4

Electromagnetic Energy Loss in Liquid Argon

Contents

The energy loss of particles in liquid argon has important implications for the reconstruction of different particles in a LArTPC, and will be relevant for the reconstruction algorithms developed in Chapters 6 and 7 of this thesis. This chapter will cover in more detail the theory of electromagnetic energy loss in liquid argon, highlighting the important features of the energy loss for muons, electrons, and photons.

4.1 Electromagnetic Energy Loss in Matter

In matter, charged particles lose energy through a number of small successive collisions with the electrons in the material, and by radiative processes which produce additional particles in the material. The relative importance of the collision and radiative stopping power depends on the mass and the energy of the particle. For most particles, which are heavy compared to the electron, radiative energy losses are not important until very high energies, e.g. for a muon they are not important until momenta of around 100 GeV. However, radiative energy loss become important for electrons at tens of MeV [29]. As a result, different theories are used to describe the energy loss of heavy particles and electrons in matter.

4.1.1 Energy Loss for Heavy Charged Particles

For heavy particles such as muons at moderate energies, the mean rate of energy loss per unit distance is described by the Bethe equation,

$$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]. \tag{4.1}$$

The constants in this equation are detailed in reference [29]. Z and A are the atomic number and mass number of the medium, z is the charge of the scattering particle, W_{max} is the maximum energy transfer per collision, I is the average excitation energy, and δ is a density effect correction which is relevant in solids and liquids.

Three important features of the energy loss in the Bethe formula are the minimum ionising region, the relativistic rise, and the Bragg peak, these regions can be seen in Figure 4.1 which shows the dE/dx for muons in argon as a function of momentum.

Delta Rays

Another feature of the electromagnetic energy loss of heavy particles that impacts reconstruction in LArTPCs is delta rays. Delta rays are energetic electrons which are knocked out of their atoms when they collide with the heavy particle, in liquid argon detectors these electrons are seen as small electron tracks which protrude from muon tracks.

4.1.2 Energy Loss for Electrons

Electrons and positrons undergo different electromagnetic scattering processes in matter, Møller scattering and Bhabha scattering respectively [**TODO**]. These processes, which dominate electron and positron energy loss at low energies, have

