Performance of a 250L liquid Argon TPC for sub-Gev charged particle identification

J-PARC T32 collaboration

Abstract

We have constructed a LArTPC detector with fiducial mass of 150 kg as a part of the R&D program of the next generation neutrino and nucleon decay detector.

This paper describes a study of particle identification performance of the detector using well-defined charged particles (pions, kaons, and protons) with momentum of 800 MeV/c obtained at J-PARC K1.1Br beamline.

Keywords:

1. Introduction

- Advantage of LArTPC: total-absorption, fine-grain, ...
- We are interested in application of next generation neutrino and nucleon decay (100 kt LArTPC)
- $p \to K^+\nu$: LArTPC is expected to have much better physics sensitivity than WC (300 MeV/c Kaon ID can not seen in WC)
- P32 and GLACIER program.
- Two types of R&D: (1) Make bigger detector, (2) Understand property of LArTPC for more reliable physics sensitivity estimation
- Study using not cosmic, not neutrino beam, but charged particle (Kaon, pion, proton) from beam is important
- We have constructed 250L LArTPC
- Oct/2010 beam test at J-PARC K1.1Br beamline: Collected Kaon, pion, proton, and electron data
- Establish reconstruction, for pion, proton, and Kaon
- Develop realistic simulation
- By Comparing data and MC in detail, we can understand basic property of the LArTPC detector
- Section 2 describes experimental setup, Section 3 describes collected data sample, Section 4 Simulated event, Section 5 pion, Section 6 proton, , Section 5 Kaon

2. Experimental Setup

We have described details of the experimental setup in ref.[1], and in this paper we only discuss the issues which are relevant.

2.1. K1.1Br Beamline

- Designed and constructed for TREK experiment
- 30 GeV proton + target, ESS for good particle separation (Max $K/\pi = 1$)
- highest intensity at 3kW proton beam on target: $\sim$ 1 kHz
- 800 MeV/c particles, pion, Kaon, positron, proton
- For T32 test, we reduce beam intensity to $\sim$ 10 Hz (Max $K/\pi = 1/4$)

2.2. 250L Detector

- Cryostat, purification system
- TPC

2.3. Beamline Equipment

We have several beam counters to identify beam particles. There are two beam defining counters (BDC and T32 BDC) which determine acceptance of the beam, a Fitch-type Cherenkov counter (FC), and a Gas Cherenkov counter (GC), and two time of flight counters (TOF1 and TOF2).

Two TOF counters are 3.5m apart, and has ~200 ps of time resolution. Figure 1 shows the flight time distribution between TOF1 and TOF2 obtained from 800 MeV/c beam particles which contain all K^+, π+, e^+, and p. Three peaks which correspond to π+e^+, K^+, and p, respectively, are well separated.

FC has 5 cm of acrylic plate as Cherenkov light radiator and photo-multipliers which are aligned in circles with two different emission angles (K-ring and π-ring) as photo detector. It is designed to have maximum separation of K^+ and π^+ with momentum of 800 MeV/c. Top plot in Fig.2 shows response of FC for the 800 MeV/c beam particles. Horizontal axis and vertical axis are hit multiplicity of the π-ring and K-ring, respectively. $K^+(\pi)$ is identified as event with signal in K-ring (π-ring) but no signal in π-ring (K-ring). In case of no signals in both rings, the particle is considered as proton. TOF and FC can not distinguish e^+ and π^+ Additional separation between e^+ from π^+ is provided by GC which uses atmospheric air as Cherenkov radiator. Filled histograms in bottom plot of Fig.**??** shows selected K^+ event with FC information. FC can identify K^+ with almost very high efficiency. After removing residual π^+ using TOF, we can obtain almost 100% purity K^+ sample.

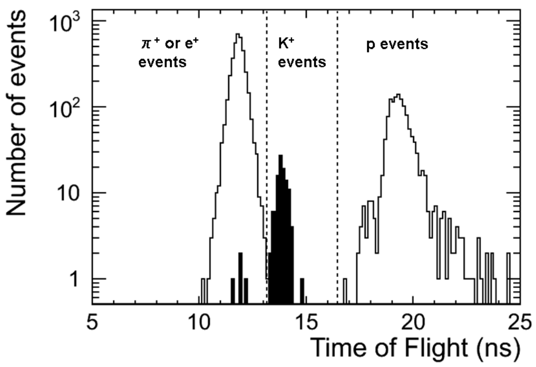

Figure 1: TOF distribution.

