The first pion-Ar cross-section measurement with the LArIAT experiment

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Abstract. A complete understanding of neutrinos properties requires a study and a characterization of the interactions of the daughter particles created in a neutrino-nucleus interaction. The Liquid Argon In A Testbeam (LArIAT) experiment is a small-scale liquid argon detector situated in the Fermilab Test Beam Facility. The LArIAT experiment is exposed to a tertiary beam comprised of mostly pions along with a mix of muons, protons, kaons, and electrons. LArIAT’s goal is to characterize the response of the Liquid Argon Time Projection Chamber (LArTPC) to known incoming charged particles and measure their interactions in Argon, in order to understand their cross-sections and to help developing and tuning simulations and reconstruction algorithms for LArTPC neutrino experiments. The world’s first measurement of a pion cross-section on an Argon target, made with the LArIAT detector, is presented here.

1. Introduction
The LArIAT experiment [1, 2] is part of the international US Neutrino Program. The aim of the accelerator neutrino physics program at Fermilab is to investigate neutrino flavor oscillations and the existence of sterile neutrinos. A beam of neutrinos is fired into the detector and the secondary particles produced by their interactions are detected and utilized to reconstruct the info about the neutrino.

Liquid Argon Time Projection Chambers (LArTPC) technology has been utilized for many accelerator neutrino detectors. In a TPC, planes of angled wires collect the electrons that are produced by ionization of charged particles in the active medium and drifted along a uniform electric field. Liquid argon is chosen as the active medium because it is relatively dense, ensuring higher scattering centers density. It has an high electron lifetime - electrons are not absorbed while crossing the medium - and it has also an high scintillation light yield, being also transparent to its own scintillation light. The LArTPCs scalability, low energy threshold, calorimetric resolution, and ability to reconstruct particle interactions in 3D with mm-resolution make them ideal for the detection of the charged products from neutrino interactions [3].

The US Neutrino Program is based on the use of the liquid argon TPC technology. TPCs of varying scales are planned or already in operation for the Fermilab Short-Baseline (MicroBooNE, SBND, ICARUS) and Long-Baseline (DUNE) neutrino program. Considering this long-term plan for neutrino-argon interactions studies with LArTPCs, a dedicated calibration of this emerging technology is invaluable. The LArIAT experiment aims to characterize LArTPC performance in the energy range relevant to these neutrino experiments by operating the
refurbished ArgoNeuT detector [4] in a tunable testbeam at Fermilab. It explores particle response calibration, technical R&D, and several physics topics relevant to current and future liquid argon detectors.

2. The LArIAT Experiment

The LArIAT experiment is a 0.26 ton active mass Liquid Argon Time Projection Chamber (LArTPC) located at the Fermilab Test Beam Facility (FTBF). The TPC is exposed to a tertiary charged particles beam comprised of pions ($\pi^\pm$) along with a mix of muons ($\mu^\pm$), protons (p), kaons ($K^\pm$) and electrons ($e^\pm$) in the range between 200 MeV and 2 GeV. The beamline is equipped with detectors that aid to identification and selection of particle species and momenta, in order to characterize the response of the LArTPC to known incoming particles. These results can then be used to tune simulation and reconstruction algorithms for future LArTPC experiments.

2.1. The Fermilab Test Beam

Primary protons (120 GeV) from the Fermilab Main Injector are shot onto an Al target. A tunable secondary pion beam is produced (8 to 64 GeV). Those pions hit a Cu target that is placed at the entrance of the test beam enclosure and a tertiary beam of charged particles, mainly pions, is produced.

2.2. The beamline auxiliary detectors

Several auxiliary detectors are disposed along the beamline to monitor the tertiary beam impinging on the TPC, see Figs. 1 and 2. The 4 Multi Wire Proportional Chambers (MWPCs) and the bending magnets allow the momentum reconstruction before the particle enters the TPC. The dipole magnets allow to have a tunable momentum in 0.2 - 2 GeV/c range and to select positive and negative polarities. There are also two Time Of Flight (TOF) counters at the start and at the end of the beam line. Utilizing the TOF in conjunction with the reconstructed momentum it can be possible to discriminate among several particle species.

