First Results from Singe-Phase ProtoDUNE at CERN Neutrino Platform

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NuFACT2019, Daegu, KOREA
- New beam at Fermilab (1.2 MW@80 GeV protons, upgradeable to 2.4 MW), 1300 km baseline (Chris Densham's talk)
- On-Axis 40 kton Liquid Argon Time Projection Chamber (LArTPC) Far Detector at Sanford Underground Research Facility, South Dakota, 1.5 km underground
- Highly-capable near detector at Fermilab (Alan Bross's talk, Kim Siyeon/Sunwoo Gwon's poster) $\nu_e$ appearance and $\nu_\mu$ disappearance $\Rightarrow$ Measure MH, CPV and mixing angles (Kim Siyeon’s talk)
- Large detector, deep underground $\Rightarrow$ Nucleon decay, supernova burst neutrinos, atmospheric neutrinos, etc (Kihyeon Cho's talk)

DUNE Overview: Jae Yu’s plenary tomorrow
Far Detectors: Liquid Argon Time Projection Chamber (LArTPC)

- High resolution 3D track reconstruction
  - Charged particle tracks ionize argon atoms
  - Ionized electrons drift to anode wires (~ms) for XY-coordinate
  - Electron drift time projected for Z-coordinate
- Argon scintillation light (~ns) detected by photon detectors, providing $t_0$
Far Detector: Single-Phase LArTPC

- Anode wire planes (2 induction, 1 collection) immersed in LAr
- Anode and Cathode Plane Assemblies (APA, CPA) suspended from ceiling
- Drift distance: 3.6 m, wire pitch: 5 mm
- Induction wires $\pm 37.7^\circ$ to collection wires, wrapped around APA
- Photon detectors: light guides+SiPMs, embedded in APAs
Far Detector: Dual-Phase LArTPC

- Electrons extracted from LAr to gaseous volume
- Signal amplified by Large Electron Multiplier (LEM) in gas phase
- Charge collected and recorded on 2-D segmented anode
- Drift distance: 12 m (vertical)
- Accessible electronics, better Signal/Noise
- Photon detectors: PMT below cathode

S. Murphy, https://indico.cern.ch/event/649662/
**ProtoDUNE** at CERN

- Two major DUNE prototype LArTPCs at CERN
  - One single phase and one dual phase
  - 770 t LAr mass each
  - Exposed to H2 (DP) and H4 (SP) testbeams at CERN, momentum-dependent beam composition contains $e^-, K^\pm, \mu, p, \pi^\pm$

- Strategic Goals
  - Prototyping production and installation procedures
  - Validating the design from basic detector performance
  - Accumulating large test-beam data for detector response understanding, calibration, dE/dx, PID etc.
  - Demonstrating long-term operational stability

**Status:**
ProtoDUNE-SP: First test beam data took in Sep-Dec 2018 (This talk)
ProtoDUNE-DP: Taking first data
Both ProtoDUNE cryostats and their beamlines are located near to each other in the EHN1 building at CERN.

  - New tertiary, low-mom beam line; 2 secondary targets
  - W for lower momenta (0-3 GeV/c); Cu for higher momenta (4-7 GeV/c)
  - TOF and Cherenkov counters for PID
ProtoDUNE Single Phase

- Active Volume: 6m (H) x 7m (L) x 2x3.6m (W)
- Central Cathode Plane Assembly (CPA):
  - 18 CPA modules
  - 3.6 m drift distance @180 kV
  - 500 V/cm field in drift volume
- Anode Plane Assembly (APA):
  - 2 APA planes, each with 3 APAs
  - APA module: 6m high, 2.3m wide
  - Photodetectors integrated in APA
- Field cage: surrounds the open sides of the drift region, ensuring uniform electric field
- Cold electronics: directly attached to the top of the APA (2560 wires/APA, 15360 total wires)
- Photon detectors (PDS): 3 designs integrated into APA frame bars
ProtoDUNE-SP: Anode Plane Assembly (APA)

- APA: 3 wire planes (U/V,X) + 1 grid plane (G)
  - Grid plane prevents induction currents from drifting charge in drift volume
  - Induction wires (U, V): inclined at +/- 35.7°, transparent to charges
  - Collection wires (X): collect charge forming unipolar signal
  - Grounding Mesh shields photon detectors

Wrapped wires reduces # of electronic channels and allows more active volume, all electronics on top
Cold Electronics (CE)

- Cold Electronics (CE): Both Front-End and ADC ASICs submerged in liquid argon
- FEMB (Front End Mother Board) mounted on top of the APA
- Assembled APA and cold electronics tested in Cold Box (150K nitrogen gas) before installation
- Front-End ASIC worked well, R&D to improve ADC ASIC for DUNE

