Running of ProtoDUNE-SP (NP04) and ProtoDUNE-DP (NP02) After Long Shutdown 2

The DUNE Collaboration[1]

I. Introduction

The two ProtoDUNE detectors (NP02 and NP04) serve a critical role in validating the designs of the DUNE far detectors. The DUNE Collaboration plans to use the single-phase (SP) technology for at least two of its four modules and the dual-phase (DP) technology for at least one module. A SP pixel-readout scheme has been proposed as a possible technology for the fourth module. An Interim Design Report (IDR) published in 2018 describes the DP and SP technologies and the physics reach of the DUNE experiment [1].

The construction of the ProtoDUNE-SP detector (NP04) was successfully completed, on schedule, in July 2018, and the detector is now collecting valuable hadron-beam and cosmic-ray data. One of the first events recorded in the ProtoDUNE-SP Time Projection Chamber (TPC) is shown in Figure 1. The ProtoDUNE-DP detector (NP02) is in the final stages of assembly (Fig. 2). We expect to close the ProtoDUNE-DP cryostat with two of four charge readout planes (CRPs) installed in early 2019, with cosmic-ray data collection beginning in March/April 2019. The two ProtoDUNE detectors are located in two similar cryostats. However, the single and dual-phase cryostats each have a unique arrangement of feedthroughs on the top face that are specific to the technologies being tested.

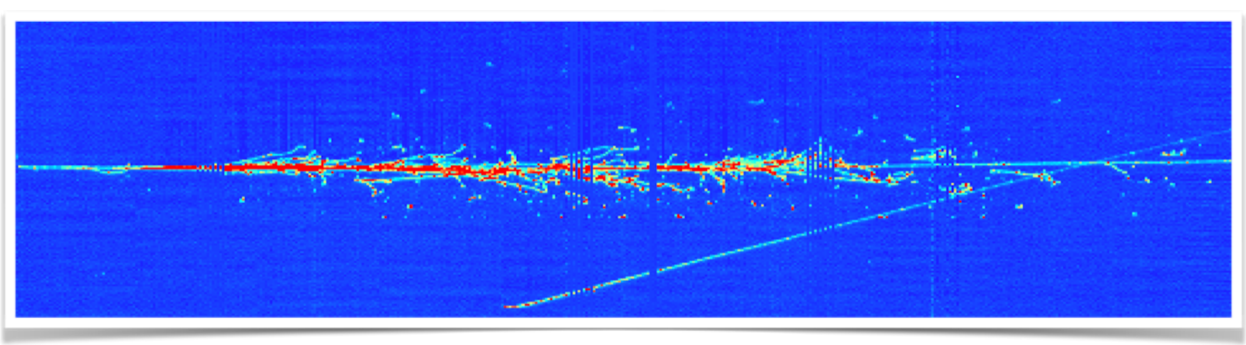

Figure 1: A beam halo muon initiating an electromagnetic shower in ProtoDUNE-SP.

The current schedule allows initial data from both ProtoDUNE detectors to provide the information required for finalizing the DUNE far detector TDR in 2019. Future needs for ProtoDUNE-SP and DP running are difficult to define precisely at this point, particularly for beam data, since they depend on the success of data taking during the coming months. Additional running would allow us to complete the beam-based program described in the original protoDUNE proposals [2].

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In addition, we also expect some changes to the components to be installed in DUNE for both readout technologies independent of the results of this initial data collection. We therefore believe it will be critical to operate the ProtoDUNE detectors again following the Long Shutdown 2 (LS2) to perform a test of the exact hardware to be installed in the DUNE cryostats in South Dakota.

There are some aspects of the design that cannot be directly tested in the protoDUNE cryostats, mainly related to the 12m height of the final DUNE detector. These include the full 12m drift for the DP detector and the two-APA assembly for the SP detector. Dedicated tests of these design aspects will have to be performed elsewhere.

Future ProtoDUNE running will provide unique samples of known particle interactions in the single and dual phase detectors that may prove critical to analyzing data from the DUNE far detectors. These data sets can be used for calibration, and for algorithm development and validation. There are also unique physics measurements that can be performed, for example, the determination of hadron-argon cross sections and searches for boosted dark matter.