![Figure 1: Schematic view of the LArIAT beamline.](image-url)

2.3. The LArIAT TPC and light collection system

The LArIAT experiment uses preexisting components from the ArgoNeuT experiment, such as the cryostat and the TPC. The cryostat hosts the 550 liters of liquid argon (LAr) and it is vacuum insulated. The LArIAT TPC has an active volume of 90 cm $\times$ 47 cm $\times$ 40 cm (length $\times$ width $\times$ height) with the width serving as the drift direction and the length is along the
beam axis. There are three planes of wires (Shield, Induction and Collection) of which two are instrumented with dedicated cold front-end electronics to collect the electrons created during the charged particle interactions in the argon, which drift across the argon volume under a 500 V/cm nominal drift field. Each of the two planes consists of 240 wires oriented at ± 60° relative to the beam axis, with 4 mm anode wire spacing. Pulse signals on the wires are processed and analyzed through a custom version of LArSoft [5], a dedicated software for LArTPCs automated signals and tracks reconstruction.

In addition to the collection of the ionization charge from the TPC, the detection of the scintillation light produced in LAr is an actual point of interest, both for its trigger function for the TPC events collection and for the possibility of using also this information to improve the energy resolution of this detector technology [6]. The LArIAT light collection system consists of an array of two high quantum efficiency cryogenic photomultiplier tubes (PMT) - a 3” Hamamatsu R-11065 and a 2” ETL D757KFL - and three Silicon PhotoMultiplier Detectors (SiPMs) with custom made cold pre-amplification boards - one SensL single-channel SiPM and two Hamamatsu SiPM Arrays - which are deployed in liquid argon and mounted behind the wire planes of the TPC. The PMTs and the SiPMs are mostly sensitive to optical photons, while Ar scintillation wavelength is 128 nm. Wavelength shifting tetraphenyl butadiene (TPB) coated foils covering the TPC walls have been utilized to shift the argon scintillation light into the visible spectrum (blue). This technique provides enhanced light collection efficiency and uniformity.

In Fig.3 the LArIAT’s TPC and light collection system are shown.

3. LArIAT’s data taking and analyses
The LArIAT experiment started taking data in May 2015: Run I lasted 3 months. Run II lasted from February to July 2016: 5 times more statistics than Run I was acquired and the beam tuning was improved, ensuring higher-quality data. Run III is planned for next year (2017) and it will be more R&D focused.

LArIAT offers analyses covering detector calibration as well as physics topics relevant to current and upcoming LArTPC-based neutrino experiments. Each analysis relies on software-
based automated reconstruction of signals from the beamline detectors, TPC, and light collection system. An example of a real LArIAT data event showing a candidate kaon decay is reported in Fig. 4, 2-D views from the wire-planes and 3-D reconstruction.

Calibration studies include measuring the drift electron lifetime, the electronics response calibration (improvement in signal-to-noise ratio using cold front-end electronics for the TPC), and the charge recombination as a function of electric field. The primary higher-level physics analyses on the collected data are the measurement of charged hadron-Ar interaction cross sections and the study of exclusive channels, $e/\gamma$ shower identification, $\mu$ sign determination in the absence of a magnetic field, study of nuclear effects in argon, and Geant4 validation for hadrons interaction models. Regarding the detector technical characterization, other studies are ongoing: the optimization of the event reconstruction algorithms, the light collection system characterization, and the improvement of the energy resolution through a combined study of ionization and scintillation light.

![LArIAT's TPC inside the cryostat.](image1)

![LArIAT's light collection system.](image2)

**Figure 3:** (a) LArIAT cryostat hosting the TPC. The TPC structure and electronic readout is outlined. (b) Cryostat flange hosting the LArIAT’s light collection system.