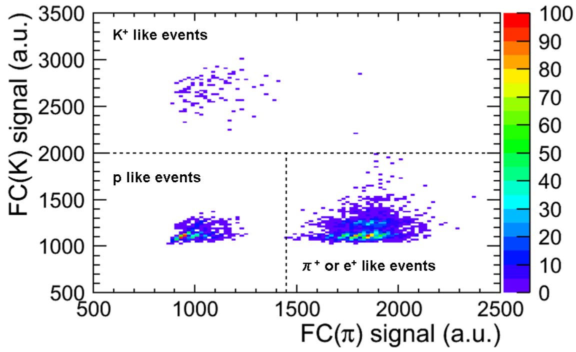

Figure 2: FC

2.4. Oct/2010 Beam Test Configuration

by using the beam counters, we define three types of trigger

- non-bias trigger: simply require signal in two BDCs and two TOFs
- Kaon trigger: in addition to no-bias require K id with FC information
- electron trigger: non-bias + electron ID with GC information

Beam Momentum

- Materials located from proton target to LArTPC detector (beam counters, beam windows, air, etc) degrade beam particle momentum
- the effect is estimated by looking at TOF of proton, average prton beam momentum is 730 MeV/c
- For other particles (K, pi,e e), TOF does not have enough resolution to determin momentum, and the degradation is directly estimated by counting the energy deposition to the materials using GEANT based simulation. For example Kaon momentum is xxx MeV/c on average.

We measured beam profile in front of 250LAr TPC beam window by using plastic scintillation counters. The beam is relatively narrow in vertical direction (within 5 cm), but spread in horizontal direction (~ 10 cm).

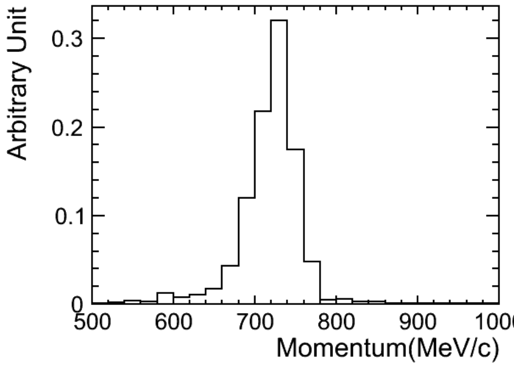

Figure 3: Top plot shows ΔTOF distribution of TOF counters with proton data, and bottom plot shows proton momentum estimated by ΔTOF of TOF counters information

3. Data Sample and Basic Reconstruction

3.1. Collected Data

Table 1 shows list of the collected data while Oct/2010 Run. 800 MeV/c π^+ is expected to pass-through the detector as almost minimum ionizing, and have uniform energy deposition to all the TPC channels. So this data set is useful for calibrating the detector response (See Sec. 6). 800 MeV/c proton stops after 15 cm of flight distance inside the TPC fiducial volume with relatively large dE/dx. So we use the proton data set for validation of the detector response at high dE/dx region(See Sec. 7). We have collected three different K^+ data by varying thickness of the degrader. 540, 630, 680 MeV/c correspond to the momentum degraded by 2 lead glass, 1 lead glass + 1 lead block, and 1 lead glass, respectively, and such K^+ stops after 10 cm, 50 cm, and 65 cm of flight distance inside TPC fiducial volume.

