Multi-Purpose Detector Descoping Options

HPgTPC subgroup

March 2019

Email from Ed and Stefan

The December LBNC meeting report included the following recommendation regarding the near detector:

"Include in the TDR and the 2019 review a clear linkage between the physics drivers and the technical requirements arising from those drivers for the detector performance. This should support scope decisions should resource limitations need to be applied."

They also noted their focus on "components of the near detector system which directly and quantifiably reduce systematic errors for the long-baseline neutrino program in CP violation."

To help us respond to the LBNC, we are asking all ND sub-groups to address these recommendations, and in particular, to assess the impact of descoping their detector component. As we understand it, the current MPD concept envisages a high-pressure argon gas TPC in a magnetic field surrounded by electromagnetic calorimetry composed of a segmented tile/bar scintillator with radiator layers.
Specifically, could you please address the following points?

1. Articulate (concisely) the goals of the MPD system with regard to measurements that will be performed to impact the neutrino oscillation measurements at DUNE.

2. Investigate and propose other configurations that minimize cost, including:

   - a one atmosphere absolute pressure GArTPC
   - a descoped spectrometer system that fulfills the need to track muons from the LAr target.

Describe the tradeoffs/compromises between these descoped systems and the current concept with regards to impact on the DUNE oscillation measurements.

We would like to have an initial response to these issues by the end of March. Your input will be very valuable for defining our future strategy in response to the LBNC.

If there are any questions, we are happy to discuss them.

Thanks very much.

Ed and Stefan

Response to email

1.) Articulate (concisely) the goals of the MPD system with regard to measurements that will be performed to impact the neutrino oscillation measurements at DUNE.

The strength of the MPD is in its complementarity to the LArTPC. Below are a few examples of its strengths relative to the LArTPC:

- High-resolution imaging of particles emerging from the ν-Ar vertex (including nucleons). The reconstruction threshold in the gas phase is very small (e.g., a proton requires only 3.7 MeV kinetic energy to make a 2 cm track in the argon).
- High-fidelity particle charge determination via magnetic curvature
- Precise and independent measurement of particle momentum, via magnetic curvature, will allow the measurement of the momentum of higher-energy charged particles without requiring containment. This extends the utility of the ND, especially for the high-energy beam tune. The absolute momentum scale is easily calibrated in the magnetic spectrometer and provides a cross-check on energy loss through ionization measurements.
- Particle identification through dE/dx. The gaseous argon TPC has better separation power of particle species by dE/dx than the liquid.
- The measurement of energetic neutrons through time-of-flight with ECAL is a potential game-changer for validating energy reconstruction. Preliminary studies of the HPgTPC+ECAL system indicate that an average neutron detection efficiency of 60% can be achieved via a time-of-flight analysis. A study of the impact of backgrounds is underway, but initial studies are encouraging.
- Better acceptance at high angles than the LArTPC (which is more similar to the FD)
- The MPD neutrino event sample, while obviously much smaller than the LArTPC sample, is a statistically independent sample. Moreover, the systematic uncertainties of the MPD will be very different than the LArTPC and likely smaller in many cases. This will allow the MPD to act as a systematics constraint for the LArTPC.

The goals of the MPD, with regard to measurements that will impact the DUNE neutrino oscillation analysis are listed below. In this list, we focus on the importance of the magnetized HPgTPC-ECAL system in ensuring the MPD reaches those goals:

- **Provide data to constrain the neutrino-nucleus interaction systematic uncertainties**

  In current long-baseline analyses (i.e., NOvA and T2K), the largest uncertainties arise from cross section and flux. It is well known that neutrino-nucleus interaction models are not reliable, and it is likely that our first measurement of the (flux times cross section) in the near detector will be in disagreement with our models. A very capable near detector is necessary for telling us what we got wrong in the cross section model. It is built to address the known unknowns, but needs to also have the possibility to address unknown unknowns. The level of precision that we are trying to reach in DUNE requires expanded capability relative to what NOvA and T2K have achieved.