Figure 2: (left panel) Drift volume of the SP ProtoDUNE detector with an Anode Plane on the left and a Cathode Plane on the right; (right panel) first Charge Readout Plane being installed in the DP ProtoDUNE detector.

II. Current Status of ProtoDUNE Detectors

<u>ProtoDUNE-SP (NP04)</u>

The ProtoDUNE-SP detector was designed to test the design of the DUNE 10 kton single-phase far detector modules. About two years were required from the start of detector component fabrication to first data collection with ProtoDUNE-SP in September

2018. This success validates the adopted modular approach to detector construction, with work distributed among construction sites and confirms estimates of the construction schedule.

From the construction and integration phases of the detector components, the cold test procedures and the assembly in a confined space inside the cryostat, as completed in mid-June 2018, some immediate lessons have been learned regarding:

- Modular design and production tooling and methods for the six Anode Plane Assemblies (APAs), which were successfully constructed at sites in the US and the UK.
- Factory model for production of detector components in multiple sites.
- Integration of three different photon detector designs, using light-guide bars and the Arapuca light-trapping system, into the APA frames.
- Operation of a full-size detector unit in cold nitrogen gas with a dedicated cold box as a model for a future Integration and Test Facility (ITF).
- Quality assurance for all systems and quality control procedures

The subsequent cryogenic commissioning phase, completed in September 2018, allows us to draw some initial conclusions:

- The basic concept of a membrane cryostat - developed for industrial applications - is well suited also for the more demanding research/science applications.
- The membrane cryostat heat load and corresponding cryogen consumption for cooling is found to be within the expected range.
- The development of an exoskeleton mechanical design was fully validated with deformations monitored and is found to be within expected range.
- The membrane cryostat mechanical design allows for significant adjustments and tailoring to cope with:
    - complex and sizable detector components installation inside (side port - Technical Construction Opening - and its sealing, top side with multiple penetrations),
    - liquid-argon operation (side penetration for forced liquid-argon recirculation, overpressure operation and regulation capability),
    - high liquid-argon purity reach (air evacuation by gaseous-argon piston purging successfully accomplished, research grade purity reached with lifetime in the ms range). The ultimate level of impurity concentration at recirculation equilibrium with intrinsic impurity release is still to be determined during the ongoing test.
- Functionality of the argon recirculation/filtration circuit (and overall cryogenic plant) for gaseous and liquid argon, and liquid-nitrogen cooling has been demonstrated.
- Cryo-instrumentation for precise and continuous monitoring of liquid-argon (and logged by a fully automated system) has been validated.

- The validation of the HV distribution system design is particularly crucial: demonstration of achieving and stably maintaining the target drift electric field (500 V/cm) for the LArTPC operation across the long drift of 3.6 m is considered the most critical step of the protoDUNE activation and operation, relevant for the DUNE far detector design. This goal has been achieved with a smooth ramp up to the target HV of 180 kV, which has so far been maintained for a period of five weeks of continued operation. Some issues have been diagnosed in the external portion of the HV circuit - in particular, with faulty behavior of the HV power supply (PS) and some detected flaws of the HV resistive filters. The faulty PS has been replaced and the mechanical design of the resistive filters must be improved.

The physics performance of a SP liquid-argon Time Projection Chamber (LArTPC) is a function of many intertwined detector parameters: argon purity, drift distance, electric field strength, wire pitch, wire length and noise levels in the readout electronics. For a TPC on the surface, space charge effects (SCE) are another leading detector effect impacting physics performance. With the data taken during the current phase of detector operation with beam and cosmic trigger - Oct. 6 to Nov. 11, 2018 - we expect to perform a full characterization of the detector performance. A core calibration from detected charge to deposited energy converting *dQ/dx* (ADC/cm) to *dE/dx* (MeV/cm) includes

- Electronics calibration;
- Space charge effects;
- Electron lifetime;
- Recombination effects;
- Muon and pion based calibrations.

