# Tests of ProtoDUNE Beamline Time-of-Flight Detectors

Final Report

Summer Internship in Fermilab 2016

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# Preface and acknowledgment

This paper summarizes the two months of work conducted within the summer internship project at Fermi National Accelerator Laboratory. The time-of-flight detectors which have been proposed to be used in protoDUNE beamline are introduced. These large-area picosecond photodetectors for measuring the time-of-arrival of relativistic particles with resolutions less than 50 picoseconds are currently being developing by scientific groups from the University of Chicago, Argonne National Lab, Fermilab and Berkeley Lab. Two prototype detectors were loaned to Fermilab for the purpose of testing their characteristics.

I would like to express my thank to my supervisor Jon Paley for his helpfulness and kindness. Working under his supervision was a great pleasure for me and it gave me many experiences as well as it broadened my horizons in physics and working with hardware.

I am also thankful to Miloš Lokajíček who is responsible for Czech students participation in summer internship at Fermilab and to Jan Smolík who provided me financial support.

# 1 Introduction into DUNE and protoDUNE experiments

## 1.1 Deep Underground Neutrino Experiment (DUNE)

The DUNE experiment is large project which is going to be constructed at Fermilab and at Sanford Underground Research Facility in South Dakota, USA. The construction should start in 2017. The proposed DUNE experiment establishes 3 main goals:

1. Measuring neutrino oscillations in order to find out why we live in a matter-dominated universe.

2. Looking for neutrinos coming from the explosion of a star to discover the formation of a black hole.

3. Searching for proton decay.

An important part of DUNE project is Long-Baseline Neutrino Facility (LBNF) which will comprise neutrino beam and the infrastructure necessary to support massive far detectors at the Sanford Underground Research Facility as well as near detectors in Fermilab. The experiment design can be seen in Fig. 1. The LBNF neutrino beamline would use protons from existing Main Injector and accelerate them up a small hill and then point the beam to graphite target. The collisions will lead to secondary particle productions which will generate neutrinos while passing 680-foot-long tunnel. The neutrino beam will go through a near detector where the composition of the beam at the beginning of its journey will be measured. The beam will then travel 800 miles (1300 km) to Sanford Lab in South Dakota where the far detector will be installed 4850 feet deep underground.

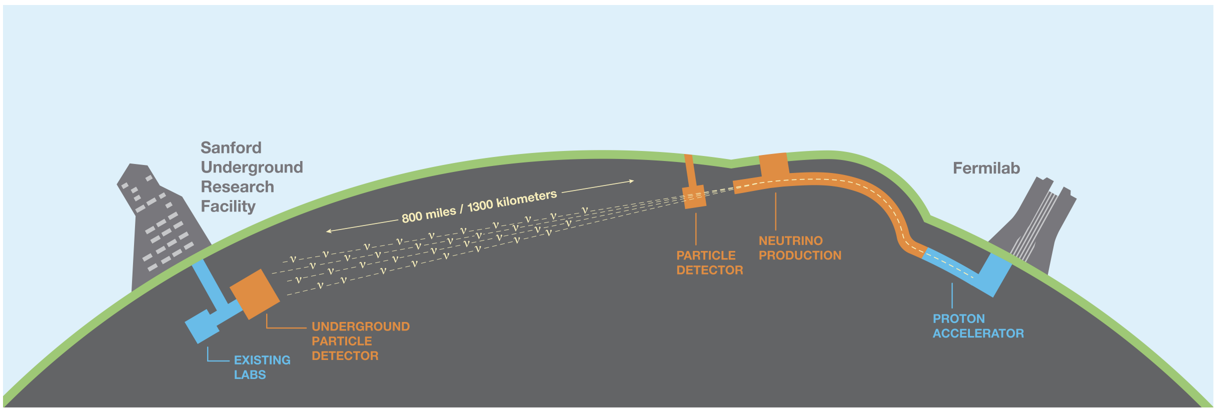



Fig.1: DUNE - experiment design.

The DUNE far detector will consist of four liquid argon time projections chambers (LArTPC), see Fig. 2. Each module will be filled with 17000 tons of liquid argon. Cryogenic equipment will be installed in the cavern to cool argon to -186 °C.

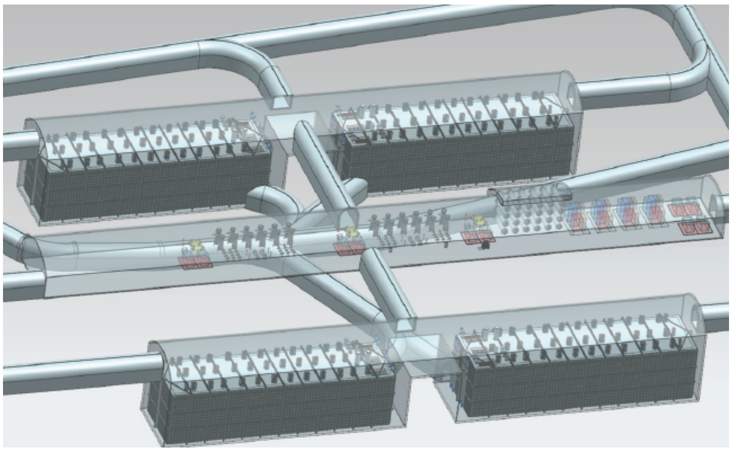


Fig.2: DUNE - far detectors.

### 1.2 ProtoDUNE

ProtoDUNE is a CERN experimental program designed to test and validate the technologies and design that will be applied to the construction of the DUNE Far Detector at the Sanford Underground Research Facility. Two apparati will be used in the CERN beam test: single-phase (SP) [2] and dual-phase (DP) [3] LArTPC detectors. The schematic of protoDUNE experiment and beamlines is in Fig. 3. The protoDUNE experiment will use a charged-particle beam to measure:

- Detector calorimetric response for hadronic particles and electromagnetic showers.
- Study e/$\gamma$-separation capabilities.
- Event reconstruction efficiencies as a function of energy and particle type.
- Performance of particle identification algorithms as function of energy.
- Validate accuracy of Monte Carlo simulations.

The problem of particle identification will be discussed further in following section.

## 2 Particle Separation

The charged-particle beam which will be used in protoDUNE experiment will consists of particles such as protons, pions, kaons and electrons. There is a need to identify the particles in the beam before they enter the LArTPC in order to determine response of each particle in LArTPC. The objective is to perform particle identification over the beam momentum range, from 1 GeV/c to 10 GeV/c. The momentum will be determined from curvature of beam trajectory in magnetic field. However, particle ID is difficult to determine since the beam profile is large (10 cm), the momentum of particles is high and the demand for detectors is to be inexpensive and non-destructive (not destroy the beam).

