

Abstract

Measurement of (π^- -Ar) and (K^+ -Ar) total hadronic cross sections in the LArIAT experiment

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6 Abstract goes here. Limit 750 words.

7 **Measurement of (π^- -Ar) and (K^+ -Ar)**

8 **total hadronic cross sections in the**

9 **LArIAT experiment**

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16 by
17 Elena Gramellini

18 Dissertation Director: Bonnie T. Fleming

19 Date you'll receive your degree

²⁰

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²¹

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22

A mia mamma e mio babbo,

23

grazie per le radici e grazie per le ali.

24

To my mom and dad,

25

thank you for the roots and thank you for the wings.

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¹¹⁰ – Articolo 31, Tanqi Funky, 1996 –

¹¹¹ “*At last, I thank everyone.*

¹¹² *Especialiy my mom who made me so funky.”*

¹¹³ – Articolo 31, Tanqi Funky, 1996 –

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¹¹⁷ being a physicists in the US might mean and wanted more. I came to this vast (and
¹¹⁸ at times inhospitable) land thinking I would learn a lot of physics (which I did) and
¹¹⁹ trying to keep doing research for as long as I could (which I’m fortunate enough to
¹²⁰ say I’ll still do for a while). Little did I know that getting my PhD would be first and
¹²¹ foremost a journey to self discovery, the beginning of a path to asymptotically tend
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132 always believing I could make it, even at the bottom of my doubts; thanks for the
133 laughters, thanks for leading by example, thanks for letting me part of the most
134 wonderful research group ;

¹³⁵ Introduction

¹³⁶ This thesis work concerns the first measurement of the (π^- -Ar) total hadronic cross
¹³⁷ section in the 100-1000 MeV kinetic energy range and the first measurement of the
¹³⁸ (K^+ -Ar) total hadronic cross section in the 100-650 MeV kinetic energy range. We
¹³⁹ performed these measurements at the LArIAT experiment, a small (0.25 ton) Liquid
¹⁴⁰ Argon Time Projection Chamber (LArTPC) on a beam of charged particles at the
¹⁴¹ Fermilab Test Beam Facility. Albeit particle and nuclear physics have a long history
¹⁴² of hadronic cross section measurements, the work outlined in this thesis presents a
¹⁴³ new methodology – the “thin slice method” – for cross section measurements, possible
¹⁴⁴ only thanks to the detection capabilities of the LArTPC technology. The LArTPC
¹⁴⁵ technology allows to see unprecedented details of particle interactions in argon given
¹⁴⁶ its full 3D-imaging with millimeter resolution and precise calorimetric reconstruction.
¹⁴⁷ A renewed interest for precision measurements of hadronic cross sections, particularly
¹⁴⁸ in argon, arises from the current panorama of experimental particle physics at the
¹⁴⁹ intensity frontier.

¹⁵⁰ The discovery of the Higgs boson in 2012 marked the triumph of the Standard
¹⁵¹ Model of Particle Physics; exploring what lays beyond is the real challenge in our field
¹⁵² today. Since their formulation in 1930, neutrinos have been a source of surprises (and
¹⁵³ Nobel Prizes) for particle physicists, tiny cracks in our understanding of Nature. In
¹⁵⁴ particular, the discovery of neutrino oscillation represents the first evidence of physics
¹⁵⁵ Beyond the Standard Model (BSM). From a theoretical point of view, the field is

156 developing new theories to account for the small but non-zero mass of neutrinos,
157 while trying to remain consistent with the rest of the Standard Model. From an
158 experimental point of view, we are developing technologies and huge collaborations to
159 probe these theories. Even today, neutrinos might hold the key to the next generation
160 of discoveries in particle physics.

161 According to the latest Particle Physics Project Prioritization Panel [107], the US
162 particle physics panorama is directing a substantial effort towards the exploration of
163 the intensity frontier. In particular, the near future will see the development of a
164 Short Baseline Neutrino Program (SBN) and long baseline neutrino program with
165 DUNE as far detector. Both these program are based on the Liquid Argon Time
166 Projection Chamber (LArTPC) detector technology. The US liquid argon program
167 has the potential to answer many of the fundamental open questions in particle physics
168 today, such as: is there a fourth generation neutrino? is CP violated in the lepton
169 sector? are there any additional symmetries? And, can we find an indication of
170 Grand Unified Theories?

171 The SBN program at Fermilab is tasked with conclusively addressing the existence
172 of a fourth neutrino generation in the $\Delta m^2 = \Delta m_{14}^2 \sim [0.1 - 10] \text{ eV}^2$ parameter space.
173 The SBN program entails three surface LArTPCs positioned on the Booster Neutrino
174 Beam at different distances from the neutrino production in oder to fully exploit the
175 L/E dependence of the oscillation pattern: SBND (100 m from the decay pipe),
176 MicroBooNE (450 m), and ICARUS (600 m). SBN will also perform an extensive
177 program of neutrino cross section measurements, fundamental to abate systematics
178 in the oscillation analyses in both SBN and DUNE.

179 The long baseline neutrino program and DUNE in particular has a wide physics
180 program. For what it concerns neutrino physics, oscillation analyses in DUNE have
181 the capability of solving the mass hierarchy and octant problem, and discovering CP
182 violation in the neutrino sector. Besides its neutrino program, DUNE can open an

183 experimental window on Grand Unified Theories (GUTs). GUTs could potentially
184 answer fundamental questions such as the existence of non-zero neutrino masses and
185 matter-antimatter asymmetry, explaining some “accidents” in the Standard Models,
186 such as the exact cancellation of the proton and the electron charge. Directly probing
187 GUTs at the unification energy scale is impossible by any foreseeable collider exper-
188 iment. We then need an indirect proof such as baryon number violation, which is
189 predicted by almost every GUT in the form of proton decay, bounded nucleon decay
190 or $n - \bar{n}$ oscillations on long time-scales. Historically, the dominant technology used in
191 these searches has been water Cherenkov detectors, with Super-Kamiokande setting
192 all the current experimental limits on the decay lifetimes at the order of $\sim 10^{34}$ years.
193 The DUNE far detector and its non-accelerator physics program is a interesting new
194 actor on this stage. LArTPCs can in fact complement nucleon decay searches in
195 modes where water Cherenkov detectors are less sensitive, especially $p \rightarrow K^+ \bar{\nu}$ [11].

196 **Brief history of nu detectors**

197 • Brief history of nu detectors

198 • Calibration : LArIAT

199 • The measurements

200 LArTPCs provide excellent electron/photon separation [9] lacking in Cherenkov
201 detectors which can be leveraged to abate the photon background from neutral current
202 interactions in ν_e searches. LArTPCs share superb tracking capability with bubble
203 chamber detectors, with several additional benefits. They are electronically read out
204 and self triggered detectors; they provide full 3D-imaging with millimeter resolution,
205 precise calorimetric reconstruction and excellent particle identification. Plus, female
206 physicists are actually writing code and running experiments, not (only) staring at
207 images – Too much? – [69].

208 The complexity of the LArTPC technology for neutrino detection is due to several
209 reasons. Argon is a fairly heavy element, which means that nuclear effects play an
210 important role in the looks of the interaction topology. Also, data on charged particle
211 interaction in argon is scarce; no measurement of hadronic cross sections for pions or
212 kaons is available for argon. Secondly,

213 LArIAT [38], a small (0.25 ton) LArTPC on a beam of charged particles at the
214 Fermilab Test Beam Facility, is performing precise cross section measurements of
215 charged particles in argon. The LArIAT suite of cross section measurements is a
216 critical set of results which will be employed by both the short- and long- baseline
217 neutrino programs. This work is a measurement of the negative pion argon and the
218 positive kaon-argon total hadronic differential cross sections.

219 The (π^- -Ar) hadronic cross section is a fundamental input for neutrino detectors
220 in liquid argon. In fact, reconstructing neutrino interactions at the GeV scale where
221 pion production is abundant.

222 The total hadronic differential cross sections is of particular interest for proton
223 decay searches in DUNE, whose most interesting proton decay channel is $p \rightarrow K^+ \bar{\nu}$.

224 The cross section analyses exploit the totality of LArIAT's experimental handles;
225 they rely on beam line detector information as well as both calorimetry and tracking
226 in the TPC. These analyses are LArIAT's first physics results.

227 The (K^+ -Ar) total hadronic differential cross section in LArIAT is particularly
228 relevant for a high identification efficiency in the context of proton decay searches in
229 DUNE in the $p \rightarrow K^+ \bar{\nu}$ channel. In fact, the kaon-argon cross section affects the
230 kaon topology by modifying the kaon tracking and energy reconstruction, impacting
231 the basis for kaon identification in a LArTPC.

232 A series of additional studies and calibrations were necessary to perform the cross
233 section analyses. Appendix ?? shows a measurement of the LArIAT LArTPC electric
234 field using cosmic data. Appendix ?? shows an optimization of the tracking algorithms

235 geared towards maximizing the efficiency of finding the hadronic interaction point.
236 Appendix ?? shows the calorimetry calibration of the LArIAT LArTPC, which is a
237 pivotal measurement to enable any physics analysis with TPC data.

238 In order to measure the kaon-argon differential cross section, several steps were
239 necessary. The analysis starts by identifying a sample of kaons in the beam line and
240 assessing the beam line contaminations. It proceeds with tracking the kaon candi-
241 dates in the TPC and measuring their calorimetry. Then, the hadronic interaction
242 point is identified and distinguished from weak interaction cases. The last step of the
243 analysis, which is the energy unfolding, is now ongoing. With this measurement, I ac-
244 quired extensive experience in tracking hadrons and measuring their energy inside the
245 TPC. This entailed both an in-depth study of the tracking algorithms performances
246 on data and a dive into the GEANT4 transportation models. Since no previous kaon
247 measurement has been performed on argon, simulation packages such as GEANT4
248 currently interpolate the kaon transportation on (scarce) data from lighter and heav-
249 ier nuclei. This is suboptimal for proton decay searches. In fact, an extremely high
250 signal detection efficiency, measured by testing identification algorithms on simula-
251 tion, is extremely difficult to obtain if the simulation is not reliable. By adding the
252 experimental data points for kaon-argon cross section to the simulation, my thesis
253 analysis will cover this gap of knowledge.

254

255 This body of work is divided in 8 chapters. We provide a description of the
256 theoretical framework for the measurements in Chapter 1. Chapter 2 outlines the
257 LArTPC detector technology, while Chapter 3 describes LArIAT experimental setup.
258 We present the event selection for both the pion and kaon analyses, as well as the
259 “thin-slice method” in Chapter 4. Chapter 5 describes the work done on the data
260 and Monte Carlo samples in preparation of the cross section analyses. Chapter 6
261 shows the results for the (π^- -Ar) total hadronic cross section measurement. Chapter

₂₆₂ 7 shows the results for the (K^+ -Ar) total hadronic cross section measurement. We
₂₆₃ draw the final remarks on this work in Chapter 8

²⁶⁴ **Chapter 1**

²⁶⁵ **The theoretical framework**



²⁶⁶

– J. S. Bach, 1720 ca. –

²⁶⁷ In this chapter, we set the (π^- - Ar) and (K^+ - Ar) total hadronic cross section
²⁶⁸ measurements into the greater theoretical and phenomenological framework. We start
²⁶⁹ by briefly describing the Standard Model (Section 1.1), with particular attention to
²⁷⁰ neutrinos and neutrino interactions (Section 1.2). We then describe some of the
²⁷¹ open questions in neutrino physics today and Beyond Standard Model theories (1.3)
²⁷² setting the stage for the measurements reported in this work (Section 1.4).

²⁷³ **1.1 The Standard Model**

²⁷⁴ The Standard Model (SM) of particle physics is the most accurate theoretical descrip-
²⁷⁵ tion of the subatomic world and, in general, one of the most precisely tested theories
²⁷⁶ in the history of physics. The SM describes the strong, electromagnetic and weak
²⁷⁷ interactions among elementary particles in the framework of quantum field theory,

278 accounting for the unification of electromagnetic and weak interactions for energies
279 above the vacuum expectation value (VEV) of the Higgs field. The SM does not
280 describe gravity or general relativity.

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

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

282 where the subscripts C indicates the conserved strong charge (color), and the
283 subscripts Y indicates the conserved hypercharge. If we indicated with T the weak
284 isospin T and with T3 its third component, hypercharge can be related to the electric
285 charge Q through the Gell-Mann-Nishijima relation:

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

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

293 Quarks can interact via all three the fundamental forces; they are triplets of
294 $SU(3)_C$, that is they can exist in three different colors. If one chooses a base where
295 u , c and t quarks are simultaneously eigenstates of both the strong and the weak
296 interactions, the remaining eigenstates are usually written as d , s and b for the strong
297 interaction and d' , s' and b' for the weak interaction, because the latter ones are
298 the result of a CKM rotation on the first ones. Charged leptons interact via the
299 weak and the electromagnetic forces, while neutrinos only interact via the weak force.

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	μ_R	τ_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 fermionic fields. The subscripts L and R indicate respectively the negative chirality (left-handed) and the positive chirality (right-handed).

300 The gauge group univocally determines the number of gauge bosons that carry the
 301 interaction; the gauge bosons correspond to the generators of the group: eight gluons
 302 (g) for the strong interaction, one photon (γ) and three bosons (W^\pm , Z^0) for the
 303 electroweak interaction. A gauge theory by itself cannot provide a description of
 304 massive particles, but it is experimentally well known that most of the elementary
 305 particles have non-zero masses. The introduction of massive fields in the Standard
 306 Model lagrangian would make the theory not gauge invariant, resulting ill-defined.
 307 This problem is solved in the SM by the introduction of a scalar iso-doublet $\Phi(x)$, the
 308 Higgs field, which gives mass to W^\pm and Z^0 gauge bosons through the electroweak
 309 symmetry breaking mechanism and to the fermions through Yukawa coupling [76, 77].
 310 The discovery of the Higgs boson in 2012 by the LHC experiments [41, 42] marked
 311 the ultimate confirmation of a long history of successful predictions by the SM.

312 1.2 Neutrinos: tiny cracks in the Standard Model

313 To our current knowledge, neutrinos are the most abundant fermion in the Universe.
314 And yet, they are maybe the most mysterious particle in the SM: they generate
315 theoretical puzzles and experimental challenges. In this section, we treat neutrinos
316 within and beyond the SM and describe the make up of their interaction with matter.

317 1.2.1 Neutrinos in the Standard Model

318 Neutrino can be introduced in the SM as left-handed massless Weyl spinors. The
319 Dirac equation of motion for a free field

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

320 for a fermionic field

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

321 is equivalent to the equations

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

322

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

323 for the chiral fields ψ_R and ψ_L , whose evolution in space and time is coupled
324 through the mass m . If the fermion is massless, the chiral fields decouple and the
325 fermion can be described by a single Weyl spinor with two independent compo-
326 nents [116]. Pauli initially rejected the description of a physical particle through
327 a single Weyl spinor because of its implication of parity violation. In fact, since
328 the spatial inversion operator throws $\psi_R \leftrightarrow \psi_L$, parity is conserved only if both chi-
329 ral components exist at the same time. For the neutrino introduction in the SM,
330 experiments came in help of the theoretical description. The constraint of parity

³³¹ conservation weakened after Wu's experiment in 1957 [119]. Additionally, there was
³³² no experimental indication for massive neutrinos, nor evidence of interaction via the
³³³ neutrino right-handed component.

³³⁴ The symmetry group $SU(2)_L \otimes U(1)_Y$ is the only group relevant for neutrino
³³⁵ interactions. The SM electroweak lagrangian is the most general renormalizable la-
³³⁶ grangian invariant under the local symmetry group $SU(2)_L \otimes U(1)_Y$. The lagrangian
³³⁷ couples the weak isotopic spin doublets and singlets described in Table 1.1 with the
³³⁸ gauge bosons A_a^μ ($a = 1, 2, 3$) and B^μ , and Higgs doublet $\Phi(x)$:

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

³³⁹ The first two lines of the lagrangian summarize the kinetic terms for the fermionic
³⁴⁰ fields and their coupling to the gauge bosons $A_a^{\mu\nu}$, $B^{\mu\nu}$ ¹. The third line describes
³⁴¹ the kinetic terms and the self-coupling terms of the gauge bosons. The forth line is
³⁴² the Higgs lagrangian, which results in the spontaneous symmetry breaking. The last
³⁴³ three lines describe the Yukawa coupling between fermions and the Higgs field, origin
³⁴⁴ of the fermions' mass.

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

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

349 1.2.2 Neutrino Oscillations

350 The determination of the flavor of a neutrino dynamically arises from the correspond-
351 ing charged lepton associated in a change current interaction; for example, a ν_e is a
352 neutrino which produces an e^- , a $\bar{\nu}_\mu$ is a neutrino which produces a μ^+ , *etc.* The
353 neutrino flavor eigenstates $|\nu_\alpha\rangle$, with $\alpha = e, \mu, \tau$, are orthogonal to each other and
354 form a base for the weak interaction matrix.

355 Overwhelming experimental data show that neutrinos change flavor during their
356 propagation [102]. This phenomenon, called “neutrino oscillations”, was predicted
357 first by Bruno Pontecorvo in 1957 [103]. Neutrino oscillations are possible only if
358 the neutrino flavor eigenstate are not identical to the mass eigenstates. Thus, the
359 observation of neutrino oscillation results in the first evidence of physics beyond the
360 Standard Model. A minimal extension of the SM introduces three mass eigenstates,
361 $|\nu_i\rangle$ ($i = 1, 2, 3$), whose mass m_i is well defined. The unitary Pontecorvo-Maki-
362 Nakagawa-Sakata matrix transforms the mass base into the flavor base as follows

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

363 with

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

364 where c e s stand respectively for cosine and sine of the corresponding mixing
 365 angles (θ_{12} , θ_{23} and θ_{13}), δ is the Dirac CP violation phase, α_1 and α_2 are the eventual
 366 Majorana CP violation phases. Experimental results on neutrino oscillations are
 367 generally reported in terms of the mixing angles and of the squared mass splitting
 368 $\Delta m_{ab}^2 = m_a^2 - m_b^2$, where a and b represent the mass eigenstates. A summary of the
 369 current status of experimental results, albeit partial, is given in table 1.2.

Table 1.2: Summary of experimental results on neutrino oscillation parameters. **ADD CITATIONS**

	Value	Precision	Experiment
θ_{23}	45°	9.0%	Super Kamiokande, MINOS,
$-\Delta m_{32}^2$	$2.5 \cdot 10^{-3} \text{ eV}^2$	1.8%	Nova, MACRO
θ_{12}	34°	5.8%	SNO, Gallex,
$-\Delta m_{12}^2$	$7.4 \cdot 10^{-5} \text{ eV}^2$	2.8%	SAGE, KamLAND
θ_{13}	9°	4.7%	DAYA Bay,
$-\Delta m_{32}^2$	$2.5 \cdot 10^{-3} \text{ eV}^2$	1.8%	RENO

370 1.2.3 Make up of Neutrino Interactions

371 All neutrino experiments involving the detection of single neutrinos are concerned
 372 with neutrino interactions (and neutrino cross sections) on nuclei. Given the invis-
 373 ible nature of the neutrino, characterizing the products of its interaction is the only
 374 method to a) assess the neutrino presence, b) detect its flavor in case of a charge
 375 current interaction and c) eventually reconstruct its energy.

376 Historically, neutrino interactions with the nucleus in the GeV region are divided
 377 into three categories into three categories whose contributions change as a function

378 of increasing neutrino energy:: quasi elastic (QE), resonant (RES), and deep inelastic
379 (DIS) scattering. All current and forthcoming oscillation experiments on neutrino
380 beams live in the 0.1-10 GeV transition region, which encompasses the energy where
381 the QE neutrino-nucleus interaction transitions into RES and then into DIS. For
382 scattering off free nucleons, neutrino and antineutrino QE charge current scattering
383 refers to the process $\nu_l n \rightarrow l^- p$ and $\bar{\nu}_l p \rightarrow l^+ n$ where a charged lepton and single
384 nucleon are ejected in the elastic interaction. Resonant scattering refers to an inelas-
385 tic collision producing a nucleon excited state (Δ, N^*) – the resonance – which then
386 quickly decays, most often to a nucleon and single-pion final state. DIS refers to the
387 head-on collision between the neutrino and a parton inside the nucleon, producing
388 hadronization and subsequent abundant production of mesons and nucleons. In addi-
389 tion to such interactions between the neutrino and a single component of the nucleus,
390 neutrinos can also interact with the nucleus as a whole, albeit more rarely, a well
391 documented process called coherent meson production scattering [58]; the signature
392 of such process is the production of a distinctly forward-scattered single meson final
393 state, most often a pion. This simple picture of neutrino interactions works rather
394 well for scattering off of light nuclear targets, such as the H₂ and D₂ of bubble cham-
395 ber experiments [64], but the complexity of the nuclear structure for heavier nuclei
396 such as argon complicates this model.

397 As we will discuss in Chapter 2, the properties of argon make it a good candidate
398 for an interacting medium in neutrino experiments; in particular the density of its
399 interaction centers increases the yield of neutrino interactions and allows for relatively
400 compact detectors. Though, the choice of a relatively heavy nuclear target comes at
401 the cost of enhancing nuclear effects which modify the kinematic and final state of
402 the neutrino interaction products.

403 Nuclear effects can potentially affect neutrino event rates, final state particle emis-
404 sion, neutrino energy reconstruction, and the neutrino/antineutrino ratios, carrying

405 deep implications for oscillation experiments. Even in the case of “simple” QE scat-
406 tering, intra-nuclear hadron rescattering and correlation effects between the target
407 nucleons can cause the ejection of additional nucleons in the final state, modifying
408 the final state kinematics and topology. In the case of resonant and DIS scattering,
409 the hadronic interactions of meson and nucleons produced in the decay of the res-
410 onance or during hadronization complicate this picture even more. A large source
411 of uncertainty in modeling nuclear effects in neutrino interactions come from mesons
412 interactions (and re-interactions) in the nucleus, e.g., pion re-scattering, charge ex-
413 change, and absorption.

414 A renewed interest for neutrino cross section measurements surged in recent years,
415 along with a lively discussion on the data reporting; the historical method of reporting
416 the neutrino cross section as a function of the neutrino energy or momentum trans-
417 fered shakes under the weight of its dependency on the chosen nuclear model. On one
418 hand, correcting for nuclear effects in neutrino interaction can introduce unwanted
419 sources of uncertainty and model dependency especially due to the mis-modeling of
420 the meson interactions. On the other, avoiding this correction makes a comparison
421 between neutrino interactions on different target nuclei extremely difficult.

422 Data on neutrino scattering off many different nuclei are available for both charged
423 current (CC) and neutral current (NC) channels, as summarized in [64]. A summary
424 of the results on QE, resonant and DIS scattering for neutrinos and antineutrinos from
425 accelerators on different target is reported in Figure 1.1, where the (NUANCE) [37]
426 event generator is used as comparison with the theory.

427 1.3 Beyond the Standard Model

428 The discovery of neutrino oscillation and its implication of non-zero neutrino mass
429 mark the beginning of a new, exciting era in neutrino physics: the era of physics Be-

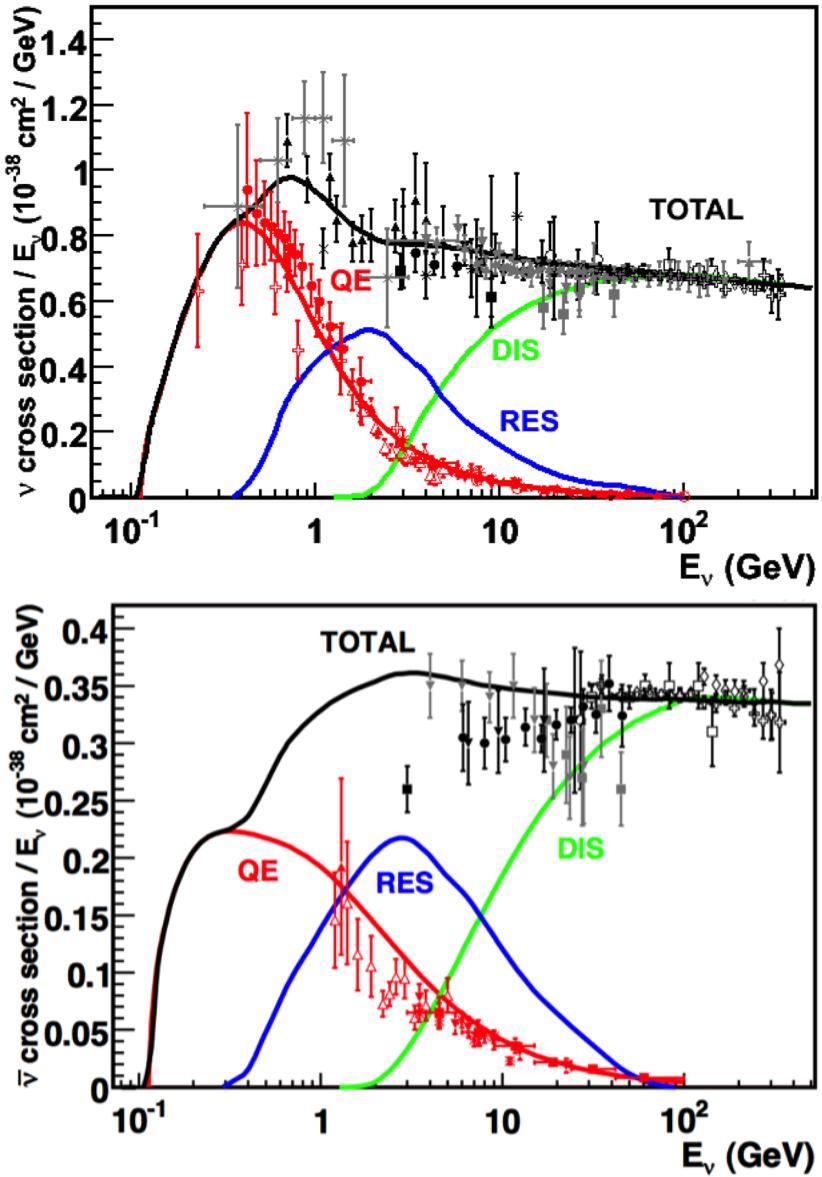


Figure 1.1: Total neutrino (top) and antineutrino (bottom) CC cross sections per nucleon divided by neutrino energy as a function of energy as reported in [64]. Predictions for the total (black), the QE (red), resonant (blue) and DIS (green) are provided by the NUANCE generator. The quasi-elastic scattering data and predictions have been averaged over neutron and proton targets (isoscalar target).

430 yond the Standard Model (BSM) at the intensity frontier. We are currently searching
431 for new, deeper theories that can accommodate neutrinos with tiny but non-zero
432 masses, while remaining consistent with the rest of the Standard Model.

433 1.3.1 Open Questions in Neutrino Physics

434 On one hand, the last three decades of experiments in neutrino oscillations brought
435 spectacular advancements in the understanding of the oscillations pattern, measuring
436 the neutrino mixing angles and mass splitting with a precision of less than 10%. On
437 the other, they opened the field for a series of questions needing experimental answers.

438 **Sterile neutrinos.** Hints to the existence of at least one additional neutrino,
439 in the form of various anomalies, have been puzzling physicists almost from the be-
440 ginning of neutrino oscillation searches. Originally designed to look for evidence of
441 neutrino oscillation, the Liquid Scintillator Neutrino Detector (LSND) [54] provided
442 a first conflicting result with the Standard Model expectation of only three neutrinos.
443 A second conflicting result has also been provided by the MiniBooNE experiment [50].

444 The LSND and MiniBooNE ν_e and $\bar{\nu}_e$ appearance results, known as the “LSND and
445 MiniBooNE anomalies” [14, 15, 23], may be interpreted under the assumption of a new
446 right-handed neutrino. The additional neutrino needs to be “sterile”, i.e needs not
447 to couple with the electroweak force carriers, in order to meet the constraint imposed
448 by the measurement of the width of the Z boson [2]. The new sterile neutrino would
449 mainly be composed of a heavy neutrino ν_4 with mass m_4 such that $m_1, m_2, m_3 \ll m_4$
450 and $\Delta m^2 = \Delta m_{14}^2 \sim [0.1 - 10] \text{ eV}^2$. The introduction of sterile neutrinos is an ap-
451 pealing line of thinking, since this renormalizable generalization of the SM has the
452 potential to impact long standing questions in high energy physics and cosmology:
453 light sterile neutrinos are candidates for dark matter particles and there are ideas
454 that the theory could be adjusted to explain the baryon asymmetry of the Universe
455 via leptogenesis [72].

456 **CP Violation In Lepton Sector.** The measurement of non-zero value for the
 457 oscillation parameter θ_{13} allows the exploration of low-energy CP violation in the lep-
 458 ton sector at neutrino long baseline oscillation experiments, enabling the possibility
 459 to measure the Dirac CP-violating phase δ . Exciting theoretical results tie δ directly
 460 to the generation of the baryon asymmetry of the Universe at the Grand Unified
 461 Theory scale **a couple of cit would be nice**. According to the theoretical model de-
 462 scribed in [101], for example, leptogenesis can be achieved if $|\sin \theta_{13} \sin \delta| > 0.11$, i.e.
 463 $\sin \delta > 0.7$.
 464 The asymmetry in the oscillation probability of neutrinos and antineutrinos is the ob-
 465 servable sensitive to the Dirac CP-violating phase δ leveraged in neutrino oscillation
 466 experiments. Using the parameterization of the PMNS matrix shown in Equation
 467 1.9, the difference between the probability of $\nu_e \rightarrow \nu_\mu$ oscillation and the probability
 468 of $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ oscillation can be parametrized as follows [39],

$$P_{\nu_e \rightarrow \nu_\mu} - P_{\bar{\nu}_e \rightarrow \bar{\nu}_\mu} = J \cos \left(\pm \delta - \frac{\Delta_{31} L}{2} \right) \sin \left(\frac{\Delta_{21} L}{2} \right) \sin \left(\frac{\Delta_{31} L}{2} \right) \quad (1.10)$$

469 where

$$J = \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \quad (1.11)$$

470 is the Jarlskog invariant [82], L the neutrino baseline, i.e. the distance between
 471 the neutrino production and detection points, and Δ_{ab} a factor proportional to the
 472 sign and magnitude of the mass splitting. From these equations, it is clear how the
 473 relative large value of θ_{13} is a happy accident necessary not to completely suppress
 474 the sensitivity to CP violation. The equations also show how the sensitivity to δ is
 475 tied to the measurement of the least precisely measured mixing angle, θ_{23} (via the
 476 $\sin 2\theta_{23}$ term) and to an other unknown quantity, the neutrino “mass hierarchy” (via
 477 the Δ_{ab} terms). The precise determination of θ_{23} is often referred as to “the octant
 478 problem”. Current experimental results [3, 12] are consistent with $\theta_{23} = 45^\circ$, which

479 would imply maximal mixing between ν_μ - ν_τ , hinting to an intriguing new symmetry.
480 Therefore, a precise measurement of θ_{23} is of great interest for theoretical models of
481 quark-lepton universality [75, 93, 106], whose quark and lepton mixing matrices are
482 proportional to the deviation of θ_{23} from 45°.

483 **Neutrino mass hierarchy.** The “mass hierarchy” problem refers to the unknown
484 ordering of the value of absolute mass of the neutrino mass eigenstates. Current
485 oscillation experiments are sensitive only to the magnitude of the mass splitting, and
486 not directly to its sign. In a framework where the lightest neutrino mass (arbitrarily)
487 corresponds to the first eigenstate m_1 , it is unknown whether $m_2 - m_1 < m_3 - m_1$
488 (Normal Hierarchy) or $m_2 - m_1 > m_3 - m_1$ (Inverted Hierarchy). The mass hierarchy
489 affects not only the sensitivity to CP violation searches in long baseline oscillation
490 experiments, but also the sensitivity to determine whether neutrinos are Majorana
491 particles in neutrinoless double beta decay experiments.

492 **Majorana or Dirac?** Evidence of neutrino oscillations demands the introduction
493 of a mechanism which can give mass to the neutrinos. This mechanism should possibly
494 also explain why neutrino masses are at least six orders of magnitude lower than the
495 electron mass (the second lightest SM fermion). In a description of neutrinos as Dirac
496 4-component spinors, the neutrino field acquires mass via the Higgs mechanism as
497 any other fermion of the SM. In this case, the neutrino mass is given by $m_a = \frac{y_a^\nu v}{\sqrt{2}}$,
498 where v is the Higgs VEV and y_a^ν is the Yukawa coupling between the Higgs and the
499 neutrino. The smallness of neutrino masses can only be pinned on a tiny Yukawa
500 coupling which is not justified by the theory.

501 In 1937, Majorana demonstrated that the introduction of a two components spinor is
502 sufficient to describe a massive fermion [92]. The Dirac equations of motion for the
503 chiral fields (equations 1.5 and 1.6) hold true in the case of two components spinor
504 under the assumption that the chiral components ψ_R and ψ_L are correlated through
505 the charge conjugation matrix \mathcal{C} , $\psi_R = \mathcal{C}\bar{\psi}_L$. Therefore the theory is applicable only

506 to neutral fermions. Neutrinos are the only neutral elementary particles in the SM
507 – the only possible Majorana particle candidate. This theory constructs a neutrino
508 Majorana mass term \mathcal{L}_5 of the following form in the Higgs unitary gauge

$$\mathcal{L}_5 = \frac{1}{2} \frac{gv^2}{\mathcal{M}} \nu_L^T \mathcal{C}^\dagger \nu_L, \quad (1.12)$$

509 where g is the coupling coefficient, v the Higgs VEV and \mathcal{M} a constant with the
510 dimension of the mass proportional to the scale of new physics. The \mathcal{L}_5 term would
511 introduce a non-renormalizable term in the lagrangian, since it has dimensions of
512 energy to the fifth power. This is not allowed in the SM lagrangian; however, the
513 existence of such terms is plausible if we consider the SM as an effective theory
514 at low energy, manifestation of the symmetry breaking of a more general theory at
515 higher energy, e.g. a Grand Unified Theory (GUT), and not the definitive theory.
516 The mass term in eq 1.12 implies the neutrino mass to be $m = \frac{gv^2}{\mathcal{M}}$. The coupling
517 coefficient can be of the order of any other fermion's coupling coefficient, since the
518 smallness of neutrino masses is achieved by the big value of the new physics mass
519 scale alone. This vanilla formulation is the conceptual basis for many flavors of *see-*
520 *saw mechanism* [121], which we will not discuss here in any detail. However, it is
521 fascinating how the puzzle of the neutrino mass hints to the existence of a deeper and
522 more complete theory.

523 From a kinematic point of view, Dirac and Majorana neutrinos satisfy the same
524 energy-momentum dispersion relationship. Thus, it is impossible to discern the neu-
525 trino nature through kinematic effects such as neutrino oscillations. Neutrinoless
526 double beta decay searches are the most promising way to understand the nature of
527 the neutrino and are therefore subject of great theoretical and experimental interest.
528 Observation of the lepton number violating process $0\nu\beta\beta$ would imply neutrinos have
529 a Majorana component. Depending on the mass hierarchy, the theory also predicts

530 $0\nu\beta\beta$ exclusion regions and confirmation of the sole Dirac component for neutrinos [44].

532

533 1.3.2 Towards a more fundamental theory: GUTs

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

536 The SM does not include a suitable dark matter candidate and a mechanisms
537 that accounts for the baryon asymmetry of the universe. Additionally, up to a total
538 of 25 parameters remain seemingly arbitrary and need to be fitted to data: 3 gauge
539 couplings, 9 charged fermion masses, 3 mixing angles and one CP phase in the CKM
540 matrix, the Higgs mass and quartic coupling, θ_{QCD} , 3 neutrino mixing angles, 1 Dirac
541 phase and, eventually, 2 Majorana phases.

542 From a group theory perspective, the SM has a rather complex group structure,
543 where a gauge group is formed with the direct product of other three groups as shown
544 in eq. 1.1. Drawing a parallel with the electroweak symmetry breaking mechanism,
545 where the $SU(2)_L \otimes U(1)_Y$ is recovered from $U(1)_{EM}$, an interesting line of simplification
546 for the SM group structure would be to devise a similar mechanism where
547 $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ is recovered from an hypothetical larger group. IS THIS
548 CORRECT? Just as the electroweak unification becomes evident at energies higher
549 than the Higgs VEV, a direct manifestation of Grand Unification Theories (GUTs)
550 would occur at even higher energies.

551 As the smallness of neutrino masses suggests the existence of a higher mass scale,
552 an other, even stronger, hint to Grand Unification comes from the slope of running
553 of the coupling constants. The coupling constants for the electromagnetic, weak and
554 strong interactions in the SM vary as a function of the interaction energy as shown
555 in figure 1.2; they do not exactly meet under the current experimental constraints,

556 but their trend is interesting enough to push for the construction of theories where
557 perfect unification is achieved through the addition of new particles.

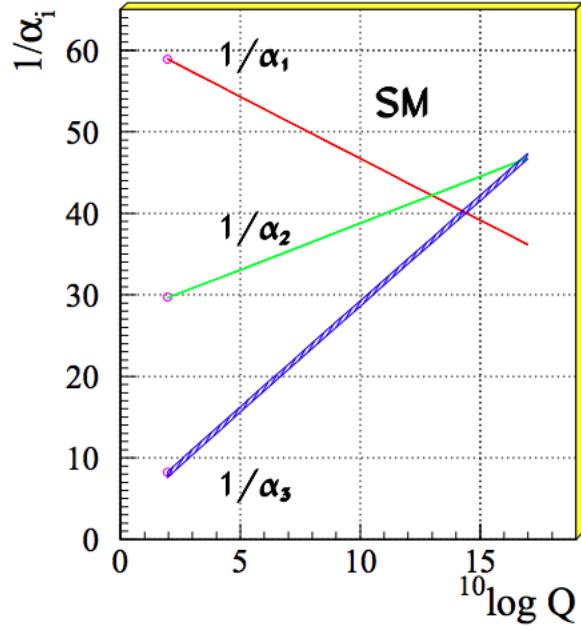


Figure 1.2: Evolution of the inverse of the three coupling constants in the Standard Model as a function of the momentum transferred, [86].

SU(5). The smallest simple group containing $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ is SU(5), as shown first by Georgi and Glashow in [68]. Quarks and leptons in this group fit the $\bar{5}$ and 10 representations. The representation for left-handed fermions are the following

$$\bar{5} = (\nu_e, e^-)_L + \bar{d}_L \quad (1.13)$$

$$10 = e_L^+ + \bar{u}_L + (u, d)_L, \quad (1.14)$$

558 while the boson structure gains a new couple of super heavy bosons (X,Y)

$$24 = \underbrace{(8, 1)}_{\text{gluons}} + \underbrace{(1, 3) + (1, 1)}_{W^\pm, Z, \gamma} + \underbrace{(3, 2) + (\bar{3}, 2)}_{X, Y \text{ bosons}}. \quad (1.15)$$

559 Nice features such as charge quantization and the identity between the positron

and proton charge value come directly from the group structure. The new super heavy bosons are colored and form a weak doublet. Their are the mediator of the interaction that turns quarks into leptons, leading to predict the existence of processes that violate baryon number, such as $p \rightarrow \pi^0 + e^+$ (see fig 1.8, right). The prediction for proton decay lifetime, $\tau_p \sim \frac{M_X^4}{m_p^5} \sim 10^{30 \pm 1.5}$ years, is unfortunately experimentally disproved by IMB and Super-Kamiokande [4, 28].

SO(10). More complicated group structures, such as SO(10) are still viable candidates for GUT. SO(10) includes the same type of X and Y bosons as SU(5). Right-handed massive neutrinos are embedded in the construction of the irreducible representation of SO(10). Different patterns of SO(10) symmetry breaking to recover the SM are possible and lead to different predictions for the proton decay lifetime; some of these predictions are not excluded by the experiments [87].

SUSY GUTs. Supersymmetry theories allow for another family of GUTs. In SUSY, every fundamental particle in the SM has a “superpartner”, identical in each quantum number except for the spin-statistics: the fermion supersymmetric partners are bosons and vice versa. Collider experiments (mainly LHC) constrain the mass of the supersymmetric partners to be very heavy [?]. The SU(5), SU(10) groups with a SUSY twist are the basic groups for SUSY GUTs. From the phenomenology point of view, SUSY models tend to push the proton decay life time higher by a factor of four, they solve the “hierarchy problem”, and they also predict new channels for the proton decay. In particular they predict the presence of kaons in the final product, with a dominant mode of $p \rightarrow K^+ \bar{\nu}$. Predictions on the proton decay lifetime depend on the chosen SUSY model; again, some of the predictions are not excluded by the experiments [90, 91, 110].

584 **1.4 Motivations for Hadronic Cross Sections in Ar-**
585 **gon**

586 Critical challenges await the next decade of high energy physics at the intensity
587 frontier. Following the recommendation of the latest Particle Physics Project Priori-
588 tization Panel [107], the US is dedicating substantial resources to the development of
589 a short- and long- baseline neutrino program to address many of open questions in
590 neutrino physics today. This program pivots on the Liquid Argon Time Projection
591 Chamber (LArTPC) detector technology which will be described in Chapter 2.

592 The main goals of these research programs include:

- 593 - the assessment of the existence of right-handed sterile neutrinos via the study
594 of accelerator neutrinos on a short baseline (SBN),
- 595 - the determination of the sign of Δm_{13}^2 (or Δm_{23}^2), i.e., the neutrino mass hier-
596 archy via the study of accelerator neutrinos on a long baseline (DUNE),
- 597 - the determination of the octant, i.e. whether θ_{23} is maximal, via the study of
598 accelerator neutrinos on a long baseline (DUNE),
- 599 - the determination the status of CP symmetry in the lepton sector, via the study
600 of accelerator neutrinos on a long baseline (DUNE),
- 601 - the search for observables predicted by GUTs, such as proton decay via the
602 study of non accelerator physics in massive underground detectors (DUNE).

603 **1.4.1 Pion-Argon Total Hadronic Cross Section**

604 This section outlines the importance of the pion-argon total hadronic cross section in
605 the context of the current and upcoming liquid argon neutrino experiments, SBN and
606 DUNE. We describe the signal signature and historic measurements of pion-nucleus

607 cross section, as well as the implementation of these cross sections in the current
608 version of the simulation package used by LArIAT.

609 **π^- Ar Cross Section in the Context of Neutrino Searches**

610 As outlined in 1.2.3, neutrino experiments use the products of neutrino interactions
611 to identify the energy and flavor of the incoming neutrino. Pions are a common
612 product of neutrino interaction, especially in resonant scattering, DIS and coherent
613 pion production. For neutrino experiments in argon, there are two main reasons
614 why understanding pion hadronic interactions with argon is important: to model the
615 behavior of the pion inside the target nucleus and to model the behavior of the pion
616 during its propagation inside the detector medium.

