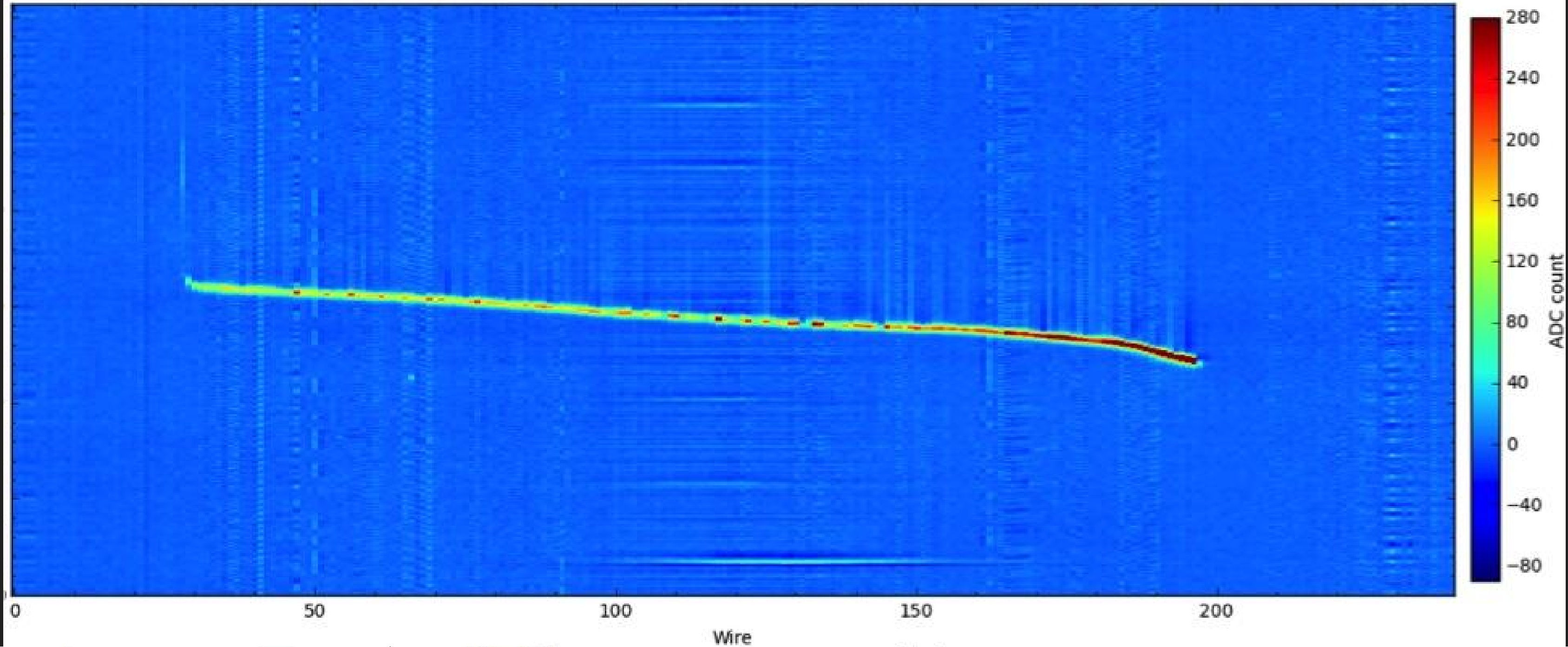
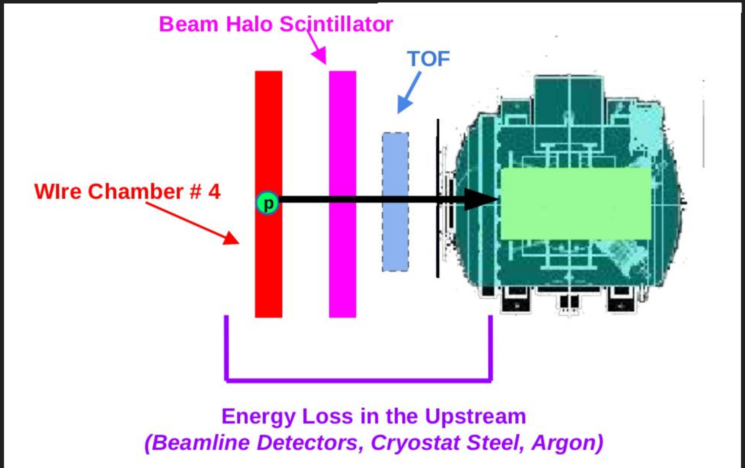
Proton Calorimetry Study: Update



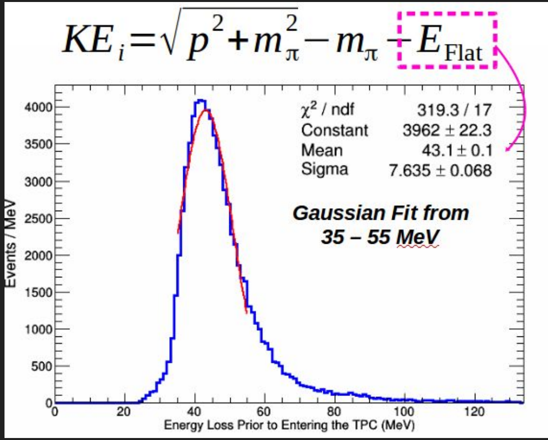
Zachary Williams

Motivation

- **Current analyses account for the energy loss by particles between Wire Chamber 4 and the beginning of the TPC by subtracting a flat number**
  - This number is found as the peak of MC distribution tracking all the energy deposited for the particular particle species
    - E.g. for pions this is ~43 MeV and is subtracted to estimate the initial Kinetic Energy in the TPC
- **Perhaps there is a better method we can use and validate using data and MC?!**
  - Stopping protons seem to be the ideal sample



Schematic of the upstream beamline



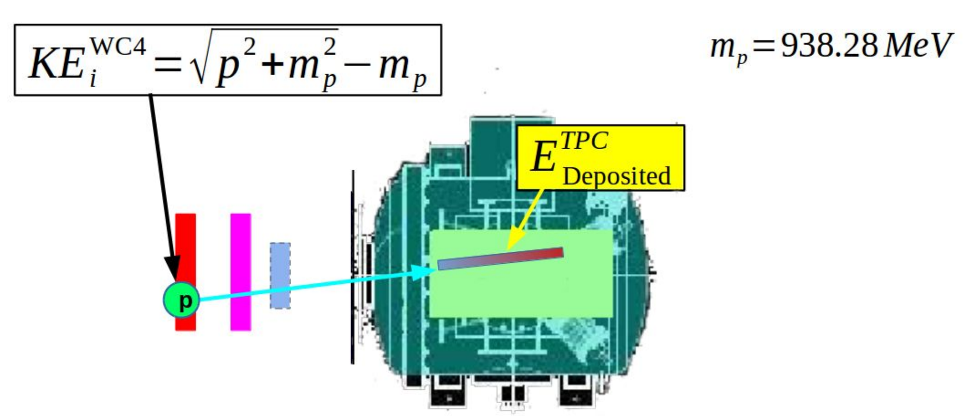
Energy loss used in the Pion analysis

Why stopping protons?

- **In principle, when we are accounting for all the energy of a proton, the only thing we don't measure directly is the energy loss upstream ($E_{Loss}^{Upstream}$)**
  - Particle ID from the beamline can ensure we have a sample of protons in data
  - We can select events in the TPC where the proton stops without interacting

$$E_{Total} = KE_i^{WC4} - E_{Loss}^{Upstream} - E_{Deposited}^{TPC}$$

- **Better, we can use the MC to validate all the pieces and develop a new method to estimate the energy loss upstream**

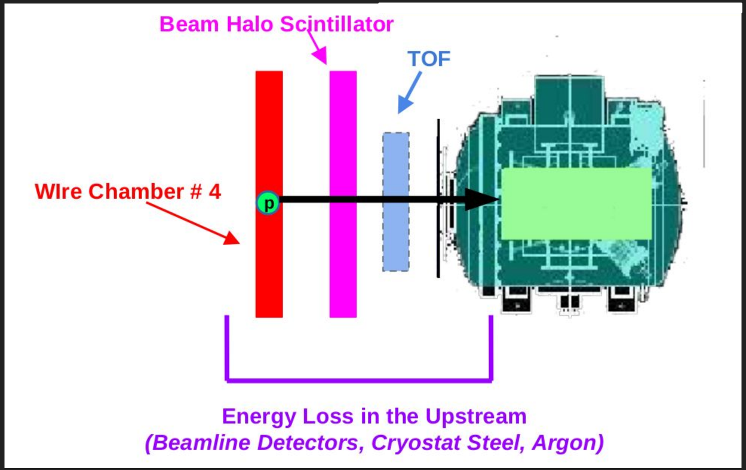


How we hope this will benefit the analyses

1. Better model the energy loss in the upstream region of the beamline prior to reaching the TPC and reduce the systematic on this (for the pions currently 3.5%).
2. Aid in the measurement of the hadronic cross section for protons/kaons where the energy loss upstream is likely to be larger than for the pions.

More backstory can be found in:

DocDB #2235
DocDB #2360



Current Upstream Energy Loss Model: The Flat Method for protons

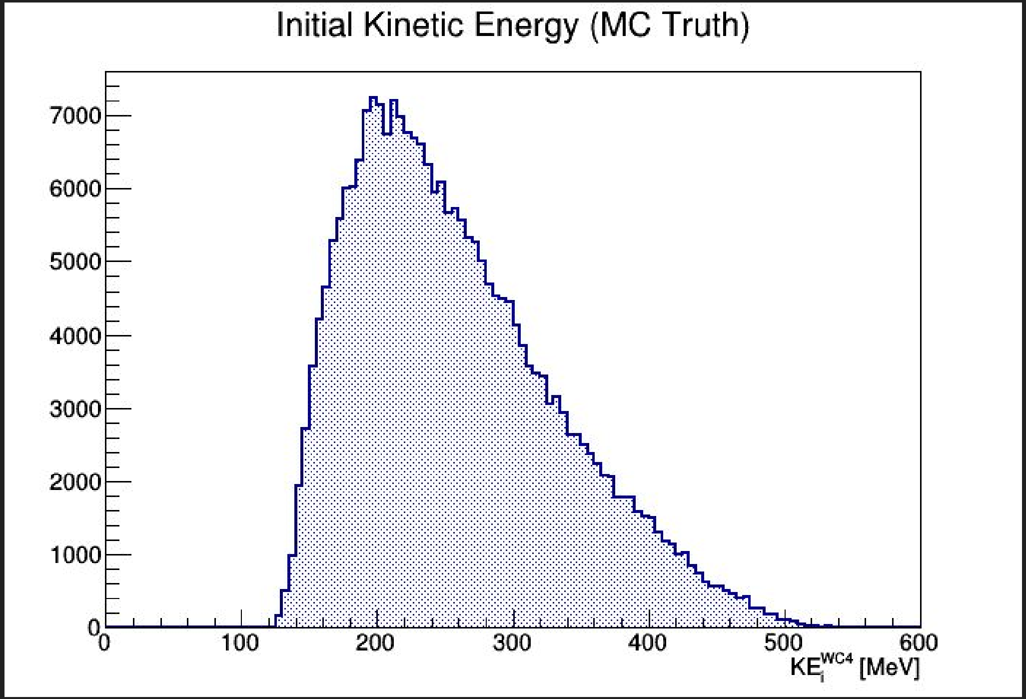
MC Sample Used

- We use a sample of MC Stopping Protons.
  - The MC was generated by using the single particle gun being fired from z = -100 cm, which is the location of Wire Chamber 4 (I basically made a bunch of different versions of the ‘prodsingle_proton_0_500MeV.fcl’ file over the different ranges of energies).
- For MC True Stopping Protons:
  - Because this is MC, we use truth information of the endpoint of the particle (within the fiducial volume) to classify it as a stopping proton, whether or not it was the primary particle (process_primary[iG4] == 1), and it has a pdg code of 2212.
- For Reco on the MC Sample:
  - We require that there is at least a single point reconstructed in the fiducial boundaries of the TPC ($0 < x < 47$ cm, $-20 < y < 20$ cm) and is within the first 14 cm in the beamline ($0 < z < 14$ cm) and the track’s end point is within the fiducial volume of the TPC. We then match the most upstream point of the track to the MC truth track and the difference between the X and Y’s should be sufficiently small to identify them as the same.

New MC:

	New MC
Version	v06.44.00
# of Stopping Protons	245,543
# of Stopping Protons with Reco Info	226,891

Quick Look at Parameters About to be Used (MC)

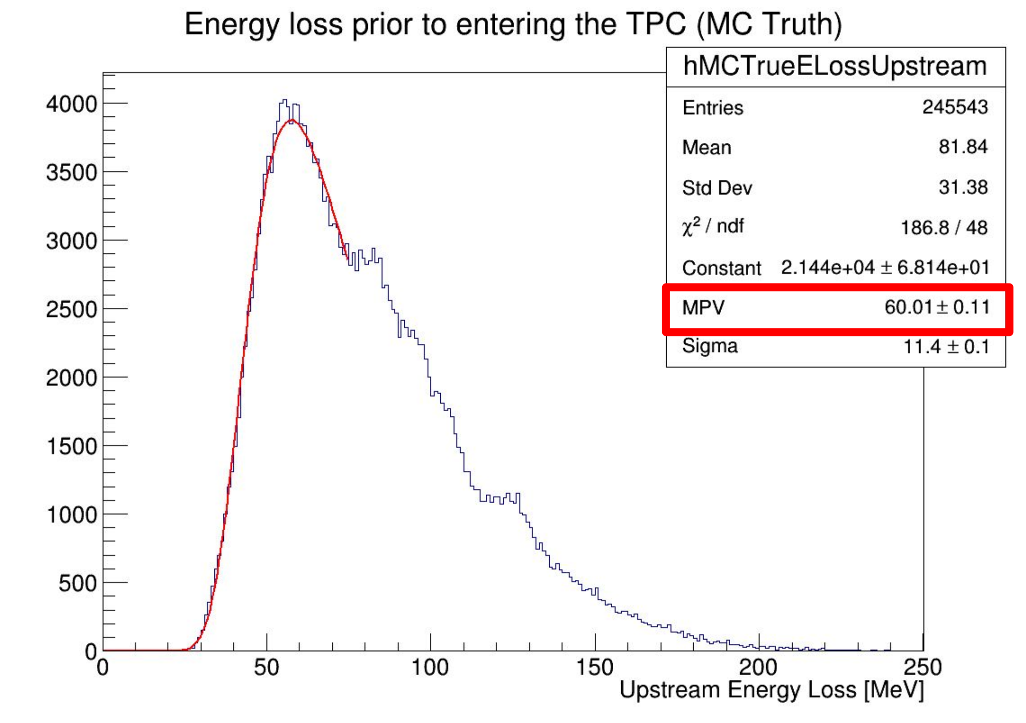


Initial Kinetic Energy for stopping protons

$$E_{\text{Total}} = \boxed{KE_i^{\text{WC4}}} - E_{\text{Loss}}^{\text{Upstream}} - E_{\text{Deposited}}^{\text{TPC}}$$

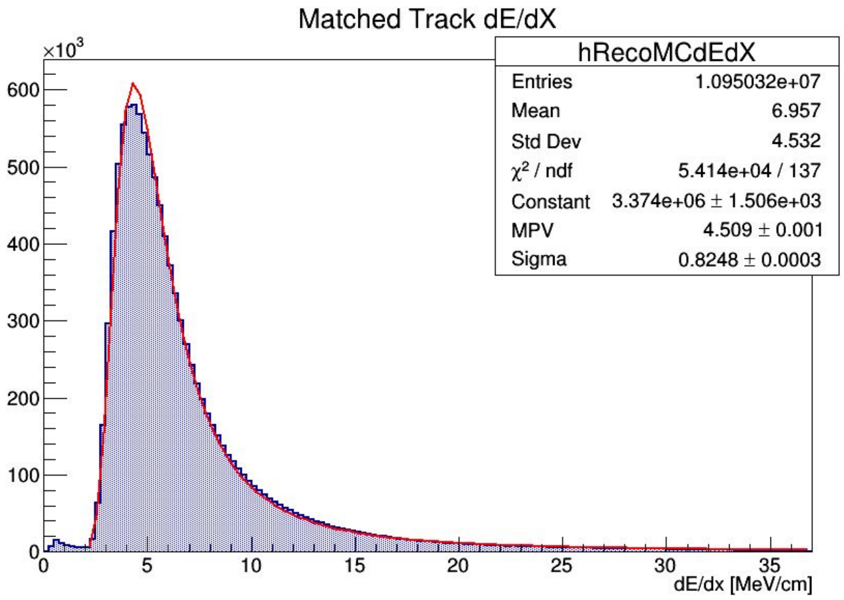
Quick Look at Parameters About to be Used (MC)

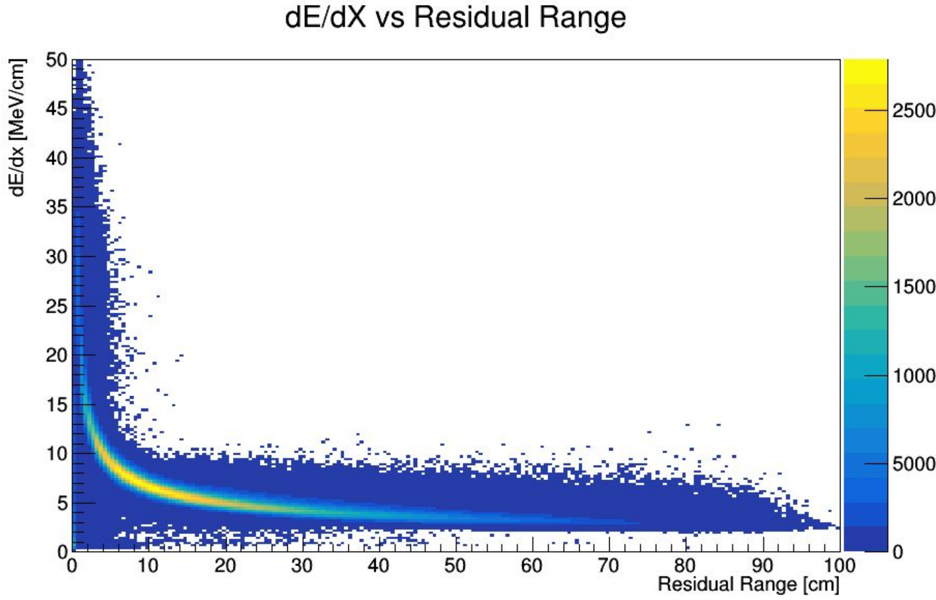
The current method for approximating the energy loss by protons in the upstream region of the beamline is to use a single value for the energy loss of all proton events taken from a fit to a MC stopping proton sample's true upstream energy loss. This is shown in the plot, and the value for the energy loss upstream by a proton for the flat method is found to be: 60.01 MeV.



