MEASUREMENT OF PION-ARGON TOTAL CROSS SECTIONS

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on behalf of the LArIAT Collaboration

Outline

1. Preliminaries
   - With what kind of raw data do we start?

2. The Reconstruction Chain:
   - How do we get quality events from our test beam data?

3. Analysis using LArIAT Data
   - How do we get a cross section from quality events?

4. Future* Work

Preliminaries: What does the raw data look like?

Run Number	Magnet Setting	Polarity
6100	60 A	Negative
6101	60 A	Negative
6102	60 A	Negative
6103	60 A	Negative
6104	60 A	Negative
6105	60 A	Negative
6111	60 A	Negative
6326	100 A	Negative

Altogether, there are ~4860 spills, with an average of ~20 events/spill, so we have maybe 97,200 total events

Pre-Analysis Reconstruction Chain Overview

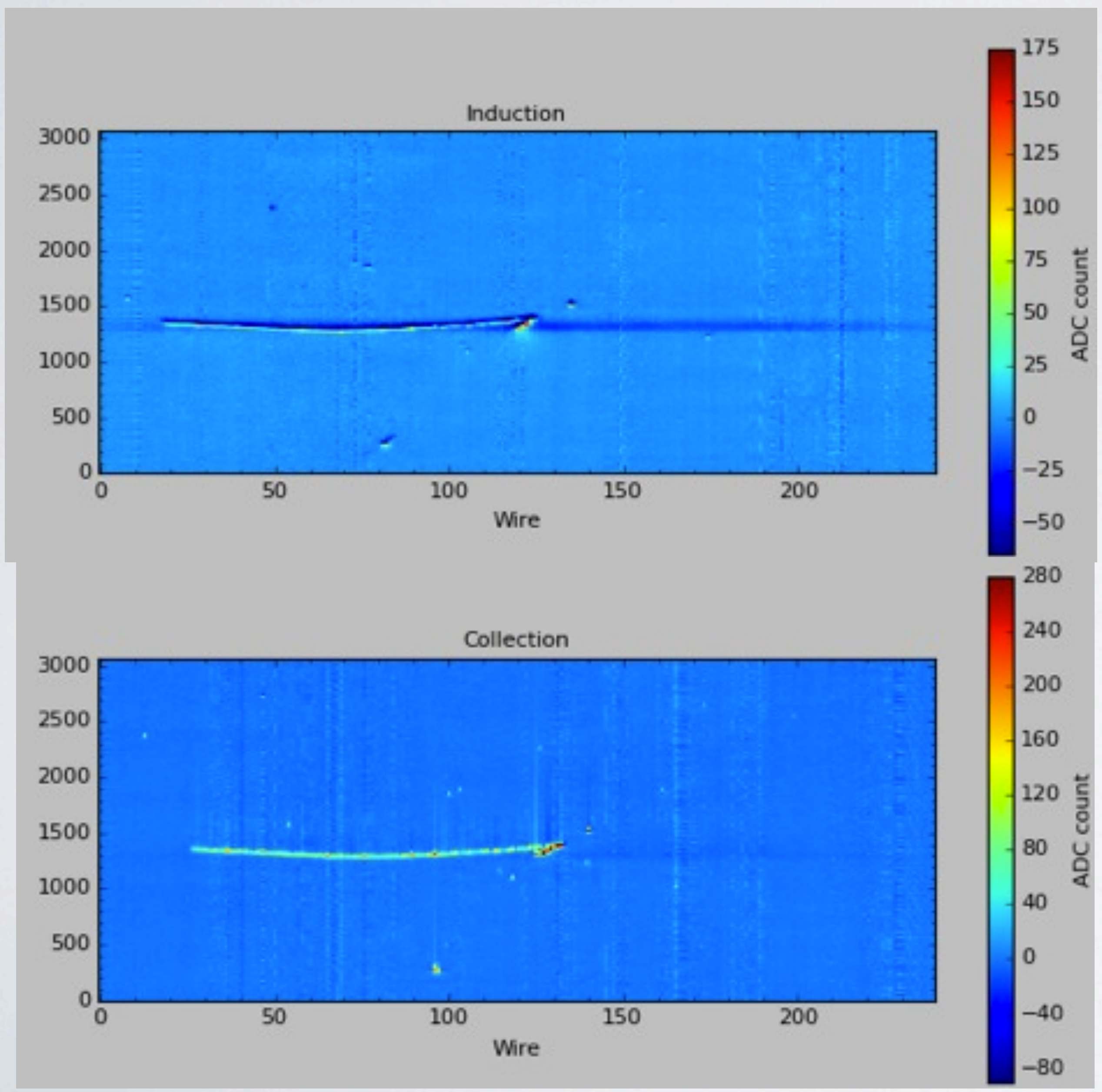
Big Question: How do we get quality events from our test beam data?

Quality events: events that we believe to contain pions and ones that allow us to associate initial energies with TPC tracks.

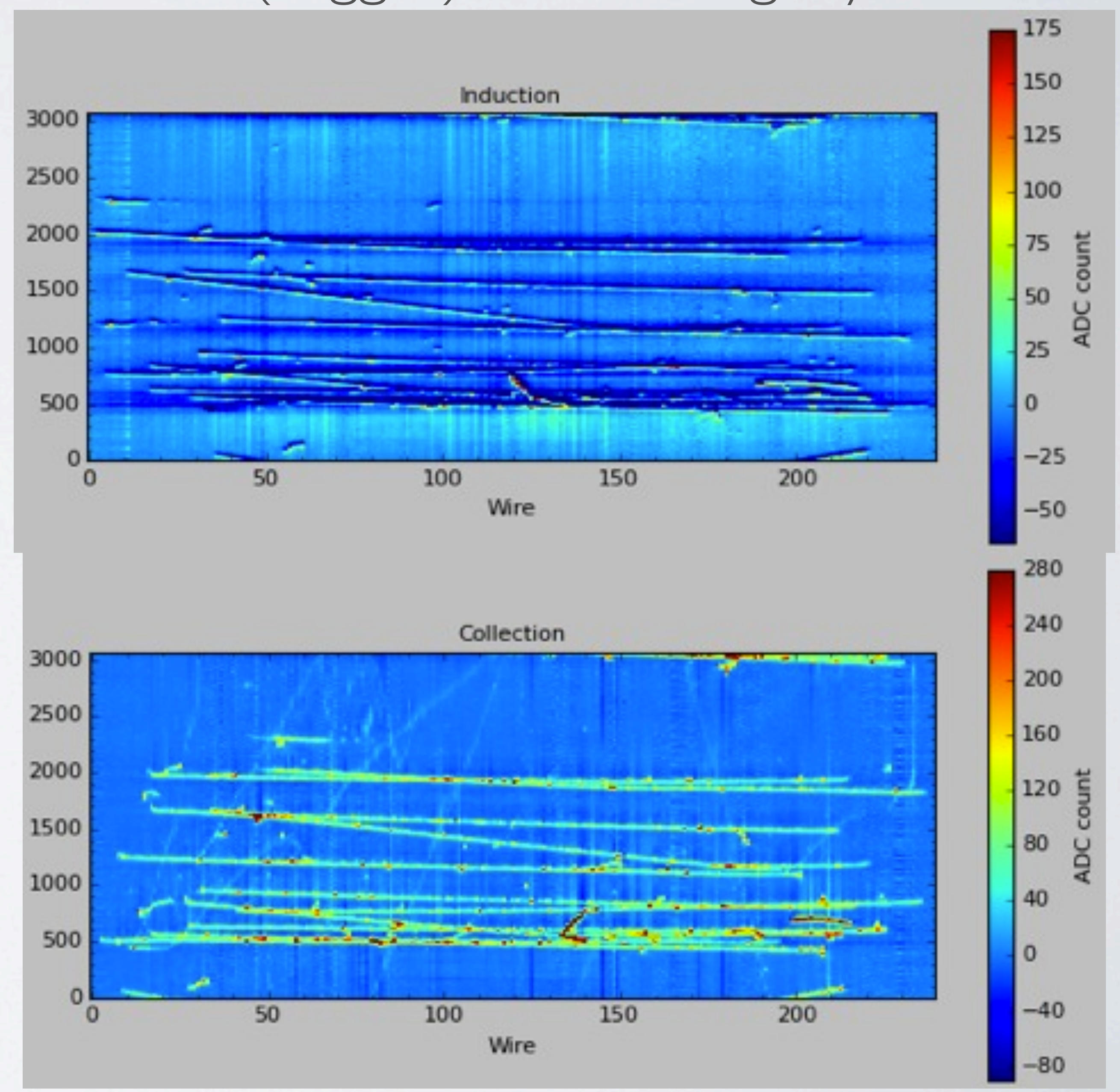
1.) Slicing of all data
2.) First filter: BEAMON and no PILEUP
3.) Beamline Reconstruction: WCTracks
4.) TPC Reconstruction
5.) Second Filter: WCTrack Existence
6.) Third Filter: TPC Primary Selection
7.) Fourth Filter: Stub Tracks
8.) Track Matching Quality Cuts
9.) Track Fixing/Merging

First: to keep things simple and avoid future track matching ambiguity, we want very simple event topologies: **one visible primary particle in the TPC.**

Example desired event (trigger):



Example undesired event (trigger) with ambiguity:



First Filter: BEAMON and PILEUP

Sliced Data

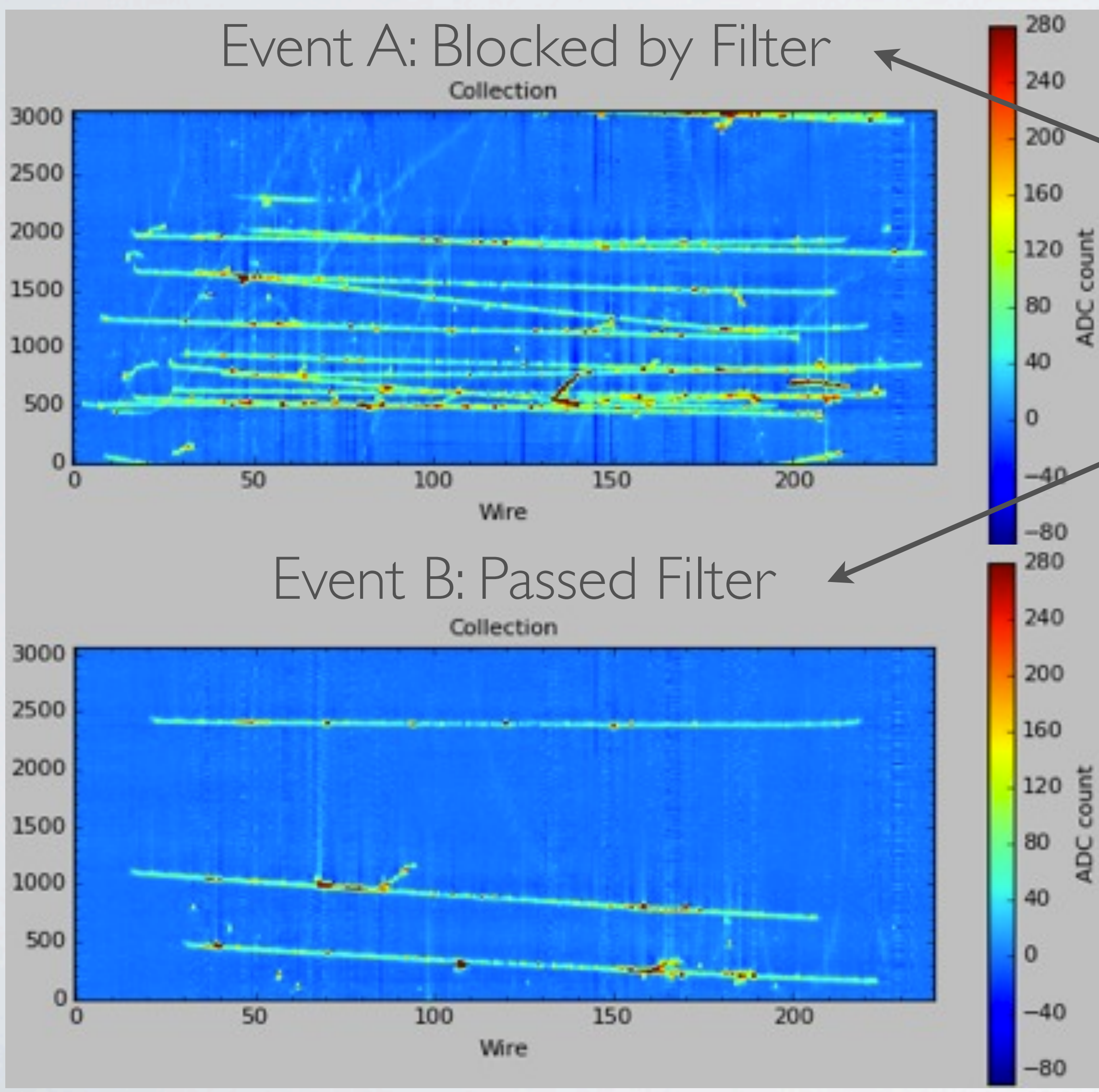
BEAMON:
- All beam events (first ~4 seconds)

COSMICON
- Any events in the next ~30 seconds)

→ **Filter** →

Post-Filter

Only events with BEAMON and no PILEUP signal



Important note: the PILEUP trigger bit has some inefficiency:

Pre-Filter Event Count	Post-Filter Event Count
~97,200	10,322

Reconstruction Module Specifics

WCTracking:	`lariat_wctrackbuilder`
Calibration:	`lariat_calroi`
Hit Finding:	`standard_clustercrawlerhit`
Cluster Finding:	`standard_linecluster`
Track Finding:	`standard_pmalgtrackmaker`

Second Filter: WCTrack Existence

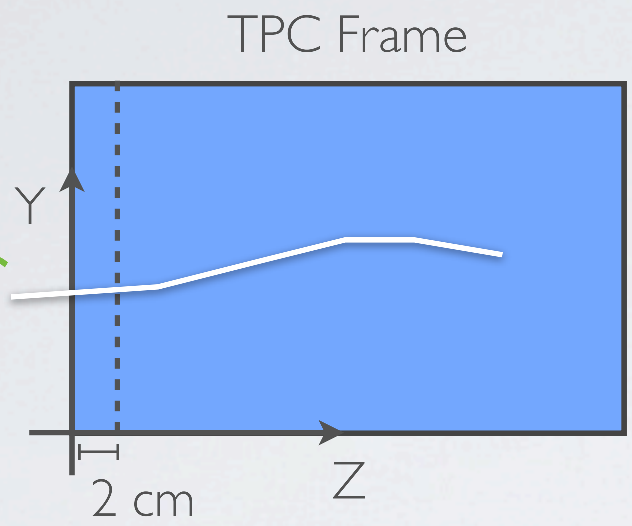
Note: The WCTrackBuilder module currently creates a maximum of one WCTrack for an event.

