# Kaons and Other 6+ GeV Beam Data

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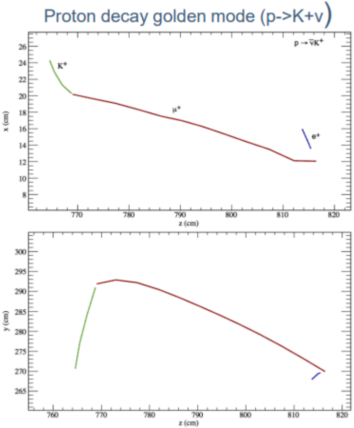
# Kaons in DUNE

The goal is to be able to reconstruct kaons if protons decay into them and a neutrino. One single kaon that stops, decays into a muon and decays to a Michel.




Hypothetical DUNE event display of a kaon decay (From Jennifer Raaf and Michael Sorel)

# Goals of ProtoDUNE for DUNE

In order of need for DUNE:

1. Study the Bragg peak of a kaon decaying into a muon. This is the only way to know for sure it is a kaon (barring machine learning).
2. Measure the cross section for kaons at different energies.
3. Understand inelastic scatters of kaons.

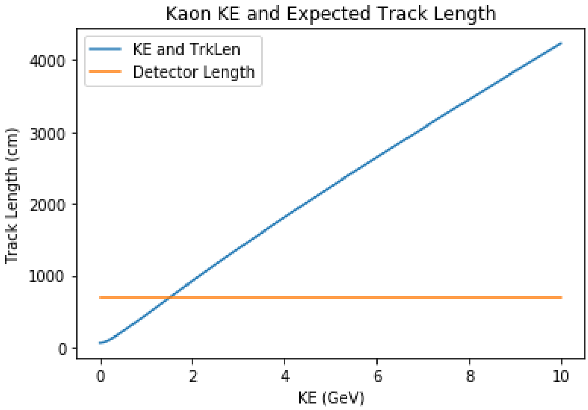
# Why kaons in ProtoDUNE are no good for kaons in DUNE

Kaons only appear at 3 GeV. Protons, if they decay, will eject a kaon with approximately 350 MeV in momentum.

| P (GeV/c) | # of Spills | # of $e^+$ | # of $K^+$ | # of $\mu^+$ | # of $p$ | # of $\pi^+$ | Total # of Events | Beam Time (days) |
|---|---|---|---|---|---|---|---|---|
| 1 | 70K | 84K | $\approx 0$ | 70K | 689K | 625K | 1.5M | 19.4 days |
| 2 | 16K | 19K | 9K | 36K | 336K | 572K | 1.0M | 4.4 days |
| 3 | 13K | 16K | 26K | 17K | 181K | 540K | 780K | 3.6 days |
| 4 | 11K | 13K | 19K | 16K | 107K | 510K | 660K | 3.1 days |
| 5 | 11K | 13K | 29K | 13K | 96K | 510K | 660K | 3.1 days |
| 6 | 11K | 13K | 36K | 12K | 94K | 510K | 660K | 3.1 days |
| 7 | 11K | 13K | 42K | 8K | 87K | 510K | 660K | 3.1 days |
| Total | 143K | 171K | 161K | 172K | 1.6M | 3.8M | 5.9M | 39.7 days |

Beam Run Plan for ProtoDUNE-SP I

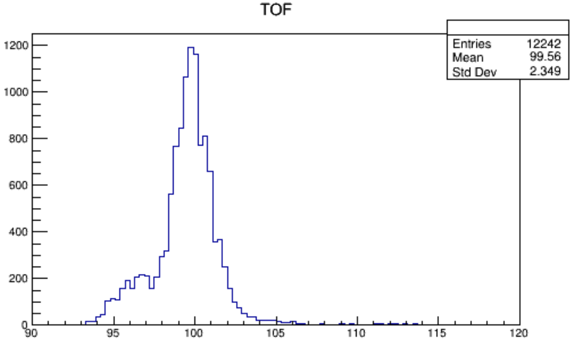
# Why kaons in ProtoDUNE are no good for kaons in DUNE




Expected kaon track length as a function of kinetic energy. We only see 3 GeV kaons, so it is difficult to get them to stop on average

