The Role ProtoDUNE-SP Plays in Future DUNE Oscillation Physics

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NOW 2022
UNIVERSITÄT BERN
DEEP UNDERGROUND NEUTRINO EXPERIMENT

For more information on DUNE oscillation physics, please refer to the plenary talk

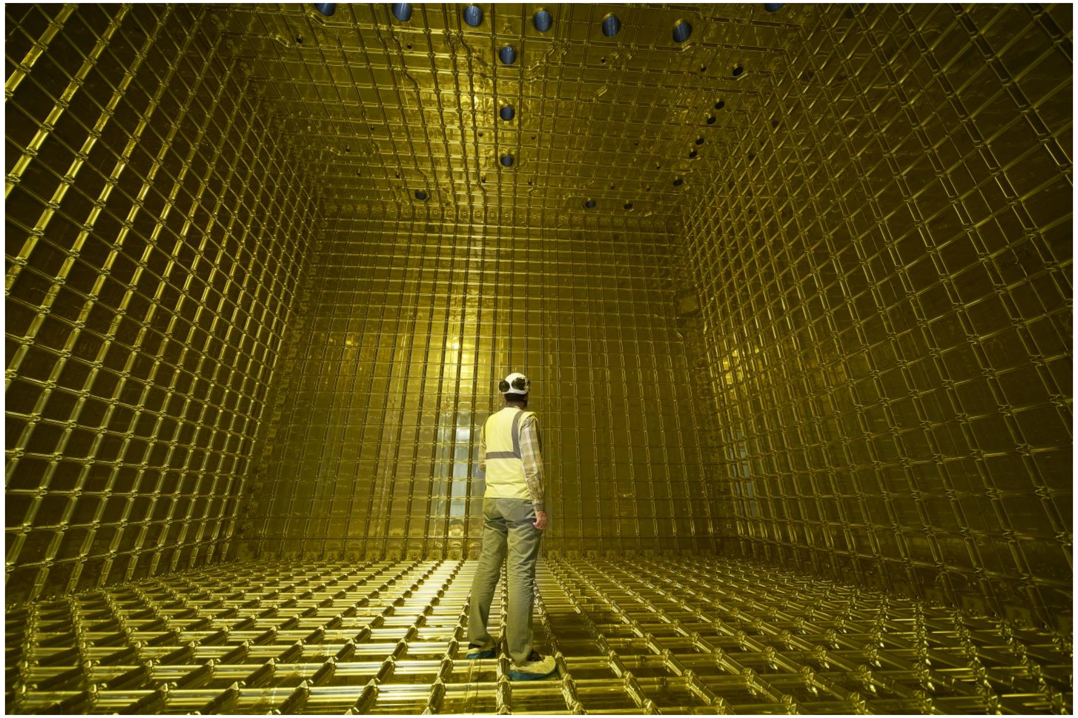
History and Future of ProtoDUNEs at CERN

- ProtoDUNE at CERN Neutrino Platform began in 2018 with ProtoDUNE Single Phase (ProtoDUNE-SP) and ProtoDUNE Dual Phase
  - Both detectors are TPCs
  - ProtoDUNE-SP is a horizontally drifting LAr time projection chamber, similar to first DUNE FD Module planned.
- ProtoDUNE Horizontal Drift and ProtoDUNE Vertical Drift planned for the next year.
  - ProtoDUNE Horizontal Drift can be viewed as a successor to ProtoDUNE-SP.