617 Assumptions on the nuclear modeling and on the interaction of hadrons inside the
618 nucleus performed at the level of the neutrino event generator bridge the measure-
619 ment of the products of a neutrino interaction to the reconstruction of the neutrino
620 energy and flavor. Thus, understanding pion hadronic interactions with the nucleus is
621 particularly important to model correctly resonant, DIS and coherent pion production
622 in neutrino interactions. For example, in case of resonant scattering,

$$\nu_l + N \rightarrow l + \Delta/N^* \rightarrow l + \pi + N', \quad (1.16)$$

623 the Δ and N^* and excited states will decay hadronically in matters of $\sim 10^{-24}$ s
624 inside the nucleus producing pions which will have many chances to re-interact
625 as they exit the target medium. The decay modes for the lower mass Δ (1232) and
626 $N^*(1440)$ are listed in table 1.3.

627 The key elements of a neutrino event generators for resonance and DIS events
628 are the nuclear model and the hadron treatment (both production and transporta-
629 tion). We illustrate here the conceptual basis of the GENIE Neutrino Generator [18]

630 as an example, since GENIE is one the most popular event generators for liquid ar-
631 gon experiments. For example, the nuclear model used by GENIE for all processes
632 is a Relativistic Fermi Gas (RFG) model modified to incorporate nucleon-nucleon
633 correlations [30]. This means that the initial momentum and binding energy of the
634 struck nucleon is determined by assuming nucleons inside the nucleus are quasi-free,
635 acting independently in the mean field of the nucleus. For $A > 20$ such as argon, the
636 2-parameter Woods-Saxon shell model for density function is used. The GENIE mod-
637 ule INTRANUKE [85] is used to simulate final-state interactions (FSI) which model
638 hadron re-interactions inside the nucleus. This module places the outgoing parti-
639 cles in the nucleus and propagates them using the “hA model”. In the INTRANUKE
640 hA model, hadrons can undergo at most one FSI per event. When possible, external
641 hadron-nucleus scattering data are used to tune INTRANUKE. Since no data is avail-
642 able for Argon, GENIE uses an interpolation of data from heavier and lighter nuclei
643 for the pion-argon cross section leading to large (10?s of %) resultant uncertainties in
644 the INTRANUKE module.

645 Once the pion has left the target nucleus, the pion-argon hadronic cross section also
646 plays an important role in the pion transportation inside the argon medium: processes
647 such as pion absorption or pion charge exchange can greatly modify the topology of
648 a neutrino interactions in the detector and lead to significant modifications in the
649 event classification. Being able to reconstruct the details of pions inside the detector
650 is an imperative for modern liquid argon neutrino experiment to achieve the design
651 resolution for their key physics measurements.

652 π^- -Ar Hadronic Interaction: Signal Signatures

653 Strong hadronic interaction models [49, 70] predict the pion interaction processes with
654 argon in the [100 - 1200] MeV energy range. The total hadronic π^- -Ar interaction
655 cross section is defined as the one related to the single process driven only by the

656 strong interaction which is dominant in the considered energy range. In measuring
657 the “total” cross section, we include both the elastic and reaction channels, regardless
658 of the final state,

$$\sigma_{Tot} = \sigma_{Elastic} + \sigma_{Reaction}; \quad (1.17)$$

659 the reaction channel is further characterized by several exclusive channels with defined
660 topologies,

$$\sigma_{Reaction} = \sigma_{Inelastic} + \sigma_{abs} + \sigma_{chex} + \sigma_{\pi prod}. \quad (1.18)$$

661 A summary of the pion final states in order of pion multiplicity for the reaction
662 channel is given in table 1.4. Pion capture and pion decay at rest dominate the
663 cross section under 100 MeV. We define pion capture as the process determining the
664 formation of a pionic atom and the subsequent pion’s end of life. Stopping negative
665 pions can form pionic argon, where the negative pion plays the role of an orbital
666 electron. Since the pion mass is two orders of magnitude greater than the electron
667 mass, the spatial wave form of the pion will overlap more with the nucleus compared
668 to the electron case. After the electromagnetic formation of the pionic atom, the
669 pion will get quickly absorbed by the nucleus, which is put in an excited state. The
670 nucleus then de-excites with the emission of low energy nucleons and photons. Pion
671 capture is dominant compared to pion decay, the other important process for very
672 low energy pions. The decay of a pion is governed by the weak force; the pion decay
673 life time is $\tau_\pi = 2.6 \times 10^{-8}$ s and the main decay mode is $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$ (BR 99.98%).
674 Since pion capture can be considered an electromagnetic process and pion decay is a
675 weak process, this energy region is purposely excluded from the hadronic cross section
676 measurement.

677 **Previous measurements: Lighter and Heavier Nuclei**

678 Many experiments with pion beams have studied the hadronic interaction of pions on
679 light and heavy materials, such as He, Li, C, Fe, Pb [36]. However, data on argon are
680 rare: the total differential hadronic cross section has never been measured before on
681 argon. Simulation packages such as Geant4 base their pion transportation for argon
682 on data from lighter and heavier nuclei: the goal of LArIAT’s dedicated measurement
683 on argon is to bridge this gap in data, thus reducing the uncertainties related to pion
684 interactions in argon in both neutrino event generators and in simulation packages of
685 pion transportation.

686 The shape of the pion-nucleus interaction cross section in the energy range con-
687 sidered shows the distinct features indicating the presence of a resonance. In fact, the
688 mean free path of a pion of kinetic energy between 100 and 400 MeV is much shorter
689 than the average distance between nucleons (which is of the order of 1 fm). There-
690 fore, the pion interacts with surface nucleons. A Δ resonance is often produced in
691 the interaction, which subsequently decays inside the nucleus. Experimental results
692 on several nuclei as reported in [36] are shown in Figure 1.3; it is interesting to notice
693 here how the shape of the Δ resonance becomes less pronounced as a function of the
694 mass number of the target nucleus. Pion interactions with heavier nuclei also shift the
695 peak of the resonance at lower energy; this effect is due to kinematic considerations
696 and to the difference in propagation of the Δ inside the nucleus. Multiple scattering
697 effect modify the resonance width, which is larger than the natural-decay width. As
698 an example of a fairly well studied target, Figure 1.4 reports the negative pion cross
699 section on Carbon for the elastic and reaction² channels, and their sum [55].

2. This paper calls “inelastic interaction” what we refer as to “reaction channel”.

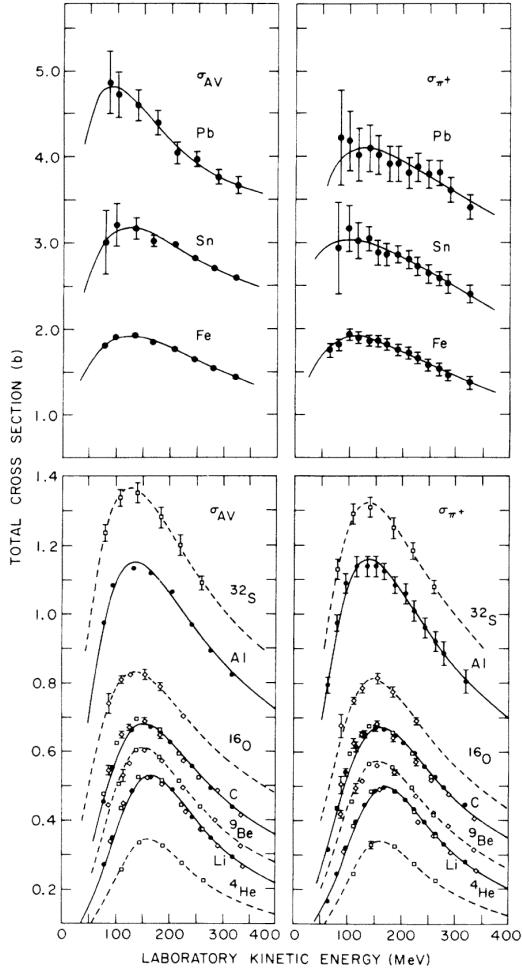


Figure 1.3: Pion-nucleus total cross sections: σ_{π^+} for positive pions (right) and σ_{AV} (left) for the average between positive and negative pions $\sigma_{AV} = \frac{\sigma_{\pi^+} + \sigma_{\pi^-}}{2}$ in the Δ resonance region. The error bars include estimates of systematic uncertainties. The curves are the results of fits to the data assuming a Breit-Wigner shape. This summary plot is reported in [36] and uses data from [52, 117].

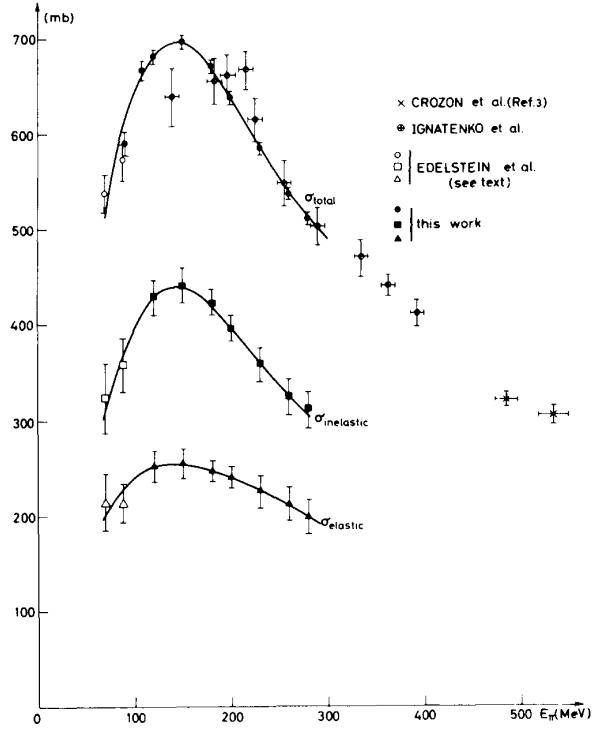


Figure 1.4: Negative pion nucleus total, elastic and reaction cross sections on ^{12}C as from [55].

700 Negative Pion Interaction Cross Section in Simulation Packages

701 LArIAT uses Geant4 as the default simulation package. In particular, pions (and
 702 kaons) transportation is achieved through the Geant4 FTFP_BERT physics list. In
 703 this physics list, Geant4 uses the Bertini cascade model [118] to simulate the products
 704 of the pion-nucleus interaction as well as secondary hadronic re-interactions inside
 705 the target nucleus (intra-nuclear cascade). The target nucleus is represented as a
 706 continuous gas where the nuclear potential follows concentrical shells whose depths
 707 approximate the Woods-Saxon shape. The CERN-HERA compilations [114, 115] of
 708 hadron-nucleon interaction data is the data base used for the decision making process
 709 after the cascade is invoked. The cross section model determines if the pion inter-
 710 acts, the eventual type of interaction and the interaction multiplicity. For hadron
 711 projectiles with energy less than 20 GeV, Geant4 reports the uncertainty on the cross

712 section model to be about the size of the error bars on the data used, or about 10%,
713 increasing to 20-30% in energy regions where data is sparse.

714 The relevance of the GENIE generator for neutrino physics and its basic working
715 principles have been outlined earlier in this section. Given GENIE’s modularity,
716 information on hadron-nucleus interactions can be extracted from the INTRANUKE
717 module and directly compared against the Geant4 predictions. The work in [98]
718 reviews the current status of negative and positive pion simulation in Geant4 and
719 GENIE for ^{12}C , ^{56}Fe , and ^{40}Ca . From that work, we report the results for ^{12}C in
720 Figure 1.5 as it allows a direct comparison between Geant4, GENIE and and pion
721 re-scattering data. Geant4 predictions for π^- on Carbon are in good agreement with
722 data over the entire spectrum spectrum, while GENIE predictions seem to show some
723 features at around 500 MeV and 900 MeV, maybe due to higher resonances in the hA
724 model. From the same work, we also report the negative pion cross section on ^{40}Ca
725 in Figure 1.6, since this is the nuclear medium closest to argon. The predictions from
726 both Geant4 and GENIE agree with data in the high energy region; the Geant4 and
727 GENIE predictions diverge in the resonance region, where data is not available. These
728 few examples highlight how cross section data for the specific nucleus considered in
729 the neutrino experiments is fundamental to inform the Monte Carlo simulation.

730 For the LArIAT simulation of the MC sample used in the π^- argon total hadronic
731 cross section measurement we use the Geant4 Bertini Cascade model, whose predic-
732 tions for the total, elastic and reaction hadronic cross sections are show in Figure
733 1.7.

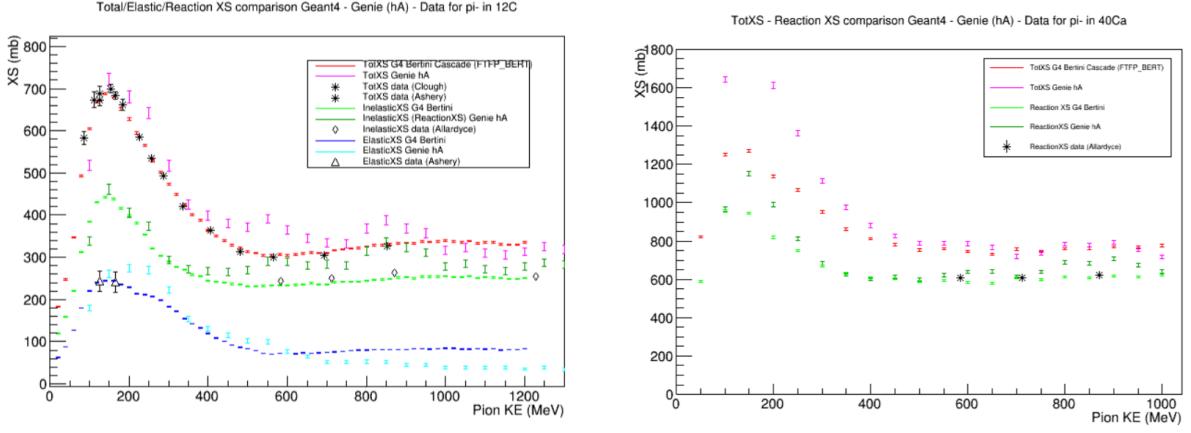


Figure 1.5: Total, elastic and reaction cross section for π^- on ^{12}C . Comparison between results from Geant4 simulation (Bertini cascade model), Genie simulation (hA model), and experimental data [22, 52, 53, 109].

Figure 1.6: Total, elastic and reaction cross section for π^- on ^{40}Ca . Comparison between results from Geant4 simulation (Bertini cascade model), Genie simulation (hA model), and experimental data [53].

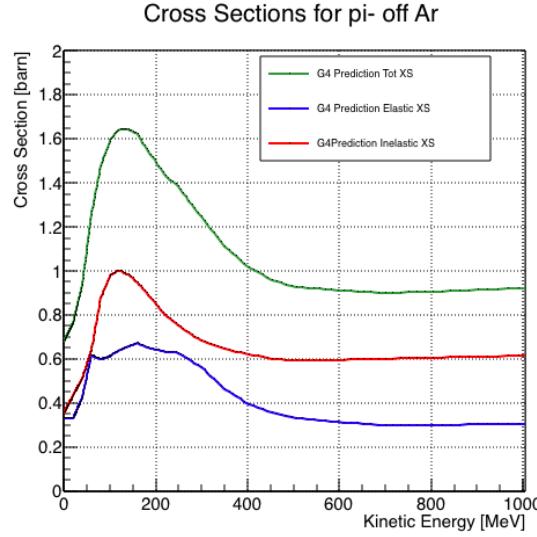


Figure 1.7: Total, elastic and reaction hadronic cross section for π^- -argon implemented in Geant4 10.01.p3.

Resonance	Decay Mode	Lifetime (s)
Δ (1232) $3/2^+$	$\Delta^{++}(\text{uuu}) \rightarrow p\pi^+$ $\Delta^+(\text{uud}) \rightarrow n\pi^+$ $\Delta^+(\text{uud}) \rightarrow p\pi^0$ $\Delta^0(\text{udd}) \rightarrow n\pi^0$ $\Delta^0(\text{udd}) \rightarrow p\pi^-$ $\Delta^-(\text{ddd}) \rightarrow n\pi^-$	$\sim 5.6 \times 10^{-24}$
N^* (1440) $1/2^+$	$N^* \rightarrow N\pi$ $N^* \rightarrow N\pi\pi$	$\sim 2.2 \times 10^{-24}$

Table 1.3: Main decay modes of the lightest Delta resonance and Nucleon excited state.

N π in FS	Channel Name	Reaction	Notes
0	Pion Absorption, σ_{abs}	$\pi^-(np) \rightarrow nn$ (2-body abs) $\pi^-(nnp) \rightarrow nnn$ (3-body abs) $\pi^-(npp) \rightarrow pnn$ (3-body abs) $\pi^-(nnpp) \rightarrow pmn$ (Multi-body abs)	Suppressed on single nucleon by energy conservation: the process occurs on at least two nucleons system.
1	Elastic Scattering, σ_{el}	$\pi^- + N \rightarrow \pi^- + N$	Scattering on nucleon or nucleus, the target is left in ground state
1	Charge Exchange, σ_{chea}	$\pi^- + p \rightarrow \Delta^0 \rightarrow \pi^0 + n$ $\pi^- + N \rightarrow \pi^+ + \text{nucleons}$	Single charge exchange: charged pion converts into neutral pion Double charge exchange: charged pion converts into opposite charge pion
1	Inelastic Scattering, σ_{inel}	$\pi^- + p \rightarrow \Delta^0 \rightarrow \pi^- + p$ (knock-out) $\pi^- + n \rightarrow \Delta^- \rightarrow \pi^- + n$ (knock-out)	Other possible reactions: Pure Inelastic scattering: population of low energy bound excited states Nuclear break-up with nucleons or fragments knock-out
2+	Pion Production, $\sigma_{\pi prod}$	$\pi^- + N \rightarrow \geq 2\pi + \text{nucleons}$	Possible if pion K.E ≥ 500 MeV/c

Table 1.4: Summary of negative pion hadronic interactions of the reaction channel as a function of the pion multiplicity in the final state in the energy range [100-1200] MeV.

734 1.4.2 Kaon-Argon Total Hadronic Cross Section

735 This section outlines the importance of the kaon-argon total hadronic cross section.
736 We start by discussing the measurement in the context of nucleon decay searches. We
737 then describe the signal signature and historical measurements of kaon-nucleus cross
738 section, as well as the implementation of this cross sections in the current version of
739 the simulation package used by LArIAT.

740 K⁺Ar Cross section in the Context of Nucleon Decay Searches

741 Baryon number is accidentally conserved in the Standard Model. Even though no
742 baryon number violation has been experimentally observed thus far, no underlying
743 symmetry in line with the Noether paradigm [97] explains its conservation. As shown
744 in section 1.3.2, almost all Grand Unified Theories predict at some level baryon num-
745 ber violation in the form of nucleon decay on long time-scales. Given the impossibil-
746 ity to reach grand unification energy scales with collider experiments (Energy Scale
747 $> 10^{15}$ GeV), an indirect proof of GUTs is needed. The experimental observation of
748 nucleon decay may be the only viable way to explore these theories.

749 In case of nucleon decay discovery, the dominant decay mode may uncover addi-
750 tional information about the GUT type. Supersymmetric GUTs [24, 46] prefer the
751 presence of kaons in the products of the decay, e.g. $p \rightarrow K^+ \bar{\nu}$ (see fig 1.8, left).
752 Gauge mediated GUTs, in which new gauge bosons are introduced that allow for the
753 transformation of quarks into leptons, and vice versa, prefer the mode $p \rightarrow e^+ \pi^0$ (see
754 fig 1.8, right).

755 LArIAT tiny active volume makes it impossible for the experiment to place com-
756 petitive limits on nucleon decay searches. However, LArIAT provides excellent data
757 to characterize kaons in liquid argon for the “LAr golden mode”, $p \rightarrow K^+ \bar{\nu}$. The
758 result of these studies will affect future proton decay searches in LArTPCs. Previous
759 work has been done to assess the potential identification efficiency for different decay

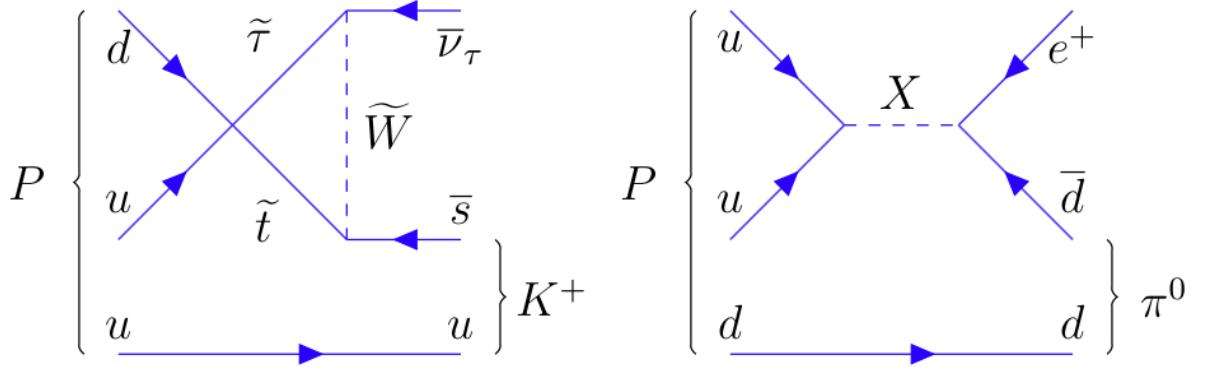


Figure 1.8: Feynman diagrams for proton decay “golden modes”: $p \rightarrow K^+\bar{\nu}$ for supersymmetric GUTs on the left and $p \rightarrow e^+\pi^0$ for gauge-mediated GUTs on the right.

760 modes in a LArTPC [51], but, as the time of this writing, no study of kaon selection
 761 efficiency in LArTPCs has been performed on data. The K^+ -Ar interaction cross
 762 section has never been measured before and can affect the possibility of detecting
 763 and measuring kaons when produced in a proton decay event. Kaon interactions with
 764 argon can distort the kaon energy spectrum as well as change the topology of single
 765 kaon events. In a LArTPC, non-interacting kaons appear as straight tracks with a
 766 high ionization depositions at the end (Bragg peak). The topology of interacting
 767 kaons can be quite different. In case of elastic scattering, a distinct kink will be
 768 present in the track. In case of inelastic scattering the Bragg peak will not be present
 769 and additional tracks will populate the event. Performing the total hadronic K^+ -Ar
 770 cross section measurement on data serves the double purpose of identifying the rate
 771 of “unusual” topologies (kinks and additional tracks) and of developing tools for kaon
 772 tracking in LAr.

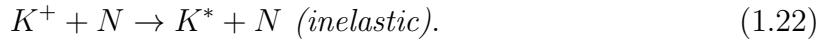
773 **K^+ Ar Hadronic Interaction: Signal Signatures**

The interaction of a mildly relativistic charged kaon with an argon nucleus is determined largely by the strong force. The total hadronic K^+ -Ar interaction cross section

is defined as the one related to the single (hadronic) process driven only by the strong interaction. In this case, “total” indicates all strong interactions regardless of the final state. This condition purposefully includes both elastic and inelastic (reaction) channels. Indeed, the total cross section section can be then decomposed into

$$\sigma_{Tot} = \sigma_{Elastic} + \sigma_{Reaction}.$$

774 For the LArIAT cross section analysis, the kaons considered span a momentum
775 inside the TPC from 100 MeV/c to 800 MeV/c. In this energy range, the relevant
776 K-Nucleon interactions are according to [63]:



777 **Previous Measurements: Lighter and Heavier Nuclei**

778 In general, measurements on kaon cross sections are extremely scarce. The mea-
779 surement of the kaon interaction cross section would bring the additional benefit
780 of reducing the uncertainties associated with hadron interaction models adopted in
781 MC simulations for argon targets, beneficial for both proton decay studies and kaon
782 production from neutrino interaction studies, where the uncertainties for final state
783 interaction models are big [47].

784 Figure 1.9 shows a 1997 measurement on several elements as performed by Fried-
785 mann et al. [65]. As a reference, this paper measures a σ_{Tot} for Si of 366.5 ± 4.8
786 mb and a σ_{Tot} for Ca of 494.6 ± 7.7 mb at 488 MeV/c. The cross section for argon

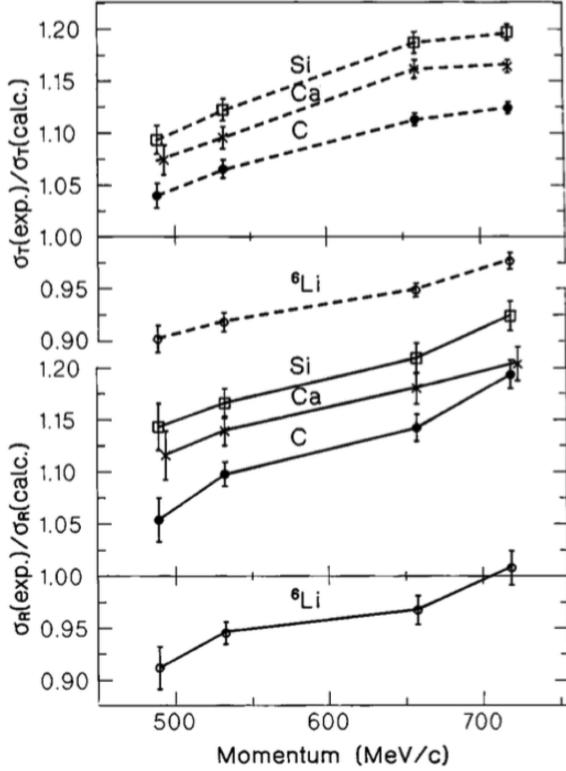


Figure 1.9: Ratios between experimental and calculated cross sections as from [65].
Top: Total cross sections.
Bottom: reaction cross sections.

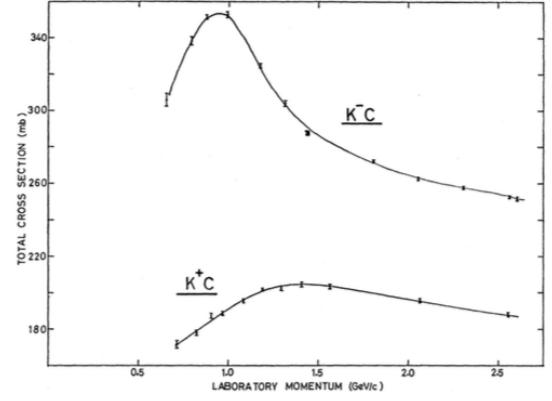


Figure 1.10: Total K^+ and K^- cross sections on carbon as from [32].

is expected to lie in between these two measurements. Additional data on the kaon cross section are provided by Bugg et al. [32]. Bugg performs a measurement of the total K^+ and K^- cross sections on protons and deuterons over the range of 0.6-2.65 GeV/c, as well as a measurement of the total K^+ and K^- cross sections on carbon for a number of momenta; the results of this paper on carbon are reported in Figure 1.10.

793 Kaon Interaction Cross Section for thin target in Geant4

Since the kaon cross section in argon has never been measured before, simulation packages tune kaon transportation in argon by extrapolation from lighter and heavier nuclei. LArIAT uses the Geant4 suite for particle transportation. Since kaon data on

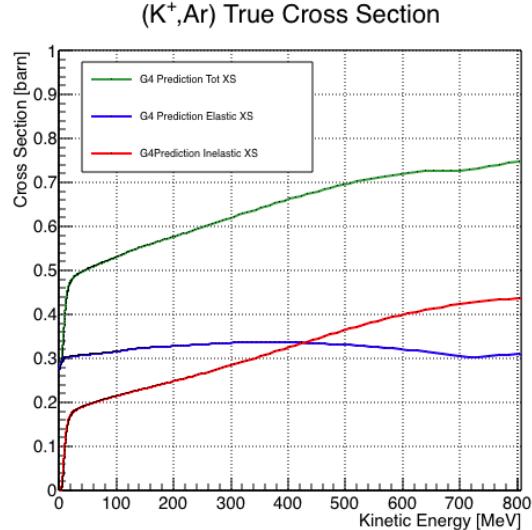
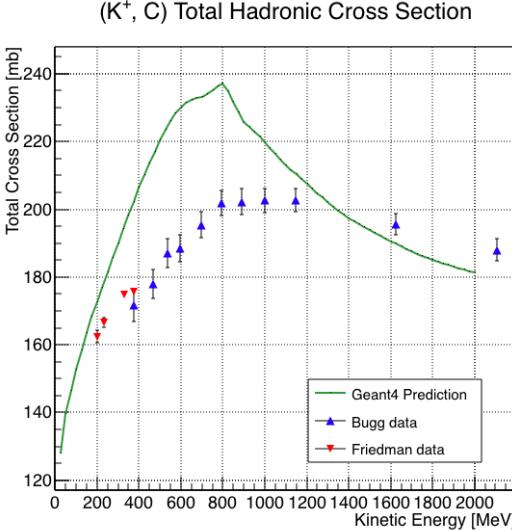


Figure 1.11: Total hadronic cross section for carbon implemented in Geant4 10.01.p3 with overlaid with the Bugg and Friedman data.

Figure 1.12: Total, elastic and reaction hadronic cross section for K^+ -argon implemented in Geant4 10.01.p3.

carbon are available, we used it as a metric to evaluate the Geant4 prediction performances. Figure 1.11 shows the total hadronic cross section for carbon implemented in Geant4 10.01.p3 overlaid with the Bugg and Friedman data. Unfortunately, version 10.01.p3³ of Geant4, which is the version used for the simulation in this work, does not reproduce the data for carbon closely. On one hand, this evidence makes us even more wary when using the Monte Carlo in simulating the kaon-argon interactions. On the other, it further highlights the importance of the kaon measurement. For the LArIAT simulation of the MC sample used in the K^+ argon total hadronic cross section measurement we use the Geant4 Bertini Cascade model, whose predictions for the total, elastic and reaction hadronic cross sections are show in Figure 1.12.

3. It should be noted that the latest Geant4 version, 10.03.p3, uses a different parametrization for the kaon cross section and retrieves a better agreement with data.

807 **Chapter 2**

808 **Liquid Argon Detectors at the**
809 **Intensity Frontier**

810 “*Don’t you know, honey,*
811 *Ain’t nobody ever gonna love you, the way I try to do?*”
812 – Janis Joplin, 1971 –

813 In the next few years, LArTPCs will be the tools to answer some of the burning
814 questions in neutrino physics today. This chapter illustrates the operational principles
815 of this detector technology, as well as the scope of the key detectors in the US liquid
816 argon program – SBN, DUNE and LArIAT.

817 **2.1 The Liquid Argon Time Projection Chamber**
818 **Technology**

819 In this section, we outline an extremely brief history of Time Projection Chambers
820 as particle detectors, focusing on their incarnation as Argon detectors for neutrino
821 physics. We further describe the working principles of Liquid Argon Time Projection

822 Chambers, leading to the description of the event reconstruction in LArTPC.

823 2.1.1 TPCs, Neutrinos & Argon

824 David Nygren designed the first Time Projection Chamber (TPC) in the late 1970s [99]
825 for the PEP-4 experiment, a detector apt to study electron-positron collisions at the
826 PEP storage ring at the SLAC National Accelerator Laboratory. From the original
827 design in the seventies – a cylindrical chamber filled with methane gas – the TPC
828 detector concept has seen many incarnations, the employment of several different
829 active media and a variety of different particle physics applications, including, but
830 not limited to the study of electron/positron storage rings (e.g. PEP4, TOPAZ,
831 ALEPH and DELPHI), heavy ions collisions in fixed target and collider experiments
832 (e.g. EOS/HISSL and ALICE), dark matter (ArDM), rare decays and capture (e.g.
833 TRIUMF, MuCap), neutrino detectors and nucleon decay (ICARUS, SBN, DUNE),
834 and neutrino less double beta decay (Next). A nice review of the history of TPCs
835 and working principles is provided in [78].

836 Several features of the TPC technology make these detectors a more versatile tool
837 compared to other ionization detectors and explain such a wide popularity. TPCs are
838 the only electronically read detector which deliver simultaneous three-dimensional
839 track information and a measurement of the particle energy loss. Leveraging on both
840 tracking and calorimetry, particle identification (PID) capabilities are enhanced over
841 a wide momentum range.

842 Historically, the active medium in ionization detectors has been in the gaseous
843 form. Carlo Rubbia first proposed the use of a Liquid Argon TPC for a neutrino
844 experiment, ICARUS [108], in 1977. Using nobles elements in the liquid form for
845 neutrino detectors is advantageous for several reasons. The density of liquids is \sim 1000
846 times greater than gases, augmenting the number of targets for neutrino's interaction
847 in the same volume, in a effort to balance the smallness of neutrino cross section. Since

Element	LAr	LXe
Atomic Number	18	54
Atomic weight A	40	131
Boiling Point Tb at 1 atm	87.3 K	165.0 K
Density	1.4 g/cm ³	3.0 g/cm ³
Radiation length	14.0 cm	2.8 cm
Moliere Radius	10.0 cm	5.7 cm
Work function	23.6 eV	15.6 eV
Electron Mobility at $E_{field} = 10^4$ V/m	0.047 m ² /Vs	0.22 m ² /Vs
Average dE/dx MIP	2.1 MeV/cm	3.8 MeV/cm
Average Scintillation Light Yield	40000 γ /MeV	42000 γ /MeV
Scintillation λ	128 nm	175 nm

Table 2.1: LAr, LXe summary of properties relevant for neutrino detectors.

the energy loss of charged particle is proportional to the target material density, as shown in the Bethe-Block equation (eq. 2.1), the increased density reflects into a proportionally higher energy loss, enhancing the calorimetry capability of detectors with a liquid active medium. Additionally, the ionization energy of liquids is smaller than gasses by the order of tens of eV. Thus, at the passage of charged particles, liquids generally produce more ionization electrons than gases for the same deposited energy, forcing the particles to deposit more energy in a shorter range. The downside of using noble liquid elements in experiments is that they require expensive cryogenic systems to cool the gas until it transitions to its the liquid form. The properties of liquid argon in comparison liquid xenon – a popular choice for dark matter and neutrinoless double beta decay detectors – are summarized in table 2.1. Albeit xenon would be more desirable than argon given some superior properties such as lower ionization energy and higher density and light yield, argon relative abundance abates the cost of argon compared to xenon, making argon a more viable choice for the construction of ton (and kilo-ton) scale neutrino detectors.

LArTPCs are some times referred as to “electronic” bubble-chambers, for the similarity in the tracking and energy resolution which is coupled with an electronic readout of the imaging information in LArTPCs. Compared to these historic detectors

866 however, LArTPC bestow tridimensional tracking and a self triggering mechanism
867 provided by the scintillation light in the liquid argon. An event display of a ν_μ CC
868 interaction candidate in the MicroBooNE detector is shown in picture 2.1 to display
869 the level of spatial details these detectors are capable of; the color scale of the image
870 is proportional to the energy deposited, hinting to these calorimetry capabilities of
the detectors.

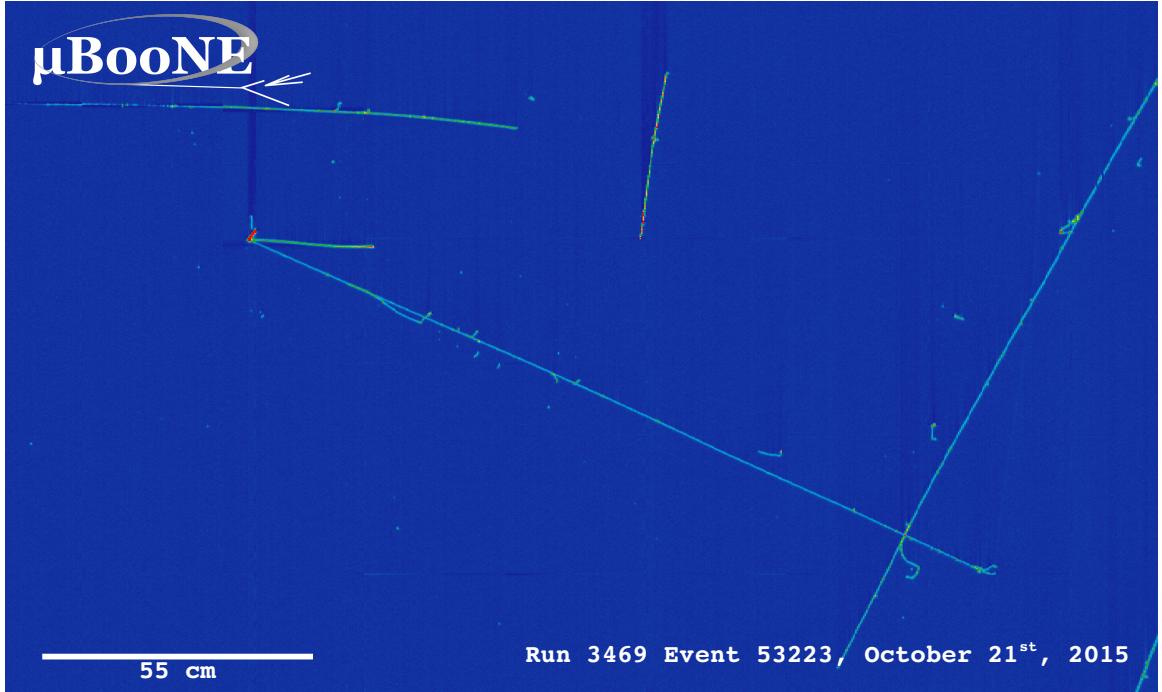


Figure 2.1: Event display of a ν_μ CC interaction candidate in the MicroBooNE detector.

871

872 2.1.2 LArTPC: Principles of Operation

873 To the bare bones, a LArTPC is a bulk of liquid argon sandwiched in a flat capacitor,
874 equipped with a light collection system, as the cartoon in 2.2 shows. A uniform
875 electric field of the order of 500 V/cm is maintained constant between the faces of the
876 capacitor. The anode is sensitive to ionization charge and it is usually made of two
877 or more planes segmented into several hundreds parallel sense wires a few millimeters
878 apart; different geometries for the anode segmentation are under study [48].

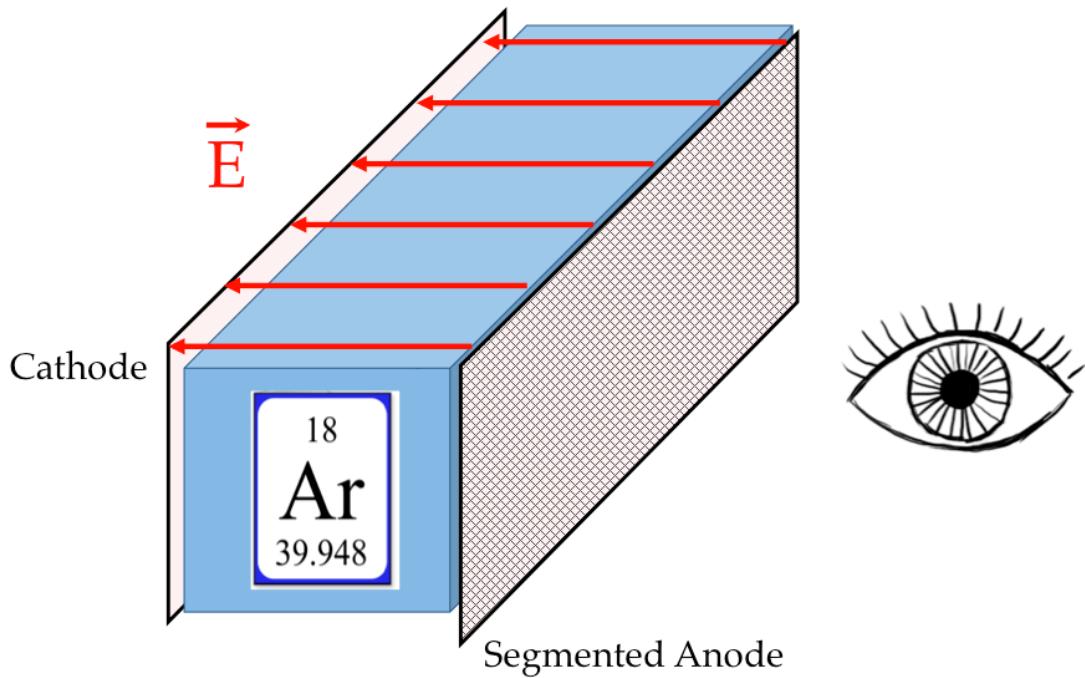


Figure 2.2: A cartoonish sketch of a LArTPC.

Argon ionization and scintillation are the processes leveraged to detect particles in the LArTPC active volume. When a ionizing radiation traverses the argon active volume it leaves a trail of ionization electrons along its trajectory and it excites the argon producing scintillation light – details on the production and detection of ionization charge and scintillation light are provided in 2.1.4 and 2.1.4 respectively. The optical detector sees the argon scintillation light in matters of nanoseconds. This flash of light determines the start time of an event in the chamber, t_0 . The uniform electric field drifts the ionization electrons from the production point towards the anode in order of hundreds of microseconds or more depending on the chamber dimensions¹. The anode sense wires see either an induced current by the drifting ionization charge (on induction planes) or an injection of such charge (collection

1. The ionized argon also drifts, but in the opposite directions compared to the electrons. Since the drift time is proportional to the particle mass, the ions' drift time is much longer than the electrons'. Ionized argon is collected on the cathode which is not instrumented, so it is not used to infer information about the interactions in the chamber.

890 plane). An appropriate choice of the voltage bias on each wire plane assures ideal
891 charge transparency, so that all the ionization charge is collected on the collection
892 plane and none on the induction planes.

893 The arrival time of the charge on the anode sense wires is used to measure the
894 position of the original ionizing radiation in the drift direction. In fact, since the
895 constant electric field implies that the drift velocity is also constant, the position of
896 the original ionization is simply given by the multiplication of the drift velocity by the
897 drift time, where the “drift time” is the difference between t_0 and the charge arrival
898 time on the wire planes. The spacial resolution on this dimension is limited by the
899 time resolution of the electronics or by longitudinal diffusion of the electrons. The
900 spatial information on the different wire planes maps a bi-dimensional projection of
901 the interaction pattern in the plane perpendicular to the drift direction. The spacial
902 resolution on this dimension is limited by the transverse electron diffusion in argon
903 and by the grain of the anode segmentation, i.e. the spacing between the wires in
904 the sense planes [45]. The off-line combination of the 2-D information on the wire
905 planes with the timing information allows for the 3D reconstruction of the event in
906 the chamber.

