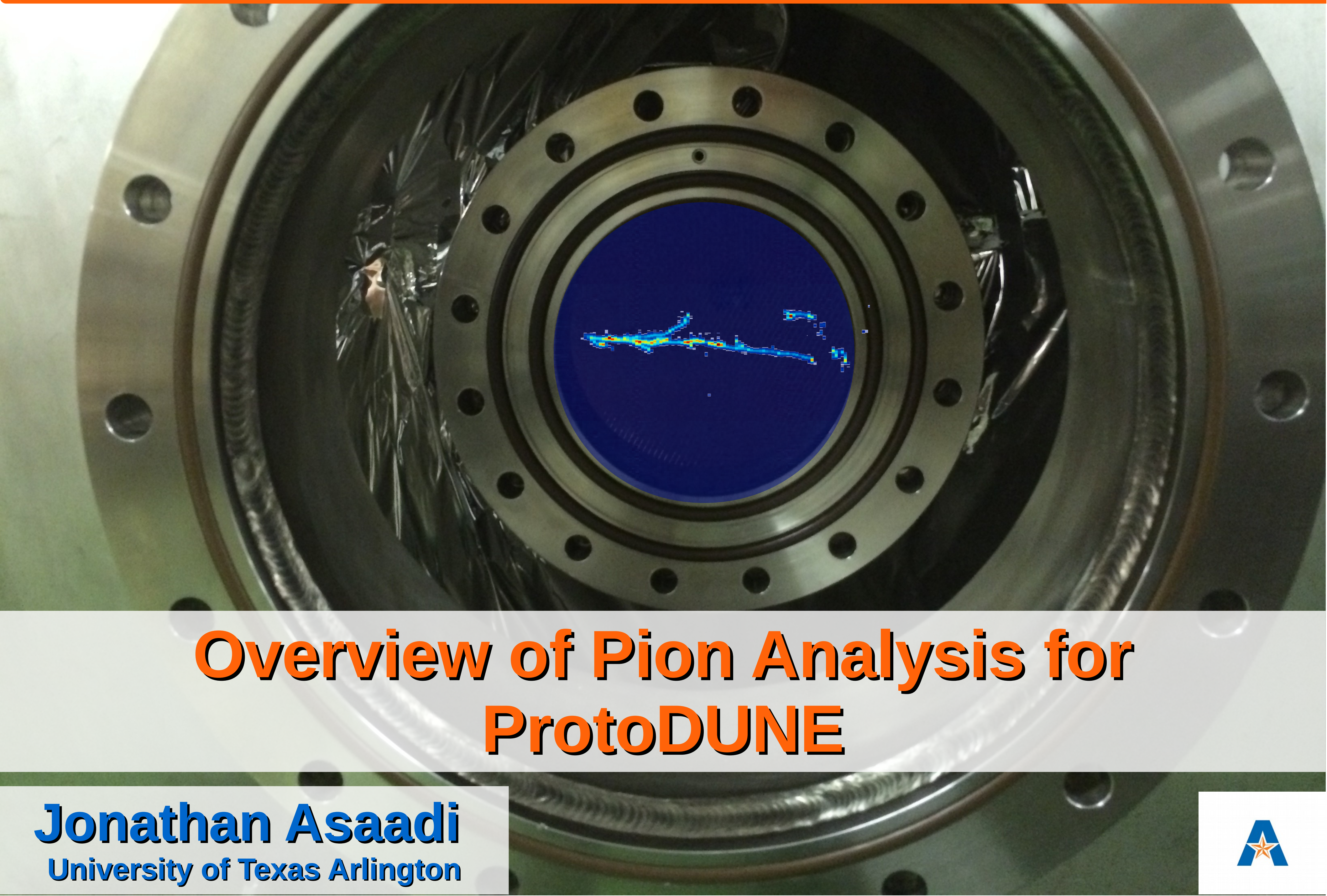
Liquid Argon in a Test Beam (LArIAT) Experiment



Overview of Pion Analysis for ProtoDUNE

Jonathan Asaadi
University of Texas Arlington

Let's start at the beginning...