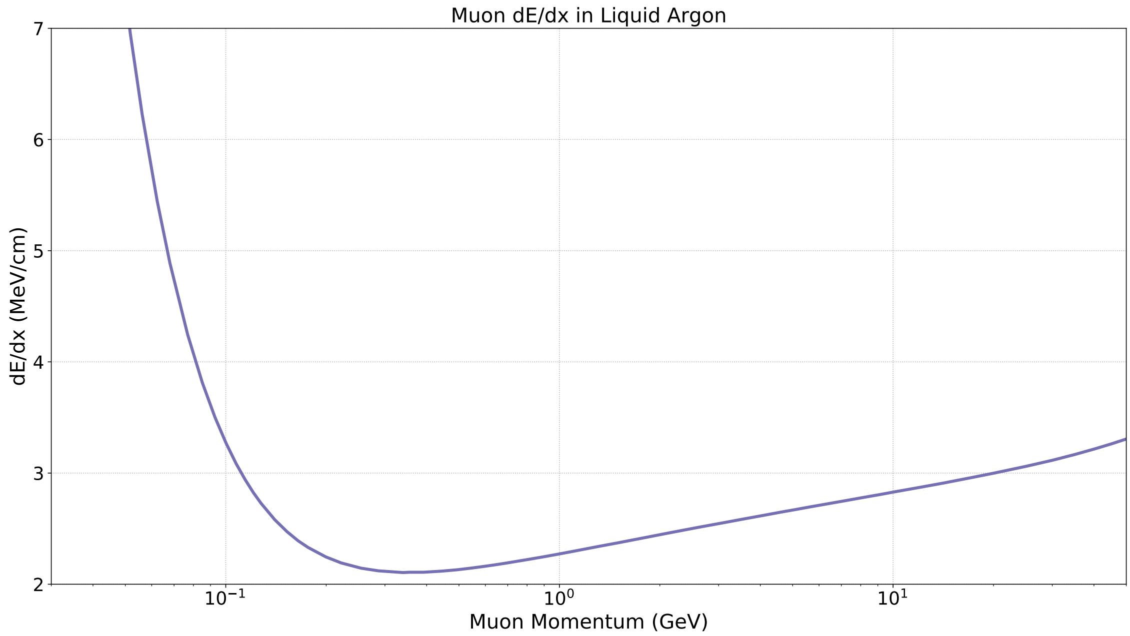


Figure 4.1: Stopping power as a function of energy for muons in liquid argon. Data from [77].

different cross sections which modify the energy loss in each case. At higher energies, radiative processes such as bremsstrahlung dominate. The two components of the electron stopping power are known as the collision stopping power and the radiative stopping power.

Collision Stopping Power

The collision stopping power of electrons and positrons is calculated with a similar method to the heavy particle stopping power, where individual collisions are considered in succession. The main difference in the calculations is the cross sections used in the calculations, for electrons the Møller scattering cross section is used, and for positrons Bhabha scattering is considered. Due to the electrons and positrons having the same mass as their targets, the maximum energy transfer in a single collision, W_{max}, is the total kinetic energy. However, this value is halved for the case of electrons, due to the convention of calculating the stopping power for the final state electron with higher kinetic energy.

The stopping power based on Møller scattering of electrons gives,

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{1}{2} K \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \frac{m_e c^2 \beta^2 \gamma^2 \left\{ m_e c^2 (\gamma - 1)/2 \right\}}{I^2} + (1 - \beta^2) - \frac{2\gamma - 1}{\gamma} + \frac{1}{8} \left(\frac{\gamma - 1}{\gamma} \right)^2 - \delta \right],$$

while Bhabha scattering, which governs the positron stopping power, gives,

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{1}{2} K \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \frac{m_e c^2 \beta^2 \gamma^2 \left\{ m_e c^2 (\gamma - 1) \right\}}{2 I^2} + 2 \ln 2 - \frac{\beta^2}{12} \left(23 + \frac{14}{\gamma + 1} + \frac{10}{(\gamma + 1)^2} + \frac{4}{(\gamma + 1)^3} \right) - \delta \right],$$

where the terms have the same meanings as in Equation 4.1 [29].

Radiative Stopping Power

Above a few tens of MeV, electrons lose most of their energy through the emission of bremsstrahlung photons. Detailed discussion of the energy loss due to bremsstrahlung emission is beyond the scope of this thesis, detailed discussions are provided by [29, 78]. Here, we discuss a simplified model which highlights the important factors relevant for the work in this thesis.

At high energies, where the radiative energy loss is dominant, the energy of the electron can be approximated as an exponential decay over a length scale known as the radiation length, X_0,

$$E = E_0 \, e^{-x/X_0}.$$

In this approximation, the energy loss per unit distance due to bremsstrahlung is,

$$-\left(\frac{dE}{dx} \right)_{brem} = \frac{E}{X_0}.$$

The radiation length, X_0, can be parametrised as,

$$\begin{aligned} \frac{1}{X_0} &= 4 \alpha r_e^2 \frac{N_A}{A} \left\{ Z^2 \left[L_{rad} - f(Z) \right] + Z L'_{rad} \right\} \\ f(Z) &= \alpha^2 Z^2 \left[\frac{1}{1 + \alpha^2 Z^2} + 0.20206 - 0.0369 \alpha^2 Z^2 + 0.0083 \alpha^4 Z^4 - 0.0002 \alpha^6 Z^6 \right], \end{aligned} \tag{4.2}$$

where L_{rad} and L'_{rad} are the so–called radiation logarithms, which depend on the atomic number of the material[78].

