Hadron-argon Cross Section Measurements in ProtoDUNE-SP

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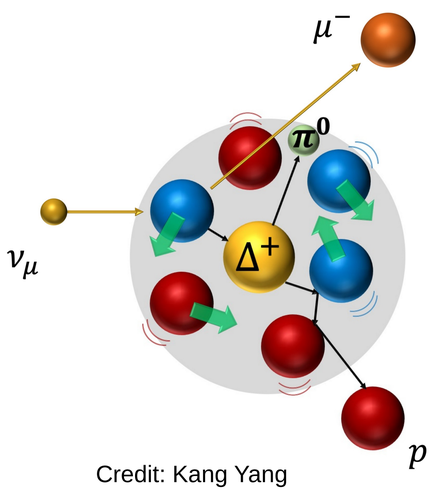
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

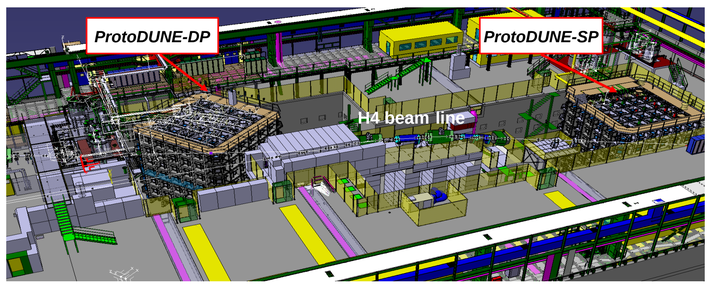
I. Final State Interactions



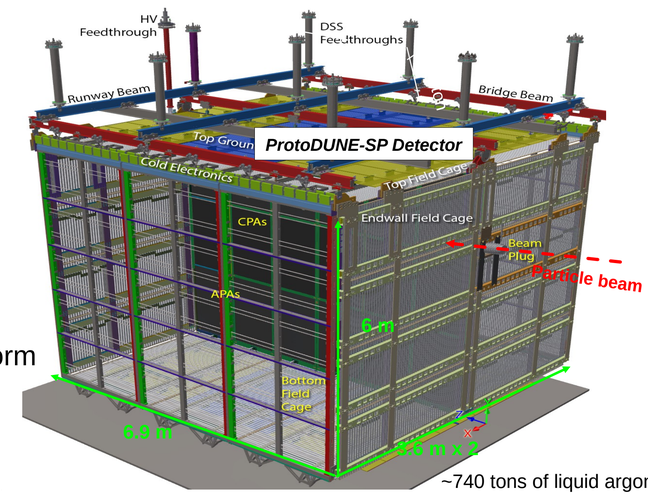
Credit: Kang Yang

- Final state interactions (FSI):
  Hadrons produced in a neutrino interaction can re-interact with the nuclear medium before leaving the nucleus
- Probability of hadron re-interaction is high
  ~80% for pions, ~40-50% for protons in Ar
  (typical hadron KE~0(1 GeV))
  → Nuclear effect needs to be taken into account in neutrino-nucleus interactions
- FSI modelling is the major source of systematic uncertainty on oscillation analyses
- Very few measurements of hadron interactions on liquid argon
- ProtoDUNE's measurements of hadron scattering in argon can provide **important experimental constrains on FSI modelling**

II. ProtoDUNE-SP



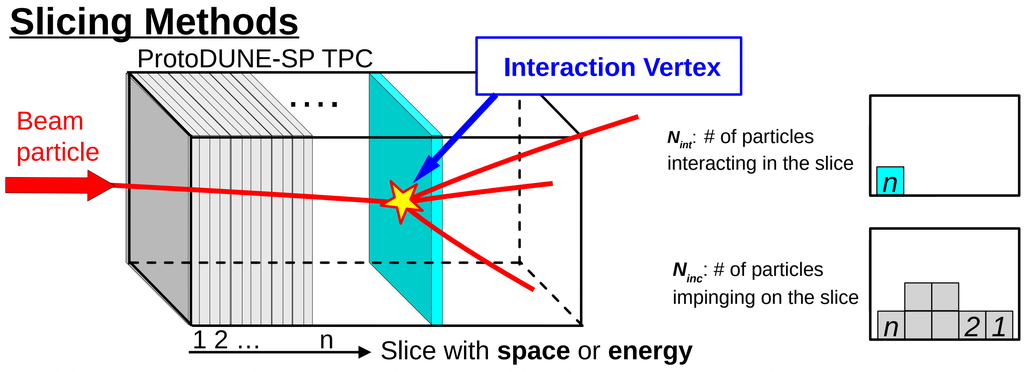
- One of the 2 prototypes for DUNE at CERN Neutrino Platform
- Controlled environment
  CERN H4 beamline with known particle type and incident energies
- A variety of test-beam particles in broad range of momenta
  0.5-7 GeV/c (π^+/p/K^+/μ^+/e^+)
- Rich data to study hadron-Ar interactions
  Over 4 million beam events collected (all momenta)



