

1                           **Abstract**

2     **Measurement of total hadronic differential cross**  
3       **sections in the LArIAT experiment**

4                           Elena Gramellini

5                           2018

6    Abstract goes here. Limit 750 words.

<sup>7</sup> **Measurement of total hadronic differential  
8 cross sections in the LArIAT experiment**

<sup>9</sup>                   A Dissertation  
<sup>10</sup> Presented to the Faculty of the Graduate School  
<sup>11</sup>                   of  
<sup>12</sup>                   Yale University  
<sup>13</sup>                   in Candidacy for the Degree of  
<sup>14</sup>                   Doctor of Philosophy

<sup>15</sup>                   by  
<sup>16</sup>                   Elena Gramellini

<sup>17</sup>                   Dissertation Director: Bonnie T. Fleming

<sup>18</sup>                   Date you'll receive your degree

<sup>19</sup>

Copyright © 2017 by Elena Gramellini

<sup>20</sup>

All rights reserved.

# <sup>21</sup> Contents

<sup>22</sup>	<b>Acknowledgements</b>	vii
<sup>23</sup>	<b>0 Introduction</b>	1
<sup>24</sup>	<b>1 The theoretical framework</b>	2
<sup>25</sup>	1.1 The Standard Model . . . . .	2
<sup>26</sup>	1.2 Neutrinos: tiny cracks in the Standard Model . . . . .	4
<sup>27</sup>	1.2.1 Neutrinos in the Standard Model . . . . .	4
<sup>28</sup>	1.2.2 Neutrino Oscillations . . . . .	6
<sup>29</sup>	1.2.3 Make up of Neutrino Interactions . . . . .	7
<sup>30</sup>	1.3 Beyond the Standard Model . . . . .	11
<sup>31</sup>	1.3.1 Open Questions in Neutrino Physics . . . . .	11
<sup>32</sup>	1.3.2 Towards a more fundamental theory: GUTs . . . . .	15
<sup>33</sup>	1.4 Motivations for Hadronic Cross Sections in Argon . . . . .	18
<sup>34</sup>	1.4.1 Pion-Argon Total Hadronic Cross Section . . . . .	19
<sup>35</sup>	1.4.2 Kaon-Argon Total Hadronic Cross Section . . . . .	29
<sup>36</sup>	<b>2 Liquid Argon Detectors at the Intensity Frontier</b>	34
<sup>37</sup>	2.1 The Liquid Argon Time Projection Chamber Technology . . . . .	34
<sup>38</sup>	2.1.1 TPCs, Neutrinos & Argon . . . . .	34
<sup>39</sup>	2.1.2 LArTPC: Principles of Operation . . . . .	37

40	2.1.3	Liquid Argon: Ionization Charge . . . . .	39
41	2.1.4	Liquid Argon: Scintillation Light . . . . .	45
42	2.1.5	Signal Processing and Event Reconstruction . . . . .	49
43	2.2	The Intensity Frontier Program . . . . .	53
44	2.2.1	Prospects for LArTPCs in Neutrino Physics: SBN and DUNE	53
45	2.2.2	Prospects for LArTPCs in GUT Physics: DUNE . . . . .	55
46	2.2.3	Enabling the next generation of discoveries: LArIAT . . . . .	56
47	<b>3</b>	<b>LArIAT: Liquid Argon In A Testbeam</b>	<b>59</b>
48	3.1	The Particles Path to LArIAT . . . . .	59
49	3.2	LArIAT Tertiary Beam Instrumentation . . . . .	62
50	3.2.1	Bending Magnets . . . . .	62
51	3.2.2	Multi-Wire Proportional Chambers . . . . .	64
52	3.2.3	Time-of-Flight System . . . . .	66
53	3.2.4	Punch-Through and Muon Range Stack Instruments . . . . .	67
54	3.2.5	LArIAT Cosmic Ray Paddle Detectors . . . . .	69
55	3.3	In the Cryostat . . . . .	70
56	3.3.1	Cryogenics and Argon Purity . . . . .	70
57	3.3.2	LArTPC: Charge Collection . . . . .	73
58	3.3.3	LArTPC: Light Collection System . . . . .	76
59	3.4	Trigger and DAQ . . . . .	79
60	3.5	Control Systems . . . . .	80
61	<b>4</b>	<b>Hadron Interactions in Argon: Cross Section</b>	<b>86</b>
62	4.1	How to Measure a Hadron Cross Section in LArIAT . . . . .	86
63	4.1.1	Event Selection . . . . .	87
64	4.1.2	Wire Chamber to TPC Match . . . . .	89
65	4.1.3	The Thin Slice Method . . . . .	90

66	4.1.4	Procedure testing with truth quantities . . . . .	93
67	<b>5</b>	<b>Samples Preparation</b>	<b>96</b>
68	5.1	LArIAT Data . . . . .	96
69	5.2	LArIAT Monte Carlo . . . . .	96
70	5.2.1	G4Beamline . . . . .	97
71	5.2.2	Data Driven MC . . . . .	97
72	5.3	Energy Calibration . . . . .	99
73	5.4	Tracking Studies . . . . .	103
74	5.4.1	Selection Study for the Wire Chamber to TPC Match . . . . .	103
75	5.4.2	Interaction Point Optimization . . . . .	106
76	5.4.3	Tracking spatial and angular resolution . . . . .	107
77	<b>6</b>	<b>Background subtraction</b>	<b>108</b>
78	6.1	Assessing Beamline Contamination . . . . .	108
79	6.1.1	Electron and Muon contamination . . . . .	109
80	6.1.2	Contamination from secondaries . . . . .	111
81	6.2	Beamline Background Subtraction . . . . .	111
82	6.3	Capture and decay . . . . .	114
83	<b>7</b>	<b>Negative Pion Cross Section Measurement</b>	<b>117</b>
84	7.1	Estimate of $E_{loss}$ before the TPC . . . . .	117
85	7.2	Interacting and Incident Distributions . . . . .	120
86	7.3	Total Hadronic Negative Pion-Argon Differential Cross Section . . . . .	120
87	<b>8</b>	<b>Uncertainty budget</b>	<b>121</b>
88	8.1	Pure beam of pions . . . . .	121
89	8.1.1	Uncertainty on $E_{Beam}^{kin}$ . . . . .	122
90	8.1.2	Systematics on $E_{loss}$ . . . . .	122

91	8.1.3 Uncertainty on $dE/dx$ and pitch . . . . .	123
92	8.1.4 Uncertainty on track end, aka efficiency correction . . . . .	123
93	<b>A Measurement of LArIAT Electric Field</b>	<b>124</b>

# <sup>94</sup> Acknowledgements

<sup>95</sup> A lot of people are awesome, especially you, since you probably agreed to read this

<sup>96</sup> when it was a draft.

<sub>97</sub> Chapter 0

<sub>98</sub> Introduction

<sub>99</sub> **Chapter 1**

<sub>100</sub> **The theoretical framework**

<sub>101</sub> **1.1 The Standard Model**

<sub>102</sub> The Standard Model (SM) of particle physics is the most accurate theoretical descrip-  
<sub>103</sub> tion of the subatomic world and, in general, one of the most precisely tested theories  
<sub>104</sub> in the history of physics. The SM describes the strong, electromagnetic and weak  
<sub>105</sub> interactions among elementary particles in the framework of quantum field theory,  
<sub>106</sub> accounting for the unification of electromagnetic and weak interactions for energies  
<sub>107</sub> above the vacuum expectation value (VEV) of the Higgs field. The SM does not  
<sub>108</sub> describe gravity or general relativity.

<sub>109</sub> The Standard Model is a gauge theory based on the local group of symmetry

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

<sub>110</sub> where the subscripts indicate the conserved charges: the strong charge, or color C,  
<sub>111</sub> the weak isospin T (or rather its third component T3) and the hypercharge Y. These  
<sub>112</sub> quantities can be related to the electric charge Q through the Gell-Mann-Nishijima  
<sub>113</sub> relation:

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

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

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

114        In the quantum field framework, the elementary particles correspond to the ir-  
 115        reducible representations of the  $G_{SM}$  symmetry group. In particular, the particles  
 116        are divided in two categories, fermions and bosons, according to their spin-statistics.  
 117        Described by the Fermi-Dirac statistics, fermions have half-integer spin and are some-  
 118        times called “matter-particles”. Bosons or “force carriers” have integer spin, follow  
 119        the Bose-Einstein statistics and mediate the interaction between fermions. The fun-  
 120        damental fermions and their quantum numbers are listed in Tab 1.1.

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

130 the group: eight gluons (g) for the strong interaction, one photon ( $\gamma$ ) and three bosons  
 131 ( $W^\pm$ ,  $Z^0$ ) for the electroweak interaction. A gauge theory by itself cannot provide  
 132 a description of massive particles, but it is experimentally well known that most of  
 133 the elementary particles have non-zero masses. The introduction of massive fields in  
 134 the Standard Model lagrangian would make the theory non-renormalizable, and - so  
 135 far - mathematically impossible to handle. This problem is solved in the SM by the  
 136 introduction of a scalar iso-doublet  $\Phi(x)$ , the Higgs field, which gives mass to  $W^\pm$  and  
 137  $Z^0$  gauge bosons through the electroweak symmetry breaking mechanism and to the  
 138 fermions through Yukawa coupling [69, 70]. The discovery of the Higgs boson in 2012  
 139 by the LHC experiments [36, 37] marked the ultimate confirmation of a long history  
 140 of successful predictions by the SM.

## 141 **1.2 Neutrinos: tiny cracks in the Standard Model**

### 142 **1.2.1 Neutrinos in the Standard Model**

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

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

145 for a fermionic field

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

146 is equivalent to the equations

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

147

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

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

150 fermion can be described by a single Weyl spinor with two independent components [107]. Pauli initially rejected the description of a physical particle through  
 151 a single Weyl spinor because of its implication of parity violation. In fact, since the  
 152 spatial inversion operator throws  $\psi_R \leftrightarrow \psi_L$ , parity is conserved only if the both the  
 153 chiral components exist at the same time. For the neutrino introduction in the SM,  
 154 experiments came in help of the theoretical description. The constraint of parity  
 155 conservation weakened after Wu's experiment in 1957 [110]. Additionally, there was  
 156 no experimental indication for massive neutrinos, nor evidence of interaction via the  
 157 neutrino right-handed component.  
 158

159 The symmetry group  $SU(2)_T \otimes U(1)_Y$  is the only group relevant for neutrino  
 160 interactions. The SM electroweak lagrangian is the most general renormalizable la-  
 161 grangian invariant under the local symmetry group  $SU(2)_T \otimes U(1)_Y$ . The lagrangian  
 162 couples the weak isotopic spin doublets and singlets described in Table 1.1 with the  
 163 gauge bosons  $A_a^\mu$  ( $a = 1,2,3$ ) and  $B^\mu$ , and Higgs doublet  $\Phi(x)$ :  
 164

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

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

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

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

### 174 1.2.2 Neutrino Oscillations

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

180 Overwhelming experimental data show that neutrinos change flavor during their  
181 propagation [94]. This phenomenon, called “neutrino oscillations”, was predicted  
182 first by Bruno Pontecorvo in 1957 [95]. Neutrino oscillations are possible only if the  
183 neutrino flavor eigenstate are not identical to the mass eigenstates, thus resulting in  
184 the first evidence of physics beyond the Standard Model. A minimal extension of the  
185 SM introduces three mass eigenstates,  $|\nu_i\rangle$  ( $i = 1, 2, 3$ ), whose mass  $m_i$  is well defined.  
186 The unitary Pontecorvo-Maki-Nakagawa-Sakata matrix transforms the spinor wave  
187 functions ( $\psi$ ) of each component between the flavor and mass bases as follows

---

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

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

188 with

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

189 where  $c$  e  $s$  stand respectively for cosine and sine of the corresponding mixing  
190 angles ( $\theta_{12}$ ,  $\theta_{23}$  and  $\theta_{13}$ ),  $\delta$  is the Dirac CP violation phase,  $\alpha_1$  and  $\alpha_2$  are the eventual  
191 Majorana CP violation phases. Experimental results on neutrino oscillations are  
192 generally reported in terms of the mixing angles and of the squared mass splitting  
193  $\Delta m_{ab}^2 = m_a^2 - m_b^2$ , where  $a$  and  $b$  represent the mass eigenstates. A summary of the  
194 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
$\theta_{23}$	$45^\circ$	9.0%	Super Kamiokande, MINOS,
$\Delta m_{23}^2$	$2.5 \cdot 10^{-3} \text{ eV}^2$	1.8%	No $\nu$ a, MACRO
$\theta_{12}$	$34^\circ$	5.8%	SNO, Gallex,
$\Delta m_{12}^2$	$7.4 \cdot 10^{-5} \text{ eV}^2$	2.8%	SAGE, KamLAND
$\theta_{13}$	$9^\circ$	4.7%	DAYA Bay,
$\Delta m_{13}^2$	$2.5 \cdot 10^{-3} \text{ eV}^2$	1.8%	RENO

### 195 1.2.3 Make up of Neutrino Interactions

196 All neutrino experiments involving the detection of single neutrinos are concerned  
197 with neutrino interactions (and neutrino cross sections) on nuclei. Given the invis-  
198 ible nature of the neutrino, characterizing the products of its interaction is the only

199 method to a) assess the neutrino presence, b) detect its flavor in case of a charge  
200 current interaction and c) eventually reconstruct its energy.

201 Historically, neutrino interactions with the nucleus in the GeV region are divided  
202 into three categories as a function of increasing neutrino energy: quasi elastic (QE),  
203 resonant (RES), and deep inelastic (DIS) scattering. All current and forthcoming  
204 oscillation experiments live in the 0.1-10 GeV transition region, which encompasses  
205 the energy where the QE neutrino-nucleus interaction transitions into RES and the  
206 energy where RES transitions into DIS. Schematically, neutrino and antineutrino QE  
207 charge current scattering refers to the process  $\nu_l n \rightarrow l^- p$  and  $\bar{\nu}_l p \rightarrow l^+ n$  where a  
208 charged lepton and single nucleon are ejected in the elastic interaction, leaving the  
209 target nucleus in its ground state. Resonant scattering refers to an inelastic colli-  
210 sion producing a nucleon excited state ( $\Delta, N^*$ ) – the resonance, indeed – which then  
211 quickly decays, most often to a nucleon and single-pion final state. DIS refers to the  
212 head-on collision between the neutrino and a parton inside the nucleon, producing  
213 hadronization and subsequent abundant production of mesons and nucleons. In addi-  
214 tion to such interactions between the neutrino and a single component of the nucleus,  
215 neutrinos can also interact with the nucleus as a whole, albeit more rarely, a well  
216 documented process called coherent meson production scattering [53]; the signature  
217 of such process is the production of a distinctly forward-scattered single meson final  
218 state, most often a pion. This simple picture of neutrino interactions works rather  
219 well for scattering off of light nuclear targets, such as the H<sub>2</sub> and D<sub>2</sub> of bubble cham-  
220 ber experiments [59], but the complexity of the nuclear structure for heavier nuclei  
221 such as argon complicates this model.

222 As we will discuss in Chapter 2, the properties of argon make it a good candidate  
223 for interacting medium in neutrino experiments; in particular the density of its in-  
224 teraction centers augments the yield of neutrino interactions and allows for relatively  
225 compact detectors. Though, the choice of a relatively heavy nuclear target comes at

226 the cost of enhancing nuclear effects which modify the kinematic and final state of  
227 the neutrino interaction products.

228 Nuclear effects can potentially affect the neutrino event rates, nucleon emission,  
229 neutrino energy reconstruction, and the neutrino/antineutrino ratios, carrying deep  
230 implications for oscillation experiments. Even in the case of “simple” QE scattering,  
231 intra-nuclear hadron rescattering and correlation effects between the target nucleons  
232 can cause the ejection of additional nucleons in the final state, modifying the final  
233 state kinematics and topology. In case of resonant and DIS scattering, the hadronic  
234 interactions of meson and nucleons produced in the decay of the resonance or dur-  
235 ing hadronization complicate this picture even more. A large source of uncertainty  
236 in modeling nuclear effects in neutrino interactions come from mesons interactions  
237 (and re-interactions) in the nucleus, e.g., pion re-scattering, charge exchange, and  
238 absorption.

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

247 Data on neutrino scattering off many different nuclei are available for both charged  
248 current (CC) and neutral current (NC) channels, as summarized in [59]. A summary  
249 of the results on QE, resonant and DIS scattering for neutrinos and antineutrinos from  
250 accelerators on different target is reported in Figure 1.1, where the (NUANCE) [33]  
251 event generator is used as comparison with the theory.

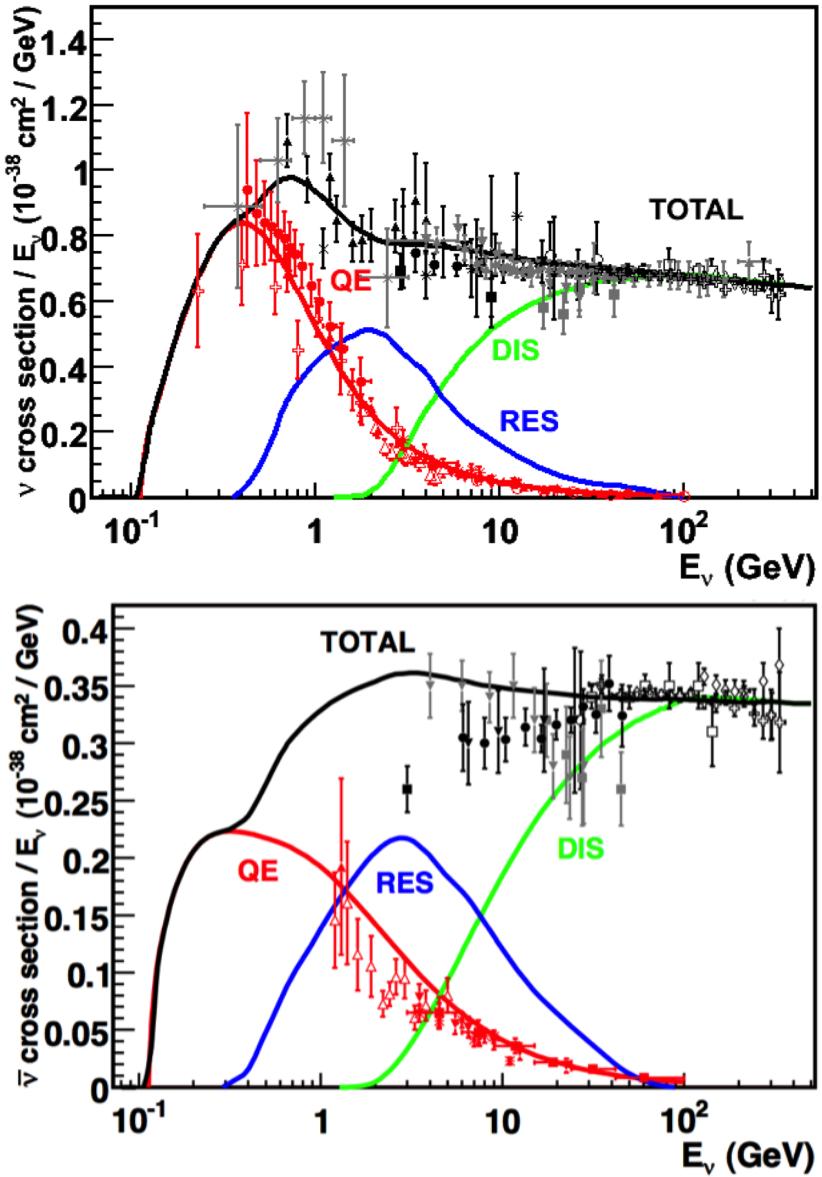


Figure 1.1: Total neutrino (top) and antineutrino (bottom) CC cross sections per nucleon divided by neutrino energy as a function of energy as reported in [59]. Predictions for the total (black), the QE (red), resonant (blue) and DIS (green) are provided by the NUANCE generator. The quasi-elastic scattering data and predictions have been averaged over neutron and proton targets (isoscalar target).

252 **1.3 Beyond the Standard Model**

253 The discovery of neutrino oscillation and its implication of non-zero neutrino mass  
254 mark the beginning of a new, exciting era in neutrino physics: the era of physics Be-  
255 yond the Standard Model (BSM) at the intensity frontier. We are currently searching  
256 for new, deeper theories that can accommodate neutrinos with tiny but non-zero  
257 masses, while remaining consistent with the rest of the Standard Model.

258 **1.3.1 Open Questions in Neutrino Physics**

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

263 **Sterile neutrinos.** Hints to the existence of at least one additional neutrino,  
264 in the form of various anomalies, have been puzzling physicists almost from the be-  
265 ginning of neutrino oscillation searches. Originally designed to look for evidence of  
266 neutrino oscillation, the Liquid Scintillator Neutrino Detector (LSND) [49] provided  
267 a first conflicting result with the Standard Model expectation of only three neutrinos.  
268 A second conflicting result has also been provided by the MiniBooNE experiment [45].

269 The LSND and MiniBooNE  $\nu_e$  and  $\bar{\nu}_e$  appearance results, known as the “LSND and  
270 MiniBooNE anomalies” [13, 14, 21], may be interpreted under the assumption of a new  
271 right-handed neutrino. The additional neutrino needs to be “sterile”, i.e needs not  
272 to couple with the electroweak force carriers, in order to meet the constraint imposed  
273 by the measurement of the width of the Z boson [1]. The new sterile neutrino would  
274 mainly be composed of a heavy neutrino  $\nu_4$  with mass  $m_4$  such that  $m_1, m_2, m_3 \ll m_4$   
275 and  $\Delta m^2 = \Delta m_{14}^2 \sim [0.1 - 10]$  eV<sup>2</sup>. The introduction of sterile neutrinos is an ap-  
276 pealing line of thinking, since this renormalizable generalization of the SM has the

277 potential to impact long standing questions in high energy physics and cosmology:  
 278 light sterile neutrinos are candidates for dark matter particles and there are ideas  
 279 that the theory could be adjusted to explain the baryon asymmetry of the Universe  
 280 via leptogenesis [65].

281 **CP Violation In Lepton Sector.** The measurement of non-zero value for the  
 282 oscillation parameter  $\theta_{13}$  allows the exploration of low-energy CP violation in the lep-  
 283 ton sector at neutrino long baseline oscillation experiments, enabling the possibility  
 284 to measure the Dirac CP-violating phase  $\delta$ . Exciting theoretical results tie  $\delta$  directly  
 285 to the generation of the baryon asymmetry of the Universe at the Grand Unified  
 286 Theory scale **a couple of cit would be nice**. According to the theoretical model de-  
 287 scribed in [93], for example, leptogenesis can be achieved if  $|\sin \theta_{13} \sin \delta| > 0.11$ , i.e.  
 288  $\sin \delta > 0.7$ .

289 The asymmetry in the oscillation probability of neutrinos and antineutrinos is the ob-  
 290 servable sensitive to the Dirac CP-violating phase  $\delta$  leveraged in neutrino oscillation  
 291 experiments. Using the parameterization of the PMNS matrix shown in Equation  
 292 1.9, the difference between the probability of  $\nu_e \rightarrow \nu_\mu$  oscillation and the probability  
 293 of  $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$  oscillation can be parametrized as follows [34],

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

294 where

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

295 is the Jarlskog invariant [74],  $L$  the neutrino baseline, i.e. the distance between  
 296 the neutrino production and detection points, and  $\Delta_{ab}$  a factor proportional to the  
 297 sign and magnitude of the mass splitting. From these equations, it is clear how the  
 298 relative large value of  $\theta_{13}$  is a happy accident necessary not to completely suppress the  
 299 sensitivity to CP violation. The equations also show how the sensitivity to  $\delta$  is tied

300 to the measurement of the least precisely measured mixing angle,  $\theta_{23}$  (via the  $\sin 2\theta_{23}$   
301 term) and to an other unknown quantity, the neutrino “mass hierarchy” (via the  $\Delta_{ab}$   
302 terms). The precise determination of  $\theta_{23}$  is often referred as to “the octant problem”.  
303 Current experimental results [2, 11] are consistent with  $\theta_{23} = 45^\circ$ , which would imply  
304 maximal mixing between  $\nu_\mu - \nu_\tau$ , hinting to an intriguing new symmetry. Therefore,  
305 a precise measurement of  $\theta_{23}$  is of great interest for theoretical models of quark-lepton  
306 universality [68, 85, 97], whose quark and lepton mixing matrices are proportional to  
307 the deviation of  $\theta_{23}$  from  $45^\circ$ .

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

317 **Majorana or Dirac?** Evidence of neutrino oscillations demands the introduction  
318 of a mechanism which can give mass to the neutrinos. This mechanism should possibly  
319 also explain why neutrino masses are at least six orders of magnitude lower than the  
320 electron mass (the second lightest SM fermion). In a description of neutrinos as Dirac  
321 4-component spinors, the neutrino field acquires mass via the Higgs mechanism as  
322 any other fermion of the SM. In this case, the neutrino mass is given by  $m_a = \frac{y_a^\nu v}{\sqrt{2}}$ ,  
323 where  $v$  is the Higgs VEV and  $y_a^\nu$  is the Yukawa coupling between the Higgs and the  
324 neutrino. The smallness of neutrino masses can only be pinned on a tiny Yukawa  
325 coupling which is not justified by the theory.

326 In 1937, Majorana demonstrated that the introduction of a two components spinor is

327 sufficient to describe a massive fermion [84]. The Dirac equations of motion for the  
 328 chiral fields (equations 1.5 and 1.6) hold true in the case of two components spinor  
 329 under the assumption that the chiral components  $\psi_R$  and  $\psi_L$  are correlated through  
 330 the charge conjugation matrix  $\mathcal{C}$ ,  $\psi_R = \mathcal{C}\bar{\psi}_L$ . Therefore the theory is applicable only  
 331 to neutral fermions. Neutrinos are the only neutral elementary particles in the SM  
 332 – the only possible Majorana particle candidate. This theory constructs a neutrino  
 333 Majorana mass term  $\mathcal{L}_5$  of the following form in the Higgs unitary gauge

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

334 where  $g$  is the coupling coefficient,  $v$  the Higgs VEV and  $\mathcal{M}$  a constant with the  
 335 dimension of the mass proportional to the scale of new physics. The  $\mathcal{L}_5$  term would  
 336 introduce a non-renormalizable term in the lagrangian, since it has dimensions of  
 337 energy to the fifth power. This is not allowed in the SM lagrangian; however, the  
 338 existence of such terms is plausible if we consider the SM as an effective theory  
 339 at low energy, manifestation of the symmetry breaking of a more general theory at  
 340 higher energy, e.g. a Grand Unified Theory (GUT), and not the definitive theory.  
 341 The mass term in eq 1.12 implies the neutrino mass to be  $m = \frac{gv^2}{\mathcal{M}}$ . The coupling  
 342 coefficient can be of the order of any other fermion's coupling coefficient, since the  
 343 smallness of neutrino masses is achieved by the big value of the new physics mass  
 344 scale alone. This vanilla formulation is the conceptual basis for many flavors of *see-*  
 345 *saw mechanism* [112], which we will not discuss here in any detail. However, it is  
 346 fascinating how the puzzle of the neutrino mass hints to the existence of a deeper and  
 347 more complete theory.

348 From a kinematic point of view, Dirac and Majorana neutrinos satisfy the same  
 349 energy-momentum dispersion relationship. Thus, it is impossible to discern the neu-  
 350 trino nature through kinematic effects such as neutrino oscillations. Neutrinoless

351 double beta decay searches are the most promising way to understand the nature of  
352 the neutrino and are therefore subject of great theoretical and experimental interest.  
353 Observation of the lepton number violating process  $0\nu\beta\beta$  would imply neutrinos have  
354 a Majorana component. Depending on the mass hierarchy, the theory also predicts  
355  $0\nu\beta\beta$  exclusion regions and confirmation of the sole Dirac component for neutrinos  
356 [39].

357

### 358 1.3.2 Towards a more fundamental theory: GUTs

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

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

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

376 As the smallness of neutrino masses suggests the existence of a higher mass scale,

377 an other, even stronger, hint to Grand Unification comes from the slope of running  
 378 of the coupling constants. The coupling constants for the electromagnetic, weak and  
 379 strong interactions in the SM vary as a function of the interaction energy as shown  
 380 in figure 1.2; they do not exactly meet under the current experimental constraints,  
 381 but their trend is interesting enough to push for the construction of theories where  
 382 perfect unification is achieved through the addition of new particles.

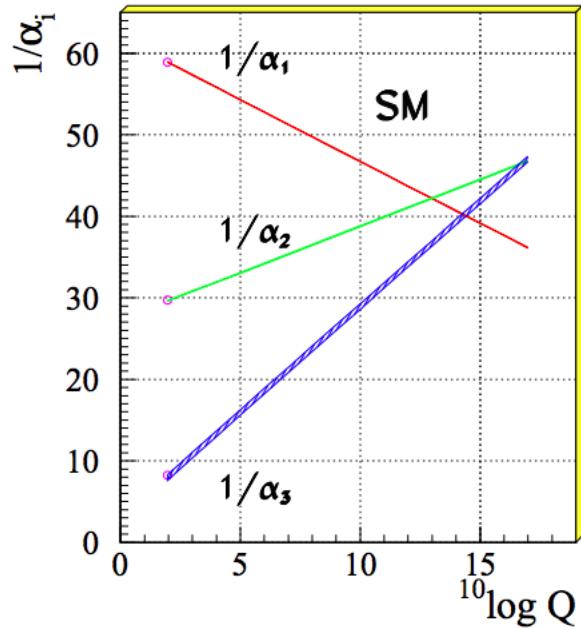


Figure 1.2: Evolution of the inverse of the three coupling constants in the Standard Model as a function of the momentum transferred, [78].

**SU(5).** The smallest simple group containing  $SU(3)_C \otimes SU(2)_T \otimes U(1)_Y$  is SU(5), as shown first by Georgi and Glashow in [62]. Quarks and leptons in this group fit the  $\bar{5}$  and 10 representations. The representation for left-handed fermions are the following

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

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

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

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

384 Nice features such as charge quantization and the identity between the positron  
385 and proton charge value come directly from the group structure. The new super  
386 heavy bosons are colored and form a weak doublet. Their are the mediator of the  
387 interaction that turns quarks into leptons, leading to predict the existence of processes  
388 that violate baryon number, such as  $p \rightarrow \pi^0 + e^+$  (see fig 1.8, right). The prediction  
389 for proton decay lifetime,  $\tau_p \sim \frac{M_X^4}{m_p^5} \sim 10^{30 \pm 1.5}$  years, is unfortunately experimentally  
390 disproved by IMB and Super-Kamiokande [3, 26].

391 **SO(10).** More complicated group structures, such as SO(10) are still viable  
392 candidates for GUT. SO(10) includes the same type of  $X$  and  $Y$  bosons as SU(5).  
393 Right-handed massive neutrinos are embedded in the construction of the irreducible  
394 representation of SO(10). Different patterns of SO(10) symmetry breaking to recover  
395 the SM are possible and lead to different predictions for the proton decay lifetime;  
396 some of these predictions are not excluded by the experiments [79].

397 **SUSY GUTs.** Supersymmetry theories allow for another family of GUTs. In  
398 SUSY, every fundamental particle in the SM has a “superpartner”, identical in each  
399 quantum number except for the spin-statistics: the fermion supersymmetric partners  
400 are bosons and vice versa. Collider experiments (mainly LHC) constrain the mass of  
401 the supersymmetric partners to be very heavy [?]. The SU(5), SU(10) groups with  
402 a SUSY twist are the basic groups for SUSY GUTs. From the phenomenology point  
403 of view, SUSY models tend to push the proton decay life time higher by a factor of  
404 four, they solve the “hierarchy problem”, and they also predict new channels for the  
405 proton decay. In particular they predict the presence of kaons in the final product,  
406 with a dominant mode of  $p \rightarrow K^+ \bar{\nu}$ . Predictions on the proton decay lifetime depend

407 on the chosen SUSY model; again, some of the predictions are not excluded by the  
408 experiments [82, 83, 101].

## 409 **1.4 Motivations for Hadronic Cross Sections in Ar-** 410 **gon**

411 Critical challenges await the next decade of high energy physics at the intensity  
412 frontier. Following the recommendation of the latest Particle Physics Project Priori-  
413 tization Panel [98], the US is dedicating substantial resources to the development of  
414 a short- and long- baseline neutrino program to address many of open questions in  
415 neutrino physics today. This program pivots on the Liquid Argon Time Projection  
416 Chamber (LArTPC) detector technology which will be described in Chapter 2.

417 The main goals of these research programs include:

- 418 - the assessment of the existence of right-handed sterile neutrinos via the study  
419 of accelerator neutrinos on a short baseline (SBN),
- 420 - the determination of the sign of  $\Delta m_{13}^2$  (or  $\Delta m_{23}^2$ ), i.e., the neutrino mass hier-  
421 archy via the study of accelerator neutrinos on a long baseline (DUNE),
- 422 - the determination of the octant, i.e. whether  $\theta_{23}$  is maximal, via the study of  
423 accelerator neutrinos on a long baseline (DUNE),
- 424 - the determination the status of CP symmetry in the lepton sector, via the study  
425 of accelerator neutrinos on a long baseline (DUNE),
- 426 - the search for observables predicted by GUTs, such as proton decay via the  
427 study of non accelerator physics in massive underground detectors (DUNE).

428 **1.4.1 Pion-Argon Total Hadronic Cross Section**

429 This section outlines the importance of the pion-argon total hadronic cross section in  
430 the context of the current and upcoming liquid argon neutrino experiments, SBN and  
431 DUNE. We describe the signal signature and historic measurements of pion-nucleus  
432 cross section, as well as the implementation of this cross sections in the current version  
433 of the simulation package used by LArIAT.

434  **$\pi^-$ -Ar Cross Section in the Context of Neutrino Searches**

435 As outlined in 1.2.3, neutrino experiments use the products of neutrino interactions  
436 to identify the energy and flavor of the incoming neutrino. Pions are a common  
437 product of neutrino interaction, especially in resonant scattering, DIS and coherent  
438 pion production. For neutrino experiments in argon, there are two main reasons  
439 why understanding pion hadronic interactions with argon is important: to model  
440 the behavior of the pion inside the nucleus struck by the neutrino and to model the  
441 behavior of the pion during its propagation inside the detector medium.

442 Assumptions on the nuclear models and on the interaction of hadrons inside the  
443 nucleus performed at the level of the neutrino event generator bridge the measure-  
444 ment of the products of a neutrino interaction to the reconstruction of the neutrino  
445 energy and flavor. Thus, understanding pion hadronic interactions with the nucleus  
446 is particularly important to model correctly resonant, DIS and coherent pion produc-  
447 tion in neutrino interactions, where the presence of pions in the nucleus is abundant.  
448 For example, in case of resonant scattering,

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

449 the  $\Delta$  and  $N^*$  and excited states will decay hadronically in matters of  $\sim 10^{-24}$  s inside  
450 the nucleus producing pions which will bounce within the nuclear medium. The decay

451 modes for the lower mass  $\Delta$  (1232) and  $N^*(1440)$  are listed in table 1.3.

452 The key elements of a neutrino event generators for resonance and DIS events are  
453 the nuclear model and the hadron treatment (both production and transportation).  
454 We illustrate here the conceptual basis of the GENIE Neutrino Generator [17] as  
455 an example, since GENIE is one the most popular event generators for liquid argon  
456 experiments. For example, the nuclear model used by GENIE for all processes is  
457 a relativistic Fermi gas (RFG) modified to incorporate short range nucleon-nucleon  
458 correlations [28]. This means that the initial momentum and binding energy of the  
459 struck nucleon is determined by assuming nucleons inside the nucleus are quasi-free,  
460 acting independently in the mean field of the nucleus. For  $A > 20$  like argon, the  
461 2-parameter Woods-Saxon shell model for density function is used. The GENIE mod-  
462 ule INTRANUKE [77] is used to simulate the final-state interactions (FSI) which is  
463 the hadron re-interaction inside the nucleus. This module places the outgoing parti-  
464 cles in the nucleus and propagates them using the “hA model”. In the INTRANUKE  
465 hA model, hadrons can undergo at most one FSI per event. When possible, exter-  
466 nal hadron-nucleus scattering data are used to tune INTRANUKE. Since no data is  
467 available for Argon, GENIE uses an interpolation of data from heavier and lighter nu-  
468 clei for the pion-argon cross section leading to big uncertainties in the INTRANUKE  
469 module.

470 Once the pion has left the target nucleus, the pion-argon hadronic cross section  
471 plays an important role in the pion transportation inside the argon medium: processes  
472 like pion absorption with emission of nucleons or pion charge exchange can greatly  
473 modify the topology of a neutrino interactions in the detector and lead to errors in the  
474 event classification. Being able to reconstruct the details of pions inside the detector  
475 is an imperative for modern liquid argon neutrino experiment to achieve the design  
476 resolution for their key physics measurements.

