

**Abstract**

**Measurement of the positive kaon-argon total  
hadronic differential cross section in the LArIAT  
experiment**

Elena Gramellini

2018

Abstract goes here. Limit 750 words.

**Measurement of the positive kaon-argon  
total hadronic differential cross section in  
the LArIAT experiment**

A Dissertation  
Presented to the Faculty of the Graduate School  
of  
Yale University  
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Doctor of Philosophy

by  
Elena Gramellini

Dissertation Director: Bonnie T. Fleming

Date you'll receive your degree

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# Chapter 1

## Introduction

### 1.1 The Standard Model

The Standard Model (SM) of particle physics is the most accurate theoretical description of the subatomic world and, more generically, one of the most precisely tested theories in the history of physics. The SM describes the strong, electromagnetic and weak interactions among elementary particles in the framework of quantum field theory, accounting for the unification of electromagnetic and weak interactions for energies above the vacuum expectation value of the Higgs field. The SM does not describe gravity or general relativity.

The Standard Model is a gauge theory based on the local group of symmetry

$$G_{SM} = SU(3)_C \otimes SU(2)_T \otimes U(1)_Y \quad (1.1)$$

where the subscripts indicate the conserved charges: the strong charge, or color C, the weak isospin T (or rather its third component T<sub>3</sub>) and the hypercharge Y. These quantities can be related to the electric charge Q through the Gell-Mann-Nishijima relation:

$$Q = \frac{Y}{2} + T_3. \quad (1.2)$$

Generation	I	II	III	T	Y	Q
Leptons	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	1/2 -1/2	-1 -1	0 -1
	$e_R$	$\mu_R$	$\tau_R$	0	-2	1
Quarks	$\begin{pmatrix} u \\ d' \end{pmatrix}_L$	$\begin{pmatrix} c \\ s' \end{pmatrix}_L$	$\begin{pmatrix} t \\ b' \end{pmatrix}_L$	1/2 -1/2	1/3 1/3	2/3 -1/3
	$u_R$ $d'_R$	$c_R$ $s'_R$	$t_R$ $b'_R$	0 0	4/3 -2/3	2/3 -1/3

Table 1.1: SM elementary fermions. The subscripts L and R indicate respectively the negative helicity (left-handed) and the positive helicity (right-handed).

In the quantum field framework, the elementary particles correspond to the irreducible representations of the  $G_{SM}$  symmetry group. In particular, the particles are divided in two categories, fermions and bosons, according to their spin-statistics. Described by the Fermi-Dirac statistics, Fermions have half-integer spin and are sometimes called “matter-particles”. Bosons or “force carriers” have integer spin, follow the Bose-Einstein statistics and mediate the interaction between fermions. The fundamental fermions and their quantum numbers are listed in Tab 1.1.

Quarks can interact via all three the fundamental forces; they are triplets of  $SU(3)_C$ , that is they can exist in three different colors: C = R, G, B. If one chooses a base where  $u$ ,  $c$  and  $t$  quarks are simultaneously eigenstates of both the strong and the weak interactions, the remaining eigenstates are usually written as  $d$ ,  $s$  and  $b$  for the strong interaction and  $d'$ ,  $s'$  and  $b'$  for the weak interaction, because the latter ones are the result of a Cabibbo rotation on the first ones. Charged leptons interact via the weak and the electromagnetic forces, while neutrinos only interact via the weak force. The gauge group univocally determines the number of gauge bosons that carry the interaction; the gauge bosons correspond to the generators of

the group: eight gluons (g) for the strong interaction, one photon ( $\gamma$ ) and three bosons ( $W^\pm$ ,  $Z^0$ ) for the electroweak interaction. A gauge theory by itself can not provide a description of massive particles, but it is experimentally well known that most of the elementary particles have non-zero masses. The introduction of massive fields in the Standard Model lagrangian would make the theory non-renormalizable, and - so far - mathematically impossible to handle. This problem is solved in the Standard Model by the introduction of a scalar iso-doublet  $\Phi(x)$ , the Higgs field, which gives mass to  $W^\pm$  and  $Z^0$  gauge bosons through the electroweak symmetry breaking and to the fermions through Yukawa coupling [1,2].

## 1.2 Neutrinos: in and beyond the Standard Model

### 1.2.1 Neutrino in the SM

Neutrino were introduced in the SM as left-handed massless Weyl spinors. The Dirac equation of motion

$$(i\gamma^\mu \partial_\mu - m)\psi = 0 \quad (1.3)$$

for a fermionic field

$$\psi = \psi_L + \psi_R \quad (1.4)$$

is equivalent to the equaitons

$$i\gamma^\mu \partial_\mu \psi_L = m\psi_R \quad (1.5)$$

$$i\gamma^\mu \partial_\mu \psi_R = m\psi_L \quad (1.6)$$

for the chiral fields  $\psi_R$  and  $\psi_L$ , whose evolution in space and time is coupled through the mass  $m$ . If the fermion is massless, the chiral fields decouple and the

fermion can be described by a single Weyl spinor with two independent components. Pauli initially rejected the description of a physical particle through a single Wyle spinor because of its implication of parity violation. In fact, since the spatial inversion operator throws  $\psi_R \leftrightarrow \psi_L$ , parity is conserved only if the both the chiral components exist at the same time. **ADD CITATIONS**. For the neutrino introduction in the SM, experiments came in help of the theoretical description: the constraint of parity conservation weakened after Wu's experiment **ADD CITATIONS AND DATES**, there was no experimental indication for massive neutrinos and neutrinos likely interacted only via the left-handed component.

The symmetry group  $SU(2)_T \otimes U(1)_Y$  is the only group relevant for neutrino interactions. The SM electroweak lagrangian is the most general renormalizable lagrangian invariant under the local symmetry group  $SU(2)_T \otimes U(1)_Y$ . The lagrangian couples the weak isotopic spin doublets and singlets described in 1.1 with the gauge bosons  $A_a^\mu$  ( $a = 1,2,3$ ) and  $B^\mu$ , and Higgs doublet  $\Phi(x)$ :

$$\begin{aligned}
\mathcal{L} = & i \sum_{\alpha=e,\mu,\tau} \bar{L}'_{\alpha L} \not{D} L'_{\alpha L} + i \sum_{\alpha=1,2,3} \bar{Q}'_{\alpha L} \not{D} Q'_{\alpha L} \\
& + i \sum_{\alpha=e,\mu,\tau} \bar{l}'_{\alpha R} \not{D} l'_{\alpha R} + i \sum_{\alpha=d,s,b} \bar{q}'^D_{\alpha R} \not{D} q'^D_{\alpha R} + i \sum_{\alpha=u,e,t} \bar{q}'^U_{\alpha R} \not{D} q'^U_{\alpha R} \\
& - \frac{1}{4} A_{\mu\nu} A^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \\
& + (D_\rho \Phi)^\dagger (D^\rho \Phi) - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2 \\
& - \sum_{\alpha,\beta=e,\mu,\tau} \left( Y'^n_{\alpha\beta} \bar{L}'_{\alpha L} \Phi l'_{\beta R} + Y'^{l*}_{\alpha\beta} \bar{l}'_{\beta R} \Phi^\dagger L'_{\alpha L} \right) \\
& - \sum_{\alpha=1,2,3} \sum_{\beta=d,s,b} \left( Y'^D_{\alpha\beta} \bar{Q}'_{\alpha L} \Phi q'^D_{\beta R} + Y'^{D*}_{\alpha\beta} \bar{q}'^D_{\beta R} \Phi^\dagger Q'_{\alpha L} \right) \\
& - \sum_{\alpha=1,2,3} \sum_{\beta=u,c,t} \left( Y'^U_{\alpha\beta} \bar{Q}'_{\alpha L} \tilde{\Phi} q'^U_{\beta R} + Y'^{U*}_{\alpha\beta} \bar{q}'^U_{\beta R} \tilde{\Phi}^\dagger Q'_{\alpha L} \right). \tag{1.7}
\end{aligned}$$

The first two lines of the lagrangian summarize the kinetic terms for the fermionic

fields and their coupling to the gauge bosons  $A_a^{\mu\nu}$ ,  $B^{\mu\nu}$ <sup>1</sup>. The third line describes the kinetic terms and the self-coupling terms of the gauge bosons. The forth line is the Higgs lagrangian, which results in the spontaneous symmetry breaking. The last three lines describe the Yukawa coupling between fermions and the Higgs field, origin of the fermion's mass.

The coupling between left-handed and right-handed field generates the mass term for fermions. The SM assumes only left-handed components for neutrinos, thus implying zero neutrino mass. Since any linear combination of massless fields results in a massless field, the flavor eigenstates are identical to the mass eigenstates in the SM.

### 1.2.2 Neutrino Oscillations

The determination of the flavor of a neutrino dynamically arises from the corresponding charged lepton associated in a CC interaction; for example, a  $\nu_e$  is a neutrino which produces an  $e^-$ , a  $\bar{\nu}_\mu$  is a neutrino which produces a  $\mu^+$ , etc. The neutrino flavor eigenstates  $|\nu_\alpha\rangle$ , with  $\alpha = e, \mu, \tau$ , are orthogonal to each other and form a base for the the weak interaction matrix.

Overwhelming experimental data show neutrinos change flavor during their propagation. This phenomenon, predicted by Bruno Pontecorvo in 1957, is called “neutrino oscillations” and it is possible only if the flavor eigenstate are not identical to the mass eigenstates. A minimal extension of the Standard Model introduces three mass eigenstates,  $|\nu_i\rangle$  ( $i = 1, 2, 3$ ), whose mass  $m_i$  is well defined. The unitary Pontecorvo-Maki-Nakagawa-Sakata matrix transforms the spinor wave functions ( $\psi$ ) of each component between flavor and mass bases as follows

$$\sum \psi_\alpha |\nu_\alpha\rangle = \sum \psi_i |\nu_i\rangle, \rightarrow \psi_\alpha = U_{PMNS} \psi_i, \quad (1.8)$$

---

1. In gauge theories the ordinary derivative  $\partial_\mu$  is substituted with the covariant derivative  $D_\mu$ . Here  $D_\mu = \partial_\mu + igA_\mu \cdot I + ig'B_\mu \frac{Y}{2}$ , where I and Y are the SU(2)<sub>L</sub> and U(1)<sub>Y</sub> generators, respectively.

with

$$U_{PMNS} = \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (1.9)$$

where  $c$  e  $s$  stand respectively for cosine and sine of the corresponding mixing angles ( $\theta_{12}$ ,  $\theta_{23}$  and  $\theta_{13}$ ),  $\delta$  is the Dirac CP violation phase,  $\alpha_1$  and  $\alpha_2$  is the eventual Majorana CP violation phases.

### Experimental results summary

## 1.3 Beyond the Standard Model

The discovery of neutrino oscillation and its implication of non-zero neutrino mass mark the beginning of a new, exciting era in neutrino physics: the era of physics Beyond the Standard Model (BSM) in the neutrino sector. We are currently searching for new, deeper theories that can accommodate neutrinos with non-zero mass, while remaining consistent with the rest of the Standard Model.

### Open Questions in Neutrino Physics

On one hand, the last X decades of experiments in neutrino oscillations brought spectacular advancements in the understanding of the oscillations pattern, measuring the neutrino mixing angles and mass splitting with a precision of less than 10%. On the other, it opened the field for a series of questions needing experimental answers. Critical challenges in the next decade will entail an even deeper understanding of the neutrino mixing pattern, investigation of the neutrino mass origin, neutrino number and nature, and assessing CP violation in the lepton sector.

Following the recommendation of the latest Particle Physics Project Prioritization Panel [3], the US is dedicating substantial resources to the development of a short- and long- baseline neutrino program to address many of these fundamental questions. This program pivots on the Liquid Argon Time Projection Chamber (LArTPC) detector technology which will be described in 2.

The main goals of these research programs include:

- Assessment of the existence of right-handed sterile neutrinos.
- Determination of the sign of  $\Delta m_{13}^2$  (or  $\Delta m_{23}^2$ ), i.e., the “neutrino mass ordering” .
- Determination of the octant, i.e. whether  $\theta_{23}$  is maximal.
- Determination the status of CP symmetry in the lepton sector.

### Smallness of neutrino masses, link to GUTs

### Towards a more fundamental theory

Despite its highly predictive power, a number of conceptual issues arise in the SM which disfavor it to be a good candidate for a fundamental theory.

The SM rather complex group structure, where a gauge group is formed with the direct product of other three groups as shown in eq. 1.1, is unexplained. Also, the SM fails to include a suitable dark matter candidate and a mechanisms that accounts for the baryon asymmetry of the universe. Within the SM, a total of 25 parameters remain seemingly arbitrary and need to be fitted to data: 3 gauge couplings, 9 charged fermion masses, 3 mixing angles and one CP phase in the CKM matrix, the Higgs mass and quartic coupling,  $\theta_{QCD}$ , 3 neutrino masses, 3 neutrino mixing angles, 1 Dirac phase and, eventually, 2 Majorana phases.

## Chapter 2

# Liquid Argon Detectors at the Intensity Frontier

In the next few years, LArTPC experiments – such as the Short-Baseline Neutrino program (SBN) and DUNE – will be major players in the intensity frontier field.