- Liquid argon time projection chamber (LArTPC)
  Excellent tracking & calorimetric capabilities

III. Cross Section Determination Methods: Slicing & Reweighting

Slicing Methods



- Thin slice method originally developed by the LArIAT experiment
  - Each slice is considered as an independent experiment
- ProtoDUNE's new versions of slicing methods:

(1) Thin-slice
- **Thicker slice** (10 cm) as thin target
- **XS formula**

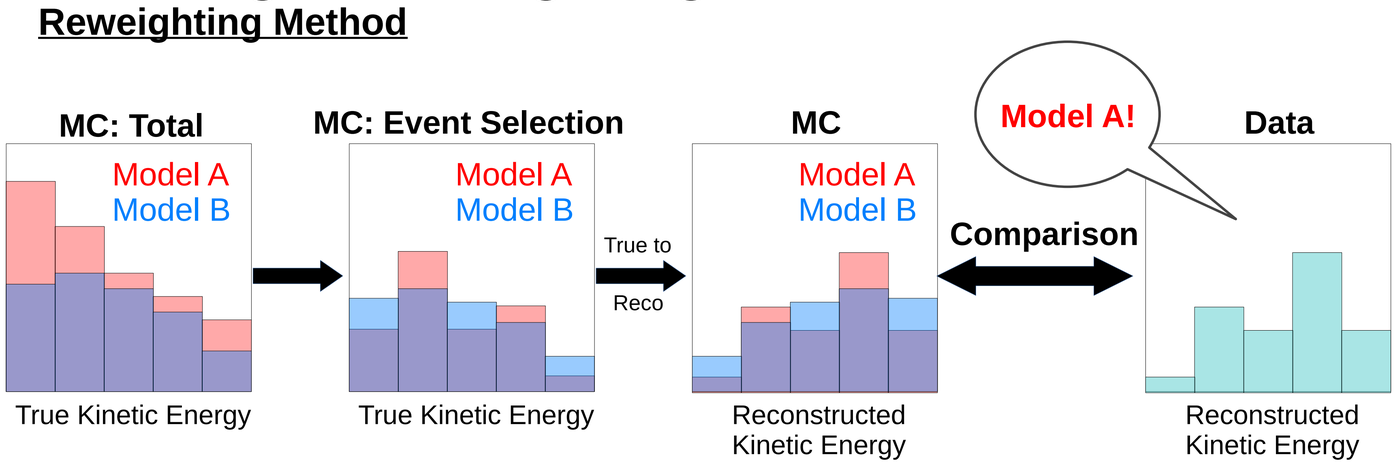
$$\sigma = \frac{M_{Ar}}{\rho N_A \Delta X} ln\left(\frac{N_{inc}(X)}{N_{inc}(X) - N_{int}(X)}\right)$$

