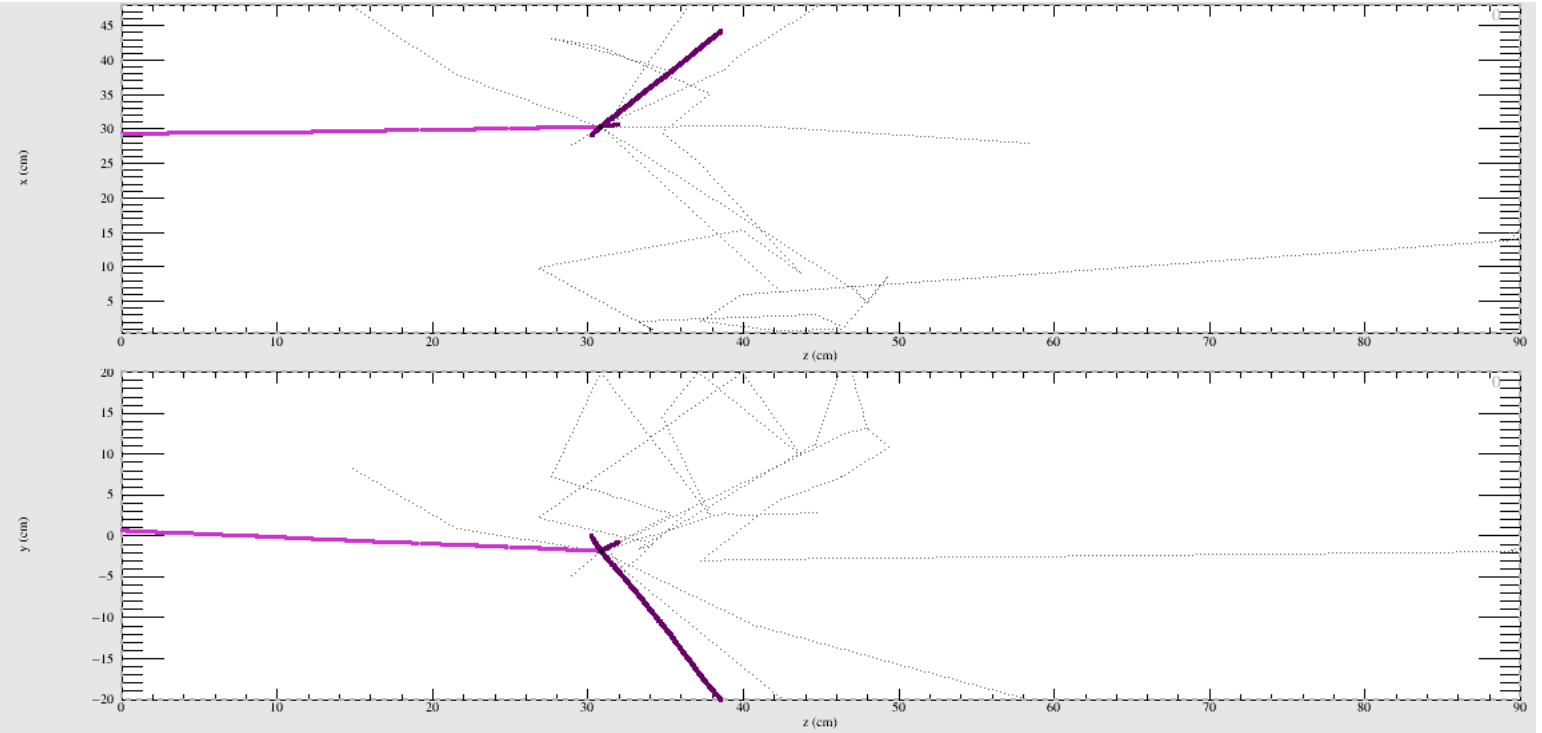
Monte Carlo Study of Pion Absorption+Charge Exchange Events



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Overview

- Motivation
- Definition of Pion Absorption+Charge Exchange Signal
- Simulation and Reconstruction Parameters
- Analysis
  - Event Topology Filter
  - Likelihood-Based PID
  - Event Selection Criteria
  - Results
  - Pathologies
- Conclusions and Future Work

Importance to Neutrino Experiments

- Knowledge of pion absorption cross sections can help constrain nuclear effects on the final state of neutrino-nucleus interactions
  - Pions produced in neutrino-nucleon interactions can be absorbed in a parent nucleus
  - Pions can also charge exchange

Operating Definition of Signal

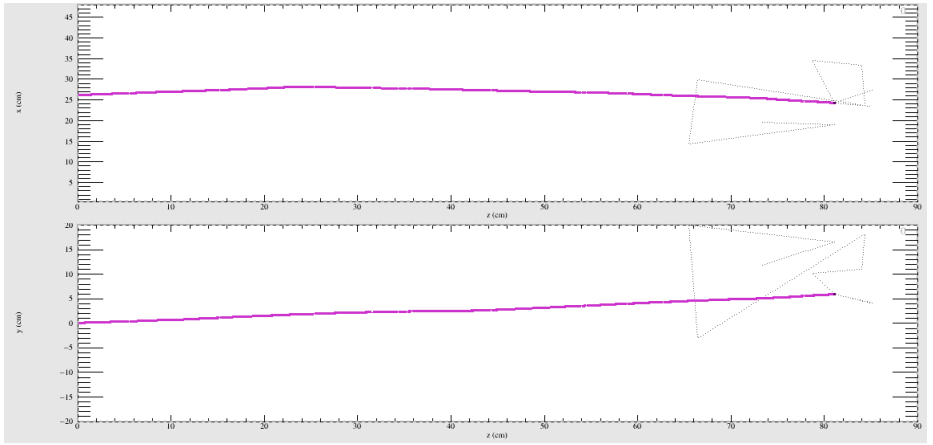
- Originally started with the definition of pion absorption as:

  An event in which a pion enters the TPC and no pions or muons leave the TPC

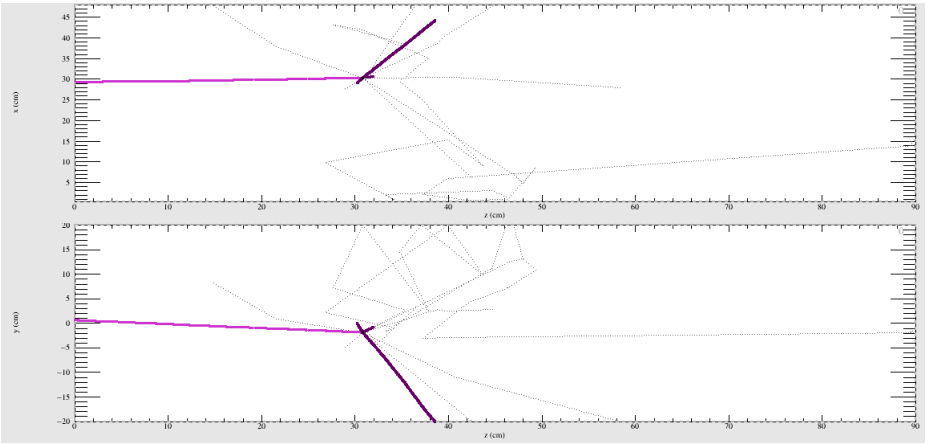
- Decided to broaden Monte Carlo study to pion absorption+charge exchange because:
  - Discussion of results from Duet experiment
  - Easier to avoid working with shower reconstruction to remove pion charge exchange events for now
- Signal for this study:

  An event in which a pion enters the TPC and no charged pions or muons leave the interaction vertex

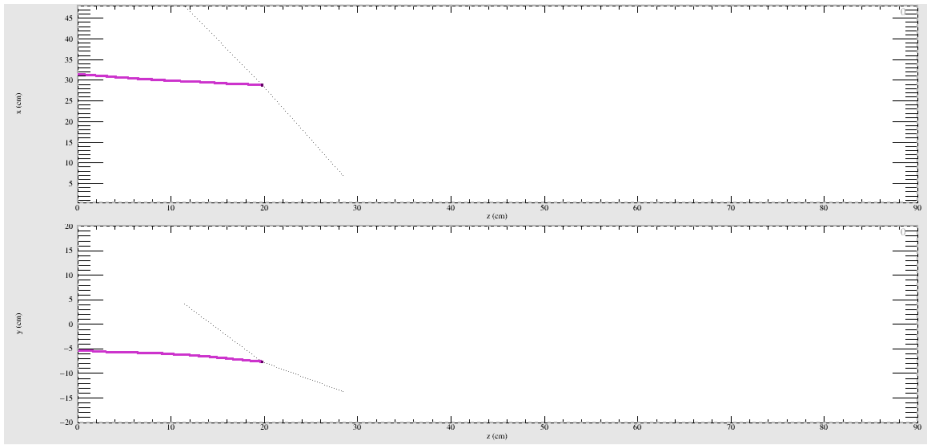
Examples of Pion Absorption+Charge Exchange Events



