π^+ inclusive cross-section studies

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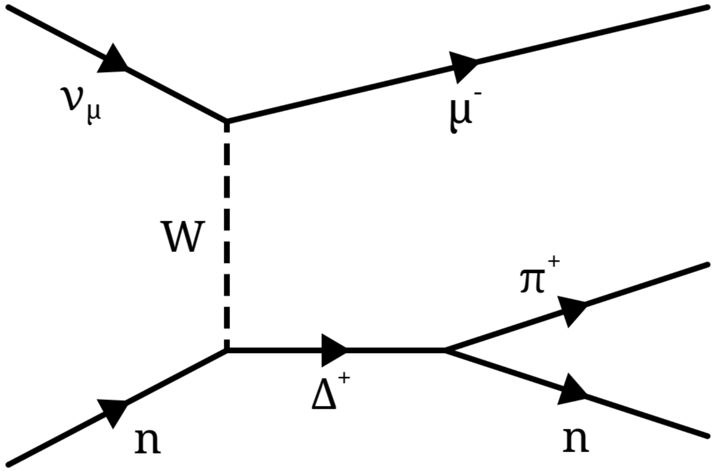
Thanks to Tingjun Yang and Glenn Horton-Smith for all the suggestions and feedback.

Outline of the talk:

- **Pion interaction in Liquid Argon.**
- **Thin Slice Method**
- **True Cross-Section Studies (Monte-Carlo simulation)**
- **Monte Carlo reconstruction analysis**
- **Future Strategy**

pion cross-section measurement

- Flavor and energy of neutrinos are identified based on the products of the neutrino interactions.
- **Pions** are a common product in the neutrino interaction processes.
- Very important to model their(Pi+) behavior inside the target nucleus & during its propagation inside the detector medium.
- Example: Neutrino resonant scattering



- Not been many experimental measurements of pion cross section on Liquid Argon (LArIAT has measurements in 100MeV-1050MeV Kinetic Energy range). No experimental results in 1-7GeV.
- Predictions are made based on the pion cross-section on heavier and lighter target nucleus.

π^+ Hadronic interaction Channels

Pion absorption channel:

$\pi^+(nn)$ --> np (two body absorption)

$\pi^+(nnn)$ ---> nnp (three body absorption)

$\pi^+(nnp)$ --->npp (three body absorption)

$\pi^+(nnnp)$---->ppn (multi-body absorption)

Charge Exchange Channel:

$\pi^+ + n \text{--->} \Delta^+ \text{----->} \pi^0 + p$

Inelastic Scattering channel:

$\pi^+ + n \text{----->} \Delta^+ \text{----->} \pi^+ + n$

$\pi^+ + p \text{------>} \Delta^+ \text{--------->} \pi^+ + p$

Pion production channel:

$\pi^+ + N$ -----> >= 2π + nucleons

Reaction Channels

*LArSoft classifies all these channels as Inelastic interaction.

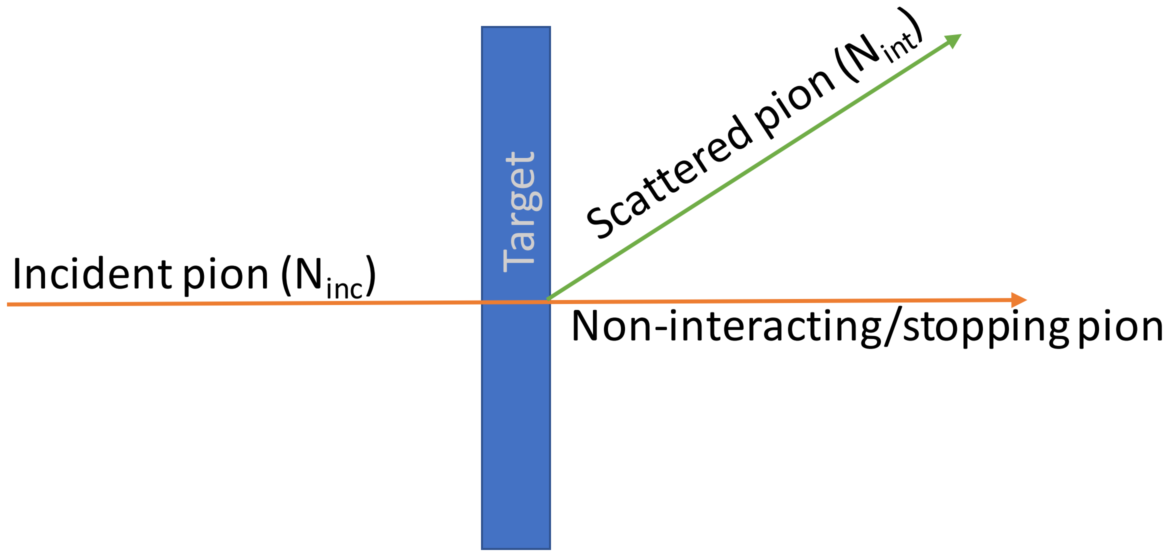
In the subsequent slides Reaction channel and Inelastic channels should be taken as synonyms.

Elastic Scattering channel:

$\pi^+ + N \text{--->} \pi^+ N$, N stands for nucleon

***LArSoft:** It is a software package for simulation, reconstruction and analysis with the Liquid Argon Time Projection Chambers.

Cross-section measurement



Simple experiment to find the cross-section using a thin target material.

Cross-section is given by,

$$\sigma = \frac{N_{int}}{N_{inc}} \cdot \frac{A}{\rho L N_a}$$

Where, A=atomic mass

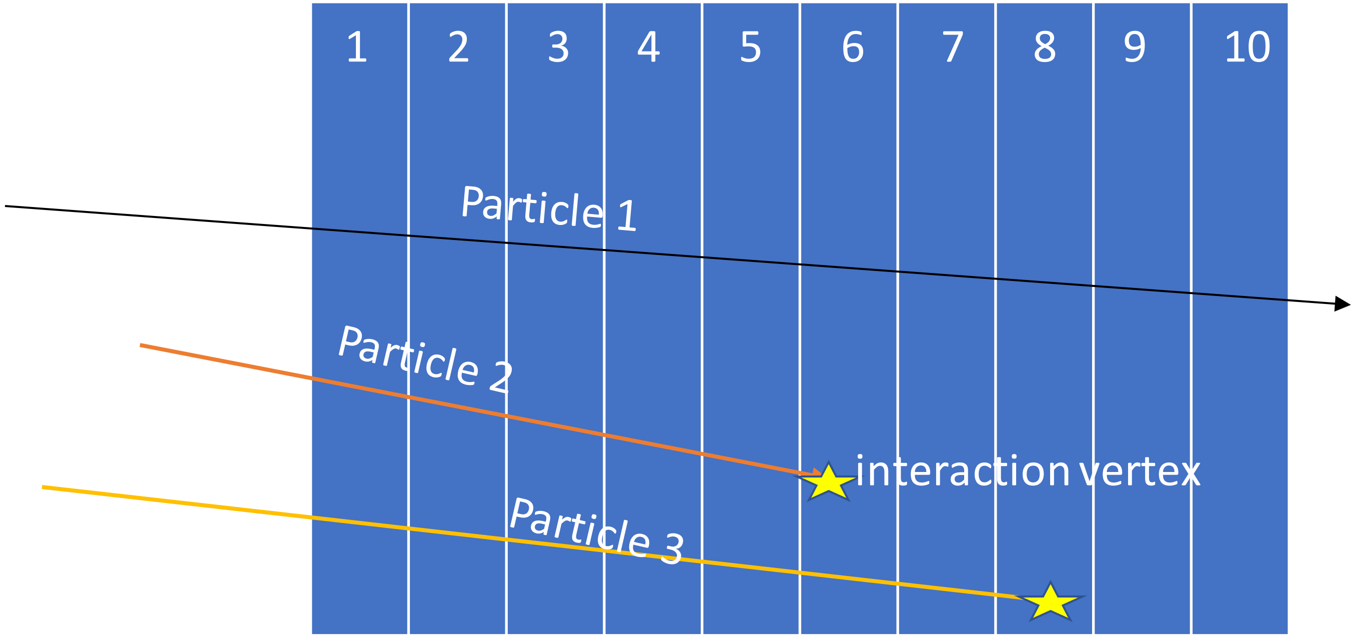
N_a=Avogadro's number

ρ=density

L=thickness of the target nucleus

Thin Slice Method

Although protoDUNE has a total length of ~695cm we can divide this into thin slices based on the wire pitch.



In this method we consider each slice as a different independent experiment, with two possibilities i.e., the particle either interacts or does not in each slice.

We calculate the energy of the particle as it propagates through different slices using,

$KE_i = KE_{inc} - \sum_{k=0}^{k=i-1} (dE/dx)_k \cdot dx_k$

where dx_k is the distance between consecutive hits

Cross-section is calculated as a function of energy, we used 50MeV energy bins.