  In its 1-ton gaseous argon fiducial volume, the MPD will see 1.6 million charged current muon neutrino interactions per year (plus 517k neutral current muon neutrino interactions). The very low energy threshold for reconstruction of tracks in the HPgTPC gives it a view of interactions that is vastly more refined than what is seen in the LAr, and on the same target nucleus. The associated ECAL provides excellent ability to detect neutral pions, enabling the MPD to measure this important component of total event energy while also tagging the presence of these pions for interaction model studies. These aspects of the MPD will enable it to identify and measure interactions more accurately than can be done in the LArTPC, and will provide data to allow us to check that what we think we're seeing in the LAr really is what we're seeing in the LAr. The largest uncertainties are actually the things we *don't know* about the cross sections, and having a near detector that can see one level deeper than the far detector will give us the ability to reduce uncertainties in the underlying nuclear models that cause large uncertainties in cross sections via processes like multinucleon effects.

As an example of a known unknown, one MPD-based cross section constraint that will soon be implemented in the DUNE long-baseline oscillation analysis is π^+ and π^- multiplicity vs. neutrino energy (from high-purity samples of CC-0π, CC-1π, and CC-multiπ events in the gaseous argon). The magnetized MPD will make it possible to easily distinguish π^+ from μ^- (or π^- from μ^+), as has been done in T2K near-detector fits for oscillation analyses. This is a significant advantage over the LArTPC, which is not magnetized. While efforts are ongoing to distinguish pions from muons in current LArTPCs, none have yet been proven effective, so we should not rely on being able to do so at high purity in the liquid argon. Most of the ability to distinguish pions in the HPgTPC relies on the fact that it is magnetized, and that this would therefore be true of any magnetized detector, but for low momentum pions and muons, the HPgTPC will also have the benefit of using dE/dx measurements to distinguish these particles. In either case, it is important to note that the results will only translate directly to a constraint in the LArTPC (both near and far LArTPC detectors) if the magnetized detector uses argon as a nuclear target. The charged current samples from both the LArTPC and the HPgTPC at the near detector can be separated into slices of pion multiplicity; we expect that both detectors will be imperfect, so there will be some contamination of true CC-0π events in the CC-1π sample and vice-versa. This contamination, however, will be different in the two detectors, so having two independent measurements will allow the analysis to constrain the true individual cross sections.

In addition, the HPgTPC neutrino energy reconstruction for the CC-1π and CC-multiπ events (which are expected to form a significant portion of all events in DUNE) is better than that in LAr, as the pion energy can be measured by curvature or ECAL energy deposition and added back into the neutrino energy; this cannot be achieved as well in LAr because energetic pions often have hadronic interactions (which are much less likely in the gaseous argon because the interaction length is so much longer). This is a specific advantage of using the HPgTPC as part of the MPD.

- **Precisely and accurately measure all components of the neutrino flux** The HPgTPC will collect a sample of $\sim$ 20k CC-ν_e events per year, with very little background due to NC-π^0 production (the dominant background to selecting ν_e interactions in the LArTPC) because the photon conversion length in gas is much larger than in the liquid, meaning that photons from π^0 decay will rarely convert in the HPgTPC. The ECAL, however, will have excellent ability to detect the π^0 decays, enabling the MPD to reject π^0 events as background to ν_e's. The measured rate of CC-ν_e intrinsic events in the MPD is directly applicable to far detector analyses. A measurement of ν_e's would not be possible at all if the MPD were replaced by a simple muon range detector.

  The magnetic field of the MPD is necessary to precisely measure the momenta of particles, particularly those that do not stop in the detector material. Because the near detector is necessarily smaller than the far detector, near-far differences arising from the different containment fractions are compensated by the fact that the near detector has a magnetic spectrometer. Higher-energy particles from the neutrino interaction will be measured better in the MPD than in the liquid ND and even the far detector, constraining the effects of energy feed-down in the liquid detectors.

  The charge-signing functionality afforded by the magnetic field allows the HPgTPC to measure the relative contributions of ν_μ and $\bar{\nu}_\mu$ in both the neutrino beam and the antineutrino beam, as well as distinguishing ν_e from $\bar{\nu}_e$ components. These components are important to anchor in the oscillation fit, otherwise reliance on the beam modeling is needed to predict the small but uncertain fractions of wrong-sign neutrinos in the beams. Stopping muons' Michel signatures can be used in the Far Detector as they differ for μ^+ and μ^-, but that is after oscillation has distorted the spectrum, and no corresponding test is present for ν_e.