$$E_{\text{Total}} = KE_i^{\text{WC4}} - \boxed{E_{\text{Loss}}^{\text{Upstream}}} - E_{\text{Deposited}}^{\text{TPC}}$$

Quick Look at Parameters About to be Used (MC)

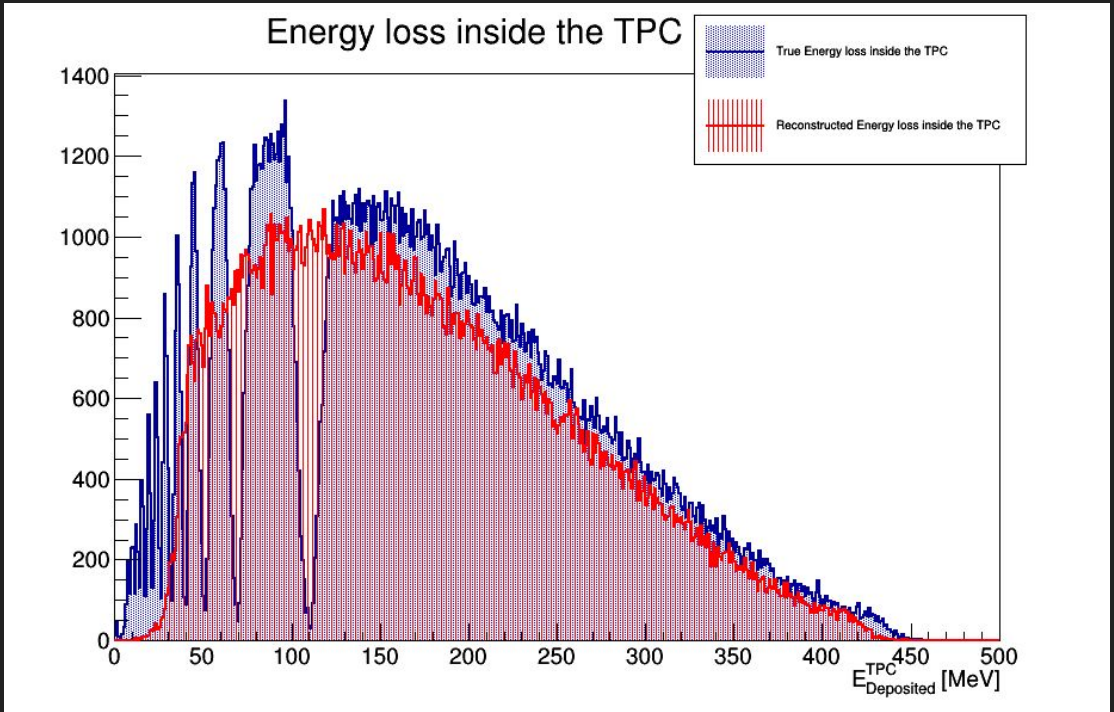




dE/dx for MC stopping protons

dE/dx vs Residual Range for MC stopping protons

Quick Look at Parameters About to be Used (MC)



The spikey structure in the "True" energy loss is associated with the physics list used by GEANT4

We use this physics list for the study here because it is the same used by the pion/kaon/proton analyses

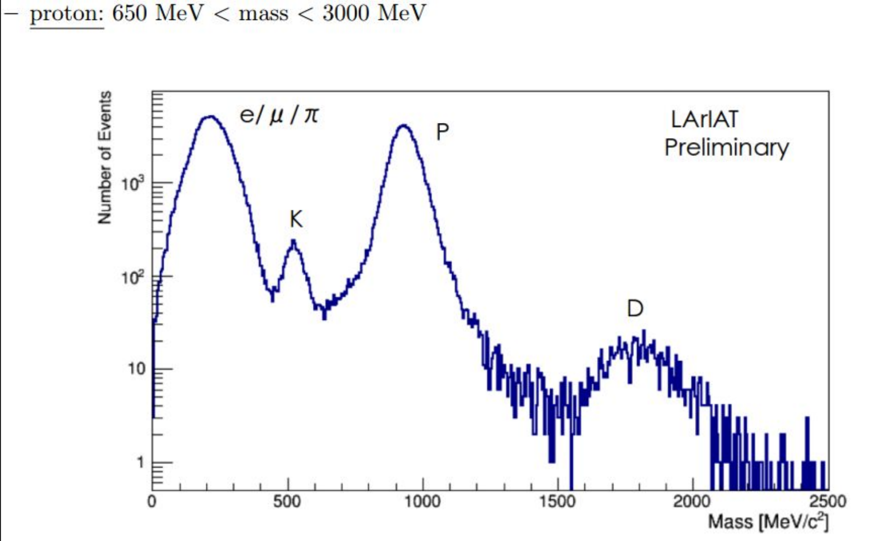
Total energy deposited in the TPC for stopping protons

$$E_{\text{Total}} = KE_i^{\text{WC4}} - E_{\text{Loss}}^{\text{Upstream}} - \boxed{E_{\text{Deposited}}^{\text{TPC}}}$$

The Data Sample

Run I Information

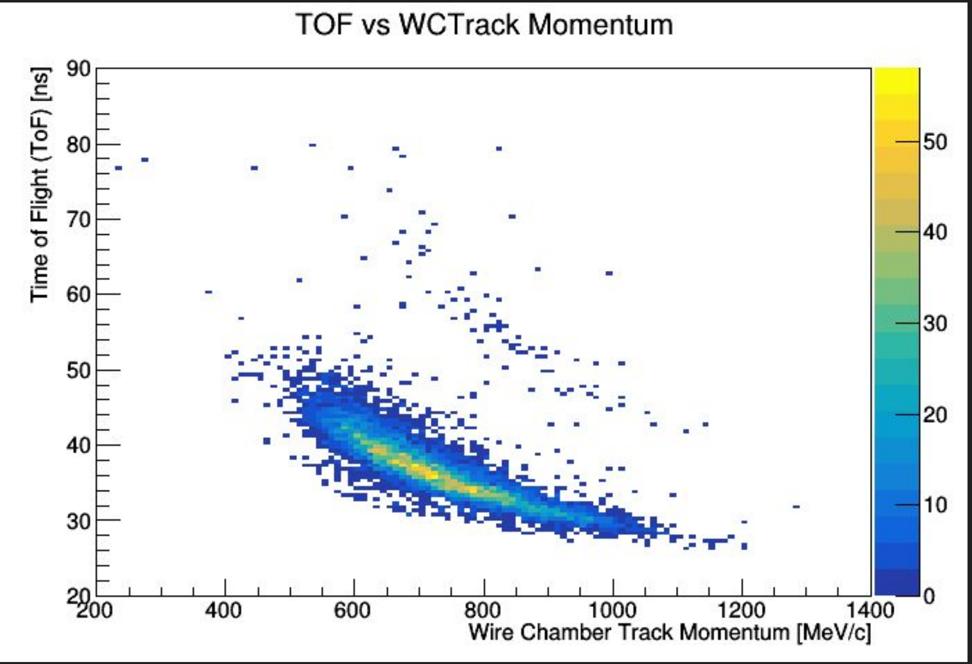
1. Run-I Picky Track Proton Mass Filter Data
   a. Mean momentum ~ 730 MeV/c
2. Same sample that was used on the dE/dx calibration here: DocDB #2513



$$mass = \frac{p}{c}\sqrt{(\frac{TOF \times c}{l})^2 - 1}$$

Event Selection	Run-I Negative Polarity π, μ, e	Run-I Positive Polarity π, μ, e	Run-I Positive Polarity Proton
Beam Filter	113,336	140,954	140,954
Mass Selection	5,909	5,349	9,104
$>$ 1 Track Reconstructed in the TPC	5,722	5,223	8,062
$<$ 3 Tracks Reconstructed with length $<$ 5 cm	4,323	4,058	6,561
Unique match between WC and TPC Track	2,464	2,446	3,373

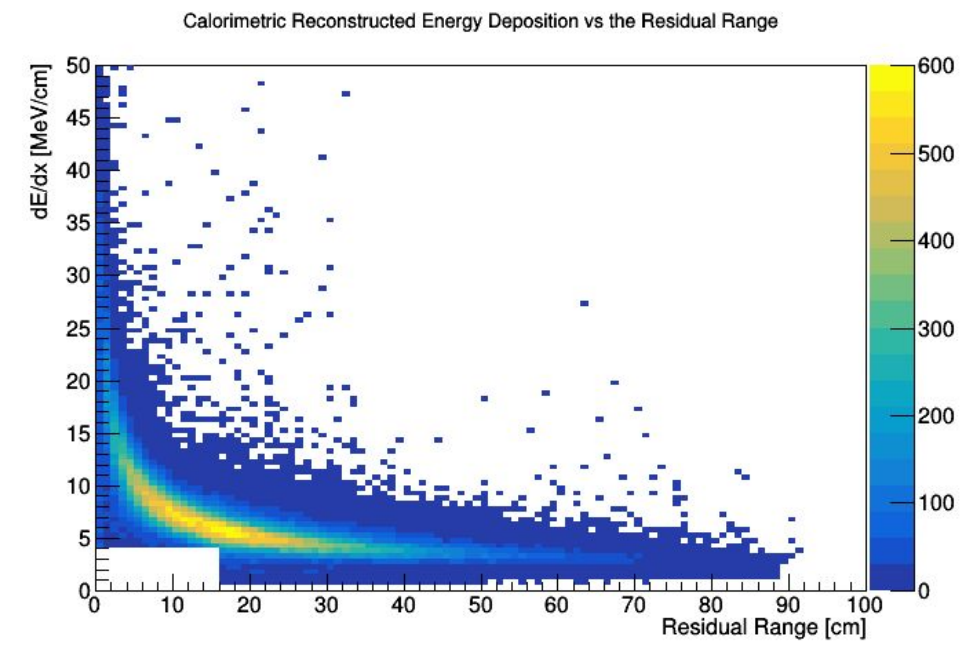
Run I ToF vs WC Track Momentum Histogram



- **TOF vs WC-Track momentum for all Run-I proton data**
  - Slight deuteron contamination
  - Ignored for this study

Run I Event Reduction Table	
Total Number of Events	**9014**
Events w/ WC Track & TOF Object	**9014**
Events w/ TOF > 0 ns and < 90 ns	**9010**
Events w/ Good TPC Info (nHits > 0)	**9005**
Events w/ PID Consistent w/ proton (450 MeV < P < 1100 MeV, 28 ns < TOF < 55 ns)	**8903**
Events w/ Trk Z < 2	**7211**
Events w/ < 8 Trks in the First 14 cm of TPC	**7021**
Events That Are Not Shower Like (< 3 tracks with length < 5 cm)	**5738**
Events w/ ONE WC Trk Matched	**3211**
Events w/ Stopping Proton in TPC Within Fiducial Boundaries (z > 2 cm, z < 85 cm, y > -15 cm, y < 15 cm, x > 5 cm, x < 42 cm) (RR < 16 cm with dE/dX > 4 MeV/cm)	**1587**

Run I dE/dx vs Residual Range Histogram

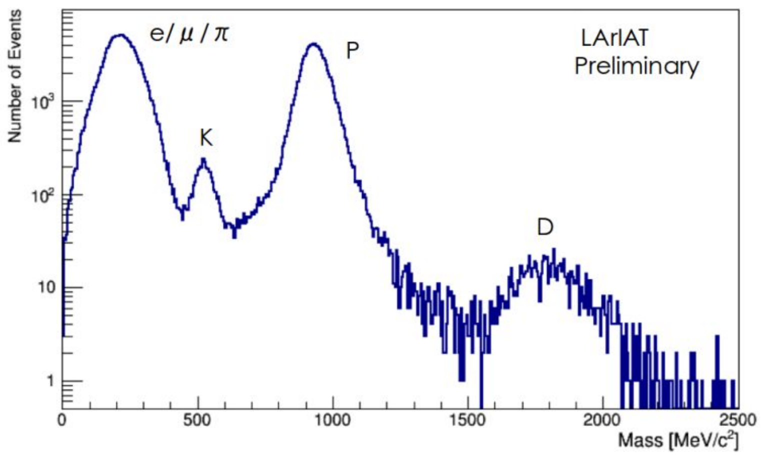


- **dE/dX vs RR for stopping proton sample**
  - We remove tracks which have a low dE/dX at small residual range to help reduce contamination from mismatched minimum ionizing tracks
  - dE/dX < 4 MeV/cm in the last 16 cm of the track

Run II Information

1. Run-II Picky Track Proton Mass Filter Data
   a. Mean momentum ~ 725 MeV/c
2. Same sample that was used on the dE/dx calibration here: DocDB #2513

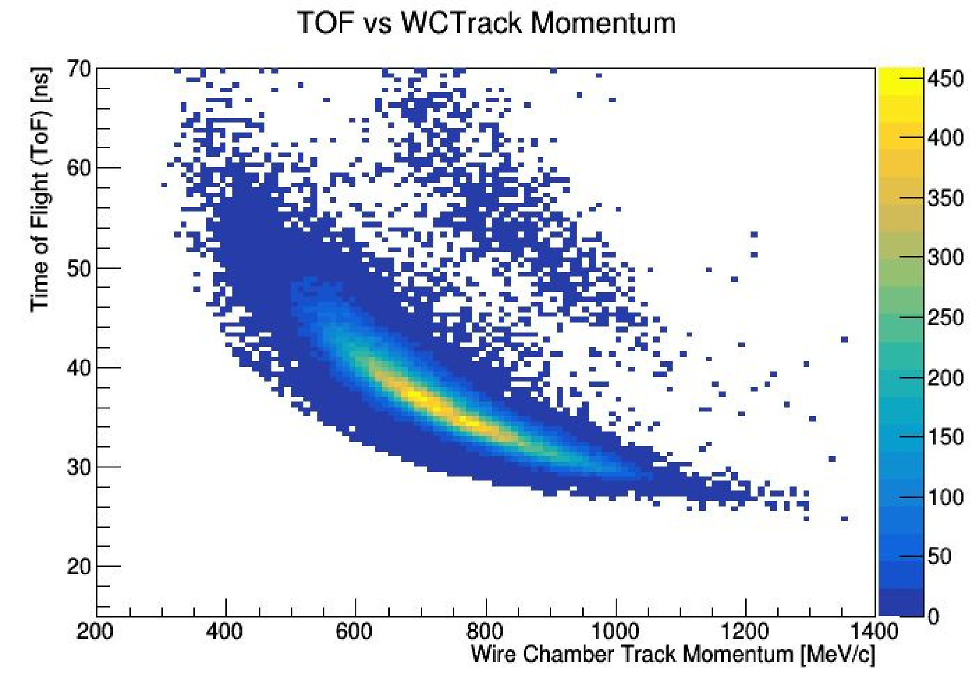
– proton: 650 MeV $<$ mass $<$ 3000 MeV



$$mass = \frac{p}{c}\sqrt{(\frac{TOF \times c}{l})^2 - 1}$$

Event Selection	Run-II Negative Polarity π, μ, e	Run-II Positive Polarity π, μ, e	Run-II Positive Polarity Proton
Beam Filter	1,585,598	1,555,402	1,555,402
Mass Selection	124,965	89,561	94,210
$>$ 1 Track Reconstructed in the TPC	117,869	86,918	82,099
$<$ 3 Tracks Reconstructed with length $<$ 5 cm	88,717	69,509	68,847
Unique match between WC and TPC Track	48,076	43,547	36,278

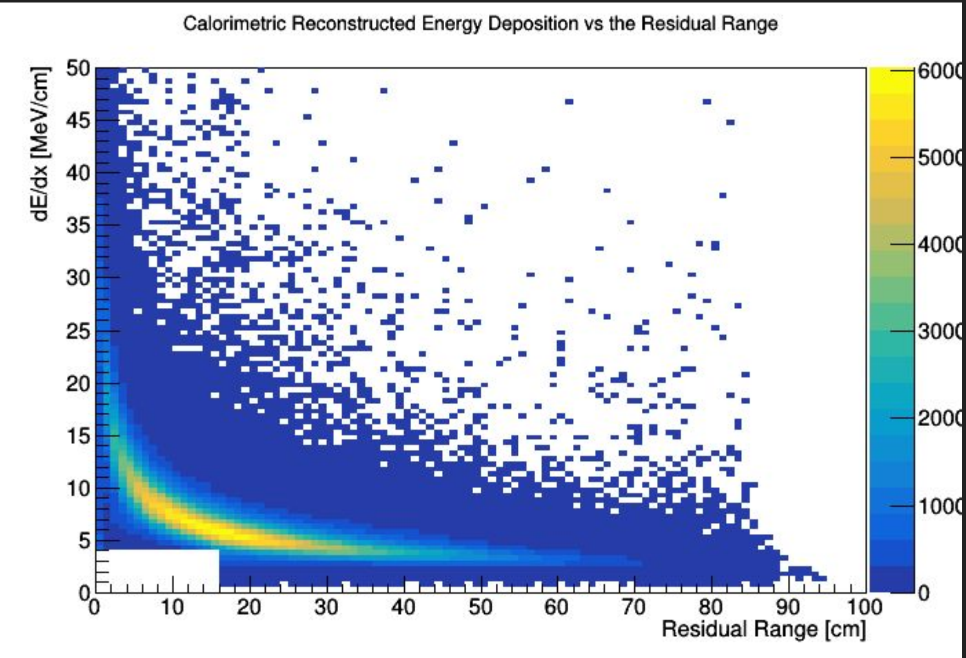
Run II ToF vs WC Track Momentum Histogram



- **TOF vs WC-Track momentum for all Run-II proton data**
  - Slight deuteron contamination
  - Ignored for this study