Example for thin slice method:

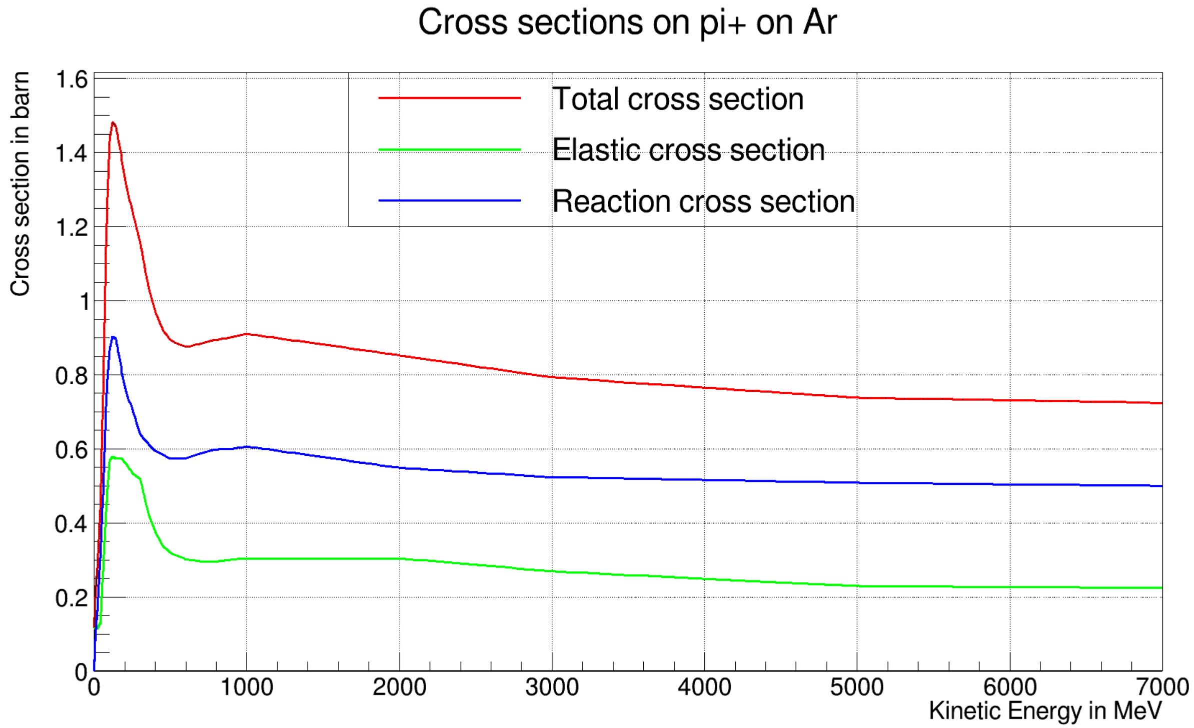
Consider particle 2:

For slices 1-5 there is no interaction, so $N_{inc}(KE_i)=N_{inc}(E_i)+1$ and $N_{int}(E_i)=N_{int}(E_i)+0$;

While, for slice 6 there is an interaction, here, $N_{inc}(KE_i)=N_{inc}(E_i)+1$ and $N_{int}(E_i)=N_{int}(E_i)+1$;

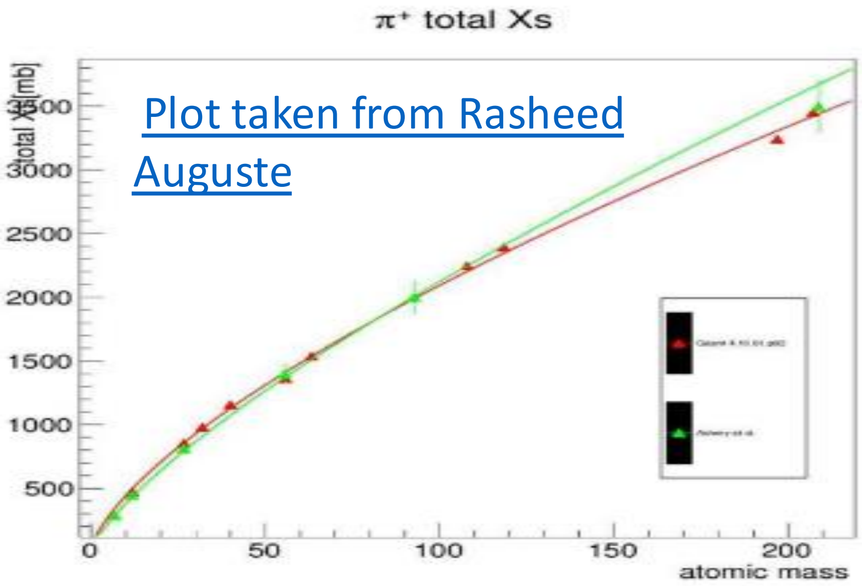
Finally, $\sigma(KE_i)=(N_{int}(KE_i)/N_{inc}(E_i)) * A/(d.L.N_a)$

Geant4 cross-section predictions



Geant 4.10.5

Geant 4 predicts the pi+ cross-section on Liquid Argon based on pi+ cross-section on other lighter and heavier nuclei like C, Fe etc., for which there are measurements.



[Plot taken from Rasheed Auguste]

Total pion cross section vs Atomic mass (G4 Simulated in red and Ashery data in Green)

Here, $\sigma_{tot} = \sigma_{elastic} + \sigma_{reaction}$

$\sigma_{reaction} = \sigma_{inelastic} + \sigma_{absorption} + \sigma_{charge\text{-}exchange} + \sigma_{\pi production}$

Validation of Thin Slice method measurements in LArSoft framework using Monte-Carlo truth information:

50,000 pi+ events generated with the following conditions:

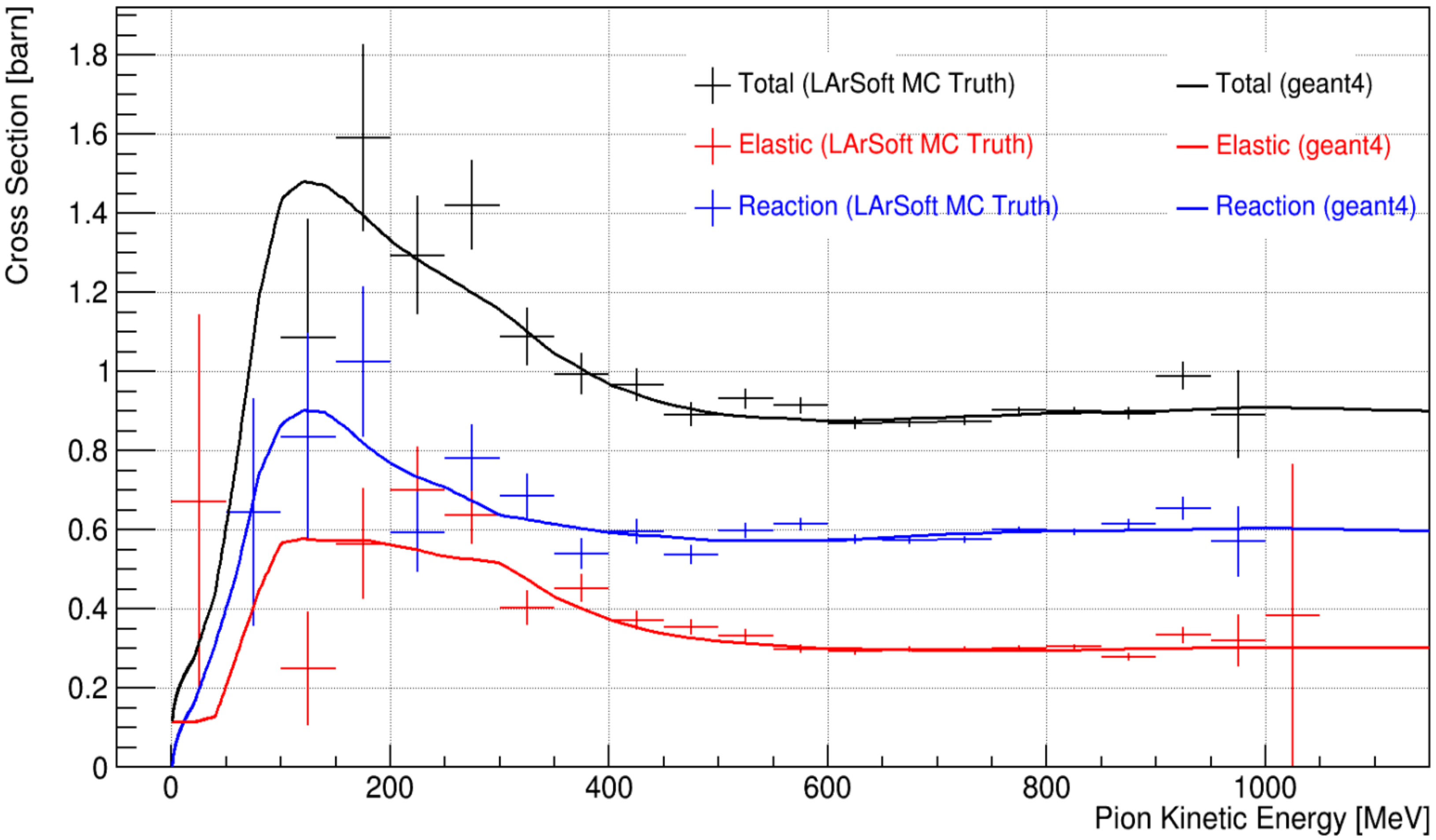
- Incident Momentum: 1.0 GeV/c with a Gaussian spread of 5%.
- Start X, Y and Z position: (-80cm , 420cm , -10cm) outside the detector
- Generated π^+ is passed through Liquid Argon in the geant4 stage.
- Treat protoDUNE TPC as comprising of many thin slices (with thickness 0.4792cm--collection plane wire gap) of Liquid Argon.
- Used thin slice method for calculating the cross section as a function of Kinetic Energy.