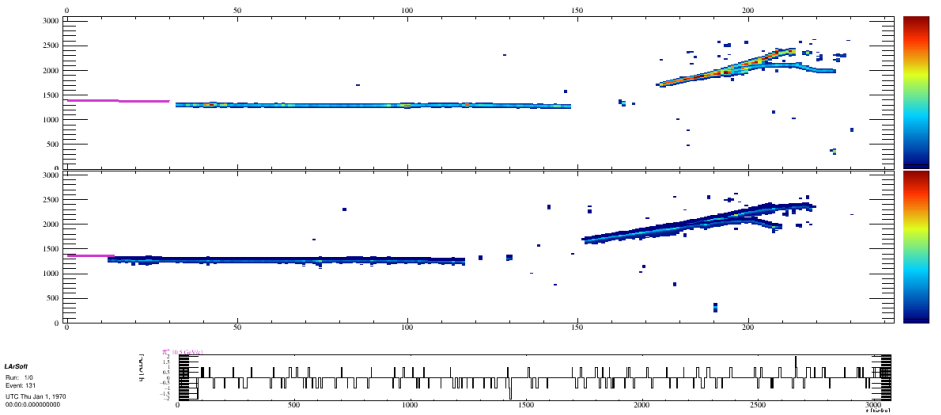
Charge Exhcange



Absorption



Absorption with Very Short Proton



Charge Exhcange in TWQ View

Simulation

- Ideally, want Monte Carlo sample with momentum spectrum of the tertiary beam
- To save time, decided to generate particles with a flat momentum spectrum and reweight final histograms to match beam
- Worked in lariatsoft v01_10_00 frozen release to keep reconstruction paramters and modules stable
- Used FHICL files from Jonathan's generator jobs to generate the following samples:
  - 18000 π+ with momenta between 0MeV/c and 1500MeV/c
  - 10000 p+, K+, and μ+ with momenta between 0MeV/c and 1500MeV/c
- Started particles at the titanium window volume, z=-39.5388cm
- Used random_seedservice to make sure that separate jobs used independent strings of random numbers

Reconstruction

- Reco_MC.fcl
  - lariat_calroi
  - gaus_hitfinder
  - standard_clustercrawlerhit
  - standard_clustercrawler
  - standard_linecluster
  - standard_cosmictracker
  - standard_pmalgtrackmaker
  - standard_cctrackmaker
  - standard_calomc
  - standard_chi2pid
- Fcl files available upon request
- Green = used for analysis

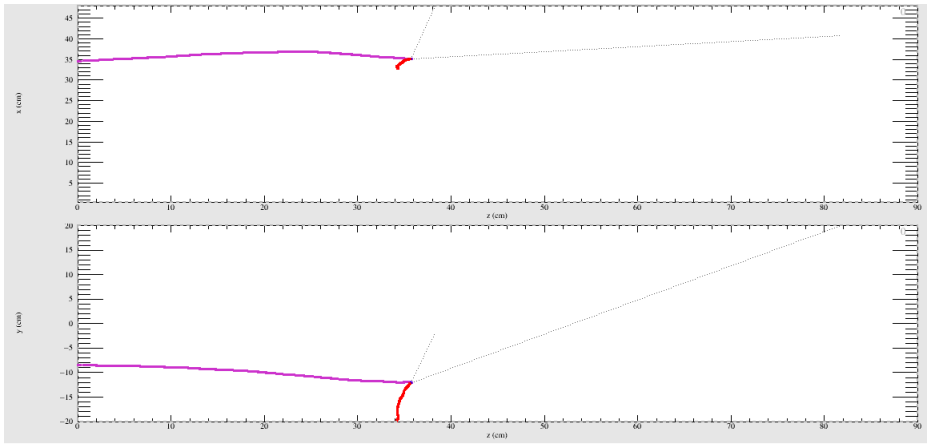
Event Topology Filter

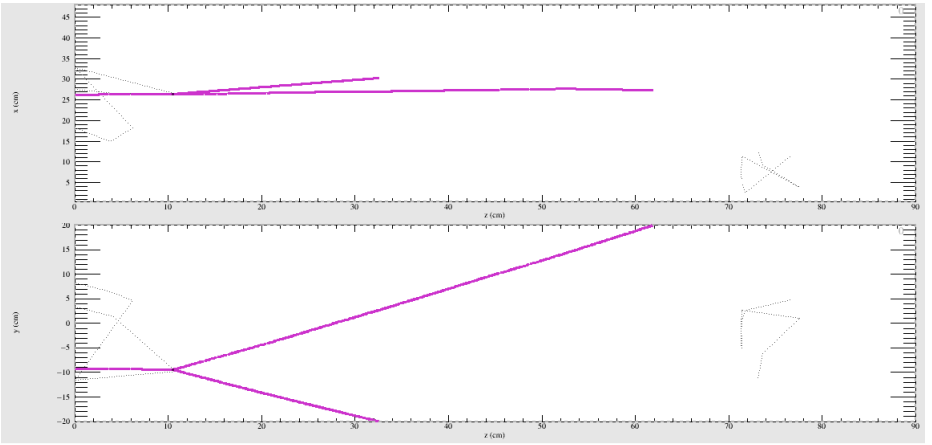
- Simple LArSoft filter module to select events based on:
  - Only MC truth information
  - A list of allowed secondary particles
  - Can allow specific or arbitrary number of each particle species
  - Requires that primary vertex be contained within some margin of each face of the TPC
- Extensively tested with pion absorption and pion charge exchange events, but may be applicable to other analyses
- Flag to invert filter ('!' operator mentioned in ART documentation and mu2e sources does not seem to be accepted by FHICL parser?)

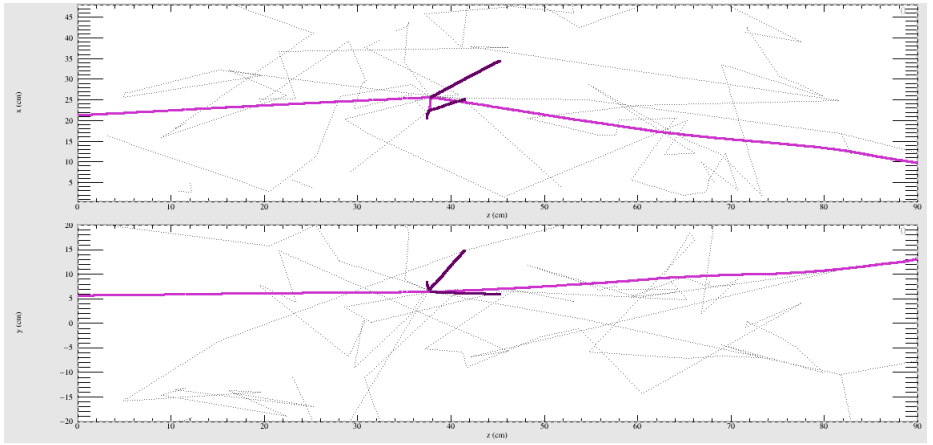
Applying the Event Topology Filter

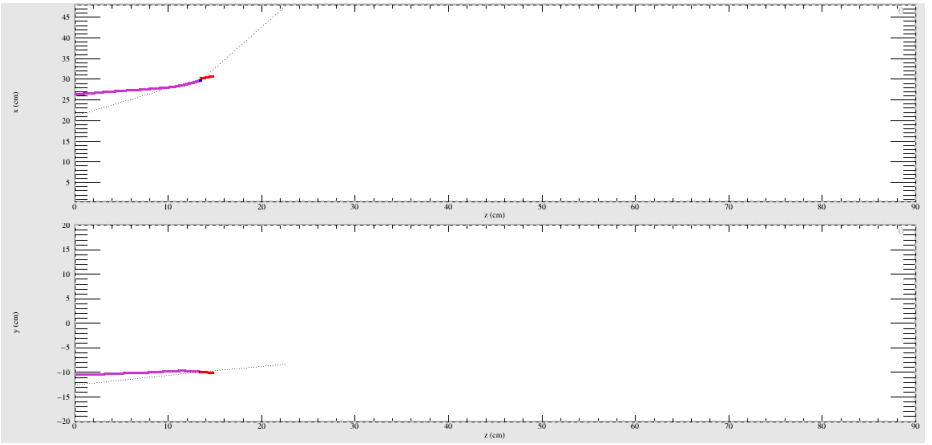
- Set up two filter configurations for this study:
  - Pass pion absorption and charge exchange
    - Allow any number of PDG codes 2212 (proton), 2112 (neutron), 111 (neutral pion), 22 (photon) as secondaries
    - Allow single and multiple charge exchange
  - Fail pion absorption and charge exchange
    - Same as above, but with negation flag
    - Passes pion absorption and charge exchange events when the primary particle is not contained

