold in a gas TPC, we can also sample neutrino interactions on argon with lower detection thresholds than liquid argon TPCs. A gaseous-argon TPC can better reconstruct low-energy protons and pions and distinguish between primary and secondary interactions than a liquid argon TPC. If the TPC is completely inside the magnet it can better distinguish neutrinos and anti-neutrinos. It can also measure neutrino interactions over all directions, unlike the ND-LAr, which loses acceptance at high angles. An example of a simulated and track-reconstructed neutrino event in a gaseous argon TPC is shown in Fig. 3. Therefore, a gaseous-argon TPC provides a valuable and complimentary sample of argon interactions to better understand neutrino-argon interactions, in detail. To ensure adequate statistics of more than 1 million events per year in a reasonably sized detector, this gaseous-argon TPC will need to operate at approximately 10 atmospheres.

To detect neutrons and photons (mainly from neutral pions), the TPC must be surrounded by a calorimeter. A muon system outside the magnet is needed to help separate muons and charged pions. Putting all of these general requirements together leads to the complete ND-GAr concept, with a central high-pressure gaseous-argon TPC surrounded by a calorimeter and a 0.5 T magnetic field, and a muon tagger system. More details of the current detector concept can be found in Section 4.
2 Physics Motivation

The complete ND-GAr detector is required for DUNE to reach its full physics potential and is endorsed by the Long-Baseline Neutrino Committee (LBNC), a committee charged by the Fermilab Director to review the scientific, technical, and managerial progress, plans and decisions associated with the LBNF and DUNE. Ideally, the entire suite of near detectors would be ready for the start of DUNE operations, resource limitations may require a staged approach. DUNE’s baseline plan for a Day-One detector replaces ND-GAr with a simpler system, a range stack containing alternating layers of steel and scintillators planes that are immersed in a magnetic field; this is the Temporary Muon Spectrometer (TMS). It will use its magnetic field for sign-selection of neutrino vs. antineutrino events, but will use particle range to estimate momenta. The TMS is considered to be a well-costed and “safe” backup solution, based on established technology. As the name suggests, the Temporary Muon Spectrometer would eventually need to be replaced by ND-GAr.

The full physics program of DUNE is described in [2, 3, 4]. ND-GAr extends and enhances the capabilities of the near detector complex. It does this by providing a system that will measure the momentum and sign of charged particles exiting ND-LAr. For neutrino interactions on gaseous argon target, it will extend charged-particle measurement capabilities to lower energies than achievable in the far or near LArTPCs. It will also greatly extend the particle ID (PID) performance, particularly for proton-pion separation. These capabilities enable further constraints of systematic uncertainties for the long-baseline oscillation analysis. Since the target nucleus in ND-GAr is the same as in the near and far LArTPCs, this information helps constrain interaction models, by minimizing contributions from nuclear physics effects.
2.1 Oscillation Physics

Figure 4 shows the early running (left) and ultimate impact (right) of the ND-GAr detector on the long-baseline oscillation sensitivity to CP violation. As seen in the left panel, if Nature is kind enough to provide maximal CP violation, there is not much difference between the exposure required to achieve sensitivity with $3\sigma$ significance using TMS (labeled as “ND-LAr + TMS”) and ND-GAr (labeled as “Reference Near Detector”). Maximal CP violation is the most favorable case for DUNE’s sensitivity, but a more realistic assessment of sensitivity is given by looking at the full range of possible values of $\delta_{CP}$ (or some fraction of that range of values). The right panel shows DUNE’s expected sensitivity to 50% of all $\delta_{CP}$ values, for the same detector configurations. In this case, the experiment with TMS may possibly never reach the $5\sigma$ significance level even with very long exposures. The full ND-GAr detector is ultimately needed to achieve DUNE’s scientific goal for CP violation. This need becomes more critical after DUNE reaches an exposure of approximately 200 kt-MW-years.

![Figure 4: Impact of various near detector configurations on CP violation sensitivity, shown for maximal CP violation (left) and for 50% coverage of $\delta_{CP}$ space.](image)

In addition to its critical role in the DUNE long-baseline oscillation program, ND-GAr will collect a significant number of neutrino interactions per year on its gaseous argon target, enabling a broad stand-alone physics program of neutrino interaction cross-section measurements and Beyond Standard Model or exotic physics searches.

