Status of Measuring Cross Sections of Hadrons on Argon with ProtoDUNE-SP

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For more information on the DUNE program, please refer to the general talk

History of ProtoDUNE-SP at CERN

- ProtoDUNE Single Phase (SP) is an approximately 700-ton monolithic liquid argon time projection chamber (TPC).
  - Contains two drift chambers with wire readout for the anode plane.
  - Considered first engineering test of DUNE Far Detector Module 1.
- Collected test beam data in 2018 and cosmic data until summer 2020.
- Will be succeeded by ProtoDUNE Horizontal Drift.

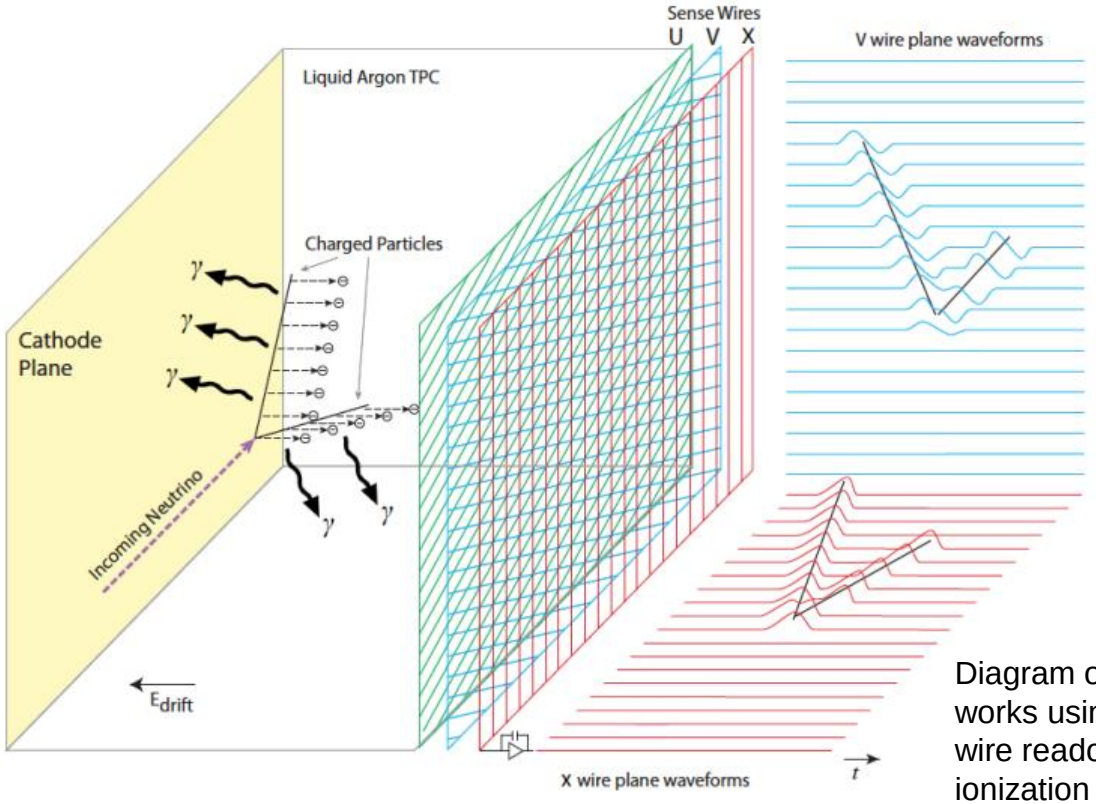


Diagram of how a liquid argon time projection chamber works using a neutrino interaction as an example. The wire readout records the charge that drifts after the ionization of argon, similar to a drift chamber.

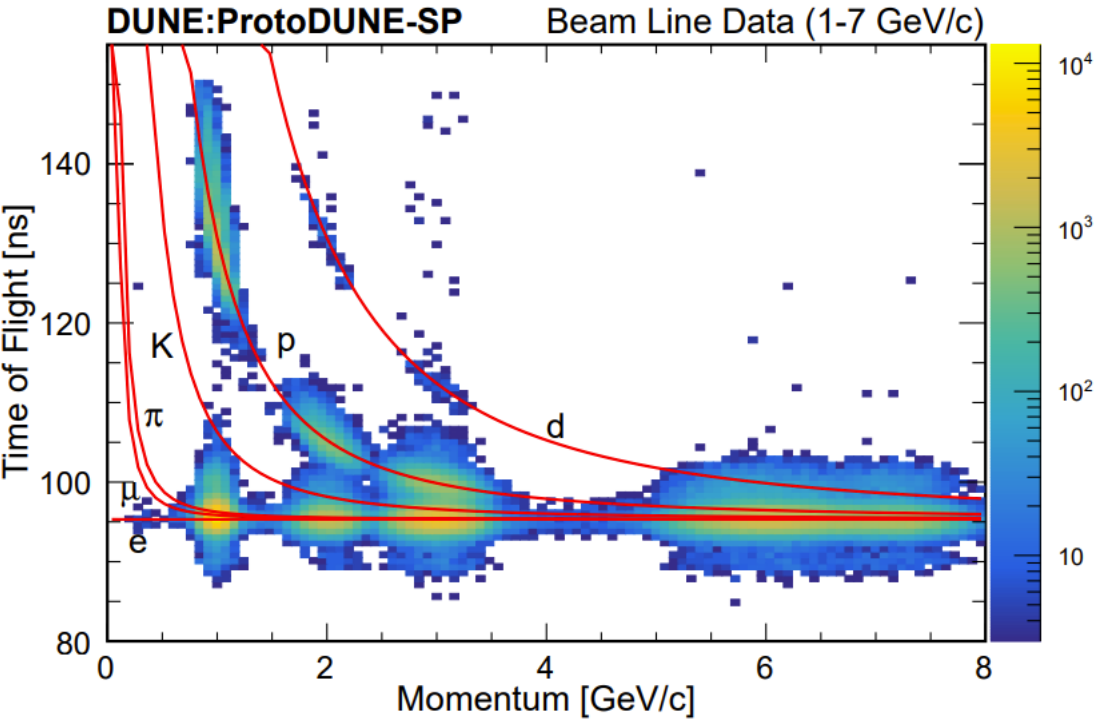
Panoramic view of the CERN Neutrino Platform with ProtoDUNE-SP cryostat (bottom). Beam travels from top to bottom.

