The LArIAT experiment: first measurement of the inclusive total pion cross-section in Argon

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Abstract. In light of future large neutrino experiments such as DUNE, an excellent understanding of LArTPCs is required. The Liquid Argon In A Test-beam (LArIAT) experiment, located in the Fermilab Test Beam Facility, is designed to characterize the perfomance of LArTPCs and improve the reconstruction algorithms but also to measure the cross-sections of charged particles in Argon. The goals and experimental layout will be presented, as well as the world's first inclusive total pion interaction cross-section on Argon measured by LArIAT.

1. Introduction

Neutrinos are neutral particles, all their physics results rely entirely on the reconstruction of the particles coming out from their interactions with the detector. One must be able to identify these outgoing particles, which requires good reconstruction, optimized particle identification algorithms and background control. LArIAT, the **L**iquid **Ar**gon TPC **I**n **A** **T**est-beam experiment, located in the Fermilab Test Beam Facility (Fig. 1) will allow the characterization of LArTPCs with a test beam, contributing to improve reconstruction and PID of charged particles.

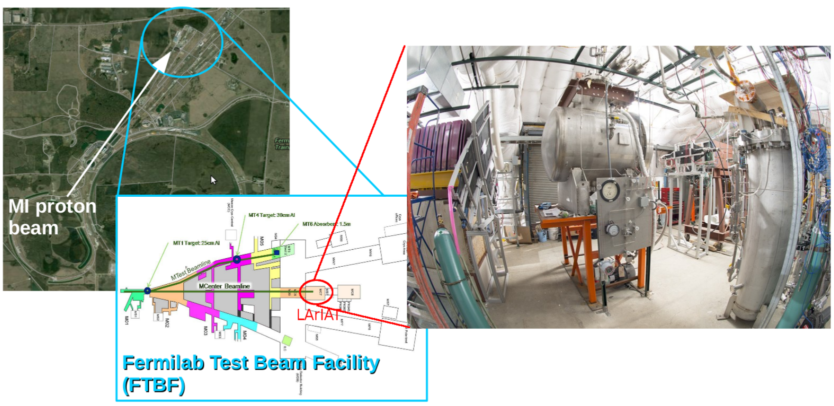

Figure 1. The Fermilab Test Beam Facility at Fermilab, Batavia IL, USA.

One of the most challenging backgrounds in neutrino electron appearance studies are neutral pions, since π^0 decay photons cannot be distinguished from the electrons produced by ν_e interactions in traditional water Cherenkov and scintillator-based detectors. LArTPCs can separate these two types of particles using the first few centimeters of the electromagnetic shower: photons convert into e^+/e^- pairs thus deposit double the energy than an electron shower. LArIAT will study the electron vs photon separation power of LArTPCs.

LArIAT will also help reduce the systematic errors on neutrino related measurements by measuring hadron cross-sections on Argon. These results will contribute to validate simulation software such as GENIE[1] and GEANT4[2]. The total pion cross-section on Argon measurement with LArIAT's data will be shown.

2. The LArIAT experiment

The LArIAT experiment is located in the Fermilab Test Beam Facility (FTBF) at Fermilab. The experiment can be divided in two parts: the test-beam with the beamline detectors, and the TPC itself.

2.1. The test-beam and beamline instrumentation

LArIAT uses a dedicated tertiary beam. The beam energy is tunable, thus can be adjusted to cover relevant energy regions for both short baseline experiments, like MicroBooNE[3], SBND and Icarus[4]; and long baseline experiments like DUNE[5].

