Interactions in ICARUS

Francesca Pucci
Supervisor: Minerba Betancourt

October 7, 2019

1 Introduction: ICARUS

ICARUS is a detector using Liquid Argon to detect the tracks of ionising particles produced by cosmic rays and by neutrinos. This technology conceptually represents the evolution of the famous bubble chamber. Nowadays, the Icarus collaboration aims at investigating signs of physics that may point to a new kind of neutrino called the sterile neutrino. Other experiments have made measurements that suggest a departure from the standard three-neutrino model. Icarus is also investigating the various probabilities of a neutrino interacting with different types of matter as well as neutrino-related astrophysics topics.
The technology of the liquid-Argon Time Projection Chamber (LArTPC) was proposed by scientist Carlo Rubbia in 1977 and it was conceived as a tool for detecting neutrinos with high accuracy. Icarus has been the first large-scale detector exploiting this detection technique and it is the biggest LArTPC ever realized, with a cryostat containing 760 tons of liquid argon. Its construction was the culmination of many years of Icarus collaboration R&D studies, with larger and larger prototypes. Nowadays, it represents the state of the art of this technique, and it marks a major milestone in the practical realization of large-scale liquid-argon detectors.

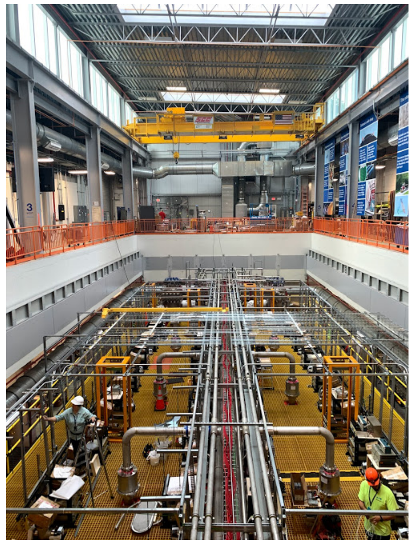


Figure 1: A picture of the ICARUS detector hall, during its installation in August 2019

1.1 The detector

The main advantage of having a liquid Argon detector is in the excellent spatial and calorimetric resolution which makes a perfect visualization of tracks of the charged particles possible.
When a neutrino strikes an argon atom inside the 760-ton ICARUS detector, the interaction creates other particles, which in turn release ion-electron pairs from the argon atoms. The chain reaction results in a streak of released electrons in the giant vat of liquid argon, as shown in Fig 2.

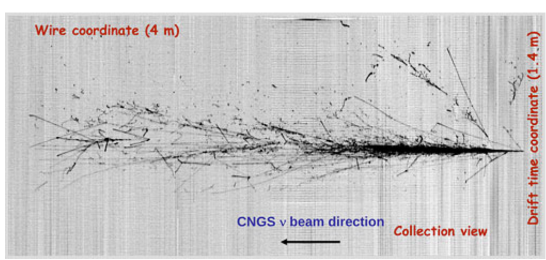


Figure 2: An example of a neutrino interacion in Icarus, during its period in the Gran Sasso Laboratory, when the neutrino beam was coming from CERN

Inside this vat, some wires creates a uniform electric field. A certain fraction of the ion-electron pairs (depending on the field intensity and on the density of ion pairs) will not recombine and will immediately start to drift parallel to the field in opposite directions. Only the motion of the much faster electrons induces a current on a number of parallel wire planes located at the end of the sensitive volume. Those wires transmit the signal to computers outside the detector. Reading the collected data, scientist are able to obtain information about the neutrino that kicked the whole process off. A schematic representation of the experimental setup is show in Fig. 3.

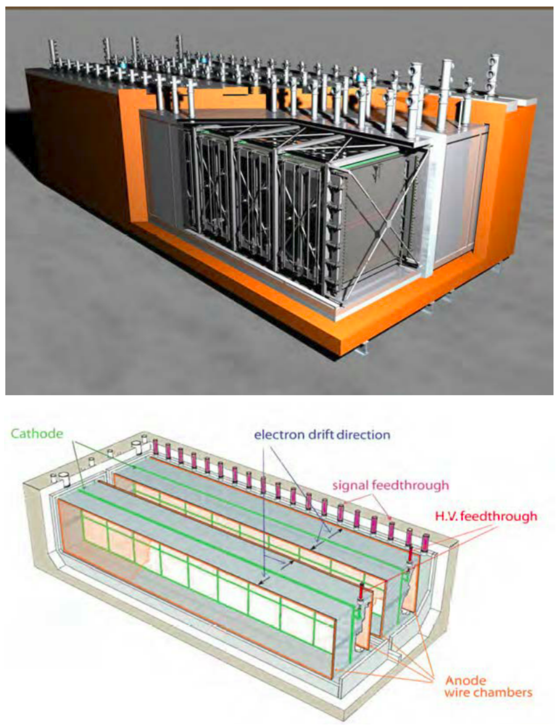


Figure 3: Schematic representation of the Icarus detector

The Icarus detector itself is composed by two semi-independent, symmetric modules filled with liquid argon, each approximately 3.6 m high, 3.9 m meters wide and 19.9 m long. In each half vessel there are two TPCs, mounted on the internal walls with the cathode at the centre, so to maximise the liquid Argon sensitive volume (corresponding to about 480 tons in mass). The read-out chamber scheme consists of three parallel planes of wires, one of which is horizontal, one rotated by $+60°$ and one by $-60°$).