## **2.1 The SBN Program**

### **2.1.1 SBN Goals**

### **2.1.2 Neutrino Interactions and Detection**

## **2.2 DUNE**

### **2.2.1 DUNE Non-Accelerator Physics Program**

### **2.2.2 Rare Decay Searches: Experimental Limit**

### **2.2.3 Nucleon Decay Detection in LAr**

## **2.3 Liquid Argon Time Projection Chambers at the Intensity Frontier**

### **2.3.1 Time Projection Chamber**

### **2.3.2 Ionization Detectors with Noble Liquids**

### **2.3.3 LArTPC: Principles of Operation**

### **2.3.4 Liquid Argon Ionization Charge Detection**

Electron Life Time & purity

Space Charge Effect

Recombination Effect

### **2.3.5 Liquid Argon scintillation Light Detection**

LAr Scintillation Process

Wavelength Shifting of LAr Scintillation Light

# Chapter 3

## LArIAT: Liquid Argon In A Testbeam

LArIAT, a small Liquid Argon Time Projection Chamber (LArTPC) in a test beam, is designed to perform an extensive physics campaign centered on charged particle cross section measurements while characterizing the detector performance for future LArTPCs. LArTPC represents one of the most advanced experimental technologies for physics at the Intensity Frontier due to its full 3D-imaging, excellent particle identification and precise calorimetric energy reconstruction. This complex technology however needs a thorough calibration and dedicated measurements of some key quantities to achieve the precision required for the next generation of discoveries at the Intensity Frontier which LArIAT can provide.

The LArIAT LArTPC is deployed in a dedicated calibration test beamline at Fermilab. We use the LArIAT beamline to characterize the charge particles before they enter the TPC: the particle type and initial momentum is known from beamline information. The precise calorimetric energy reconstruction of the LArTPC technology enables the measurement of the total differential cross section for tagged hadrons. The Pion-Nucleus and Kaon-Nucleus total hadronic interaction cross section have

never been measured before in argon and they are a fundamental step to shed light on light meson interaction in nuclei. Additionally, these measures provides a key input to neutrino physics and proton decay studies in future LArTPC experiments like SBN and DUNE.

### 3.1 The Particles Path to LArIAT

LArIAT’s home at Fermilab is the Fermilab Test Beam Facility (FTBF), where the experiment characterizes a beam of charge particles downstream from the Meson Center beam line.

LArIAT’s particles history begins in the Fermilab accelerator complex with a beam of protons. The process of protons acceleration develops in gradual stages, see picture 3.1: gaseous hydrogen is ionized in order to form  $H^-$  ions; these ions are boosted to 750 keV by a Cockcroft-Walton accelerator and injected to the Linac linear accelerator that increases their energy up to 400 MeV; then,  $H^-$  ions pass through a carbon foil and lose the two electrons; the resulting protons are then injected into a rapid cycling synchrotron, called Booster; at this stage protons reach 8 GeV of energy and are compacted into bunches; the next stage of acceleration is the Main Injector, a synchrotron which accelerates the bunches up to 120 GeV; in the Main Injector, several bunches are merged into one and used for the injection in the last stage.

The Fermilab accelerator complex works in supercycles of roughly 60 seconds in duration. The beam is then split by electrostatic septa and delivered at different experimental halls all over the lab. A 120  $GeV/c$  primary proton beam with variable intensity is extracted in four-second “spills” and sent to the Meson Center beam line. Here, this primary beam is focused onto a tungsten target to create LArIAT’s secondary beam. The composition of the secondary particle beam is mainly positive pions. For the LArIAT data considered in this work the secondary beam peak mo-

mentum was fixed at  $64 \text{ GeV}/c$ , although the beam is tunable in momentum between  $8\text{-}80 \text{ GeV}/c$ ; this was deemed a secondary beamline configuration which allowed a stable beam operation of the FTBF. The beam of pions impinges then on a copper target within a steel collimator inside the LArIAT experimental hall (MC7) to create LArIAT tertiary beam, whose geometry in MC7 has been optimized for LArIAT (shown in Fig. 3.1). The steel collimator selects particles produced with a  $13^\circ$  production angle at the target down the beamline. The particles are then bend by  $10^\circ$  through a pair of dipole magnets. Tuning the magnets field intensity results in a range of particle momenta from  $0.2$  to  $1.4 \text{ GeV}/c$ . The tertiary beam composition counts mostly pions and protons with a small fraction of electrons, muons, and kaons present as well. It is the job of the LArIAT beamline detectors to select the particles polarity, to perform particle identification (beamPID) and to measure the momentum of the tertiary beam particles before they get to the LArTPC. The LArIAT detectors are described in the following paragraphs.

## 3.2 LArIAT Tertiary Beam Instrumentation

The instrumentation of LArIAT tertiary beam and the TPC components have changed several times during the three years of LArIAT data taking. The following paragraphs describe the components operational during the data taking period relevant to the hadron cross section measurements (a.k.a. Run II).

The components of the tertiary beamline instrumentation key for the hadron cross section analyses are the target and collimators system, the two bending magnets (in a similar configuration used for the MINERvA T-977 test beam calibration [?]) a set of four wire chambers (WCs) and two time-of-flight scintillating paddles (TOF) and, of course, the LArTPC. The magnets determine the polarity of the particles in the tertiary beam; the combination of magnets and wire chambers determine the particles

## Fermilab Accelerator Complex

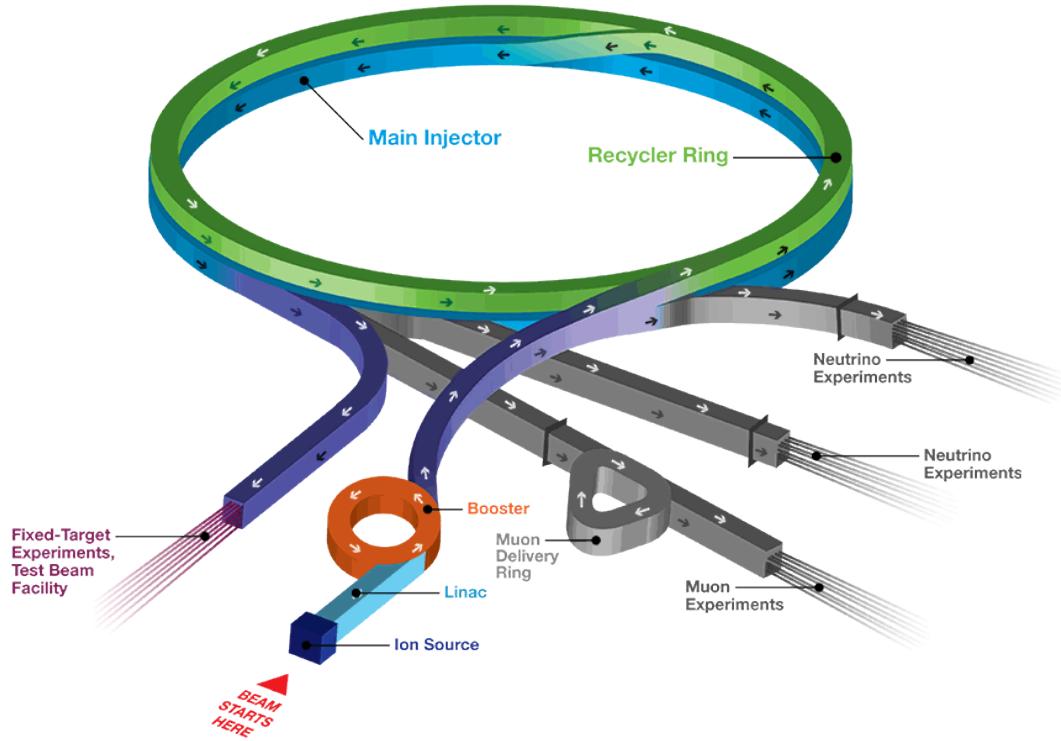


Figure 3.1: Layout of Fermilab Acellerator complex.

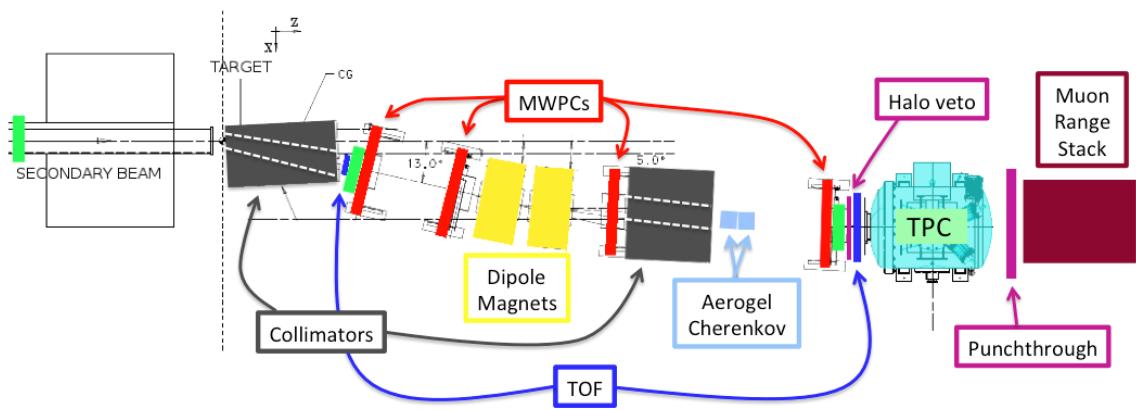


Figure 3.2: Birds eye view of the LArIAT tertiary beamlne. In grey: upstream and downstream collimators; in yellow: bending magnets in yellow; in red: wire chambers; in blue: time of flight; in green: liquid argon TPC volume; in maroon: muon range statck.

momentum, which is used to determine the particle species in conjunction with the TOF. A muon range stack downstream from the TPC and two sets of cosmic paddles configured as a telescope surrounding the TPC are also used for calibration purposes.

### 3.2.1 Bending Magnets

LArIAT uses a pair of identical Fermilab type “NDB” electromagnets, recycled from the Tevatron’s anti-proton ring [CITE CDF?](#). The magnets are a fundamental piece of the LArIAT beamline as they are used in all the three tasks of the LArIAT beamline: the sign of the current in the magnet provide the selection of either positively or negatively charged particles, the value of the magnetic field is used in the momentum determination and the subsequent particle identification.

We describe here the characteristics and response of one magnet. We expect the second one have a similar response, being identical in shape and with a similar history. The magnet aperture measures the gap dimensions to be 14.224 cm of height, 31.75 cm width, and 46.67 cm length. The wire chambers aperture ( $\sim$ 12.5 cm) is smaller than the magnet aperture, thus, only the central part of the magnet gap is utilized. The field is extremely uniform over this limited aperture and was measured with two Hall probes, both calibrated with nuclear magnetic resonance probes. The probes measured the excitation curve shown in Figure 3.3.

The current being passed through the magnets at a given time is identical in both magnets. For Run II period, the current settings explored were 60A ( $B \sim$ 0.21 T) and 100A ( $B \sim$ 0.35 T) in both polarities. Albeit advantageous to enrich the tertiary beam composition with high mass particles such as kaons, we never pushed the magnets current over 100 A, not to incur in overheating. During operation, we operated a air and water cooling system on the magnets and we remotely monitored the magnets temperature.

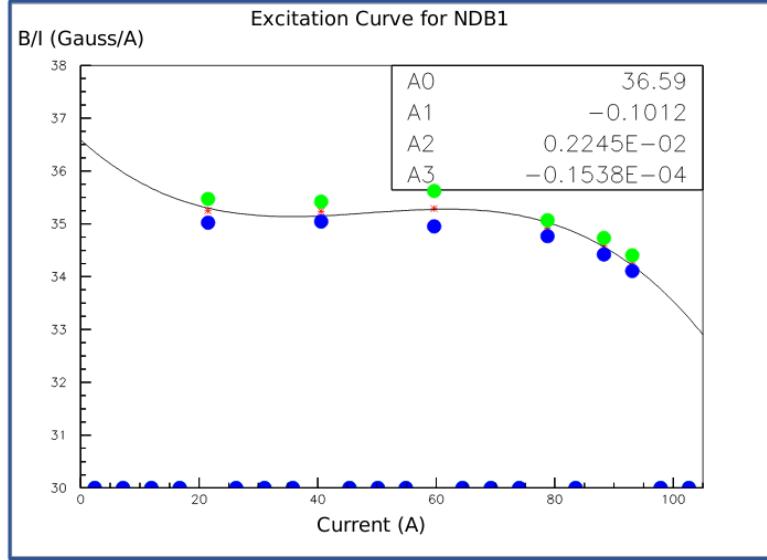


Figure 3.3: Magnetic field over current as a function of the current, for one NDB magnet (excitation curve). The data was collected using two Hall probes (blue and green). We fit the readings with a cubic function (black) to average of measurements (red) given in the legend.

### 3.2.2 Multi-Wire Proportional Chambers

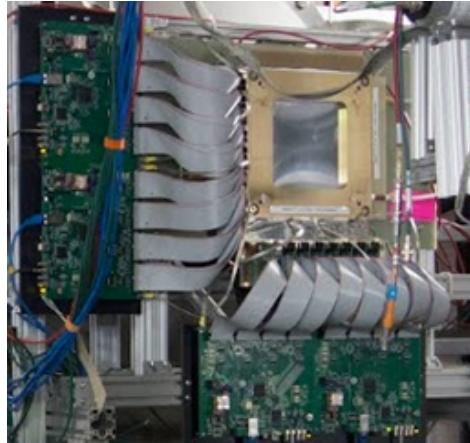


Figure 3.4: One of the four Multi Wire Proportional Chambers (WC) used in the LArIAT tertiary beamline.

LArIAT uses four Multi-Wire proportional chambers, or wire chambers (WC) for short, two upstream and two downstream from the bending magnets. The geometry of one chamber is shown in Figure 3.4: the WC effective aperture is a square of 12.8 cm perpendicular to the beam direction. Inside the chamber, the 128 horizontal

and 128 vertical wires hang at a distance of 1 mm from each other in a mixture of 85% Argon and 15% isobutane gas. The WC operating voltage is between 2400 V and 2500 V. LArIAT wire chambers are an upgraded version of the Fenker Chambers [?], where an extra grounding improves the signal to noise ratio of the electronic readout.

Two ASDQ chips [?] mounted on a mother board plugged into the chamber serve as front end amplifier/discriminator. The chips are connected to a multi-hit TDC [?] which provides a fast OR output used as first level trigger. The TDC time resolution is 1.18 ns/bin and can accept 2 edges per 9 ns. The maximum event rate acceptable by the chamber system is of 1 MHz: this rate is not a limiting factor considering that the rate of the tertiary particle beam at the first wire chamber is estimated to be less than 15 kHz. A full spill of data occurring once per supercycle is stored on the TDC board memory at once and read out by a controller specially designed controller. We use LVDS cables to carry both power and data between the controller and the TDCs and from the controller to the rest of the DAQ.