- **Measure energetic neutrons from ν-Ar interactions via time-of-flight with the ECAL**

  Neutron production in neutrino and antineutrino interactions is highly uncertain, and is a large source of neutrino energy misreconstruction. In the HPgTPC+ECAL system, a preliminary study of the time-of-flight from the HPgTPC neutrino interaction point to hits in the ECAL is encouraging, indicating that TOF can be used to detect and correctly identify neutrons. With the current ECAL design, an average neutron detection efficiency of 60% is achieved by selecting events in which an ECAL cell has one hit with more than 3 MeV. This is still very preliminary work, and further studies to understand the impact of backgrounds and ECAL design (strip vs. tile) are underway.

If demonstrated, measurement of neutrons would provide a direct constraint on the LArTPC ν_μ CC energy spectrum. The combination of the excellent charged particle resolution of the HPgTPC and the neutron measurements in the ECAL would give a better measurement of the neutrino energy than can be achieved in the LArTPC.

- **Reconstruct neutrino energy via spectrometry and calorimetry**

  Although all neutrals from an event must be measured with the ECAL in the MPD, the HPgTPC will be able to make very precise momentum measurements of exiting charged tracks. In addition, short and/or stopping tracks will be measured via dE/dx. The sum of this capability provides a complementary event sample to that obtained in the LAr, whose much higher density leads to many secondary interactions for charged particles. The two methods of measurement in the MPD will help in understanding the LAr energy resolution.

- **Constrain LArTPC detector response and selection efficiency**

  An accurate measurement of backgrounds to the ν_e appearance measurement is a critical input for far detector oscillation analyses. The MPD provides a unique capability to constrain backgrounds that are misidentified as CC-ν_e in the LArTPC, since the HPgTPC will collect a background-free sample of $\sim$ 20k CC-ν_e events per year, which will also have event-by-event wrong-sign tagging from the magnetic field. Having measured the ν_e intrinsics on argon in the MPD, the measurement can scaled to the LArTPC density and volume, and subtracted from the LArTPC ν_e measurement to obtain a measurement of ν_e backgrounds in the liquid argon. As stated above, this measurement of ν_e's would not be possible at all if the MPD were replaced by a simple muon range detector. It would also not be easy to extrapolate to the LArTPC if the target material of the MPD were not argon.

  The MPD will collect data in exclusive neutrino interaction channels, such as CC coherent pion ($\sim$ 8500 events per year in the 1-ton fiducial volume), on the same target nucleus as the LArTPC. The high purity of the samples and low detection threshold for outgoing particles will constrain the cross section, and will give a way to benchmark or constrain LArTPC detector response and selection efficiency for those channels. Every kinematic distribution in every ν-Ar channel that will be used to constrain the flux can be directly cross-checked, and usually cross-checked over an extended range of that variable, with the MPD.

- **Measure particles that leave the LAr near detector component and enter the MPD**

  The LAr component of the DUNE Near Detector will not fully contain high-energy muons. A downstream MPD will be able to determine the charge sign and measure the momenta of the muons that enter its acceptance, using the curvature of the associated track in the magnetic field. This is true of any magnetized downstream detector, but it is clear that the size of the MPD will be an important factor in its angular acceptance of particles exiting the upstream LArTPC. A preliminary study of geometries shows that reducing the HPgTPC diameter by more than 1 meter, or reducing the length by more than 1.5 meters would have significant consequences on the acceptance. Reducing the HPgTPC diameter from its nominal 5 meters to a slightly smaller 4.5 meters while increasing its length in the direction transverse to the neutrino beam improves acceptance, since the HPgTPC would better match the LArTPC 7 meter width in the transverse direction. It should be noted that reducing the diameter may actually result in a higher-cost MPD, since we would not be able to use the ALICE TPC readout chambers in the configuration for which they were designed. Increasing the length of the HPgTPC is feasible, but will require additional studies of high voltage stability in the gas, since HV breakdown in gas is proportional to the pressure (in the absence of field enhancements). The HPgTPC operating pressure will be nominally 10 times that of ALICE, so extending the drift distance from 2.5 meters to 3 meters while keeping the same drift velocity will require raising the drift HV by approximately 20 kV.

2.) Descoping options

In considering possible descoping options, we must learn from current long-baseline oscillation experiments, particularly T2K and NOvA. DUNE simulations are not yet at a sophisticated enough level to do quantitative analyses with the full near detector suite, so we turn to NOvA and T2K to understand the impact of systematics on the far detector oscillation analysis. The difference for DUNE is in the precision of measurements we aim to achieve: T2K and NOvA report systematic uncertainties on the far detector prediction after near detector constraints $\sim 5 - 10\%$ [1, 2]; to achieve DUNE's goals we require uncertainties $\sim O(1\%)$. Reaching this level of precision requires expanded near-detector capabilities relative to NOvA and T2K: in particular when considering descoping, it is important to incorporate what these experiments have found to be most valuable so that we don't end up with a near detector that is less capable than the current generation.