907 Since the charge deposited by the ionizing radiation is proportional to the de-
908 posited energy and the charge collected on the sense plane is a function of the de-
909 posited charge, LArTPCs allow the measurement of the energy deposit in the active
910 volume. Effects due to the presence of free charge and impurities in the active vol-
911 ume, such as a finite electron lifetime, recombination and space charge, complicate
912 the relationship between deposited and collected charge affecting the measurement of
913 the particle’s energy, as described in the next section.

914 **2.1.3 Liquid Argon: Ionization Charge**

915 The mean rate of energy loss by moderately relativistic elementary charge particles
 916 heavier than electrons is well described by the modified Bethe-Bloch [102] equation

$$-\frac{dE}{dx} = K z^2 \frac{Z}{A} \varrho \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} \right], \quad (2.1)$$

917 where z is the number of unit charge of the ionizing radiation, Z , A and ϱ are the
 918 atomic number, mass number and density of the medium, m_e is the electron mass,
 919 $\gamma = \frac{\beta}{\sqrt{1-\beta^2}}$ is the Lorentz factor of the ionizing radiation, T_{max} is the maximum kinetic
 920 energy which can be imparted to a free electron in a single collision, I is the mean
 921 excitation energy on eV, δ is the density correction and $K = 0.307075 \text{ MeV g}^{-1} \text{ cm}^2$ is
 922 a numerical conversion factor. The Bethe-Bloch treats the energy loss by an ionizing
 923 radiation via quantum-mechanical collisions producing ionization or an excitation in
 924 the medium as an uniform and continuous process. The density correction terms
 925 becomes relevant for incident particle with high energy, where screening effects due
 926 to the polarization of the medium by high energy particles occur.

927 Excitation and ionization of the detector medium occur in similar amounts. Since
 928 the ionizing collisions occur randomly, we can parametrize their number k in a segment
 929 of length s along the track with a Poissonian function

$$P(k) = \frac{s^k}{k! \lambda^k} e^{-s/\lambda}, \quad (2.2)$$

930 where $\lambda = 1/N_e \sigma_i$, with N_e being the electron density of σ_i the ionization cross-
 931 section per electron. About 66% of the ionizing collisions in Argon produce only
 932 a single electron/ion pair [78]; in the other cases, the transferred kinetic energy is
 933 enough for the primary electron to liberate one or more secondary electrons, which
 934 usually stay close to the original pair. Occasionally, electrons can receive enough

935 energy to be ejected with high energy, forming a so-called “ δ -ray”: a detectable short
936 track off the particle trajectory, as shown in figure 2.3. The average number of δ -ray
937 with energy $E > E_0$ per cm follows the empirical form

$$P(E > E_0) \sim \frac{y}{\beta^2 E_0}, \quad (2.3)$$

938 where y is an empirical factor depending on the medium (0.114 for gaseous Ar), and
939 β is v/c .

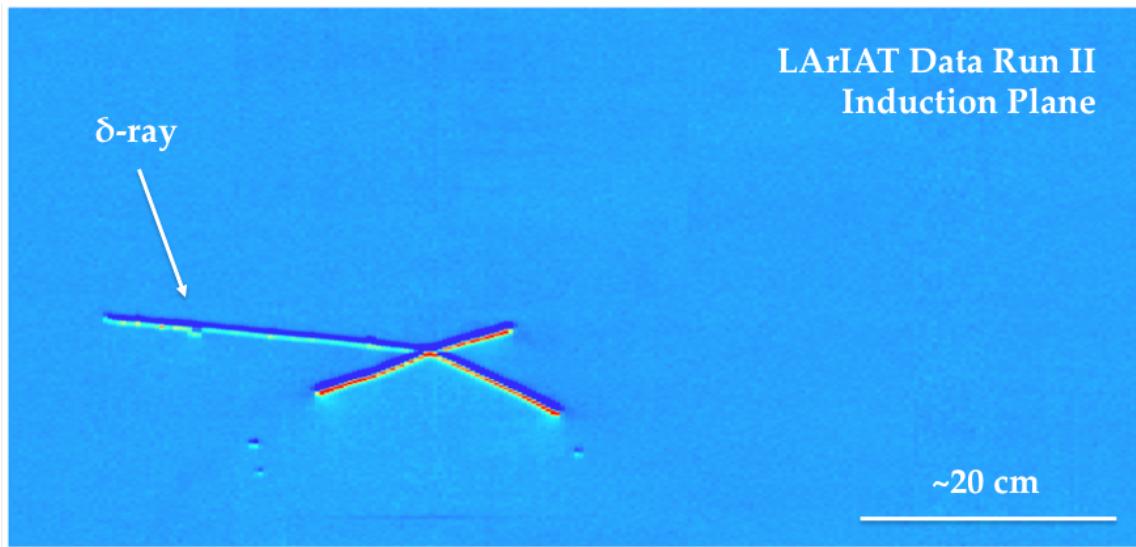


Figure 2.3: Events display for a LArIAT pion absorption candidate on the induction plane, with highlighted delta ray.

940 Purity & Electron Life Time

941 The presence of electronegative contaminants in liquid argon, such as oxygen O_2
942 and water H_2O , is particularly pernicious, since these molecules quench the charge
943 produced by the ionizing radiation. Thus, amount of charge per unit of length dQ/dx
944 collected on the collection plane depends on the charge's production point in the
945 detector: ionization produced close to the cathode will see more impurities along its
946 journey to the collection plane than ionization produced close to the anode, resulting

947 in greater attenuation of its charge. As a result, the amount of charge collected on
 948 the sense wires as a function of the traveled distance follows an exponential decay
 949 trend. The traveled distance is generally measured in terms of drift time and the
 950 characteristic time constant of the exponential decay is called electron lifetime τ_e .
 951 Figure 2.4 shows the typical life time for LArIAT data. The procedure to measure
 952 the electron lifetime in LArIAT is outlined in [105]. LArIAT small drift distance (47
 953 cm) allows for a relatively short electron life time. The life time for bigger detectors
 954 such as MicroBooNE, whose drift distance is 2.6 m, needs to be of the order of
 955 tens of milliseconds to allow a charge collection usable for physics analyses. Energy
 956 reconstruction in LArTPC applies a correction for the finite lifetime to calibrate the
 957 detector calorimetric response; details for LArIAT are provided in Section B.

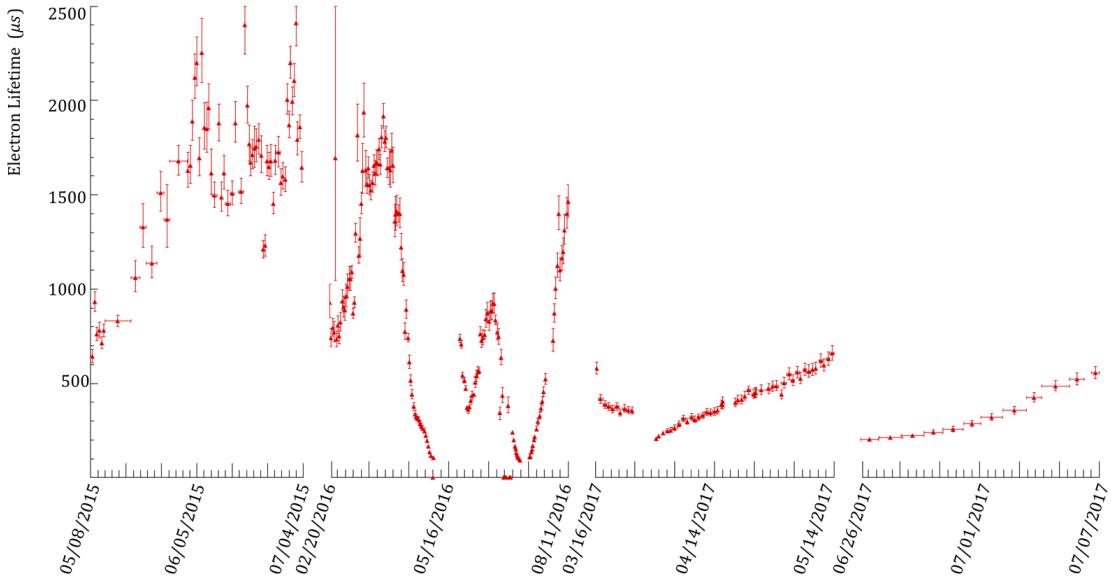


Figure 2.4: Electron lifetime during the LArIAT run period [43].

958 LArTPCs use hermetically sealed and leak-checked vessels to abate the leakage
959 and diffusion of contaminants into the system. The liquid argon filling of the volume
960 occurs after the vessel is evacuated or purged with gaseous argon [10] to reduce re-
961 maining gases in the volume. Even so, the construction of a pure tank of argon is
962 unviable, as several sources of impurity remain. In particular, impurities can come
963 from the raw argon supply, the argon filtration system and from the outgassing from
964 internal surfaces. Outgassing is a continuous diffusive process producing contami-
965 nants, especially water, even after the vessel is sealed, particularly from materials in
966 the ullage region². Since research-grade argon comes from the industrial distillation
967 of air, the impurities with the highest concentration are nitrogen, oxygen and water,
968 generally maintained under the 1 part per million level by the vendor. Even so, a
969 higher level of purity is necessary to achieve a free electron life time usable in meter
970 scale detectors. Thus, argon is constantly filtered in the cryogenic system, which
971 reduce the oxygen and water contamination to less than 100 parts per trillion. The
972 filtration system depends on the size and drift distance of the experiment and, for
973 experiments on several meters scale, it includes an argon recirculation system.

974 Recombination Effect

975 After production, ionization electrons thermalize with the surrounding medium and
976 may recombine with nearby ions. Recombination might occur either between the
977 electron and the parent ion through Coulomb attraction, as described in the geminate
978 theory [100], or thanks to the collective charge density of electrons and ions from
979 multiple ionizations in a cylindrical volume surrounding the particle trajectory, as
980 described in the columnar model [81]. Consideration on the average electron-ion
981 distance and the average ion-ion distance for argon show that the probability of

2. While the liquid argon low temperature reduces outgassing in the liquid, this process remains significant for absorptive material (such as plastic) above the surface of the liquid phase.

982 geminate recombination is low; thus recombination in argon is mainly due to collective
983 effects [5]. Since protons, kaons and stopping particles present a higher ionization
984 compared to MIPs, recombination effects are more prominent when considering the
985 reconstruction of energy deposited by these particles.

986 Theoretical descriptions of recombination based on the Birks model and the Box
987 model are provided in [29] and [113], respectively. The Birks model assumes a gaus-
988 sian spatial distribution around the particle trajectory during the entire recombina-
989 tion phase and identical charge mobility for ions and electrons. The Box model also
990 assumes that electron diffusion and ion mobility are negligible in liquid argon during
991 recombination. In these models, the fraction of ionization electrons surviving recom-
992 bination is a function of the number of ion-electron pairs per unit length, the electric
993 field, the average ion-electron separation distance after thermalization and the angle
994 of the particle with respect to the direction of the electric field – plus the diffusion
995 coefficient in the Birks model. Given the stringent assumptions, it is perhaps not sur-
996 prising that these models are in accordance to data only in specific regimes: the Birks
997 model is generally used to describe recombination for low dE/dx , the Box model for
998 high dE/dX . In LArTPC, the ICARUS and ArgoNeut experiments have measured
999 recombination in [16] and [5] respectively. Since LArIAT uses the refurbished Ar-
1000 goNeut TPC and cryostat at the same electric field, LArIAT currently corrects for
1001 recombination using the ArgoNeut measured recombination parameters in [5].

1002 **Space Charge Effect**

1003 Slow-moving positive argon ions created during ionization can build-up in LArTPC,
1004 causing the distortion of the electric field within the detector. This effect, called
1005 “space charge effect” leads to a displacement in the reconstructed position of the
1006 signal ionization electrons. In surface LArTPCs the space charge effect is primarily
1007 due to the rate of ionization produced by cosmic rays which is slowly drifting in the

1008 chamber at all times. Surface LArTPC of the size of several meters are expected
1009 to be modestly impacted from the space charge effect, where charge build-up create
1010 anisotropy of the electric field magnitude of the order of 5% at a drift field of 500
1011 V/cm [94]. The smallness of the LArIAT drift volume and its relatively high electric
1012 field are such that the effect of space charge is expected to be negligible.

1013 2.1.4 Liquid Argon: Scintillation Light

1014 Liquid argon emits scintillation light at the passage of charged particles. LArTPCs
1015 leverage this property to determine when the ionization charge begins to drift towards
1016 the anode plane.

1017 Scintillation Process

1018 Scintillation light in argon peaks in the ultraviolet at a 128 nm, shown in comparison
1019 to Xenon and Kypton in Figure 2.5, from [95]. The light yield collected by the optical
1020 detector depends on the argon purity, the electric field, the dE/dx and particle type,
1021 averaging at the tens of thousands of photons per MeV.

1022 The de-excitation of Rydberg dimers in the argon is responsible for the scintillation
1023 light. Rydberg dimers exist in two states: singlets and a triplets. The time constant
1024 for the singlet radiative decay is 6 ns, resulting in a prompt component for the scin-
1025 tillation light. The decay of the triplet is delayed by intersystem crossing, producing
1026 a slow component with a time constant of \sim 1500 ns. “Self-trapped exciton lumines-
1027 cence” and “recombination luminescence” are the two processes responsible for the
1028 creation of the Rydberg dimers [84]. In the first process, a charged particle excites an
1029 argon atom which becomes self-trapped in the surrounding bulk of argon, forming a
1030 dimer; the dimer is in the singlet state 65% of the times and in the triplet state 35%
1031 of the times. In case of recombination luminescence, the charged particle transfers
1032 enough energy to ionize the argon. The argon ion forms a charged argon dimer state,

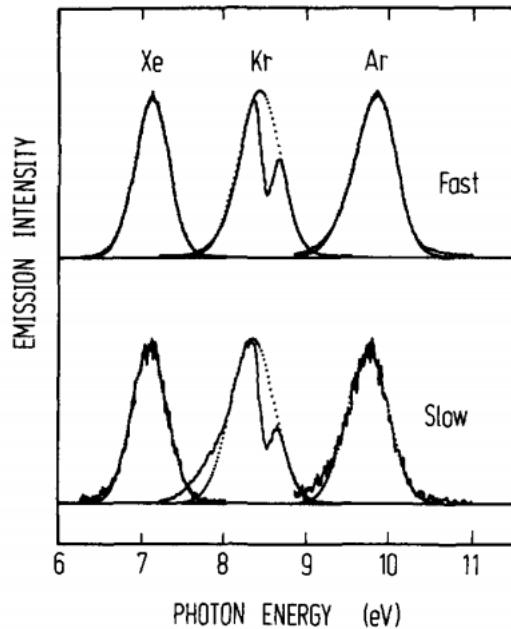


Figure 2.5: Emission spectra of the fast and slow emission components in Xenon, Krypton and Argon according to [95]. The dotted lines correspond to the Gaussian fits.

which quickly recombines with the thermalized free electron cloud. Excimer states
 are produced in the recombination, roughly half in the singlet and half in the triplet
 state. The light yield dependency on the electric field, on the dE/dx and particle
 type derives from the role of free charge in the recombination luminescence process.
 The spacial separation between the argon ions and the free electron cloud depends on
 the electric field. On one hand, a strong electric field diminishes the recombination
 probability, leading to a smaller light yield; on the other, it increases the free charge
 drifting towards the anode plane. Hence, the amount of measurable charge and light
 anti-correlates as a function of the electric field. Ionizing particles in the argon mod-
 ify the local density of both free electrons and ions depending on their dE/dx . Since
 the recombination rate is proportional to the square of the local ionization density,
 highly ionizing particles boost recombination and the subsequent light yield compared
 to MIPs. The possibility to leverage this dependency for pulsedshape-based particle
 identification has been shown in [31, 89].

1047 **Effects Modifying the Light Yield**

1048 The production mechanism through emission from bound excimer states implies that
1049 argon is transparent to its own scintillation light. In fact, the photons emitted from
1050 these metastable states are not energetic enough to re-excite the argon bulk, greatly
1051 suppressing absorption mechanisms. In a LArTPC however, several processes modify
1052 the light yield in between the location where light is produced and the optical detector.
1053 In a hypothetical pure tank of argon, Rayleigh scattering would be the most important
1054 processes modifying the light yield. Rayleigh scattering changes the path of light
1055 propagation in argon, prolonging the time between light production and detection.
1056 The scattering length has been measured to be 66 cm [79] , shorter than the theoretical
1057 prediction of ~ 90 cm [112]; this value is short enough to be relevant for the current
1058 size of LArTPCs detectors. In fact, Rayleigh scattering worsen the resolution on t_0 ,
1059 the start time for charge drifting, and alters the light directionality, complicating the
1060 matching between light and charge coming from the same object in case of multiple
1061 charged particles in the detector.

1062 Traces of impurities in argon such as oxygen, water and nitrogen also affect the
1063 light yield, mainly via absorption and quenching mechanisms. Absorption occurs as
1064 the interaction of a 128 nm photon directly with the impurity dissolved in the liquid
1065 argon. Differently, quenching occurs as the interaction of an argon excimer and an
1066 impurity, where the excimer transfers its excitation to the impurity and dissociates
1067 non-radiatively. Given this mechanism, it is evident how quenching is both a function
1068 of the impurity concentrations and the excimer lifetime. Since the triplet states
1069 live much longer than the singlet states, quenching occurs mainly on triplet states,
1070 affecting primarily the slow component of the light, reducing the scintillation yield
1071 and a shortening of the scintillation time constants.

1072 The stringent constraints for the electron life time limit the presence of oxygen and
1073 water to such a low level that both absorption and quenching on these impurity is not

1074 expected to be significant. Contrarily, the nitrogen level is not bound by the electron
1075 life time constraints – nitrogen being an inert gas, expensive to filter. Thus, nitrogen
1076 is often present at the level provided by the vendor. The effects of nitrogen on argon
1077 scintillation light have been studied in the WArP R&D program and at several test
1078 stands. The quenching process induced by nitrogen in liquid Ar has been measured
1079 to be proportional to the nitrogen concentration, with a rate constant of ~ 0.11
1080 μs^{-1} ppm $^{-1}$; appreciable decreasing in lifetime and relative amplitude of the slow
1081 component have been shown for contamination as high as a few ppm of nitrogen [6].
1082 For a nitrogen concentration of 2 parts per million, typical of the current generation
1083 of LArTPC, the attenuation length due to nitrogen has been measured to be ~ 30
1084 meters [83].

1085 **Wavelength Shifting of LAr Scintillation Light**

1086 Liquid argon scintillation light is invisible for most optical detectors deployed in a
1087 LArTPC, such as cryogenic PMTs and SiPMs, since a wavelength of 128 nm is gen-
1088 erally too short to be absorbed from most in glasses, polymers and semiconductor
1089 materials. Research on prototype SiPMs absorbing directly VUV light and their
1090 deployment in noble gasses experiment is ongoing but not mature [120]. Thus, ex-
1091 periments need to shift the wavelength of scintillation light to be able to detect it.
1092 Albeit deployed in different ways, neutrinos and dark matter experiments commonly
1093 use 1,1,4,4-tetraphenyl-butadiene (TPB) to shift the scintillation light. TPB absorbs
1094 the vacuum ultraviolet (VUV) light and emits in the visible at ~ 425 nm [33], with
1095 a ratio of visible photon emitted per VUV photon absorbed of $\sim 1.2:1$ [66].

1096 Neutrino experiments typically coat their optical detector system evaporating a
1097 layer of TPB either directly on the PMTs glass surface or on acrylic plates mounted in
1098 front of the PMTs [60]; this technique allows the fast detection light coming directly
1099 from the neutrino interaction. Dark matter experiments typically evaporate TPB on

1100 reflective foils mounted on the inside walls of the sensitive volume and detect the
1101 light after it has been reflected; this technique leads to a higher and more uniform
1102 light yield, though scattering effects for both the visible and VUV light augment
1103 the propagation time and hinder directionality information [61]. In order to take
1104 advantage of both these techniques, hybrid systems with PMT coating and foils are
1105 being considered for the next generation of large neutrino detectors.

1106 2.1.5 Signal Processing and Event Reconstruction

1107 In this section we illustrate the processing and reconstruction chain of the TPC sig-
1108 nals, from the pulses on the sense wire to the construction of three dimensional objects
1109 with associated calorimetry. Different experiments can chose different software pack-
1110 ages for their off line signal processing and event reconstruction, but a popular choice
1111 for US based LArTPCs is LArSoft [40]. Based on the Art framework [73], LArSoft is
1112 an event-based toolkit to perform simulation, analysis and reconstruction of LArT-
1113 PCs events.

1114

1115 LArTPC signal processing develops in several consecutive stages that we summa-
1116 rize here in the following categories: *Deconvolution, Hit Reconstruction, 2D Cluster-*
1117 *ing, 3D Tracking, Calorimetry Reconstruction*. A visualization of the signal processing
1118 workflow is shown in figure 2.6.

1119

1120 **Deconvolution.** Induction and collection planes have different field responses,
1121 given the different nature of the signals on these planes: the wires on the induction
1122 planes see the inductive signal of the drifting charge, while the wires on the collection
1123 planes see the current derived from the charge entering the conductor. Thus, signals
1124 on the induction plane are bi-polar pulse and signal on the collection plane are unipo-
1125 lar pulses, see Figure 2.6 panel a). The first step in signal processing is deconvolution,

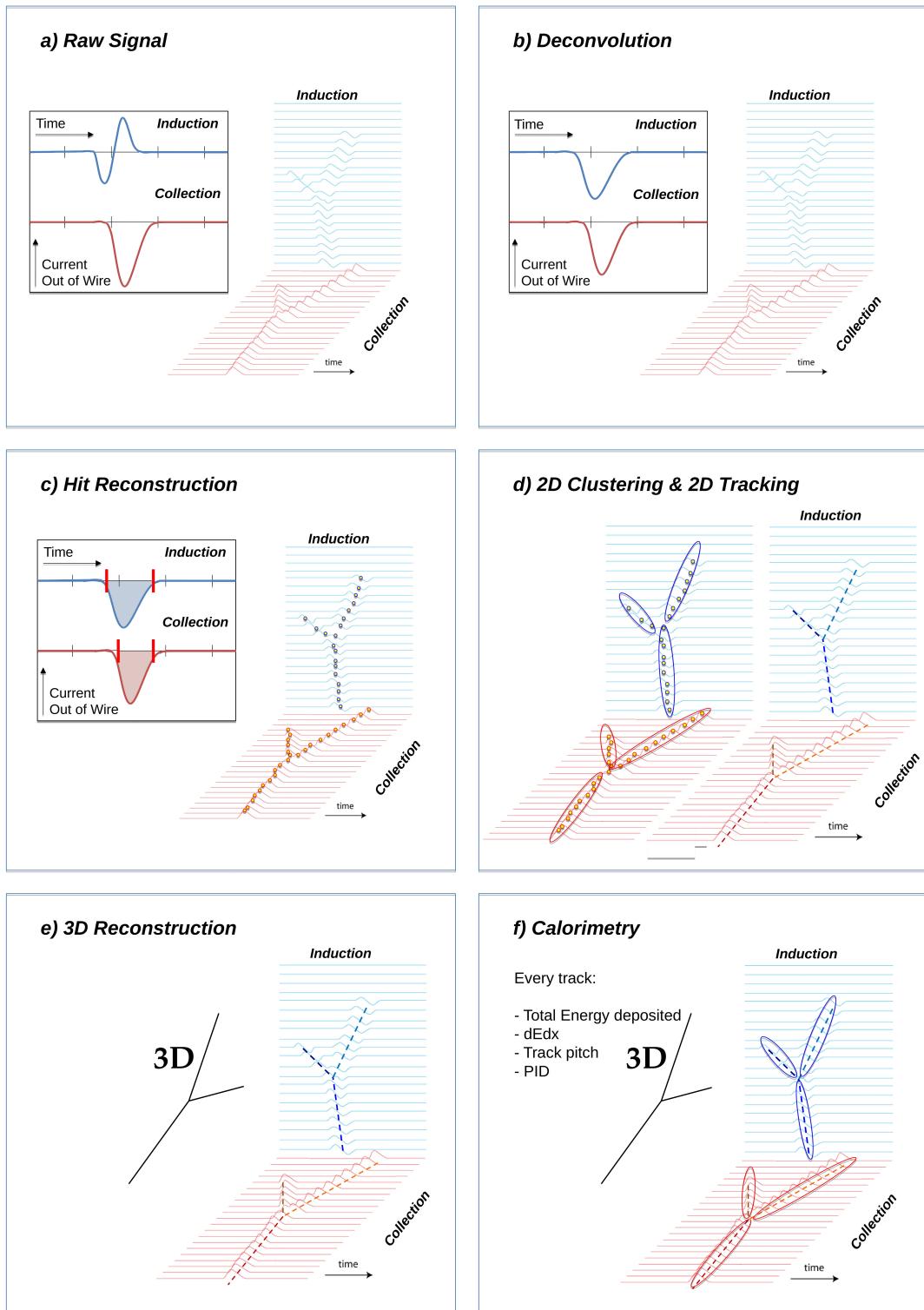


Figure 2.6: A scheme of a typical signal processing workflow in LArSoft.

1126 that is a series of off-line algorithms geared towards undoing the detector effects. The
1127 result of the deconvolution step is the production of a comparable set waveforms on
1128 all planes presenting unipolar, approximately gaussian-like pulses (Figure 2.6 panel
1129 b). Signal from all planes are treated on equal footage beyond this point. Some
1130 LArTPC apply noise filtering in the frequency domain just after the deconvolution
1131 to clean up wire cross talk. Since signals from the LArIAT TPC are extremely clean,
1132 noise filtering is not necessary.

1133

1134 **Hit Reconstruction.** The second stage of the signal processing is the recon-
1135 struction of hits, indicating an energy deposition in the detector. A peak finder scans
1136 the deconvolved TPC waveforms for each wire on the whole readout time looking for
1137 spikes above the waveform’s baseline. It then fits these peaks with gaussian shapes
1138 and stores the fit parameters such as the quality of the fit, the peak time, height and
1139 area under the gaussian fit. The information resulting from this process on a single
1140 spike form a single reconstructed “hit”, see Figure 2.6 panel c). The next steps in
1141 the event reconstruction chain will then decide if rejecting hits with poor fits. It is
1142 important to notice how the height and width of the hit depend on the topology of
1143 the event: for example, a particle running parallel to the wire planes will leave a series
1144 of sharp hits on many consecutive wires, while a particle traveling towards the planes
1145 will leave a long, wide hit on very few wires. The height of the hits and their integral
1146 is proportional to the charge collected on the wire, so it depends on the particle type.

1147

1148 The event reconstruction chain uses collection of hits to form more complex objects
1149 associated with the particles in the detector. The development of different approaches
1150 to accomplish this task is an extremely hot topic in LArTPC event reconstruction
1151 which spans from more traditional approaches such as line-clustering [26] to the use of
1152 machine learning tools [59]. Generally speaking, the scope of hit clustering and event

1153 reconstruction to provide shower-like or track like-objects with an associated energy
1154 reconstruction. This is because different particles have different topology in the de-
1155 tector – electrons and photon create electromagnetic showers, resulting in shower-like
1156 topologies, while muons and hadrons leave track-like signals. For the scope of these
1157 thesis, we will describe only LArIAT’s approach to track reconstruction even if we
1158 recognize the breath of LArTPC event reconstruction is much wider. We are inter-
1159 ested in the reconstruction of pions and kaons in the active volume, whose topology
1160 is track-like.

1161

1162 **2D Clustering Reconstruction.** The LArIAT reconstruction of track-like ob-
1163 jects starts by clustering hits on the collection and induction planes separately with
1164 the use of the TrajCluster clustering package [25]. TrajCluster looks for a collection
1165 of hits in the wire-time 2D space which can be described with a line-like 2D trajec-
1166 tory. TrajCluster reconstructs trajectories by adding trajectory points to the leading
1167 edge of the trajectory while stepping through the 2D space of hits. Several factors
1168 determine whether a hit is added to the trajectory, including but not limited to

- 1169 1. the goodness of the fit of the single hit,
- 1170 2. the charge of the hit compared to the average charge and RMS of the hits
1171 already forming the trajectory,
- 1172 3. the goodness of trajectory fit with and without the hit addition,
- 1173 4. the angle between the two lines formed by the collection of hits before and after
1174 the considered hit in the trajectory.

1175 The final product of this reconstruction stage is the collection of bidimensional clusters
1176 on each wire plane, see Figure 2.6 panel d).

1177 **3D Tracking.** The 3D tracking set of algorithms uses clusters close in time on
1178 the induction and collection planes as starting point to form a 3D track. Firstly, it

1179 construct a tentative 3D trajectory using the edges of the clusters. Then, it projected
1180 back the tentative trajectory on to the planes and adjusts the parameters of the 3D
1181 track fit such that they minimize the distance between the fit projections and the
1182 track hits in all wire planes simultaneously. Tridimensional tracking can use multiple
1183 clusters in one plane, but it can never break them in smaller groups of hits. This
1184 algorithm was first developed for the ICARUS collaboration [20]. The final product
1185 of this reconstruction stage is the formation of tridimensional objects in the TPC
1186 active volume, see Figure 2.6 panel e).

1187

1188 **Calorimetry.** The last step in the event reconstruction chain is to assign calorimetric
1189 information to the track (or shower) objects. Calorimetry is performed separately
1190 on the different planes. A multi-step procedure is needed to retrieve the energy
1191 deposited in the TPC from the charge seen by the wires. For each hit associated with
1192 the track object, the calorimetry algorithms calculate the charge seen on every wire
1193 using the area underneath the gaussian fit; then, they correct this raw charge by the
1194 electron life time, the electronic noise on the considered wire and the recombination
1195 effect. Lastly an overall calibration of the energy, explained in detail in section B,
1196 is applied and the calorimetric information for the given track is assigned. Even if
1197 calorimetry is done in 2D, it benefits from the 3D tracking information; typical information
1198 available after the calorimetric reconstruction are the total energy deposited
1199 by the particle and its stopping power dE/dx at each “track pitch”, i.e. at each 2D
1200 projection on the wire plane of the 3D trajectory.

1201 2.2 The Intensity Frontier Program

1202 This section highlights the role of Liquid Argon Time Projection Chambers at the
1203 Intensity frontier. In particular, we show the prospects for the exploration of neutrino

1204 physics (Section 2.2.1) and GUT models (Section 2.2.2) in current and forthcoming
1205 LAr experiments. In Section , we introduce LArIAT and its role in the Intensity
1206 Frontier panorama.

1207 **2.2.1 Prospects for LArTPCs in Neutrino Physics: SBN and**
1208 **DUNE**

1209 The ArgoNeut experiment [17] together the LAr R&D experiments TallBo and the
1210 Yale TPC initiated the US LArTPC neutrino program. Following the success of the
1211 ArgoNeut small TPC on the NuMI beam, a wide program of LArTPCs on neutrino
1212 beams has flourished. The construction of LArTPCs as near and far detectors at
1213 different baseline allows for the exploration of some of the fundamental questions in
1214 neutrino physics today illustrated in section 1.3.1.

1215 The Short-Baseline Neutrino (SBN) [21] program at Fermilab is tasked with con-
1216 clusively assess the nature of the “LSND and MiniBooNE anomalies” [14, 15, 23],
1217 resolving the mystery of sterile neutrinos at the eV² scale. The SBN program entails
1218 three surface LArTPCs positioned on the Booster Neutrino Beam at different dis-
1219 tances from the neutrino production in oder to fully exploit the L/E dependence of
1220 the oscillation pattern: SBND (100 m from the decay pipe), MicroBooNE (450 m),
1221 and ICARUS (600 m). Within the oscillation context, the choice of the LArTPC tech-
1222 nology for the SBN detectors changes the set of systematics with respect to LSND
1223 and MiniBooNE, whose detection techniques were both based on Cherenkov light.
1224 In particular, LArTPCs provide excellent electron/photon separation [9] lacking in
1225 Cherenkov detectors which can be leveraged to abate the photon background from
1226 neutral current interactions in ν_e searches. MicroBooNE [8], the first detector of the
1227 SBN program to be fully operational, started its first neutrino run in October 2015.
1228 MicroBooNE is a 89 ton active volume LArTPC, single drift chamber with TPC di-
1229 mensions of 2.6 m (drift) x 2.3 m (heigh) x 10.4 m (depth). MicroBooNE is positioned

at a very similar L/E on the Booster neutrino beam as MiniBooNE has the scope to directly cross check the MiniBooNE oscillation measurement. In case MicroBooNE confirms the presence of the “low energy excess” anomaly, SBND and ICARUS will provide the full measurement of the oscillation parameters. SBND and ICARUS are both dual drift chambers, whose active volume is respectively 112 ton and 600 ton. ICARUS is scheduled to become operational by the end of 2018 and SBND shortly after. Besides the oscillation analysis, the second main goals of SBN is to perform an extensive campaign of neutrino cross section measurements in argon. Given the importance of nuclear effects in (relatively) heavy materials, as discussed in section 1.2.3, both the oscillation analysis of the SBN program and the measurements of neutrino properties in DUNE will benefit from such a campaign.

On a different neutrino beam and baseline, the DUNE experiment, née LBNE [11], is the flagship experiment on the medium-long term of US-based neutrino physics, scheduled to start data taking in 2026. Shooting neutrinos from Fermilab for 800 miles to the SURF laboratory in South Dakota, DUNE is tasked with performing conclusive measurements of CP violation in the lepton sector, the neutrino mass ordering and the θ_{23} octant. The DUNE far detector will count four 10 kton LArTPCs, roughly of dimensions of 19 m (horizontally) x 18 m (vertically) x 66 m (depth).

2.2.2 Prospects for LArTPCs in GUT Physics: DUNE

The experimental exploration of a manifestation of Grand Unified Theory is possible in DUNE thanks to its sheer mass. In particular, proton decay searches are a capital topic of DUNE’s wide non-accelerator physics program. The key elements for a rare decay experiment are: massive active volume, long exposure, high identification efficiency and low background. Figure 2.7 shows the current best experimental limits on nucleon decay lifetime over branching ratio (dots). Historically, the dominant technology used in these searches has been water Cherenkov detectors: all the best

1256 experimental limits on every decay mode are indeed set by Super-Kamiokande [?, ?].
 1257 As shown in section 1.3.2, different family of GUTs predict the proton to decay in
 1258 different modes. In particular, SUSY flavored GUTs prefer the presence of kaons
 1259 in the decay products, e.g. $p \rightarrow K^+ \bar{\nu}$. It is particularly important to notice that
 1260 the kaon energy for the proton decay mode $p \rightarrow K^+ \bar{\nu}$ is under Cherenkov threshold
 1261 in water. Thus, Super-Kamiokande set the limit on the lifetime for the $p \rightarrow K^+ \bar{\nu}$
 1262 mode by relying on photons from nuclear de-excitation and on the muon tagging in
 1263 the kaon decay leptonic mode. For this reason, an attractive alternative approach to
 1264 identifying nucleon decay is the use of a LArTPCs, where the kaon is directly visible
 1265 in the detector. According to [11], DUNE will have an active volume large enough,
 1266 have sufficient shielding from the surface, and will run for lengths of time sufficient
 1267 to compete with Hyper-K, opening up the opportunity for the discovery of nucleon
 1268 decay.

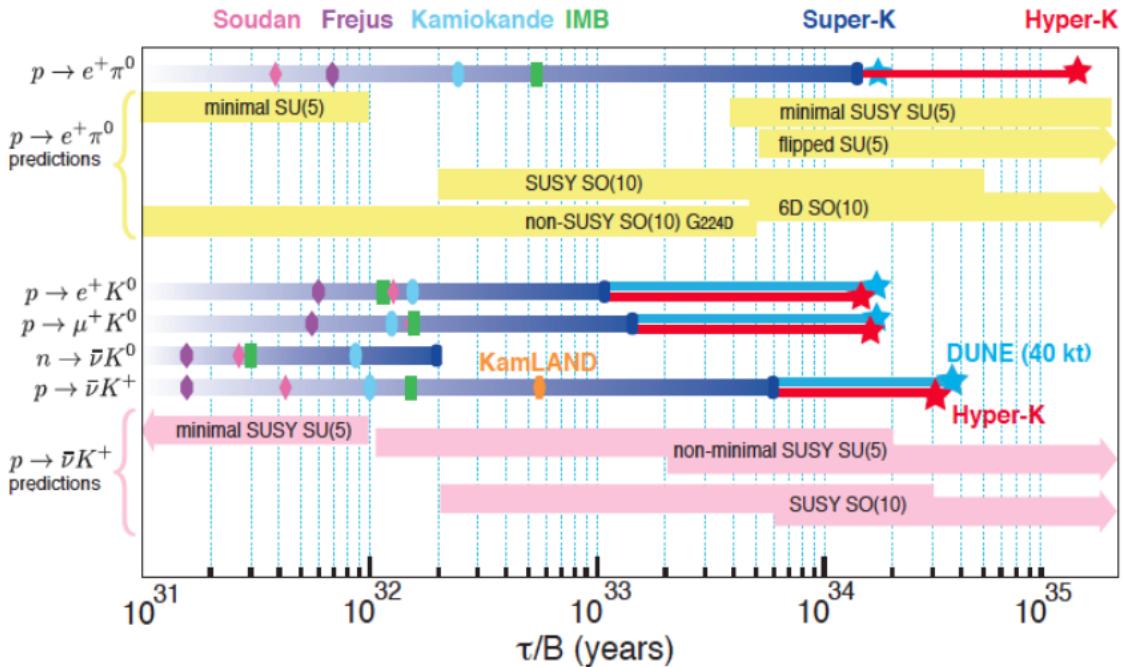


Figure 2.7: Proton decay lifetime limits from passed and future experiments.

1269 2.2.3 Enabling the next generation of discoveries: LArIAT

1270 LArIAT, a small LArTPC in a test beam, is designed to perform an extensive physics
1271 campaign centered on charged particle cross section measurements while characteriz-
1272 ing the detector performance for future LArTPCs. Since LArTPCs represent the most
1273 advanced experiments for physics at the Intensity Frontier, their complex technology
1274 needs a thorough calibration and dedicated measurements of some key quantities to
1275 achieve the precision required for the next generation of discoveries. LArIAT’s goal
1276 is to provide such calibration and dedicated measurements. The LArIAT LArTPC is
1277 deployed in a dedicated calibration test beamline at Fermilab. We use the LArIAT
1278 beamline to characterize the charge particles before they enter the TPC: the particle
1279 type and initial momentum is known from beamline information. The precise calori-
1280 metric energy reconstruction of the LArTPC technology enables the measurement of
1281 the total differential cross section for tagged hadrons. The Pion-Nucleus and Kaon-
1282 Nucleus total hadronic interaction cross section have never been measured before in
1283 argon and they are a fundamental step to shed light on light meson interaction in nu-
1284 clei per se, while providing a key input to neutrino physics and proton decay studies
1285 in future LArTPC experiments like SBN and DUNE.

1286 In order to showcase LArIAT’s utility to SBN and DUNE, we illustrate briefly
1287 two comparisons as examples: one regarding neutrino interactions and the second
1288 regarding proton decay studies.

1289 The left side of figure 2.8 shows the distribution of products in momentum spectrum
1290 and particle type as simulated in a ν_e CC interaction in DUNE (according to [88]);
1291 the range of these distribution is to compare with the momentum distribution of
1292 light particles in the LArIAT beamline – shown on the right side of figure 2.8. The
1293 momentum spectrum in the LArIAT beamline for electrons, muons and pions – the
1294 most abundant particles produced in a ν_e CC interaction – covers a wide range of the
1295 expected momentum distribution in a neutrino event.

1296 The signature of a proton decay event in the “LAr golden mode” is the presence of
 1297 a single kaon of about 400 MeV in the detector; the momentum spectrum of the kaon
 1298 pre and post FSI in such an event as simulated by GENIE is shown on the left side
 1299 of figure 2.9. The right side of figure 2.9 shows the momentum spectrum of kaons in
 1300 the LArIAT beamline. Kaons arriving to the LArIAT TPC are ideal for proton decay
 1301 studies, since their momentum in the beamline is just above the typical momentum
 1302 for kaons in a proton decay event: the majority of LArIAT kaons slow down in the
 1303 TPC enough to enter the desired momentum window.

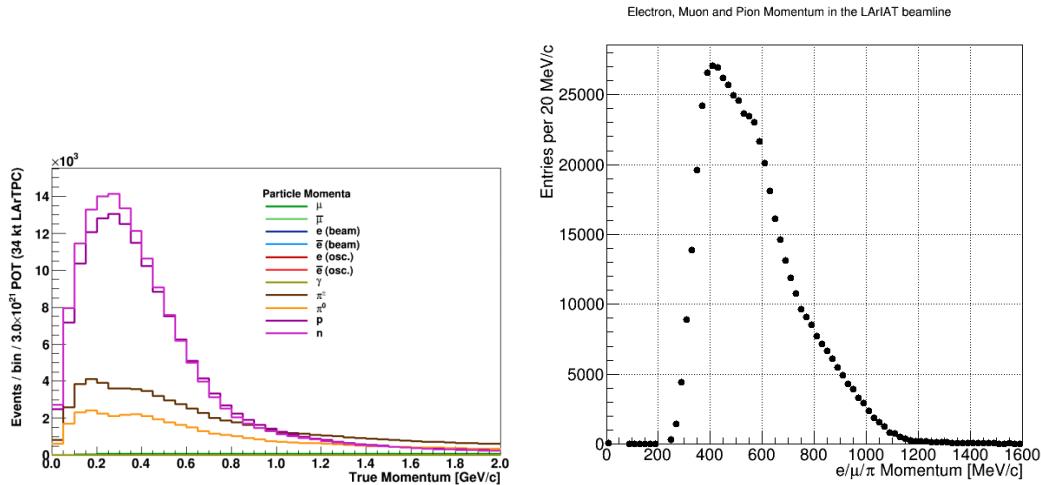


Figure 2.8: *Left.* Simulation of the products of a ν_e CC interaction in DUNE, both in particles type and momentum.
Right. Momentum spectrum for low mass particles (e, μ, π) in the LArIAT beamline, negative tune, Run II, Picky Tracks see section 3.2.2.