Information is read by electric charge induction on the first two readout planes encountered by drifting electrons and by electric charge collection on the last readout plane. The signals from the three wire planes, together with measurement of the drift time, provide a (redundant) full 3-D image reconstruction of the event. Figure 4 shows a schematic representation of one of the two modules and of its operating principles.

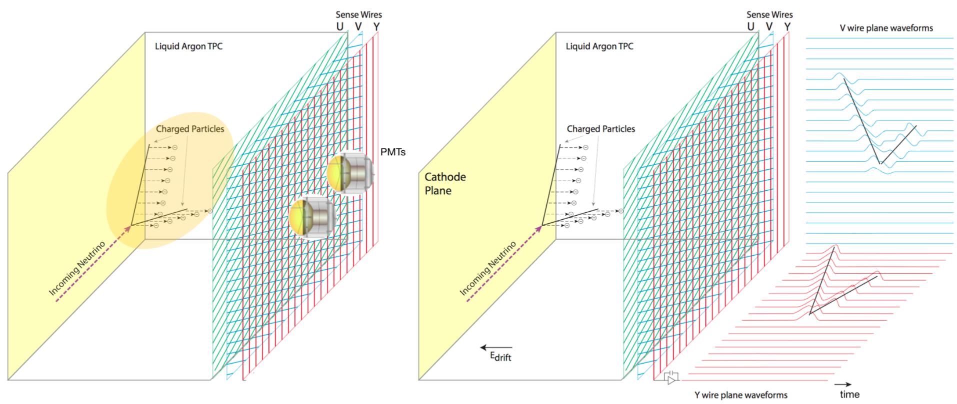


Figure 4: This figure shows a schematic representation of one of the two modules that the Icarus detector is composed of. It also displays a scheme of a neutrino interaction in the detector and its operating principles.

The choice of liquid Argon was driven by some considerations. Firstly, an excellent insulator available at an extremely high purity level is needed, in order to make sure that free electrons produced by ionisation can drift in the liquid over long distances. Secondly, this insulator must have a high electron-ion pair yield with respect to the energy deposited in the liquid and last, it must be easily available in large quantities, which is the case for argon, a natural component of the Earth's atmosphere (1%).

1.2 The program

The ICARUS T600 detector was previously installed in the underground Italian INFN Gran Sasso National Laboratory and was the first large-mass LArTPC operating as a continuously sensitive general-purpose observatory. The European laboratory CERN, located 730 km away in Switzerland, provided a beam of neutrinos that travelled undisturbed straight through Earth to the Icarus detector at the Italian laboratory. This was known as the CERN Neutrinos to Gran Sasso beam-line, or CNGS beam-line.

Beside the excellent detector performance as tracking device and as homogeneous calorimeter, Icarus demonstrated a remarkable capability in electron-photon separation and particle identification, exploiting the measurement of dE/dx versus range, including also the reconstruction of the invariant mass of photon pairs to reject to unprecedented level the NC background to ν_e events.

The tiny intrinsic ν_e component in the CNGS muon neutrino beam allowed Icarus to perform a sensitive search for anomalous $\nu_\mu \mapsto \nu_e$ oscillations. Globally, seven electron-like events have been observed, consistent with the 8.5 ± 1.1 events expected from intrinsic beam νe component and with standard oscillations providing the limit on the oscillation probability $P(\nu_\mu \mapsto \nu_e) \leq 3.86 \cdot 10^3$ at 90% CL and $P(\nu_\mu \mapsto \nu_e) \leq 7.76 \cdot 10^3$ at 99% CL. After four years of running in the Italian laboratory, the detector was moved to CERN, where it was upgraded and improved. In 2017 it was moved to Fermilab, to become part of its great neutrino program.

Many global analyses of experimental results have been performed fitting to models, including one or more sterile neutrinos. Even after 20 years, the Liquid Scintillator Neutrino Detector (LSND) result is still the dominating one in terms of significance in all global sterile neutrino fits, but it has not been fully confirmed or rejected yet. An experimental configuration, the Fermilab Short Baseline Neutrino (SBN) program, to search for possible sterile neutrino states mediating short-baseline oscillations has been proposed to include three LArTPC detectors located on axis in the Booster Neutrino Beamline (BNB) at Fermilab. The SBN program aims at a definitive clarification of the LSND sterile neutrino puzzle.

The near detector, called the Short-Baseline Near Detector, or SBND, with an active mass of 112 tons, will be located 110 m from the BNB target. The MicroBooNE detector, which has been taking data with the BNB since 2015 with its 89-ton active mass, is located at 470 m from the target. The far detector is the ICARUS T600, with 476 tons of active mass and located in a new building 600 m from the BNB target.