### **Multi-Wire Proportional Chambers functionality**

We use the wire chamber system together with the bending magnets to measure the particles momentum.

In the simplest scenario, only one hit on each and every of the four wire chambers is recorder during a single readout of the detector systems. Thus, we use the hits position in the two wire chambers upstream to the magnets to form a trajectory before the bent and the hits position in the two wire chambers downstream to the magnets to form a trajectory after the bent. We use the angles in the XZ plane between the upstream and downstream trajectories to calculate the z component of the momentum as follows:

$$P_z = \frac{B_{eff}L_{eff}}{3.3(\sin(\theta_{DS}) - \sin(\theta_{US}))}, \quad (3.1)$$

where  $B_{eff}$  is the effective maximum field in a square field approximation,  $L_{eff}$  is the effective length of both magnets (twice the effective length of one magnet) and  $3.3 c^{-1}$  the conversion factor from  $T^*m$  to  $\text{MeV}/c$ . By using the hit positions on WC3 and WC4, we estimate the azimuthal and polar angles of the particle trajectory, and we are able to calculate the other components of the momentum.

This simple scenario can get complicated in two ways: the presence of multiple hits in a single wire chamber or by the absence of hits in one (or more) wire chamber. The first complication is due to beam pile up, while the latter is due to wire chamber inefficiency. Even in the case of multiple hits, at most one wire chamber track is reconstructed per event; since the magnets bend particles only in the X direction, we assume the particle trajectory to be roughly constant in the YZ plane, thus we keep the combination of hits most coplanar on YZ plane. It is possible to reconstruct the particle momentum even in case of wire chamber inefficiency, if the information is missing in either of the two middle wire chambers (WC2 or WC3).

**BETTER EXPLANATION OF HIGH YIELD UNCERTAINTY ON MOMENTUM MEASUREMENT** Events satisfying the simplest scenario of one single hit in each of the four wire chambers form the so called "Picky track" sample. We construct an other, higher statistics sample where we loose the requirements on single hit and wire chamber efficiency called "High Yield". For LArIAT Run II, the "High Yield" sample is **HIGH YIELD increase in stat** the "Picky Tracks" sample. We use Picky tracks for calibration purposes: **I DONT UNDERSTAND THIS** Plotting the fractional error of the corrected three-point momentum compared to the known four-point momentum shows an uncertainty of approximately 2%.

### 3.2.3 Time-of-Flight System

Two scintillator paddles, one upstream to the first set of WCs and one downstream to the second set of WCs form LArIAT time-of-flight (TOF) detector system.

**find exact dimentions** The upstream paddle is made of a 10 x 6 x ? cm scintillator piece, read out by two **Hamamatsu 2 inch** PMTs mounted on the beam left side which collect the light from light guides mounted on all four edges of the scintillator. The downstream paddle dimensions are 14 x 14 x ? cm and it is read out by two **Hamamatsu 2 inch** PMTs on the opposite ends of the scintillator. The relatively thin width on the beamline direction minimizes energy loss of the particles coming from the target in the scintillator material.

The CAEN 1751 digitizer is used to digitize the TOF PMTs signals at a sampling rate of 1 GHz. The 12 bit samples are stored in a circular memory buffer. At trigger time, data from the TOF PMTs are recorded to output in a 28.7  $\mu$ s windows starting approximately 8.4  $\mu$ s before the trigger time.

## TOF functionality

The TOF signals rise time (10-90%) is 4 ns and a full width, half-maximum of 9 ns consistent in time. The signal amplitudes from the upstream TOF and downstream TOF are slightly different: 200 mV for the upstream PMTs but only 50 mV for downstream PMTs. The time of the pulses was calculated utilizing an oversampled template derived from the data itself. We take the pulse pedestal from samples far from the pulse and subtract it to the pulse amplitude. We then stretch vertically a template to match the pedestal-subtracted pulse amplitude and we move it horizontally to find the time. With this technique, we find a pulse time-pickoff resolution better than 100 ps. The pulse pile up is not a significant problem given the TOF timing resolution and the rate of the particle beam. Leveraging on the pulses width uniformity of any given PMT (sigma of 400 ps), we flag events where two pulses overlap as closely in time as 4 ns with an 90% efficiency according to simulation.

We combine the pulses from the two PMTs on each paddle to determine the particles' arrival time by averaging the time measured from the single PMT, so to

minimize errors due to optical path differences in the scintillator. However, a time spread of approximately 300 ps is present in both the upstream and downstream detectors, likely due to transit time jitter in the PMTs themselves. There is no evidence of systematic timing drift over long data-taking periods such as 3-4 months: the maximum variation of the average time differences between pairs of PMTs reading out the same scintillator is of the order of 150 ps.

calculated TOF with error

### 3.2.4 Punch-Through and Muon Range Stack Instruments

The punch-thorough and the muon range stack (MuRS) detectors are located downstream of the TPC. These detectors provide a sample of TPC crossing tracks without relying on TPC information and can be used to improve particle ID for muons and pions with momentum higher than 450 MeV/c.

The punch-thorough is simply a ? x ? x ? cm scintillator piece, read out by two? Hamamatsu? 2? inch PMTs. The MuRS is a segmented block of steel with four slots instrumented with scintillation bars. The four steel layers in front of each instrumented slot are 2 cm, 2 cm, 14 cm and 16 cm wide in the beam direction. Each instrumented slot is equipped with four scintillation bars each, positioned vertically in the direction orthogonal to the beam. Each scintillator bar measures ? x ? x 2 cm and it is read out by two? Hamamatsu? 2? inch PMTs.

The signals from both the punch-thorough and the MuRS PMTs are digitized in the CAEN V1740, same as the TPC; the details of this discriminator are laid out in 3.3.2. It is worth noticing that the sampling time of the CAEN V1740 is slow (of the order of 128 ns), so pulse shape information from the PMT is lost. Punch-thorough and MuRS hits are formed utilizing the OR between the PMTs digital discriminator signals under threshold at a given time, where we obtain the threshold for each PMT directly on data distributions.

### 3.2.5 LArIAT Cosmic Ray Paddle Detectors

Besides on beam data, LArIAT also triggers on cosmic rays events by using two sets of cosmic ray paddle detectors (a.k.a. “cosmic towers”). The cosmic towers frame the LArIAT cryostat, as one sits in the downstream left corner and the other sits in the upstream right corner of the cryostat. Two paddle sets of four scintillators pieces each, an upper and a lower set, make up each cosmic tower. Of the four paddles, a couple of two matched paddles stands upright while the a second matched pair lies across the top of the assembly in the top sets (or across the bottom of the assembly in the bottom sets). The horizontal couple is used as a veto for particles traveling from the TPC out. The four signals from the vertical paddles along one of the body diagonals of the TPC are combined in a logical “AND”. This allows to select cosmic muons crossing the TPC along one of its diagonals. Cosmic ray tracks crossing both anode and cathode populate the events triggered this way. This particularly useful sample of tracks (which we can safely assume to be associated with 5 GeV muons MIPs) can be used for many tasks; for example, we use anode-cathode piercing tracks to cross check the TPC electric field on data (see ??), to calibrate the charge response of the TPC wires for the full TPC volume and to measure the electron lifetime in the chamber [ADD reference to different chapters](#).

All the paddles are 3.02 *cm* thick and are trapezoidal in shape. The paddles come in two sizes: the smaller version has bases 32.2 *cm* and 26.7 *cm*, and 61.0 *cm* height, while the bigger version has bases 33.2 *cm* and 27.0 *cm*, and 70.8 *cm* height. A Zener-diode Hamamatsu H5783 PMT collects the light from a wavelength-shifting optical fiber which runs along one of the long sides of each paddle. A custom-made PMT Amplifier and Discrimination (PAD) circuit mounted at one end of the paddle collects signals from the PMTs and sends them to the Control and Concentrator Unit (CCU). We use the same connection to power the PMT, control voltage and threshold, and output the PMT signal as logic ECL pulse. We retrieved the scintillation paddles from

the decommissioning of the CDF detector at Fermilab and we used only the paddles with a counting efficiency greater than 95% and low noise at working voltage. The measured trigger rate of the whole system is  $0.032\text{Hz}$ , corresponding to  $\sim 2$  muons per minute.



Figure 3.5: Photograph of one of the scintillation counters used in the cosmic towers.

### 3.3 In the Cryostat

#### 3.3.1 Cryogenics and Argon Purity

LArIAT repurposed the ArgoNeuT cryostat [?] in order to use it in a beam of charge particles. We also added a new process piping and a new liquid argon filtration system in FTBF. Inside the LArIAT experimental hall, the cryostat sits on the beam of charge particles with its horizontal main axis oriented parallel to the beam.

Two volumes make up LArIAT cryostat, shown in Figure 3.6: purified liquid argon fills the inner vessel, while the outer volume insulates it with a vacuum jacket equipped with layers of aluminized mylar superinsulation. The inner vessel is a cylinder of 130 cm length and 6.2 cm diameter, containing about 550 L of LAr, corresponding to a mass of 0.76 ton. We run the signal cables for the LArTPC and the high voltage feedthrough through a “chimney” at the top and mid-length of the cryostat.

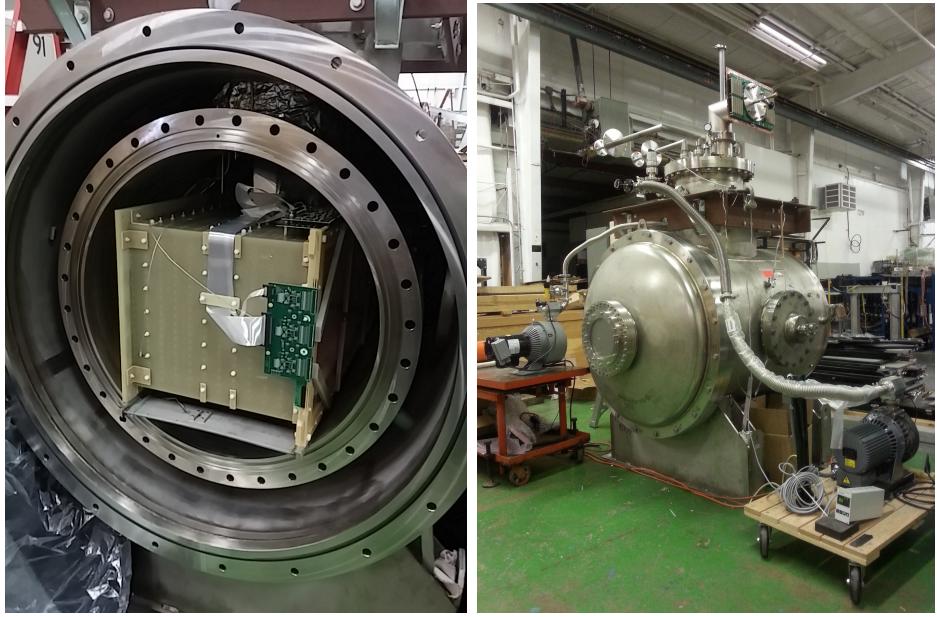


Figure 3.6: (*left*) The LArIAT cryostat open with the TPC placed in the inner volume. (*right*) The LArIAT cryostat fully sealed during initial commissioning prior to installation at Fermilab Testbeam Facility. Access to the internal volume is possible by opening the upstream end caps of the inner and outer vessels.

Given the different scopes of the ArgoNeuT and LArIAT detectors, we made several modifications to the ArgoNeuT cryostat in order to use it in LArIAT. In particular, the modifications shown in Figure 3.7 were necessary to account for the beam of charged particles entering the TPC and to employ the new FTBT liquid argon purification system. We added a “beam window” on the front outer end cap and an “excluder” on the inner endcap, with the scope of minimizing the amount of dead material upstream of the TPC’s active volume. Doing so, we reduced the amount of uninstrumented material before the TPC from  $\sim 1.6$  radiation lengths ( $X_0$ ) (ArgoNeuT) to less than  $0.3 X_0$  (LArIAT). To allow studies of the scintillation light, we added a side port feedthrough which enables the mounting of the light collection system, as well as the connections for the corresponding signal and high-voltage cables (see Section 3.3.3). We modified the bottom of the cryostat adding Conflat and ISO flange sealing to connect the liquid argon transfer line to the new argon cooling and purification system.



Figure 3.7: Pictures of the modified components of the cryostat. 1) The addition of an outlet to the bottom of the cryostat to allow connections to the purification system; 2) The “beam-window” on the outer endcap and the concave inner surface of the inner endcap (referred to as the excluder) to reduce the amount of material through which beam particles must travel before entering the TPC; 3) The modified side port for the LArIAT light collection system.

As in any other LArTPC, argon purity is a crucial parameter for LArIAT. Indeed, the presence of contaminants effects both the basic working principles of a LArTPC: electronegative contaminants such as oxygen and water decrease the number of ionization electrons collected on the wires after drifting through the volume, while contaminants such as Nitrogen decrease the light yield from scintillation light, especially in its slow component. In LArIAT, contaminations should not exceed the level of 100 parts per trillion (ppt). We achieve this level of purity in several stages. The specifics required for the commercial argon bought for LArIAT are 2 parts per million (ppm) oxygen, 3.5 ppm water, and 10 ppm nitrogen. This argon is monitored with the use of commercial gas analyzer. Argon is stored in a dewar external to LArIAT hall and filtered before filling the TPC. LArIAT uses a filtration system designed for the Liquid Argon Purity Demonstrator (LAPD) [?]: half of a 77 liter filter contains a 4A molecular sieve (Sigma-Aldrich [?]) apt to remove mainly water,

while the other half contains BASF CU-0226 S, a highly dispersed copper oxide impregnated on a high surface area alumina, apt to remove mainly oxygen [?]. A single pass of argon in the filter is sufficient to achieve the necessary purity, unless the filter is saturated. In case the filter saturates, the media needs to be regenerated by using heated gas; this happened twice during the Run II period<sup>1</sup>. The filtered argon reaches the inner vessel via a liquid feedthrough on the top of the cryostat. Argon is not recirculated in the system, but it rather boils off and vent to the atmosphere. During data taking, we replenish the argon in the cryostat several times per day to keep the TPC high voltage feedthrough and cold electronics always submerged. In fact, we need to monitor the level, temperatures, and pressures of the argon both in the commercial dewar and inside the cryostat.

