ARIADNE: Beam Time and Resources Request

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Abstract

The ARIADNE research programme is based around developing an optical readout system for use in LAr TPC detectors, which could potentially have a number of benefits over the currently used segmented anode planes - particularly in matters of scalability for future kilo-tonne scale detectors, ease of installation, use and maintenance, and reconstruction resolution. As detailed in our previously submitted Letter of Intent (CERN-SPSC-2016-008 [SPSC-I-244]), ARIADNE itself is a 1-tonne, two-phase LAr TPC detector, designed and built at the University of Liverpool, which uses an array of EMCCD cameras as its optical readout system, alongside PMTs for scintillation light observation and a THGEM for charge readout. Once construction and initial calibration is completed at Liverpool, the detector's capabilities should be fully studied and characterised, and we would like to request 2 weeks of on-beam time at the CERN T9 beam line in the Spring of 2018 for this purpose. Due to the purity requirements and cryogenic nature of the experiment, we would also need an additional 3 weeks prior to the on-beam time for commissioning the detector (which could take place before the beam is turned on, so as to minimise the impact for other beam users), and half a week afterward for decommissioning.

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1 Introduction

The ARIADNE research programme - standing for ***AR**gon **I**m**A**ging **D**etectio**N** Chamb**E**r* and funded by the ERC - centres around developing an optical imaging system as an alternative approach to charge readout in large-scale two-phase liquid argon (LAr) TPC detectors, which is currently achieved using segmented anode planes. An optical system offers a number of benefits and advantages over anode planes, particularly in the areas of scalability, ease of access and technology maturity.

Building on work originally performed at the University of Liverpool using a 40l proof-of-concept demonstrator, ARIADNE is a 1-tonne, two-phase LAr TPC detector, equipped with PMTs for observing primary scintillation light from the LAr, a field cage for drifting free electrons through the liquid phase, a THGEM for electron multiplication and subsequent creation of secondary scintillation light in the gas phase, and EMCCD cameras for directly observing the secondary scintillation light.

In order to test the capabilities of the readout system and characterise the detector as a whole, we have previously proposed to use one of the charged particle beams at CERN for data-taking and subsequent physics analyses - that Letter of Intent (CERN-SPSC-2016-008 [SPSC-I-244]) was submitted to the SPS Committee for consideration at their January 2016 meeting [1], and as a result, it was suggested that ARIADNE could use one of the independent beam lines - T9 or T10 - located in the East Hall.

Subsequent development of the research programme and detector has proceeded with this consideration in mind, and with construction of the main detector well underway at the time of writing, we are now proposing to make use of the T9 beam line at CERN in early 2018. This particular beam line would be ideal due to the variety of particles available (which allows for a better characterisation of the detector's response and PID studies), the wide range of low energies it can operate at (allowing for better containment of particle tracks within the TPC - as ARIADNE is a relatively small detector, high momentum particles such as those in the North Area beams would not be well contained), and its physical characteristics which allow the use of additional hardware operating alongside the main ARIADNE detector.

Following on from the original Letter of Intent, this document has been prepared in order to provide more detailed information on our proposed use of the T9 beam line. Section 2 gives a brief description of the ARIADNE detector and other external hardware we intend to use (including a more detailed discussion of some of the advantages of using an optical readout system over a segmented anode plane, and additional comments regarding our choice of the T9 beam line), and our physics goals are discussed in Section 3. Finally, a breakdown and summary of our proposed beam, time and other resource requirements is given in Section 4.

2 The ARIADNE Hardware

2.1 The Main Detector

The main ARIADNE detector is shown in Figure 1, and further details on the major components - both internal and external - are given below.

Cryostat

The ARIADNE cryostat is constructed from stainless steel, and stands 2.1m tall and 1.3m in diameter, with a total internal volume of 1500l. It is double-walled, allowing for the presence of a vacuum jacket (which will be maintained using a turbopump) in order to minimise heat losses, PED-certified under EN-13458 (up to 4 bar internal pressure) and CE marked. During normal operation of the detector, approximately 1000l of LAr at a temperature of 87K (which will be maintained using a cryocooler) will be present inside the cryostat.