ProtoDUNE Dual Phase

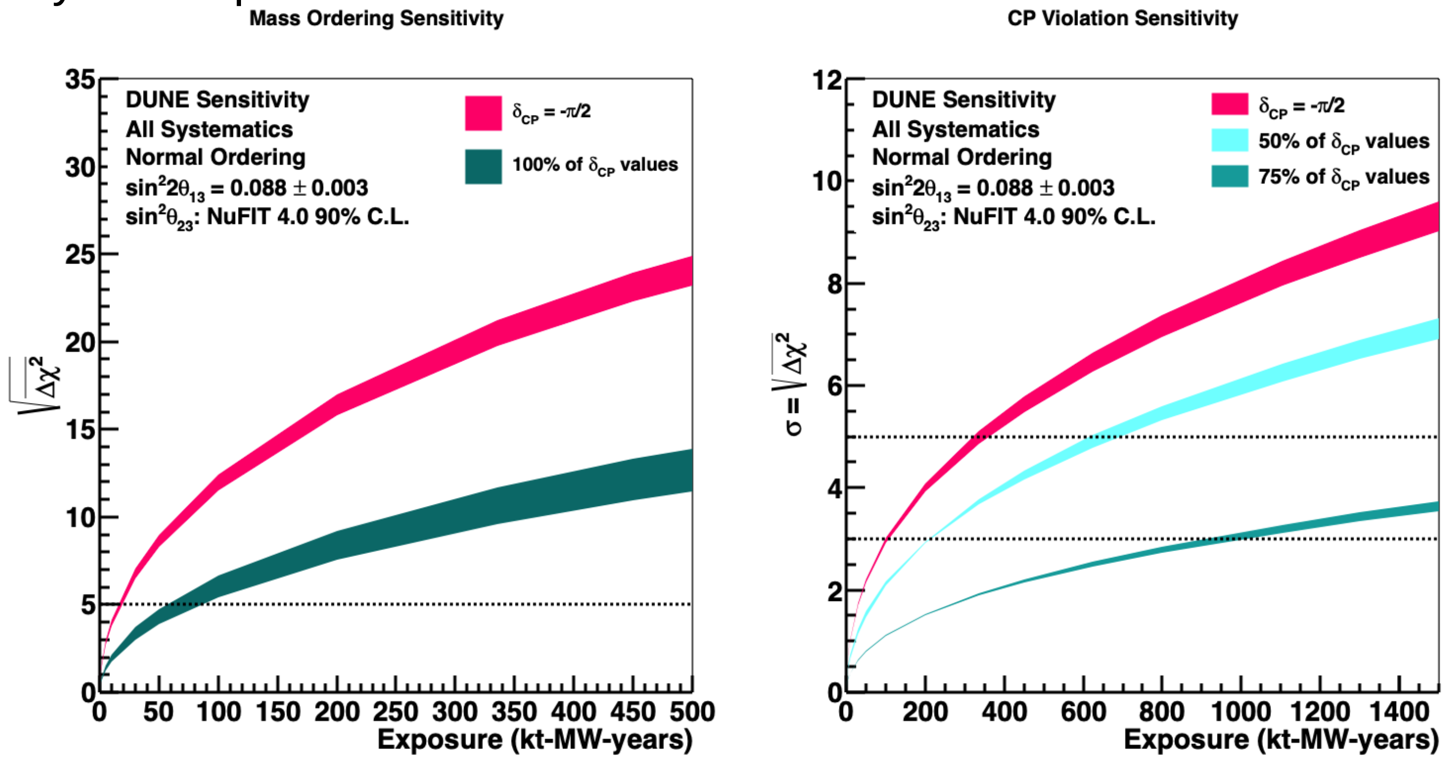
ProtoDUNE-SP

Inside of the ProtoDUNE Dual Phase cryostat (Both images from CERN)



DUNE and Its Long-Baseline Oscillation Physics

- Current sensitivity paper from DUNE: [*The European Physical Journal C* **80** (2020) 978].
- Analysis take assumptions on energy resolution and detector performance.
  - This study uses simulated Far Detector with 3 ms drift electron lifetime.
  - Detector uncertainty on the electric field (1%)
  - Applying uncertainty on energy reconstructions with different parameters used for different expected particles.
- ProtoDUNE-SP can verify and improve on the uncertainties assumed in the studies.



Sensitivities from most recent paper for determining the mass hierarchy and CP-violating phase.

DUNE and Its Long-Baseline Oscillation Physics

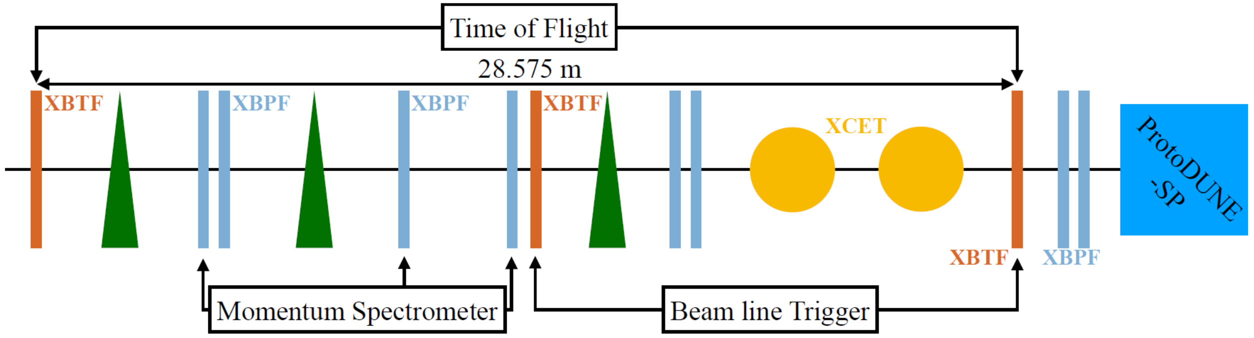
- To achieve sensitivities, technical specifications were developed for DUNE Far Detector Modules.

ID	System	Parameter	Physics Requirement Driver	Requirement	Goal
1	HVS	Minimum drift field	Limit recombination, diffusion and space charge impacts on particle ID. Establish adequate signal-to-noise (S/N) for tracking.	>250 V/cm	500 V/cm
2	TPC Elec	System noise	The noise specification is driven by pattern recognition and two-track separation.	<1000 enc	ALARA
3	PDS	Light yield	The light yield shall be sufficient to measure time of events with visible energy above 200 MeV. Goal is 10% energy measurement for visible energy of 10 MeV.	>0.5 pe/MeV	>5 pe/MeV
4	PDS	Time resolution	The time resolution of the photon detection system shall be sufficient to assign a unique event time.	< 1 μs	< 100 ns
5	all	liquid argon purity	The LAr purity shall be sufficient to enable drift e- lifetime of 3 (10)ms	< 100 ppt	< 30 ppt

Table of high-level physics requirements for the Far Detector Module 1 (*JINST* **15** 2020 T08009).

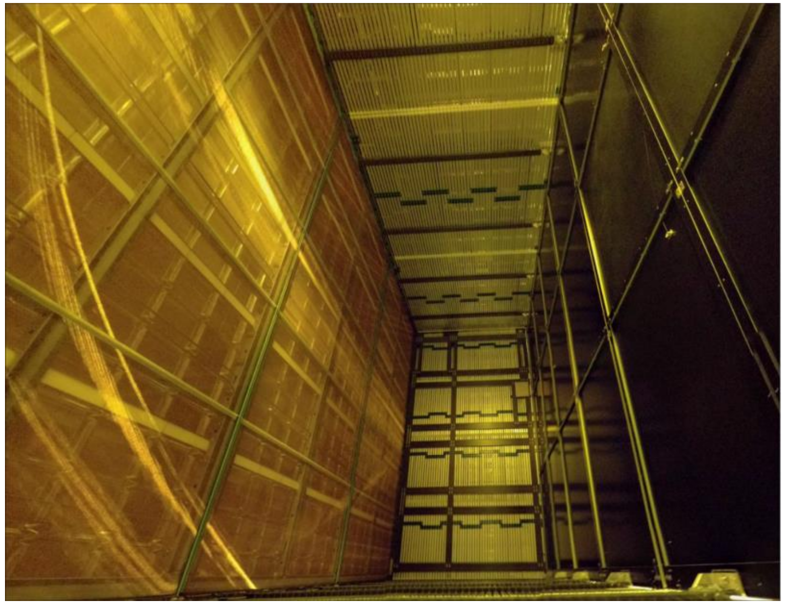
ProtoDUNE-SP and its History Taking Data

