Status and Plans of ProtoDUNE-SP (NP04)

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On behalf of the NP04 Collaboration

149th Meeting of the SPSC
May 10, 2023

- Analysis updates
  - Publication status
  - Hadron-argon cross sections
  - Other TPC and photon detector analyses
- Status and plans for ProtoDUNE-HD (run II)

Publication Status

- **Separation of track- and shower-like energy deposits in ProtoDUNE-SP using a convolutional neural network**
  - Published in Eur. Phys. J. C 82, 903 (2022).
- **Identification and reconstruction of low-energy electrons in the ProtoDUNE-SP detector**
  - arXiv:2211.01166
  - Currently under consideration in PRD.
- **Reconstruction of interactions in the ProtoDUNE-SP detector with Pandora**
  - arXiv:2206.14521
  - Currently under consideration in EPJC.

Hadron – argon cross sections

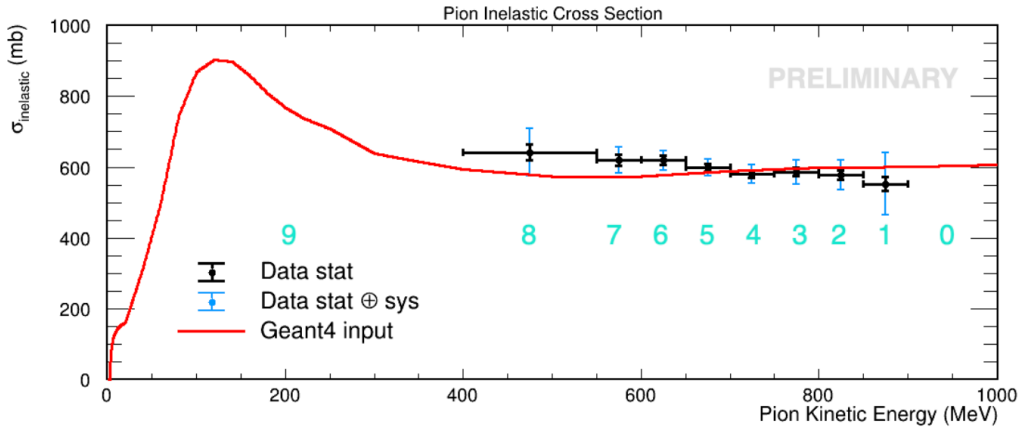
- ProtoDUNE accumulated data to measure hadron-argon cross sections for various beam particles (pion, proton, kaon) over a wide range of energies (0.3 – 7 GeV/c).
- Such measurements are important for neutrino interaction modelling:
  - Interactions of primary pions and protons within the argon nucleus
  - Interactions of primary hadrons as they propagate from the neutrino interaction
- Make use of the thin-slice method from LArIAT
  - Effectively divide the TPC into separate detectors in the beam direction
  - Modified to divide based on energy instead of distance (E-slice method)
  - Cross section is proportional to the ratio of incident and interacting hadrons per slice

$$\sigma = \frac{M_{\mathrm{Ar}}}{\rho N_A \Delta E} \frac{dE}{dx}(E) \ln\left(\frac{N_{\mathrm{inc}}(E)}{N_{\mathrm{inc}}(E) - N_{\mathrm{int}}(E)}\right)$$

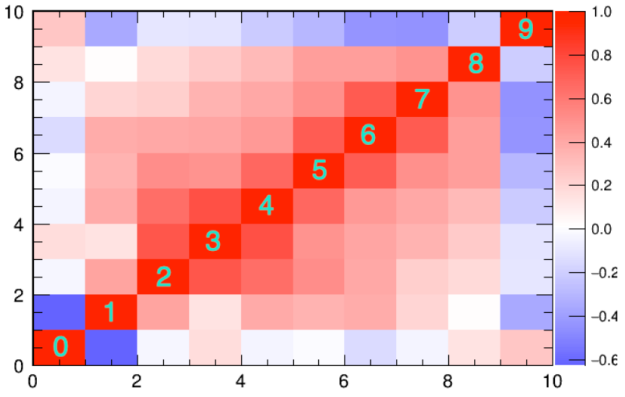
- **Many preliminary data results are available.**

Pi-Ar Inelastic Cross Section

- Analysis of the inelastic cross section
  - Includes all possible final states
- Purity of selected events is over 80%.
- Data-driven background estimation
- Multi-dimensional unfolding
- First data results using 1 GeV/c data with preliminary systematic uncertainties are available.
- The 2 and 3 GeV/c analyses are ongoing.