Example Event Topology Filter Pion Background Events

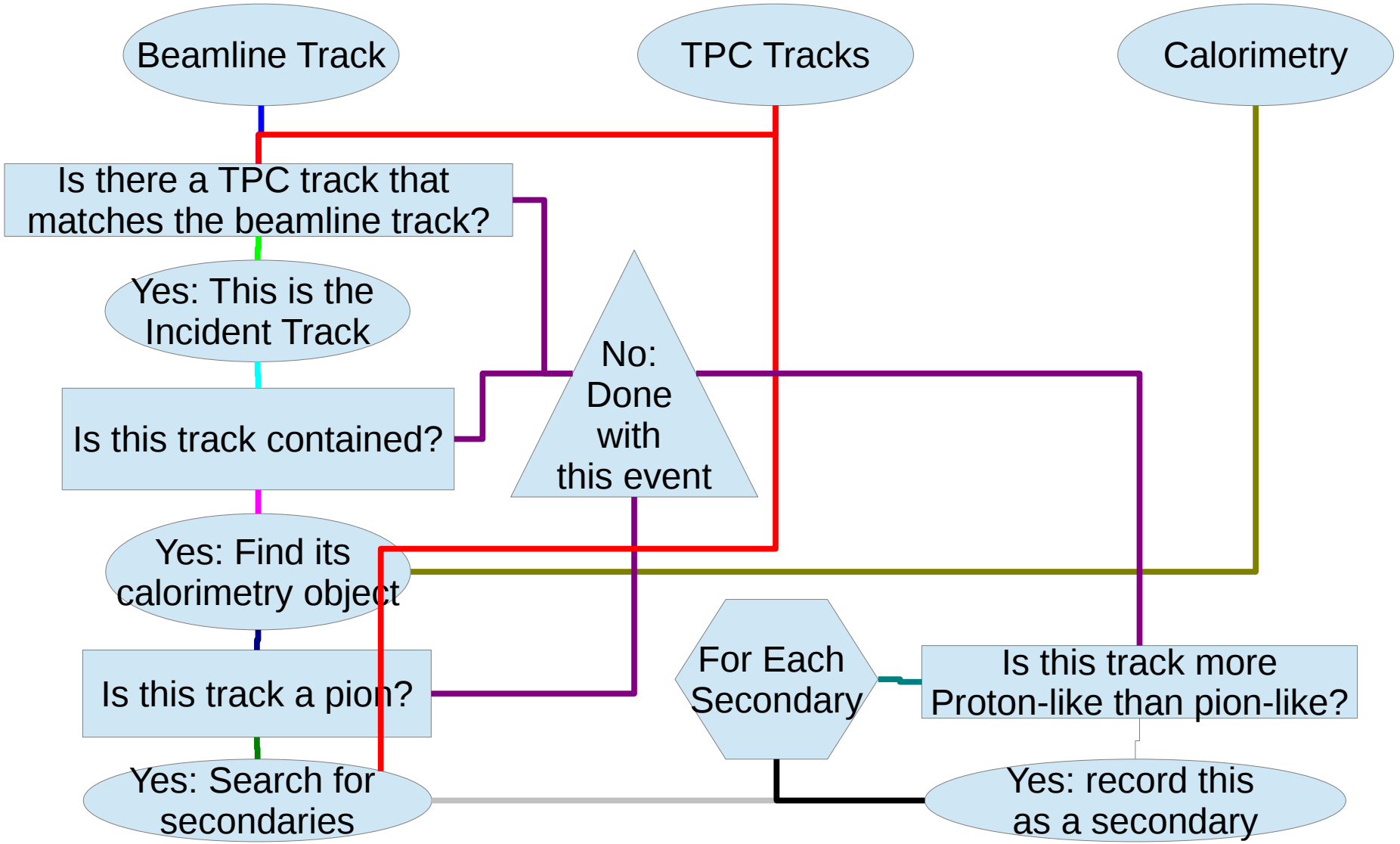








Signal Selection Algorithm Outline



„Beamline“ Information

- Kinetic Energy: can be found from beamline momentum and PID
- Position and direction upstream of TPC front face: currently using titanium window
- Using truth track (simb::MCParticle) as a placeholder for this study
- May increase effieciency by using only beamline PID, but using only using TPC PID for this study

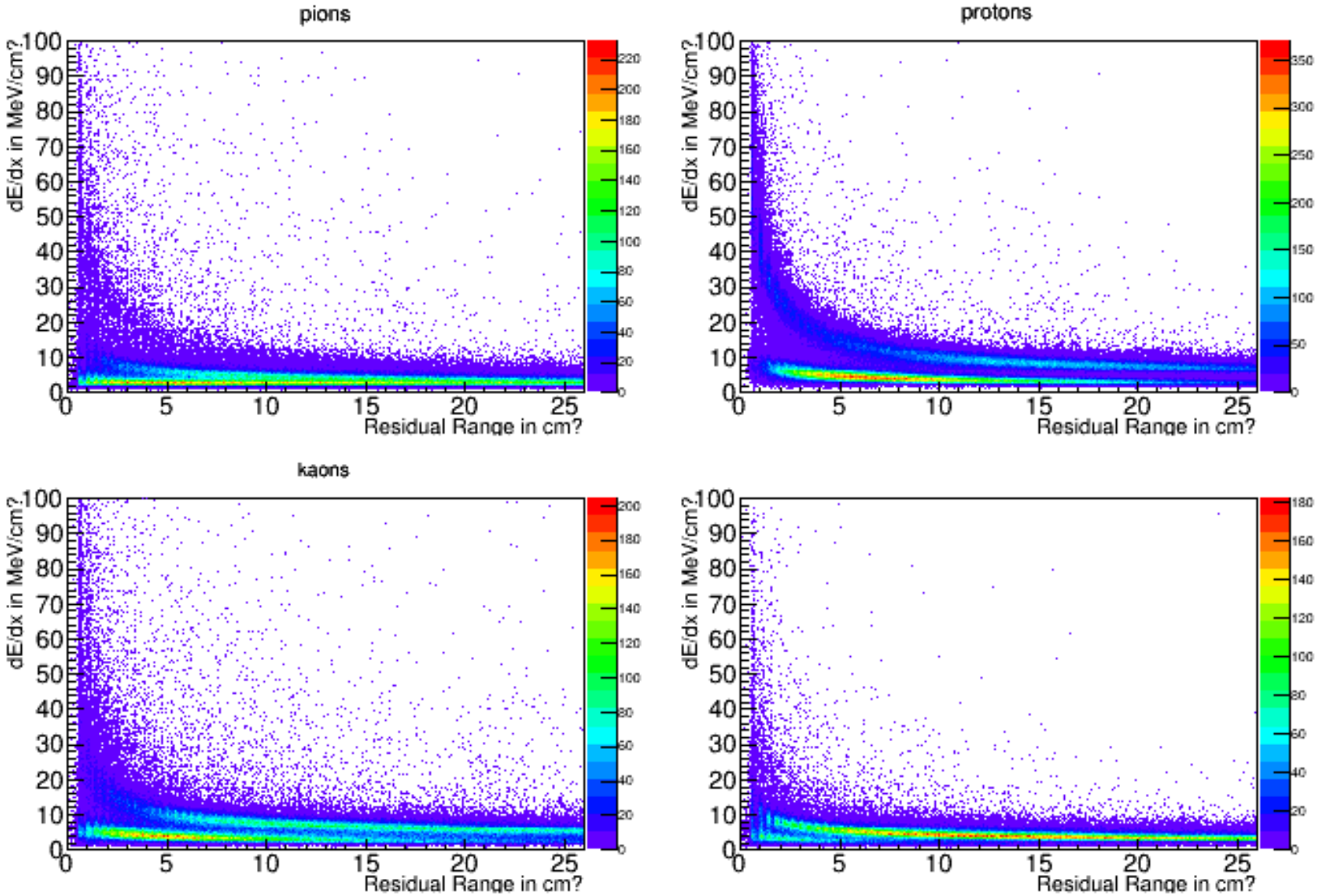
Finding the Incident Track

- Project beamline point in a straight line onto the front face of the TPC
- Finding best TPC match to beamline track
  - For each reconstructed track, find proximity to beamline point
    - Maximum allowed proximity: 2cm
    - Check both end points in case track is reversed
    - Remember track that starts or ends closest to beamline projection
  - Find angle with beamline
    - Maximum angle allowed: 0.1 radians
    - Check both end points in case track is reversed
    - Remember track with smallest start or end angle to beamline
- If no best match is identified or the best angle and the best proximity are not the same track, skip this event

Particle Identification

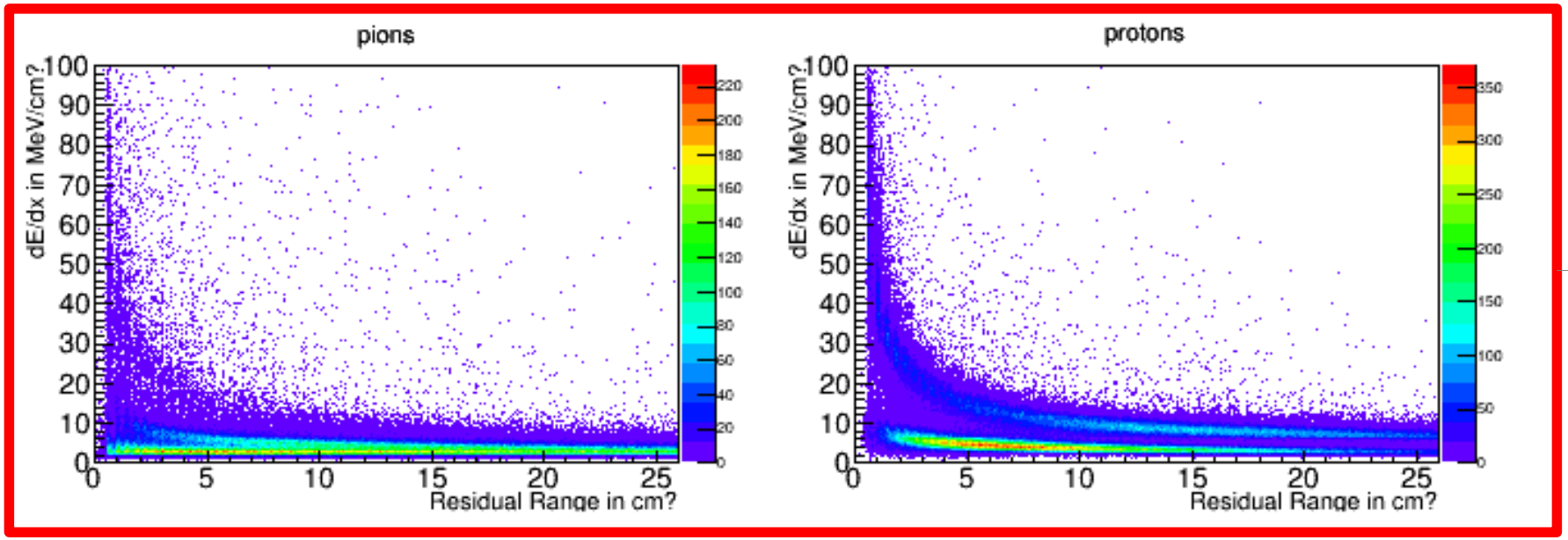
- Using 2 forms of likelihood-based PID
  - 4-particle hypothesis
    - Applied to incident particle
    - Provide PDFs for π+, p+, K+, and μ+
    - Calculate a ln(likelihood) value for each particle species
    - Identify this particle as the species with the largest ln(likelihood) value
  - 2-particle hypothesis
    - Applied to immediate daughters of incident particle track
    - Provide PDFs for π+ and p+
    - Calculate 2 ln(likelihood) values
    - Identify this particle as MIP or Not-a-MIP based on larger ln(likelihood) value
    - Fails pions and muons while allowing protons and probably kaons
  - Both forms need a calorimetry object: currently using plane 1 because plane 0 calorimetry objects are usually empty or filled with crazy values