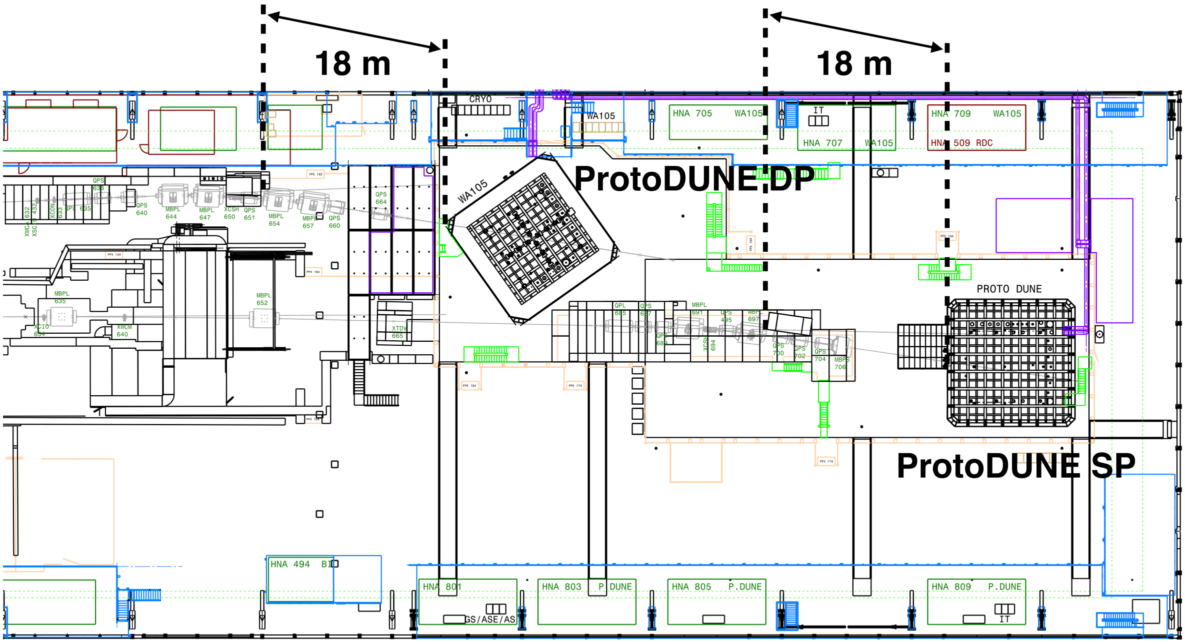



Fig.3: The schematic of protoDUNE beamlines. The TOF detectors are placed in front of LArTPCs, the distance between them will be probably 18 m.

One option how to solve the problem is to use time-of-flight (TOF) measurements with high timing resolution.

The concept of determining particle ID is based on measuring time-of-flight $t$ between two detectors in distance $l$. Once the momentum $\vec{p}$ of all particles in the beam is same $t$ will depend only on particle mass $m$ which can be easily calculated using $\vec{p} = m \cdot \vec{v} \cdot \gamma$ and $v = \frac{l}{t}$. The problem of protoDUNE beamline is that the momenta of the particles is high so the demand on timing resolution is very high. Such a high timing resolution could be achieved by using large-area picosecond photodetectors (LAPPD). These Detectors are described in section 3.

## 2.1 Simulation of particle separation

The separation of pions, kaons and protons presents in the beam was studied for different beam's momentum $p$ and different TOF detector's timing resolution. The ideal time-of-flight was calculated from

$$t = \frac{l}{c}\sqrt{\frac{c^2 \cdot p^2}{m^2} + 1}, \tag{1}$$

where $l$ is the distance between TOF detectors, $c$ the velocity of light and, $p$ is the beam's momentum and $m$ is particle's mass. Then the simulation of real TOF for single particle was calculated using

$$TOF_i = t + t_1 - t_2, \tag{2}$$

where $t$ is given by (1) and $t_1$, $t_2$ are random numbers taken from the gaussian distribution with mean value in $t$ and with sigma corresponding to timing resolution of detectors. In Fig. 4 and Fig. 5 are TOF distributions calculated for timing resolutions 50 ps and 170 ps, range of beam momenta from 1 to 10 GeV/c and supposed distance between TOF detectors 23 m (but the distance will be probably in fact 18 m as illustrated in Fig. 3). We can see that for higher beam momentum the peaks for pion and kaon are overlaping. The ability of pion and kaon separation for different beam momenta and timing resolution is illustrated in Fig. 6 where number of sigmas was calculated from

$$\#\sigma = \frac{\Delta TOF}{\sqrt{RMS_1^2 + RMS_2^2}}, \tag{3}$$

where $\Delta TOF$ is the difference between $TOF_1$ and $TOF_2$ for two particles (the mean value of TOF distribution) and $RMS_1$ resp. $RMS_2$ corresponds to the width of those $TOF$ distribution for two particles. From Fig. 6 results that if we want to identify pions and kaons in all beam momentum range the timing resolution about 20 ps is needed. Similar plots are in Fig. 7 and Fig. 8 where also the uncertainty in determining of beam momentum is taken into account. The uncertainty in momentum determining was calculated based on the assumption that it has gaussian distribution from which random numbers were taken.

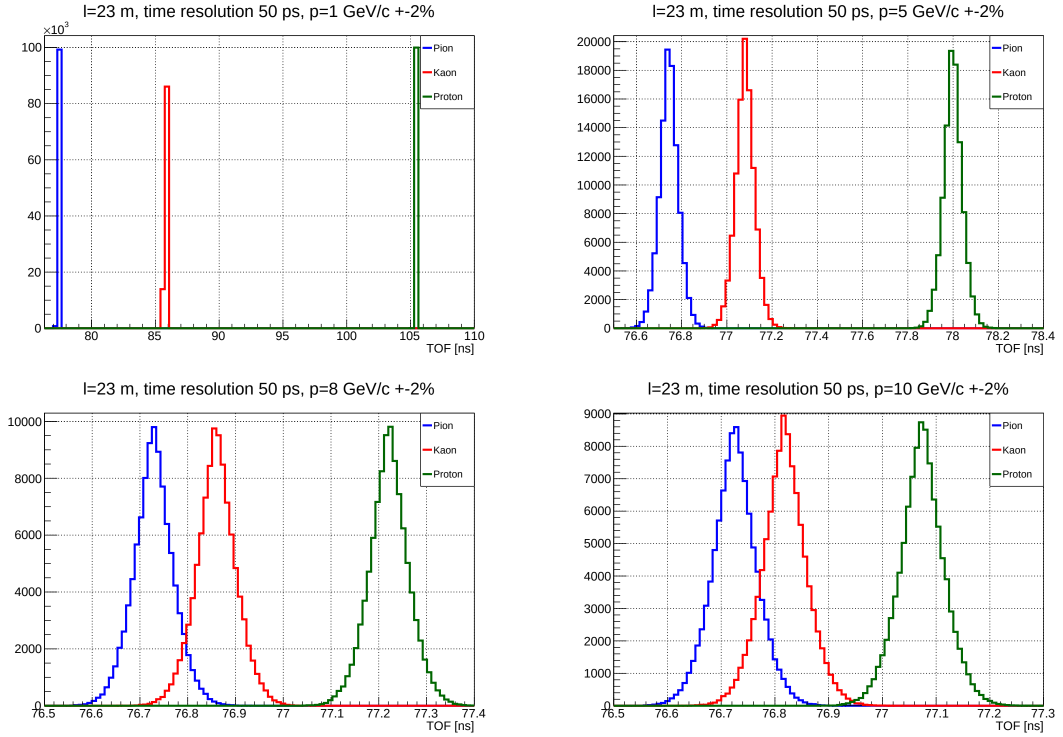



Fig.4: Particle separation with TOF resolution 50 ps for different beam momentum.