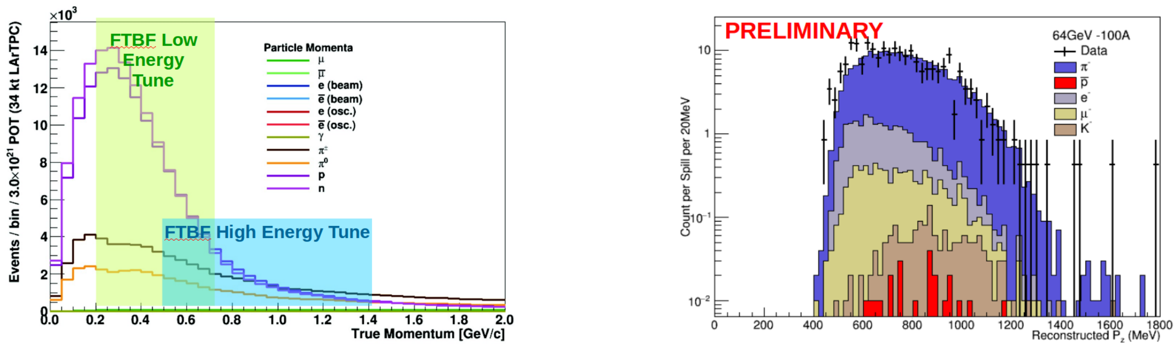

Figure 2. The left-hand plot shows a simulation of the expected outgoing particles spectra for the DUNE ν_e charged-current analysis and the energy ranges covered by the 2 LArIAT test-beam tunes. The right-hand plot shows the breakdown into particles for the LArIAT test-beam high-energy tune.

The advantage of using a test-beam is that the incoming particles are known. For this, a series of detectors (Fig. 3) are used:

- 4 multi-wire proportional chambers (MWPC), with 2 bending magnets, for single particle momentum reconstruction, momentum and polarity selection;
- a time-of-flight system, which combined with the MWPCs information allows to do particle identification;
- 2 aerogel Cherenkov detectors with different indexes;
- a muon range stack to tag through-going particles;
- halo and punch-through vetoes.

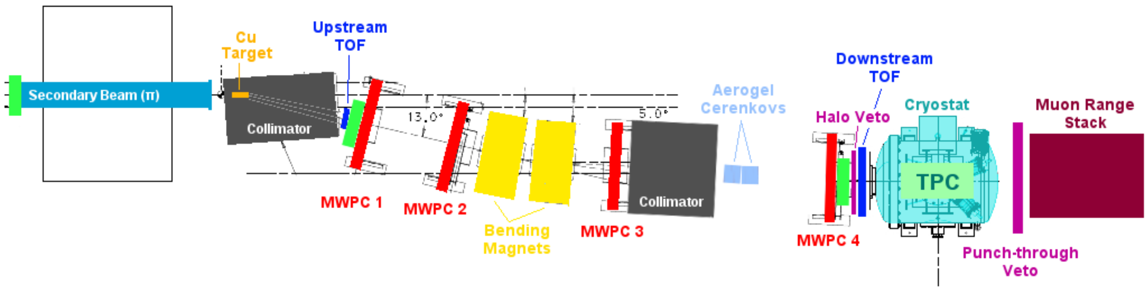

Figure 3. LArIAT beamline detectors layout.

2.2. The LArIAT TPC

LArIAT uses the refurbished ArgoNeuT[6] TPC and cryostat. The experiment characteristics are as follows:

- an active volume of 170L ($40cm \times 90cm \times 47cm$ drift), placed inside a 550L cryostat;
- a new Ti beam window on the cryostat's front flange;
- 3 wire planes (240 wires each, 4mm wire pitch), 2 are instrumented (induction and collection planes);
- a tunable electric field set at a nominal value of 500 V/cm;
- a light collection system made out of 2 standard cryogenic photomultipliers, 3 silicon photomultipliers, and wavelength shifting reflector foils lining the inner TPC walls;
- cold front-end electronics, which use MicroBooNE ASICs on custom motherboards;

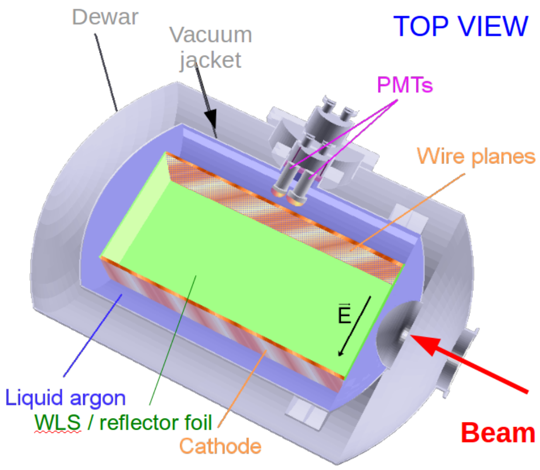

Figure 4. LArIAT schematic top view.