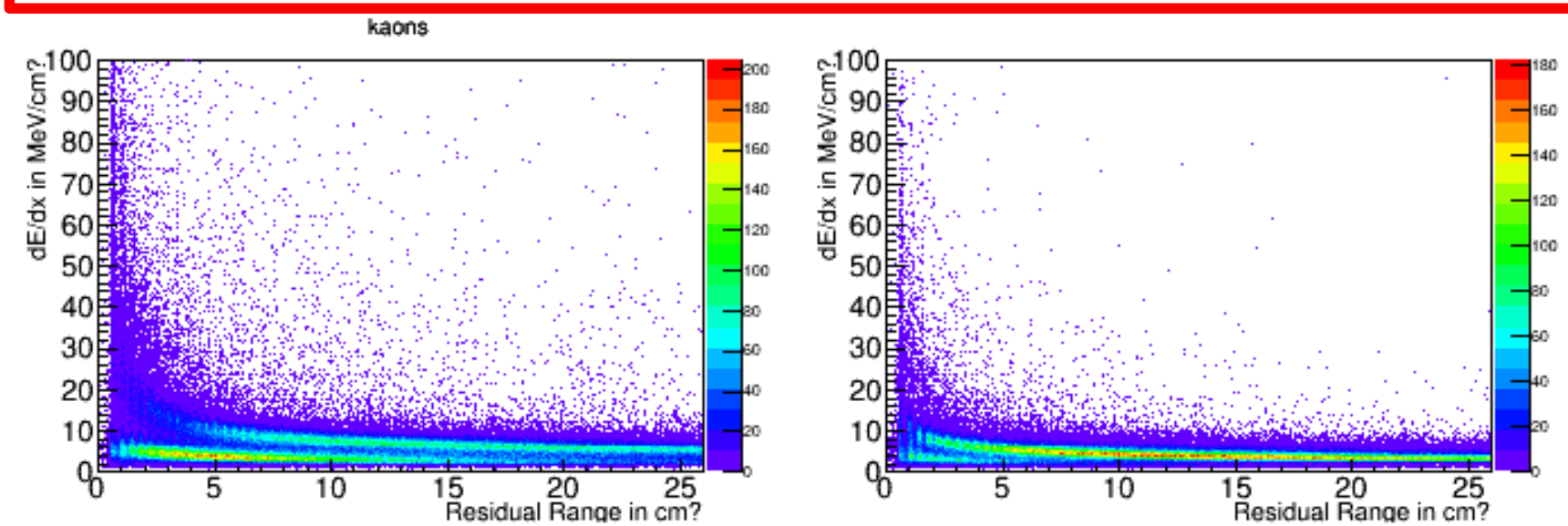
Likelihood PID PDFs



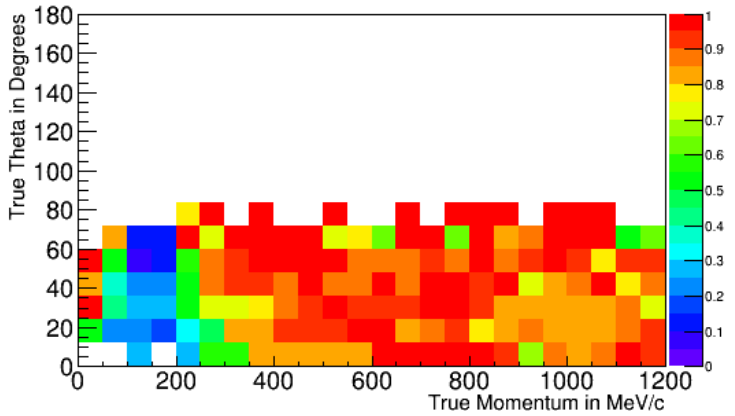
Likelihood PID PDFs

Only these two
For binary PID!

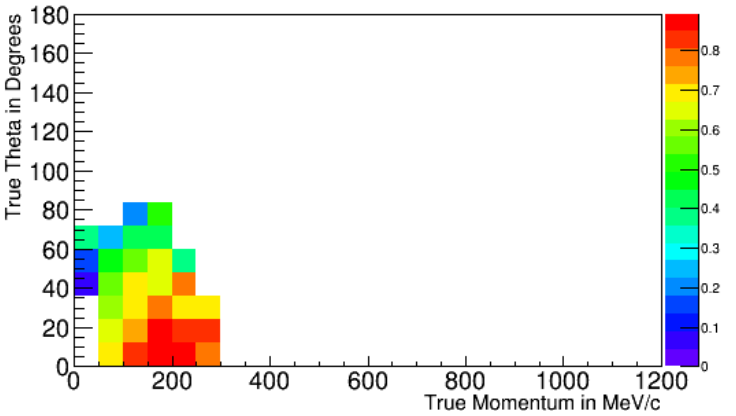




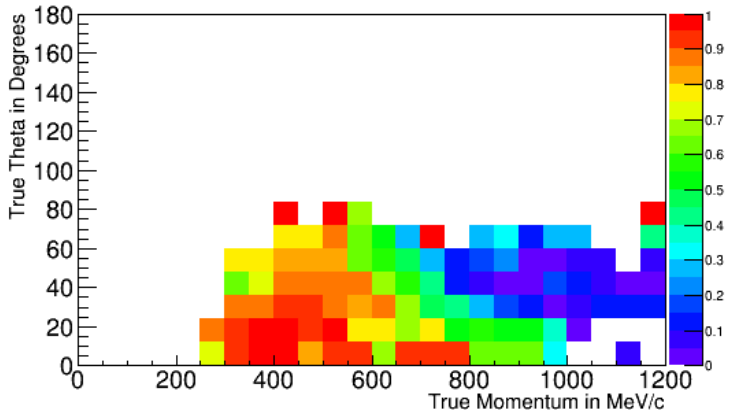
Test of Likelihood PID Efficiencies on Sample with Large Angles