Even though preliminary, some indications can already be drawn:

- In the TPC, 99.7% of the 15,360 channels are alive and responsive.
- The cold electronics noise is within expected range (from 500 to 700 ENC for the collection and induction planes, respectively). Previously known and therefore expected ADC issues are found in a limited number of channels. An offline mitigation procedure is being applied.
- The LAr purity, after a few cycles of recirculation through the filters, reached and exceeded the target level for physics operation. The current value of the electron lifetime is of 5.5 ms, corresponding to about 50 ppt residual concentration of O2 equivalent impurities.
- The signal-to-noise ratio (S/N) is in an extremely comfortable range over the entire TPC as demonstrated by the clear display of tracks and showers even with low purity conditions. Figure 3, for example, shows a 7 GeV pion crossing three APAs.
- The S/N, determined from the ionization charge from cosmic muon tracks (~mip) and the equivalent noise charge (ENC) from the cold electronics read-out of

individual TPC wires, is about 60 for the collection wire plane, exceeding expectations.

- Online and near-online data processing provide immediate feedback during data taking. Offline event reconstruction and analysis perform very well.

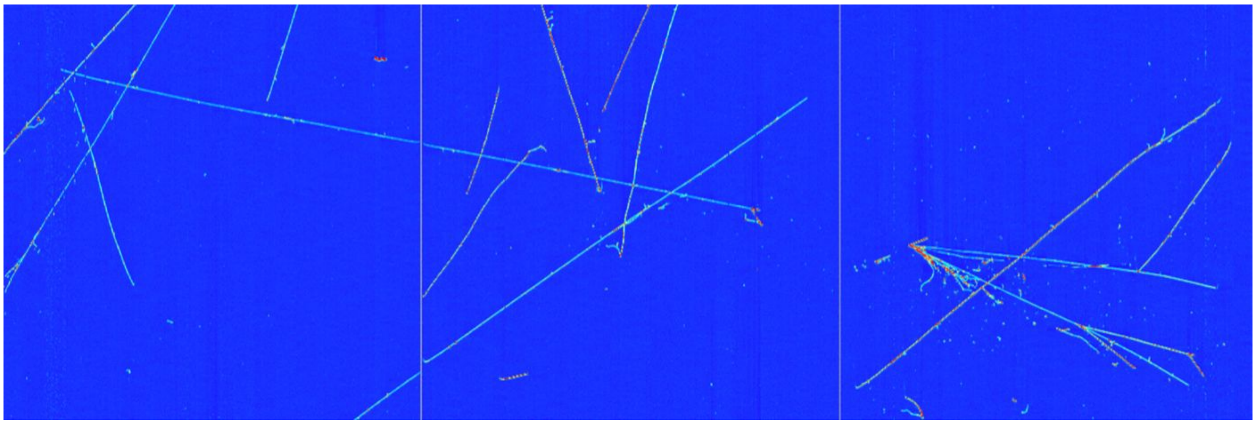

Figure 3: A 7 GeV beam pion observed in three APAs (corresponding to the three panels). The total length is 7 m.

Demonstrating the long-term operational stability of the detector is one of the main goals of ProtoDUNE. This motivates extended running for recording cosmic-ray data beyond the end of the current operation with particle beams. The liquid-argon technology is sufficiently new that long-term testing of the prototypes is highly desirable to reduce the risks of problems arising during the >10 year operation period of the DUNE far detector modules.

The long-term operational stability of the detector is thus part of the risk mitigation program ahead of the construction of the first 10 kton far detector module. This provides a strong argument for extended cosmic-ray operation through 2019. For cosmic-ray operation, the data storage requirements will be relatively low as we only need to record a fraction of the potential trigger rate. Data will be taken and analyzed to monitor the following properties as a function of time:

- The uniformity of response, i.e., no degradation, of the charge signal of the TPC and read-out cold electronics (e.g., signal/noise and noise r.m.s.) and the stability of calibration from ADC counts to energy using the *dE/dx* distribution for cosmic muon tracks.
- The uniformity of the response of the light signal collected by the ARAPUCA photon detector system and the light guide bars.
- Long-term tests of the cryogenics and recirculation/purification system, in particular the sustainability of the ultra-high level of purity necessary for physics operation - in the tens of ppt concentration of O_2 equivalent residual electro-negative impurities. We also need to test the operation of the purity

monitors, potentially exposed to degradation of the photocathode and optical fibers, over an extended time period.