477  **$\pi^-$ -Ar Hadronic Interaction: Signal Signatures**

478 Strong hadronic interaction models [44, 63] predict the pion interaction processes with  
479 argon in the [100 - 1200] MeV energy range. The total hadronic  $\pi^-$ -Ar interaction  
480 cross section is defined as the one related to the single process driven only by the  
481 strong interaction which is dominant in the considered energy range. In measuring  
482 the “total” cross section, we include both the elastic and reaction channels, regardless  
483 of the final state,

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

484 the reaction channel is further characterized by several exclusive channels with defined  
485 topologies,

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

486 A summary of the pion final states in order of pion multiplicity for the reaction  
487 channel is given in table 1.4. Pion capture and pion decay at rest dominate the  
488 cross section under 100 MeV. We define pion capture as the process determining the  
489 formation of a pionic atom and the subsequent pion’s end of life. Stopping negative  
490 pions can form pionic argon, where the negative pion plays the role of an orbital  
491 electron. Since the pion mass is two orders of magnitude greater than the electron  
492 mass, the spatial wave form of the pion will overlap more with the nucleus compared  
493 to the electron case. After the electromagnetic formation of the pionic atom, the  
494 pion will be quickly absorbed by the nucleus, which is put in an excited state. The  
495 nucleus then de-excites with the emission of low energy nucleons and photons. Pion  
496 capture is predominant compared to pion decay, the other important process for very  
497 low energy pions. The decay of a pion is governed by the weak force; the pion decay  
498 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%).  
499 Since pion capture can be considered an electromagnetic process and pion decay is a  
500 weak process, this energy region is purposely excluded from the hadronic cross section

501 measurement.

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

503 Many experiments with pion beams have studied the hadronic interaction of pions on  
504 light and heavy materials, such as He, Li, C, Fe, Pb [32]. However, data on argon are  
505 rare: the total differential hadronic cross section has never been measured before on  
506 argon. Simulation packages like Geant4 base their pion transportation for argon on  
507 data from lighter and heavier nuclei: the goal of LArIAT’s dedicated measurement on  
508 argon is to bridge this gap in data, thus reducing the uncertainties related to pions  
509 interaction in argon in both neutrino event generators and in simulation packages of  
510 pion transportation.

511 The shape of the pion-nucleus interaction cross section in the energy range con-  
512 sidered shows the distinct features indicating the presence of a resonance. In fact, the  
513 mean free path of a pion of kinetic energy between 100 and 400 MeV is much shorter  
514 than the average distance between nucleons (which is of the order of 1 fm). There-  
515 fore, the pion interacts with surface nucleons. A  $\Delta$  resonance is often produced in  
516 the interaction, which subsequently decays inside the nucleus. Experimental results  
517 on several nuclei as reported in [32] are shown in Figure 1.3; it is interesting to notice  
518 here how the shape of the  $\Delta$  resonance becomes less pronounced as a function of the  
519 mass number of the target nucleus. Pion interactions with heavier nuclei also shift the  
520 peak of the resonance at lower energy; this effect is due to kinematic considerations  
521 and to the difference in propagation of the  $\Delta$  inside the nucleus. Multiple scattering  
522 effect modify the resonance width, which is larger than the natural-decay width. As  
523 an example of a fairly well studied target, Figure 1.4 reports the negative pion cross  
524 section on Carbon for the elastic and reaction<sup>2</sup> channels, and their sum [50].

---

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

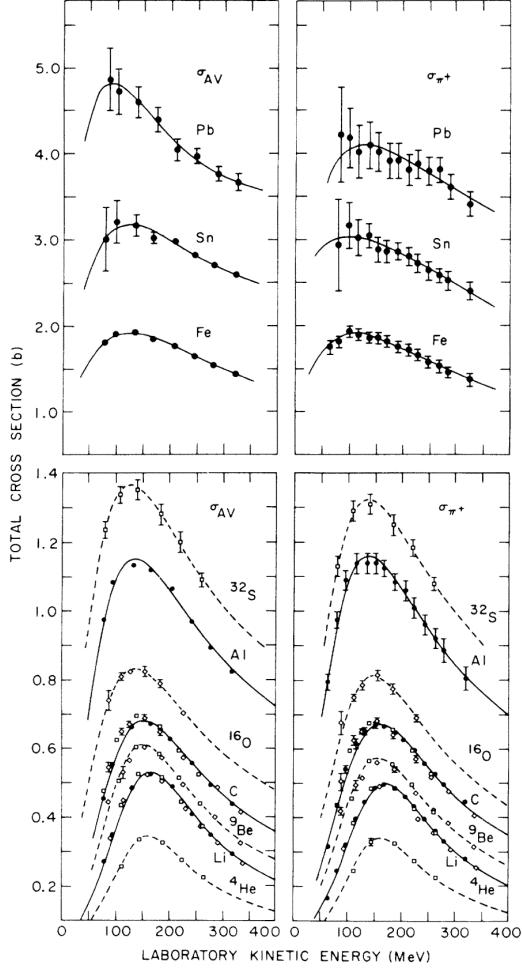


Figure 1.3: Pion-nucleus total cross sections:  $\sigma_{\pi^+}$  for positive pions (right) and  $\sigma_{AV}$  (left) for the average between positive and negative pions  $\sigma_{AV} = \frac{\sigma_{\pi^+} + \sigma_{\pi^-}}{2}$  in the  $\Delta$  resonance region. The error bars include estimates of systematic uncertainties. The curves are the results of fits to the data assuming a Breit-Wigner shape. This summary plot is reported in [32] and uses data from [47, 108].

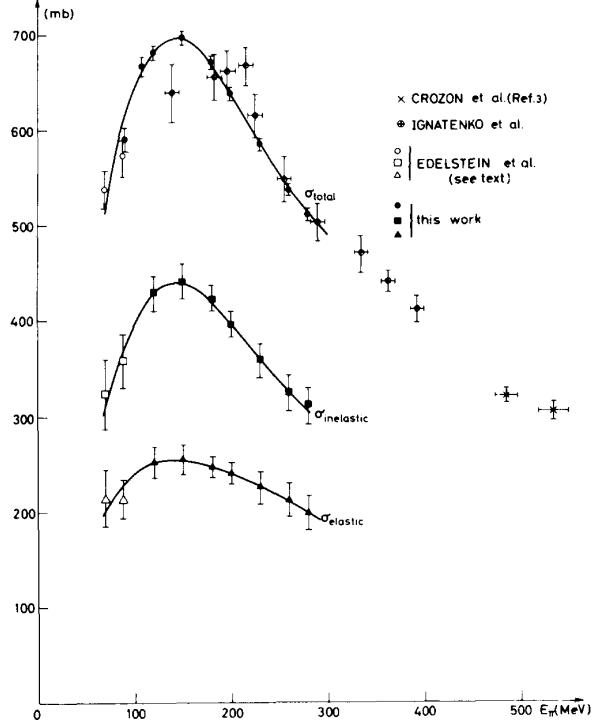


Figure 1.4: Negative pion nucleus total, elastic and reaction cross sections on  $^{12}\text{C}$  as from [50].

## 525 Negative Pion Interaction Cross Section in Simulation Packages

526 LArIAT uses Geant4 as the default simulation package. In particular, pions (and  
 527 kaons) transportation is achieved through the Geant4 FTFP\_BERT physics list. In  
 528 this physics list, Geant4 uses the Bertini cascade model [109] to simulate the products  
 529 of the pion-nucleus interaction as well as the secondary hadrons re-interactions inside  
 530 the target nucleus (intra-nuclear cascade). The target nucleus is represented as a  
 531 continuous gas where the nuclear potential follows concentrical shells whose depths  
 532 approximate the Woods-Saxon shape. The CERN-HERA compilations [105, 106] of  
 533 hadron-nucleon interaction data is the data base used for the decision making process  
 534 after the cascade is invoked. The cross section model determines if the pion inter-  
 535 acts, the eventual type of interaction and the interaction multiplicity. For hadron  
 536 projectiles with energy less than 20 GeV, Geant4 reports the uncertainty on the cross

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

539       The relevance of the GENIE generator for neutrino physics and its basic working  
540 principles have been outlined earlier in this section. Given GENIE’s modularity,  
541 information on hadron-nucleus interactions can be extracted from the INTRANUKE  
542 module and directly compared against the Geant4 predictions. The work in [90]  
543 reviews the current status of negative and positive pion simulation in Geant4 and  
544 GENIE for  $^{12}\text{C}$ ,  $^{56}\text{Fe}$ , and  $^{40}\text{Ca}$ . From that work, we report the results for  $^{12}\text{C}$   
545 in Figure 1.5 as it allows a direct comparison between Geant4, GENIE and data.  
546 Geant4 predictions for  $\pi^-$  on Carbon are in good agreement with data over all the  
547 spectrum, while GENIE predictions seem to show some features at around 500 MeV  
548 and 900 MeV, maybe due to higher resonances in the hA model. From the same  
549 work, we also report the negative pion cross section on  $^{40}\text{Ca}$  in Figure 1.6, since this  
550 is the nuclear medium closest argon with some available data. The predictions from  
551 both Geant4 and GENIE agree with data in the high energy region; the Geant4 and  
552 GENIE predictions diverge in the resonance region, where data is not available. These  
553 few examples highlight how cross section data for the specific nucleus considered in  
554 the neutrino experiments is fundamental to inform the Monte Carlo simulation.

555       For the LArIAT simulation of the MC sample used in the  $\pi^-$  argon total hadronic  
556 cross section measurement we use the Geant4 Bertini Cascade model, whose predic-  
557 tions for the total, elastic and reaction hadronic cross sections are show in Figure  
558 1.7.

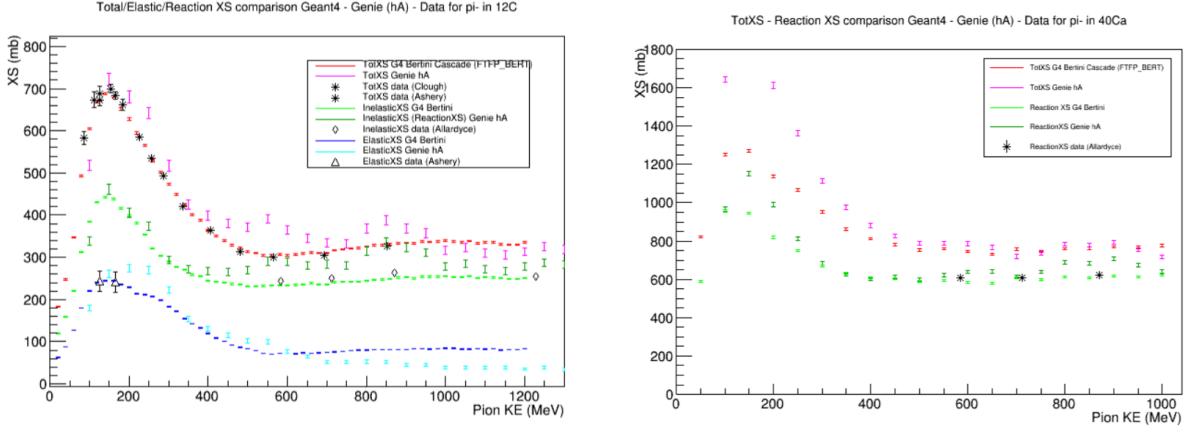


Figure 1.5: Total, elastic and reaction cross section for  $\pi^-$  on  $^{12}\text{C}$ . Comparison between results from Geant4 simulation (Bertini cascade model), Genie simulation (hA model), and experimental data [20, 47, 48, 100].

Figure 1.6: Total, elastic and reaction cross section for  $\pi^-$  on  $^{40}\text{Ca}$ . Comparison between results from Geant4 simulation (Bertini cascade model), Genie simulation (hA model), and experimental data [48].

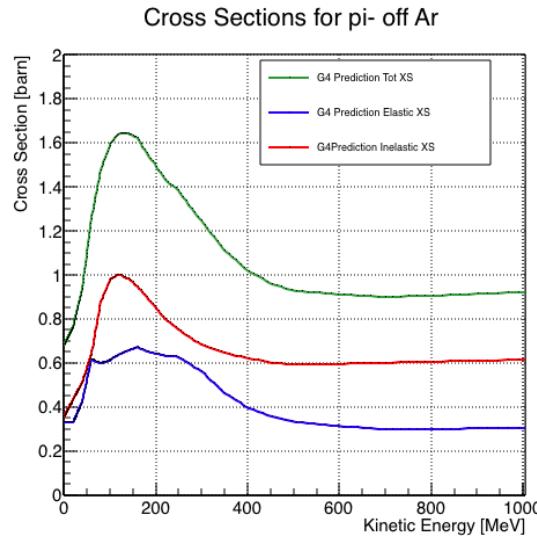


Figure 1.7: Total, elastic and reaction hadronic cross section for  $\pi^-$ -argon implemented in Geant4 10.01.p3.

Resonance	Decay Mode	Lifetime (s)
$\Delta$ (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 $\pi$ in FS	Channel Name	Reaction	Notes
0	Pion Absorption, $\sigma_{abs}$	$\pi^-(np) \rightarrow nn$ (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, $\sigma_{el}$	$\pi^- + N \rightarrow \pi^- + N$	Scattering on nucleon or nucleus, the target is left in ground state
1	Charge Exchange, $\sigma_{chea}$	$\pi^- + p \rightarrow \Delta^0 \rightarrow \pi^0 + n$ $\pi^- + N \rightarrow \pi^+ + \text{nucleons}$	Single charge exchange: charged pion converts into neutral pion Double charge exchange: charged pion converts into opposite charge pion
1	Inelastic Scattering, $\sigma_{inel}$	$\pi^- + p \rightarrow \Delta^0 \rightarrow \pi^- + p$ (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 $\geq 500$ 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.

559 **1.4.2 Kaon-Argon Total Hadronic Cross Section**

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

565 **K<sup>+</sup>Ar Cross section in the Context of Nucleon Decay Searches**

566 Baryon number is accidentally conserved in the Standard Model. Even though no  
567 baryon number violation has been experimentally observed thus far, no underlying  
568 symmetry in line with the Noether paradigm [89] explains its conservation. As shown  
569 in section 1.3.2, almost all Grand Unified Theories predict at some level baryon num-  
570 ber violation in the form of nucleon decay on long time-scales. Given the impossibil-  
571 ity to reach grand unification energy scales with collider experiments (Energy Scale  
572 > 10<sup>15</sup> GeV), an indirect proof of GUTs is needed. The experimental observation of  
573 nucleon decay may be the only viable way to explore these theories.

574 In case of nucleon decay discovery, the dominant decay mode may uncover addi-  
575 tional information about the GUT type. Supersymmetric GUTs [22, 41] prefer the  
576 presence of kaons in the products of the decay, e.g.  $p \rightarrow K^+ \bar{\nu}$  (see fig 1.8, left).  
577 Gauge mediated GUTs, in which new gauge bosons are introduced that allow for the  
578 transformation of quarks into leptons, and vice versa, prefer the mode  $p \rightarrow e^+ \pi^0$  (see  
579 fig 1.8, right).

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

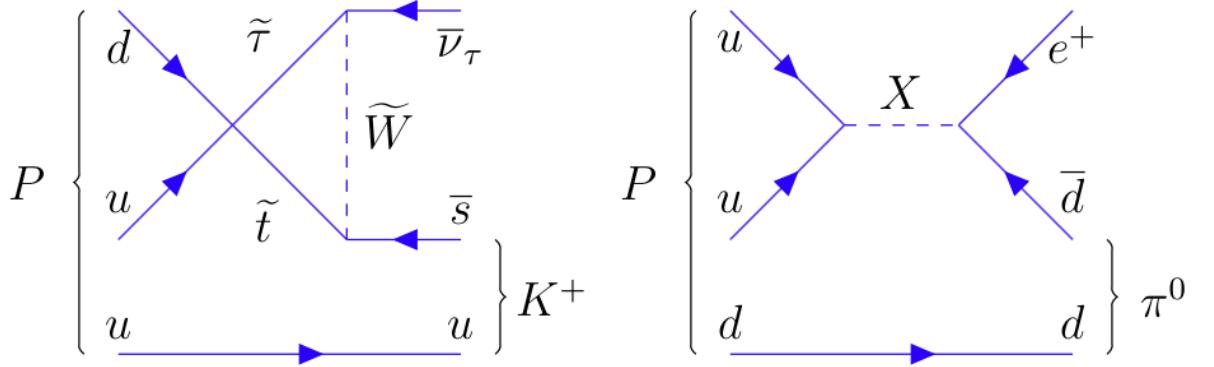


Figure 1.8: Feynman diagrams for proton decay “golden modes”:  $p \rightarrow K^+\bar{\nu}$  for supersymmetric GUTs on the left and  $p \rightarrow e^+\pi^0$  for gauge-mediated GUTs on the right.

585 modes in a LArTPC [46], but, as the time of this writing, no study of kaon selection  
 586 efficiency in LArTPCs has been performed on data. The  $K^+$ -Ar interaction cross  
 587 section has never been measured before and can affect the possibility of detecting  
 588 and measuring kaons when produced in a proton decay event. Kaon interactions with  
 589 argon can distort the kaon energy spectrum as well as change the topology of single  
 590 kaon events. In a LArTPC, non-interacting kaons appear as straight tracks with a  
 591 high ionization depositions at the end (Bragg peak). The topology of interacting  
 592 kaons can be quite different. In case of elastic scattering, a distinct kink will be  
 593 present in the track. In case of inelastic scattering the Bragg peak will not be present  
 594 and additional tracks will populate the event. Performing the total hadronic  $K^+$ -Ar  
 595 cross section measurement on data serves the double purpose of identifying the rate  
 596 of “unusual” topologies (kinks and additional tracks) and of developing tools for kaon  
 597 tracking in LAr.

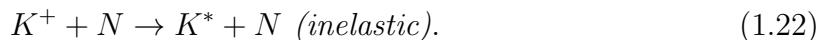
### 598 $K^+$ Ar Hadronic Interaction: Signal Signatures

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

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

599        For the LArIAT cross section analysis, the kaons considered span a momentum  
 600      inside the TPC from 100 MeV/c to 800 MeV/c. In this energy range, the relevant  
 601      K-Nucleon interactions are according to [58]:



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

603      In general, measurements on kaon cross sections are extremely scarce. The mea-  
 604      surement of the kaon interaction cross section would bring the additional benefit  
 605      of reducing the uncertainties associated with hadron interaction models adopted in  
 606      MC simulations for argon targets, beneficial for both proton decay studies and kaon  
 607      production from neutrino interaction studies, where the uncertainties for final state  
 608      interaction models are big [42].

609      Figure 1.9 shows a 1997 measurement on several elements as performed by Fried-  
 610      mann et al. [60]. As a reference, this paper measures a  $\sigma_{Tot}$  for Si of  $366.5 \pm 4.8$   
 611      mb and a  $\sigma_{Tot}$  for Ca of  $494.6 \pm 7.7$  mb at 488 MeV/c. The cross section for argon

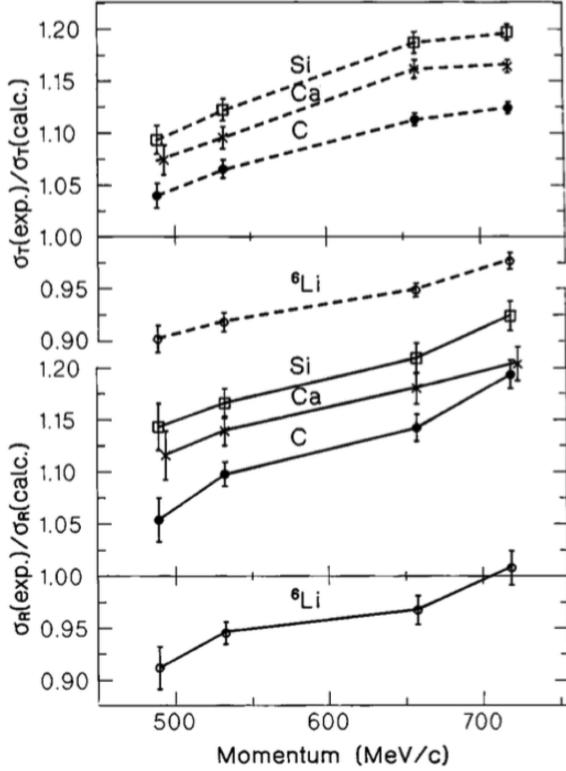


Figure 1.9: Ratios between experimental and calculated cross sections as from [60].  
Top: Total cross sections.  
Bottom: reaction cross sections.

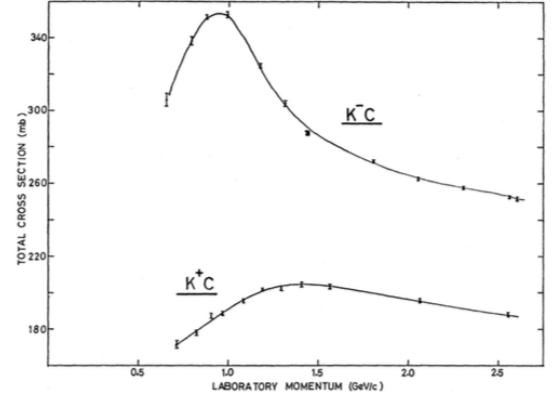


Figure 1.10: Total  $K^+$  and  $K^-$  cross sections on carbon as from [30].

is expected to lie in between these two measurements. Additional data on the kaon cross section are provided by Bugg et al. [30]. 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.

### 618    **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

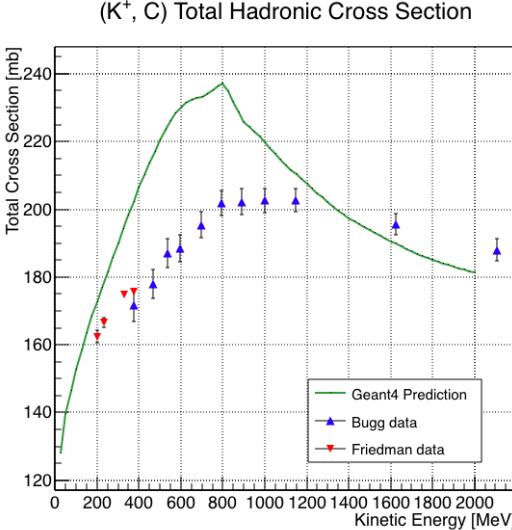


Figure 1.11: Total hadronic cross section for carbon implemented in Geant4 10.01.p3 with overlaid with the Bugg and Friedman data.

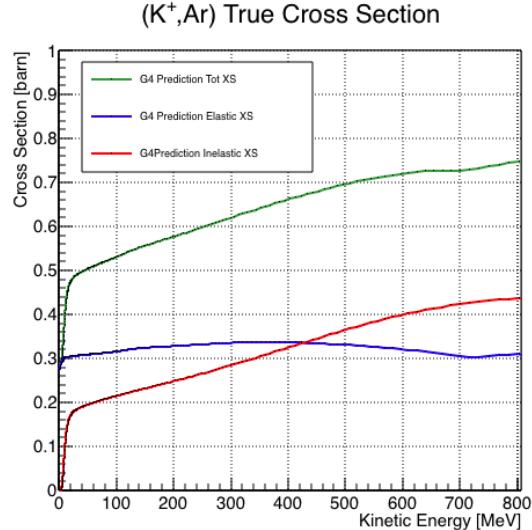


Figure 1.12: Total, elastic and reaction hadronic cross section for  $K^+$ -argon implemented in Geant4 10.01.p3.

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, the current version of Geant4 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.

# 632 Chapter 2

## 633 **Liquid Argon Detectors at the** 634 **Intensity Frontier**

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

### 639 **2.1 The Liquid Argon Time Projection Chamber** 640 **Technology**

#### 641 **2.1.1 TPCs, Neutrinos & Argon**

642 David Nygren designed the first Time Projection Chamber (TPC) in the late 1970s [91]  
643 for the PEP-4 experiment, a detector apt to study electron-positron collisions at the  
644 PEP storage ring at the SLAC National Accelerator Laboratory. From the original  
645 design in the seventies – a cylindrical chamber filled with methane gas – the TPC  
646 detector concept has seen many incarnations, the employment of several different  
647 active media and a variety of different particle physics applications, including, but

648 not limited to the study of electron/positron storage rings (e.g. PEP4, TOPAZ,  
649 ALEPH and DELPHI), heavy ions collisions in fixed target and collider experiments  
650 (e.g. EOS/HISSL and ALICE ), dark matter (ArDM), rare decays and capture (e.g.  
651 TRIUMF, MuCap), neutrino detectors and nucleon decay (ICARUS, SBN, DUNE),  
652 and neutrino less double beta decay (Next). A nice review of the history of TPCs  
653 and working principles is provided in [71].

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

660 Historically, the active medium in ionization detectors has been in the gaseous  
661 form. Carlo Rubbia first proposed the use of a Liquid Argon TPC for a neutrino  
662 experiment, ICARUS [99], in 1977. Using nobles elements in the liquid form for  
663 neutrino detectors is advantageous for several reasons. The density of liquids is  $\sim$ 1000  
664 times greater than gases, augmenting the number of targets for neutrino's interaction  
665 in the same volume, in a effort to balance the smallness of neutrino cross section. Since  
666 the energy loss of charged particle is proportional to the target material density, as  
667 shown in the Bethe-Block equation (eq. 2.1), the increased density reflects into a  
668 proportionally higher energy loss, enhancing the calorimetry capability of detectors  
669 with a liquid active medium. Additionally, the ionization energy of liquids is smaller  
670 than gasses by the order of tens of eV. Thus, at the passage of charged particles, liquid  
671 generally produce more ionization electrons than gas for the same deposited energy  
672 and force the particles to deposit more energy in a shorter range. The downside of  
673 using noble liquid elements in experiments is that they require expensive cryogenic  
674 systems to cool the gas until it transitions to its the liquid form. The properties

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 <sup>3</sup>	3.0 g/cm <sup>3</sup>
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 <sup>2</sup> /Vs	0.22 m <sup>2</sup> /Vs
Average dE/dx MIP	2.1 MeV/cm	3.8 MeV/cm
Average Scintillation Light Yield	40000 $\gamma$ /MeV	42000 $\gamma$ /MeV
Scintillation $\lambda$	128 nm	175 nm

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

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 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 however, LArTPC bestow tridimensional tracking and a self triggering mechanism provided by the scintillation light in the noble gas. An event display of a  $\nu_\mu$  CC interaction candidate in the MicroBooNE detector is shown in picture 2.1 to display the level of spatial details these detectors are capable of; the color scale of the image is proportional to the energy deposited, hinting to the calorimetry capabilities of the detectors.

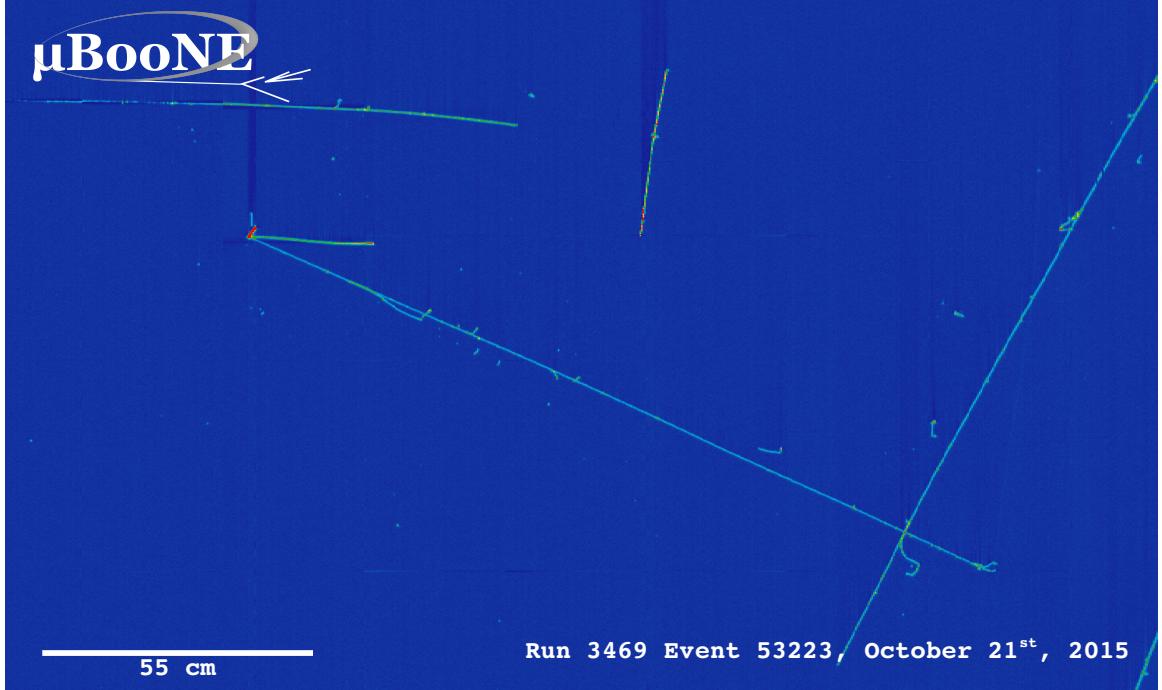


Figure 2.1: Event display of a  $\nu_\mu$  CC interaction candidate in the MicroBooNE detector.

### 690 2.1.2 LArTPC: Principles of Operation

691 To the bare bones, a LArTPC is a bulk of liquid argon sandwiched in a flat capacitor,  
 692 equipped with a light collection system. A uniform electric field of the order of  
 693 500 V/cm is maintained constant between the faces of the capacitor. The anode is  
 694 sensitive to ionization charge and it is usually made of two or more planes segmented  
 695 into several hundreds parallel sense wires a few millimeters apart; different geometries  
 696 for the anode segmentation are under study [43].

697 Argon ionization and scintillation are the processes leveraged to detect particles  
 698 in the LArTPC active volume. When a ionizing radiation traverses the argon active  
 699 volume it leaves a trail of ionization electrons along its trajectory and it excites the  
 700 argon producing of scintillation light – details on the production and detection of  
 701 ionization charge and scintillation light are provided in 2.1.4 and 2.1.4 respectively.  
 702 The optical the detector sees the argon scintillation light in matters of nanoseconds.

703 This flash of light determines the start time of an event in the chamber,  $t_0$ . The  
704 uniform electric field drifts the ionization electrons from the production point towards  
705 the anode in order of hundreds of microseconds or more depending on the chamber  
706 dimensions<sup>1</sup>. The anode sense wires see either an induced current by the drifting  
707 charge (on induction planes) or an injection of the ionization charge (collection plane).  
708 An appropriate choice of the voltage bias on each wire plane assures ideal charge  
709 transparency, so that all the ionization charge is collected on the collection plane and  
710 none on the induction planes.

711 The arrival time of the charge on the anode sense wires is used to measure the  
712 position of the original ionizing radiation in the drift direction. In fact, since the  
713 constant electric field implies that the drift velocity is also constant, the position of  
714 the original ionization is simply given by the multiplication of the drift velocity by the  
715 drift time, where the “drift time” is the difference between  $t_0$  and the charge arrival  
716 time on the wire planes. The spacial resolution on this dimension is limited by the  
717 time resolution of the electronics or by longitudinal diffusion of the electrons. The  
718 spatial information on the different wire planes maps a bi-dimensional projection of  
719 the interaction pattern in the plane perpendicular to the drift direction. The spacial  
720 resolution on this dimension is limited by the transverse electron diffusion in argon  
721 and by the grain of the anode segmentation, i.e. the spacing between the wires in  
722 the sense planes [40]. The off-line combination of the 2-D information on the wire  
723 planes with the timing information allows for the 3D reconstruction of the event in  
724 the chamber.

725 Since the charge deposited by the ionizing radiation is proportional to the de-  
726 posited energy and the charge collected on the sense plane is a function of the de-

---

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.

727 posited charge, LArTPC allow the measurement of the energy deposit in the active  
 728 volume. Effects due to the presence of free charge and impurities in the active vol-  
 729 ume, such as a finite electron lifetime, recombination and space charge, complicate  
 730 the relationship between deposited and collected charge affecting the measurement of  
 731 the particle's energy, as described in the next section.

### 732 2.1.3 Liquid Argon: Ionization Charge

733 The mean rate of energy loss by moderately relativistic elementary charge particles  
 734 heavier than electrons is well described by the modified Bethe-Bloch [94] equation

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

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

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

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

748 where  $\lambda = 1/N_e \sigma_i$ , with  $N_e$  being the electron density of  $\sigma_i$  the ionization cross-section  
 749 per electron. About 66% of the ionizing collisions in Argon produce only a single  
 750 electron/ion pair [71]; in the other cases, the transferred kinetic energy is enough  
 751 for the primary electron to liberate one or more secondary electrons, which usually  
 752 stay close to the original pair. Occasionally, electrons can receive enough energy to  
 753 be ejected with high energy, forming so-called “ $\delta$ -ray”: a detectable ionization short  
 754 track off the particle trajectory, as shown in figure 2.2. The average number of  $\delta$ -ray  
 755 with energy  $E > E_0$  per cm follows the empirical form

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

756 where  $y$  is an empirical factor depending on the medium (0.114 for gaseous Ar), and  
 757  $\beta$  is  $v/c$ .

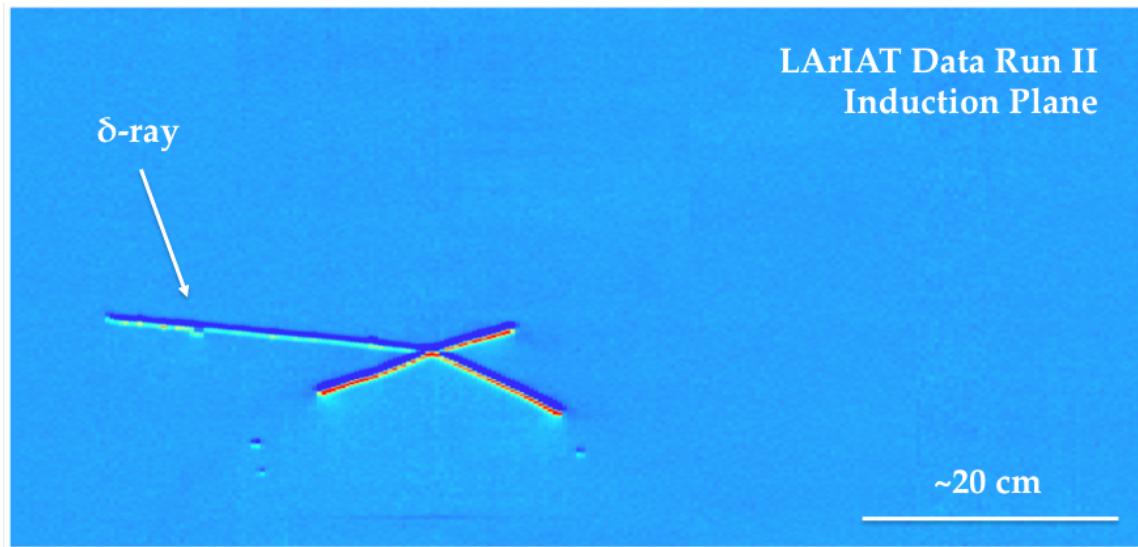


Figure 2.2: Events display for a LArIAT pion absorption candidate on the induction plane, with highlighted delta ray.

758 **Purity & Electron Life Time**

759 The presence of electronegative contaminants in liquid argon, such as oxygen and  
760 water, is particularly pernicious, since these molecules quench the charge produced  
761 by the ionizing radiation. Thus, amount of charge per unit of length  $dQ/dx$  collected  
762 on the collection plane depends on the charge's production point in the detector:  
763 ionization produced close to the cathode will see more impurities along its journey to  
764 the collection plane than ionization produced close to the anode, resulting in greater  
765 attenuation of its charge. As a result, the amount of charge collected on the sense wires  
766 as a function of the traveled distance follows an exponential decay trend. The traveled  
767 distance is generally measured in terms of drift time and the characteristic time  
768 constant of the exponential decay is called electron lifetime  $\tau_e$ . Figure 2.3 shows the  
769 typical life time for LArIAT data. The procedure to measure the electron lifetime in  
770 LArIAT is outlined in [96]. LArIAT small drift distance (47 cm) allows for a relatively  
771 short electron life time. The life time for bigger detectors such as MicroBooNE, whose  
772 drift distance is 2.5 m, needs to be of the order of tens of milliseconds to allow charge  
773 collection usable for physics analyses. Energy reconstruction in LArTPC applies a  
774 correction for the finite lifetime to calibrate the detector calorimetric response; details  
775 for LArIAT are provided in Section 5.3.