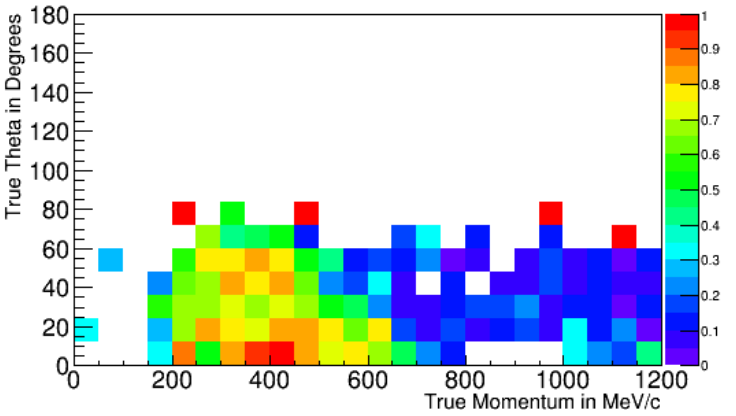
Pion PID Efficiency



Muon PID Efficiency

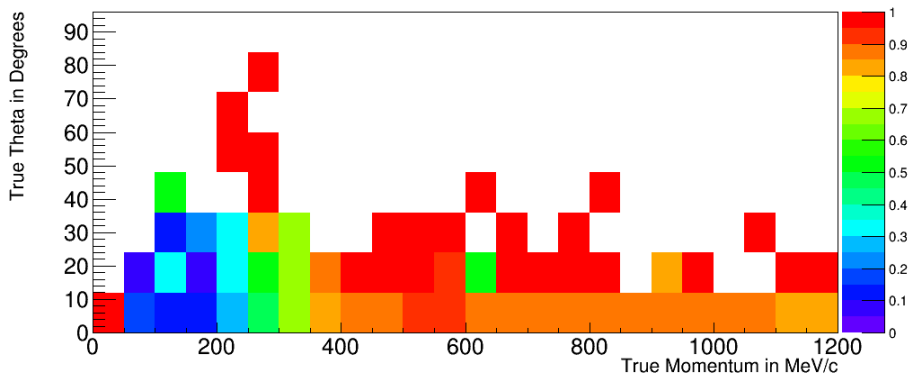


Proton PID Efficiency

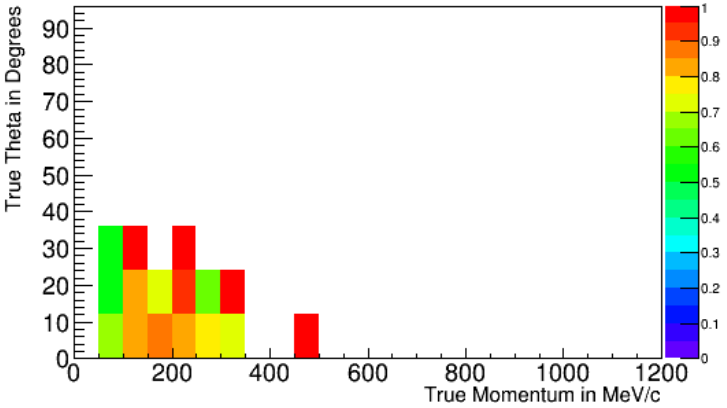


Kaon PID Efficiency

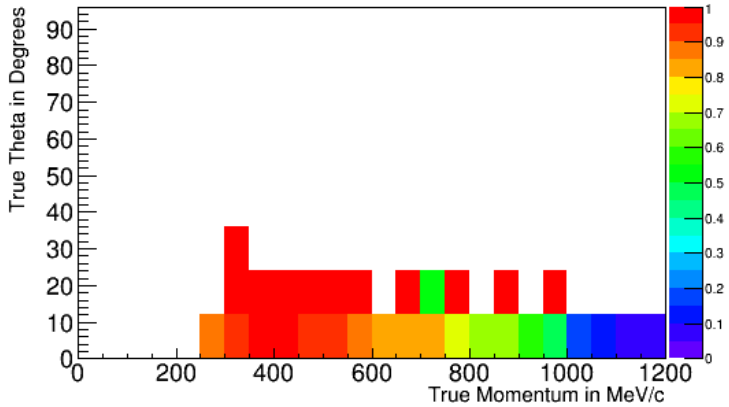
Likelihood PID Efficiencies on Beam-like MC Sample Primaries



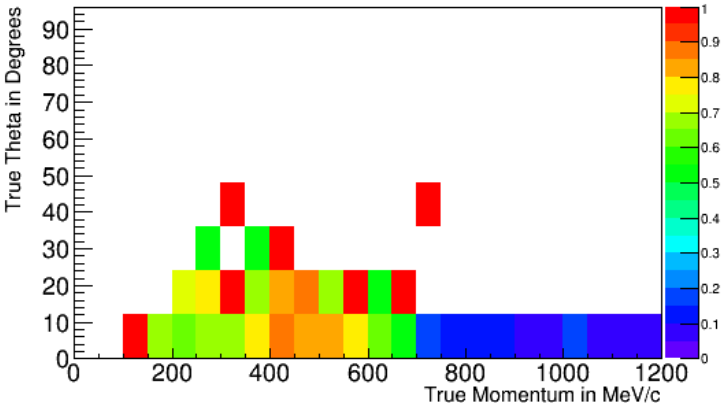
Pion PID Efficiency



Muon PID Efficiency

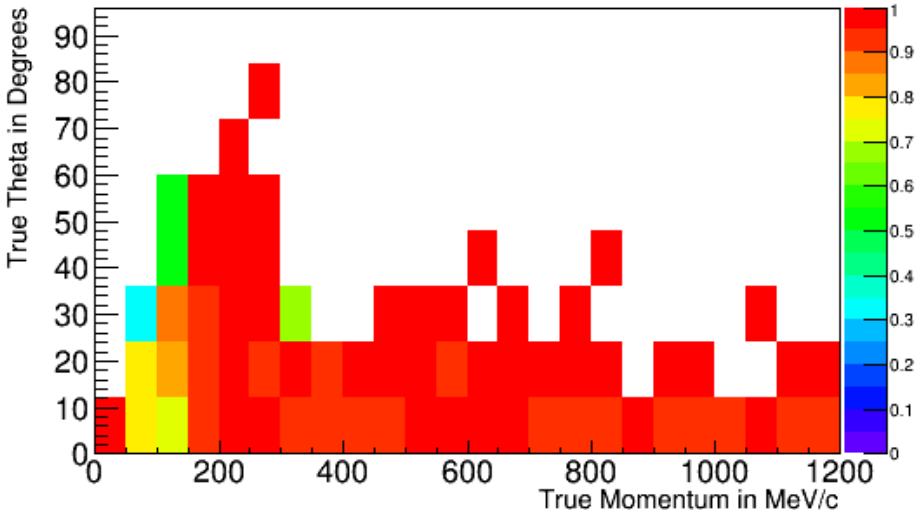


Proton PID Efficiency

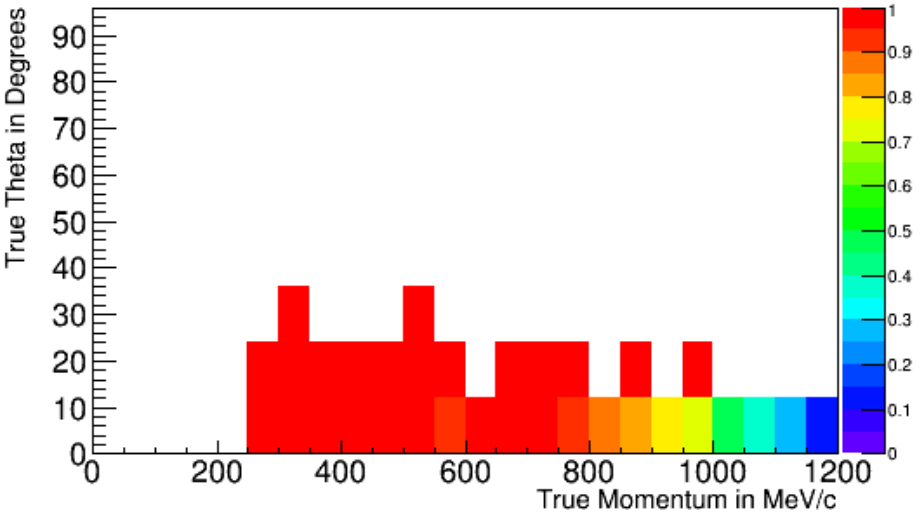


Kaon PID Efficiency

Binary Likelihood PID Efficiencies for Beam-like MC Sample Primaries



Pion PID Efficiency



Proton PID Efficiency

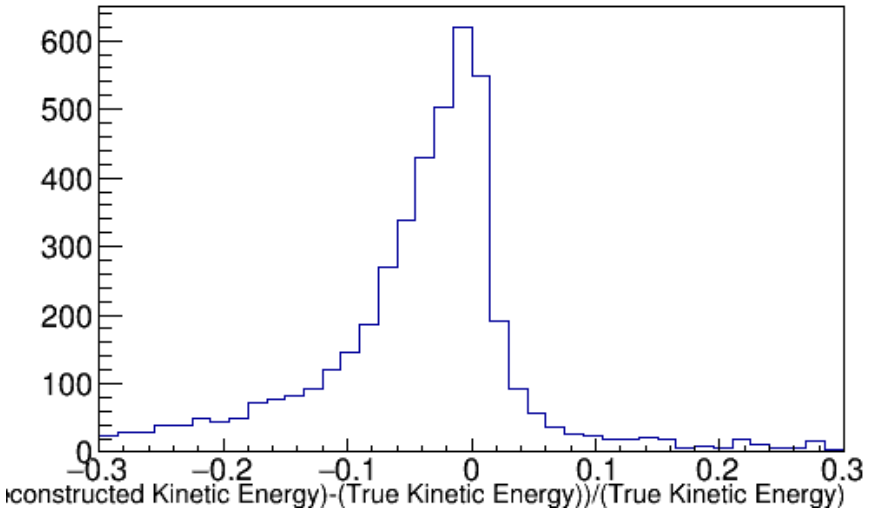
Pion Absorption and Charge Exchange Event Selection

- Have already found the incident particle
- Look for tracks that start or end within 2cm of incident particle's end point
- Want to only allow events with no pions and no muons exiting the incident particle's vertex
  - Binary PID
  - This should remove events that scatter inelastically
  - Should also remove events where pion decays
- Events with no secondaries are also absorption events
- Photon showers from charge exchange events should not often be close enough to end of primary track