A number of dedicated tests are also envisaged to assess new developments advancing and improving the currently implemented technical solutions. These include modifications of the DAQ system and of the external part of the HV system. The effect of the variation of the working parameters of the cryogenic/recirculation system on the overall performance of the detector also needs to evaluated. Recently proposed calibration methods, such as neutron guns and/or radioactive gamma sources, need to be tested in-situ. Test of these systems may be included in the plan of the long-duration test following the end of the current beam run.

ProtoDUNE-DP (NP02)

ProtoDUNE-DP (formerly known as WA105) was conceived to test the final components designed for the DUNE 10 kton dual-phase far detector module. The charge collection units for both NP02 and the DUNE-DP far detector are the Charge Readout Planes (CRPs). They integrate 50x50 cm^2 Large Electron Multiplier (LEM) - anode sandwiches on a 3x3 m^2 planar mechanical structure. The CRPs ensure the extraction of the electrons from the liquid to the gas phase and their multiplication and collection in two segmented anode views.

The NP02 detector also includes a field cage and cathode assembly, a photon detection system based on cryogenic photomultipliers, a slow control system, analog cryogenic electronics, digital front-end electronics, and a DAQ system. The construction of NP02 is currently being completed. The closure of the cryostat Temporary Construction Opening (TCO) is expected to occur in January 2019.

In its current implementation, NP02 includes two fully instrumented CRPs and two CRPs that are at not equipped with LEM-anode sandwiches. The two non-active CRPs complete the anode surface at the top of the field cage and ensure the closure of the drift field lines and the extraction and collection of the electrons from the liquid phase. The configuration with two active CRPs allows us to validate the technical performance of the dual-phase design for the DUNE 10-kton detector with cosmic rays by also assessing interface aspects among adjacent CRPs. This is the main goal for NP02 in view of the completion of the DUNE TDR in 2019.

The configuration with only two active CRPs will not be optimal for the study of hadronic showers in possible beam data taking after LS2. The instrumentation of the two non-active CRPs can occur at the end of the technical run, before the end of LS2. The CRPs underwent cold box tests since July 2018, which demonstrated the high voltage stability of the system including the LEM and the extraction grid.

The design of the LEM, mounted on the two active CRPs of NP02, has been improved with respect to the one implemented on the 3x1x1 prototype in order to ensure stable operation at nominal voltages. The analog and digital front-end electronics and the DAQ system have been completed in view of the four active CRP operation. The photon detection system including 36 cryogenic photomultipliers and their calibration system has also been procured for the four-CRP configuration.

The production and integration experience accumulated so far for NP02 has been fundamental for assessing all these aspects in view of the construction of a DP far detector module for DUNE. The components implemented in NP02 for the electronics and the photon-detection system correspond to those foreseen for a DUNE 10-kton module.

A subset of all the elements of the analog and digital electronics chains designed for DUNE has been operational since the fall of 2016 on the 3x1x1 m^3 prototype for the readout of 1280 channels. Five cryogenic photomultipliers, identical to the ones foreseen for DUNE, have also been operating in the 3x1x1 detector in various readout configurations. The field cage and cathode elements of NP02 have the same design modularity as required for DUNE. The DUNE field cage/cathode elements may incorporate some small structural changes related to the implementation of these elements in order to cover the larger far detector field cage dimensions.

The current CRPs incorporate LEMs with a conservative design, with only 86% active area, in order to ensure stable operation. It is likely that the design can be optimized by increasing the LEM active area. New LEMs, with larger active area, would have an intrinsic performance not different with respect to the LEMs that are going to be tested in NP02. However, new HV stability issues may appear on the CRPs by extending the LEM active surface. The new LEMs will be checked with respect to HV stability in dedicated CRP cold box tests. This procedure allows us to validate new LEMs with a larger active area in parallel to NP02 operations. Beam data taking with NP02 after LS2 could then also profit from the possibility of instrumenting the two non-active CRPs with LEMs with larger active area.