1.3 Internship

This internship collocates itself in this scenario.
The installation of the detector is going on very fast, in order for the experiment to start commissioning as soon as expected (by the end of this year). Part of the job, therefore, was helping during this process, installing some parts of Icarus.
On the other hand, the software part is also being developed, so to have all

the needed tools once real data will begin to arrive. On this side, most of this work is focused on purity measurements and analysis and on the online monitoring of this quantity. Indeed, it is fundamental to be able to keep purity under control all the time, once the detector is running.

2 Hardware

The Short Baseline Neutrino Far Detector (SBN-FD) is located inside the Fermilab, in the neutrino campus (see Fig. 5). It was moved to this detector hall in 2018 ad its installation is ongoing and almost complete. Commissioning is, indeed, expected to begn in the end of 2019, therefore in a few months.

The work needed for completing the installation is a lot and taking part in this process was part of this internship.

2.1 Cable trays and mini-racks

The installation of some cable trays was one of the most urgent things to take care of: without those, the high voltage and the signal cables had no route to go through and they could not be connected to the detector.
The vertical cable trays had to be prepared before being installed in the mezzanine floor. Some bolts were needed to insure a secured positioning of the trays. Figure 6 shows this work. There are two cable trays for each mini rack, since each of those will need both the high voltage and the signal cables.

The mini racks are located in the mezzanine floor as well. They had been installed in the first phases of the installation process, but they needed to be cabled. This procedure required the writing of a work plan, which needed to be approved. Once the approval was obtained, the cabling had be done following one mini rack installed first as a model. Firstly, cables from the power supply were connected to the power cord of the rack by routing the cables via the left side of the frames, securing them with cable

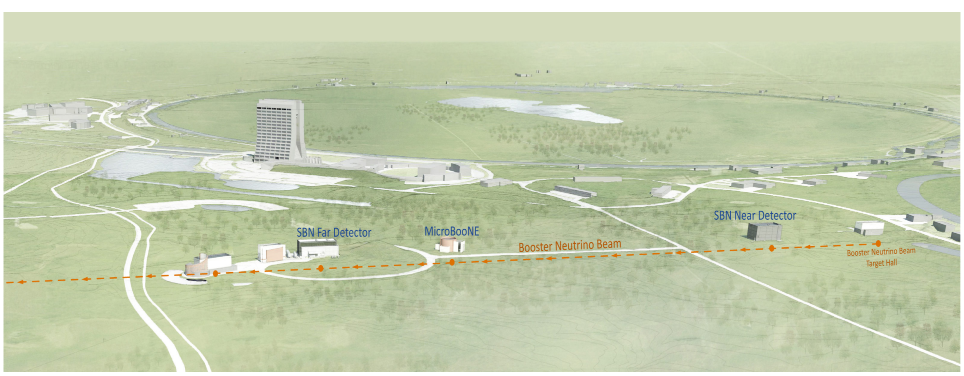
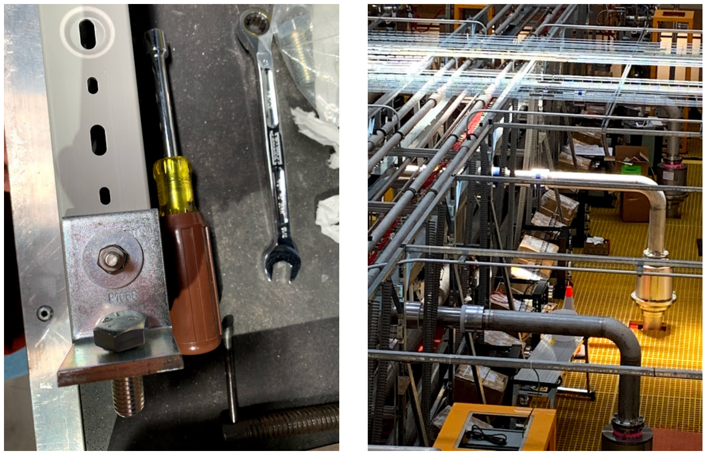


Figure 5: Neutrino campus inside Fermilab



(a) *Preparation of the cable trays, before the assembly on the mezzanine floor.*

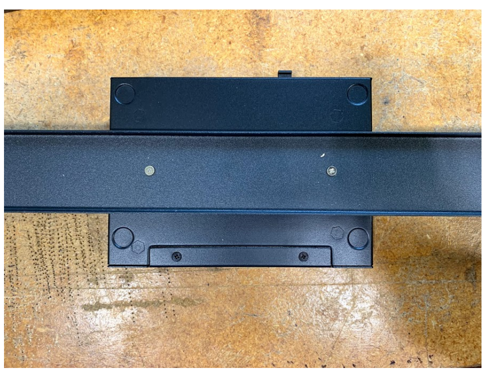
(b) *Cable trays installed along the whole length of the detector.*

Figure 6: Cable trays installation

ties. Afterwards, the modem needed to be mounted on a bar, which would have then be placed on the back of the mini rack. In order to do that, two holes were drilled on each bar and the modem was then screwed in. Once the bar was in place, a cable was connected from the modem to the power supply, routing it via the right side of the frame and secured with cable ties. Once all of that was accomplished, the Ethernet cables were connected from the modem to the back of the power supply. The cabling had to be done carefully, in order to avoid loose cables and also to avoid the Ethernet cables running parallel to other cables. Indeed, those are very sensitive to external magnetic field and false signals want to be avoided. Figure 7 shows different parts of this process.