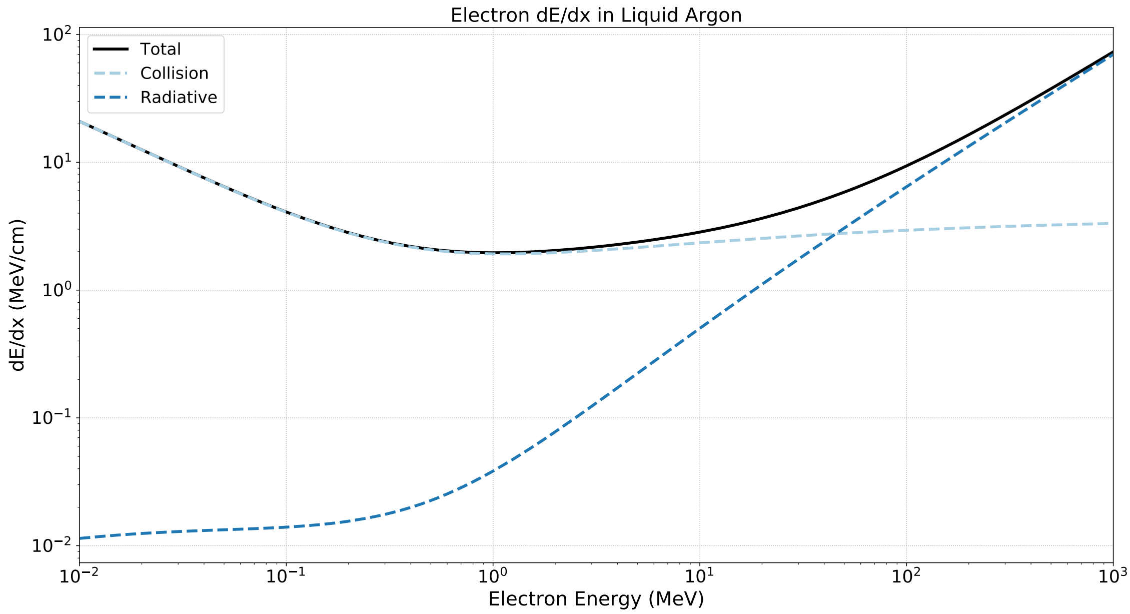


Figure 4.2: Stopping power as a function of energy for electrons in liquid argon. Data from [80].

Critical Energy

The critical energy is often defined as the energy at which the collision and radiative stopping power are equivalent, other definitions are also used, such as the definition by Rossi, the energy where the ionisation loss per radiation length is equal to the electron energy [79]. Rossi's definition is equivalent to using the approximate dE/dx calculated above[29]. The value of the critical energy has important implications for reconstruction algorithms, because different approaches are often required above and below the critical energy.

The critical energy is slightly different for electrons and positrons, in liquid argon they are both around 32 MeV, based on the Rossi definition [77]. This can be seen in Figure 4.2, which shows the total electron stopping power in liquid argon, in addition to the collision and radiative components which make up the total stopping power.

4.1.3 Energy Loss for Photons

A number of processes contribute to the energy loss of photons in matter, brief descriptions of the main processes are given below.

Photoelectric Effect

The photoelectric effect occurs when a photon collides with an atom, X, the photon is absorbed and electron is emitted from the atom. As a result, the atom is ionised.

$$\gamma + X \rightarrow e^- + X^+$$

Compton Scattering

Compton scattering occurs when a photon scatters incoherently from an electron within an atom. The electron is typically liberated from the atom, and the photon loses some of it's energy.

$$\gamma + e^- \rightarrow \gamma + e^-$$

Pair Production

Pair production is the production of an electron positron pair, in the vicinity of an external electric field. During this process, the photon is destroyed to produce the electron positron pair. In matter, the electric field could be provided by either the electrons in the atom, or the nucleus of the atom.

$$\gamma \rightarrow e^+ + e^-$$

The cross section for these effects vary as a function of photon energy. The cross sections for each process in liquid argon, as well as the total photon cross section, are given in Figure 4.3. The Compton scattering cross section is dominant from around 0.1 MeV to 10 MeV, after which the pair production cross section dominates.