The DUNE DP far detector construction organization relies on three dual-phase specific Consortia: CRP, DP-Photon Detection and DP-Electronics and 3 joint SP-DP consortia (High Voltage, Cryogenic Instrumentation and Slow Control, DAQ). These consortia are developing the TDR design based on the experience accumulated with the NP02 activities. The construction of the NP02 prototype allowed us to establish the fabrication and QA/QC procedures and to validate the schedule and integration aspects and costing. Some immediate conclusions can be drawn regarding:

- LEMs production and testing procedures.
- CRPs modular design, production tooling and methods and cold box testing.
- Electronics production, testing and operation (already performed with the 3x1x1 prototype).
- Photon-detection system production, wavelength shifter coating, testing and operation (already performed with the 3x1x1 prototype).

- Field cage and cathode modular design, production and integration (the field cage design has also most of its basic components in common with NP04).
- The slow control system, which has also many elements in common with SP design.

Aspects concerning the cryostat and cryogenics are in common with NP04, and already benefit from experience with cryogenic operation of NP04.

The DP ProtoDUNE detector at NP02 will not have had beam exposure before LS2. It will focus on the technical demonstration of the detector and the assessment of its performance with cosmic rays in view of the DUNE TDR. The NP02 detector operation after the TCO closure in January 2019 aims at achieving the detector performance assessment by the end of spring of 2019, still in time to inform the DUNE TDR process.

The NP02 run may then be extended for the rest of 2019 to the beginning of 2020 in order to assess long-term detector stability. During 2020, it will be possible to empty the detector and upgrade it by instrumenting the other two CRPs in order to prepare for post LS2 beam data taking. On this occasion, it will also be possible to implement small changes motivated by the operation experience of NP02.

III. Future operation of ProtoDUNE-SP and DP to verify final DUNE design

It is critical to perform a full system test of the final components to be installed in the DUNE far detectors. Many components will be similar or identical to those currently installed in ProtoDUNE-SP and DP, while others will need to be modified. Some systems, such as a laser system for calibration, were not part of the current ProtoDUNE scope, but must be included in a system test before installation in DUNE. Here, we summarize systems where an additional run of the ProtoDUNE detectors is technically motivated. Current running may suggest additional design changes not described below. The motivation for collection of test-beam data with both ProtoDUNE detectors is addressed in the following section.

SP Anode Plane Assemblies: There will be some minor mechanical changes to the APA design related to cable routing for electronics and the photon detector system. These changes alone would not require additional beam running in ProtoDUNE. The modified APAs will be required, however, to perform final tests of other systems (e.g., photon detection system).

DP Charge Readout Planes. The current CRP design has been tested in a cold box, verifying only that voltages can be maintained. The first test with drift charges and amplification will occur in ProtoDUNE-DP. The current CRP incorporates a conservative LEM design with 86% active area. It is likely that this design will be revised to achieve greater active area. Any new design will be tested in a cold box, but should also have a final test in ProtoDUNE-DP.

SP TPC Electronics: An additional run of ProtoDUNE-SP is considered a critical test the final electronics system, either the 3-ASIC solution (FE amplifier+custom ADC+data handling ASIC) or the CRYO ASIC. The current ProtoDUNE run uses a different ADC and data handling chip (an FPGA) than either final design option.

DP TPC Electronics: No significant changes are planned for this system.

SP photon detection system: The current ProtoDUNE-SP detector includes three options for the photon detection system. The baseline system, using ARAPUCA light-trap devices, has already evolved from the version deployed in ProtoDUNE-SP. A new run of ProtoDUNE-SP would

- incorporate the final ARAPUCA design, which will collect light from both sides;
- include circuits for active ganging of SiPMs, which is critical to test for compatibility with the TPC electronics;
- use the SiPMs planned for installation in DUNE.

The photon system could use of reflective foils on the field cage and/or cathode plane to improve light detection uniformity and efficiency. This scheme must be tested in ProtoDUNE before being approved for deployment in DUNE.

DP photon detection system. No significant changes are planned for this system.