[1] Meeting minutes: https://cds.cern.ch/record/2125724/files/SPSC-120.pdf

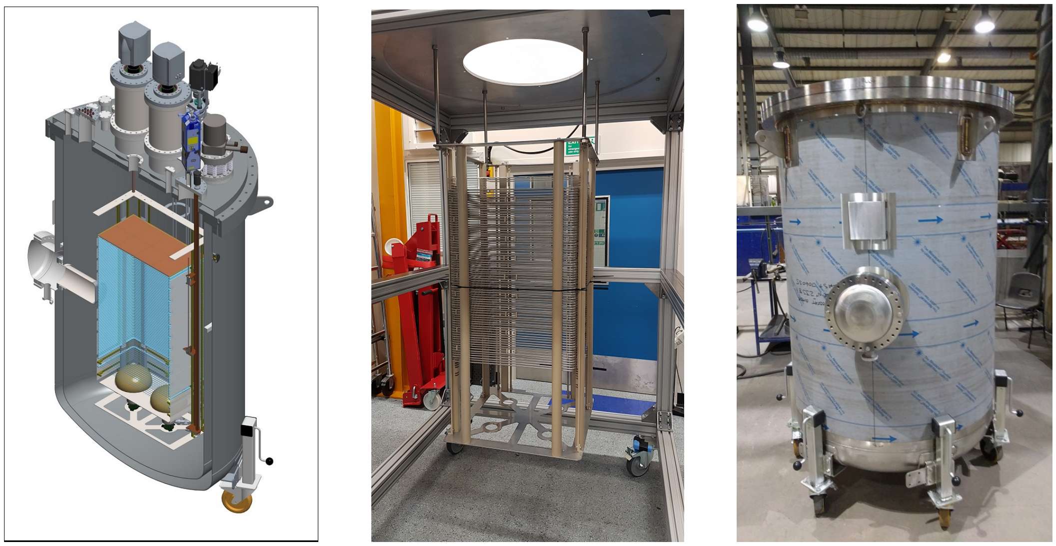

Figure 1: (Left) Section-view schematic of ARIADNE, showing the TPC field rings (blue), 2 of the 4 PMTs (bottom, gold), THGEM (brown) and beam plug (far-left, silver) all located inside the vacuum-jacketed cryostat, with the cryocooler head (top-right, dark grey) and 2 of the 4 EMCCD cameras also visible on top of the detector. (Centre) View of the TPC suspended from a temporary construction frame. (Right) The ARIADNE cryostat and beam plug, prior to being shipped from the manufacturer to the University of Liverpool.

TPC

At the heart of the detector is the 0.8m-tall TPC, which consists of 79 equally-spaced field rings, the cathode grid located below the rings, and the extraction grid above them. The cathode and extraction grids are held at $-48,000$V and -8000V respectively, giving an electric field gradient inside the TPC field cage of 500 V/cm along the $+z$ axis.

The volume of LAr within the TPC is denoted as the *active volume*, with the *dead volume* being the LAr outside it.

PMTs

An array of 4 20cm-diameter TPB-coated Hamamatsu R5912 PMTs is located below the TPC, and these are used to directly observe the primary and secondary scintillation light pulse induced by a charged particle traversing the detector. The PMTs are read out using a CAEN v1720 (8-channel) digitizer - this particular digitizer has been chosen for its 250 MS/s (4ns per sample) readout rate, which has been shown to be fast enough to observe even the very short duration primary light pulses expected from higher momentum particles such as cosmic muons.

THGEM

ARIADNE uses a 53cm-wide square THGEM (a prototype of which is shown in Figure 2), located 1cm above the extraction grid within the gas phase, and perforated by many thousands of holes - each with a diameter of 0.5mm and an inter-hole pitch of 0.8mm - to amplify the charge originating from drift electrons.

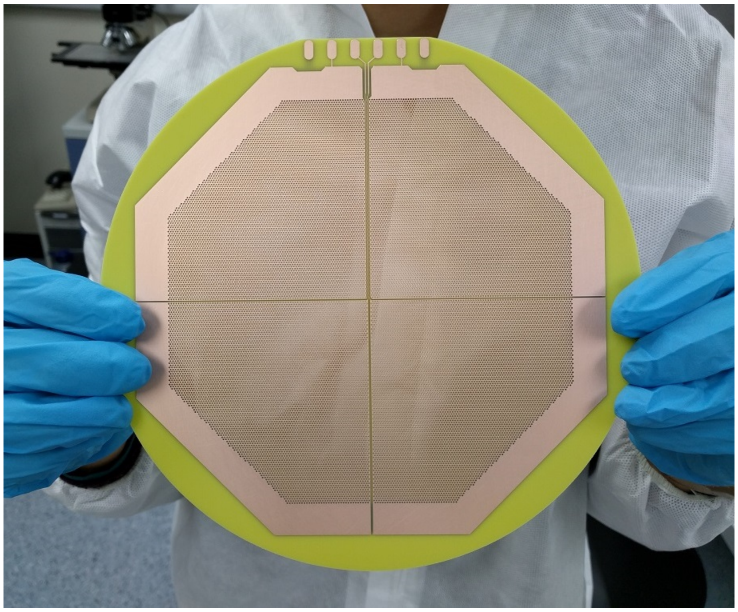

Figure 2: A prototype of the ARIADNE THGEM. This version is octagonal in shape, with 4 charged-separated pads, and has been used on the 40l proof-of-concept demonstrator.

The top and bottom copper surfaces of the THGEM are individually biased, allowing an electric field to be set up vertically through the THGEM holes. When the drift electrons pass through the holes, they *avalanche* - producing more electrons and so amplifying the charge signal. The precise amplification factor - the *THGEM gain* - is dependent on the exact voltages on the top and bottom surfaces, but it is expected that ARIADNE will operate with a constant THGEM gain of approximately 100.

The top surface of the THGEM is sub-divided into a 4 by 4 grid of smaller charge-separated *pads* - a design which allows the spatial localisation of the charge signal into a particular 2-dimensional area of the THGEM, aiding both energy and track reconstruction. Each pad is individually biased - but with all 16 power supplies originating from the same input HV feedthrough. This allows the pads to be completely charge-separated, and read out independently, while still all operating at precisely the same voltage (which is essential in order to avoid discharges between pads at different biases).