Photon Mean Free Path

The mean free path of a photon is defined as the distance travelled by the photon before it interacts with the material. The mean free path for photons has two main components for photons in the MeV range, which are due to Compton scattering and pair production. The mean free path is given by $\lambda = 1/(n\sigma)$, where n is the number density of targets and σ is the cross section per target. The contribution to the mean

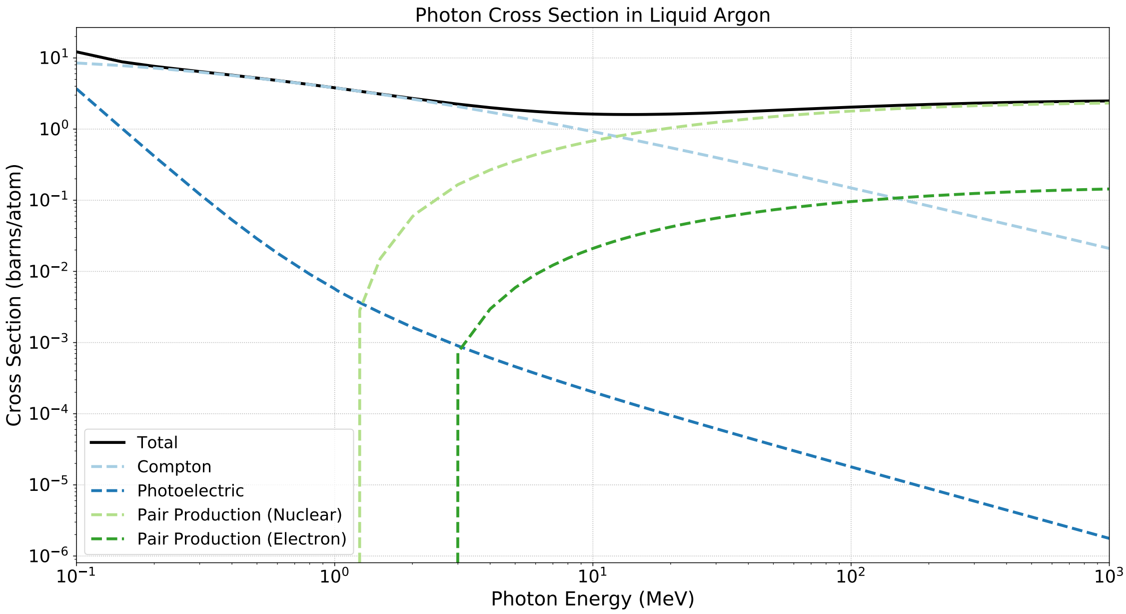


Figure 4.3: Photon interaction cross sections in liquid argon. Data from [81].

