PROCEEDINGS OF SCIENCE

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

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ProtoDUNE-SP was a large-scale prototype of the single phase DUNE far detector which took test beam data in Fall 2018. The charged particle beam consisted of positrons, pions, kaons, muons, and protons, and this data is being used to measure the various hadron-Ar interaction cross sections. Uncertainties in these interaction cross sections are a significant systematic uncertainty in long baseline neutrino oscillation analyses. These measurements will provide important constraints for the nuclear ground state, final state interaction, and secondary interaction models of argon-based neutrino-oscillation and proton-decay experiments such as DUNE. This talk will report the results of the cross-section measurements of pions, protons and kaons that interact inelastically with argon.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

[*] Speaker

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PoS(ICHEP2024)162

1. Introduction

The Deep Underground Neutrino Experiment (DUNE) [1] is a next-generation neutrino observatory hosted by Fermi National Accelerator Laboratory (Fermilab) and is currently under construction. DUNE is designed to answer some of the most fundamental questions such as the neutrino mass ordering as well as the value of the charge-parity (CP) violation phase δ in the Pontecorvo-Maki-Nagakawa-Sakata (PMNS) matrix [1]. DUNE will be utilising its near and far detectors to measure neutrinos produced by one of the most intense neutrino beams. The neutrino beam will have a power of 1.2 MW after the Proton Improvement Plan-II (PIP-II) and it is upgradable to 2.4 MW. Figure 1 shows the setup of DUNE.

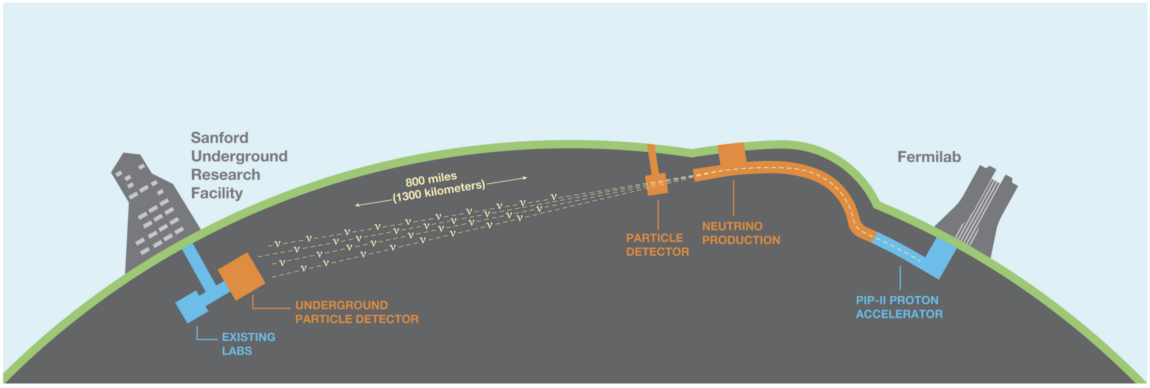


Figure 1: Schematic of DUNE's near-far detector setup. The near detector is marked as "particle detector" and the far detector is marked as "underground particle detector" [1].

The near-far detector configuration is motivated by the neutrino production mechanism employed in DUNE. The near detector is going to be located inside Fermilab, adjacent to the beam. Meanwhile, the far detector (FD) is installed 1500 m underground in Sanford Underground Research Facility (SURF), which is approximately 1300 km away from Fermilab. The DUNE FD has four liquid argon time projection chamber (LArTPC) modules, each contains 17.5 kt of liquid argon [2].

The primary physics goals of DUNE include determining the neutrino mass ordering and measuring the value of the CP violation phase in the PMNS matrix accomplished by measuring the $\nu_e/\bar{\nu}_e$ appearance probabilities. Within 3 years, DUNE can deliver a 5σ sensitivity on neutrino mass ordering for 100% of the possible δ values. In terms of the value of δ, DUNE is able to scan 75% of the possible values with a 3σ significance in the long run [3].

Nuclear effects is one of the challenges faced by DUNE. Neutrino interactions are well understood and modelled on isolated and static nucleon. However, utilising argon as the target, DUNE is subjected to final state interactions (FSIs) of hadrons within argon nucleus that can affect the kinematic of the interaction and even change the final state topology. Therefore, more effort on modelling FSIs is required for DUNE to minimise its systematic uncertainties.