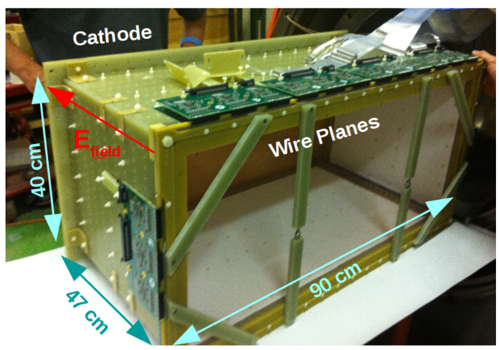

Figure 5. The LArIAT TPC, front-end cold electronics mounted.

The experiment has had 2 data taking periods: Run I from May to July 2015, and Run II from February to July 2016. In both cases data was taken with both beam polarities, and at both high and low energy tunes. A third run is expected to start in February 2017, focused mainly on R&D such as studying the effects of different wire pitches (3mm vs 5mm), and new light collection systems.

3. Total pion cross-section on Argon measurement

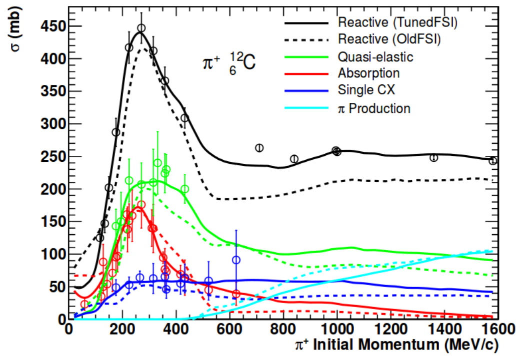

Figure 6. Pion cross-sections vs pion initial momentum. [7]

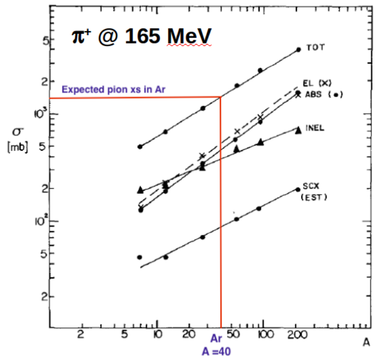

Figure 7. Total cross-section for π^+ at 165 MeV vs number of nucleons. [8]

Pions produced by neutrino interactions in experiments like DUNE are expected to be in the 100 to 500 MeV region. As shown on Fig. 6, pion cross-sections are boosted in that energy range. Because the largest systematic errors in neutrino cross-section measurements come from final state interactions (FSI) and secondary interactions, it becomes crucial to have a measurement of the different pion cross-sections. In Argon, FSI will lead to a large fraction of pions being absorbed and thus modified outgoing particles kinematics. So far no measurement has been made on Argon and all calculations rely only on extrapolations of data taken on other nuclei (Fig. 7).

3.1. Selection

The definition of total pion cross-section for our measurement is as follows:

$$\sigma_{tot} = \sigma_{elastic} + \sigma_{absorption} + \sigma_{charge-exchange} + \sigma_{\pi-prod} + \sigma_{ineslatic} \quad (1)$$