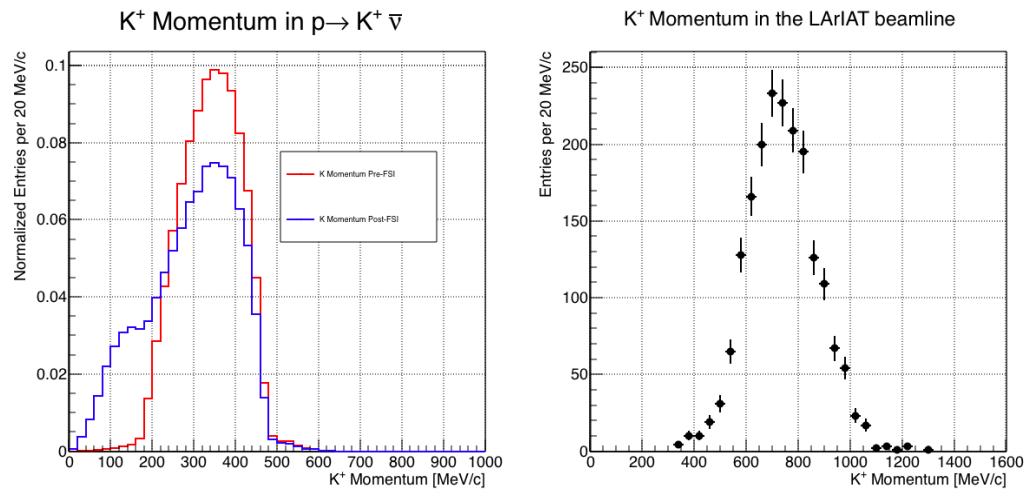


Figure 2.9: *Left.* Momentum of the kaon outgoing a proton decay $p \rightarrow K^+ \bar{\nu}$ event as simulated by the Genie 2.8.10 event generator in argon. The red line represents the kaon momentum distribution before undergoing the simulated final state interaction inside the argon nucleus, while the blue line represents the momentum distribution after FSI.

Right. Positive Kaon momentum spectrum in the LArIAT beamline, positive tune, Run II, Picky Tracks see section 3.2.2.

1304 **Chapter 3**

1305 **LArIAT: Liquid Argon In A**

1306 **Testbeam**

1307 “*But, hey we need to be somewhat foolish...*”

1308 – Agnes Obel, 2010 –

1309 In this chapter, we describe the LArIAT experimental setup. We start by illus-
1310 trating the journey of the charged particles in the Fermilab accelerator complex, from
1311 the gaseous thermal hydrogen at the Fermilab ion source to the delivery of the LAr-
1312 IAT tertiary beam at MC7. We then describe the LArIAT beamline detectors, the
1313 LArTPC, the DAQ and the monitoring system.

1314 **3.1 The Particles’ Path to LArIAT**

1315 LArIAT’s particle history begins in the Fermilab accelerator complex with a beam of
1316 protons. The process of proton acceleration develops in gradual stages (see picture
1317 3.1): gaseous hydrogen is ionized in order to form H^- ions; these ions are boosted
1318 to 750 keV by a Cockcroft-Walton accelerator and injected into the linear accelerator
1319 (Linac) that increases their energy up to 400 MeV; then, H^- ions pass through a

1320 carbon foil and lose the two electrons; the resulting protons are then injected into a
1321 rapid cycling synchrotron, called the Booster; at this stage, protons reach 8 GeV of
1322 energy and are compacted into bunches; the next stage of acceleration is the Main
1323 Injector, a synchrotron which accelerates the bunches up to 120 GeV; in the Main
1324 Injector, several bunches are merged into one and are ready for delivery.

1325 The Fermilab accelerator complex works in supercycles of 60 seconds in duration.
1326 A 120 GeV primary proton beam with variable intensity is extracted in four-second
1327 “spills” and sent to the Meson Center beam line.

1328 LArIAT’s home at Fermilab is the Fermilab Test Beam Facility (FTBF), where
1329 the experiment characterizes a beam of charged particles in the Meson Center beam
1330 line. At FTBF, the primary beam is focused onto a tungsten target to create LAr-
1331 IAT’s secondary beam. The secondary beamline is set such that the composition of
1332 the secondary particle beam is mainly positive pions. The momentum peak of the
1333 secondary beam was fixed at 64 GeV/c for the LArIAT data considered in this work,
1334 although the beam is tunable in momentum between 8-80 GeV/c; this configuration
1335 of the secondary beamline assured a stable beam delivery at the LArIAT experimental
1336 hall.

1337 The secondary beam impinges then on a copper target within a steel collimator
1338 inside the LArIAT experimental hall (MC7) to create the LArIAT tertiary beam,
1339 (shown in Fig. 3.2). The steel collimator selects particles produced with a 13° pro-
1340 duction angle. The particles are then bent by roughly 10° through a pair of dipole
1341 magnets. By configuring the field intensity of the magnets we allow the particles of
1342 LArIAT’s tertiary beam to span a momentum range from 0.2 to 1.4 GeV/c. The
1343 polarity of the magnet is also configurable and determines the sign of the beamline
1344 particles which are focused on the LArTPC. If the magnet polarity is positive the
1345 tertiary beam composition is mostly pions and protons with a small fraction of elec-
1346 trons, muons, and kaons. It is the job of the LArIAT beamline equipment to select the

Fermilab Accelerator Complex

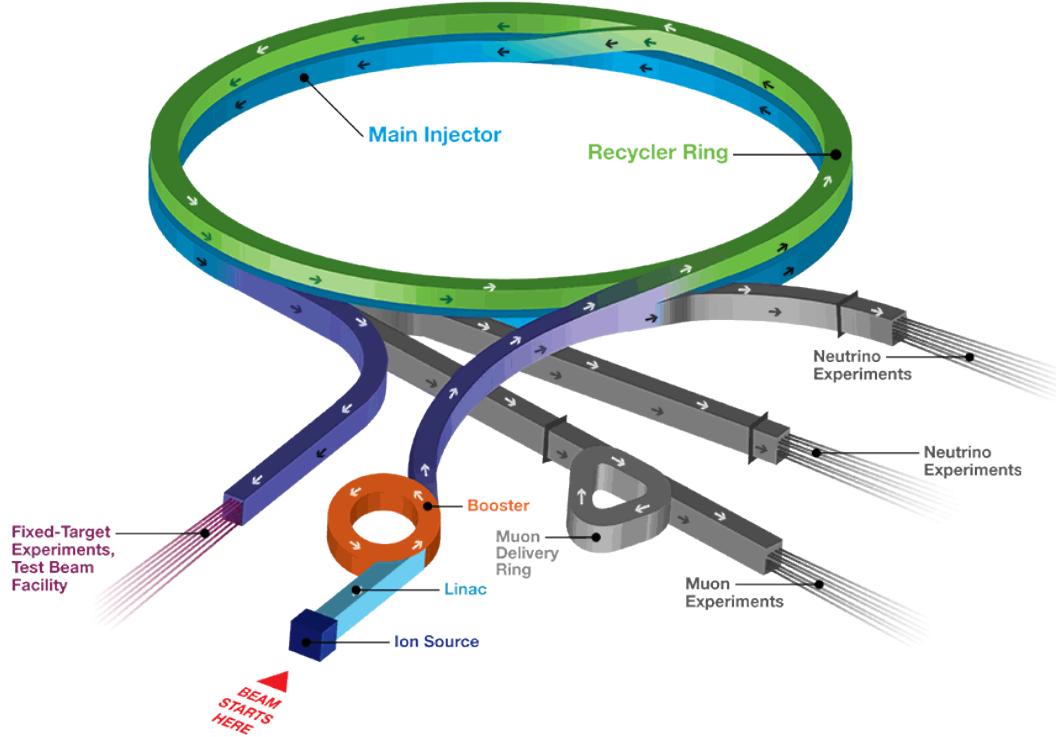


Figure 3.1: Layout of Fermilab Accelerator complex.

1347 particles polarity, to perform particle identification in the beamline and to measure
1348 the momentum of the tertiary beam particles before they get to the LArTPC. The
1349 LArIAT detectors are described in the following paragraphs.

1350 3.2 LArIAT Tertiary Beam Instrumentation

1351 The instrumentation of LArIAT tertiary beam and the TPC components have changed
1352 several times during the three years of LArIAT data taking. The following paragraphs
1353 describe the components operational during “Run II”, the data taking period relevant
1354 to the hadron cross section measurements considered in this thesis.

1355 The key components of the tertiary beamline instrumentation for the hadron cross
1356 section analyses are the two bending magnets, a set of four wire chambers (WCs)

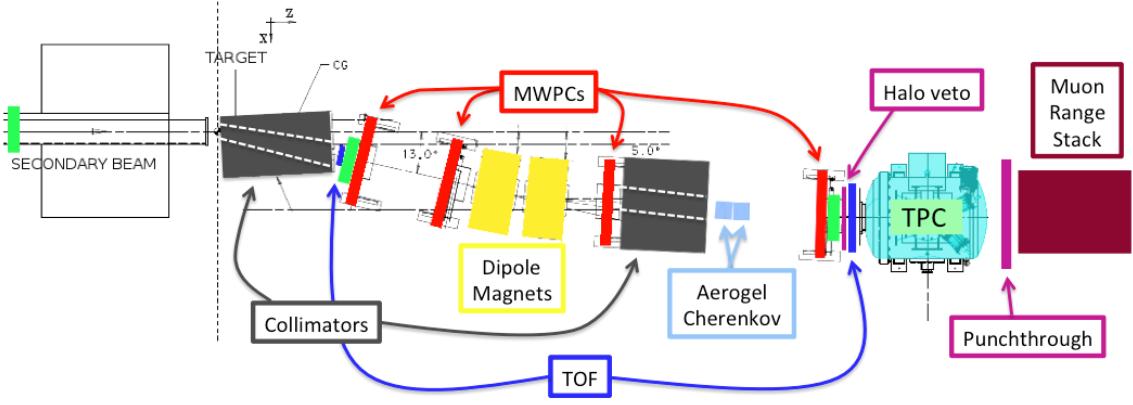


Figure 3.2: Bird’s eye view of the LArIAT tertiary beamline. In grey: upstream and downstream collimators; in yellow: bending magnets; in red: multi wire proportional chambers; in blue: time of flight; in green: liquid argon TPC volume; in maroon: muon range stack.

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 determines the particles’ momenta, 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. A couple of Aerogel Cherenkov counters, which we will not describe here as they are not used in the hadron cross section measurements, completes the beamline instrumentation.

3.2.1 Bending Magnets

LArIAT uses a pair of identical Fermilab type “NDB” electromagnets, recycled from the Tevatron’s anti-proton ring, in a similar configuration used for the MINERvA T-977 test beam calibration [56]. The magnets are a fundamental piece of the LArIAT beamline equipment, as they are used for the selection of the particle polarity and for the momentum measurement before the LArTPC. The sign of the current in the magnets allows us to select either positively or negatively charged particles; the value

1372 of the magnetic field is used in the momentum determination and in the subsequent
1373 particle identification.

1374 We describe here the characteristics and response of one magnet, as the second one
1375 has a similar response, given its identical shape and history. Each magnet is a box with
1376 a rectangular aperture gap in the center to allow for the particle passage. The magnet
1377 aperture measures 14.22 cm in height, 31.75 cm in width, and 46.67 cm in length.
1378 Since the wire chambers aperture ($\sim 12.8 \text{ cm}^2$) is smaller than the magnet aperture,
1379 only the central part of the magnet gap is utilized. The field is extremely uniform
1380 over this limited aperture and was measured with two hall probes, both calibrated
1381 with nuclear magnetic resonance probes. The probes measured the excitation curve
1382 shown in Figure 3.3.

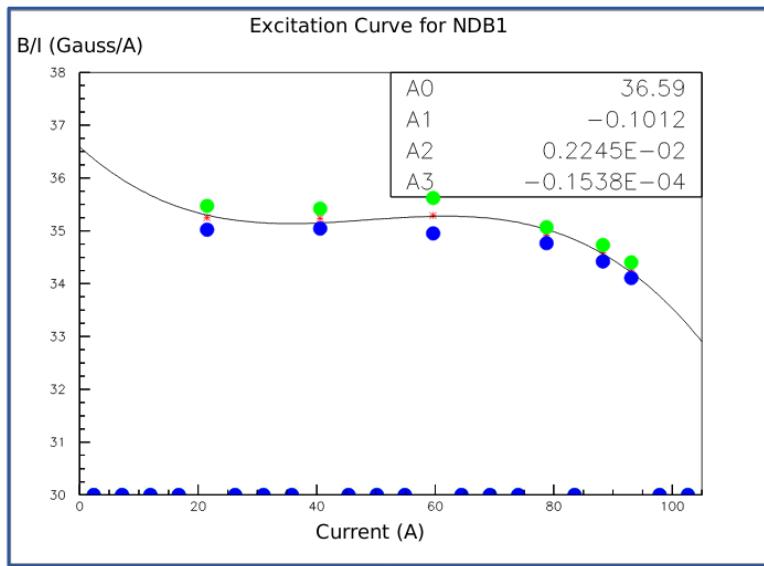


Figure 3.3: Magnetic field over current as a function of the current, for one NDB magnet (excitation curve). The data was collected using two hall probes (blue and green). We fit the readings with a cubic function (black) to average of measurements (red) given in the legend [43].

1383 The current through the magnets at a given time is identical in both magnets.
1384 For the Run II data taking period, the current settings explored were 60A ($B \sim 0.21$
1385 T) and 100A ($B \sim 0.35$ T) in both polarities. Albeit advantageous to enrich the
1386 tertiary beam composition with high mass particles such as kaons, we never pushed

1387 the magnets current over 100 A, not to incur in overheating. During operation, we
1388 operated an air and water cooling system on the magnets and we remotely monitored
1389 the magnet temperatures.

1390 **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 and related read-out electronics.

1391 LArIAT uses four multi-wire proportional chambers, or wire chambers (WC) for
1392 short, two upstream and two downstream from the bending magnets. The geometry of
1393 one chamber is shown in Figure 3.4: the WC effective aperture is a square of 12.8 cm
1394 perpendicular to the beam direction. Inside the chamber, the 128 horizontal and 128
1395 vertical wires strung at a distance of 1 mm from each other in a mixture of 85% Argon
1396 and 15% isobutane gas. The WC operating voltage is between 2400 V and 2500 V.
1397 The LArIAT wire chambers are an upgraded version of the Fenker Chambers [62],
1398 where an extra grounding improves the signal to noise ratio of the electronic readout.

1399 Two ASDQ chips [96] mounted on a mother board plugged into the chamber serve
1400 as front end amplifier/discriminator. The chips are connected to a multi-hit TDC [74]
1401 which provides a fast OR output used as first level trigger. The TDC time resolution
1402 is 1.18 ns/bin and can accept 2 edges per 9 ns. The maximum event rate acceptable
1403 by the chamber system is 1 MHz: this rate is not a limiting factor considering that

1404 the rate of the tertiary particle beam at the first wire chamber is estimated to be less
1405 than 15 kHz. A full spill of data occurring once per supercycle is stored on the TDC
1406 board memory at once and read out by a specially designed controller. We use LVDS
1407 cables to carry both power and data between the controller and the TDCs and from
1408 the controller to the rest of the DAQ.

1409 Multi-Wire Proportional Chambers functionality

1410 We use the wire chamber system together with the bending magnets to measure the
1411 particle's momentum.

1412 In the simplest scenario, only one hit on each and every of the four wire chambers
1413 is recorded during a single readout of the detector systems. Thus, we use the hit
1414 positions in the two wire chambers upstream of the magnets to form a trajectory
1415 before the bend, and the hit positions in the two wire chambers downstream of the
1416 magnets to form a trajectory after the bend. We use the angles in the XZ plane
1417 between the upstream and downstream trajectories to calculate the Z component of
1418 the momentum as follows:

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

1419 where B_{eff} is the effective maximum field in a square field approximation, L_{eff}
1420 is the effective length of both magnets (twice the effective length of one magnet),
1421 θ_{US} is the angle off the z axis of the upstream trajectory, θ_{DS} is the angle off the
1422 z axis of the downstream trajectory and $3.3 c^{-1}$ is the conversion factor from [T·m]
1423 to [MeV/c]. By using the hit positions on the third and fourth wire chamber, we
1424 estimate the azimuthal and polar angles of the particle trajectory, and we are able to
1425 calculate the other components of the momentum.

1426 The presence of multiple hits in a single wire chamber or the absence of hits in one
1427 (or more) wire chambers can complicate this simple scenario. The first complication

is due to beam pile up, while the latter is due to wire chamber inefficiency. In the case of multiple hits on a single WC, 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 which fit best with a straight line. It is still possible to reconstruct the particle’s momentum even if the information is missing in either of the two middle wire chambers (WC2 or WC3), by constraining the particle trajectory to cross the plane in between the magnets.

Events satisfying the simplest scenario of one single hit in each of the four wire chambers form the “Picky Track” sample. We construct another, higher statistics sample, where we loosen the requirements on single hit and wire chamber efficiency: the “High Yield” sample. For LArIAT Run II, the High Yield sample is about three times the Picky Tracks statistics. We assume an uncertainty of 2% for four-point WC track, momentum uncertainty as reported for the same beamline in [56].

3.2.3 Time-of-Flight System

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

The upstream paddle is made of a 10 x 6 x 1 cm scintillator piece, read out by two 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 is a 14 x 14 x 1 cm scintillator piece read out by two PMTs on the opposite ends of the scintillator, as shown in figure 3.5. The relatively thin width in the beamline direction minimizes energy loss of beam particles traveling through 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 μ s windows starting

1454 approximately 8.4 μ s before the trigger time.

1455 **TOF functionality**

1456 The TOF signals rise time (10-90%) is 4 ns and a full width, half-maximum of 9 ns
1457 consistent in time. The signal amplitudes from the upstream TOF and downstream
1458 TOF are slightly different: 200 mV for the upstream PMTs but only 50 mV for
1459 downstream PMTs. The time of the pulses was calculated utilizing an oversampled
1460 template derived from the data itself. We take the pulse pedestal from samples
1461 far from the pulse and subtract it from the pulse amplitude. We then vertically
1462 stretch a template to match the pedestal-subtracted pulse amplitude and we move
1463 it horizontally to find the time. With this technique, we find a pulse time-pickoff
1464 resolution better than 100 ps. The pulse pile up is not a significant problem given
1465 the TOF timing resolution and the rate of the particle beam. Leveraging on the
1466 pulses width uniformity of any given PMT, we flag events where two pulses overlap
1467 as closely in time as 4 ns with a 90% efficiency according to simulation.

1468 We combine the pulses from the two PMTs on each paddle to determine the
1469 particles' arrival time by averaging the time measured from the single PMT, so to
1470 minimize errors due to optical path differences in the scintillator. However, a time
1471 spread of approximately 300 ps is present in both the upstream and downstream
1472 detectors, likely due to transit time jitter in the PMTs themselves.

1473 **3.2.4 Punch-Through and Muon Range Stack Instruments**

1474 The punch-through and the muon range stack (MuRS) detectors are located down-
1475 stream of the TPC. These detectors provide a sample of TPC crossing tracks without
1476 relying on TPC information and can be used to improve particle ID for muons and
1477 pions with momentum higher than 450 MeV/c.

1478 The punch-through is simple sheet of scintillator material, read out by two PMTs.



Figure 3.5: Image of the down stream time of flight paddle, PMTs and relative support structure before mounting.

1479 The MuRS is a segmented block of steel with four slots instrumented with scintillation
1480 bars. The four steel layers in front of each instrumented slot are 2 cm, 2 cm, 14 cm
1481 and 16 cm deep in the beam direction. Each instrumented slot is equipped with
1482 four scintillation bars each, positioned horizontally in the direction orthogonal to the
1483 beam. Each scintillator bar measures $\textcolor{red}{? \times ? \times 2}$ cm and it is read out by one PMT.

1484 The signals from both the punch-thorough and the MuRS PMTs are sent to a
1485 NIM discriminator. If the signal crosses the discriminator threshold, it is digitized in
1486 the CAEN V1740, same as the TPC. The sampling time of the CAEN V1740 is slow
1487 (of the order of 128 ns) and that the pulse shape information from the PMT is lost.
1488 A Punch-thorough and MuRS signal will then be simply a “hit” at a given time in
1489 the beamline event.

1490 It is worth mentioning here the presence of an additional scintillation paddle
1491 between WC4 and the downstream paddle of the TOF system, called halo. The
1492 halo is a $39 \times 38 \times 1$ cm 3 paddle with a 6.5 cm radius hole in the center, whose original
1493 function was to reject beam particles slightly offset from the beamline center. Data

1494 from this paddle turned out to be unusable, so our data events include both particle
1495 going through the halo scintillation material or through the halo hole.

1496 **3.2.5 LArIAT Cosmic Ray Paddle Detectors**

1497 LArIAT triggers both on beam events and on cosmic rays events. We perform this
1498 latter trigger by using two sets of cosmic ray paddle detectors (a.k.a. “cosmic towers”.)
1499 The cosmic towers frame the LArIAT cryostat, as one sits in the downstream left
1500 corner and the other sits in the upstream right corner of the cryostat. Two paddle
1501 sets of four scintillators pieces each make up each cosmic tower, an upper set and a
1502 lower set per tower. Of the four paddles, a couple of two matched paddles stands
1503 upright while the a second matched pair lies across the top of the assembly in the top
1504 sets (or across the bottom of the assembly in the bottom sets). The horizontal couple
1505 is used as a veto for particles traveling from inside the TPC out. The four signals
1506 from the vertical paddles along one of the body diagonals of the TPC are combined
1507 in a logical “AND”. This allows to select track due to cosmic muons at the ground
1508 level crossing the TPC along one of its diagonals. Cosmic ray muons whose average
1509 energy is in the few GeV range crossing both anode and cathode populate the events
1510 triggered this way. This particularly useful sample of tracks is associated can be used
1511 for many tasks; for example, we use anode-cathode piercing tracks to cross check the
1512 TPC electric field on data (see Appendix ??), to calibrate the charge response of
1513 the TPC wires for the full TPC volume and to measure the electron lifetime in the
1514 chamber [105].

1515 We retrieved the scintillation paddles from the decommissioning of the CDF de-
1516 tector at Fermilab and we used only the paddles with a counting efficiency greater
1517 than 95% and low noise at working voltage. The measured trigger rate of the whole
1518 system is 0.032 Hz, corresponding to ~ 2 muons per minute.



Figure 3.6: Photograph of one of the scintillation counters used in the cosmic towers.

1519 3.3 In the Cryostat

1520 The heart of the LArIAT experiment lives in the LArIAT cryostat. In this section,
1521 we describe the cryogenic system and the argon purity (Section 3.3.1), the LArIAT
1522 TPC (Section 3.3.2) and light collection system (3.3.3).

1523 3.3.1 Cryogenics and Argon Purity

1524 LArIAT repurposed the ArgoNeuT cryostat [17] in order to use it in a beam of charged
1525 particles, and added a new process piping and a new liquid argon filtration system in
1526 FTBF. Inside the LArIAT experimental hall, the cryostat sits in the beam of charged
1527 particles with its horizontal main axis oriented parallel to the secondary beam, 3°
1528 off axis from the tertiary beam

1529 Two volumes make up LArIAT cryostat, shown in Figure 3.7: the inner vessel and
1530 the outer vessel. Purified liquid argon fills the inner vessel, while the outer volume
1531 provides insulation through a vacuum jacket equipped with layers of aluminized mylar
1532 superinsulation. The inner vessel is a cylinder of 130 cm length and 76.2 cm diameter,
1533 containing about 550 L of LAr, corresponding to a mass of 0.77 ton. We run the signal
1534 cables for the LArTPC and the high voltage feedthrough through a “chimney” at the
1535 top and mid-length of the cryostat.

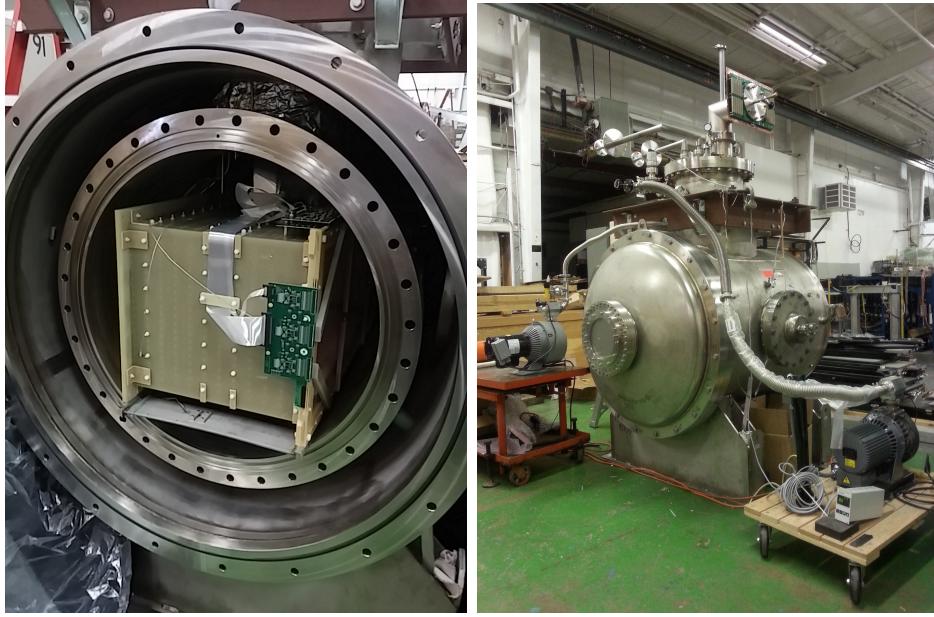


Figure 3.7: Left: the LArIAT TPC in the inner volume of the open cryostat. Right: cryostat fully sealed ready to be transported to FTBF.

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 3.8 were necessary to account for the beam of charged particles entering the TPC and to employ the new FTBF liquid argon purification system. We added a “beam window” on the front outer end cap and an “excluder” on the inner endcap, with the purpose of minimizing the amount of non-instrumented material upstream of the TPC’s active volume. The amount of non-instrumented material in front of the TPC for LArIAT corresponds to ~ 0.3 electron radiation lengths (X_0), to compare against the $\sim 1.6X_0$ of ArgoNeuT. 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.

As in any other LArTPC, argon purity is a crucial parameter for LArIAT. Indeed,

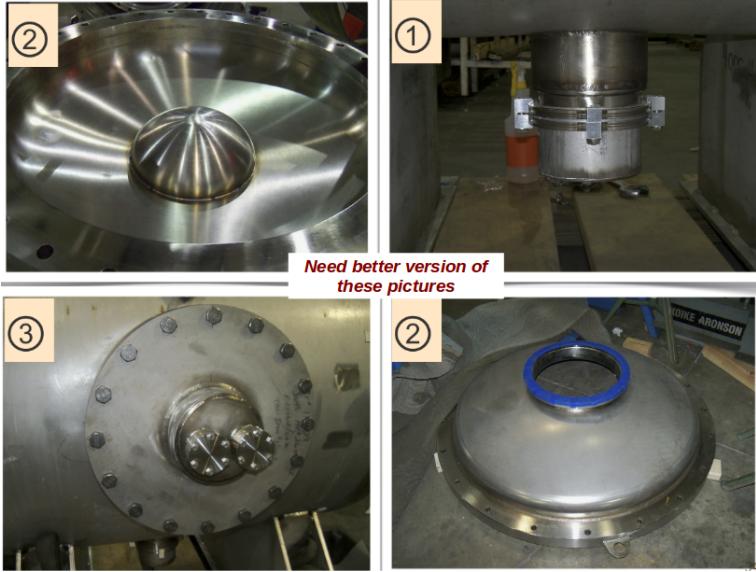


Figure 3.8: Main modifications to the ArgoNeuT cryostat: 1) outlet for connection to the purification system at the bottom of the cryostat; 2) the “beam-window” on the outer endcap and “excluder” which reduces the amount of non-instrumented material before the TPC; 3) the side port to host the light collection system.

1551 the presence of contaminants affects both the basic working principles of a LArTPC,
 1552 as shown in section 2.1.2: electronegative contaminants such as oxygen and water de-
 1553 crease the number of ionization electrons collected on the wires after drifting through
 1554 the volume. In addition, contaminants such as Nitrogen decrease the light yield
 1555 from scintillation light, especially in its slow component. In LArIAT, contaminations
 1556 should not exceed the level of 0.2 parts per billion (ppb). We achieve this level of
 1557 purity in several stages. The specifics required for the commercial argon bought for
 1558 LArIAT are 2 parts per million (ppm) oxygen, 3.5 ppm water, and 10 ppm nitrogen.
 1559 This argon is monitored with the use of commercial gas analyzer. Argon is stored in
 1560 a dewar external to LArIAT hall and filtered before filling the TPC. LArIAT uses a
 1561 filtration system designed for the Liquid Argon Purity Demonstrator (LAPD) [57]:
 1562 half of a 77 liter filter contains a 4A molecular sieve (Sigma-Aldrich [111]) able to re-
 1563 move mainly water, while the other half contains BASF CU-0226 S, a highly dispersed
 1564 copper oxide impregnated on a high surface area alumina, apt to remove mainly oxy-

1565 gen [27]. A single pass of argon in the filter is sufficient to achieve the necessary
1566 purity, unless the filter is saturated. In case the filter saturates, the media needs to
1567 be regenerated by using heated gas; this happened twice during the Run II period¹.
1568 The electron lifetime during the full LArIAT data taking are shown in Figure 2.4.
1569 The filtered argon reaches the inner vessel via a liquid feedthrough which is routed to
1570 the bottom of the cryostat. Argon is not recirculated in the system; rather, it boils
1571 off and vents to the atmosphere. During data taking, we replenish the argon in the
1572 cryostat every 6 hours to keep the TPC high voltage feedthrough and cold electronics
1573 always submerged. In fact, we constantly monitor the level, temperature, and pres-
1574 sure of the argon both in the commercial dewar and inside the cryostat during data
1575 taking.

1576 **3.3.2 LArTPC: Charge Collection**

1577 The LArIAT Liquid Argon Time Projection Chamber is a rectangular box of dimen-
1578 sions 47 cm (drift) x 40 cm (height) x 90 cm (length), containing 170 liters of Liquid
1579 Argon. The LArTPC three major subcomponents are

- 1580 1) the cathode and field cage,
- 1581 2) the wire planes,
- 1582 3) the read-out electronics.

1583 **Cathode and field cage**

1584 A G10 plain sheet with copper metallization on one of the 40 x 90 cm inner surfaces
1585 forms the cathode. A high-voltage feedthrough on the top of the LArIAT cryostat
1586 delivers the high voltage to the cathode; the purpose of the high voltage system

1. We deemed the filter regeneration necessary every time the electron lifetime dropped under 100 μs .

1587 (Figure 3.9) is to drift ionization electrons from the interaction of charged particles
 1588 in the liquid argon to the wire planes. The power supply used in this system is a
 1589 Glassman LX125N16 [71] capable of generating up to -125 kV and 16 mA of current,
 1590 but operated at -23.5kV during LArIAT Run-II. The power supply is connected via
 1591 high voltage cables to a series of filter pots before finally reaching the cathode.

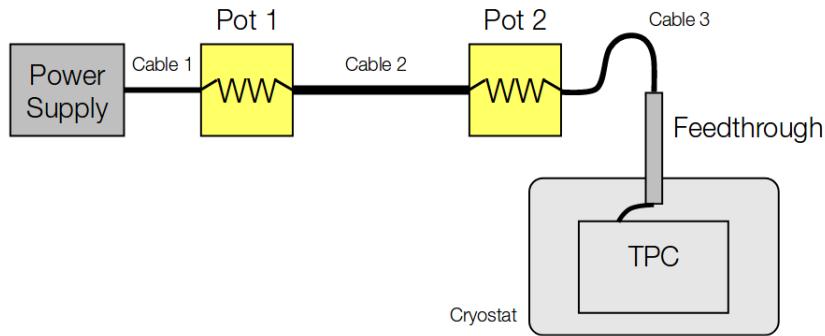


Figure 3.9: Schematic of the LArIAT high voltage system.

1592 The field cage is made of twenty-three parallel copper rings framing the inner
 1593 walls of the G10 TPC structure. A network of voltage-dividing resistors connected to
 1594 the field cage rings steps down the high voltage from the cathode to form a uniform
 1595 electric field. The electric field over the entire TPC drift volume is 486 V/cm, as
 1596 measured in appendix ???. The maximum drift length, i.e. the distance between
 1597 cathode and anode planes, is 47 cm.

1598 **Wire planes**

1599 LArIAT Run-II has three wire planes separated by 4 mm spaces: in order of increasing
 1600 distance from the cathode, they are the shield, the induction and the collection plane.
 1601 The “wire pitch”, i.e., the distance between two adjacent wires in a given plane, is
 1602 4 mm. The shield plane counts 225 parallel wires of equal length oriented vertically.
 1603 This plane is not connected with the read-out electronics; rather it shields the outer
 1604 planes from extremely long induction signals due to the ionization in the whole drift

volume. As the shield plane acts almost like a Faraday cage, the resulting shape of signals in the first instrumented plane (induction) is easier to reconstruct. Both the induction and collection planes count 240 parallel wires of different length oriented at 60° from the vertical with opposite signs. Electrons moving past the induction plane will induce a bipolar pulse on its wires; the drifting electrons will be then collected on the collection plane's wires, forming a unipolar pulse.

The three wire planes and the cathode form three drift volumes, as shown in Figure 3.10. 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 and allow for 100% transmission of the drifting electrons through the shield and the induction planes.

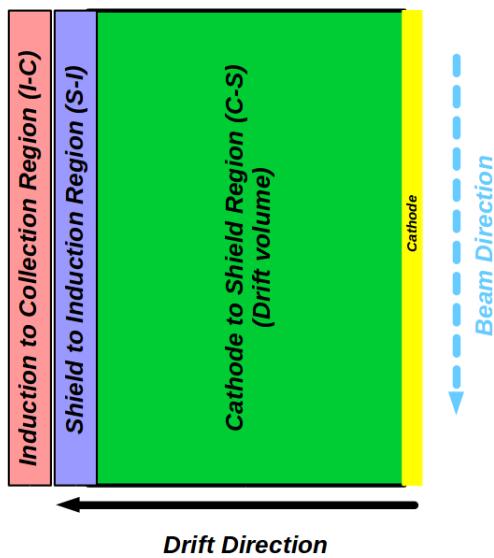


Figure 3.10: Schematic of the three drift regions inside the LArIAT TPC: the main drift volume between the cathode and the shield plane (C-S) in green, the region between the shield plane and the induction plane (S-I) in purple, and the region between the induction plane and the collection plane (I-C) in pink.

Table 3.1 provides the default voltages applied to the cathode and the shield,

1619 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

1620 **Electronics**

1621 Dedicated electronics read the induction and collection plane wires, for a total of
1622 480-channel analog signal path from the TPC wires to the signal digitizers. A digital
1623 control system for the TPC-mounted electronics, a power supply, and a distribution
1624 system complete the front-end system. Figure 3.11 shows a block diagram of the
1625 overall system. The direct readout of the ionization electrons in liquid argon forms
1626 typically small signals on the wires, which need amplification in oder to be processed.
1627 LArIAT performs the amplification stage directly in cold with amplifiers mounted
1628 on the TPC frame inside the liquid argon. The BNL ASICs adopted in LArIAT are
1629 designated as LArASIC, version 4-star and are the same used by the MicroBooNE
1630 experiment [60]. The signal from the ASICs are driven to the other end of the readout
1631 chain, to the CAEN V1740 digitizers [35]. The CAEN V1740 has a 12 bit resolution
1632 and a maximum input range of 2 VDC, resulting in about 180 ADC count for a
1633 crossing MIP.

1634 **3.3.3 LArTPC: Light Collection System**

1635 The collection of scintillation photons is the second mechanism of particle detection
1636 in argon other than the ionization electrons. Over the course of LArIAT's three years
1637 of data taking, the light collection system changed several times. We describe here
1638 the light collection system for Run II. Two PMTs, a 3-inch diameter Hamamatsu
1639 R-11065 and 2-inch diameter ETL D757KFL [7], as well as three SiPMs arrays (two
1640 Hamamatsu S11828-3344M 4x4 arrays and one single-channel SensL MicroFB-60035)

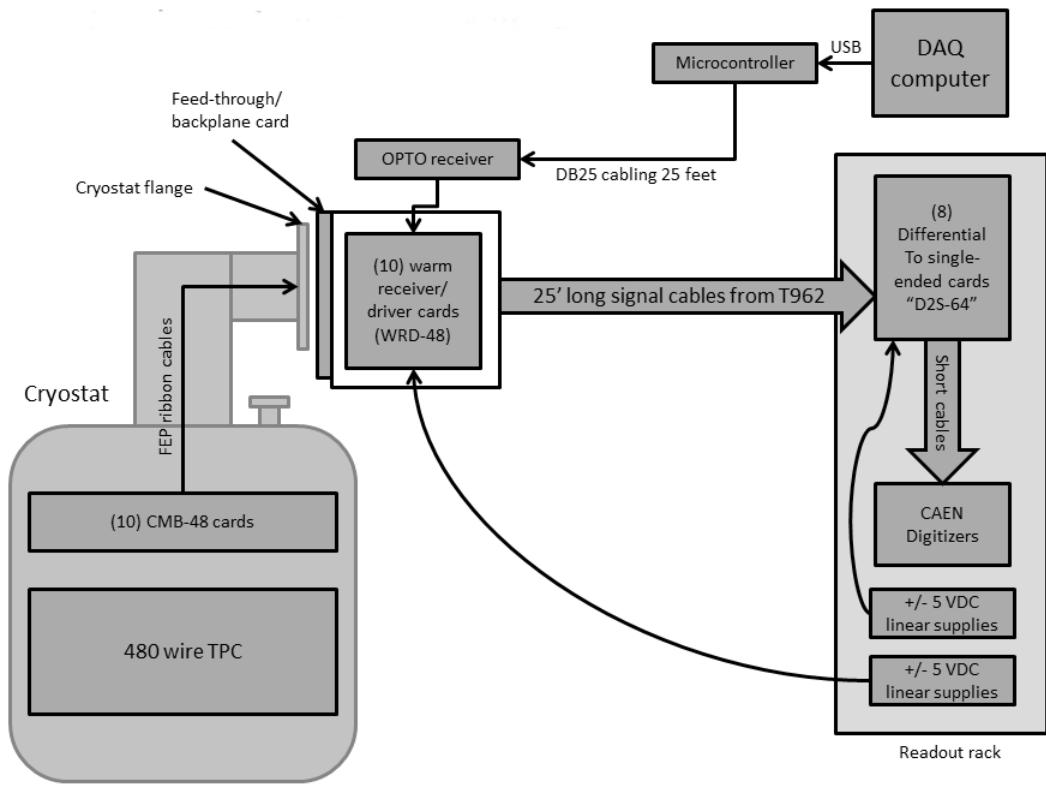


Figure 3.11: Overview of LArIAT Front End electronics.

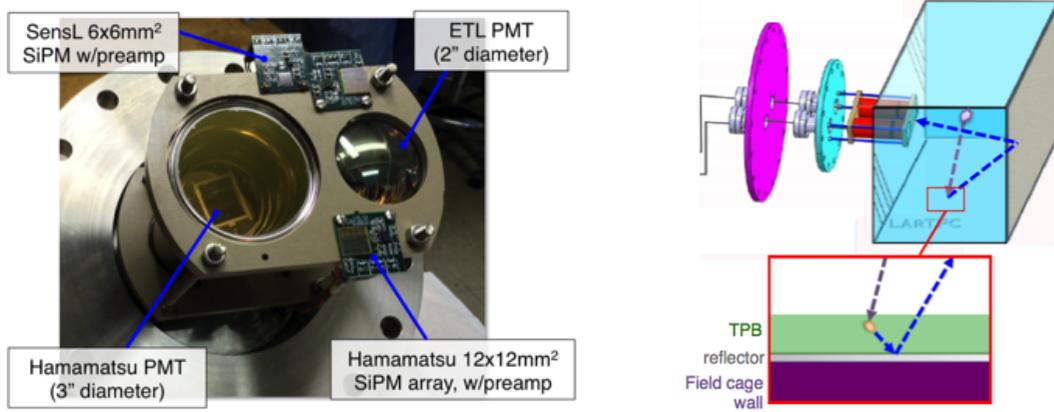


Figure 3.12: LArIAT’s photodetector system for observing LAr scintillation light inside the TPC (left), and a simplified schematic of VUV light being wavelength-shifting along the TPB-coated reflecting foils (right).

1641 are mounted on the PEEK support structure. PEEK screws into an access flange
 1642 as shown in Figure 3.12, on the anode side, leaving approximately 5 cm of clearance
 1643 from the collection plane.

1644 Liquid argon scintillates in vacuum-ultraviolet (VUV) range at 128 nm; since
 1645 cryogenic PMTs are not sensitive to VUV wavelengths, we need to shift the light to a
 1646 range that is visible to the PMTs. In LArIAT, the wavelength shifting is achieved by
 1647 installing highly-reflective 3M VIKUITI dielectric substrate foils coated with a thin
 1648 layer of tetraphenyl-butadiene (TPB) on the four unbiased walls of the TPC. The
 1649 scintillation light interaction with the TPB emits one or more visible photons, which
 1650 are then reflected into the chamber. Thus, the light yield increases and results in
 1651 higher uniformity of light across the TPC active volume, allowing the possibility of
 1652 light-based calorimetry, currently under study.

1653 For Run II, we coated the windows of the ETL PMT and the SensL SiPM with
 1654 a thin layer of TPB. In doing so, some of the VUV scintillation light converts into
 1655 visible right at the sensor faces, keeping information on the direction of the light
 1656 source. Information about the light directionality is hindered for the light reflected
 1657 on foils, as the reflection is uniform in angle.

1658 3.4 Trigger and DAQ

1659 The LArIAT DAQ and trigger system governs the read out of all the many subsystems
1660 forming LArIAT. The CAEN V1495 module [34] and its user-programmable FPGA
1661 are the core of this system. Every 10 ns, this module checks for matches between
1662 sixteen logical inputs and user-defined patterns in the trigger menu; if it finds a match
1663 for two consecutive clock ticks, that trigger fires.

1664 LArIAT receives three logic signals from the Fermilab accelerator complex related
1665 to the beam timing which we use as input triggers: a pulse just before the beam, a
1666 pulse indicating beam-on, and a beam-off pulse.

1667 The beam instruments, the cosmic ray taggers, and the light collection system
1668 provide the other NIM-standard logic pulse inputs to the trigger decision. We auto-
1669 matically log the trigger inputs configuration with the rest of the DAQ configuration
1670 at the beginning of each run.