Results for geant4 studies: Validation of thin slice method in LArSoft framework

From the plot aside:

Cross-section calculated using LArSoft truth information are comparable to Geant4 stand-alone program cross section values.

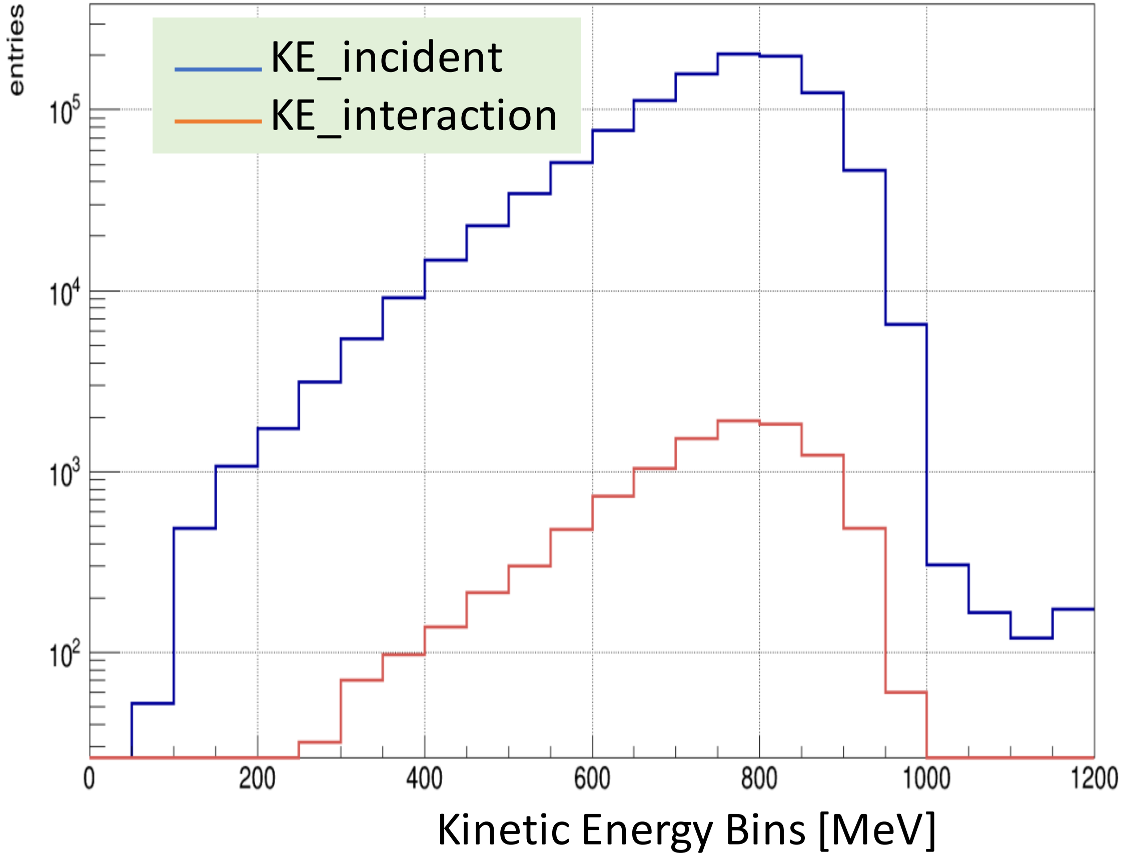
Here, I have considered only the first interaction for each track.

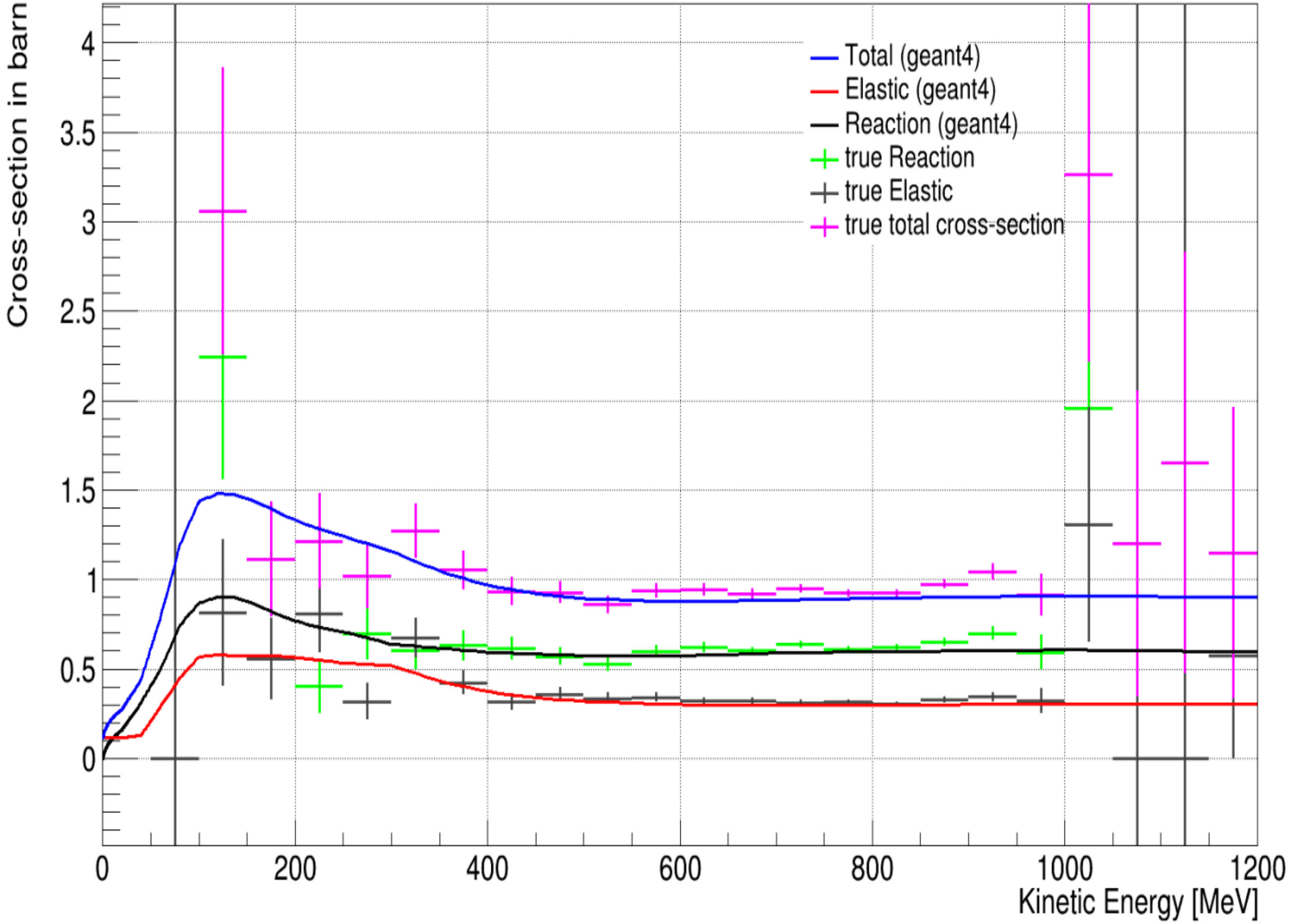


At low KE the error bars are big because of low statistics. Although I generated 50,000 1GeV Momentum (Gaussian spread of 5%) pi+, most of those pi+ interact much before losing all their Kinetic Energy so only a few reach the low Kinetic energy bins.