In order to predict the event yields for one year of neutrino running, we use the 2016 DUNE Flux, cross-sections from GENIE [5] 2.12.2 and a fiducial mass of 1 t ($\approx 55\%$ of the active mass). The gas is assumed to be 10 atm of an argon gas admixture. Table 1 gives the number of events for the following interaction channels: CC total ($\nu_{\mu}$ and $\nu_{e}$), NC total ($\bar{\nu}_{\mu}$ and $\nu_{e}$), CC coherent ($\nu_{\mu}$ and $\nu_{e}$), NC coherent ($\nu_{\mu}$ and $\nu_{e}$), neutrino-electron elastic, $\nu_{\mu}$ CC $\pi^0$ inclusive, $\nu_{\mu}$ NC $\pi^0$ inclusive, Low-$\nu$ (250 MeV), Low-$\nu$ (100 MeV) and $\bar{\nu}_{\mu}$ CC coherent ($\bar{\nu}_{\mu}$ running).
Table 1: Number of events for 1 year of neutrino running in HP GAr TPC with 1 t fiducial mass.

<table>
<thead>
<tr>
<th>Event class</th>
<th>Number of events per ton-year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ CC Total</td>
<td>$1.64 \times 10^6$</td>
</tr>
<tr>
<td>$\nu_\mu$ NC Total</td>
<td>$5.17 \times 10^5$</td>
</tr>
<tr>
<td>$\nu_\mu$ CC Coherent</td>
<td>$8.35 \times 10^3$</td>
</tr>
<tr>
<td>$\nu_\mu$ NC Coherent</td>
<td>$4.8 \times 10^3$</td>
</tr>
<tr>
<td>$\nu_\mu$ - electron elastic</td>
<td>135</td>
</tr>
<tr>
<td>$\nu_\mu$ CC $\pi^0$ inclusive</td>
<td>$4.47 \times 10^5$</td>
</tr>
<tr>
<td>$\nu_\mu$ NC $\pi^0$ inclusive</td>
<td>$1.96 \times 10^5$</td>
</tr>
<tr>
<td>$\nu_\mu$ Low $\nu$ (250 MeV)</td>
<td>$2.16 \times 10^5$</td>
</tr>
<tr>
<td>$\nu_\mu$ Low $\nu$ (100 MeV)</td>
<td>$7.93 \times 10^4$</td>
</tr>
<tr>
<td>$\nu_\mu$ CC Coherent ($\bar{\nu}$ mode)</td>
<td>$6.90 \times 10^3$</td>
</tr>
<tr>
<td>$\nu_e$ CC Total</td>
<td>$1.89 \times 10^4$</td>
</tr>
<tr>
<td>$\nu_e$ NC Total</td>
<td>$5.98 \times 10^3$</td>
</tr>
<tr>
<td>$\nu_e$ CC Coherent</td>
<td>93</td>
</tr>
<tr>
<td>$\nu_e$ NC Coherent</td>
<td>52</td>
</tr>
</tbody>
</table>

2.2 Cross Section Physics

The ND-GAr event sample will be used to measure ratios of inclusive, semi-exclusive, and exclusive cross sections as functions of neutrino energy, where the flux cancels in the ratio. The cross-section ratios will be measured separately for NC and CC events, and the NC to CC ratio itself will be measured precisely with the ND-GAr. Cross-sections for different pion, proton, and kaon multiplicity will help constrain interaction models used in the near and far liquid argon detectors.

Secondary interactions are a significant effect in liquid argon detectors [6], where the hadronic interaction length of pions is $\lambda \sim 1$ m. By contrast, in 10 atm of gaseous argon, $\lambda \sim 90$ m. The relative lack of secondary interactions for particles formed in neutrino interactions in the gaseous argon fiducial volume (FV) will provide event samples with a less model-dependent connection to the particles produced in the primary interaction. This validation of the re-interaction model is expected to be useful in understanding the full energy response of the liquid detectors.

Since the target nucleus in ND-GAr is the same as that in the ND-LAr and far detectors, this information feeds directly into the interaction model constraints without complicating nuclear physics concerns.