arXiv:2002.03005

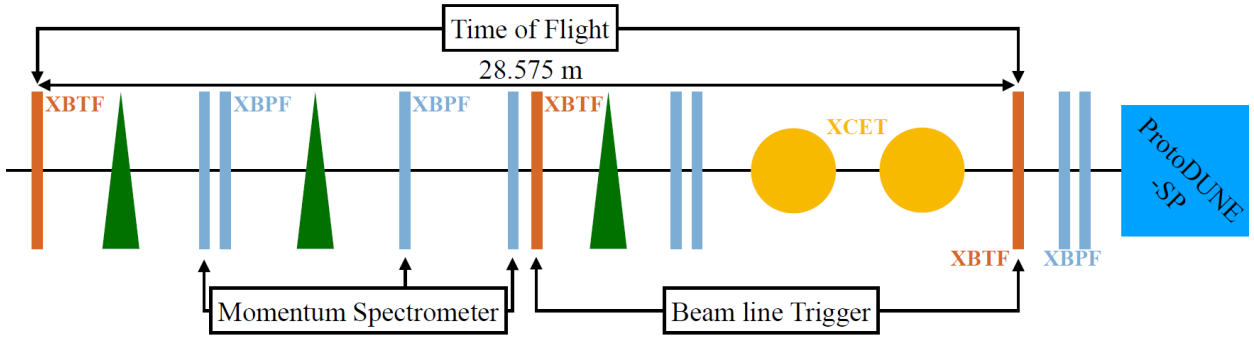
ProtoDUNE-SP's Beam Data-Taking Campaign

- Beam is a tertiary hadron beam originating from CERN SPS (*Phys. Rev. Accel. Beams* **22**, 061003).
- Beamline instrumentation provided:
  - Particle identification (using TOF and Cherenkov)
  - Initial momentum measurements (using deflection in a magnet)
- Beam travels in a pipe to both get to and past the cryostat.

Time-of-flight information as a function of beamline momentum for all momentum settings.



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



Number of beamline events from the beam data-taking period categorized by momentum setting of the beam and the beamline instrumentation particle identification data.

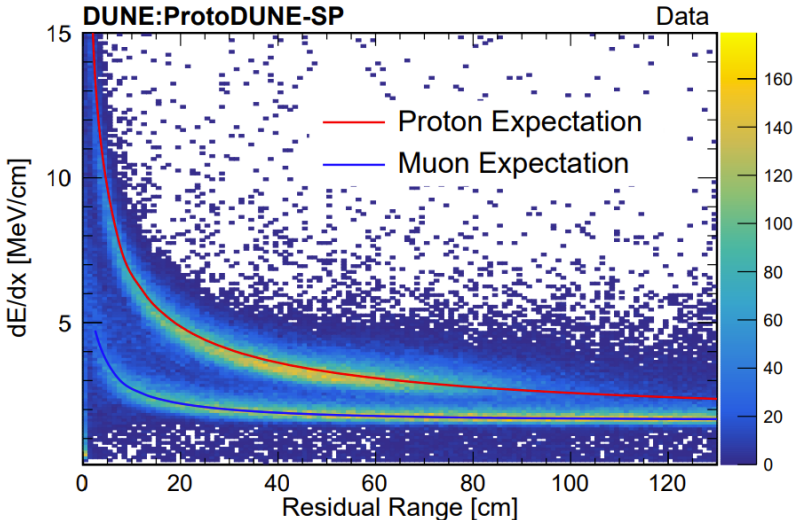
Momentum (GeV/c)	Pion-like (k)	Proton-like (k)	Electron-like (k)	Kaon-like (k)
1	381.8	420.8	262.7	0
6	394.5	70.1	197.0	27.9
7	343.7	58.4	112.9	28.2

JINST **15** P12004

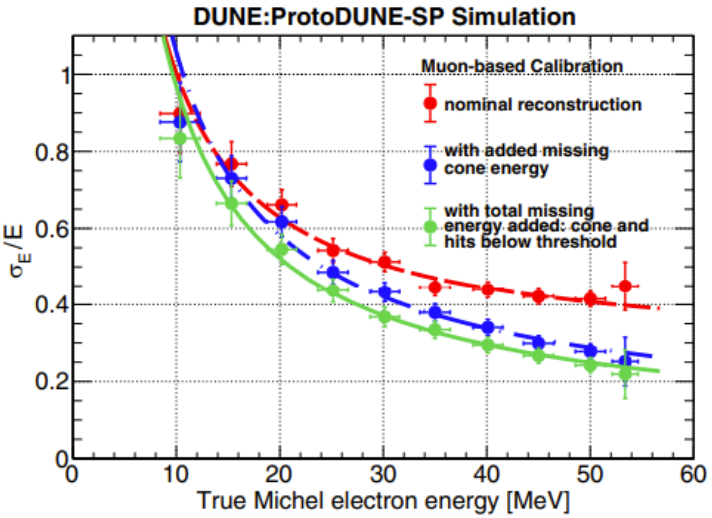
ProtoDUNE-SP Detector Performance

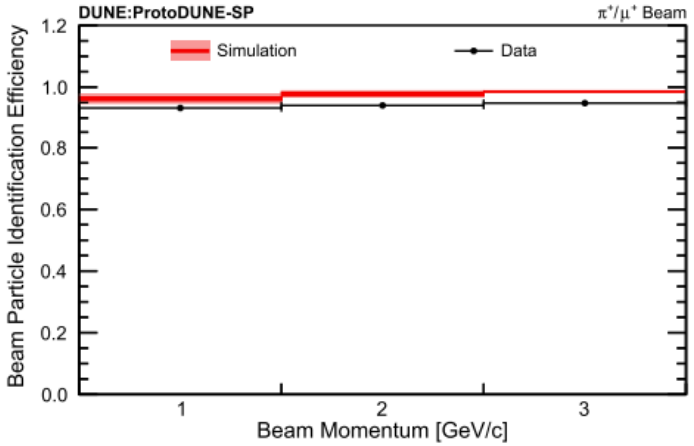
- ProtoDUNE-SP has published five papers on its performance:
  - Detector physics (*JINST* **15** P12004)
  - Design and operation (*JINST* **17** P01005)
  - Michel electron reconstruction (*Phys. Rev. D* **107**, 092012)
  - Reconstruction of cosmic/beam using Pandora (*EPJC* **83** 618)
  - Track/shower separation using a CNN (*EPJC* **82** 903)

Calibrated dE/dx for a selection of stopping muons and beam protons (*JINST* **15** P12004).