Repeated the studies in previous slide for MC SCE OFF sample: dataset definition---- "PDSPProd2_MC_1GeV_reco_sce_off"

# of entries for KE_incident and KE_interaction bins for total cross-section estimates





Again, at low KE the error bars are big because of low statistics. Although the sample has 1GeV Momentum pi+, most of those pi+ interact much before losing all their Kinetic Energy so only a few reach the low Kinetic energy bins.

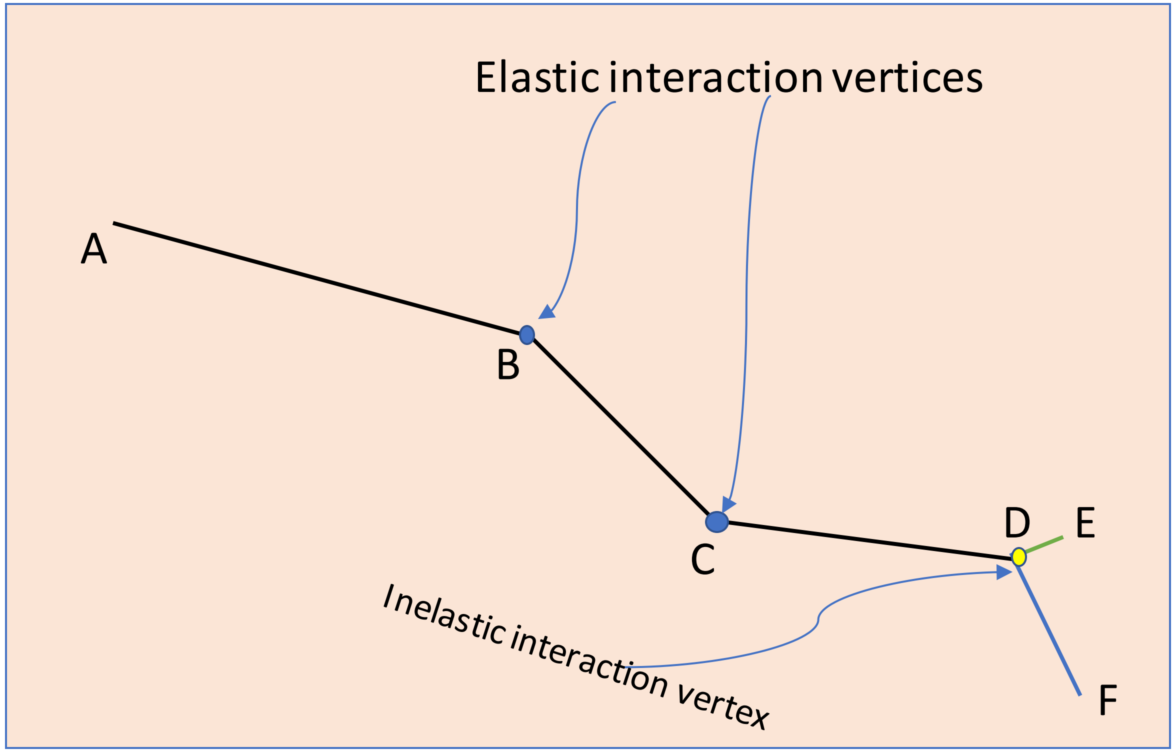
How Geant4 treats a particle trajectory:

In the figure aside there are two Elastic interaction vertices (B and C) and one Inelastic interaction vertex D.

In Monte Carlo there is no break in ***true trajectory*** of the primary particle in case of Elastic interaction.

The primary particle trajectory stops if its KE energy drops to 0 (stopping pion) or the first inelastic Scattering occurs. In the fig aside, from A to D we have the same true trajectory while DE and DF are different trajectories.

Fig:pi+ interaction event



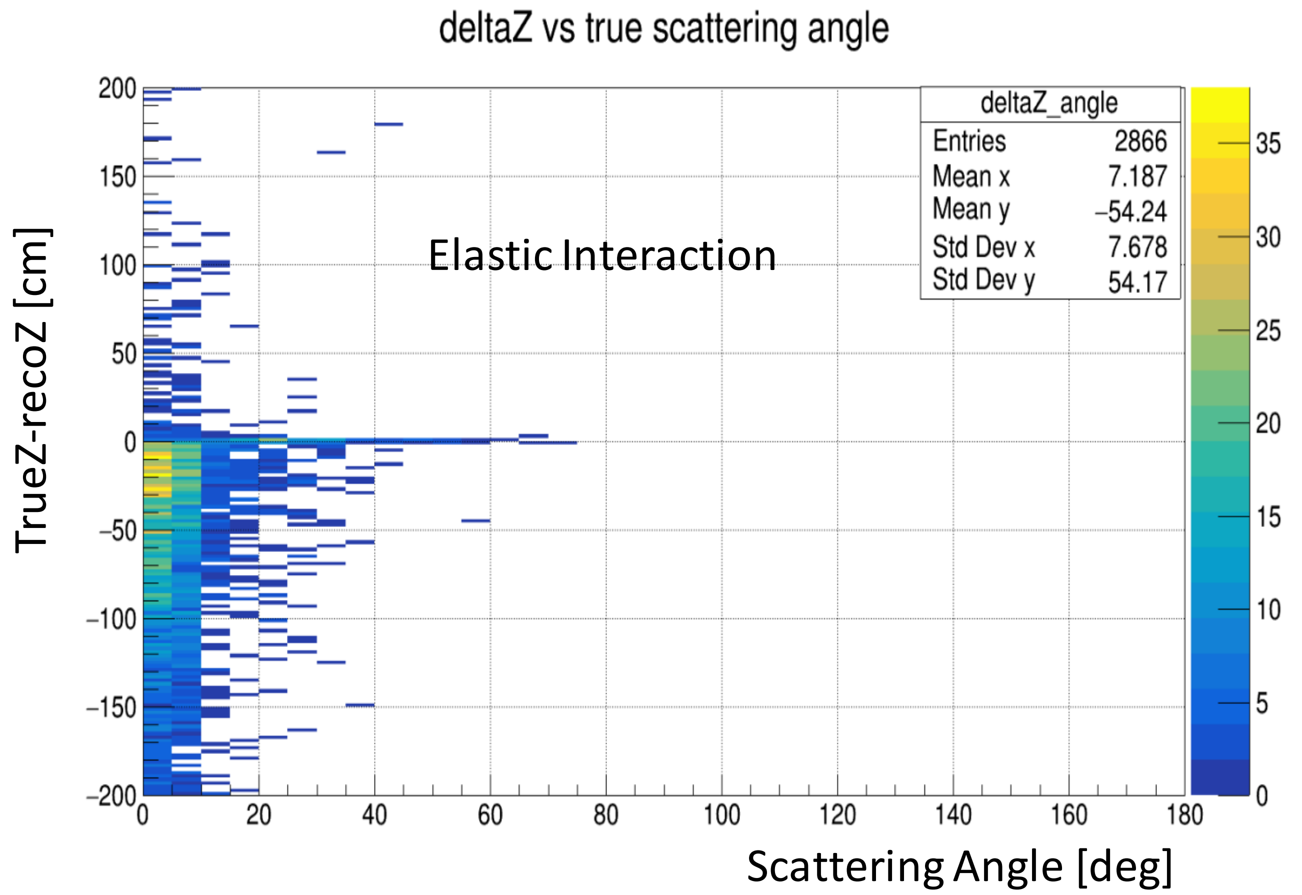
While ***reconstructed primary trajectory*** may or may not end at the elastic interaction vertex depending on the elastic scattering angle or other criteria set in the reconstruction algorithms.