The following systems are common to single and dual phase:

High Voltage. Possible modifications of cathode/field cage for the photon detection system (mentioned above) and the laser system could impact the HV system and must be tested. No other modifications are expected if the current ProtoDUNE-SP tests are successful. For the DP far detector, a new cathode concept is under study. It is based on the use of resistive materials to mitigate effects due to the large energy stored between cathode and ground surfaces. In case of a second run with ProtoDUNE DP, this concept could be tested up to the nominal voltage (-600 kV) together with the new power supply and feed-through when they are available from the joint R&D venture with Heinzinger.

DAQ. Beginning in the post-run period in 2018, ProtoDUNE-SP will be used as a demonstrator platform for the TDR DAQ design. This demonstration is essential, as ProtoDUNE offers the only sufficiently realistic environment to study detector noise, trigger performance, calibration strategy, etc. Initially, DAQ tests will be parasitic, but in late 2019, we plan to replace key elements of the existing readout system with components more similar to those for DUNE FD. These modifications will include a more sophisticated trigger system, capable of triggering on cosmics and calibration sources. In addition, ProtoDUNE will play a key role as an integration testbed for DAQ and the FD subdetectors, for both SP and DP, including the calibration systems discussed below.

Cryogenic Instrumentation and Monitoring. Any changes based on current ProtoDUNE experience will need to be tested in final ProtoDUNE run. Additional instrumentation is likely to be added to that currently deployed in ProtoDUNE-DP.

Calibration systems. Except for an external cosmic ray/muon tagging system for ProtoDUNE-SP, no calibration systems were included in the current ProtoDUNE run. Testing of calibration systems planned for the DUNE far detector is a priority for a post-LS2 run. We anticipate testing three systems in ProtoDUNE:

1. Laser system
2. Neutron source
3. Radioactive sources

iV. Motivation for Collection of Test Beam Data

The motivation for collection of charged particle beam data in the ProtoDUNE detectors was described in the ProtoDUNE-SP TDR (arXiv:1706.07081) and the WA105 (ProtoDUNE-DP) TDR (SPSC-TDR-004). Large samples of beam data of different particle species at different known energies allow us to obtain an in-depth understanding of the detector response. These data are useful for calibration, and would enable precision studies of the hadronic cross sections to improve the nuclear re-scattering models and the modeling of the neutrino energy reconstruction. The beam data will allow us to study a variety of issues direct relevant to DUNE physics analyses:

1. Electron identification and electron/π^0 separation by using π^0 from secondary hadronic vertices;
2. Particle identification studies by using particles tagged by the beam instrumentation.
3. The identification of kaons in the beam will provide useful information to DUNE's nucleon decay search.
4. Energy scale and energy resolution for electromagnetic and hadronic showers;
5. The electromagnetic content in hadron-initiated cascades, in particular the π^0 multiplicity and EM energy fraction as a function of primary hadron incident energy,
6. Recombination for different particle species and angle dependance;
7. Constraining the GEANT4 physics models for interactions of hadrons in argon. The pion charge exchange cross section is very important for understanding the background uncertainty in the DUNE far detector oscillation analysis. The branching ratio of this process is small (approximately 10% at 1 GeV), therefore a large data sample is required to measure this cross section precisely.

The level at which systematics in DUNE can be constrained through analysis of ProtoDUNE test-beam data is being evaluated and the precise number of beam events required is not yet determined. A run period for ProtoDUNE-SP of approximately 6 weeks in the test beam (with positive beam polarity) is currently been taken (ending

Nov. 11, 2018). The ProtoDUNE-DP installation schedule precludes collection of beam data before the shutdown. Beam operation after LS2 in 2021 would allow ProtoDUNE-SP to collect negative polarity data and additional positive charge beam data if the current run is not sufficient, and will allow ProtoDUNE-DP to perform its proposed beam-based program, including 120 days of beam data, yielding the collection of 175 million beam triggers.