Each THGEM pad has 2 readout channels - one with a low gain, and the other with a high gain. These channels operate independently, which allows the THGEM a much greater dynamic range of measurable charge signals than if there was only a single readout channel per pad with a fixed gain. (For clarity, it should be noted that these low and high gains - which are determined by the THGEM's readout pre-amp electronics - are completely unrelated to the voltage-dependent THGEM gain described previously). All 32 THGEM channels are read out using a CAEN v1740 (64-channel) digitizer.

Beam Plug and Window

The beam plug, shown in Figure 3, has been designed to minimise the amount of material along the path of particles entering the detector. As such, the outer window is constructed of 0.9mm-thick stainless steel, the internal volume will be evacuated to vacuum, and the inner window - positioned 11mm from the field rings - is constructed of 2mm-thick stainless steel. These thicknesses have been optimised according to studies of particle loss vs. the ability of the beam plug to safely contain the vacuum.

Although this design potentially still leaves 11mm of dead LAr for particles to pass through (and interact in), the beam plug cannot be positioned any closer to the field rings, in order to avoid discharges between the rings and the inner window. Instead, a block of polyethylene - molded to fit around the field rings - will be placed in this 11mm gap, both displacing the dead LAr and acting as an insulation against discharges.

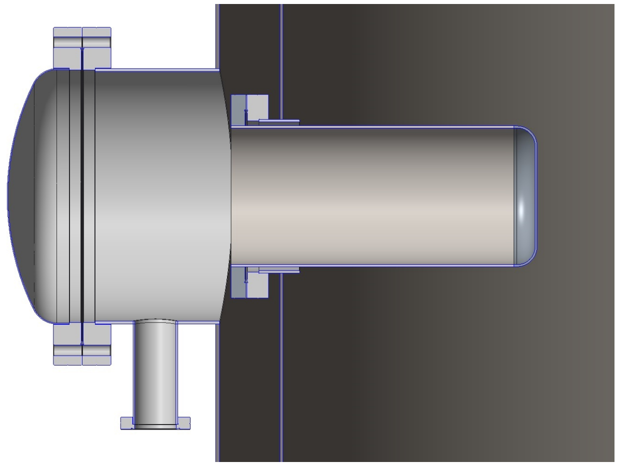

Figure 3: Schematic cross-section of the ARIADNE beam plug. Particles enter from the left, through the (curved) outer window, and pass through the vacuum volume before entering the detector itself through the inner window (shown in blue on the right).

Other Detector Components

ARIADNE uses an internal recirculation system - housed inside the cryostat next to the TPC - to purify and circulate the LAr. This system is centred around a single filtration cartridge working in tandem with a bespoke 2-bellow fluid pump that has been designed and built entirely at the University of Liverpool specifically for ARIADNE, and is capable of circulating the entire internal LAr volume of the cryostat approximately once every 4 hours.

The ARIADNE detector can be equipped with both an internal radioactive source and a UV laser system. Both of these will in fact be used to calibrate the detector prior to beam running, but will be removed before it is transported, as we do not intend to use them while at CERN.

Various ports on the detector's top flange will be used for monitoring purposes - such as for housing temperature and pressure sensors, as well as a number of cryo-safe webcams to directly observe the inside of the detector. In addition, for safety purposes the detector is equipped with both pressure relief valves and bursting disks, to ensure that no unsafe over-pressurisation occurs at any time during transport, commissioning, beam running or decommissioning.

2.2 Optical Readout System

All other dual-phase neutrino detectors currently in operation use a segmented anode plane of some form - usually strips arranged in 2 orthogonal directions - to collect the avalanche electrons produced in the THGEM holes. However, since the THGEM is positioned within the gas phase of the detector, the avalanches also produce a secondary scintillation light pulse - delayed in time with respect to the primary one observed by the PMTs, but considerably more intense and broader in time.

ARIADNE is the first detector to be specifically designed around the idea of imaging this secondary scintillation light directly with a camera.

The detector is equipped with 4 Andor iXon Ultra 888 EMCCD cameras, positioned 1.1m above the top surface of the THGEM in a 2 x 2 grid and each coupled to a commercially available 50mm lens. Taken together with a TPB-coated glass plate positioned between the THGEM and the cameras (which acts to shift the 128nm-wavelength LAr scintillation light into the visible spectrum), this arrangement is capable of viewing the entire 53 x 53cm THGEM plane.

The readout rate of each camera is dependent on both the CCD sensor size and pixel binning being used, and both of these are in turn related to the desired spatial resolution we wish to achieve. Operating each camera at the maximum possible sensor size of 1024 x 1024 pixels and a binning of 4 x 4 pixels gives a spatial resolution of 0.98 mm/pixel (assuming no overlap between adjacent camera images), and at these settings the readout speed per camera is 92 frames per second. The spatial resolution can be reduced to just 0.488 mm/pixel by using a binning of 2 x 2 pixels, but this will also reduce the readout speed to 50 frames per second.

Although these readout speeds are significantly slower than those of the CAEN digitizer readouts being used by the PMTs and THGEM, the ARIADNE DAQ has been designed such that all readout devices are triggered by the cameras - i.e. the slowest readout rate, thus removing the possibility that the various components will be read out asynchronously due to their differing rates.

An optical readout system such as ARIADNE's offers certain benefits over the usual anode plane method, primarily relating to the ability to scale the designs up for use in future kilo-tonne scale neutrino detectors.