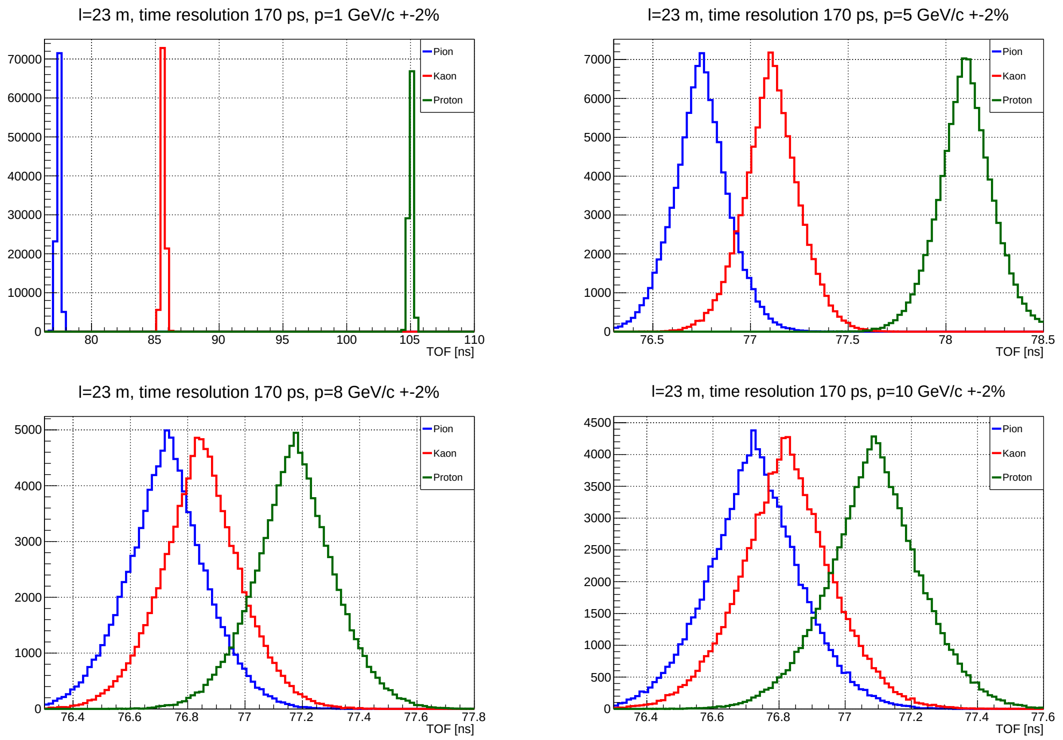



Fig.5: Particle separation with TOF resolution 170 ps for different beam momentum.

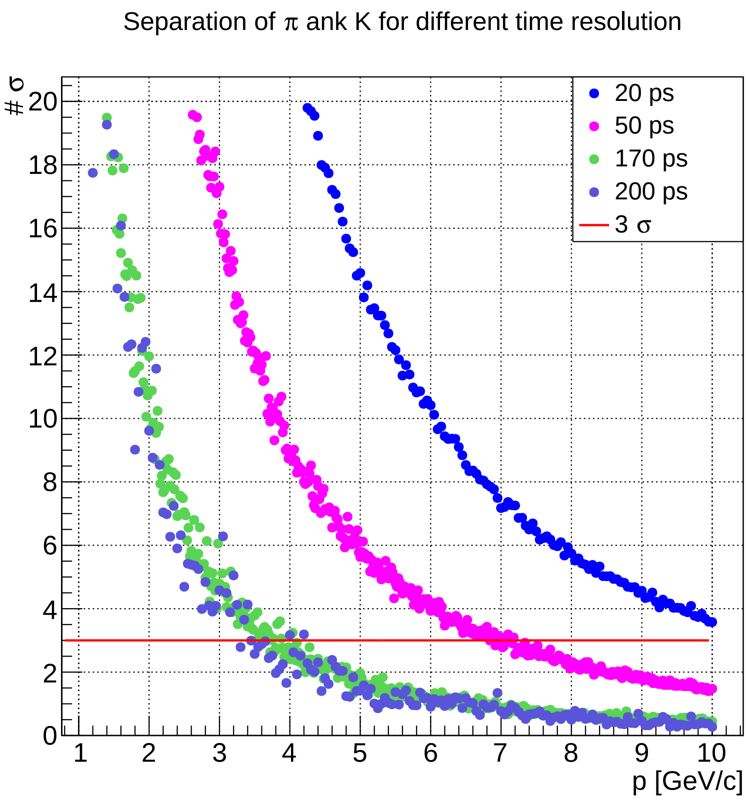



Fig.6: Number of sigmas for pion and kaon separation as a function of beam momentum.

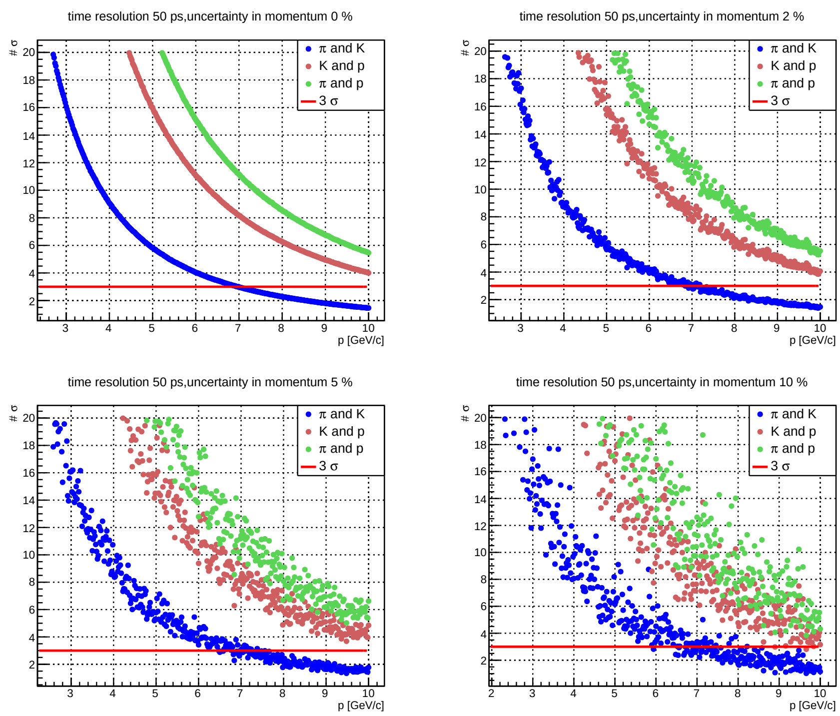



Fig.7: Particle separation with TOF resolution 50 ps for different uncertainty in momentum determinig.