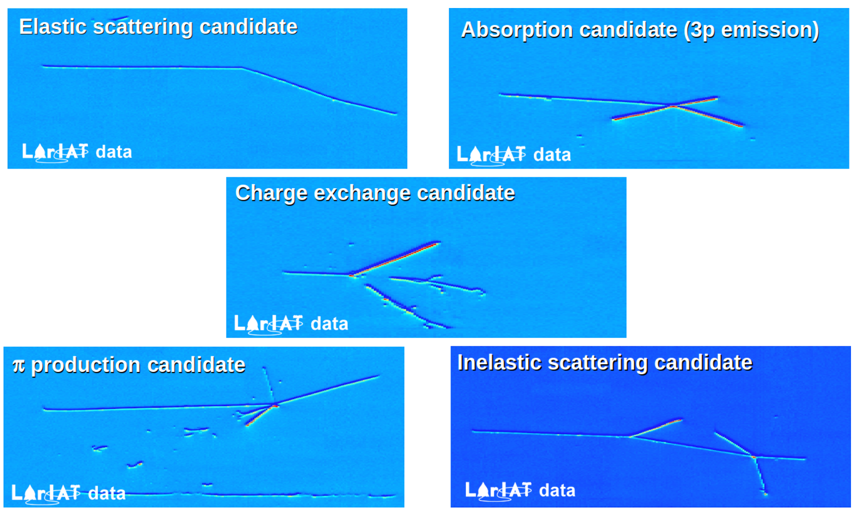

Figure 8. Pion candidates from LArIAT data.

The first step of the analysis is selecting pion-like events (Fig. 8). A pion candidate is an event where:

- the incoming particle is compatible with the pion hypothesis (combination of momentum and time-of-flight information);
- the event is not a cosmic ray;
- the reconstructed TPC track starts within the first few centimeters of the TPC;
- there is no pile-up in the event and the wire-chamber track can be uniquely matched to a reconstructed track inside the TPC;
- the event is not shower-like.

We apply these cuts to LArIAT Run I, negative polarity runs only (Tab. 1). The number of pion candidates after reduction is 2 290.

Table 1. Pion candidate selection cut flow.

	Number of events
Initial number of candidates	32 064
$\pi/\mu/e$ ID (beamline info + not cosmic)	15 448
Upstream track ($z_{init} < 2cm$)	14 330
No pile-up	9 281
MWPC/TPC track matching	2 864
Not shower-like (topology based)	2 290

From simulations, we know that the beam is composed of 48.4% π^- before the selection and of 91.04% π^- after cuts, thus the pion selection efficiency is 74.5% (Tab. 2).

Table 2. Beam composition from simulation before and after cuts.

	π^-	e^-	γ	μ^-	K^-
Before cuts	48.4%	40.9%	8.46%	2.2%	0.04%
After cuts	91.04%	3.7%	0.2%	5%	0.06%

This sample contains four types of background that have yet to be subtracted:

- pion decay, estimated at 2%;
- pion capture, ~9%;
- crossing muon contamination, ~10%;
- electron contamination, partially removed by the shower filter.

3.2. Method

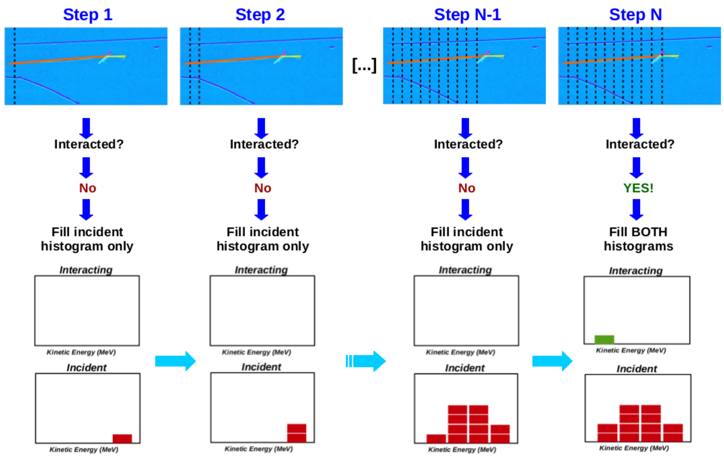

Figure 9. Thin slice method applied to a pion event in LArIAT.

To measure the total pion cross-section on Argon, we chose the thin target approach. In this case, the interaction probability for a thin target slab can be written as:

$$P_{interaction} = 1 - P_{survival} = 1 - e^{-\sigma n z} \approx 1 - (1 - \sigma n z + O(z^2)) \tag{2}$$

where σ is the cross-section per nucleon, n the medium density and z the slab thickness.