An anode plane design requires individual readout channels for each strip - which could easily number in the millions at large scales, and the resolution of any position and track reconstruction is physically limited to the pitch of the strip.

In contrast, by using commercial and proven CCD technology, an optical readout system can be scaled up for a large detector by simply adding more cameras to an existing design, with the number of readout channels simply being equal to the number of cameras, and the track reconstruction resolution limited only by the number of pixels which view each THGEM hole - i.e. the pixel density, which continues to increase as general CCD technology matures.

One final notable benefit of an optical readout system such as ARIADNE's is ease of access for installation, maintenance and upgrade - since the cameras are mounted externally, accessing them does not involve opening, closing and re-preparing the inside of the detector for use.

2.3 External Components

Time of Flight (ToF) System

Before reaching the experimental area, the T9 beam line contains two air-gaps separated by 20m. We intend to use these gaps for the ARIADNE Time of Flight (ToF) system - comprising two identical assemblies, each consisting of a 0.15mm-thick plastic scintillator film coupled via light-guide to a 2-inch diameter PMT. Both PMTs are read out using a CAEN v1761 (2-channel) digitizer operating at 4GS/s (250ps per sample) per channel, and for each event, the difference in time between the PMT signal peaks is related to the particle mass, and therefore its species. This particular digitizer has been specifically chosen for its high sampling rate - providing a high enough resolution to cleanly distinguish $\pi^{\pm}$ from $p/\overline{p}$ at particle energies up to 5GeV, and $e^{\pm}$ from $\pi^{\pm}$ at energies up to 2GeV.

When combined with the more general $e^{\pm}$ vs. non-$e^{\pm}$ discrimination provided by the gas-Cerenkov system (see below), the ToF system will therefore be used as an independent PID system, acting as a cross-check for any PID results from the main detector.

The ToF system will also be an important part of the overall ARIADNE trigger system: to remove cosmic particles, the overall detector readout will only be triggered when a particle has passed through *both* ToF assemblies *and* the detector itself - i.e. only if the particle travelled along the beam line, rather than entering the detector from above or below (as a cosmic particle would) and therefore not producing a signal in either ToF assembly. It should be noted, however, that due to the volume of the detector and the per-event recording time window of 0.5ms width, there is still a small possibility of pileup between a beam event and a cosmic particle.

The ToF system is the primary reason why we would like to use the T9 beam line, rather than T10 - which is both shorter (producing smaller differences between different particles' flight times, and therefore requiring a faster digitizer, or a lower particle momentum, in order to distinguish them), and has only a single air-gap before its experimental area (meaning that either the main detector itself would have to function as the second ToF assembly, removing any independence of the two systems, or that the detector would need to be pushed away from the beam line to allow space for the second ToF assembly, therefore requiring the beam to propagate through a substantial volume of air before reaching the detector).

Gas-Cerenkov (GC) System

We have been informed that there is a small Cerenkov detector available for use on the T9 beam line, consisting of a thin container of gas coupled to a PMT for readout. The choice of gas acts as a PID system, since each particle species will emit Cerenkov light only in a specific gas, and the particle momentum is related to the internal gas pressure - i.e. for a given pressure, only particles above a certain momentum will emit Cerenkov light. According to information kindly provided to us by Lau Gatignon, the container is currently filled with CO_2 gas - useful for $e^{\pm}$ identification.

In conjunction with the ToF system described above, we intend to use this gas-Cerenkov (referred to hereafter as GC) system as an initial $e^{\pm}$ veto for the ARIADNE DAQ, effectively splitting our beam time into two *running modes*:

- $e^{\pm}$ running - the detector is triggered by (near) simultaneous signals from *both* the ToF and GC, i.e. the ToF identified that a particle entered the detector, and the GC identified it as an $e^{\pm}$
- non-$e^{\pm}$ running - the detector is triggered by *only* a signal from the ToF, identifying that a particle entered the detector, and - because there is no signal from the GC - it is *not* an $e^{\pm}$

3 Physics Goals

3.1 PID Studies

The amount of energy that a particle deposits in a material per unit distance that it travels, denoted by $\frac{dE}{dx}$, is well known as a very reliable method of particle species identification (PID).

ARIADNE will be able to perform PID studies on a variety of different particle species at a number of energies through measurements of $\frac{dE}{dx}$. This will utilise ARIADNE's full readout capabilities: camera image and PMT signal data for 3D track reconstruction and THGEM data for energy reconstruction. The ToF system will also be used to provide an independent check of the main detector's results.

Generally, the measurement of $\frac{dE}{dx}$ requires a certain level of track and energy containment within a detector. Figure 4 shows the results of simulated containment studies performed for ARIADNE, where the containment is defined as:

$$\frac{\text{Energy Deposited in Active LAr Volume}}{\text{Total Energy Deposited in Active and Dead LAr Volumes}} \tag{1}$$

At 0.5 GeV/c, $e^{\pm}$ energy containment is approximately 60%, and this decreases to 30% at 3.5 GeV/c. This containment is certainly sufficient for EM shower reconstruction and PID, since the key region of the shower is around the starting vertex (see Section 3.2 below). Low-momentum (< 0.8 GeV/c) p are completely contained, but this decreases sharply to 10% containment at 2 GeV/c. However, given that $\frac{dE}{dx}$ can still be performed on even short particle tracks, this should not pose a problem for PID studies on p. A similar situation occurs for $\pi^{\pm}$, which have between 30% (0.5 GeV/c) and 5% (3.5 GeV/c) containment - sufficient for calorimetry and reconstruction of the $\pi^{\pm}$ track through the TPC (see Section 3.3 below).