**Figure 4:** Example of LArIAT event imaging: kaon decay candidate. Event views on the Collection and Induction TPC planes and the reconstructed 3-D tracks.
4. Total $\pi^-$ - Ar cross section measurement in LArIAT

One of the goals of the LArIAT experiment is the experimental measurement of charged pion cross section on Ar in a wide energy range. Prior to this analyses, no experimental measurement of this cross section on argon had been preformed. Predictions for only few energies come from interpolation between lighter and heavier nuclei.

4.1. Cross-section definition

The total $\pi^-$ - Ar interaction cross section $\sigma_{tot}$ measured in this analysis is defined as the one related to strong interaction processes (including both elastic and reaction channels). In case of the “thin target” approximation, the measured rate of interactions for a given slab of Ar can be used to calculate the total cross section as a function of energy (see Eq. 1).

$$\sigma_{tot}(E) \approx \frac{1}{n_z} \frac{N_{interacting}(E)}{N_{incident}(E)}$$

where $z$ is the target thickness (in cm) along the incident pion direction, and $n$ is the scattering centers density in the target, $n = \rho N_A$ (in cm$^{-3}$).

The LArIAT TPC active volume (90-cm thick LAr ) can not be considered a thin target for pion interactions in the energy range of interest. Therefore a new technique called the “sliced TPC” method was developed which makes possible an accurate measurement of the pion cross section dependence on energy in the “thick target” LArTPC environment [7], as shown in Figure 5. Using the granularity of the LArTPC, it is possible to treat the wire-to-wire spacing as a series of “thin-slab” targets of $\Delta z \approx 4.5$ mm thickness along the z axis, i.e. direction of the incident particles (pions), if the energy of the pion incident to each slice is measured. Each slice can be considered as a “thin target” and it is possible apply the cross section calculation from Eq.1 iteratively, evaluating the actual kinetic energy of the pion as it enters each slice, exploiting the precise calorimetric reconstruction along the track.

![Figure 5: Representation of the analysis of reconstructed tracks with “sliced TPC” technique.](image)

4.2. Analysis on LArIAT’s Data

This analysis uses data collected during LArIAT’s Run I - Negative Polarity runs.

Selection criteria on beamline detectors response and on TPC events topology were applied to select $\pi^-$ candidate events. Separation of $\pi/\mu/e$ from (anti-)protons and late bunches from the beam was obtained through the TOF vs momentum measurement. A clean and unique match between extrapolated Wire Chamber track (from the MWPCs) and the start of TPC track was required. Electron-initiated shower events in the TPC were rejected in order to remove the electron contamination from the pion sample. The muon contamination was estimated through Monte Carlo simulation. The performance of the other auxiliary beam line detectors to improve the sample purity is being investigated (e.g aerogel and muon range stack to tag $\mu^-$/e backgrounds).
In the preliminary analysis, the traditional strong processes as well as background processes are currently included in the cross section result presented below in Fig. 6. The background processes involve: negative pion capture at rest and pion decay events. Further studies on data and Monte Carlo to remove $\pi^-$ capture and decay events from the sample are currently underway. The result shows a relatively good agreement between data and Monte Carlo in a wide energy range except in the first energy bin, in which deficiencies in the Monte Carlo simulation are suspected. A revised simulation of the LArIAT beamline may resolve this discrepancy. The main systematic uncertainties on the cross section are related to: calibration of the energy deposition (dE/dx) in the TPC (5%), energy loss prior to entering the TPC (3.5%), through-going muons contamination (3%), and wire chamber (initial) momentum reconstruction (3%) [8].

![Figure 6: LArIAT Preliminary results on the $\pi^-$ - Ar cross section analysis [8]. (a) Interacting $N_{\text{interacting}}(E)$ and Incident $N_{\text{incident}}(E)$ energy distributions. (b) Total $\pi^-$ - Ar cross section.](image)

5. Conclusions
The data sample from LArIAT’s initial run is utilized to make the first measurement of the $\pi^-$ - Ar cross section and is compared to the expectation from Monte Carlo. More analyses are forthcoming from the LArIAT collaboration utilizing additional data collected in the second beam run which took place between February and August 2016.

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