We consider the most significant lessons learned from the T2K and NOvA oscillation analyses (in terms of near detector capability) to be:

- **Importance of magnetic field**

  The T2K oscillation analysis fits near detector data in bins of muon candidate momentum and angle; this requires selecting a muon candidate with high efficiency and purity. In interactions producing a muon along with one or more charged pions, T2K relies on the magnetic field of the near detector to do so: the selection identifies the highest-momentum, negative-curvature (positive-curvature) track in each interaction as the μ^- (μ^+) candidate. An additional requirement, to cut down on π^+ (π^-) misidentification, is that the highest-momentum track in a ν_μ ($\bar{\nu}_\mu$) interaction has negative-curvature (positive-curvature).

  T2K has also found that it is vital to be able to distinguish neutrino from antineutrino interactions when running with an antineutrino beam. The wrong-sign contamination in the antineutrino beam at T2K is 30% neutrinos (and the neutrino beam contains a wrong-sign contamination of 4% antineutrinos). With the constraints from the near detector in the oscillation fit, T2K was able to reduce flux uncertainties on the wrong-sign ν_μ contamination in the antineutrino-mode beam to roughly 5% [1]. By comparison, the wrong-sign contamination seen by NOvA (which does not have a magnetized near detector) is 11% in the antineutrino $\bar{\nu}_\mu$ sample and 3% in the neutrino ν_μ sample, with an uncertainty of around 10% [2].

  Without a magnetic field, DUNE would have to rely on simulations of the neutrino contamination in the antineutrino beam instead of being able to measure it directly, and the near detector selection could suffer from significant contamination due to misidentifying a pion as the muon candidate.

- **Importance of target nucleus**

  It is well known in the neutrino interaction community that extrapolating interaction uncertainties from one nucleus to another can incur large, often unknown (or not well quantified) additional uncertainties. A direct demonstration of this can be seen by considering the change in uncertainties in the T2K oscillation analysis when including water-target data at the near detector. The uncertainty on the predicted number of events at the far detector for T2K is shown in table 1. When using only carbon-target data at the T2K near detector, including the near detector data reduces the uncertainty on the number of ν_μ events from 12.0% to 7.7%, demonstrating the impact of the near detector fit. However, including also water-target data from the near detector further reduces the uncertainty to 5.0%; showing the importance of including data from the same target material at the near and far detectors.

	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
Without ND fit	12.0%	11.9%	12.5%	13.7%
Using ND fit without water data	7.7%	6.8%	11.6%	11.0%
Using ND fit with water data	5.0%	5.4%	5.2%	6.2%

Table 1: Fractional uncertainty on number of predicted events in each sample at the far detector from T2K oscillation analysis [3].

The approach of using the same target material at near and far detectors has also been very successful for the NOvA experiment. The functionally identical nature of the NOvA detectors allows NOvA to guarantee the same target nucleus mix which aids the cancellation of neutrino cross-section uncertainties and also makes the signal and background detection efficiencies and energy resolutions nearly identical to the far detector, greatly reducing near-far uncertainties.

We believe it is clear from the experience of these current experiments that a magnetic field and an argon target are crucial for the MPD, and that if either were removed it would result in a significantly less capable detector. With that in mind, we have considered the following descoping options:

1. **Reducing HPgTPC pressure to 1 atmosphere**

   Reducing the pressure to 1 atmosphere and making no other changes will not affect the cost very much, as the pressure vessel is not a major cost driver. The gas system needed for 1 atm operation is very similar to that needed for 10 atm operation, apart from needing different pressure relief valves and regulators.

   At 1 atm, the reconstruction threshold will be lower than at 10 atm, because tracks of the same energy are even longer in the lower density medium, but the statistical uncertainties will be worse because we will see a factor of 10 fewer events overall. Generally, selection criteria will have to be tightened due to the fact that while the number of neutrino interactions per spill in the gas will decrease, the number of interactions in surrounding materials like the ECAL and magnet will remain the same, so our signal-to-background ratio will be degraded.