1671 Fundamental inputs to the trigger card come from the TOF (see section 3.2.3)
1672 and the wire chambers (see section 3.2.2), as activity in these systems points to the
1673 presence of a charged particle in tertiary beam line. In particular, the discriminated
1674 pulses from the TOF PMTs form a NIM logic pulse for the trigger logic. We ask
1675 for a coincidence within a 20 ns window for all the pulses from the PMTs looking at
1676 the same scintillator block and use a delayed coincidence between the upstream and
1677 downstream paddle to inform the trigger decision. In order to form a coincidence
1678 between the upstream and downstream paddles, we delay the upstream paddle coin-
1679 cidence by 20 ns and widen it by 100 ns. The delay and widening are necessary to
1680 account for both lightspeed particles and slower particles (high-mass) to travel the
1681 6.5 m between the upstream and the downstream paddles. For the read out of the
1682 wire chambers, we use a total of sixteen multi-hit TDCs [74], four per chamber: two
1683 TDC per plane (horizontal and vertical), sixty-four wires per TDC. In each TDC, we
1684 keep the logical “OR” for any signal over threshold from the sixty-four wires. We

1685 then require a coincidence between the “OR” for the horizontal TDCs and the “OR”
1686 for the vertical TDCs: with this logic we make sure that at least one horizontal wire
1687 and one vertical wire saw significant signal in one wire chamber. The single logical
1688 pulse from each of the four wire chambers feeds into the first four inputs to the V1495
1689 trigger card. We require a coincidence within 20 ns of at least three logical inputs to
1690 form a trigger.

1691 The cosmic towers (see Section 3.2.5) provide another primary input to the trigger,
1692 in order to capture long tracks from cosmic muons crossing the TPC. We use NIM
1693 modules to require coincidences between one upper and one lower paddle set of any
1694 opposite cosmic towers. The OR all the opposite towers’ coincidences is fed as an
1695 input to the trigger card.

1696 We use the signal from the cryogenic PMTs (see Section 3.3.3) to form several
1697 interesting triggers. The coincidence of signals from all the PMT pulses within \sim 20 ns
1698 is an indication of ionizing radiation in the TPC and forms a trigger input. The
1699 coincidence of two subsequent scintillation logic pulses delayed by a maximum of $7 \mu\text{s}$
1700 forms the Michel electron trigger.

1701 **3.5 Control Systems**

1702 LArIAT is a complex ensemble of systems which needed to be monitored simultane-
1703 ously during data taking. We performed the monitoring of the systems operations
1704 with a slow control system, a DAQ monitoring system and a low level data quality
1705 monitoring described in the following sections.

1706 **Slow Control**

1707 We used the Synoptic Java Web Start framework [19] as a real-time display of subsys-
1708 tem conditions. Synoptic provides a Graphical User Interface that talks to the Fer-

milab Accelerator Control System via the ACNET protocol. Its simple GUI allowed us to change the operating parameters and to graph the trends of several variables of interest for all of 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 magnet temperatures. 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 MCcenter beamline. For example, the horizontal and vertical position of the beam at the first two wire chambers (WC1 and WC2) are shown in 3.14 as seen by the shifter during data taking.

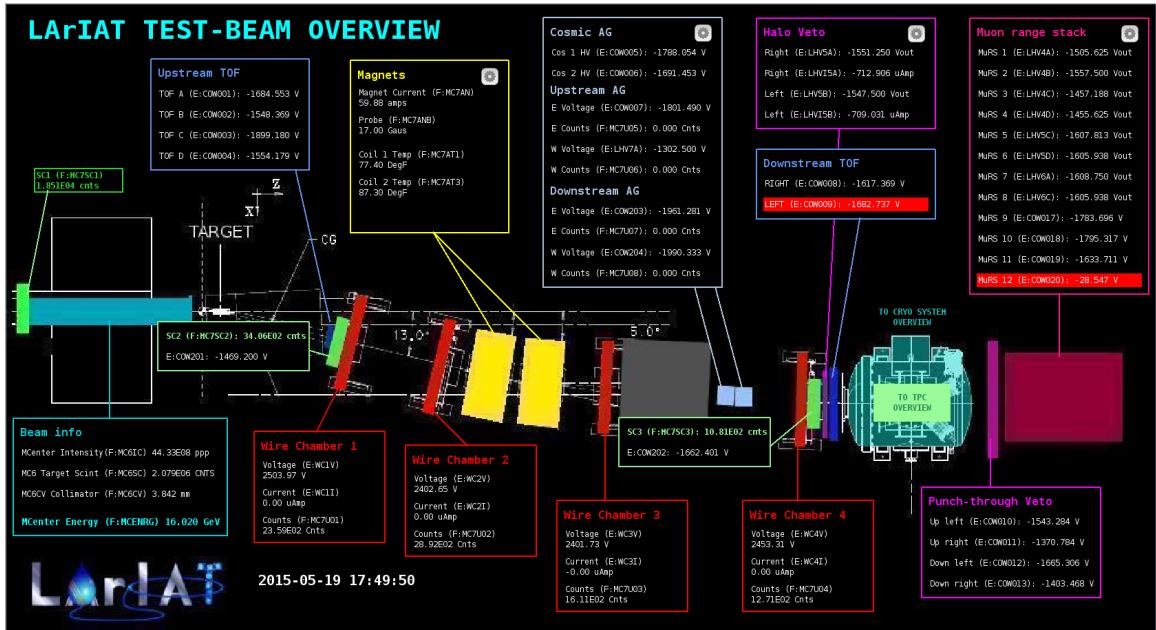


Figure 3.13: Interface of the Synoptic slow control system

1720 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

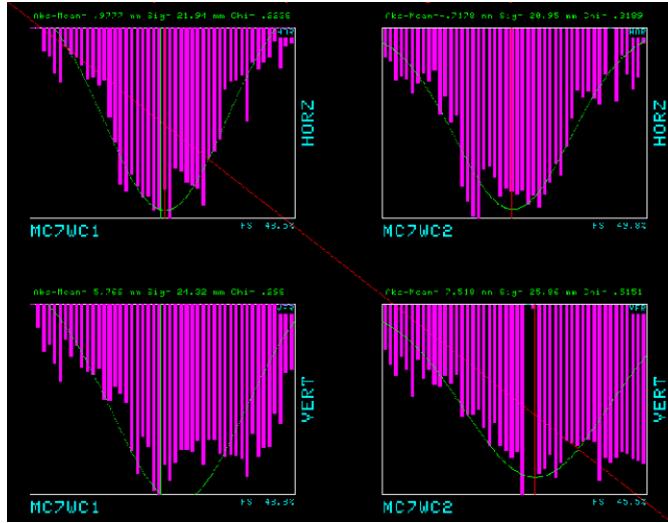


Figure 3.14: Beam position at the upstream wire chambers monitored with ACNET.

1723 page displays, among other information, the total number of triggers in the event,
 1724 the total number of detectors triggered during a beam spill, the trigger patterns, the
 1725 number of times a particular trigger pattern was satisfied during a beam spill, and
 1726 the current time relative to the Fermilab accelerator complex supercycle. A screen
 1727 shot of the page is show in figure 3.15.

1728 Data Quality Monitoring

1729 We employ two systems to ensure the quality of our data during data taking: the
 1730 Near-Real-Time Data Quality Monitoring and the Event Viewer.

1731 The Near-Real-Time Data Quality Monitoring (DQM) is a webpage which receives
 1732 updates from all the VME boards in the trigger system and displays the results of
 1733 a quick analysis of the DAQ stream of raw data on a spill-by-spill basis. The DQM
 1734 allows the shifter to monitor almost in real time (typically with a 2-minute delay)
 1735 a series of low level-quantities and compare them to past collections of beam spills.
 1736 Some of the variables monitored in the DQM are the pedestal mean and RMS on
 1737 CAEN digitizer boards of the TPC wires and PMTs of the beamline detectors, the
 1738 hit occupancy and timing plots on the wire chambers, and number of data fragments

1739 recorded that are used to build a TPC event. Abnormal values for low-level quantity
1740 in the data activates a series of alarms in the DQM; this quick feedback on the DAQ
1741 and beam conditions is fundamental to assure a fast debugging of the detector and a
1742 very efficient data taking during beam uptime.

1743 The online Event Viewer displays a two dimensional representation (Wire vs Time)
1744 of LArIAT TPC events on both the Induction and the Collection planes in near real
1745 time. The raw pulses collected by the DAQ on each wire are plotted as a function
1746 of drift time, resulting in an image of the TPC event easily readable by the shifter.
1747 This tool guarantees a particularly good check of the TPC operation which activate
1748 an immediate feedback for troubleshooting a number of issues. For example, it is
1749 easy for the shifter to spot high occupancy events and request a reduction of the
1750 primary beam intensity, or to spot a decrease of the argon purity which requires the
1751 regeneration of filters, or to catch the presence of electronic noise and reboot the
1752 ASICs. An example of high occupancy event is shown in 3.16.

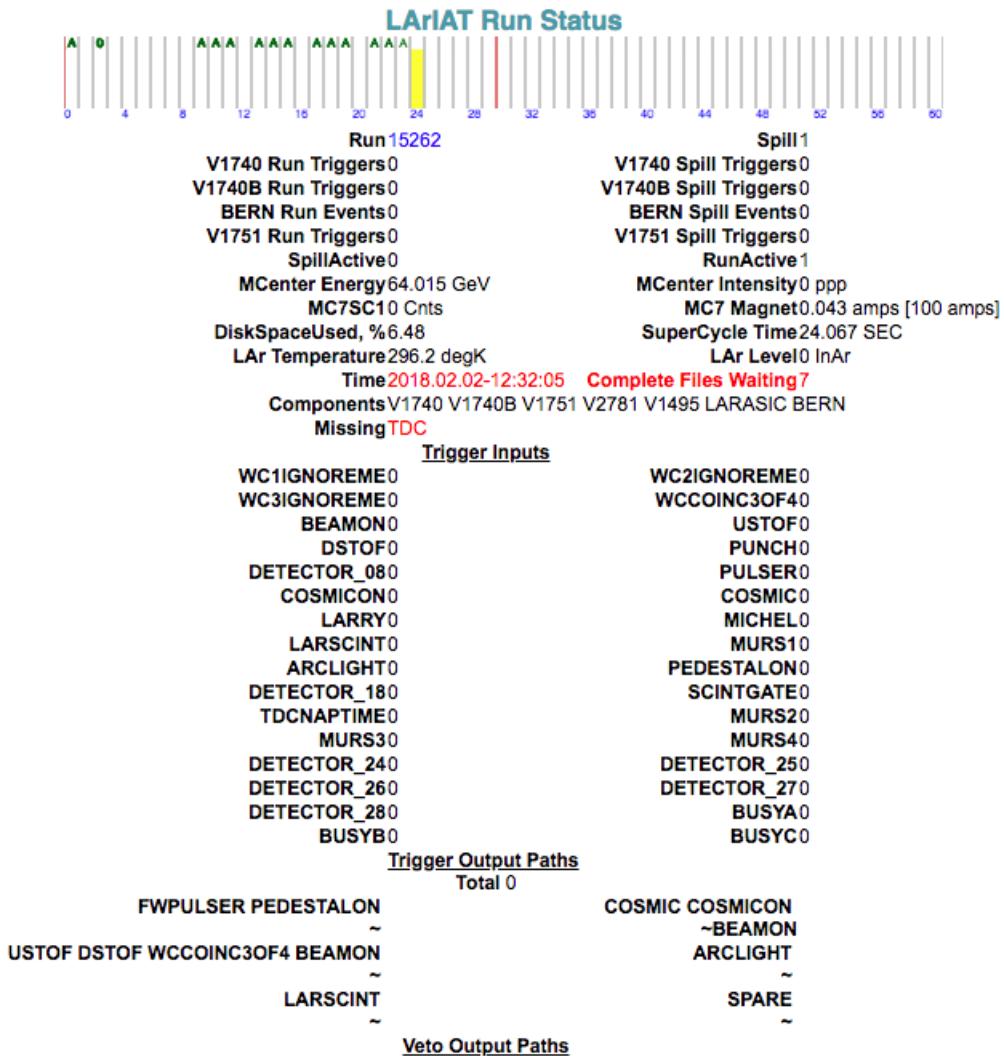


Figure 3.15: Run Status page at LArIAT downtime. At the top the yellow bar displays the current position in the Fermilab supercycle. Interesting information to be monitored by the shifter were the run number and number of spills, time elapsed from data taking (here in red), the energy of the secondary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

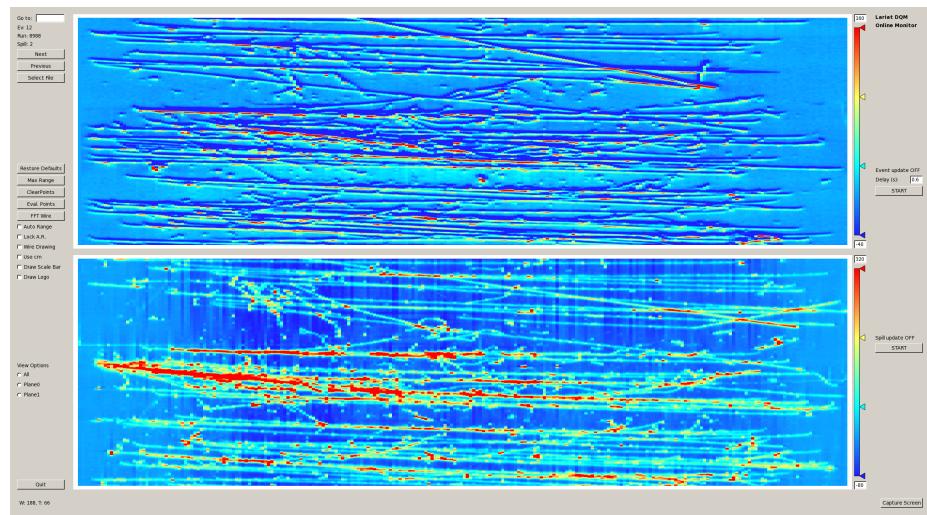


Figure 3.16: High occupancy event display: induction plane (top) and collection plane (bottom).

¹⁷⁵³ **Chapter 4**

¹⁷⁵⁴ **Total Hadronic Cross Section**

¹⁷⁵⁵ **Measurement Methodology**

¹⁷⁵⁶ “Like a lemon to the lime and the bubble to the bee”

¹⁷⁵⁷ – Eazy-E, 1993 –

¹⁷⁵⁸ This chapter describes the general procedure employed to measure a total hadronic
¹⁷⁵⁹ differential cross section in LArIAT. Albeit with small differences, both the (π^- ,Ar)
¹⁷⁶⁰ and (K^+ ,Ar) total hadronic cross section measurements rely on the same procedure.
¹⁷⁶¹ We start by selecting the particle of interest using a combination of beamline detectors
¹⁷⁶² and TPC information (Section 4.1). We then perform a handshake between the
¹⁷⁶³ beamline information and the TPC tracking to assure the selection of the correct
¹⁷⁶⁴ TPC track (Section 4.2). Finally, we apply the “thin slice” method and measure the
¹⁷⁶⁵ “raw” hadronic cross section (Section 4.3). A series of corrections are then evaluated
¹⁷⁶⁶ to obtain the “true” cross section (Section 4.3.3).

¹⁷⁶⁷ At the end of this chapter, we show a sanity check of the methodology by applying
¹⁷⁶⁸ the thin slice method employing only MC truth information and retrieving the Geant4
¹⁷⁶⁹ tabulated cross section for pions and kaons (Section 4.4).

4.1 Event Selection

The measurement of the (π^- ,Ar) and (K^+ ,Ar) total hadronic cross section in LArIAT starts by selecting the pool of pion or kaon candidates and measuring their momentum. This is done through the series of selections on beamline and TPC information described in the next sections. The summary of the event selection in data is reported in Table 4.1.

4.1.1 Selection of Beamline Events

As shown in equation 4.5, we leverage the beamline particle identification and momentum measurement before entering the TPC as an input to evaluate the kinetic energy for the hadrons used in the cross sections measurements. Thus, we select the LArIAT data to keep only events whose wire chamber and time of flight information is registered (line 1 in Table 4.1). Additionally, we perform a check of the plausibility of the trajectory inside the beamline detectors: given the position of the hits in the four wire chambers, we make sure the particle's trajectory does not cross any impenetrable material such as the collimator and the magnets steel (line 2 in Table 4.1).

	Run-II Neg Pol	Run-II Pos Pol
1. Events Reconstructed in Beamline	158396	260810
2. Events with Plausible Trajectory	147468	240954
3. Beamline $\pi^-/\mu^-/e^-$ Candidate	138481	N.A.
4. Beamline K^+ Candidate	N.A	2837
5. Events Surviving Pile Up Filter	108929	2389
6. Events with WC2TPC Match	41757	1081
7. Events Surviving Shower Filter	40841	N.A.
8. Available Events For Cross Section	40841	1081

Table 4.1: Number of data events for Run-II Negative and Positive polarity

1786 **4.1.2 Particle Identification in the Beamline**

1787 In data, the main tool to establish the identity of the hadron of interest is the LArIAT
1788 tertiary beamline, in its function of mass spectrometer. We combine the measurement
1789 of the time of flight, TOF , and the beamline momentum, p_{Beam} , to reconstruct the
1790 invariant mass of the particles in the beamline, m_{Beam} , as follows

$$m_{Beam} = \frac{p_{Beam}}{c} \sqrt{\left(\frac{TOF * c}{l}\right)^2 - 1}, \quad (4.1)$$

1791 where c is the speed of light and l is the length of the particle's trajectory between
1792 the time of flight paddles.

1793 Figure 4.1 shows the mass distribution for the Run II negative polarity runs on
1794 the left and positive polarity runs on the right. We perform the classification of events
1795 into the different samples as follows:

- 1796 • $\pi/\mu/e$: mass $< 350 \text{ MeV}/c^2$
1797 • kaon: $350 \text{ MeV} < \text{mass} < 650 \text{ MeV}/c^2$
1798 • proton: $650 \text{ MeV} < \text{mass} < 3000 \text{ MeV}/c^2$.

1799 Lines 3 and 4 in Table 4.1 show the number of negative $\pi/\mu/e$ and positive K
1800 candidates which pass the mass selection for LArIAT Run-II data.

1801 **4.1.3 TPC Selection: Halo Mitigation**

1802 The secondary beam impinging on LArIAT secondary target produces a plethora of
1803 particles which propagates downstream. The presence of upstream and downstream
1804 collimators greatly abates the number of particles tracing down the LArIAT tertiary
1805 beamline. However, it is possible that more than one particle sneaks into the LArTPC
1806 during its readout time: the TPC readout is triggered by the particle firing the

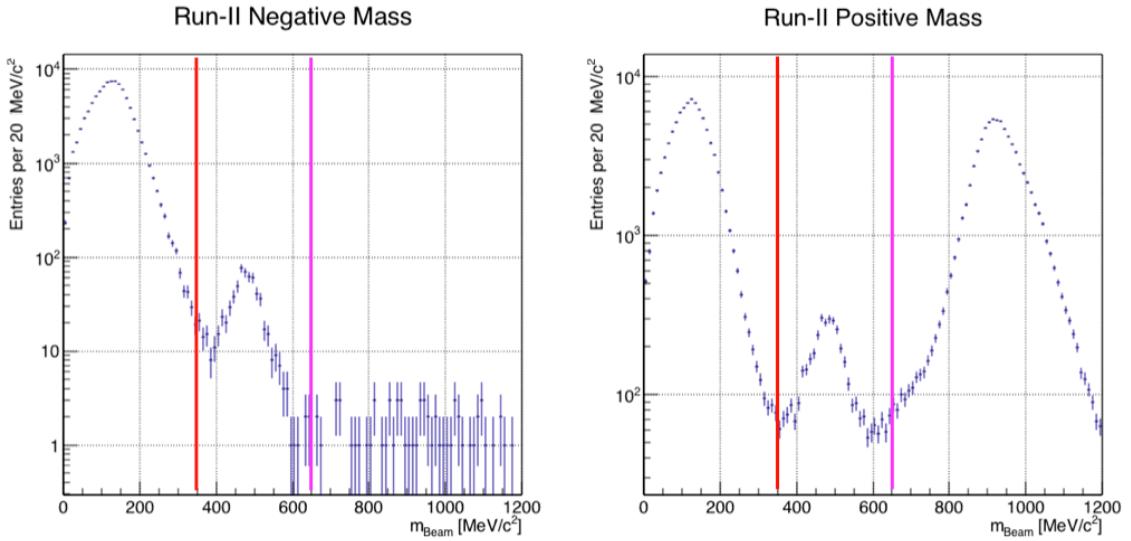


Figure 4.1: Distribution of the beamline mass as calculated according to equation 4.1 for the Run-II events reconstructed in the beamline, negative polarity runs on the left and positive polarity runs on the right. The classification of the events into $\pi^\pm/\mu^\pm/e^\pm$, K^\pm , or (anti)proton is based on these distributions, whose selection cut are represented by the vertical colored lines.

1807 beamline detectors, but particles from the beam halo might be present in the TPC at
1808 the same time. We call “pile up” the additional traces in the TPC. We adjusted the
1809 primary beam intensity between LArIAT Run I and Run II to reduce the presence of
1810 events with high pile up particles in the data sample. For the cross section analyses,
1811 we remove events with more than 4 tracks in the first 14 cm upstream portion of the
1812 TPC from the sample (line 5 in in Table 4.1).

1813 4.1.4 TPC Selection: Shower Removal

1814 In the case of the (π^-,Ar) cross section, the resolution of beamline mass spectrometer
1815 is not sufficient to select a beam of pure pions. In fact, muons and electrons survive
1816 the selection on the beamline mass. It is important to notice that the composition of
1817 the negative polarity beam is mostly pions, as will be discussed in section 5.2.1. Still,
1818 we devise a selection on the TPC information to mitigate the presence of electrons

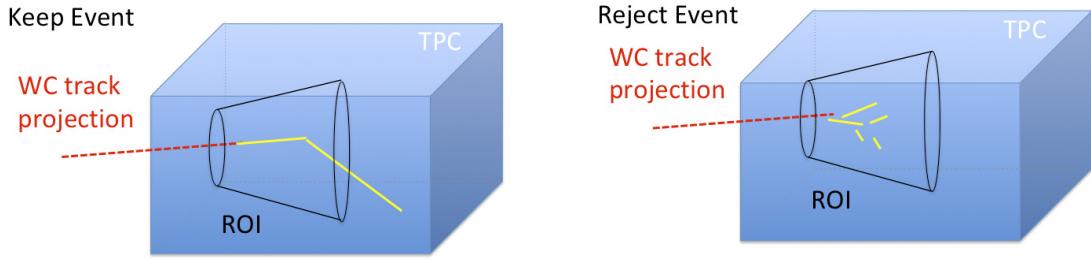


Figure 4.2: Visual rendering of the shower filter. The ROI is a cut cone, with a small radius of 4 cm, a big radius of 10 cm and an height of 42 cm (corresponding to 3 radiation lengths for electrons in Argon).

in the sample used for the pion cross section. The selection relies on the different topologies of a pion and an electron event in the argon: while the former will trace a track inside the TPC active volume, the latter will tend to “shower”, i.e. interact with the medium, producing bremsstrahlung photons which pair convert into several short tracks. In order to remove the shower topology, we create a region of interest (ROI) around the TPC track corresponding to the beamline particle. We look for short tracks contained in the ROI, as depicted in figure 4.4: if more than 5 tracks shorter than 10 cm are in the ROI, we reject the event. Line 7 in Table 4.1 shows the number of events surviving this selection.

4.2 Beamline and TPC Handshake: the Wire Chamber to TPC Match

For each event passing the selection on its beamline information, 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” (WC2TPC for short). In general, the TPC tracking algorithm will reconstruct more than one track in the event, partially due to the fact that hadrons interact in the chamber and partially because of pile up particles during the triggered TPC readout time, as shown in

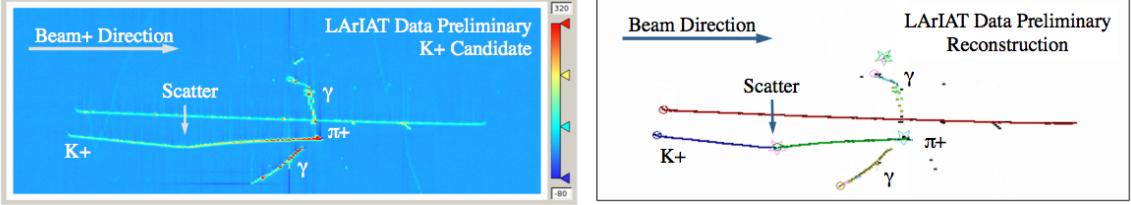


Figure 4.3: Kaon candidate event: on the right, event display showing raw quantities; on the left, event display showing reconstructed tracks. In the reconstructed event display, different colors represent different track objects. A kink is visible in the kaon ionization, signature of a hadronic interaction: the tracking correctly stops at the kink position and two tracks are formed. An additional pile-up track is so present in the event (top track in red).

1836 figure 4.3.

1837 We attempt to uniquely match one wire chamber track to one and only one recon-
 1838 structed TPC track. In order to determine if a match is present, we apply a geomet-
 1839 rical selection on the relative the position of the wire chamber and TPC tracks. We
 1840 start by considering only TPC tracks whose first point is in the first 2 cm upstream
 1841 portion of the TPC for the match. We project the wire chamber track to the TPC
 1842 front face where we define the coordinates of the projected point as x_{FF} and y_{FF} . For
 1843 each considered TPC track, we define ΔX as the difference between the x position of
 1844 the most upstream point of the TPC track and x_{FF} . ΔY is defined analogously. We
 1845 define the radius difference, ΔR , as $\Delta R = \sqrt{\Delta X^2 + \Delta Y^2}$. We define as α the angle
 1846 between the incident WC track and the TPC track in the plane that contains them.
 1847 If $\Delta R < 4$ cm, $\alpha < 8^\circ$, a match between WC-track and TPC track is found. We
 1848 describe how we determine the value for the radius and angular selection in Section
 1849 A.0.1. We discard events with multiple WC2TPC matches. We use only those TPC
 1850 tracks that are matched to WC tracks in the cross section calculation. Line 6 in Table
 1851 4.1 shows the number of events where a unique WC2TPC match was found.

1852 In MC, we mimic the matching between the WC and the TPC track by construct-
 1853 ing a fake WC track using truth information at wire chamber four. We then apply
 1854 the same WC to TPC matching algorithm as in data.

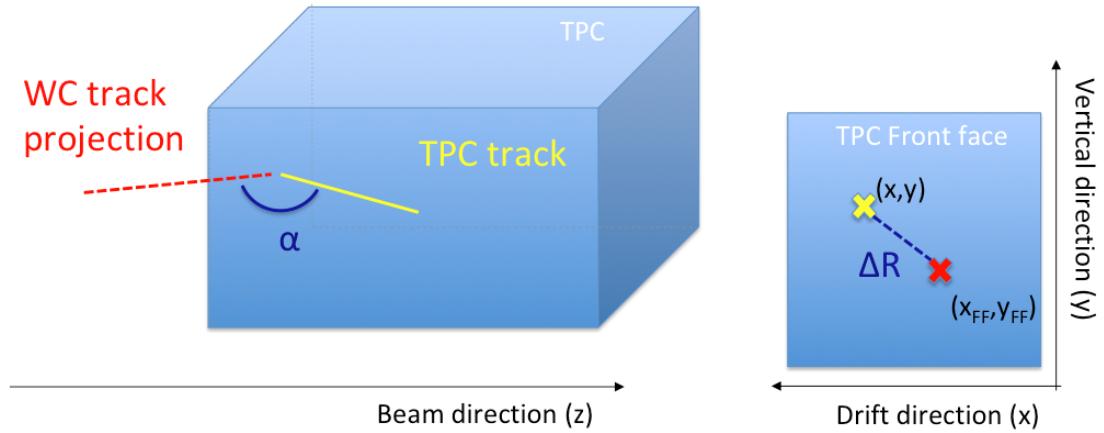


Figure 4.4: Visual rendering of the wire chamber to TPC match.

1855 4.3 The Thin Slice Method

1856 Once we have selected the pool of hadron candidates and we have identified the TPC
1857 track corresponding to the beamline event, we apply the thin slice method to measure
1858 the cross section, as the following sections describe.

1859 4.3.1 Cross Sections on Thin Target

1860 Cross section measurements on a thin target have been the bread and butter of
1861 nuclear and particle experimentalists since the Geiger-Marsden experiments [67]. At
1862 their core, this type of experiments consists in shooting a beam of particles with a
1863 known flux on a thin slab of material and recording the outgoing flux.

1864 In general even in the case of thin target, the target is not a single particle,
1865 but rather a slab of material containing many diffusion centers. The so-called “thin
1866 target” approximation assumes that the target centers are uniformly distributed in
1867 the material and that the target is thin compared to the projectile interaction length,
1868 so that no center of interaction sits in front of another. In this approximation, the
1869 ratio between the number of particles interacting in the target N_{Int} and the number of
1870 incident particles N_{Inc} on the target determines the interaction probability $P_{\text{Interacting}}$,

1871 which is the complementary to one of the survival probability $P_{Survival}$. Equation 4.2

$$P_{Survival} = 1 - P_{Interacting} = 1 - \frac{N_{Int}}{N_{Inc}} = e^{-\sigma_{TOT}n\delta X} \quad (4.2)$$

1872 describes the probability for a particle to survive the thin target. This formula relates
1873 the interaction probability to the total hadronic cross section (σ_{TOT}), the density of
1874 the target centers (n)¹ and the thickness of the target along the incident hadron
1875 direction (δX). If the target is thin compared to the interaction length of the process
1876 considered, we can Taylor expand the exponential function in equation 4.2 and find
1877 a simple proportionality relationship between the cross section and the number of
1878 incident and interacting particles, as shown in equation 4.3:

$$1 - \frac{N_{Int}}{N_{Inc}} = 1 - \sigma_{TOT}n\delta X + O(\delta X^2). \quad (4.3)$$

1879 Solving for the cross section, we find:

$$\sigma_{TOT} = \frac{1}{n\delta X} \frac{N_{Int}}{N_{Inc}}. \quad (4.4)$$

1880 4.3.2 Not-so-Thin Target: Slicing the Argon

1881 The interaction length of pions and kaons in argon is expected to be of the order
1882 of 50 cm for pions and 100 cm for kaons. Thus, the LArIAT TPC, with its 90 cm
1883 of length, is not a thin target. However, the fine-grained tracking of the LArIAT
1884 LArTPC allows us to treat the argon volume as a sequence of many adjacent thin
1885 targets.

1886 As described in Chapter 3, LArIAT wire planes consist of 240 wires each. The
1887 wires are oriented at +/- 60° from the vertical direction at 4 mm spacing, while the

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

beam direction is oriented 3 degrees off the z axis in the XZ plane. The wires collect
 signals proportional to the energy loss of the hadron along its path in a $\delta X = 4$
 $\text{mm}/(\sin(60^\circ)\cos(3^\circ)) \approx 4.7$ mm slab of liquid argon. Thus, one can think to slice
 the TPC into many thin targets of $\delta X = 4.7$ mm thickness along the direction of the
 incident particle, making a measurement at each wire along the path.

Considering each slice j a “thin target”, we can apply the cross section calculation
 from Equation 4.4 iteratively, evaluating the kinetic energy of the hadron as it enters
 each slice, E_j^{kin} . For each WC2TPC matched particle, the energy of the hadron
 entering the TPC is known thanks to the momentum and mass determination by the
 tertiary beamline,

$$E_{FrontFace}^{kin} = \sqrt{p_{Beam}^2 - m_{Beam}^2} - m_{Beam} - E_{loss}, \quad (4.5)$$

where E_{loss} is a correction for the energy loss in the uninstrumented material between
 the beamline and the TPC front face. The energy of the hadron at 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

$$E_j^{kin} = E_{FrontFace}^{kin} - \sum_{i < j} E_{Dep,i}, \quad (4.6)$$

where $E_{Dep,i}$ 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 $N_{Inc}(E^{kin})$ in the energy bin corresponding
 to its kinetic energy in that slice. If it interacts in the slice, it also contributes
 to $N_{Int}(E^{kin})$ 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 $\frac{N_{Int}(E^{kin})}{N_{Inc}(E^{kin})}$.

Our goal is to measure the total interaction cross section, independently from the
 topology of the interaction. Thus, we determine that a hadron interacted simply by

	min	max
X	1 cm	46 cm
Y	-15 cm	15 cm
Z	0 cm	86 cm

Table 4.2: Fiducial volume boundaries used to determine cross section interaction point.

requiring that the last point of the WC2TPC matched track lies inside the fiducial volume, whose boundaries are defined in Table 4.2. If the TPC track stops within the fiducial volume, its last point will be the interaction point; if the track crosses the boundaries of the fiducial volume, the track will be considered “through going” and no interaction point will be found. The only points of the hadronic candidate track considered to fill the N_{Inc}) and N_{Inc} plots are the ones contained in the fiducial volume.

4.3.3 Corrections to the Raw Cross Section

Equation 4.4 is a prescription for measuring the cross section in case of a pure beam of the hadron of interest and 100% efficiency in the determination of the interaction point. For example, if LArIAT had a beam of pure pions and were 100% efficient in determining the interaction point within the TPC, the pion cross section in each energy bin would be given by

$$\sigma_{TOT}^{\pi^-}(E_i) = \frac{1}{n\delta X} \frac{N_{\text{Int}}^{\pi^-}(E_i)}{N_{\text{Inc}}^{\pi^-}(E_i)}. \quad (4.7)$$

Unfortunately, this is not the case. In fact, the selection used to isolate pions in the LArIAT beam allows for the presence of some muons and electrons as background, while the kaon selection allows for a small percentage of protons (see Section 5.2.1). Also, the LArIAT TPC is not 100% efficient in determining the interaction point. Therefore we need to apply two corrections evaluated on the MC in order to

1928 extract the true cross section from LArIAT data: the background subtraction and
 1929 the efficiency correction. Still using the pion case as example, we estimate the pion
 1930 cross section in each energy bin changing Equation 4.7 into

$$\sigma_{TOT}^{\pi^-}(E_i) = \frac{1}{n\delta X} \frac{N_{Int}^{\pi^-}(E_i)}{N_{Inc}^{\pi^-}(E_i)} = \frac{1}{n\delta X} \frac{\epsilon^{Inc}(E_i)[N_{Int}^{TOT}(E_i) - B_{Int}(E_i)]}{\epsilon^{Int}(E_i)[N_{Inc}^{TOT}(E_i) - B_{Inc}(E_i)]}, \quad (4.8)$$

1931 where $N_{Int}^{TOT}(E_i)$ and $N_{Inc}^{TOT}(E_i)$ is the measured content of the interacting and
 1932 incident histograms for events that pass the event selection, $B_{Int}(E_i)$ and $B_{Inc}(E_i)$
 1933 represent the contributions from the background to the interacting and incident his-
 1934 tograms respectively, and $\epsilon^{Int}(E_i)$ and $\epsilon^{Inc}(E_i)$ are the efficiency corrections for said
 1935 histograms.

1936 As we will show in section 5.3, the background subtraction for the interacting
 1937 and incident histograms can be translated into a corresponding relative pion content
 1938 $C_{Interacting}^{\pi MC}(E_i)$ and $C_{Incident}^{\pi MC}(E_i)$ and the cross section re-written as follows

$$\sigma_{TOT}^{\pi^-}(E_i) = \frac{1}{n\delta X} \frac{\epsilon^{Inc}(E_i)}{\epsilon^{Int}(E_i)} \frac{C_{Int}^{\pi MC}(E_i)}{C_{Inc}^{\pi MC}(E_i)} \frac{N_{Int}^{TOT}(E_i)}{N_{Inc}^{TOT}(E_i)}. \quad (4.9)$$

1939 4.4 Procedure testing with truth quantities

1940 The (π^-, Ar) and (K^+, Ar) total hadronic cross section implemented in Geant4 can be
 1941 used as a tool to validate the measurement methodology. We describe here a closure
 1942 test done on Monte Carlo to prove that the methodology of slicing the TPC retrieves
 1943 the underlying cross section distribution implemented in Geant4 within the statistical
 1944 uncertainty.

1945 For pions and kaons in the considered energy range, the Geant4 inelastic model
 1946 adopted is “BertiniCascade”; the pion elastic cross sections are tabulated from on
 1947 Chips, while the kaon elastic cross sections are tabulated on Gheisha and Chips.

1948 For the validation test, we fire a sample of pions and a sample of kaons inside the

1949 LArIAT TPC active volume using the Data Driven Monte Carlo (see section 5.2.2).
1950 We apply the thin-sliced method using only true quantities to calculate the hadron
1951 kinetic energy at each slab in order to decouple reconstruction effects from possible
1952 issues with the methodology. For each slab of 4.7 mm length along the path of the
1953 hadron, we integrate the true energy deposition as given by the Geant4 transportation
1954 model. Then, we recursively subtracted it from the hadron kinetic energy at the TPC
1955 front face to evaluate the kinetic energy at each slab until the true interaction point is
1956 reached. Since the MC is a pure beam of the hadron of interest and truth information
1957 is used to retrieve the interaction point, no correction is applied. Doing so, we obtain
1958 the true interacting and incident distributions for the considered hadron, from which
1959 we derive the true MC cross section as a function of the hadron true kinetic energy.

1960 Figure 4.5 shows the total hadronic cross section for argon implemented in Geant4
1961 10.03.p1 (solid lines) overlaid with the true MC cross section as obtained with the
1962 sliced TPC method (markers) for pions on the left and kaons on the right; the total
1963 cross section is shown in green, the elastic cross section in blue and the inelastic
1964 cross section in red. The nice agreement with the Geant4 distribution and the cross
1965 section obtained with the sliced TPC method gives us confidence in the validity of
1966 the methodology.

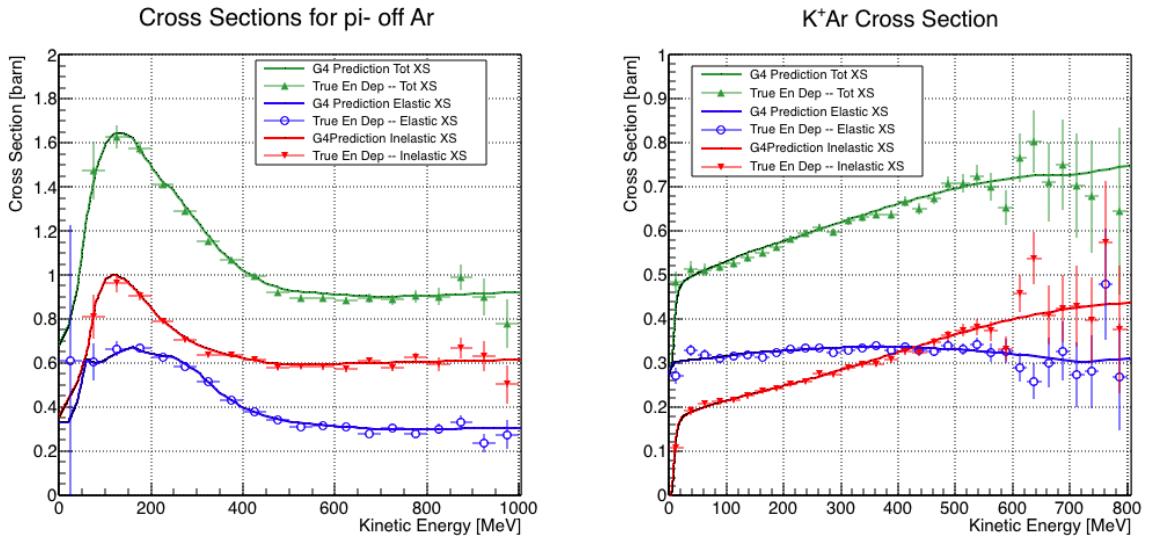


Figure 4.5: Hadronic cross sections for (π^- ,Ar) on the left and (K^+ ,Ar) on the right as implemented in Geant4 10.03.p1 (solid lines) overlaid the true MC cross section as obtained with the sliced TPC method (markers). The total cross section is shown in green, the elastic cross section in blue and the inelastic cross section in red.

¹⁹⁶⁷ Chapter 5

¹⁹⁶⁸ Data and MC preparation for the ¹⁹⁶⁹ Cross Section Measurements

¹⁹⁷⁰ “*Il dolce non lo mangi mai, ma qualche volta ti rifai.*
¹⁹⁷¹ *Abbracciami*”
¹⁹⁷² – Pietro Ciampi, 1971 –

¹⁹⁷³ This chapter describes the work done on the data and Monte Carlo samples in
¹⁹⁷⁴ preparation for the cross section analyses. This entails the choice of the datasets
¹⁹⁷⁵ and the production of the information needed to construct the Monte Carlo Simula-
¹⁹⁷⁶ tion (Section 5.1), the construction and use of said Monte Carlo simulation (section
¹⁹⁷⁷ 5.2), the study of backgrounds for the pion cross section (Section 5.3), the study of
¹⁹⁷⁸ the energy loss between WC4 and TPC (Section 5.4), the study of the tracking in the
¹⁹⁷⁹ TPC (Section 5.5), and study of the calorimetry response (Section 5.6).

¹⁹⁸⁰ 5.1 Cross Section Analyses Data Sets

¹⁹⁸¹ We choose LArIAT Run-II as the data period for the (π^- ,Ar) and (K^+ ,Ar) total
¹⁹⁸² hadronic cross section analyses. Data taking for the this period started on 03/15/2016

1983 and ended on 07/31/2016. Since we are interested in beamline and TPC information,
1984 we ask basic requirements on the operational status of the time of flight, wire chambers
1985 and TPC to form the good run list for this period, which we informally call “lovely
1986 runs”.

1987 The subset of lovely runs chosen for the (π^- ,Ar) total hadronic cross section
1988 analysis includes only the -60A and -100A magnet configurations in negative polarity,
1989 even if LArIAT explored several other beamline configurations during Run-II. The -
1990 60A and -100A combined data set accounts for approximately 90% of the total Run-II
1991 negative polarity runs. The choice of the main two beamline settings limits the need
1992 for the production of many different MC sets and related corrections, still maintaining
1993 a high number of events.

1994 Similarly, the subset of lovely runs chosen for the (K^+ ,Ar) total hadronic cross
1995 section analysis includes only the +60A and +100A magnet configurations in positive
1996 polarity. It should be noted that kaons are extremely rare in the +60A sample, thus
1997 the data sample for the (K^+ ,Ar) cross section after the mass selection is about 90%
1998 +100A runs, as shown in Table 5.1.

1999 For the first measurements in LArIAT that uses both beamline and TPC infor-
2000 mation, we choose strict requirements on the reconstruction of the WC tracks, the
2001 so-called “Picky Track” sample (see Section 3.2.2). This choice presents two ad-
2002 vantages: the uncertainty on the momentum reconstruction for the “Picky Tracks”
2003 sample is smaller compared to the “High Yield” sample, and the comparison with
2004 the beamline MC results is straightforward. A possible future update and cross check
2005 of these analysis would be the use of the High Yield sample, where the statistics is
2006 about three times higher.