# Why kaons in ProtoDUNE are no good for kaons in DUNE

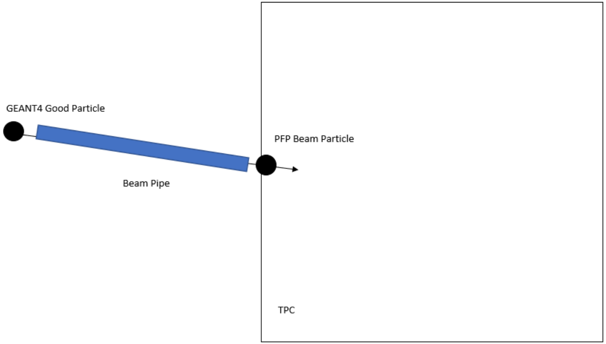
Unfortunately, we cannot select 3 GeV kaons with a good amount of purity. They look too much like protons.




TOF from beam instrumentation at 3 GeV for a kaon/proton trigger. The smaller peak on the left is from kaons, but notice how much the proton distribution bleeds into it.

# Selecting ProtoDUNE Kaons in Simulation

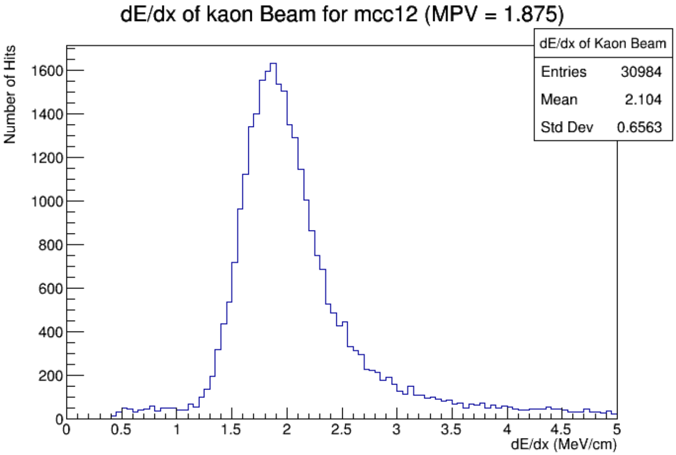
Use Geant4 Beam Particle as a stand-in for the beam instrumentation.




Cartoon of MC Beam Particle Selection

# Kaon dE/dx in MCC with SCE simulated and calibrated

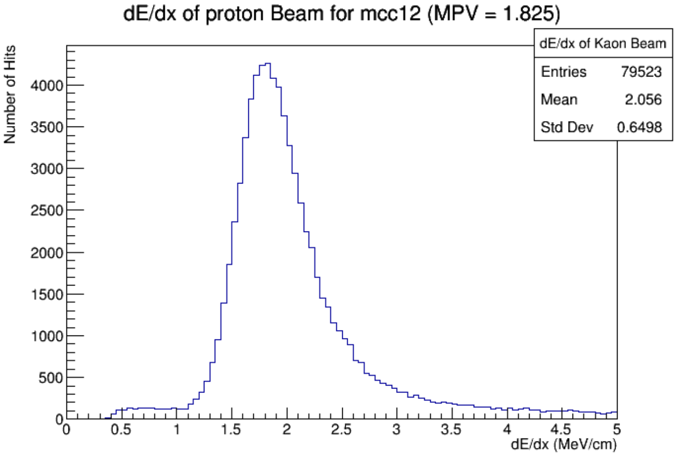
They are all in good agreement given Bethe-Bloche predicts MPV as 1.89 MeV/cm