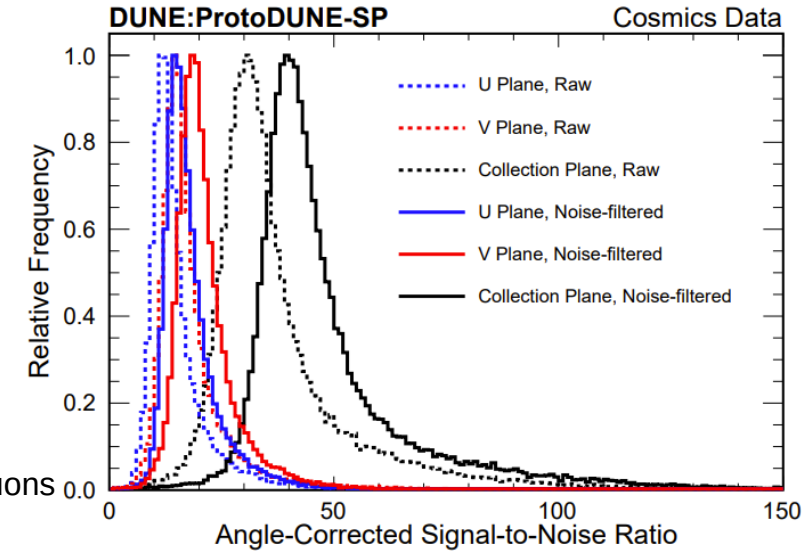


Resolution of reconstructing the energy of a Michel electron using various method with calibration taken from *JINST* **15** P12004 (*Phys. Rev. D* **107**, 092012)



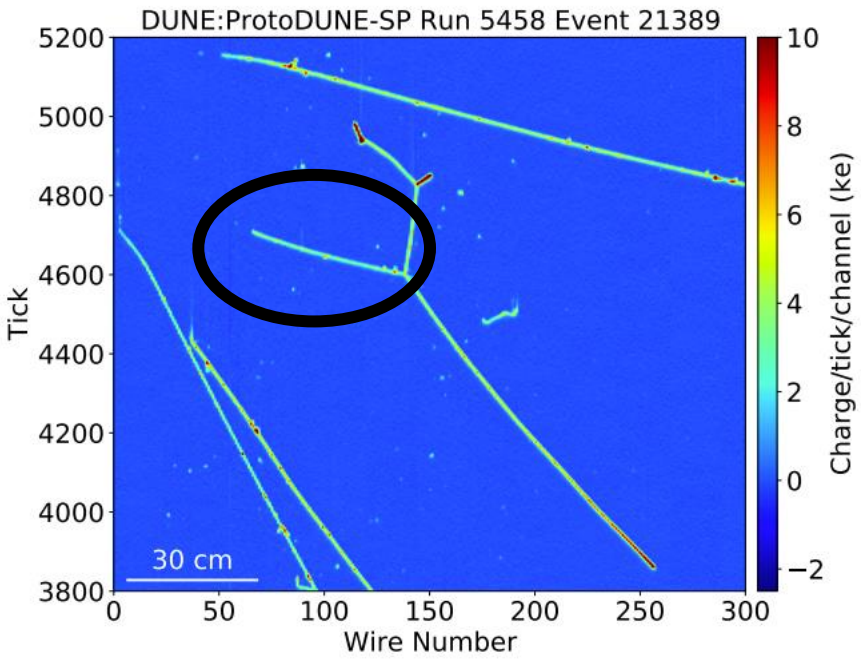


Selection efficiency for muons and pions and beam momentum of particles in the TPC using Pandora (top, *EPJC* **83** 618).



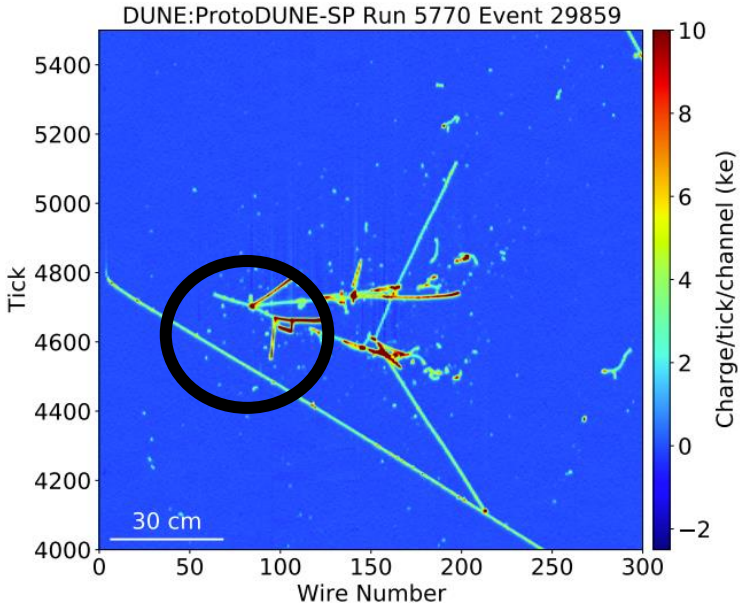
Signal-to-noise measurements from cosmic-ray muons between all three planes (right, *JINST* **15** P12004).

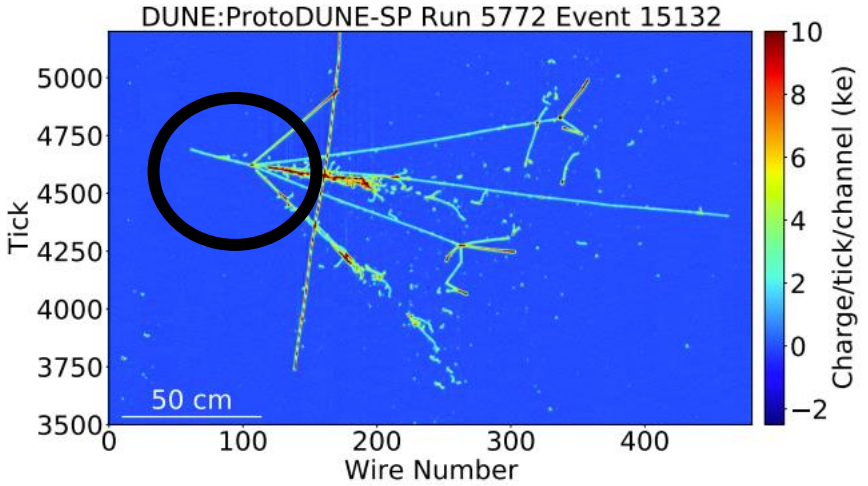
ProtoDUNE-SP Event Displays



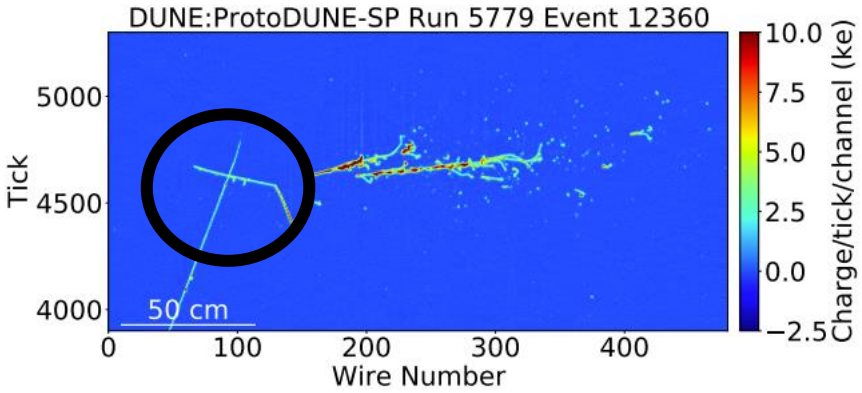
1 GeV/c pion candidate inelastic interaction