- Collected data from a tertiary hadron beam originating from CERN SPS for approximately two months (*Phys. Rev. Accel. Beams* **22**, 061003).
- Then collected cosmic muon data samples from November 2018 to mid-2020.
- Wire-based readout, same as DUNE Far Detector Module 1.
    - Referred to as Anode Plane Array



Beamline instrumentation with the Cherenkov detectors, trigger counters (XBTF), and profiling monitors (XBPF). The magnets that steer the particles into the detector and are used to measure the momentum are the green triangles.

Inside ProtoDUNE-SP cryostat with the wire readout of the Anode Plane Array (APA) (left) and cathode plane assembly (CPA) (right).



Momentum (GeV/c)	Pion-like (k)	Proton-like (k)	Electron-like (k)	Kaon-like (k)
0.3	0	0	242.5	0
0.5	1.5	1.5	296.3	0
1	381.8	420.8	262.7	0
2	333.0	128.1	173.5	5.4
3	284.1	107.5	113.2	15.6
6	394.5	70.1	197.0	27.9
7	343.7	58.4	112.9	28.2

Event statistics from the beam data-taking period from beamline monitoring systems. Long data-taking with beams from 0.3 to 1 GeV/c planned for ProtoDUNE-HD.

JINST **15** P12004

A Non-Neutrino Detector for Neutrino Physics

- ProtoDUNE-SP has six APAs with a CPA in the middle of the detector.
  - Works as two separate TPCs in one cryostat.
  - APA has two induction wire planes (U,V) and one collection wire plane (Z).
  - Readout electronics in the cold.
- Electrons drift horizontally in the x-direction, beam travels in a slight angle primarily in the z-direction.

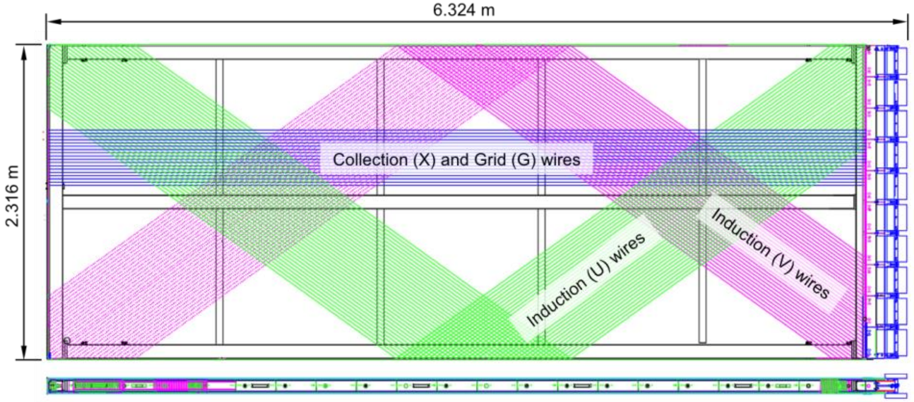
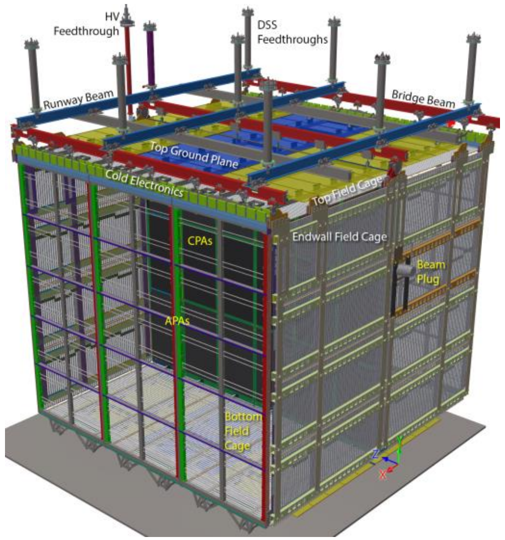


Diagram of APA wire planes used for readout. The diagram is rotated by 90 degrees clockwise from how it is installed to improve visualization.



Technical drawing of ProtoDUNE-SP. Three additional APAs are on the other side of the CPA.

[*JINST* **15** P12004]