2007 The breakdown of beamline events as a function of the magnets settings is shown
2008 in Table 5.1. The choice of the data sets determines the production of beamline MC
2009 and serves as basis for the production of Data Driven MC, as shown in the next

2010 sections.

2011 **5.2 Construction of a Monte Carlo Simulation for** 2012 **LArIAT**

2013 For the simulation of LArIAT events and for the simulation of the datasets' particle
2014 make up, we use a combination of two MC generators: the G4Beamline Monte Carlo
2015 and the Data Driven single particle Monte Carlo (DDMC). We use the G4Beamline
2016 MC to simulate the particle transportation in the beamline and calculate the particle
2017 composition of the beam just after the fourth Wire Chamber (WC4). In order to
2018 simulate the beamline particles after WC4 and in the TPC, we use the DDMC.

2019 **5.2.1 G4Beamline**

2020 G4Beamline simulates the beam collision with the LArIAT secondary target, the
2021 energy deposited by the particles in the LArIAT beamline detectors, and the action
2022 of the LArIAT magnets, effectively accounting for particle transportation through the
2023 beamline from the LArIAT target until “Big Disk”, a fictional, void detector located
2024 just before the LArIAT cryostat. At the moment of this writing, G4Beamline does
2025 not simulated the responses of the beamline detectors. It is possible to interrogate the
2026 truth level information of the simulated particles in several points of the geometry.
2027 In order to ease the handshake between G4Beamline and the DDMC, we ask for
2028 the beam composition just after WC4. Since LArIAT data are taken under different

	I = 60 A	I = 100 A	Total
Data Events after $\pi/\mu/e$ Mass Selection	67068	71413	138481
Data Events after K Mass Selection	274	2563	2837

Table 5.1: Number of data events which fit the $\pi/\mu/e$ or K mass hypothesis as a function of magnet settings.

beam conditions, we need to simulate separately the beam composition according to the magnets' settings and the secondary beam intensity with G4Beamline. For the pion cross section analysis the relevant beam conditions are secondary beam energy of 64 GeV, negative polarity magnet with current of 100 A and 60 A. For the kaon cross section analysis the relevant beam conditions is a secondary beam energy of 64 GeV, positive polarity magnet with current of 100 A.

Beam Composition for Negative Pion Cross Section

Even if pions are by far the biggest beam component in negative polarity runs, the LArIAT tertiary beam is not a pure pion beam. While useful to discriminate between pions, kaons, and protons, the beamline detectors are not sensitive enough to discriminate among the lighter particles in the beam: electrons, muons and pions fall under the same mass hypothesis. Thus, we need to assess the contamination from beamline particles other than pions in the event selections used for the pion cross section analysis and correct for its effects. The first step of this process is assessing the percentage of electrons and muons in the $\pi/\mu/e$ beamline candidates via the G4Beamline MC. Since the beamline composition is a function of the magnet settings, we simulate separately events for magnet current of -60A and -100A. Figure 5.1 shows the momentum predictions from G4Beamline overlaid with data for the 60A runs (left) and for the 100A runs (right). The predictions for electrons, muons and pions have been staggered and their sum is area normalized to data. Albeit not perfect, these plots show a reasonable agreement between the momentum shapes in data and MC. We attribute the difference in shape to a two approximations performed in the MC. Firstly, G4Beamline lacks the simulation of the WC efficiency which is momentum dependent and leads to enhance the number events in the center of the momentum distribution. Secondly, G4Beamline stop tracking pions and their products if they decay in after WC1; in data, pion decays in flight can still create a

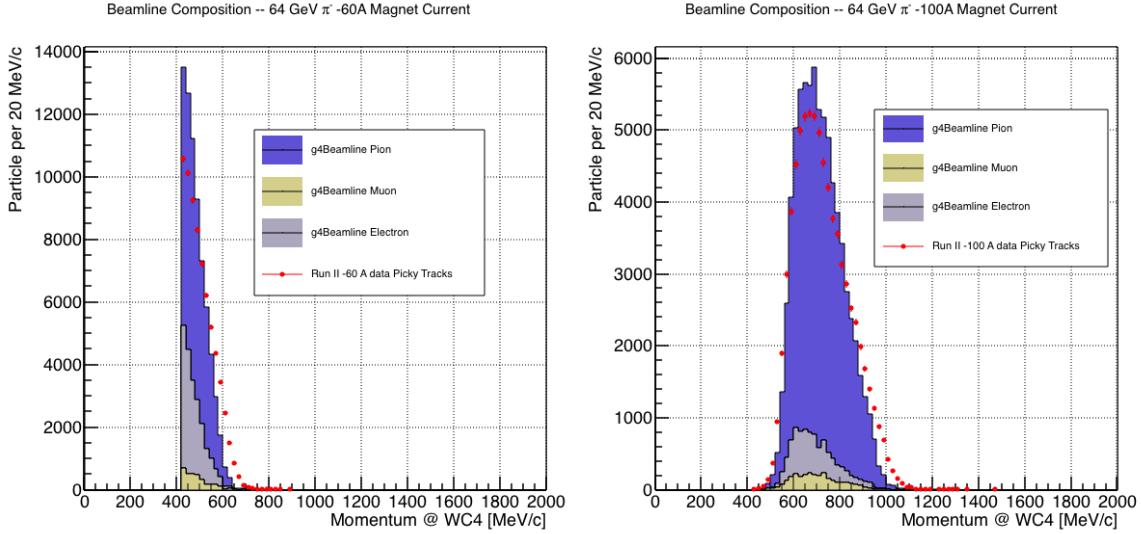


Figure 5.1: Beam composition for the -60A runs (left) and -100A runs (right). The solid blue plot represents the simulated pion content, the yellow plot represents the simulated muon content and the grey plot represents the simulated electron content. The plots are area normalized to the number of data events, shown in red.

	I = -60 A	I = -100 A
G4Pions	68.8 %	87.4 %
G4Muons	4.6 %	3.7 %
G4Electrons	26.6 %	8.9 %

Table 5.2: Simulated beamline composition per magnet settings

2055 trigger if the produced muon travels thought the beamline detectors. In the pion cross
 2056 section analysis, these differences between data and G4Beamline are accounted for as
 2057 a systematic uncertainty related to the beam composition (see Section 6.2.1).

2058 Table 5.2 shows the beam composition per magnet setting after the mass selection
 2059 according to the G4Beamline simulation.

2060 The estimated beam composition is used as a basis to estimate the background
 2061 contamination in the (π^-, Ar) cross section measurement, whose full treatment is
 2062 described in section 5.3.

2063 **Beam Composition for Positive Kaon Cross Section**

2064 In the positive polarity runs, the tertiary beam composition is mainly pions and
2065 protons. The left side of Figure 5.2 shows the predictions for the momentum spectra
2066 for the 100A positive runs according to G4Beamline (solid colors) overlaid with data
2067 (black points). Since the LArIAT beamline detectors can discriminate between kaons
2068 and other particles, we do not rely on the G4Beamline simulation to estimate the
2069 beamline contamination in the pool of kaon candidates (as in the case of the pion
2070 cross section), but rather we use a data driven approach. The basic idea of this data
2071 driven approach is to estimate the bleed over from high and low mass peaks under
2072 the kaon peak by fitting the tails of the $\pi/\mu/e$ and proton mass distributions, as
2073 shown in Figure 5.2 right side. Since the shape of the tails is unknown, the estimate
2074 is done multiple times varying the range and shape for reasonable functions. For
2075 example, to estimate the proton content under the kaon peak, we start by fitting the
2076 left tail of the proton mass distribution with a gaussian function between $650 \text{ MeV}/c^2$
2077 and $750 \text{ MeV}/c^2$. We extend the fit function under the kaon peak and integrate the
2078 extended fit function between $350-650 \text{ MeV}/c^2$. We integrate the mass histogram
2079 in the same range and calculate the proton contamination as the ratio between the
2080 two integrals. We repeat this procedure for several fit shapes (gaussian, linear and
2081 exponential functions) and tail ranges. Finally, we calculate the contamination as
2082 the weighted average of single estimates, where the weights are calculated to be the
2083 $1./|1 - \chi^2|$ of the tail fits. The procedure is repeated for lighter particles mass peak
2084 independently. With 12 iterations of this method we find a proton contamination of
2085 $5.0 \pm 2.0 \%$ and a contamination from the lighter particles of $0.2 \pm 0.5 \%$. The
2086 estimate of the proton background is currently not used in the kaon cross section
2087 analysis, but it is a fundamental step to retrieve the true kaon cross section which
2088 will be implemented in the further development of the analysis.

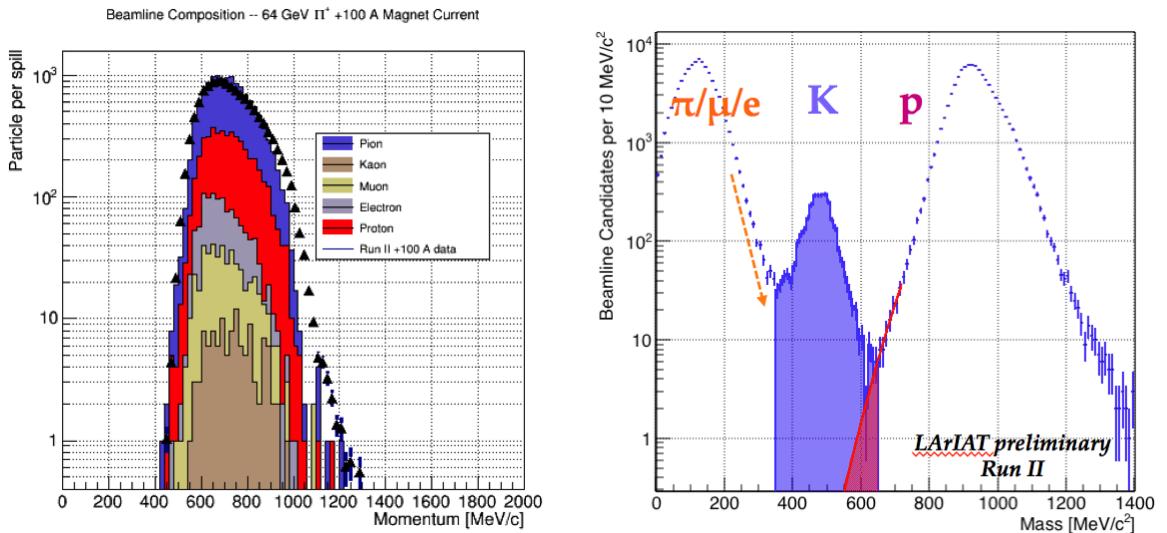


Figure 5.2: *Left:* Beam composition for the +100A runs after WC4 (no mass selection applied). The solid colors represent the contributions from the G4Beamline simulated particles: blue plot represents the simulated pion content, the yellow plot represents the simulated muon content and the grey plot represents the simulated positron content, the red the proton content and the mustard the kaon content. The plots are area normalized to the number of data events, shown in black. *Right:* Mass distribution for the Run-II positive runs, where the area under the kaon mass peak is highlighted in purple. The area under the extension of a possible fit for the proton tail is highlighted in red.

2089 **5.2.2 Data Driven MC**

2090 The Data Driven single particle Monte Carlo (DDMC) is a single particle gun which
2091 simulates the particle transportation from WC4 into the TPC leveraging on the beam-
2092 line data information. The DDMC uses the data momentum and position at WC4
2093 to derive the event generation: a general sketch of the DDMC workflow is shown in
2094 Figure 5.3.

2095 When producing a DDMC sample, beamline data from a particular running pe-
2096 riod and/or running condition are selected first. For example, data for the negative
2097 60A runs and for the negative 100A runs inform the event generation stage of two
2098 different DDMC samples. Figure 5.4 schematically shows the data quantities of in-
2099 terest leveraged from data: the momentum (P_x, P_y, P_z) and position (X, Y) at WC4.
2100 For each data event, we obtain the particle position (X, Y) at WC4 directly from the
2101 data measurement; we calculate the components of the momentum using the beam-
2102 line measurement of the momentum magnitude in conjunction with the hits on WC3
2103 and WC4 to determine the direction of the momentum vector, as described in section
2104 3.2.2. The momentum and position of the selected data form a 5-dimensional tuple,
2105 which we sample thousands of times through a 5-dimensional hit-or-miss sampling
2106 procedure to generate the MC events. This sampling generates MC events with the
2107 same momentum and position distributions as data, with the additional benefit of
2108 accounting for the correlations between the P_x, P_y, P_z, X, Y variables. As an example,
2109 the results of the DDMC generation compared to data for the kaon +100A sample
2110 are shown in figure 5.5 for the P_z, X and Y distributions; as expected, MC and data
2111 agree within the statistical uncertainty by construction. A LArSoft simulation mod-
2112 ule then launches single particle MC from $z = -100$ cm (the location of the WC4)
2113 using the generated events. The particles are free to decay and interact in their path
2114 from WC4 to the TPC according to the Geant4 simulation.

2115 Using the DDMC technique ensures that the MC and data particles have very

2116 similar momentum, position and angular distributions at WC4 and allows us to use
 2117 the MC sample in several occasions: to estimate the background contamination to
 2118 the pion cross section (see Section 5.3), to calibrate the energy loss upstream of the
 2119 TPC (see Section 5.4), or to study the tracking and the calorimetric performance
 2120 (sections 5.5 and 5.6). A small caveat is in order here: the DDMC is a single particle
 2121 Monte Carlo, which means that the beam pile-up is not simulated.

2122 We generate six samples for the pion cross section measurement: three samples
 2123 of ~ 330000 pions, muons and electrons to simulate the negative 60A runs, and three
 2124 samples of ~ 340000 pions, muons and electrons for the negative 100A runs. We
 2125 generate a sample of 195000 kaons for the kaon cross section analysis.

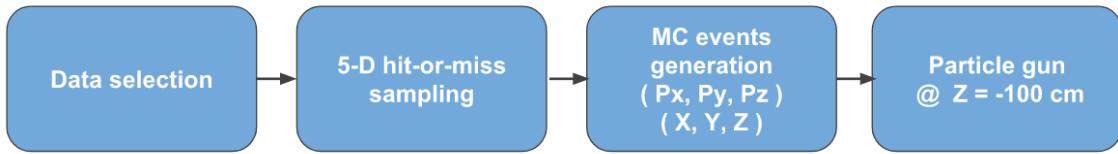


Figure 5.3: Workflow for Data Driven single particle Monte Carlo production.

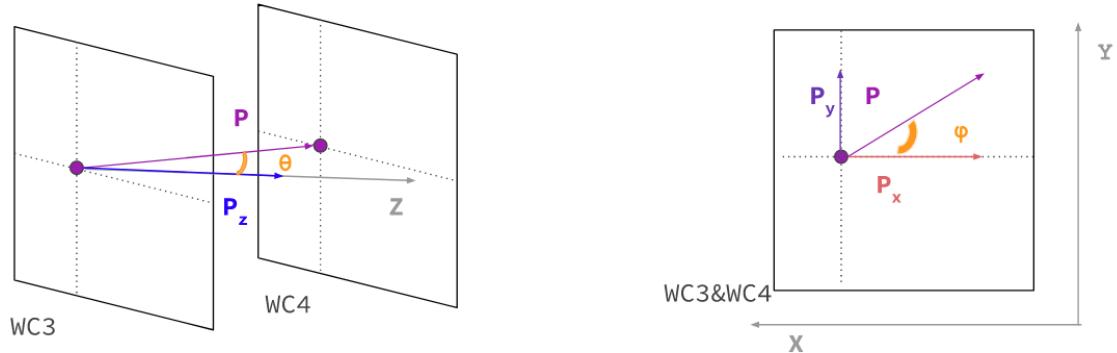


Figure 5.4: Scheme of the quantities of interest for the DDMC event generation:
 P_x, P_y, P_z, X, Y at WC4.

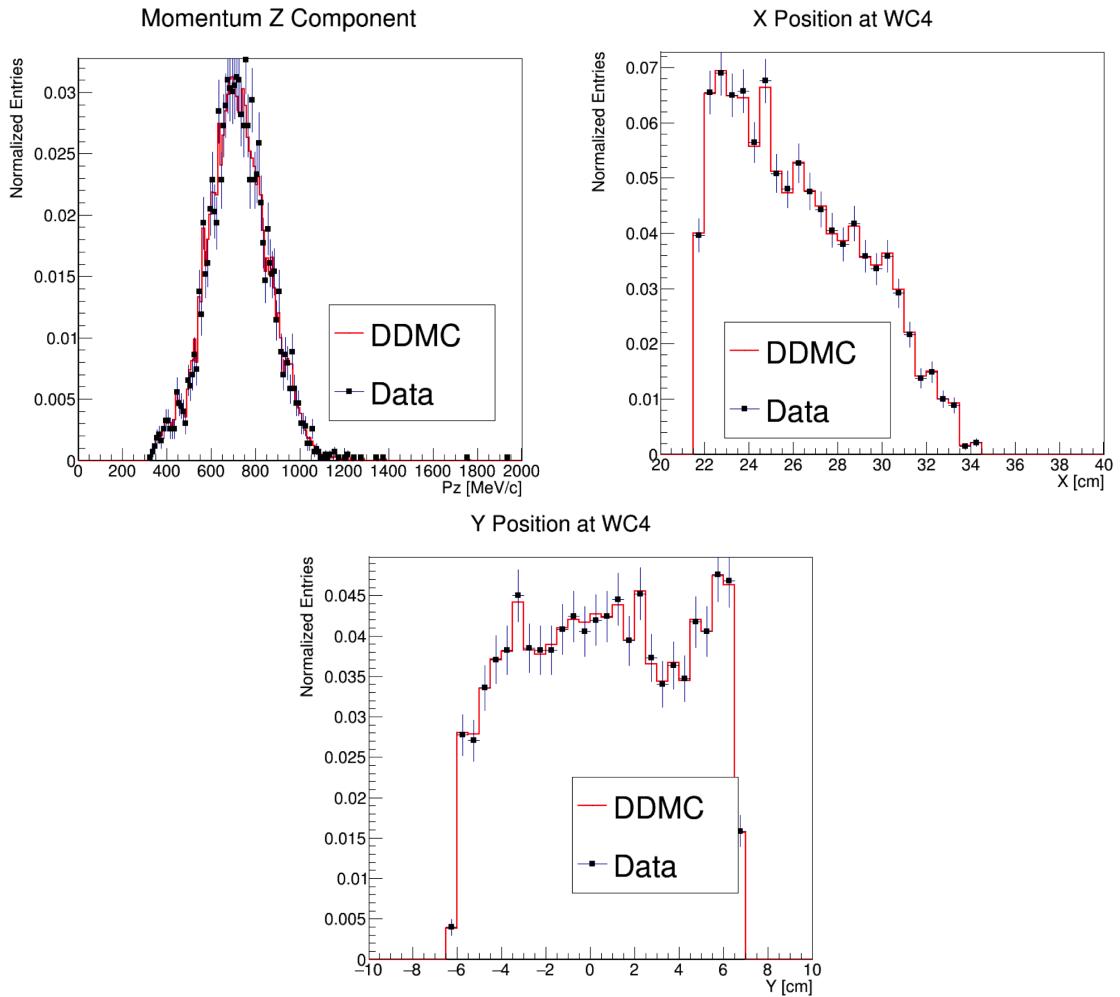


Figure 5.5: Comparison between generated quantities and data distributions for the 100A kaon sample: Z component of the momentum at WC4 (top left), X position at Wire Chamber 4 (top right), Y position at Wire Chamber 4 (bottom).

2126 **5.3 Estimate of Backgrounds in the Pion Cross
2127 Section**

2128 We use the beamline simulation and the DDMC simulation to estimate the back-
2129 ground in the total hadronic pion cross section. Two categories of background exists
2130 for the negative pion cross section measurement: the one related to the pion interac-
2131 tion in the chamber, discussed in Section 5.3.1 and the one related to the beamline
2132 contamination, discussed in Section 5.3.2.

2133 **5.3.1 Background from Pion Capture and Decay**

2134 Our goal is to measure the total hadronic cross section for negative pions in argon.
2135 Since pion capture can be classified as an electromagnetic process and pion decay is a
2136 weak process, capture and decay represent unwanted interactions. We present here a
2137 study of capture and decay in Monte Carlo and the solution we adopted to mitigate
2138 their occurrence in the data sample.

2139 For this MC study, we use a sample of MC pions generated according to the
2140 –60A beam profile with the DDMC (see Section 5.2.2). It is important to notice
2141 that capture occurs predominantly at rest, while decay may occur both in flight and
2142 at rest. Thus, we can highly mitigate capture and decay at rest by removing pions
2143 which would release all their energy in the TPC and stop. This translates into a
2144 momentum selection, where we keep only events whose WC momentum is above a
2145 certain threshold. Figure 5.6 shows the true momentum distribution for the primary
2146 pions¹ that arrive to the TPC (pink), that capture (green) or decay (blue) inside the
2147 TPC, on a linear scale (left) and on a log scale (right) vertical axis.

2148 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.

2148 In order to choose the selection value for the wire chamber momentum, it is
2149 beneficial to estimate the ratio of events which capture or decay that survive the
2150 selection in MC as a function of the momentum threshold, and compare it with the
2151 survival ratio for all the 60A events. This is done in figure 5.7. We define the survival
2152 ratio simply as the number of events surviving the true momentum selection divided
2153 by the number of events of that category. We calculate the survival ratio separately
2154 for the three event categories explained above: total (pink), capture (green) and decay
2155 (blue). Selecting pions with momentum greater than 420 MeV/c reduces the capture
2156 events by 99% while maintaining about 80% of the 60A data sample and almost
2157 the entire 100A sample. Figure 5.8 shows the ratio of events which end their life in
2158 capture (green) or decay (blue) over the total number of events as a as a function of
2159 the true momentum at wire chamber four. This ratio is slightly dependent on the
2160 inelastic cross section implemented in Geant4, as we are able to register a pion capture
2161 (or decay) only if it did not interact inelastically in the TPC. We choose a momentum
2162 threshold of 420 MeV/c because the percentage of capture events drops below 1% and
2163 the percentage of decays is never above 2% for momenta greater than 420 MeV/c.
2164 After the momentum selection, we evaluate the contribution of capture and decay to
2165 be a negligibly small background to the cross section measurement compared to the
2166 background related to the beamline which we will address in the next section.

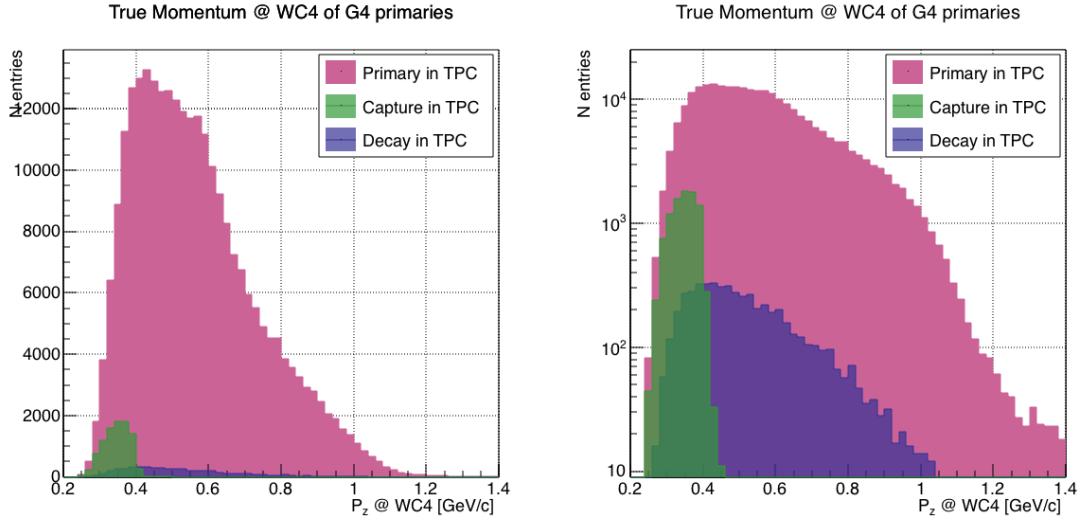


Figure 5.6: True momentum distribution at wire chamber 4 for every simulated pion arriving in the TPC (pink), ending its life in capture (green) or in decay (blue) in the TPC, linear vertical axis on the left, logarithmic on the right.

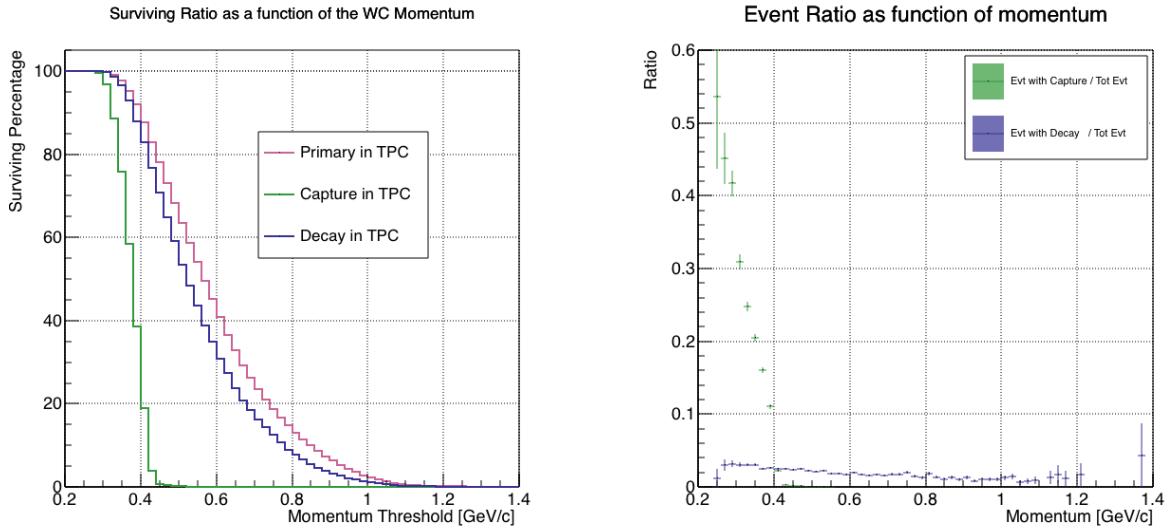


Figure 5.7: Survival ratio as a function of selection threshold on true momentum at wire chamber four for every simulated pion arriving in the TPC (pink), capture (green) or in decay (blue).

Figure 5.8: 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.

2167 **5.3.2 Contributions from the Beamline Background**

2168 We define beamline background every TPC track matched to the WC track which is
2169 not a primary pion. Potentially, there are 4 different types of beamline background:

2170 1) electrons,

2171 2) muons,

2172 3) secondaries from pion events,

2173 4) matched pile up events.

2174 The first step to quantify the effect of the beamline background on the pion cross
2175 section is to estimate what percentage of events used in the cross section calculation
2176 is not a primary pion. We start by noting that the last type of background, the
2177 “matched pile up” events, is a negligible fraction, because of the definition of the
2178 WC2TPC match: we deem the probability of a single match with a halo particle in
2179 the absence of a beamline particle² negligibly small. As shown in Section 5.2.1, we
2180 use G4Beamline to estimate the percentage of pions, muons and electrons at WC4,
2181 obtaining the composition shown in Table 5.2. The next step is to simulate those
2182 pions, muons and electrons from WC4 to the TPC with the DDMC and evaluate their
2183 contribution to the cross section. To do so, we start by simulating the same number
2184 of electrons, muons and pions with the DDMC and we apply the same selection chain
2185 (i.e. track multiplicity rejection, WC2TPC acceptance and shower rejection) on the
2186 three samples. The number of events per particle species surviving this selection is
2187 shown on table 5.3. In order to reproduce the closest make up of the beam to data,
2188 we weight each event of a given particle species according to the estimated beam
2189 composition. In case of 60A runs, for example, the weights are 0.688 for pions, 0.046
2190 for muons and 0.266 for electrons.

2. Events with multiple WC2TPC matches are always rejected.

	Magnet Current -60A			Magnet Current -100 A		
	MC π^-	MC μ^-	MC e^-	MC π^-	MC μ^-	MC e^-
Total Initial events	334500	334500	334500	344500	344500	344500
After Multiplicity Rejection	330668	333420	198065	326576	344208	201380
After WC2TPC Selection	218239	296333	91139	230418	300228	98834
Evts After Shower Rejection	208063	288914	20293	219882	293585	17780
Selection Survival Rate	62.3%	86.6%	6.1%	63.8%	85.5%	5.2%
Beam Composition @WC4	68.8%	4.6 %	26.6 %	87.4 %	3.7 %	8.9 %
Beam Composition @TPC FF	88.5%	8.2%	3.3 %	94.0%	5.3%	0.7%

Table 5.3: MC selection flow per particle species.

2191 It should be noted that pions may interact hadronically in the steel or in the
 2192 non-instrumented argon upstream to the TPC front face while travelling the length
 2193 of between WC4 and the TPC. Or, they could decay in flight between WC4 and the
 2194 TPC. One of the interaction products can leak into the TPC and be matched with the
 2195 WC track, contributing to the pool of events used for the cross section calculation. We
 2196 call this type of particles “secondaries” from pion events, with a terminology inspired
 2197 by Geant4. We estimate the number of secondaries using the DDMC pion sample.
 2198 The percentage of secondaries is given by the number of matched WC2TPC tracks
 2199 whose corresponding particle is not flagged as primary by Geant4. The secondary to
 2200 pion ratio is 4.9% in the 60A sample and 4.3% in the 100A sample.

2201 We evaluate the beamline background contribution to the cross section by pro-
 2202 ducing the interacting and incident histograms for the events surviving the selection,
 2203 staggering the contributions for each particle species, as shown in Figure 5.9. From
 2204 those histograms, we are able to evaluate the contribution of pions and beamline
 2205 backgrounds to each bin of the interacting and incident histograms separately and
 2206 obtain the relative pion content. The relative pion content in each bin for the inter-
 2207 acting and incident histograms represents the correction applied to data. We take

here the interacting histogram as example, noting that the derivation of the correction for the incident histogram is identical. The number of entries in each bin of the interacting plot (Figure 5.9 left) is $N_{\text{Int}}^{\text{TOT}}(E_i)$, equal to the sum of the pions and beamline backgrounds in that bin, namely

$$N_{\text{Int}}^{\text{TOT}}(E_i) = N_{\text{Int}}^{\pi}(E_i) + \underbrace{N_{\text{Int}}^{\mu}(E_i) + N_{\text{Int}}^e(E_i) + N_{\text{Int}}^{\text{Secondary}}(E_i)}_{B_{\text{Int}}(E_i)}. \quad (5.1)$$

Thus, the relative pion content to each bin in MC can be calculated as follows

$$C_{\text{Int}}^{\pi MC}(E_i) = \frac{N_{\text{Int}}^{\pi MC}}{N_{\text{Int}}^{\text{TOTMC}}(E_i)} = \frac{N_{\text{Int}}^{\text{TOTMC}}(E_i) - B_{\text{Int}}^{MC}(E_i)}{N_{\text{Int}}^{\text{TOTMC}}(E_i)}. \quad (5.2)$$

In order to evaluate the pion content of each bin in data, we scale the measured bin by the corresponding relative pion content found in MC, as follows

$$N_{\text{Int}}^{\pi RecoData} = N_{\text{Int}}^{\text{TOTData}}(E_i) - B_{\text{Int}}^{\text{Data}}(E_i) = C_{\text{Int}}^{\pi MC}(E_i)N_{\text{Int}}^{\text{TOTData}}(E_i). \quad (5.3)$$

The pion content is evaluated separately in the interacting and incident histograms. Their ratio determines a correction to the measured raw cross section. For example, the measured raw cross section of a sample with enhanced muons content will tend to be lower than the raw cross section of a muon free sample. This is because most of the muons will cross the TPC without stopping, thus contributing almost exclusively to the incident histogram, forcing the pion content to be lower in the incident histogram than in the interacting; thus, the correction will tend to enhance the cross section.

5.4 Estimate of Energy Loss before the TPC

The beamline particles travel a path from where their momentum is measured in the beamline until they are tracked again inside the TPC. In the LArIAT geometry, a particle leaving the WC4 will encounter the materials listed in Table 5.4 before being registered again. The energy lost by the particle in this non-instrumented material modifies the particle's kinetic energy and directly affects the cross section measurement, as shown in equation 4.5.

Material	density [g/cm ³]	width [cm]
Fiberglass laminate (G10)	1.7	1.28
Liquid Argon	1.4	3.20
Stainless Steel	7.7	0.23
Titanium	4.5	0.04
Air	$1.2 \cdot 10^{-3}$	89.43
Plastic Scintillator	1.03	1.20 (+ 1.30)

Table 5.4: LArIAT material budget from WC4 to the TPC Front Face.

We derive an estimate of the energy loss between the beamline momentum measurement and the TPC (E_{loss}) from the pion and kaon DDMC samples, since this quantity is not measurable directly on data. The E_{loss} distribution for the 60A and 100A pion sample is shown in figure 5.10, left and right respectively. The E_{loss} distribution for the whole kaon sample is shown in figure 5.11. A clear double peaked structure is visible, which is due to the particles either missing or hitting the HALO paddle: a schematic rendering of this occurrence is shown in figure 5.12. The kinematic at WC4 determines the trajectory of a particle and whether or not it will hit the halo paddle. In figure 5.13 , we plot the true horizontal component of the momentum P_x versus the true X position at WC4 for pions missing the halo paddle (left) and for pions hitting the halo paddle (right) for the -60A MC simulation runs – analogous plots are obtained with the -100A pion simulation and with the kaon simulation. These distributions can be separated drawing a line in this position-momentum space.

We use a logistic regression [13] as a classifier to find the best separating line, shown in both plots as the red line. We classify as “hitting the halo paddle” all pions whose P_x and X are such that

$$P_x + 0.02 * X - 0.4 < 0$$

and as “missing the halo paddle” all pions whose P_x and X are such that

$$P_x + 0.02 * X - 0.4 > 0,$$

where the coefficients of the line are empirically found by the logistic regression estimation. Overall, this simple method classifies in the right category (hit or miss) about 86% of the pion events. In MC, we assign $E_{loss} = 32 \pm 4$ MeV for pion events classified as “hitting the halo paddle”; we assign $E_{loss} = 24 \pm 3$ MeV for pion events classified as “missing the halo paddle”. We apply the same classifier on data.

A scan of the simulated geometry showed an excess of 3 cm of uninstrumented argon compared with the surveyed detector geometry. We account for this difference by assigning in data $E_{loss} = 24 \pm 6$ MeV for pion events classified as “hitting the halo paddle” and $E_{loss} = 17 \pm 6$ MeV for pion events classified as “missing the halo paddle”, where the uncertainty is derived as the standard deviation of the double peaked distribution.

The summary of the values for used for E_{Loss} for the pion sample is listed in table 5.5 with the analogous results for the study on the kaon case.

	E_{loss} [MeV]	
	Hitting Halo	Missing Halo
Pion MC	32 ± 4	24 ± 3
Pion Data	25 ± 6	17 ± 6
Kaon MC	38 ± 6	31 ± 5
Kaon Data	26 ± 7	22 ± 7

Table 5.5: Energy loss for pions and kaons.

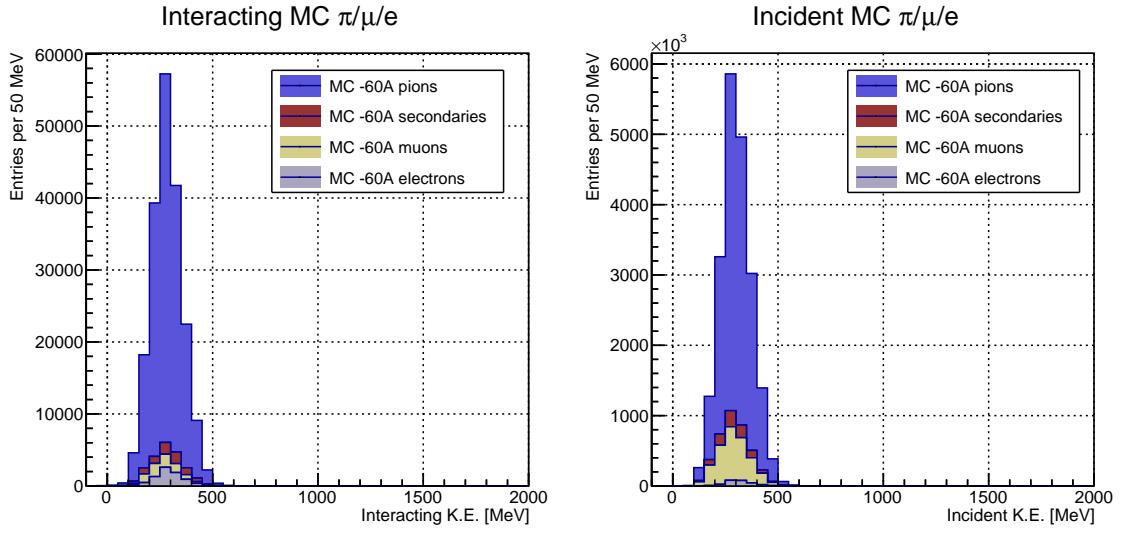


Figure 5.9: Left: staggered contributions to the interacting kinetic energy distribution for electron (grey), muons (yellow) and pion (blue) in the 60A simulation sample. Right: staggered contributions to the incident kinetic energy distribution for electron (grey), muons (yellow) and pion (blue) in the 60A simulation sample.

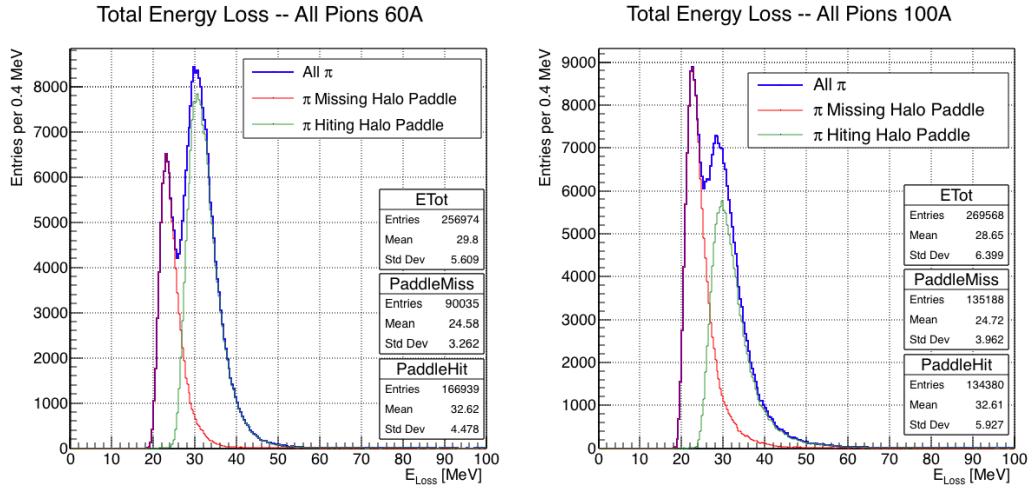


Figure 5.10: True energy loss between WC4 and the TPC front face according to the MC simulation of negative pions of the 60A runs (left) and of the 100A runs (right). The distribution for the whole data sample is shown in blue, the distribution for the pions missing the halo is shown in red, and the distribution for the pions hitting the halo is shown in green.

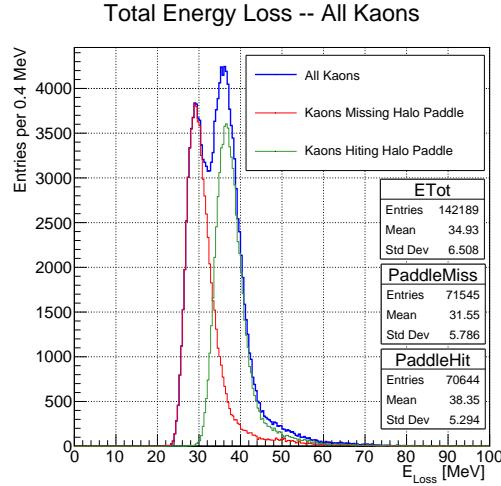


Figure 5.11: True energy loss between WC4 and the TPC front face according to the MC simulation of positive kaons in the 60A and 100A combined sample. The distribution for the whole data sample is shown in blue, the distribution for the kaons missing the halo is shown in red, and the distribution for the kaons hitting the halo is shown in green.

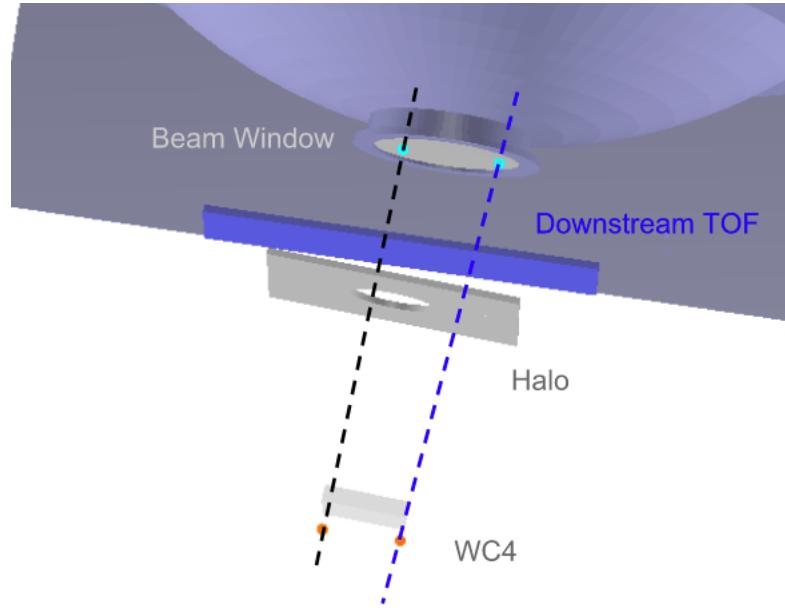


Figure 5.12: Schematic rendering of the particle path between WC4 and the TPC front face. The paddle with the hollow central circle represents the Halo paddle. We illustrate two possible trajectories: in black, a trajectory that miss the paddle and goes through the hole in the Halo, in blue a trajectory that hits the Halo paddle and goes through the scintillation material.