Table 1: List of collected data

Particle	Initial Momentum (MeV/c)	Number of Events
Pion	800	3,000
Proton	800	1,500
Kaon	540 (2LG)	7,000
Kaon	630 (1LG+1LB)	40,000
Kaon	680 (1LB)	35,000
electron	800	2,500
electron	200	10,000
pion	200	10,000

Top plot in Fig. 4 shows 2D display of an event taken with 800 MeV/c electron trigger. Horizontal axis corresponds to TPC channel number where zero means most upper stream strip. Since strip pitch is 1 cm, this is equivalent to distance from beam injection point in cm. Vertical axis corresponds to electron drift time in μs where t=0 means trigger timing. In 250L TPC, anode and cathode is located at top and bottom of the detector, respectively, drift direction is from bottom to top of the detector. With 200 V/cm of electric field, drift velocity is about 0.8 m/ms, and drift time of full detector (40 cm) is about 500 μs. Color strength of the plot corresponds to the TPC signal pulse height in ADC counts. In this event, triggered electron can be clearly identified in the center of the detector as an electromagnetic shower, while there are two other particles accidentally overlapped with the triggered electron. Track at t=100 μs is considered as a proton which stops after 15 cm of flight distance and has large dE/dx around the stopped point. Track at t=400 μs is considered as a pion which passes-through the detector and has uniform dE/dx over the TPC channels. Bottom plot in Fig. 4 shows a typical $K^+ \to \mu^+\nu$ like event. We can clearly identify a kink of the track at 60 cm which is considered as stopped point of Kaon and it decays to $\mu^+\nu$. Energy deposition of the track is about MIP at the injection point and gradually increase towards the stopped point at 60 cm.

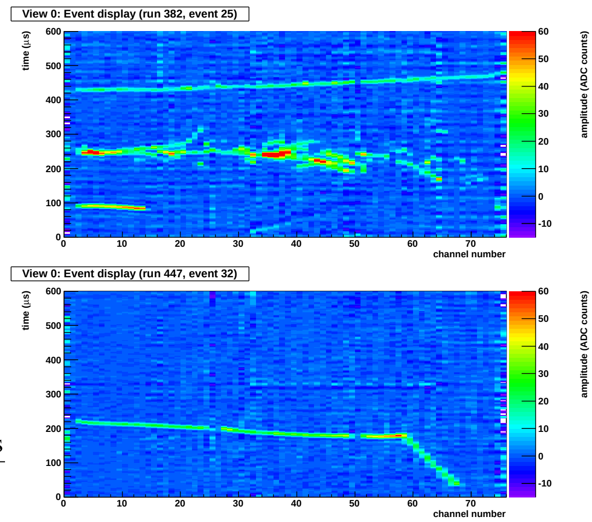

Figure 4: Event display of 800 MeV/c electron triggered event (top) accidentally overlapped with a proton and a pion, and Kaon 630 MeV/c triggered event (bottom)

3.2. Noise Reduction

Dotted line in top plots of Fig. 5 shows raw waveform of the TPC signal before applying any noise reduction. the waveform shown in this plot are channel

13 in Fig. 4 which are around the proton stopped point. Signal-to-noise ratio for this particular case is poor and pion signal which is supposed to be t=400 μs is almost hidden by the noise. While time width of TPC signal is few μs which is determined by drift time between anode and anode-grid, dominant noise component looks higher frequency. To reduce such noises, we have applied FFT (Fast Flourier Transformation) filter to cut the high frequency component. Bottom plot in Fig. 5 shows amplitude as a function of frequency for the same event. This clearly shows dominant noise component with > 200 kHz has good separation with signal component (< 100 kHz). Solid line in top plot of Fig. 5 shows waveform after removing high frequency (> 80 kHz) component by the FFT filter. Signal-to-noise ratio is dramatically improved. On the other hand, we expect certain bias to the signal charge measurement by this filter, and it will be discussed in Section x.

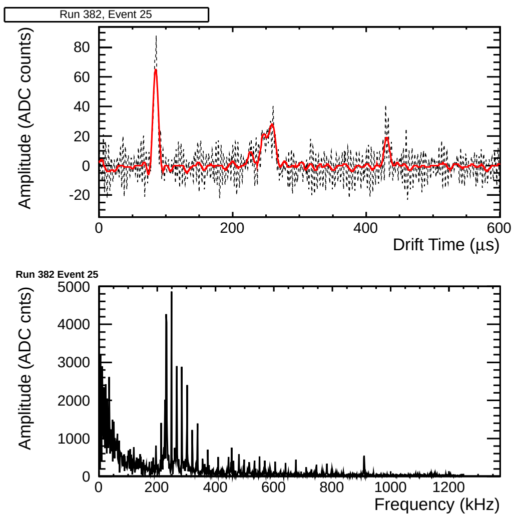

Figure 5: Top: Typical TPC signal waveform before (dotted line) and after (solid line) applying FFT low pass filter with threshold of 80 kHz, Bottom: FFT frequency amplitude distribution