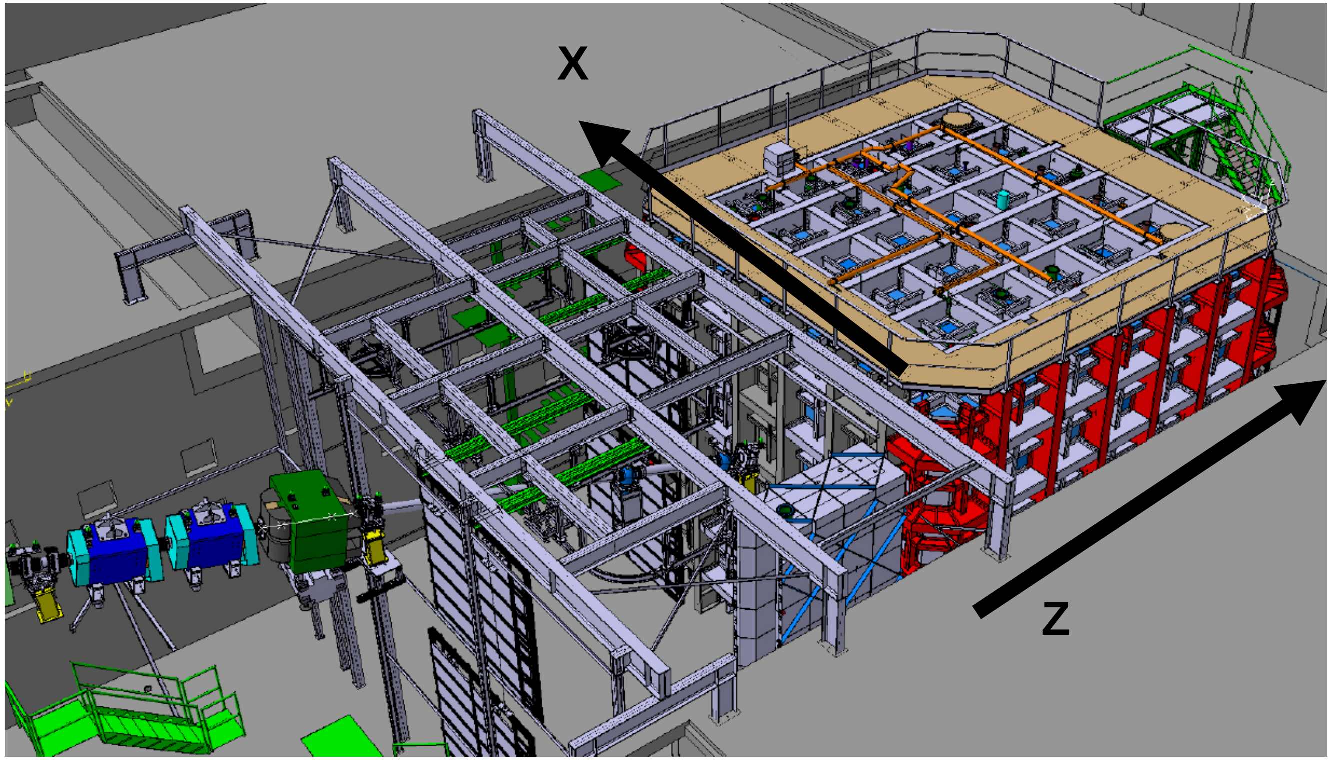
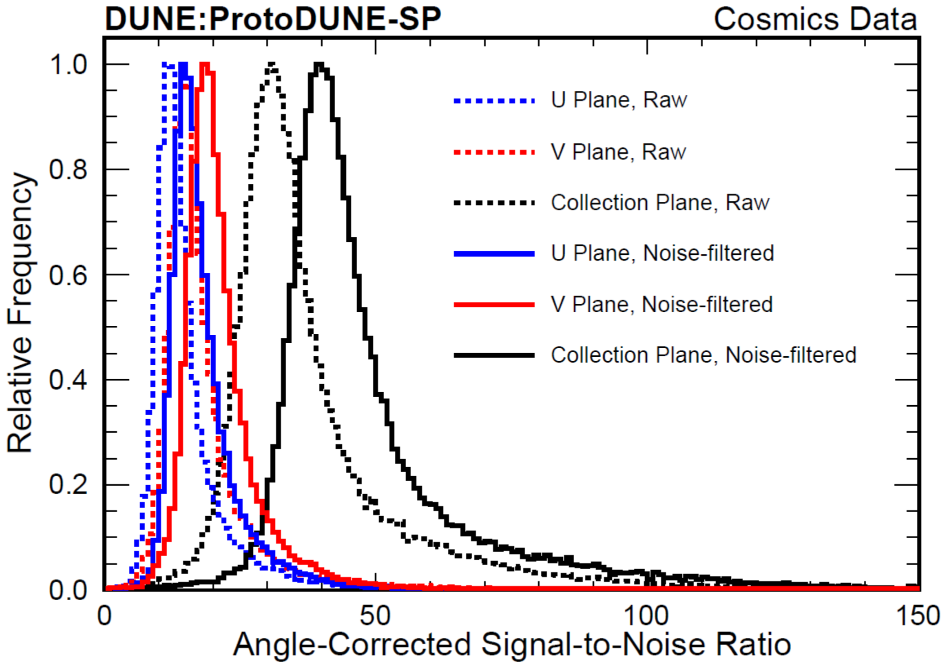


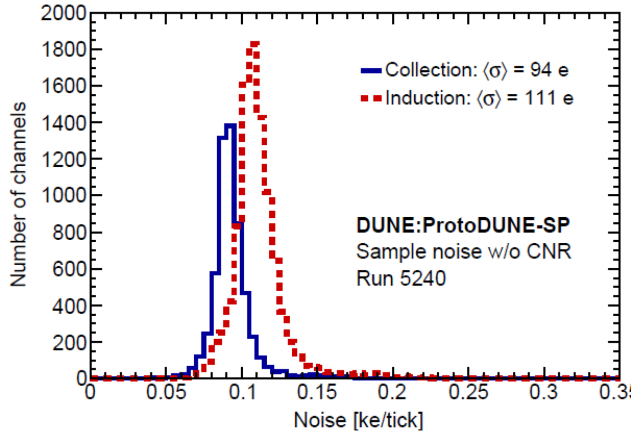
Image of CERN Neutrino Platform 4 with ProtoDUNE-SP. The beam comes in from left to right into the cryostat. The hanging scintillator in grey are the front Cosmic Ray Taggers.