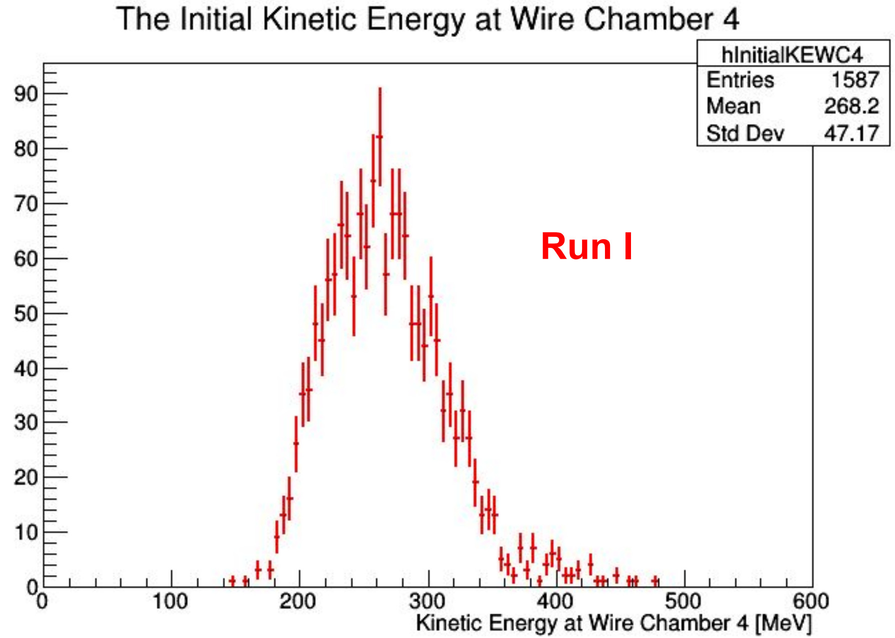
Run-II Event Reduction Table	
Total Number of Events	**94210**
Events w/ WC Track & TOF Object	**94210**
Events w/ TOF > 0 ns and < 90 ns	**94122**
Events w/ Good TPC Info (nHits > 0)	**92873**
Events w/ PID Consistent w/ proton (450 MeV < P < 1100 MeV, 28 ns < TOF < 55 ns)	**90890**
Events w/ Trk Z < 2	**68158**
Events w/ < 8 Trks in the First 14 cm of TPC	**67414**
Events That Are Not Shower Like (< 3 tracks with length < 5 cm)	**55838**
Events w/ ONE WC Trk Matched	**30037**
Events w/ Stopping Proton in TPC Within Fiducial Boundaries (z > 2 cm, z < 85 cm, y > -15 cm, y < 15 cm, x > 5 cm, x < 42 cm) (RR < 16 cm with dE/dX > 4 MeV/cm)	**17804**

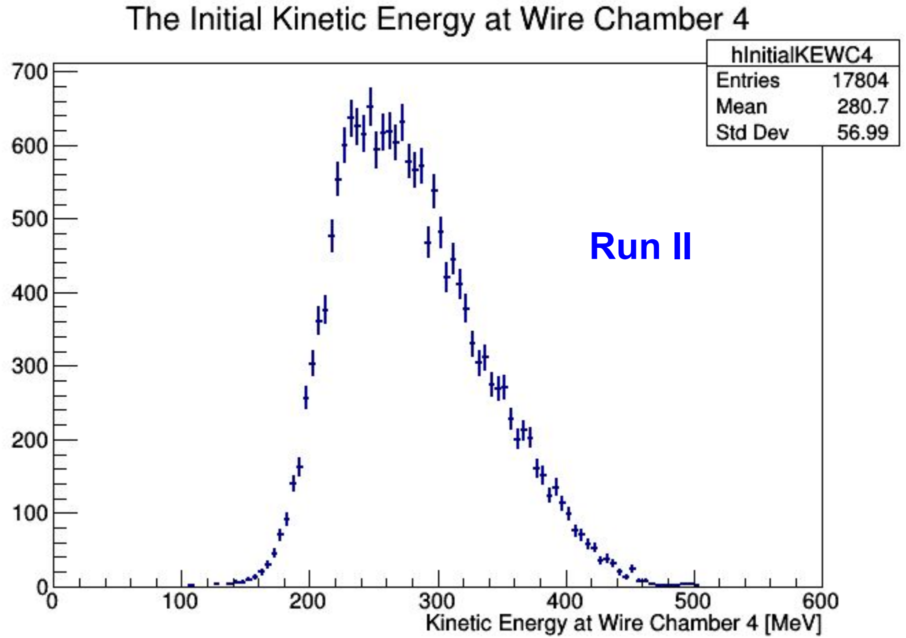
Run II dE/dx vs Residual Range Histogram



- **dE/dX vs RR for stopping proton sample**
    - We remove tracks which have a low dE/dX at small residual range to help reduce contamination from mismatched minimum ionizing tracks
    - dE/dX < 4 MeV/cm in the last 16 cm of the track

Quick Look at Parameters About to be Used

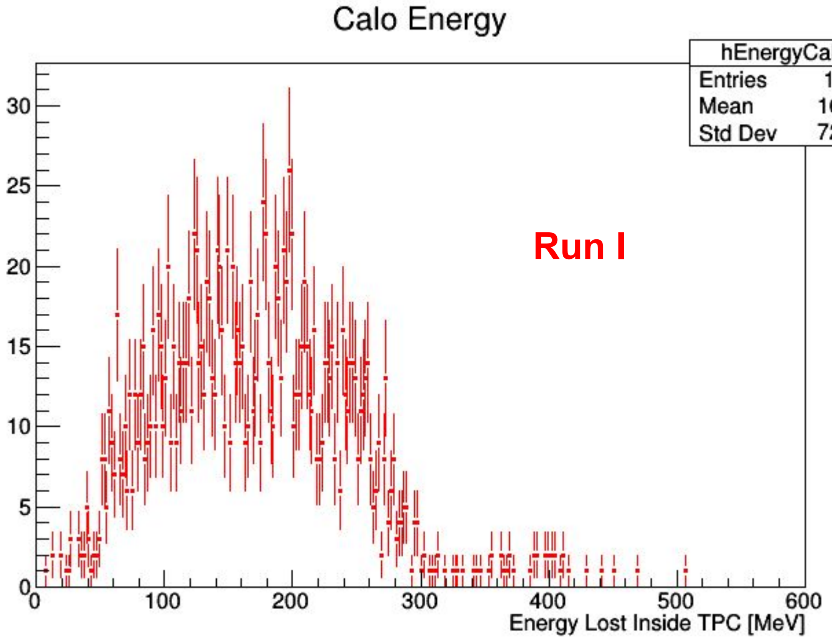


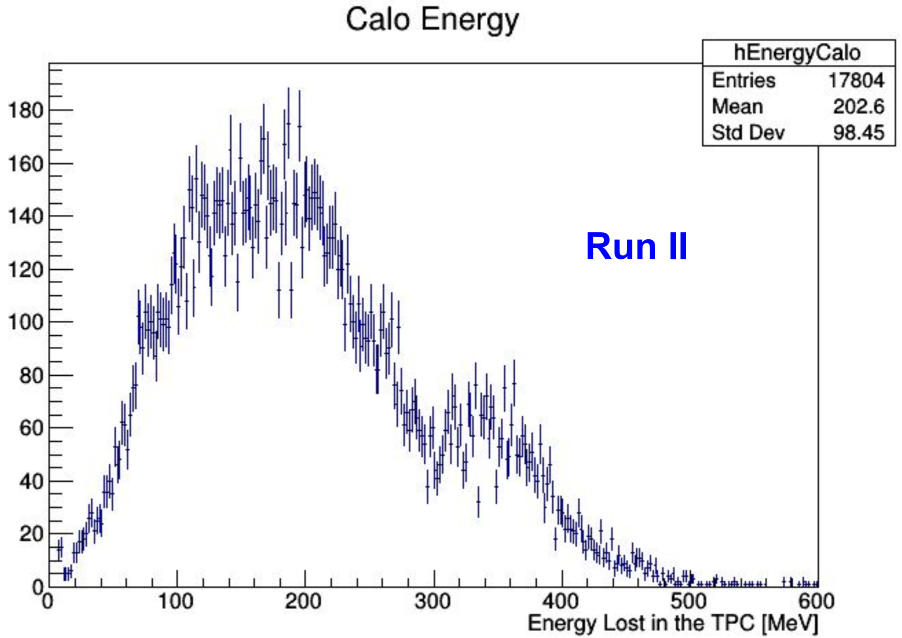


These are the distributions of the parameter for the initial Kinetic Energy at WC4 on stopping proton data from Run I and Run II of LArIAT.

$$E_{\text{Total}} = \boxed{KE_i^{\text{WC4}}} - E_{\text{Loss}}^{\text{Upstream}} - E_{\text{Deposited}}^{\text{TPC}}$$

Quick Look at Parameters About to be Used

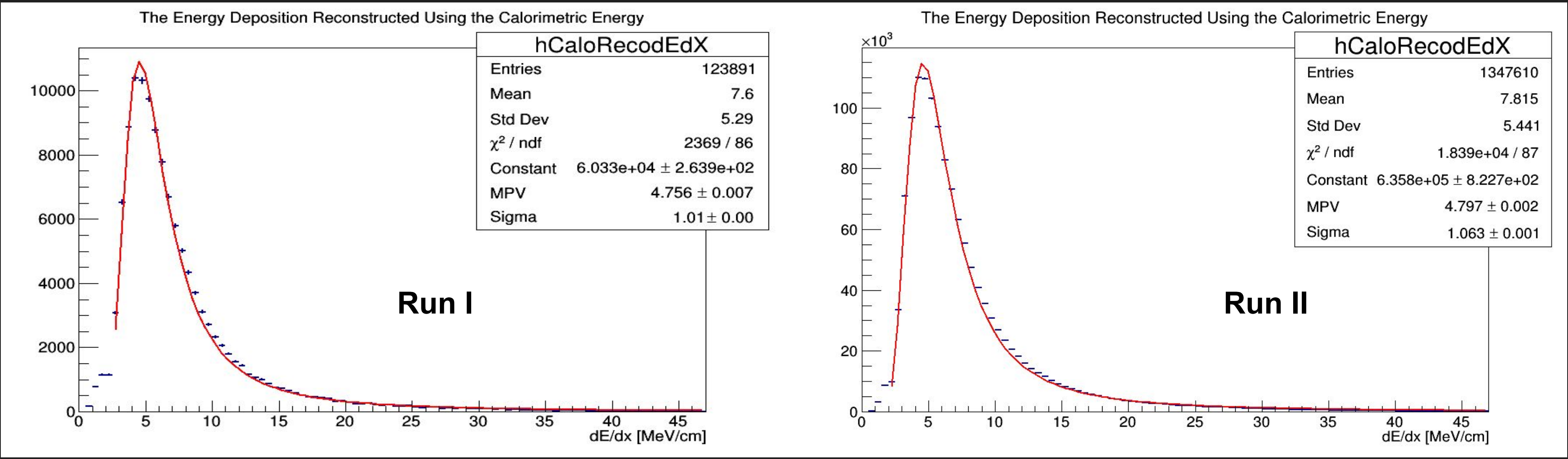




These are the distributions of the parameter for the energy lost inside of the TPC on stopping proton data from Run I and Run II of LArIAT.

$$E_{\text{Total}} = KE_i^{\text{WC4}} - E_{\text{Loss}}^{\text{Upstream}} - \boxed{E_{\text{Deposited}}^{\text{TPC}}}$$

Run I and Run II dE/dx Fit

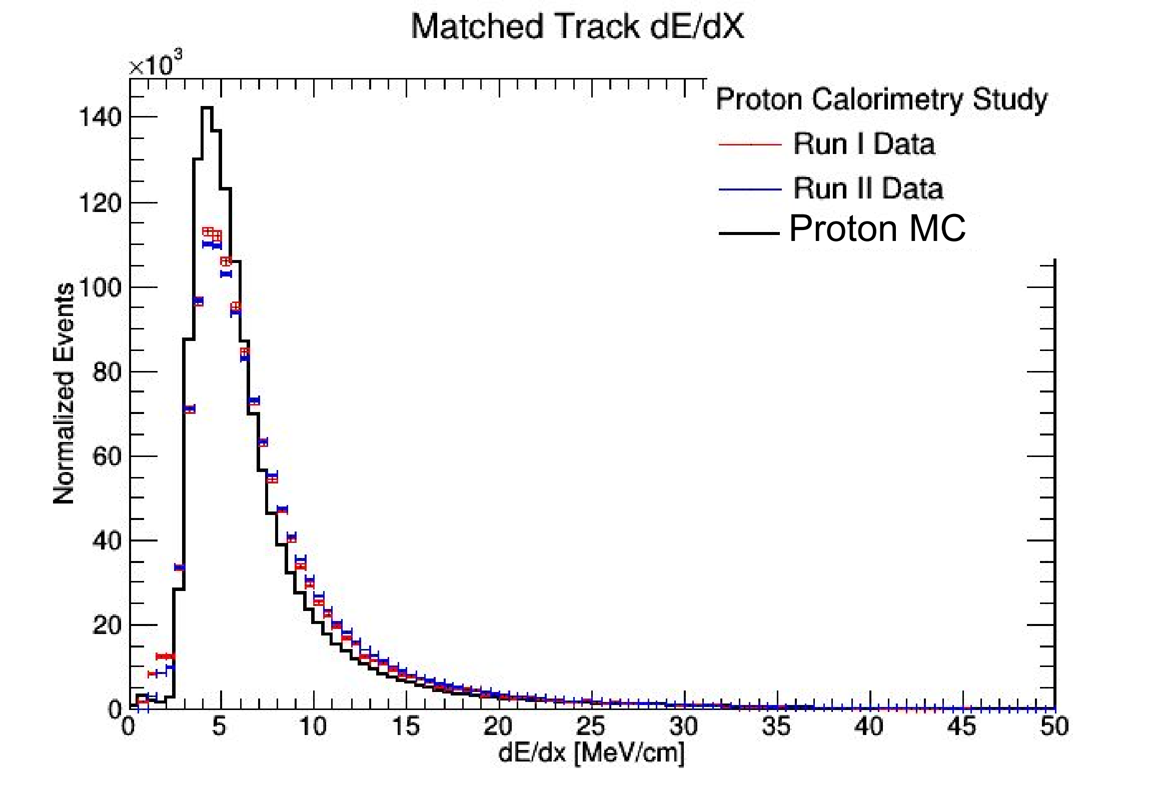


dE/dX for Run-I and Run-II data

(Since this is the sample which was used to tune the calorimetry, there agreement is by construction)

dE/dx Data and MC

This plot is to show the agreement between the data and the MC.



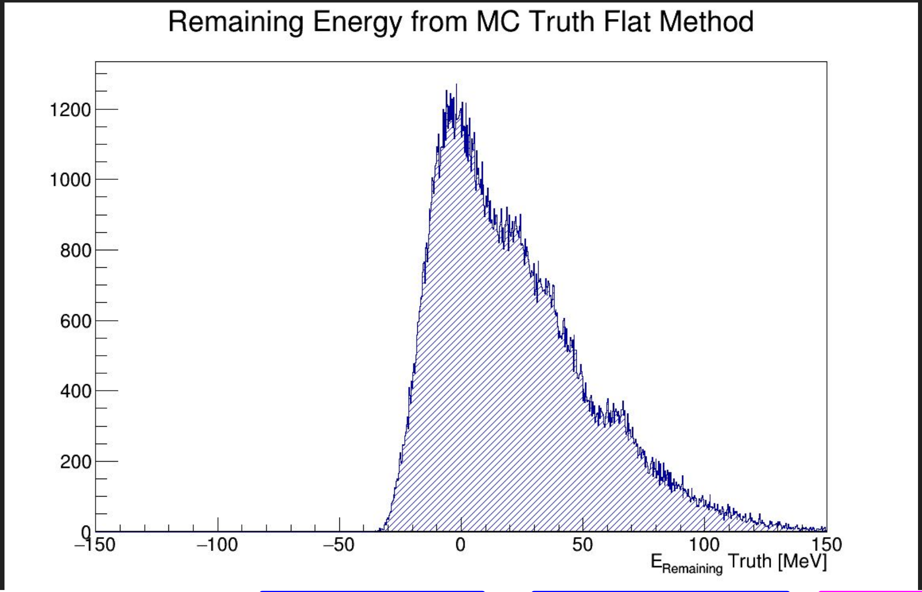
How the Flat Method Performs on MC and Data

- **We can now check to see how using the flat estimate of the energy loss upstream does on both the MC and data sample of stopping protons**

$$E_{\text{Remaining}} = KE_i^{\text{WC4}} - E_{\text{Deposited}}^{\text{TPC}} - E_{\text{Loss}}^{\text{Flat}}$$

- **For MC, we have perfect information for the initial kinetic energy, and the energy deposited in the TPC**
  - We also have reconstructed energy deposited in the TPC, so we can see the effect of using reco information
- **For data, we only have reconstructed information...but we can compare how that looks to the MC to make sure they are similar**

Energy Remaining (MC)

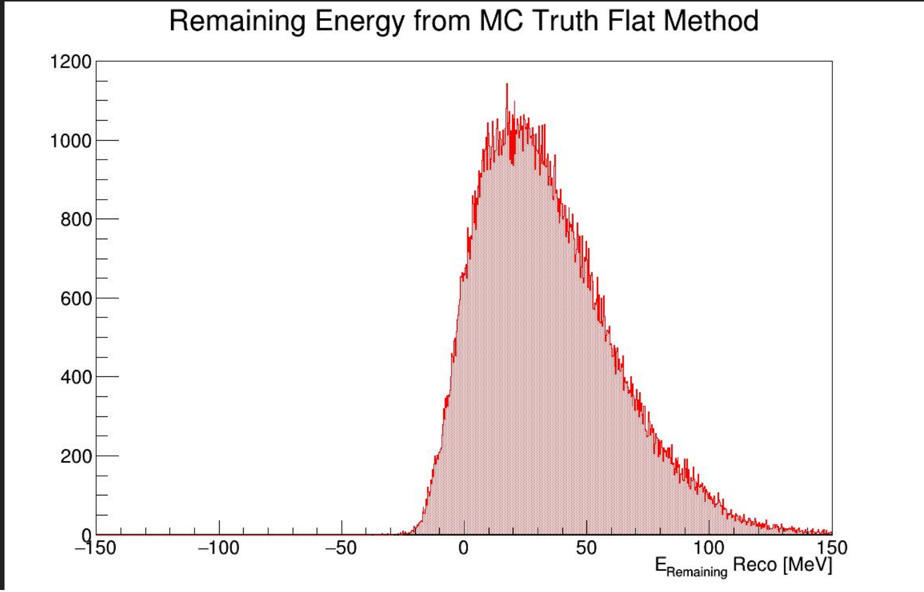


$$E_{\text{Remaining}} = \boxed{KE_i^{\text{WC4}}} - \boxed{E^{\text{TPC}}_{\text{Deposited}}} - \boxed{E^{\text{Flat}}_{\text{Loss}}}$$

Using truth information

Using "flat" number

Energy Remaining (MC)



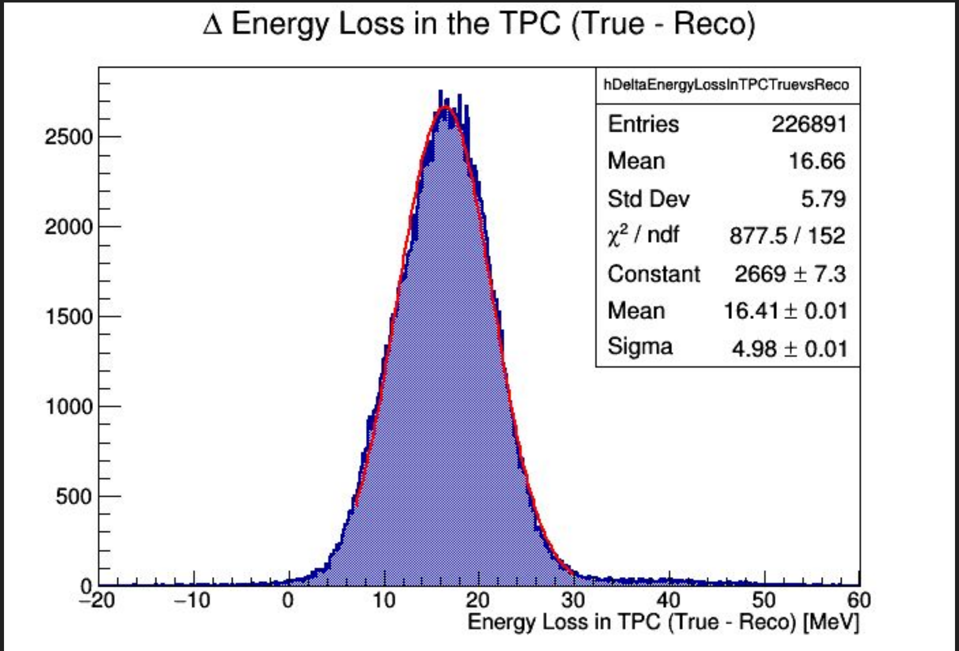
$$E_{\text{Remaining}} = \boxed{KE_i^{\text{WC4}}} - \boxed{E^{\text{TPC}}_{\text{Deposited}}} - \boxed{E^{\text{Flat}}_{\text{Loss}}}$$

Using truth information

Using reco information

Using "flat" number

Aside: How well does reconstructed energy in the TPC do?