(a) *Top view of a cabled mini-rack (Ethernet cable missing).*

(b) *Cables secured on the left side of th frame.*



(c) *Modem installed on a bar.*

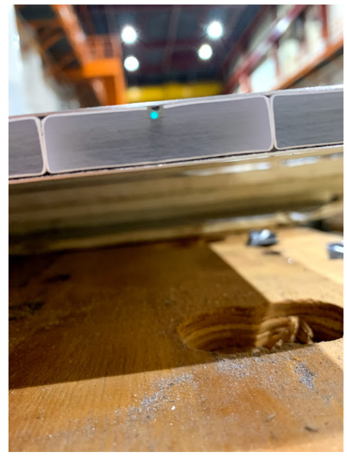
(d) *Rear view of a mini-rack.*

Figure 7: Cable trays installation

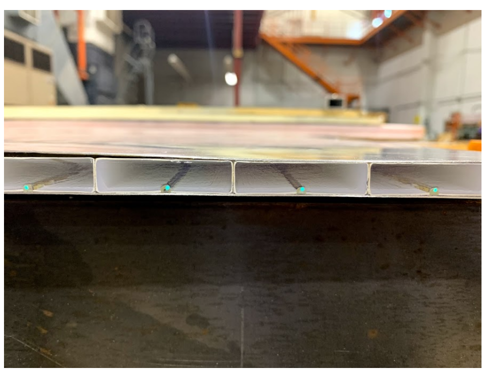
2.2 Scintillators

Some scintillator will be installed for the cosmics rejection in the Icarus detector. They were delivered in long slabs and the sawed. Therefore, sandpaper was needed to smooth their surface. Once sanded, they have been torched and then cleaned. Some reflection paper was mounted at the end of the scintillator, in order to make sure that all the light ends up inside the module. Then, the whole module has been fixed and isolated with electric tape. Indeed, it is fundamental to avoid light leaks. For this reason, all the prepared modules were also tested with a light source. All of them passed the test and are now ready to be installed. Different parts of this work are showed in Figure 8.

(a) *Scintillator before treating it with sandpaper.*



(b) *Scintillator after treating it with sandpaper.*



(c) *Scintillator after torching.*

(d) *Isolated scintillator, ready for the installation.*

Figure 8: Steps of the preparation of the scintillators for the cosmics rejection in Icarus.

3 Software

Besides the hardware work, a huge part of the work presented is software based. The starting point was a code written by Christian Farnese (researcher at the INFN of Pavia) to measure the purity of the detector.

3.1 Angular and track length distributions

The first step has concerned the validation of the results of the code. In order to do that, the results of the code have been compared with an event display. From the code, one can obtain information on the track length both in space and time and then it is possible to check that the event display shows the expected tracks. Figure 9 shows the display of the 31^{st} event of the 6^{st} run on the TPC 1. This event has been clearly seen in the display and in the code.

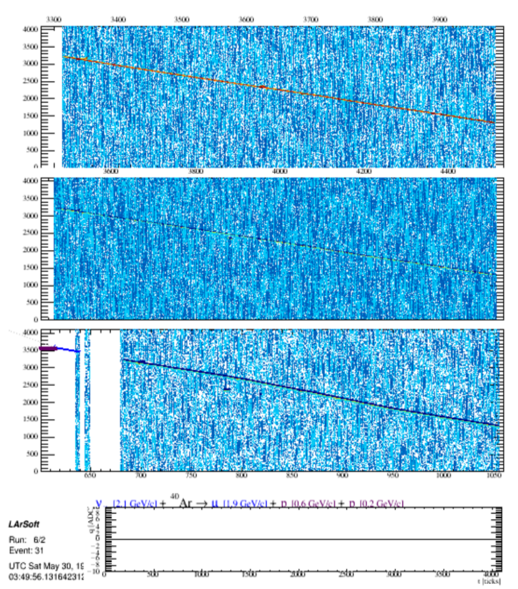
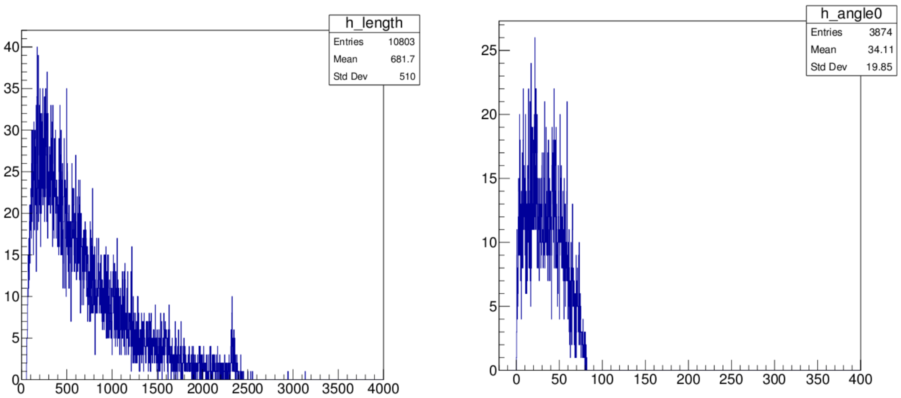