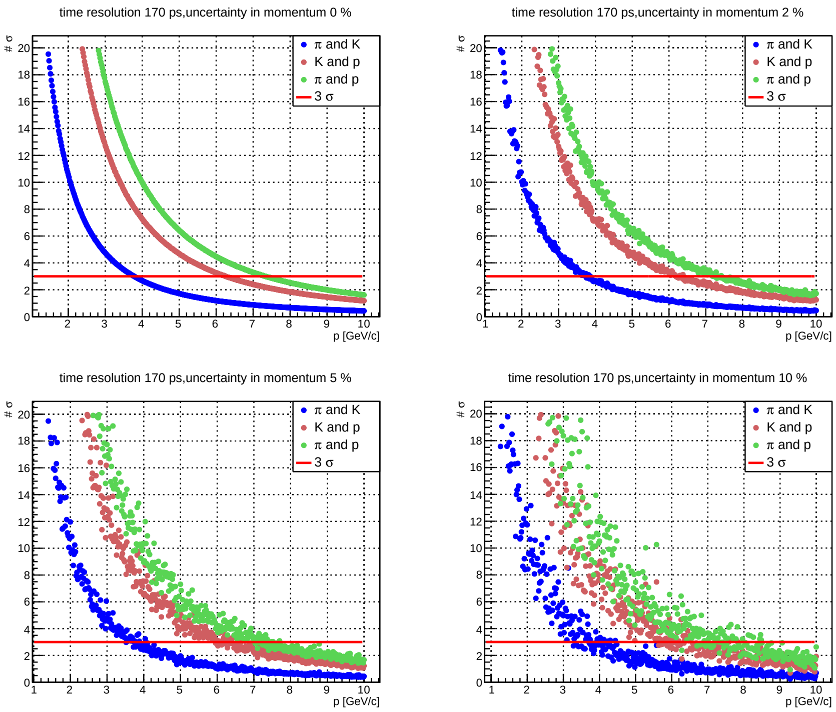


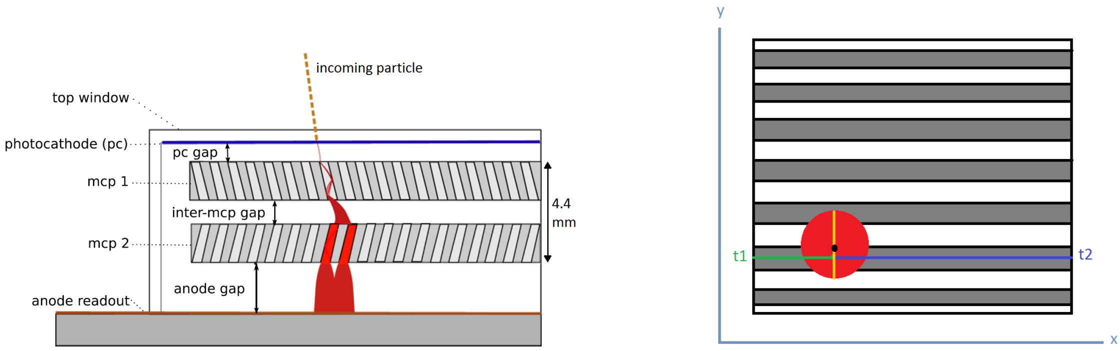

Fig.8: Particle separation with TOF resolution 170 ps for different uncertainty in momentum determining.

# 3 Large-Area Picosecond PhotoDetectors

The collaboration between The University of Chicago, Argonne National Lab, Fermilab and Berkeley Lab has developed prototype large-area systems to measure the time-of-arrival of relativistic particles with picosecond timing [4].

The principle of detection is demonstrated in Fig. 9 *a)*. The incoming particle strikes the photocatode, producing photoelectron which is then accelerated across a potential gap toward a pair of microchannel plates (MCP) with high secondary electron emission enhanced by microscopic pores. Each electron entering a pore accelerates and strikes the pore walls. This leads to the avalanche of secondary electrons. The avalanche grows until the amplified pulse exits the bottom of the second MCP.

This electrical signal is then collected on an anode. Anode coverage over large-areas is achieved by using 50 $\Omega$ stripline design which allows to determine position of incoming particle strike. As signal from each strip is read out separately and from both sides the position in direction of axis x can be determined from time difference between signal arrivals $t_1$ and $t_2$, see Fig. 9 *b)*. The red circle in Fig. 9 *b)* represents the profile of electron shower striking the photocatode. The position in direction of axis y could be determined by calculating the amount of charge collected on adjacent strips. The position resolution along the strip (x axis) is about 1 mm and along y axis it is about 2 mm.




*a)* *b)*

Fig.9: ***a)*** LAPPD: principle of detection. Taken from [1]. ***b)*** Photocatode stripline design (top view) and determining position of incoming particle.

# 4 pLAPPD testing at Fermilab

Fermilab received two 6 × 6 cm$^2$ prototype LAPPDs (pLAPPDs) #52 and #53 on loan from Argonne National Lab in order to test their characteristics. The photo of one of those pLAPPDs mounted on readout board is in Fig. 10. Unfortunately, the pLAPPD testing was accompained by setbacks from the beginning.

Firstly, one board (#53) was installed in LArIAT beamline in Fermilab Test Beam Facility (FTBF). Unfortunately, it was only few days before planned summer accelerator shutdown and it turned out that the used board was originally missing some essential components and did not function properly, see Fig. 11. There was no time to change the devices and get some data because shortly after this discovery the beam turned off. The "bad board" #53 was send back to Argonne for repair.

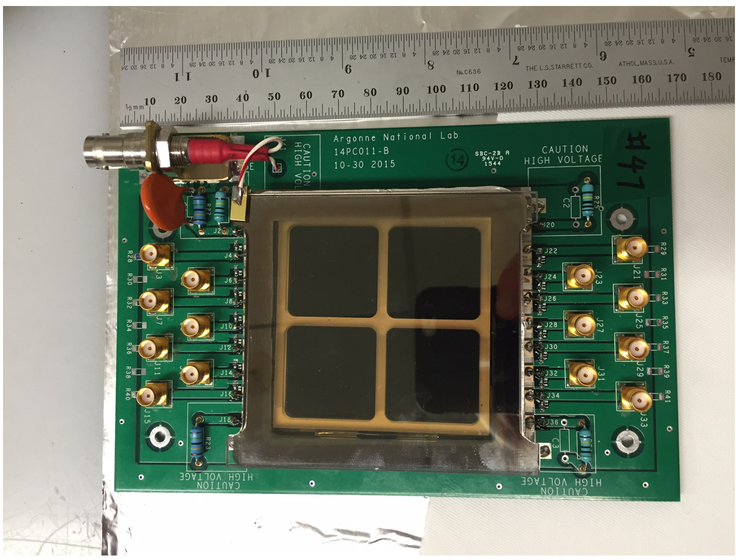



Fig.10: pLAPPD board with 7 output channels on each side corresponding to seven anode strips.