Beam data samples to be collected include:

- **Pion and proton** beams in an energy range from about 0.5 to 2 GeV will be used primarily to study hadronic interaction mechanisms and secondary particle production. At higher energies (up to 7 GeV) hadron beams will be used to study hadron shower reconstruction and hadron energy calibration.
- **Electrons** in the available energy range will be used to benchmark and tune electron/photon separation algorithms, to study electromagnetic cascade processes and to calibrate electromagnetic showers at higher energies.
- **Charged kaons** produced in the tertiary beamline are rare but are copiously produced by the pion beam interactions inside the detector. These will be extremely useful for characterizing kaon identification efficiency for proton decay sensitivity studies.
- **Muons** stopping with Michel electrons from muon decay (or without Michel electrons, in the case of negative muon capture) will be used for energy calibrations in the low-energy range of the SN neutrino events and for the development of charge-sign determination methods.

V. Beyond the Standard Model Physics Opportunity

In addition to validating the liquid-argon detector design, future ProtoDUNE running can also take advantage of the considerable active volume of the two ProtoDUNE detectors to perform searches for new physics. We propose to search for relativistic scattering signatures induced by boosted dark matter (BDM) in these detectors through its inelastic scattering final states as the first beyond the standard model (BSM) physics result of DUNE. This search also provides an excellent means of validating the entire detector readout chain under realistic conditions, and in particular the trigger system, which will be entirely new for this run. Self-triggering on this challenging signal, in the presence of realistic backgrounds, and with proper estimation of efficiency and acceptance, will require the definition of a realistic data selection strategy that will in turn inform our planning for the full DUNE experiment.

This dark matter scenario assumes two stable dark matter species, the heavier species denoted by χ_0 and the lighter by χ_1, where the former indirectly couples to Standard Model (SM) particles through the latter. This implies that a pair of χ_0 annihilates into a pair of χ_1 in, for example, the galactic halo. The mass gap between the two species allows χ_1 to acquire a large boost factor and undergo relativistic scattering in terrestrial detectors. A possible scenario is that χ_1 enters in the detector, undergoes an inelastic scattering off an electron/proton in liquid-argon, and "transits" to an unstable dark-sector state χ_2, which subsequently disintegrates back to χ_1 together with possibly visible secondary particles in addition to the primary target recoil. We label this class of processes as inelastic scattering modes of boosted dark matter, or iBDM [2].

Since the final state of iBDM interactions contains not only an electron or proton but two additional electrons at an associated secondary vertex, the resulting signature is very distinctive. Therefore, it is feasible to carry out such a search at the ProtoDUNE detectors, using the cosmic ray data triggered through the sum of the photon detector signals. This trigger should be tuned to be sensitive to one electron resulting from the atmospheric electron neutrinos, and hence would likely contain events not only from electron neutrinos but also from iBDM scattering. A recently completed study on the 3 electron final state shows that even though the detectors are on the surface, potential backgrounds from all expected sources can be reduced to a negligible level [3].

Assuming a dark photon scenario to describe the interactions between SM particles and χ_1, we can interpret the results in terms of the dark-photon parameter space. For example, Fig. 4 shows parameter coverage achievable with the ProtoDUNE detectors in the plane of the dark photon (X) mass versus parameterizing kinetic mixing ε between the dark photon and the SM photon. Exclusion limits differ for the case where the dark photon mass is greater than twice the mass of χ_1 [Fig. 4(a)] compared to the opposite case [Fig. 4(b)]. Current exclusions at the 90% C.L. are shown as shaded regions, and the associated boundary values are extracted from Refs. [4] and [5] for the two cases.