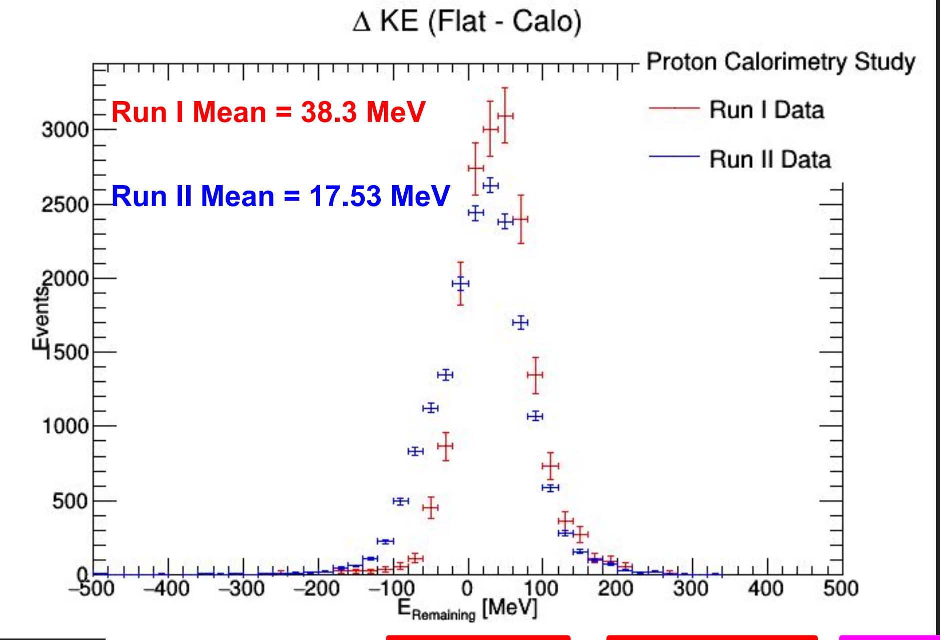


$$\Delta E^{\mathrm{TPC}}_{\mathrm{Deposited}} = E^{\mathrm{TPC}}_{\mathrm{True\ Deposited}} - E^{\mathrm{TPC}}_{\mathrm{Reco\ Deposited}}$$

$$E^{\mathrm{TPC}}_{\mathrm{Reco\ Deposited}} = \sum \left(\frac{dE}{dX}\right) \times (track\ pitch)$$

This gives some sense of how good we will ever do given the current reconstruction of the tracks dE/dX

Energy Remaining (Data)



$$E_{Remaining} = \boxed{KE_i^{WC4}} - \boxed{E_{Deposited}^{TPC}} - \boxed{E_{Loss}^{Flat}}$$

Using WC Reco

Using reco information

Using "flat" number

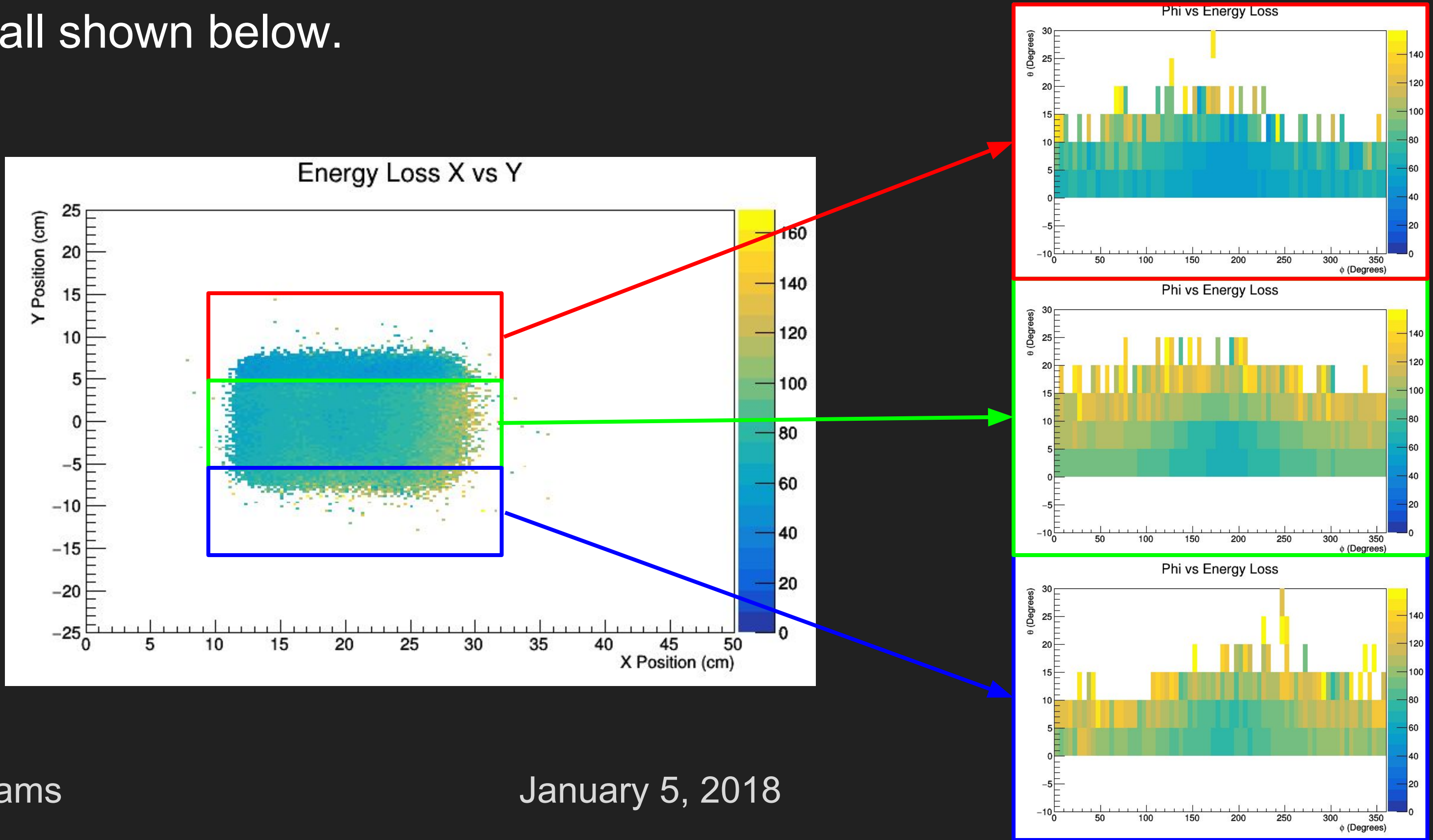
New Upstream Energy Loss Model: The Map Method

Our First Idea

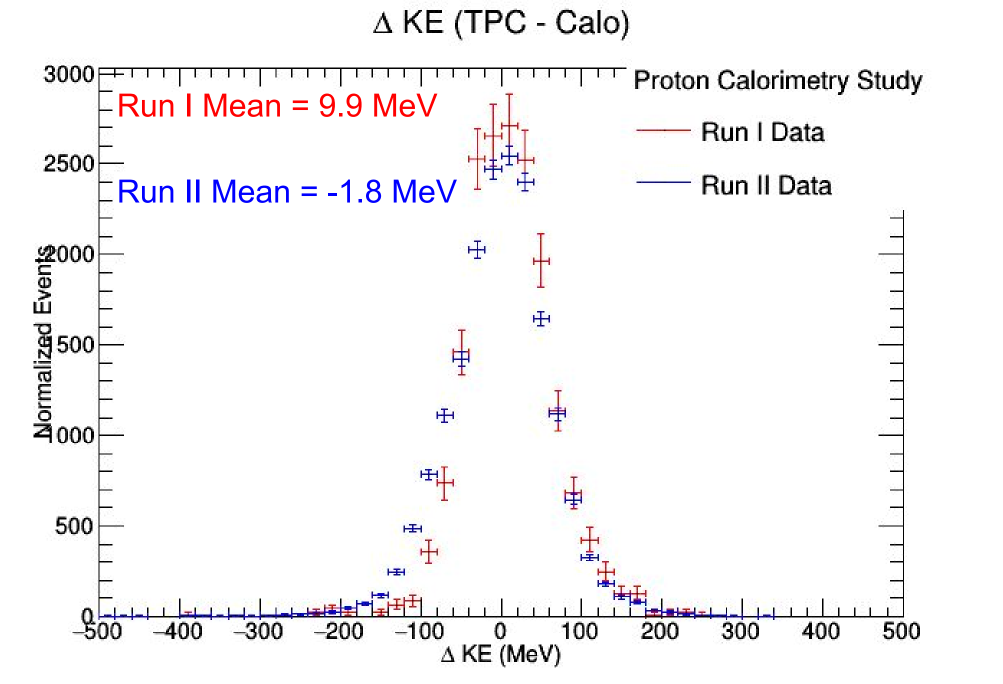
(which we are improving on here)

The Previous Map

The previous map that I presented on over the summer was broken into three maps which are all shown below.



Previously Presented Map Method Results



This is a plot of the energy remaining when using the **OLD** Map Method on data for both Run I and Run II.

$$KE^{TPC} = KE_i^{WC4} - E_{Map}$$

$$KE^{Calo} = \sum_i \left(\frac{dE}{dx}\right)_i \times (TrackPitch)_i$$

$$\Delta KE = KE^{TPC} - KE^{Calo}$$

Suggested Changes

At the collaboration meeting over the summer, suggestions for how to possibly improve the map method were made, which were:

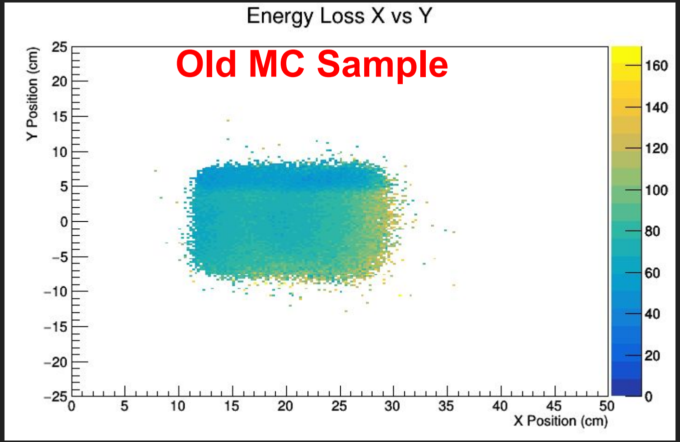
1. Generate a new MC sample of protons shot through a larger area of the TPC Cryostat’s upstream face.
2. Make a finer grained map method.

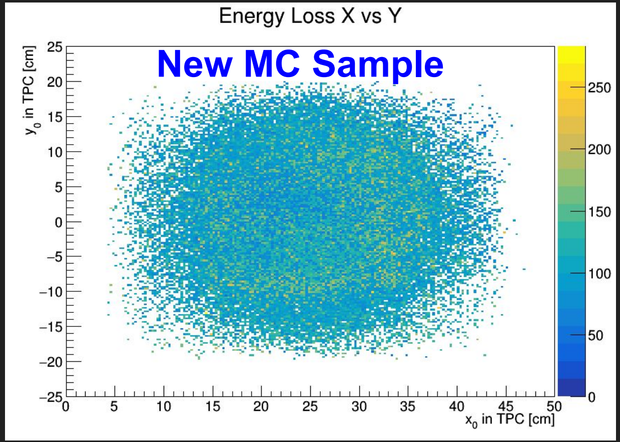
Generating a New MC Sample...

Making a New Sample of Stopping Protons

Changes from the old MC sample:

1. A newer version of LArIATSoft was used.
2. The protons were given a wider gaussian distribution over their spherical coordinate angles, which means that they will have a larger area of initial position with the TPC's upstream face.

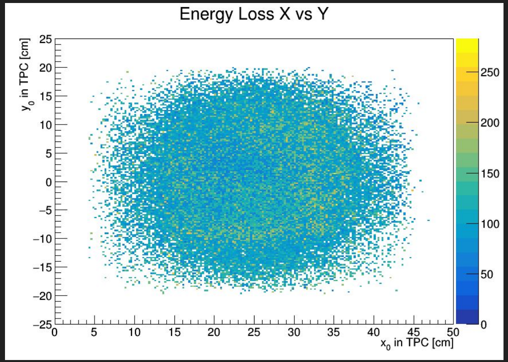


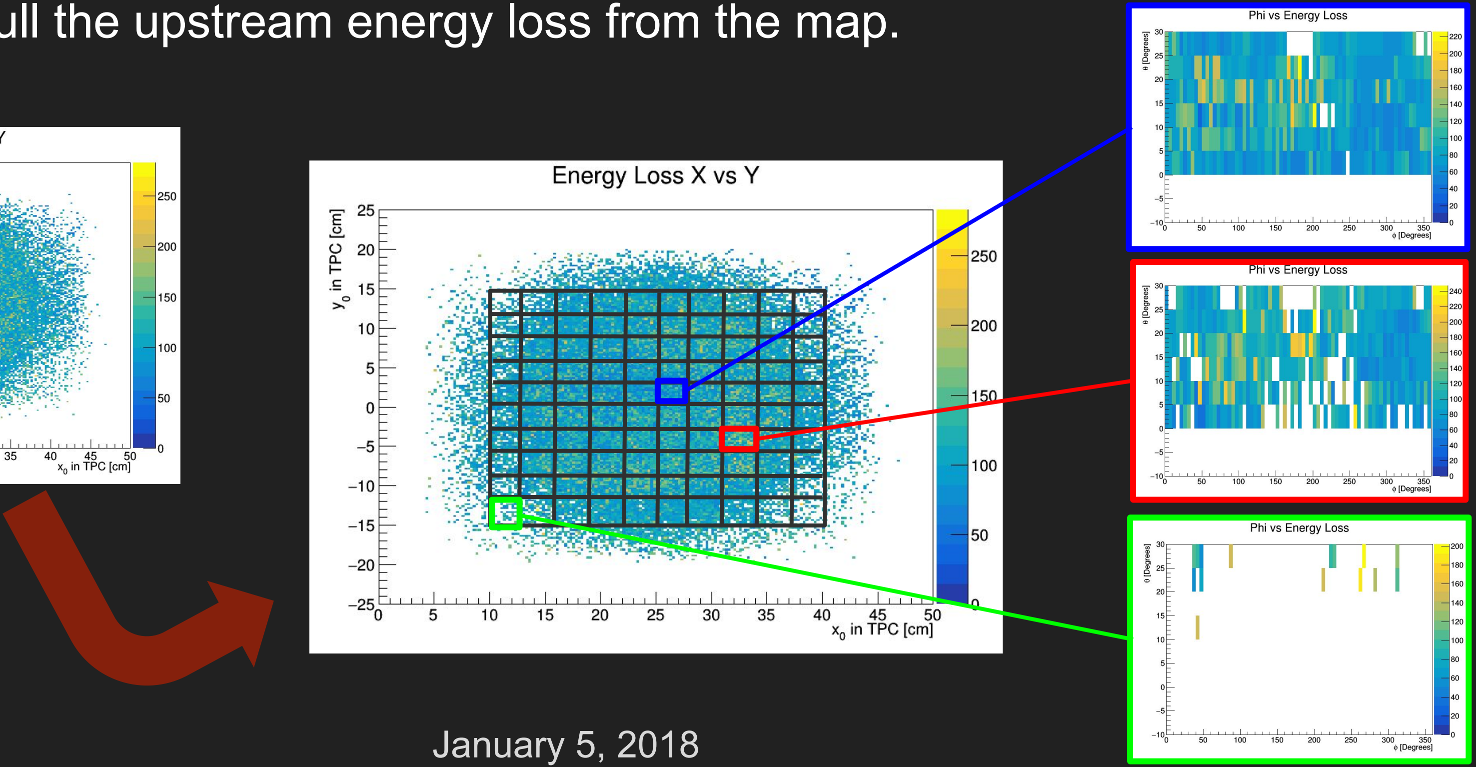


The New Map for the Map Method

The New Map

The new map is broken into 100 individual upstream energy loss maps based off of the proton's initial x and y coordinates inside of the TPC and then using the theta and phi of the proton to pull the upstream energy loss from the map.