Figure 9: Image of the event display. A track recognised as a cosmic muon track is shown here. It was possible to find coherence between this track and the results given by the code. The event is the 31^{st} of the 6^{st} run

Once realised that there was coherence between the code and the display, the track length and the angular distributions of the tracks have been studied. Figure 10 shows the results for a large statistic. The angular distribution has the expected shape for cosmics.



(a) *Track length distribution of cosmic muons coming from about 800 MonteCarlo simulation files.*

(b) *Angular distribution of cosmic muons coming from about 800 MonteCarlo simulation files. The distribuition presents the expected trend for cosmics.*

Figure 10: Track length and angular distribution of cosmics.

At first, it was believed that these distributions could have been used for distinguishing muons and neutrinos. Plotting the distributions for neutrinos, anyway, highlighted the impossibility of doing that. Figure 11 shows the track length distribution of some simulated neutrino events.

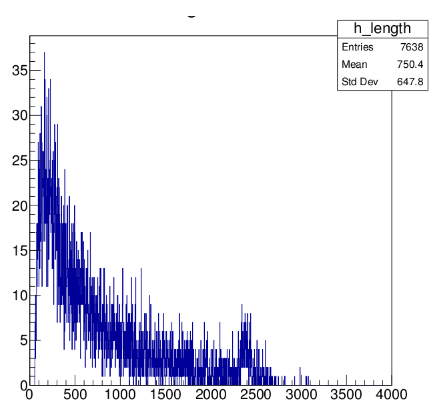


Figure 11: Track length distribution of simulated neutrino events files. The trend of this distribution is very similar to the trend of the cosmics distribution showed i the previous figure.

After some work, it has been realised that the code has to be improved, if such a distinction wants to be performed. Indeed, the code was born as a fast code, intended for purity measurements done with cosmics in a fast way. Therefore, it only uses information coming from the collection plane of the detector. Using more planes could definitely help in the particle identification. Furthermore, the code only considers one hit per wire of the plane, taking the most intense one if there are multiple hits. Nevertheless, when it comes to neutrino interactions, there often are more hits per wire. Taking away so many information results in a fast code (that is what is needed to control the purity), but has the drawback of being a bit imprecise. The distributions of neutrinos and of cosmics are not distinguishable with this code.

To make the distinction possible, Christian Farnese is working on developing a new code, which is able to take into account the different hits on each wire, in order to provide a good particle identification Since Icarus is not underground, the cosmic background will be very big and this distinction fundamental.

3.2 Purity measurements

The reconstruction of the events collected in a LAr-TPC is based on the ionization signals produced by the charged particles in Liquid Argon, collected using a uniform electric field on the anode that is made by 3 wire planes. The LiquidArgon is chosen also because of its high purity: being a noble gas, it does not tend to take electrons. The presence of an electronegative purity i the Liquid Argon can strongly reduce the ionisation signal that can be collected. If Q_0 is the produced charge, t is the drift time to reach the anode, the collected charge $Q(t)$ is reduced because of electronegative impurities and it can be computed as

$$Q(t) = Q_0 \cdot e^{-\frac{t}{\tau}} \tag{1}$$

where τ is defined as the electron lifetime. Therefore, measuring τ allows to correct this attenuation effect and provides the corrected value of the charge Q produced by the ionising particle. This parameter can be measured studying the charge attenuation as a function of the drift time along the collected cosmic muon tracks.

In the code, the collected charge is represented by the area of the hit. Fitting the measurement of the area as a function of time, it is possible to obtain a value for the attenuation. The attenuation is the inverse of the purity and it is Gaussian distributed. For this reason, it is convenient to work with this value. Indeed, the purity has a distribution with large tails, which makes the study of the parameter harder and less precise.

In order to obtain the purity values, the code analyses the tracks in the following way:

- The physical signals (hits) are extracted from the signals recorded on the wire of the collection plane using a fast identification method
- Only one hit per wire is recorded and it is the one with the highest signal (the efficiency of this part depends on the noise conditions)
- The hits are grouped in clusters, based on the relative distance of different points and on the intensity of the hits on the wire
- Tracks which are "good for purity measurements" are selected, based on their spatial and temporal length
- A single fit of the hit area versus the hit time is performed to extract $1/\tau_{ele}$

One value of attenuation can be extracted from each single hit, so from each single track. It is possible to plot the value obtained per each track, as shown in Figure 12.