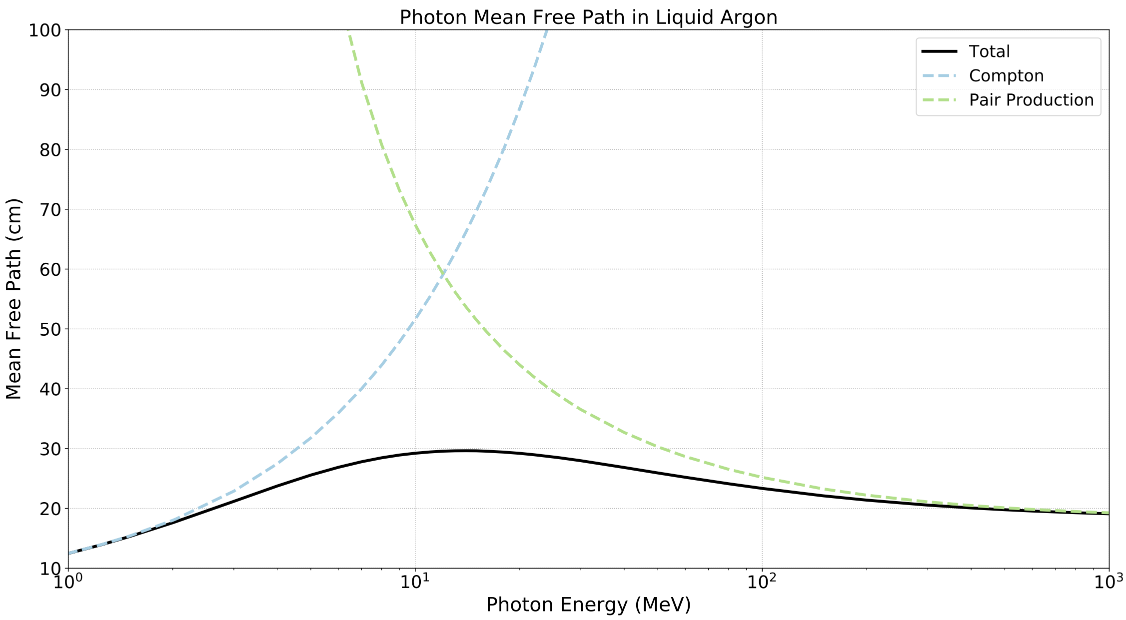


Figure 4.4: Photon mean free path in liquid argon. Data from [81].

free path from pair production is related to the radiation length for electrons, X_0 from Equation 4.2, by $\lambda_{PP} = (9/7)\ X_0$ [29]. The mean free path for photons in the MeV range is shown in Figure 4.4, along with the main contributing cross sections.

4.1.4 Typical Interaction Signatures in ProtoDUNE–SP

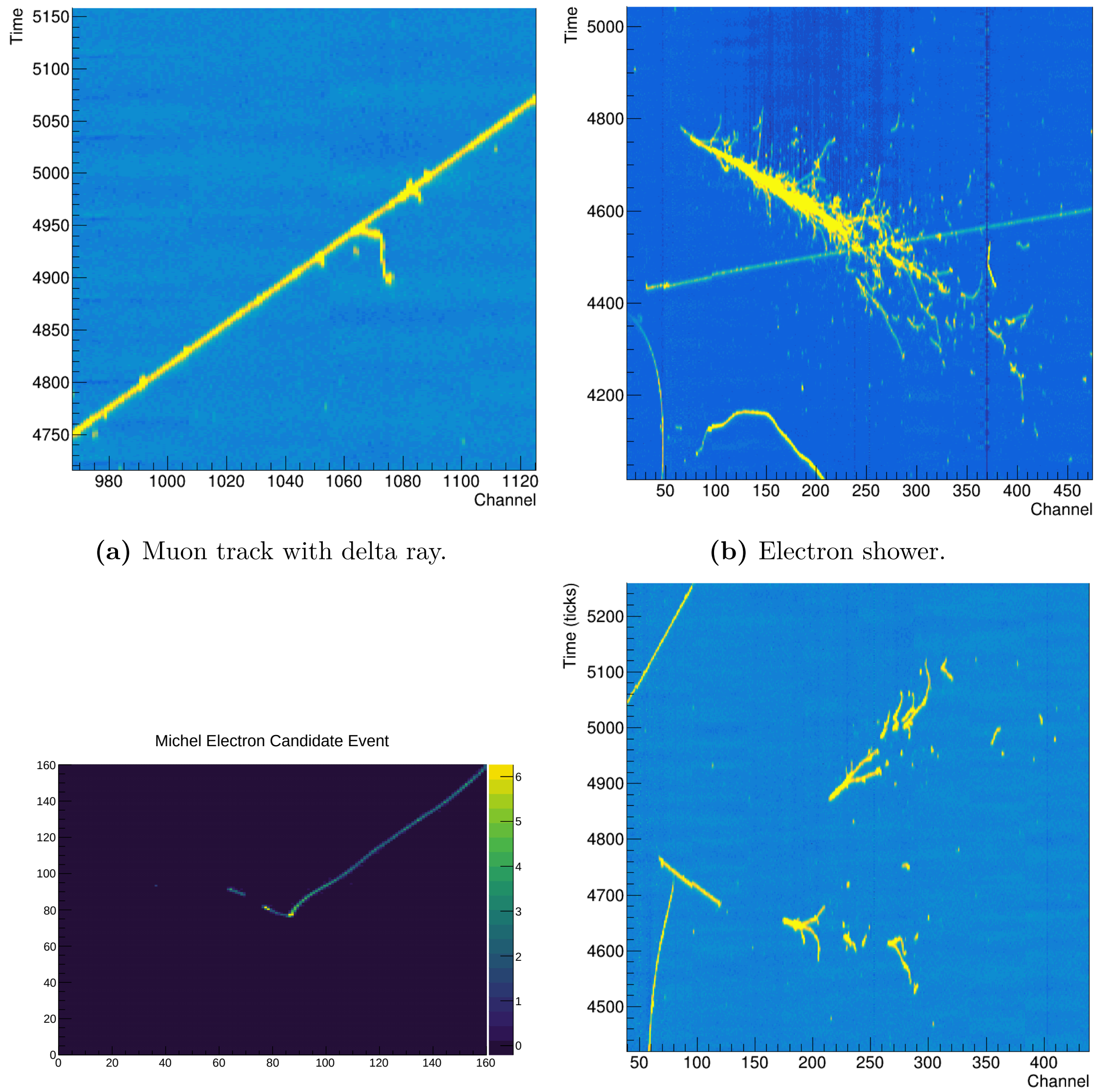
As a result of the differences in energy loss which depend on particle species and energy, different particles leave distinct signatures in the detector. Figure 4.5 shows the typical signatures of four types of interaction in a liquid argon TPC for events from ProtoDUNE–SP data.