### 3.3.2 LArTPC: Charge Collection

The LArIAT Liquid Argon Time Projection Chamber is a rectangular box of dimensions 47 cm (width) x 40 cm (height) x 90 cm (length), containing 170 liters of Liquid Argon. The LArTPC three major subcomponents are

- 1) the cathode and field cage,
- 2) the wire planes,
- 3) the read-out electronics.

#### Cathode and field cage

A G10 plain sheet with copper metallization on one of the 40x90 cm inner surfaces forms the cathode. A high-voltage feedthrough on the top of the LArIAT cryostat delivers the high voltage to the cathode; scope of the high voltage system (Figure 3.8)

---

1. We deemed the filter regeneration necessary every time the electron lifetime dropped under 100  $\mu\text{s}$

is to drift ionization electrons from the interaction of charged particles in the liquid argon to the wire planes. The power supply used in this system is a Glassman LX125N16 [?] capable of generating up to -125 kV and 16 mA of current, but operated at -23.5kV during LArIAT Run-II. The power supply is connected via high voltage cables to a series of filter pots before finally reaching the cathode.

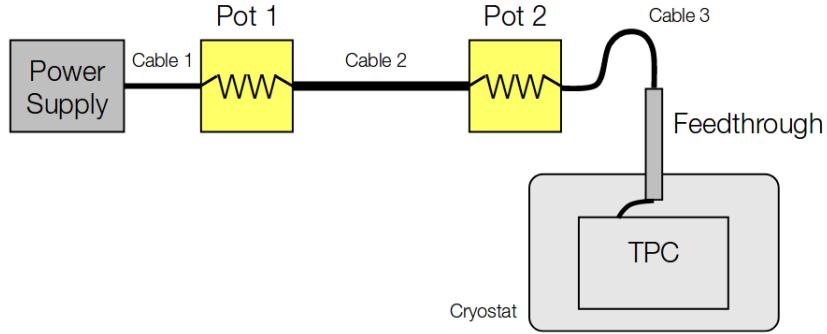


Figure 3.8: Schematic of the LArIAT high voltage system.

The field cage is made of **13 parallel copper rings** framing the inner walls of the G10 TPC structure. A network of voltage-dividing resistors connected to the field cage rings steps down the high voltage from the cathode to form a uniform electric field. The electric field over the entire TPC drift volume is 486 V/cm (see ??). The maximum drift length, i.e. the distance between cathode and anode planes, is 47 cm.

## Wire planes

The wire planes measure the charge deposited in the TPC active volume. The drifting charge induces a current on the wire of the inner planes and it is collected on the collection plane wires. LArIAT counts three wire planes separated by 4 mm spaces: in order of distance from the cathode, they are the shield, the induction and the collection plane. The distance between two consecutive wires in each given plane (aka wire pitch) is 4 mm. The shield plane counts 225 parallel wires of equal length oriented vertically. This plane is not connected with the read-out electronics; rather

it shields the outer planes from extremely long induction signals due to the ionization chamber in the whole drift volume. As the shield plane acts almost like a Faraday cage, the shape of signals in the first instrumented plane (induction) results easier to reconstruct. Both the induction and collection planes count 240 parallel wires of different length oriented at  $60^\circ$  from the vertical with opposite signs. Moving electrons moving past the induction plane will induce a bipolar pulse on its wires and will form a unipolar pulse when collected on the last plane wires.

The three wire planes and the cathode form three drift volumes, as shown in Figure 3.9. The main drift volume is defined as the region between the cathode plane and the shield plane (C-S). The other two drift regions are those between the shield plane and the induction plane (S-I), and between the induction plane and the collection plane (I-C). The electric field in these regions is chosen to satisfy the charge transparency condition to allow for 100% transmission of the drifting electrons through the shield and then the induction planes.

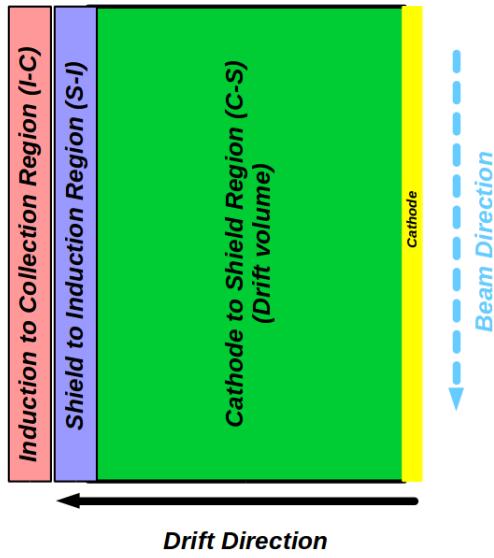


Figure 3.9: Schematic of the three drift regions inside the LArIAT TPC: the main drift volume between the cathode and the shield plane (C-S) in green, the region between the shield plane and the induction plane (S-I) in purple, and the region between the induction plane and the collection plane (I-C) in pink.

Table 3.1 provides the default voltages applied to the cathode and the shield, induction, and collection plane.

Table 3.1: Cathode and anode planes default voltages

Cathode	Shield	Induction	Collection
-23.17 kV	-298.8 V	-18.5 V	338.5 V

## Electronics

Dedicated electronics read the induction and collection plane wires, for a total of 480-channel analog signal path from the TPC wires to the signal digitizers. A digital control system for the TPC-mounted electronics, a power supply, and a distribution system complete the front-end system. Figure 3.10 shows a block diagram of the overall system. The direct readout of the ionization electrons in liquid argon forms typically small signals on the wires, which needs to be amplified in order to be processed. LArIAT performs the amplification stage directly in cold with amplifiers developed by Brookhaven National Lab (BNL) and mounted on the TPC frame inside the liquid argon, achieving a remarkable Signal-to-Noise ratio. The signal from the ASICs are driven to the other end of the readout chain, to the CAEN V1740 digitizers. The CAEN V1740 has a 12 bit resolution and a maximum input range of 2 VDC, resulting in about 180 ADC count for a crossing MIP.

### 3.3.3 LArTPC: Light Collection System

The mechanism of particle detection in argon other than drift electrons is the collection of scintillation photons. Over the course of LArIAT three years of data taking, the light collection system changed several times. We describe here the light collection system for Run II. Two PMTs, a 3-inch diameter Hamamatsu R-11065 and 2-inch diameter ETL D757KFL [?], as well as three SiPMs arrays (two Hamamatsu S11828-3344M 4x4 arrays and one single-channel SensL MicroFB-60035 ) are mounted on the

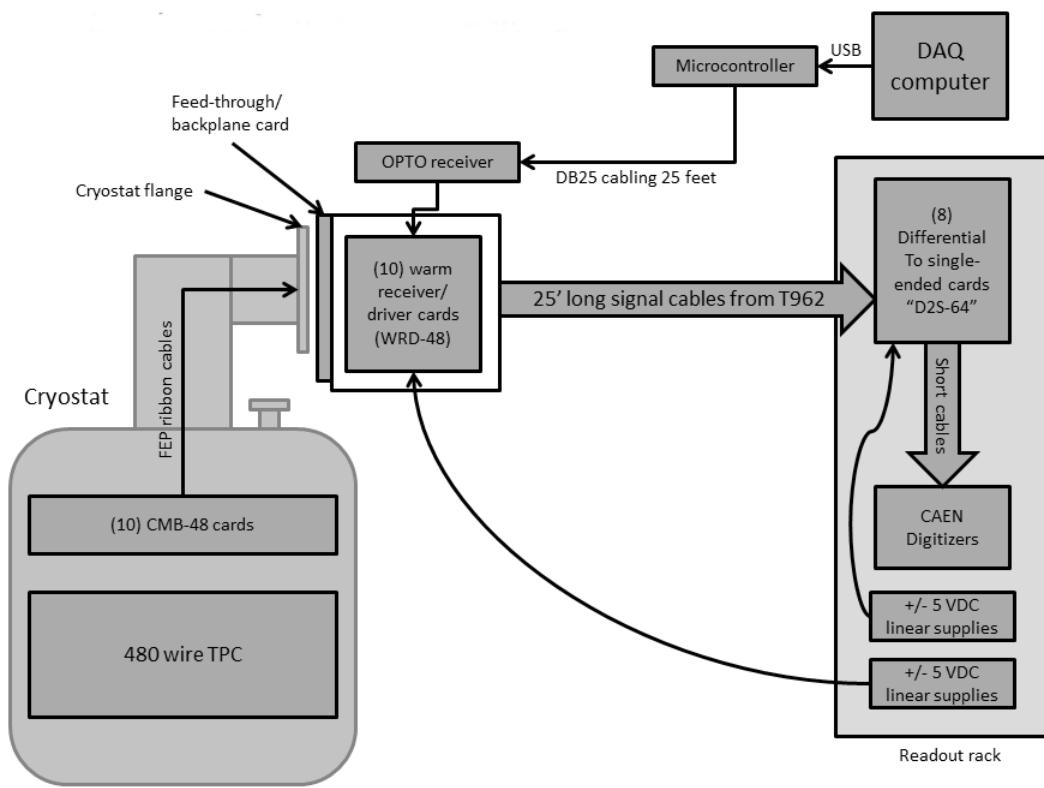


Figure 3.10: Overview of LArIAT Front End electronics.

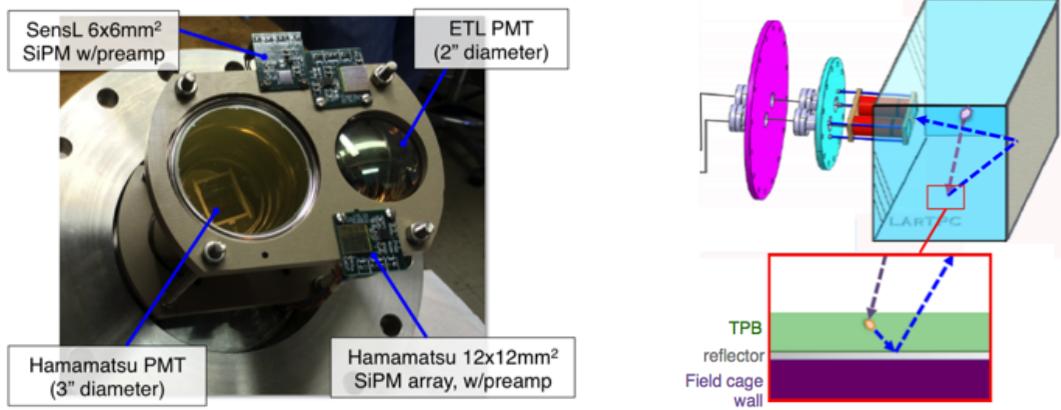


Figure 3.11: LArIAT’s photodetector system for observing LAr scintillation light inside the TPC (left), and a simplified schematic of VUV light being wavelength-shifting along the TPB-coated reflecting foils (right).

PEEK support structure. PEEK screws into an access flange as shown in Figure 3.11, on the anode side, leaving approximately 5 cm of clearance from the collection plane.

Liquid argon scintillates in vacuum-ultraviolet (VUV) range at 128 nm; since cryogenic PMTs are not sensitive to VUV wavelengths, we need to shift the light in a region visible to the PMTs. In LArIAT, the wavelength shifting is achieved by installing on the four walls of the TPC highly-reflective VIKUITY dielectric substrate foils coated with a thin layer of tetraphenyl-butadiene (TPB) (see Figure ??). One or more visible photons are emitted and reflected into the chamber during the interaction of a VUV photon with the TPB. Thus, the light yield is increased and made more uniform across the TPC active volume, allowing the possibility of light-based calorimetry (under study).

For Run II, we coated both the windows of the ETL PMT and SensL SiPM with a thin layer of TPB. In doing so, some of the VUV scintillation light converts into visible right at the sensor faces, keeping information on the direction of the light source. Information about the light directionality is lost for light reflected on foils, as the reflection is uniform in angle. For Run-II, the voltage dividers for the PMTs were configured for positive bias with a DC-coupled anode (AC-coupled anode with

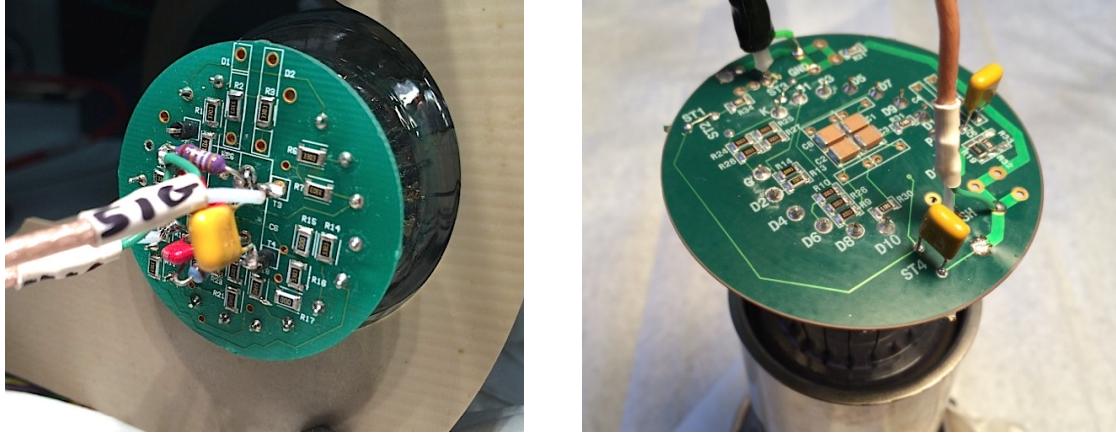


Figure 3.12: Photos of the voltage divider bases for the ETL PMT (left) and the Hamamatsu PMT (right) used in Run-II. The cable connections to the bases seen here were used for powering and testing prior to installation. The yellow through-hole signal coupling capacitors seen on both bases are 18 nF (X7R) and are rated to 2 kV.

grounded photocathode) to minimize induced noise on the TPC wires and modify the PMT bases accordingly.