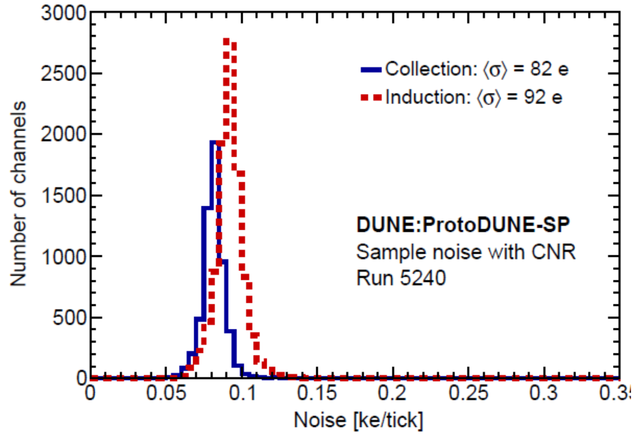
ProtoDUNE-SP Publications

- ProtoDUNE-SP has published three papers on detector physics.
  - Performance paper (*JINST* **15** P12004)
  - Design paper (*JINST* **17** P01005)
  - Cold electronics readout system (*NIMA* **936** 271-273)
- Example below highlights of noise and signal-to-noise ratio measurements:



JINST **15** P12004 Signal-to-noise ratio measured using cosmic ray muons.



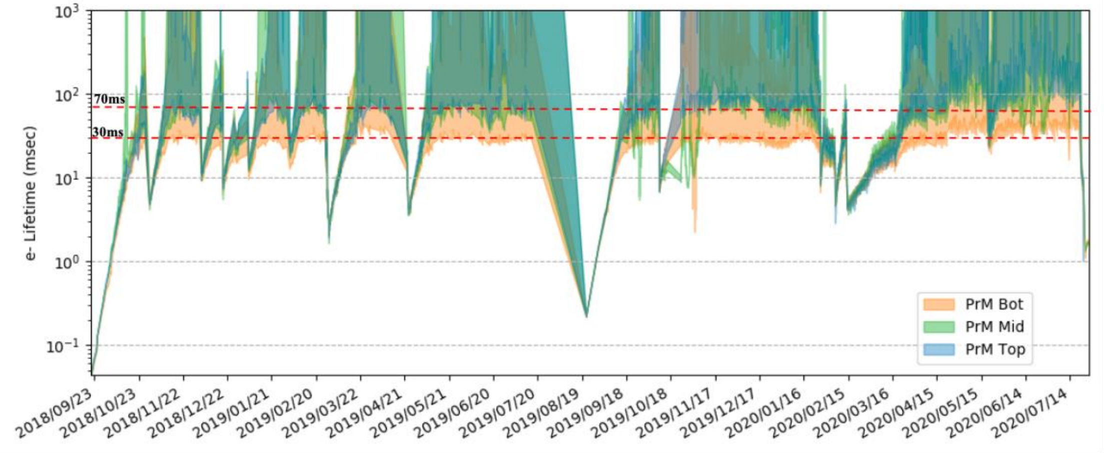


Noise measured for a TPC hit using cosmic ray muons with correlated noise removal not used (top) and used (bottom). Determined that noise is 550 ENC for the collection plane and 650 e ENC for the induction plane (<1000 e ENC required). One timing tick is 500 ns.

ProtoDUNE-SP Detector Physics Measurements

All Far Detector Module 1 requirements surpassed!

- Measurements made on the drift electron lifetime.
  - >20 ms, much larger than the 3 ms requirement.
  - Made with purity monitors and cosmic muon tracks in TPC.
- Energy scale determinations (ADC->ionized electrons->MeV)
  - Used calibration scheme from MicroBooNE, adapted from MINOS ([C. Adams *et al* 2020 *JINST* **15** P03022]())
- Light yield (1.9 photons/MeV, >0.5 photons/MeV) and timing resolution (14 ns, <100 ns)

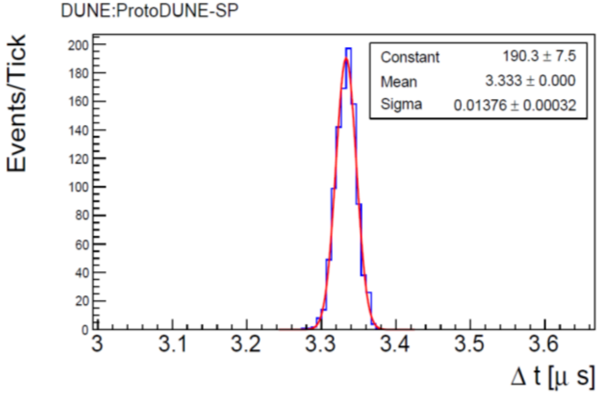


Drift electron lifetimes measured by the three purity monitors installed.

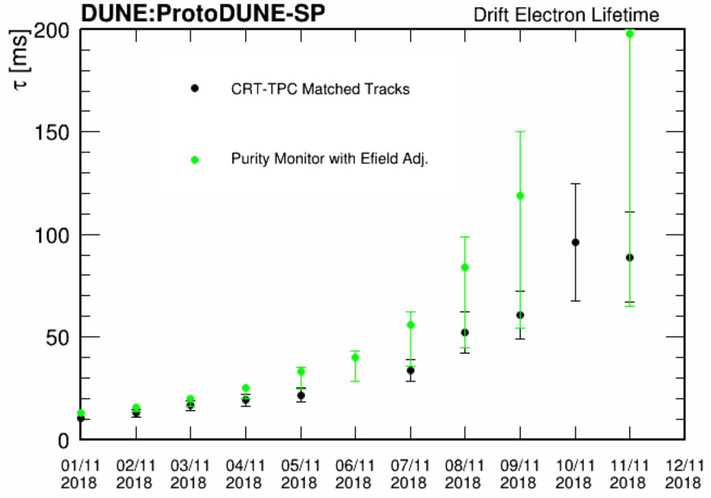
Detector parameter	ProtoDUNE-SP performance	DUNE specification
Average drift electric field	500 V/cm	250 V/cm (min) 500 V/cm (nominal)
LAr e-lifetime	> 20 ms	> 3 ms
TPC+CE Noise Signal-to-noise ⟨SNR⟩	 (C) 550 e, (I) 650 e ENC (raw) (C) 48.7, (I) 21.2 (w/CNR)	 < 1000 e ENC
CE dead channels	0.2%	< 1%
PDS light yield	1.9 photons/MeV (@ 3.3 m distance)	> 0.5 photons/MeV (@ cathode distance - 3.6 m)
PDS time resolution	14 ns	< 100 ns