We filter out events where there is no WCTrack.

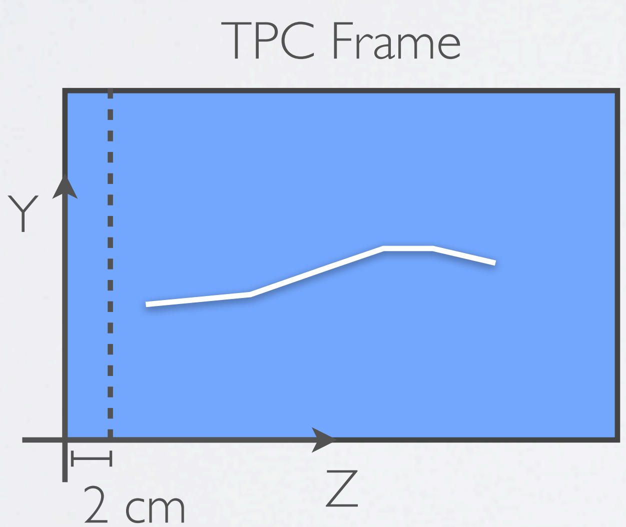
Pre-Cut Event Count	Post-Cut Event Count
10,322	3,772

Third Filter: TPC Primary Selection

Passes filter



Is killed by filter

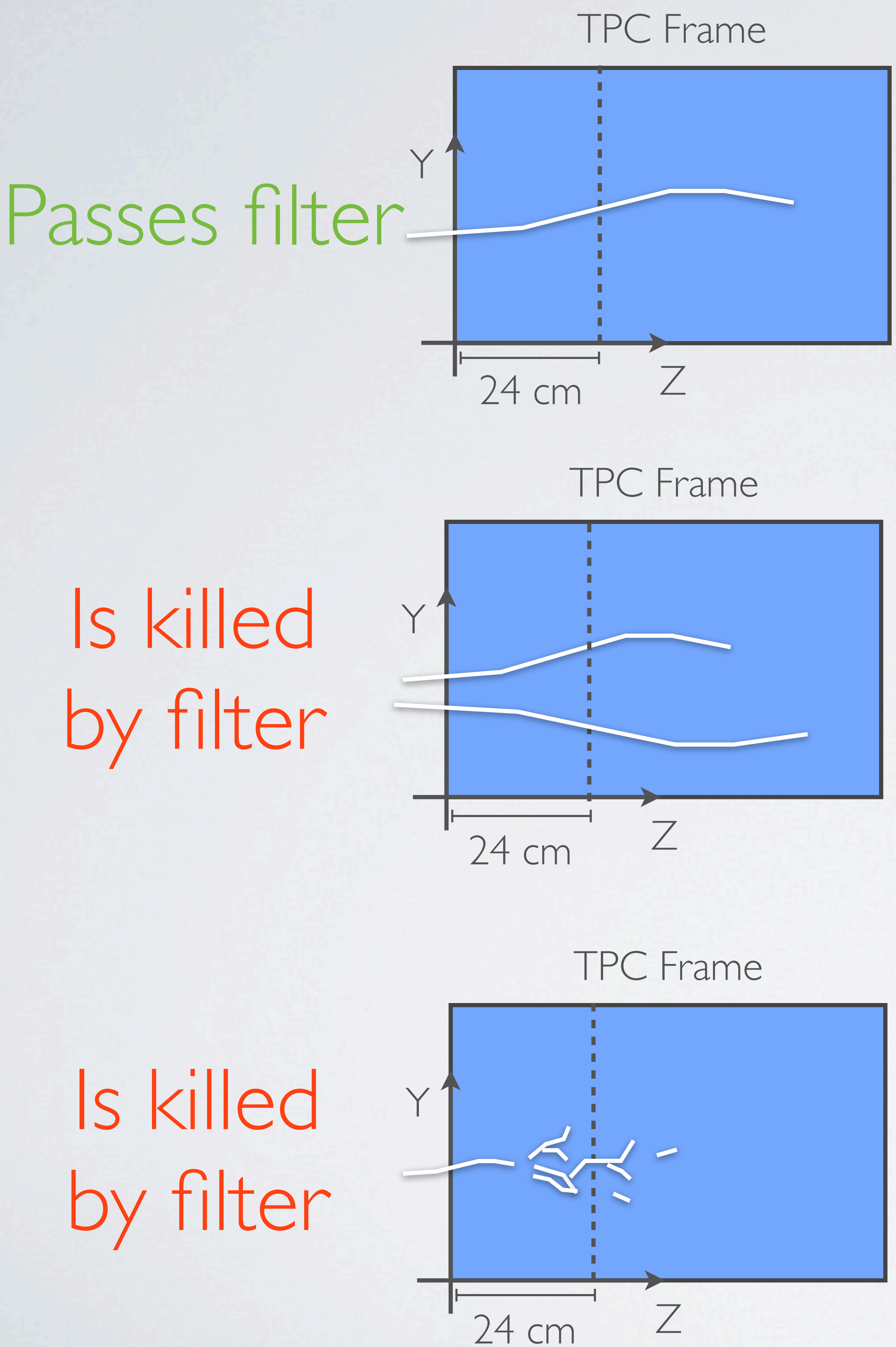


Condition 1:

The track must have a space point within 2 cm in Z of the upstream face. This space point must also be within the X and Y bounds of the TPC face.

- Ensures that we're looking at a primary from the beam

Third Filter: TPC Primary Selection



Condition 2:

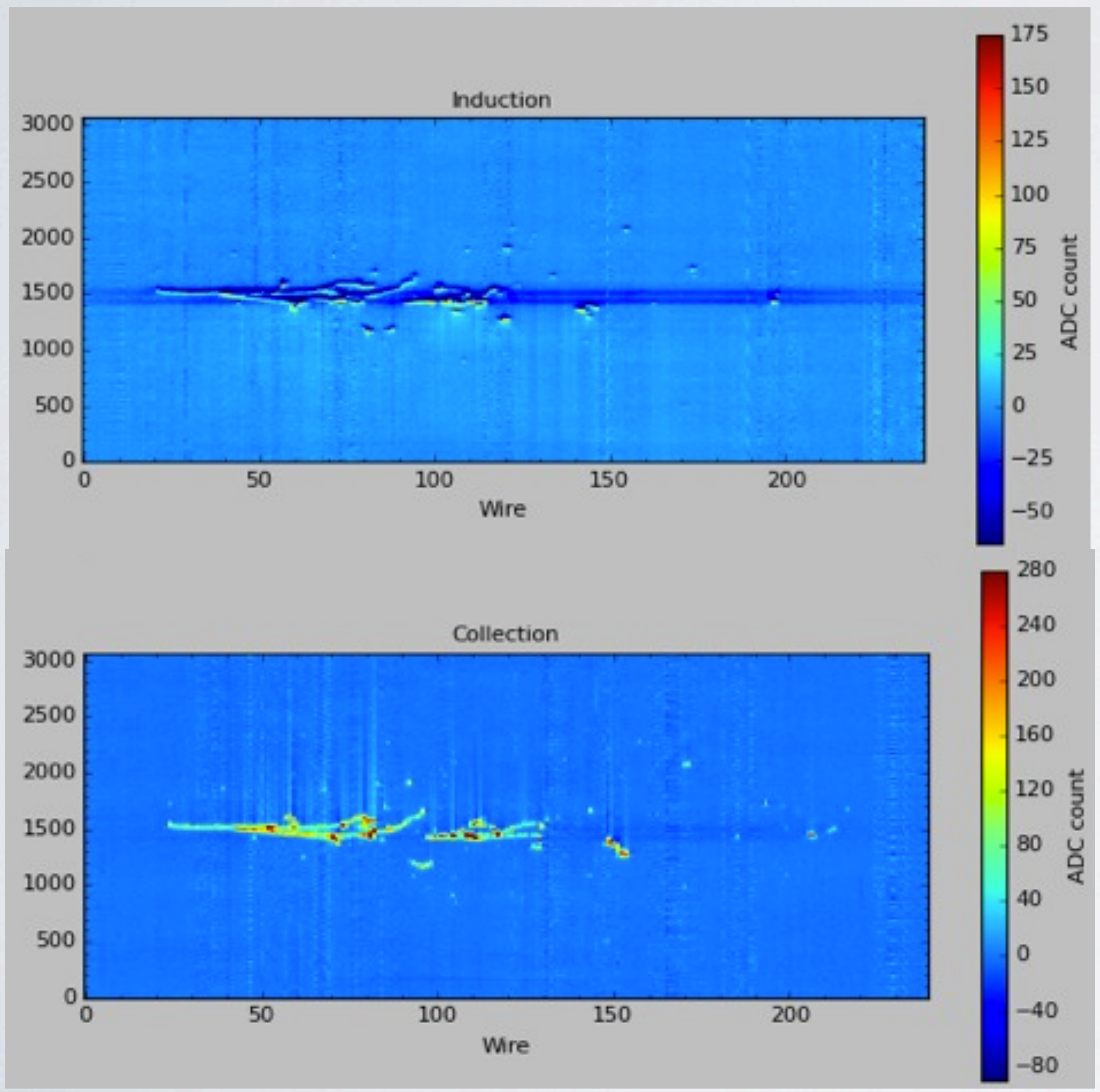
There must be only 1 track with a space point within 24 cm in Z of the upstream face of the TPC

- Helps reinforce the "no PILEUP" rule
- Helps filter out showers from beam electrons
- Establishes an upstream edge to the fiducial volume: 24 cm.

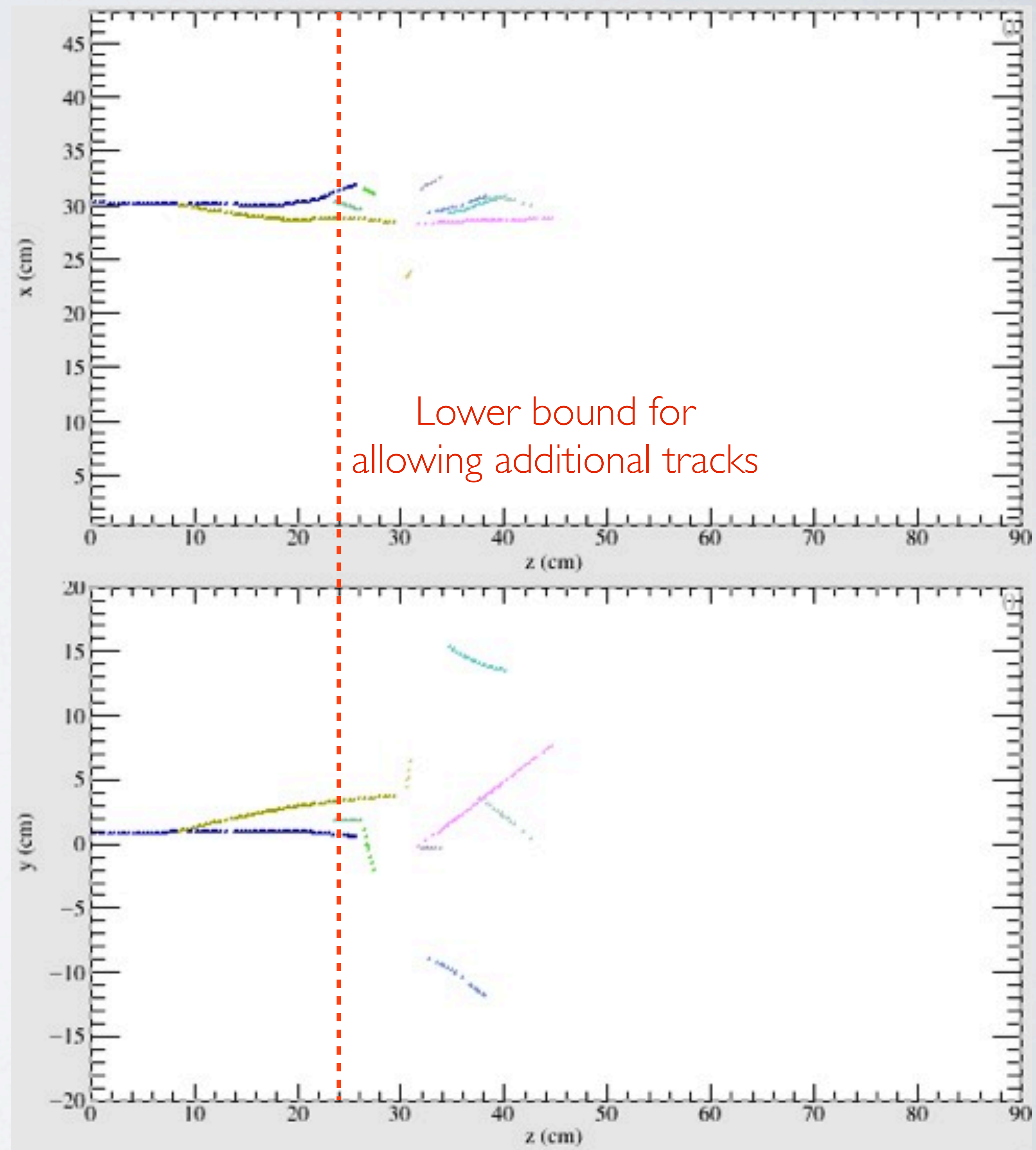
Pre-Cut Event Count	Post-Cut Event Count
3,772	862