### 3.4 Trigger and DAQ

The LArIAT DAQ and trigger system governs the read out of all the many detectors forming LArIAT. The CAEN V1495 module featuring a user-programmable FPGA is the core of this system. Every 10 ns, this module checks for matches between sixteen logical inputs and user-defined patterns in the trigger menu; if it finds a match for two consecutive clock ticks, that trigger fires.

### 3.5 Control Systems

LArIAT is a complex ensemble of systems which needed to be monitored at once during data taking. We performed the monitoring of the systems operations with a slow control system, a DAQ monitoring system and a low level data quality monitoring described in the following sections.

## Slow Control

We used the Synoptic Java Web Start framework as a real-time display of subsystem conditions. Its simple Graphical User Interface allowed us to change the operating parameters and to graph the trends of several variables of interest for all the tertiary beam detectors. Among the most important quantities monitored by Synoptic there are the level of argon in both the inner vessel and the external dewar, the operating voltages of cathode and wire planes, of the PMTs and SiPMs, and of the four wire chambers, as well as the magnets temperature. Figure 3.13 shows an example of the monitoring system. LArIAT uses the Accelerator Control NETwork system (ACNET) to monitor the beam conditions of the MCenter beamline. For example, the X and Y position of the beam at the first two wire chambers (WC1 and WC2) are shown in 3.14.

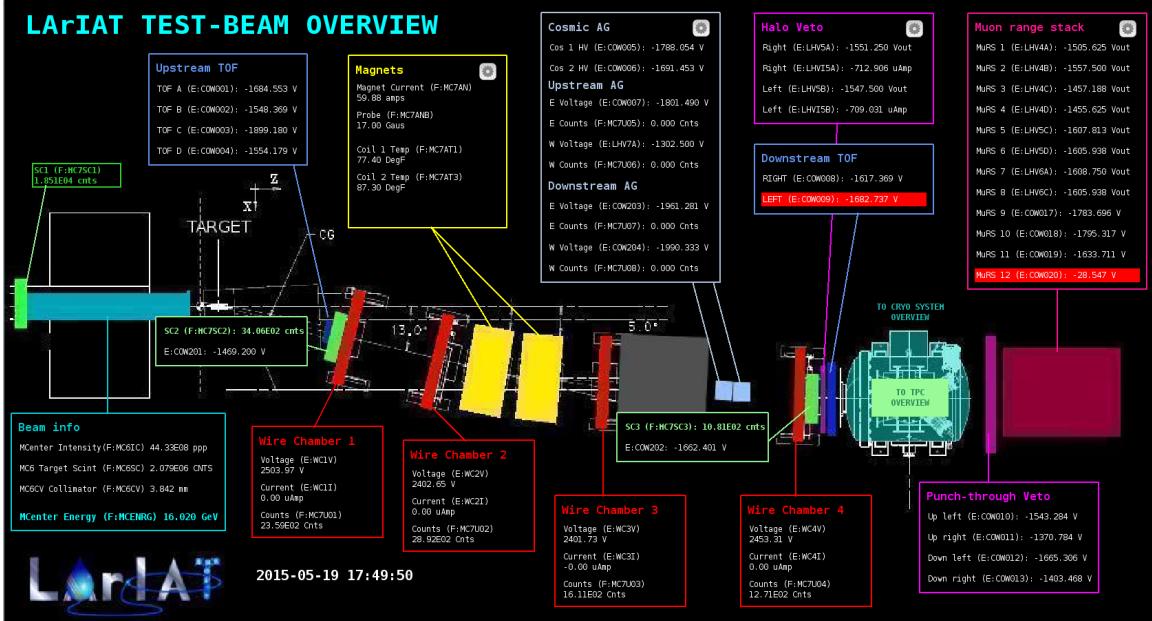


Figure 3.13: Interface of the Synoptic slow control system

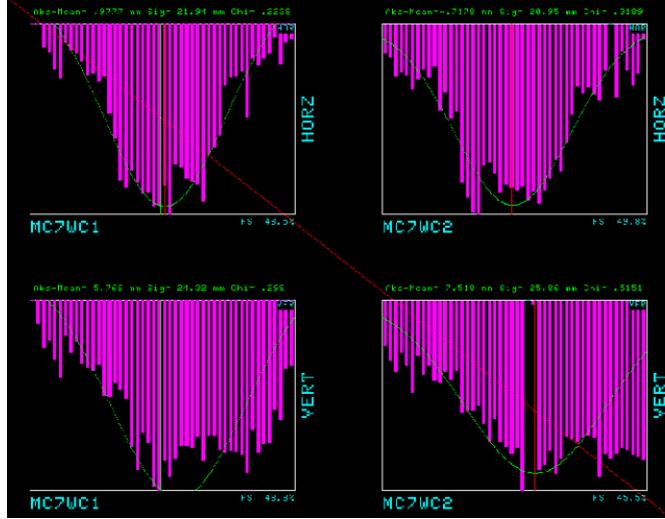


Figure 3.14: Beam position at the upstream wire chambers monitored with ACNET.

## DAQ Monitoring

We monitor the data taking and the run time evolution with the Run Status Webpage (<http://lariat-wbm.fnal.gov/lariat/run.html>), a webpage updated in real-time. The page displays, among other information, the total number of triggers in the event per CAEN digitizer board, the total number of detectors triggered during a beam spill, the trigger patterns (the number of times a particular trigger pattern was satisfied during a beam spill) and current time relative to the Fermilab accelerator complex supercycle. A screen shot of the page is show in figure 3.15.

## Data Quality Monitoring

We employ two systems to ensure the quality of our data during data taking: the Near-real-time Data Quality Monitoring and the Event Viewer.

The Near-real-time Data Quality Monitoring (DQM). This webpage receives updates from all the VME boards in the trigger system and displays the results of a quick analysis of the DAQ stream of raw data on a spill-by-spill basis. The DQM allows the shifter to monitor almost in real time (typically with a 2-minute delay) a series of low level-quantities and compare them to past collections of beam spills. Some of the

variables monitored in the DQM are the pedestal mean and RMS on CAEN digitizer boards of the TPC wires and PMTs of the beamline detectors, the hit occupancy and timing plots on the multi-wire chambers, and number of data fragments recorded that are used to build a TPC event. Abnormal values for low-level quantity in the data activate a series of alarms in the DQM; this quick feedback on the DAQ and beam conditions is fundamental to assure a fast debugging of the detector and a very efficient data taking during beam uptime.

The online Event Viewer displays a two dimensional representation of LArIAT TPC events on both the Induction and the Collection planes in near real time. The raw pulses collected by the DAQ on each wire are plotted as a function of drift time, resulting in an image of the TPC event easily readable by the shifter. This tool guarantees a particularly good check of the TPC operation which activate an immediate feedback for troubleshooting a number of issues. For example, it is easy for the shifter to spot high occupancy events and request a reduction of the primary beam intensity, or to spot a decrease of the argon purity which requires the regeneration of filters, or to catch the presence of electronic noise and reboot the ASICs. An example of high occupancy event is shown in 3.16.

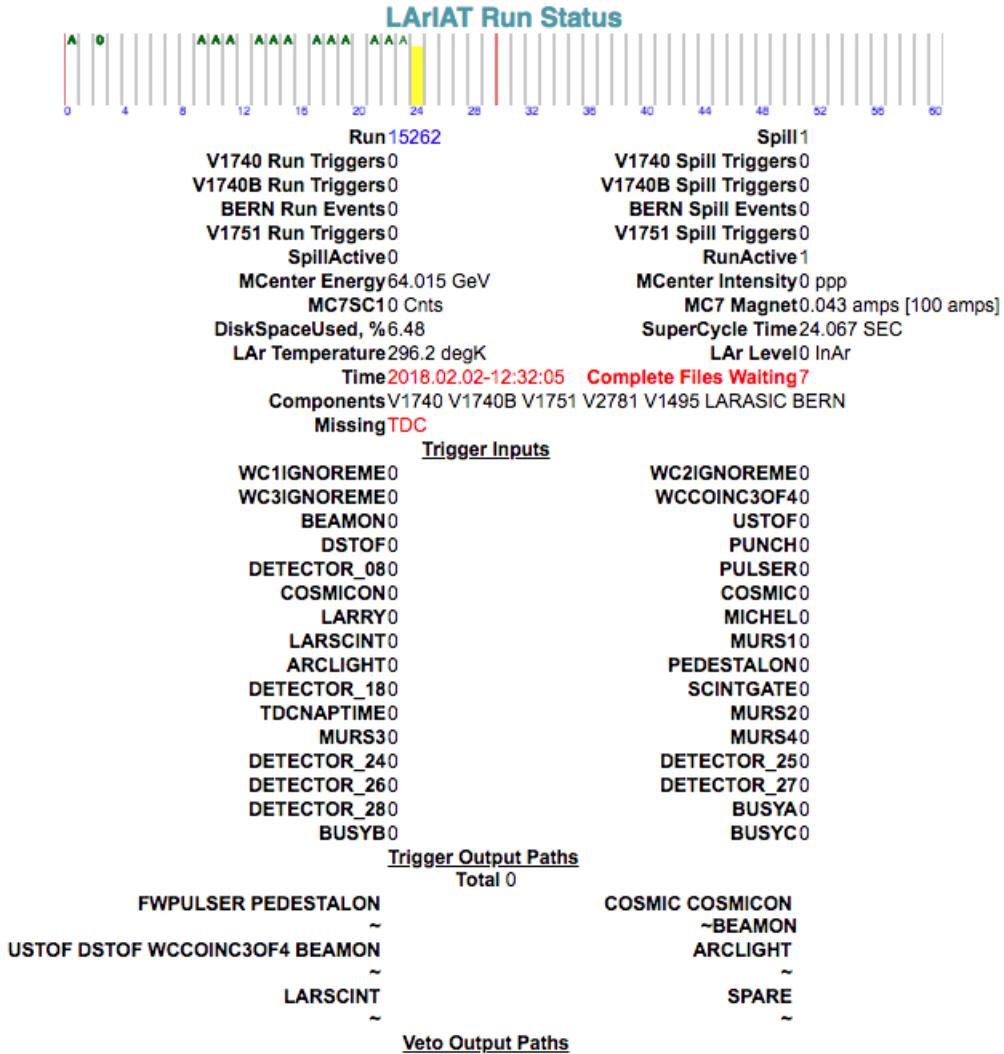


Figure 3.15: Run Status page at LArIAT downtime. At the top the yellow bar displays the current position in the Fermilab supercycle. Interesting information to be monitored by the shifter were the run number and number of spills, time elapsed from data taking (here in red), the energy of the secondary beam and the trigger paths.

Figure 3.16: High occupancy event display.

# **Chapter 4**

## **Kaons Interactions in Argon: Cross Section**

### **4.1 Literature Review**

### **4.2 How to Measure Hadron Cross Section in LAr-IAT**

We use both the LArIAT beamline detectors and the LArTPC information in order to measure hadronic cross sections in argon. Albeit with small differences, both the  $\pi^-$ -Ar and  $K^+$ -Ar total hadronic cross section measurements rely on the same procedure described in details in the following paragraphs: we select the particle of interest using a combination of beamline detectors and TPC information (paragraph 4.2.1), we perform a handshake between the beamline information and the TPC tracking to assure we are selecting the right TPC track (paragraph 4.2.2), and we apply the “thin slice” method to get to the final result (paragraph 4.2.3).

### 4.2.1 Particle Selection

### 4.2.2 Wire Chamber to TPC Match

After an event passes the selection described in the previous paragraph, we need to identify the track inside the TPC corresponding to the particle which triggered the beamline detectors, a procedure we refer to as “WC to TPC match”. In general, the tracking algorithm will reconstruct more than one track in the event, partially due to the fact that hadrons interact in the chamber, as shown in figure , and partially because of pile up events where the beam of charge particle is too intense compared to the drift time, as shown in figure. **EVENT DISPLAYS**

### 4.2.3 The Thin Slice Method

#### Cross Sections on Thin Target

Cross section measurements on a thin target have been the bread and butter of nuclear and particle Iexperimentalists since the Rutherford experiments **NEED CITATION**. At their core, this type of experiments consists in shooting a beam of particles with a known flux on a thin target and recording the outgoing flux.

In general, the target is not a single particle, but rather a slab of material containing many diffusion centers. The so-called “thin target” approximation assumes that the target centers are uniformly distributed in the material and that the target is thin compared to the interaction length so that no center of interaction sits in front of another. In this approximation, the ratio between the number of particles interacting in the target  $N_{Interacting}$  and number of incident particles  $N_{Incident}$  determines the interaction probability  $P_{Interacting}$ , which is the complementary to one of the survival probability  $P_{Survival}$ . Equation 4.1

$$P_{Survival} = 1 - P_{Interacting} = 1 - \frac{N_{Interacting}}{N_{Incident}} = e^{-\sigma_{TOT} n \delta X} \quad (4.1)$$

describes the probability for a particle to survive the thin target. This formula relates the total cross section  $\sigma_{TOT}$ , the density of the target centers  $n$  and the thickness of the target along the incident hadron direction  $\delta X$ , to the interaction probability<sup>1</sup>. If the target is thin compared to the interaction length of the process considered, we can Taylor expand the exponential function in equation 4.1 and find a simple proportionality relationship between the number of incident and interacting particles, and the cross section, as shown in equation 4.2:

$$1 - \frac{N_{Interacting}}{N_{Incident}} = 1 - \sigma_{TOT} n \delta X + O(\delta X^2). \quad (4.2)$$

Solving for the cross section, we find:

$$\sigma_{TOT} = \frac{1}{n \delta X} \frac{N_{Interacting}}{N_{Incident}}. \quad (4.3)$$

### Not-so-Thin Target: Slicing the Argon

The LArIAT TPC, with its 90 cm of length, is not a thin target. **Find expected interaction length for hadrons and kaons.** However, the fine-grained tracking of the LArIAT LArTPC allows us to treat the argon volume as a sequence of many adjacent thin targets.