Kaon MCC 12 dE/dx for first 20 cm in Z

# Proton dE/dx in MCC with SCE simulated and calibrated

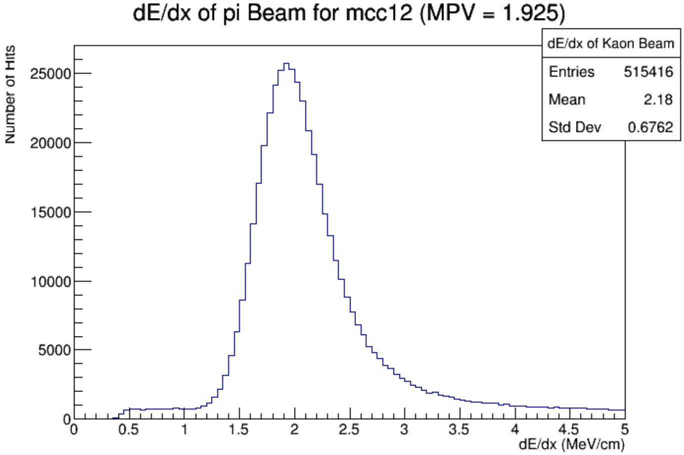
Bethe-Bloche predicts MPV as 1.86 MeV/cm




Proton MCC 12 dE/dx for first 20 cm in Z

# Pion dE/dx in MCC with SCE simulated and calibrated

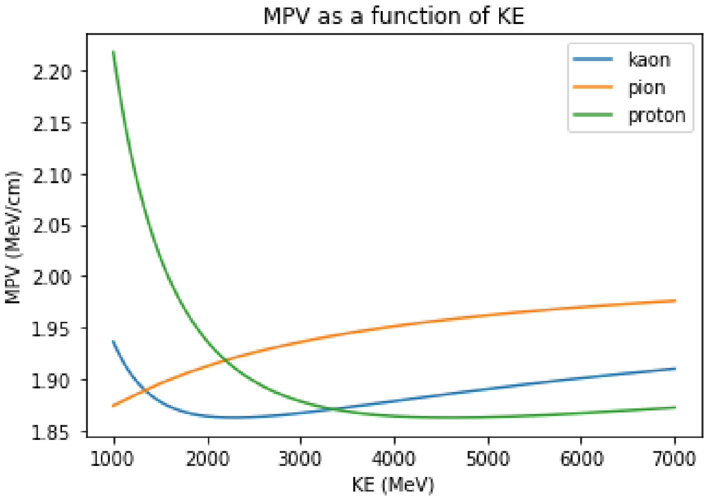
Bethe-Bloche predicts MPV as 1.96 MeV/cm




Pion MCC 12 dE/dx for first 20 cm in Z

# Should the dE/dx be so similar?

Ajib wrote a function to predict the MPV from dE/dx. We would be blind to contamination without more information.



# Testing 6 GeV Beam Selection in Simulation

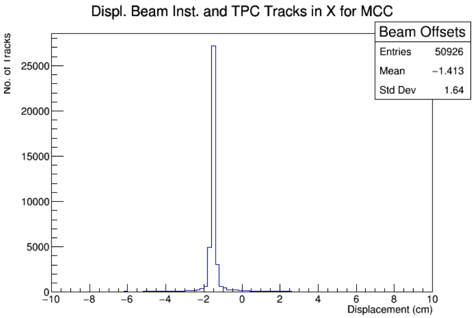
Compared GEANT4 particle determined as the beam candidate in simulation to the Pandora particle reconstructed as beam to measure purity of reco.

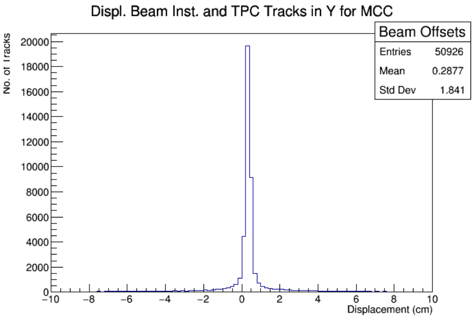
| Candidates | $\pi$+ | $\pi$- | $K$ | $\mu$ | e | p | $\gamma$ | other (nuclei) |
|---|---|---|---|---|---|---|---|---|
| $\pi$+ | 80.5% | 3.1% | 0.44% | 6.7% | negl. | 7.7% | 1.27% | 0.5% |
| p+ | 4.8% | 2.5% | negl. | 5.1% | negl. | 85.9%. | 0.8% | 0.6% |
| K+ | 3.7% | 2.7% | 72.3% | 12.1% | negl. | 7.7% | 1.0% | 0.3%. |

Beam particle from MCTruth separated as a percentage of Geant Good Particle candidates, the equivalent of beam inst. for MCC, in MCC12 at p6GeV.