Summary table of ProtoDUNE-SP performance compared to the DUNE Far Detector Module 1 technical requirements.

[*JINST* **15** P12004]()



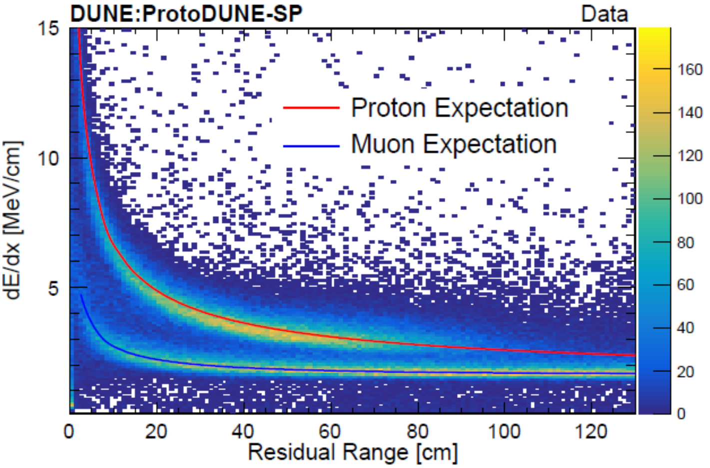
Fit of time difference measured between two light pulses to determine timing resolution.

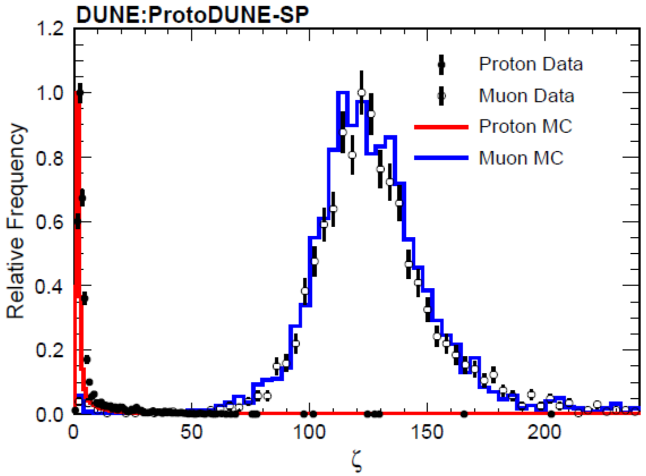


Comparisons of the drift electron lifetimes measured between the top purity monitor and with cosmic muons in the TPC. Adjustments made to correct for different electric fields between the purity monitors and the TPC.

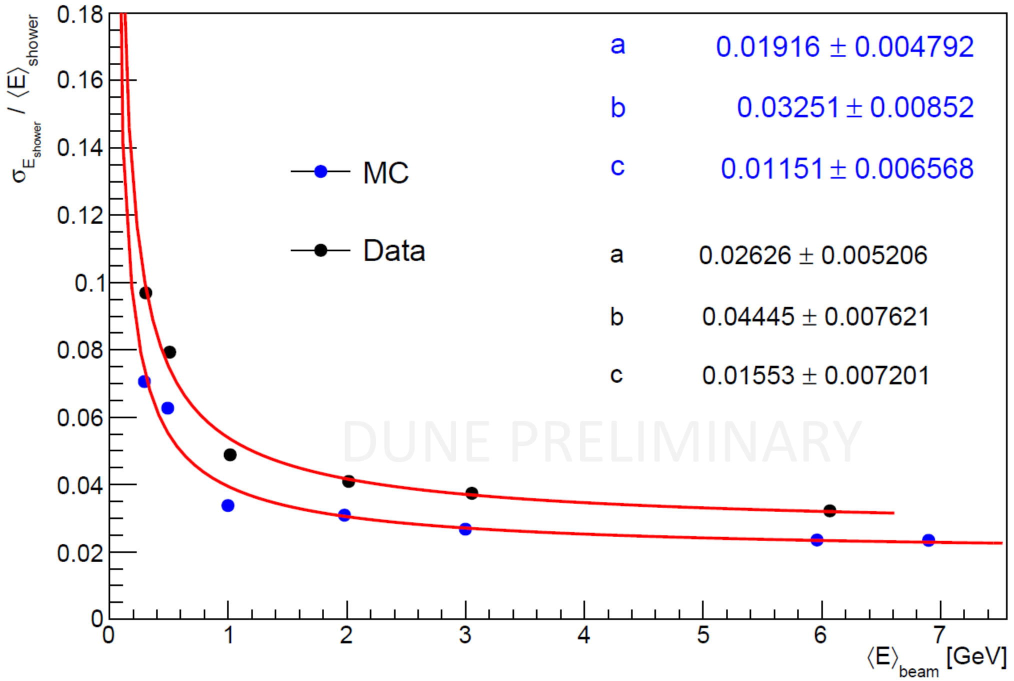
ProtoDUNE-SP Energy Reconstruction Studies

- Electron energy reconstruction resolution across the ProtoDUNE-SP beam.
    - Important for motivating energy smearing uncertainty for electrons.
- Proton/muon separation.





dE/dx of stopping beam muons and protons (left) and the value of a likelihood metric (ζ) used to separate stopping muons and protons with 0 representing a proton candidate (right).