(2) E-slice
- Use energy bins as thin target

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

ΔX|ΔE: Slice thickness ρ: Ar density M_{Ar}: Ar mass
XS: Cross section

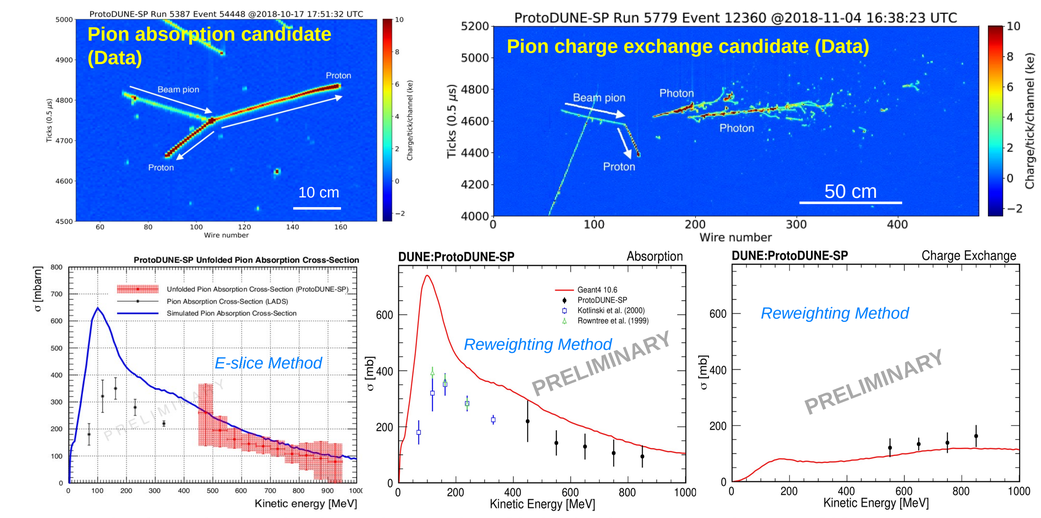
Reweighting Method



- Reweighting: Alternative method to measure cross section
- Fit event rate [1] to extract cross section from the measured interacting energy spectrum
- Full development of fit machinery to extract XS completed (including systematic uncertainties)

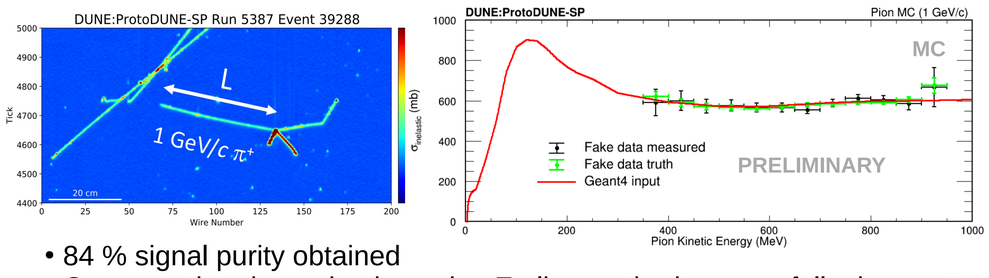
IV. Hadron-argon Cross Section Measurements: Pion, Proton, Kaon, Neutron

Pion Exclusive Cross Sections



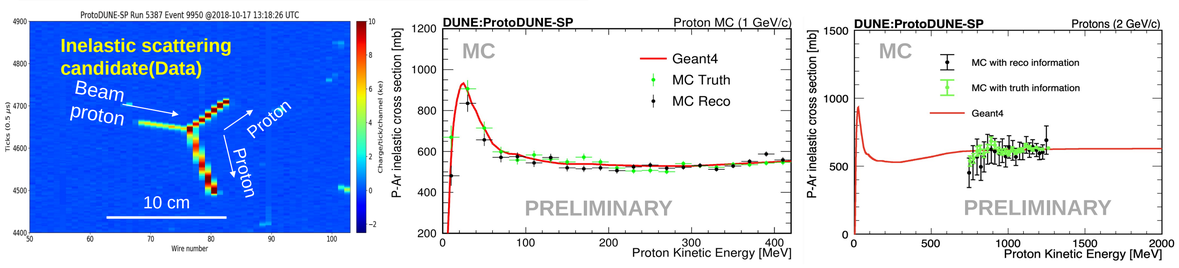
- Exclusive channel: pion absorption [2,3] & charge exchange [3]
- Preliminary result of absorption shows lower cross section than Geant4
  - Same feature is observed in LADS experiment [4,5]

Pion Inelastic Cross Section



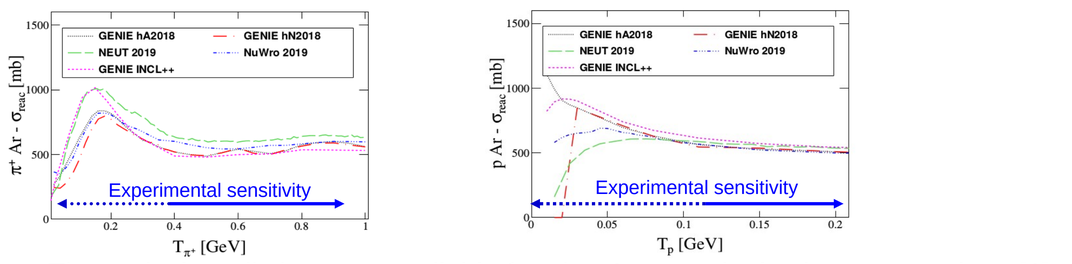
- 84 % signal purity obtained
- Cross section determination using E-slice method successfully demonstrated