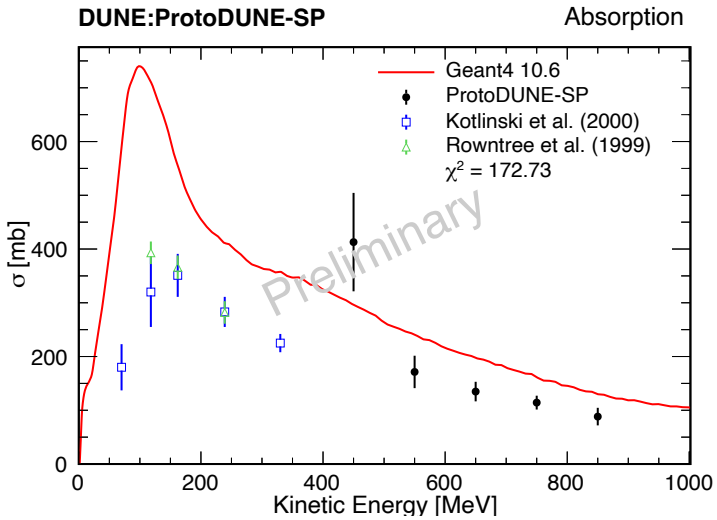


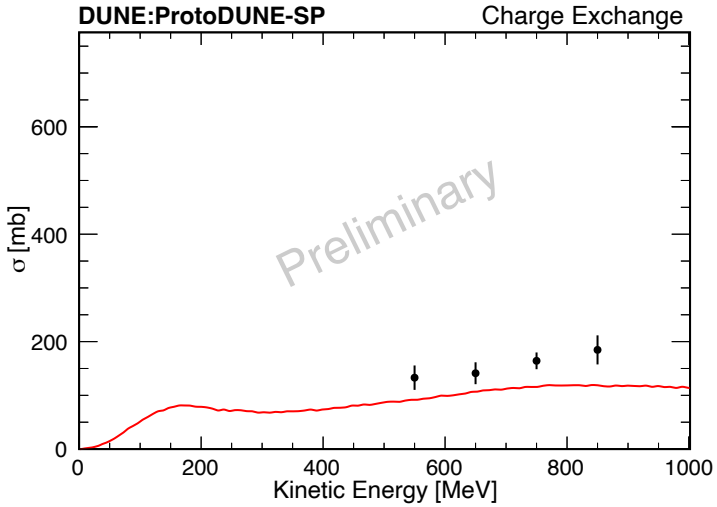
Correlation Matrix



Pi-Ar Exclusive Channels

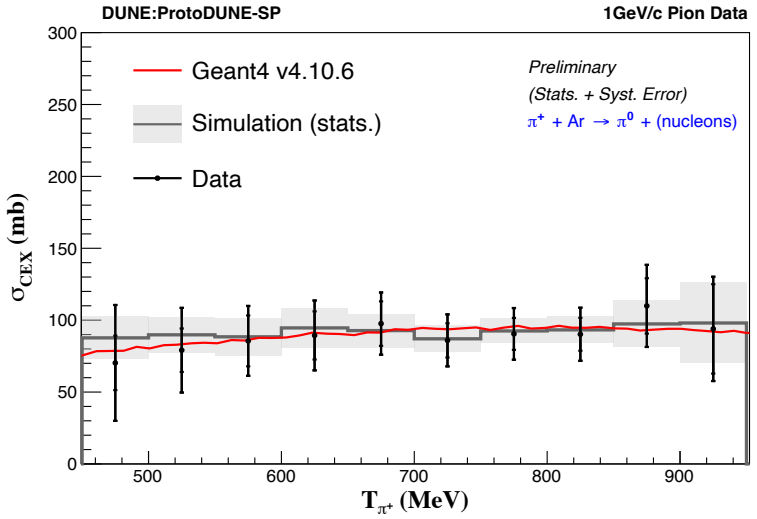
- Look at two channels:
  - Absorption: no pions in final state
  - Charge exchange: pi-zero(s) but no charged pions in final state
- A likelihood-fit-based analysis.
- Preliminary results show discrepancies with G4 predictions.
- A paper draft is currently under DUNE ARC review.