This will be the first attempt at PID using an optical readout system - and so, aside from characterising the most basic physics capabilities of ARIADNE, this is a very useful comparative test of our unique design and hardware against existing PID methods, and will also provide an opportunity for better understanding and developing the various software analyses to be used.

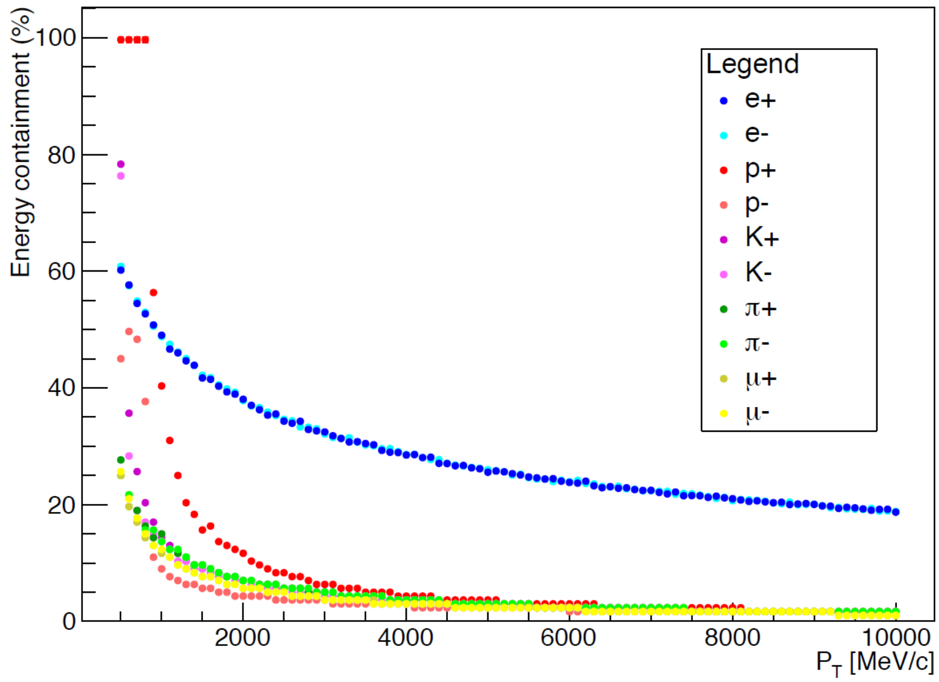

Figure 4: The energy containment of the ARIADNE detector, as given by Equation 1, for a variety of particle species at different momenta.

3.2 e/γ Separation using EM Showers

The charged current (CC) interaction involving an atomic e^- and an incident $\overline{\nu}_e$ is shown in Figure 5. If the recoiling electron from this process has sufficient energy (> a few MeV), it subsequently produces an *electron-induced* EM shower via a chain of many successive Bremsstrählung and pair production occurrences.

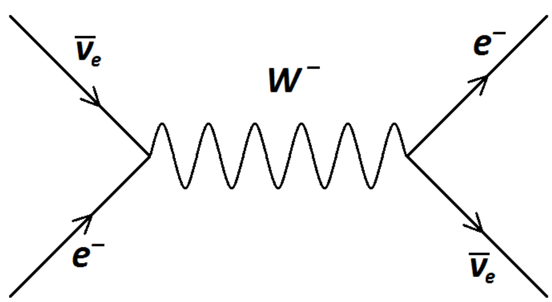

Figure 5: The charged current interaction between an atomic e^- and an $\overline{\nu}_e$ incident on the material containing the former. This elastic scattering leads to the ejection of the e^- from its atom, and - if it has sufficient energy - an electron-induced EM shower.

An incident γ with enough energy can also directly produce a *gamma-induced* EM shower if it undergoes pair production, producing $e^\pm$ pairs that continue the Bremsstrählung → pair production chain. Gamma-induced EM showers are of particular concern in long-baseline neutrino experiments, where π^0 contamination can be present in the ν beam. The primary decay of π^0 is to a γ pair, and so if these γ's travel into the neutrino detector's active volume, the resulting gamma-induced EM showers act as a background to the CC interaction shown above, which - as noted - produces an electron-induced EM shower as its signal. Therefore, having a reliable method of distinguishing between the two types of EM shower is a key requirement of any experiment seeking to observe the CC interaction.

Figure 6 shows simplified schemes of the initial vertices in both an electron- and gamma-induced EM shower. (These diagrams are not meant to be realistic in any way - they are simply used to illustrate the concepts being discussed.)