The most common interaction in ProtoDUNE–SP is that of a cosmic ray muon, seen in Figure 4.5a. Muons, and other heavy particles, leave long tracks in the detector which deposit around 2.1 MeV/cm in the minimum ionising region. Alongside muon tracks, relatively high energy electrons, known as delta rays, are occasionally produced. Delta rays can be seen as electron activity along the length of the muon track.

Electrons in ProtoDUNE–SP have two distinct signatures, which depend on the energy of the electron. For high energy electrons, with energies above around 300 MeV, radiative energy loss dominates and showers are produced, an example of an electron shower can be seen in Figure 4.5b. These showers are the result of a cascade of electrons, which are produced by a chain of bremsstrahlung photons and electron positron pairs.

At energies in the tens of MeV range electrons have a different signature, which consists of a small electron track accompanied by a number of small ionisation energy deposits due to radiated photons. A common source of these electrons in ProtoDUNE–SP are Michel electrons, which are the electrons produced when a muon decays at rest in the detector. An example of a typical Michel electron event is shown in Figure 4.5c. The Michel electron is accompanied by the incoming Muon in the image, which cannot be separated in the ionisation signal due to the slow drift of the ionisation.

As with electrons, photon interactions in liquid argon have two distinct signatures at high and low energies. Low energy photons are typically produced by the interactions of low energy electrons in the liquid argon, such as the Michel electron interaction in Figure 4.5c. When these photons interact they produce small isolated



(a) Muon track with delta ray.

(b) Electron shower.

(c) Michel electron.

(d) Photon showers from a π^0 decay.

Figure 4.5: Typical particle interactions in ProtoDUNE–SP for different particle species.

energy deposits, which are created by the ionisation caused by the Compton scattered electron of electron positron pair.

At high energies, photons produce similar interactions to high energy electrons, which produce electromagnetic showers in the liquid argon. Their is a slight difference in the dE/dx in the first few cm of these showers which can allow for electron and photon showers to be distinguished [82]. A common source of photon showers in ProtoDUNE–SP are π^0 decays, shown in Figure 4.5d, which produce a pair of photons.