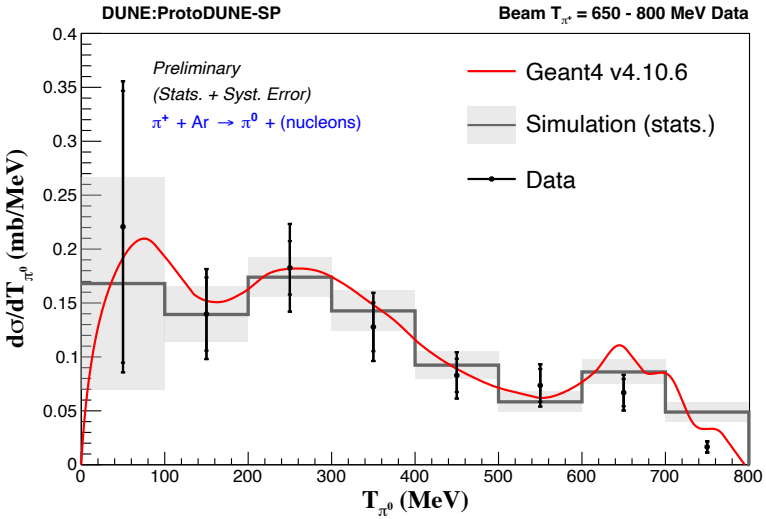




Differential Pion Charge Exchange Cross Section

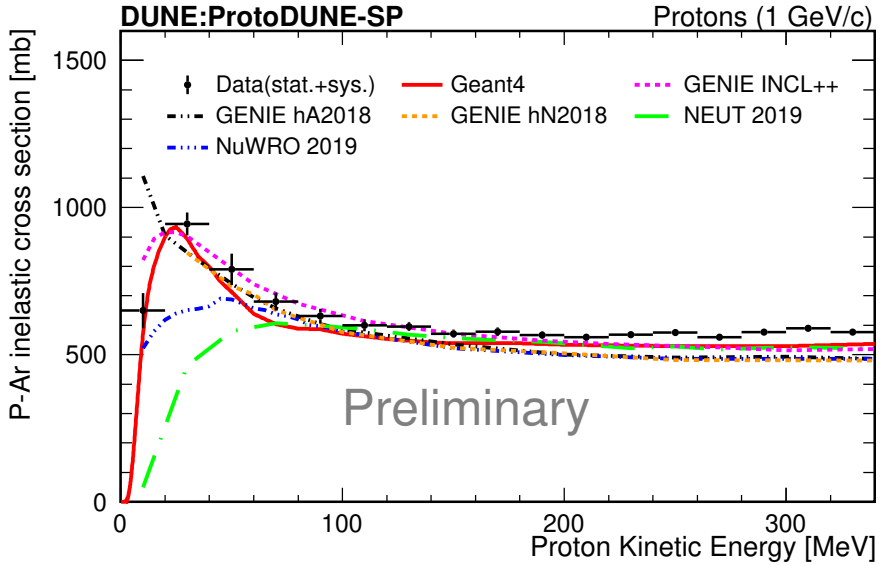
- Use E-slice method to measure pion charge exchange cross section – different approach from the last slide.
  - On-going investigation to understand the difference between the two results
- Selection purity is 70%.
- Data-driven background estimation.
- Measure cross section as a function of
  - Incoming π^+ KE
  - Outgoing π^0 KE





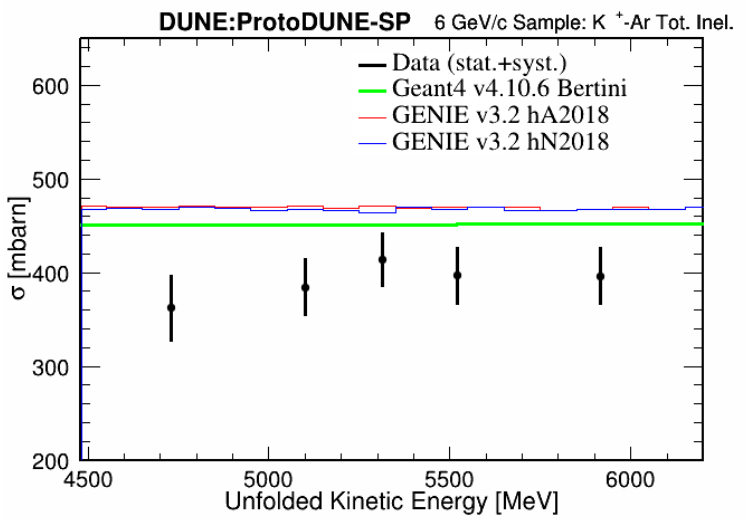
Proton Inelastic Cross Section

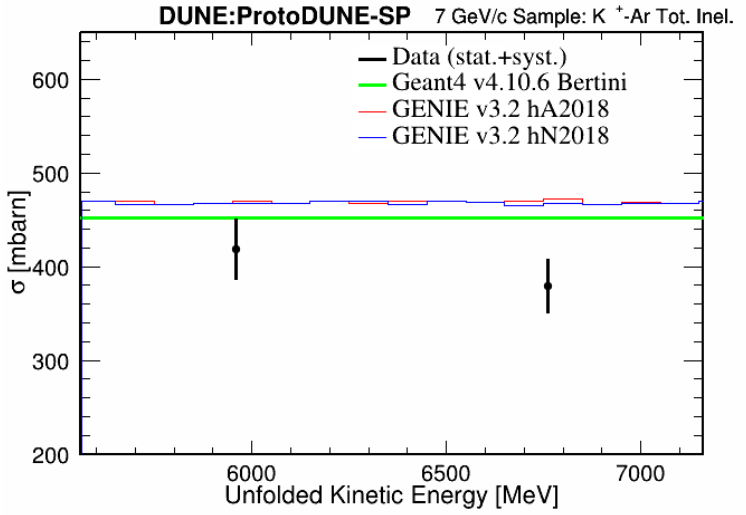
- Analysis similar to pion inelastic cross section.
- Select inelastically interacting beam protons.
- Main backgrounds from elastically scattering protons and mis-id of secondary protons.
- First data results using 1 GeV/c data with preliminary systematic uncertainties are available.
- The 2 and 3 GeV/c analyses are ongoing.