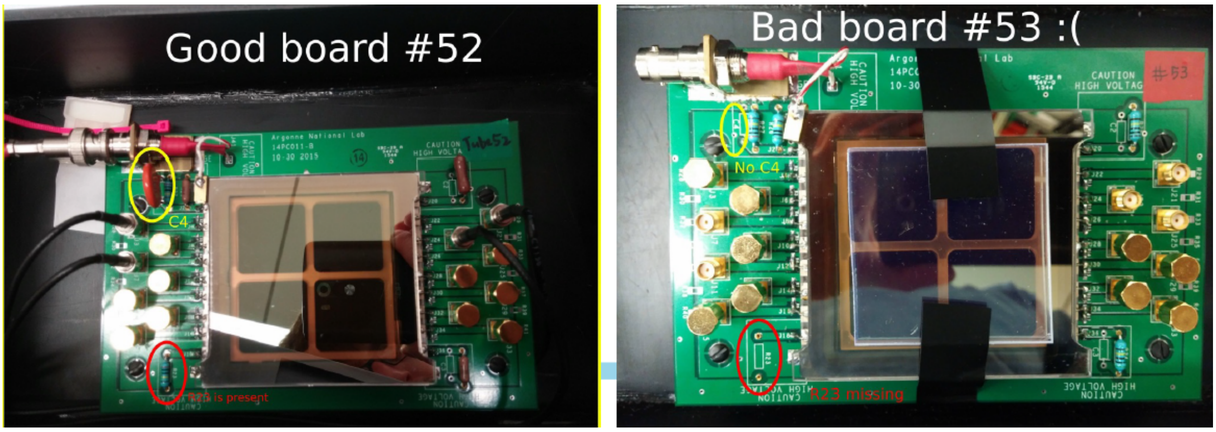



Fig.11: "Good board" #52 and "bad board" #53 missing resistor and capacitor.

In the meantime the "good board" #52 was tested with digital oscilloscope. The pulses corresponding to single photoelectron noise coming from the spontaneous thermal emission were recorded. The high voltage which provides the acceleration potential between photocathode and anode was set to 2.7 kV. The pulse shapes were taken from all channels and with different cable lengths so it was also necessary to make several RG-174U signal cables with demanded lengths and provided with SMA and MCX connectors. In order to minimize the light noise the readout board was placed in special black box and covered with black plastic. The tests required connecting and disconnecting cables from board many times as well as turning high voltage on and off. In the end of first series of measurements the board started to misbehave and the signal became very noisy so at that point the measurement had to be interrupted. The results from these measurements are presented in next section.

The board #52 was then sent back to Argonne for checking but nothing wrong was found. In the meanwhile the board #53 were repaired. So the following plan was to test pulse shapes from board #53 and to complete the measurements with board #52. Unfortunately, another problems occurred. When the HV was on, the signal from LAPPD behaved very noisy and the current was about 1 mA which was very high compared to previous measurements when it was about 180 $\mu$A. First surmise was that there was something wrong with the board again but it turned out that the problems came from the HV suply. We then changed the HV supply. However with the other HV supply we were not able to raise the voltage by steps smaller than 500 V and we also could not control the current. As a result of quick HV raise and probably high current the readout boards started to misbehave again and in addition to that two channels in digital oscilloscope broke down. We realized that when the HV was set above 2 kV the sparks apeared in one place on both readout boards. Both boards where then send to Argonne again in order to fix the problem.

As a results of those malfunctions we were not able to finish the pulse shapes tests with digital oscilloscope and the actions planned with pLAPPDs where delayed. The next plan was installing pLAPPDs into cosmic ray telescope which had been already running at FTBF. The existing telescope consisted of two scintillators, four wire chambers and one detector of calorimetric type. The pLAPPDs were planned to be mounted between the pairs of wire chambers as can be seen in the scheme in Fig. 12. Two scintillators serve as a coincidence trigger since we would like to calculate only those events when cosmic particle such as muon fly through all detectors in telescope. The position of particle hit will be determined from two pairs of wire chambers. By comparing the data from wire chambers and LAPPD we will be able to determine position resolution of LAPPDs as well as determine their efficiency as a function of position.

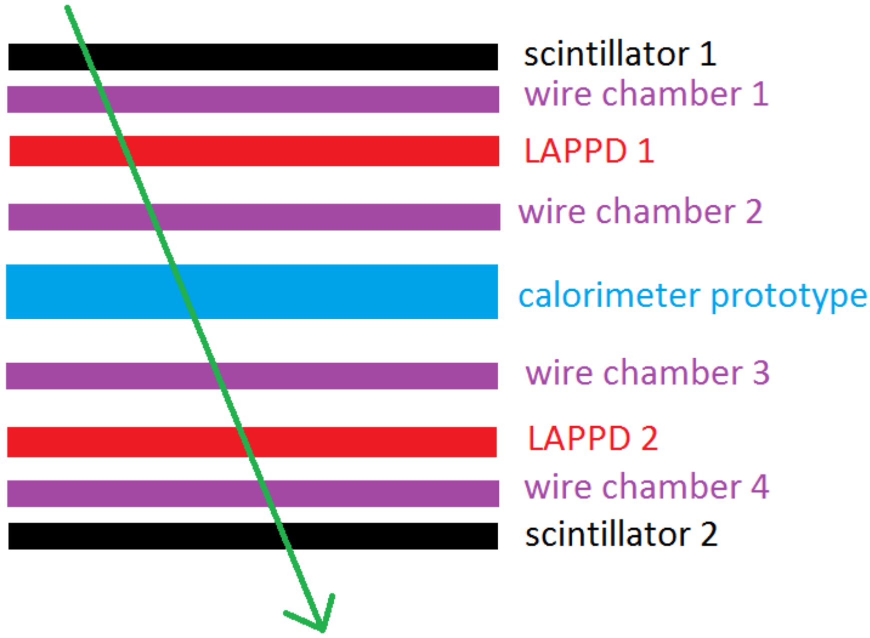



Fig.12: The structure of cosmic ray telescope.