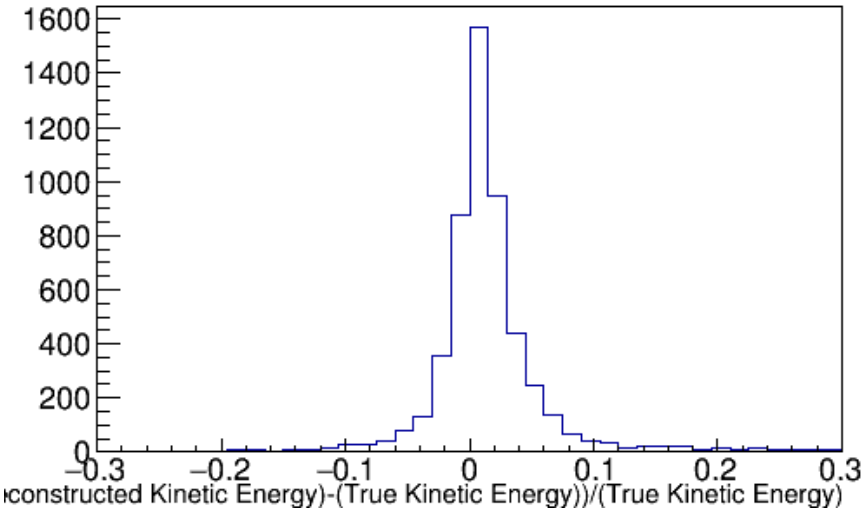
Kinetic Energy Values in Plots

- True Interaction Kinetic Energy
  - $M_0(\gamma-1)$
  - Taken at second-to-last point on true trajectory
  - Last point always seems to have 0 kinetic energy for interacting pions
- Reconstructed Interaction Kinetic Energy
  - Start with „beamline“ kinetic energy: taken from truth kinetic energy at titanium window for this study
  - Subtract 8.6 MeV as done by total pion cross section group (may be changed in the future)
  - Calorimetry provides kinetic energy and total range
    - Option 1: Subtract kinetic energy (in TPC) from estimated kinetic energy at TPC front face
    - Option 2: Take average dE/dx to be 2.3 MeV/cm for all pions in this study. Subtract 2.3MeV/cm*Range from estimated kinetic energy at TPC front face
    - Use method with less deviation from true values

Fractional Interaction Kinetic Energy Resolution

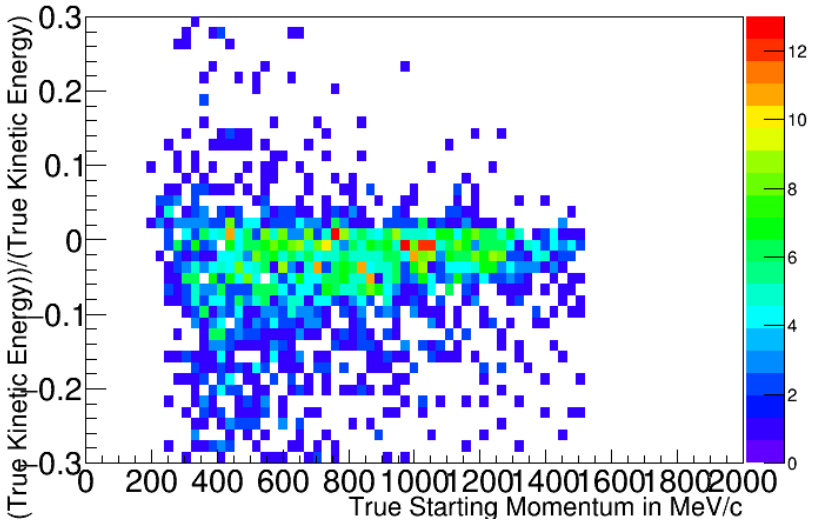


Calorimetry

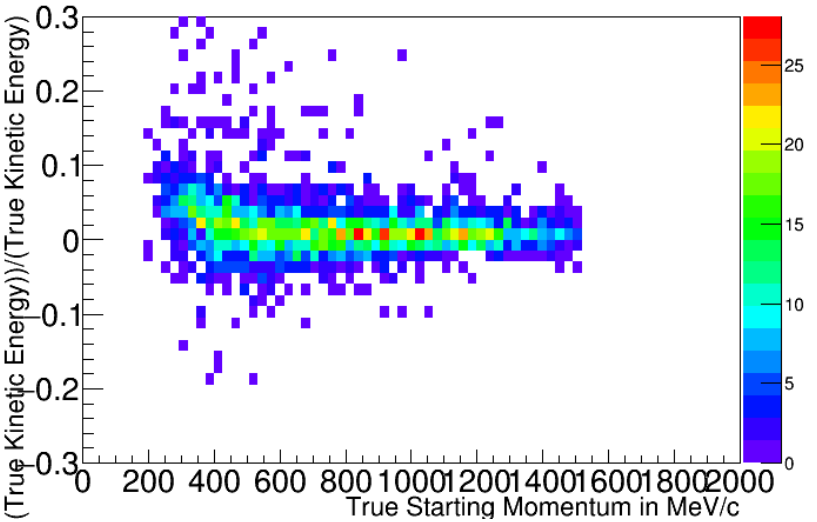


Flat dE/dx value

Interaction Kinetic Energy Resolution Versus True Starting Momentum

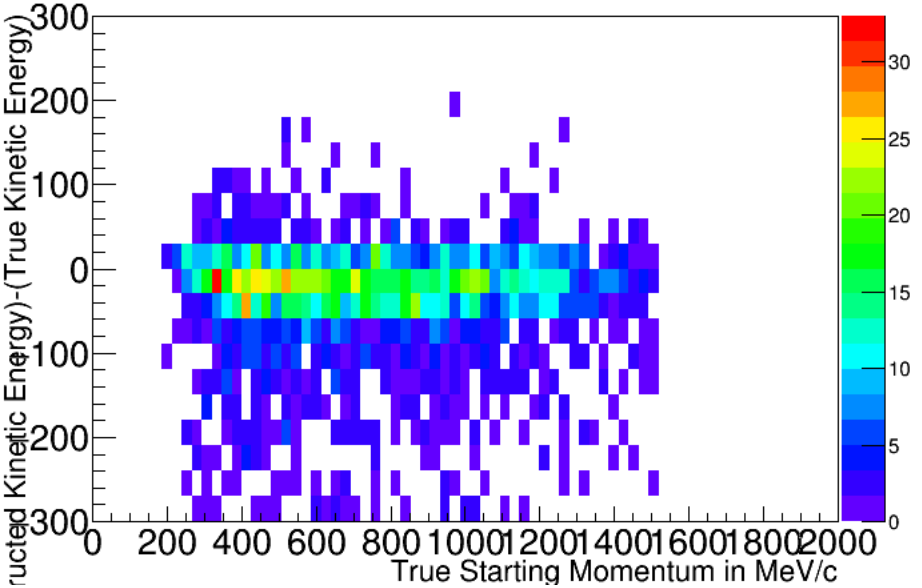


Calorimetry

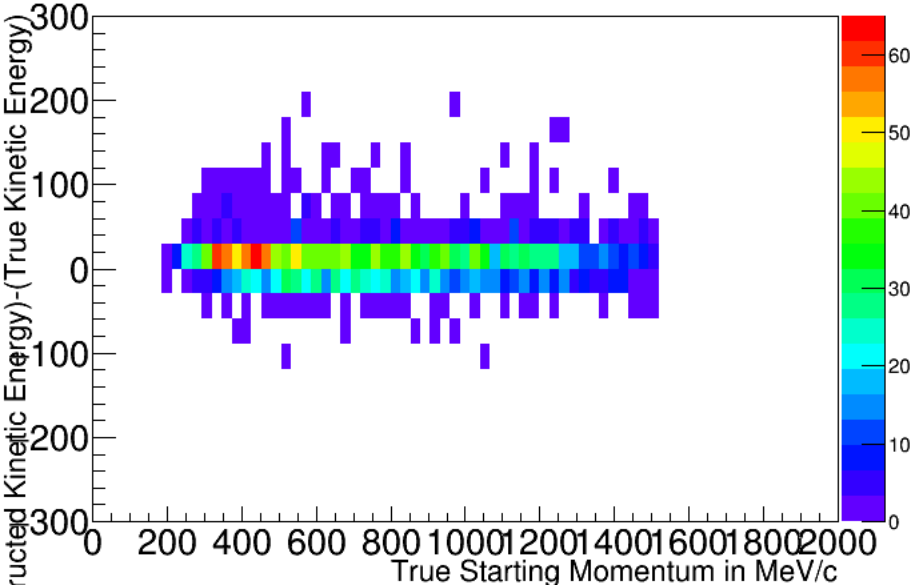


Flat dE/dx value

Interaction Kinetic Energy Difference Resolution Versus True Starting Momentum



Calorimetry

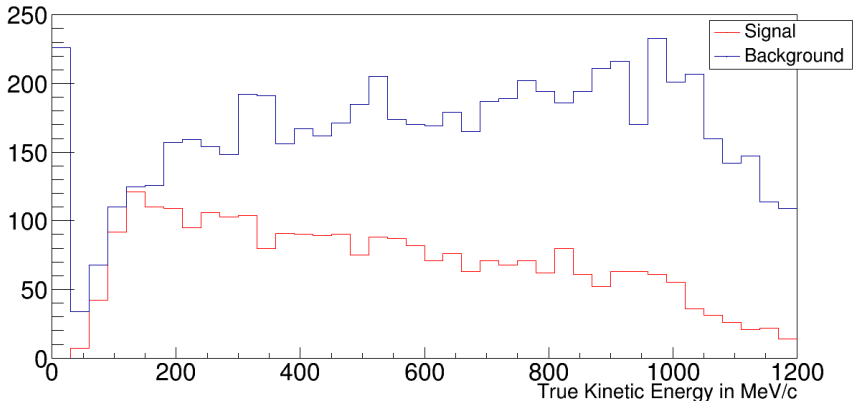


Flat dE/dx value

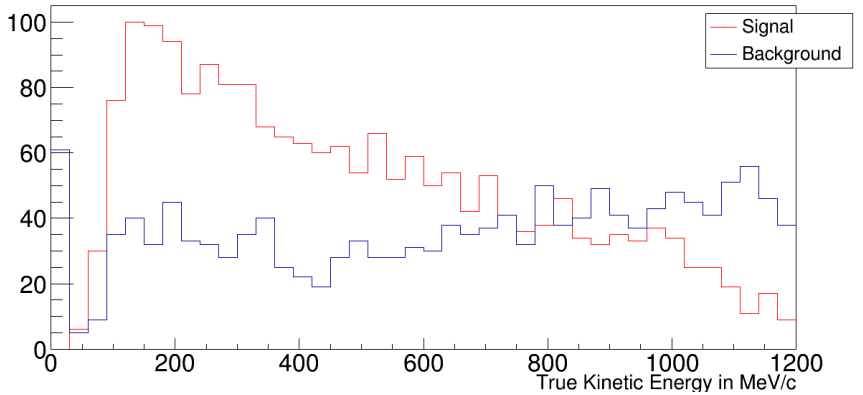
Pion Absorption+Charge Exchange Selection Performance