Proton Inelastic Cross Sections



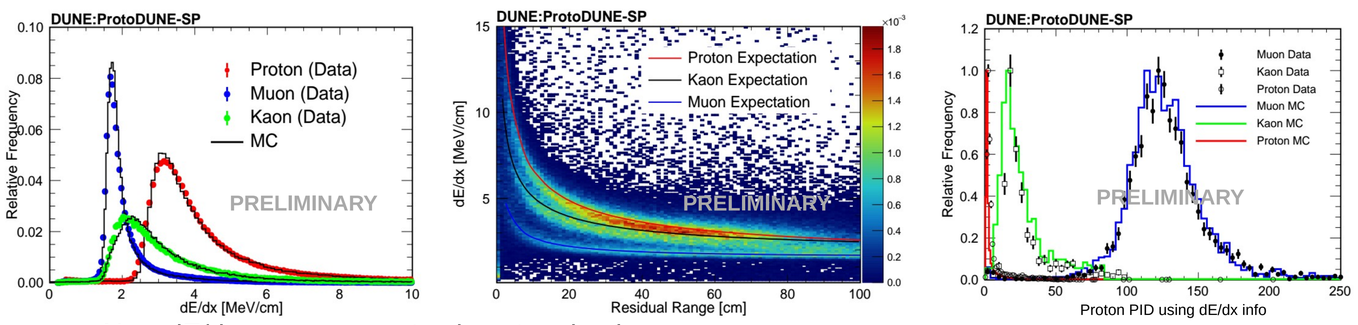
- ~80 % signal purities obtained for both 1 GeV/c & 2 GeV/c beam protons
- Successful demonstration of cross section determination using slicing methods

Theoretical Predictions on Inelastic Channels



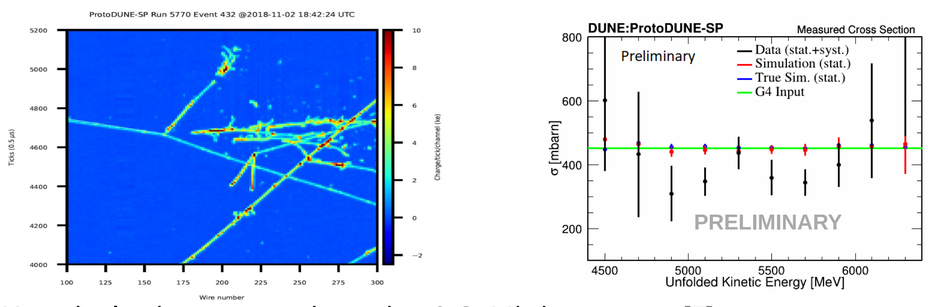
- Theoretical predictions are available for pion & proton inelastic cross sections [6]
- **ProtoDUNE can provide our measurements!**

New Kaon dE/dx Measurement



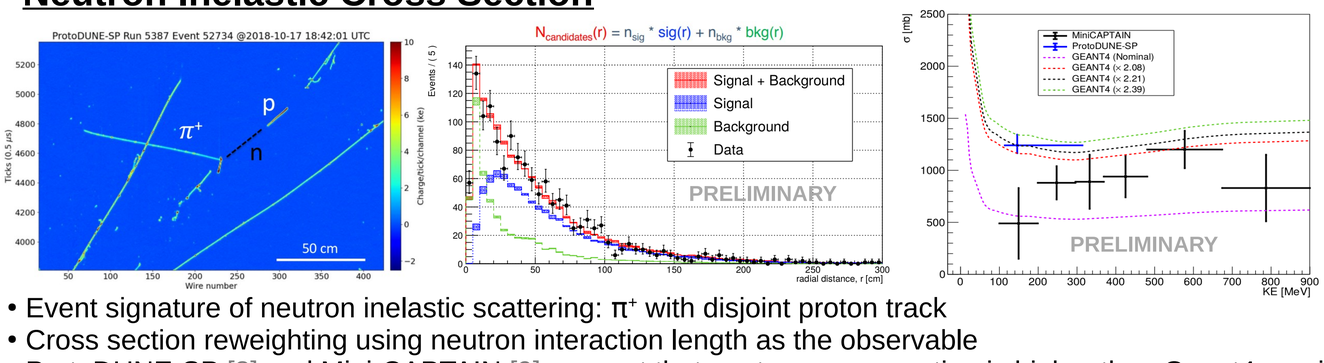
- New dE/dx measurement using stopping kaons
  - Select stopping secondary kaons from 6 and 7 GeV/c primary beams
  - 90% purity achieved, good dE/dx agreement between data and MC