776 LArTPCs use hermetically sealed and leak-checked vessels to abate the leakage  
777 and diffusion of contaminants into the system. The liquid argon filling of the vol-  
778 ume occurs after the vessel is evacuated or purged with gaseous argon [9] to reduce  
779 remaining gases in the volume. Even so, the construction of a pure tank of argon is  
780 unviable, as several sources of impurity remain. In particular, impurities can come  
781 from the raw argon supply, the argon filtration system and from the outgassing from  
782 internal surfaces. Outgassing is a continuous diffusive process producing contami-  
783 nants, especially water, even after the vessel is sealed, particularly from materials in

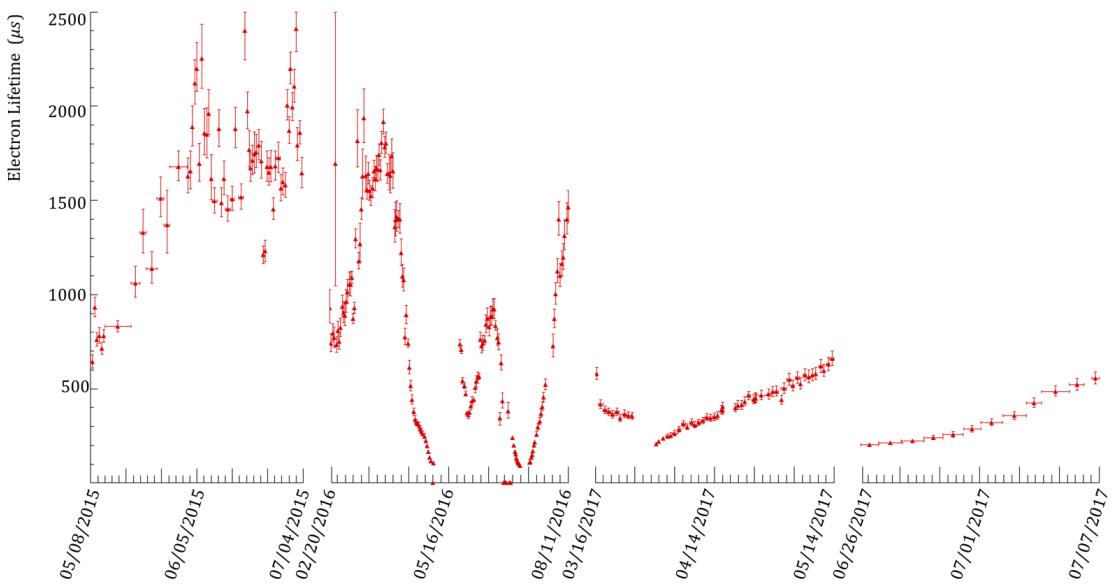


Figure 2.3: Electron lifetime during the LArIAT run period [38].

784 the ullage region<sup>2</sup>. Since research-grade argon comes from the industrial distillation  
785 of air, the impurities with the highest concentration are nitrogen, oxygen and water,  
786 generally maintained under the 1 part per million level by the vendor. Even so, a  
787 higher level of purity is necessary to achieve a free electron life time usable in meter  
788 scale detectors. Thus, argon is constantly filtered in the cryogenic system, which  
789 reduce the oxygen and water contamination to less than 100 parts per trillion. The  
790 filtration system depends on the size and drift distance of the experiment and, for  
791 experiments on several meters scale, it includes an argon recirculation system.

## 792 Recombination Effect

793 After production, ionization electrons thermalize with the surrounding medium and  
794 may recombine with nearby ions. Recombination might occur either between the  
795 electron and the parent ion through Coulomb attraction, as described in the geminate  
796 theory [92], or thanks to the collective charge density of electrons and ions from  
797 multiple ionizations in a cylindrical volume surrounding the particle trajectory, as  
798 described in the columnar model [73]. Consideration on the average electron-ion  
799 distance and the average ion-ion distance for argon show that the probability of  
800 geminate recombination is low; thus recombination in argon is mainly due to collective  
801 effects [4]. Since protons, kaons and stopping particles present a higher ionization  
802 compared to MIPs, recombination effects are more prominent when considering the  
803 reconstruction of energy deposited by these particles.

804 Models for a theoretical descriptions of recombination based on the Birks model  
805 and the Box model are provided in [27] and [104], respectively. The Birks model as-  
806 sumes a gaussian spatial distribution around the particle trajectory during the entire  
807 recombination phase and identical charge mobility for ions and electrons. The Box

---

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.

808 model also assumes that electron diffusion and ion mobility are negligible in liquid  
809 argon during recombination. In these models, the fraction of ionization electrons  
810 surviving recombination is a function of the number of ion-electron pairs per unit  
811 length, the electric field, the average ion-electron separation distance after thermal-  
812 ionization and the angle of the particle with respect to the direction of the electric field –  
813 plus the diffusion coefficient in the Birks model. Given the stringent assumptions, it  
814 is perhaps not surprising that these models are in accordance to data only in specific  
815 regimes: the Birks model is generally used to describe recombination for low  $dE/dx$ ,  
816 the Box model for high  $dEdX$ . In LArTPC, the ICARUS and ArgoNeut have mea-  
817 sured recombination in [15] and [4] respectively. Since LArIAT uses the refurbished  
818 ArgoNeut TPC and cryostat at the same electric field, LArIAT currently corrects for  
819 recombination using the ArgoNeut measured recombination parameters in [4].

820 **Space Charge Effect**

821 Slow-moving positive argon ions created during ionization can build-up in LArTPC,  
822 causing the distortion of the electric field within the detector. This effect, called  
823 “space charge effect” leads to a displacement in the reconstructed position of the  
824 signal ionization electrons. In surface LArTPCs the space charge effect is primarily  
825 due to the rate of ionization produced by cosmic rays which is slowly drifting in the  
826 chamber at all times. Surface LArTPC of the size of several meters are expected  
827 to be modestly impacted from the space charge effect, where charge build-up create  
828 anisotropy of the electric field magnitude of the order of 5% at a drift field of 500  
829 V/cm [86]. The smallness of the LArIAT drift volume is such that effect of space  
830 charge on the electric field is expected to be even smaller. **CHIEDI A FLAVIO**

831 **2.1.4 Liquid Argon: Scintillation Light**

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

835 **Scintillation Process**

836 Scintillation light in argon peaks in the ultraviolet at a 128 nm, shown in comparison  
837 to Xenon and Kypton in Figure 2.4, from [87]. The light yield collected by the optical  
838 detector depends on the argon purity, the electric field, the  $dE/dx$  and particle type,  
839 averaging at the tens of thousands of photons per MeV.

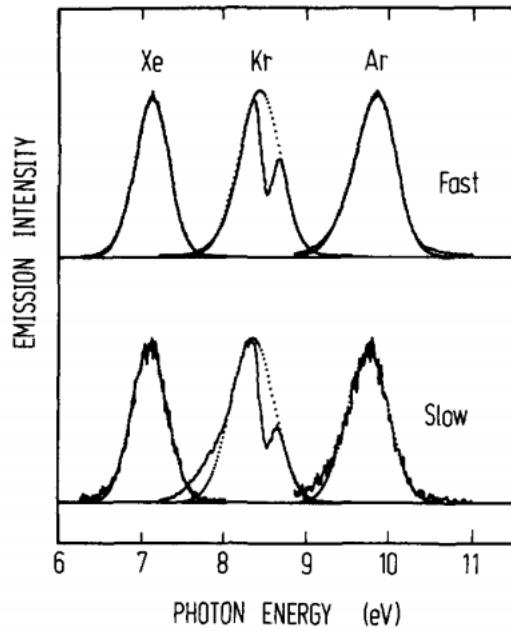


Figure 2.4: Emission spectra of the fast and slow emission components in Xenon, Krypton and Argon according to [87]. The dotted lines correspond to the Gaussian fits.

840 The de-excitation of Rydberg dimers in the argon is responsible for the scintillation  
841 light. Rydberg dimers exist in two states: singlets and a triplets. The time constant  
842 for the singlet radiative decay is 6 ns, resulting in a prompt component for the scin-

843 tillation light. The decay of the triplet is delayed by intersystem crossing, producing  
844 a slow component with a time constant of  $\sim$  1500 ns. “Self-trapped exciton lumines-  
845 cence” and “recombination luminescence” are the two processes responsible for the  
846 creation of the Rydberg dimers [76]. In the first process, a charged particle excites an  
847 argon atom which becomes self-trapped in the surrounding bulk of argon, forming a  
848 dimer; the dimer is in the singlet state 65% of the times and in the triplet state 35%  
849 of the times. In case of recombination luminescence, the charged particle transfers  
850 enough energy to ionize the argon. The argon ion forms a charged argon dimer state,  
851 which quickly recombines with the thermalized free electron cloud. Excimer states  
852 are produced in the recombination, roughly half in the singlet and half in the triplet  
853 state. The light yield dependency on the electric field, on the  $dE/dx$  and particle  
854 type derives from the role of free charge in the recombination luminescence process.  
855 The spacial separation between the argon ions and the free electron cloud depends on  
856 the electric field. On one hand, a strong electric field diminishes the recombination  
857 probability, leading to a smaller light yield; on the other, it increases the free charge  
858 drifting towards the anode plane. Hence, the amount of measurable charge and light  
859 anti-correlates as a function of the electric field. Ionizing particles in the argon mod-  
860 ify the local density of both free electrons and ions depending on their  $dE/dx$ . Since  
861 the recombination rate is proportional to the square of the local ionization density,  
862 highly ionizing particles boost recombination and the subsequent light yield compared  
863 to MIPs. The possibility to leverage this dependency for pulseshape-based particle  
864 identification has been shown in [29, 81].

### 865 Effects Modifying the Light Yield

866 The production mechanism through emission from bound excimer states implies that  
867 argon is transparent to its own scintillation light. In fact, the photons emitted from  
868 these metastable states are not energetic enough to re-excite the argon bulk, greatly

869 suppressing absorption mechanisms. In a LArTPC however, several processes modify  
870 the light yield in between the location where light is produced and the optical detector.  
871 In a hypothetical pure tank of argon, Rayleigh scattering would be the most important  
872 processes modifying the light yield. Rayleigh scattering changes the path of light  
873 propagation in argon, prolonging the time between light production and detection.  
874 The scattering length has been measured to be 66 cm [72] , shorter than the theoretical  
875 prediction of  $\sim$  90 cm [103]; this value is short enough to be relevant for the current  
876 size of LArTPCs detectors. In fact, Rayleigh scattering worsen the resolution on  $t_0$ ,  
877 the start time for charge drifting, and alters the light directionality, complicating the  
878 matching between light and charge coming from the same object in case of multiple  
879 charged particles in the detector.

880 Traces of impurities in argon such as oxygen, water and nitrogen also affect the  
881 light yield, mainly via absorption and quenching mechanisms. Absorption occurs as  
882 the interaction of a 128 nm photon directly with the impurity dissolved in the liquid  
883 argon. Differently, quenching occurs as the interaction of an argon excimer and an  
884 impurity, where the excimer transfers its excitation to the impurity and dissociates  
885 non-radiatively. Given this mechanism, it is evident how quenching is both a function  
886 of the impurity concentrations and the excimer lifetime. Since the triplet states  
887 live much longer than the singlet states, quenching occurs mainly on triplet states,  
888 affecting primarily the slow component of the light, reducing the scintillation yield  
889 and a shortening of the scintillation time constants.

890 The stringent constraints for the electron life time limit the presence of oxygen and  
891 water to such a low level that both absorption and quenching on these impurity is not  
892 expected to be significant. Contrarily, the nitrogen level is not bound by the electron  
893 life time constraints – nitrogen being an inert gas, expensive to filter. Thus, nitrogen  
894 is often present at the level provided by the vendor. The effects of nitrogen on argon  
895 scintillation light have been studied in the WArP R&D program and at several test

896 stands. The quenching process induced by nitrogen in liquid Ar has been measured  
897 to be proportional to the nitrogen concentration, with a rate constant of  $\sim 0.11$   
898  $\mu\text{s}^{-1}$  ppm $^{-1}$ ; appreciable decreasing in lifetime and relative amplitude of the slow  
899 component have been shown for contamination as high as a few ppm of nitrogen [5].  
900 For a nitrogen concentration of 2 parts per million, typical of the current generation  
901 of LArTPC, the attenuation length due to nitrogen has been measured to be  $\sim 30$   
902 meters [75].

### 903 Wavelength Shifting of LAr Scintillation Light

904 Liquid argon scintillation light is invisible for most optical detectors deployed in a  
905 LArTPC, such as cryogenic PMTs and SiPMs, since a wavelength of 128 nm is gen-  
906 erally too short to be absorbed from most in glasses, polymers and semiconductor  
907 materials. Research on prototype SiPMs absorbing directly VUV light and their  
908 deployment in noble gasses experiment is ongoing but not mature [111]. Thus, ex-  
909 periments need to shift the wavelength of scintillation light to be able to detect it.  
910 Albeit deployed in different ways, neutrinos and dark matter experiments commonly  
911 use 1,1,4,4-tetraphenyl-butadiene (TPB) to shift the scintillation light. TPB absorbs  
912 the vacuum ultraviolet (VUV) light and emits in the visible at  $\sim 425$  nm [31], with  
913 a ratio of visible photon emitted per VUV photon absorbed of  $\sim 1.2:1$  [61].

914 Neutrino experiments typically coat their optical detector system evaporating a  
915 layer of TPB either directly on the PMTs glass surface or on acrylic plates mounted in  
916 front of the PMTs [55]; this technique allows the fast detection light coming directly  
917 from the neutrino interaction. Dark matter experiments typically evaporate TPB on  
918 reflective foils mounted on the inside walls of the sensitive volume and detect the  
919 light after it has been reflected; this technique leads to a higher and more uniform  
920 light yield, though scattering effects for both the visible and VUV light augment  
921 the propagation time and hinder directionality information [56]. In order to take

922 advantage of both these techniques, hybrid systems with PMT coating and foils are  
923 being considered for the next generation of large neutrino detectors.

924 **2.1.5 Signal Processing and Event Reconstruction**

925 In this section we illustrate the processing and reconstruction chain of the TPC sig-  
926 nals, from the pulses on the sense wire to the construction of three dimensional objects  
927 with associated calorimetry. Different experiments can chose different software pack-  
928 ages for their off line signal processing and event reconstruction, but a popular choice  
929 for US based LArTPCs is LArSoft [35]. Based on the Art framework [66], LArSoft is  
930 an event-based toolkit to perform simulation, analysis and reconstruction of LArT-  
931 PCs events.

932

933 LArTPC signal processing develops in several consecutive stages that we summa-  
934 rize here in the following categories: *Deconvolution*, *Hit Reconstruction*, *2D Cluster-*  
935 *ing*, *3D Tracking*, *Calorimetry Reconstruction*. A visualization of the signal processing  
936 workflow is shown in figure 2.5.

937

938 **Deconvolution.** Induction and collection planes have different field responses,  
939 given the different nature of the signals on these planes: the wires on the induction  
940 planes see inductive signal of the drifting charge, while the wires on the collection  
941 planes see the current derived from the charge entering the conductor. Thus, signals  
942 on the induction plane are bi-polar pulse and signal on the collection plane are unipo-  
943 lar pulses, see Figure 2.5 panel a. The first step in signal processing is deconvolution,  
944 that is a series of off-line algorithms geared towards undoing the detector effects. The  
945 result of the deconvolution step is the production of a comparable set waveforms on  
946 all planes presenting unipolar, approximately gaussian-like pulses (Figure 2.5 panel  
947 b). Signal from all planes are treated on equal footage beyond this point. Some

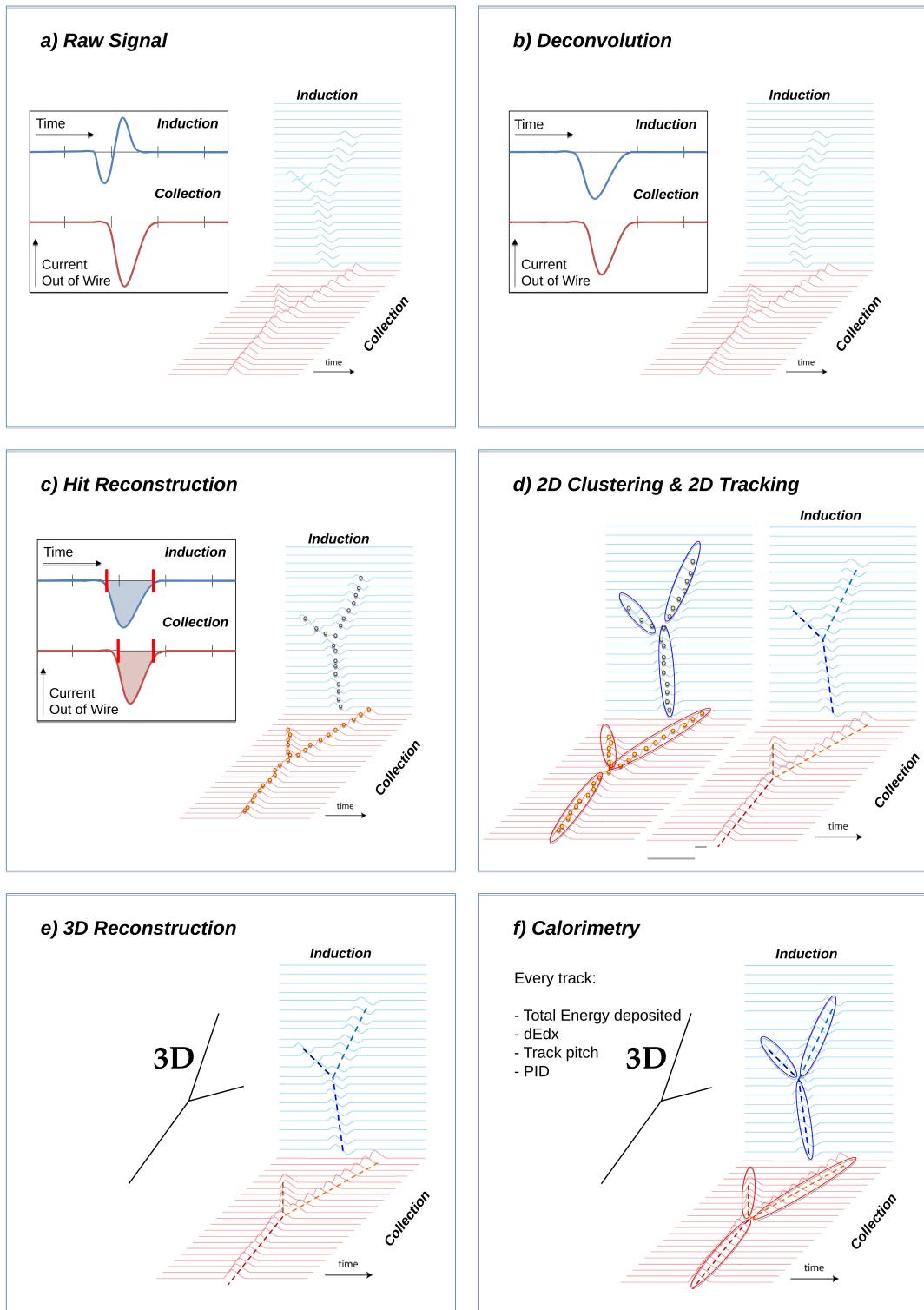


Figure 2.5: A scheme of a typical signal processing workflow in LArSoft.

948 LArTPC apply noise filtering in the frequency domain just after the deconvolution  
949 to clean up wire cross talk. Since signals from the LArIAT TPC are extremely clean,  
950 noise filtering is not necessary.

951

952     **Hit Reconstruction.** The second stage of the signal processing is the recon-  
953 struction of hits, indicating an energy deposition in the detector. A peak finder scans  
954 the deconvolved TPC waveforms for each wire on the whole readout time looking for  
955 spikes above the waveform’s baseline. It then fits these peaks with gaussian shapes  
956 and stores the fit parameters such as the quality of the fit, the peak time, height  
957 and area under the gaussian fit. The information resulting from this process a single  
958 spike form a single reconstructed “hit”. The next steps in the event reconstruction  
959 chain will then decide if rejecting hits with poor fits. It is important to notice how  
960 the height and width of the hit depend on the topology of the event: for example, a  
961 particle running parallel to the wire planes will leave a series of sharp hits on many  
962 consecutive wires, while a particle traveling towards the planes will leave a long, wide  
963 hit on very few wires. The height of the hits and their integral is proportional to the  
964 charge collected on the wire, so it depends on the particle type.

965

966     The event reconstruction chain uses collection of hits to form more complex objects  
967 associated with the particles in the detector. The development of different approaches  
968 to accomplish this task is an extremely hot topic in LArTPC event reconstruction  
969 which spans from more traditional approaches such as line-clustering [24] to the use of  
970 machine learning tools [54]. Generally speaking, the scope of hit clustering and event  
971 reconstruction to provide shower-like or track like-objects with an associated energy  
972 reconstruction. This is because different particles have different topology in the de-  
973 tector – electrons and photon create electromagnetic showers, resulting in shower-like  
974 topologies, while muons and hadrons leave track-like signals. For the scope of these

975 thesis, we will describe only LArIAT’s approach to track reconstruction even if we  
976 recognize the breath of LArTPC event reconstruction is much wider. We are inter-  
977 ested in the reconstruction of pions and kaons in the active volume, whose topology  
978 is track-like.

979

980       **2D Clustering Reconstruction.** The LArIAT reconstruction of track-like ob-  
981 jects starts by clustering hits on the collection and induction planes separately with  
982 the use of the TrajCluster clustering package [23]. TrajCluster looks for a collection  
983 of hits in the wire-time 2D space which can be described with a line-like 2D trajec-  
984 tory. TrajCluster reconstructs trajectories by adding trajectory points to the leading  
985 edge of the trajectory while stepping through the 2D space of hits. Several factors  
986 determine whether a hit is added to the trajectory, including but not limited to

- 987       1. the goodness of the fit of the single hit,  
988       2. the charge of the hit compared to the average charge and RMS of the hits  
989              already forming the trajectory,  
990       3. the goodness of trajectory fit with and without the hit addition,  
991       4. the angle between the two lines formed by the collection of hits before and after  
992              the considered hit in the trajectory.

993       **3D Tracking.** The 3D tracking set of algorithms uses clusters close in time on  
994 the induction and collection planes as starting point to form a 3D track. Firstly, it  
995 construct a tentative 3D trajectory using the edges of the clusters. Then, it projected  
996 back the tentative trajectory on to the planes and adjusts the parameters of the 3D  
997 track fit such that they minimize the distance between the fit projections and the  
998 track hits in all wire planes simultaneously. The track algorithm can use multiple  
999 clusters in one plane, but it can never break them in smaller groups of hits. This

1000 algorithm was first developed for the ICARUS collaboration [18].

1001

1002 **Calorimetry.** The last step in the event reconstruction chain is to assign calorimetric information to the track (or shower) objects. Calorimetry is performed separately on the different planes. A multi-step procedure is needed to retrieve the energy deposited in the TPC from the charge seen by the wires. For each hit associated with the track object, the calorimetry algorithms calculate the charge seen on every wire using the area underneath the gaussian fit; then they correct this raw charge by the electron life time, the electronic noise on the considered wire and the recombination effect. Lastly an overall calibration of the energy, explained in detail in section 5.3, is applied and the calorimetric information for the given track is assigned. Even if calorimetry is done in 2D, it benefits from the 3D tracking information; typical information available after the calorimetric reconstruction are the total energy deposited by the particle and its stopping power  $dE/dx$  at each “track pitch”, i.e. at each 2D projection on the wire plane of the 3D trajectory.

## 1015 2.2 The Intensity Frontier Program

### 1016 2.2.1 Prospects for LArTPCs in Neutrino Physics: SBN and 1017 DUNE

1018 The ArgoNeut experiment [16] initiated the US LArTPC neutrino program. Following  
1019 the success of this small TPC on the NuMI beam, a wide program of LArTPCs  
1020 on neutrino beams has flourished. The construction of LArTPCs as near and far  
1021 detectors at different baseline allows for the exploration of different fundamental  
1022 questions in neutrino physics today.

1023 The Short-Baseline Neutrino (SBN) [19] program at Fermilab is tasked with con-  
1024 clusively addressing the “LSND and MiniBooNE anomalies” [13, 14, 21], whose  $\nu_e$

and  $\bar{\nu}_e$  appearance results may be interpreted under the assumption of a new sterile neutrino. The SBN program entails three surface LArTPCs positioned on the Booster Neutrino Beam at different distances from the neutrino production in order to fully exploit the L/E dependence of the oscillation pattern: SBND (100 m from the decay pipe), MicroBooNE (450 m), and ICARUS (600 m). Within the oscillation context, the choice of the LArTPC technology for the SBN detectors changes the set of systematics with respect to LSND and MiniBooNE, whose detection techniques were both based on Cherenkov light. In particular, LArTPCs provide excellent electron/photon separation [8] lacking in Cherenkov detectors which can be leveraged to abate the photon background from neutral current interactions in  $\nu_e$  searches. MicroBooNE [7], the first detector of the SBN program to be fully operational, started its first neutrino run in October 2015. MicroBooNE is a 89 ton active volume LArTPC, single drift chamber with TPC dimensions of 2.6 m (drift) x 2.3 m (height) 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, 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 [10], 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

1052 to the SURF laboratory in South Dakota, DUNE is tasked with preforming conclusive  
1053 measurements of CP violation in the lepton sector, the neutrino mass ordering and  
1054 the  $\theta_{23}$  octant. The DUNE far detector will count four 10 kton LArTPCs, roughly of  
1055 dimensions of 19 m (horizontally) x 18 m (vertically) x 66 m (depth).

## 1056 2.2.2 Prospects for LArTPCs in GUT Physics: DUNE

1057 The experimental exploration of a manifestation of Grand Unified Theory is possible  
1058 in DUNE thanks to its sheer mass. In particular, proton decay searches are a capital  
1059 topic of DUNE's wide non-accelerator physics program. The key elements for a  
1060 rare decay experiment are: massive active volume, long exposure, high identification  
1061 efficiency and low background. Figure 2.6 shows the current best experimental limits  
1062 on nucleon decay lifetime over branching ratio (dots). Historically, the dominant  
1063 technology used in these searches has been water Cherenkov detectors: all the best  
1064 experimental limits on every decay mode are indeed set by Super-Kamiokande [?,?].  
1065 As shown in section 1.3.2, different family of GUTs predict the proton to decay in  
1066 different modes. In particular, SUSY flavored GUTs prefer the presence of kaons  
1067 in the decay products, e.g.  $p \rightarrow K^+ \bar{\nu}$ . It is particularly important to notice that  
1068 the kaon energy for the proton decay mode  $p \rightarrow K^+ \bar{\nu}$  is under Cherenkov threshold  
1069 in water. Thus, Super-Kamiokande set the limit on the lifetime for the  $p \rightarrow K^+ \bar{\nu}$   
1070 mode by relying on photons from nuclear de-excitation and on the muon tagging in  
1071 the kaon decay leptonic mode. For this reason, an attractive alternative approach to  
1072 identifying nucleon decay is the use of a LArTPCs, where the kaon is directly visible  
1073 in the detector. According to [10], DUNE will have an active volume large enough,  
1074 have sufficient shielding from the surface, and will run for lengths of time sufficient  
1075 to compete with Hyper-K, opening up the opportunity for the discovery of nucleon  
1076 decay.

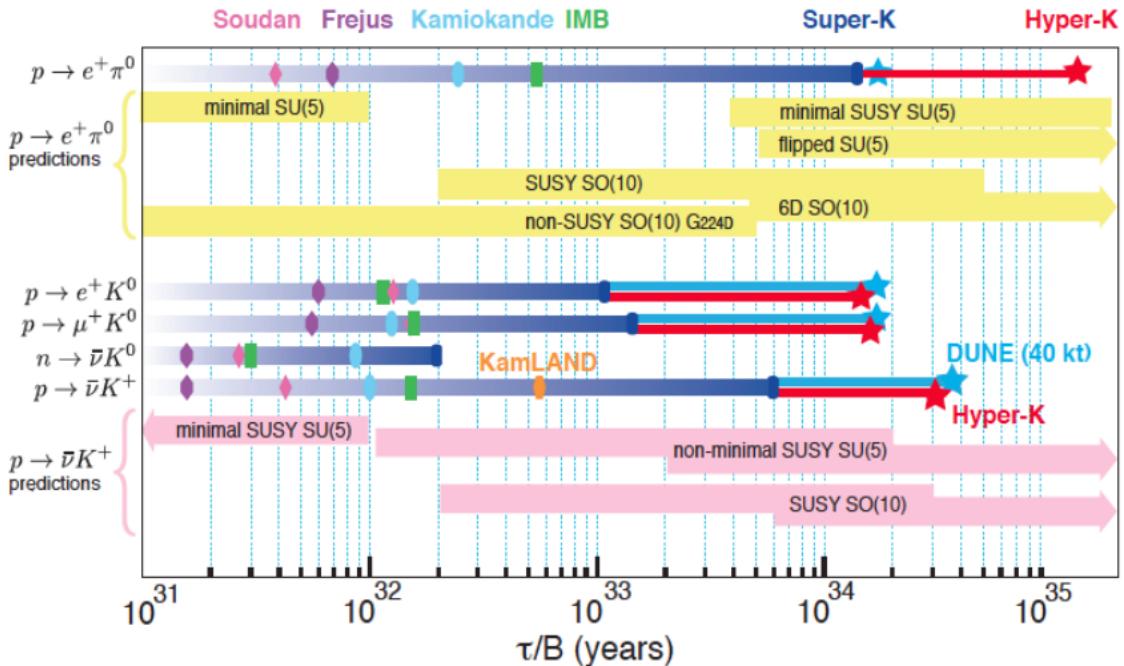


Figure 2.6: Proton decay lifetime limits from passed and future experiments.

### 1077 2.2.3 Enabling the next generation of discoveries: LArIAT

1078 LArIAT, a small LArTPC in a test beam, is designed to perform an extensive physics  
 1079 campaign centered on charged particle cross section measurements while characteriz-  
 1080 ing the detector performance for future LArTPCs. Since LArTPCs represent the most  
 1081 advanced experiments for physics at the Intensity Frontier, their complex technology  
 1082 needs a thorough calibration and dedicated measurements of some key quantities to  
 1083 achieve the precision required for the next generation of discoveries. LArIAT's goal  
 1084 is to provide such calibration and dedicated measurements. The LArIAT LArTPC is  
 1085 deployed in a dedicated calibration test beamline at Fermilab. We use the LArIAT  
 1086 beamline to characterize the charge particles before they enter the TPC: the particle  
 1087 type and initial momentum is known from beamline information. The precise calori-  
 1088 metric energy reconstruction of the LArTPC technology enables the measurement of  
 1089 the total differential cross section for tagged hadrons. The Pion-Nucleus and Kaon-  
 1090 Nucleus total hadronic interaction cross section have never been measured before in

1091 argon and they are a fundamental step to shed light on light meson interaction in nu-  
1092 clei per se, while providing a key input to neutrino physics and proton decay studies  
1093 in future LArTPC experiments like SBN and DUNE.

1094 In order to showcase LArIAT’s utility to SBN and DUNE, we illustrate briefly  
1095 two comparisons as examples: one regarding neutrino interactions and the second  
1096 regarding proton decay studies.

1097 The left side of figure 2.7 shows the distribution of products in momentum spectrum  
1098 and particle type as simulated in a  $\nu_e$  CC interaction in DUNE (according to [80])  
1099 as a comparative example to the momentum distribution of particles in the LAr-  
1100 IAT beamline – shown on the right side of figure 2.7. The momentum spectrum in  
1101 the LArIAT beamline for electrons, muons and pions – the most abundant particles  
1102 produced in a  $\nu_e$  CC interaction – covers a wide range of the expected momentum  
1103 distribution in a neutrino event.

1104 The signature of a proton decay event in the “LAr golden mode” is the presence of  
1105 a single kaon of about 400 MeV in the detector; the momentum spectrum of the kaon  
1106 pre and post FSI in such an event is shown on the left side of figure 2.8. The right  
1107 side of figure 2.8 shows the momentum spectrum of kaons in the LArIAT beamline.  
1108 Kaons arriving to the LArIAT TPC are ideal for proton decay studies, since their  
1109 momentum in the beamline is just above the typical momentum for kaons in a proton  
1110 decay event: the majority of LArIAT kaons slow down in the TPC enough to enter  
1111 the desired momentum window.

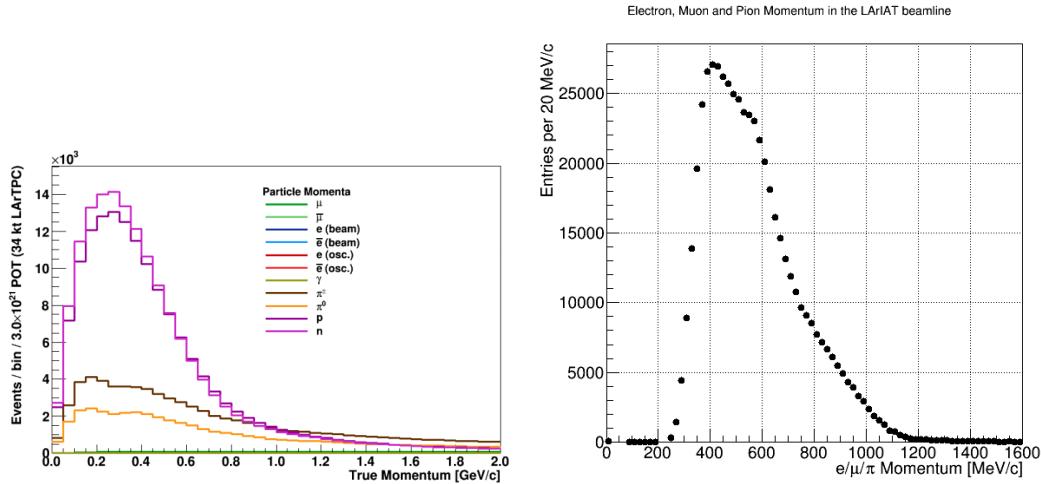


Figure 2.7: *Left.* Simulation of the products of a  $\nu_e$  CC interaction in DUNE, both in particles type and momentum.  
*Right.* Momentum spectrum for low mass particles ( $e, \mu, \pi$ ) in the LArIAT beamline, negative tune, Run II, Picky Tracks see section 3.2.3.

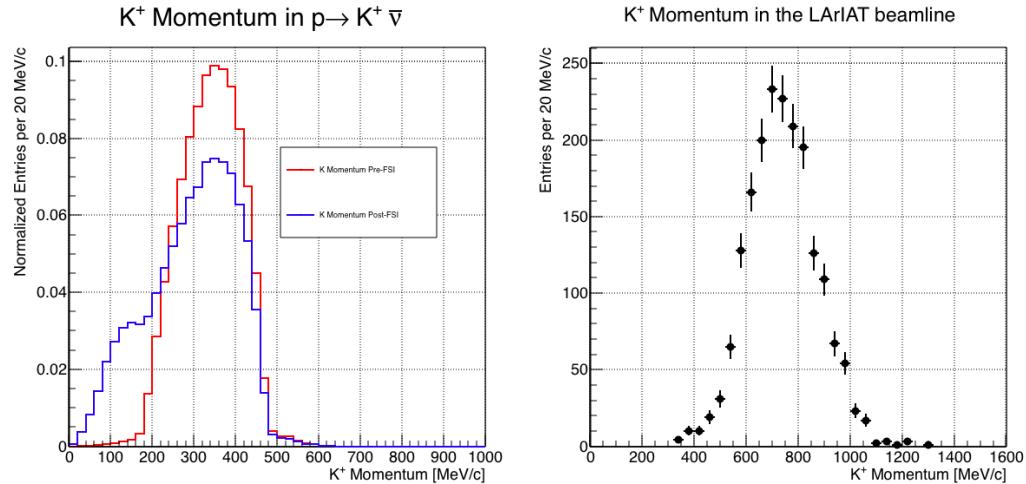


Figure 2.8: *Left.* Momentum of the kaon outgoing a proton decay  $p \rightarrow K^+ \bar{\nu}$  event as simulated by the Genie 2.8.10 event generator in argon. The red line represents the kaon momentum distribution before undergoing the simulated final state interaction inside the argon nucleus, while 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 3.2.3.

# 1112 Chapter 3

## 1113 LArIAT: Liquid Argon In A

### 1114 Testbeam

1115 In this chapter, we describe the LArIAT experimental setup. We start by illustrating  
1116 the journey of the charge particles in the Fermilab accelerator complex, from  
1117 the gaseous thermal hydrogen at the Fermilab ion source to the delivery of the LAr-  
1118 IAT tertiary beam at MC7. We then describe the LArIAT beamline detectors, the  
1119 LArTPC, the DAQ and the monitoring system.