ND-GAr, with its full solid-angle acceptance and MeV-level proton tracking threshold, is ideal for performing exclusive final-state measurements. In the exclusive channels, $\nu + A \rightarrow \ell + \text{hadrons} + A'$, where the final-state hadrons are measured, the details of the intranuclear dynamics of the interactions can be precisely extracted by exploring momentum conservation in the transverse plane to the neutrino direction, regardless of the unknown neutrino energy. This technique of measuring Transverse Kinematic Imbalance (TKI) in neutrino interactions [7, 8, 9, 10] has been successfully applied in MINERvA [11, 12, 13] and T2K [14, 15]. With the state-of-the-art tracking resolution, ND-GAr will use TKI to further explore neutrino-argon interactions with unprecedented precision [1].
One unique advantage of the ND-GAr, compared to other DUNE ND components, is its flexibility to use various gas mixtures as interaction targets. A safe and hydrogen-rich gas mixture, with the help of the superb tracking, would enable measurements of event-by-event neutrino-hydrogen interactions [7, 16], providing direct access to the more fundamental neutrino-hydrogen reactions for the first time in 40 years.

2.3 Physics Beyond the Standard Model

LBNF’s high-intensity proton beam will provide a large neutrino flux that can be sampled by ND-GAr. In addition to the opportunity to uncover deviations from the present three-flavor neutrino mixing paradigm, this will enable DUNE to discover new particles and unveil new interactions and symmetries beyond those predicted in the Standard Model (beyond the standard model or BSM). In particular, ND-GAr can search for anomalous tau neutrinos, $\nu_\tau$ that come from short-baseline mixing with sterile neutrinos, trident interactions, heavy neutral leptons (HNL), light dark matter, and heavy axions [17].

Searches for several possible HNL decay channels, including those with $\nu e^+ e^-$, $\nu e^+/\mu^-/\mu^+$, $\nu \mu^+ \mu^-$, $\nu \pi^0$, $e^+/\pi^-/\pi^+/-\pi^-/\pi^+$, and $\mu^+/\mu^-/-\pi^-/\pi^+$ final states, can be undertaken in the near detector complex [18]. Neutrino interactions such as neutral-current neutral pion (NC $\pi^0$) interactions can act as backgrounds to some of these HNL decay channels. In ND-GAr, we will be able to reject these background events, effectively. In specific, the pressurized gas argon medium of ND-GAr can track charged particles with kinetic energies as low as 5 MeV, providing hadronic information right at the interaction vertex. Therefore, we can reject a significant fraction of the NC $\pi^0$ background events using the hadronic activity at the vertex. We can also use the calorimeter that surrounds the pressurized gas argon medium of ND-GAr to effectively reconstruct photons that result from the Dalitz decay of a $\pi^0$. Another example of a dominant background (particularly for HNL channels with $\nu \mu^+ \mu^-$, and $\mu^+/\mu^-/-\pi^-/\pi^+$ final states) include the muon neutrino charged-current charged pion events, where the muons are misidentified as pions. The pressurized gaseous argon medium in ND-GAr will enable us to sample more ionization per unit track length, allowing for extensive muon-pion separation using dE/dx. For even better muon-pion separation, we can use the calorimeter of ND-GAr. In addition to PID in the HPgTPC, the calorimeter and the muon tagger system will help in reducing the confusion between pions and muons.

ND-GAr can also search for light dark matter. In particular, one of the main light dark matter signals that can be captured with the near detector complex includes a single-electron final state (DM $e \rightarrow$ DM e). The neutrino-electron scattering ($\nu e \rightarrow$ and $\nu e$) and electron neutrino charged current quasi-elastic scattering interactions ($\nu e \rightarrow e p$) can look very similar to this particular signal and can act as backgrounds. According to a study done in [19], the $\nu e \rightarrow e p$ is easily reducible using energy and angular information of the single-electron final state in ND-LAr. In ND-GAr, we can take advantage of the low detection threshold and use the vertex information to reduce this background even further. From the same reference [19], however, the electron scattering interactions are irreducible in ND-LAr, while in ND-GAr, the number of electron scattering events is very small to start with (135 per kton per year per Tabel 1), enabling a nearly background free light dark matter selection in ND-GAr.

There are also opportunities to search for heavy axions in the near detector complex [20]. Two main signatures of an axion-like particle are ones with $\gamma \gamma$ and hadrons in final states. The NC $\pi^0$ events act as backgrounds to these axion-like particle signals, but as mentioned above, we can
easily reject these backgrounds by focusing on the rich hadronic information at the vertex of the 
neutrino interactions in ND-GAr.