Example shower that is killed by filter: Run 6105, Spill 181, Event 3

Raw, Wire Planes

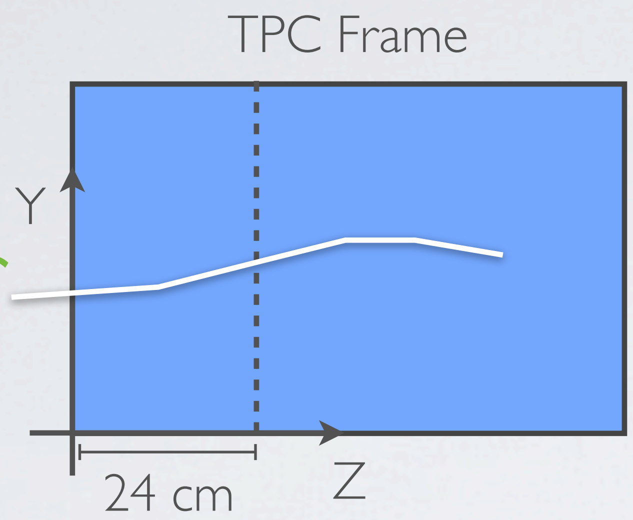


Reconstructed, XZ and YZ "projections"



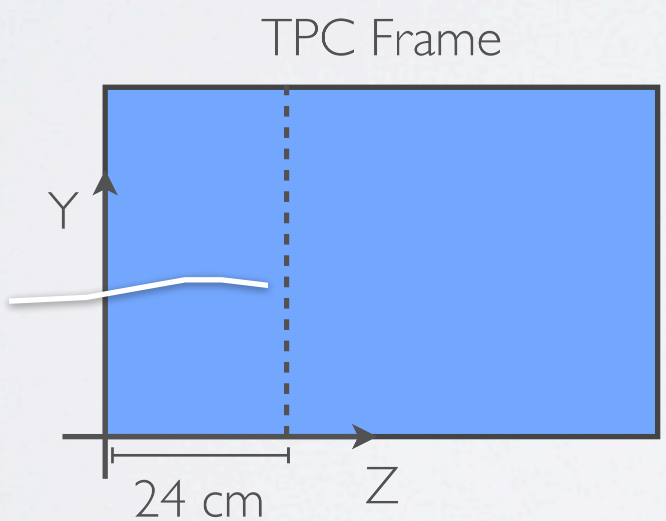
Fourth Filter: Stub Tracks

Passes filter



The track's highest-Z space point must end downstream of Z=24 cm to be considered for analysis.

Is killed by filter



Pre-Cut Event Count	Post-Cut Event Count
862	698

Track Matching and Quality Cuts

Now we have:
- 1 WC Track
- 1 TPC Track touching the upstream face

Want to make match quality cuts to be confident that our match is correct.

Cuts on 2 quantities:
- α: angle between the WCTrack and the TPC Track direction vectors at the US face
- ΔY at US TPC Face = (TPCTrack Y - WCTrackY)

Important for confidently assigning initial energy to TPC track
- Large α or ΔY suggestive of significant scatter inside dead region of cryostat: energy loss hard to approximate

Track Matching and Quality Cuts: **α**

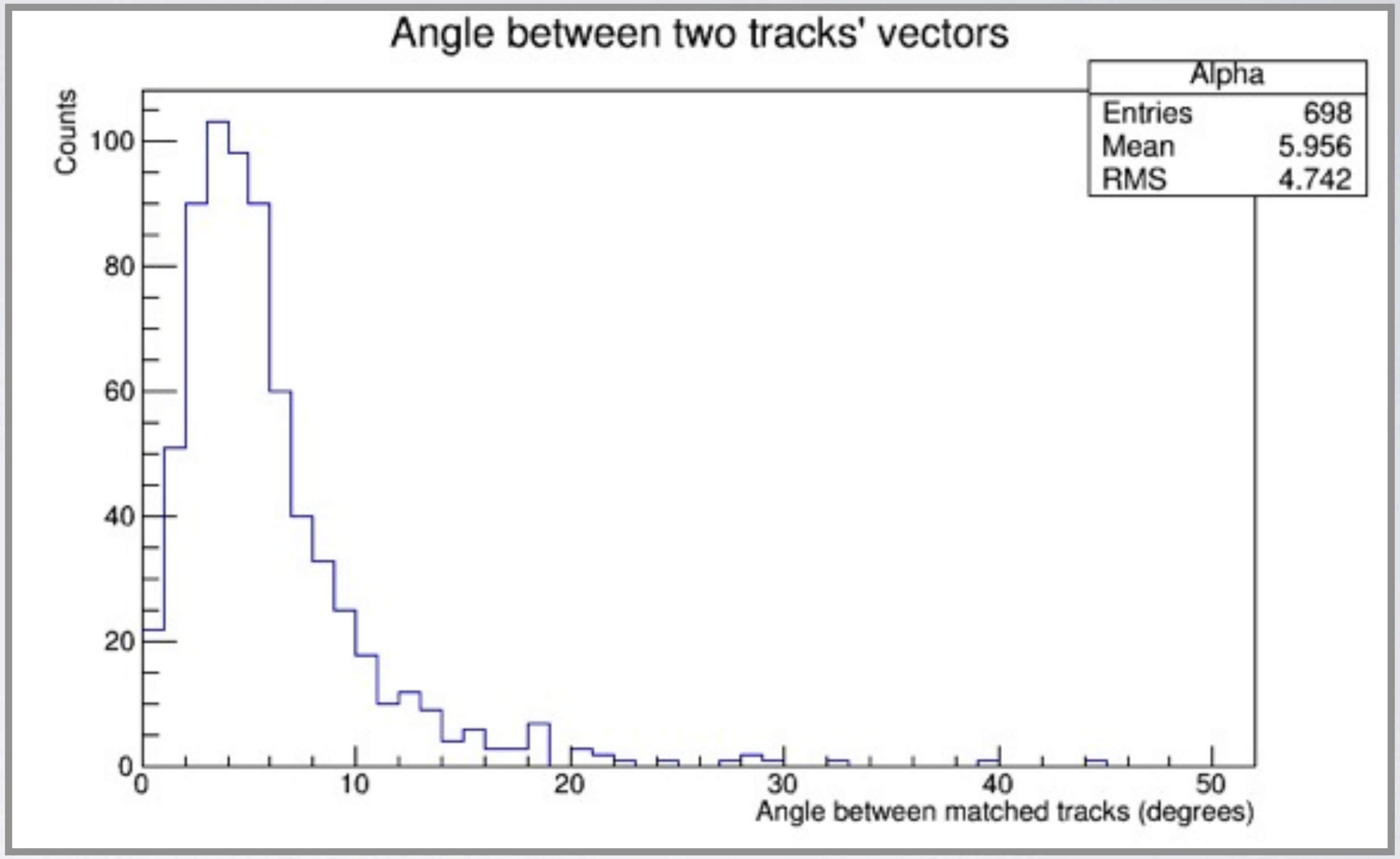
- Find peak slightly offset from 0°: reasonable

  + Small-angle scattering possible in the pre-TPC steel and dead argon

- Find a few angles near 30°-40°: reasonable

  + from occasional hard scatter or multiple scattering in dead region

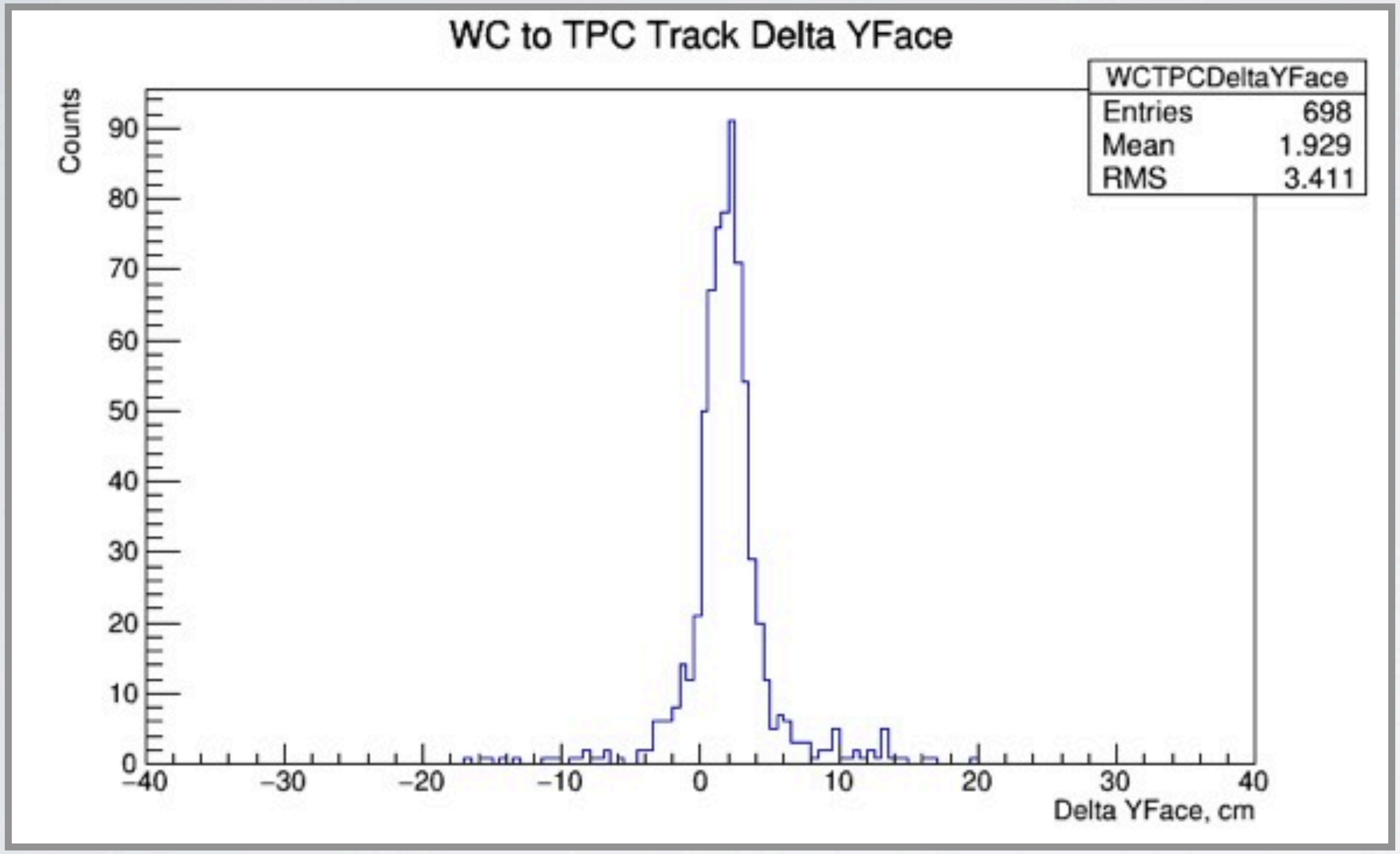
We make a cut, keeping only angles of **<20°**



Pre-Cut Event Count	Post-Cut Event Count
698	684

Track Matching and Quality Cuts: ΔY at TPC Face

To avoid the ambiguity between a late track and a track entering early at large X, we ignore the agreement in X and only assess the agreement in Y.



* This is the distribution for all of the single-track events: no alpha cut yet

- Systematic ΔY offset: suggests corrections to WC/TPC alignment

- This Gaussian falls between roughly **-3 and 8 cm.** Cuts made here.