Kaon Inelastic Cross Section

- High energy inelastic cross section measurement
  - 6 and 7 GeV/c K^+ beam
- Use the E-slice method.
- Preliminary result suggests G4 overestimates the measured cross section
- A paper draft is currently under DUNE ARC review.



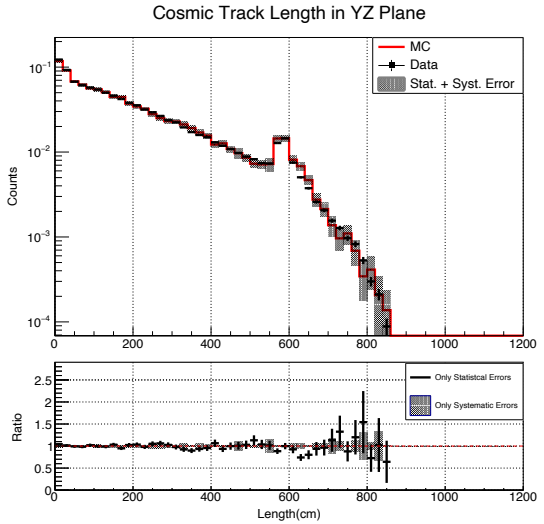


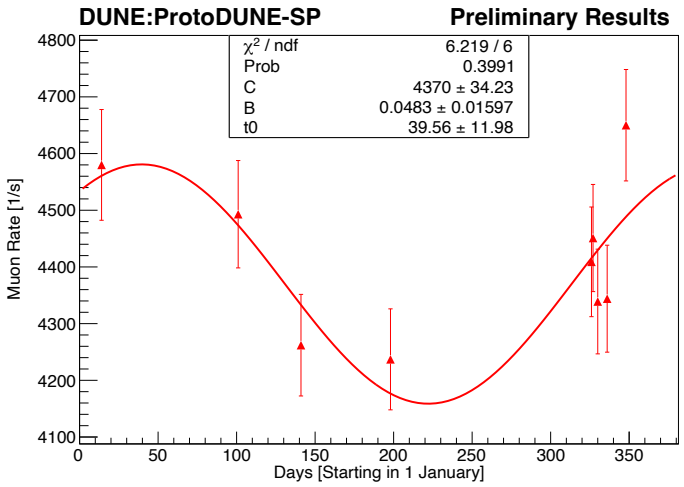
Cosmic Muon Seasonal Variation

- Expect to see seasonal variations in cosmic ray rates due to changes in atmospheric temperature
- Good agreement for the selected cosmic ray muon sample between data and MC
- Measure the rate in data for a number of different runs and fit the distribution:

$$g(t) = C * \left(1 + B * \cos\left[\frac{2\pi}{P}(t - t_0)\right]\right)$$

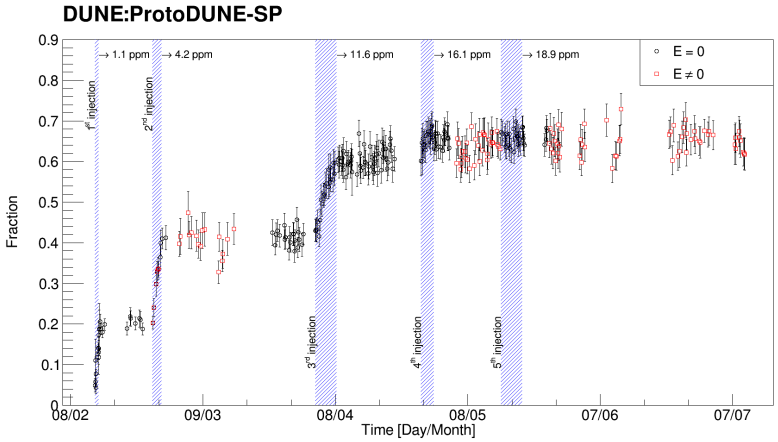
  - See a clear signal at 3 σ
  - Amplitude = 4.2 ± 1.6%
  - Maximum rate on day 40 ± 12 days
- In agreement with other surface experiments
- Analysis currently under group review.