- Efficiency
  - Defined as: Fraction of signal events that survive the selection criteria
  - Overall: 1985/3748 events
- Background Rejection
  - Here, I will illustrate this by comparing kinetic energy spectra before and after selection
  - Would eventually like to find purity, but this will require reweighting

True Interaction Kinetic Energy Spectra of Pion Events

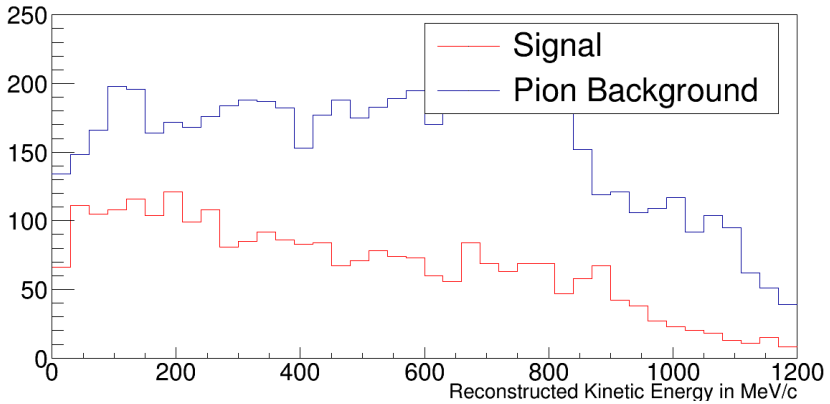


Before Selection

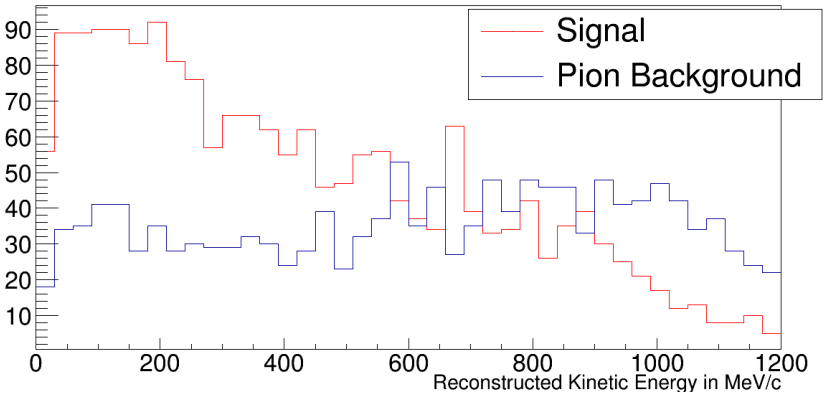


After Selection

Reconstructed Interaction Kinetic Energy Spectra of Pion Events

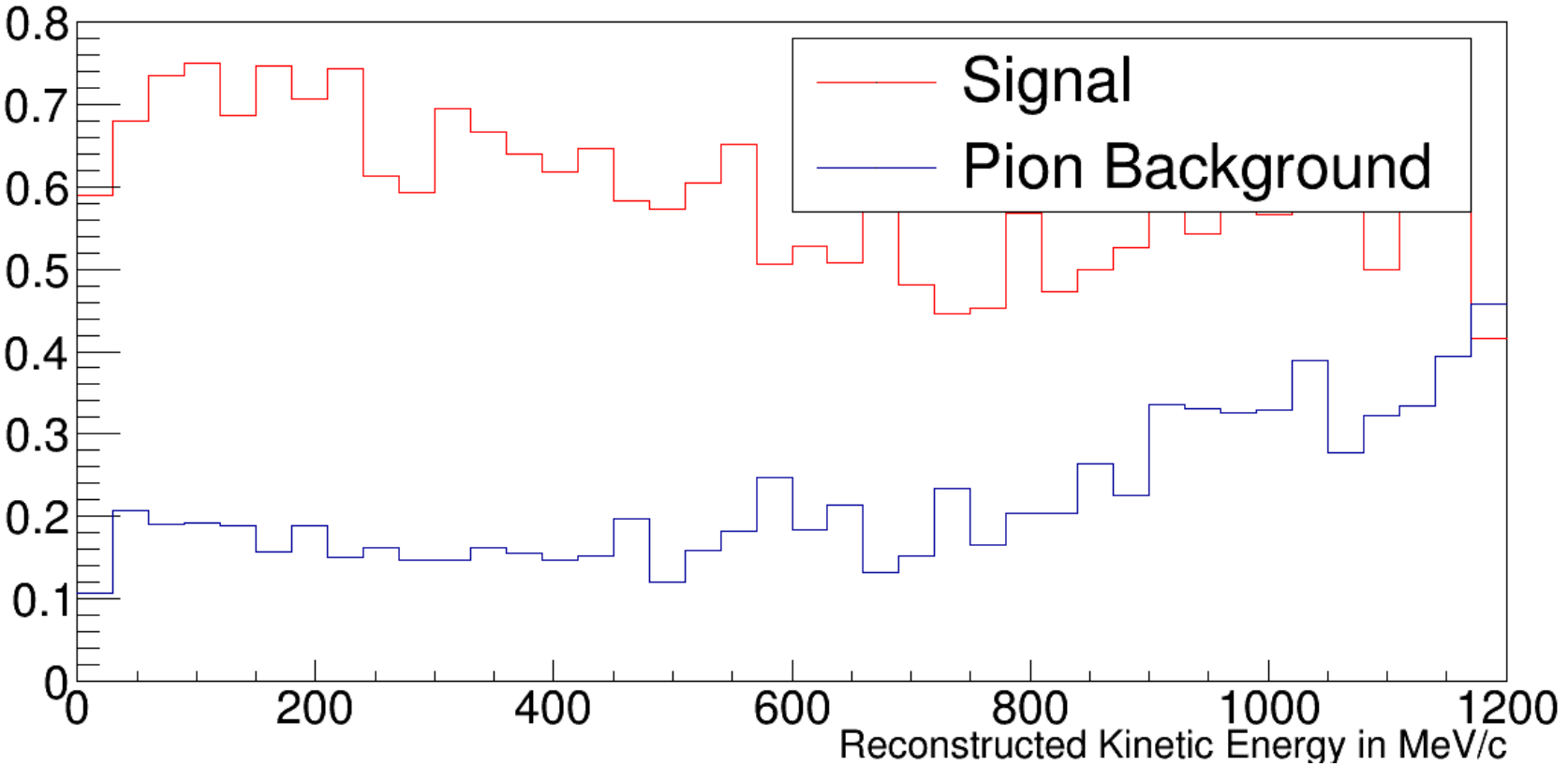


Before Selection

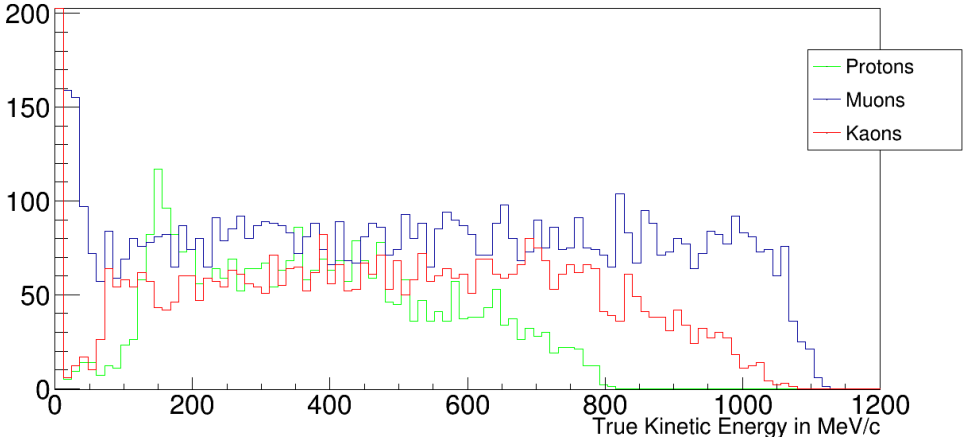


After Selection

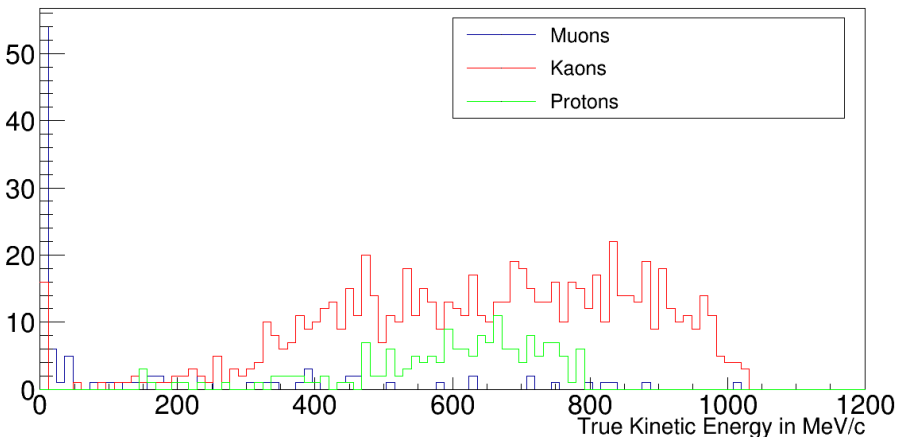
Pion Efficiencies on Signal and Background