Pre-Cut Event Count	Post-Cut Event Count
684	629

Filtering Summary

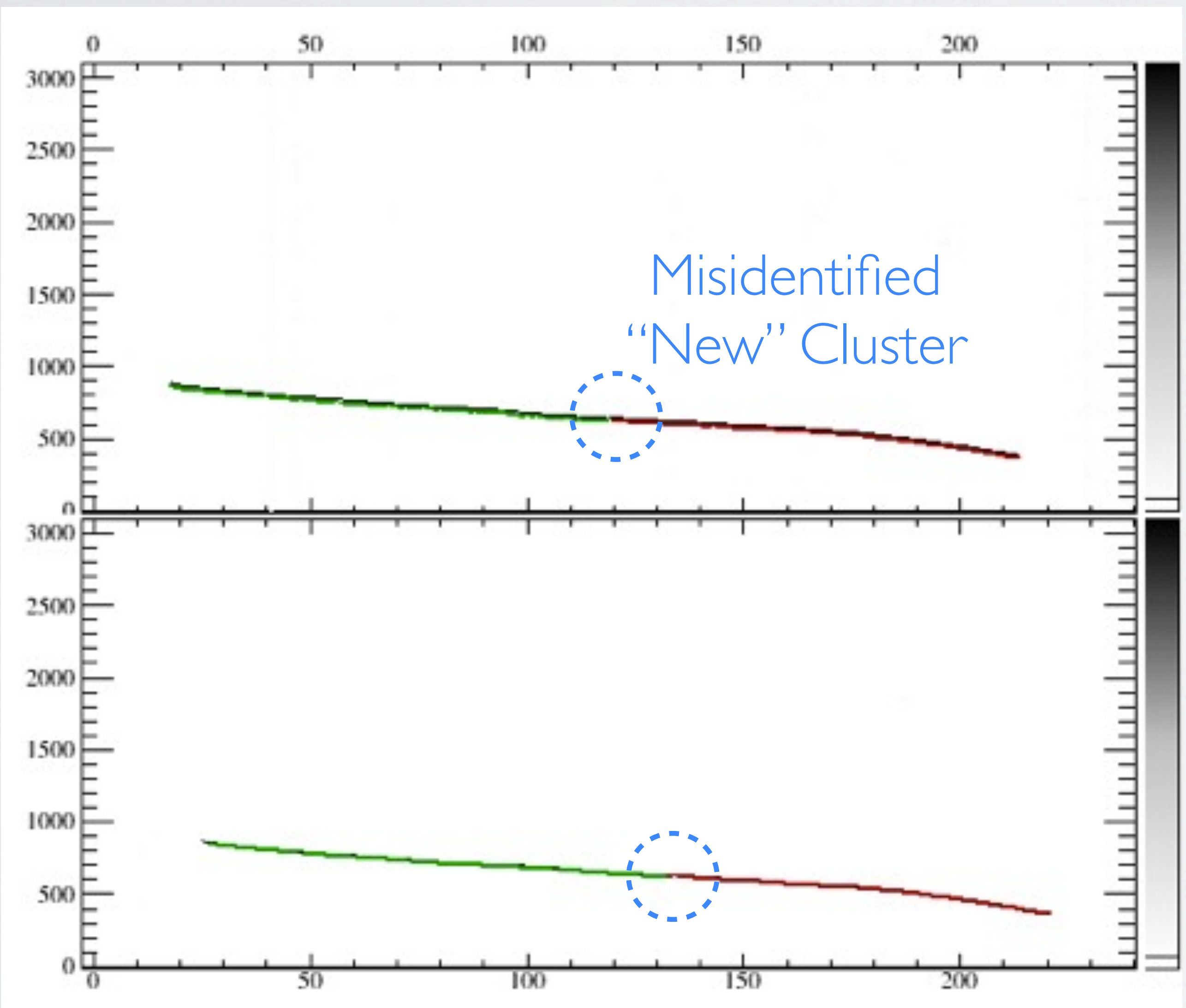
Filter Order	Filter Type	Remaining Events
0	#NoFilter	~97,200
1	+BEAMON-PILEUP	10,322
2	1 WCTrack	3,772
3	TPC Primary Selection	862
4	Stub Tracks	698
5	α Cut	684
6	ΔY Cut	629

Track Merging/Fixing

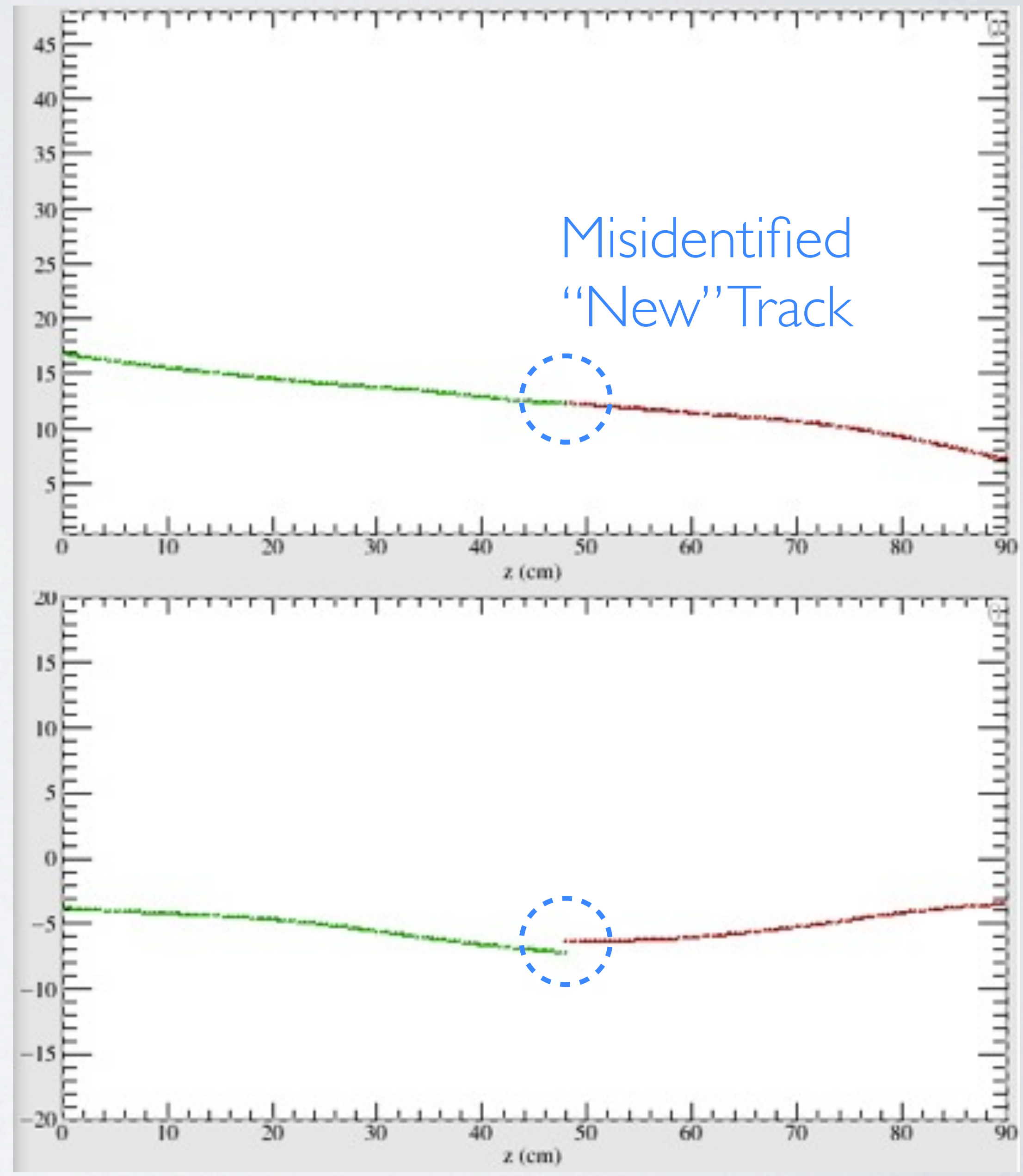
Clustering/Tracking is really good, but isn't perfect.

- Will occasionally split contiguous tracks into 2 separate tracks:

Reconstructed, Wire Planes



Reconstructed, XZ and YZ Projections



Track Merging/Fixing

To fix this, I merge 2 tracks if both of the following are satisfied:

- The most upstream point of one is within 2 cm of the most downstream point of the other

- The angle between the direction vectors at the close ends is below 5°.

Bulk Event Quality

Looked through 150 of the 582 events to assess purity, good reconstruction:

Event Type	Number of Events	Percentage of Events
Electron/Photon Shower	3	2%
Straight track, bad reco: unfixable	18	12%
Straight track, bad reco: fixable	16	11%
Straight track, good reco	113	75%
Total	150	100%

Overall, ~86% of our events are good-quality events.

Analysis Overview

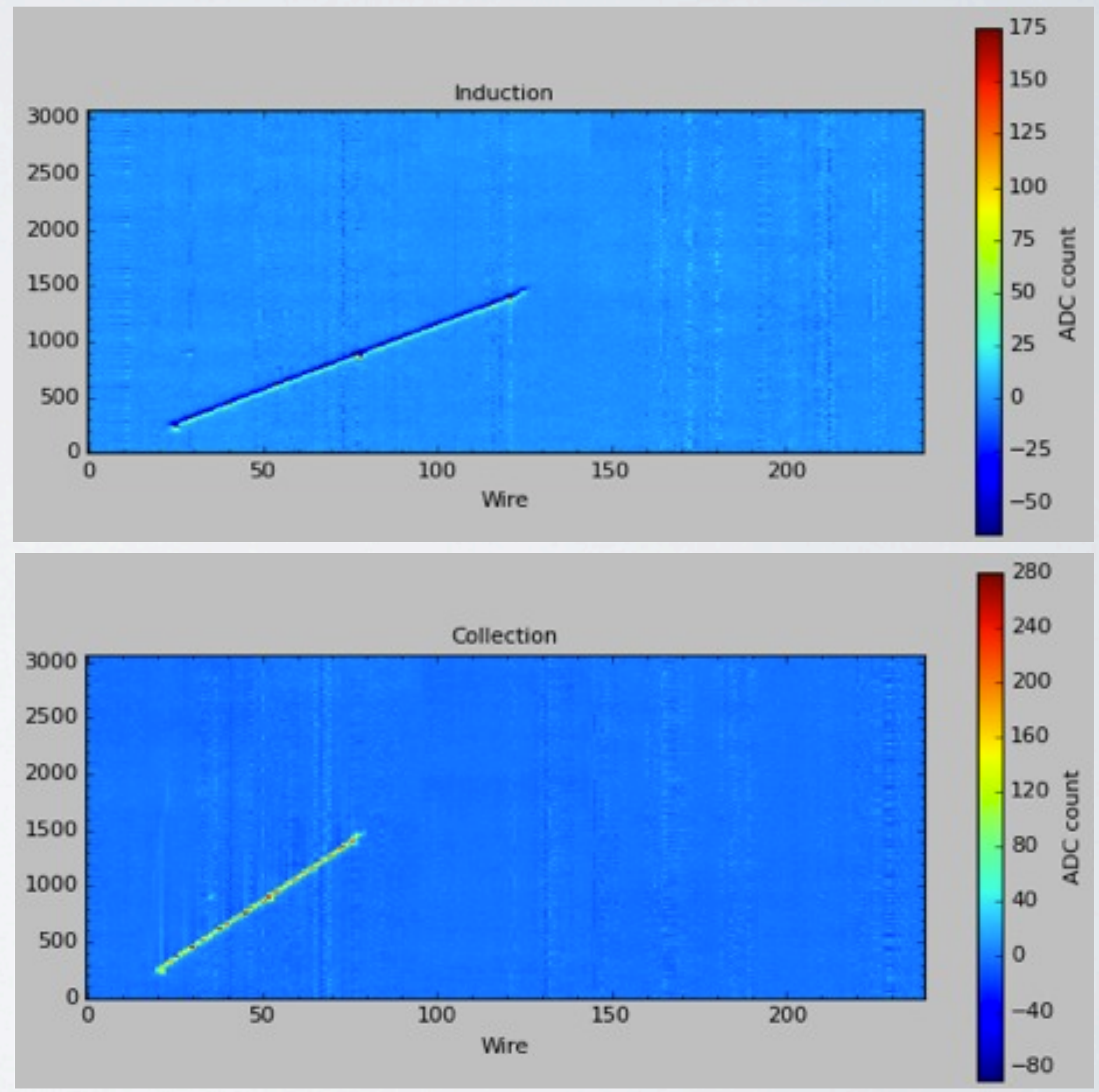
Big Question: How do we get a cross section from our good events?

1.) Preliminary Calorimetry
2.) The Thin-Slab Method
3.) The Many-Thin-Slab Method
4.) Cross Section Results and Interpretation

Calorimetry - Event Selection

Needed a quick estimate of the conversion between [ADC*TimeTicks] and MeV.

Run 6326, Spill 260, Event 27



Filtered several spills on COSMICON and COSMIC triggers.
- Looking for throughgoing muons

Found a sample of 477 events.

Reconstructed these events:
- Hit finding
- Cluster finding
- Track finding

Selected only those events where # tracks = 1
- Done to eliminate blank events and showering events

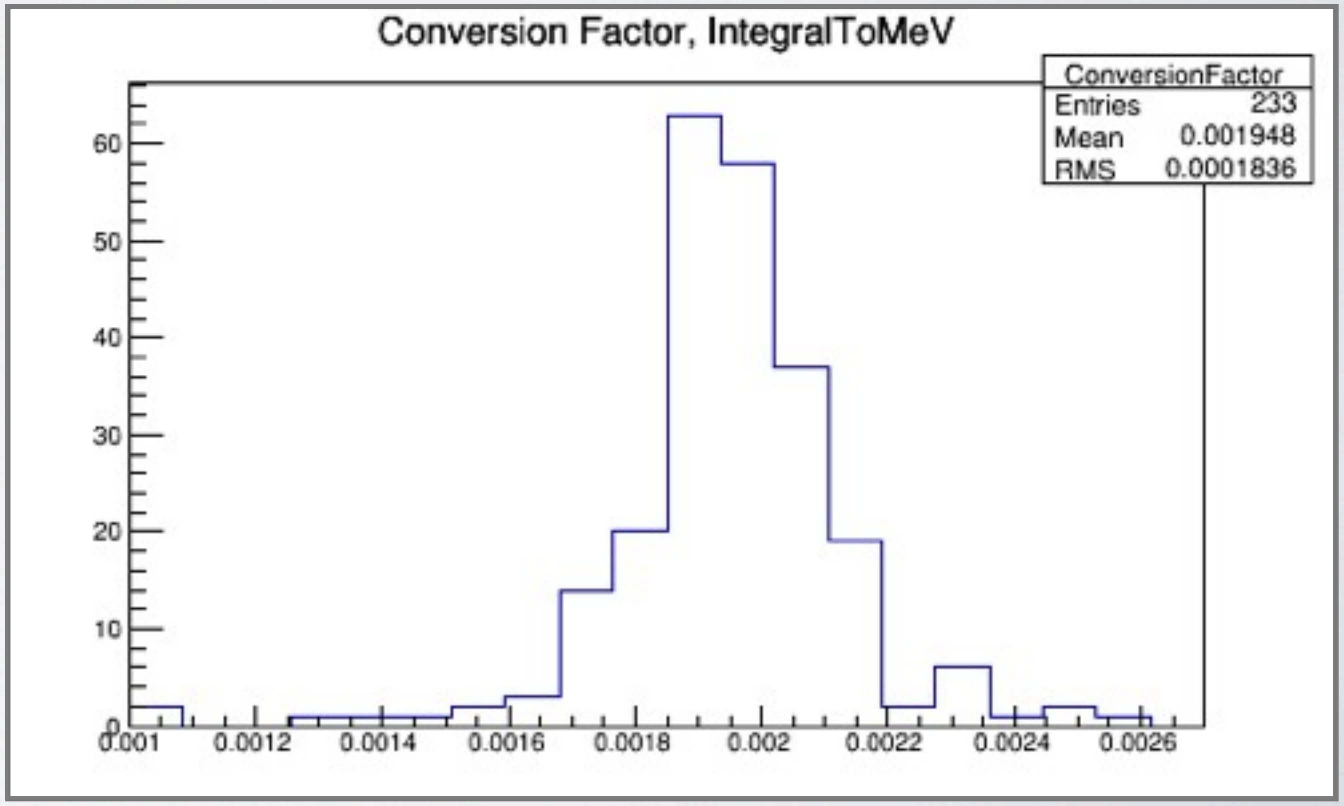
Calorimetry - Conversion Finding

- For each collection plane hit in a muon track:
  + Find uncorrected integral: I_u
  + Correct integral for electron lifetime:

$$I_c = I_u e^{t/\tau}$$

Where: t is the hit's drift time (in μs)
τ is the electron lifetime (~900 μs)
I_c is the corrected integral