6 GeV/c kaon candidate interaction





2 GeV/c pion candidate interaction



2 GeV/c pion candidate charge exchange interaction

JINST **15** P12004

ProtoDUNE-SP Hadron Cross Sections in a Time Projection Chamber

- Ongoing analyses on protons, pions, kaons and neutrons.
- All analyses use some version of the thin-slice equation pioneered by LArIAT (*Phys. Rev. D* **106**, 052009):
  1. Count number of slices of the detector the particle travels.
  2. Sort if interaction slice or non-interacting (incident) slice.
  3. Measure cross section, using equation below, with:
     - n: number density
     - M_{Ar}: mass of argon nucleus
     - $N_{Avo.}$: Avogadro's number
     - r: pitch between wires
     - ρ: liquid argon density:

$$N_{inc.} - N_{int.} = N_{inc.} \exp\left(-\sigma r_{trk.pitch} n\right) = N_{inc.} \exp\left(-\frac{\sigma \rho_{Ar} r_{trk.pitch} N_{avo.}}{M_{Ar}}\right)$$

$$\sigma\left(KE\right) = \frac{M_{Ar}}{N_{avo.} r \rho} \ln\left[\frac{N_{inc.}(KE)}{N_{inc.}(KE) - N_{int.}(KE)}\right]$$

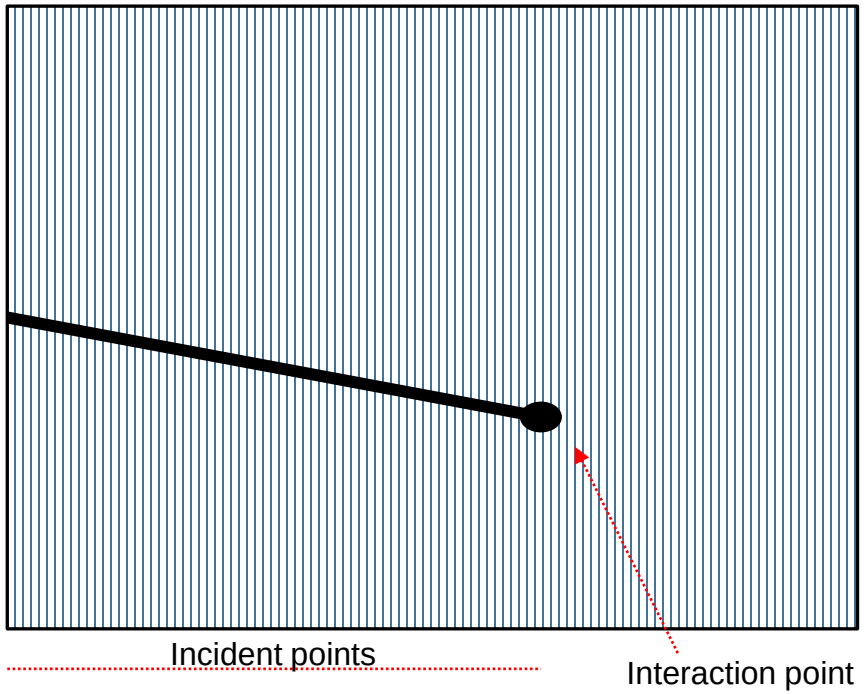
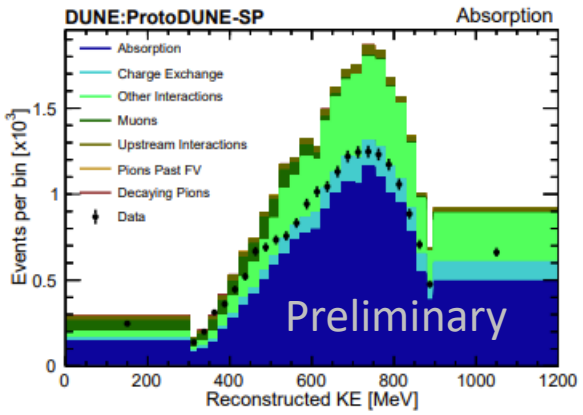


Diagram of a beam particle (black) traveling through a volume. The blue strips represent slices of the detector.

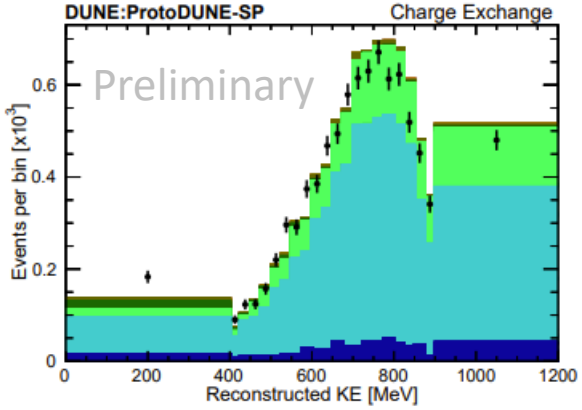
- While the same general concept is used, each ProtoDUNE analysis has different ways of translating the reconstructed histograms to truth-space.