Installation of LAPPDs into cosmic ray telescope required some preparation work such as mounting VME crate with CAEN V1751 digitizer and NIM crate with power supply and also making RG-174U signal cables with SMA and MCX connectors (Fig. 13 and Fig. 14). As already mentioned above the installation of LAPPDs into the telescope was delayed because of the sparks occuring in operation under HV above 2 kV. By the end of the summer internship almost everything was prepared except detectors themselves.

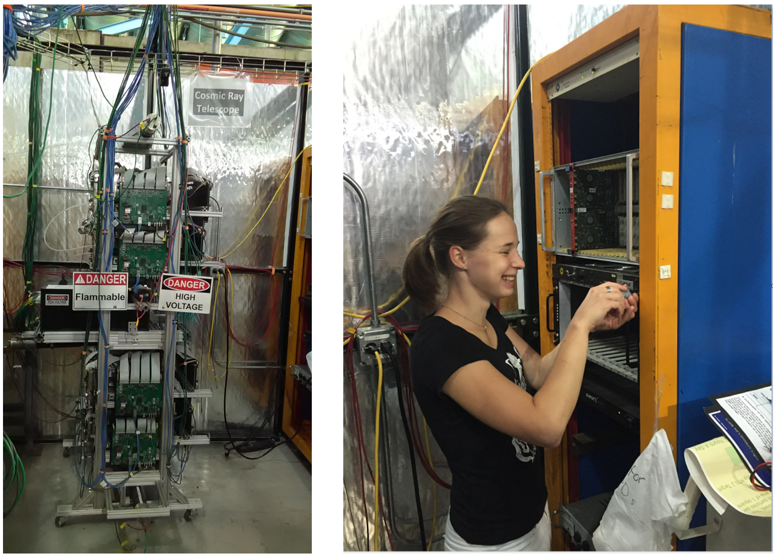



Fig.13: The cosmic ray telescope in FTBF and installation of devices for pLAPPDs runnig and readout.

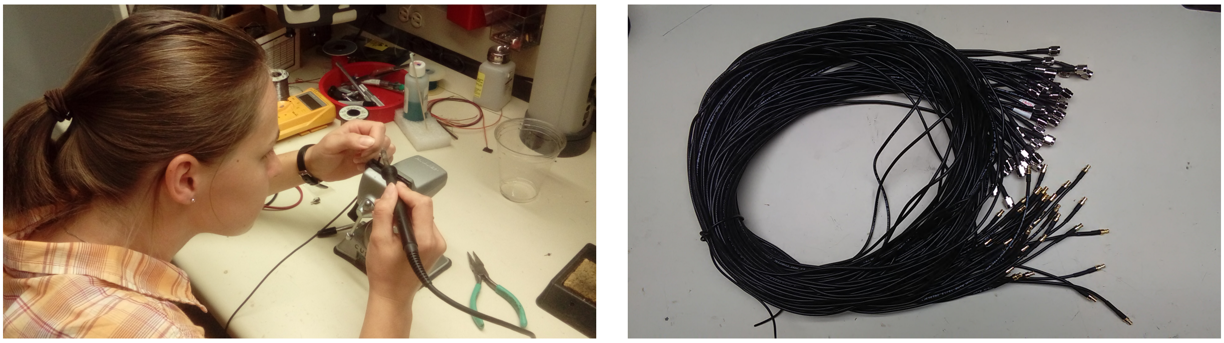


Fig.14: Making cables for LAPPD.

# 5 Results from pulse shape analysis

The pulse shapes from all 14 channels of board #52 where recorded. We collected 30 digitized waveforms from single photoelectron (SPE) in each channel with threshold for amplitude 5 mV. In addition to that we recorded pulses with threshold 15 mV from 4 channels in order to measure the signal from cosmic rays. Same measurements was performed with plastic scintillator attached to the LAPPD. However, there were no significant difference between the signals measured with and without scintillator so the signal very likely did not belong to cosmic ray but also to the SPE from spontaneous thermal emission. Finally, the signals measured with different cable lengths were compared.

In Fig. 15 the 30 pulses from one channel are shown. It is clear that the position of pulse maximum $t_{max}$ depends on the amplitude. This can be also seen in Fig. 16 where the $t_{max}$ is calculated using $5^{\text{th}}$ order differentiation method and determing of the time when derivative passes zero threshold. The distribution of $t_{max}$ from one channel (from measurement with and without scintillator) is in Fig. 17. From that distribution the time resolution seems to be about 170 ps. However in real measurement the resolution is supposed to be better because we will be able to correct the effect of amplitude. The Fig. 18 shows the slope of leading edge of pulses as a function of amplitude. This function is linear so from that it results that the rise time should be constant for all pulses. However the measured data in Fig. 18 shows that the fluctuations of rise time[1] is mostly within 200 ps but we have to take into acount the fact that those waveforms were digitized and the distance between two points was 25 ps. Unfortunately, we did not have opportunity to make more precise measurement since we had those technical troubles mentioned above.

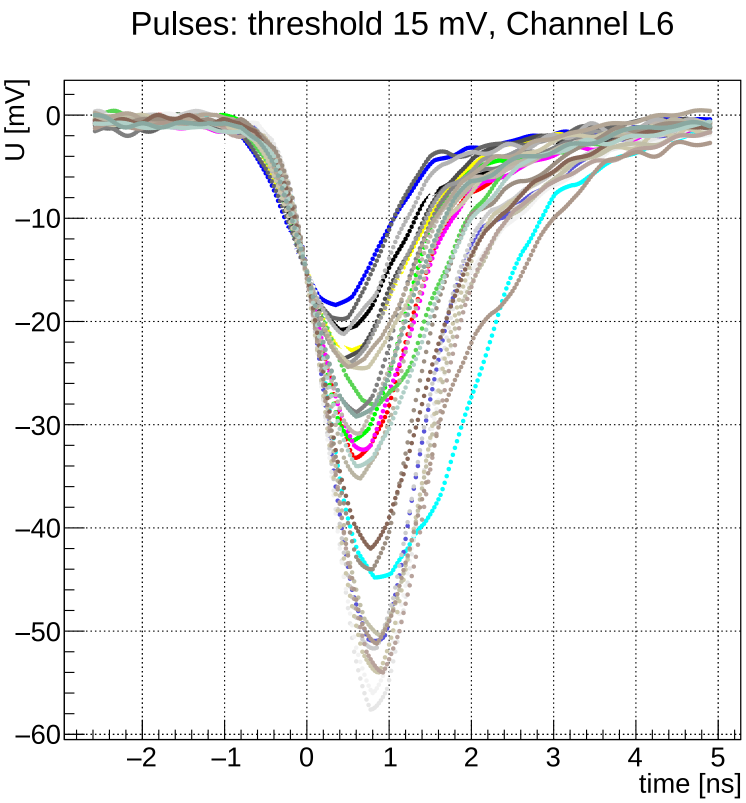



Fig.15: Pulses from SPE measured in one channel with threshold 15 mV.