- Sum over all hits
- Divide by total track length
- This should roughly be equal to 2.1 MeV/cm, so find the constant of proportionality:



Found rough gaussian, used mean for conversion factor

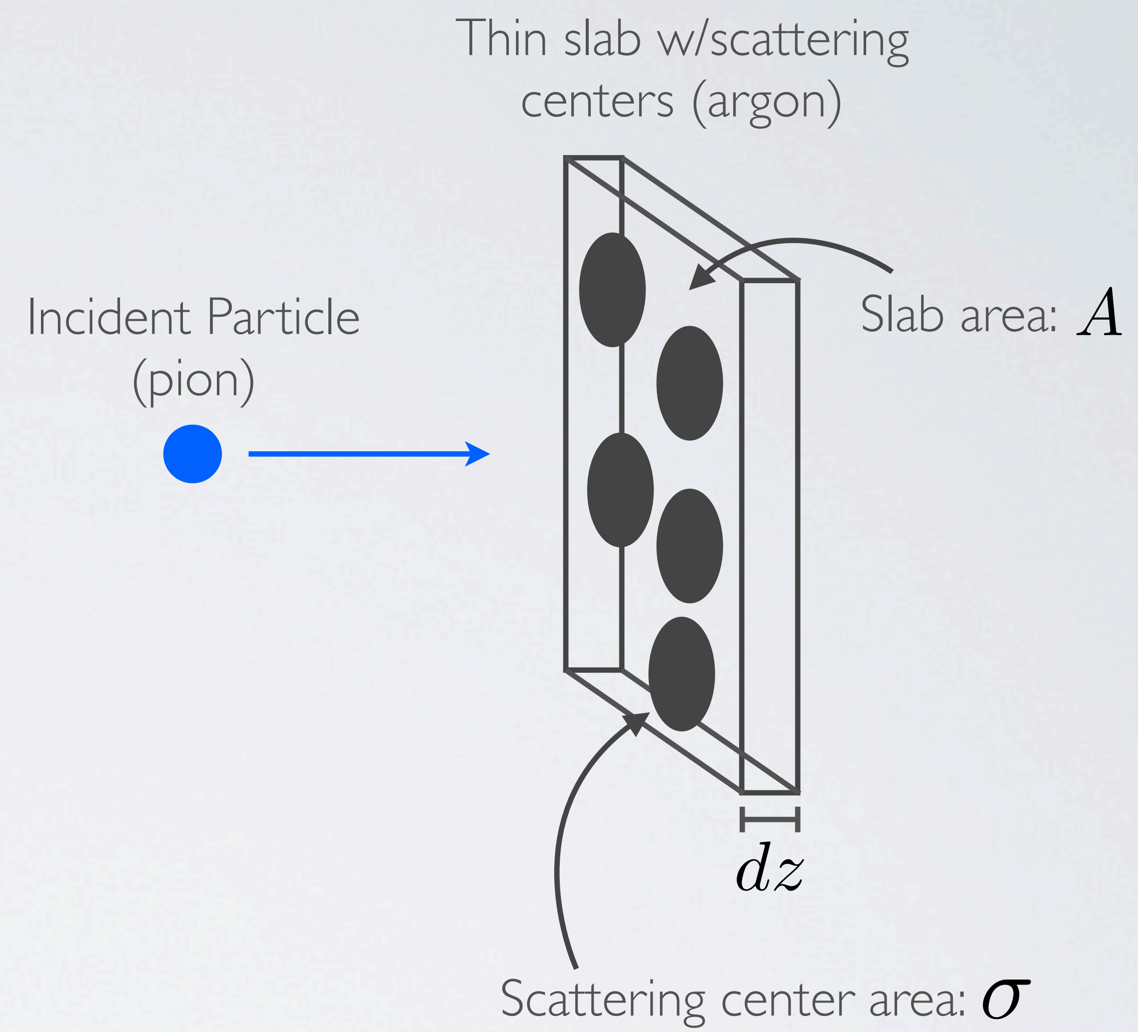
The Thin Slab Method

Suppose we have scattering centers in a thin slab with:

- Slab Area: A
- Number density: n
- Thickness: dz
- Scatterer Area: σ

$$P(scatter) = \frac{area\ of\ scatterers}{total\ area}$$

$$P(scatter) = \frac{(dz)An\sigma}{A} = (dz)n\sigma$$



But we can interpret P(scatter) as:

$$P(scatter) = \frac{\#\ particles\ scattered}{\#\ particles\ incident} = \frac{N_s}{N_i}$$

So that we find: $$\sigma = \frac{N_s}{N_i}\frac{1}{n(dz)}$$

*NOTE: All of this is for a specific incident pion energy range!

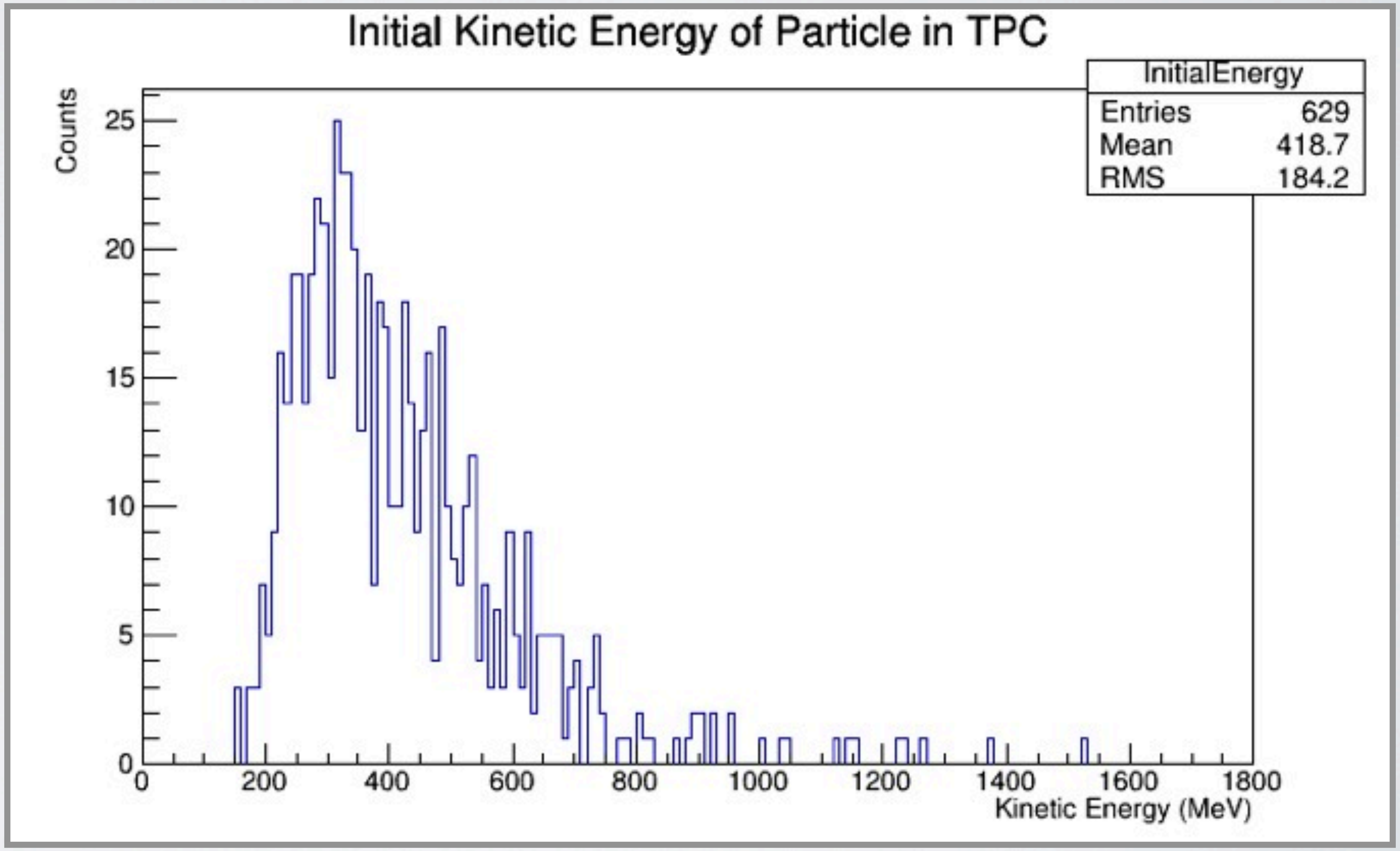
The Many-Thin-Slab Method

LArIAT is not a thin slab, so we have to adapt and use the many-thin-slab method, with the following steps for a given event:

1.) Assume all tracks are from pions and convert WCTrack momentum to kinetic energy

2.) Subtract 8.6 MeV for approximate energy loss in the front TPC dead region (from Flavio's calculations)

Resulting Distribution:



Run 6100, Subrun 335, Event 1

3.) Define a thin slab as a volume of LAr with 1 cm thickness

4.) Find the energy of the particle as it is incident on a given slab using corrected hit integrals in collection plane