### 1120 3.1 The Particles Path to LArIAT

1121 LArIAT's particles history begins in the Fermilab accelerator complex with a beam of  
1122 protons. The process of protons acceleration develops in gradual stages (see picture  
1123 3.1): gaseous hydrogen is ionized in order to form  $H^-$  ions; these ions are boosted to  
1124 750 keV by a Cockcroft-Walton accelerator and injected to the Linac linear accelerator  
1125 that increases their energy up to 400 MeV; then,  $H^-$  ions pass through a carbon  
1126 foil and lose the two electrons; the resulting protons are then injected into a rapid  
1127 cycling synchrotron, called Booster; at this stage, protons reach 8 GeV of energy  
1128 and are compacted into bunches; the next stage of acceleration is the Main Injector,

1129 a synchrotron which accelerates the bunches up to 120 GeV; in the Main Injector,  
1130 several bunches are merged into one and used for the injection in the last stage.

1131 The Fermilab accelerator complex works in supercycles of roughly 60 seconds in  
1132 duration. The beam is split by electrostatic septa and delivered at different exper-  
1133 imental halls all over the lab. A 120 GeV/c primary proton beam with variable  
1134 intensity is extracted in four-second “spills” and sent to the Meson Center beam line.

1135 LArIAT’s home at Fermilab is the Fermilab Test Beam Facility (FTBF), where  
1136 the experiment characterizes a beam of charge particles downstream from the Meson  
1137 Center beam line. Here, the primary beam is focused onto a tungsten target to create  
1138 LArIAT’s secondary beam. The composition of the secondary particle beam is mainly  
1139 positive pions. The momentum peak of the secondary beam was fixed at 64 GeV/c for  
1140 the LArIAT data considered in this work, although the beam is tunable in momentum  
1141 between 8-80 GeV/c; this configuration of the secondary beamline assured a stable  
1142 beam delivery at the LArIAT experimental hall.

1143 The secondary beam impinges then on a copper target within a steel collimator  
1144 inside the LArIAT experimental hall (MC7) to create the LArIAT tertiary beam,  
1145 (shown in Fig. 3.2). The steel collimator selects particles produced with a 13° pro-  
1146 duction angle at the target down the beamline. The particles are then bent by 10°  
1147 through a pair of dipole magnets. By configuring the field intensity of the magnets we  
1148 allow the particles of LArIAT’s tertiary beam to span a momentum range from 0.2 to  
1149 1.4 GeV/c. The polarity of the magnet is also configurable and determines the sign of  
1150 the beamline particles which are focused on the LArTPC. If the magnets polarity is  
1151 positive the tertiary beam composition counts mostly pions and protons with a small  
1152 fraction of electrons, muons, and kaons. It is the job of the LArIAT beamline detec-  
1153 tors to select the particles polarity, to perform particle identification in the beamline  
1154 and to measure the momentum of the tertiary beam particles before they get to the  
1155 LArTPC. The LArIAT detectors are described in the following paragraphs.

## Fermilab Accelerator Complex

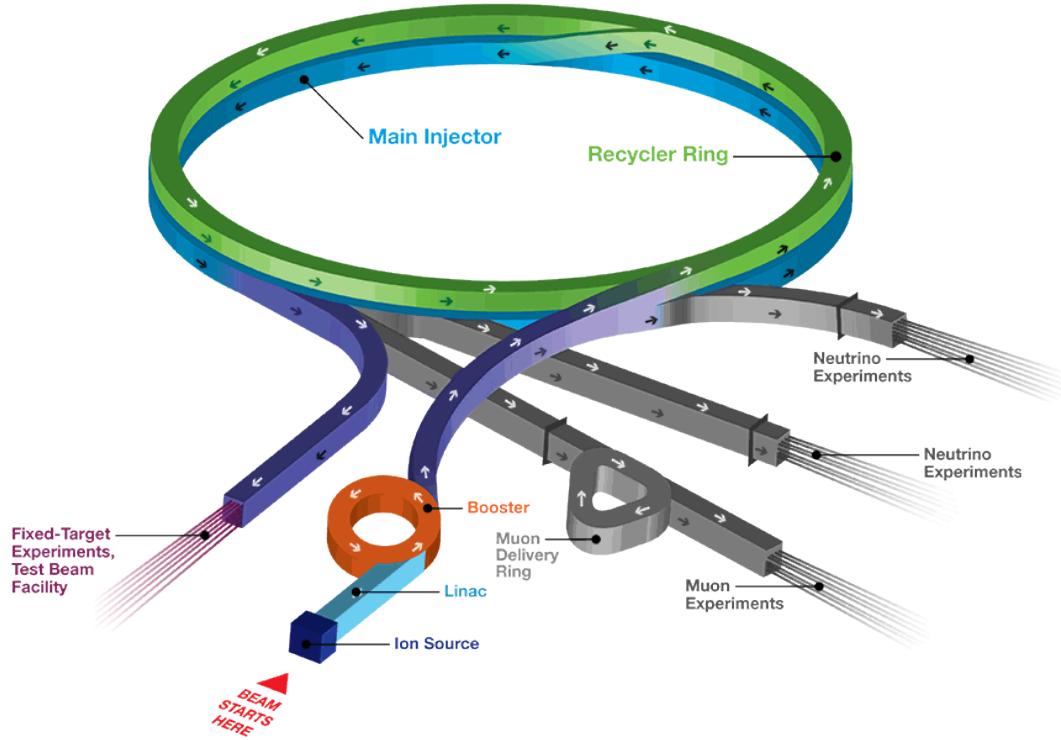


Figure 3.1: Layout of Fermilab Acellerator complex.

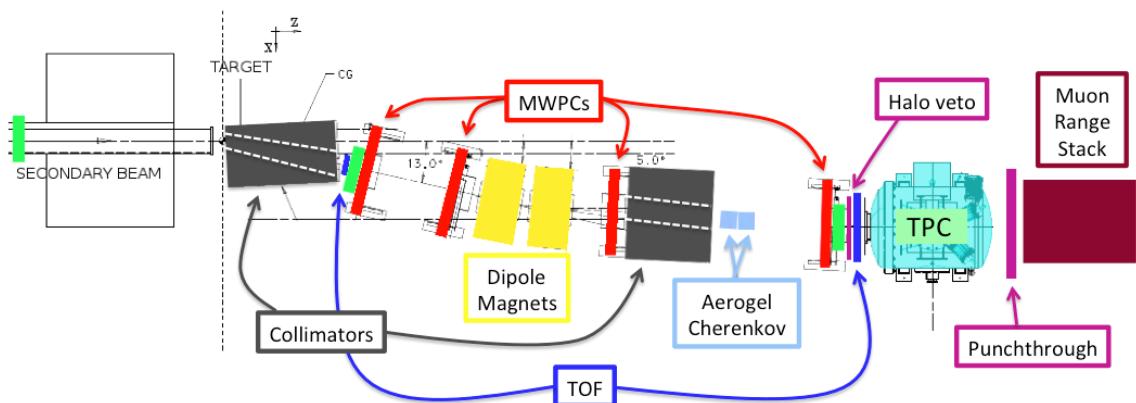


Figure 3.2: Bird's eye view of the LArIAT tertiary beamline. In grey: upstream and downstream collimators; in yellow: bending magnets; in red: wire chambers; in blue: time of flight; in green: liquid argon TPC volume; in maroon: muon range stack.

## **1156 3.2 LArIAT Tertiary Beam Instrumentation**

**1157** The instrumentation of LArIAT tertiary beam and the TPC components have changed  
**1158** several times during the three years of LArIAT data taking. The following paragraphs  
**1159** describe the components operational during “Run II”, the data taking period relevant  
**1160** to the hadron cross section measurements.

**1161** The key components of the tertiary beamline instrumentation for the hadron cross  
**1162** section analyses are the two bending magnets, a set of four wire chambers (WCs)  
**1163** and two time-of-flight scintillating paddles (TOF) and, of course, the LArTPC. The  
**1164** magnets determine the polarity of the particles in the tertiary beam; the combination  
**1165** of magnets and wire chambers determines the particles’ momentum, which is used  
**1166** to determine the particle species in conjunction with the TOF. A muon range stack  
**1167** downstream from the TPC and two sets of cosmic paddles configured as a telescope  
**1168** surrounding the TPC are also used for calibration purposes.

### **1169 3.2.1 Bending Magnets**

**1170** LArIAT uses a pair of identical Fermilab type “NDB” electromagnets, recycled from  
**1171** the Tevatron’s anti-proton ring, in a similar configuration used for the MINERvA T-  
**1172** 977 test beam calibration [51]). The magnets are a fundamental piece of the LArIAT  
**1173** beamline equipment, as they are used for both particle identification and momentum  
**1174** measurement before the LArTPC. The sign of the current in the magnets allows us to  
**1175** select either positively or negatively charged particles; the value of the magnetic field  
**1176** is used in the momentum determination and in the subsequent particle identification.

**1177** We describe here the characteristics and response of one magnet, as the second one  
**1178** has a similar response, given its identical shape and history. Each magnet is a box with  
**1179** a rectangular aperture gap in the center to allow for the particle passage. The magnet  
**1180** aperture measures 14.224 cm in height, 31.75 cm in width, and 46.67 cm in length.

1181 Since the wire chambers aperture ( $\sim 12.8 \text{ cm}^2$ ) is smaller than the magnet aperture,  
 1182 only the central part of the magnet gap is utilized. The field is extremely uniform  
 1183 over this limited aperture and was measured with two hall probes, both calibrated  
 1184 with nuclear magnetic resonance probes. The probes measured the excitation curve  
 1185 shown in Figure 3.3.

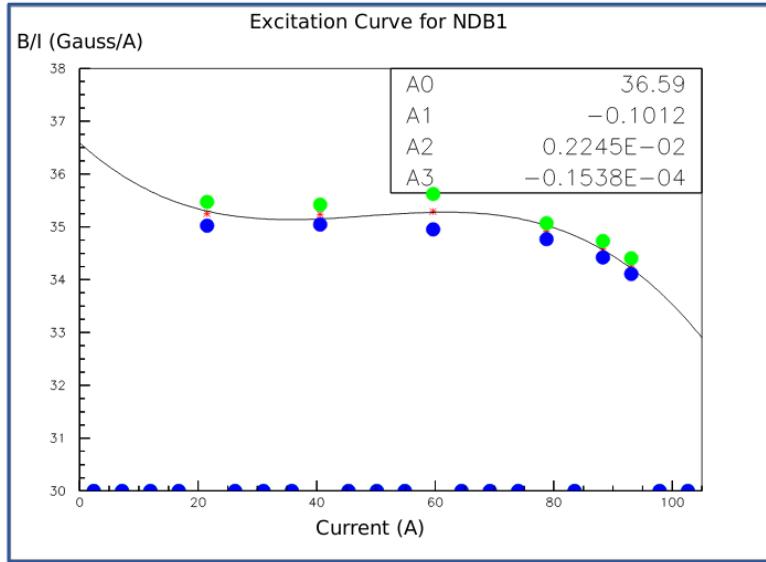


Figure 3.3: Magnetic field over current as a function of the current, for one NDB magnet (excitation curve). The data was collected using two hall probes (blue and green). We fit the readings with a cubic function (black) to average of measurements (red) given in the legend.

1186 The current through the magnets at a given time is identical in both magnets.  
 1187 For the Run II data taking period, the current settings explored were 60A ( $B \sim 0.21$   
 1188 T) and 100A ( $B \sim 0.35$  T) in both polarities. Albeit advantageous to enrich the  
 1189 tertiary beam composition with high mass particles such as kaons, we never pushed  
 1190 the magnets current over 100 A, not to incur in overheating. During operation, we  
 1191 operated a air and water cooling system on the magnets and we remotely monitored  
 1192 the magnets temperature.



Figure 3.4: One of the four Multi Wire Proportional Chambers (WC) used in the LArIAT tertiary beamline and relative read-out electronics.

### **1193 3.2.2 Multi-Wire Proportional Chambers**

1194 LArIAT uses four multi-wire proportional chambers, or wire chambers (WC) for short,  
1195 two upstream and two downstream from the bending magnets. The geometry of one  
1196 chamber is shown in Figure 3.4: the WC effective aperture is a square of 12.8 cm  
1197 perpendicular to the beam direction. Inside the chamber, the 128 horizontal and 128  
1198 vertical wires hang at a distance of 1 mm from each other in a mixture of 85% Argon  
1199 and 15% isobutane gas. The WC operating voltage is between 2400 V and 2500 V.  
1200 The LArIAT wire chambers are an upgraded version of the Fenker Chambers [57],  
1201 where an extra grounding improves the signal to noise ratio of the electronic readout.

1202 Two ASDQ chips [88] mounted on a mother board plugged into the chamber serve  
1203 as front end amplifier/discriminator. The chips are connected to a multi-hit TDC [67]  
1204 which provides a fast OR output used as first level trigger. The TDC time resolution  
1205 is 1.18 ns/bin and can accept 2 edges per 9 ns. The maximum event rate acceptable  
1206 by the chamber system is of 1 MHz: this rate is not a limiting factor considering that  
1207 the rate of the tertiary particle beam at the first wire chamber is estimated to be less  
1208 than 15 kHz. A full spill of data occurring once per supercycle is stored on the TDC  
1209 board memory at once and read out by a specially designed controller. We use LVDS  
1210 cables to carry both power and data between the controller and the TDCs and from

1211 the controller to the rest of the DAQ.

## 1212 Multi-Wire Proportional Chambers functionality

1213 We use the wire chamber system together with the bending magnets to measure the  
1214 particle's momentum.

1215 In the simplest scenario, only one hit on each and every of the four wire chambers  
1216 is recorded during a single readout of the detector systems. Thus, we use the hit  
1217 positions in the two wire chambers upstream of the magnets to form a trajectory  
1218 before the bend, and the hit positions in the two wire chambers downstream of the  
1219 magnets to form a trajectory after the bend. We use the angles in the XZ plane  
1220 between the upstream and downstream trajectories to calculate the  $Z$  component of  
1221 the momentum as follows:

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

1222 where  $B_{eff}$  is the effective maximum field in a square field approximation,  $L_{eff}$   
1223 is the effective length of both magnets (twice the effective length of one magnet),  
1224  $\theta_{US}$  is the angle off the  $z$  axis of the upstream trajectory,  $\theta_{DS}$  is the angle off the  
1225  $z$  axis of the downstream trajectory and  $3.3 c^{-1}$  is the conversion factor from [T·m]  
1226 to [MeV/c]. By using the hit positions on the third and fourth wire chamber, we  
1227 estimate the azimuthal and polar angles of the particle trajectory, and we are able to  
1228 calculate the other components of the momentum.

1229 The presence of multiple hits in a single wire chamber or the absence of hits in one  
1230 (or more) wire chambers can complicate this simple scenario. The first complication  
1231 is due to beam pile up, while the latter is due to wire chamber inefficiency. In the  
1232 case of multiple hits on a single WC, at most one wire chamber track is reconstructed  
1233 per event. Since the magnets bend particles only in the X direction, we assume  
1234 the particle trajectory to be roughly constant in the YZ plane, thus we keep the

1235 combination of hits which fit best with a straight line. It is still possible to reconstruct  
1236 the particle's momentum even if the information is missing in either of the two middle  
1237 wire chambers (WC2 or WC3), by constraining the particle trajectory to cross the  
1238 plane in between the magnets.

1239 Events satisfying the simplest scenario of one single hit in each of the four wire  
1240 chambers form the “Picky Track” sample. We construct another, higher statistics  
1241 sample, where we loosen the requirements on single hit and wire chamber efficiency:  
1242 the “High Yield” sample. For LArIAT Run II, the High Yield sample is about three  
1243 times the Picky Tracks statistics. For the first measurements of the LArIAT hadronic  
1244 cross section, we use the Picky Tracks sample because the uncertainty on the momen-  
1245 tum is smaller and the comparison with the beamline MC results is straightforward  
1246 compared with the High Yield sample; a possible future update and cross check of  
1247 these analysis would be the use of the High Yield sample.

1248 **Four point track momentum uncertainty**

1249 **3.2.3 Time-of-Flight System**

1250 Two scintillator paddles, one upstream to the first set of WCs and one downstream  
1251 to the second set of WCs form LArIAT time-of-flight (TOF) detector system.

1252 The upstream paddle is made of a 10 x 6 x 1 cm scintillator piece, read out by  
1253 two PMTs mounted on the beam left side which collect the light from light guides  
1254 mounted on all four edges of the scintillator. The downstream paddle is a 14 x 14 x  
1255 1 cm scintillator piece read out by two PMTs on the opposite ends of the scintillator.  
1256 The relatively thin width on the beamline direction minimizes energy loss of the  
1257 particles coming from the target in the scintillator material.

1258 The CAEN 1751 digitizer is used to digitize the TOF PMTs signals at a sampling  
1259 rate of 1 GHz. The 12 bit samples are stored in a circular memory buffer. At trigger  
1260 time, data from the TOF PMTs are recorded to output in a 28.7  $\mu$ s windows starting

1261 approximately 8.4  $\mu$ s before the trigger time.

1262 **TOF functionality**

1263 The TOF signals rise time (10-90%) is 4 ns and a full width, half-maximum of 9 ns  
1264 consistent in time. The signal amplitudes from the upstream TOF and downstream  
1265 TOF are slightly different: 200 mV for the upstream PMTs but only 50 mV for  
1266 downstream PMTs. The time of the pulses was calculated utilizing an oversampled  
1267 template derived from the data itself. We take the pulse pedestal from samples far  
1268 from the pulse and subtract it to the pulse amplitude. We then stretch vertically a  
1269 template to match the pedestal-subtracted pulse amplitude and we move it horizon-  
1270 tally to find the time. With this technique, we find a pulse time-pickoff resolution  
1271 better than 100 ps. The pulse pile up is not a significant problem given the TOF  
1272 timing resolution and the rate of the particle beam. Leveraging on the pulses width  
1273 uniformity of any given PMT, we flag events where two pulses overlap as closely in  
1274 time as 4 ns with an 90% efficiency according to simulation.

1275 We combine the pulses from the two PMTs on each paddle to determine the  
1276 particles' arrival time by averaging the time measured from the single PMT, so to  
1277 minimize errors due to optical path differences in the scintillator. However, a time  
1278 spread of approximately 300 ps is present in both the upstream and downstream  
1279 detectors, likely due to transit time jitter in the PMTs themselves. There is no  
1280 evidence of systematic timing drift over long data-taking periods such as 3-4 months:  
1281 the maximum variation of the average time differences between pairs of PMTs reading  
1282 out the same scintillator is of the order of 150 ps.

1283 **3.2.4 Punch-Through and Muon Range Stack Instruments**

1284 The punch-thorough and the muon range stack (MuRS) detectors are located down-  
1285 stream of the TPC. These detectors provide a sample of TPC crossing tracks without



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

1286 relying on TPC information and can be used to improve particle ID for muons and  
1287 pions with momentum higher than 450 MeV/c.

1288 The punch-thorough is simple sheet of scintillator material, read out by two PMTs.  
1289 The MuRS is a segmented block of steel with four slots instrumented with scintillation  
1290 bars. The four steel layers in front of each instrumented slot are 2 cm, 2 cm, 14 cm  
1291 and 16 cm wide in the beam direction. Each instrumented slot is equipped with  
1292 four scintillation bars each, positioned horizontally in the direction orthogonal to the  
1293 beam. Each scintillator bar measures ? x ? x 2 cm and it is read out by one PMT.

1294 The signals from both the punch-thorough and the MuRS PMTs are digitized in  
1295 the CAEN V1740, same as the TPC; the details of this discriminator are laid out  
1296 in 3.3.2. It is worth noticing that the sampling time of the CAEN V1740 is slow  
1297 (of the order of 128 ns), so pulse shape information from the PMT is lost. Punch-  
1298 thorough and MuRS hits are formed utilizing the digital discriminator signals under  
1299 threshold at a given time, where we obtain the threshold for each PMT directly on  
1300 data distributions.

1301 **3.2.5 LArIAT Cosmic Ray Paddle Detectors**

1302 LArIAT triggers both on beam events and on cosmic rays events. We perform this  
1303 latter trigger by using two sets of cosmic ray paddle detectors (a.k.a. “cosmic towers”.)  
1304 The cosmic towers frame the LArIAT cryostat, as one sits in the downstream left  
1305 corner and the other sits in the upstream right corner of the cryostat. Two paddle  
1306 sets of four scintillators pieces each make up each cosmic tower, an upper set and a  
1307 lower set per tower. Of the four paddles, a couple of two matched paddles stands  
1308 upright while the a second matched pair lies across the top of the assembly in the top  
1309 sets (or across the bottom of the assembly in the bottom sets). The horizontal couple  
1310 is used as a veto for particles traveling from inside the TPC out. The four signals  
1311 from the vertical paddles along one of the body diagonals of the TPC are combined  
1312 in a logical “AND”. This allows to select cosmic muons crossing the TPC along one  
1313 of its diagonals. Cosmic ray tracks crossing both anode and cathode populate the  
1314 events triggered this way. This particularly useful sample of tracks (which we can  
1315 safely assume to be associated with 5 GeV muons) can be used for many tasks; for  
1316 example, we use anode-cathode piercing tracks to cross check the TPC electric field  
1317 on data (see Appendix A), to calibrate the charge response of the TPC wires for the  
1318 full TPC volume and to measure the electron lifetime in the chamber (see section  
1319 ??).

1320 A Zener-diode Hamamatsu H5783 PMT collects the light from a wavelength-  
1321 shifting optical fiber which runs along one of the long sides of each paddle. A custom-  
1322 made PMT Amplifier and Discrimination (PAD) circuit mounted at one end of the  
1323 paddle collects signals from the PMTs and sends them to the Control and Concentra-  
1324 tor Unit (CCU). We use the same connection to power the PMT, control voltage and  
1325 threshold, and output the PMT signal as logic ECL pulse. We retrieved the scintilla-  
1326 tion paddles from the decommissioning of the CDF detector at Fermilab and we used  
1327 only the paddles with a counting efficiency greater than 95% and low noise at working

1328 voltage. The measured trigger rate of the whole system is 0.032 Hz, corresponding  
1329 to  $\sim 2$  muons per minute.



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

### 1330 3.3 In the Cryostat

#### 1331 3.3.1 Cryogenics and Argon Purity

1332 LArIAT repurposed the ArgoNeuT cryostat [16] in order to use it in a beam of charge  
1333 particles, and added a new process piping and a new liquid argon filtration system in  
1334 FTBF. Inside the LArIAT experimental hall, the cryostat sits on the beam of charge  
1335 particles with its horizontal main axis oriented parallel to the beam.

1336 Two volumes make up LArIAT cryostat, shown in Figure 3.7: the inner vessel and  
1337 the outer vessel. Purified liquid argon fills the inner vessel, while the outer volume  
1338 provides insulation through a vacuum jacket equipped with layers of aluminized mylar  
1339 superinsulation. The inner vessel is a cylinder of 130 cm length and 6.2 cm diameter,  
1340 containing about 550 L of LAr, corresponding to a mass of 0.76 ton. We run the  
1341 signal cables for the LArTPC and the high voltage feedthrough through a “chimney”  
1342 at the top and mid-length of the cryostat.

1343 Given the different scopes of the ArgoNeuT and LArIAT detectors, we made

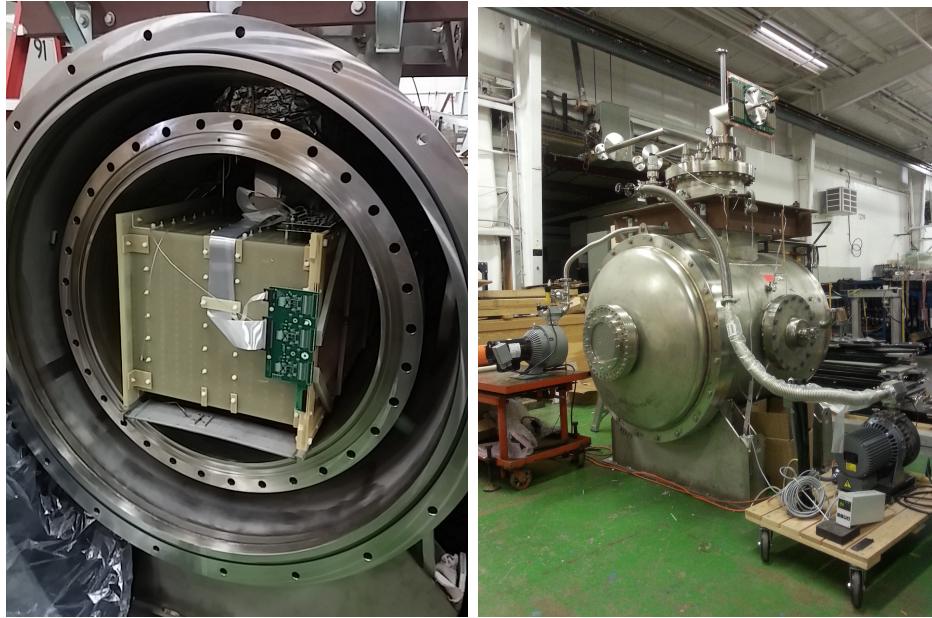


Figure 3.7: Left: the LArIAT TPC in the inner volume of the open cryostat. Right: cryostat fully sealed ready to be transported to FTBF.

1344 several modification to the ArgoNeuT cryostat in order to use it in LArIAT. In par-  
 1345 ticular, the modification shown in Figure 3.8 were necessary to account for the beam  
 1346 of charged particles entering the TPC and to employ the new FTBT liquid argon  
 1347 purification system. We added a “beam window” on the front outer end cap and an  
 1348 “excluder” on the inner endcap, with the scope of minimizing the amount of dead  
 1349 material upstream of the TPC’s active volume. Doing so, we reduced the amount  
 1350 of uninstrumented material before the TPC from  $\sim 1.6$  radiation lengths ( $X_0$ ) (ArgoNeuT)  
 1351 to less than  $0.3 X_0$  (LArIAT). To allow studies of the scintillation light, we  
 1352 added a side port feedthrough which enables the mounting of the light collection sys-  
 1353 tem, as well as the connections for the corresponding signal and high-voltage cables  
 1354 (see Section 3.3.3). We modified the bottom of the cryostat adding Conflat and ISO  
 1355 flange sealing to connect the liquid argon transfer line to the new argon cooling and  
 1356 purification system.

1357 As in any other LArTPC, argon purity is a crucial parameter for LArIAT. Indeed,  
 1358 the presence of contaminants effects both the basic working principles of a LArTPC,



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 reduce the amount of non-instrumented material before the TPC; 3) the side port to host the light collection system.

as shown in section 2.1.2: electronegative contaminants such as oxygen and water decrease the number of ionization electrons collected on the wires after drifting through the volume. In addition, contaminants such as Nitrogen decrease the light yield from scintillation light, especially in its slow component. In LArIAT, contaminations should not exceed the level of 100 parts per trillion (ppt). We achieve this level of purity in several stages. The specifics required for the commercial argon bought for LArIAT are 2 parts per million (ppm) oxygen, 3.5 ppm water, and 10 ppm nitrogen. This argon is monitored with the use of commercial gas analyzer. Argon is stored in a dewar external to LArIAT hall and filtered before filling the TPC. LArIAT uses a filtration system designed for the Liquid Argon Purity Demonstrator (LAPD) [52]: half of a 77 liter filter contains a 4A molecular sieve (Sigma-Aldrich [102]) apt to remove mainly water, while the other half contains BASF CU-0226 S, a highly dispersed copper oxide impregnated on a high surface area alumina, apt to remove mainly oxygen [25]. A single pass of argon in the filter is sufficient to achieve the necessary

1373 purity, unless the filter is saturated. In case the filter saturates, the media needs to  
1374 be regenerated by using heated gas; this happened twice during the Run II period<sup>1</sup>.  
1375 The filtered argon reaches the inner vessel via a liquid feedthrough on the top of  
1376 the cryostat. Argon is not recirculated in the system, rather it boils off and vent to  
1377 the atmosphere. During data taking, we replenish the argon in the cryostat several  
1378 times per day to keep the TPC high voltage feedthrough and cold electronics always  
1379 submerged. In fact, we constantly monitor the level, temperature, and pressure of  
1380 the argon both in the commercial dewar and inside the cryostat during data taking.

### 1381 **3.3.2 LArTPC: Charge Collection**

1382 The LArIAT Liquid Argon Time Projection Chamber is a rectangular box of dimen-  
1383 sions 47 cm (width) x 40 cm (height) x 90 cm (length), containing 170 liters of Liquid  
1384 Argon. The LArTPC three major subcomponents are

- 1385 1) the cathode and field cage,  
1386 2) the wire planes,  
1387 3) the read-out electronics.

#### 1388 **Cathode and field cage**

1389 A G10 plain sheet with copper metallization on one of the 40 x 90 cm inner surfaces  
1390 forms the cathode. A high-voltage feedthrough on the top of the LArIAT cryostat  
1391 delivers the high voltage to the cathode; scope of the high voltage system (Figure 3.9)  
1392 is to drift ionization electrons from the interaction of charged particles in the liquid  
1393 argon to the wire planes. The power supply used in this system is a Glassman  
1394 LX125N16 [64] capable of generating up to -125 kV and 16 mA of current, but

---

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

1395 operated at -23.5kV during LArIAT Run-II. The power supply is connected via high  
1396 voltage cables to a series of filter pots before finally reaching the cathode.

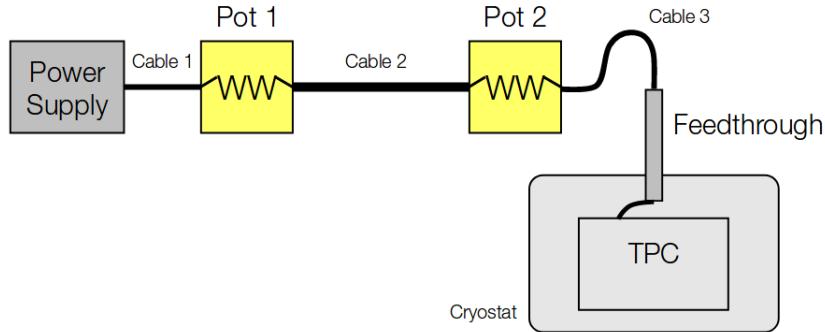


Figure 3.9: Schematic of the LArIAT high voltage system.

1397 The field cage is made of twenty-three parallel copper rings framing the inner  
1398 walls of the G10 TPC structure. A network of voltage-dividing resistors connected to  
1399 the field cage rings steps down the high voltage from the cathode to form a uniform  
1400 electric field. The electric field over the entire TPC drift volume is 486 V/cm (see  
1401 A). The maximum drift length, i.e. the distance between cathode and anode planes,  
1402 is 47 cm.

1403 **Wire planes**

1404 The wire planes measure the charge deposited in the TPC active volume. The drifting  
1405 charge induces a current on the wire of the inner planes and it is collected on the  
1406 collection plane wires. LArIAT counts three wire planes separated by 4 mm spaces:  
1407 in order of increasing distance from the cathode, they are the shield, the induction  
1408 and the collection plane. The “wire pitch”, i.e., the distance between two consecutive  
1409 wires in a given plane, is 4 mm. The shield plane counts 225 parallel wires of equal  
1410 length oriented vertically. This plane is not connected with the read-out electronics;  
1411 rather it shields the outer planes from extremely long induction signals due to the  
1412 ionization chamber in the whole drift volume. As the shield plane acts almost like a

1413 Faraday cage, the shape of signals in the first instrumented plane (induction) results  
1414 easier to reconstruct. Both the induction and collection planes count 240 parallel wires  
1415 of different length oriented at  $60^\circ$  from the vertical with opposite signs. Electrons  
1416 moving past the induction plane will induce a bipolar pulse on its wires; the drifting  
1417 electrons will be then collected on the collection plane's wires, forming a unipolar  
1418 pulse.

1419 The three wire planes and the cathode form three drift volumes, as shown in Figure  
1420 3.10. The main drift volume is defined as the region between the cathode plane and the  
1421 shield plane (C-S). The other two drift regions are those between the shield plane and  
1422 the induction plane (S-I), and between the induction plane and the collection plane  
1423 (I-C). The electric field in these regions is chosen to satisfy the charge transparency  
1424 condition and allow for 100% transmission of the drifting electrons through the shield  
1425 and the induction planes.

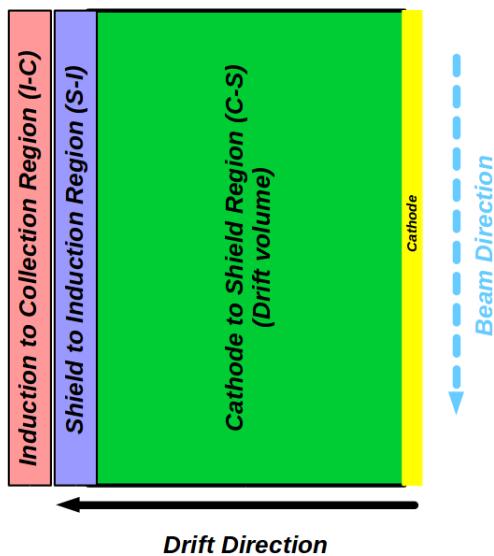


Figure 3.10: Schematic of the three drift regions inside the LArIAT TPC: the main drift volume between the cathode and the shield plane (C-S) in green, the region between the shield plane and the induction plane (S-I) in purple, and the region between the induction plane and the collection plane (I-C)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

1426 Table 3.1 provides the default voltages applied to the cathode and the shield,

1427 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

1428 **Electronics**

1429 Dedicated electronics read the induction and collection plane wires, for a total of  
1430 480-channel analog signal path from the TPC wires to the signal digitizers. A digital  
1431 control system for the TPC-mounted electronics, a power supply, and a distribution  
1432 system complete the front-end system. Figure 3.11 shows a block diagram of the  
1433 overall system. The direct readout of the ionization electrons in liquid argon forms  
1434 typically small signals on the wires, which need amplification in oder to be processed.  
1435 LArIAT performs the amplification stage directly in cold with amplifiers mounted on  
1436 the TPC frame inside the liquid argon, achieving a remarkable Signal-to-Noise ratio.  
1437 The signal from the ASICs are driven to the other end of the readout chain, to the  
1438 CAEN V1740 digitizers. The CAEN V1740 has a 12 bit resolution and a maximum  
1439 input range of 2 VDC, resulting in about 180 ADC count for a crossing MIP.

1440 **3.3.3 LArTPC: Light Collection System**

1441 The collection of scintillation photons is the second mechanism of particle detection  
1442 in argon other than the ionization electrons. Over the course of LArIAT's three years  
1443 of data taking, the light collection system changed several times. We describe here  
1444 the light collection system for Run II. Two PMTs, a 3-inch diameter Hamamatsu  
1445 R-11065 and 2-inch diameter ETL D757KFL [6], as well as three SiPMs arrays (two  
1446 Hamamatsu S11828-3344M 4x4 arrays and one single-channel SensL MicroFB-60035)  
1447 are mounted on the PEEK support structure. PEEK screws into an access flange

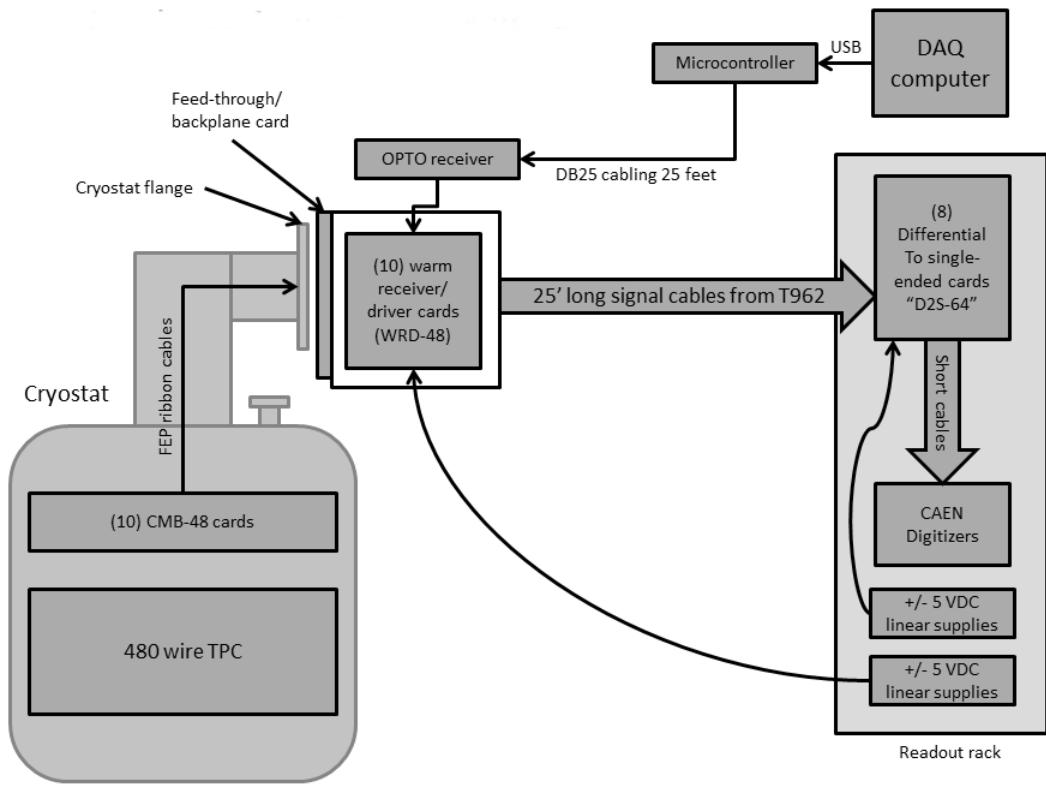


Figure 3.11: Overview of LArIAT Front End electronics.