3.3. *Hit Finding/Clustering*

After noise reduction we find signal hits and create clusters associated to single tracks. Hit is defined as bump over given threshold in a channel. Threshold of hit finding is 6 ADC counts, which is about 2.5σ from typical data noise level (as shown in Fig 5) and keeping more than 99% of Kaon hit finding efficiency in simulation. ADC count distribution is fitted by Gaussian plus step function to estimate the charge of hit in ADC $\times$ μs unit. Fitting χ^2 < 3 and 2.5 < (time width of hit) < 8 μs are required to remove noise hits further. After finding all hits in an event, we construct cluster by merging adjacent hits. The example of hit finding and clustering using Fig 4 event is shown in Fig 6, which indicates reasonable hit and cluster findings.

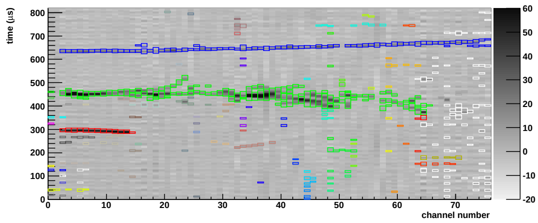

Figure 6: Example of hit finding and clustering. A colored box corresponds to a hit and colors represent different clusters.

4. Detector Calibration

4.1. *Channel-by-Channel Calibration*

Figure 7 shows the hit charge as a function of the TPC channel number obtained from the 800 MeV/c π^+ data. This figure is obtained from ~300 events of well-selected Pion passing-through the TPC. Gray-scale contours show hit charge distributions for each channel and black points correspond to average of the hit charge distribution. Although we expect the energy deposition of the through-going pion to be uniform, we observe relatively large channel dependence. This is mainly because of the distortion of the TPC drift field. We use this average charge as channel-by-channel normalization scale.

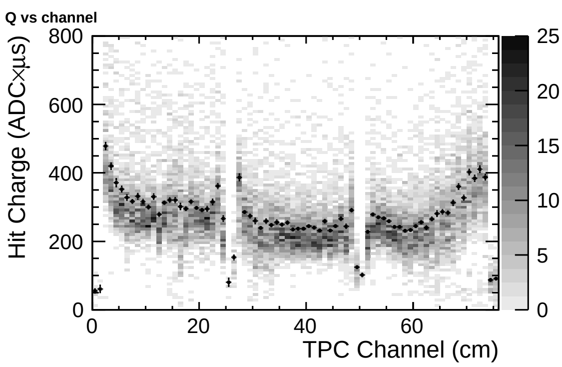

Figure 7: 800 MeV/c pion average hit charge

Figure 8 shows electric field of the TPC in V/cm which is calculated using a 2D FEM (Finite Element

Method) package [6], where horizontal axis, vertical axis, and color strength correspond to the beam line direction, the drift direction, the electric field in V/cm, respectively. Cathode, Anode, and Anode grid are located at of z=-200 mm, z=200 mm, and z=210 mm. respectively. There are significant distortion of the electric field around 4 corners of the TPC fiducial volume, and also around x=±120 mm where support structure of the Cathode and Anode grids exists. We found this field distortion is the main cause of the non-uniformity of the TPC response.

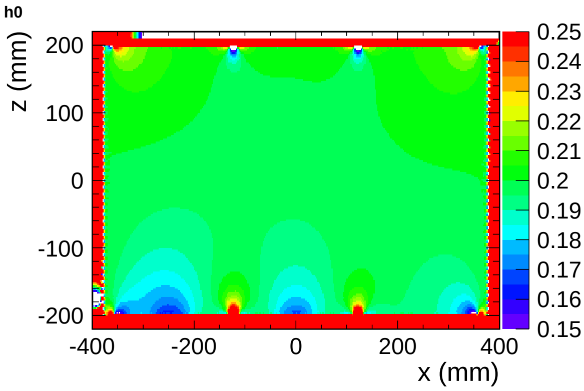

Figure 8: Electric field map obtained with 2D FEM where horizontal axis corresponds to the beam line direction, and vertical axis corresponds to drift direction, and color strength corresponds to electric field strength in V/cm.