# Improving 6 GeV Beam Selection in Simulation

Use Jake's method to find where the beam should hit the TPC by plotting a track from the beam inst. onto the TPC, tracking distortion plots were made to find better cuts to increase purity.



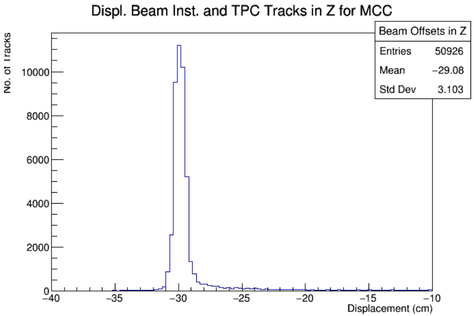



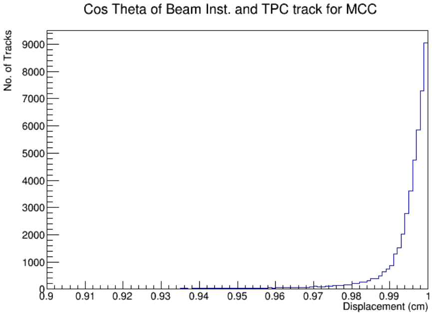

dX for MCC (left) and dY for MCC (right)

# Improving 6 GeV Beam Selection in Simulation

Based on the plots I made the following, harsh, cuts:

- MCC: -3<dx<3, -2<dy<2, -32<dz<-22, cos>.996




dZ (left) and cosine between the track directions for MCC (right)

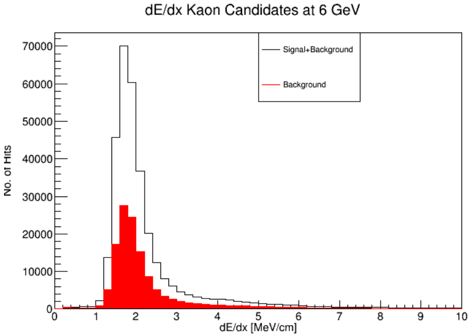
# New Beam Composition after Cuts

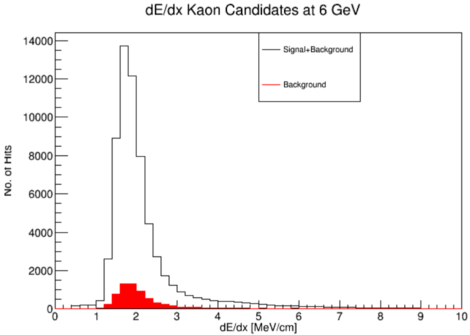
All cosmics were cut.

| Candidates | $N_{tot}$ | $N_{cuts}$ | $\pi$ | $\mu$ | p | k | other |
|---|---|---|---|---|---|---|---|
| $\pi+$ | 41466 | 17963 | 95.2% | 2.6% | 1.2% | 0.1% | 0.9% |
| p+ | 7039 | 2777 | 2.1% | 0.1% | 97.6% | 0% | 0.2% |
| K+ | 2421 | 1073 | 1.2% | 7.7% | 1.8% | 89% | 1.3% |