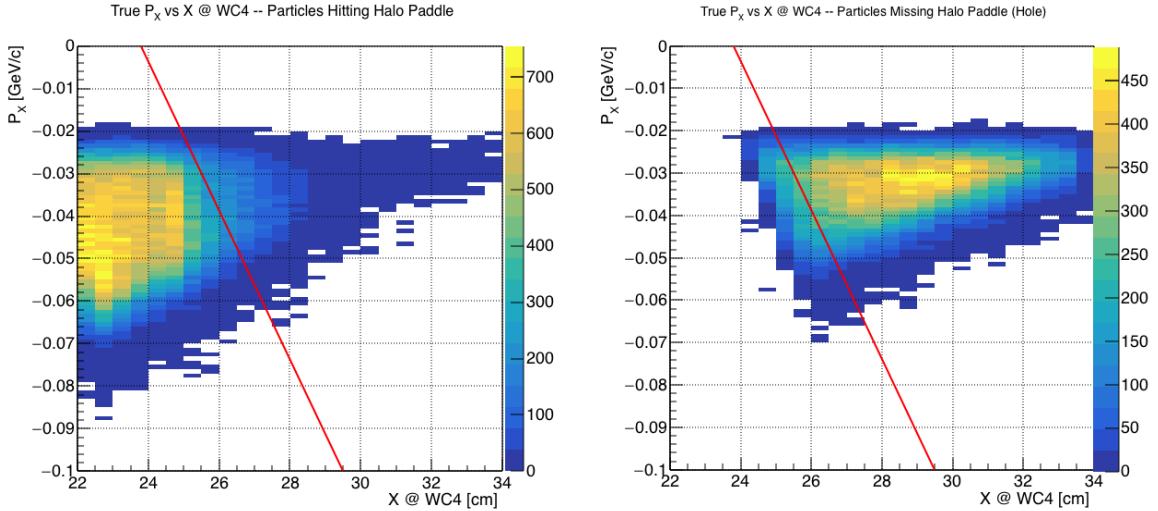


Figure 5.13: Horizontal component of the true momentum vs the horizontal position at WC4 for MC simulated pions of the 60A runs. The plot on the left shows the distribution for pion that miss the halo paddle and the plot on the right shows the distributions for pions that hit the halo. The form of the classifier is overlaid to both plots (red line).

2243 5.5 Tracking Studies

2244 The tracking of hadrons in the TPC determines both the beamline to TPC hand-
 2245 shake and the identification of the interaction point within the TPC. Thus, it plays
 2246 a fundamental role in the cross section measurements. We performed several studies
 2247 geared towards the optimization of the package for tracking in the TPC. In particular,
 2248 we studied a suitable set of parameters for the WC2TPC match and we optimized
 2249 the clustering algorithm to maximize the efficiency of finding the interaction point on
 2250 MC. Given the technical nature of these studies, we report them in Appendix A. We
 2251 report here the evaluation of the angular resolution of the tracking algorithm in data
 2252 and MC, due to its implication on the physics measurement.

2253 5.5.1 Angular Resolution

2254 Scope of this study is to understand and compare the tracking performances and
 2255 angular resolution of the TPC tracking on data and MC. We use the angular resolution

2256 of the tracking to determine the value of smallest angle that we can reconstruct with
2257 a non-zero efficiency, effectively determining a selection on the angular distribution
2258 of the cross section measurement due to the tracking performance.

2259 We start by selecting all the WC2TPC matched tracks used for the cross section
2260 analysis. These tracks can contain from a minimum of 3 3D-space points to a maxi-
2261 mum of 240 3D-space points. We fit a line to all the 3D-space points associated with
2262 the track. For each track we calculate the average distance between each point in
2263 space and the fit line as follows

$$\bar{d} = \frac{\sum_i^N d_i}{N}, \quad (5.4)$$

2264 where N is the number of 3D-space points of the track and d_i is the distance of the
2265 i -th space point to the line fit. Several tests to compare the goodness of fit between
2266 data and MC have been considered. We decided to use \bar{d} for its straightforward
2267 interpretation. The \bar{d} distribution for data and MC is shown in Figure 5.16 for pions
2268 and in Figure 5.18 for kaons and shows a relatively good agreement between data and
2269 MC.

2270 A visual representation of the procedure used to evaluate the angular resolution
2271 is shown in Figure 5.14. For each track, we order the space points according to their
2272 Z position along the positive beam direction (panel a) and we split them in two sets:
2273 the first set contains all the points belonging to the first half of the track and the
2274 second set contains all the points belonging the second half of the track. We remove
2275 the last four points in the first set and the first four points in the second set, so to
2276 have a gap in the middle of the original track (panel b). We fit the first and the second
2277 set of points with two lines (panel c). We then calculate the angle between the fit of
2278 the first and second half α (panel d). The angle α determines the spatial resolution
2279 of the tracking. The distributions for data and MC for α are given in Figure 5.17 for
2280 pions and in Figure 5.19 for kaons. The mean of the data and MC angular resolution
2281 are reported in Table tab:AngRes for pions and kaons in data and MC.

2282 Interaction angles smaller than the angle resolution are indistinguishable for the
 2283 reconstruction. Therefore, we assess our ability to measure the cross section to be
 2284 limited to interaction angles greater than 5.0 deg. More accurate studies of the angular
 2285 resolution as a function of the kinetic energy and track length, albeit interesting, are
 2286 left for an improvement of the analysis.

2287 It is beneficial to take a moment to describe the definition of interaction angle.
 2288 In case of elastic scattering, the definition is straightforward: the interaction angle is
 2289 the angle between the incoming and outgoing hadron, i.e.

$$\theta = \cos^{-1} \left(\frac{\vec{p}_{\text{incoming}} \cdot \vec{p}_{\text{outgoing}}}{|\vec{p}_{\text{incoming}}| |\vec{p}_{\text{outgoing}}|} \right). \quad (5.5)$$

2290 In case of inelastic scattering, the presence of several topologies requires a more
 2291 complex definition, as shown in figure 5.15. We define the scattering angle as the
 2292 biggest of the angles between the incoming hadron and the visible daughters, where
 2293 the visible daughters are charged particles that travel more than 0.47 cm in the
 2294 detector (see panel a); in case all the daughters are invisible, the angle is assigned
 2295 to be 90 deg (see panel b). We chose this working definition of scattering angle
 2296 for inelastic scattering keeping in mind how our tracking reconstruction works: the
 2297 tracking will stop correctly non of the daughters are is visible in the detector and it
 2298 is likely to stop correctly if multiple daughters form an interaction vertex. The only
 2299 “dangerous” case is the production of one charged daughter plus neutrals, which we
 2300 can study with this working definition of scattering angle (see panel c).

2301 We can see the effects of the angular resolution on the cross section by plotting the
 2302 true Geant4 cross section for interaction angles greater than a minimum interaction

	Data	MC
Pions	$\bar{\alpha}_{Data} = (5.0 \pm 4.5) \text{ deg}$	$\bar{\alpha}_{MC} = (4.5 \pm 3.9) \text{ deg}$
Kaons	$\bar{\alpha}_{Data} = (4.3 \pm 3.7) \text{ deg}$	$\bar{\alpha}_{MC} = (4.4 \pm 3.6) \text{ deg}$

Table 5.6: Angular resolution for Pion and Kaon tracking in both data and MC.

angle. Figure 5.20 shows the true Geant4 cross section for interaction angles greater than 0 deg (green), 4.5 deg (red), 5.0 deg (blue) and 9.0 deg (yellow). A small 0.5 deg systematic shift between the mean of the data and MC angular resolution is present.

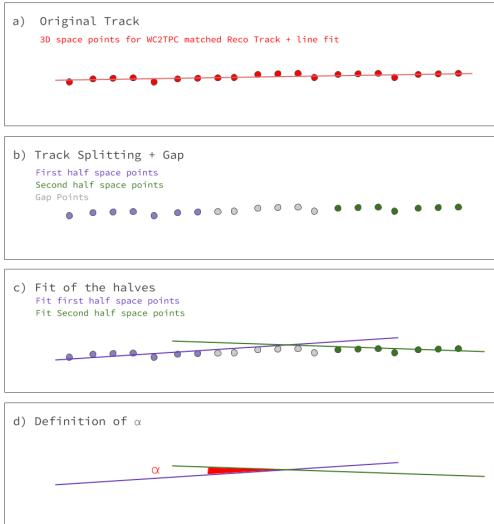


Figure 5.14: A visual representation of the procedure used to evaluate the angular resolution.

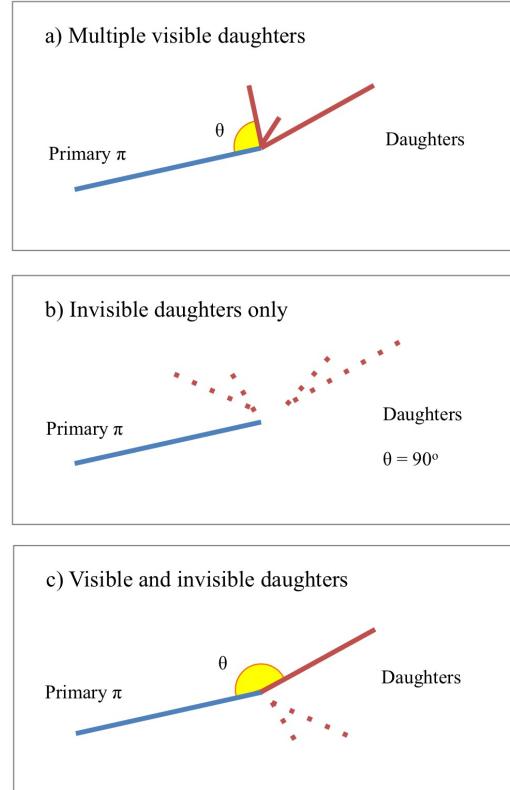


Figure 5.15: A visual representation of the scattering angle definition in case of inelastic scattering.

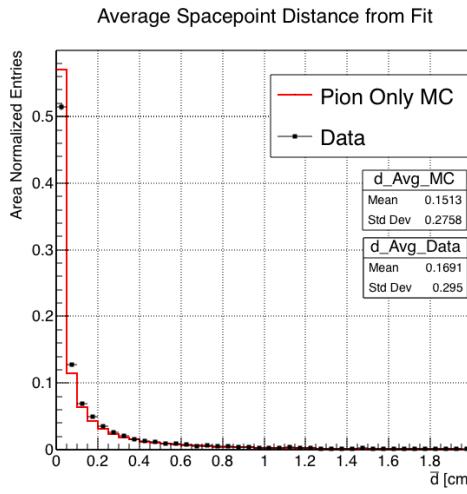


Figure 5.16: Distributions of the average distance between each 3D point in space and the fit line, \bar{d} for the data used in the pion cross section analysis and the pion only DDMC. The distributions are area normalized.

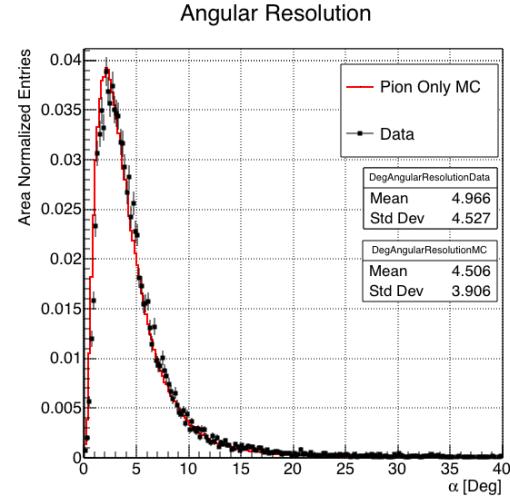


Figure 5.17: Distributions of angular resolution α for data used in the pion cross section analysis and pion only DDMC. The distributions are area normalized.

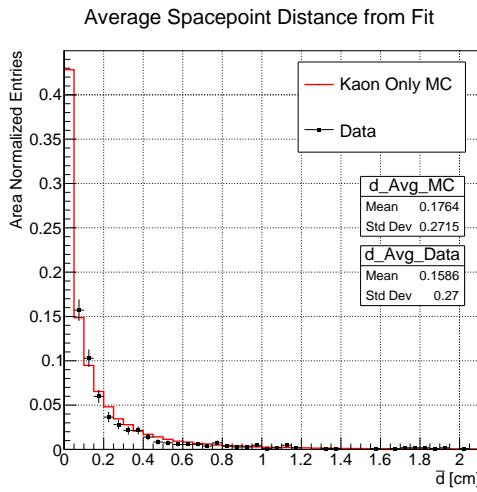


Figure 5.18: Distributions of the average distance between each 3D point in space and the fit line, \bar{d} for the data used in the kaon cross section analysis and the kaon only DDMC. The distributions are area normalized.

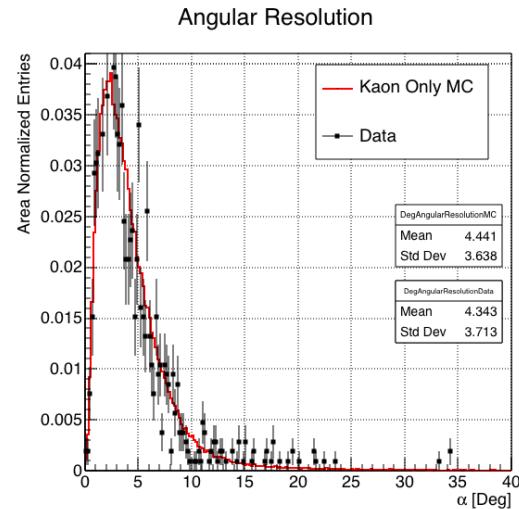


Figure 5.19: Distributions of angular resolution α for data used in the kaon cross section analysis and kaon only DDMC. The distributions are area normalized.

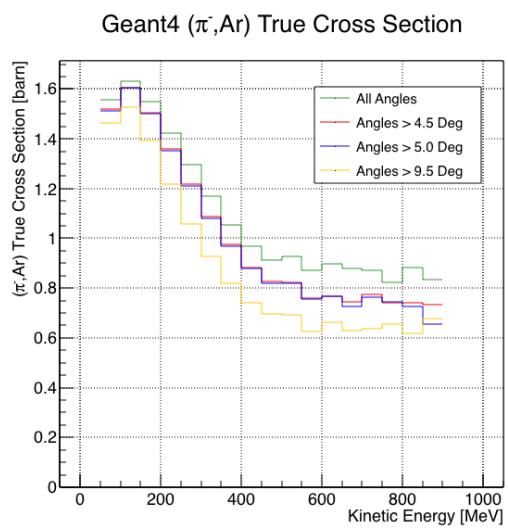


Figure 5.20: True (π^- , Ar) cross section for interaction angles greater than 0 deg (green), 4.5 deg (red), 5.0 deg (blue) and 9.0 deg (yellow).

2306 **5.6 Calorimetry Studies**

2307 The measured kinetic energy of a hadron candidate at each argon slab determines
2308 which bins of the interacting and incident histograms a selected event is going to fill.
2309 Thus, the energy measurement provided by the LArTPC is fundamental for the cross
2310 section analysis. In Appendix B, we describe how we calibrate the TPC calorimetric
2311 response. In the following section, we describe how we measure the kinetic energy of
2312 the hadrons in the TPC.

2313 **5.6.1 Kinetic Energy Measurement**

2314 In this section, we define the measurement on the kinetic energy and determine the
2315 related uncertainty. We will propagate this uncertainty into the cross section mea-
2316 surement, as discussed in Section 6.1.2 for the pion cross section and in Section ??
2317 for the kaon cross section.

2318 The kinetic energy of a hadron at the j^{th} slice of argon in the TPC is given by

$$KE_j = \sqrt{p_{\text{Beam}}^2 + m_{\text{Beam}}^2} - m_{\text{Beam}} - E_{\text{Loss}} - E_{\text{FF-j}}, \quad (5.6)$$

2319 where p_{Beam} is the momentum measured by the beamline detectors, m_{Beam} is the
2320 mass of the hadron as reported in the PDG, E_{Loss} is the energy loss between the
2321 beamline and the TPC, and $E_{\text{FF-j}}$ is the energy that the hadron deposited from the
2322 TPC front face until the j^{th} slice. The uncertainty on KE_j is then given by

$$\delta KE_j = \sqrt{\delta p_{\text{Beam}}^2 + \delta E_{\text{Loss}}^2 + \delta E_{\text{dep FF-j}}^2}, \quad (5.7)$$

2323 where we have dropped the uncertainty on the mass, since it is orders of magnitude
2324 smaller than the other uncertainties. We assume the relative uncertainty on p_{Beam} to
2325 be 2%, and the uncertainty on the energy loss upstream to be 7 MeV, as calculated

2326 in Section 5.4. We describe the estimate of the uncertainty on $E_{\text{FF-j}}$ in the rest of
2327 this section.

2328 The energy deposited by the hadron from the TPC front face until the j^{th} slice is
2329 the sum of the measured energy deposited in each previous slabs E_i , i.e.

$$E_{\text{FF-j}} = \sum_{i < j} E_i, \quad (5.8)$$

2330 where E_i is measured in each slab as the product of the stopping power, dE/dX_i ,
2331 and the track pitch, Pitch_i , for that point. If we assume conservatively that the
2332 measurements of E_i are not independent from one another, the uncertainty on $E_{\text{FF-j}}$
2333 becomes

$$\delta E_{\text{FF-j}} = (j - 1)\delta E_i, \quad (5.9)$$

2334 where δE_i is the uncertainty on the energy loss in one slab of argon.

2335 The left side of Figure 5.21 shows the distribution of the energy deposited in each
2336 slab of argon, for the 60A negative pion dataset in black and for the pion only MC
2337 in blue. The analogous plot for the -100A negative pion data set is show on the right
2338 side of Figure 5.21. The distributions are fitted with a landau displayed in red for
2339 data and in teal for MC. The uncertainty on E_i is given by the width of the Landau
2340 fit to the data. A small systematic uncertainty is given by a 1.0% difference between
2341 the most probable value of the landau fits in data and MC.

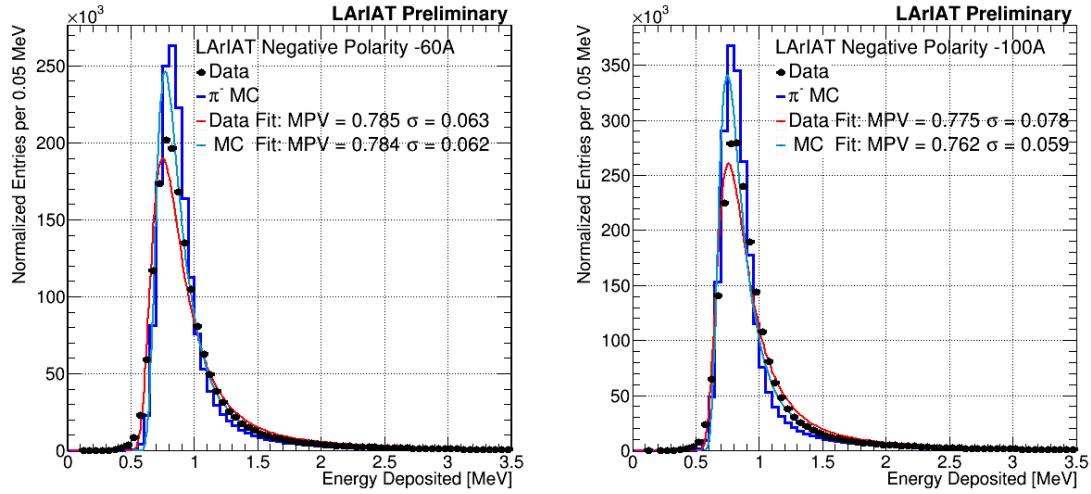


Figure 5.21: Energy deposited E_i in a single slab of argon for the pion -60A runs (left) and -100A runs (right). The data is shown in black, the MC in blue. The distributions are fitted with a landau displayed in red for data and in teal for MC.

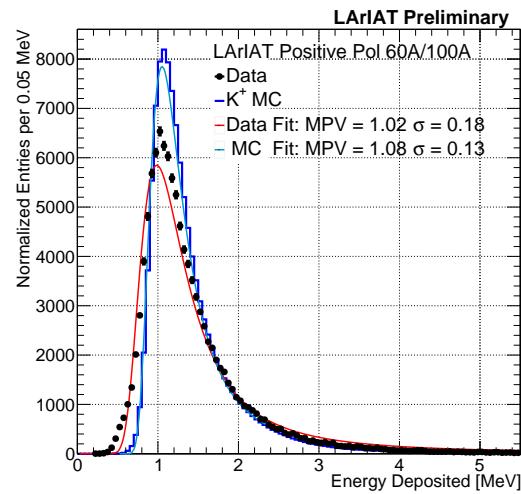


Figure 5.22: Energy deposited E_i in a single slab of argon for the kaons of the +60A runs and +100A runs. The data is shown in black, the MC in blue. The distributions are fitted with a landau displayed in red for data and in teal for MC.

2342 **Chapter 6**

2343 **Negative Pion Cross Section**

2344 **Measurement**

2345 “*Y ella es flama que se eleva, Y es un pájaro a volar.*
2346 *En la noche que se incendia, estrella de oscuridad*
2347 *que busca entre la tiniebla, la dulce hoguera del beso.*”
2348 – Lila Downs, 2002 –

2349 In this chapter, we show the result of the thin slice method to measure the (π^- -
2350 Ar) total hadronic cross section. In Section 6.1, we start by measuring the raw
2351 cross section, i.e. the cross section obtained exclusively using data reconstruction,
2352 without any additional corrections. In Section 6.2, we apply a statistical subtraction
2353 of the background contributions based on simulation and a correction for detection
2354 inefficiency. The final results are presented in Section 6.3.

2355 **6.1 Raw Cross Section**

2356 We measure the raw (π^- -Ar) total hadronic cross section as a function of the kinetic
2357 energy in the two chosen data sets, the -60A and -100A negative runs. As we will

clarify in Section 6.2, the corrections to the raw cross section depend on the beam conditions and need to be calculated independently for the two datasets. Thus, we present here the measurement of the raw cross section on the two datasets separately.

As stated in section 4.3.2, the raw cross section is given by the equation 4.4

$$\sigma_{TOT}(E_i) = \frac{1}{n\delta X} \frac{N_{Int}^{TOT}(E_i)}{N_{Inc}^{TOT}(E_i)}, \quad (6.1)$$

where N_{Int}^{TOT} is the measured number of particles interacting at kinetic energy E_i , N_{Inc}^{TOT} is the measured number of particles incident on an argon slice at kinetic energy E_i , n is the density of the target centers and δX is the thickness of the argon slice. The density of the target centers and the slab thickness are $n = 0.021 \cdot 10^{24} \text{ cm}^{-3}$ and $\delta X = 0.47 \text{ cm}$, respectively.

Figure 6.1 shows the distribution of N_{Int}^{TOT} as a function of the kinetic energy for the 60A dataset on the left and for the 100A dataset on the right. The data central points are represented by black dots, the statistical uncertainty is shown in black, while the systematic uncertainty is shown in red. Data is displayed over the N_{Int}^{TOT} distribution obtained with a MC mixed sample of pions, muon and electrons (additional details on the composition will be provided in Section ??). The contribution from the simulated pions is shown in blue, the one from secondaries in red, the one from muons in yellow and the ones from electrons in gray. The simulated pion's and backgrounds' contributions are stacked; the sum of the integrals from each particle species is normalized to the integral of the data.

Figure 6.2 shows the distribution of N_{Inc}^{TOT} for the 60A dataset on the left and for the 100A dataset on the right. Data is displayed over the MC. The same color scheme and normalization procedure is used for both the interacting and incident histograms.

Figure 6.3 shows the raw cross section for the 60A dataset on the left and for the 100A dataset on the right, statistical uncertainty in black and systematic uncertainty

2382 in red. The raw data cross section is overlaid to the reconstructed cross section for
 2383 the MC mixed sample, displayed in azure. Since the background contributions and
 2384 the detector effects for the 60A and 100A sample are different, it is premature to
 2385 compare the raw cross sections obtained from the two samples at this point.

2386 We describe the calculation of the statistical uncertainty for the interacting, in-
 2387 cident and cross section distributions in Section 6.1.1; we describe the procedure to
 2388 calculate the corresponding systematics uncertainty on Section 6.1.2.

2389 6.1.1 Statistical Uncertainty

2390 The statistical uncertainty for a given kinetic energy bin of the cross section is cal-
 2391 culated by error propagation from the statistical uncertainty on $N_{\text{Inc}}^{\text{TOT}}$ and $N_{\text{Int}}^{\text{TOT}}$
 2392 correspondent bin. Since the number of incident particles in each energy bin is given
 2393 by a simple counting, we assume that $N_{\text{Inc}}^{\text{TOT}}$ is distributed as a poissonian with mean
 2394 and variance equal to $N_{\text{Inc}}^{\text{TOT}}$ in each bin. On the other hand, $N_{\text{Int}}^{\text{TOT}}$ follows a bino-
 2395 mial distribution: a particle in a given energy bin might or might not interact. The
 2396 variance for the binomial is given by

$$\text{Var}[N_{\text{Int}}^{\text{TOT}}] = \mathcal{N}P_{\text{Interacting}}(1 - P_{\text{Interacting}}). \quad (6.2)$$

2397 Since the interaction probability $P_{\text{Interacting}}$ is $\frac{N_{\text{Int}}^{\text{TOT}}}{N_{\text{Inc}}^{\text{TOT}}}$ and the number of tries \mathcal{N} is
 2398 $N_{\text{Inc}}^{\text{TOT}}$, equation 6.2 translates into

$$\text{Var}[N_{\text{Int}}^{\text{TOT}}] = N_{\text{Inc}}^{\text{TOT}} \frac{N_{\text{Int}}^{\text{TOT}}}{N_{\text{Inc}}^{\text{TOT}}} \left(1 - \frac{N_{\text{Int}}^{\text{TOT}}}{N_{\text{Inc}}^{\text{TOT}}}\right) = N_{\text{Int}}^{\text{TOT}} \left(1 - \frac{N_{\text{Int}}^{\text{TOT}}}{N_{\text{Inc}}^{\text{TOT}}}\right). \quad (6.3)$$

2399 $N_{\text{Inc}}^{\text{TOT}}$ and $N_{\text{Int}}^{\text{TOT}}$ are not independent. The statistical uncertainty on the cross
 2400 section is thus calculated as

$$\delta\sigma_{\text{TOT}}(E) = \sigma_{\text{TOT}}(E) \left(\frac{\delta N_{\text{Int}}^{\text{TOT}}}{N_{\text{Int}}^{\text{TOT}}} + \frac{\delta N_{\text{Inc}}^{\text{TOT}}}{N_{\text{Inc}}^{\text{TOT}}} \right) \quad (6.4)$$

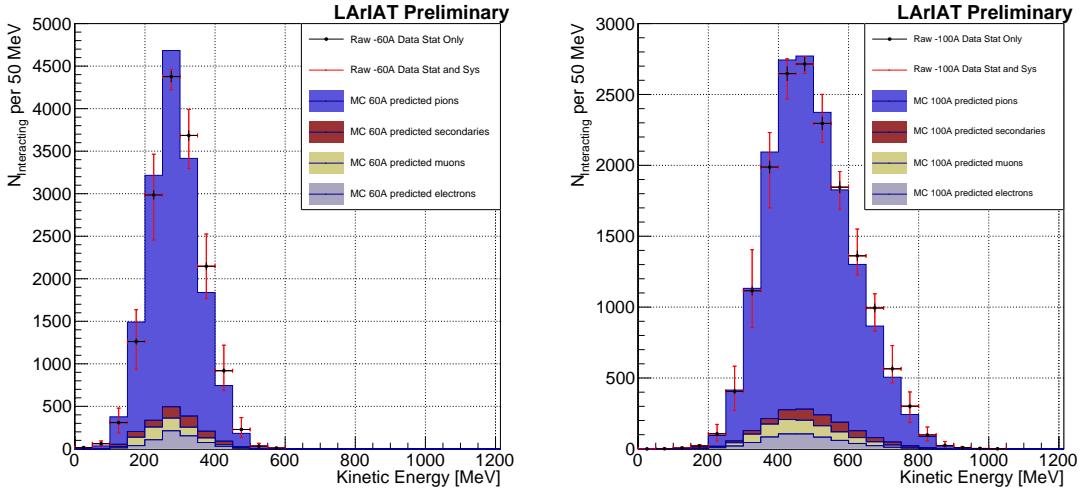


Figure 6.1: Raw number of interacting pion candidates as a function of the reconstructed kinetic energy for the 60A runs (left) and for the 100A runs (right). The statistical uncertainties are shown in black, the systematic uncertainties in red.

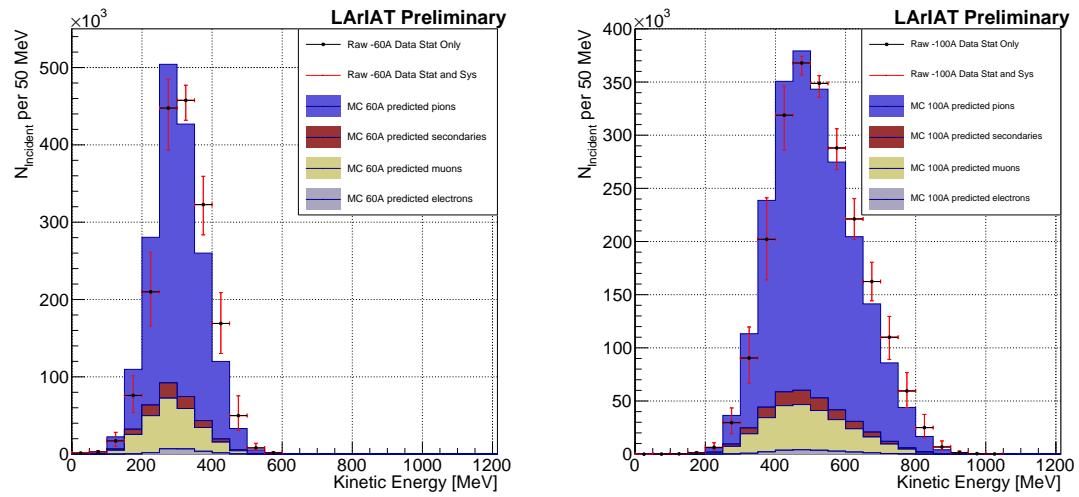


Figure 6.2: Raw number of incident pion candidates as a function of the reconstructed kinetic energy for the 60A runs (left) and for the 100A runs (right). The statistical uncertainty is shown in black, the systematic uncertainty in red.

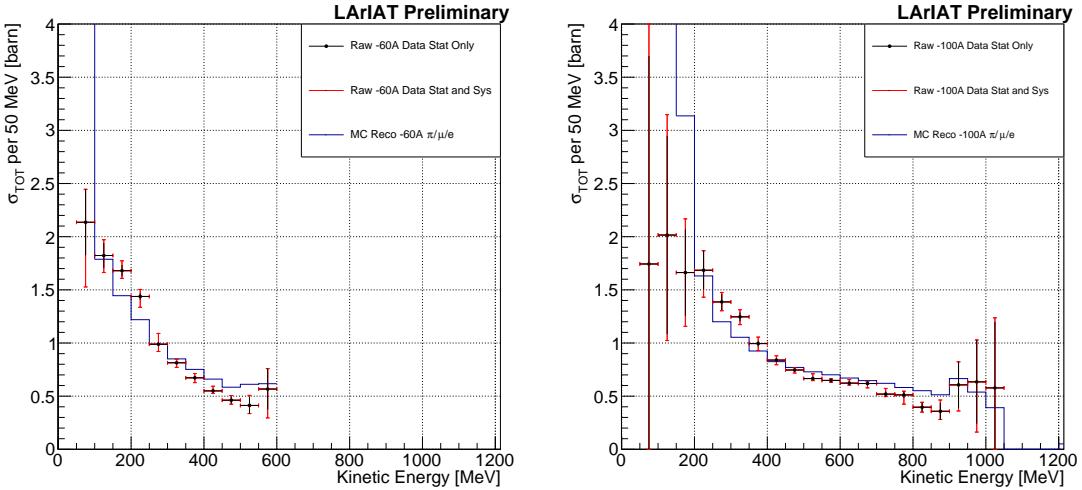


Figure 6.3: Raw (π^- -Ar) total hadronic cross section for the 60A runs (left) and for the 100A runs (right). The statistical uncertainty is shown in black, the systematic uncertainties in red. The raw cross section obtained with a MC mixed sample of pions, muon and electrons in the percentage predicted by G4Beamline is shown in azure.

2401 where:

$$\delta N_{\text{Inc}}^{\text{TOT}} = \sqrt{N_{\text{Inc}}^{\text{TOT}}} \quad (6.5)$$

$$\delta N_{\text{Int}}^{\text{TOT}} = \sqrt{N_{\text{Int}}^{\text{TOT}} \left(1 - \frac{N_{\text{Int}}^{\text{TOT}}}{N_{\text{Inc}}^{\text{TOT}}}\right)}. \quad (6.6)$$

2402 6.1.2 Treatment of Systematics

2403 The only systematic effect considered in the measurement of the raw cross section
 2404 results from the propagation of the uncertainty associate with the measurement of
 2405 the kinetic energy at each argon slab. As shown in Section 5.6.1, the uncertainty on
 2406 the kinetic energy of a pion candidate at the j^{th} slab of argon is given by

$$\delta KE_j = \sqrt{\delta p_{\text{Beam}}^2 + \delta E_{\text{Loss}}^2 + \delta E_{\text{dep FF-j}}^2} \quad (6.7)$$

$$= \sqrt{(2\% p_{\text{Beam}})^2 + (6 \text{ [MeV]})^2 + (j - 1)^2 (\sim 0.08 \text{ [MeV]})^2}. \quad (6.8)$$

2407 We propagate this uncertainty by varying the energy measurement KE_j at each
 2408 argon slab. We measure $N_{\text{Inc}}^{\text{TOT}}$, $N_{\text{Int}}^{\text{TOT}}$ and the cross section in three cases: first
 2409 assigning the measured KE_j at each kinetic energy sampling, then assigning $KE_j +$
 2410 δKE_j , and finally assigning $KE_j - \delta KE_j$. The difference between the values obtained
 2411 using the KE_j sampling and the maximum and minimum values in each kinetic energy
 2412 bin determines the systematic uncertainty.

2413 **6.2 Corrections to the Raw Cross Section**

2414 As described in section 4.3.3, we need to apply a background correction and an
 2415 efficiency correction in order to derive the true pion cross section from the raw cross
 2416 section. The true cross section is given in equation 4.9,

$$\sigma_{\text{TOT}}^{\pi^-}(E_i) = \frac{1}{n\delta X} \frac{\epsilon^{\text{Inc}}(E_i)}{\epsilon^{\text{Int}}(E_i)} \frac{C_{\text{Int}}^{\pi MC}(E_i)}{C_{\text{Inc}}^{\pi MC}(E_i)} \frac{N_{\text{Int}}^{\text{TOT}}(E_i)}{N_{\text{Inc}}^{\text{TOT}}(E_i)}. \quad (4.9)$$

2417 Section 6.2.1 describes the evaluation of pion content in the interacting and inci-
 2418 dent histograms, ($C_{\text{Int}}^{\pi MC}(E_i)$ and $C_{\text{Inc}}^{\pi MC}(E_i)$) and the propagation to the cross section
 2419 measurement of the relative systematic uncertainties.

2420 Section 6.2.2 describes the procedure employed to obtain the efficiency corrections
 2421 $\epsilon^{\text{Int}}(E_i)$ and $\epsilon^{\text{Inc}}(E_i)$ and the propagation to the cross section measurement of the
 2422 relative uncertainties.

2423 **6.2.1 Background subtraction**

2424 We use the procedure described in 5.3.2 to evaluate the relative pion content in
 2425 the interacting histogram $C_{\text{Int}}^{\pi MC}(E_i)$ and the relative pion content in the incident
 2426 $C_{\text{Inc}}^{\pi MC}(E_i)$. We start by evaluating the relative pion content assuming the beamline
 2427 composition simulated by G4Beamline, whose pion, muon and electron percentages
 2428 per beam condition are reported again in the first line of Table 6.1. The left side of

2429 Figure 6.4 shows the MC estimated relative pion content for the interacting histogram
2430 as function of kinetic energy for the 60A runs (top) and 100A runs (bottom). The
2431 right side of the same figure shows the MC estimated relative pion content for the
2432 incident histogram as function of kinetic energy for the 60A runs (top) and 100A
2433 runs (bottom). In Figure 6.4 the central curves displayed in light blue are obtained
2434 using the beamline composition as predicted by G4Beamline: these are the correction
2435 curves for the relative pion content applied to data.

2436 So, the question now becomes: how well do we know the beamline composition?
2437 In absence of additional data constraints, we take a 100% systematic uncertainty on
2438 the electron content, reported in lines 3 and 4 of Table 6.1. The effect of doubling or
2439 halving the electron percentage in the beam on the pion relative content is displayed
2440 in red in Figure 6.4. We reserve a slightly different treatment for the muon content.
2441 Since G4Beamline tracks only particles which cross all the wire chambers, pion events
2442 that decay in flight from WC1 to WC4 are not recorded by G4Beamline. Pion decays
2443 in the beamline could be trigger the beamline detectors in data, if the produced muon
2444 proceeds in the beamline. Thus, we take the G4Beamline prediction for muons as a
2445 lower bound in the composition: the effect of doubling the muon content (line 2 in
2446 Table 6.1) is shown in blue on Figure 6.4. A future study of data from additional
2447 beamline detectors such as the Aerogel Chernkov detectors [43] or the muon range
2448 stack (see Section 3.2.4) has the potential of a narrowing the systematics uncertainty
2449 coming from the beamline composition.

2450 We propagate the uncertainty on the beamline composition as a systematic un-
2451 certainty to the cross section by varying the beam composition for all the cases listed
2452 in Table 6.1 and evaluating variation of obtained data cross sections in each bin. This
2453 systematic uncertainty is summed in quadrature with the statistical uncertainty and
2454 the systematic uncertainty related to the kinetic energy measurement.

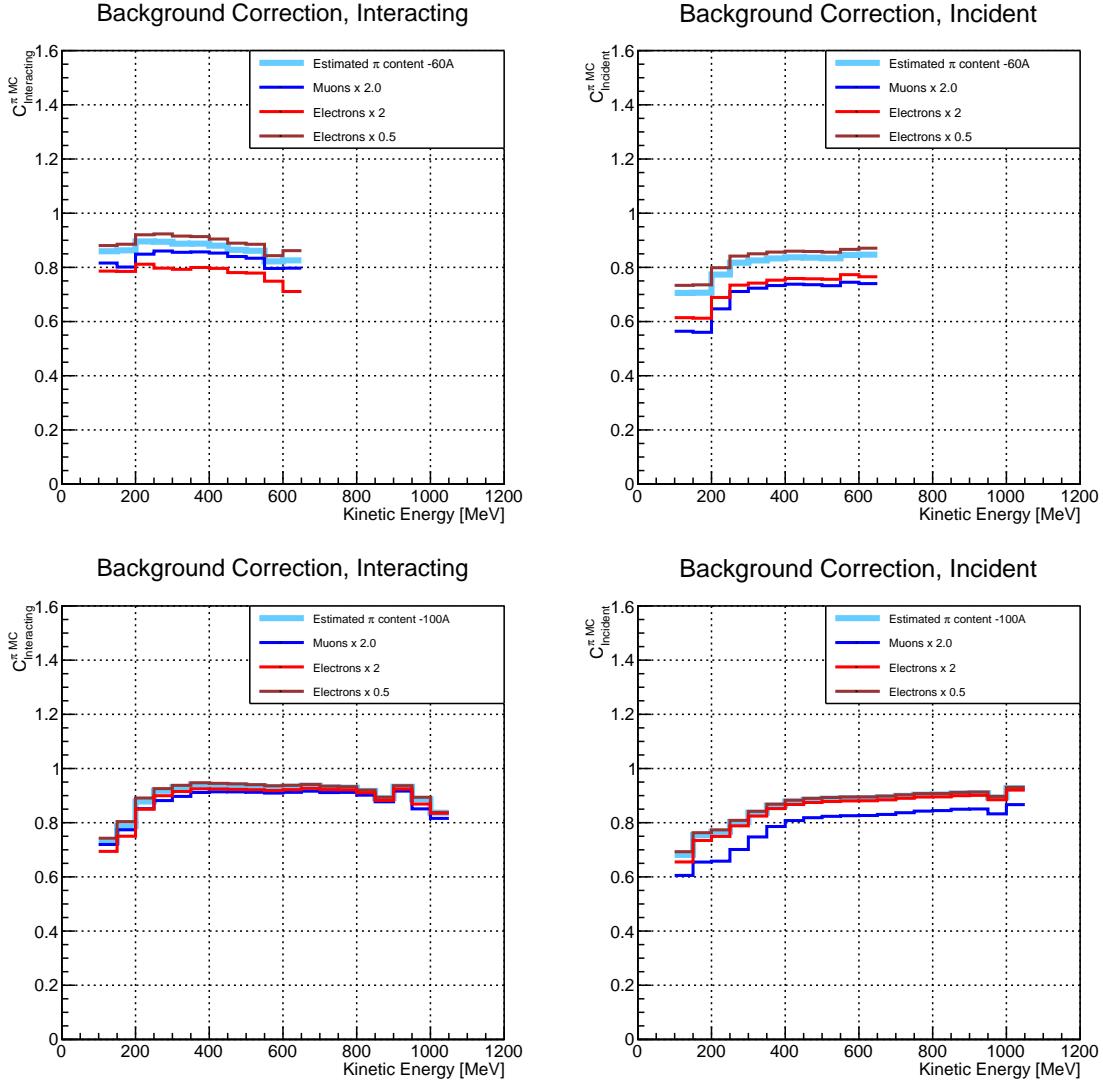


Figure 6.4: *Left:* MC estimated relative pion content for interacting histogram a function of kinetic energy for the 60A runs (top) and 100A runs (bottom), predicted background content in azure and muon and electron content variation in blue and red. *Right:* MC estimated relative pion content for incident histogram a function of kinetic energy for the 60A runs (top) and 100A (bottom), predicted background content in azure and muon and electron content variation in blue and red

2455 6.2.2 Efficiency Correction

2456 The interaction point for a track used in the total hadronic cross section analysis
2457 is defined to be the last point of the WC2TPC matched track which lies inside the
2458 fiducial volume. This definition is independent from the topology of the interaction.
2459 If the TPC track stops within the fiducial volume, its last point will be the interaction
2460 point, no matter what the products of the interaction look like; if the track crosses the
2461 boundaries of the fiducial volume, the track will be considered “through going” and no
2462 interaction point will be found. Given this definition, it is evident that we rely on the
2463 tracking algorithm to discern where the interaction occurred in the TPC and correctly
2464 stop the tracking. The tracking algorithm has an intrinsic angle resolution as shown
2465 in section 5.5.1, which limits its efficiency, especially in the case of elastic scattering
2466 occurring at low angles. Thus, we need to apply an efficiency correction to data in order
2467 to retrieve the true cross section. The efficiency correction is evaluated separately for
2468 the interacting and incident histograms, namely ϵ_i^{int} and ϵ_i^{inc} , and propagated to the
2469 cross section as shown in equation 4.9.