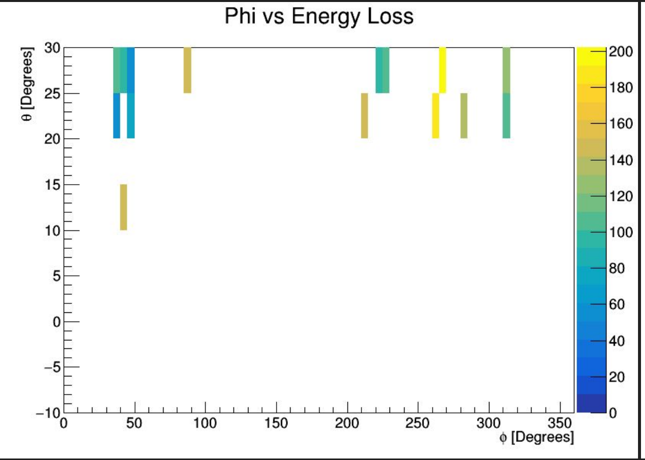


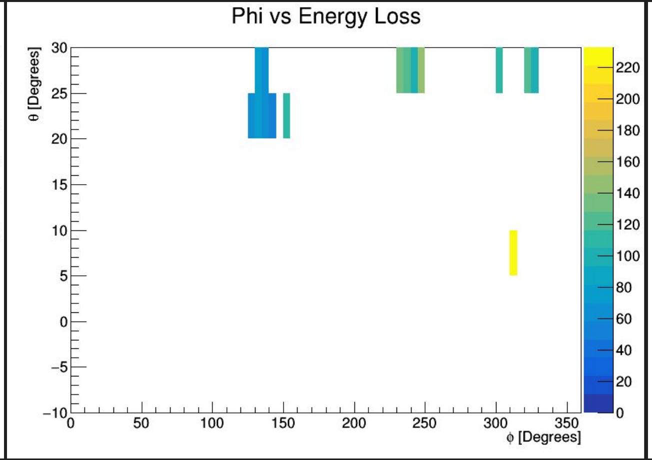


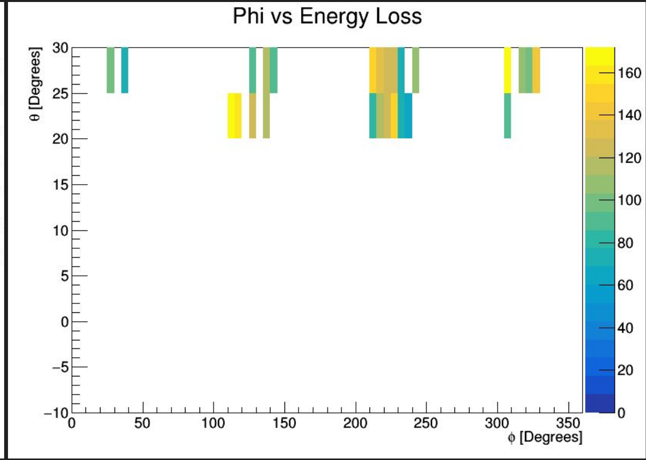
Upstream Energy Loss Pulling From Map

Because of the large amount of maps, there are a few maps that are very sparsely populated. Which means that most of the time, if a proton's initial x and y position caused a sparsely populated theta and phi map to be pulled from, the upstream energy loss that would be pulled from the map the majority of the time would be zero…

To deal with that I pull from the true energy loss distribution.

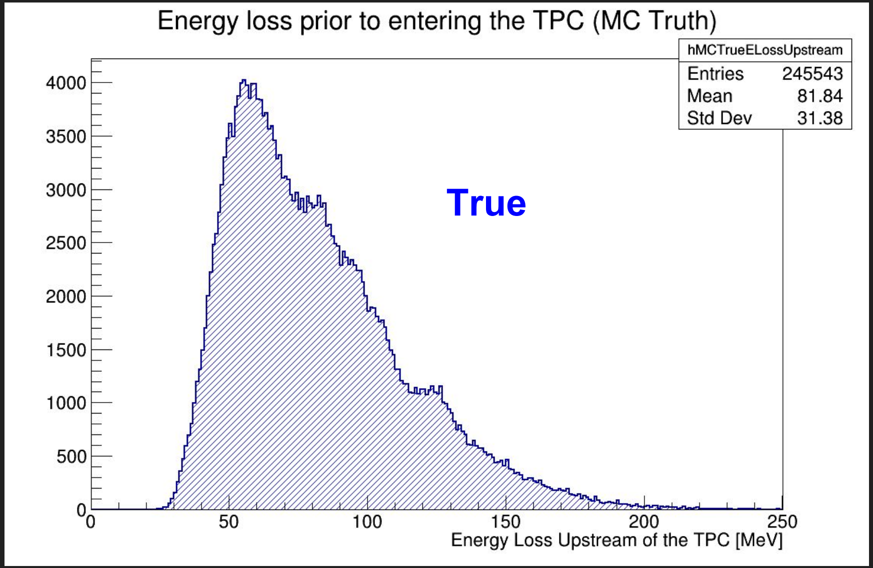


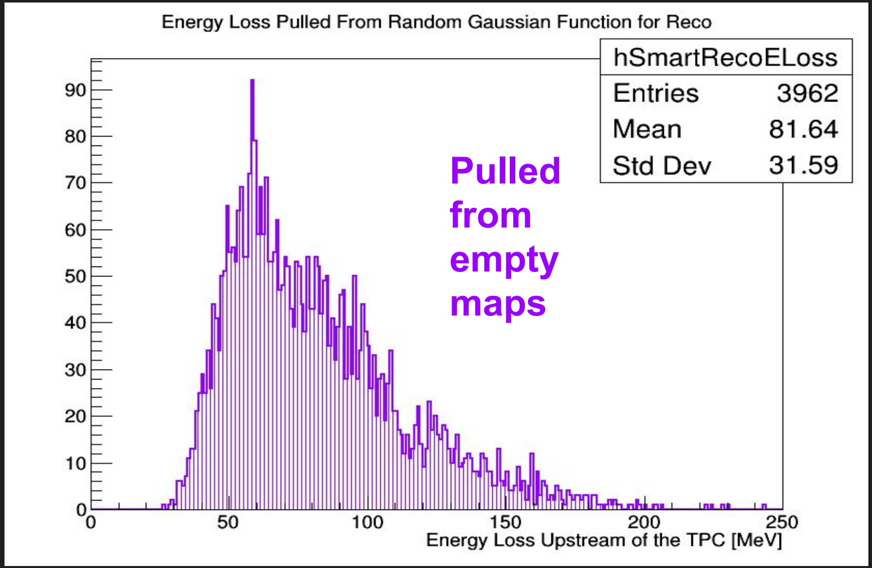




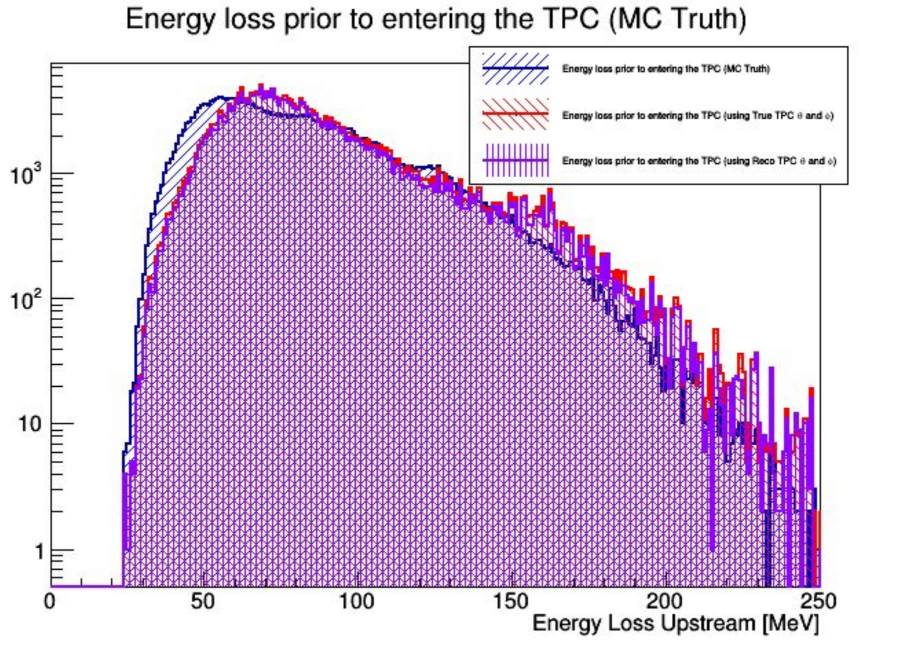
New Way of Grabbing from an Empty Bin

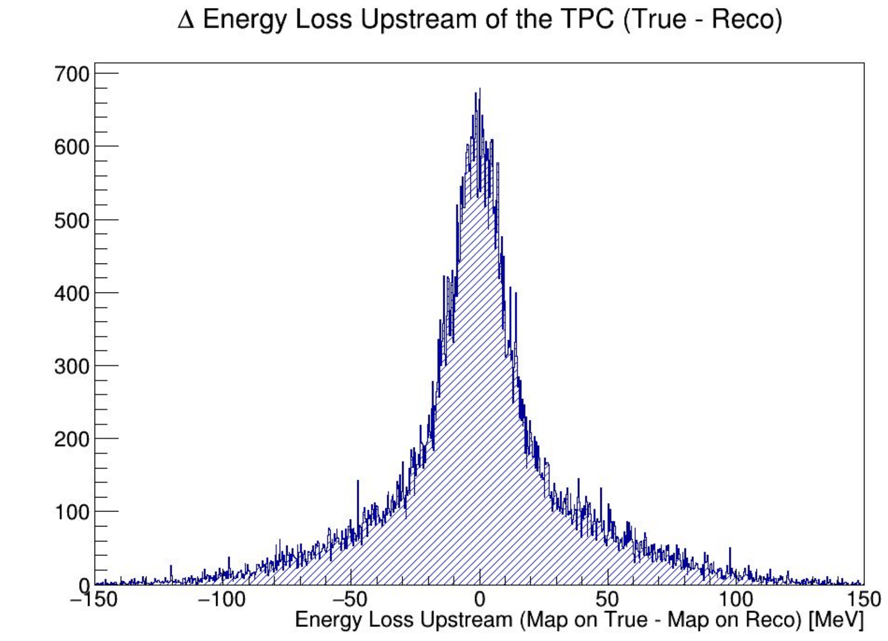
If you grab an energy loss from an empty bin, instead of returning zero, we pull randomly from the MC true energy loss upstream histogram (plot on the left). The histogram of pulled energy losses from an empty map bin is shown on the bottom right





Upstream Energy Loss of the New MC

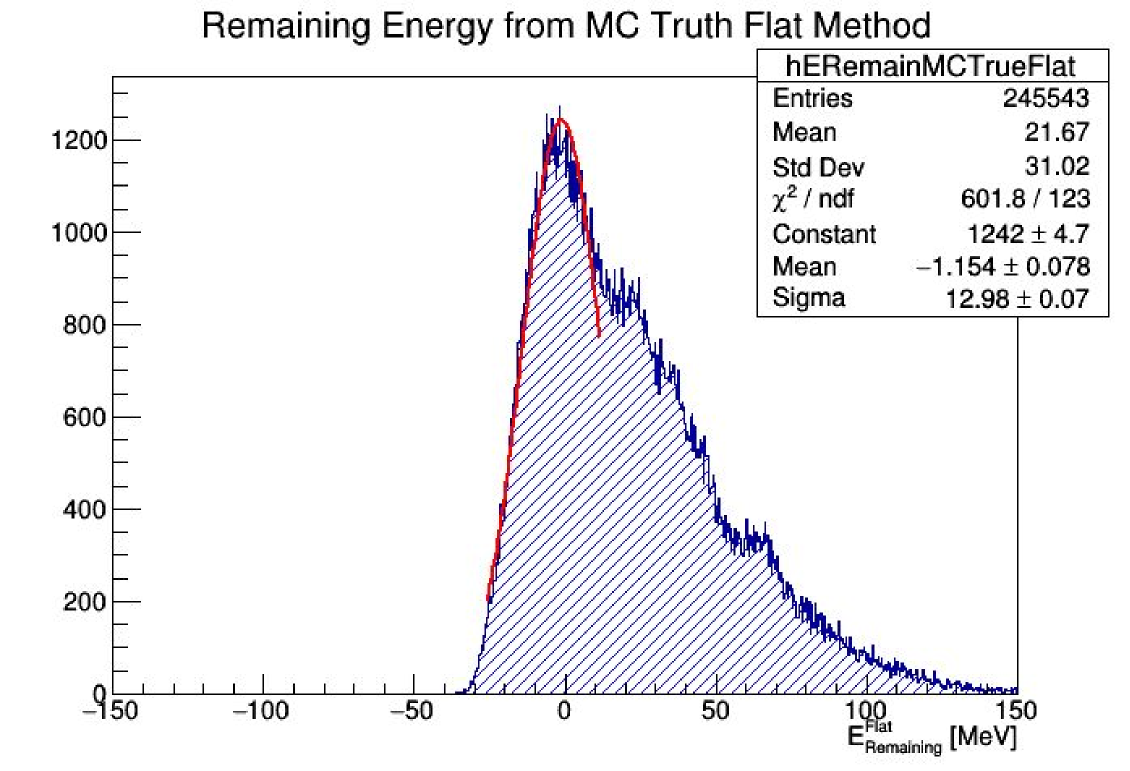




The left plot is the upstream energy loss by the map method using MC True theta and phi, using reconstructed theta and phi, and plotted with the MC True energy loss upstream. The right plot shows the difference between the upstream energy loss from the map method using MC True theta and phi and the Reco theta and phi. Ideally, the right plot would be a delta function with a single sharp peak at 0 MeV.

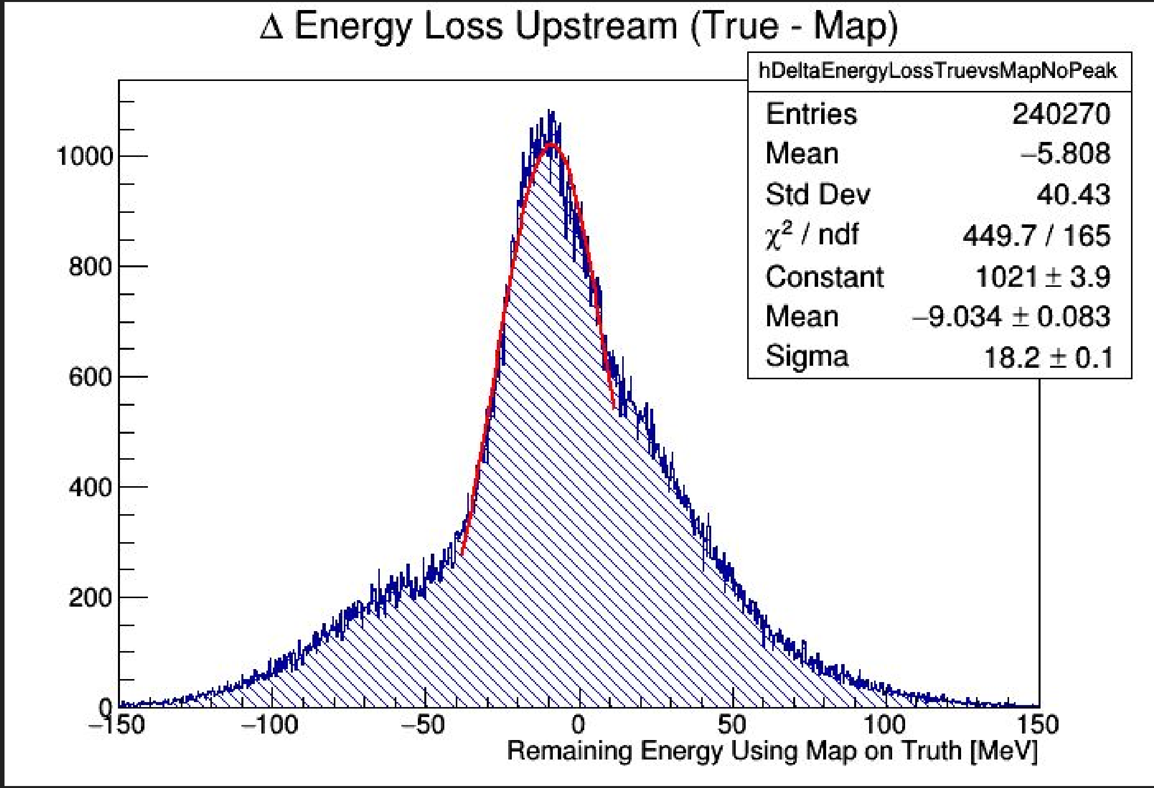
Using Flat Method on Truth Parameters

The plot on the right is the remaining energy of the protons whenever the Flat Method. Ideally, this would be a delta function at 0 MeV.