ND-GAr also offers a physics program geared towards anomalous $\nu_\tau$s. The $\nu_\tau$s result in high 
energy muons. The TMS can analyze muons up to $\sim 6\text{ GeV}/c$ before they range out, however, since 
ND-GAr uses curvature to reconstruct the momentum, it can reconstruct muon tracks well up to 
$10\text{ GeV}/c$ and beyond.

In general, the background contributions in searches for some of the new physics mentioned 
above are due to beam neutrinos interacting in the detectors. These backgrounds scale directly with 
the detector mass hence the liquid argon near detector tends to suffer more significantly from such 
backgrounds. A combined analysis with gaseous argon near detector is necessary to constraint 
such backgrounds and reach the ultimate BSM physics reach of the near detector complex.

3 Detector Performance Requirements

Fulfilling the DUNE ND requirements leads to a set of derived detector capabilities for the ND-
GAr. These are extensively detailed in [1], and the key performance capabilities are summarized 
below.

Derived ND-GAr detector capabilities

- The DUNE near detector must classify interactions and measure outgoing particles in a 
  LArTPC with performance comparable to or exceeding that of the FD. It must measure parti-
  cles in neutrino-argon interactions with uniform acceptance, lower thresholds than LArTPC,
  and minimal secondary interaction effects. To achieve these goals, the ND-GAr must be 
  able to **constrain the muon energy scale with an uncertainty of 1% or better** to achieve 
  the oscillation sensitivity described in volume-II of the DUNE FD TDR[4]. The strongest 
  constraint comes from the calibrated magnetic field of the HPgTPC coupled with *in-situ* 
  measurements of strange decays.

- The DUNE ND must be able to measure muons with a **momentum resolution of less than 
  4%** the core, with an RMS $< 10\%$ in the tails. Simulations indicate that a high-pressure 
  gaseous argon TPC should achieve or exceed this resolution.

- The near detector must be able to detect, identify, measure the momentum of protons emitted 
  from neutrino-argon interactions. To fulfill this, the ND must have a tracking threshold low 
  enough to **measure the energy spectrum of protons emitted due to FSI in CC interac-
  tions**. Theoretical studies, such as those reported in [21, 22, 23], suggest that FSI cause a 
  dramatic increase in final state nucleons with kinetic energies in the range of a few 10s of 
  MeV. ND-GAr is suitable for measuring such low-energy protons. The threshold in ND-GAr 
  is an interplay between the argon gas density, readout pixel size, and ionization electron dis-
  persion. Performance studies indicate that a tracking threshold of 5 MeV (or a momentum 
  of 97 MeV/c) is achievable and satisfies this requirement.

- The ND must be able to **characterize the charged pion energy spectrum in $\nu_\mu$ and $\bar{\nu}_\mu$ CC 
  interactions from a few GeV down to the low energy region** where FSI are expected to 
  have their largest effect.
Theoretical studies, such as those reported in [24], predict that FSI are expected to cause a large increase in the number of pions with kinetic energies between 20-150 MeV and a decrease in the range 150-400 MeV. A kinetic energy of 20 MeV corresponds to a momentum of 77 MeV/c. ND-GAr must be able to measure 70 MeV/c charged pions with an efficiency of at least 50% so as to keep the overall efficiency for measuring events with three pions at the 70 MeV/c threshold above 10%.

ND-GAr must also have the ability to measure the pion multiplicity and charge in 1, 2, and 3 pion final states so as to inform the pion mass correction in the ND and FD LArTPC. This capability is most important for pions with an energy above a few 100 MeV since those pions predominantly shower in LAr.

- The ND-GAr must be able to detect and measure $\pi^0$s, using their decay photons, over the same momentum range as for charged pions.
- The ND-GAr must be able to identify electrons, muons, charged pions, charged kaons, and protons. ND-GAr addresses this requirement using a combination of $dE/dx$ in the HPgTPC, $E/p$ using the energy measured in the calorimeter, and the momentum measured by magnetic spectroscopy in the HPgTPC, and by penetration through the calorimeter and muon system.