4.2. *Liquid Argon Purity*

Attenuation of the drift electron depends on purity of LAr since electronegative impurities capture it [5]. Thus we need to apply correction to TPC signal charge according to the drift time. We use cosmic ray events triggered by inner PMT at off-beam timing for measuring the LAr purity, and use this to correct the beam data. Figure 9 shows an event display of typical cosmic muon event crossing TPC channels. The attenuation of readout charge depending on drift time is clearly seen in the right plot. We use multiple events to cancel Landau effect and apply channel response correction to estimate LAr purity.

We select cosmic ray event with more than 20 TPC channels which corresponds to zenith angle of more than 27° and consistent with straight line by χ^2 fit. We fit readout charge by Landau function in each drift time bin to estimate average charge deposit. Figure 10 shows an drift electron lifetime as a function of duration after initial LAr filling. Drift electron lifetime was 600 μs at

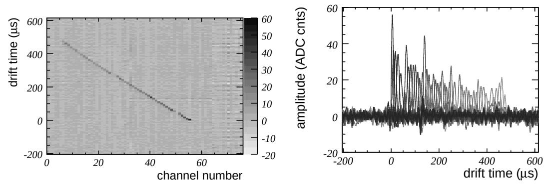

Figure 9: Left: Typical cosmic muon event crossing TPC channels. Right: Charge deposit as a function of drift time.

60 hours, and 400 μs after 150 hours. The degradation is possibly due to impurity from micro leak or out-gassing penetrating faster than purification by gas recirculation. But we kept enough drift electron lifetime during data taking period. The effects from noise, field distortion, and FFT give about 10% (to be confirmed) of systematic uncertainty in LAr purity estimation.

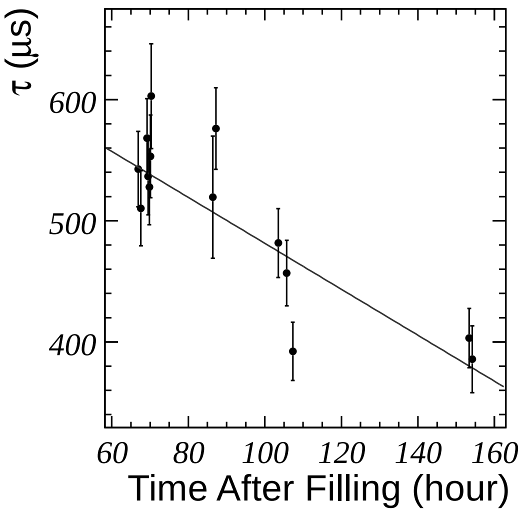

Figure 10: Drift electron lifetime as a function of duration after initial LAr filling. The lifetime is used to correct the beam data.

4.3. *Cross Talk*

TBD

5. Simulation Tuning

Development of the realistic simulation is one of the main task of this experiment. We try to put all the effects (Field distortion, LAr purity, cross talk, etc) into this simulation, and see if the properties of LArTPC in data can be reproduced using the simulated sample.

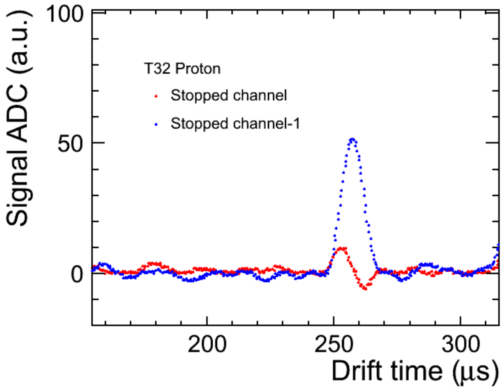

Figure 11: Left plot shows signal wave form of stopped channel and the front channel, and right plot shows hit charge distribution of stopped channel

5.1. Signal Simulation

We use GEANT3 for simulating energy deposition of initial beam particles and secondary particles to the TPC detector and beam line counters. Maximum step of GEANT is set to 0.5 mm which is enough smaller than the TPC readout pitch of 1 cm. We set energy cut-off for soft electron/photon emission to 10 keV which is minimum possible energy can be set in GEANT3. Recombination of electron and Argon ion depends on the electric field E and dE/dx, and explained by the following equation (Birks law)

$$Q = A \frac{Q_0}{1 + (k/E) \times (dE/dx) \times (1/\rho)} \quad (1)$$

where Q_0 is initial ionization charge, ρ is density of liquid Argon (=1.4 g/cm^3). For A and k, we use the measurement by ICARUS collaboration [3]. Electric field is given by Fig.8.