2470 Efficiency Correction: Procedure

2471 We describe here the procedure to calculate the efficiency correction taking the in-
2472 teracting histogram as example and noting that the procedure is identical for the
2473 incident histogram.

2474 We derive the correction on a set of pure pion MC, calculating its value bin by
2475 bin as the ratio between the true bin content and the correspondent reconstructed
2476 bin content. The correction is then applied to the relevant bin in data. In formulae,
2477 the efficiency correction is calculated to be

$$\epsilon^{\text{Int}}(E_i) = \frac{N_{\text{Interacting}}^{\pi \text{ Reco MC}}(E_i)}{N_{\text{Interacting}}^{\pi \text{ True MC}}(E_i)}, \quad (6.9)$$

2478 where $N_{\text{Int}}^{\pi \text{ True MC}}(E_i)$ is the content of the i -th bin in for the true interacting
 2479 histogram, and $N_{\text{Int}}^{\pi \text{ Reco MC}}(E_i)$ is the content of the i -th bin in for the reconstructed
 2480 interacting histogram. The correction is applied to data as follows

$$N_{\text{Int}}^{\pi \text{ True Data}}(E_i) = \frac{N_{\text{Int}}^{\pi \text{ Reco Data}}(E_i)}{\epsilon^{\text{Int}}(E_i)} = N_{\text{Int}}^{\pi \text{ Reco Data}}(E_i) \frac{N_{\text{Int}}^{\pi \text{ True MC}}(E_i)}{N_{\text{Int}}^{\pi \text{ Reco MC}}(E_i)}. \quad (6.10)$$

2481 where $N_{\text{Int}}^{\pi \text{ Reco Data}}(E_i)$ is the background subtracted bin content of the i -th bin in
 2482 for the reconstructed interacting histogram for data, i.e.

$$N_{\text{Int}}^{\pi \text{ Reco Data}}(E_i) = N_{\text{Int}}^{\text{TOT Data}}(E_i) - B_{\text{Int}}^{\text{Data}}(E_i) = C_{\text{Int}}^{\pi \text{ MC}}(E_i) N_{\text{Int}}^{\text{TOT Data}}(E_i). \quad (6.11)$$

2483 In section 5.5.1, we estimated the angular resolution for data and MC to be
 2484 $\bar{\alpha}_{\text{Data}} = (5.0 \pm 4.5)$ deg and $\bar{\alpha}_{\text{MC}} = (4.5 \pm 3.9)$ deg, respectively. Most interaction
 2485 angles smaller than the angular resolution will thus be indistinguishable for the re-
 2486 construction. Thus, we claim we are able to measure the cross section for interaction
 2487 angles greater than 5.0 deg. Geant4 simulates interactions at all angles, as shown in
 2488 figure 6.7. In order to calculate the efficiency correction, we select events which have
 2489 an interaction angle greater than a given α_{res} to construct the true interacting and
 2490 incident histograms (the denominator of the efficiency correction). The systematics
 2491 on the efficiency correction is estimated by varying the value of α_{res} between 0 deg
 2492 and 4.5 deg and propagating the uncertainty on the cross section.

2493 Figure 6.5 shows $\epsilon^{\text{Int}}(E_i)$ in the left side and $\epsilon^{\text{Inc}}(E_i)$ on the right as a function of
 2494 the kinetic energy for the 60A runs and their systematic uncertainty. Similarly, figure
 2495 6.6 shows $\epsilon^{\text{Int}}(E_i)$ in the left side and $\epsilon^{\text{Inc}}(E_i)$ on the right as a function of the kinetic
 2496 energy for the 100A runs and their systematic uncertainty.

	Magnet Current -60A			Magnet Current -100 A		
	MC π^-	MC μ^-	MC e^-	MC π^-	MC μ^-	MC e^-
Expected Composition	68.8 %	4.6 %	26.6 %	87.4 %	3.7 %	8.9 %
Composition 2x Muons	64.2 %	9.2 %	26.6 %	83.7 %	7.4 %	8.9 %
Composition 2x Electrons	42.2 %	4.6 %	53.2 %	78.5 %	3.7 %	17.8 %
Composition 0.5x Electrons	82.1 %	4.6 %	13.3 %	91.9 %	3.7 %	4.4 %

Table 6.1: Beam composition variation for the study of systematics due to beam contamination.

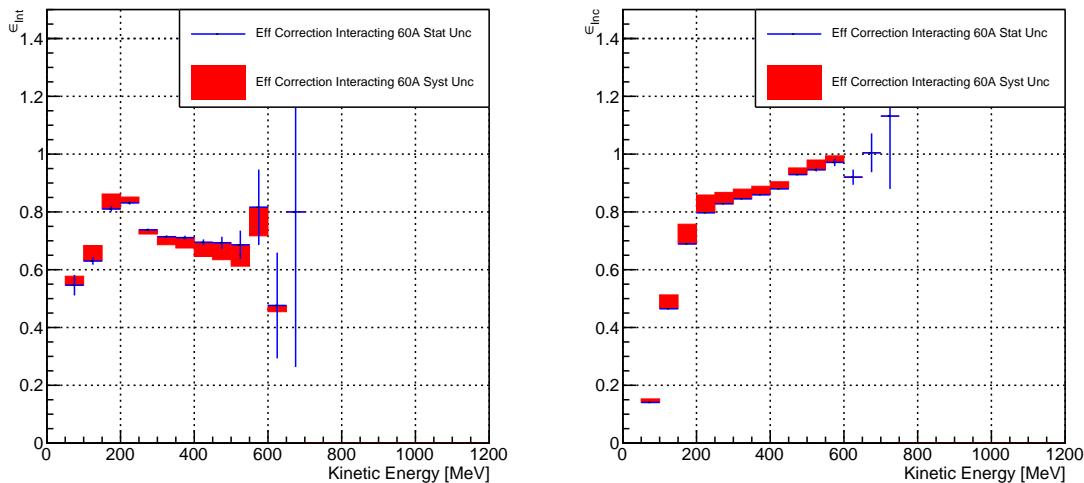


Figure 6.5: *Left:* Efficiency correction on the 60A interacting histogram, statistical uncertainty in blue, systematic uncertainty in red. *Right:* Efficiency correction on the 60A incident histogram, statistical uncertainty in blue, systematic uncertainty in red.

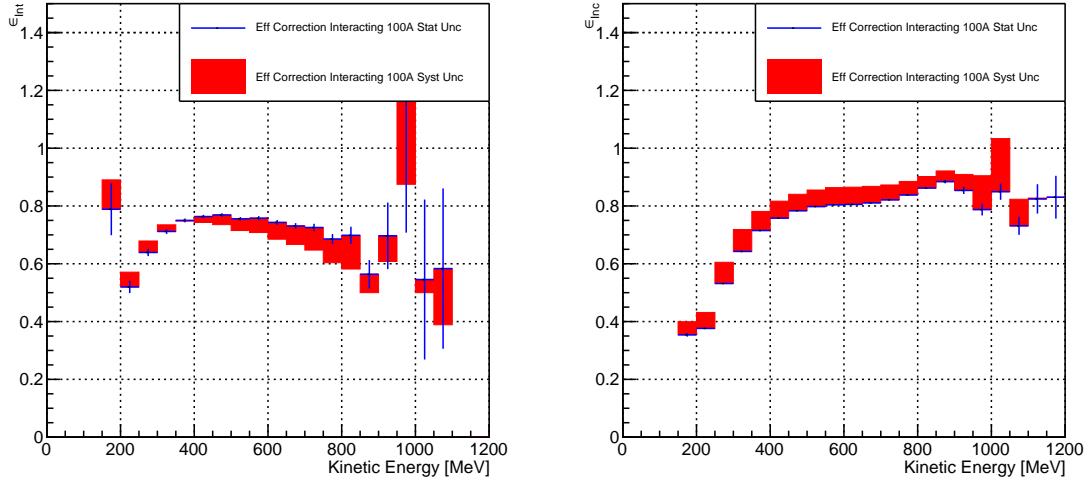


Figure 6.6: *Left*: Efficiency correction on the 100A interacting histogram, statistical uncertainty in blue, systematic uncertainty in red. *Right*: Efficiency correction on the 100A incident histogram, statistical uncertainty in blue, systematic uncertainty in red.

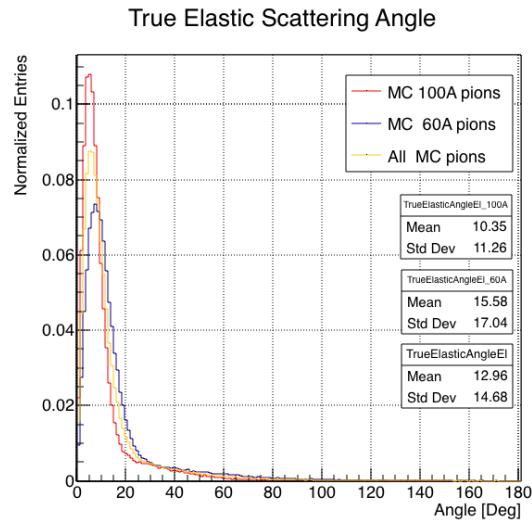


Figure 6.7: Distribution of the true scattering angle for a pion elastic scattering off the argon nucleus as simulated by Geant4.

2497 **6.3 Results**

2498 Figure 6.8 show the measurement of the (π^- -Ar) total hadronic cross section for
2499 scattering angles greater than 5° , as the result of the background subtraction and
2500 efficiency correction to the raw cross section. The top left plot is the measurement
2501 obtained on the 60A data, statistical uncertainty in black and systematic uncertainty
2502 in red. The top right plot is the measurement obtained on the 100A data, statistical
2503 uncertainty in black and systematic uncertainty in blue. The bottom plot shows the
2504 two measurements overlaid. In all three plot, the Geant4 prediction for the total
2505 hadronic cross section for angle scattering greater than 5° is displayed in green.

2506 The systematic uncertainty on the cross section is the sum in quadrature of the
2507 statistical uncertainty, the systematic uncertainty related to the kinetic energy mea-
2508 surement, the systematic uncertainty related to the beam composition and the sys-
2509 tematic uncertainty related to the efficiency correction.

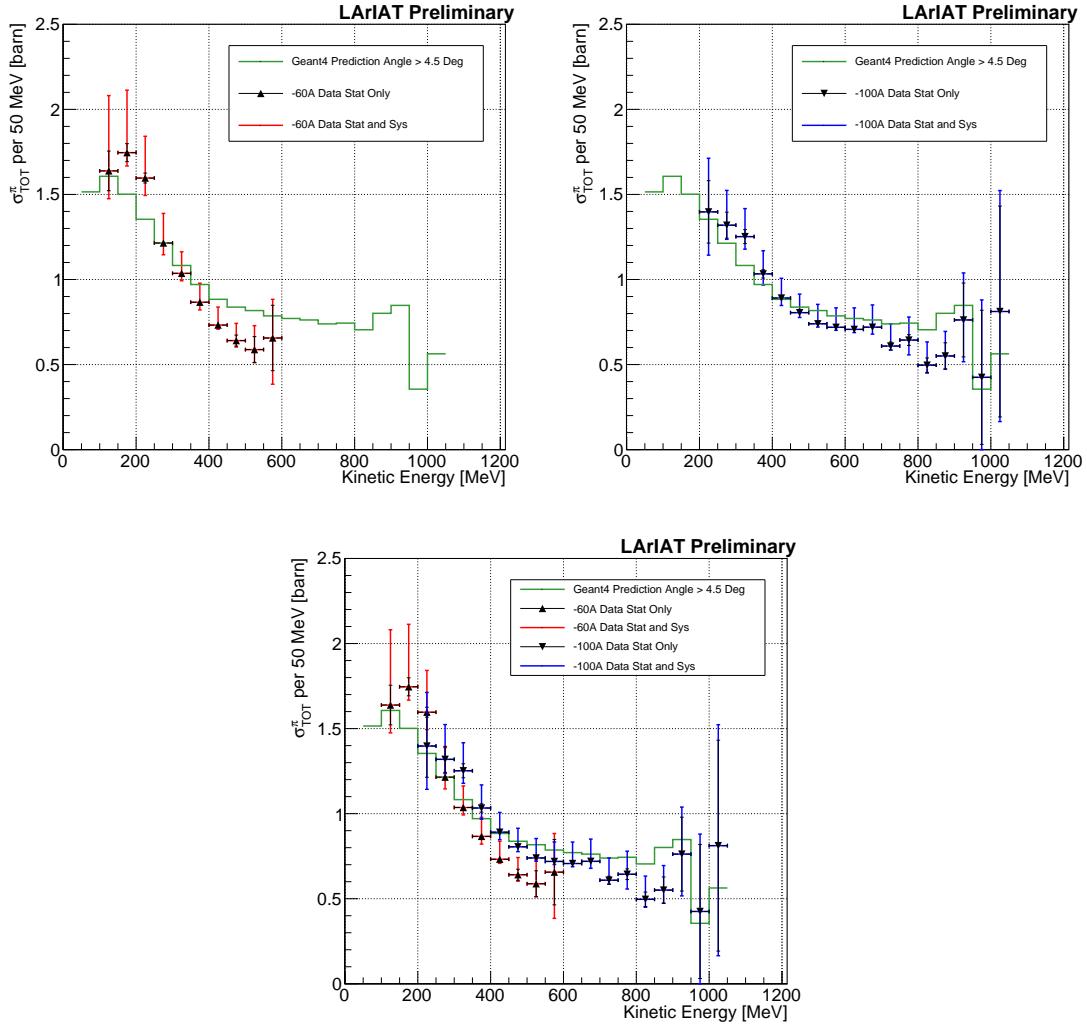


Figure 6.8: *Top Left:* (π^- -Ar) total hadronic cross section for scattering angles greater than 5° measured in the 60A sample, statistical uncertainty in black and systematic uncertainty in red. The Geant4 prediction for the total hadronic cross section for angle scattering greater than 5° is displayed in green.

Top Right: (π^- -Ar) total hadronic cross section for scattering angles greater than 5° measured in the 100A sample, statistical uncertainty in black and systematic uncertainty in blue. The Geant4 prediction for the total hadronic cross section for angle scattering greater than 5° is displayed in green.

Bottom: (π^- -Ar) total hadronic cross section measurements in the 60A and 100A samples overlaid with the Geant4 prediction (green).

2510 **Chapter 7**

2511 **Positive Kaon Cross Section**

2512 **Measurement**

2513 “Beat-up little seagull, on a marble stair
2514 Tryin’ to find the ocean, lookin’ everywhere.”
2515 – Nina Simone, 1978 –

2516 In this chapter, we show the result of the thin slice method to measure the (K^+ -
2517 Ar) total hadronic cross section. In Section 7.1, we start by measuring the raw
2518 cross section. In Section 7.2, we apply a statistical subtraction of the background
2519 contributions based on simulation and a correction for detection inefficiency. The
2520 final results are presented in Section 7.3.

2521 **7.1 Raw Cross Section**

2522 We measure the raw (K^+ -Ar) total hadronic cross section as a function of the kinetic
2523 energy in the combined +60A and +100A dataset.

2524 Similar to the pion case, the raw cross section is given by the equation 4.4

$$\sigma_{TOT}(E_i) = \frac{1}{n\delta X} \frac{N_{Int}^{TOT}(E_i)}{N_{Inc}^{TOT}(E_i)}, \quad (7.1)$$

2525 where N_{Int}^{TOT} is the measured number of particles interacting at kinetic energy E_i ,
2526 N_{Inc}^{TOT} is the measured number of particles incident on an argon slice at kinetic energy
2527 E_i , n is the density of the target centers and δX is the thickness of the argon slice.
2528 The density of the target centers and the slab thickness are $n = 0.021 \cdot 10^{24} \text{ cm}^{-3}$ and
2529 $\delta X = 0.47 \text{ cm}$, respectively.

2530 As in the case of pions, kaons might decay or interact between WC4 and the TPC
2531 front face. Some of the interaction products may be wrongly matched to the WC
2532 track, forming the “secondary” particle’s background in the kaon sample. We estimate
2533 the effect of the contamination of secondaries through the DDMC kaon sample. Figure
2534 7.1 shows the distribution of N_{Int}^{TOT} as a function of the kinetic energy. The data
2535 central points are represented by black dots, the statistical uncertainty is shown in
2536 black, while the systematic uncertainty is shown in red. Data is displayed over the
2537 N_{Int}^{TOT} distribution obtained with a DDMC sample of kaons shot from WC4. The
2538 contribution from the simulated kaons which interact hadronically is shown in pink,
2539 the contributions from kaon decay is shown in orange and the one from secondaries
2540 in red. The simulated kaon’s and secondaries’ contributions are stacked; the sum of
2541 their integrals is normalized to the integral of the data.

2542 Figure 7.2 shows the distribution of N_{Inc}^{TOT} . Data is displayed over the MC. For the
2543 N_{Inc}^{TOT} distribution we do not make a distinction between kaons that decay or interact
2544 hadronically because any kaon independently from its final interaction contributes
2545 to the flux of incident particles at given kinetic energy. The same normalization
2546 procedure is used for both the interacting and incident histograms.

2547 Figure 7.3 shows the raw cross section, statistical uncertainty in black and system-

atic uncertainty in red. The raw data cross section is overlaid to the reconstructed cross section for the MC mixed sample, displayed in azure. We calculate the statistical uncertainty for the interacting, incident and cross section distributions in a similar fashion to the pion case as described in Section 6.1.1.

As in the pion case, the only systematic effect considered in the measurement of the raw cross section results from the propagation of the uncertainty associate with the measurement of the kinetic energy at each argon slab. For kaons, the uncertainty on the kinetic energy of a candidate at the j^{th} slab of argon is given by

$$\delta KE_j = \sqrt{\delta p_{Beam}^2 + \delta E_{Loss}^2 + \delta E_{dep\ FF-j}^2} \quad (7.2)$$

$$= \sqrt{(2\% p_{Beam})^2 + (7\text{ [MeV]})^2 + (j - 1)^2(\sim 0.18\text{ [MeV]})^2}. \quad (7.3)$$

We propagate this uncertainty by varying the energy measurement KE_j at each argon slab. We measure N_{Inc}^{TOT} , N_{Int}^{TOT} and the cross section in three cases: first assigning the measured KE_j at each kinetic energy sampling, then assigning $KE_j + \delta KE_j$, and finally assigning $KE_j - \delta KE_j$. The difference between the values obtained using the KE_j sampling and the maximum and minimum values in each kinetic energy bin determines the systematic uncertainty.

7.2 Corrections to the Raw Cross Section

As described in section 4.3.3, we need to apply a background correction and an efficiency correction in order to derive the true Kaon cross section from the raw cross section. The true cross section is given in equation 4.9,

$$\sigma_{TOT}^{K^+}(E_i) = \frac{1}{n\delta X} \frac{\epsilon^{Inc}(E_i)}{\epsilon^{Int}(E_i)} \frac{C_{Int}^{KMC}(E_i)}{C_{Inc}^{KMC}(E_i)} \frac{N_{Int}^{TOT}(E_i)}{N_{Inc}^{TOT}(E_i)}. \quad (4.9)$$

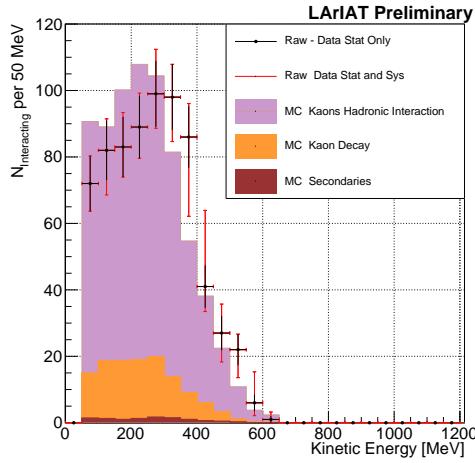


Figure 7.1: Raw number of interacting kaon candidates as a function of the reconstructed kinetic energy. The statistical uncertainties are shown in black, the systematic uncertainties in red.

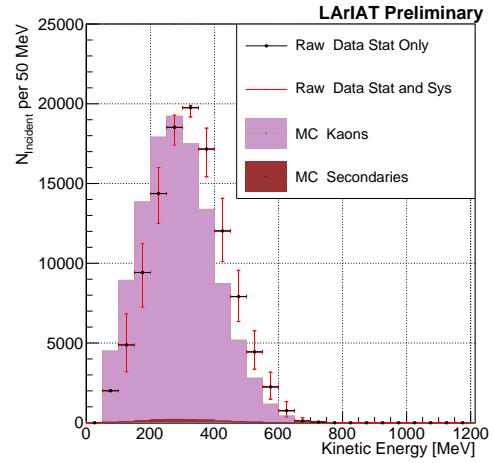


Figure 7.2: Raw number of incident kaon candidates as a function of the reconstructed kinetic energy. The statistical uncertainty is shown in black, the systematic uncertainties in red.

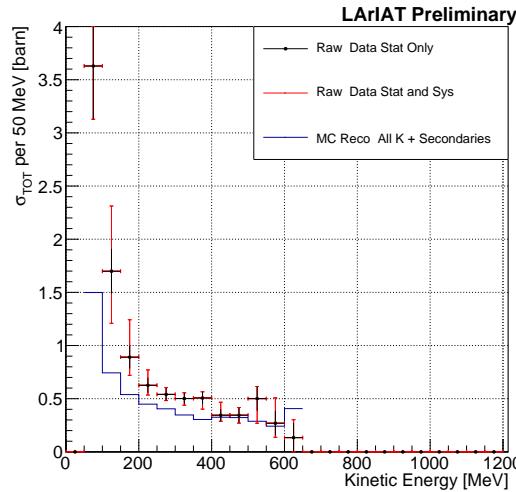


Figure 7.3: Raw (K^+ -Ar) total hadronic cross section. The statistical uncertainty is shown in black, the systematic uncertainties in red. The raw cross section obtained with a MC sample of kaons is shown in blue. For the MC cross section, we include the contributions from secondaries.

2566 Currently, the only background considered for the kaon hadronic cross section
2567 comes from the presence of secondaries. A further development of the analysis will
2568 need to account for the presence of a small proton contamination. Figure 7.4 shows
2569 the relative kaon content for the interacting and incident histograms.

2570 As described in 6.2.2 for the pion case, we derive the correction on a set of pure
2571 kaon MC, calculating its value bin by bin as the ratio between the true bin content
2572 and the correspondent reconstructed bin content. The correction is then applied to
2573 the relevant bin in data. The efficiency correction is evaluated separately for the
2574 interacting and incident histograms, namely ϵ_i^{int} and ϵ_i^{inc} , and propagated to the cross
2575 section as shown in equation 4.9.

2576 In section 5.5.1, we estimated the angular resolution for data and MC to be
2577 $\bar{\alpha}_{\text{Data}} = (4.3 \pm 3.7)$ deg and $\bar{\alpha}_{\text{MC}} = (4.4 \pm 3.6)$ deg, respectively. Most interaction
2578 angles smaller than the angular resolution will thus be indistinguishable for the re-
2579 construction. Thus, we claim we are able to measure the cross section for interaction
2580 angles greater than 4.5 deg. Geant4 simulates interactions at all angles: in order to
2581 calculate the efficiency correction, we select events which have an interaction angle
2582 greater than a α_{res} to construct the true interacting and incident histograms (the de-
2583 nominator of the efficiency correction). The systematics on the efficiency correction
2584 is estimated by varying the value of α_{res} between 0 deg and 4.5 deg and propagating
2585 the uncertainty on the cross section.

2586 Figure 7.5 shows $\epsilon^{\text{Int}}(E_i)$ in the left side and $\epsilon^{\text{Inc}}(E_i)$ on the right as a function of
2587 the kinetic energy for the kaon sample and their systematic uncertainty.

2588 7.3 Results

2589 Figure 7.6 show the measurement of the (K^+ -Ar) total hadronic cross section for
2590 scattering angles greater than 5° , as the result of the background subtraction and

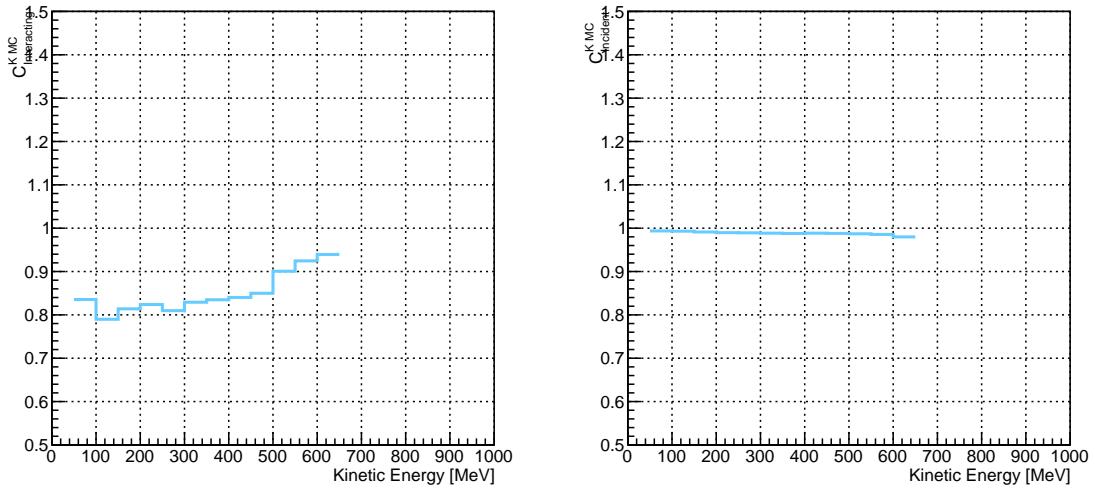


Figure 7.4: *Left:* MC estimated relative kaon content for kaons interacting hadronically as function of kinetic energy. *Right:* MC estimated relative kaon content for incident histogram a function of kinetic energy.

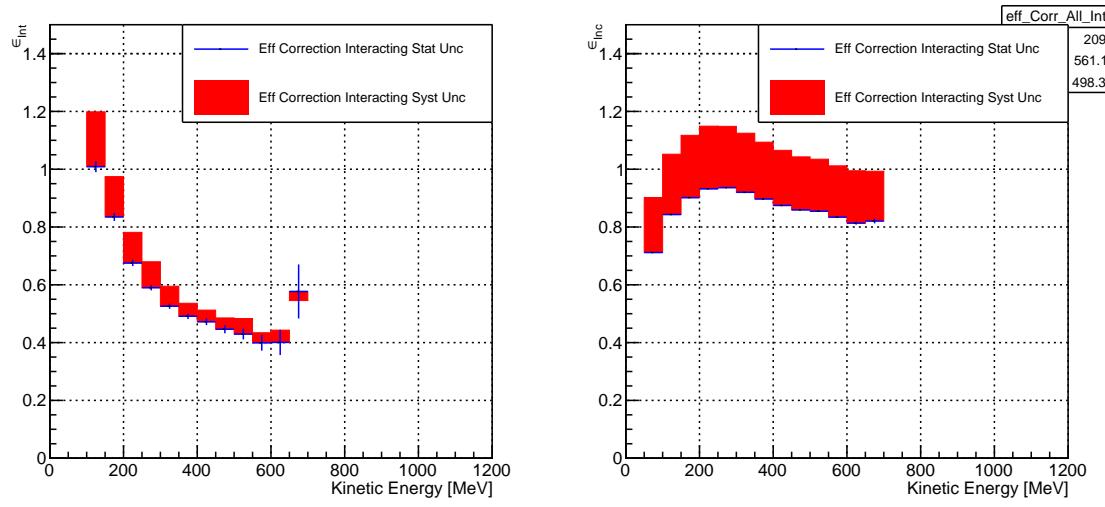


Figure 7.5: *Left:* Efficiency correction on the interacting histogram, statistical uncertainty in blue, systematic uncertainty in red. *Right:* Efficiency correction on the incident histogram, statistical uncertainty in blue, systematic uncertainty in red.

efficiency correction to the raw cross section. The plot shows the measurement obtained on the full dataset, statistical uncertainty in black and systematic uncertainty in red. The Geant4 prediction for the total hadronic cross section for angle scattering greater than 5° is displayed in green.

The systematic uncertainty on the cross section is the sum in quadrature of the statistical uncertainty, the systematic uncertainty related to the kinetic energy measurement and the systematic uncertainty related to the efficiency correction.

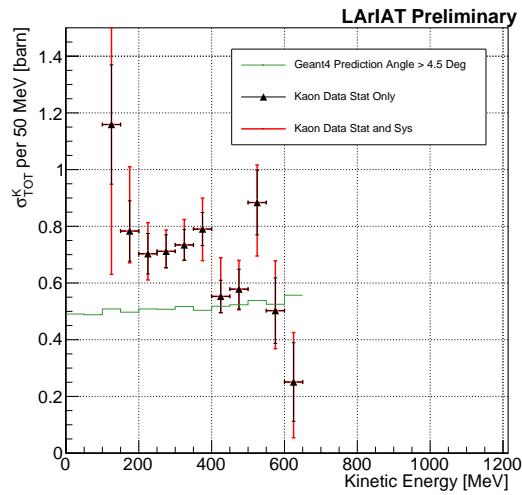


Figure 7.6: (K^+ -Ar) total hadronic cross section for scattering angles greater than 5° measured in the 60A sample, statistical uncertainty in black and systematic uncertainty in red. The Geant4 prediction for the total hadronic cross section for angle scattering greater than 5° is displayed in green.

²⁵⁹⁸ **Chapter 8**

²⁵⁹⁹ **Conclusions**

2600 **Appendix A**

2601 **Additional Tracking Studies for**
2602 **LArIAT Cross Section Analyses**

2603 In this section, we describe two studies. The first is a justification of the selection
2604 criteria for the beamline handshake with the TPC information. We perform this
2605 study to boost the correct identification of the particles in the TPC associated with
2606 the beamline information, while maintaining sufficient statistics for the cross section
2607 measurement. The second study is an optimization of the tracking algorithm, with
2608 the scope of maximizing the identification of the hadronic interaction point inside the
2609 TPC. These two studies are related, since the optimization of the tracking is per-
2610 formed on TPC tracks which have been matched to the wire chamber track; in turn,
2611 the tracking algorithm for TPC tracks determines the number of reconstructed tracks
2612 in each event used to try the matching with the wire chamber track. Starting with
2613 a sensible tracking reconstruction, we perform the WC2TPC matching optimization
2614 first, then the tracking optimization. The WC2TPC match purity and efficiency are
2615 then calculated again with the optimized tracking.

2616 **A.0.1 Study of WC to TPC Match**

2617 Plots I want in this section:

2618 1. WC2TPC MC DeltaX, DeltaY and α

2619 Scope of this study is assessing the goodness of the wire chamber to TPC match
2620 on Monte Carlo and decide the selection values we will use on data. A word of caution
2621 is necessary here. With this study, we want to minimize pathologies associated with
2622 the presence of the primary hadron itself, e.g. the incorrect association between the
2623 beamline hadron and its decay products inside the TPC. Assessing the contamination
2624 from pile-up¹, albeit related, is beyond the scope of this study.

2625 In MC, we are able to define a correct WC2TPC match using the Geant4 truth
2626 information. We are thus able to count how many times the WC tracks is associated
2627 with the wrong TPC reconstructed track.

2628 We define a correct match if the all following conditions are met:

- 2629 - the length of the true primary Geant4 track in the TPC is greater than 2 cm,
- 2630 - the length of the reconstructed track length is greater than 2 cm,
- 2631 - the Z position of the first reconstructed point is within 2 cm from the TPC
2632 front face
- 2633 - the distance between the reconstructed track and the true entering point is the
2634 minimum compared with all the other reconstructed tracks.

2635 In order to count the wrong matches, we consider all the reconstructed tracks
2636 whose Z position of the first reconstructed point lies within 2 cm from the TPC front
2637 face. Events with true length in TPC < 2 cm are included. Since hadrons are shot

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

2638 100 cm upstream from the TPC front face, the following two scenarios are possible
2639 from a truth standpoint:

2640 [Ta] the primary hadron decays or interact strongly before getting to the TPC,

2641 [Tb] the primary hadron enters the TPC.

2642 As described in Section 4.2, we define a WC2TPC match according to the relative
2643 position of the WC and TPC track parametrized with ΔR and the angle between
2644 them, parametrized with α . Once we choose the selection values r_T and α_T to de-
2645 termine a reconstructed WC2TPC match, the following five scenarios are possible in
2646 the truth to reconstruction interplay :

2647 1) only the correct track is matched

2648 2) only one wrong track is matched

2649 3) the correct track and one (or more) wrong tracks are matched

2650 4) multiple wrong tracks matched.

2651 5) no reconstructed tracks are matched

2652 Since we keep only events with one and only one match, we discard cases 3), 4)
2653 and 5) from the events used in the cross section measurement. For each set of r_T and
2654 α_T selection value, we define purity and efficiency of the selection as follows:

$$\text{Efficiency} = \frac{\text{Number of events correctly matched}}{\text{Number of events with primary in TPC}}, \quad (\text{A.1})$$

$$\text{Purity} = \frac{\text{Number of events correctly matched}}{\text{Total number of matched events}}. \quad (\text{A.2})$$

2655 Figure A.1 shows the efficiency (left) and purity (right) for WC2TPC match as
2656 a function of the radius, r_T , and angle, α_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. Since we are studying a single particle gun Monte Carlo sample, the wrong matches can occur only for mis-tracking of the primary or for association with decay products; decay products will tend to be produced at large angles compared to the primary, but could be fairly close to the in x and y projection of the primary. 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 particles of a pure species will lead to a better measurement. Obviously, purity should be balanced with a sensible efficiency to avoid rejecting the whole sample.

We choose $(\alpha_T, r_T) = (8 \text{ deg}, 4 \text{ cm})$ and get a MC 85% efficiency and 98% purity for the kaon sample and a MC 95% efficiency and 90% purity for the pion sample.

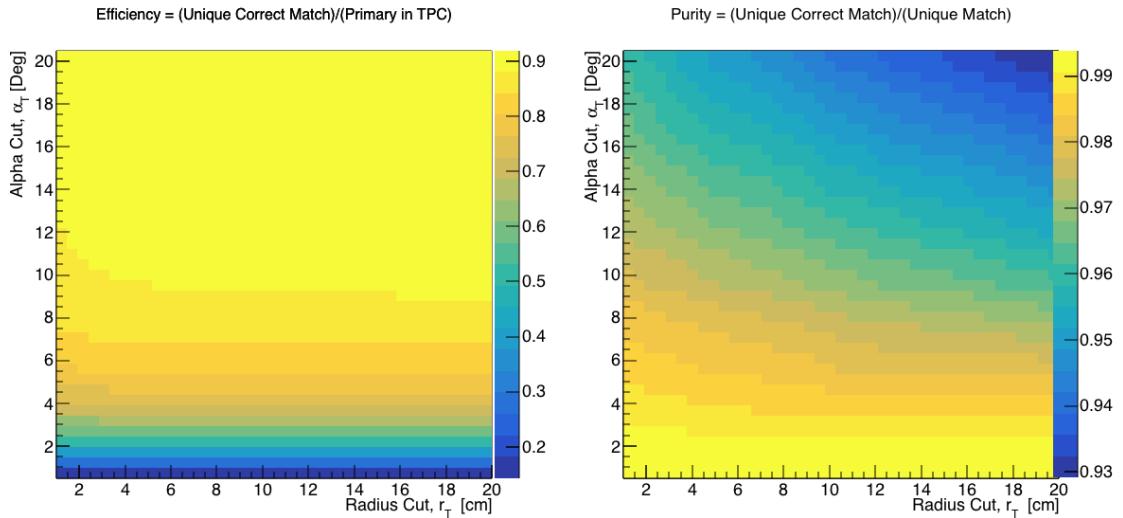


Figure A.1: Efficiency (left) and purity (right) for WC2TPC match as a function of the radius and angle selections for the kaon sample.

A.0.2 Tracking Optimization

2670 **Appendix B**

2671 **Energy Calibration**

2672 Scope of the energy calibration is to identify the factors which convert the charge
2673 collected (dQ) to energy deposited in the chamber (dE). As described in section
2674 2.1.5, this is a multi-step procedure. In LArIAT, we first correct the raw charge by
2675 the electronic noise on the considered wire [104], then by the electron lifetime [105],
2676 and then by the recombination using the ArgoNeut recombination values. Lastly, we
2677 apply overall calibration of the energy, i.e. we determine the “calorimetry constants”
2678 using the procedure described in this section.

2679 We independently determine the calorimetry constants for Data and Monte Carlo
2680 in the LArIAT Run-II Data samples using a parametrization of the stopping power
2681 (a.k.a. energy deposited per unit length, dE/dX) as a function of momentum. This is
2682 done by comparing the stopping power measured on reconstructed quantities against
2683 the Bethe-Bloch theoretical prediction for various particle species (see Equation 2.1).
2684 We obtain the theoretical expectation for the dE/dX most probable value of pions
2685 (π), muons (μ), kaons (K), and protons (p) in the momentum range most relevant
2686 for LArIAT (Figure B.1) using the tables provided by the Particle Data Group [102]
2687 for liquid argon [1].

2688 The basic idea of this calibration technique is to utilize a sample of beamline

2689 events with known particle species and momentum to measure the dE/dX of the
2690 corresponding tracks in the TPC. In particular, we decided to use positive pions as
2691 calibration sample and samples from all the other particle species as cross check. Once
2692 the dE/dX of the positive pion sample has been measured at various momenta, we
2693 tune to calorimetry constants within the reconstruction software to align the measured
2694 values to match the theoretical ones found in Figure B.1.

2695 In data, we start by selecting a sample of beamline positive pion beamline can-
2696 didates without any restriction on their measured momentum¹. We then apply the
2697 WC2TPC match and subtract the energy loss upstream to the TPC front face, de-
2698 termining the momentum at the TPC front face. For each surviving pion candidate,
2699 we measure the dE/dx at each of the first 12 spacepoints associated the 3D recon-
2700 structed track, corresponding to a ~ 5 cm portion. These dE/dX measurements are
2701 then put into a histogram that corresponds to measured momentum of the track.
2702 The dE/dX histograms are sampled every 50 MeV/c in momentum (e.g. 150 MeV/c
2703 $< P < 200$ MeV/c, 200 MeV/c $< P < 250$ /c MeV, etc...). This process of selecting,
2704 sampling, and recording the dE/dX for various momentum bins is repeated over the
2705 entire sample of events, allowing us to collect sufficient statistic in most of the mo-
2706 mentum bins between 150 MeV/c and 1100 MeV/c. On average, pions and muons
2707 only lose ~ 10 MeV in this 5 cm section of the track and protons lose ~ 20 MeV. Thus
2708 choosing 50 MeV/c size bins for our histograms covers the energy spread within those
2709 bins due to energy loss from ionization for all the particle species identifiable in the
2710 beamline. Each 50 MeV/c momentum binned dE/dX histogram is now fit with a
2711 simple Landau function. The most probable value (MPV) and the associated error
2712 on the MPV from the fit are extracted and plotted against the theoretical prediction
2713 Figure B.1. Depending on the outcome of the data-prediction comparison, we modify
2714 the calorimetry constants and we repeat the procedure until a qualitative agreement

1. it should be noted that some muon and position contamination is present in the π^+ sample

2715 is achieved. We perform this tuning for the collection and induction plane separately.
 2716 As a cross check to the calorimetry constants determined using the positive pions,
 2717 we lock the constants and plot the dE/dx versus momentum distribution of all the
 2718 other particle species identifiable in the beamline data ($\pi/\mu/e$, K , p, in both polarities)
 2719 against the corresponding Beth-Bloch prediction. The agreement between data
 2720 from the other particle species and the predictions is the expected result of this cross
 2721 check. The results of the tuning and cross check for Run-II data on the collection
 2722 plane is shown in Figure B.2 negative polarity data on top, positive polarity data on
 2723 the bottom.

2724 In MC, we simulate the corresponding positive pion sample with the DDMC (see
 2725 section 5.2.2) and follow the same steps as in data. More details on the calorimetry
 2726 tuning can be found in [80].

2727 **Add agreement between data and MC for dedx for pions**

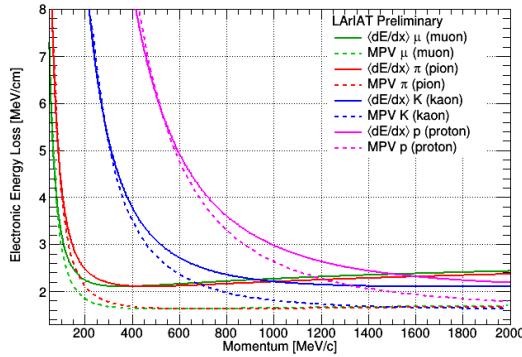


Figure B.1: Stopping power for pions, muons, kaons, and protons in liquid argon over the momentum range most relevant for LArIAT according to the Beth-Bloch equation. The solid lines represent the prediction for the mean energy dE/dX , while the dashed lines are the predictions for the MPV.

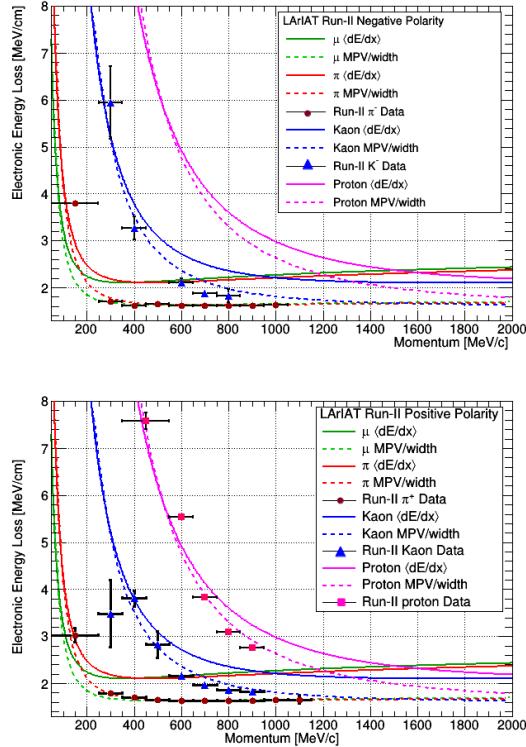


Figure B.2: Stopping power versus Momentum for Run-II negative (top) and positive (bottom) polarity data. We achieve the agreement between the Bethe-Bloch predictions and the distribution obtained with of the positive pions (top plot, red dots) by tuning the calorimetry constants. Once the calorimetry constants are locked in, the agreement between the other particle species and the Bethe-Bloch predictions follows naturally.

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