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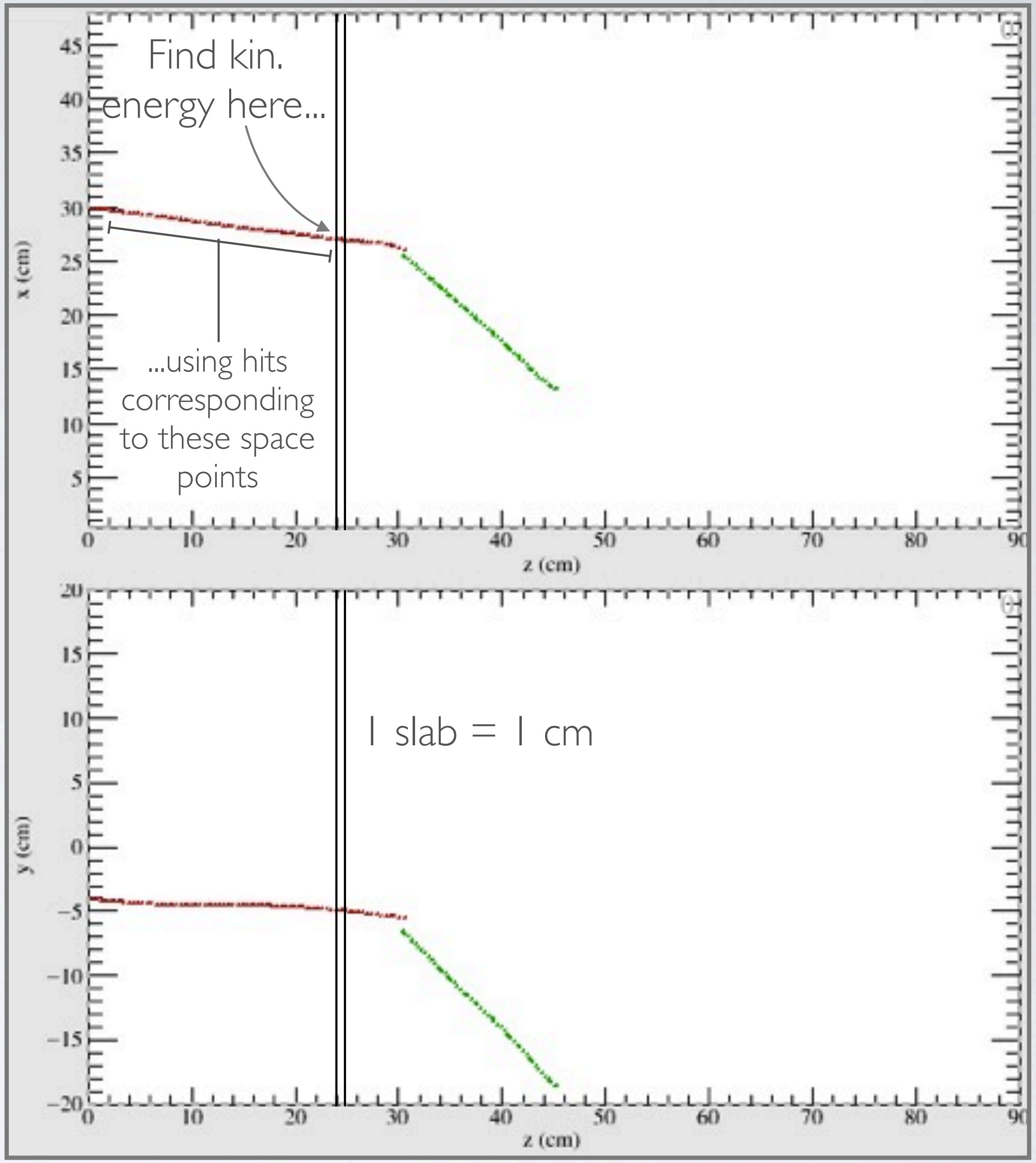
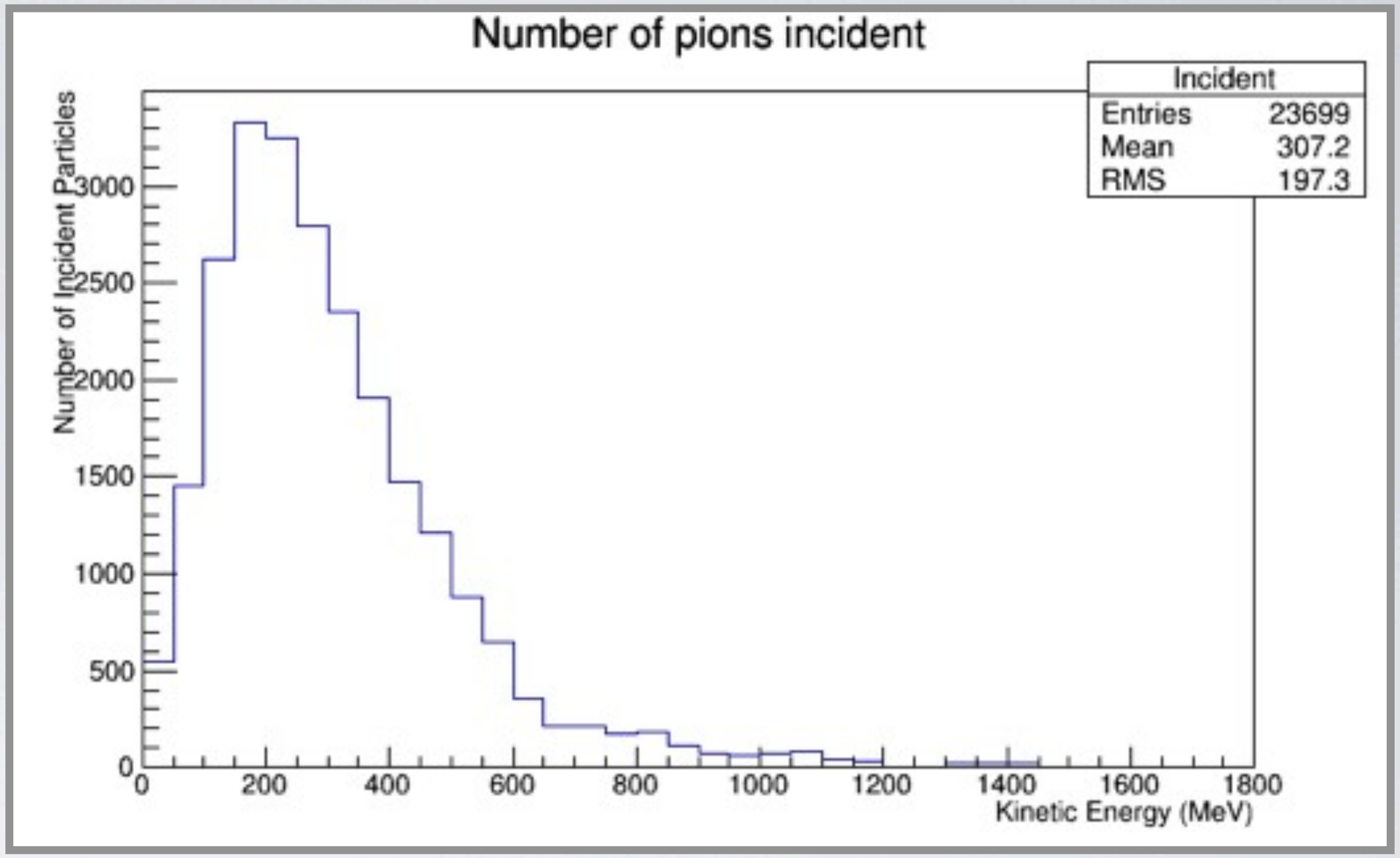


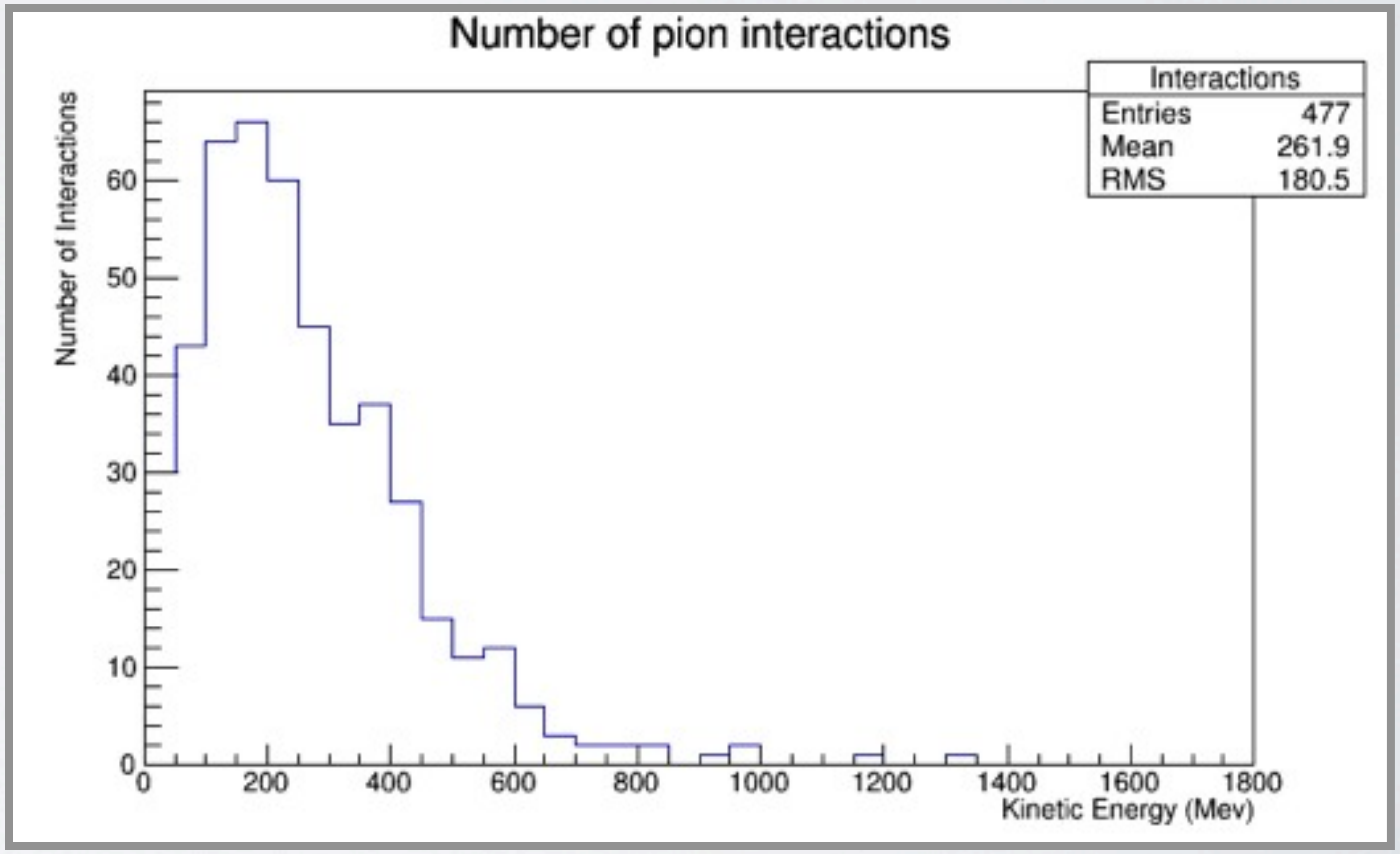
5.) For each slab that a particle enters, increment the bin of an "incident" histogram corresponding to the energy of the particle as it enters the slab.

- Equivalent to incrementing N_i for a given energy range.



6.) If the particle interacts in a slab, increment the bin of an "interactions" histogram corresponding to the energy of the particle as it enters the slab

- Equivalent to incrementing N_s for a given energy range

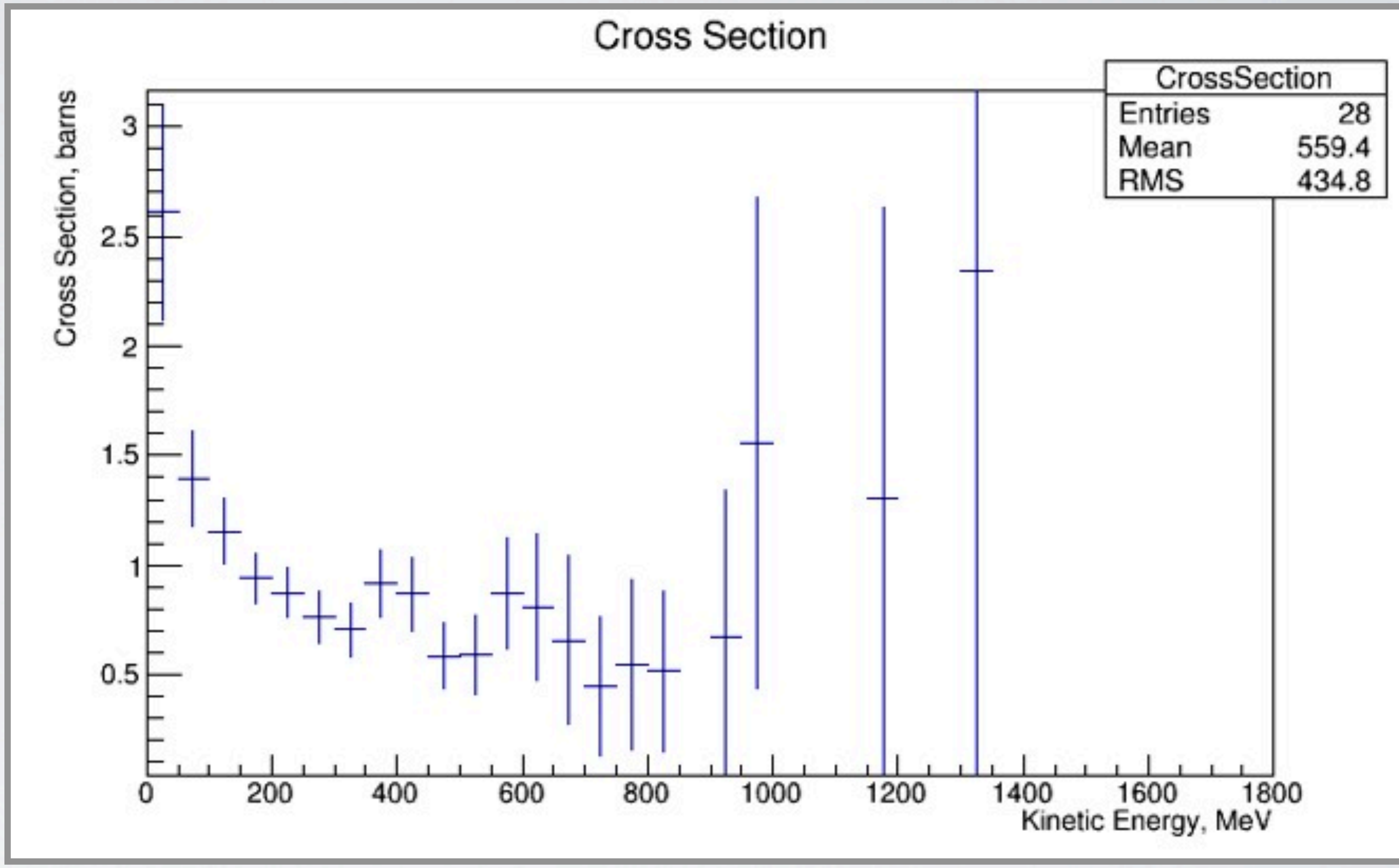


Measured Pion-Argon Total Cross Section

We then just use

$$\sigma = \frac{N_s}{N_i}\frac{1}{n(dz)}$$

bin by bin to find the cross section.