New beam composition with beam cuts

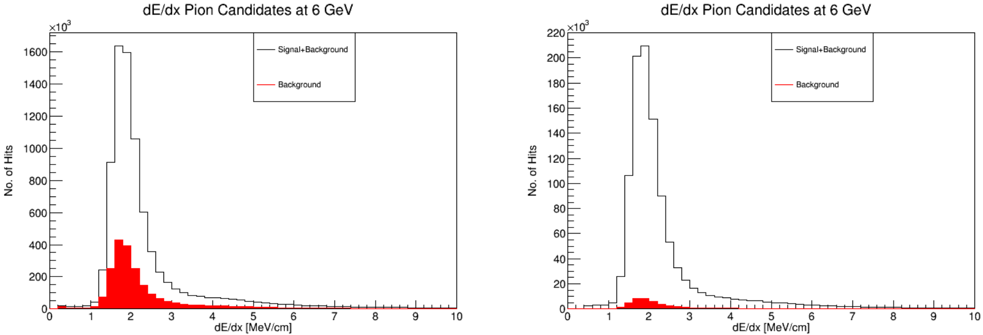
# Kaon dE/dx after Cuts



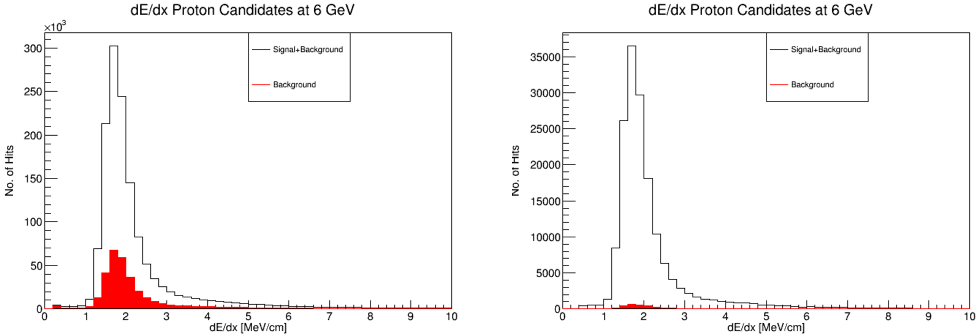

Signal and background dE/dx for kaons without cuts (left) and with cuts (right) in MCC.

# Pion dE/dx after Cuts




Signal and background dE/dx for pions without cuts (left) and with cuts (right) in MCC.

# Proton dE/dx after Cuts




Signal and background dE/dx for protons without cuts (left) and with cuts (right) in MCC.

# Selecting ProtoDUNE Kaons in Real Life

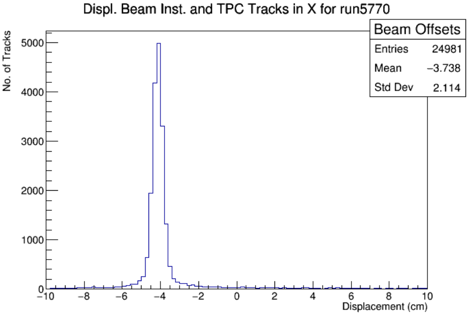
From Alex Booth and Jake Calcultt:

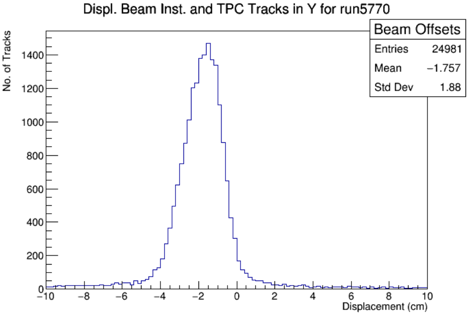
| Candidates | High Pressure Cherenkov | Low Pressure Cherenkov |
|---|---|---|
| $\pi+$ | 1 | 1 |
| p+ | 0 | 0 |
| K+ | 1 | 0 |

Beam Instrumentation Tagging for 6-7 GeV

No need for TOF other than as a QA-check. Purely logical candidate selection.

# Beam Tracking in Run 5770



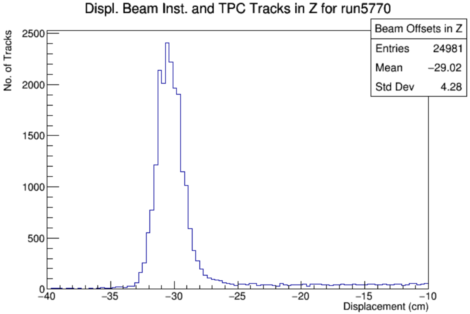



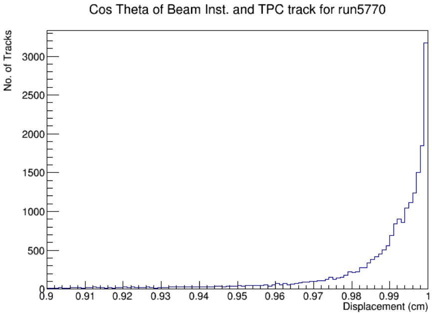

dX (left) and dY (right) for run5770.