1 GeV/c Pion-Ar Exclusive Cross Sections

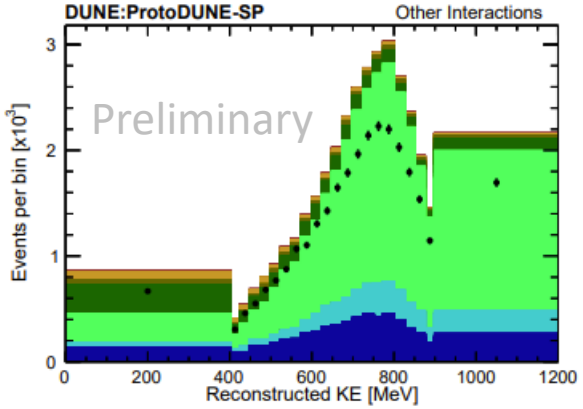
- Pion production common in ν-Ar interactions.
- First measurement of absorption and charge exchange at these energies.
- Measures cross sections using a likelihood-fitter (example).
  - Classifies five different categories of events with interaction points:
    - Signal: Absorption, charge exchange, and other
    - Sideband: Past fiducial volume, Michel-like endpoint suggesting it was a muon



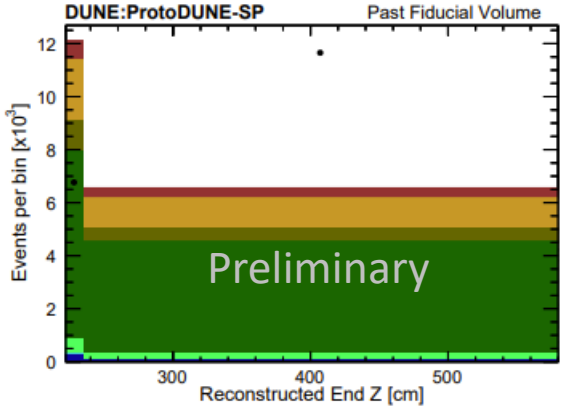
(a)



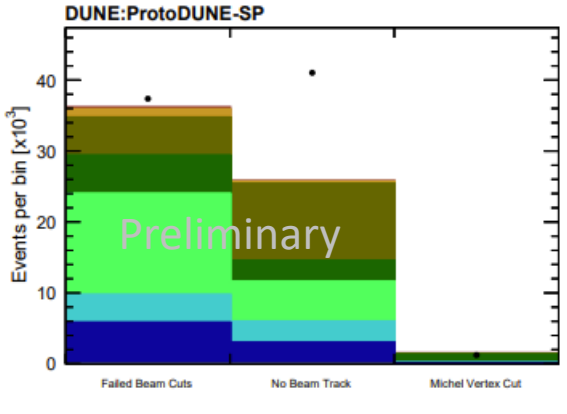
(b)



(c)



(d)



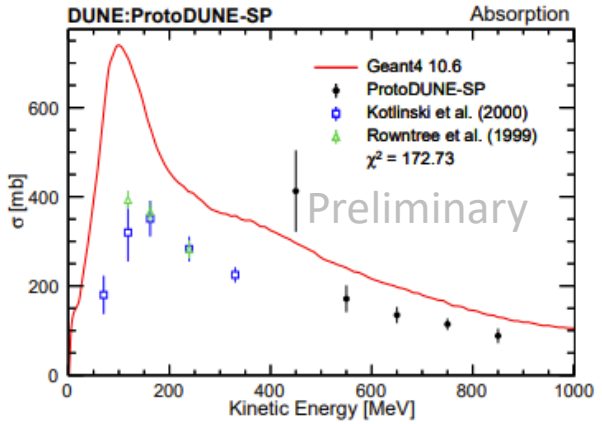
(e)

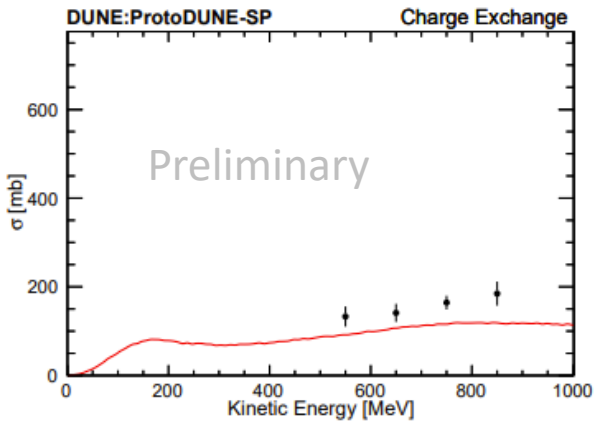
Distributions of number of interactions measured in the fiducial volume for pion absorption (a), charge exchange (b), other (c), events with beam tracks past the fiducial volume (d), and other selection cuts (e).

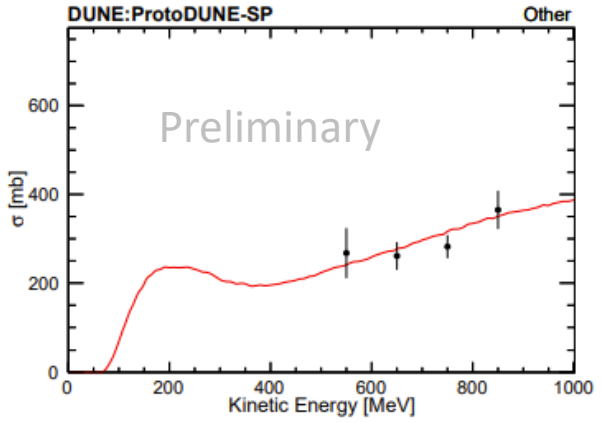
Reminder: For the T2K 2020 CP-violating phase analysis, pion recattering and final interaction modeling uncertainties were 1.6% of the 6% systematic uncertainty budget (*Nature* **580** (2020) 339–344).

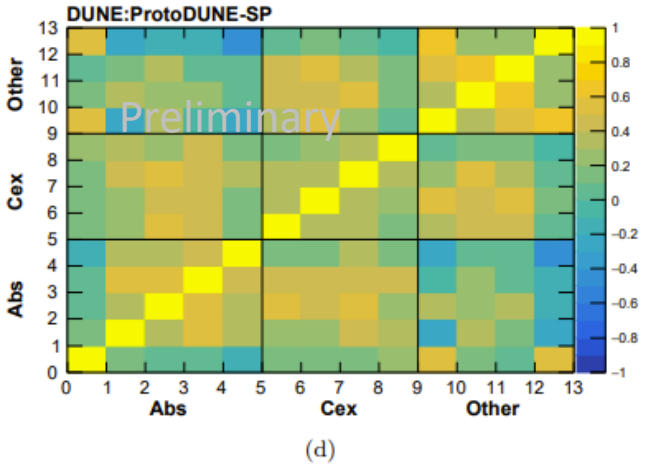
1 GeV/c Pion-Ar Exclusive Cross Sections

- Likelihood-fit translates the fit of reconstructed quantities to truth-level quantities, enabling a post-fit cross section measurement using the thin-slice equation.
  - Fit all categories simultaneously allowing differential cross section measurements.