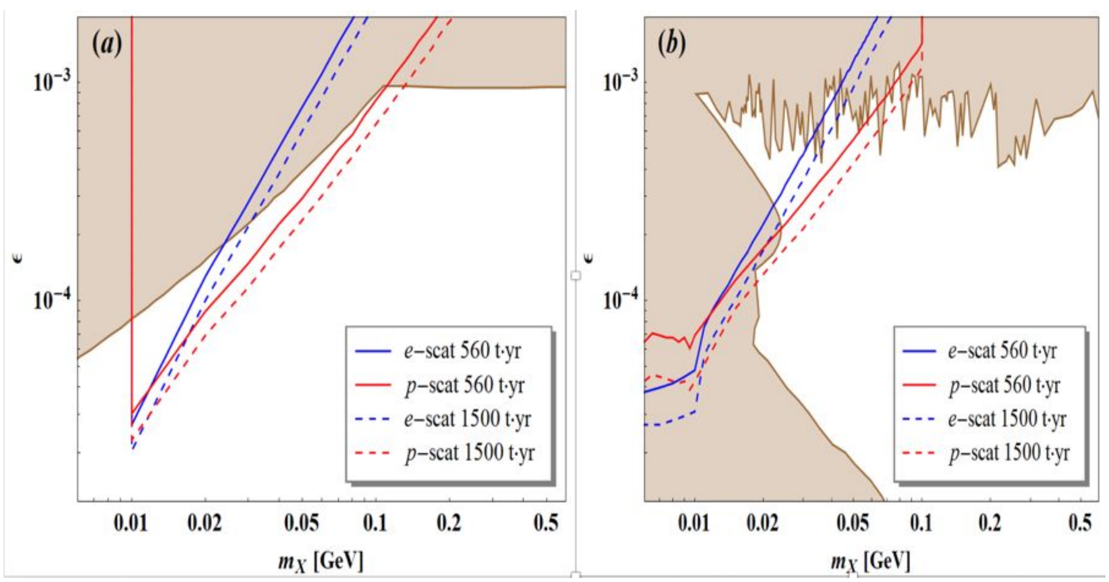

Figure 4: Experimental sensitivities in the m_χ *-* ε *plane. (a) The case of* $m_\chi > 2m_1$ *(b) The case of* $m_\chi < 2m_1$*. The values of the other parameter are fixed. We assume potential background events are sufficiently suppressed to perform zero-background searches.*

We assume that the threshold energies for electrons (blue lines) and protons (red lines) are 30 MeV, and accept events with all final state particles appearing in the fiducial volume of each ProtoDUNE detector, corresponding to a ~30% reduction of the active volume from each detector. For the proton + two-electron final state, we further require the recoil energy to be less than 2 GeV, beyond which the proton itself may break apart. All the results in the figure are shown at the 90% C.L. limit assuming zero background.

We assume 1.5 years of data collection (solid lines) for a total 375 t fiducial volume for the initial period of ProtoDUNE data taking, followed by an additional two-year data collection (dashed lines) at a total of 470 t fiducial volume which includes the full active volume ProtoDUNE Dual Phase detector. The results depicted in Fig. 4(a) and Fig. 4(b) show that ProtoDUNE can significantly extend the coverage of the unexplored parameter space for both dark-photon scenarios. Comparing the electron and proton channels, we can see that as m_χ increases, the proton scattering channel becomes more sensitive.

In conclusion, an additional two years of data taking with both detectors with their full active volume will enable the ProtoDUNE detectors to extend the reach for BDM searches. This proposal provides an unprecedented opportunity to produce the first BSM physics search result in DUNE at ProtoDUNE, and an additional opportunity to study performance of the detectors in their intended mode of data collection.

VI. Resources Required

The support of the CERN Neutrino Platform (NP) has been crucial for the success of the ProtoDUNE program. We are working to assess resources required for the ProtoDUNE detectors to operate after LS2. Required resources include

- Collaboration resources to produce, test, and install new detector components.
- Collaboration resources to commission new detector elements and run data collection shifts.
- NP resources to fill NP02 and NP04 with liquid argon.
- NP support for cryogenics systems for fill and running period.
- NP support for all cryostat operations: re-opening of cryostats, replacement of detector components, re-closinging cryostats
- NP support of data collection.
- Computing and data storage.

We expect that the international partners responsible for detector components within the consortia will include adequate costing for future operation of the ProtoDUNE detectors on the Neutrino Platform.

VII. Summary

We propose future running of the ProtoDUNE single and dual-phase detectors. The main goal is to demonstrate and test the final hardware configuration for both technologies before the DUNE far detectors are constructed. Future running will also allow us to demonstrate the long-term stability that is required for operating the DUNE far detectors over a period of several decades. The ProtoDUNE data sets will also be crucial for further algorithm development and validation, and to develop and perform calibration procedures. An additional motivation is an interesting physics program including measurements of cross sections on argon and searching for boosted dark matter signatures.

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