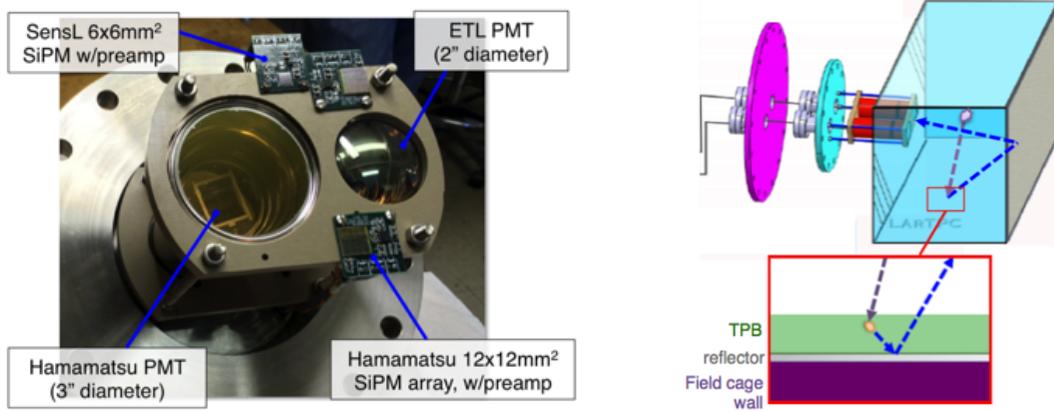


Figure 3.12: LArIAT’s photodetector system for observing LAr scintillation light inside the TPC (left), and a simplified schematic of VUV light being wavelength-shifting along the TPB-coated reflecting foils (right).

as shown in Figure 3.12, on the anode side, leaving approximately 5 cm of clearance from the collection plane.

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

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

## 1464 3.4 Trigger and DAQ

1465 The LArIAT DAQ and trigger system governs the read out of all the many subsystems  
1466 forming LArIAT. The CAEN V1495 module and its user-programmable FPGA are  
1467 the core of this system. Every 10 ns, this module checks for matches between sixteen  
1468 logical inputs and user-defined patterns in the trigger menu; if it finds a match for  
1469 two consecutive clock ticks, that trigger fires.

1470 LArIAT receives three logic from the Fermilab accelerator complex related to the  
1471 beam timing which we use as input triggers: a pulse just before the beam, a  
1472 pulse indicating beam-on, and a beam-off pulse.

1473 The beam instruments, the cosmic ray taggers, and the light collection system  
1474 provide the other NIM-standard logic pulse inputs to the trigger decision. We auto-  
1475 matically log the trigger inputs configuration with the rest of the DAQ configuration  
1476 at the beginning of each run.

1477 Fundamental inputs to the trigger card come from the TOF (see Sec. 3.2.3) and  
1478 the wire chambers (see Sec. 3.2.2), as activity in these systems points to the presence  
1479 of a charged particle in tertiary beam line. In particular, the discriminated pulses  
1480 from the TOF PMTs form a NIM logic pulse for the trigger logic. We ask for a  
1481 coincidence within a 20 ns window for all the pulses from the PMTs looking at the  
1482 same scintillator block and use the coincidence between the upstream and downstream  
1483 paddle to inform the trigger decision. In order to form a coincidence between the  
1484 upstream and downstream paddles, we delay the upstream paddle coincidence by  
1485 20 ns and widen it by 100 ns. The delay and widening are necessary to account for  
1486 both lightspeed particles and slower particles (high-mass) to travel the 6.5 m between  
1487 the upstream and the downstream paddles. For the read out of the wire chambers,  
1488 we use a total of sixteen multi-hit TDCs, four per chamber: two TDC per plane  
1489 (horizontal and vertical), sixty-four wires per TDC. In each TDC, we keep the logical  
1490 “OR” for any signal over threshold from the sixty-four wires. We then require a

1491 coincidence between the “OR” for the horizontal TDCs and the “OR” for the vertical  
1492 TDCs: with this logic we make sure that at least one horizontal wire and one vertical  
1493 wire saw significant signal in one wire chamber. The single logical pulse from each of  
1494 the four wire chambers feeds into the first four inputs to the V1495 trigger card. We  
1495 require a coincidence within 20 ns of at least three logical inputs to form a trigger.

1496 The cosmic towers (see Section 3.2.5) provide another primary input to the trigger,  
1497 in order to capture long tracks from cosmic muons crossing the TPC. We use NIM  
1498 modules to require coincidences between one upper and one lower paddle set of any  
1499 opposite cosmic towers. The OR all the opposite towers’ coincidences is fed as an  
1500 input to the trigger card.

1501 We use the signal from the cryogenic PMTs (see Section ??) to form several  
1502 interesting triggers. The coincidence of signal from all the PMT pulses within  $\sim$ 20 ns  
1503 is an indication of ionizing radiation in the TPC and forms a trigger input. The  
1504 coincidence of two subsequent scintillation logic pulses delayed by a maximum of  $7\ \mu s$   
1505 forms the Michel electron trigger.

## 1506 **3.5 Control Systems**

1507 LArIAT is a complex ensemble of systems which needed to be monitored at once  
1508 during data taking. We performed the monitoring of the systems operations with a  
1509 slow control system, a DAQ monitoring system and a low level data quality monitoring  
1510 described in the following sections.

### 1511 **Slow Control**

1512 We used the Synoptic Java Web Start framework as a real-time display of subsystem  
1513 conditions. Its simple Graphical User Interface allowed us to change the operating  
1514 parameters and to graph the trends of several variables of interest for all the tertiary

beam detectors. Among the most important quantities monitored by Synoptic there  
 are the level of argon in both the inner vessel and the external dewar, the operating  
 voltages of cathode and wire planes, of the PMTs and SiPMs, and of the four wire  
 chambers, as well as the magnets temperature. Figure 3.13 shows an example of the  
 monitoring system. LArIAT uses the Accelerator Control NETwork system (ACNET)  
 to monitor the beam conditions of the MCenter beamline. For example, the 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.

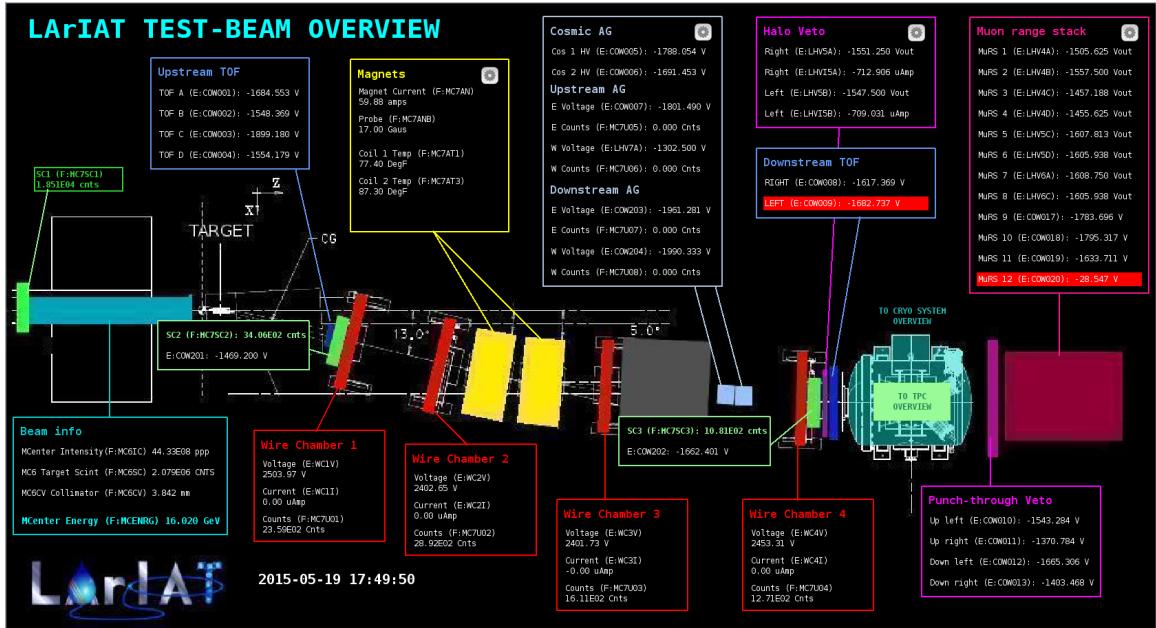


Figure 3.13: Interface of the Synoptic slow control system

## 1523 DAQ Monitoring

We monitor the data taking and the run time evolution with the Run Status Webpage  
 (<http://lariat-wbm.fnal.gov/lariat/run.html>), a webpage updated in real-time. The  
 page displays, among other information, the total number of triggers in the event,  
 the total number of detectors triggered during a beam spill, the trigger patterns, the  
 number of times a particular trigger pattern was satisfied during a beam spill, and

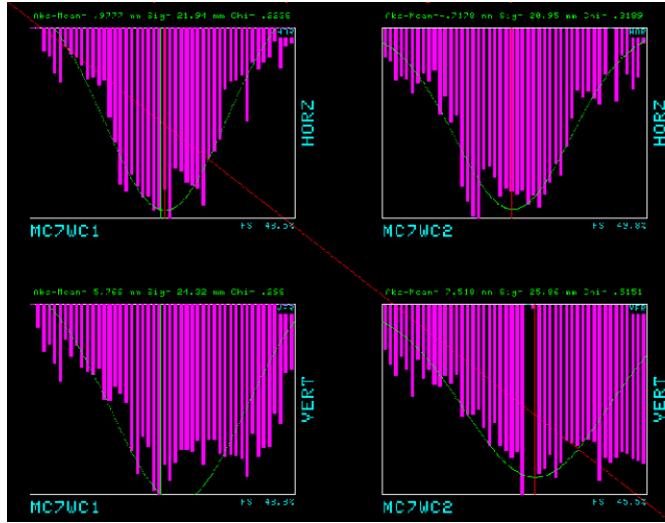


Figure 3.14: Beam position at the upstream wire chambers monitored with ACNET.

1529 the current time relative to the Fermilab accelerator complex supercycle. A screen  
 1530 shot of the page is show in figure 3.15.

### 1531 Data Quality Monitoring

1532 We employ two systems to ensure the quality of out data during data taking: the  
 1533 Near-Real-Time Data Quality Monitoring and the Event Viewer.

1534 The Near-Real-Time Data Quality Monitoring (DQM) is a webpage which receives  
 1535 updates from all the VME boards in the trigger system and displays the results of  
 1536 a quick analysis of the DAQ stream of raw data on a spill-by-spill basis. The DQM  
 1537 allows the shifter to monitor almost in real time (typically with a 2-minute delay)  
 1538 a series of low level-quantities and compare them to past collections of beam spills.  
 1539 Some of the variables monitored in the DQM are the pedestal mean and RMS on  
 1540 CAEN digitizer boards of the TPC wires and PMTs of the beamline detectors, the  
 1541 hit occupancy and timing plots on the wire chambers, and number of data fragments  
 1542 recorded that are used to build a TPC event. Abnormal values for low-level quantity  
 1543 in the data activate a series of alarms in the DQM; this quick feedback on the DAQ  
 1544 and beam conditions is fundamental to assure a fast debugging of the detector and a

1545 very efficient data taking during beam uptime.

1546 The online Event Viewer displays a two dimensional representation of LArIAT  
1547 TPC events on both the Induction and the Collection planes in near real time. The  
1548 raw pulses collected by the DAQ on each wire are plotted as a function of drift  
1549 time, resulting in an image of the TPC event easily readable by the shifter. This  
1550 tool guarantees a particularly good check of the TPC operation which activate an  
1551 immediate feedback for troubleshooting a number of issues. For example, it easy for  
1552 the shifter to spot high occupancy events and request a reduction of the primary beam  
1553 intensity, or to spot a decrease of the argon purity which requires the regeneration of  
1554 filters, or to catch the presence of electronic noise and reboot the ASICs. An example  
1555 of high occupancy event is shown in 3.16.

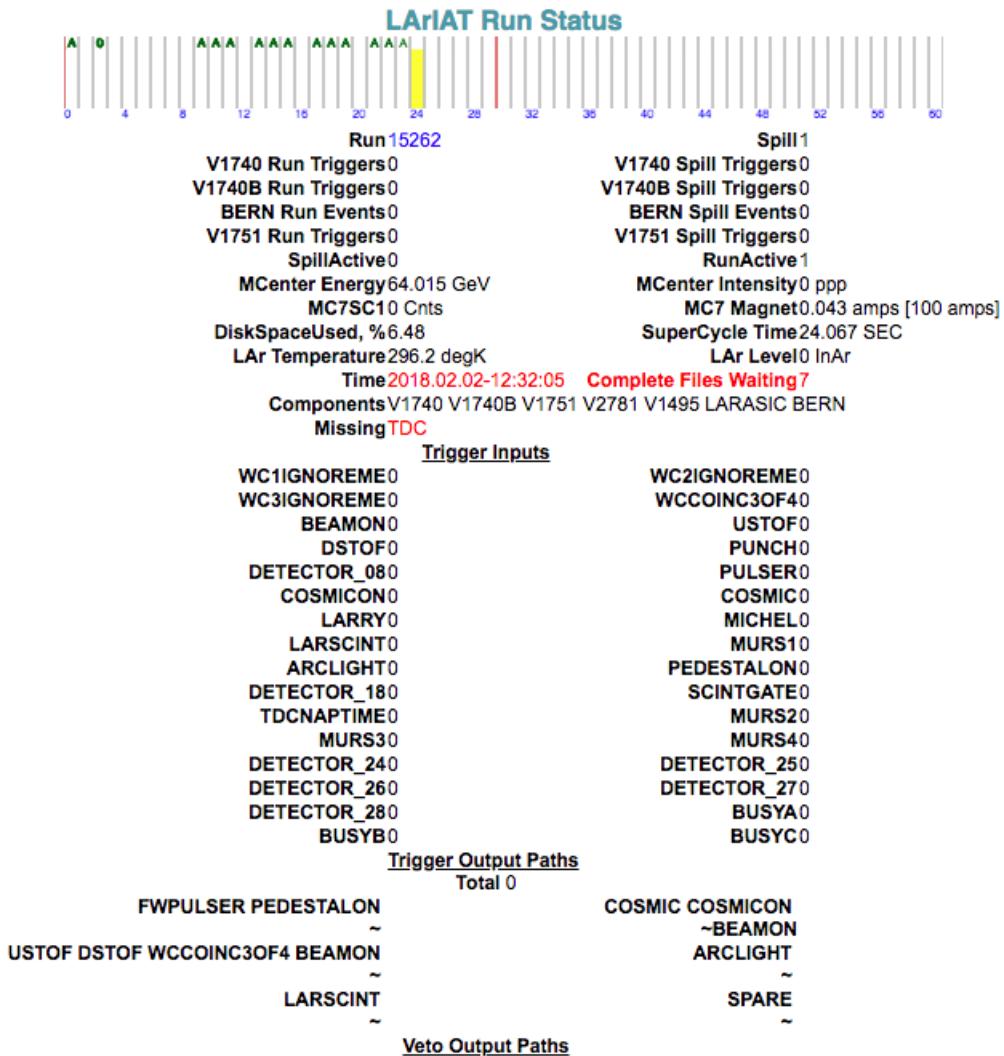


Figure 3.15: Run Status page at LArIAT downtime. At the top the yellow bar displays the current position in the Fermilab supercycle. Interesting information to be monitored by the shifter were the run number and number of spills, time elapsed from data taking (here in red), the energy of the secondary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

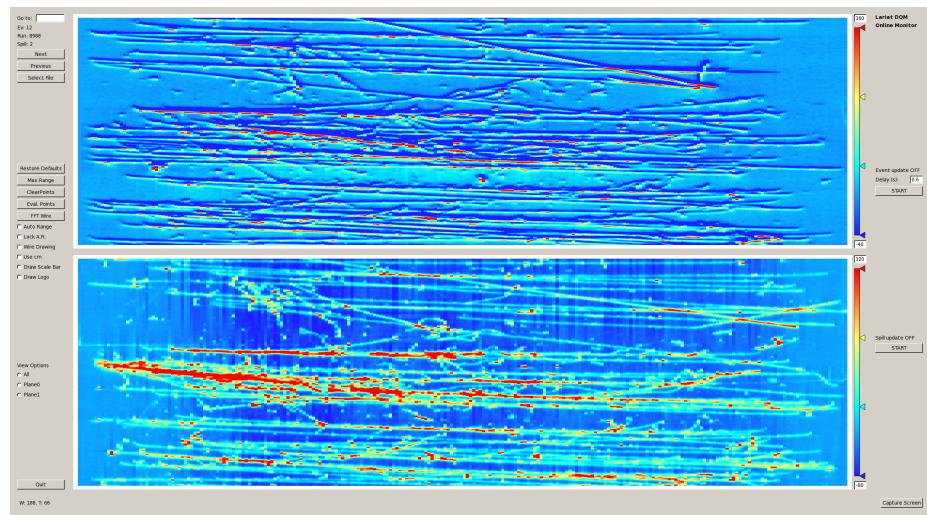


Figure 3.16: High occupancy event display: induction plane (top) and collection plane (bottom).

1556 **Chapter 4**

1557 **Hadron Interactions in Argon:**  
1558 **Cross Section**

1559 **4.1 How to Measure a Hadron Cross Section in**  
1560 **LArIAT**

1561 We use both the LArIAT beamline detectors and the LArTPC information to measure  
1562 hadronic cross sections in argon. Albeit with small differences, both the  $\pi^-$  - Ar  
1563 and  $K^+$  - Ar total hadronic cross section measurements rely on the same procedure  
1564 described in details in the following paragraphs: we select the particle of interest  
1565 using a combination of beamline detectors and TPC information (paragraph 4.1.1),  
1566 we perform a handshake between the beamline information and the TPC tracking to  
1567 assure we are selecting the right TPC track (paragraph 4.1.2), and we apply the “thin  
1568 slice” method to get to the final result (paragraph 4.1.3). At the end of this chapter,  
1569 we show a cross check of this method against MC truth information (paragraph 4.1.4).

1570 **4.1.1 Event Selection**

1571 **Beamline events**

1572 As will be clear in paragraph 4.1.3, beamline particle identification and momentum  
1573 measurement before entering the TPC are fundamental information for the hadronic  
1574 cross sections measurements in LArIAT. Thus, we scan the LArIAT data to keep only  
1575 events whose wire chamber and time of flight information is registered. Additionally,  
1576 we perform a check of the plausibility of the trajectory inside the beamline detectors:  
1577 given the position of the hits in the four wire chambers, we make sure the particle  
1578 trajectory does not cross any impenetrable material such as the collimator and the  
1579 magnets steel.

1580 **Particle Identification in the beamline**

1581 In data, the main tool to establish the identity of the hadron of interest is the LArIAT  
1582 tertiary beamline, in its function of mass spectrometer. We combine the measurement  
1583 of the time of flight,  $TOF$ , and the beamline momentum,  $p_{Beam}$ , to reconstruct the  
1584 invariant mass of the particles in the beamline,  $m_{Beam}$ , as follows

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

1585 where  $c$  is the speed of light and  $l$  is the length of the particle trajectory between the  
1586 time of flight paddles.

1587 Figure 4.1 shows the mass distribution for the Run II negative polarity runs on  
1588 the left and positive polarity runs on the right. We perform the classification of events  
1589 into the different samples as follows:

1590 •  $\pi, \mu, e$ :  $0 \text{ MeV} < \text{mass} < 350 \text{ MeV}$

1591 • kaon:  $350 \text{ MeV} < \text{mass} < 650 \text{ MeV}$

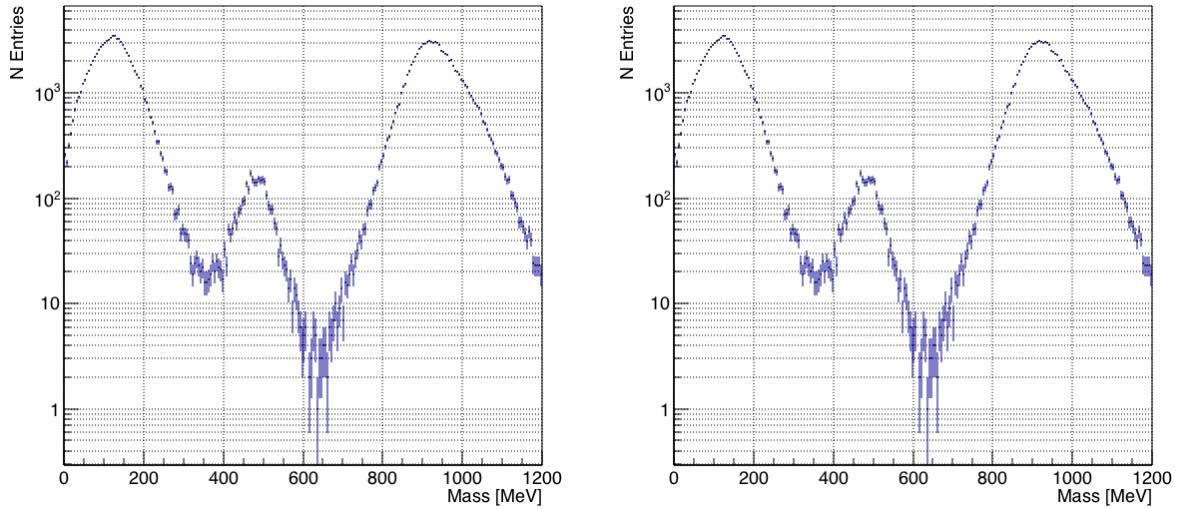


Figure 4.1: The mass plotted for a sample of Run-II events reconstructed in the beamline, negative polarity runs on the left and positive polarity runs on the right. The classification of the events into  $\pi$ ,  $\mu$ ,  $e$ , kaon, or proton is based on this distribution.  
**CHANGE PLOTS**

- 1592     • proton:  $650 \text{ MeV} < \text{mass} < 3000 \text{ MeV}$ .

1593     **Additional Particle Identification technique**

1594     In the case of the  $\pi^-$ -Ar cross section, the resolution of beamline mass spectrometer is  
 1595     not sufficient to select a beam of pure pions. In fact, muons and electrons survive the  
 1596     selection on the beamline mass value. It is important to notice that the composition  
 1597     of the negative polarity beam is mostly pions, as discussed in ???. Anyhow, we devise  
 1598     a selection on the TPC information to mitigate the presence of electrons in the sample  
 1599     used for the pion cross section. The selection relies on the different topologies of a  
 1600     pion and an electron event in the argon: while the former will trace a track inside the  
 1601     TPC active volume, the latter will tend to “shower”, i.e. interact with the medium,  
 1602     produce bremsstrahlung photons which pair convert into several short tracks. We  
 1603     provide details of this selection in section ??.

1604 **Pile up mitigation**

1605 The secondary beam impinging on LArIAT secondary target produces a plethora  
1606 of particles. The presence of upstream and downstream collimators greatly abates  
1607 the number of particles tracing down the LArIAT beamline. However, more than one  
1608 beamline particles, or particles produced from the beam interaction with the beamline  
1609 detectors, may sneak into the LArTPC during its readout time. The TPC readout  
1610 is triggered by the actual particle firing the beamline detectors; we call “pile up”  
1611 the additional traces in the TPC. We adjusted the primary beam intensity between  
1612 LArIAT Run I and Run II to minimize the presence of events with high pile up  
1613 particles in the data sample. For the cross section analyses, we remove events with  
1614 more than 4 tracks in the first 14 cm upstream portion of the TPC from the sample.  
1615 probably need to do a better job explaining pile up

1616 **4.1.2 Wire Chamber to TPC Match**

1617 For each event passing the selection on its beamline information we need to identify  
1618 the track inside the TPC corresponding to the particle which triggered the beamline  
1619 detectors, a procedure we refer to as “WC to TPC match” (WC2TPC for short).  
1620 In general, the TPC tracking algorithm will reconstruct more than one track in the  
1621 event, partially due to the fact that hadrons interact in the chamber, as shown in  
1622 figure ??, and partially because of pile up particles during the triggered TPC drift  
1623 time, as shown in figure ??.

ADD EVENT DISPLAYS

1624 We attempt to uniquely match one wire chamber track to one and only one re-  
1625 constructed TPC track. In data, this match leverages on a geometrical selection  
1626 exploiting both the position of the wire chamber and TPC tracks, and the angle  
1627 between them. We consider only TPC tracks whose first point is in the first 2 cm up-  
1628 stream portion of the TPC for the match. We project the wire chamber track to the  
1629 TPC front face where we define the  $x_{FF}$  and  $y_{FF}$  coordinates used for evaluating the

1630 match. We define  $\Delta X$  as the difference between the  $x$  position of the most upstream  
1631 point of the TPC track and  $x_{FF}$ .  $\Delta Y$  is defined analogously. We define the radius  
1632 difference,  $\Delta R$ , as  $\Delta R = \sqrt{\Delta X^2 + \Delta Y^2}$ . The angle between the incident WC track  
1633 and the TPC track in the plane that contains them defines  $\alpha$ . If  $\Delta R < 4$  cm,  $\alpha < 8^\circ$ ,  
1634 a match between WC-track and TPC reconstructed track is found. We describe how  
1635 we determinate the best value for the radius and angular selection in sec 5.4.1. In  
1636 MC, we mimic the matching between the WC and the TPC track by constructing  
1637 a fake WC track using truth information at wire chamber four. We then apply the  
1638 same WC to TPC matching algorithm as in data. We discard events with multi-  
1639 ple WC2TPC matches. We use only TPC track matched to WC tracks in the cross  
1640 section calculation.

#### 1641 4.1.3 The Thin Slice Method

##### 1642 Cross Sections on Thin Target

1643 Cross section measurements on a thin target have been the bread and butter of nuclear  
1644 and particle experimentalists since the Rutherford experiments NEED CITATION.  
1645 At their core, this type of experiments consists in shooting a beam of particles with  
1646 a known flux on a thin target and recording the outgoing flux.

1647 In general, the target is not a single particle, but rather a slab of material con-  
1648 taining many diffusion centers. The so-called “thin target” approximation assumes  
1649 that the target centers are uniformly distributed in the material and that the target is  
1650 thin compared to the interaction length so that no center of interaction sits in front of  
1651 another. In this approximation, the ratio between the number of particles interacting  
1652 in the target  $N_{Interacting}$  and number of incident particles  $N_{Incident}$  determines the  
1653 interaction probability  $P_{Interacting}$ , which is the complementary to one of the survival

1654 probability  $P_{Survival}$ . Equation 4.2

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

1655 describes the probability for a particle to survive the thin target. This formula relates  
1656 the total cross section  $\sigma_{TOT}$ , the density of the target centers  $n$  and the thickness of  
1657 the target along the incident hadron direction  $\delta X$ , to the interaction probability<sup>1</sup>.

1658 If the target is thin compared to the interaction length of the process considered,  
1659 we can Taylor expand the exponential function in equation 4.2 and find a simple  
1660 proportionality relationship between the number of incident and interacting particles,  
1661 and the cross section, as shown in equation 4.3:

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

1662 Solving for the cross section, we find:

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

### 1663 Not-so-Thin Target: Slicing the Argon

1664 The LArIAT TPC, with its 90 cm of length, is not a thin target. [Find expected](#)  
1665 [interaction length for hadrons and kaons](#). However, the fine-grained tracking of the  
1666 LArIAT LArTPC allows us to treat the argon volume as a sequence of many adjacent  
1667 thin targets.

1668 As described in section 3, LArIAT wire planes count 240 wires each. The wires  
1669 are oriented at +/- 60° from the vertical direction at 4 mm spacing, while the beam  
1670 direction is oriented 3 degrees off the  $z$  axis in the  $XZ$  plane. [review this math](#) The

---

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

wires collect signals proportional to the energy loss of the hadron along its path in  
 a  $\delta X = 4 \text{ mm}/\sin(60^\circ) \approx 4.7 \text{ mm}$  slab of liquid argon. Thus, one can think to slice  
 the TPC into many thin targets of  $\delta X = 4.7 \text{ mm}$  thickness along the direction of the  
 incident particle.

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

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

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

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

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

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

$$\frac{N_{Interacting}(E^{kin})}{N_{Incident}(E^{kin})}.$$

The statistical uncertainty for each energy bin is calculated by error propagation  
 from the statistical uncertainty on  $N_{Incident}$  and  $N_{Interacting}$ . Since the number of

1693 incident hadrons in each energy bin is given by a simple counting, we assume that  
 1694  $N_{Incident}$  is distributed as a poissonian with mean and  $\sigma^2$  equal to  $N_{Incident}$  in each  
 1695 bin. On the other hand,  $N_{Interacting}$  follows a binomial distribution: a particle in a  
 1696 given energy bin might or might not interact. The square of the variance for the  
 1697 binomial is given by

$$\sigma^2 = \mathcal{N}P_{Interacting}(1 - P_{Interacting}); \quad (4.7)$$

1698 since the interaction probability  $P_{Interacting}$  is  $\frac{N_{Interacting}}{N_{Incident}}$  and the number of tries  
 1699  $\mathcal{N}$  is  $N_{Incident}$ , equation 4.7 translates into

$$\sigma^2 = N_{Incident} \frac{N_{Interacting}}{N_{Incident}} \left(1 - \frac{N_{Interacting}}{N_{Incident}}\right) = N_{Interacting} \left(1 - \frac{N_{Interacting}}{N_{Incident}}\right). \quad (4.8)$$

1700  $N_{Incident}$  and  $N_{Interacting}$  are not independent. The uncertainty on the cross section  
 1701 is thus calculated as

$$\delta\sigma_{tot}(E) = \sigma_{tot}(E) \left( \frac{\delta N_{Interacting}}{N_{Interacting}} + \frac{\delta N_{Incident}}{N_{Incident}} \right) \quad (4.9)$$

1702 where:

$$\delta N_{Incident} = \sqrt{N_{Incident}} \quad (4.10)$$

$$\delta N_{Interacting} = \sqrt{N_{Interacting} \left(1 - \frac{N_{Interacting}}{N_{Incident}}\right)}. \quad (4.11)$$

#### 1703 4.1.4 Procedure testing with truth quantities

1704 The  $\pi^-$ -Ar and  $K^+$ -Ar total hadronic cross section implemented in Geant4 can be  
 1705 used as a tool to validate the measurement methodology. We describe here a closure  
 1706 test done on Monte Carlo to prove that the methodology of slicing the TPC retrieves  
 1707 the underlying cross section distribution implemented in Geant4 within the statistical  
 1708 error.

1709        For pions in the considered energy range, the Geant4 inelastic model adopted to  
1710      is “BertiniCascade”, while the elastic model “hElasticLHEP”. For kaons, the Geant4  
1711      inelastic model adopted to is “BertiniCascade”, while the elastic model “hElasti-  
1712      cLHEP”.

1713        For the validation test, we fire about 390000 pions and 140000 kaons inside the  
1714      LArIAT TPC active volume using the DDMC (see sec ??). We apply the thin-sliced  
1715      method on using true quantities to calculate the hadron kinetic energy at each slab  
1716      in order to decouple reconstruction effects to eventual issues with the methodology.  
1717      For each slab of 4.7 mm length on the path of the hadron, we integrate the true  
1718      energy deposition as given by the Geant4 transportation model. Then, we recursively  
1719      subtracted it from the hadron kinetic energy at the TPC front face to evaluate the  
1720      kinetic energy at each slab until the true interaction point is reached. Doing so, we  
1721      obtain the true interacting and incident distributions for the considered hadron and  
1722      we obtain the true MC cross section as a function of the hadron true kinetic energy.

1723        Figure ?? shows the total hadronic cross section for argon implemented in Geant4  
1724      10.01.p3 (solid lines) overlaid with the true MC cross section as obtained with the  
1725      sliced TPC method (markers) for pions on the left and kaons on the right; the total  
1726      cross section is shown in green, the elastic cross section in blue and the inelastic  
1727      cross section in red. The nice agreement with the Geant4 distribution and the cross  
1728      section obtained with the sliced TPC method gives us confidence in the validity of  
1729      the methodology.

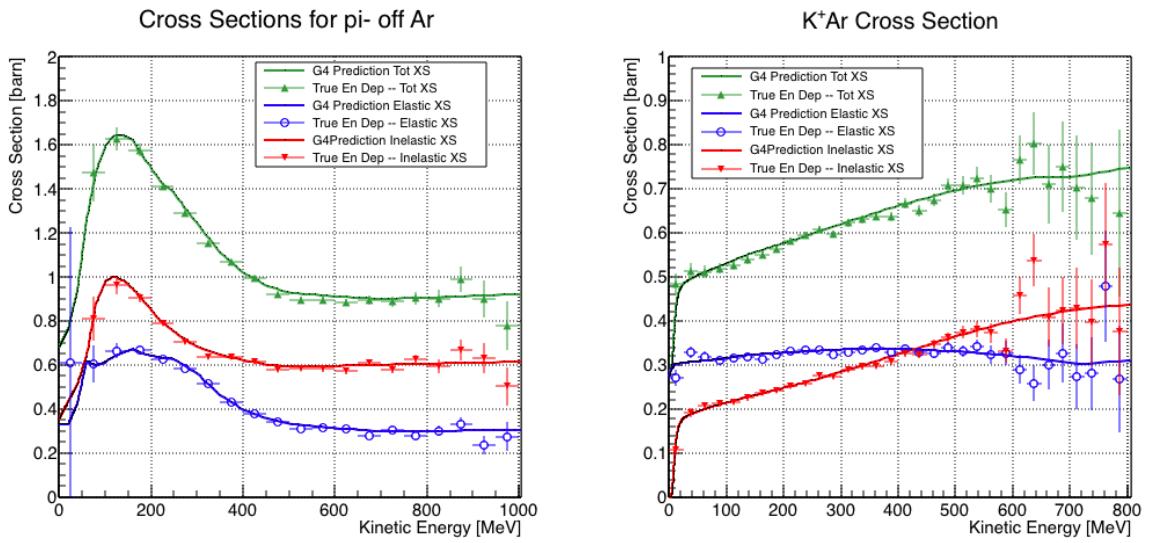


Figure 4.2: Hadronic cross sections for  $\pi^-$ -Ar (left) and  $K^+$ -Ar (right) implemented in Geant4 10.01.p3 (solid lines) overlaid the true MC cross section as obtained with the sliced TPC method (markers). The total cross section is shown in green, the elastic cross section in blue and the inelastic cross section in red.

<sup>1730</sup> **Chapter 5**

<sup>1731</sup> **Samples Preparation**

<sup>1732</sup> This chapter describes the preparation of the data and Monte Carlo samples used for  
<sup>1733</sup> the cross section analyses. This entails:

<sup>1734</sup> 1. the beamline event selection on data,

<sup>1735</sup> 2. the MC production,

<sup>1736</sup> 3. the energy calibration of the detector both in data and MC,

<sup>1737</sup> 4. the optimization of the tracking algorithm for the total cross section analyses.

<sup>1738</sup> **5.1 LArIAT Data**

<sup>1739</sup> **5.2 LArIAT Monte Carlo**

<sup>1740</sup> For the simulation of LArIAT events and their particle make up, we use a combination  
<sup>1741</sup> of two MC generators: the G4Beamline Monte Carlo and the Data Driven single  
<sup>1742</sup> particle Monte Carlo (DDMC). We use the G4Beamline MC to simulate the particle  
<sup>1743</sup> transportation in the beamline and calculate the particle composition of the beam just

1744 past the fourth Wire Chamber (WC4). In order to simulate the beam line particles  
1745 after WC4 and in the TPC, we use the DDMC.

### 1746 5.2.1 G4Beamline

1747 G4Beamline simulates the beam collision with the LArIAT secondary target, the  
1748 energy deposited by the particles in the LArIAT beamline detectors and the action  
1749 of the LArIAT magnets, effectively accounting for particle transportation through  
1750 the beam line from the LArIAT target until “Big Disk”, a fictional, void detector  
1751 located just before the cryostat. At the moment of this writing, G4Beamline does  
1752 not simulated the responses of the beam line detectors. It is possible to interrogate  
1753 the truth level information of the simulated particles in several points of the geometry.