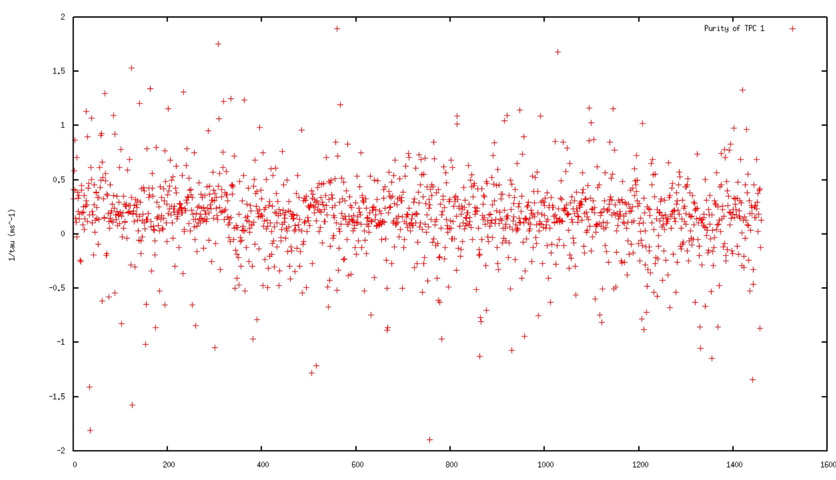
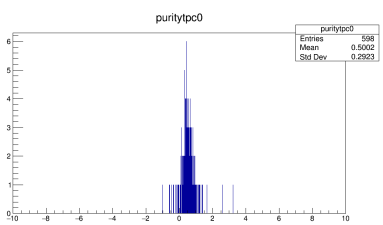
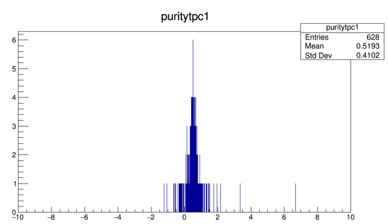


Figure 12: Plot of the attenuation done with a large statistics for the TPC 1. The MonteCarlo files used simulate cosmics with a mean electron lifetime of 6ms.

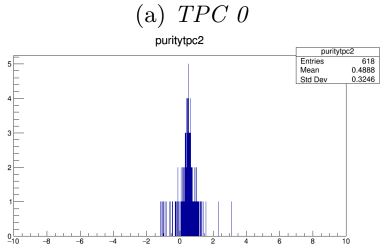
Evidently, there are many fluctuations on the single value of purity, also due to the asymmetric Landau distribution of dE/dx. Therefore, it is much more meaningful to study a sample of cosmic tracks and to average on the values extracted track by track. The best way to do that is using histograms. On the other hand, a validation of the measurements of the code was needed. In order to do that, some MC files with a known mean electron lifetime were used. Indeed, the mean electron lifetime is another way to call the purity and the attenuation only is the inverse of this value. For each TPC a different histogram was done, since it is important to check tat each TPC has an acceptable value of purity. Since they are physically separated, indeed, they could undergo different problems or processes.



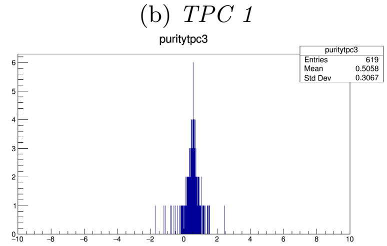
(a) *TPC 0*



(b) *TPC 1*

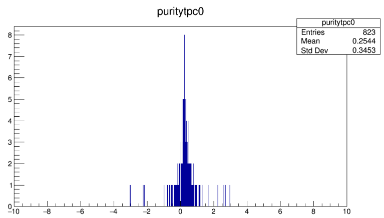


(c) *TPC 2*

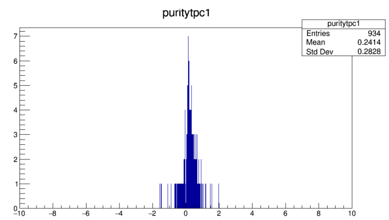


(d) *TPC 3*

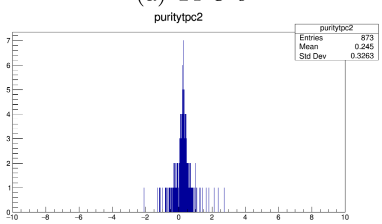
Figure 13: Histograms of the attenuation for each of the four TPC, done using MonteCarlo files with a mean electron lifetime of 2 ms. The expected mean value of the attenuation, therefore, is $0.5ms^{-1}$