As described in section 3, LArIAT wire planes count 240 wires each. The wires are oriented at  $+/- 60^\circ$  from the vertical direction at 4 mm spacing, while the beam direction is oriented 3 degrees off the  $z$  axis in the  $XZ$  plane. **review this math** The wires collect signals proportional to the energy loss of the hadron along its path in a  $\delta X = 4 \text{ mm}/\sin(60^\circ) \approx 4.7 \text{ mm}$  slab of liquid argon. Thus, one can think to slice the TPC into many thin targets of  $\delta X = 4.7 \text{ mm}$  thickness along the direction of the incident particle.

---

1. The scattering center density in the target,  $n$ , relates to the argon density  $\rho$ , the Avogadro number  $N_A$  and the argon molar mass  $m_A$  as  $n = \frac{\rho N_A}{m_A}$ .

Considering each slice  $j$  a “thin target”, we can apply the cross section calculation from Eq. 4.3 iteratively, evaluating the kinetic energy of the hadron as it enters each slice,  $E_j^{kin}$ . For each WC-to-TPC matched particle, the energy of the hadron entering the TPC is known thanks to the momentum and mass determination by the tertiary beamline,

$$E_{FrontFace}^{kin} = \sqrt{p_{Beam}^2 - m_{Beam}^2} - E_{loss}, \quad (4.4)$$

where  $E_{loss}$  is a correction for the energy loss in the dead material between the beamline and the TPC front face (more on ??). The energy of the hadron at the each slab is determined by subtracting the energy released by the particle in the previous slabs. For example, at the  $j^{th}$  point of a track, the kinetic energy will be

$$E_j^{kin} = E_{FrontFace}^{kin} - \sum_{i < j} \Delta E_i, \quad (4.5)$$

where  $\Delta E_i$  is the energy deposited at each argon slice before the  $j^{th}$  point as measured by the calorimetry associated with the tracking.

If the particle enters a slice, it contributes to  $N_{Incident}(E^{kin})$  in the energy bin corresponding to its kinetic energy in that slice. If it interacts in the slice, it then also contributes to  $N_{Interacting}(E^{kin})$  in the appropriate energy bin. The cross section as a function of kinetic energy,  $\sigma_{TOT}(E^{kin})$  will then be proportional to the ratio  $\frac{N_{Interacting}(E^{kin})}{N_{Incident}(E^{kin})}$ .

The statistical uncertainty for each energy bin is calculated by error propagation from the statistical uncertainty on  $N_{Incident}$  and  $N_{Interacting}$ . Since the number of incident hadrons in each energy bin is given by a simple counting, we assume that  $N_{Incident}$  is distributed as a poissonian with mean and  $\sigma^2$  equal to  $N_{Incident}$  in each bin. On the other hand,  $N_{Interacting}$  follows a binomial distribution: a particle in a given energy bin might or might not interact. The square of the variance for the

binomial is given by

$$\sigma^2 = \mathcal{N}P_{Interacting}(1 - P_{Interacting}); \quad (4.6)$$

since the interaction probability  $P_{Interacting}$  is  $\frac{N_{Interacting}}{N_{Incident}}$  and the number of tries  $\mathcal{N}$  is  $N_{Incident}$ , equation 4.6 translates into

$$\sigma^2 = N_{Incident} \frac{N_{Interacting}}{N_{Incident}} \left(1 - \frac{N_{Interacting}}{N_{Incident}}\right) = N_{Interacting} \left(1 - \frac{N_{Interacting}}{N_{Incident}}\right). \quad (4.7)$$

$N_{Incident}$  and  $N_{Interacting}$  are not independent. The uncertainty on the cross section is thus calculated as

$$\delta\sigma_{tot}(E) = \sigma_{tot}(E) \left( \frac{\delta N_{Interacting}}{N_{Interacting}} + \frac{\delta N_{Incident}}{N_{Incident}} \right) \quad (4.8)$$

where:

$$\delta N_{Incident} = \sqrt{N_{Incident}} \quad (4.9)$$

$$\delta N_{Interacting} = \sqrt{N_{Interacting} \left(1 - \frac{N_{Interacting}}{N_{Incident}}\right)}. \quad (4.10)$$

#### 4.2.4 Procedure testing with truth quantities

The  $\pi^-$ -Ar and  $K^+$ -Ar total hadronic cross section implemented in Geant4 can be used as a tool to validate the measurement methodology. We describe here a closure test done on Monte Carlo to prove that the methodology of slicing the TPC retrieves the underlying cross section distribution implemented in Geant4 within the statistical error.

For pions in the considered energy range, the Geant4 inelastic model adopted to is “BertiniCascade”, while the elastic model “hElasticLHEP”. For kaons, the Geant4 inelastic model adopted to is “BertiniCascade”, while the elastic model “hElasti-

cLHEP”.

For the validation test, we fire about 390000 pions and 140000 kaons inside the LArIAT TPC active volume using the DDMC (see sec 6.1.2). We apply the thin-sliced method on using true quantities to calculate the hadron kinetic energy at each slab in order to decouple reconstruction effects to eventual issues with the methodology. For each slab of 4.7 mm length on the path of the hadron, we integrate the true energy deposition as given by the Geant4 transportation model. Then, we recursively subtracted it from the hadron kinetic energy at the TPC front face to evaluate the kinetic energy at each slab until the true interaction point is reached. Doing so, we obtain the true interacting and incident distributions for the considered hadron and we obtain the true MC cross section as a function of the hadron true kinetic energy.

Figure 4.2.4 shows the total hadronic cross section for argon implemented in Geant4 10.01.p3 (solid lines) overlaid with the true MC cross section as obtained with the sliced TPC method (markers) for pions on the left and kaons on the right; the total cross section is shown in green, the elastic cross section in blue and the inelastic cross section in red. The nice agreement with the Geant4 distribution and the cross section obtained with the sliced TPC method gives us confidence in the validity of the methodology.

#### 4.2.5 Uncertainty budget

Measuring an hadronic cross section in LArIAT translates into counting how many hadrons impinged on a slab of argon at a given energy and how many of those hadrons interacted at said energy. So, the key questions here are:

- a) how well do we know the kinetic energy at each point of the tracking?
- b) how well do we know when the tracking stops?
- c) are there any systematic shifts?

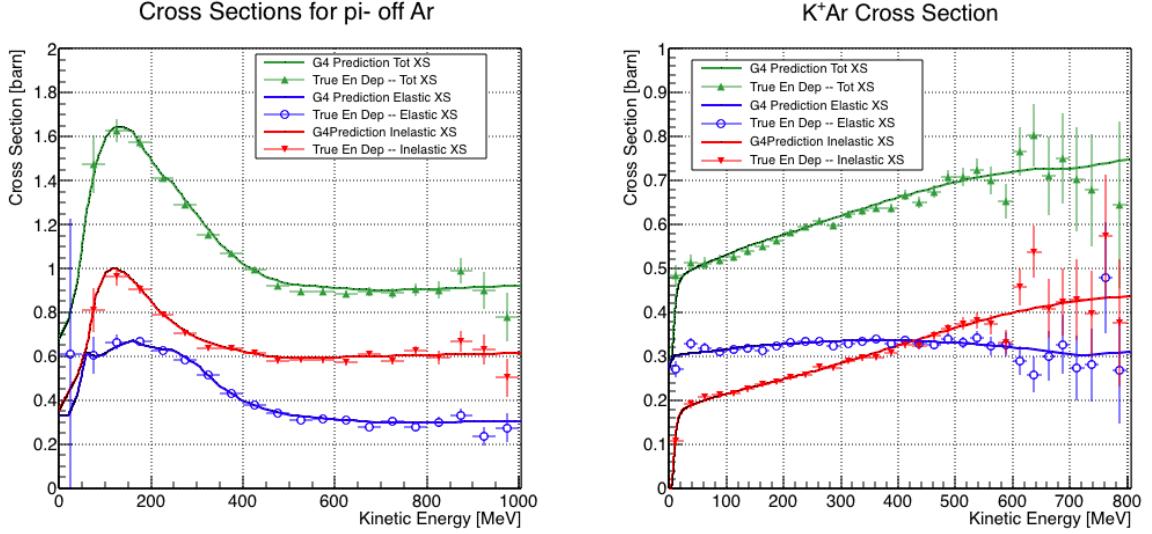


Figure 4.1: Hadronic cross sections for  $\pi^-$ -Ar (left) and  $K^+$ -Ar (right) implemented in Geant4 10.01.p3 (solid lines) overlaid the true MC cross section as obtained with the sliced TPC method (markers). The total cross section is shown in green, the elastic cross section in blue and the inelastic cross section in red.

In order to answer this question, will discuss first a simple scenario were our beam is 100% made of pions which arrive as primaries in the TPC (no decay in the beam and no inelastic interaction before the TPC front face). We will then add a layer of complexity by discussing how we handle beamline contamination.

### Pure beam of pions

#### Handling beamline contamination

What is the beamline contamination? It is whatever TPC track is matched to the WC track and it is not a pion. There are 4 different types of beamline contaminations:

- 1) electrons,
- 2) muons,
- 3) secondary pions,
- 4) matched pile up events;

we estimate the matched pile up events to be a negligible fraction, because of the definition of the WC2TPC match: we deem the probability of a single match<sup>2</sup> with a pile up event in the absence of a real particle within a four centimeter radius from the WC track projection extremely small.

---

2. Events with multiple matches are rejected.

# **Chapter 5**

## **Data Collection**

Your first chapter is probably an introduction. But who knows.

# **Chapter 6**

## **LArIAT Monte Carlo**

### **6.1 Beamline**

#### **6.1.1 G4Beamline**

#### **6.1.2 Data Driven MC**

### **6.2 TPC MC**

# Chapter 7

## Energy Calibration

Your first chapter is probably an introduction. But who knows.

# Chapter 8

## Tracking Optimization

Understanding how kaons and pions are tracked inside the TPC and optimizing the reconstruction algorithms to maximize the correct identification of the interaction point is a fundamental step of the analysis.

### 8.1 MC sample and WC2TPC match

The optimization is performed on a MC sample of 191000 kaons and 359000 pions produced with the DDMC technique. DDMC particles are shot from the WC4 location into the TPC following the beam profile. We mimic the matching between the WC and the TPC track on Monte Carlo by constructing a fake WC track using truth information at wire chamber four. We then apply the same WC to TPC matching algorithm as in data.

Plots I want in this section:

1. WC2TPC MC DeltaX, DeltaY and  $\alpha$
2. Delta L, reco - true
3. Delta L, reco - true Elastic, Delta L, reco - true Inelastic, other

4. Length Quality cut
5. Efficiency as a function of true KE and Angle

## 8.2 Wire chamber-to-TPC match

### 8.2.1 Wire chamber-to-TPC match: importance and definition

something something about why this match is important

In data, we attempt to uniquely match one WC-Track to one and only one reconstructed TPC track. This match is done by using in the  $X$  and  $Y$  coordinate of the extrapolated WC-Track to the upstream most point of the reconstructed TPC Track and by using the angle between the incoming track angle and the reconstructed TPC. We define  $\Delta X$  as the difference between the  $x$  position of the most upstream point of the TPC track and the  $x$  position of the WC track as projected to the TPC front face.  $\Delta Y$  is defined analogously. We define  $\Delta R$  as  $\Delta R = \sqrt{\Delta X^2 + \Delta Y^2}$ . The angle between the incident WC Track and the TPC track in the plane that contains them defines  $\alpha$ .

We define a match between WC-track and TPC reconstructed track if  $\Delta R < r_T$ ,  $\alpha < \alpha_T$  and the Z position of the first reconstructed point of the TPC track is within 2 cm from the TPC front face. The determination of the best  $r_T$  and  $\alpha_T$  is the scope of the following section.

In MC, we mimic the matching between the WC and the TPC track on Monte Carlo by constructing a fake WC track using truth information at wire chamber four. We then apply the same WC to TPC matching algorithm as in data.

### 8.2.2 Matching optimization

Scope of this optimization study is assessing the goodness of the wire chamber-to-TPC match on Monte Carlo and porting the optimized selection cuts to data. A word of caution is necessary here. With this study, we want to minimize pathologies associated with the presence of the primary kaon itself, like the incorrect association between the beamline kaon its decay products inside the TPC. Assessing the contamination from pile-up<sup>1</sup>, albeit related, is beyond the scope of this study.

In MC, we are able to define a correct WC2TPC match using the Geant4 truth information. We are thus able to count how many times the WC tracks is associated with the wrong TPC reconstructed track.

We define a correct match if the all following conditions are met:

- the length of the true primary Geant4 track in the TPC is greater than 2 cm,
- the length of the reconstructed track length is greater than 2 cm,
- the Z position of the first reconstructed point is within 2 cm from the TPC front face
- the distance between the reconstructed track and the true entering point is the minimum compared with all the other reconstructed tracks.

In order to count the wrong matches, we consider all the reconstructed tracks whose Z position of the first reconstructed point lies within 2 cm from the TPC front face. Events with true length in TPC < 2 cm are included. Since kaons are shot 100 cm upstream from the TPC front face, the following two scenarios are possible from a truth standpoint:

[*Ta* ] the primary kaon decays or interact strongly before getting to the TPC,

---

1. We remind the reader that the DDMC is a single particle Monte Carlo, where the beam pile up is not simulated.

[ $Tb$ ] the primary kaon enters the TPC.