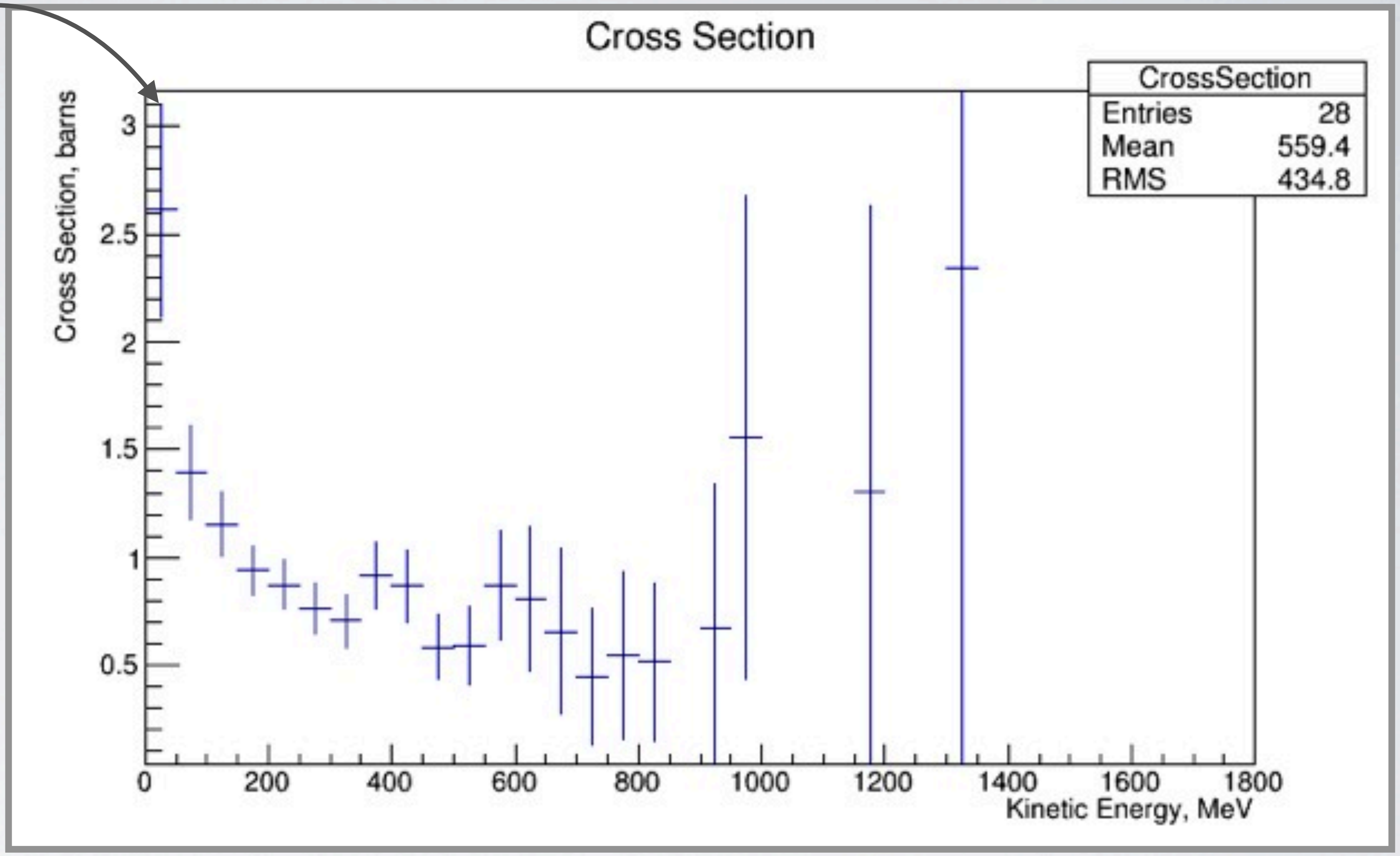
Low-E Bin Elimination

The lowest-energy bin must be disposed of.

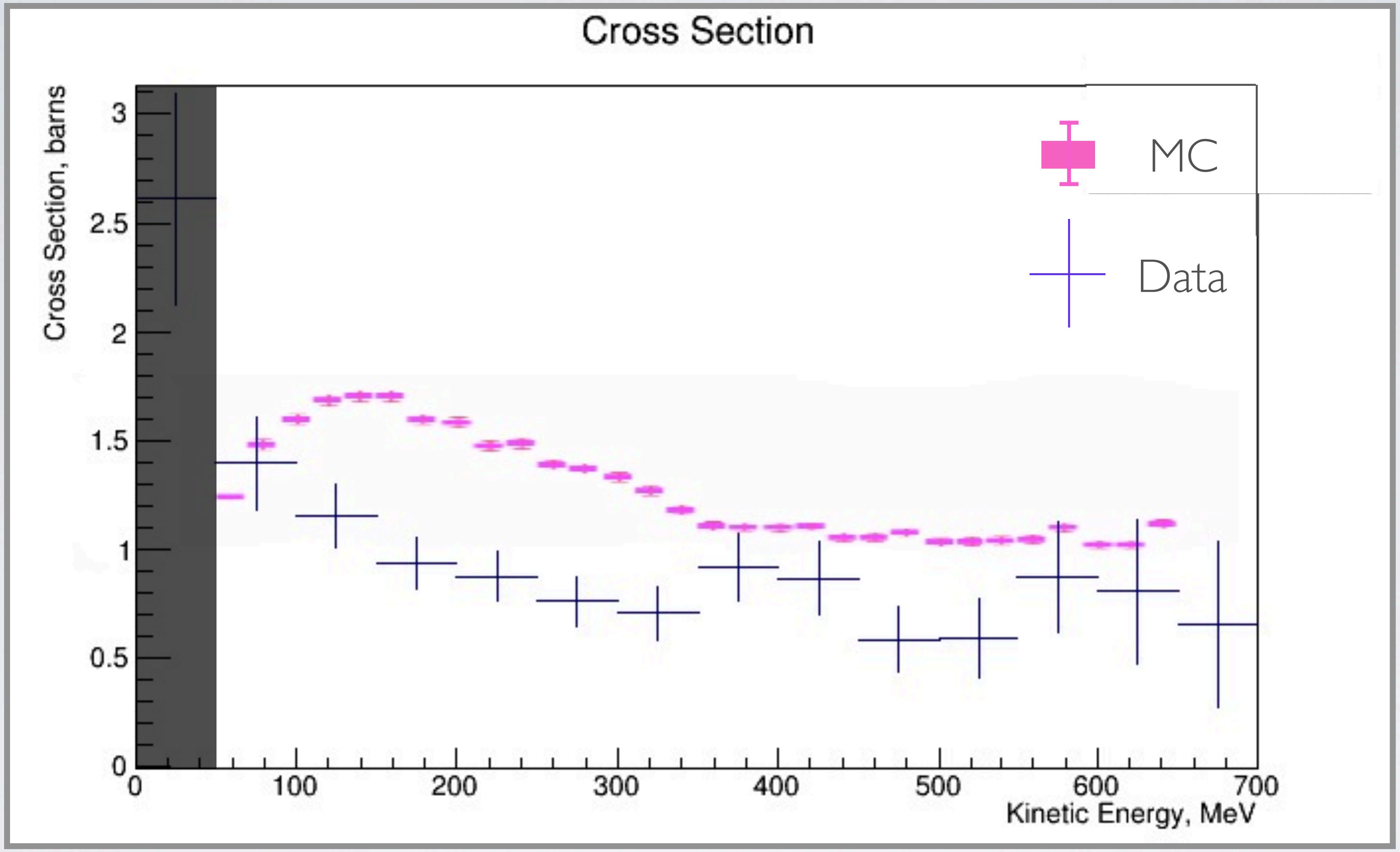
- Contaminated by stopping pion events where there was no interaction

- Currently, reconstruction is not aimed at distinguishing the two

  + Cross section plot reflects interactions AND stopping



How Does it Compare to Geant4 Total XS predictions?



Find 2 regions of disparity:

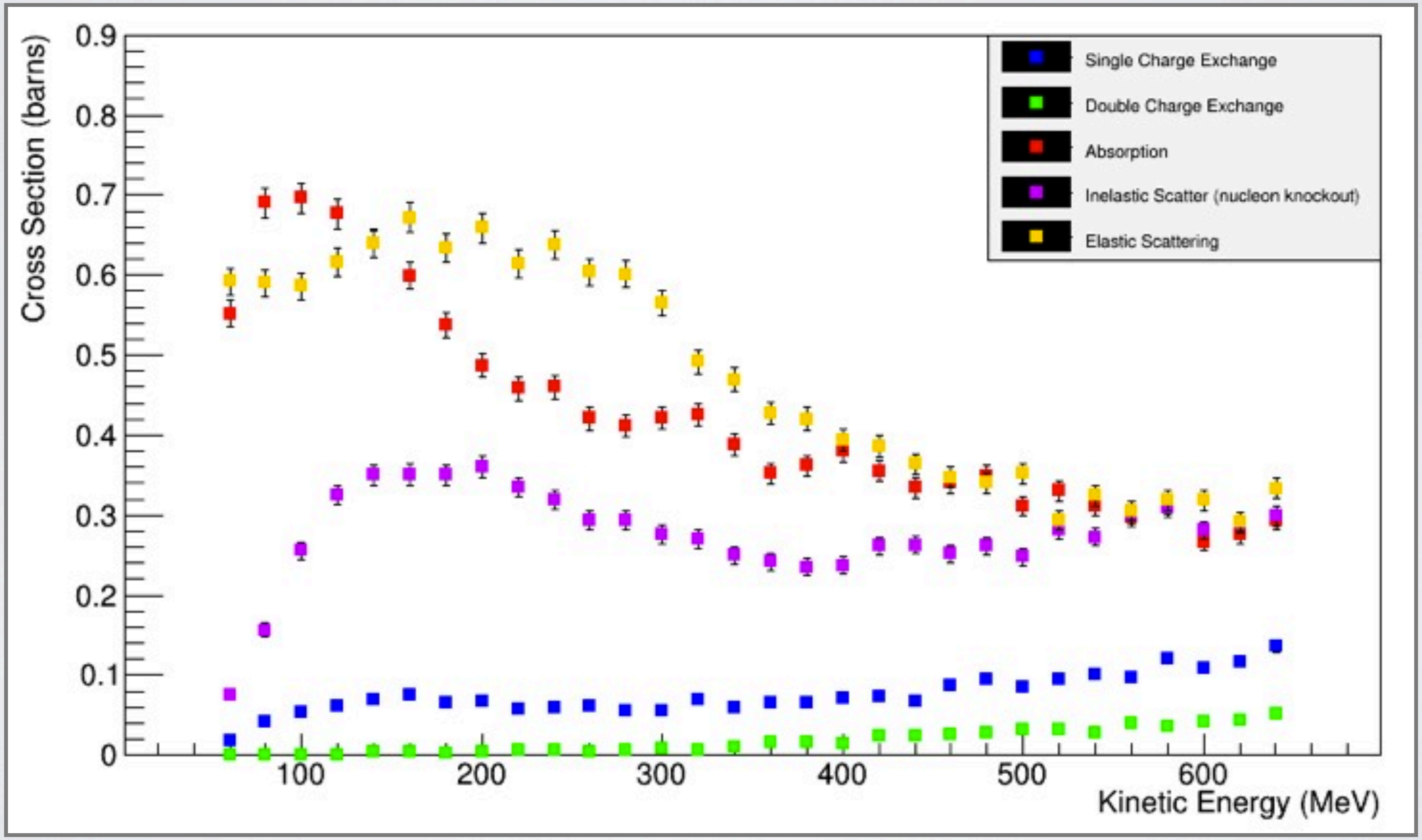
- Higher E (300-650 MeV): Data is between 0.2 and 0.5 barns below MC
- Lower E (100-300 MeV): Data is consistently ~0.5-0.6 barns below MC

What could cause this?

Well, systematics, for one.
- Muon tracks would cause deficits in the cross section across the board.

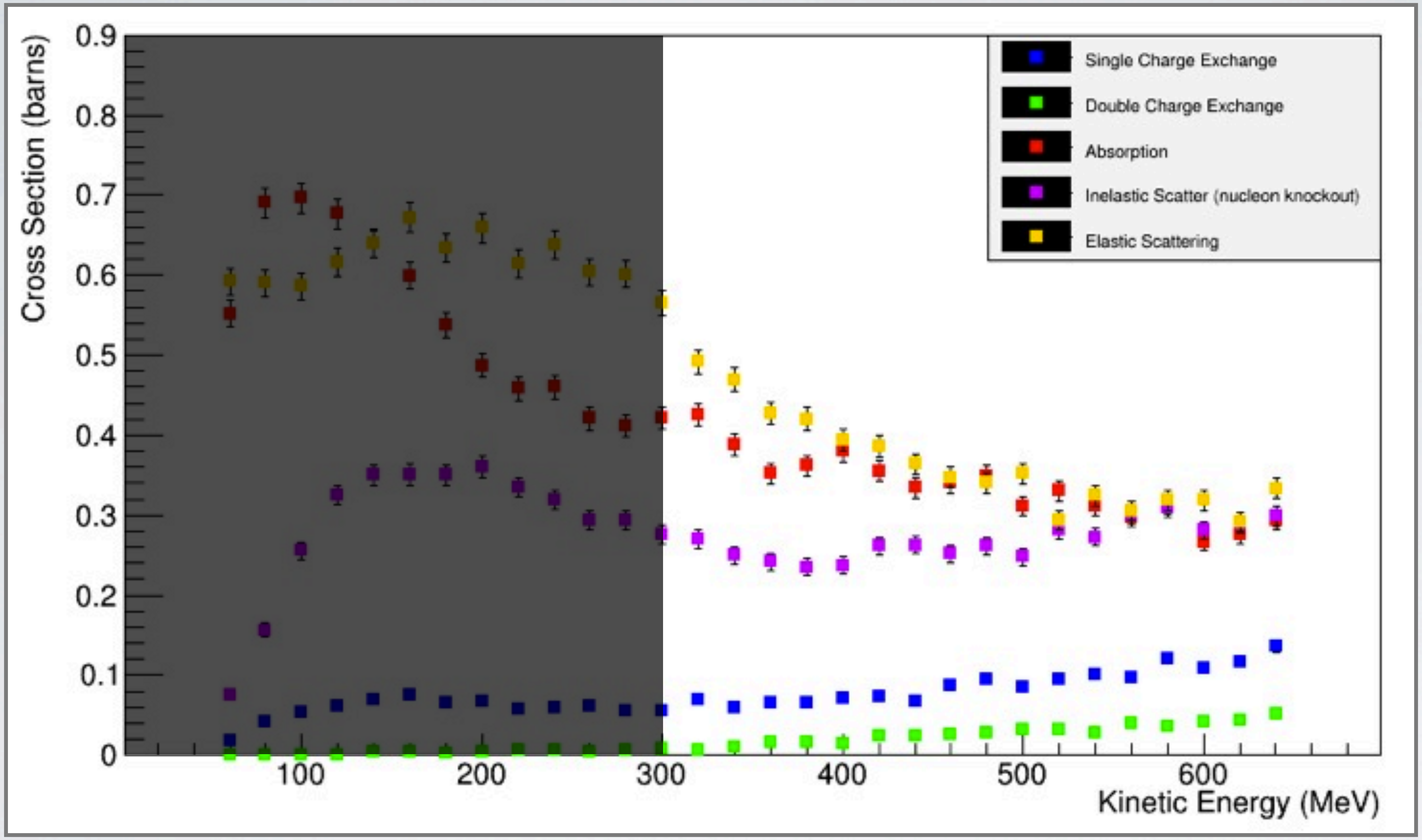
But let's ignore those for now, and look to Geant4 simulation:

π^- – Ar cross section, broken into different interaction modes:



What could cause this?