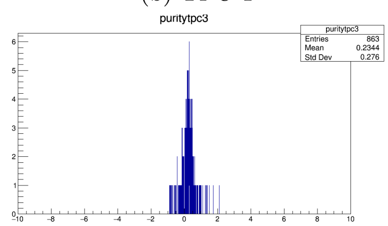
(a) *TPC 0*



(b) *TPC 1*

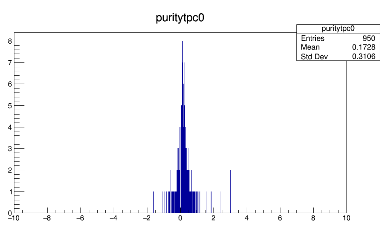


(c) *TPC 2*

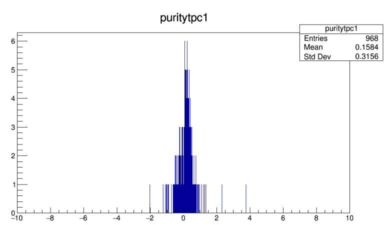


(d) *TPC 3*

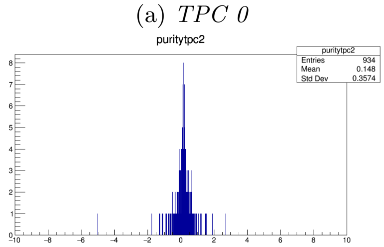
Figure 14: Histograms of the attenuation for each of the four TPC, done using MonteCarlo files with a mean electron lifetime of 4 ms. The expected mean value of the attenuation, therefore, is 0.25 ms^{-1}



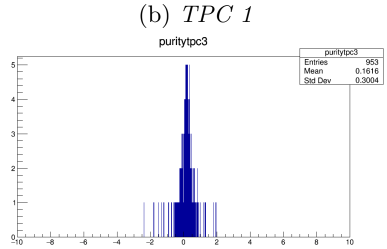
(a) *TPC 0*



(b) *TPC 1*

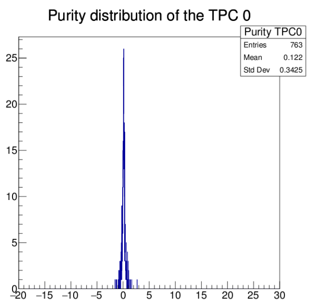


(c) *TPC 2*

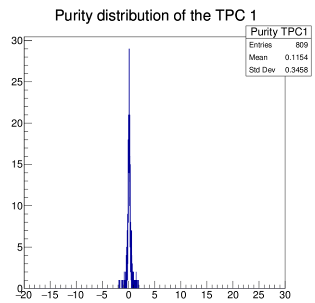


(d) *TPC 3*

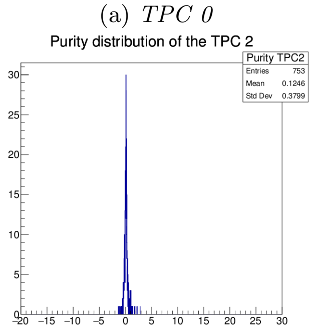
Figure 15: Histograms of the attenuation for each of the four TPC, done using MonteCarlo files with a mean electron lifetime of 6 ms. The expected mean value of the attenuation, therefore, is 0.167 ms^{-1}



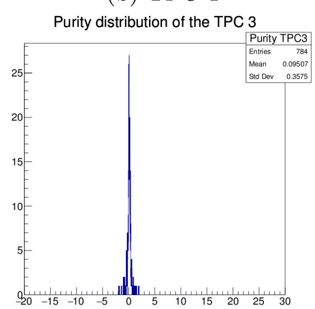
(a) *TPC 0*



(b) *TPC 1*



(c) *TPC 2*



(d) *TPC 3*

Figure 16: Histograms of the attenuation for each of the four TPC, done using MonteCarlo files with a mean electron lifetime of 8 ms. The expected mean value of the attenuation, therefore, is 0.125 ms^{-1}

Figures 13, 14, 15, 16 show the four histograms of each TPC for each of the four different values of the mean electron lifetime in the provided files. In this way, the purity measurements have been validated. The mean values of each histogram are within one standard deviation from the expected values, thus, the code correctly computes the attenuation.

3.3 Online Monitoring

The Short Baseline Neutrino (SBN) Program is making an effort to have a website where the detectors can be kept under control and some results can be shown. ICARUS is making this effort as well. In the website created for this experiment, a page concerning the purity was missing.
As aforementioned, for any Liquid Argon detector, the purity is one of the most important parameter and thus, is has to be monitored. A lowering of the purity, indeed, could cause mistakes in the results. Having this monitor online has many advantages. First of all, it can be controlled from any place.

Secondly, it can be constantly monitored. Any kind of problem can be immediately identified and measures to solve it can be taken. In addition, it can provide a real time analysis of the results.
Therefore, this page has been created. The first step was creating a link in the website, to the purity page. Afterwards, the purity code was improved, so that the good results of the attenuation were sent to the database, together with the information on the TPC which recorded the event. The online monitoring system reads information from this database and manages to divide those coming from different TPCs. Then, the type of plot to be shown had to be chosen. Two different types of plots have been selected. There is a plot (Figure 17), showing one single value of attenuation every 5 minutes for each TPC.