After the recombination, drift of the ionization electrons to anode is simulated using a simple step simulation with step size of 0.1 mm. Drift velocity of the ionization electron depends on the liquid Argon temperature, and the electric field. We use a measurement by ICARUS collaboration [4], and electric field in Fig.8. Typical drift velocity with 200 V/cm of the drift field and temperature of 92K is 0.8 m/ms. Diffusion of the drift electron is considered and we assume coefficient for the transverse diffusion and and lateral diffusion are 9.0 mm^2/m and 2.3 mm^2/m, respectively (need reference).

- Simulate Signal waveform: Gaussian

simulation of recombination, drift, waveform is done for every GEANT step, and the resulting waveform is summed up for all the particles in the event. After ending of the event process, noise waveform which describes in the next section is added to the signal waveform, and then the signal charge is digitized.

5.2. Noise Simulation

- We generate noise from FFT amplitude distribution such as in Fig.5
- By using empty event, prepare template distribution of amplitude for each channel and each frequency bin
- Obtain waveform by generating random number from the template
- Coherent noise is added board by board

Figure 12 shows simulated event of 630 MeV/c $K^+ \to \mu\nu$.

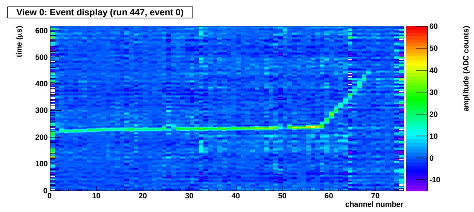

Figure 12: Event display of simulated events for 630 MeV/c K^+.

6. Through-going Pion

- Explain Landau distribution ("bare" track and "dressed" track)
- pion track (800 MeV/c) and soft electron (~10 keV) has different dE/dx = recombination
- Set delta-ray cut off = 10 keV in simulation, and take ICARUS measurement of recombination.
- Hit charge distribution is in good agreement between data and MC.

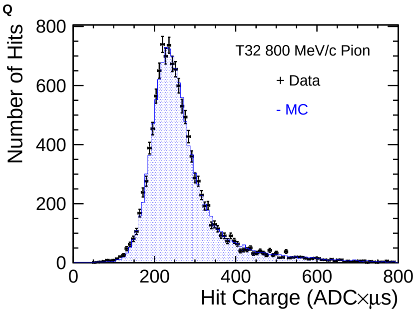

Figure 13: Hit charge distribution for 800 MeV/c through-going π^+ sample. Points and histograms correspond to data and MC, respectively

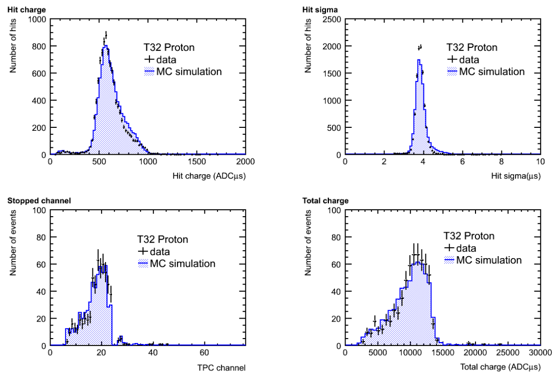

Figure 14: Hit Charge, Hit Sigma, Stopped Channel, Cluster Charge

7. Stopped Proton

Proton event selection

- Protons are selected by the information of beam counters.
- Drift time of the hit at the injection point: 150*mus* to 300μs which corresponds with T32 BDC fiducial volume.
- Total number of hits in the cluster is greater than 5.
- Only one cluster in the event

For good proton events, we compare each parameter between data and MC. Figure14 shows the comparison of the distribution of Hit Charge, Hit Sigma, Stopped Channel and Cluster Charge between data and MC. All four distributions of MC reproduce data well. Especially, the agreement of stopped channel distribution shows the consistent the momentum estimation by TOF information with the initial momentum of the particles injected to 250L detector.