Once we choose the selection cuts to determine a reconstructed wire chamber-to-TPC match  $r_T$  and  $\alpha_T$ , the following four scenarios are possible :

- 1) no reconstructed tracks are matched
- 2) the correct track and one (or more) wrong tracks are matched
- 3) only the correct track is matched
- 4) one (or more) wrong track is matched.

If we keep only events with one and only one match, we discard cases 1) and 2) from the cross section measurement. For each set of  $r_T$  and  $\alpha_T$  selection value, we define purity and efficiency of the selection as follows:

$$\text{Efficiency} = \frac{\text{Number of events correctly matched}}{\text{Number of events with primary in TPC}} \quad (8.1)$$

$$\text{Purity} = \frac{\text{Number of events correctly matched}}{\text{Total number of matched events}}. \quad (8.2)$$

Figure 8.1 shows the efficiency (left) and purity (right) for wire chamber-to-TPC match as a function of the radius,  $r_T$ , and angle,  $\alpha_T$ , selection value. It is apparent how both efficiency and purity are fairly flat as a function of the radius selection value at a given angle. This is not surprising, given the fact that the wrong matches can occur in a single particle gun MC only for mis-tracking of the primary or for association with decay products, which are generally different in angle, but might be more similar in  $x$  and  $y$  projection. The radius cut would play a key role in removing pile up events.

For LArIAT cross section measurements, we generally prefer purity over efficiency, since a sample of particle of a pure species will lead to a better measurement. In the

case of kaons however, efficiency needs not to drop too low, given the smallness of the kaon sample. We choose  $(\alpha_T, r_T) = (8 \text{ deg}, 4 \text{ cm})$  and get a MC 85% efficiency and 98% purity.

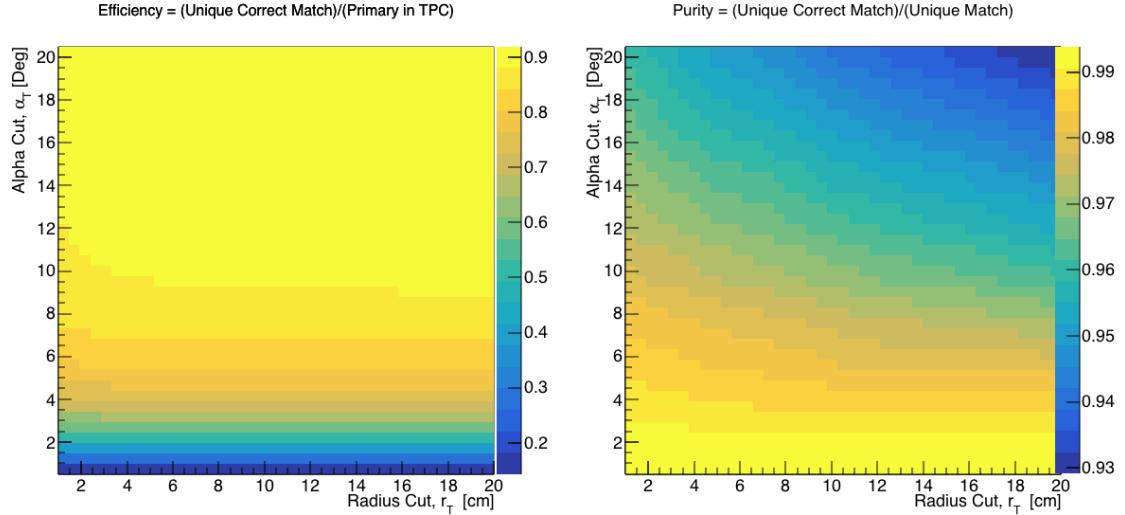


Figure 8.1: Efficiency (left) and purity (right) for wire chamber-to-TPC match as a function of the radius and angle selections.

### 8.2.3 Porting optimization to data

# **Chapter 9**

## **Kaon Cross Section Measurement**

Your first chapter is probably an introduction. But who knows.

# Appendix A

## Measurement of LArIAT Electric Field

ch:AppendixA The electric field of a LArTPC in the drift volume is a fundamental quantity for the proper functionality of this technology, as it affects almost every reconstructed quantity such as the position of hits or their collected charge. Given its importance, we calculate the electric field for LArIAT with a single line diagram from our HV circuit and we cross check the obtained value with a measurement relying only on TPC data.

Before getting into the details of the measurement procedures, it is important to explicit the relationship between some quantities in play. The electric field and the drift velocity ( $v_{drift}$ ) are related as follows

$$v_{drift} = \mu(E_{field}, T)E_{field}, \quad (\text{A.1})$$

where  $\mu$  is the electron mobility, which depends on the electric field and on the temperature (T). The empirical formula for this dependency is described in [?] and shown in Figure A.1 for several argon temperatures.

The relationship between the drift time ( $t_{drift}$ ) and the drift velocity is trivially

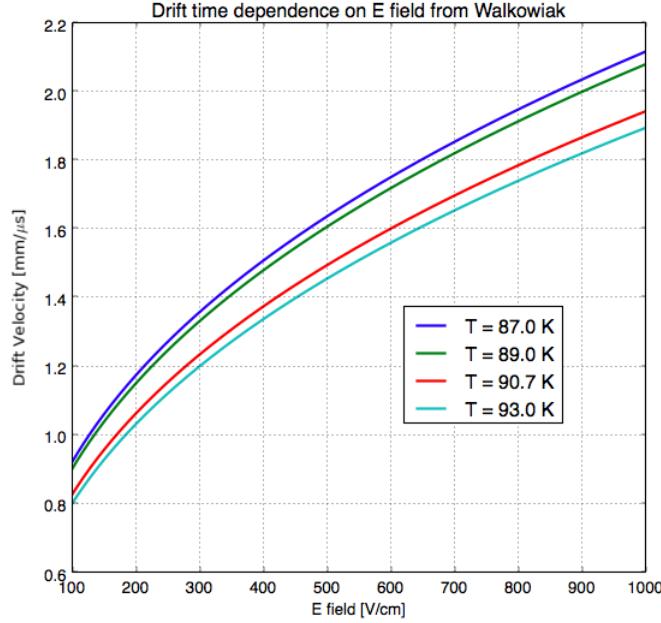


Figure A.1: Drift velocity dependence on electric field for several temperatures. The slope of the line at any one point represents the electron mobility for that given temperature and electric field.

Table A.1: Electric field and drift velocities in LArIAT smaller drift volumes

	Shield-Induction	Induction-Collection
$E_{filed}$	700.625 V/cm	892.5 V/cm
$v_{drift}$	1.73 mm/μs	1.90 mm/μs
$t_{drift}$	2.31 μs	2.11 μs

given by

$$t_{drift} = \Delta x / v_{drift}, \quad (\text{A.2})$$

where  $\Delta x$  is the distance between the edges of the drift region. Table A.1 reports the values of the electric field, drift velocity, and drift times for the smaller drift volumes.

With these basic parameters established, we can now move on to calculating the electric field in the main drift region (between the cathode and the shield plane).

## Single line diagram method

The electric field strength in the LArIAT main drift volume can be determined knowing the voltage applied to the cathode, the voltage applied at the shield plane, and the distance between them. We assume the distance between the cathode and the shield plane to be 470 mm and any length contraction due to the liquid argon is negligibly small ( $\sim 2$  mm).

The voltage applied to the cathode can be calculated using Ohm's law and the single line diagram shown in Figure A.2. A set of two filter pots for emergency power dissipation are positioned between the Glassman power supply and the cathode, one at each end of the feeder cable, each with an internal resistance of  $40 \text{ M}\Omega$ . The output current of the Glassman power supply is then used to determine the electric field strength. Figure A.3 shows an average current of 0.004172 mA from the Glassman power supply.

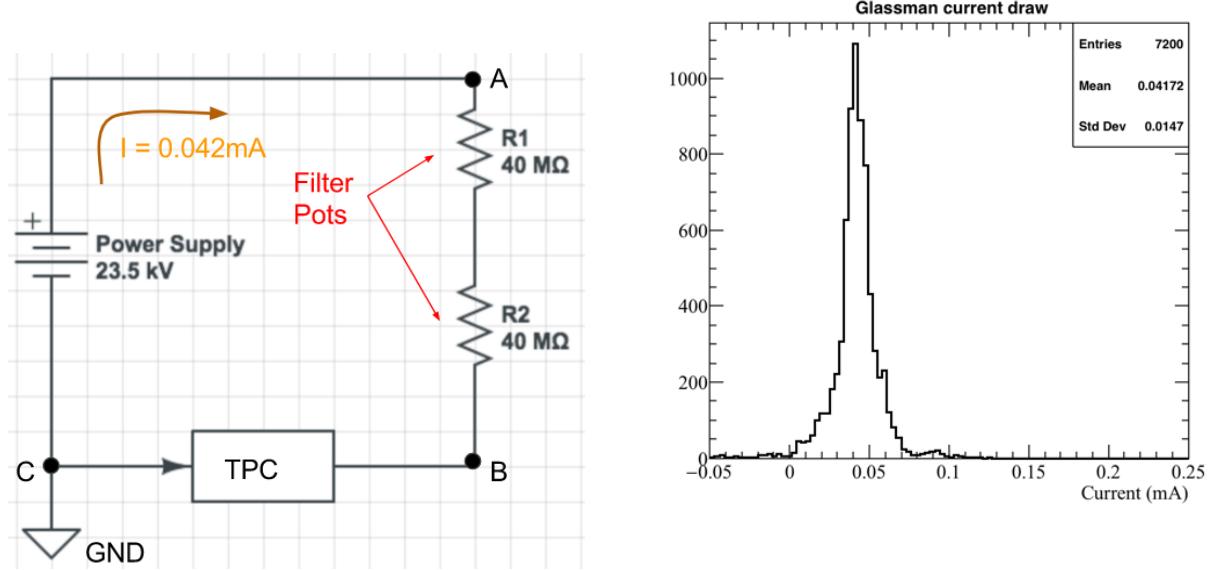


Figure A.2: get rid of current line LArIAT HV simple schematics.

Figure A.3: **the axis is wrong!!** Current reading from the Glassman between May 25th and May 30th, 2016 (typical Run-II conditions).

Using this current, the voltage at the cathode is calculated as

$$V_{BC} = V_{PS} - (I \times R_{eq}) = -23.5 \text{ kV} + (0.00417 \text{ mA} \times 80 \text{ M}\Omega) = -23.17 \text{ kV}, \quad (\text{A.3})$$

where  $I$  is the current and  $R_{eq}$  is the equivalent resistor representing the two filter pots. The electric field, drift voltage, and drift time are then calculated to be

$$E_{\text{field}} = \frac{V_{BC} - V_{\text{shield}}}{\Delta x} = 486.54 \text{ V/cm} \quad (\text{A.4})$$

## E field using cathode-anode piercing tracks

We devise an independent method to measure the drift time (and consequently drift velocity and electric field) using TPC cathode to anode piercing tracks. We use this method as a cross check to the single line method. The basic idea is simple:

0. Select cosmic ray events with only 1 reconstructed track
1. Reduce the events to the one containing tracks that cross both anode and cathode
2. Identify the first and last hit of the track
3. Measure the time difference between these two hits ( $\Delta t$ ).

This method works under the assumptions that the time it takes for a cosmic particle to cross the chamber ( $\sim \text{ns}$ ) is small compared to the charge drift time ( $\sim \text{hundreds of } \mu\text{s}$ ).

We choose cosmic events to allow for a high number of anode to cathode piercing tracks (ACP tracks), rejecting beam events where the particles travel almost perpendicularly to drift direction. We select events with only one reconstructed track to maximize the chance of selecting a single crossing muon (no-michel electron). We utilize ACP tracks because their hits span the full drift length of the TPC, see figure

A.4, allowing us to define where the first and last hit of the tracks are located in space regardless of our assumption of the electric field.

One of the main features of this method is that it doesn't rely on the measurement of the trigger time. Since  $\Delta t$  is the time difference between the first and last hit of a track and we assume the charge started drifting at the same time for both hits, the measurement of the absolute beginning of drift time  $t_0$  is unnecessary. We boost the presence of ACP tracks in the cosmic sample by imposing the following requirements on tracks:

- vertical position (Y) of first and last hits within  $\pm 18$  cm from TPC center (avoid Top-Bottom tracks)
- horizontal position (Z) of first and last hits within 2 and 86 cm from TPC front face (avoid through going tracks)
- track length greater than 48 cm (more likely to be crossing)
- angle from the drift direction (phi in figure A.5) smaller than 50 deg (more reliable tracking)
- angle from the beam direction (theta in figure A.5) grater than 50 deg (more reliable tracking)

Tracks passing all these selection requirements are used for the  $\Delta t$  calculation.

For each track passing our selection, we loop through the associated hits in order to retrieve the timing information. The analysis is performed separately on hits on the collection plane and induction plane, but lead to consistent results. As an example of the time difference, figures A.6 and A.7 represent the difference in time between the last and first hit of the selected tracks for Run-II Positive Polarity sample on the collection and induction plane respectively. We fit with a Gaussian to the peak of the  $\Delta t$  distributions to extract the mean drift time and the uncertainty associated with

it. The long tail at low  $\Delta t$  represent contamination of non-ACP tracks in the track selection. We apply the same procedure to Run-I and Run-II, positive and negative polarity alike.