Kaon Inelastic Cross Section



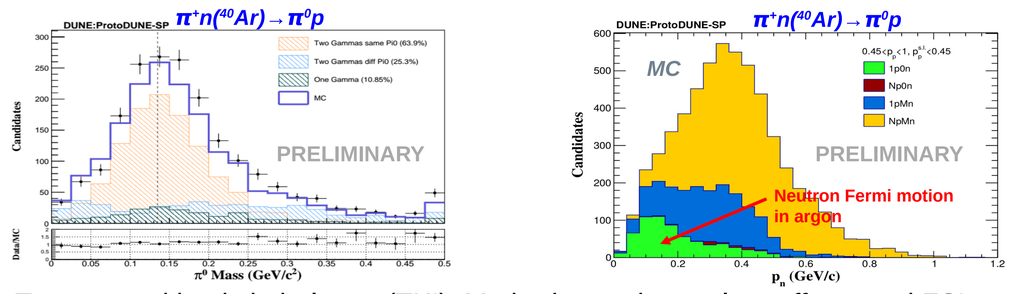
- Kaon inelastic cross section using 6 GeV/c beam runs [7]
- Successful reconstruction of kaon cross section using thin slice method

Neutron Inelastic Cross Section



- Event signature of neutron inelastic scattering: π^+ with disjoint proton track
- Cross section reweighting using neutron interaction length as the observable
- ProtoDUNE-SP [8] and Mini-CAPTAIN [9] suggest that neutron cross-section is higher than Geant4 nominal

Transverse Kinetic Imbalance for Pions



- Transverse kinetic imbalance (TKI): Method to probe nuclear effects and FSI
- ProtoDUNE's TKI channel: pion charge exchange
- Reconstruction: Data/MC well agree with π^0 mass peak
- Pn variable provides a way to measure the Fermi motion of nucleon inside Ar nucleus directly
  → Fermi motion of the struck neutron in Ar is observed (MC)

V. Summary

- ProtoDUNE has made lots of great progresses on cross section analyses
- We are moving forward to publish the cross section results

References

[1] J. Calcutt et al, "Geant4Reweight: a framework for evaluating and propagating hadronic interaction uncertainties in Geant4", JINST 16 P08042(2021)
[2] Francesca Stocker, "Measurement of the Pion Absorption Cross-Section with the ProtoDUNE Experiment", Ph.D Thesis, Universität Bern (2021)
[3] Jacob Calcutt, "Measurement of π+ -- Argon Absorption and Charge Exchange Interactions Using ProtoDUNE-SP", Ph.D Thesis, Michigan State University (2021)
[4] LADS Collaboration, "Pion absorption reactions on N, Ar and Xe", European Physics Journal A 9.4, pp. 537-552 (2000)
[5] LADS Collaboration, "pi+ absorption on N and Ar", Phys. Rev. C 60, p. 054610 (1999)
[6] S. Dytman et al., "Comparison of validation methods of simulations for final state interactions in hadron production experiments", PRD 104 053006 (2021)
[7] Richard Diurba, "Evaluating the ProtoDUNE-SP Detector Performance to Measure a 6 GeV/c Positive Kaon Inelastic Cross Section on Argon", Ph.D Thesis, University of Minnesota (2021)
[8] David Rivera, "Neutron Cross Section Measurement in the Protodune-SP Experiment", Ph.D Thesis, University of Pennsylvania (2021)
[9] CAPTAIN Collaboration, "First Measurement of the Total Neutron Cross Section on Argon between 100 and 800 MeV", Phys. Rev. Lett. 123, 042502 (2019)