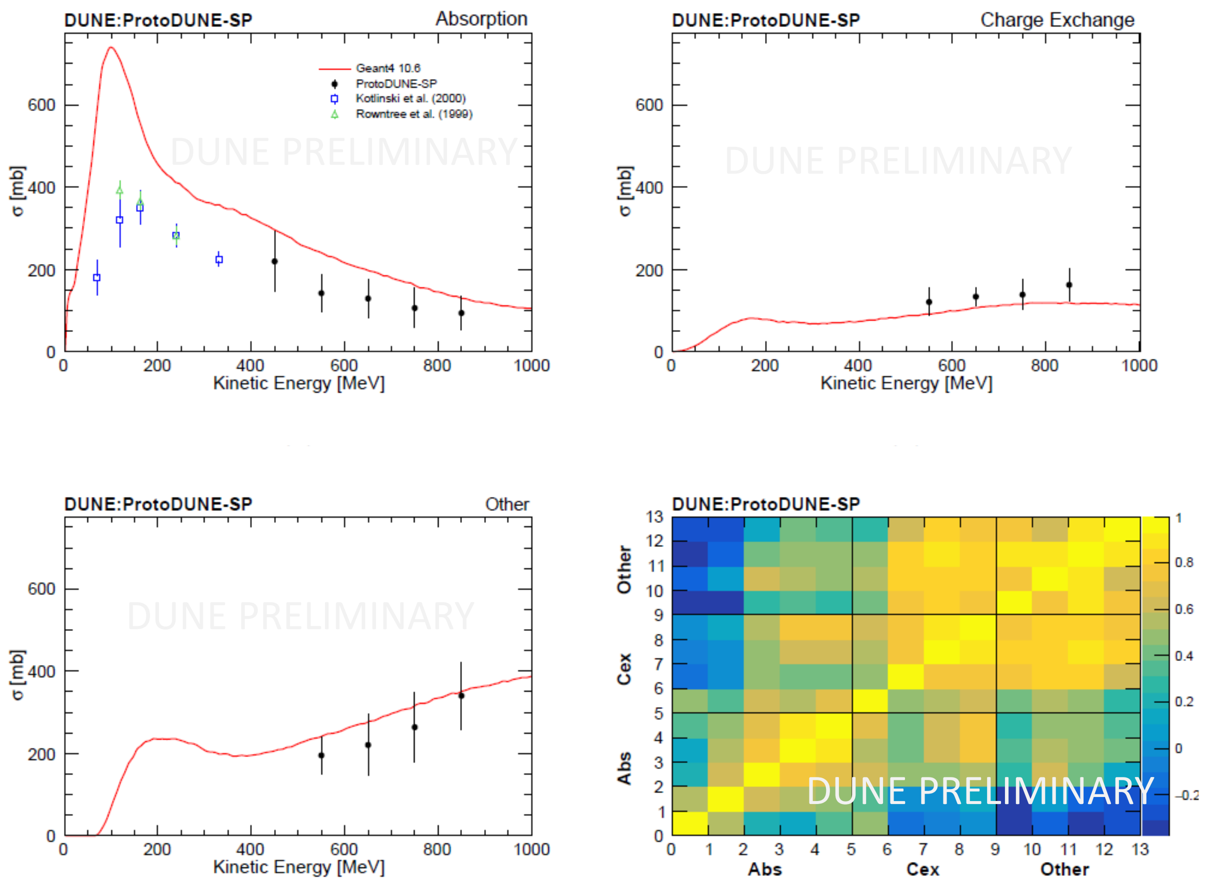
Energy resolution of electrons across the beam energy of ProtoDUNE-SP with corrections made for ProtoDUNE-SP beam energy spread.

JINST **15** P12004

Hadron-Ar Measurements of ProtoDUNE-SP

- Final state interactions can impact event classification and energy resolution.
  - Can factor this into systematic uncertainties of:
    - Neutrino cross section modeling.
    - Re-scattering in the argon, impacting reconstruction
  - DUNE beam peaks from 1-4 GeV, so modeling pions extremely important.
- Current analysis uses:
  - a likelihood fitter,
  - the 1 GeV/c pion beam.
  - selection cuts to measure the pion absorption and charge exchange cross section.
- Cross section has data points in unexplored regions for all targets.
- **Paper in preparation**