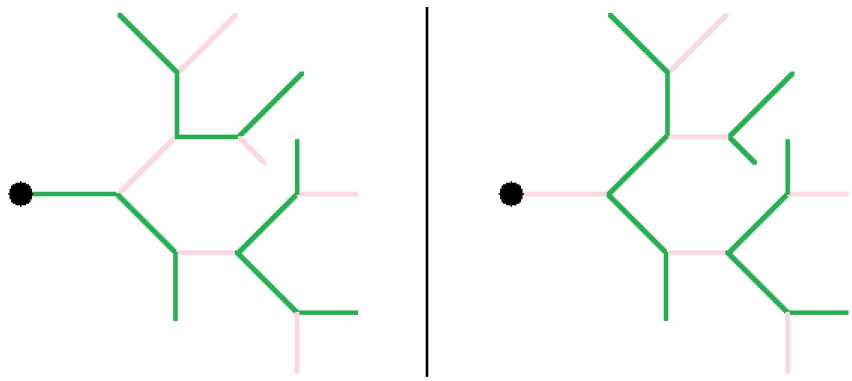

Figure 6: Simplified schemes of electron-induced (left) and gamma-induced (right) EM showers with $e^{\pm}$ shown in green, and γ in pink. The (known) point at which the incident particle enters the detector volume is denoted by the black spot.

Given that γ's are not directly observed (being neutral, they do not produce any direct ionisation or excitations in scintillator), it can be seen that the distributions of the remaining ($e^{\pm}$) tracks are subtly different between the two types of EM shower. In particular, the electron-induced shower begins with a single ionisation track beginning at the beam entry point and containing a very distinct "elbow" shape, whereas the gamma-induced shower will have a clear gap between the beam entry point and the first observed vertex - a two-pronged fork. These differences become less and less obvious as the shower propagates, as the sheer number of overlapping $e^{\pm}$ tracks in such a small volume make it considerably more difficult to distinguish between individual tracks, as well as between $e^{\pm}$ tracks and γ gaps.

One of the primary goals of ARIADNE is to develop a method of distinguishing between electron- and gamma-induced EM showers based on these initial differences in their vertex and track distributions, using a combination of camera images and bespoke track and vertex reconstruction algorithms to probe the regions immediately before and after the first vertex of each shower. We aim to demonstrate that our optical readout system and separation methodology can achieve - at minimum - a comparative level of accuracy and reliability to that which was recently achieved by the ArgoNeut experiment [2], using $\frac{dE}{dx}$ instead of shower reconstruction for e/γ separation.

3.3 Total $\pi^{\pm}$ Cross-section in LAr

The probability dW of a particle of energy E interacting within a thin slab of material with depth dx and number density n is most generally given by:

[2] R. Acciarri *et al.*, *First observation of low energy electron neutrinos in a liquid argon time projection chamber*, Phys. Rev. D **95**, 072005 (April 2017)

$$dW(E) = dx\, n\, \sigma(E) \tag{2}$$

where $\sigma(E)$ denotes the *cross section* of the interaction at energy E. The probability dW can also be thought of as the ratio between the absolute number of particles interacting in the slab ($I(E)$) and the absolute number of particles incident on the slab (P). Given also that the number density n is simply the ratio of the mass density (ρ) to the atomic mass (Au, for mass number A and unified atomic mass unit u), the above expression for dW can be rearranged to give an expression for $\sigma(E)$:

$$\sigma(E) = \frac{Au}{\rho} \frac{1}{dx} \frac{I(E)}{P} \tag{3}$$

To apply this to a measurement of $\sigma(E)$ in the ARIADNE detector, the active volume within the TPC can be considered as being made up of vertical slabs, each with thickness dx equal to some number of camera pixels (the exact number is still to be determined), and then track and vertex reconstruction will be used to find the value of $I_s(E)$ in each slab s. The value of P_1 (P for the first slab) is known from the ToF system, and for any subsequent slab s is equal to $(P_{s-1} - I_{s-1})$.

There has only been one other measurement of a π cross-section in LAr - performed by the LArIAT experiment in 2016 [3], but that measurement only covered the momentum range below 1.2 GeV/c, and was only performed using π^-. Using the T9 beam line operating at momenta between 0.5 and 4 GeV/c, and with both positive and negative beam polarities, ARIADNE can extend the current π^- total LAr cross-section measurement into a previously unmeasured momentum range, and also produce a first measurement of the total π^+ LAr cross section.

3.4 Nuclear Spectral Function of Argon

A complete description of neutrino oscillations requires that the various complexities of neutrino interactions in matter be understood first, and in particular, the neutrino-nucleus cross section. One part of this is the *nuclear spectral function* - the distribution of the probability that a nucleon of initial momentum p_n and energy E_n is found in a given nucleus' ground state - which, if correctly known and understood, can help to avoid the use of nuclear models in which the nucleus is considered as a collection of independent, non-interacting nucleons (such models have been used for a number of years, but have shown recently to result in considerable discrepancies between simulation and real-world results).

The nuclear spectral function can in general be determined using the cross section of the quasi-elastic $e + N_A \to e' + p + N_{A-1}$ process, where A is the atomic number of the nucleus N_A, and the cross section can in turn be related to the 4-momenta (E, $\boldsymbol{p}$) of the incident e^- and the final-state e^- and p. We will therefore attempt to characterise this process by first identifying e^- interactions where the observable final state consists of a short but intense straight-line ionisation track indicative of the recoiling p alongside the scattered e^-, and then reconstructing their energy, position and timing information. The same e^- data that will be collected for the aforementioned PID and e/γ separation studies will be used for this observation, meaning that no extra beam time needs to be devoted to collecting data specifically for this study.