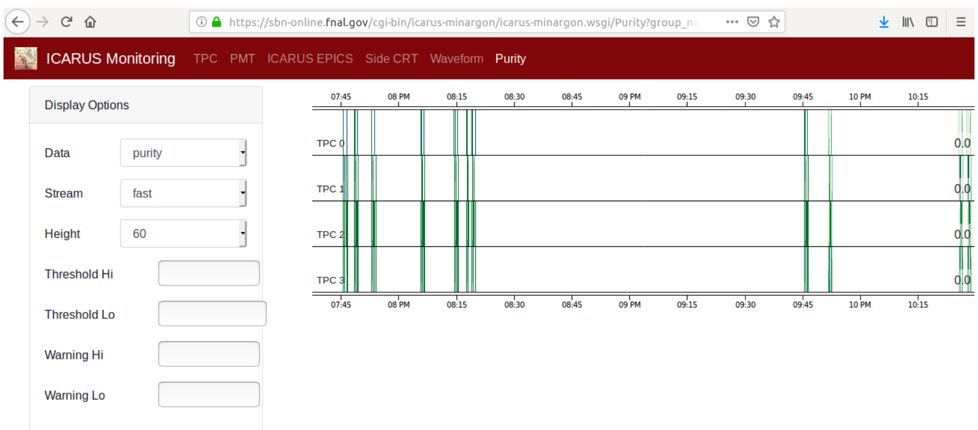


Figure 17: The website shows one value of attenuation per TPC every five minutes. This value is obtained as the average of the good values collected during that time.

The other plot, instead, is a scatter plot (Figure 18). It shows the trend of the attenuation with time. From a panel the start time and the end time of this plot can be selected, in order to be able to take a look to a certain interval only. In this way, the webpage not only is useful to monitor the detector in real time, but also to look at variables in a specific time window and to make a first analysis of the results.

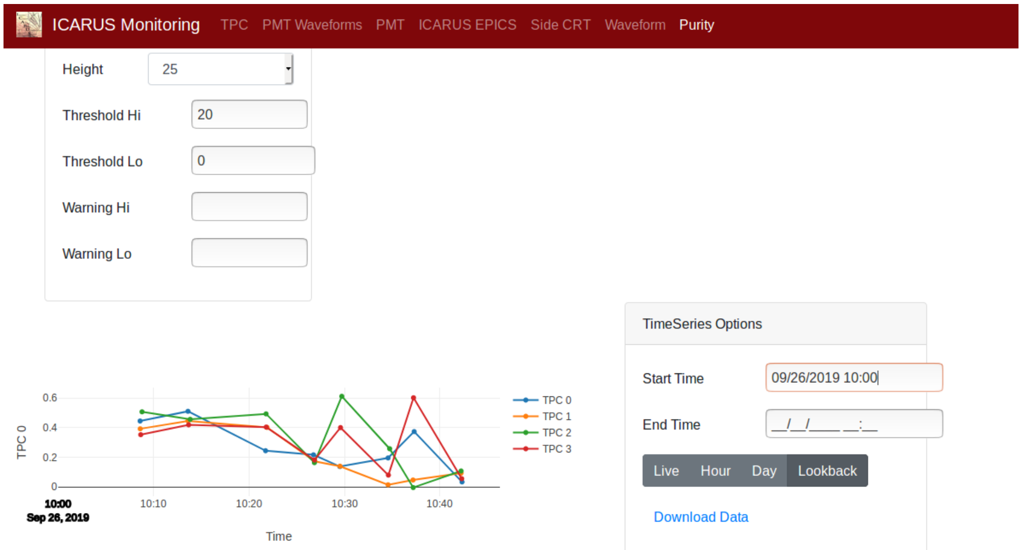


Figure 18: This image shows the scatter plot in the ICARUS webpage. Each TPC is represented by a line of a different colour and each of them can be monitored at the same time.

After setting up this online monitoring system (with the great help of Gray Putnam), a fast and rough check of the results was performed. The program has been run with MonteCarlo files with increasing mean electron lifetime, expecting to see a decreasing trend in the attenuation values online. Figure 18 shows the result. The overall trend is not bad and it is possible to recognise a tendency to decrease. Anyway, the trend is not totally visible, mainly because a poor statistics has been used. A further analysis with a larger statistics is required and strongly expected to give better results.

4 Conclusions

In conclusion, the code for the purity measurements is ready and validated. There is some more work to perform, in order to make this same code able to distinguish cosmics and neutrinos, but there are all the basis to think of a way of doing that.
The website is ready to be used when commissioning will start. Some more implementations can be done and will probably be brought on, but the page concerning purity is totally set up.
The detector also is almost ready for commissioning. Some troubles due to the failing of some sump pump, which caused water to enter in the detector hall, are being faced, but there should not be any major delay in the beginning of data taking.

Figure 19: Image of the outside of the ICARUS detector hall.