2. The ProtoDUNE Single Phase (SP) detector

The ProtoDUNE-SP detector is a decommissioned prototype of the DUNE far detector horizontal drift (HD) module located in the neutrino platform in CERN. The detector contained 770 tonnes

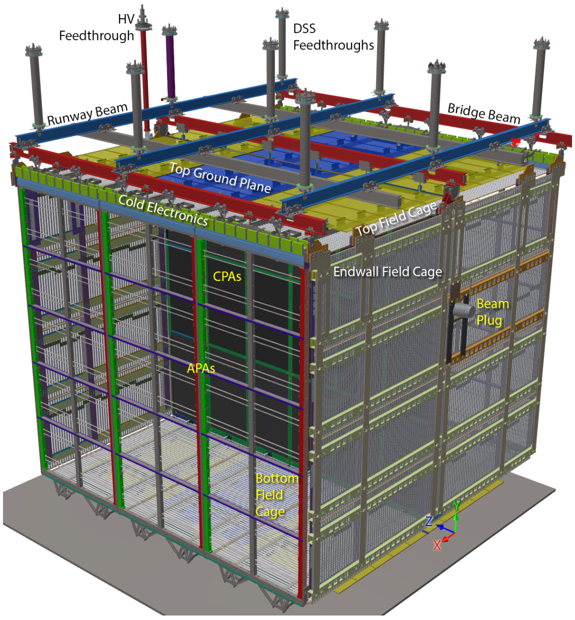


Figure 2: A 3D schematic of the ProtoDUNE-SP detector [5].

of liquid argon, which was the largest monolithic LArTPC ever built [5]. The detector started data-taking in Fall 2018 and was decommissioned in 2020.

Besides its role as a prototype, the ProtoDUNE-SP detector was exposed to a particle beam named as H4 Very Low Energy (VLE). The H4-VLE beam injected charged particles including positrons, pions, kaons, muons and protons from 0.3 to 7 GeV, which endows ProtoDUNE-SP its own physics programme [4]. The ProtoDUNE-SP detector can measure cross sections of test beam particles on argon nucleus and improve our knowledge on FSIs. Figure 2 shows a view of the detector.

3. Methodology

3.1 Thin slice method

The thin slice method was initially proposed by the LArIAT collaboration [6]. The method considers the active volume of the detector as a pile of thin slice targets and the approach is generalised from the geometry space to kinetic energy space. The cross section can be expressed as:

$$\sigma = \frac{m_{\mathrm{Ar}}}{\rho \mathrm{N_A} \delta \mathrm{E}} \frac{d\mathrm{E}}{dx}\bigg|_{\mathrm{KE}} \ln\left(\frac{\mathrm{N_{inc.}(KE)}}{\mathrm{N_{inc.}(KE)} - \mathrm{N_{int.}(KE)}}\right), \tag{1}$$

where m_{Ar} is the molar mass of argon, ρ is the liquid argon density, $\mathrm{N_A}$ is the Avogadro constant, $\delta\mathrm{E}$ is the width of the energy slice, $d\mathrm{E}/dx|_{\mathrm{KE}}$ is the energy deposited per unit distance of the particle of interested at a certain kinetic energy, $\mathrm{N_{inc.}(KE)}$ is the number of incident particles at the given kinetic energy range, $\mathrm{N_{int.}(KE)}$ is the number of interacting particles at the given kinetic energy range.

Figure 3 shows schematically the principle which the thin slice method follows when assigning the ID according to the kinetic energy. The empty orange circle represent the actual starting point of an event but the filled orange circle is the chosen starting slice after ignoring the incomplete slice. The blue and green circles are in the slices corresponding to the interacting kinetic energy of protons. Blue circles represent protons scattered elastically while green circles represent inelastically scattered protons. The third event from the top is removed as it starts and ends in the same slice.

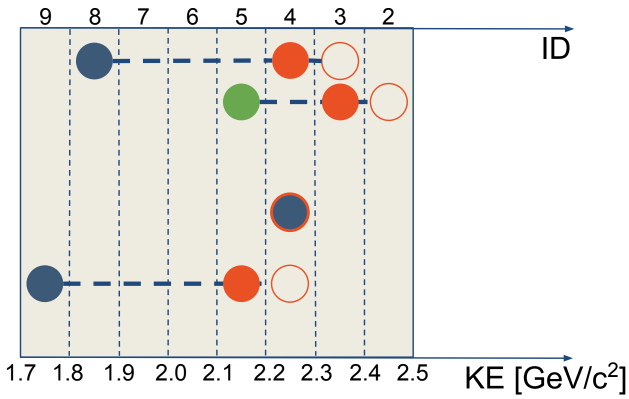


Figure 3: Schematic illustration of the thin slice method in the kinetic energy space with corresponding ID number. Circles represent the start (orange) and end points (blue and green) of an event in the kinetic energy space.

3.2 Unfolding

Unfolding refers to a procedure that estimates probability distributions without available parametric form and the data is further randomly fluctuated by the measuring effect. Analyses conducted made use of unfolding to convert reconstructed variables to measure the true cross sections, which enables comparisons among various models.

The unfolding method developed by D' Agostini [7] was used for analyses performed and a toy example can be seen in Figure 4: the measured distribution can be unfolded to obtain the true distribution using the response matrix.