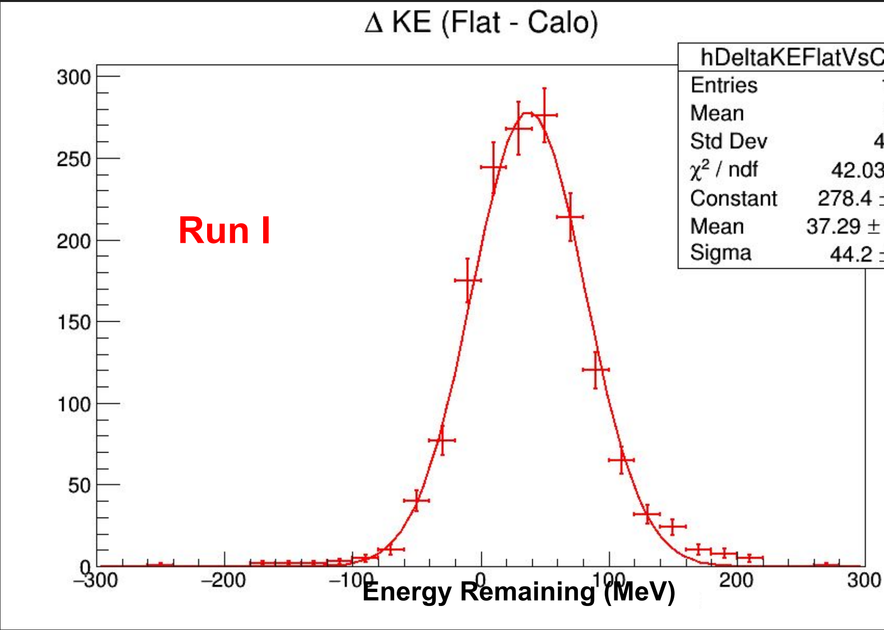
Using Map Method on Truth Parameters

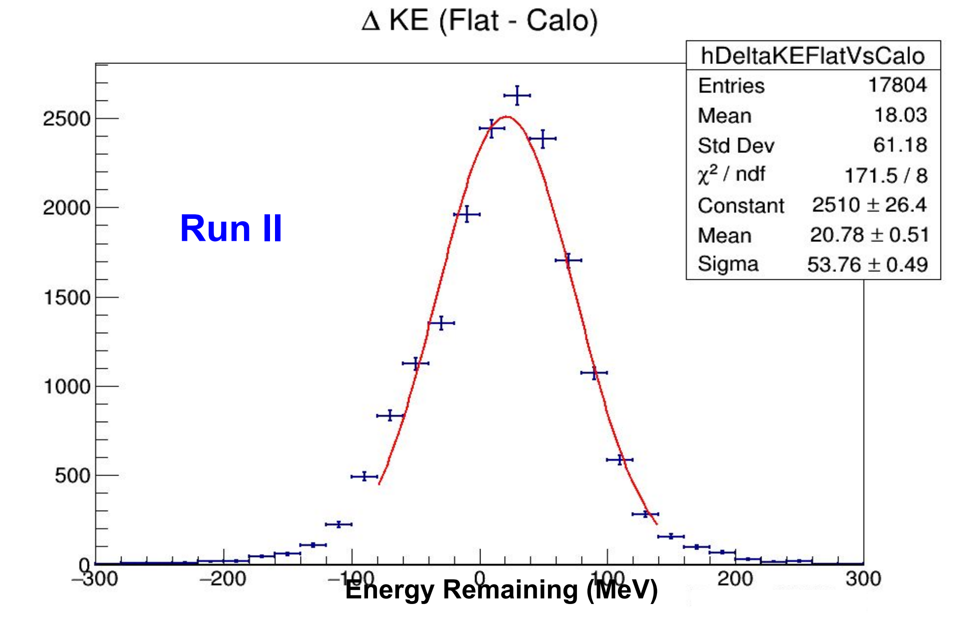
The plot on the right is the remaining energy of the protons whenever the Map Method is used using the MC True theta and phi parameters. Ideally, this would be a delta function at 0 MeV.



Assessing the Map Method’s Performance

Energy Remaining using the flat correction





$$E_{\text{Remaining}} = KE_i^{\text{WC4}} - E_{\text{Deposited}}^{\text{TPC}} - E_{\text{Loss}}^{\text{Flat}}$$

$$E_{Flat} = 60.01 \text{ MeV}$$

Energy Remaining for Run-I and Run-II data using the flat correction

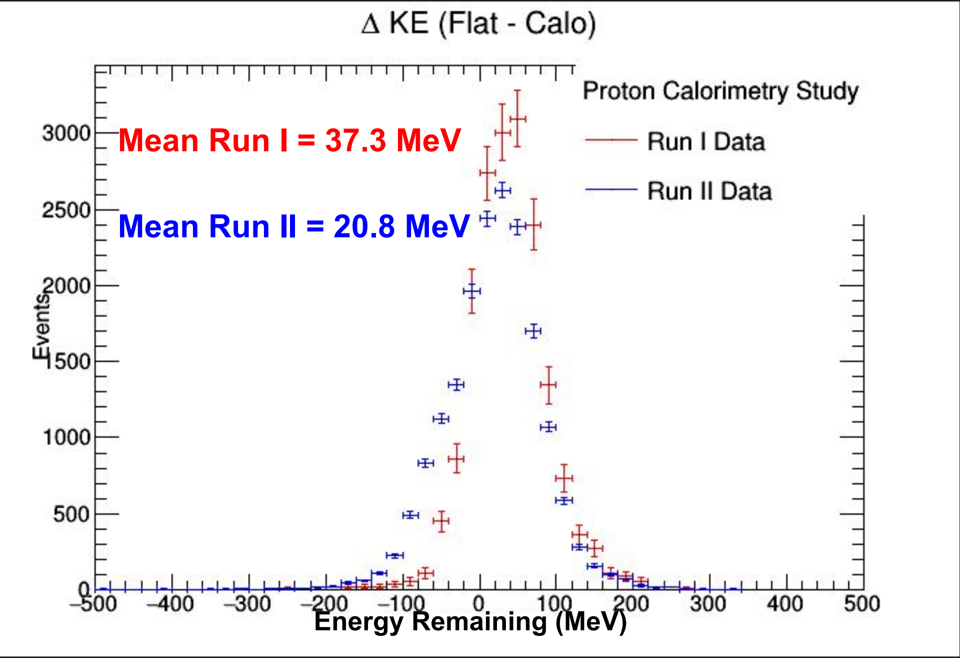
Run-I: Mean ~ 37 MeV, RMS ~ 44 MeV
Run-II Mean ~ 21 MeV, RMS ~ 54 MeV

Energy Remaining using the flat correction

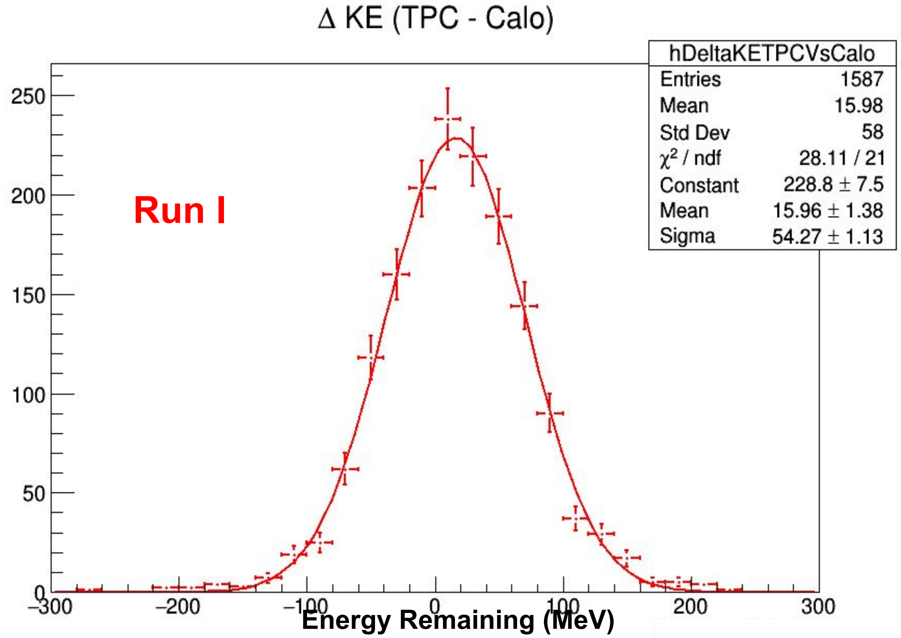
Plotting Run-I and Run-II at the same time and normalizing them to the same number of events

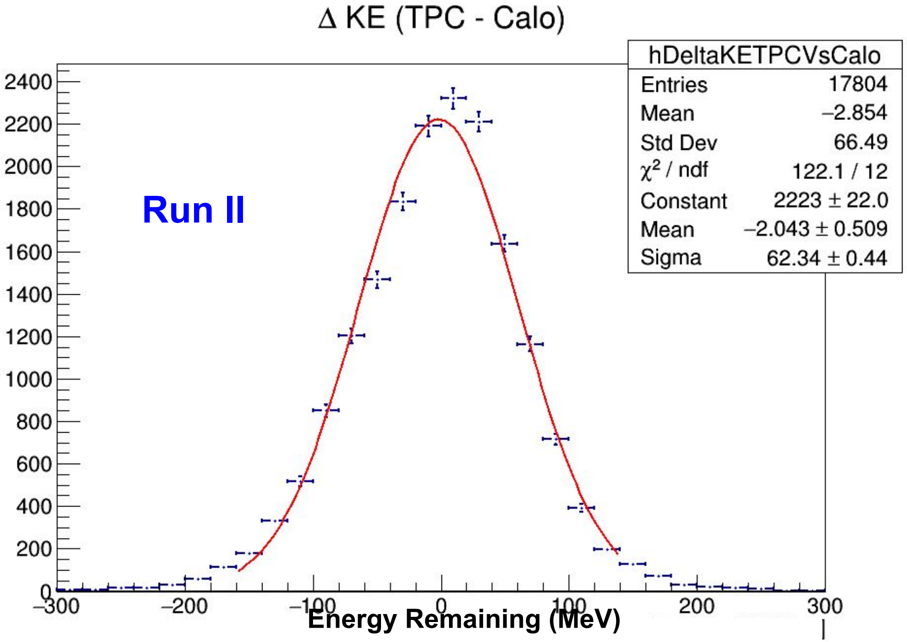
$$E_{\text{Remaining}} = KE_i^{\text{WC4}} - E_{\text{Deposited}}^{\text{TPC}} - E_{\text{Loss}}^{\text{Flat}}$$

$$E_{Flat} = 60.01 \text{ MeV}$$



Energy Remaining using the map correction



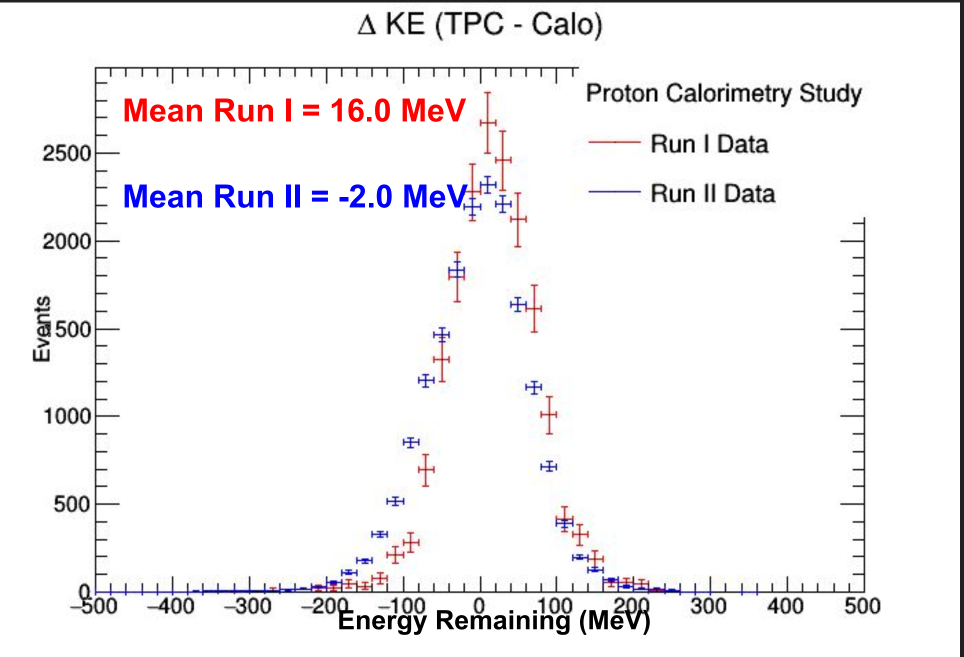


$$E_{\text{Remaining}} = KE_i^{\text{WC4}} - E_{\text{Deposited}}^{\text{TPC}} - E_{\text{Loss}}^{\text{Map}}$$

Energy Remaining for Run-I and Run-II data using the map correction

Run-I: Mean ~ 15 MeV, RMS ~ 54 MeV
Run-II Mean ~ -2 MeV, RMS ~ 62 MeV

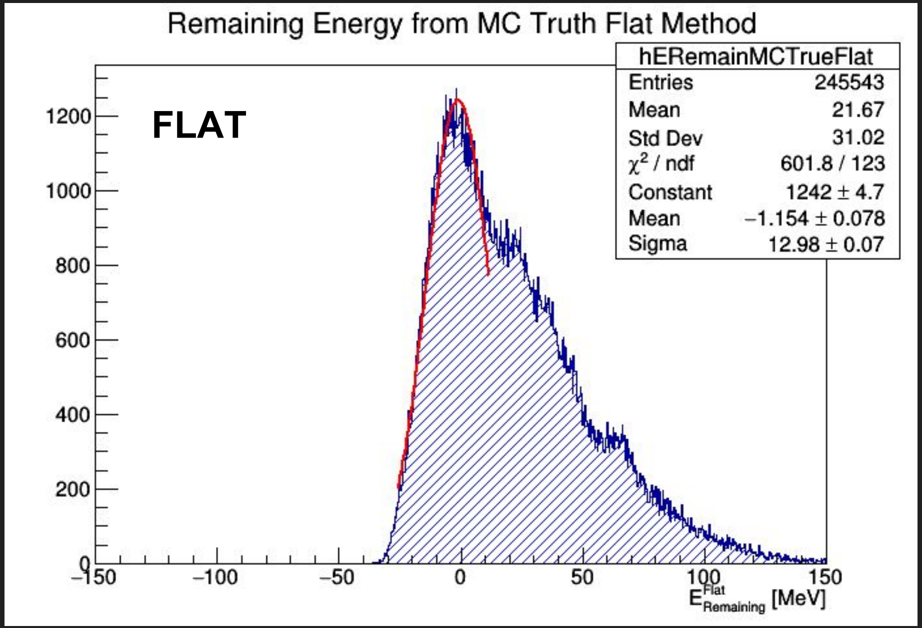
Delta KE (TPC - Calo)

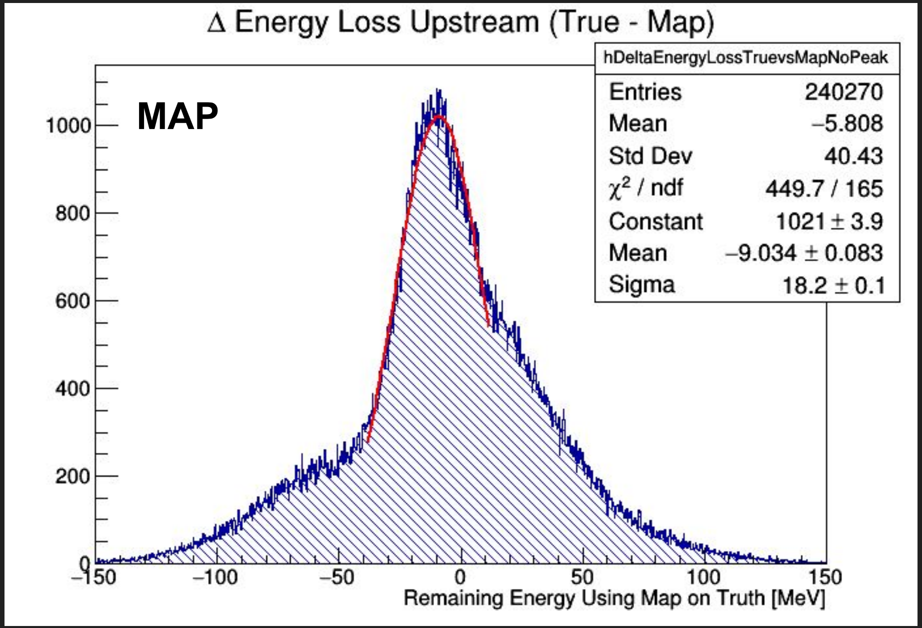


Plotting Run-I and Run-II at the same time and normalizing them to the same number of events

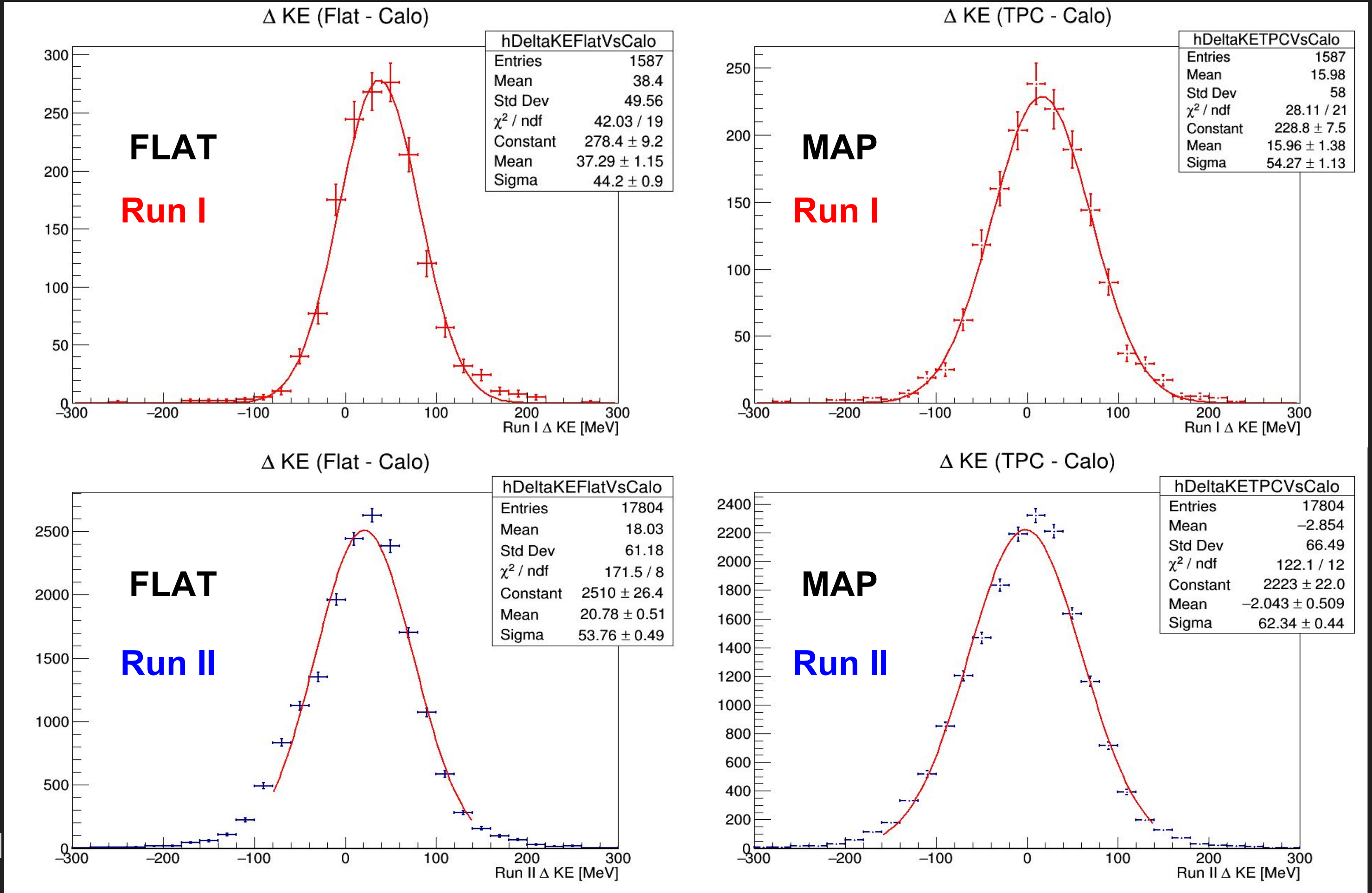
$$E_{\text{Remaining}} = KE_i^{\text{WC4}} - E_{\text{Deposited}}^{\text{TPC}} - E_{\text{Loss}}^{\text{Map}}$$