[1]Rise time was calculated from 10 % to 90 % of pulse amplitude .

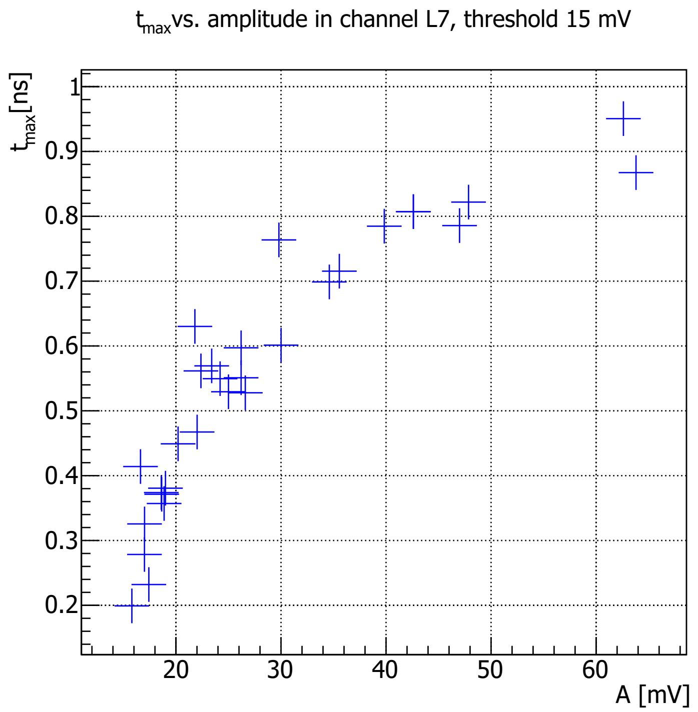



Fig.16: Position of pulse maximum as a function of amplitude in one channel with threshold 15 mV.

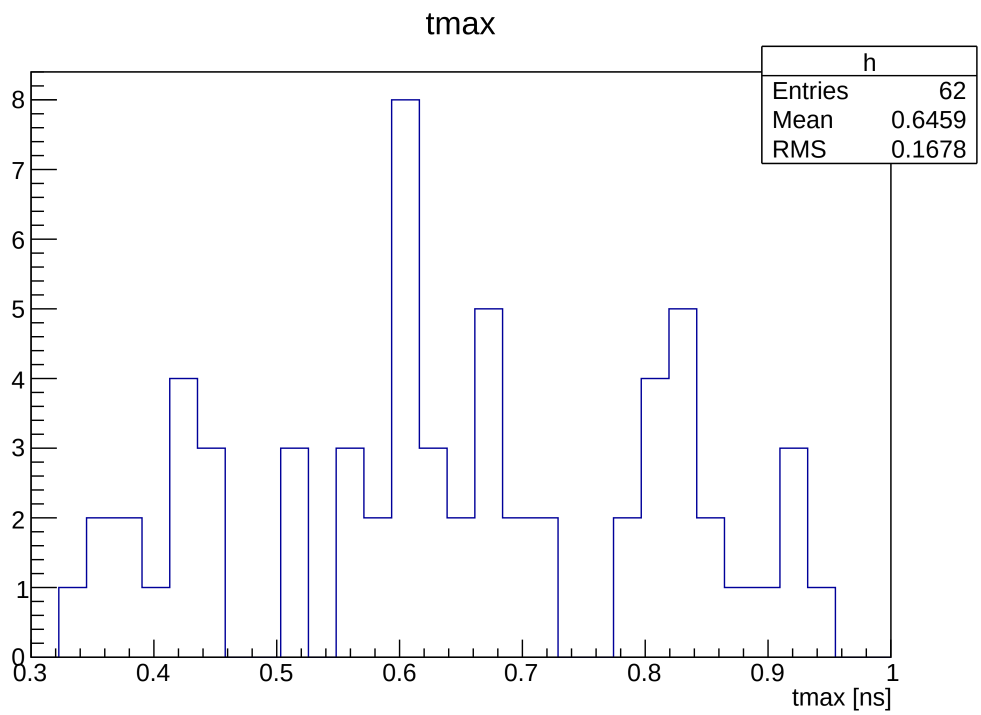



Fig.17: Distribution of position of pulse maximum as a function of amplitude in one channel with threshold 15 mV.

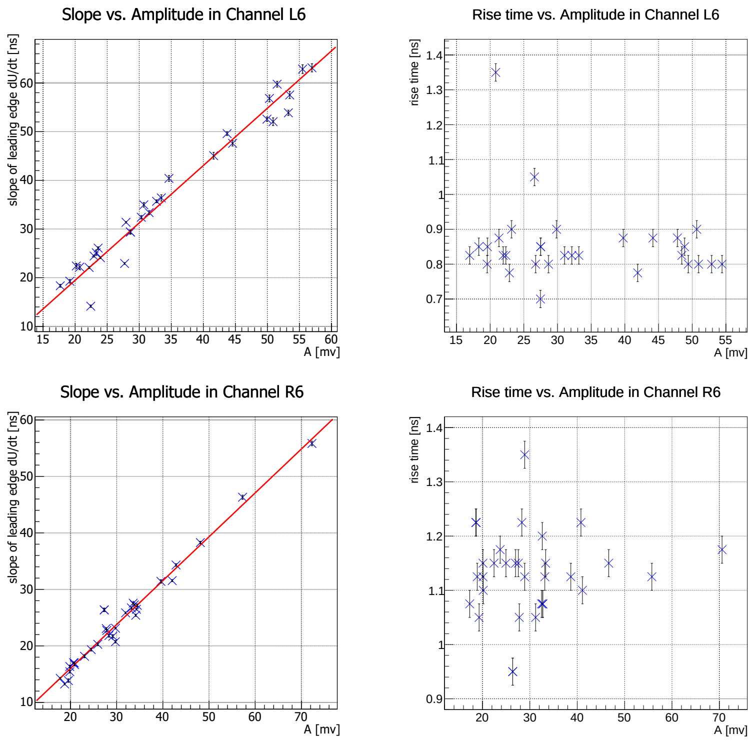



Fig.18: Slope of pulse leading edges and rise time for different amplitudes.

It was also studied how the cable length influence the pulse shape. As is shown in the picture Fig. 20 the amplitude is a decreasing function of cable length since the resistance and inductance of the cable is proportional to its length. The histograms in Fig. 21 shows the distribution of pulses's FWHM for different cable lengths. The FWHM grows with cable length. Those could be also observed in Fig. 19 where is the screenshot from oscilloscope measurement with different cable lengths. The delay of pulse measured with longer cable is also observable in the picture.