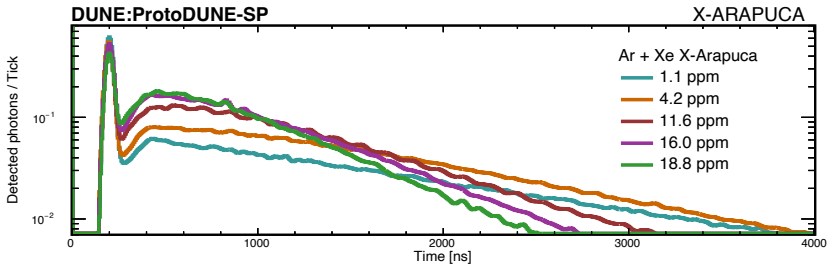


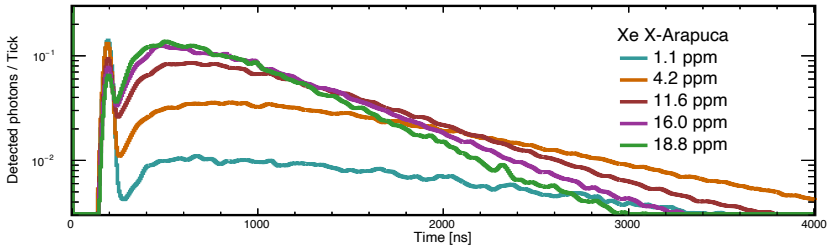


Photon Detector Analysis

- Xenon added in 2020 after N2 contamination
  - 18.9 ppm enough to recover the 70% light drop
- Light increases with Xe concentration and then saturates above ~16ppm
- With more Xe concentration, the pulses become narrower.
- Results stable over a time scale of months
- No detectable interference between TPC operation and light level from Xe
- Paper in DUNE ARC review







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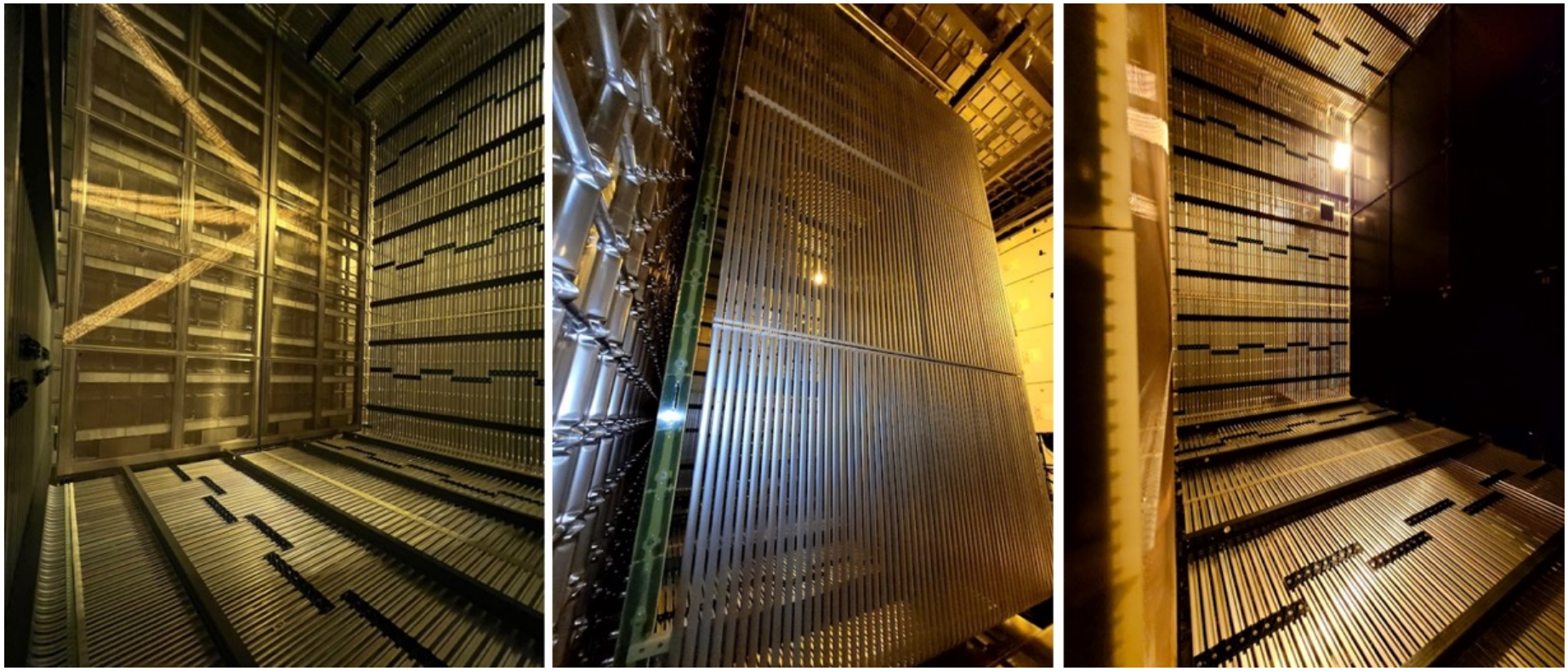
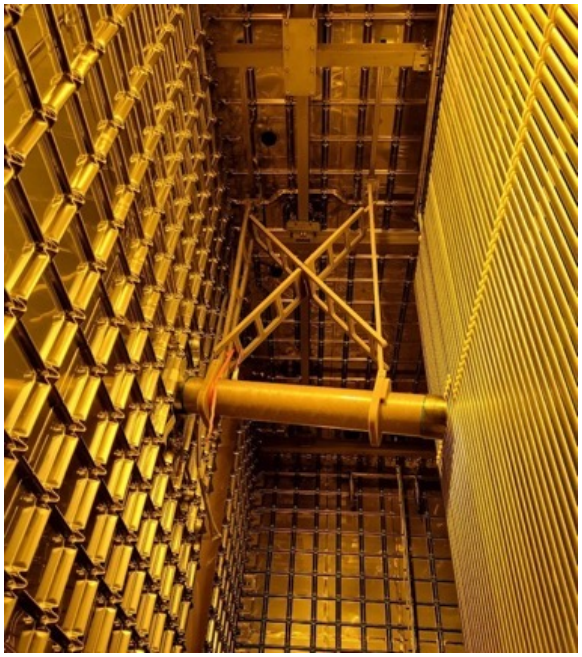
INSTALLATION