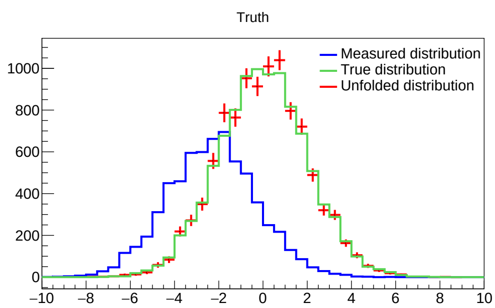
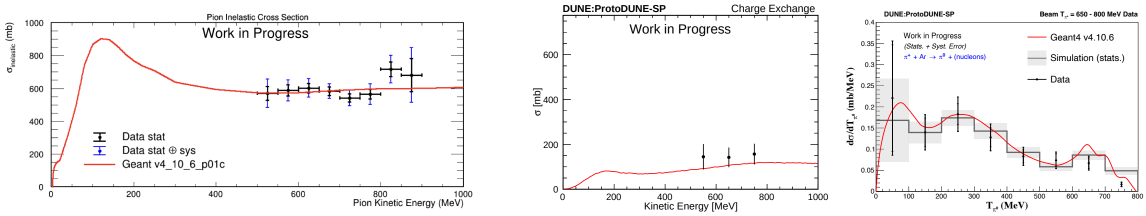


Figure 4: A toy example of unfolding.

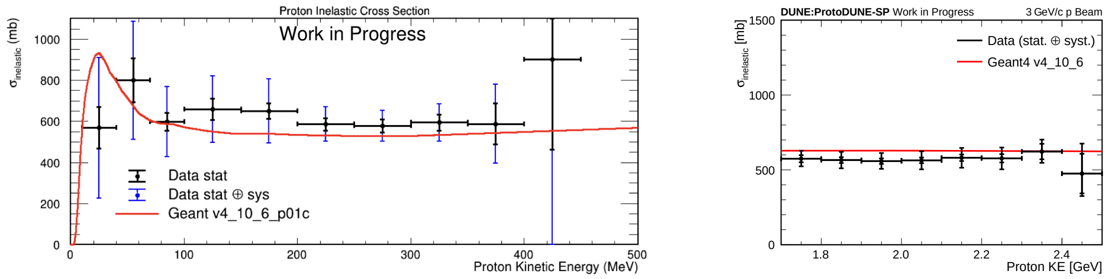
4. Results

Figure 5 shows results of 1 GeV/c π^+-argon cross-section measurements. The inclusive cross section is shown in Figure 5a and Figure 5b shows the cross section of the charge exchange interaction, which contains only the nucleon and a π^0 in the final state and the differential cross section of the process is shown in Figure 5c as a function of the kinetic energy of the final state π^0 [8]. Cross sections of 1 and 3 GeV/c proton on argon can be seen in Figure 6. Cross sections of K^+ were also measured and the results are shown in Figure 7 [9].



(a) **(b)** **(c)**

Figure 5: Results of 1 GeV/c π^+-argon cross sections: (a) shows the inelastic cross section, (b) shows the cross section of the charge exchange process and (c) shows the differential cross section as a function of the kinetic energy of the final state π^0 in the charge exchange interaction.



(a) **(b)**

Figure 6: Results of 1 GeV/c (a) and 3 GeV/c (b) proton inelastic cross section measurements.

5. Conclusion

The ProtoDUNE-SP detector finished its data-taking and is decommissioned. Apart from validating the construction of the DUNE FD module, results from ProtoDUNE will reduce the systematics in the DUNE analyses. The ProtoDUNE-HD detector that contains the finalised DUNE HD design started taking data with more measurements to come.

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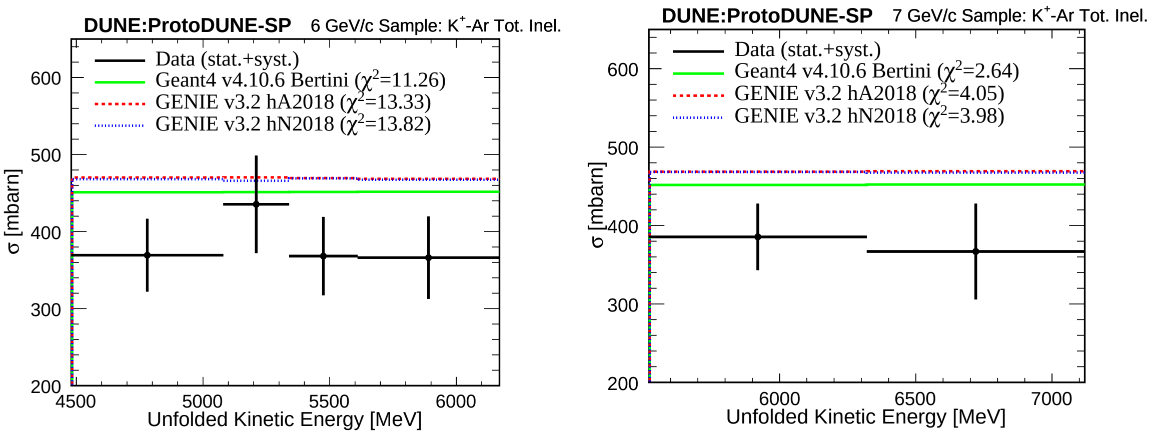

(a) **(b)**

Figure 7: Results of the 6 GeV/*c* (a) and 7 GeV/*c* (b) kaon inelastic cross section measurement [9].

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