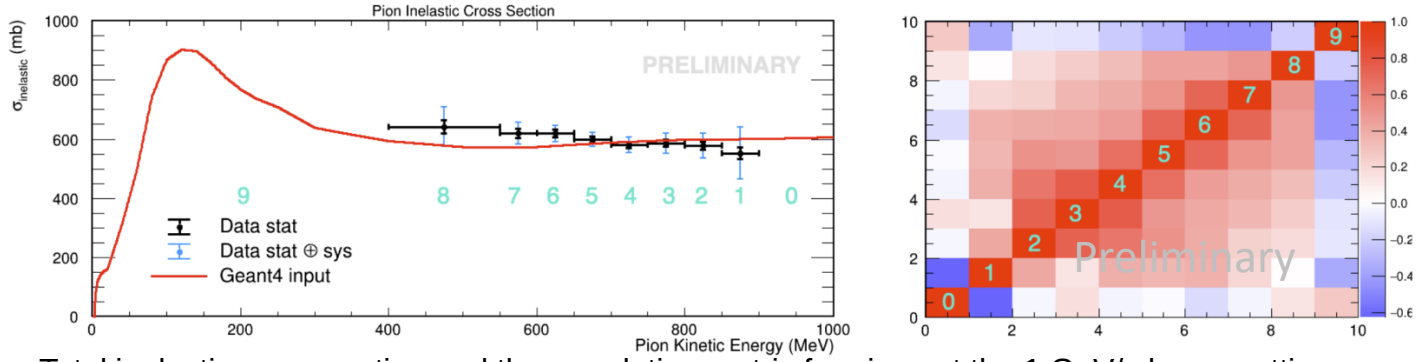


Fitted cross section in truth-space of the pion cross section for absorption (a), charge exchange (b), other interactions (c), and the correlation matrix for all three measurements (d). The results come from scaling and fitting the reconstructed distributions above and making true interacting and incident histograms from those rescaled events.

Total Pion-Ar and Pion-Ar CEX Diff. Cross Sections

Total inelastic cross section

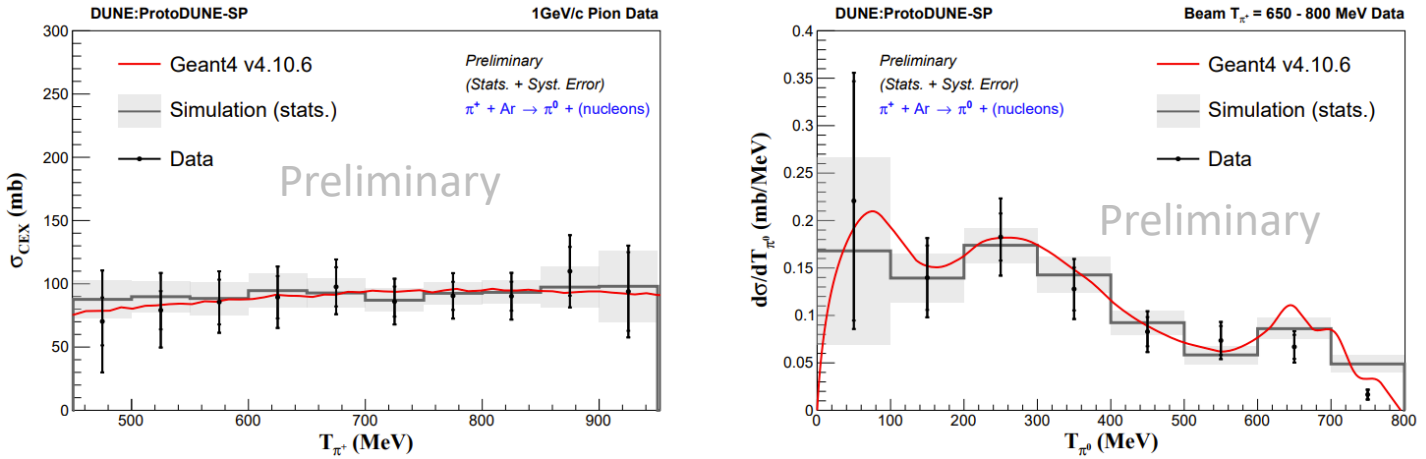
- Can do Bayes-like unfolding and exploit the narrow beam at 1 GeV/c.
- Fit the track length to measure the kinematic energy of the interaction point.
- Unfold in a multi-dimensional format so the incident and interacting slices as a function of energy can be extracted from the track length.



Total inelastic cross section and the correlation matrix for pions at the 1 GeV/c beam setting. Each bin represents a different distance traveled by the pion with bin 0 being if the pion scatters instantly and bin 9 being the pion traveled to the end of the fiducial volume.

Charge exchange differential cross section

- Uses similar methods, as above, to measure the differential cross section of the outgoing neutral pion.
- Can investigate the final state of the hadron-Ar interactions.



Total and differential cross section for charge exchange events at the 1 GeV/c data for pions. The differential cross section is from a specific bin of the total charge exchange cross section. The three peaks in the Geant4 true differential cross section are due to areas of many, some, and few nucleons produced in the final state.

Plans made to understand how different selection methods and analysis methods compare with one another.

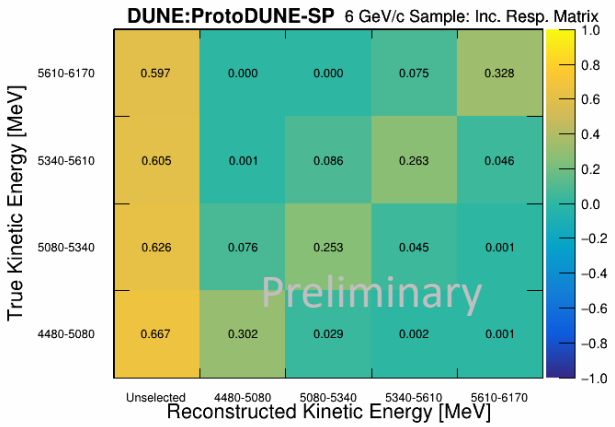
Kaon-Ar Measurements Total Inel. Cross Section

- High momentum kaons can be identified by beamline instrumentation.
- Extract a total inelastic cross section using Bayes-like unfolding.
  - Create two response matrices for incident and interacting slices and then unfold.
  - Measure the cross section using the unfolded distributions with slice as each vertical wire (r~5mm).

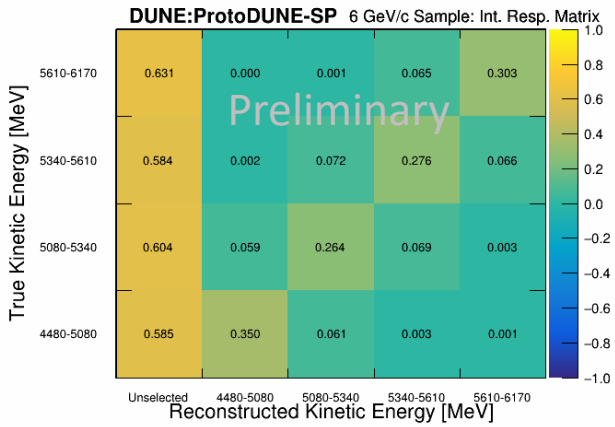
Number of beamline events from the beam data-taking period categorized by particle identification.