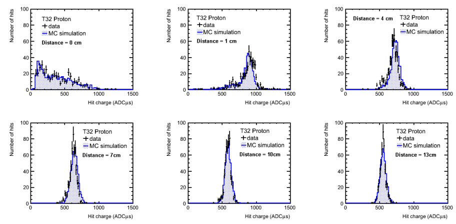

Figure 15: Hit charge distribution of each distance from stopped point

Figure15 shows the hit charge distribution of each distance from stopped point. Hit charge distributions of MC simulation are good agreements with data. Figure16 shows the mean of the hit charge distribution of each distance from stopped point. MC simulation reproduce the charge response of data in high and wide dE/dx region well.

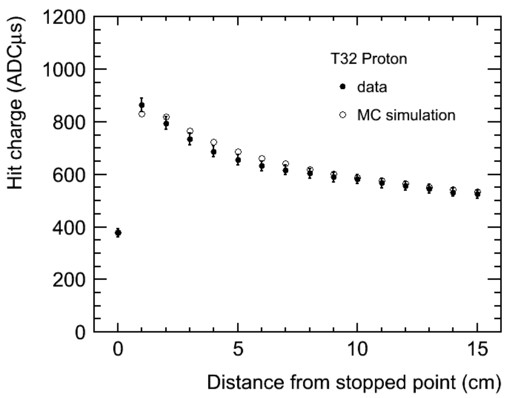

Figure 16: Data-MC comparison of the mean of hit charge distribution

7.1. Recombination Factor

For the data-MC comparison, we use parameters of the recombination factor in ICARUS measurement of Ref.[3]. In this section, we measure the recombination factor using proton (and Kaon) data.

Expression for recombination (Birks law) in Eq. 1 can can be rearranged like below:

$$\frac{Q_0}{Q} = \frac{1}{A} + \frac{(k/E)(dE/dx)(1/\rho)}{A} \tag{2}$$

In this equation, the ratio of Q_0/Q has linear dependence of stopping power dE/dx, and Q from data (See Fig. 16), Q_0 and dE/dx from MC can be determined for every distance from the stopped point. By using this we are able to extract parameters A and k. Q_0 is determined from the simulation sample without recombination (Top left plot in Fig. 17), and dE/dx per an anode channel is determined with truth information of simulation (Top right plot in Fig. 17). The result of this study is shown in bottom plot of Fig17. Vertical axis is Q_0/Q, and horizontal axis is dE/dx in this figure, this plot is fitted to straight line. As a result, we obtain fitting parameter, A = 0.832±0.009(stat.)±0.006(syst.), and k=0.0504±0.0010(stat.)±0.0013(syst.) [kV(g/cm^2)/cm/MeV]

It confirms Birks law in the range of 4 ≦ dE/dx ≦ 12 MeV/cm^2 and electric field of 200 V/cm is consistent with ICARUS measurement[3]. A = 0.800±0.003 and k=0.0486±0.0006 [kV(g/cm^2)/cm/MeV]

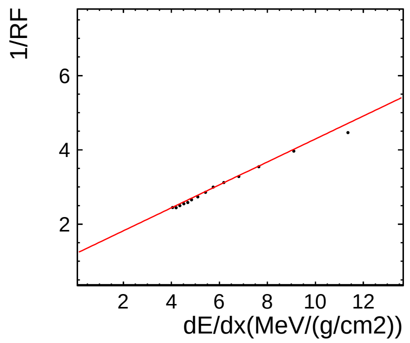

Figure 17: Q_0/Q as a function of dE/dx fitted to linear line to extract parameters of Birks law

8. Stopped Kaon

- Stopping point of the Kaon is identified as kink of the track
- For example, $K \rightarrow \mu\nu$ event (Fig. 12) is composed by two tracks, Kaon and muon, and intersection of two tracks corresponds to the stopped point.
- We develop two different algorithm to identify the Kaon stopped point, Hough and Chi2.