Comparison MC





Comparison

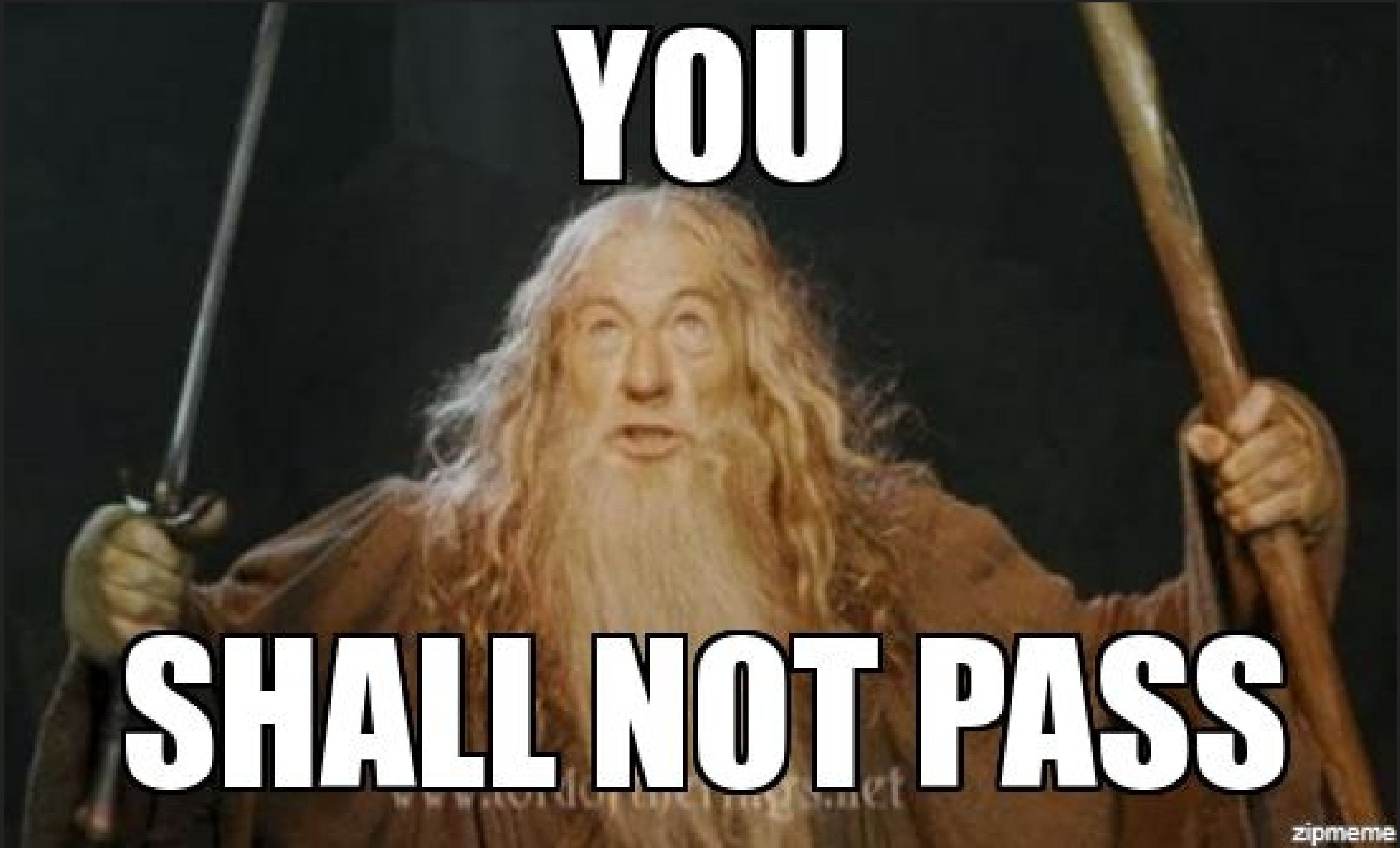

Δ KE (Flat - Calo)
hDeltaKEFlatVsCalo
Entries 1587
Mean 38.4
Std Dev 49.56
χ² / ndf 42.03 / 19
Constant 278.4 ± 9.2
Mean 37.29 ± 1.15
Sigma 44.2 ± 0.9
FLAT
Run I
Run I Δ KE [MeV]
Δ KE (TPC - Calo)
hDeltaKETPCVsCalo
Entries 1587
Mean 15.98
Std Dev 58
χ² / ndf 28.11 / 21
Constant 228.8 ± 7.5
Mean 15.96 ± 1.38
Sigma 54.27 ± 1.13
MAP
Run I
Run I Δ KE [MeV]
Δ KE (Flat - Calo)
hDeltaKEFlatVsCalo
Entries 17804
Mean 18.03
Std Dev 61.18
χ² / ndf 171.5 / 8
Constant 2510 ± 26.4
Mean 20.78 ± 0.51
Sigma 53.76 ± 0.49
FLAT
Run II
Run II Δ KE [MeV]
Δ KE (TPC - Calo)
hDeltaKETPCVsCalo
Entries 17804
Mean −2.854
Std Dev 66.49
χ² / ndf 122.1 / 12
Constant 2223 ± 22.0
Mean −2.043 ± 0.509
Sigma 62.34 ± 0.44
MAP
Run II
Run II Δ KE [MeV]

Conclusions

- **Worked to develop a different method to estimate the energy loss upstream of the TPC using reconstructed quantities**
  - Studied the performance of this “map” based method using stopping protons in MC and data
- **The method as it stands now shows a marginal improvement over the simple flat based correction**
  - The larger RMS in the energy remaining plots is pause for concern as this might lead to a larger uncertainty in the energy reconstruction
- **Next steps:**
  - Need to think about a way to improve the overall method

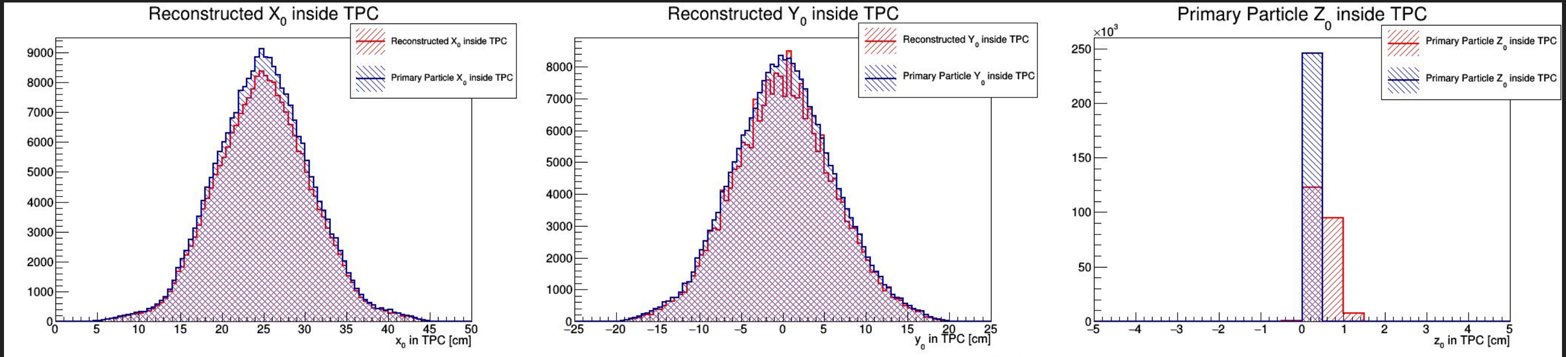
Thank you!

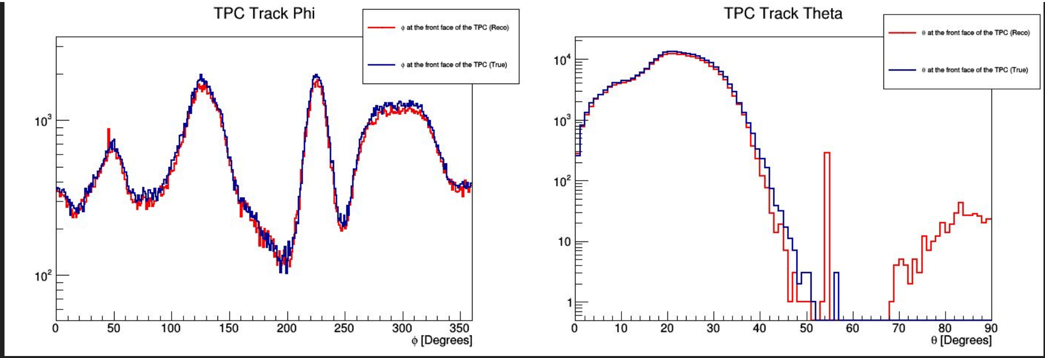
Back-up Slides

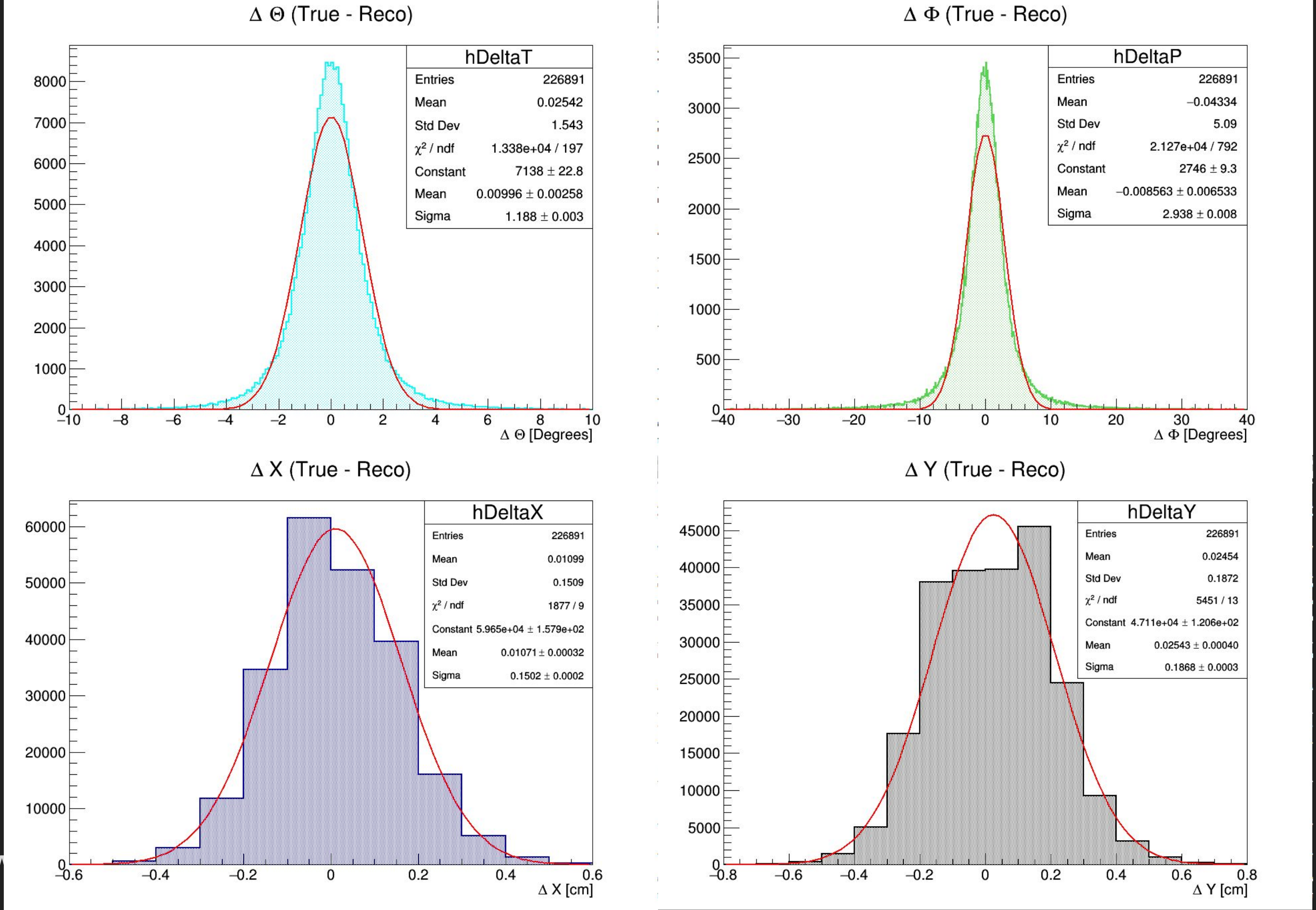


The Idea of the Map Method

The idea of the map method is simple: find parameters that we reconstruct well and then use that parameter as a way of pulling an energy loss from a map for the upstream region of the beamline. These are the parameters we used:

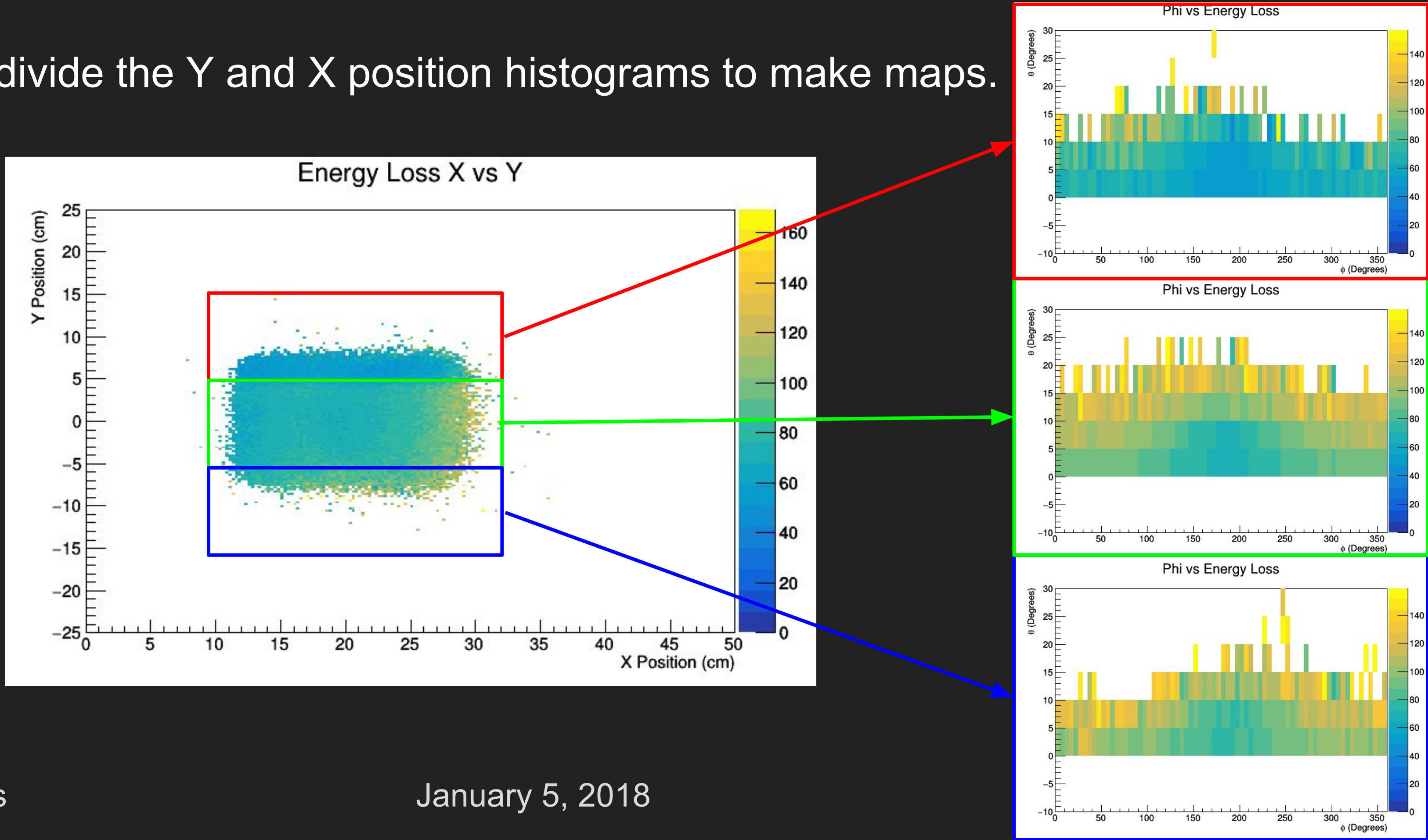


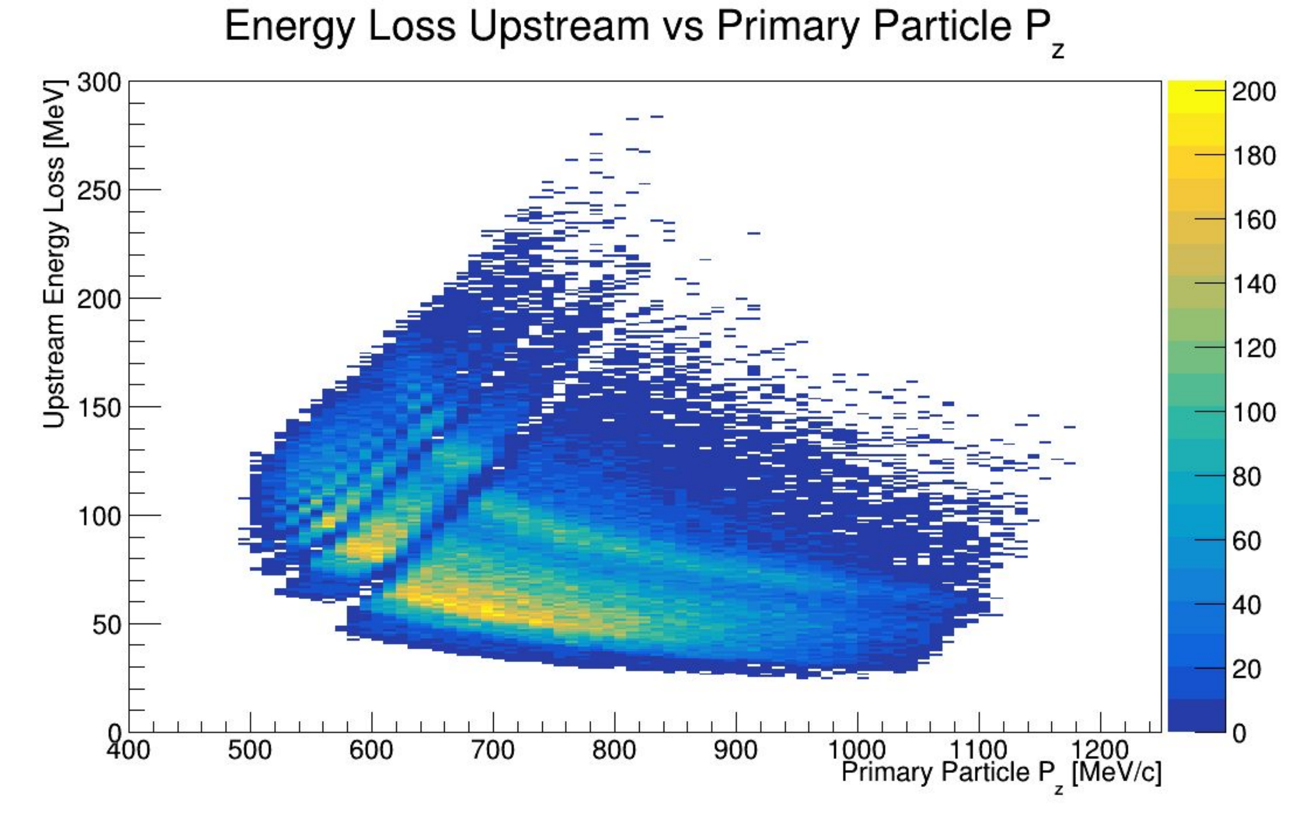



Δ Θ (True - Reco)
hDeltaT
Entries 226891
Mean 0.02542
Std Dev 1.543
χ² / ndf 1.338e+04 / 197
Constant 7138 ± 22.8
Mean 0.00996 ± 0.00258
Sigma 1.188 ± 0.003
Δ Θ [Degrees]
Δ Φ (True - Reco)
hDeltaP
Entries 226891
Mean −0.04334
Std Dev 5.09
χ² / ndf 2.127e+04 / 792
Constant 2746 ± 9.3
Mean −0.008563 ± 0.006533
Sigma 2.938 ± 0.008
Δ Φ [Degrees]
Δ X (True - Reco)
hDeltaX
Entries 226891
Mean 0.01099
Std Dev 0.1509
χ² / ndf 1877 / 9
Constant 5.965e+04 ± 1.579e+02
Mean 0.01071 ± 0.00032
Sigma 0.1502 ± 0.0002
Δ X [cm]
Δ Y (True - Reco)
hDeltaY
Entries 226891
Mean 0.02454
Std Dev 0.1872
χ² / ndf 5451 / 13
Constant 4.711e+04 ± 1.206e+02
Mean 0.02543 ± 0.00040
Sigma 0.1868 ± 0.0003
Δ Y [cm]

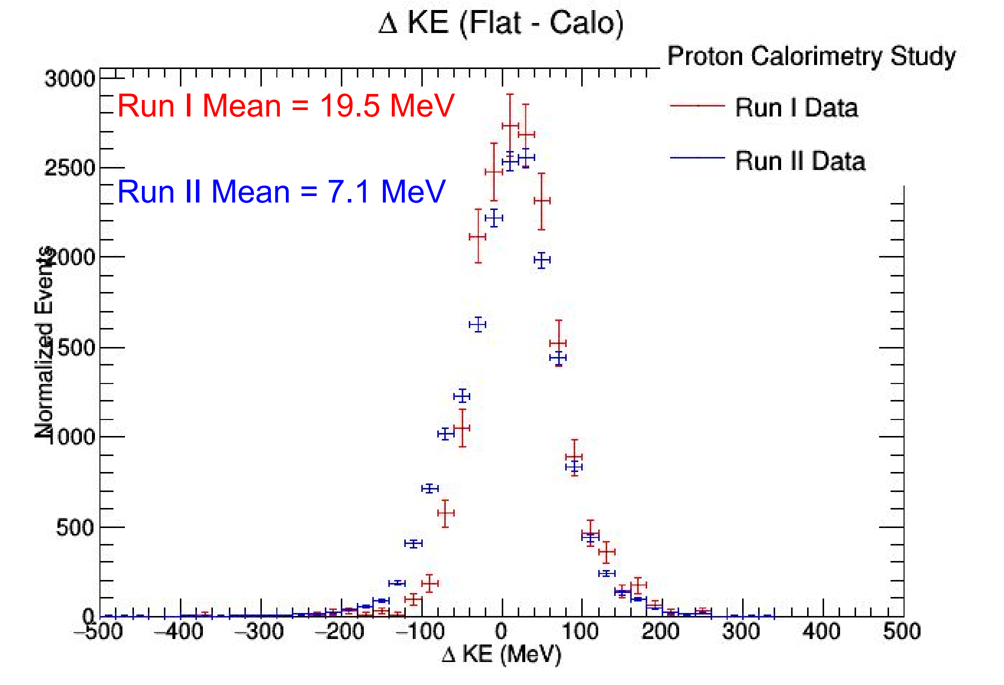
Depiction of the Map Method

We then subdivide the Y and X position histograms to make maps.




Energy Loss Upstream vs Primary Particle P_z
Upstream Energy Loss [MeV]
300
250
200
150
100
50
0
400
500
600
700
800
900
1000
1100
1200
Primary Particle P_z [MeV/c]
200
180
160
140
120
100
80
60
40
20
0

Previously Presented Flat Method Results



This is a plot of the energy remaining when using the **OLD** Flat Method on data for both Run I and Run II.

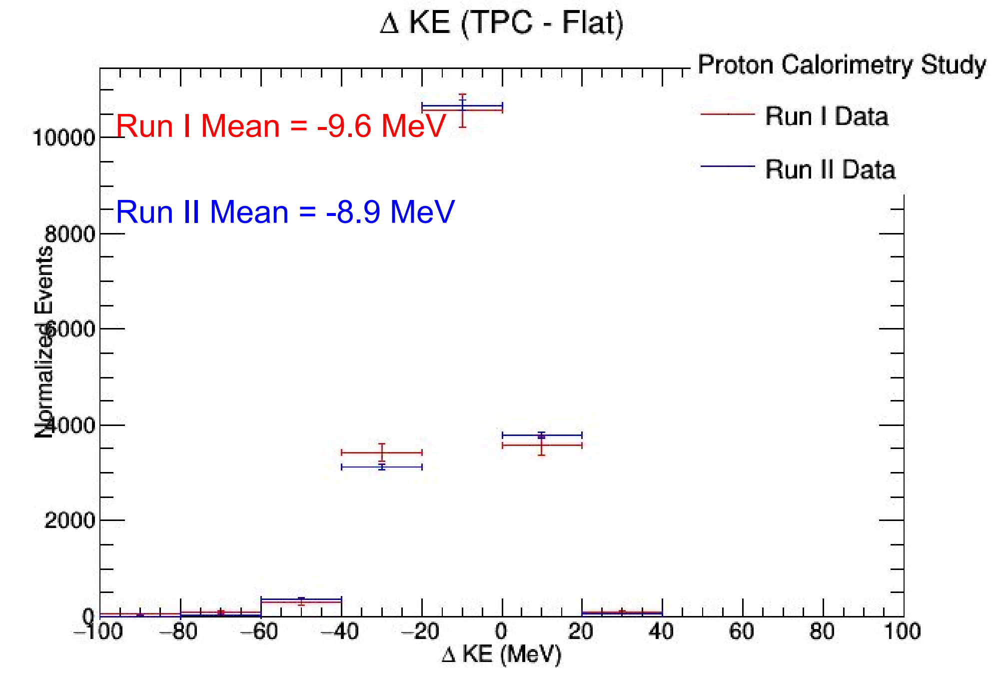
$$KE^{Flat} = KE_i^{WC4} - E_{Flat}$$

$$KE^{Calo} = \sum_i \left(\frac{dE}{dx}\right)_i \times (TrackPitch)_i$$

$$\Delta KE = KE^{Flat} - KE^{Calo}$$

$$E_{Flat} = 66.6 MeV$$

Previously Presented Map to Flat Method Results



This is a plot of the difference between the value the **OLD** Flat Method subtracted compared to what the **OLD** Map Method subtracted for the upstream region of the stopping proton sample of both Run I and Run II data.

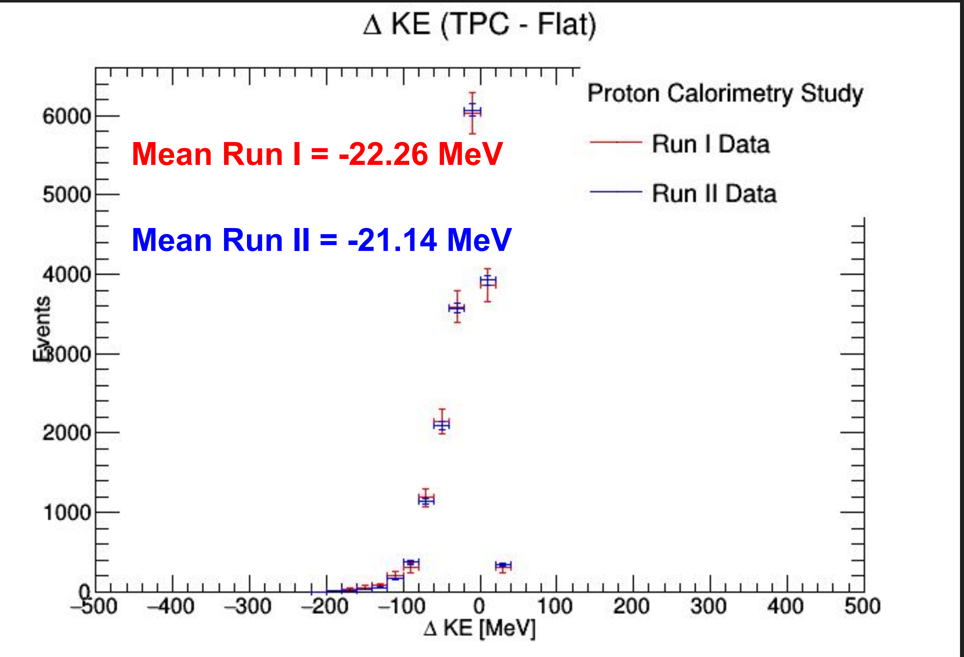
$$KE^{TPC} = KE_i^{WC4} - E_{Map}$$

$$KE^{Flat} = KE_i^{WC4} - E_{Flat}$$

$$\Delta KE = KE^{TPC} - KE^{Flat}$$

$$E_{Flat} = 66.6MeV$$

Delta KE (TPC - Flat)



$$KE^{TPC} = KE_i^{WC4} - E_{Map}$$

$$KE^{Flat} = KE_i^{WC4} - E_{Flat}$$

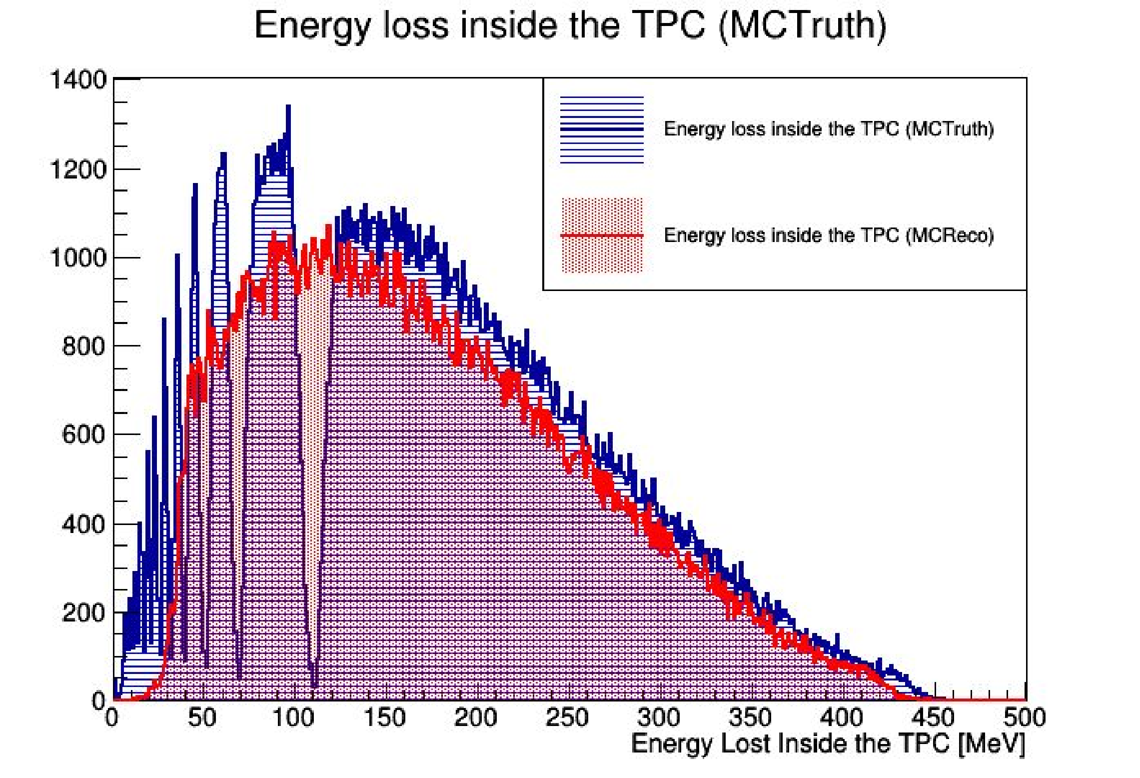
$$\Delta KE = KE^{TPC} - KE^{Flat}$$

$$E_{Flat} = 60.01 \text{ MeV}$$

Comparing Old and New:

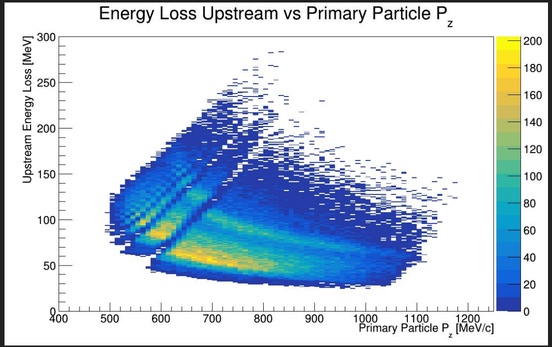
	Old MC	New MC
Version	v06.15.00	v06.44.00
# of Stopping Protons	161,231	245,543
# of Stopping Protons with Reco Info	156,084	226,891

Energy Loss Inside the TPC (Truth and Reco)

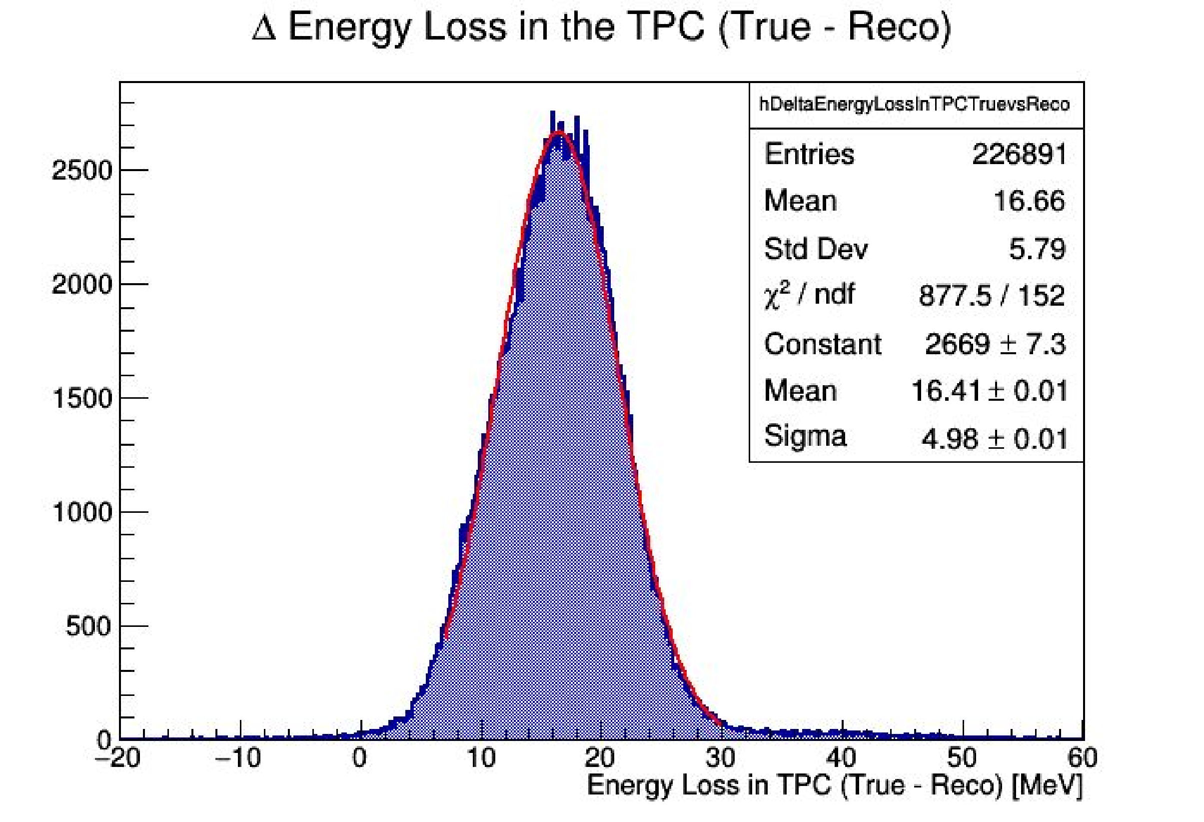


This is a look at the energy loss inside of the TPC for MC Truth and for Reco.

Truth has the strange ridge behavior which is seen in the plot below, too, and was also seen in the previous MC.



Energy Loss Inside the TPC (True - Reco)



This is the difference between the energy loss in the TPC from Truth and the energy loss in the TPC from Reco.

The plot shows that the Reco energy loss inside the TPC is actually too small on average of about ~16.4 MeV.