ENC (Equivalent Noise Charge): charge injected to detector capacitance which produces on the output side a signal with amplitude equals the output RMS noise
Photon Detection System (PDS)

- LAr is excellent scintillating medium: 20,000 photons/MeV @ 500 V/cm, wavelength=128 nm
- Wavelength shifter converts VUV to visible light readout by SiPMs
- 3 PDS designs being tested in ProtoDUNE-SP:

  Design 1: Dip-coated light guide (MIT and Fermilab): Acrylic light guide bar dip-coated with wavelength shifter

  Design 2: Double-shift light guide (Indiana University): Wavelength shifting plates + wavelength shifting light guide

  Design 3: ARAPUCA (Campinas University and Fermilab): Light trapped and wavelength-shifted by dichroic filter, 5~10x light yield increase
Detector Instrumentation and Cosmic Ray Trigger

- Purity monitors (PrM): electron lifetime (LAr purity) measurement
- Gas analyzers: check argon gas purity
- Temperature sensors: Static and Dynamic sensors to measure temperature maps
- LAr level meters: keep LAr level constant
- Cameras: Observe visible for detector operation
- Cosmic ray tagger (CRT): scintillator panels upstream/downstream

Purity Monitor Design

M. Adamowski et al., JINST 9, P07005 (2014).
Milestones of ProtoDUNE-SP construction in EHN1

- **March 2016, construction of EHN1 extension**
- **November 2016, cryostat structure assembly**
- **September 2017, cryostat completion**
- **February 2018, detector assembly**
- **August 2018, LAr filling**
- **September 19, 2018 – HV @ 180 kV ready for beam!**
### Collected beam events: Oct-Nov 2018

<table>
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<tr>
<th>Momentum (GeV/c)</th>
<th>Total Triggers Recorded (K)</th>
<th>Total Triggers Expected (K)</th>
<th>Expected Pi trig. (K)</th>
<th>Expected Proton Trig. (K)</th>
<th>Expected Electron Trig. (K)</th>
<th>Expected Kaon Trig. (K)</th>
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<td>472</td>
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<td>All momenta</td>
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<td>1693.5</td>
<td>777.5</td>
<td>1381</td>
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- 300k pion events at 1, 2, 3, 6, 7 GeV, enough for small cross section measurements
- Large statistics proton and electron data
- Some high energy kaon data
- Beamline Time of Flight (TOF) and Cherenkov measurements for PID.
Event Displays

Resolution and data quality excellent
Electronic noise under control

3 GeV - Pion Interaction(s)
(and decay)

7 GeV Pion Interaction

2 GeV Electron shower

1 GeV Pion Interaction
(Absorption $\rightarrow$ 2p)
LAr Purity from Purity Monitors

- Liquid Argon purity routinely measured by the three Purity Monitors (PrM) at 1.8 m, 3.7 m, and 5.6 m from the bottom of the cryostat.
- PrM: UV driven small TPC for electron lifetime measurement \( Q_{\text{anode}}/Q_{\text{cathode}} = e^{-t_{\text{drift}}/\tau} \)
- Gas/liquid recirculation & filtering rate \( \sim 1 \) volume/4.5 days, high purity reached
- Ar circulation pumps stoppage (electron lifetime dips) caught and alerted in time
Electronic noise and S/N ratios

Noise level measured by pedestal RMS before noise filtering:
- Collection (X): 550 e-,
- Induction: 650 e-
(DUNE goal 700 e-)

Noise filter reduces both by 100 e-

Signal-to-noise ratio measured by cosmic muons
- Collection: 38:1,
- Induction U: 14:1,
- Induction V: 17:1
Beam Event and Cosmic Ray Reconstruction

- PANDORA pattern recognition (arXiv:1708.03135) reconstructs, separates and classifies beam events and cosmic muons tracks in 3 ms TPC readout window
- Subsequent off-line analysis treats beam events and for the cosmic ray muon tracks separately
Space Charge Effects

- Space Charge Effect (SCE): E-field distortion due to accumulation of slow drifting ions induced by cosmic rays (Joshua Thompson’s poster)
- Bias reconstructed dE/dx, particle trajectory and recombination
- Critical effects to energy and position calibration
- Can be removed by E-field map correction measured in cosmic data

E-field map: +20% at cathode, -10% at anode due to SCE

Data

\[ \Delta E/E_0 [%] \quad Z_{true} = 348 \text{ cm} \]
Beam Data Events

7 GeV Charged Pion (T)
W Plane View
PANDORA reconstruction

T = Trigger Parent Particle from test beam
D_T = Daughter Track
D_S = Daughter Shower
GD_T = Granddaughter Track
GD_S = Granddaughter Shower

TPC reconstruction chain tested with real test beam data
dE/dx Reconstruction

After SCE correction, use stopping muons to determine the absolute dE/dx scale.