Only one other experiment [4] (using a pressurised gas chamber rather than a two-phase TPC) has even considered measuring the $e+N_A \to e'+p+N_{A-1}$ cross section specifically in argon, and therefore ARIADNE is in a very good position to play a key role in contributing to a better understanding of the nuclear effects in argon - vital for future kilo-tonne scale argon-based neutrino detectors.

[3] P. Hamilton, *LArIAT: Worlds First Pion-Argon Cross-Section*, arXiv:1611.00821 [hep-ex] (Nov. 2016)

[4] O. Benhar *et. al. Measurement of the Spectral Function of* ^{40}*Ar through the (e, e´ p) reaction*, arXiv: 1406.4080 [nucl-ex] (Jun. 2014)

4 Resource, Time and Beam Requirements

An overview of ARIADNE's time requirements is given in Figure 7, with more details on each task given in the corresponding sections below.

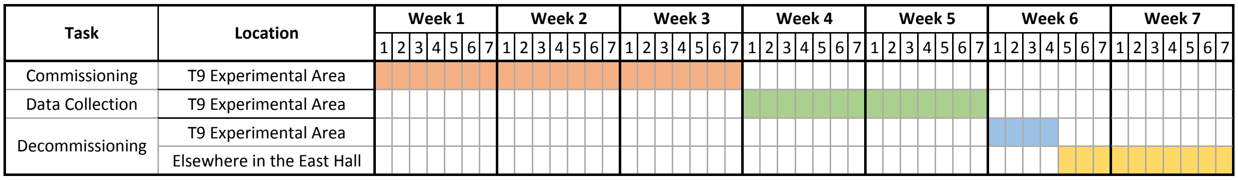

Figure 7: The proposed schedule for ARIADNE at the East Hall.

During both commissioning and data collection, we will require access to two 16A 3-phase plugs for powering our chiller and cryocooler, at least three standard mains power sockets for other electronics, an ethernet connection between the experimental area and the T9 Counting Room in order to test, operate and monitor the detector electronics and other controls remotely, and enough space in and around the experimental area to gather and move our equipment safely - approximately 4 by 4 metres for the main detector, 2 by 2 metres for electronics, and an additional 2 by 2 metres for other equipment such as the chiller and cryocooler. We will be providing our own scaffold for access to the top of the detector.

4.1 Commissioning

We anticipate requiring 3 to 4 days for the initial commissioning tasks - such as moving the detector into position in front of the T9 beam line, and connecting and testing the various cables and electronics. At the time of writing, we have contacted Andre Henriques and others in the Transport and Handling group regarding using the East Hall crane to move ARIADNE into the T9 experimental area, and they have noted that - subject to receiving various safety and technical documentation which will be provided to us by the cryostat manufacturer - there should be no mechanical issues relating to this.

Following this, ARIADNE will then require approximately 4 days to be filled with LAr. It should be noted that we will require a local supply of LAr when at the beam line, as no LAr will be transported with the detector. We anticipate requiring up to 1500l of LAr during the entire operation of ARIADNE, either in a single large shipment or several smaller ones. At the time of writing, we have initiated discussions with CERN Stores regarding how best to obtain and deliver this LAr supply in the most efficient manner.

There are a number of reasons why the detector should be filled only *after* it is in its final position directly in front of the beam line:

- Once filled, the inside of the cryostat will be kept in thermal equilibrium at 87K using a cryocooler, but for both safety reasons and to avoid damaging the cryocooler itself, the detector should not be moved with the cryocooler active.
- If the detector were to be moved while filled with LAr, the external pressure relief valves would need to be opened so as to avoid over-pressurisation, but this would expose the inside of the cryostat to air and thus introduce contamination.
- If the detector were to be filled and then moved, there is a risk that the THGEM will get "wet", severely reducing its ability to sustain a constant gain, and so it would then require extra time to first "dry".

The LAr will be purified once inside the detector - a process which will be achieved using ARIADNE's recirculation system. Depending on the initial purity of the LAr upon delivery, and the precise speed and effectiveness of the recirculation system, full LAr purification is expected to take between 1 and 2 weeks.

We therefore require **up to 3 weeks of pre-beam commissioning time**. We appreciate that this is quite a long commissioning phase, during which no other experiment can use the beam since we will be located directly in front of the beam line, and so we are also requesting to be the **first users of the T9 beam in 2018** - i.e. we can begin commissioning the detector before the scheduled start of beam time. This will allow us the required time to commission the ARIADNE detector fully and safely, without wasting beam time and otherwise impacting on other users.

4.2 Data Collection

Tables 1 and 2 give a summary of ARIADNE's momentum, particle and time requirements for positive and negative beam polarities respectively. For each [momentum, particle] combination, our desired number of incident particles is given, along with a corresponding time required to collect this population. The desired number of particles is based on the number of each particle type at each momentum that we expect to need for our physics goals, together with a certain overestimation to account for a non-perfect detector collection efficiency. The required time accounts for the T9 spill specifications and particle species production branching fractions (both kindly provided to us by Lau Gatignon), as well as the maximum detector readout rate previously discussed.