The interaction probability can also be defined as the ratio of the number of interacting particles to the total number of incident particles:

$$P_{interaction} = \frac{N_{interacting}}{N_{incident}} \tag{3}$$

By combining Eq. 2 and Eq. 3, we obtain the expression of the cross-section as a function of energy:

$$\sigma(E) = \frac{1}{nz} \frac{N(E)_{interacting}}{N(E)_{incident}} \tag{4}$$

The Argon volume inside the TPC can be considered as a series of thin slabs, where the slab thickness is given by the TPC wire pitch: ∼4 mm thick slabs in LArIAT case. To be able to calculate the cross-section as a function of the energy, we must first calculate the pion kinetic energy at each slab. For the first slab, the initial π kinetic energy is given by:

$$KE_i = \sqrt{p^2 + m_\pi^2} - m_\pi - E_{flat} \tag{5}$$

where p is the π momentum measured by the MWPCs and E_{flat} is the energy loss due to material upstream of the TPC. For each subsequent slab, the π kinetic energy is given by:

$$KE_{interaction} = KE_i - \sum_{i=0}^{N} \frac{dE}{dX_i} \times Pitch_i \tag{6}$$

where KE_i is given by Eq. 5, N is the number of slices, and dE/dX_i is the average pion energy loss in Argon.

In practice, the cross-section is proportional to the ratio of 2 histograms: the interacting KE histogram, which is filled with the kinetic energy of the pion when it interacts (only once per event); and the incident KE histogram, which is filled with the kinetic energy of the pion at each slice, including the slice when it interacts (Fig. 9).

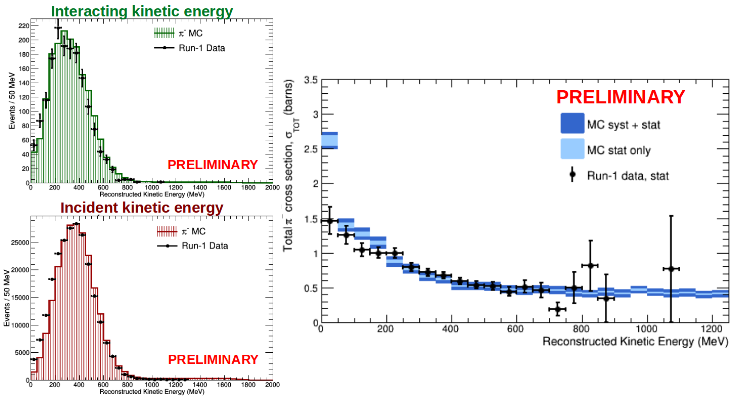

Figure 10. Top left: kinetic energy of interacting pions. Bottom left: kinetic energy of incident pions. Right: Total π^- cross-section on Argon with systematic errors.

3.3. Results

After applying the method described in the previous section, we obtain the two histograms on the left in Fig. 10. By taking the ratio of these two histograms, we extract the cross-section as a function of the pion kinetic energy shown on the right in Fig. 10. The following systematics have been included:

- dE/dX calibration error, 5%;
- uncertainty on the energy loss before entering the TPC, 3.5%;
- error due to through-going muon contamination, 3%;
- momentum uncertainty (from wire chamber reconstruction), 3%.

The simulation is in good agreement with the data but a few features, in particular at low energies, have yet to be understood.

4. Perspectives

LArIAT runs I and II were very successful and now we are ready to start the third data taking campaign. So far we have observed the excellent performance of cold electronics with a signal-to-noise ratio of 70:1 in Run II (compared to 15:1 with ArgoNeuT's warm electronics) and we are the first LArTPC experiment using a fully automated reconstruction and event selection.

LArIAT has successfully measured the total pion cross-section on Argon for the first time. The analysis is still on-going, several improvements are in progress. To decrease the statistical errors, we will include Run II data as well as the positive polarity runs from Run I. To increase the efficiency of our selection, we are working on improving the MWPC track reconstruction as well as the TOF reconstruction. Backgrounds are in the process of being subtracted, and using data from the aerogel Cherenkov detectors and the muon range stack will be very helpful.

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