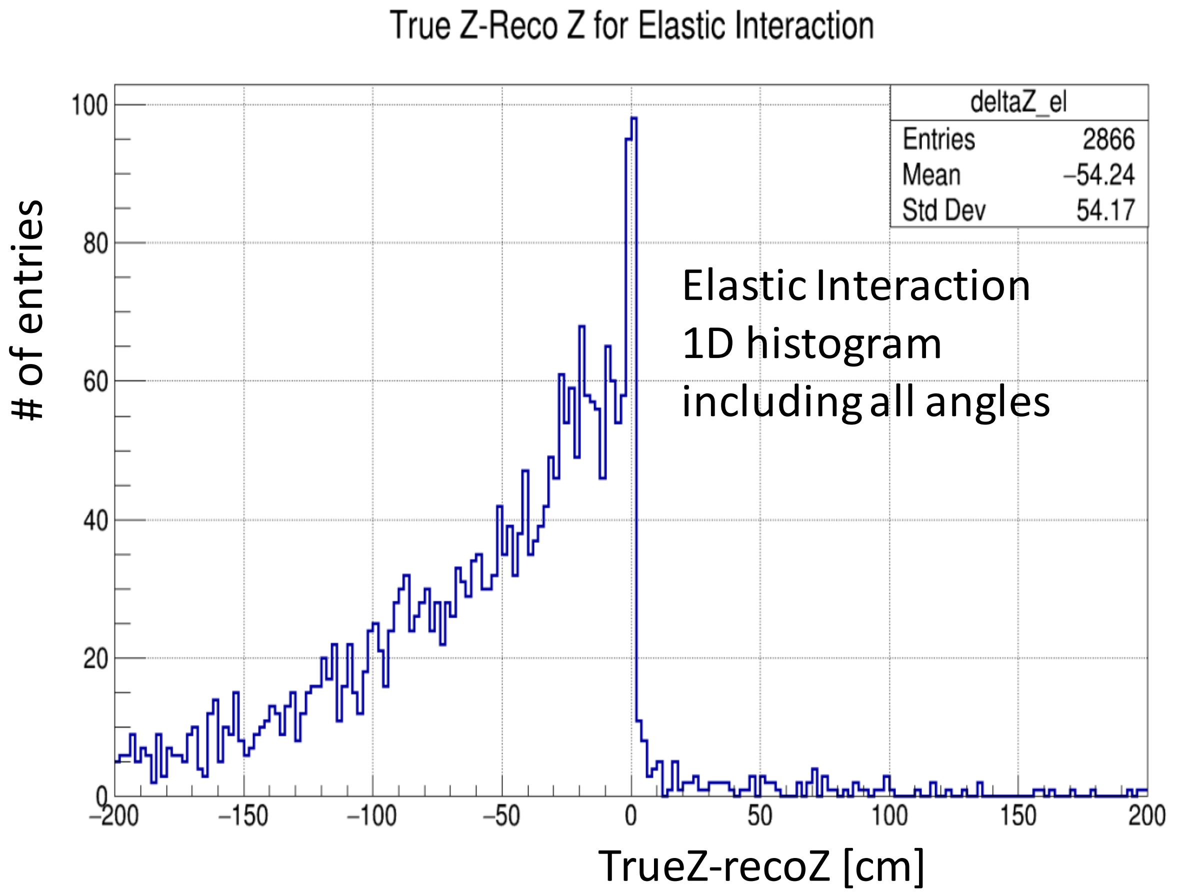
In the next few slides I will be talking about reconstructed information. Thanks to **Pandora team** for providing the reconstruction algorithms for protoDUNE.

Looking at the Reconstructed Information [**Elastic Interaction**]

For ProtoDUNE, beam is travelling along Z-axis, so comparing Z coordinate gives a good idea of the reconstruction status.

For this comparison I require, beam particle to be pi+ and primary reconstructed particle should match with the beam particle (using BackTracker service):



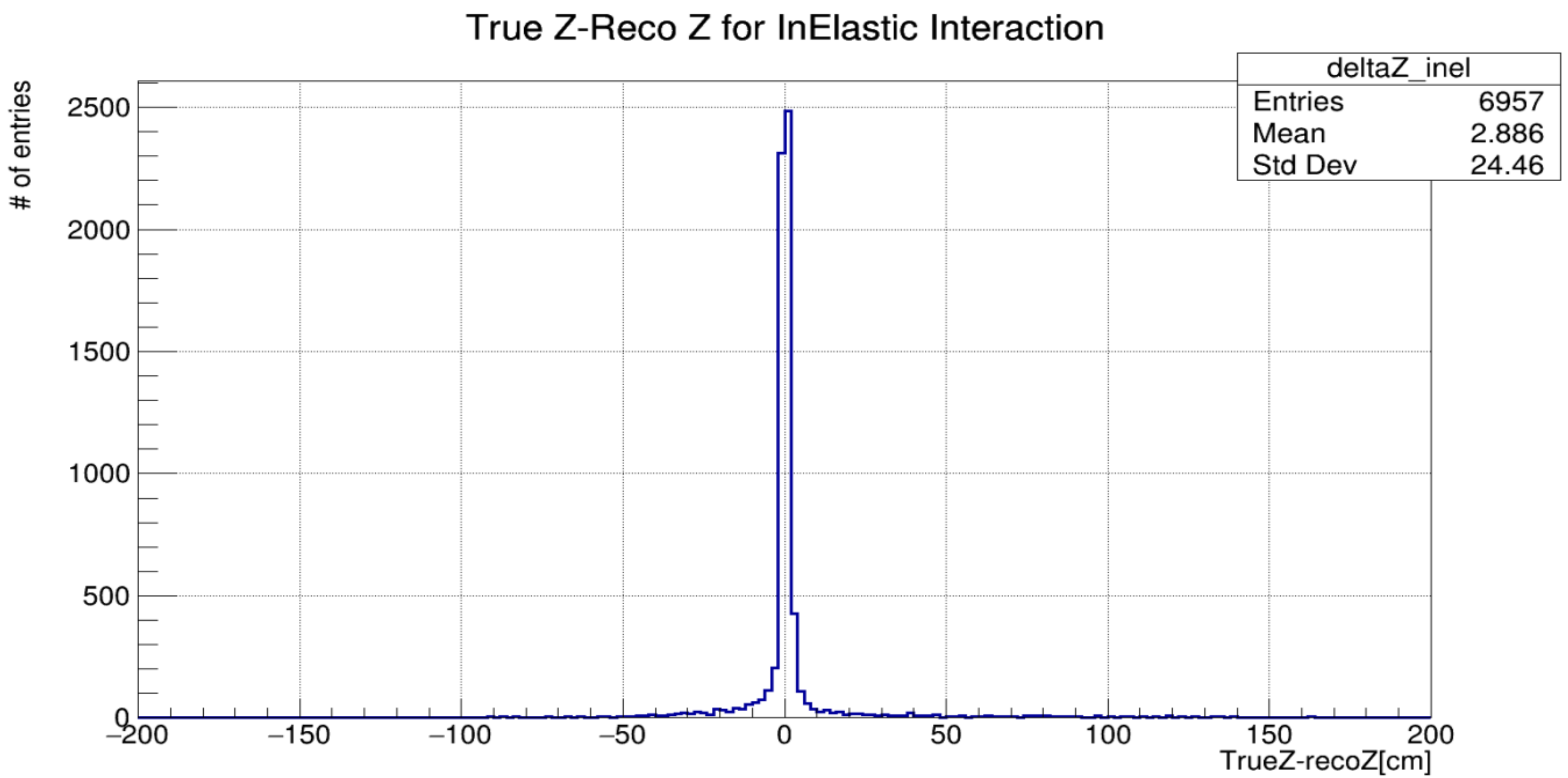


Here, TrueZ = True Z coordinate of the first Elastic Interaction vertex

RecoZ = Reconstructed End Z coordinate of the same track

Reconstructing Elastic vertices appears to be difficult even at high scattering angles.

Looking at the Reconstructed Information [**InElastic Interaction**]: :



Here, TrueZ = True Z coordinate of the first InElastic Interaction [anyway there can be maximum of 1 Inelastic vertex]
RecoZ = Reconstructed End Z coordinate of the same track
Reconstruction of the Inelastic interaction vertex looks good.

- Elastic vertex doesn't look good. InElastic vertex reconstruction looks encouraging.

- Different strategy required for Elastic and InElastic Cross-Section measurement:

Focussing on Inelastic cross-section now (MC SCE OFF sample):

Looking at the truth information for all the beam pions we see:

# of events	95745
# of incident pi+	12934
# of pi+ not reaching the TPC[no interaction process assinged in LArSoft]	2620 [possibly decaying into muons]
# of pi+ reaching the TPC	10314
#of pi+ with last interaction = InElastic	10068
#of pi+ with last interaction = Elastic	131
# of pi+ with no interaction process assigned but end inside the TPC	115[stopping pi+, or decaying into muons]

97.6% of pi+ reaching the TPC undergo Inelastic Interaction at the end of the track.

So, our strategy to assume all the end points of a track are Inelastic interaction vertices and try to purify the sample from there on.