Momentum (GeV/c)	Particle Type & Usage		
	e^+ PID, e/γ Separation	μ^+/π^+ PID, Cross-section	p PID
0.5	400000 (00:04:49)	300000 (00:07:38)	150000 (00:06:13)
0.6	400000 (00:05:31)	300000 (00:07:21)	150000 (00:06:13)
0.7	400000 (00:06:18)	300000 (00:06:37)	150000 (00:06:13)
0.8	400000 (00:07:09)	300000 (00:06:13)	150000 (00:06:13)
0.9	400000 (00:08:17)	300000 (00:06:01)	150000 (00:06:13)
1.0	400000 (00:09:48)	300000 (00:05:41)	150000 (00:05:51)
1.5	400000 (00:17:18)	300000 (00:04:44)	150000 (00:05:14)
2.0	400000 (01:00:03)	300000 (00:04:09)	150000 (00:04:44)
2.5	300000 (01:00:49)	300000 (00:03:49)	150000 (00:04:31)
3.0	300000 (01:09:05)	300000 (00:03:37)	150000 (00:03:59)

Table 1: The desired number of incident particles of each species at each momentum (unbracketed) together with their corresponding physics goal(s), and the time required for each [momentum, particle] combination (bracketed, in dd:hh:mm format) when operating in positive beam polarity.

Momentum (GeV/c)	Particle Type & Usage		
	e^- PID, e/γ Separation, Spectral Function	μ^-/π PID, Cross-section	$\overline{p}$ PID
0.5	400000 (00:03:24)	300000 (00:09:56)	150000 (00:08:50)
0.6	400000 (00:03:44)	300000 (00:07:57)	–
0.7	400000 (00:03:57)	300000 (00:06:37)	–
0.8	400000 (00:04:21)	300000 (00:05:41)	–
0.9	400000 (00:04:39)	300000 (00:05:06)	–
1.0	400000 (00:05:06)	300000 (00:04:31)	–
1.5	400000 (00:07:09)	300000 (00:03:29)	–
2.0	400000 (00:10:35)	300000 (00:02:56)	–
2.5	300000 (00:11:02)	300000 (00:02:39)	–
3.0	300000 (00:14:11)	300000 (00:02:29)	–

Table 2: The desired number of incident particles of each species at each momentum (unbracketed) together with their corresponding physics goal(s), and the time required for each [momentum, particle] combination (bracketed, in dd:hh:mm format) when operating in negative beam polarity.

Note that, due to their extremely low production branching fraction, we do not intend to explicitly collect data for $\overline{p}$ at momenta > 0.5 GeV/c - we will simply catalog any such particles that we happen to observe.

Additionally, even though the T9 beam line is capable of producing them, we do not anticipate collecting $K^{\pm}$ data at any momenta. This is due to their short lifetimes - only $K^{\pm} > 7.5$ GeV/c would reach the detector (located at a distance of 55m from the production source), and at those momenta any ionisation tracks would have extremely low containment - thus rendering any energy reconstruction impossible.

Finally, it has been determined that $\pi^{\pm}$ at momenta < 1 GeV/c will also most likely decay before reaching the detector (as the $\pi^{\pm}$ decay length at 1 GeV/c is almost exactly 55 metres), and so we expect to observe mainly $\mu^{\pm}$ at these momenta, not $\pi^{\pm}$. These $\mu^{\pm}$ are still useful for PID studies however, therefore we still intend to collect and analyse these data.

In non-$e^{\pm}$ running mode, the total time required at each momentum is simply the longest required time for any single non-e species. (For example, we will only require a total of 5 hours and 51 minutes to collect data for μ^+/π^+ and p at a momentum of 1 GeV/c, not 9 hours and 32 minutes, as in the time that it takes to collect all of the required p, all of the required μ^+/π^+ - and in fact, slightly more than required - will have already been collected.)

With this in mind, and accounting for overheads for changing between momenta and running modes (conservatively estimated at 10 minutes and 5 minutes per change respectively), we will require the following time for data collection:

8 days, 9 hours, 18 minutes (positive polarity)
5 days, 1 hour, 19 minutes (negative polarity)

13 days, 10 hours, 37 minutes (total)

4.3 Decommissioning

The detector decommissioning will be carried out in two phases - the first performed while the detector is still located in the T9 experimental area, and the second elsewhere in the East Hall.

The first phase - which we anticipate **requiring 3 to 4 days** - involves safely powering down and disconnecting the various electronics, power supplies and other connections to and from the detector.

Following the completion of this, the detector may be immediately moved out of the T9 experimental area, allowing the next users of the beam to begin their own work. The detector will *not* be emptied of LAr during the first decommissioning phase - this task is expected to take a minimum of 4 days, and so performing this task while still located in the T9 experimental area would significantly delay use of the beam line for subsequent experiments. Members of the Transport and Handling group have indicated that it should not be a problem to move the cryostat out of the T9 experimental area while it is still filled with LAr, and although the relief valves will need to be opened to avoid over-pressurisation (as noted previously in the discussion on commissioning the detector), at this point introducing contamination into the detector and/or getting the THGEM wet is not an issue.

The second phase of decommissioning - emptying the LAr from the cryostat into external dewars - can therefore be performed elsewhere in the East Hall, during which time we will require some floor space - approximately 6 by 6 metres, as well as dewars into which the LAr can be emptied from ARIADNE.