1754 In order to ease the handshake between G4Beamline and the DDMC, we ask for the  
1755 beam composition just after WC4. Since LArIAT data are taken under different  
1756 beam conditions, G4Beamline simulates separately the beam composition according  
1757 to the magnets’ settings and the secondary beam intensity. For the pion cross section  
1758 analysis the relevant beam conditions are secondary beam energy of 64 GeV, negative  
1759 polarity magnet with current of 100 A and 60 A. For the kaon cross section analysis  
1760 the relevant beam conditions is a secondary beam energy of 64 GeV, positive polarity  
1761 magnet with current of 100 A.

1762 DECIDE IF YOU WANT THE BEAM COMPOSITION HERE

### 1763 5.2.2 Data Driven MC

1764 The Data Driven single particle Monte Carlo (DDMC) is a single particle MC gun  
1765 which simulates the particle transportation from WC4 into the TPC leveraging on  
1766 the beamline data information. The DDMC uses the data momentum and position  
1767 at WC4 to derive its initial conditions: a general sketch of the DDMC workflow is  
1768 shown in Figure 5.1.

When producing a DDMC sample, beam line data from a particular running period and/or running condition are selected first. Figure 5.2 schematically shows the data quantities of interest leveraged from data: the momentum ( $P_x, P_y, P_z$ ) and position ( $X, Y$ ) at WC4. For each data event, we obtain the particle position ( $X, Y$ ) at WC4 directly from the data measurement. On the contrary, we calculate the components of the momentum using the beamline measurement of the momentum magnitude (see section 3.2.3) in conjunction with the hits on WC3 and WC4 to determine the direction of the momentum vector. The momentum and position of the selected data is sampled thousand of times through a 5-dimensional hit-or-miss sampling procedure. This produces MC distributions with the same momentum and position distributions as data, with the additional benefit of accounting for the correlations between the considered variables. A LArSoft simulation module then launches single particle MC from  $z = -100$  cm (the location of the WC4) using the sampled momentum and position distributions as a template. As an example, the results of the DDMC generation compared to data for the pion 60A sample are shown in figure ??; as expected, MC and data agree within the statistical uncertainty by construction. Using this technique ensures the MC and data particles have very similar momentum, position and angular distributions at WC4 and allow us to use the MC sample in several occasions, for example to calibrate the energy loss upstream of the TPC or account for the WC2TPC match inefficiency. A small caveat is in order here: the DDMC is a single particle Monte Carlo, which means that the beam pile-up is not simulated. Three sample of **NUMBERS** pions, muons and electrons, as well as a sample of **NUMBERS** kaons have been generated with the DDMC and are used for the MC cross section study.

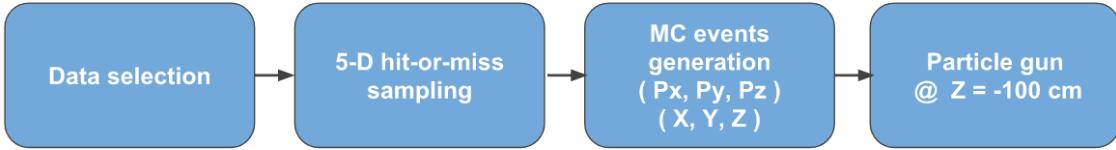


Figure 5.1: Workflow for Data Driven single particle Monte Carlo production.

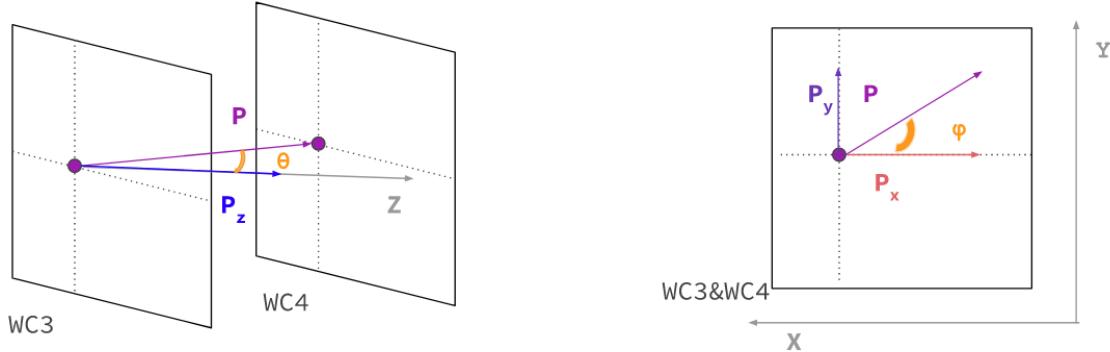


Figure 5.2: Scheme of the quantities of interest for the DDMC event generation:  $P_x, P_y, P_z, X, Y$  at WC4.

### 1793 5.3 Energy Calibration

1794 Scope of the energy calibration is to identify the factors which convert the charge  
1795 collected ( $dQ$ ) to energy deposited in the chamber( $dE$ ). As described in section 2.1.5,  
1796 this is a multi-step procedure. In LArIAT, we first correct the raw charge by the  
1797 electronic noise on the considered wire [?], then by the electron life time [?], and then  
1798 by the recombination effect using the ArgoNeut recombination values. Lastly, we  
1799 apply overall calibration of the energy, i.e. we determine the “calorimetry constants”  
1800 using the procedure described in this paragraph.

1801 The general idea is to use a parametrization of the energy deposited per unit length  
1802 ( $dE/dX$ ) as a function of momentum to independently determine the calorimetry  
1803 constants for the data and Monte Carlo in the LArIAT Run-II data samples. This is  
1804 done by comparing the stopping power measured on reconstructed quantities against  
1805 the Bethe-Bloch theoretical prediction for various particle species.

## Momentum Z Component

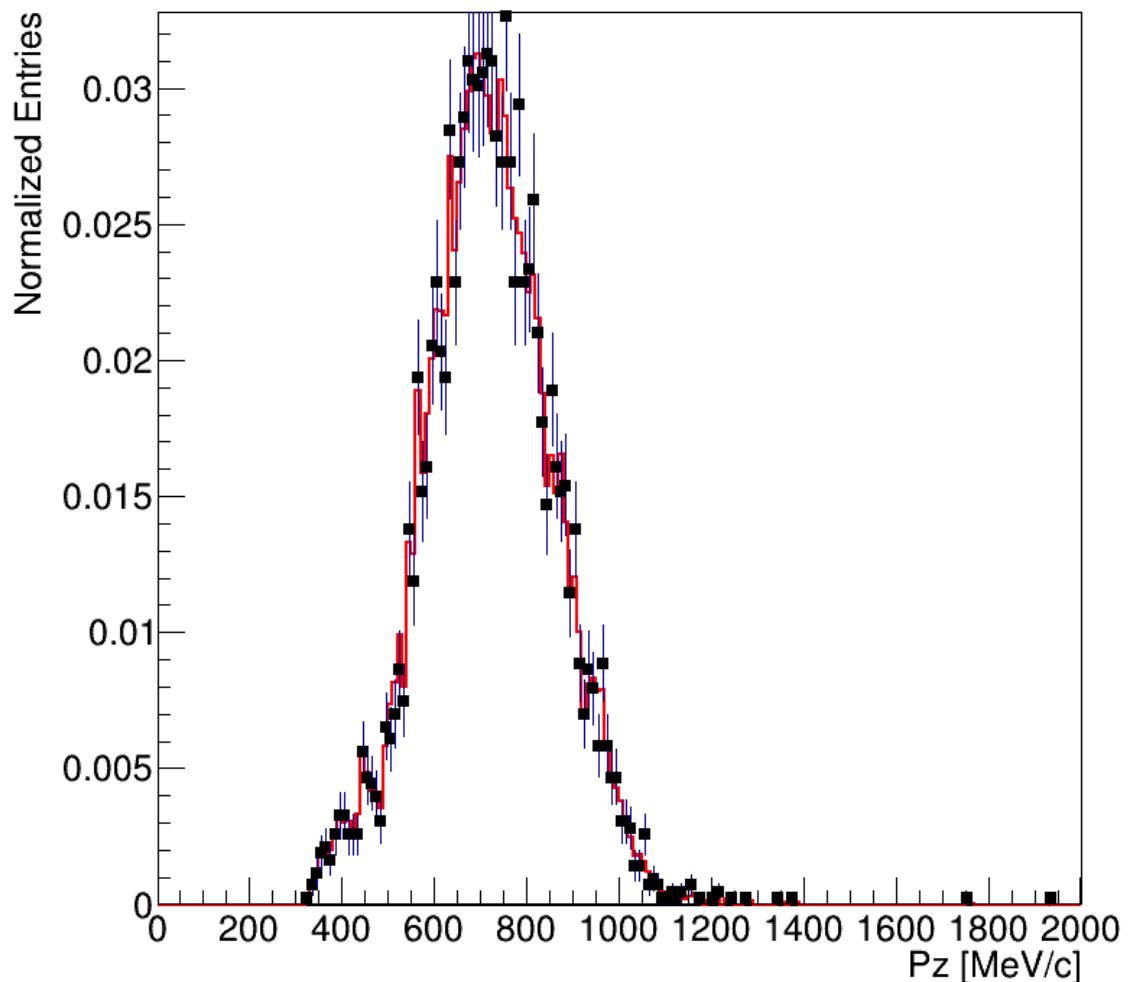


Figure 5.3: Comparison between generated quantities and data distributions for the 60A pion sample: Z component of the momentum (top left), X position at Wire Chamber 4 (top right), Y position at Wire Chamber 4 (bottom).

1806 This is best represented by Figure 5.4, taken from the Particle Data Group [?].  
1807 Using the tables provided by the PDG for liquid argon ( [?]), we calculate the theo-  
1808 retical values for the most probably value for the stopping power of pions ( $\pi$ ), muons  
1809 ( $\mu$ ), kaons ( $K$ ), and protons ( $p$ ) in the momentum range most relevant for LArIAT,  
1810 shown in Figure 5.5.

Figure 5.4: Mean energy loss in various materials over a range of particle momenta as produced in Reference [?].

Figure 5.5: Mean energy loss for pions, muons, and protons in liquid argon over the momentum range most relevant for LArIAT.

1811 Using the predictions in Figure 5.5, allows us to tune the calorimetry constants.  
1812 The goal is to have the data and the Bethe-Bloch prediction agree across the broad  
1813 range of momentum.

1814 The basic idea of this calibration technique is to utilize a portion of a track within  
1815 the LArTPC that has a well known momentum and particle species to measure the  
1816 stopping power (or energy deposited per unit length,  $dE/dX$ ) as recorded inside the  
1817 TPC. Once a sample of particles  $dE/dX$  has been measured at various momenta, we  
1818 then tune to calorimetry constants within the reconstruction software to align these  
1819 measured values to match the theoretical ones found in Figure 5.5.

1820 The calibration procedure follows the following steps:

- 1821 • **Species and Momentum Determination** We first select a sample of beam-  
1822 line events that correspond to either a sample of  $\pi, \mu, e$ , kaons or protons. This  
1823 is done by selecting based on the invariant beamline mass as shown in section  
1824 ???. The beamline particle is matched to the TPC information. In order to de-  
1825 termine the particle momentum at the TPC front face, we use the momentum  
1826 measured by the LArIAT spectrometer and we apply a flat correction for the  
1827 energy loss between the beamline and the TPC. For the Monte Carlo, no such

1828 beamline identification is done and instead we generate DDMC for each particle  
1829 species.

- 1830 • **dE/dX sampling:** With the track within the TPC identified and the momen-  
1831 tum for that track measured, we require the track to be of a minimum length  
1832 of 10 cm long (to ensure we are away from any interaction point where the  
1833 track may be broken into subsequent tracks). We then take the first twelve  
1834 spacepoints of the track (excluding the first point to avoid edge effects near  
1835 the field cage) and sample the reconstructed dE/dX for each point along the  
1836 track. On average, this samples 5 cm of the track (shown in Section ??). These  
1837 dE/dX measurements are then put into a histogram that corresponds to mea-  
1838 sured momentum of the track. The dE/dX histograms are sampled every 50  
1839 MeV in momentum (e.g.  $150 \text{ MeV} < P < 200 \text{ MeV}$ ,  $200 \text{ MeV} < P < 250 \text{ MeV}$ ,  
1840 etc...). On average, pions and muons only lose  $\sim 10$  MeV in this 5 cm section  
1841 of the track and protons lose  $\sim 20$  MeV. Thus choosing 50 MeV size bins for  
1842 our histograms covers the energy spread within those bins due to energy loss  
1843 from ionization. This process of selecting, sampling, and recording the dE/dX  
1844 for various momentum bins is now repeated over the entire sample of events,  
1845 allowing us to collect sufficient statistic in most of the momentum bins between  
1846 150 MeV and 1100 MeV.

- 1847 • **Fit, tune, repeat:** Each 50 MeV momentum binned dE/dX histogram is now  
1848 fit with a simple Landau function. The most probable value (MPV) and the  
1849 associated error on the MPV from the fit are extracted and plotted on Figure  
1850 5.5. Depending on the outcome of the fit, the calorimetry constants are either  
1851 tuned up or down. The values are tuned for both the collection and induction  
1852 plane to try to achieve the best possible match to the theoretical curve. The  
1853 exact match is left as a qualitative exercise and is not quantitatively evaluated.

Figure 5.6: Illustration of the calibration technique. Here we depict a 325 MeV wire chamber track (shown in green) which enters the TPC (taking into account the energy loss from the upstream material) and we sample the first 12 spacepoints (shown in teal) to extract the  $dE/dX$  distribution which is fit with a Landau.

## 1854 5.4 Tracking Studies

1855 In this section, we describe three studies. The first is a justification of the selection  
1856 criteria for the beamline handshake with the TPC information. We perform this  
1857 study to boost the correct identification of the particles in the TPC associated with  
1858 the beamline information, while maintaining sufficient statistics for the cross section  
1859 measurement. The second study is an optimization of the tracking algorithm, with  
1860 the scope of maximizing the identification of the hadronic interaction point inside the  
1861 TPC. These two studies are related, since the optimization of the tracking is per-  
1862 formed on TPC tracks which have been matched to the wire chamber track; in turn,  
1863 the tracking algorithm for TPC tracks determine the number of reconstructed tracks  
1864 in each event used to try the matching with the wire chamber track. Starting with  
1865 a sensible tracking reconstruction, we perform the WC2TPC matching optimization  
1866 first, then the tracking optimization. The WC2TPC match purity and efficiency are  
1867 then calculated again with the optimized tracking.

1868 We perform the following studies on a MC sample of 191000 kaons and 359000  
1869 pions produced with the DDMC technique. DDMC particles are shot from the WC4  
1870 location into the TPC following the beam profile. We mimic the matching between the  
1871 WC and the TPC track on Monte Carlo by constructing a fake WC track using truth  
1872 information at wire chamber four. We then apply the same WC to TPC matching  
1873 algorithm as in data described in 4.1.2.

### 1874 5.4.1 Selection Study for the Wire Chamber to TPC Match

1875 Plots I want in this section:

1876 1. WC2TPC MC DeltaX, DeltaY and  $\alpha$

1877 Scope of this study is assessing the goodness of the wire chamber to TPC match  
1878 on Monte Carlo and decide the selection values we will use on data. A word of caution  
1879 is necessary here. With this study, we want to minimize pathologies associated with  
1880 the presence of the primary hadron itself, e.g. the incorrect association between the  
1881 beamline hadron and its decay products inside the TPC. Assessing the contamination  
1882 from pile-up<sup>1</sup>, albeit related, is beyond the scope of this study.

1883 In MC, we are able to define a correct WC2TPC match using the Geant4 truth  
1884 information. We are thus able to count how many times the WC tracks is associated  
1885 with the wrong TPC reconstructed track.

1886 We define a correct match if the all following conditions are met:

- 1887 - the length of the true primary Geant4 track in the TPC is greater than 2 cm,  
1888 - the length of the reconstructed track length is greater than 2 cm,  
1889 - the Z position of the first reconstructed point is within 2 cm from the TPC  
1890 front face  
1891 - the distance between the reconstructed track and the true entering point is the  
1892 minimum compared with all the other reconstructed tracks.

1893 In order to count the wrong matches, we consider all the reconstructed tracks  
1894 whose Z position of the first reconstructed point lies within 2 cm from the TPC front  
1895 face. Events with true length in TPC < 2 cm are included. Since hadrons are shot  
1896 100 cm upstream from the TPC front face, the following two scenarios are possible  
1897 from a truth standpoint:

1898 [Ta ] the primary hadron decays or interact strongly before getting to the TPC,

---

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

1899 [Tb ] the primary hadron enters the TPC.

1900 Once we choose the selection cuts to determine a reconstructed wire chamber-  
1901 to-TPC match  $r_T$  and  $\alpha_T$ , the following five scenarios are possible in the truth to  
1902 reconstruction interplay :

- 1903 1) only the correct track is matched  
1904 2) only one wrong track is matched  
1905 3) the correct track and one (or more) wrong tracks are matched  
1906 4) multiple wrong tracks matched.  
1907 5) no reconstructed tracks are matched

1908 Since we keep only events with one and only one match, we discard cases 3), 4)  
1909 and 5) from the events used in the cross section measurement. For each set of  $r_T$  and  
1910  $\alpha_T$  selection value, we define purity and efficiency of the selection as follows:

$$\text{Efficiency} = \frac{\text{Number of events correctly matched}}{\text{Number of events with primary in TPC}} \quad (5.1)$$

$$\text{Purity} = \frac{\text{Number of events correctly matched}}{\text{Total number of matched events}}. \quad (5.2)$$

1911 Figure 5.7 shows the efficiency (left) and purity (right) for wire chamber-to-TPC  
1912 match as a function of the radius,  $r_T$ , and angle,  $\alpha_T$ , selection value. It is apparent how  
1913 both efficiency and purity are fairly flat as a function of the radius selection value at a  
1914 given angle. This is not surprising. Since we are studying a single particle gun Monte  
1915 Carlo sample, the wrong matches can occur only for mis-tracking of the primary or  
1916 for association with decay products; decay products will tend to be produced at large  
1917 angles compared to the primary, but could be fairly close to the in  $x$  and  $y$  projection  
1918 of the primary. The radius cut would play a key role in removing pile up events.

1919 For LArIAT cross section measurements, we generally prefer purity over efficiency,  
 1920 since a sample of particles of a pure species will lead to a better measurement. Ob-  
 1921 viously, purity should be balanced with a sensible efficiency to avoid rejecting the  
 1922 whole sample.

1923 We choose  $(\alpha_T, r_T) = (8 \text{ deg}, 4 \text{ cm})$  and get a MC 85% efficiency and 98% purity  
 1924 for the kaon sample and a MC BOH% efficiency and 98% purity for the BOH sample.

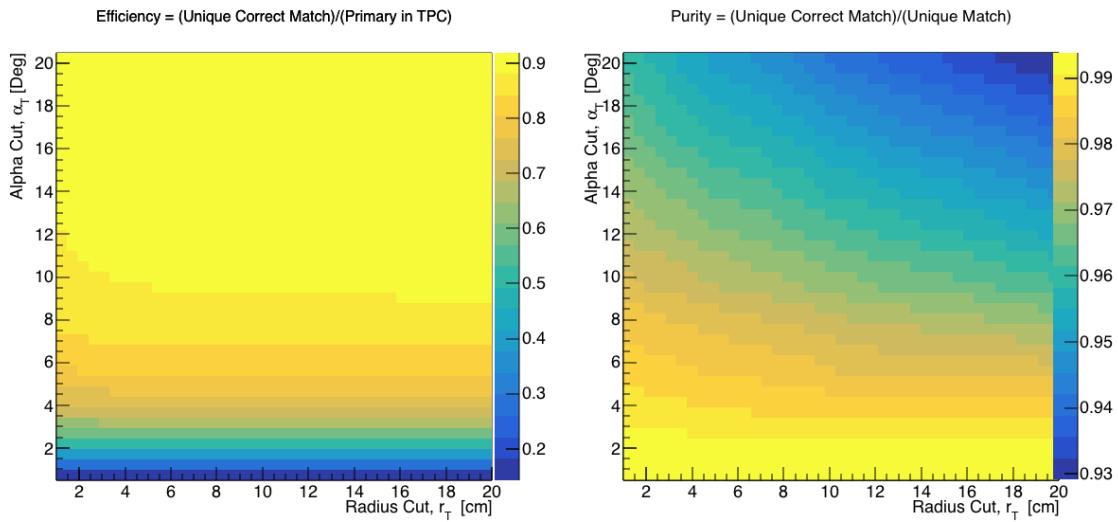


Figure 5.7: Efficiency (left) and purity (right) for wire chamber-to-TPC match as a function of the radius and angle selections.

### 1925 5.4.2 Interaction Point Optimization

1926 Scheme of this subsection

1927 **Brief Explanation of the reconstruction chain**

1928 **Explanation of clustering parameters**

1929 **Figure of merit and spanning of cluster**

1930 **Important numbers out of this optimization**

1931 Plots I want in this section:

- <sub>1932</sub> 1. Delta L, reco - true
- <sub>1933</sub> 2. Delta L, reco - true Elastic, Delta L, reco - true Inelastic, other
- <sub>1934</sub> 3. Length Quality cut
- <sub>1935</sub> 4. Efficiency as a function of true KE and Angle

### <sub>1936</sub> 5.4.3 Tracking spatial and angular resolution

<sub>1937</sub> Scope of this study is understanding and comparing the tracking spatial and angular  
<sub>1938</sub> resolution on data and MC. We start by selecting all the WC2TPC matched tracks.  
<sub>1939</sub> We fit a line on all the space points of the track and calculate the  $\chi^2$ . The  $\chi^2$   
<sub>1940</sub> distribution for data and MC is shown in Figure ??.

<sub>1941</sub> For the spatial and angular resolution study, we reject tracks with less than 14  
<sub>1942</sub> space points. For each track, we order the space points according to their Z position  
<sub>1943</sub> and we split them in two sets: the first set counts all the points belonging to the first  
<sub>1944</sub> half of the track and the second set counts all the points belonging to the second half  
<sub>1945</sub> of the track. We remove the last 5 points in the first set and the first 5 points in the  
<sub>1946</sub> second set, so to have a gap in the middle of the original track. We fit the first and  
<sub>1947</sub> the second set of points with a line separately. We reject the event entirely if the  
<sub>1948</sub>  $\chi^2$  for the fit of either of the halves is greater than four. We define a track middle  
<sub>1949</sub> plane as the plane perpendicular to the original track fit, positioned in the middle  
<sub>1950</sub> of its length. We project the tracks on the middle plane and calculate the impact  
<sub>1951</sub> parameter,  $d$ , i.e. the distance between the projected points. We also calculate the  
<sub>1952</sub> angle between the original track direction and the fit of the first and second half,  
<sub>1953</sub> called  $\alpha_1$  and  $\alpha_2$  respectively. The spatial resolution of the track will be  $\sigma_S = \frac{d}{\sqrt{2}}$   
<sub>1954</sub> while the angular resolution of the tracks will be  $\sigma_\alpha = \alpha_1 - \alpha_2$ . The distributions for  
<sub>1955</sub> data and MC for  $\sigma_\alpha$  and  $\sigma_S$  are given in ??.

# <sup>1956</sup> Chapter 6

## <sup>1957</sup> Background subtraction

### <sup>1958</sup> 6.1 Assessing Beamline Contamination

<sup>1959</sup> Even if pions are by far the biggest beam component in negative polarity runs, the  
<sup>1960</sup> LArIAT beam is not a pure pion beam. While useful to discriminate between pions,  
<sup>1961</sup> kaons, and protons, the beamline detectors are not sensitive enough to discriminate  
<sup>1962</sup> among the lighter particles in the beam: electrons, muons and pions fall under the  
<sup>1963</sup> same mass hypothesis. Thus, we need to assess the contamination from beamline  
<sup>1964</sup> particles other than pions in the event selections used for the pion cross section  
<sup>1965</sup> analysis and correct for its effects.

<sup>1966</sup> We define beamline contamination every TPC track matched to the WC track  
<sup>1967</sup> which is not a primary pion. Potentially, there are 4 different types of beamline  
<sup>1968</sup> contaminations:

- <sup>1969</sup> 1) electrons,
- <sup>1970</sup> 2) muons,
- <sup>1971</sup> 3) secondaries from pion events,
- <sup>1972</sup> 4) matched pile up events.

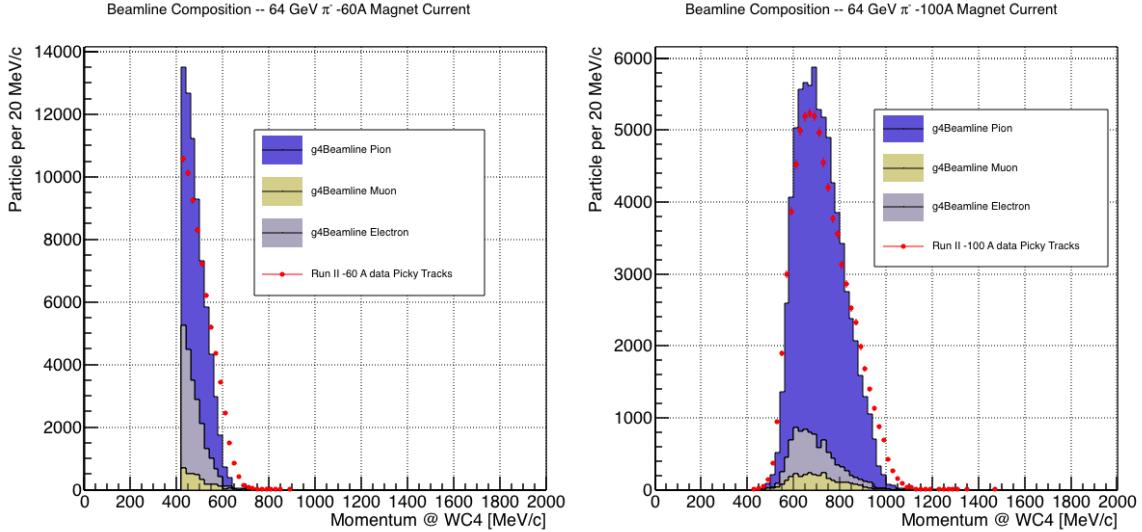


Figure 6.1: Beam composition for the -60A runs (left) and -100A runs (right). The solid blue plot represents the simulated pion content, the yellow plot represents the simulated muon content and the grey plot represents the simulated electron content. The plots are area normalized to the number of data events, shown in red.

1973     So, how do we handle this contamination? The first step is to estimate what  
 1974     percentage of events used in the cross section calculation is not a primary pion. The  
 1975     next two sections will illustrate this estimate for the electrons, muons and secondaries  
 1976     from pion event. We estimate the last type of contamination, the “matched pile up”  
 1977     events, to be a negligible fraction, because of the definition of the WC2TPC match:  
 1978     we deem the probability of a single match with a halo particle in the absence of a  
 1979     beamline particle<sup>1</sup> negligibly small.

### 1980     6.1.1 Electron and Muon contamination

1981     We estimate the percentage of electrons and muons in the beam via the G4Beamline  
 1982     MC. Since the beamline composition is a function of the magnet settings, we simulate  
 1983     separately events for magnet current of -60A and -100A.

1984     Table 6.1 shows the beam composition per magnet setting after the mass selection

---

1. Events with multiple WC2TPC matches are always rejected.

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

Table 6.1: Simulated beamline composition per magnet settings

	I = -60 A	I = -100 A	Total	w <sub>60A</sub>	w <sub>100A</sub>
N Data Events after Mass Selection	70192	76056	146248	0.48	0.52

Table 6.2: Number of data events which fit the pion mass hypothesis as a function of magnet settings. The last two columns represent the fraction of the data in the given magnet setting.

1985 according to the G4Beamline simulation.

1986 We calculate the electron to pion, as well as the muon to pion ratio on the whole  
1987 sample as the weighted sum of the corresponding ratio in the two current settings,

$$\frac{N_e}{N_{\pi} \text{Data}} = w_{60A} \frac{N_e}{N_{\pi} 60A} + w_{100A} \frac{N_e}{N_{\pi} 100A}, \quad (6.1)$$

1988

$$\frac{N_{\mu}}{N_{\pi} \text{Data}} = w_{60A} \frac{N_{\mu}}{N_{\pi} 60A} + w_{100A} \frac{N_{\mu}}{N_{\pi} 100A}, \quad (6.2)$$

1989 where the weights  $w_{60A}$  and  $w_{100A}$  are the percentage of events in the corresponding  
1990 magnet configuration passing the mass selection in data, as shown in table 6.2. Figure  
1991 6.1 shows the momentum predictions from G4Beamline overlaid with data for the 60A  
1992 runs (left) and for the 100A runs (right). The predictions for electrons, muons and  
1993 pions have been staggered and their sum is area normalized to data. Albeit not  
1994 perfect, these plots show a reasonable agreement between the momentum shapes in  
1995 data and MC. We attribute the difference in shape to the lack of simulation of the  
1996 WC efficiency in the MC which is momentum dependent and leads to enhance the  
1997 number events in the center of the momentum distribution.

1998 Once the beam composition is known, we simulate the electrons, muons and pi-  
1999 ons with the DDMC and we subject the three samples to the same selection chain

2000 (WC2TPC match, shower filter, pile up filter). The percentage of electrons and muons  
2001 surviving the selection chain weighted by the beam composition is the electron and  
2002 muon contamination in the pion cross section sample, as shown in Table 6.3.

### 2003 **6.1.2 Contamination from secondaries**

2004 Pions can travel the length of the LArIAT beamline and interact hadronically in the  
2005 steel or in the non-instrumented argon upstream to the TPC front face. One of these  
2006 products can leak into the TPC and be matched with the WC track, contributing  
2007 to the pool of events used for the cross section calculation. We call this type of  
2008 particles “secondaries” from pion events, with a terminology inspired by Geant4. We  
2009 estimate the number of secondaries using the DDMC pion sample. The percentage of  
2010 secondaries is given by the number of matched WC2TPC tracks whose corresponding  
2011 particle is not flagged as primary by Geant4 and is not a muon, to avoid double  
2012 counting with the G4Beamline estimate. The secondary to pion ratio is  $X\%$  in the  
2013 60A sample and  $Y\%$  in the 100A sample.

## 2014 **6.2 Beamline Background Subtraction**

2015 Once we estimate the contaminants to primary pion ratio, the next step is subtracting  
2016 their collective contribution from data. To do so, we simulate the same number of  
2017 electrons, muons and pions with the DDMC separately for the two magnet settings,  
2018 and we apply the same selection filters on the three samples. The number of events  
2019 per particle species surviving this selection is shown on table 6.3.

2020 We then produce the interacting and incident histograms for the events surviving  
2021 the selection for both the pions and the contaminants, weighted by the estimated  
2022 beam composition.

2023 We then evaluate the relative contribution of the contaminants bin by bin in the

	$\pi^-$ 60A	$\mu^-$ 60A	$e^-$ 60A	$\pi^-$ 100A	$\mu^-$ 100A	$e^-$ 100A
Total Initial events	334500	334500	334500			
After Multiplicity Rejection	331313	322436	186261			
After WC2TPC: Selection	201458	285686	79109			
Evts After Shower Rejection	191655	277914	17477			
Survival rate	57%	83%	5%			
Beam Composition						
After Selection	88.5%	8.5%	3%			

Table 6.3: MC selection flow per particle species.

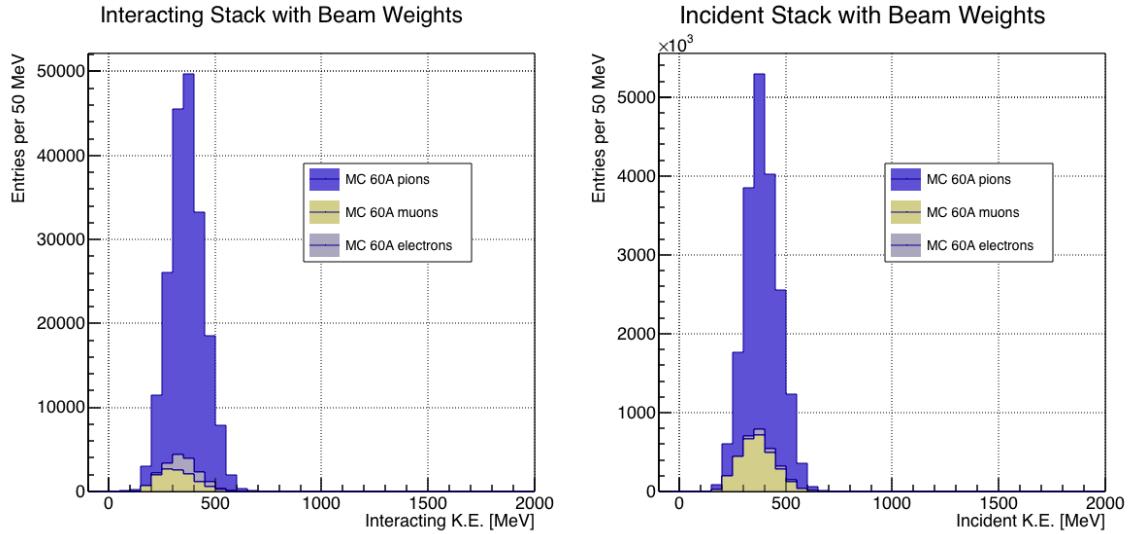


Figure 6.2: Left: staggered contributions to the interacting kinetic energy distribution for electron (grey), muons (yellow) and pion (blue) in the 60A simulation sample. Right: staggered contributions to the incident kinetic energy distribution for electron (grey), muons (yellow) and pion (blue) in the 60A simulation sample.

2024 interacting and incident histograms separately. In data, we subtract this estimated  
 2025 relative contaminants contribution on the interacting and incident histograms bin by  
 2026 bin.

2027 We estimate the systematic uncertainty on the cross section from this subtraction  
 2028 procedure by varying the electron to pion and muon to pion ratio in a suitable range  
 2029 of values. Figure

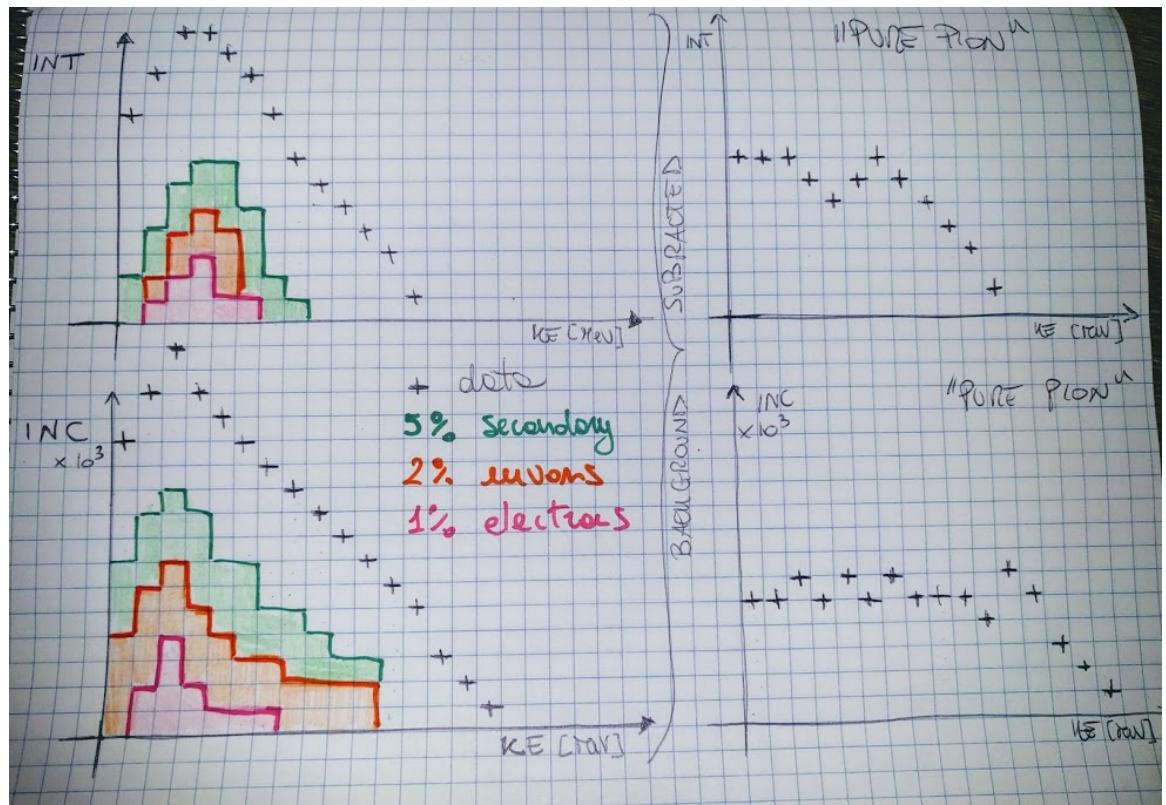


Figure 6.3: A graphical rendering of the beamline contamination background subtraction. The contribution of the contaminants is shown in green for the secondaries, in orange for the muons and in pink for electrons. The colored plots are coming from the MC and are staggered. The percentages shown in the legend are the percentages of contaminants over the total number of events passing the selection chain. We actually expect way less contamination.