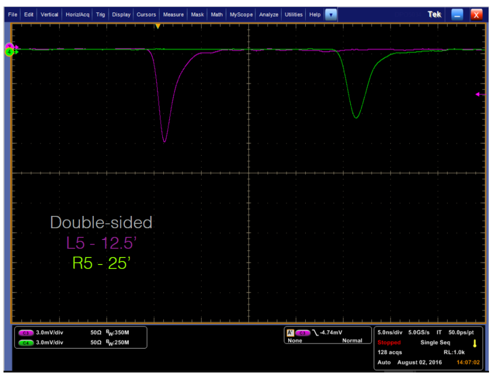



Fig.19: Pulse shapes measured with oscilloscope. The purple line represent measurement with 12.5 feet-long cable and the green one with 25 feet-long cable.

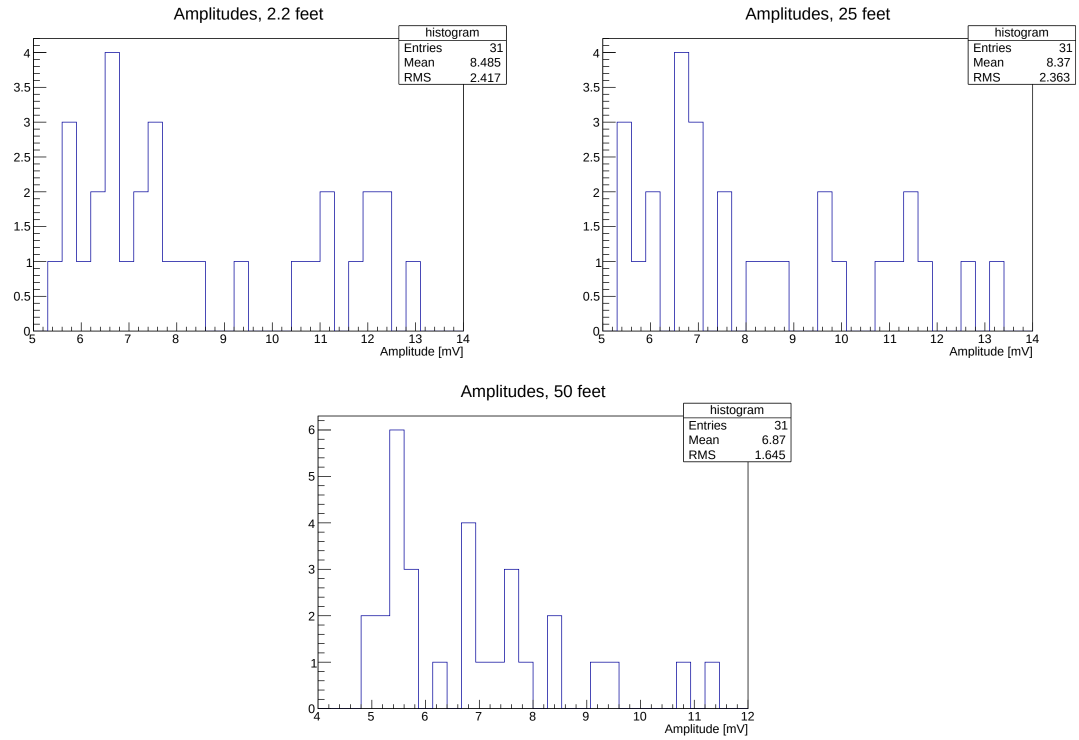



Fig.20: Distribution of amplitudes in one channel for different cable lengths (threshold 5 mV).

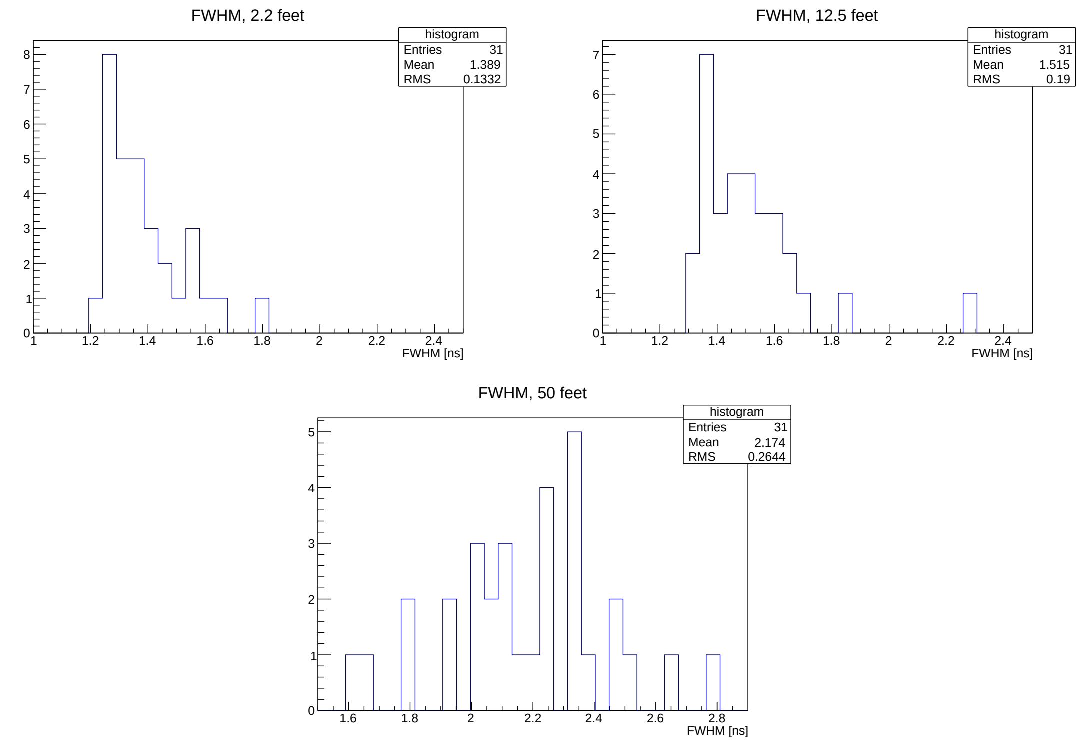



Fig.21: Distribution of FWHM in one channel for different cable lengths (threshold 5 mV).

# 6 Conclusion

As was shown by the simulations of particle separation in section 2.1, the timing resolutions around 20 ps will be needed in TOF detectors installed in protoDUNE beamline if we want to separate all types of particles from each other with resolution better than 3 sigma all over the beam momentum range. The large-area picosecond photodetectors promise to achieve that resolution. Two prototype detectors have been tested in Fermilab. Even though the testing of pLAPPDs was accompanied by many setbacks these detectors have big potential. Fortunately, the malfunctions that occured during the testing were only on readout boards but the detectors have not been damaged. The testing will continue soon.

# 7 References


[1] Bernhard W Adams, A Elagin, HJ Frisch, Razib Obaid, E Oberla, Alexander Vostrikov, Robert G Wagner, Jingbo Wang, and M Wetstein. Timing characteristics of large area picosecond photodetectors. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 795:1–11, 2015.

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[4] Large-Area Picosecond Photo-Detectors Project. http:// www.psec.uchicago.edu.