Reconstructed Interaction Kinetic Energy Spectra of non-Pion Background Events

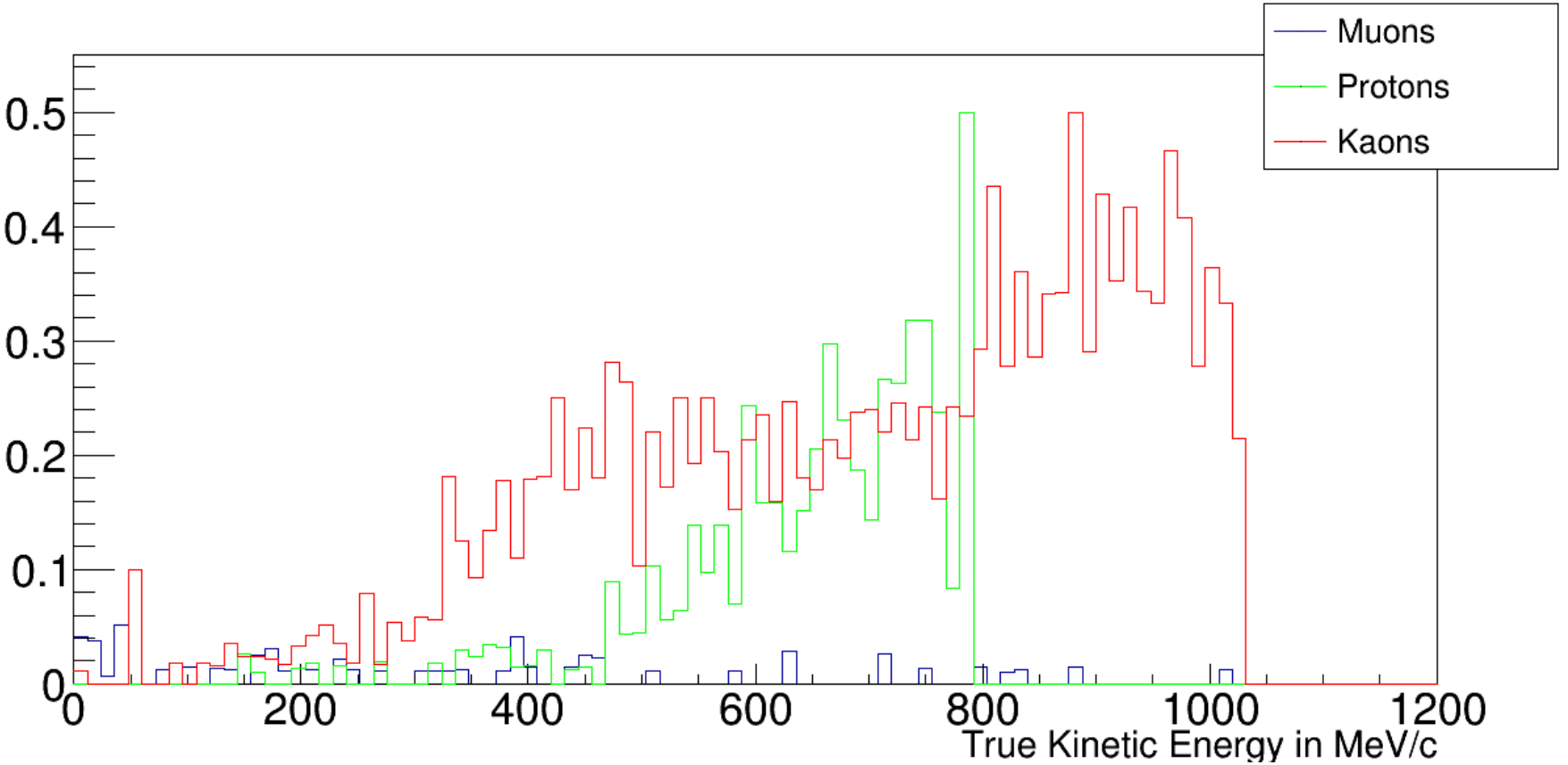


Before Selection

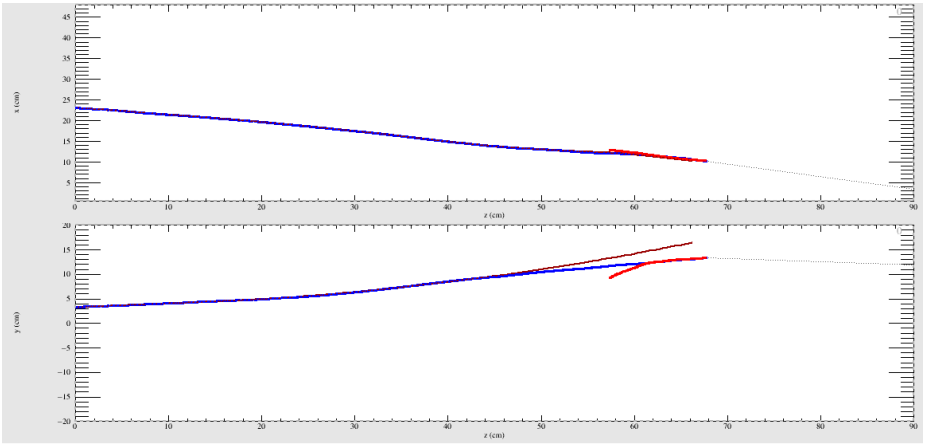


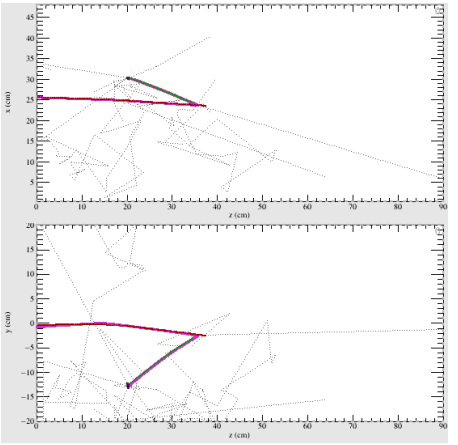
After Selection

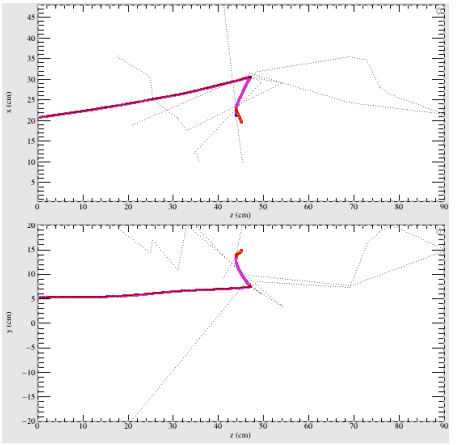
Selection Efficiencies on non-Pion Background

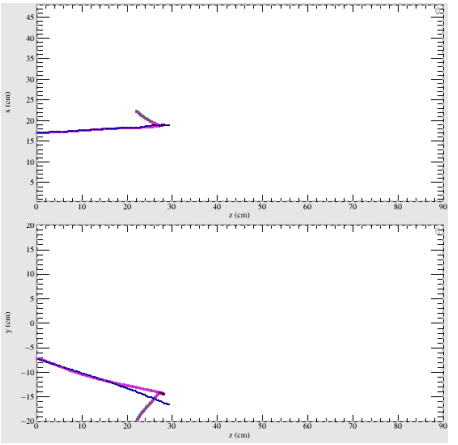


Pathologies









Conclusions

- True topology filter is effective for this study and may be useful to other LArSoft Monte Carlo studies
- Likelihood-based PID is effective for selecting pions in both 2-PDF and 4-PDF modes
- Pion absorption+charge exchange Monte Carlo study demonstrates selection of signal with usable efficiency

Future Work

- Reweight histograms to measure efficiency and purity with beam momentum spectrum
- Publish feature branch with analysis code
- Make PID and true topology filter available in lariatsoft
- Start working on applying this analysis routine to data

Backup

Backup Slides Below

Backup: Likelihood Definition

- Given some set of points $\{(x_i, y_i)\}$, (residual range, dE/dx) from an anab::Calorimetry object
- Given a probability density funciton

  f(x , y), a TH2D of dE/dx Versus Residual Range for the purposes of this presentation
- $\ln(L(x_1, x_2, \ldots, x_n, y_1, y_2, \ldots, y_n)) = \sum_i \ln\left(f\left(x_i, y_i\right)\right)$
- To make the best use of double precision values, ln(L) is calculated as a sum of natural logs rather than as a product
- $\ln(L_{pion}/L_{proton}) = \ln(L_{pion}) - \ln(L_{proton})$ is plotted in the likelihood ratio plots in this presentation

Distances Between MC Points