Momentum (GeV/c)	Kaon-like (k)
1	0
2	5.4
3	15.6
6	27.9
7	28.2

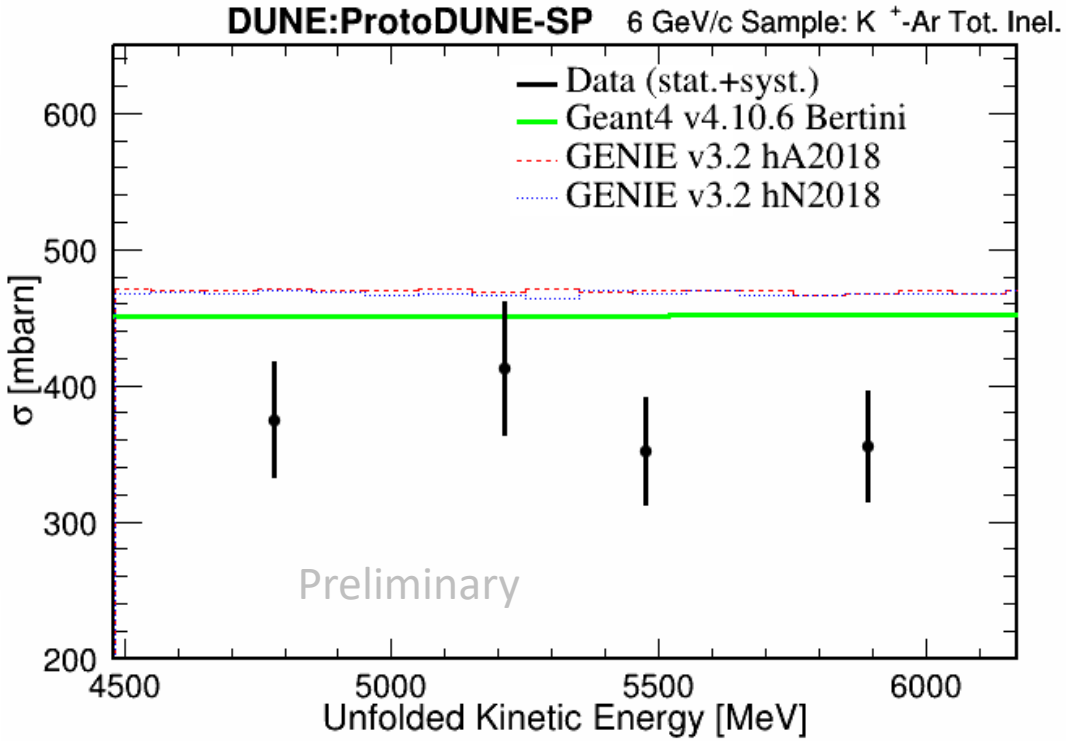
Incident Resp.



Interacting Resp.



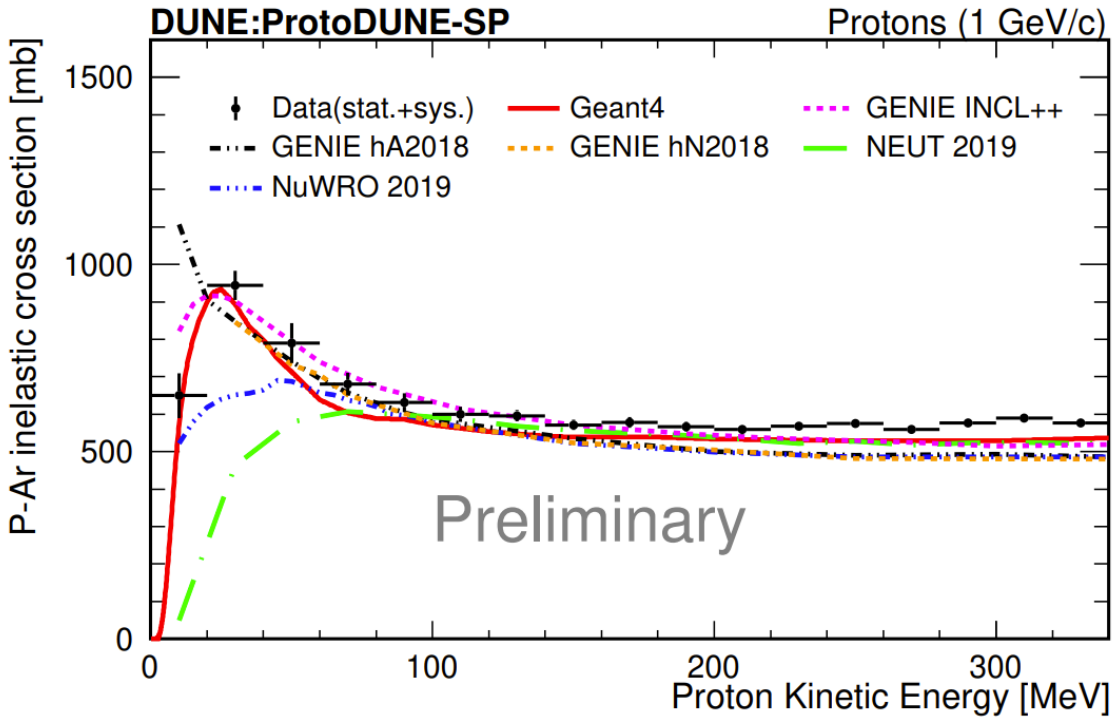
Response matrices for the incident and interacting slices. While both response matrices try to unfold the distortions in measuring the energy using the calorimetry, the selection definition between the two are different as some beam particles may pass the fiducial volume, meaning all slices are incident.