To convert  $\Delta t$  recorded for the hits on the induction plane to the drift time we utilize the formula

$$t_{drift} = \Delta t - t_{S-I} \quad (\text{A.5})$$

where  $t_{drift}$  is the time the charge takes to drift in the main volume between the cathode and the shield plane and  $t_{S-I}$  is the time it takes for the charge to drift from the shield plane to the induction plane. In Table A.1 we calculated the drift velocity in the S-I region, thus we can calculate  $t_{S-I}$  as

$$t_{S-I} = \frac{l_{S-I}}{v_{S-I}} = \frac{4mm}{1.745mm/\mu s} \quad (\text{A.6})$$

where  $l_{S-I}$  is the distance between the shield and induction plane and  $v_{S-I}$  is the drift velocity in the same region. A completely analogous procedure is followed for the hits on the collection plane, taking into account the time the charge spent in drifting from shield to induction as well as between the induction and collection plane. The value for  $\Delta t_{drift}$ , the calculated drift velocity ( $v_{drift}$ ), and corresponding drift electric field for the various run periods is given in Table A.2 and are consistent with the electric field value calculated with the single line diagram method.

### Delta $t_{drift}$ , drift v and E field with ACP tracks

Data Period	$\Delta t_{Drift}$ [ $\mu s$ ]	Drift velocity [mm/ $\mu s$ ]	E field [V/cm]
RunI Positive Polarity Induction	$311.1 \pm 2.4$	$1.51 \pm 0.01$	$486.6 \pm 21$
RunI Positive Polarity Collection	$310.9 \pm 2.6$	$1.51 \pm 0.01$	$487.2 \pm 21$
RunII Positive Polarity Induction	$315.7 \pm 2.8$	$1.49 \pm 0.01$	$467.9 \pm 21$
RunII Positive Polarity Collection	$315.7 \pm 2.7$	$1.49 \pm 0.01$	$467.9 \pm 21$
RunII Negative Polarity Induction	$315.9 \pm 2.6$	$1.49 \pm 0.01$	$467.1 \pm 21$
RunII Negative Polarity Collection	$315.1 \pm 2.8$	$1.49 \pm 0.01$	$470.3 \pm 21$
Average Values	314.1	$1.50 \pm 0.01$	$474.3 \pm 21$

Table A.2:  $\Delta t$  for the different data samples used for the Anode-Cathode Piercing tracks study.

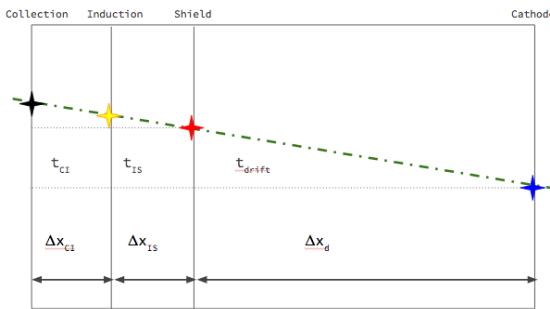


Figure A.4: Pictorial representation of the YX view of the TPC. The distance within the anode planes and between the shield plane and the cathode is purposely out of proportion to illustrate the time difference between hits on collection and induction. A ACP track is shown as an example.

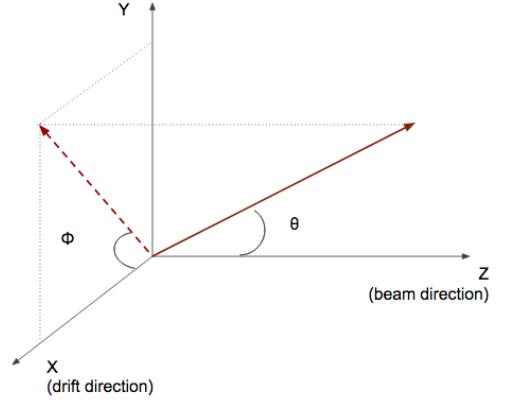


Figure A.5: Angle definition in the context of LArIAT coordinates system.

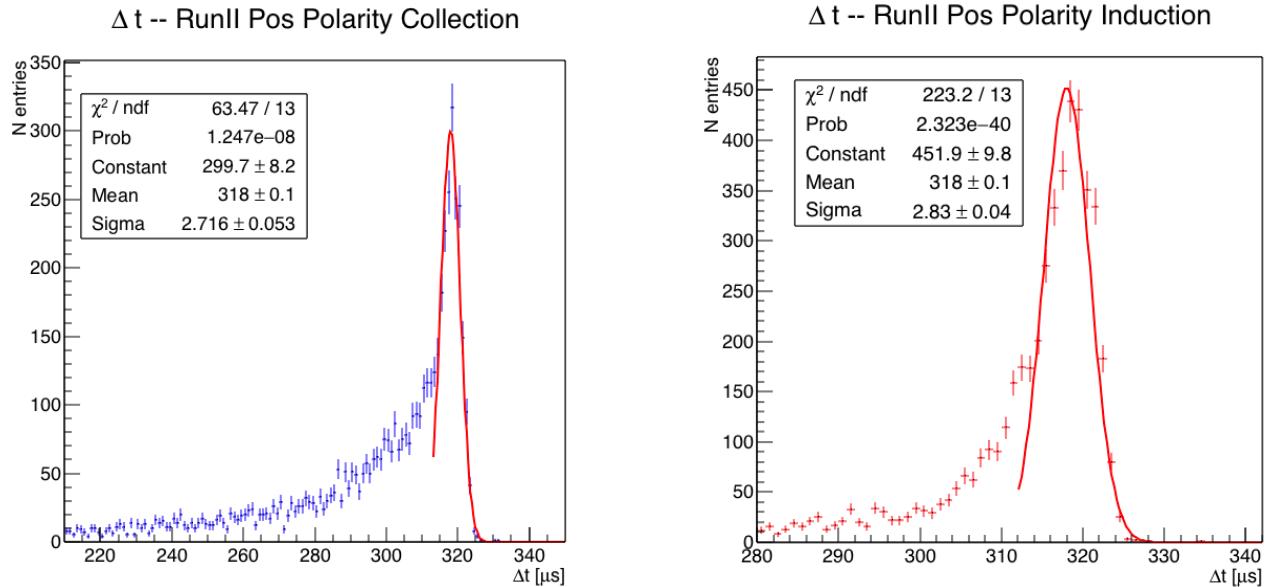


Figure A.6: Collection plane  $\Delta t$  fit for Run II positive polarity ACP data selected tracks.

Figure A.7: Induction plane  $\Delta t$  fit for Run II positive polarity ACP data selected tracks.

## **Appendix B**

# **Construction of A Cosmic Ray Tagger for MicroBooNE**

# Appendix C

## Pion Analysis

### C.0.1 Data Sample

We decided to use only the data from the -60 A, -100 A RunII configurations, because the beam composition for these 2 beamline configurations is available in G4Beamline. Run II data is better than Run I in terms of calorimetry and understanding of the detector.

The used SamWeb definition is PionAna\_RunII\_60A\_100A\_lovely1\_elenag\_00 =  
Defined as “defname: Lovely1 and data\_tier digits and lariat\_mid\_f\_mc7anb != 0  
and create\_date != '2017-06-02' and run\_number != 9276 and run\_number != 9277  
and run\_number != 8836 and run\_number != 9083 and run\_number != 9122 and  
run\_number != 8977 and run\_number != 8981 and run\_number != 8982 and run\_number  
!= 8983 and run\_number != 8984 and run\_number != 8985 and run\_number != 8991  
and run\_number != 8994 and run\_number != 8996 and run\_number != 8767 and  
run\_number != 9635”

### C.0.2 Capture and Decay

Our goal is to measure the total hadronic cross section for negative pions in argon. Since pion capture can be classified as an electromagnetic process and pion decay is

Table C.1: My caption

Stage	-100A +64 GeV	-60A +64 GeV	Number of Evt
SamWebDefinition	32.7%	67.3%	3569206
WCQuality	37.8%	63.2%	553486
$P_{WC4} > 420 \text{ MeV/c}$	50.8%	49.2%	423294
TOF Cut	32.7%	67.3%	

a week process, capture and decay represent unwanted interactions in our sample. We present here a study of capture and decay in Monte Carlo and the solution we adopted to mitigate their present in our sample.

For this MC study, we use a sample of 359000 MC pions generated according to the beam profile with the DDMC described in 6.1.2. Unlike decay – which may occur both in flight and at rest – capture occurs predominantly at rest. Thus, we can highly mitigate capture and decay at rest by removing pions whose energy is low enough to stop in the TPC. This translates into a momentum selection, where we keep only events whose WC momentum is above a certain threshold. Figure C.1 shows the true momentum distribution for the primary<sup>1</sup> pions that arrive to the TPC (pink), that capture (green) or decay (blue) inside the TPC, on a linear and log scale vertical axis.

In order to choose the selection value for the wire chamber momentum, it is beneficial to estimate the ratio of events which capture or decay that survive the selection in MC as a function of the momentum threshold, and compare it with the survival ratio for all events. This is done in figure C.2. We define the survival ratio simply as the number of events surviving the true momentum cut divided by the number of events of that given category. The survival ratio calculated separately for the three event categories explained above: total (pink), capture (green) and decay (blue). Selecting pions with momentum greater than 420 MeV/c reduces the capture

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1. We use here the Geant4 denomination "primary" to indicate that the pion considered does not undergo interactions modifying its energy before getting to the TPC. In fact, not every pion shot from wire chamber four will arrive to the TPC as primary, some will decay or interact before the TPC, as explained in [reference to WC 2 TPC chapter](#)

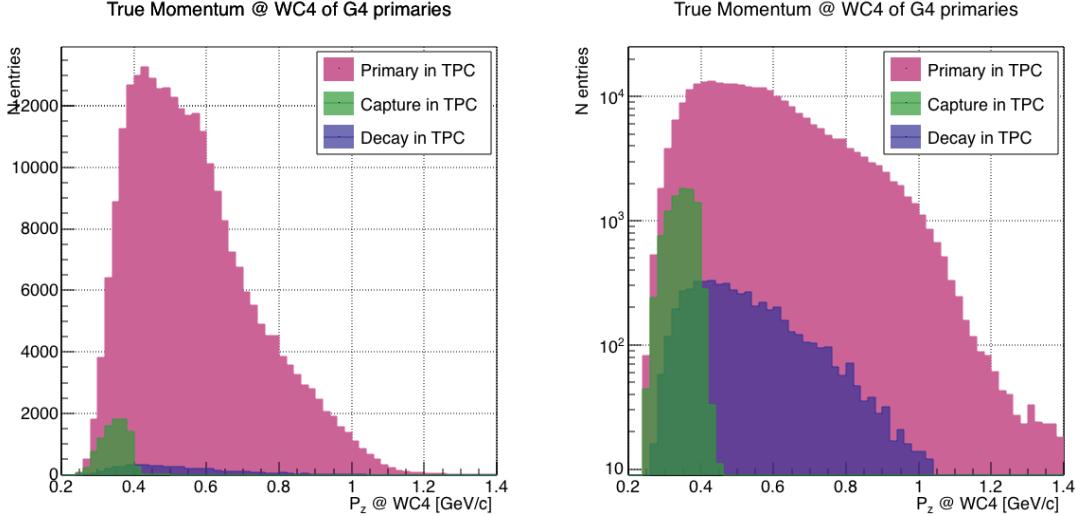


Figure C.1: True momentum distribution at wire chamber 4 for every simulated pion arriving in the TPC (pink), ending its life in capture (green) or in decay (blue) in the TPC, linear vertical axis on the left, logarithmic on the right.

events by 99% while maintaining about 80% of the total data sample. Figure C.3 shows the ratio of events which end their life in capture (green) or decay (blue) over the total number of events as a function of the true momentum at wire chamber four. This ratio is slightly dependent on the inelastic cross section implemented in Geant4, as we are able to register a pion capture (or decay) only if it doesn't interact inelastically in the TPC. For momenta greater than 420 MeV/c, the percentage of capture events drops below 1% and the percentage of decays is never above 2%.

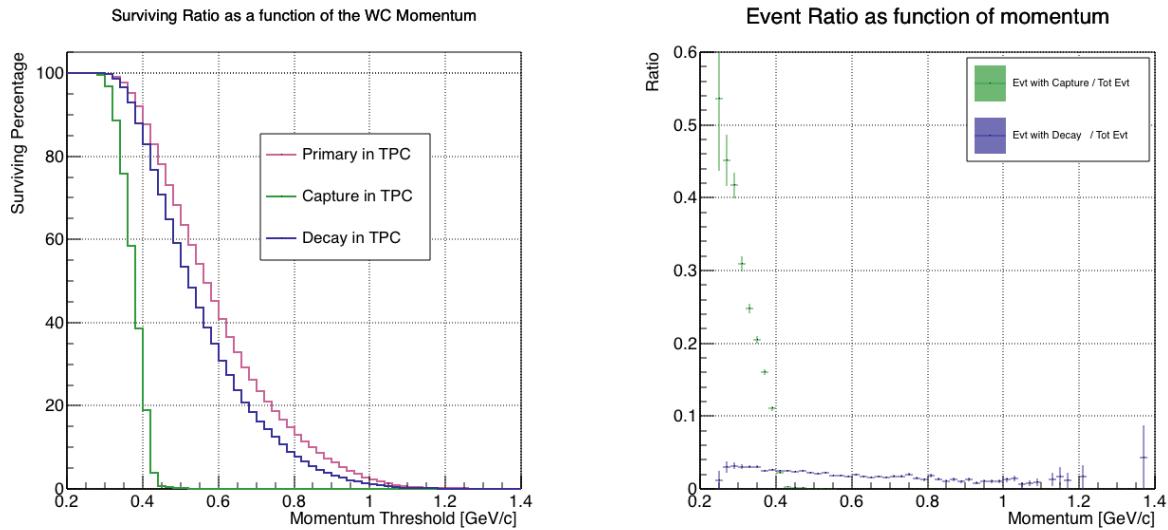


Figure C.2: Survival ratio as a function of selection threshold on true momentum at wire chamber four for every simulated pion arriving in the TPC (pink), capture (green) or in decay (blue).

Figure C.3: Ratio between the capture (green) and decay (blue) events over the total number of events as a function of the true momentum at wire chamber four.

# Bibliography

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