ND-GAr is also able to characterize the energy carried by neutrons with kinetic energies in the range 50-700 MeV well enough to be sensitive to 20% systematic variations. The 20% specification is motivated by plausible model uncertainties.
4 ND-GAr Detector Overview

The ND-GAr concept is based on a central high-pressure gaseous argon TPC (HPgTPC); the HPgTPC is surrounded by a calorimeter, with both immersed in a 0.5 T magnetic field generated by superconducting coils. A muon system is integrated with the magnet return yoke. The argon gas in the HPgTPC will be at a pressure of approximately 10 atm to increase the rate of neutrino interactions. The baseline concept of the ND-GAr HPgTPC is based closely on the design of the ALICE TPC [25], however, an opportunity exists to reconsider this design, given the extended timeline of DUNE’s funding in the US. This paper discusses the baseline design in order to present physics motivations and performance. Future R&D needs to optimize this design will be discussed later in the document.

The drift region of the ALICE TPC has a diameter of roughly 5 m and a length of roughly 5 m. For ND-GAr, a high-pressure TPC of this size would have a fiducial mass of nearly 1 ton of argon and would produce approximately 1 million neutrino interactions on argon per year (defined as an exposure of $1.1 \times 10^{21}$ protons on target) in the on-axis position. The calorimeter is inspired by the CALICE analog hadron calorimeter (AHCAL) [26]. The scintillating layers will consist of a mix of tiles and strips. A cutaway schematic of the baseline ND-GAr design is shown in Fig. 5.

Figure 5: Cutaway view of the full ND-GAr detector system showing the HPgTPC, the calorimeter, the magnet, and the iron yoke. The detectors for the muon-tagging system are not shown.

A cutaway view of the full ND-GAr system is shown in Fig. 5. More details of the HPgTPC and calorimeter for the full ND-GAr are described in [1].
4.1 Magnet and Pressure Vessel

The design of the magnet system has evolved over the past few years and no longer uses a separate pressure vessel as was described in Ref. [1]. The superconducting magnet uses a semi-continuous thin solenoid approach with 6 separate windings. The design is based on the decades-long evolution of internally wound, aluminum stabilized superconducting magnets. The required field in the warm bore is relatively low, 0.5T, therefore a single-layer coil is sufficient to provide the needed current density even with a diameter of $\approx 7$ m. The design parameters are conservative when compared to previously built magnets. The iron yoke must be asymmetric to guarantee a sufficiently low material budget between ND-LAr and ND-GAr. The magnet system design, a solenoid with a partial return yoke (SPY), makes its design rather unique.

A key feature of SPY is that the pressure containment for the 10 bar of argon gas for the HPgTPC is now provided by the solenoid’s vacuum vessel and “stayed” flat heads are supported by the magnet system yoke. Figure 6 shows the exterior of the complete detector system. The partial iron return yoke for the magnet wraps around the sides, top, and bottom of the magnet and has a window on its upstream beam face to minimize the amount of material between the ND-LAr and ND-GAr tracking regions as shown in Figure 6. The end flanges of the pressure vessel are “stayed” by the iron yoke end plates. Analysis of ND-GAr’s pressurized system was performed to meet the requirements of Fermilab’s Environment, Safety, and Health Manual (FESHM), Chapter 5031.

Many of the features of the solenoid are based on the design of the solenoid for the MPD for the Nuclotron-based Ion Collider FAcility (NICA) at JINR [27].

4.2 Muon Tagger

ND-GAr will need an active layer, the Muon Tagger, outside the iron yoke that will detect particles that penetrate the iron. These data will be used in conjunction with the calorimeter and HPgTPC to provide $\mu/\pi$ separation. The current design consists of a single layer outside the iron. The iron itself is not segmented in depth to allow for multiple measurements. Current technologies under consideration include scintillator extrusions, RPCs, or MicroMegas.

5 Future R&D Needs

While much of the DUNE ND-GAr baseline design is based on the ALICE TPC and CALICE calorimeter designs, there are several important differences and requirements. The major areas of R&D needed for the DUNE ND are outlined below.