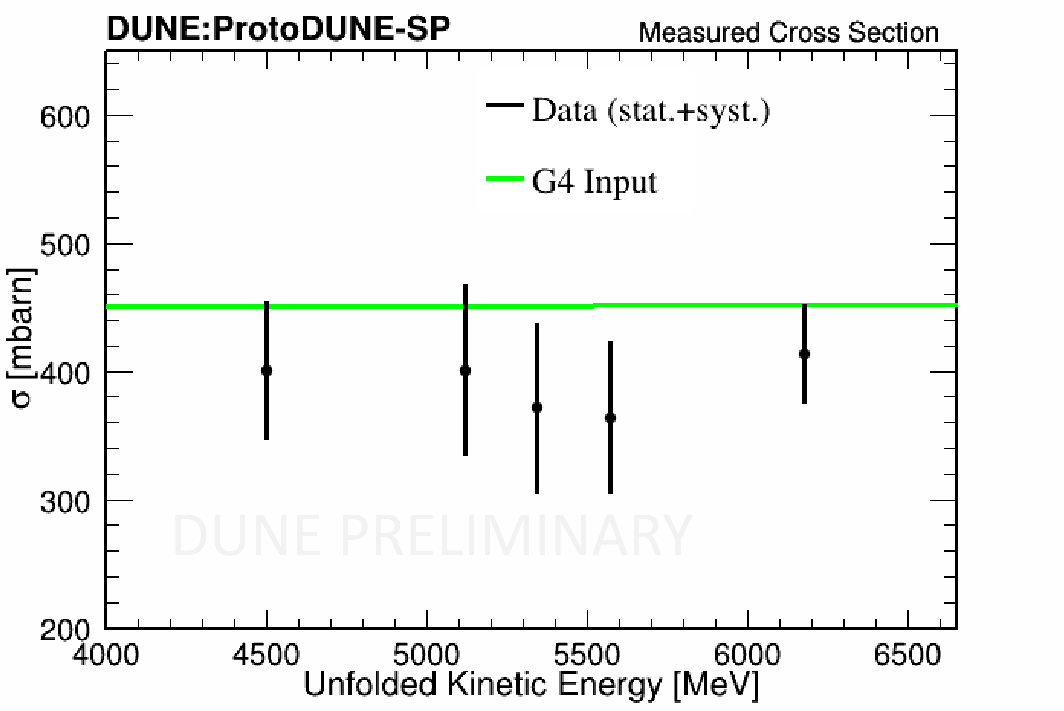
Reminder: For the T2K 2020 CP-violating phase analysis, pion recattering and final interaction modeling uncertainties were 1.6% of the 6% systematic uncertainty budget (*Nature* **580** (2020) 339–344).



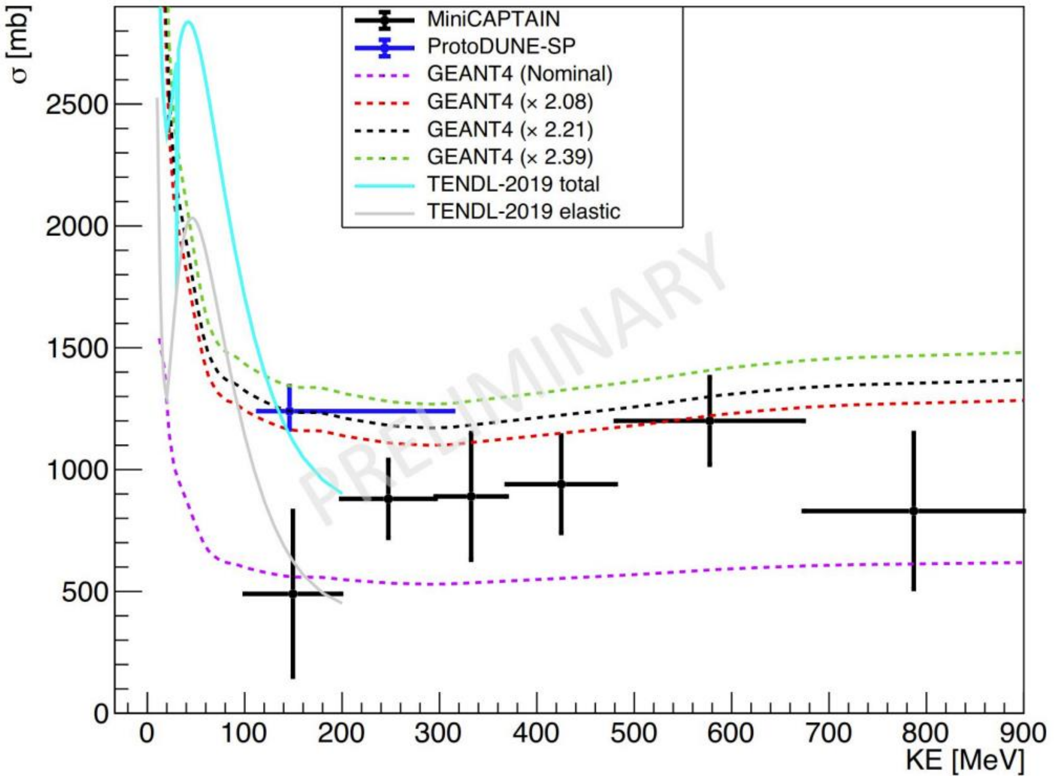
Primary beam pion cross section using a likelihood fitter compared to Geant4 (red) and external data. The following data points come from the regularized result.

Hadron-Ar Measurements of ProtoDUNE-SP

- Analyses on all primary beam hadrons (p, K).
- Also have studies on secondary particles coming from interactions:
  - Cross section of secondary neutrons
    - Tensions compared to Geant4 and MiniCAPTAIN.
  - Reconstruction of secondary kaons



Total reactive kaon cross section extracted from a Bayes-like unfolding method of 6 GeV/c primary kaons (lowest beam of kaon particles). **Paper in progress**



Neutron cross section measured by finding the radial distance to the pion scatter of a tertiary proton and fitting to simulations with different Geant4 cross sections. **Paper in progress**

Conclusion

- ProtoDUNE-SP is an important milestone for DUNE Far Detector physics.
  - Achieved all high-level technical specifications (LAr purity, noise, light detector performance, electric field magnitude).
- Ongoing ProtoDUNE-SP analyses provide LArTPC detector physics and hadron-argon physics data.
  - Leads to:
    - Better modeling/uncertainties on final state interactions and reinteractions while traveling in the argon.
    - Improved understanding of hadron passage in argon
    - Motivated low-level physics uncertainties on elements like LAr purity and electronics noise.
- DUNE will do this all over again with:
  - the new ProtoDUNE-HD, which will measure cross sections of hadrons at lower energies and use new electronics.
  - more sensitivity studies with improved systematic uncertainty methods, simulations, and analysis techniques.