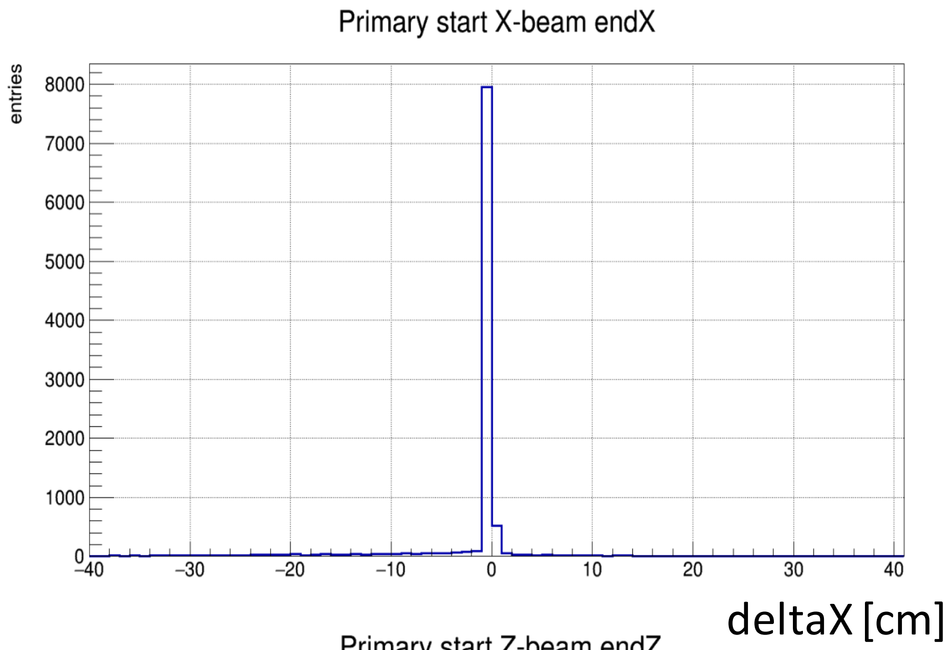
Further look at the Monte-Carlo sample:

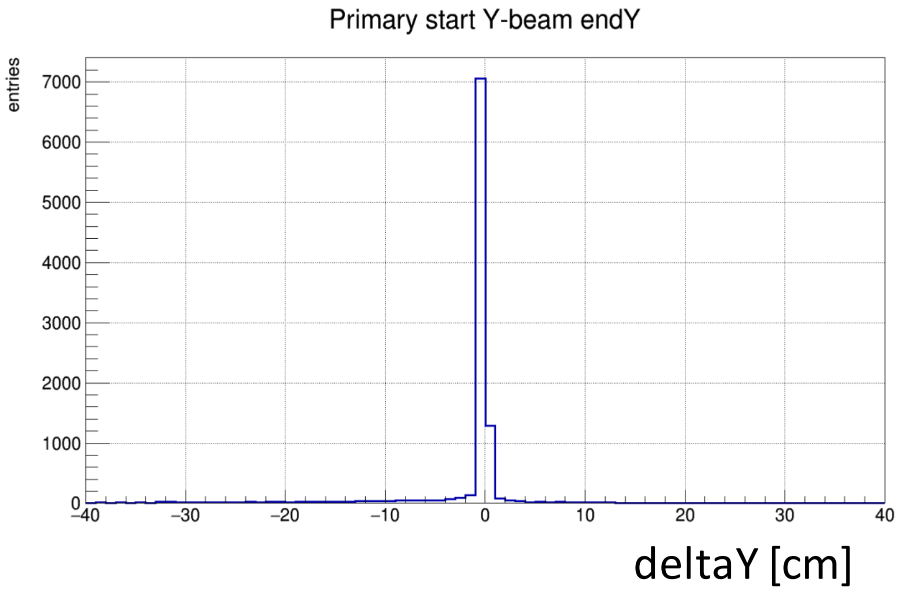
No of events	95745	
# of beam pions	12934 [13.51% of events]	
# of pions reaching TPC	10314	
# of primary particles reconstructed by Pandora	10287	
#of pi+	7964 [77.41% of primary tracks]	
Reconstructed Primary track constituents: before any data cleaning		
#of beam matched pi+	**7053 [68.56%]**	
#of protons	**1019 [9.9%]**	
# of secondary pi+	**911 [8.87%]**	
#of mu_plus	**822 [7.99%]**	
#of primary pi_minus	**98 [0.95%]**	
#of mu_minus	**208[2.02%]**	
#of positrons	**8 [0.078%]**	
#of deuterons	**29 [0.28%]**	

Defining, purity= (No of beam matched pions/No of primary tracks) = 68.56%

Background Removal:

DeltaX(Y, or Z)= Primary track startX (Y or Z)- Beam track X (Y or Z) at TPC front face
Theta = angle between beam and primary track

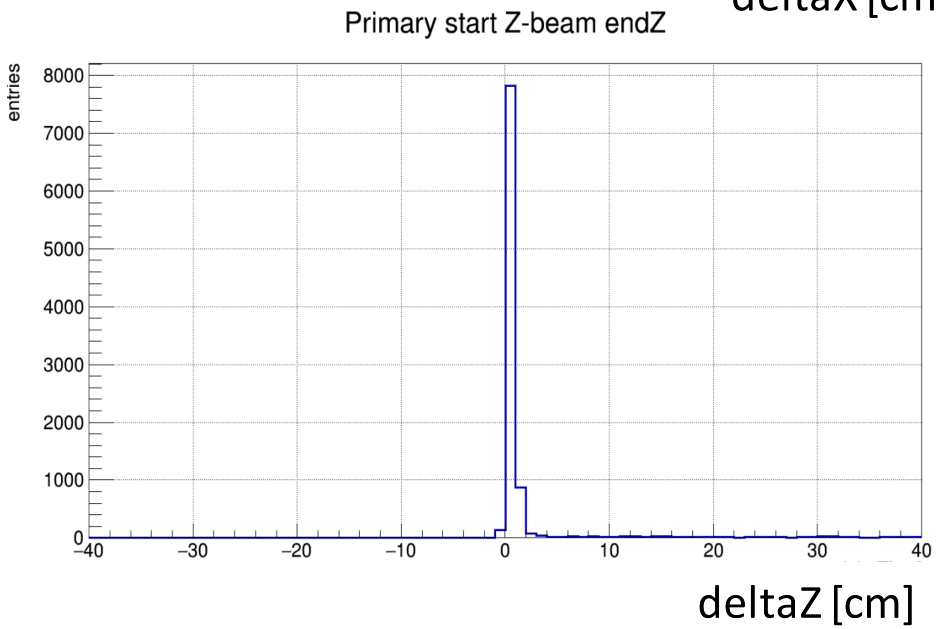


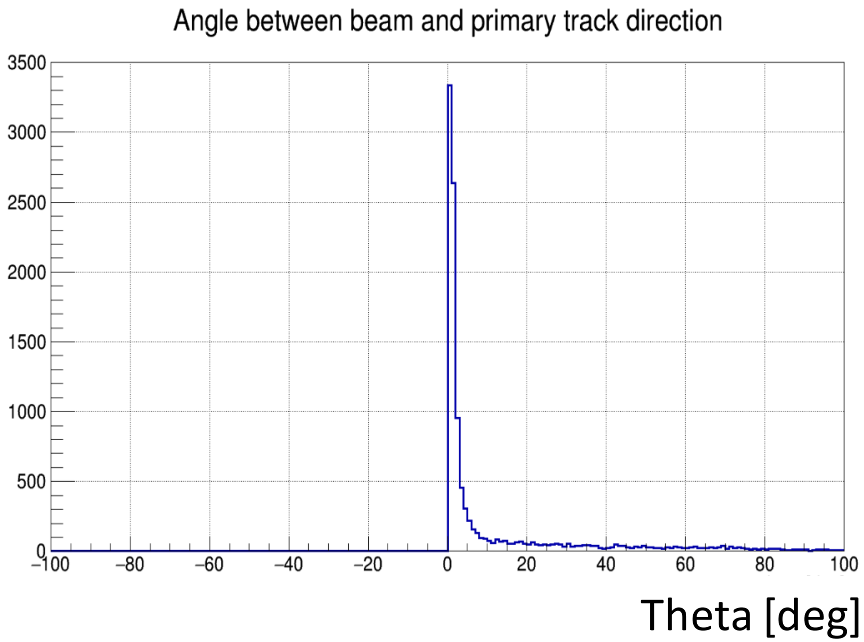


Best on the plots aside I removed tracks with:

Abs(deltaX)>2 or
Abs(deltaY)>2 or
Abs(deltaZ)>5 or

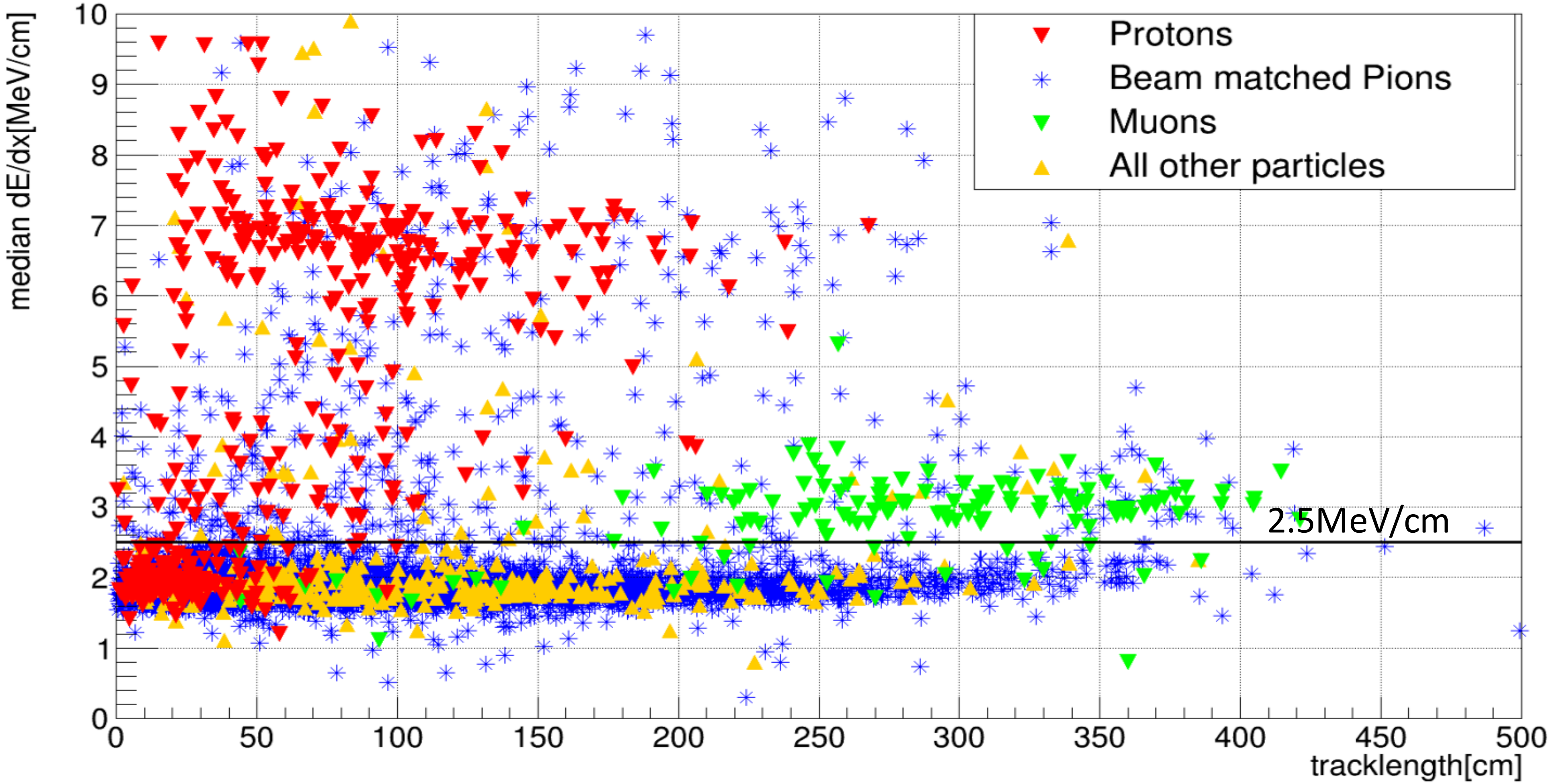
Theta>10 deg





Reconstructed dE/dx vs tracklength distribution for the remaining tracks:

Here median dE/dx is the median dE/dx value considering the hits in the final 15cm of the track [where we expect dE/dx to be higher]



- Most of the proton tracks have high dE/dx and easily separable.
- Stopping muons also seems to have higher dE/dx.
- I removed tracks with median dE/dx>2.5MeV.
- Most of the all other particles consists of secondary pions, which are identical to beam pions.

Looking at the distribution after data cleaning the cuts:

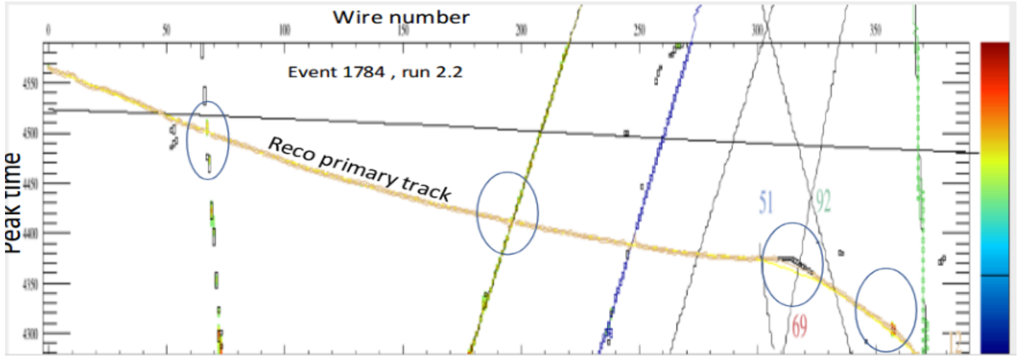
No of events	95745 (This coulumn is before cuts)	After the cuts
# of beam pions	12934 [13.51% of events]	12934 [this will not change]
# of pions reaching TPC	10314	10314
# of primary particles reconstructed by Pandora	10287	6747
#of primary pi+	7964 [77.41% of primary]	6509 [96.47% of primary particles]
Reconstructed Primary track constituents:	**before any data cleaning**	**After data cleaning cuts**
# of beam matched pi+	**7053[68.56%]**	**6237[92.44%]**
# of secondary pi+	**911[8.87%]**	**272[4.03%]**
#of protons	**1019 [9.9%]**	**153 [2.27%]**
#of mu_plus	**822 [7.99%]**	**32[0.47%]**
#of primary pi_minus	**98 [0.95%]**	**16[0.24%]**
#of mu_minus	**208[2.02%]**	**0**
#of positrons	**8 [0.078%]**	**0**
#of deuterons	**29 [0.28%]**	**12[0.18%]**

Purity=92.4% **Major Background is secondary Pions: 4.03%**

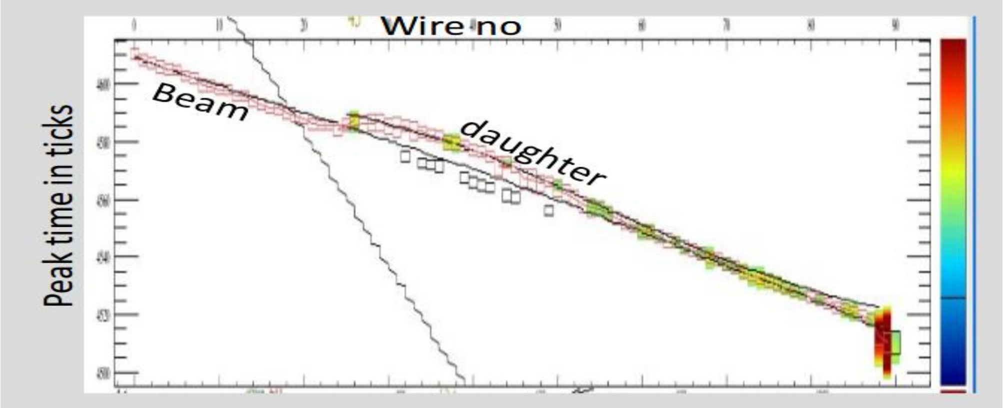
Energy Reconstruction Studies

Before going into the results let me talk briefly about some of the issues faced in energy reconstruction:
For details here is the link to my previous talk from ProtoDUNE DRA meetings.

- **pion tracks crossed by cosmic ray muons at multiple positions.** At such intersection either we have unusually high energy deposit or missing hits. So we wrote an algorithm to find if primary track is contaminated with cosmic, also if so, find the point of intersection. Then we can either remove the track or correct for charge deposit based on adjacent hits.

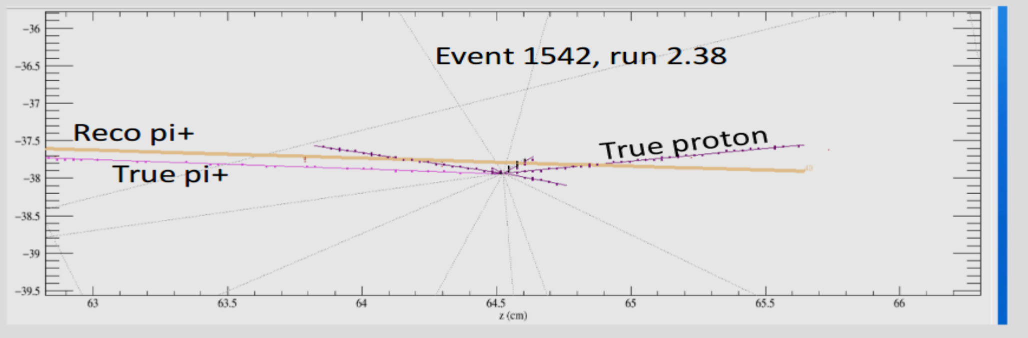


- **Daughter track overlapping** with the primary particle, these very are few. Use angle between primary and daughter to remove these.