# Beam Tracking in Run 5770

Based on the plots I made the following, harsh, cuts:

- Data: -6<dx<-3, -5<dy<0, -33<dz<-25, cos>.996

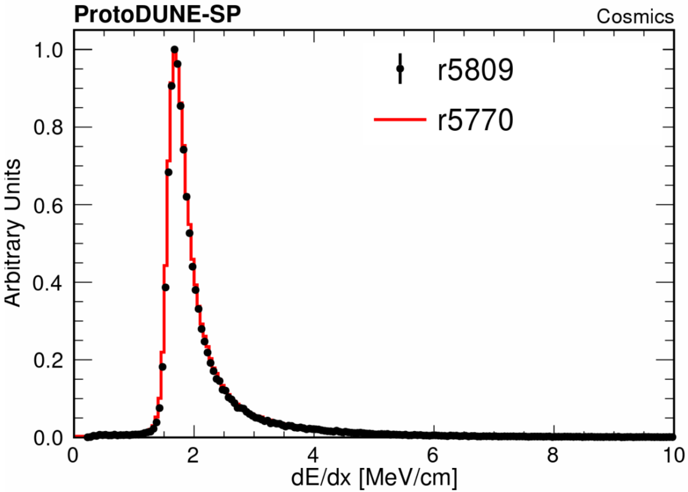


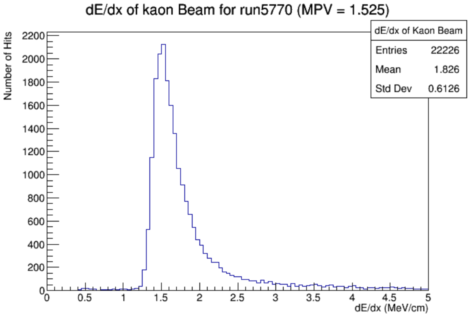

dZ (left) and cosine between the track directions (right) for run5770.

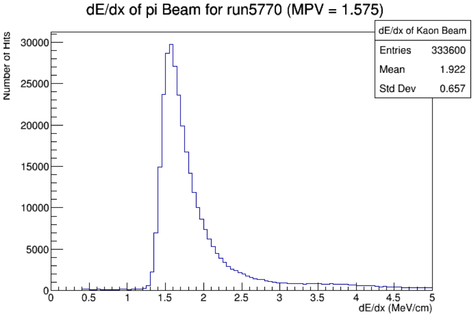
# dE/dx Calibration for Run 5770

This step is done in simulation as well, but a lot can go wrong in data, so we check to make sure the Michel calibration from Ajib looks good.



# dE/dx in Data

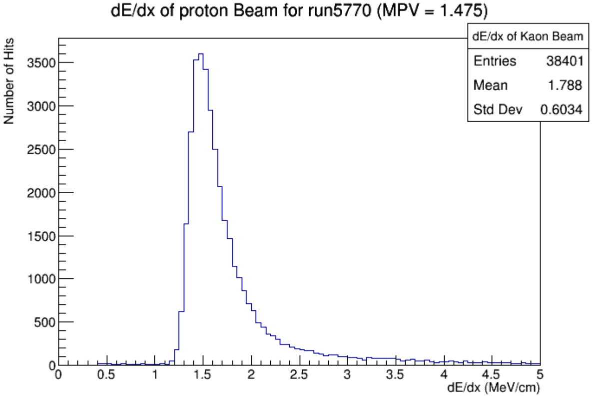



dE/dx for the first 40 cm for kaons (left) and pions (right)

# dE/dx in Data

We need to understand and debug the undershoot.




dE/dx for the first 40 cm for protons

# Moving Forward

- Continue to debug any asymmetries between simulation and data.
- Calculate the cross-section for kaons in simulation.
- Start to think about kaons from inelastic collisions of pion on liquid argon. From that, we can get kaons with an adequately low enough energy (Heavily reliant on the work of Jake and Francesca's machine learning for pion-inelastics.)