1. Gas mixture studies

The ALICE TPC operated at atmospheric pressure with a gas mixture of Ne/CO$_2$/N$_2$ or Ar/CO$_2$ during two different running periods. Neither of these is the gas mixture and pressure proposed for DUNE. Work must be done to establish a reference gas mixture for the HPgTPC and establish the breakdown voltage, gas gain, and diffusion coefficients for this mixture [16]. Additional studies will be needed for promising alternative gas mixtures, which are aiming to have unique optical properties for light production and detection while maintaining readout chamber operational stability.
Figure 6: The left image shows the full system, with the magnet return yoke shown in red. The right image shows a cutaway view of one of the end plates, where some of the “stays” that support the load of the flat heads are visible.
2. Light Collection

Diego will update this. Primary light production in pure argon in the VUV is well understood [28]. In pure argon at a pressure of 10 atm, we estimate that a minimum ionizing particle will produce approximately 400 photons/cm [29], but in typical gas TPC operation, a quenching gas or gases are added that essentially absorb all the VUV photons. Recent studies have indicated that with the addition of Xe or CF$_4$ (among others) [30] to an argon mixture, it may be possible to quench the VUV component of the scintillation (thus allowing for stable wire gain) while producing light in the visible or near-IR. With suitable instrumentation, this light signal could be used to provide a $t_0$ timestamp for events in the gas. Utilizing this light would be a novel development for a gaseous argon TPC. R&D will be needed to understand the potential wavelength-shifting properties and light yield of the argon gas mixtures under study in order to design a photon detection system. In close coordination with groups investigating the gas mixture, field cage, and HV, a conceptual design will be developed for the collection and readout of light in the gas volume, once a suitable gas mixture is identified.

3. Readout Chambers

Figure 7 indicates the locations of Inner Readout Chambers (IROCs) and Outer Readout Chambers (OROCs) in ALICE. These chambers have been removed from ALICE and can be used for DUNE. At a minimum, new readout chambers will need to be designed to cover the central area of the endcaps, which was not part of the TPC in ALICE. However, it is possible to consider a totally new design for the full circular readout plane, not based on the ALICE chambers. This could employ a different technology, such as GEM or MicroMegas readout. ALICE also had a central cathode with two-drift regions for the electrons, with the readout chambers placed on both ends of the detector. DUNE could consider a single-drift region, with the readout on one side, reducing the number of electronics channels needed, and providing a space for a light-collection system near the cathode.

4. Electronics and DAQ development

To achieve a very reasonable cost for the front-end electronics, and to maximize the synergies with the liquid argon near detector, it is conceived to use similar electronics for the HPgTPC. LArPix [32] development is in progress for ND-LAr, but some modifications are needed to adapt this for use in the HPgTPC, since the HPgTPC signal is faster and inverted compared to the liquid argon near detector (as the gaseous argon reads out an induced charge), and the gain in the gas also results in a widened dynamic range. Readout electronics will also need to be developed for a light collection system.

5. Field Cage and High Voltage

A new field cage and mechanical endcap structures will need to be constructed for the DUNE HPgTPC. Since the DUNE ND-GAr detector will be movable, this might require a fairly mechanically robust option. A buffer region of CO$_2$ gas, which has a higher breakdown voltage than that of Ar mixtures, could be used to isolate the field gas from the pressure vessel. The DUNE design is complicated by the fact that the HPgTPC will be operated at high pressure, which may necessitate a different solution to the field cage isolation from
ALICE, in order not to introduce complications related to strict regulation of differential pressures between two independent gas volumes.

6. Calibration
To precisely monitor any variations of the drift velocity and inhomogeneities in the drift field, a laser calibration system that can illuminate the entire drift volume is desirable. Its design will need to be developed in close collaboration with the HV field cage design, and R&D will need to be performed to ensure that an adequate signal amplitude can be obtained in the high-pressure gas mix.

7. Calorimeter
Frank will update this.

8. Muon system
The ND-GAr muon system is in a very preliminary stage of design, and it crucially depends on the particulars of both the calorimeter and magnet systems. The current design consists of a single layer outside the iron. The iron itself is not segmented in depth to allow for multiple measurements. Current technologies under consideration include scintillator extrusions, RPCs, or MicroMegas.

6 Summary
The complete ND-GAr detector is required in order for DUNE to reach its full physics potential. A magnetized tracker will allow for excellent momentum resolution and sign-selection for the long-baseline oscillation physics. With its wide acceptance for neutrino interactions on argon, the ND-GAr will also provide a rich physics program of cross-section measurements and will extend...
the capabilities of the DUNE ND for physics beyond the standard model. While the current design
benefits from work done on the ALICE TPC and by the CALICE calorimeter collaboration, the
design must be optimized for DUNE and additional resources will be required for the R&D and to
realize the full detector.

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Appendices