   Particle ID by ionization suffers when one lowers the pressure in the TPC. Allison and Cobb [4] show results indicating that about a factor of 2 is lost in dE/dx resolution from a factor of 10 reduction in pressure.

   This descoped option would fulfill the goals outlined earlier in this document as follows:

   - (✓) Provide data to constrain the neutrino-nucleus interaction systematic uncertainties (degraded due to decreased statistics and need to tighten selection criteria)
   - (✗) Precisely and accurately measure all components of the neutrino flux (a 1-atm HPgTPC would not produce sufficient statistics of ν_e and $\bar{\nu}_e$ interactions to make the necessary precise measurements)
   - (✓) Measure energetic neutrons from ν-Ar interactions via time-of-flight with the ECAL (degraded due to decreased statistics and need to tighten selection criteria: operation at 1 atmosphere would make the signal-to-background for neutrons in the ECAL worse by a factor of 10)
   - (✓) Neutrino energy reconstruction via spectrometry and calorimetry (degraded due to decreased dE/dx resolution at lower pressure)
   - (✓) Constrain LArTPC detector response and selection efficiency (degraded due to decreased statistics and need to tighten selection criteria)
   - ✓ Measure particles that leave the LAr near detector component and enter the MPD

2. **Simplified system (1 atm HPgTPC, no ECAL, reduced B field)**

   In this configuration, the MPD would retain its ability to catch muons exiting the LArTPC, but would lose the capability to make a precise relative measurement of neutrino flux components. The number of neutrino events would be reduced by a factor of 10, and the momentum resolution would also be degraded.

   Without an ECAL, the possibility of measuring neutrons and π^0s associated with neutrino interactions will be completely gone. In addition, the precise timing that is given by TPC-exiting-to-ECAL tracks would not be available to provide a t_0 for the neutrino interactions in the gas. This would mean that we would most likely not have a usable sample of neutrino interactions in the HPgTPC.

   This descoped option would fulfill the goals outlined earlier in this document as follows:

   - ✗ Provide data to constrain the neutrino-nucleus interaction systematic uncertainties

✗ Precisely and accurately measure all components of the neutrino flux

✗ Measure energetic neutrons from ν-Ar interactions via time-of-flight with the ECAL

✗ Neutrino energy reconstruction via spectrometry and calorimetry

✗ Constrain LArTPC detector response and selection efficiency

✓ Measure particles that leave the LAr near detector component and enter the MPD

3. **Alternative simplified system (10 atm HPgTPC, downstream-only ECAL, reduced B field)**

   An alternative intermediate descoping option for the ECAL could be to give up on full coverage of the HPgTPC surface. If only the downstream side is covered, for example, this would result in considerably lower cost, and may also reduce the integration complexity by providing free access to the endcaps and at least 50% of the barrel surface of the HPgTPC pressure vessel. It is not clear yet what the physics impact of such a scenario would be, although it would definitely limit the phase space of measurements that can be made of interactions in the gas with electromagnetic products. As a first estimate, one could imagine the following effects on the detector's ability to achieve the goals outlined earlier in the document:

   (✓) Provide data to constrain the neutrino-nucleus interaction systematic uncertainties (the detector would not be able to measure all interaction channels over the full phase space, but could provide constraints in a limited phase space)

   (✗) Precisely and accurately measure all components of the neutrino flux (degraded ability to reject π^0 backgrounds to ν_e CC events)

   (✗) Measure energetic neutrons from ν-Ar interactions via time-of-flight with the ECAL (again, this would only be possible for a reduced phase space of neutron emission angles)

   (✗) Neutrino energy reconstruction via spectrometry and calorimetry (this will be possible for the limited phase space, forward-going neutral particles)

   (✓) Constrain LArTPC detector response and selection efficiency (this may still be possible, but for a limited phase space)

   ✓ Measure particles that leave the LAr near detector component and enter the MPD

   The capabilities of an MPD descoped in this way are educated guesses for the moment, as this option has not yet been investigated in detail. Additional studies will be undertaken to assess this option.

References

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[2] Neutrino 2018: Mayly Sanchez, "NOvA Results and Prospects", Talk at XXVIII International Conference on Neutrino Physics and Astrophysics, 4-9 June 2018, Heidelberg, Germany, DOI: 10.5281/zenodo.1286757, http://doi.org/10.5281/zenodo.1286757

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