2030    **6.3 Capture and decay**

2031    Our goal is to measure the total hadronic cross section for negative pions in argon.  
2032    Since pion capture can be classified as an electromagnetic process and pion decay is a  
2033    weak process, capture and decay represent unwanted interactions. We present here a  
2034    study of capture and decay in Monte Carlo and the solution we adopted to mitigate  
2035    their present in the data sample.

2036       For this MC study, we use a sample of 359000 MC pions generated according to  
2037    the beam profile with the DDMC described in 5.2.2. It is important to notice that  
2038    capture occurs predominantly at rest, while decay may occur both in flight and at  
2039    rest. Thus, we can highly mitigate capture and decay at rest by removing pions  
2040    which would release all their energy in the TPC and stop. This translates into a  
2041    momentum selection, where we keep only events whose WC momentum is above a  
2042    certain threshold. Figure 6.4 shows the true momentum distribution for the primary<sup>2</sup>  
2043    pions that arrive to the TPC (pink), that capture (green) or decay (blue) inside the  
2044    TPC, on a linear and log scale vertical axis.

2045       In order to choose the selection value for the wire chamber momentum, it is  
2046    beneficial to estimate the ratio of events which capture or decay that survive the  
2047    selection in MC as a function of the momentum threshold, and compare it with the  
2048    survival ratio for all events. This is done in figure 6.5. We define the survival ratio  
2049    simply as the number of events surviving the true momentum selection divided by  
2050    the number of events of that category. We calculate the survival ratio separately for  
2051    the three event categories explained above: total (pink), capture (green) and decay  
2052    (blue). Selecting pions with momentum greater than 420 MeV/c reduces the capture  
2053    events by 99% while maintaining about 80% of the total data sample. Figure 6.6

---

2. 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.

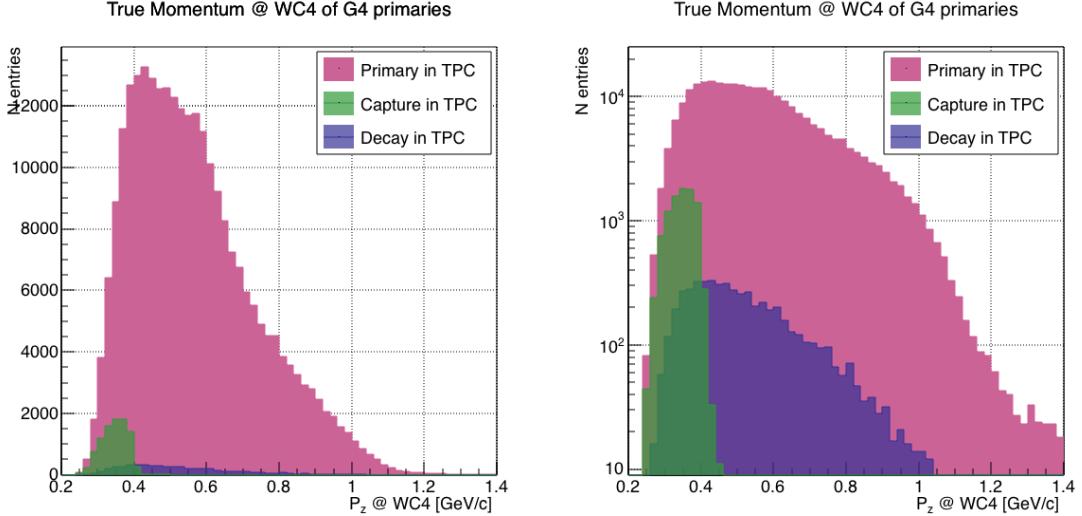


Figure 6.4: True momentum distribution at wire chamber 4 for every simulated pion arriving in the TPC (pink), ending its life in capture (green) or in decay (blue) in the TPC, linear vertical axis on the left, logarithmic on the right.

2054 shows the ratio of events which end their life in capture (green) or decay (blue) over  
 2055 the total number of events as a function of the true momentum at wire chamber  
 2056 four. This ratio is slightly dependent on the inelastic cross section implemented in  
 2057 Geant4, as we are able to register a pion capture (or decay) only if it did not interact  
 2058 inelastically in the TPC. We choose a momentum threshold of 420 MeV/c because  
 2059 the percentage of capture events drops below 1% and the percentage of decays is  
 2060 never above 2% for momenta greater than 420 MeV/c.

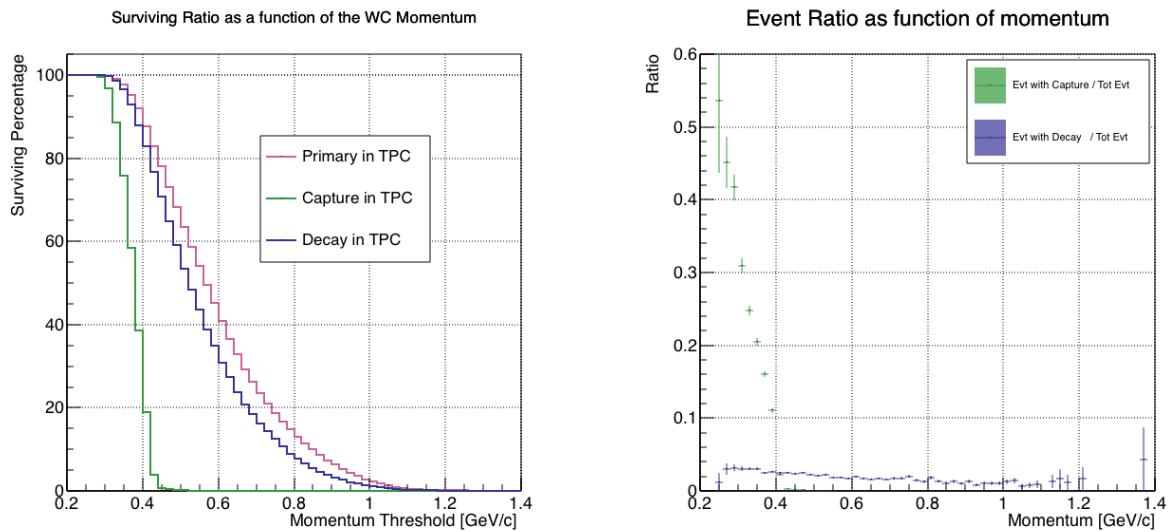


Figure 6.5: Survival ratio as a function of selection threshold on true momentum at wire chamber four for every simulated pion arriving in the TPC (pink), capture (green) or in decay (blue).

Figure 6.6: 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.

2061 **Chapter 7**

2062 **Negative Pion Cross Section**

2063 **Measurement**

2064 **7.1 Estimate of  $E_{loss}$  before the TPC**

2065 The beamline particles travel a path from when their momentum is measured by  
2066 the beamline detector, until they are tracked again inside the TPC. In the current  
2067 LArIAT geometry, a particle leaving the fourth wire chamber will encounter the  
2068 materials listed in Table 7.1 before being registered again. The energy lost by the  
2069 particle in this non-instrumented material modifies the particle's kinetic energy and  
2070 directly affects the cross section measurement, as shown in equation 4.5.

Material	density [g/cm <sup>3</sup> ]	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 7.1: LArIAT material budget from WC4 to the TPC Front Face.

We derive an estimate of the energy loss between the beamline momentum mea-

surement and the TPC ( $E_{loss}$ ) from the Data Driven Monte Carlo using the pion and kaon samples separately, since this quantity is not measurable directly on data. The  $E_{loss}$  distribution for the 60A and 100A pion sample is shown in figure 7.1, left and right respectively. 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 7.2. The kinematic at WC4 determines the trajectory of a particle and whether or not it will hit the halo paddle. In figure 7.3 , we plot the true  $X$  component of the momentum 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 simulation. These distributions can be separated drawing a line in this position-momentum space. We use a logistic regression [12] 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

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

2071 where the coefficients of the line are empirically found by the logistic regression es-  
 2072 timation. Overall, this simple classifier classifies in the right category (hit or miss)  
 2073 about 86% of the pion events. We apply the same classifier on data. We assign  
 2074  $E_{loss} = 32 \pm 4$  MeV for events classified as “hitting the halo paddle”; we assign  
 2075  $E_{loss} = 24 \pm 3$  MeV for events classified as “missing the halo paddle”.

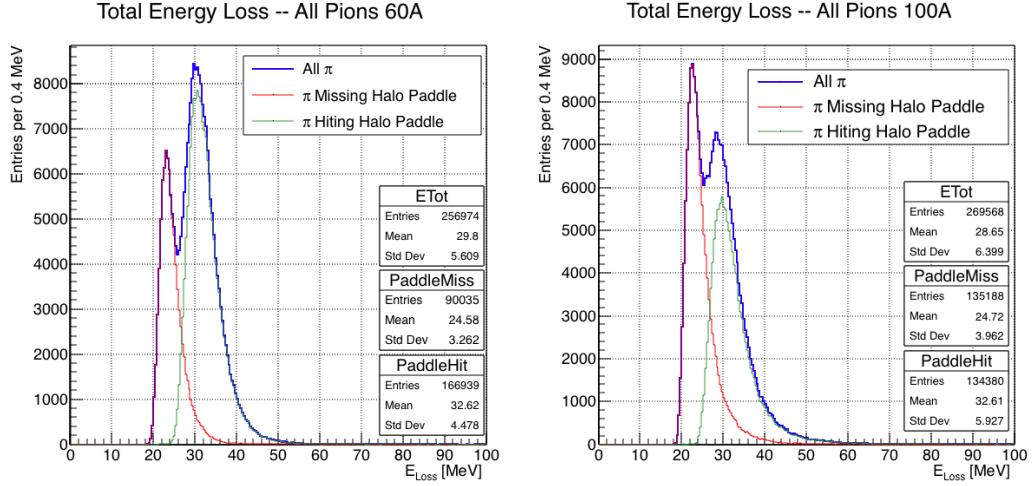


Figure 7.1: True energy loss between WC4 and the TPC front face according to the MC simulation of the 60A runs (left) and of the 100A runs (right). The distribution for the whole data sample is shown in blue, the distribution for the pions missing the halo is shown in red, and the distribution for the pions hitting the halo is shown in green.

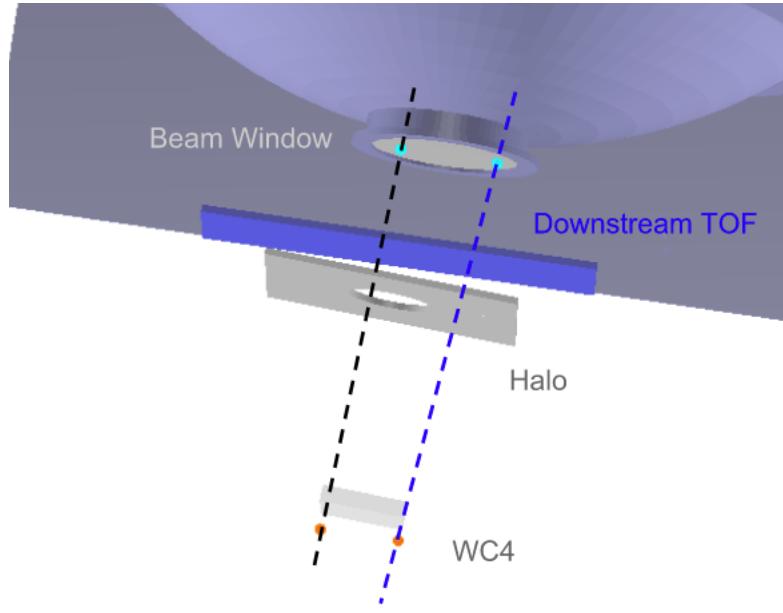


Figure 7.2: Schematic rendering of the particle path between WC4 and the TPC front face. The paddle with the hollow central circle represents the Halo paddle. We illustrate two possible trajectories: in black, a trajectory that miss the paddle and goes through the hole in the Halo, in blue a trajectory that hits the Halo paddle and goes through the scintillation material.

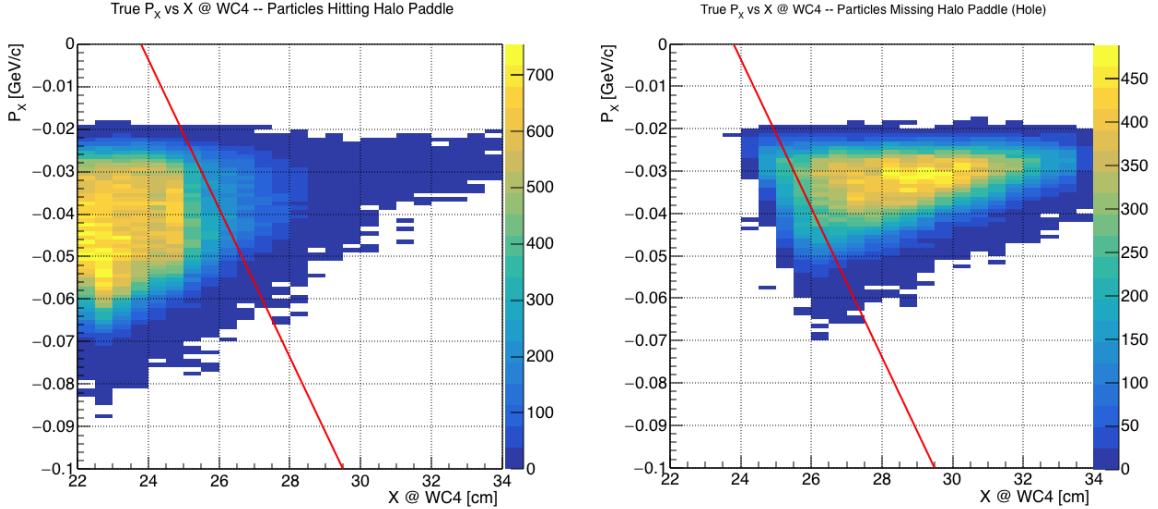


Figure 7.3: Horizontal component of the true momentum vs the horizontal position at WC4 for MC simulated pions of the 60A runs. The plot on the left shows the distribution for pion that miss the halo paddle and the plot on the right shows the distributions for pions that hit the halo. The form of the classifier is overlaid to both plots (red line).

## 2076 7.2 Interacting and Incident Distributions

## 2077 7.3 Total Hadronic Negative Pion-Argon Differen- 2078 tial Cross Section

2079 **Chapter 8**

2080 **Uncertainty budget**

2081 Measuring an hadronic cross section in LArIAT translates into counting how many  
2082 hadrons impinged on a slab of argon at a given energy and how many of those hadrons  
2083 interacted at said energy. So, the key questions here are:

- 2084     a) how well do we know the kinetic energy at each point of the tracking?  
2085     b) how well do we know when the tracking stops?  
2086     c) are there any systematic shifts?

2087     In order to answer this question, will discuss first a simple scenario were our beam  
2088 is 100% made of pions which arrive as primaries in the TPC (no decay in the beam  
2089 and no inelastic interaction before the TPC front face). We will then add a layer of  
2090 complexity by discussing how we handle beamline contamination.

2091 **8.1 Pure beam of pions**

2092 Assuming a beam of pure pions gets to the TPC, let us explicit some of the vari-  
2093 ables in the kinetic energy equation 4.6 to point out the important quantities in the  
2094 uncertainty budget,

$$E_j^{kin} = E_{Beam}^{kin} - E_{loss} - \sum_{i < j} \frac{dE_i}{dx_i} * dx_i \quad (8.1)$$

$$= \sqrt{p_{Beam}^2 - m_{Beam}^2} - m_{Beam} - E_{loss} - \sum_{i < j} \frac{dE_i}{dx_i} * dx_i. \quad (8.2)$$

### 2095 8.1.1 Uncertainty on $E_{Beam}^{kin}$

2096 Let us start by discussing the uncertainty on  $E_{Beam}^{kin}$ . Since we are assuming a beam  
 2097 of pions, the uncertainty on the value of mass of the pion ( $m_{Beam}$ ) as given by the  
 2098 pdg is irrelevant compared to the momentum uncertainties, thus  $\delta E_{Beam}^{kin} = \delta p_{Beam}^{kin}$ .  
 2099 We estimate the momentum uncertainty as follows.

2100 We estimate the uncertainty on a 4-point track. In case of 3-points track, we add  
 2101 an additional 2% coming from Greg's study. Uncertainty on a 4-point track:

- 2102 - Alignment surveys. 1mm misalignment translates to 3% in overall
- 2103 - Doug study dp/p = 2% based on field map (docdb 1710)
- 2104 - Minerva test beam paper

### 2105 8.1.2 Systematics on $E_{loss}$

2106 **Systematics** Discrepancies between the real TPC geometry and the simulated ge-  
 2107 ometry can lead to a systematic in the  $E_{loss}$  calculation. In particular, we found a  
 2108 difference in the depth of the un-instrumented argon upstream to the TPC front face,  
 2109 the MC geometry reporting  $\sim 3.3$  cm more un-instrumented argon than the TPC  
 2110 survey. For a pion MIP, this depth corresponds to 7.4 MeV which we account for as  
 2111 a double sided systematic in the determination of the pion kinetic energy.

2112 **8.1.3 Uncertainty on dE/dx and pitch**

2113 We obtain the uncertainty on dE/dx and track pitch by comparing the dE/dx and  
2114 pitch distributions in data and MC. Currently, MPV MC = 1.70 and MPV DATA =  
2115 1.72 MeV/cm ( 3% higher). TO DO HERE: calculate Argon density from mid-RTD  
2116 temperature. Compare this density with MC Argon density. Density change affects  
2117 dE/dx (in MeV/cm!). Try changing MC density up to “real one” and see if dEdX  
2118 agrees between DATA and MC

2119 **8.1.4 Uncertainty on track end, aka efficiency correction**

2120 From the MC, we obtain an efficiency correction on the interacting and incident  
2121 distributions separately. This is done by comparing the MC reconstructed with the  
2122 true MC deposition on an event by event basis. This correction is applied bin by bin on  
2123 the data interacting and incident distributions. The better our tracking, the smaller  
2124 this efficiency correction will be. So, step number one is improving the tracking. Need  
2125 to talk to Bruce about this. I don’t understand the angle cut that Dave Schmitz and  
2126 Jon Paley were so vocal about.

2127 Now, the key question remains: does the tracking behave in the same way in  
2128 data and MC? We can compare some key plots between reconstructed data and MC  
2129 which gives us confidence this is true: the track pitch, the tracks straightness and the  
2130 goodness of fit in data and MC. Does such a variable as “goodness of fit” exists in  
2131 the tracking? We should ask Bruce.

<sup>2132</sup> **Appendix A**

<sup>2133</sup> **Measurement of LArIAT Electric**  
<sup>2134</sup> **Field**

<sup>2135</sup> The electric field of a LArTPC in the drift volume is a fundamental quantity for  
<sup>2136</sup> the proper functionality of this technology, as it affects almost every reconstructed  
<sup>2137</sup> quantity such as the position of hits or their collected charge. Given its importance,  
<sup>2138</sup> we calculate the electric field for LArIAT with a single line diagram from our HV  
<sup>2139</sup> circuit and we cross check the obtained value with a measurement relying only on  
<sup>2140</sup> TPC data.

<sup>2141</sup> Before getting into the details of the measurement procedures, it is important to  
<sup>2142</sup> explicit the relationship between some quantities in play. The electric field and the  
<sup>2143</sup> drift velocity ( $v_{drift}$ ) are related as follows

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

<sup>2144</sup> where  $\mu$  is the electron mobility, which depends on the electric field and on the  
<sup>2145</sup> temperature (T). The empirical formula for this dependency is described in [?] and  
<sup>2146</sup> shown in Figure A.1 for several argon temperatures.

<sup>2147</sup> The relationship between the drift time ( $t_{drift}$ ) and the drift velocity is trivially

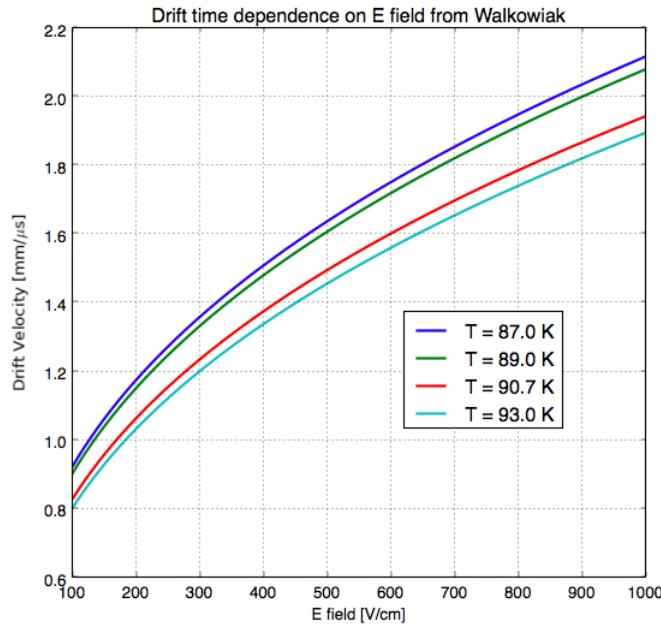


Figure A.1: Drift velocity dependence on electric field for several temperatures. The slope of the line at any one point represents the electron mobility for that given temperature and electric field.

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

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

given by

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

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

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

## 2153 Single line diagram method

2154 The electric field strength in the LArIAT main drift volume can be determined know-  
 2155 ing the voltage applied to the cathode, the voltage applied at the shield plane, and the  
 2156 distance between them. We assume the distance between the cathode and the shield  
 2157 plane to be 470 mm and any length contraction due to the liquid argon is negligibly  
 2158 small ( $\sim 2$  mm).

2159 The voltage applied to the cathode can be calculated using Ohm's law and the  
 2160 single line diagram shown in Figure A.2. A set of two of filter pots for emergency power  
 2161 dissipation are positioned between the Glassman power supply and the cathode, one at  
 2162 each end of the feeder cable, each with an internal resistance of  $40 \text{ M}\Omega$ . The output  
 2163 current of the Glassman power supply is then used to determine the electric field  
 2164 strength. Figure A.3 shows an average current of 0.004172 mA from the Glassman  
 2165 power supply.

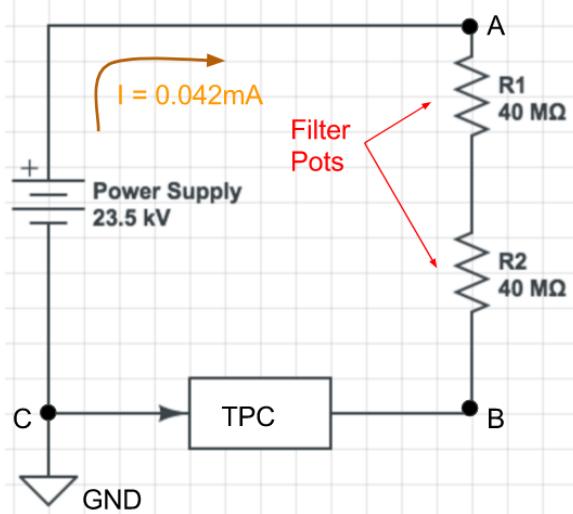


Figure A.2: get rid of current line LAr-IAT HV simple schematics.

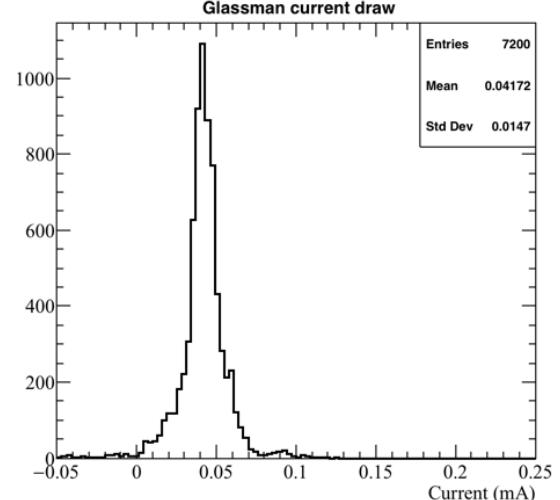


Figure A.3: **the axis is wrong!!** Current reading from the Glassman between May 25th and May 30th, 2016 (typical Run-II conditions).

2166 Using this current, the voltage at the cathode is calculated as

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

2167 where  $I$  is the current and  $R_{eq}$  is the equivalent resistor representing the two filter  
2168 pots. The electric field, drift voltage, and drift time are then calculated to be

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

2169 **E field using cathode-anode piercing tracks**

2170 We devise an independent method to measure the drift time (and consequently drift  
2171 velocity and electric field) using TPC cathode to anode piercing tracks. We use this  
2172 method as a cross check to the single line method. The basic idea is simple:

- 2173 0. Select cosmic ray events with only 1 reconstructed track
- 2174 1. Reduce the events to the one containing tracks that cross both anode and  
2175 cathode
- 2176 2. Identify the first and last hit of the track
- 2177 3. Measure the time difference between these two hits ( $\Delta t$ ).

2178 This method works under the assumptions that the time it takes for a cosmic particle  
2179 to cross the chamber ( $\sim \text{ns}$ ) is small compared to the charge drift time ( $\sim$  hundreds  
2180 of  $\mu\text{s}$ ).

2181 We choose cosmic events to allow for a high number of anode to cathode piercing  
2182 tracks (ACP tracks), rejecting beam events where the particles travel almost perpen-  
2183 dicularly to drift direction. We select events with only one reconstructed track to  
2184 maximize the chance of selecting a single crossing muon (no-michel electron). We  
2185 utilize ACP tracks because their hits span the full drift length of the TPC, see figure

2186 A.4, allowing us to define where the first and last hit of the tracks are located in space  
2187 regardless of our assumption of the electric field.

2188 One of the main features of this method is that it doesn't rely on the measurement  
2189 of the trigger time. Since  $\Delta t$  is the time difference between the first and last hit of a  
2190 track and we assume the charge started drifting at the same time for both hits, the  
2191 measurement of the absolute beginning of drift time  $t_0$  is unnecessary. We boost the  
2192 presence of ACP tracks in the cosmic sample by imposing the following requirements  
2193 on tracks:

- 2194 • vertical position (Y) of first and last hits within  $\pm 18$  cm from TPC center  
2195 (avoid Top-Bottom tracks)
- 2196 • horizontal position (Z) of first and last hits within 2 and 86 cm from TPC front  
2197 face (avoid through going tracks)
- 2198 • track length greater than 48 cm (more likely to be crossing)
- 2199 • angle from the drift direction (phi in figure A.5) smaller than 50 deg (more  
2200 reliable tracking)
- 2201 • angle from the beam direction (theta in figure A.5) grater than 50 deg (more  
2202 reliable tracking)

2203 Tracks passing all these selection requirements are used for the  $\Delta t$  calculation.

2204 For each track passing our selection, we loop through the associated hits in order  
2205 to retrieve the timing information. The analysis is performed separately on hits on the  
2206 collection plane and induction plane, but lead to consistent results. As an example  
2207 of the time difference, figures A.6 and A.7 represent the difference in time between  
2208 the last and first hit of the selected tracks for Run-II Positive Polarity sample on the  
2209 collection and induction plane respectively. We fit with a Gaussian to the peak of the  
2210  $\Delta t$  distributions to extract the mean drift time and the uncertainty associated with

2211 it. The long tail at low  $\Delta t$  represent contamination of non-ACP tracks in the track  
 2212 selection. We apply the same procedure to Run-I and Run-II, positive and negative  
 2213 polarity alike.

2214 To convert  $\Delta t$  recorded for the hits on the induction plane to the drift time we  
 2215 utilize the formula

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

2216 where  $t_{drift}$  is the time the charge takes to drift in the main volume between the  
 2217 cathode and the shield plane and  $t_{S-I}$  is the time it takes for the charge to drift from  
 2218 the shield plane to the induction plane. In Table A.1 we calculated the drift velocity  
 2219 in the S-I region, thus we can calculate  $t_{S-I}$  as

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

2220 where  $l_{S-I}$  is the distance between the shield and induction plane and  $v_{S-I}$  is the drift  
 2221 velocity in the same region. A completely analogous procedure is followed for the hits  
 2222 on the collection plane, taking into account the time the charge spent in drifting from  
 2223 shield to induction as well as between the induction and collection plane. The value  
 2224 for  $\Delta t_{drift}$ , the calculated drift velocity ( $v_{drift}$ ), and corresponding drift electric field  
 2225 for the various run periods is given in Table A.2 and are consistent with the electric  
 2226 field value calculated with the single line diagram method.

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

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

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

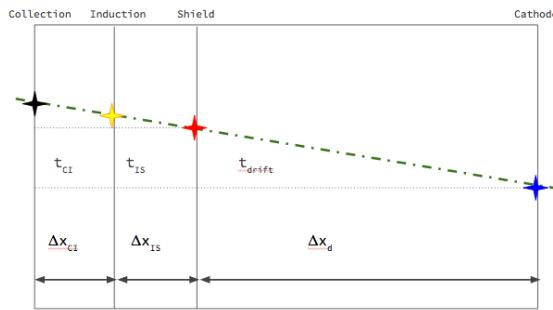


Figure A.4: Pictorial representation of the YX view of the TPC. The distance within the anode planes and between the shield plane and the cathode is purposely out of proportion to illustrate the time difference between hits on collection and induction. A ACP track is shown as an example.

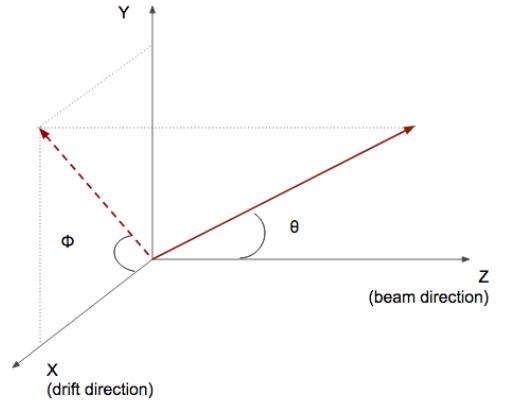


Figure A.5: Angle definition in the context of LArIAT coordinates system.

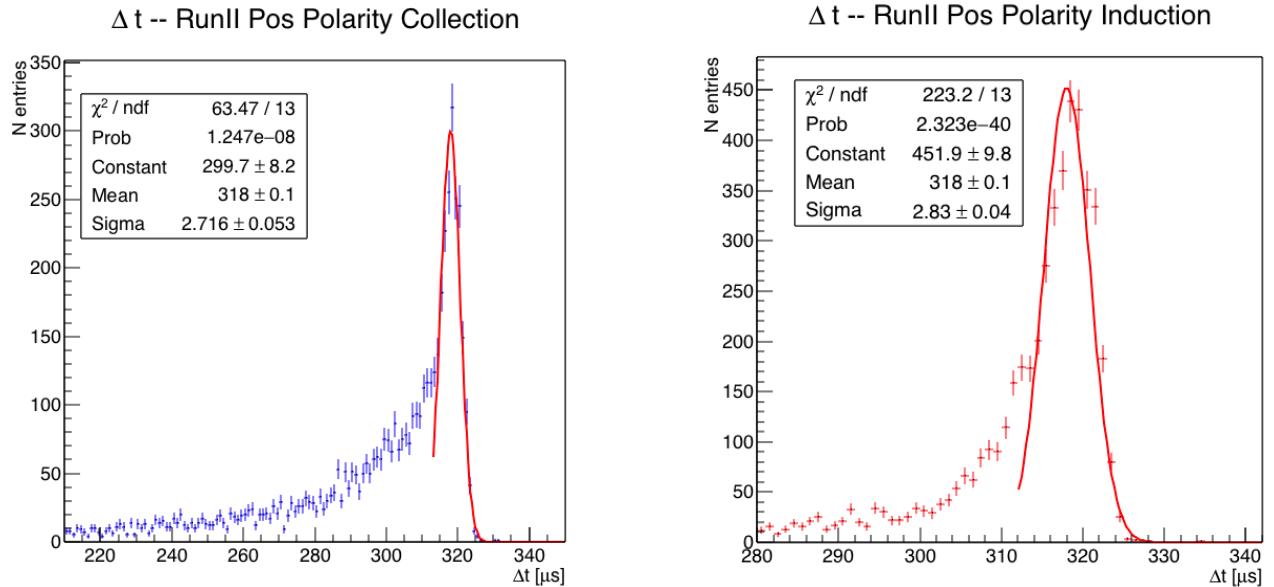


Figure A.6: Collection plane  $\Delta t$  fit for Run II positive polarity ACP data selected tracks.

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

# <sup>2227</sup> Bibliography

- <sup>2228</sup> [1] Precision electroweak measurements on the  $Z$  resonance. *Physics Reports*,  
<sup>2229</sup> 427(5):257 – 454, 2006.
- <sup>2230</sup> [2] K. Abe, J. Amey, C. Andreopoulos, M. Antonova, S. Aoki, A. Ariga, D. Au-  
<sup>2231</sup> tiero, S. Ban, M. Barbi, G. J. Barker, G. Barr, C. Barry, P. Bartet-Friburg,  
<sup>2232</sup> M. Batkiewicz, V. Berardi, S. Berkman, S. Bhadra, S. Bienstock, A. Blondel,  
<sup>2233</sup> S. Bolognesi, S. Bordoni, S. B. Boyd, D. Brailsford, A. Bravar, C. Bronner,  
<sup>2234</sup> M. Buizza Avanzini, R. G. Calland, T. Campbell, S. Cao, S. L. Cartwright,  
<sup>2235</sup> M. G. Catanesi, A. Cervera, C. Checchia, D. Cherdack, N. Chikuma,  
<sup>2236</sup> G. Christodoulou, A. Clifton, J. Coleman, G. Collazuol, D. Coplowe, A. Cudd,  
<sup>2237</sup> A. Dabrowska, G. De Rosa, T. Dealtry, P. F. Denner, S. R. Dennis, C. Densham,  
<sup>2238</sup> D. Dewhurst, F. Di Lodovico, S. Di Luise, S. Dolan, O. Drapier, K. E. Duffy,  
<sup>2239</sup> J. Dumarchez, M. Dziewiecki, S. Emery-Schrenk, A. Ereditato, T. Feusels,  
<sup>2240</sup> A. J. Finch, G. A. Fiorentini, M. Friend, Y. Fujii, D. Fukuda, Y. Fukuda,  
<sup>2241</sup> V. Galymov, A. Garcia, C. Giganti, F. Gizzarelli, T. Golan, M. Gonin, D. R.  
<sup>2242</sup> Hadley, L. Haegel, M. D. Haigh, D. Hansen, J. Harada, M. Hartz, T. Hasegawa,  
<sup>2243</sup> N. C. Hastings, T. Hayashino, Y. Hayato, R. L. Helmer, A. Hillairet, T. Hiraki,  
<sup>2244</sup> A. Hiramoto, S. Hirota, M. Hogan, J. Holeczek, F. Hosomi, K. Huang, A. K.  
<sup>2245</sup> Ichikawa, M. Ikeda, J. Imber, J. Insler, R. A. Intonti, T. Ishida, T. Ishii, E. Iwai,  
<sup>2246</sup> K. Iwamoto, A. Izmaylov, B. Jamieson, M. Jiang, S. Johnson, P. Jonsson,  
<sup>2247</sup> C. K. Jung, M. Kabirnezhad, A. C. Kaboth, T. Kajita, H. Kakuno, J. Kameda,

2248 D. Karlen, T. Katori, E. Kearns, M. Khabibullin, A. Khotjantsev, H. Kim,  
2249 J. Kim, S. King, J. Kisiel, A. Knight, A. Knox, T. Kobayashi, L. Koch, T. Koga,  
2250 A. Konaka, K. Kondo, L. L. Kormos, A. Korzenev, Y. Koshio, K. Kowalik,  
2251 W. Kropp, Y. Kudenko, R. Kurjata, T. Kutter, J. Lagoda, I. Lamont, M. Lam-  
2252 oureux, E. Larkin, P. Lasorak, M. Laveder, M. Lawe, M. Licciardi, T. Lindner,  
2253 Z. J. Liptak, R. P. Litchfield, X. Li, A. Longhin, J. P. Lopez, T. Lou, L. Ludovici,  
2254 X. Lu, L. Magaletti, K. Mahn, M. Malek, S. Manly, A. D. Marino, J. F. Martin,  
2255 P. Martins, S. Martynenko, T. Maruyama, V. Matveev, K. Mavrokordis, W. Y.  
2256 Ma, E. Mazzucato, M. McCarthy, N. McCauley, K. S. McFarland, C. McGrew,  
2257 A. Mefodiev, C. Metelko, M. Mezzetto, P. Mijakowski, A. Minamino, O. Mi-  
2258 neev, S. Mine, A. Missert, M. Miura, S. Moriyama, Th. A. Mueller, J. Myslik,  
2259 T. Nakadaira, M. Nakahata, K. G. Nakamura, K. Nakamura, K. D. Nakamura,  
2260 Y. Nakanishi, S. Nakayama, T. Nakaya, K. Nakayoshi, C. Nantais, C. Nielsen,  
2261 M. Nirko, K. Nishikawa, Y. Nishimura, P. Novella, J. Nowak, H. M. O'Keeffe,  
2262 K. Okumura, T. Okusawa, W. Oryszczak, S. M. Oser, T. Ovsyannikova, R. A.  
2263 Owen, Y. Oyama, V. Palladino, J. L. Palomino, V. Paolone, N. D. Patel,  
2264 P. Paudyal, M. Pavin, D. Payne, J. D. Perkin, Y. Petrov, L. Pickard, L. Pick-  
2265 ering, E. S. Pinzon Guerra, C. Pistillo, B. Popov, M. Posiadala-Zezula, J.-M.  
2266 Poutissou, R. Poutissou, P. Przewlocki, B. Quilain, T. Radermacher, E. Radi-  
2267 cioni, P. N. Ratoff, M. Ravonel, M. A. Rayner, A. Redij, E. Reinherz-Aronis,  
2268 C. Riccio, P. A. Rodrigues, E. Rondio, B. Rossi, S. Roth, A. Rubbia, A. Rychter,  
2269 K. Sakashita, F. Sánchez, E. Scantamburlo, K. Scholberg, J. Schwehr, M. Scott,  
2270 Y. Seiya, T. Sekiguchi, H. Sekiya, D. Sgalaberna, R. Shah, A. Shaikhiev,  
2271 F. Shaker, D. Shaw, M. Shiozawa, T. Shirahige, S. Short, M. Smy, J. T.  
2272 Sobczyk, H. Sobel, M. Sorel, L. Southwell, J. Steinmann, T. Stewart, P. Stowell,  
2273 Y. Suda, S. Suvorov, A. Suzuki, S. Y. Suzuki, Y. Suzuki, R. Tacik, M. Tada,  
2274 A. Takeda, Y. Takeuchi, H. K. Tanaka, H. A. Tanaka, D. Terhorst, R. Terri,

2275 T. Thakore, L. F. Thompson, S. Tobayama, W. Toki, T. Tomura, C. Touramanis,  
2276 T. Tsukamoto, M. Tzanov, Y. Uchida, M. Vagins, Z. Vallari, G. Vasseur,  
2277 T. Vladislavljevic, T. Wachala, C. W. Walter, D. Wark, M. O. Wascko, A. We-  
2278 ber, R. Wendell, R. J. Wilkes, M. J. Wilking, C. Wilkinson, J. R. Wilson, R. J.  
2279 Wilson, C. Wret, Y. Yamada, K. Yamamoto, M. Yamamoto, C. Yanagisawa,  
2280 T. Yano, S. Yen, N. Yershov, M. Yokoyama, K. Yoshida, T. Yuan, M. Yu, A. Za-  
2281 lewska, J. Zalipska, L. Zambelli, K. Zaremba, M. Ziembicki, E. D. Zimmerman,  
2282 M. Zito, and J. Źmuda. Combined analysis of neutrino and antineutrino oscil-  
2283 lations at t2k. *Phys. Rev. Lett.*, 118:151801, Apr 2017.