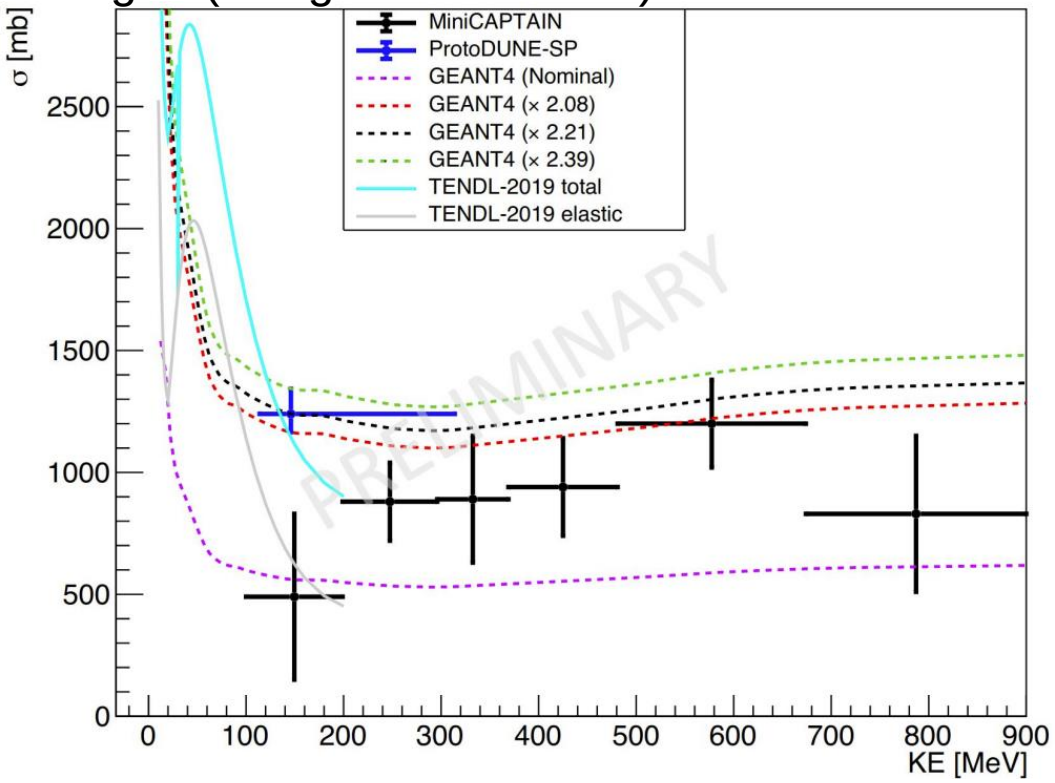
Measured cross section from unfolded distributions with full uncertainties.

Other Hadron-Ar Cross Sections

- Other cross sections ongoing include new ways to interpret cross sections as differential cross sections at different beam momentum settings.
- Highlights include the 1 GeV/c total inelastic cross section for protons (using track length metrics) and a neutron cross section measurement using secondary neutrons from pions on argon (using a likelihood fit).



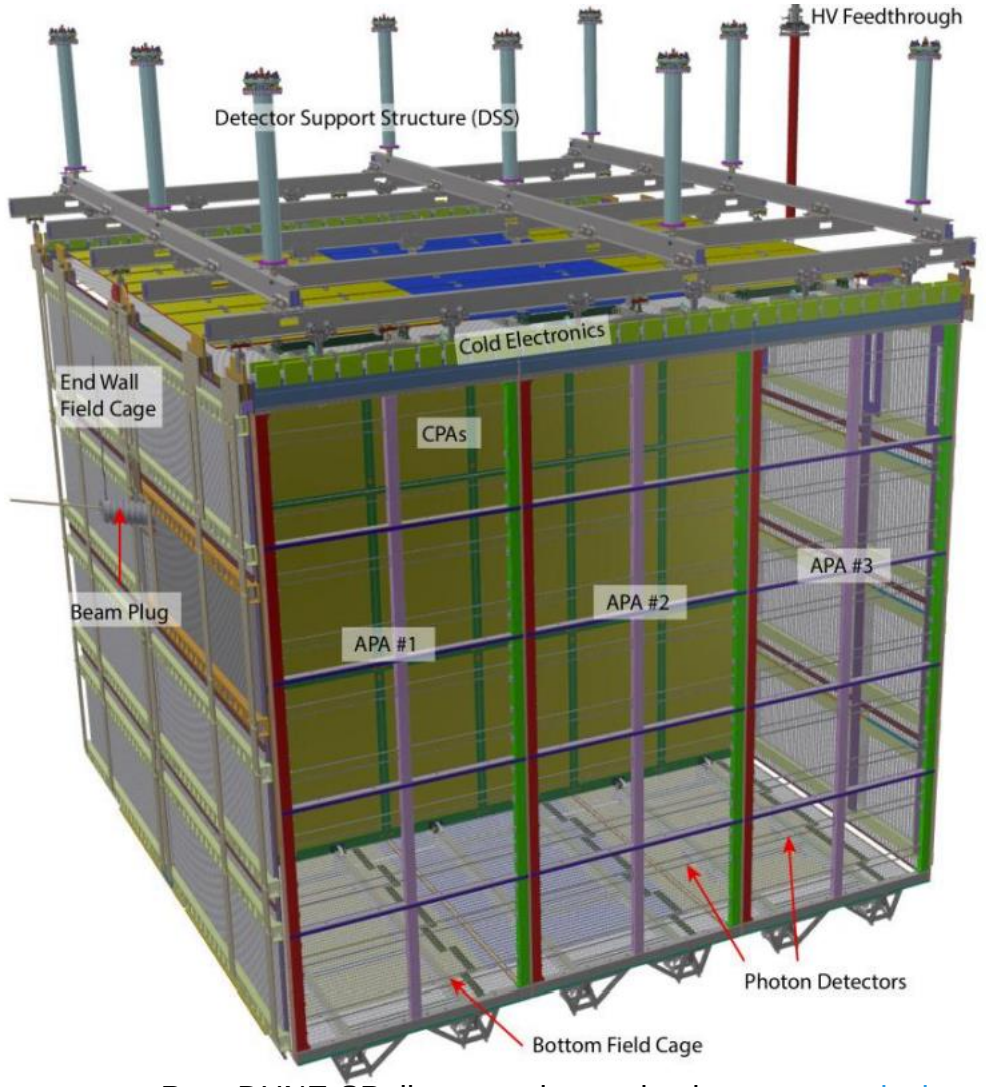
Total inelastic cross section for protons on argon compared to various event generators.



Neutron cross section measured using data from pions scattering on argon. The radial distance between the pion interaction and the neutron scattering to a proton is measured to calculate the cross section.

Conclusion

- ProtoDUNE-SP was a prototype of the DUNE Far Detector Module 1 that took hadron test beam data.
- Analyses and technical notes ongoing for many different cross sections of hadrons on argon.
  - Has led to six doctoral theses
  - Diverse set of analyses with different methods (CERN Annual Report):
    - Likelihood-fitter (Pion Absorption+Charge Exchange+Other, Neutron).
    - Bayes-like unfolding with track length fitting (Pion, Proton).
    - Unfolding with differential cross sections (Pion Charge Exchange).
    - Bayes-like unfolding of generic LArIAT formula (Kaon).
- Measurements being made to provide data for particle passage models and intranuclear cascade simulations (how particles from neutrino interactions leave the nucleus)
- Look forward to our future updates in the coming months.



ProtoDUNE-SP diagram, please checkout out our design and performance papers for more info on the program. Ongoing work is reported here.