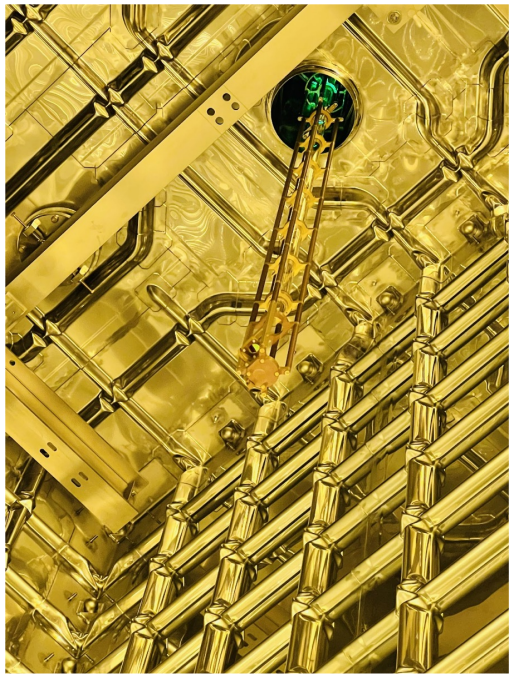
Installation of the ProtoDUNE-II TPC was completed by the end of 2022



Installation highlights



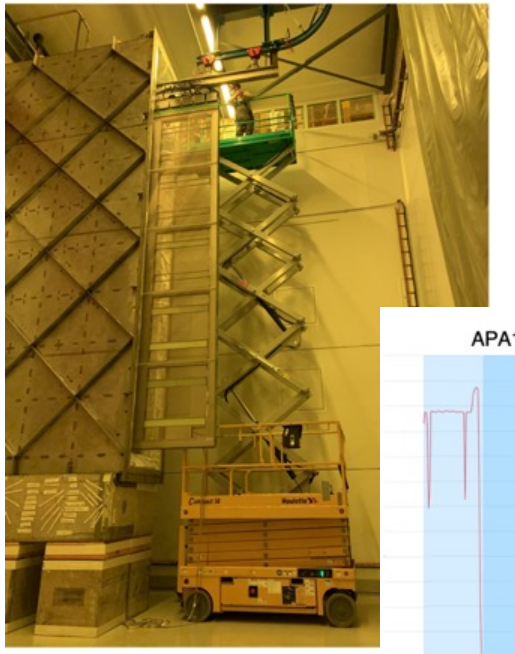
Installation of new, longer beam plug inside cryostat.