π^- – Ar cross section, broken into different interaction modes:

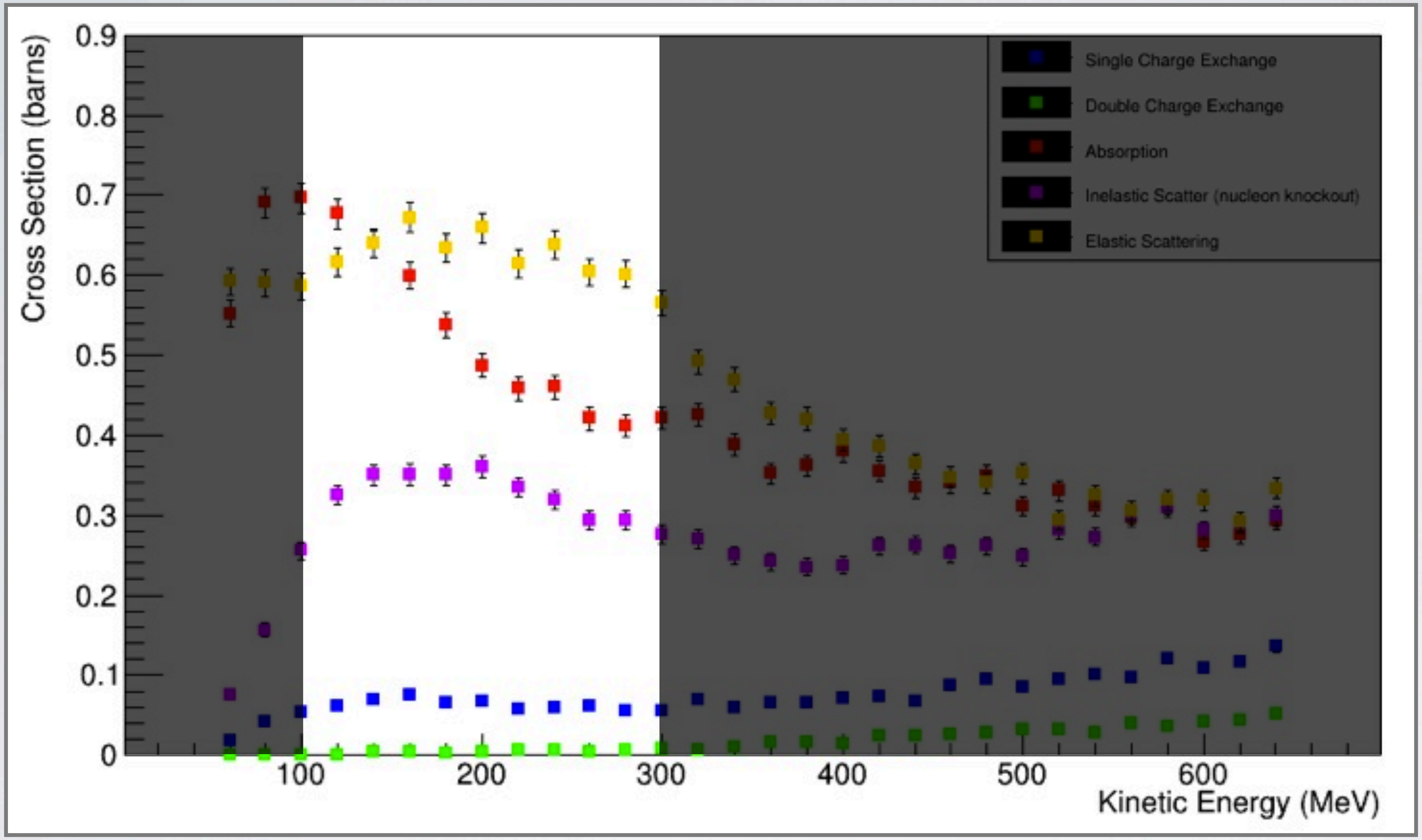


Let's take the higher-E case:

- Cross section for Elastic Scattering is ~0.3-0.4 barns
- Higher E = larger boost in forward direction, smaller scattering angle
  + Harder to reconstruct!
- Maybe we're missing these elastic scattering events in our measurement, hence the 0.2-0.5 barn deficit.

What could cause this?

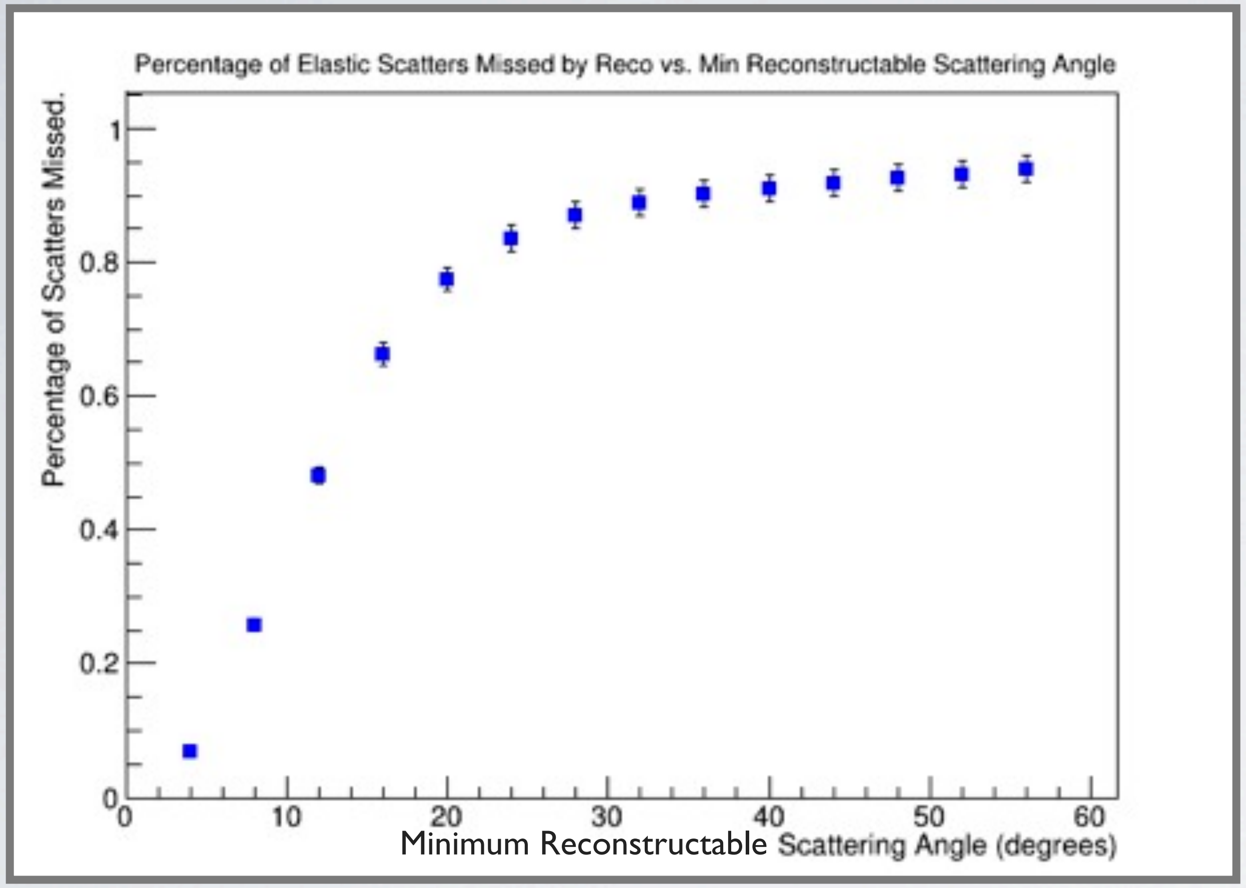
π^- – Ar cross section, broken into different interaction modes:



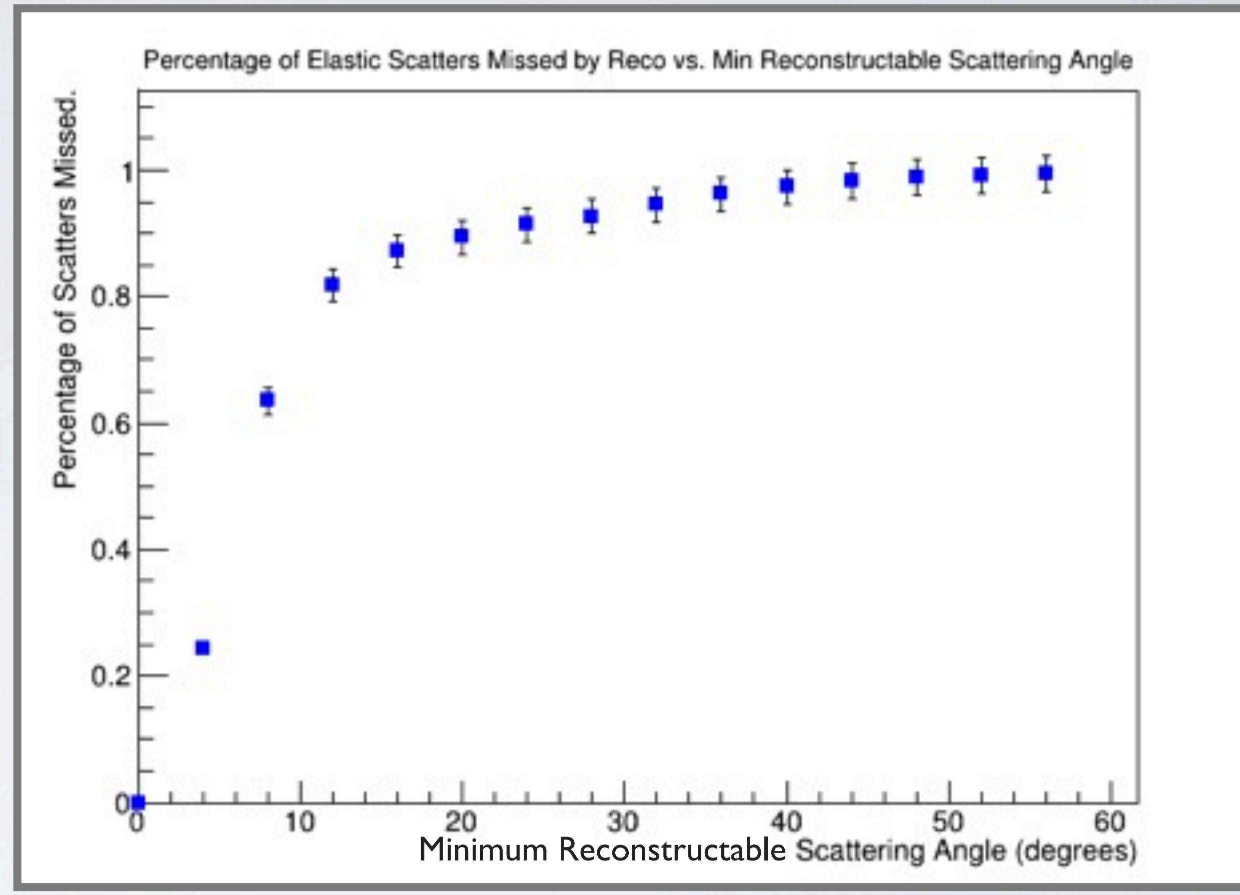
Let's take the middle-E case:

- Cross section for Elastic Scattering is ~0.5-0.6 barns
- Maybe the elastic scattering angles are still really small
    + we'd still be missing these interactions in our measurement, hence the 0.5-0.6 barn deficit.

So I did a little extra nosing around with Geant4 and looked at the percentages of elastic scatters missed, given a minimum reconstructable scattering angle:



200-250 MeV



500-550 MeV

All we'd need to miss a majority of the elastic scattering events is 15˚-20˚ for a minimum reconstructable scattering angle.

- Especially at higher energies, if our minimum angle is 15˚-20˚, we lose nearly ALL of the elastic scatters.

- Elastic scatters might plausibly make up almost all of the deficit in the cross section at these energies.

For the future...

This is just a first step forward in the total cross section measurement.

There's still a lot to be done:

1.) Run with updated slicing and reconstruction

2.) Improved calorimetry

3.) Event selection optimizations
- Fiducial volume
- Track matching cuts

4.) Corrections for elastic scattering
- Find the minimum reconstructable scattering angle
- Corrections rely on reconstruction's ability to distinguish elastic scatters from other interactions

5.) Other systematic uncertainty determination

And lastly, thank you all for the amazing last three years at Fermilab!