2284 [3] K. Abe, Y. Haga, Y. Hayato, M. Ikeda, K. Iyogi, J. Kameda, Y. Kishimoto,  
2285 M. Miura, S. Moriyama, M. Nakahata, T. Nakajima, Y. Nakano, S. Nakayama,  
2286 A. Orii, H. Sekiya, M. Shiozawa, A. Takeda, H. Tanaka, T. Tomura, R. A. Wen-  
2287 dell, R. Akutsu, T. Irvine, T. Kajita, K. Kaneyuki, Y. Nishimura, E. Richard,  
2288 K. Okumura, L. Labarga, P. Fernandez, J. Gustafson, C. Kachulis, E. Kearns,  
2289 J. L. Raaf, J. L. Stone, L. R. Sulak, S. Berkman, C. M. Nantais, H. A.  
2290 Tanaka, S. Tobayama, M. Goldhaber, W. R. Kropp, S. Mine, P. Weatherly,  
2291 M. B. Smy, H. W. Sobel, V. Takhistov, K. S. Ganezer, B. L. Hartfiel, J. Hill,  
2292 N. Hong, J. Y. Kim, I. T. Lim, R. G. Park, A. Himmel, Z. Li, E. O’Sullivan,  
2293 K. Scholberg, C. W. Walter, T. Wongjirad, T. Ishizuka, S. Tasaka, J. S. Jang,  
2294 J. G. Learned, S. Matsuno, S. N. Smith, M. Friend, T. Hasegawa, T. Ishida,  
2295 T. Ishii, T. Kobayashi, T. Nakadaira, K. Nakamura, Y. Oyama, K. Sakashita,  
2296 T. Sekiguchi, T. Tsukamoto, A. T. Suzuki, Y. Takeuchi, T. Yano, S. V. Cao,  
2297 T. Hiraki, S. Hirota, K. Huang, T. Kikawa, A. Minamino, T. Nakaya, K. Suzuki,  
2298 Y. Fukuda, K. Choi, Y. Itow, T. Suzuki, P. Mijakowski, K. Frankiewicz, J. Hig-  
2299 night, J. Imber, C. K. Jung, X. Li, J. L. Palomino, M. J. Wilking, C. Yanag-  
2300 isawa, D. Fukuda, H. Ishino, T. Kayano, A. Kibayashi, Y. Koshio, T. Mori,  
2301 M. Sakuda, C. Xu, Y. Kuno, R. Tacik, S. B. Kim, H. Okazawa, Y. Choi,

- 2302 K. Nishijima, M. Koshiba, Y. Totsuka, Y. Suda, M. Yokoyama, C. Bronner,  
2303 M. Hartz, K. Martens, Ll. Marti, Y. Suzuki, M. R. Vagins, J. F. Martin, A. Kon-  
2304 aka, S. Chen, Y. Zhang, and R. J. Wilkes. Search for proton decay via  $p \rightarrow e^+ \pi^0$   
2305 and  $p \rightarrow \mu^+ \pi^0$  in 0.31 megaton·years exposure of the super-kamiokande water  
2306 cherenkov detector. *Phys. Rev. D*, 95:012004, Jan 2017.
- 2307 [4] R Acciarri, C Adams, J Asaadi, B Baller, T Bolton, C Bromberg, F Ca-  
2308 vanna, E Church, D Edmunds, A Ereditato, S Farooq, B Fleming, H Greenlee,  
2309 G Horton-Smith, C James, E Klein, K Lang, P Laurens, D McKee, R Mehdiyev,  
2310 B Page, O Palamara, K Partyka, G Rameika, B Rebel, M Soderberg, J Spitz,  
2311 A M Szelc, M Weber, M Wojcik, T Yang, and G P Zeller. A study of electron  
2312 recombination using highly ionizing particles in the argoneut liquid argon tpc.  
2313 *Journal of Instrumentation*, 8(08):P08005, 2013.
- 2314 [5] R Acciarri, M Antonello, B Baibussinov, M Baldo-Ceolin, P Benetti,  
2315 F Calaprice, E Calligarich, M Cambiaghi, N Canci, F Carbonara, F Cavanna,  
2316 S Centro, A G Cocco, F Di Pompeo, G Fiorillo, C Galbiati, V Gallo, L Grandi,  
2317 G Meng, I Modena, C Montanari, O Palamara, L Pandola, G B Piano Mortari,  
2318 F Pietropaolo, G L Raselli, M Roncadelli, M Rossella, C Rubbia, E Segreto,  
2319 A M Szelc, S Ventura, and C Vignoli. Effects of nitrogen contamination in  
2320 liquid argon. *Journal of Instrumentation*, 5(06):P06003, 2010.
- 2321 [6] R. Acciarri et al. Demonstration and Comparison of Operation of Photomulti-  
2322 plier Tubes at Liquid Argon Temperature. *JINST*, 7:P01016, 2012.
- 2323 [7] R. Acciarri et al. Design and Construction of the MicroBooNE Detector. *JINST*,  
2324 12(02):P02017, 2017.
- 2325 [8] R. Acciarri et al. First Observation of Low Energy Electron Neutrinos in a  
2326 Liquid Argon Time Projection Chamber. *Phys. Rev.*, D95(7):072005, 2017.

- 2327 [Phys. Rev.D95,072005(2017)].
- 2328 [9] M Adamowski, B Carls, E Dvorak, A Hahn, W Jaskierny, C Johnson, H Jostlein,  
2329 C Kendziora, S Lockwitz, B Pahlka, R Plunkett, S Pordes, B Rebel, R Schmitt,  
2330 M Stancari, T Tope, E Voirin, and T Yang. The liquid argon purity demon-  
2331 strator. *Journal of Instrumentation*, 9(07):P07005, 2014.
- 2332 [10] C. Adams et al. The Long-Baseline Neutrino Experiment: Exploring Funda-  
2333 mental Symmetries of the Universe. 2013.
- 2334 [11] P. Adamson, L. Aliaga, D. Ambrose, N. Anfimov, A. Antoshkin, E. Arrieta-  
2335 Diaz, K. Augsten, A. Aurisano, C. Backhouse, M. Baird, B. A. Bambah,  
2336 K. Bays, B. Behera, S. Bending, R. Bernstein, V. Bhatnagar, B. Bhuyan,  
2337 J. Bian, T. Blackburn, A. Bolshakova, C. Bromberg, J. Brown, G. Brunetti,  
2338 N. Buchanan, A. Butkevich, V. Bychkov, M. Campbell, E. Catano-Mur, S. Chil-  
2339 dress, B. C. Choudhary, B. Chowdhury, T. E. Coan, J. A. B. Coelho, M. Colo,  
2340 J. Cooper, L. Corwin, L. Cremonesi, D. Cronin-Hennessy, G. S. Davies, J. P.  
2341 Davies, P. F. Derwent, R. Dharmapalan, P. Ding, Z. Djurcic, E. C. Dukes,  
2342 H. Duyang, S. Edayath, R. Ehrlich, G. J. Feldman, M. J. Frank, M. Gabrielyan,  
2343 H. R. Gallagher, S. Germani, T. Ghosh, A. Giri, R. A. Gomes, M. C. Goodman,  
2344 V. Grichine, R. Group, D. Grover, B. Guo, A. Habig, J. Hartnell, R. Hatcher,  
2345 A. Hatzikoutelis, K. Heller, A. Himmel, A. Holin, J. Hylen, F. Jediny, M. Judah,  
2346 G. K. Kafka, D. Kalra, S. M. S. Kasahara, S. Kasetti, R. Keloth, L. Kolupaeva,  
2347 S. Kotelnikov, I. Kourbanis, A. Kreymer, A. Kumar, S. Kurbanov, K. Lang,  
2348 W. M. Lee, S. Lin, J. Liu, M. Lokajicek, J. Lozier, S. Luchuk, K. Maan, S. Mag-  
2349 ill, W. A. Mann, M. L. Marshak, K. Matera, V. Matveev, D. P. Méndez, M. D.  
2350 Messier, H. Meyer, T. Miao, W. H. Miller, S. R. Mishra, R. Mohanta, A. Moren,  
2351 L. Mualem, M. Muether, S. Mufson, R. Murphy, J. Musser, J. K. Nelson,  
2352 R. Nichol, E. Niner, A. Norman, T. Nosek, Y. Oksuzian, A. Olshevskiy, T. Ol-

- 2353 son, J. Paley, P. Pandey, R. B. Patterson, G. Pawloski, D. Pershey, O. Petrova,  
2354 R. Petti, S. Phan-Budd, R. K. Plunkett, R. Poling, B. Potukuchi, C. Principato,  
2355 F. Psihas, A. Radovic, R. A. Rameika, B. Rebel, B. Reed, D. Rocco, P. Rojas,  
2356 V. Ryabov, K. Sachdev, P. Sail, O. Samoylov, M. C. Sanchez, R. Schroeter,  
2357 J. Sepulveda-Quiroz, P. Shanahan, A. Sheshukov, J. Singh, J. Singh, P. Singh,  
2358 V. Singh, J. Smolik, N. Solomey, E. Song, A. Sousa, K. Soustruznik, M. Strait,  
2359 L. Suter, R. L. Talaga, M. C. Tamsett, P. Tas, R. B. Thayyullathil, J. Thomas,  
2360 X. Tian, S. C. Tognini, J. Tripathi, A. Tsaris, J. Urheim, P. Vahle, J. Vasel,  
2361 L. Vinton, A. Vold, T. Vrba, B. Wang, M. Wetstein, D. Whittington, S. G. Wo-  
2362 jcicki, J. Wolcott, N. Yadav, S. Yang, J. Zalesak, B. Zamorano, and R. Zwaska.  
2363 Constraints on oscillation parameters from  $\nu_e$  appearance and  $\nu_\mu$  disappearance  
2364 in nova. *Phys. Rev. Lett.*, 118:231801, Jun 2017.
- 2365 [12] Alan Agresti. *Categorical Data Analysis*. Wiley Series in Probability and Statis-  
2366 tics. Wiley, 2013.
- 2367 [13] A. Aguilar-Arevalo et al. Evidence for neutrino oscillations from the observation  
2368 of anti-neutrino(electron) appearance in a anti-neutrino(muon) beam. *Phys.*  
2369 *Rev.*, D64:112007, 2001.
- 2370 [14] A. A. Aguilar-Arevalo et al. Improved Search for  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  Oscillations in the  
2371 MiniBooNE Experiment. *Phys. Rev. Lett.*, 110:161801, 2013.
- 2372 [15] S. Amoruso et al. Study of electron recombination in liquid argon with the  
2373 ICARUS TPC. *Nucl. Instrum. Meth.*, A523:275–286, 2004.
- 2374 [16] C. Anderson et al. The ArgoNeuT Detector in the NuMI Low-Energy beam  
2375 line at Fermilab. *JINST*, 7:P10019, 2012.
- 2376 [17] C. Andreopoulos et al. The GENIE Neutrino Monte Carlo Generator. *Nucl.*  
2377 *Instrum. Meth.*, A614:87–104, 2010.

- 2378 [18] M. Antonello, B. Baibussinov, P. Benetti, E. Calligarich, N. Canci, S. Centro,  
2379 A. Cesana, K. Cieslik, D. B. Cline, A. G. Cocco, A. Dabrowska, D. De-  
2380 qual, A. Dermenev, R. Dolfini, C. Farnese, A. Fava, A. Ferrari, G. Fiorillo,  
2381 D. Gibin, S. Gninenko, A. Guglielmi, M. Haranczyk, J. Holeczek, A. Ivashkin,  
2382 J. Kisiel, I. Kochanek, J. Lagoda, S. Mania, A. Menegolli, G. Meng, C. Monta-  
2383 nari, S. Otwinowski, A. Piazzoli, P. Picchi, F. Pietropaolo, P. Plonski, A. Rap-  
2384 poldi, G. L. Raselli, M. Rossella, C. Rubbia, P. Sala, A. Scaramelli, E. Seg-  
2385 reto, F. Sergiampietri, D. Stefan, J. Stepaniak, R. Sulej, M. Szarska, M. Ter-  
2386 rani, F. Varanini, S. Ventura, C. Vignoli, H. Wang, X. Yang, A. Zalewska,  
2387 and K. Zaremba. Precise 3d track reconstruction algorithm for the ICARUS  
2388 t600 liquid argon time projection chamber detector. *Advances in High Energy*  
2389 *Physics*, 2013:1–16, 2013.
- 2390 [19] M. Antonello et al. A Proposal for a Three Detector Short-Baseline Neutrino  
2391 Oscillation Program in the Fermilab Booster Neutrino Beam. 2015.
- 2392 [20] D. Ashery, I. Navon, G. Azuelos, H. K. Walter, H. J. Pfeiffer, and F. W.  
2393 Schlepütz. True absorption and scattering of pions on nuclei. *Phys. Rev. C*,  
2394 23:2173–2185, May 1981.
- 2395 [21] C. Athanassopoulos et al. Evidence for  $\nu(\mu) \rightarrow \nu(e)$  neutrino oscillations  
2396 from LSND. *Phys. Rev. Lett.*, 81:1774–1777, 1998.
- 2397 [22] Borut Bajc, Junji Hisano, Takumi Kuwahara, and Yuji Omura. Threshold  
2398 corrections to dimension-six proton decay operators in non-minimal {SUSY}  
2399  $\text{su}(5)$  {GUTs}. *Nuclear Physics B*, 910:1 – 22, 2016.
- 2400 [23] B. Baller. Trajcluster user guide. Technical report, apr 2016.
- 2401 [24] Gary Barker. Neutrino event reconstruction in a liquid argon TPC. *Journal of*  
2402 *Physics: Conference Series*, 308:012015, jul 2011.

- 2403 [25] BASF Corp. 100 Park Avenue, Florham Park, NJ 07932 USA.
- 2404 [26] R. Becker-Szendy, C. B. Bratton, D. R. Cady, D. Casper, R. Claus, M. Crouch,  
2405 S. T. Dye, W. Gajewski, M. Goldhaber, T. J. Haines, P. G. Halverson, T. W.  
2406 Jones, D. Kielczewska, W. R. Kropp, J. G. Learned, J. M. LoSecco, C. Mc-  
2407 Grew, S. Matsuno, J. Matthews, M. S. Mudah, L. Price, F. Reines, J. Schultz,  
2408 D. Sinclair, H. W. Sobel, J. L. Stone, L. R. Sulak, R. Svoboda, G. Thornton,  
2409 and J. C. van der Velde. Search for proton decay into  $e^+ + \pi^0$  in the imb-3  
2410 detector. *Phys. Rev. D*, 42:2974–2976, Nov 1990.
- 2411 [27] J B Birks. Scintillations from organic crystals: Specific fluorescence and relative  
2412 response to different radiations. *Proceedings of the Physical Society. Section A*,  
2413 64(10):874, 1951.
- 2414 [28] A. Bodek and J. L. Ritchie. Further studies of fermi-motion effects in lepton  
2415 scattering from nuclear targets. *Phys. Rev. D*, 24:1400–1402, Sep 1981.
- 2416 [29] Mark G. Boulay and A. Hime. Direct WIMP detection using scintillation time  
2417 discrimination in liquid argon. 2004.
- 2418 [30] D. V. Bugg, R. S. Gilmore, K. M. Knight, D. C. Salter, G. H. Stafford, E. J. N.  
2419 Wilson, J. D. Davies, J. D. Dowell, P. M. Hattersley, R. J. Homer, A. W. O'dell,  
2420 A. A. Carter, R. J. Tapper, and K. F. Riley. Kaon-nucleon total cross sections  
2421 from 0.6 to 2.65 gev/ *c*. *Phys. Rev.*, 168:1466–1475, Apr 1968.
- 2422 [31] W. M. Burton and B. A. Powell. Fluorescence of tetraphenyl-butadiene in the  
2423 vacuum ultraviolet. *Applied Optics*, 12(1):87, jan 1973.
- 2424 [32] A. S. Carroll, I. H. Chiang, C. B. Dover, T. F. Kycia, K. K. Li, P. O. Mazur,  
2425 D. N. Michael, P. M. Mockett, D. C. Rahm, and R. Rubinstein. Pion-nucleus  
2426 total cross sections in the (3,3) resonance region. *Phys. Rev. C*, 14:635–638,  
2427 Aug 1976.

- 2428 [33] D. Casper. The nuance neutrino physics simulation, and the future. *Nuclear*  
2429       *Physics B - Proceedings Supplements*, 112(1-3):161–170, nov 2002.
- 2430 [34] A. Cervera, A. Donini, M.B. Gavela, J.J. Gomez Cádenas, P. Hernández,  
2431       O. Mena, and S. Rigolin. Golden measurements at a neutrino factory. *Nu-*  
2432       *clear Physics B*, 579(1-2):17–55, jul 2000.
- 2433 [35] E. Church. LArSoft: A Software Package for Liquid Argon Time Projection  
2434       Drift Chambers. 2013.
- 2435 [36] ATLAS Collaboration. Observation of a new particle in the search for the  
2436       standard model higgs boson with the ATLAS detector at the LHC. *Physics*  
2437       *Letters B*, 716(1):1–29, sep 2012.
- 2438 [37] CMS Collaboration. Observation of a new boson at a mass of 125 gev with the  
2439       cms experiment at the lhc. *Physics Letters B*, 716(1):30 – 61, 2012.
- 2440 [38] The LArIAT Collaboration. The liquid argon in a testbeam (lariat) experiment.  
2441       Technical report, In Preparation 2018.
- 2442 [39] Stefano Dell’Oro, Simone Marcocci, Matteo Viel, and Francesco Vissani. Neu-  
2443       trinoless double beta decay: 2015 review. *Advances in High Energy Physics*,  
2444       2016:1–37, 2016.
- 2445 [40] S.E. Derenzo, A.R. Kirschbaum, P.H. Eberhard, R.R. Ross, and F.T. Solmitz.  
2446       Test of a liquid argon chamber with 20 m rms resolution. *Nuclear Instruments*  
2447       *and Methods*, 122:319 – 327, 1974.
- 2448 [41] Savas Dimopoulos, Stuart Raby, and Frank Wilczek. Proton Decay in Super-  
2449       symmetric Models. *Phys. Lett.*, B112:133, 1982.
- 2450 [42] D. Drakoulakos et al. Proposal to perform a high-statistics neutrino scattering  
2451       experiment using a fine-grained detector in the NuMI beam. 2004.

- 2452 [43] A Ereditato, C C Hsu, S Janos, I Kreslo, M Messina, C Rudolf von Rohr,  
2453 B Rossi, T Strauss, M S Weber, and M Zeller. Design and operation of  
2454 argontube: a 5 m long drift liquid argon tpc. *Journal of Instrumentation*,  
2455 8(07):P07002, 2013.
- 2456 [44] Torleif Ericson and Wolfram Weise. *Pions and Nuclei (The International Series*  
2457 *of Monographs on Physics)*. Oxford University Press, 1988.
- 2458 [45] A.A. Aguilar-Arevalo et al. The miniboone detector. *Nuclear Instruments and*  
2459 *Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors*  
2460 *and Associated Equipment*, 599(1):28 – 46, 2009.
- 2461 [46] Antonio Bueno et al. Nucleon decay searches with large liquid argon TPC de-  
2462 detectors at shallow depths: atmospheric neutrinos and cosmogenic backgrounds.  
2463 *Journal of High Energy Physics*, 2007(04):041–041, apr 2007.
- 2464 [47] A.S. Clough et al. Pion-nucleus total cross sections from 88 to 860 MeV. *Nuclear*  
2465 *Physics B*, 76(1):15–28, jul 1974.
- 2466 [48] B.W. Allardyce et al. Pion reaction cross sections and nuclear sizes. *Nuclear*  
2467 *Physics A*, 209(1):1 – 51, 1973.
- 2468 [49] C Athanassopoulos et al. The liquid scintillator neutrino detector and LAMPF  
2469 neutrino source. *Nuclear Instruments and Methods in Physics Research Section*  
2470 *A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 388(1-  
2471 2):149–172, mar 1997.
- 2472 [50] F. Binon et al. Scattering of negative pions on carbon. *Nuclear Physics B*,  
2473 17(1):168 – 188, 1970.
- 2474 [51] L. Aliaga et al. Minerva neutrino detector response measured with test beam  
2475 data. *Nuclear Instruments and Methods in Physics Research Section A: Ac-*

2476        *celerators, Spectrometers, Detectors and Associated Equipment*, 789:28 – 42,  
2477        2015.

2478        [52] M Adamowski et al. The liquid argon purity demonstrator. *Journal of Instrumentation*, 9(07):P07005, 2014.

2480        [53] P. Vilain et al. Coherent single charged pion production by neutrinos. *Physics Letters B*, 313(1-2):267–275, aug 1993.

2482        [54] R. Acciarri et al. Convolutional neural networks applied to neutrino events  
2483        in a liquid argon time projection chamber. *Journal of Instrumentation*,  
2484        12(03):P03011, 2017.

2485        [55] R. Acciarri et al. Design and construction of the MicroBooNE detector. *Journal  
2486        of Instrumentation*, 12(02):P02017–P02017, feb 2017.

2487        [56] C. E. Aalseth et al.l. DarkSide-20k: A 20 tonne two-phase LAr TPC for direct  
2488        dark matter detection at LNGS. *The European Physical Journal Plus*, 133(3),  
2489        mar 2018.

2490        [57] H Fenker. Standard beam pwc for fermilab. Technical report, Fermi National  
2491        Accelerator Lab., Batavia, IL (USA), 1983.

2492        [58] H Fesbach. Theoretical nuclear physics: Nuclear reactions. 1992.

2493        [59] J. A. Formaggio and G. P. Zeller. From ev to eev: Neutrino cross sections across  
2494        energy scales. *Rev. Mod. Phys.*, 84:1307–1341, Sep 2012.

2495        [60] E. Friedman et al. K+ nucleus reaction and total cross-sections: New analysis  
2496        of transmission experiments. *Phys. Rev.*, C55:1304–1311, 1997.

2497        [61] V.M. Gehman, S.R. Seibert, K. Rielage, A. Hime, Y. Sun, D.-M. Mei,  
2498        J. Maassen, and D. Moore. Fluorescence efficiency and visible re-emission

- 2499 spectrum of tetraphenyl butadiene films at extreme ultraviolet wavelengths.  
2500 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators,*  
2501 *Spectrometers, Detectors and Associated Equipment*, 654(1):116 – 121, 2011.
- 2502 [62] Howard Georgi and S. L. Glashow. Unity of all elementary-particle forces. *Phys.*  
2503 *Rev. Lett.*, 32:438–441, Feb 1974.
- 2504 [63] D.Y. Wong (editor) G.L. Shaw (Editor). *Pion-nucleon Scattering*. John Wiley  
2505 & Sons Inc, 1969.
- 2506 [64] Glassman High Voltage, Inc., Precision Regulated High Voltage DC Power Sup-  
2507 ply.
- 2508 [65] D S Gorbunov. Sterile neutrinos and their role in particle physics and cosmology.  
2509 *Physics-Uspekhi*, 57(5):503, 2014.
- 2510 [66] C. Green, J. Kowalkowski, M. Paterno, M. Fischler, L. Garren, and Q. Lu. The  
2511 Art Framework. *J. Phys. Conf. Ser.*, 396:022020, 2012.
- 2512 [67] S. Hansen, D. Jensen, G. Savage, E. Skup, and A. Soha. Fermilab test beam  
2513 multi-wire proportional chamber tracking system upgrade. June 2014. Interna-  
2514 tional Conference on Technology and Instrumentation in Particle Physics (TIPP  
2515 2014).
- 2516 [68] J. Harada. Non-maximal  $\theta_{23}$  , large  $\theta_{13}$  and tri-bimaximal  $\theta_{12}$  via quark-  
2517 lepton complementarity at next-to-leading order. *EPL (Europhysics Letters)*,  
2518 103(2):21001, 2013.
- 2519 [69] Peter W. Higgs. Broken symmetries and the masses of gauge bosons. *Physical*  
2520 *Review Letters*, 13(16):508–509, oct 1964.
- 2521 [70] P.W. Higgs. Broken symmetries, massless particles and gauge fields. *Physics*  
2522 *Letters*, 12(2):132–133, sep 1964.

- 2523 [71] H J Hilke. Time projection chambers. *Reports on Progress in Physics*,  
2524 73(11):116201, 2010.
- 2525 [72] N. Ishida, M. Chen, T. Doke, K. Hasuike, A. Hitachi, M. Gaudreau, M. Kase,  
2526 Y. Kawada, J. Kikuchi, T. Komiyama, K. Kuwahara, K. Masuda, H. Okada,  
2527 Y.H. Qu, M. Suzuki, and T. Takahashi. Attenuation length measurements of  
2528 scintillation light in liquid rare gases and their mixtures using an improved  
2529 reflection suppresser. *Nuclear Instruments and Methods in Physics Research*  
2530 *Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*,  
2531 384(2-3):380–386, jan 1997.
- 2532 [73] George Jaffé. Zur theorie der ionisation in kolonnen. *Annalen der Physik*,  
2533 347(12):303–344, 1913.
- 2534 [74] C. Jarlskog. A basis independent formulation of the connection between quark  
2535 mass matrices, CP violation and experiment. *Zeitschrift für Physik C Particles*  
2536 *and Fields*, 29(3):491–497, sep 1985.
- 2537 [75] B J P Jones, C S Chiu, J M Conrad, C M Ignarra, T Katori, and M Toups. A  
2538 measurement of the absorption of liquid argon scintillation light by dissolved ni-  
2539 trogen at the part-per-million level. *Journal of Instrumentation*, 8(07):P07011,  
2540 2013.
- 2541 [76] Benjamin J. P. Jones. *Sterile Neutrinos in Cold Climates*. PhD thesis, MIT,  
2542 2015.
- 2543 [77] Cezary Juszczak, Jarosław A. Nowak, and Jan T. Sobczyk. Simulations from  
2544 a new neutrino event generator. *Nuclear Physics B - Proceedings Supplements*,  
2545 159:211–216, sep 2006.

- 2546 [78] D. I. Kazakov. Beyond the standard model: In search of supersymmetry. In  
2547       *2000 European School of high-energy physics, Caramulo, Portugal, 20 Aug-2*  
2548       *Sep 2000: Proceedings*, pages 125–199, 2000.
- 2549 [79] Dae-Gyu Lee, R. N. Mohapatra, M. K. Parida, and Merostar Rani. Predictions  
2550       for the proton lifetime in minimal nonsupersymmetric  $so(10)$  models: An  
2551       update. *Phys. Rev. D*, 51:229–235, Jan 1995.
- 2552 [80] M A Leigui de Oliveira. Expression of Interest for a Full-Scale Detector Engi-  
2553       neering Test and Test Beam Calibration of a Single-Phase LAr TPC. Technical  
2554       Report CERN-SPSC-2014-027. SPSC-EOI-011, CERN, Geneva, Oct 2014.
- 2555 [81] W. H. Lippincott, K. J. Coakley, D. Gastler, A. Hime, E. Kearns, D. N. McK-  
2556       insey, J. A. Nikkel, and L. C. Stonehill. Scintillation time dependence and pulse  
2557       shape discrimination in liquid argon. *Phys. Rev. C*, 78:035801, Sep 2008.
- 2558 [82] Jorge L. Lopez and Dimitri V. Nanopoulos. Flipped  $SU(5)$ : Origins and re-  
2559       cent developments. In *15th Johns Hopkins Workshop on Current Problems*  
2560       *in Particle Theory: Particle Physics from Underground to Heaven Baltimore,*  
2561       *Maryland, August 26-28, 1991*, pages 277–297, 1991.
- 2562 [83] Vincent Lucas and Stuart Raby. Nucleon decay in a realistic  $so(10)$  susy gut.  
2563       *Phys. Rev. D*, 55:6986–7009, Jun 1997.
- 2564 [84] Ettore Majorana. Teoria simmetrica dell'elettrone e del positrone. *Il Nuovo*  
2565       *Cimento*, 14(4):171–184, apr 1937.
- 2566 [85] Hisakazu Minakata and Alexei Yu. Smirnov. Neutrino mixing and quark-lepton  
2567       complementarity. *Phys. Rev. D*, 70:073009, Oct 2004.
- 2568 [86] M. Mooney. The microboone experiment and the impact of space charge effects.  
2569       2015.

- 2570 [87] E. Morikawa, R. Reininger, P. G  rtler, V. Saile, and P. Laporte. Argon, krypton,  
2571       and xenon excimer luminescence: From the dilute gas to the condensed  
2572       phase. *The Journal of Chemical Physics*, 91(3):1469–1477, aug 1989.
- 2573 [88] FM Newcomer, S Tedja, R Van Berg, J Van der Spiegel, and HH Williams.  
2574       A fast, low power, amplifier-shaper-discriminator for high rate straw tracking  
2575       systems. *IEEE Transactions on Nuclear Science*, 40(4):630–636, 1993.
- 2576 [89] Emmy Noether. Invariant variation problems. *Transport Theory and Statistical  
2577       Physics*, 1(3):186–207, jan 1971.
- 2578 [90] I. Nutini. Study of charged particles interaction processes on ar in the 0.2 - 2.0  
2579       GeV energy range through combined information from ionization free charge  
2580       and scintillation light. Technical report, jan 2015.
- 2581 [91] D. R. Nygren. The time projection chamber: A new  $4\pi$  detector for charged  
2582       particles. Technical report, 1974.
- 2583 [92] L. Onsager. Initial recombination of ions. *Phys. Rev.*, 54:554–557, Oct 1938.
- 2584 [93] S. Pascoli, S.T. Petcov, and A. Riotto. Leptogenesis and low energy cp-violation  
2585       in neutrino physics. *Nuclear Physics B*, 774(1):1 – 52, 2007.
- 2586 [94] C. Patrignani et al. Review of Particle Physics. *Chin. Phys.*, C40(10):100001,  
2587       2016.
- 2588 [95] B. Pontecorvo. Neutrino Experiments and the Problem of Conservation of  
2589       Leptonic Charge. *Sov. Phys. JETP*, 26:984–988, 1968. [Zh. Eksp. Teor.  
2590       Fiz.53,1717(1967)].
- 2591 [96] T. Yang R. Acciarri, M. Stancari. Determination of the electron lifetime in  
2592       lariat. Technical report, March 2016.

- 2593 [97] Martti Raidal. Relation between the neutrino and quark mixing angles and  
2594 grand unification. *Phys. Rev. Lett.*, 93:161801, Oct 2004.
- 2595 [98] Steve Ritz et al. Building for Discovery: Strategic Plan for U.S. Particle Physics  
2596 in the Global Context. 2014.
- 2597 [99] C. Rubbia. The Liquid Argon Time Projection Chamber: A New Concept for  
2598 Neutrino Detectors. 1977.
- 2599 [100] L.M. Saunders. Electromagnetic production of pions from nuclei. *Nucl. Phys.*,  
2600 *B7*: 293-310(1968).
- 2601 [101] Qaisar Shafi and Zurab Tavartkiladze. Neutrino democracy, fermion mass hier-  
2602 archies, and proton decay from 5d su(5). *Phys. Rev. D*, 67:075007, Apr 2003.
- 2603 [102] Sigma-Aldrich, P.O. Box 14508, St. Louis, MO 63178 USA.
- 2604 [103] R. K. Teague and C. J. Pings. Refractive index and the lorentz–lorenz function  
2605 for gaseous and liquid argon, including a study of the coexistence curve near the  
2606 critical state. *The Journal of Chemical Physics*, 48(11):4973–4984, jun 1968.
- 2607 [104] J. Thomas and D. A. Imel. Recombination of electron-ion pairs in liquid argon  
2608 and liquid xenon. *Phys. Rev. A*, 36:614–616, Jul 1987.
- 2609 [105] D.R.O. Morrison N. Rivoire V. Flaminio, W.G. Moorhead. Compilation of  
2610 Cross Sections I:  $\pi^+$  and  $\pi^-$  Induced Reactions. *CERN-HERA*, pages 83–01,  
2611 1983.
- 2612 [106] D.R.O. Morrison N. Rivoire V. Flaminio, W.G. Moorhead. Compilation of  
2613 Cross Sections II:  $K^+$  and  $K^-$  Induced Reactions. *CERN-HERA*, pages 83–02,  
2614 1983.
- 2615 [107] Hermann Weyl. Gravitation and the electron. *Proceedings of the National  
2616 Academy of Sciences of the United States of America*, 15(4):323–334, 1929.

- 2617 [108] Colin et al Wilkin. A comparison of pi+ and pi- total cross-sections of light  
2618 nuclei near the 3-3 resonance. *Nucl. Phys.*, B62:61–85, 1973.
- 2619 [109] D. H. Wright and M. H. Kelsey. The Geant4 Bertini Cascade. *Nucl. Instrum.*  
2620 *Meth.*, A804:175–188, 2015.
- 2621 [110] C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson.  
2622 Experimental test of parity conservation in beta decay. *Phys. Rev.*, 105:1413–  
2623 1415, Feb 1957.
- 2624 [111] N Yahlali, L M P Fernandes, K Gonzlez, A N C Garcia, and A Soriano. Imaging  
2625 with sipms in noble-gas detectors. *Journal of Instrumentation*, 8(01):C01003,  
2626 2013.
- 2627 [112] T. Yanagida. Horizontal symmetry and masses of neutrinos. *Progress of Theo-*  
2628 *retical Physics*, 64(3):1103–1105, sep 1980.