Same stopping muon absolute calibration works well for beam proton data.
Photo Detector Performance

- Good energy linearity for contained beam electrons in the detector
- Working on geometry, attenuation and efficiency corrections
Summary

• First test beam data taken with the ProtoDUNE-SP LArTPC show excellent detector performance
• Calibration and reconstruction chain tested successfully with data:
  – Detector non-uniformity corrected
  – Energy scale determined
  – Excellent particle ID demonstrated
• Two papers under preparation on detector tech and performance
• Working on hadron cross section measurements to improve event generators and GEANT for DUNE
• Studying long-term operational stability
• Preparing round 2 beam test at CERN

Thank you!
Backup
Neutrino Oscillation at DUNE

$\nu_e$ appearance

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 (A-1) \Delta}{(A-1)^2}$$

$$+ 2\alpha \sin \theta_{13} \cos \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A \Delta \sin (A-1) \Delta}{A} \frac{\sin \Delta}{(A-1)}$$

$$- 2\alpha \sin \theta_{13} \sin \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A \Delta \sin (A-1) \Delta}{A} \frac{\sin \Delta}{(A-1)}$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

$$\Delta = \frac{\Delta m^2_{31} L}{4E}$$

$$A = +G_f N_e \frac{L}{\sqrt{2} \Delta}$$

- DUNE measures $\nu_e$ appearance probability and $\nu_\mu$ disappearance probability with $\nu_u$ and anti-$\nu_u$ beam.
- $\nu_e$ appearance: mass hierarchy, $\delta_{CP}$ and octant of $\theta_{23}$
- $\nu_\mu$ disappearance: high precision $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$, constrain octant
60-120 GeV protons from Fermilab Main Injector
Wide energy spectrum covers the 1st and 2nd oscillation maxima
Initial upward pitch, 101 mrad pitch to get to S. Dakota
Near Detector Hall at edge of Fermilab site
Initially 1.2 MW @ 80GeV, upgradeable to 2.4 MW
Reference design similar to NuMI, optimized to improve sensitivity to oscillation measurements
Sanford Underground Research Facility (SURF), Lead, S. Dakota

- In the Homestake gold mine
- Home of Ray Davis’s solar neutrino experiment
- 4 caverns for detector and one utility hall for DUNE
- Blast vibration study has been done
- Excavation for the first two caverns started in FY2017

DUNE facility, 4850 ft (1.5km, 4300 mwe)

Groundbreaking: 21st July, 2017
Figure 1: A schematic diagram showing the relative positions of XBTFs (orange), bending magnets (green), XBPFs (blue) and XCET (yellow) in the H4-VLE beam line. Combining data from different pieces of instrumentation can be used for triggering, reconstructing momentum and measuring time of flight, as discussed in the text.

Figure 2: A schematic diagram showing the method by which momentum is reconstructed for a given beam particle (red), as discussed in the text. Taken from [4].

Alexander Booth and Jake Calcutt (ProtoDUNE Beam Instrumentation Working Group)
ProtoDUNE-SP Analysis Plan & Goals

- Detector Performance – Information for DUNE TDR & first papers
  - LAr purity
  - Noise level, signal to noise ratio
  - Detector calibration, removing space charge effects etc.
  - dEdx of muons, protons, pions, kaons, electrons
  - Energy and momentum resolutions (w/ Charge-TPC and (in progress) Light-PDS)

- Physics measurements - physics publications
  - *(started)* Total pion cross section in [1-7] GeV range
  - *(started)* Exclusive channels Cross Section:
    - $\pi$ absorption: $\pi^\pm \to 2p$, 3p, 2p1n,..
    - $\pi^\pm \to \pi^0$ charge exchange, etc.

Tingjun Yang
(Fermilab)
Detector calibration strategy

- Remove any nonuniformity in the detector response
  - **Space charge effects (SCE)** – removed using E-field map
  - Attenuation caused by impurities – removed using muon MIP map
  - Variations in electronics gain – removed using pulser data
  - Other effects (grounded electron diverters, floating grid plane, etc.) – removed using muon MIP map

- Determine the absolute energy scale
  - Using stopping muons
    - $dE/dx$ in the MIP region is very well understood theoretically to better than 1%

Using the same method developed by MicroBooNE: [arXiv:1907.11736](https://arxiv.org/abs/1907.11736)