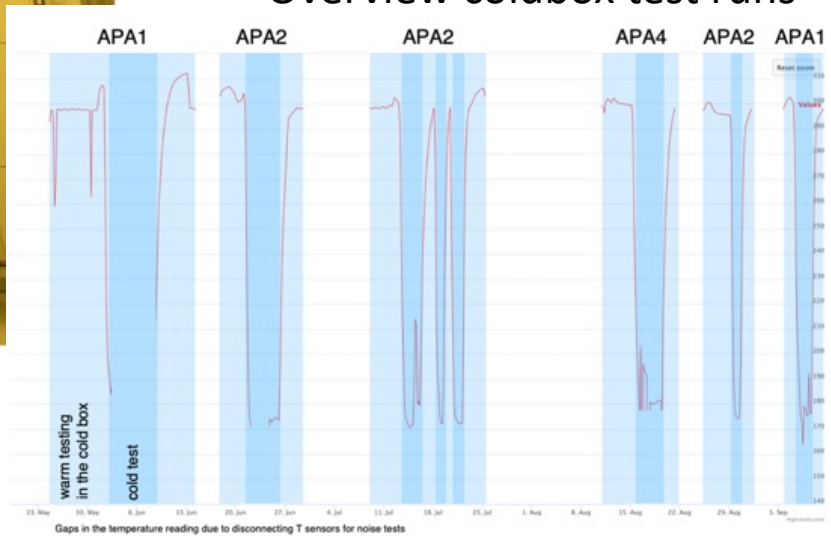
Practice installation and alignment testing of laser periscope (final installation will occur just prior to cryostat filling)

Integration Testing of Module-0 Components

- The four Module 0 APAs were outfitted with pre-production readout electronics and PD modules and successfully tested in NP04 cold box prior to their installation
- Noise performance looks good overall with a few low-level, coherent noise features still under investigation

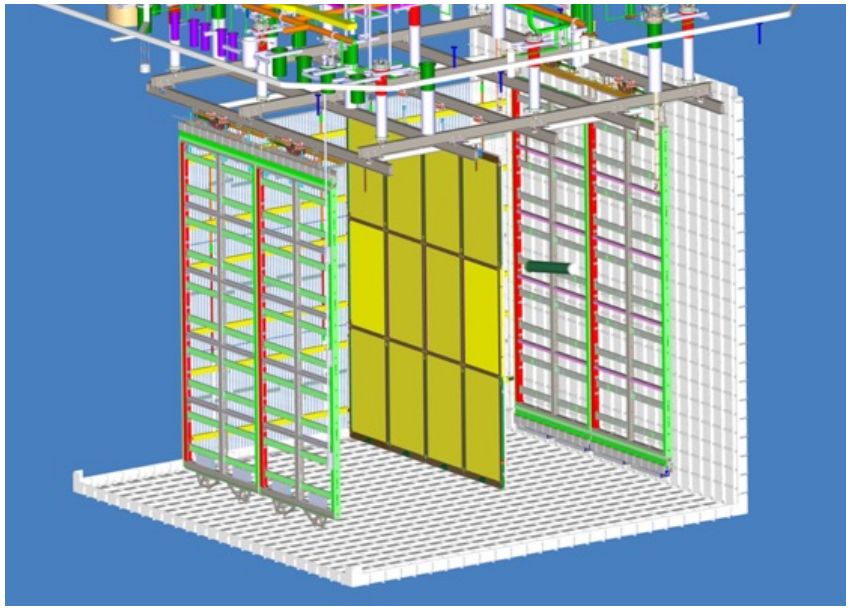


Overview coldbox test runs



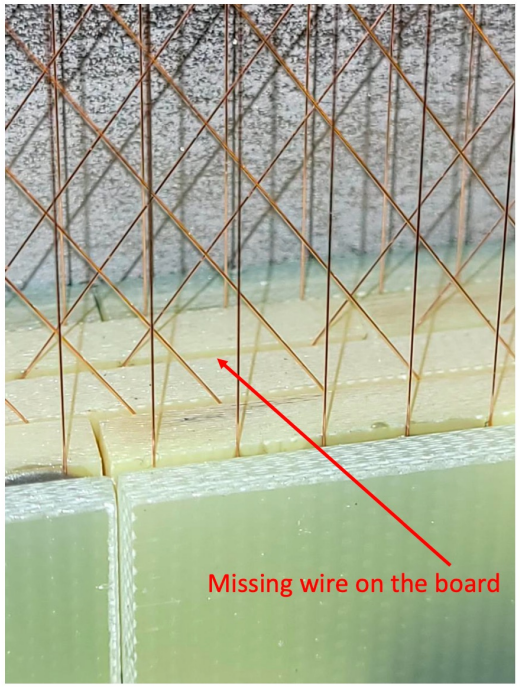
TPC alignment

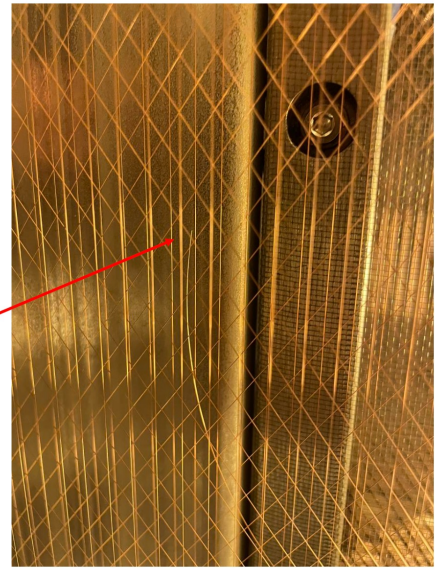
- Post-Installation survey indicates some small mis-alignments of the TPC elements
- Further adjustment of the connections between the top/bottom field cages and APAs improved the situation
- Re-alignment of residual CPA bowing is being done using the CPA restraint mechanical pieces