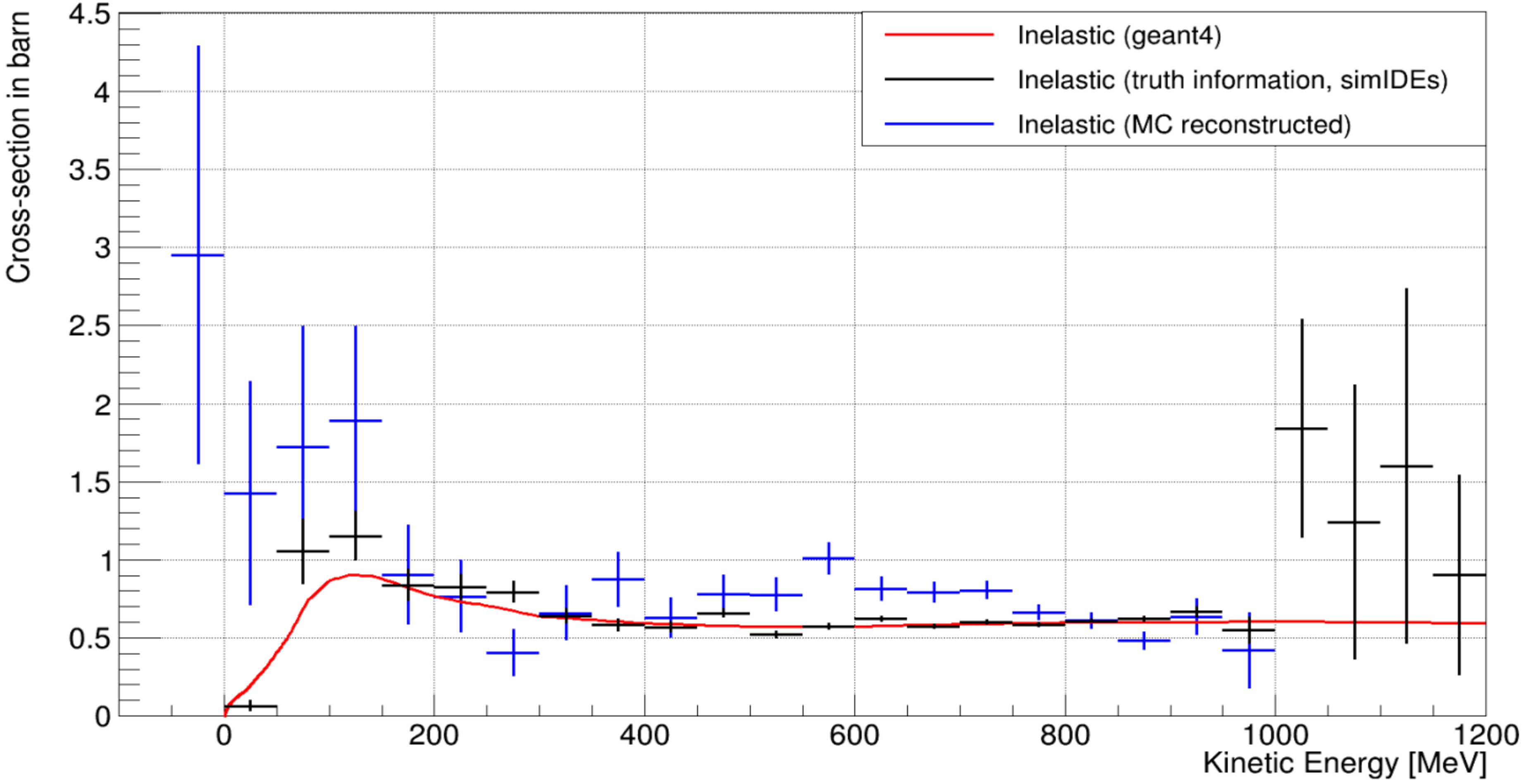
- **Daughter protons hits assigned to primary pions** specially when proton track is short, proton hits can be removed based on dE/dx values.

Proton tail assigned to a primary muons:



RESULTS:

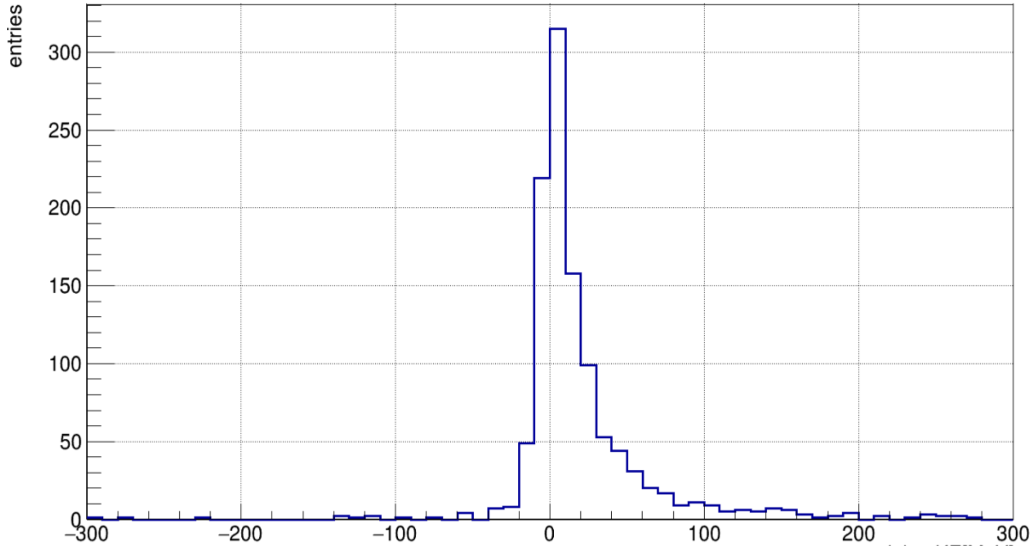
Inelastic cross-section measurements



This is still work in progress. There are many improvements we can make.

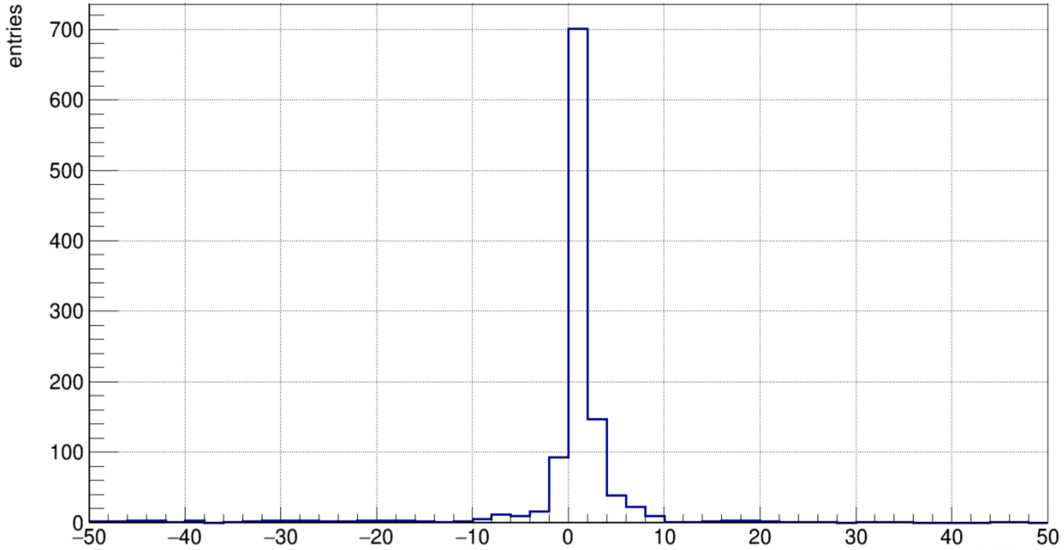
RESULTS: Plots are for the selected sample after all data cleaning cuts

KE_true-KE_reco at interaction vertex



delta_KE[MeV]

Z_true-Z_reco at interaction vertex



delta_Z[cm]

- Many tracks have higher KEinteraction_true, one common reason for this is even after the beam particle interacts, reconstruction picks up secondary pions as the primary particle and travel further thus losing more energy.

- Another common reason for discrepancy is many times reco tracks stops at Elastic interaction vertex

- We need more statistics for better results. Too many tracks are contaminated by cosmics, instead of removing those tracks we can try to correct for affected dE/dx values by using values from nearby unaffected hits.

SUMMARY:

- Pandora Reconstruction Algorithm does a good job identifying Inelastic interaction vertices.
- Performing Elastic cross-section measurements, based on vertex identification, looks very challenging at this stage.
- We have measurements for Inelastic cross-section for MC (SCE OFF) sample. We expect to make further improvements in near future.
- We have also started to look at the MC (SCE ON) sample, and soon will start looking at ProtoDUNE data.
- For future updates please connect to the ProtoDUNE DRA and Analysis meetings.

*******THANK YOU*******