Hough transform was invented for machine analysis of bubble chamber photographs by Paul.V.C.Hough.[7].

- Transform hit coordinates [TPC channel, drift time] into Hough space
- Find the straight line by choosing the most dense point in Hough space (= Kaon track)
- Hits associated with the first straight line are removed, and remaining hit coordinates are transformed into Hough space.
- Find second straight line using the same procedure (= Muon track)
- This procedure is repeated until number of remaining hits are less than three.
- Kaon stopped point is identified as the hit with maximum charge and around the intersection of two lines.

χ^2 method is the algorithm to Identify the kaon stopped point as the point which rapidly increase fit χ^2 to straight line.

- Starting from the most upstream hit in the cluster, fit the hits to straight line (Kaon track)
- Find the point which rapidly increase fit χ^2 to straight line.
- Starting from the most downstream hit in the cluster, fit the hits to straight line (Muon track)
- Find the point which rapidly increase fit χ^2 to straight line.
- Kaon stopped point is identified as the hit with maximum charge and around the intersection of the two lines.

Figure 18 shows Data and MC comparison for signal hit charge, signal width, decay point and total particle charge distribution. Data of signal charge and signal width are consistent with MC one in error by less than two % and data of cluster charge and primary charge are consistent with MC one in error by less than five %.

Figure 19 shows signal hit charge distribution in different distance from the stopped point. Data and MC are in good agreement.

Figure 20 shows data/MC ratio of signal hit charge distribution in different distance from the stopped point. Data of signal charge in different distance from stopped point are consistent with MC one with in 5%.

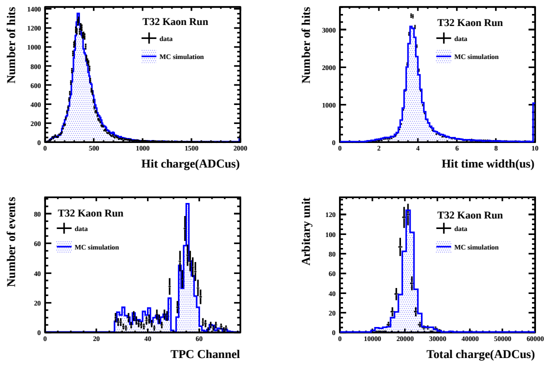

Figure 18: Data-MC comparison for hit charge, hit sigma, cluster charge, primary particle charge

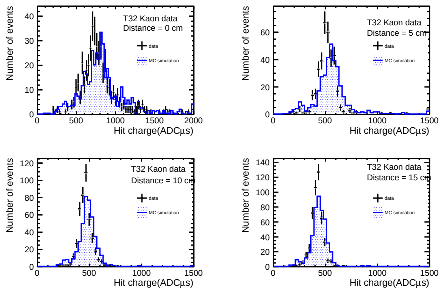

Figure 19: Data-MC comparison for hit charge distribution in different distance from the stopped point(top left:decay point,top light:decay point-5cm,bottom left:decay point-10cm,decay point-15cm)

9. Summary

- We have constructed 250L LArTPC
- Collected high purity Pion, Kaon, and proton sample
- Establish Kaon stopped point finding algorithm
- Develop realistic detector simulation
- Good understanding of Pion Landau distribution
- Good understanding of Proton and Kaon dE/dx
- Measurement of recombination using pi, K, and proton

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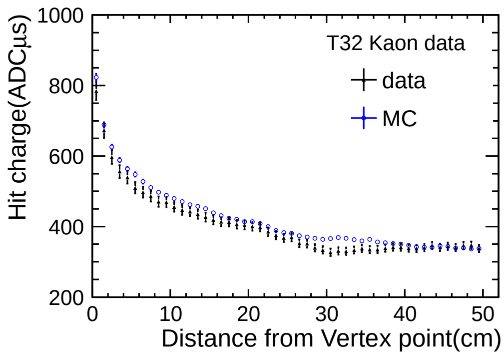

Figure 20: Top plot shows Data-MC comparison for hit charge distribution in different distance from the stopped point. Bottom plot shows Data/MC ratio for hit charge distribution in different distance from the stopped point

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