APA3 broken wire

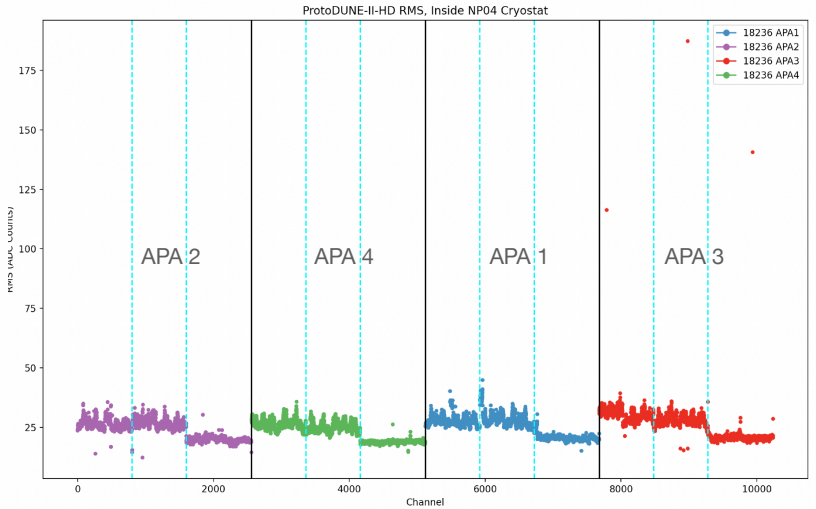
- A v-layer wire in APA #3 became electrically disconnected during the warm after the cold box testing
- Later this wire was observed to have mechanically detached from its headboard
- The wire was sent to the CERN Electron Microscopy Lab for further analysis
- Investigations presently indicate that the wire suffered from mechanical stresses during the wiring process. Action is taken at the production site.





TPC readout at warm

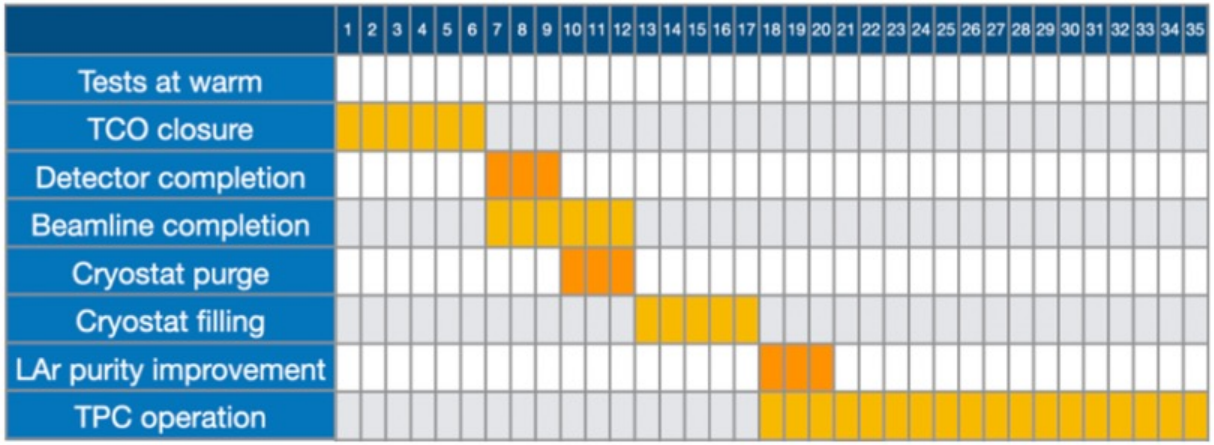
- With all APAs installed in the cryostat and connected to the DAQ system observe good noise performance even with TCO open (in the absence of other activities in/around the cryostat)
- A few wires with high noise in APA #3 related to broken wire



Status and plans for commissioning

- TCO closure contract signed. Material procurement ongoing. Work will start in July 2023.
- The procurement process to purchase the 850 tons of LAr has started:
  - Informal contacts with suppliers for price estimates established.
  - Availability of large quantities is less of a concern now.
  - Cost is still prohibitive. Earliest availability of argon would be in ~October

Tentative schedule towards NP04 operation in case of availability of LAr. Week 1 is the start of TCO closure



- In ProtoDUNE run II, we would like to take data with negative particles to measure π^--Ar cross sections and focus on the low energy region (~1 GeV).
  - Crucial information at DUNE's energy scale.