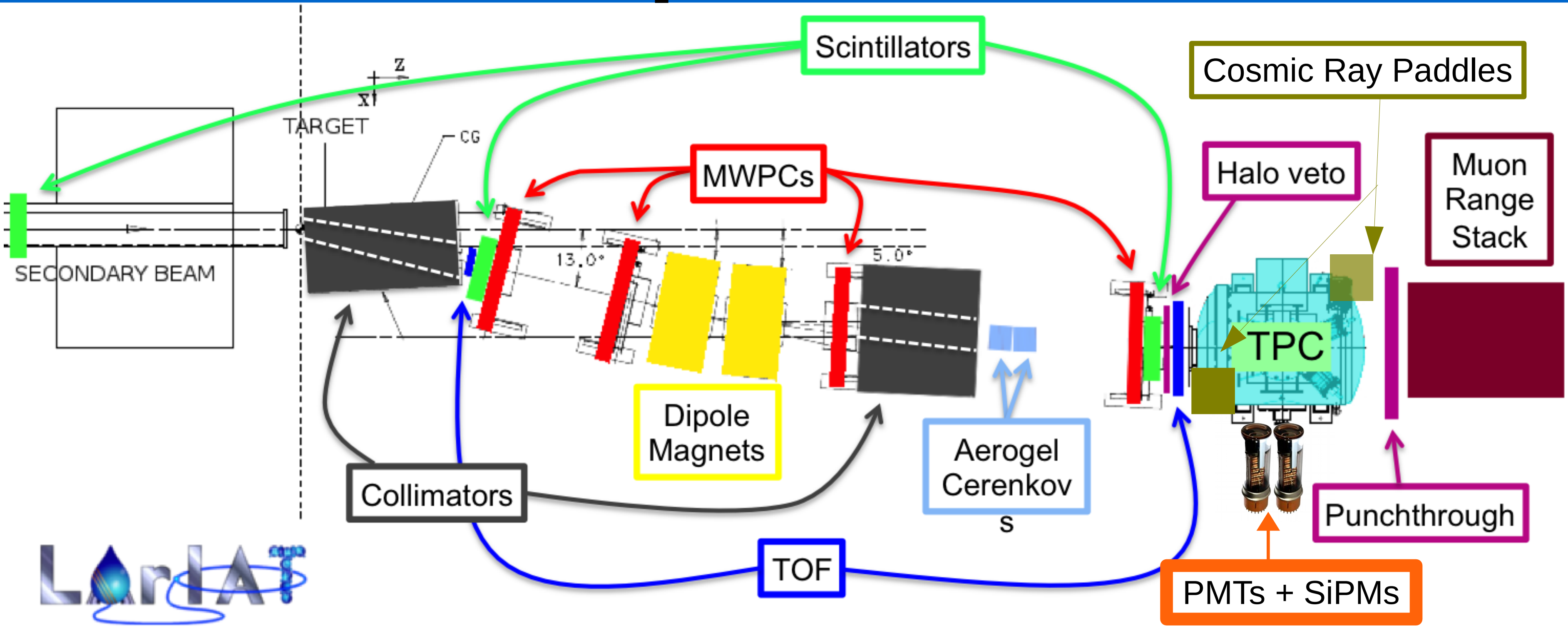
- ***"A very good place to start…."***
- **I will begin with what our data "looks" like when it is coming off the detector and how we put it together**
  - This step took awhile "to get right" for LArIAT and serves as the corner stone for our analyses!
  - This was also a way LArIAT stretched the structures of LArSoft and artDAQ which protoDUNE should benefit from without reinventing the wheel
- **I'll then move into a high level overview of our inclusive pion analysis and delve into the weeds of event selection and simulation as needed.**
  - Please stop me and ask questions as things come up
  - I'll do my best to answer, or get the question to the expert who knows it best!

Caveat!

- **Some of what I will show in this talk is still LArIAT internal**
  - In the interest of collaboration and transparency, we are lifting the veil some now
  - None of the numbers are final and should not be shared/transmitted as the final answer
    - Please don't give a seminar quoting numbers you see here as LArIAT's performance!
- **Any mistakes or problems in this talk are fully my own and shouldn't reflect the work of the LArIAT collaboration**
  - Blame me when things are unclear and/or don't make sense

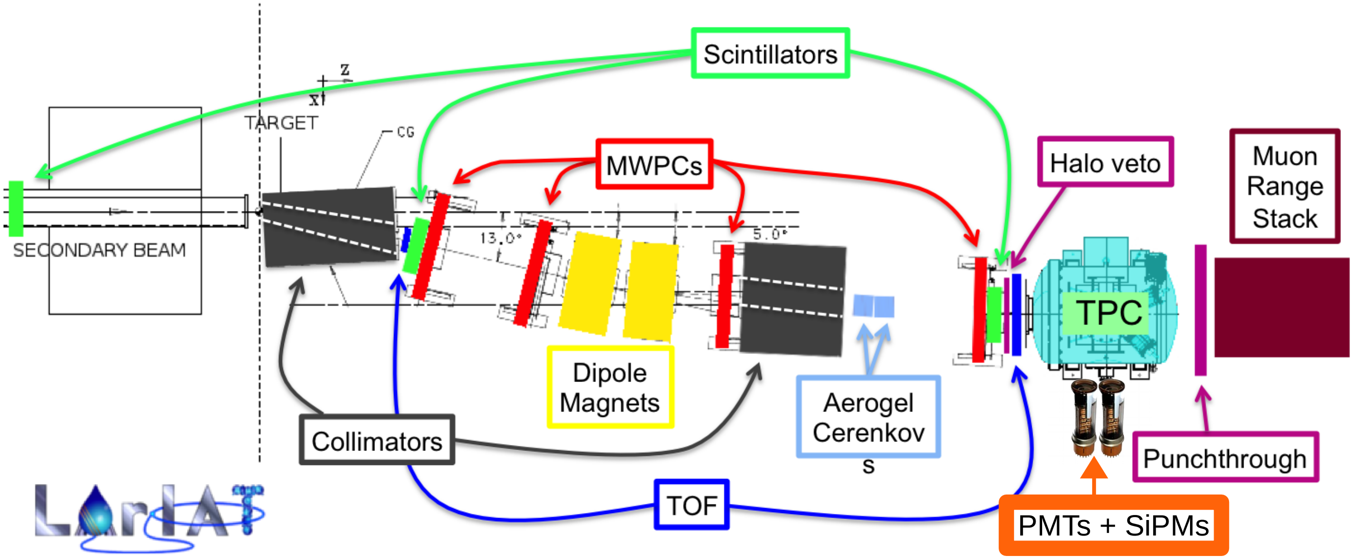
If you remember to ask at the end of the talk, I'll tell you why ponies tend to appear on LArIAT talks

What our experiment looks like



18 Detectors all read out in LArIAT DAQ

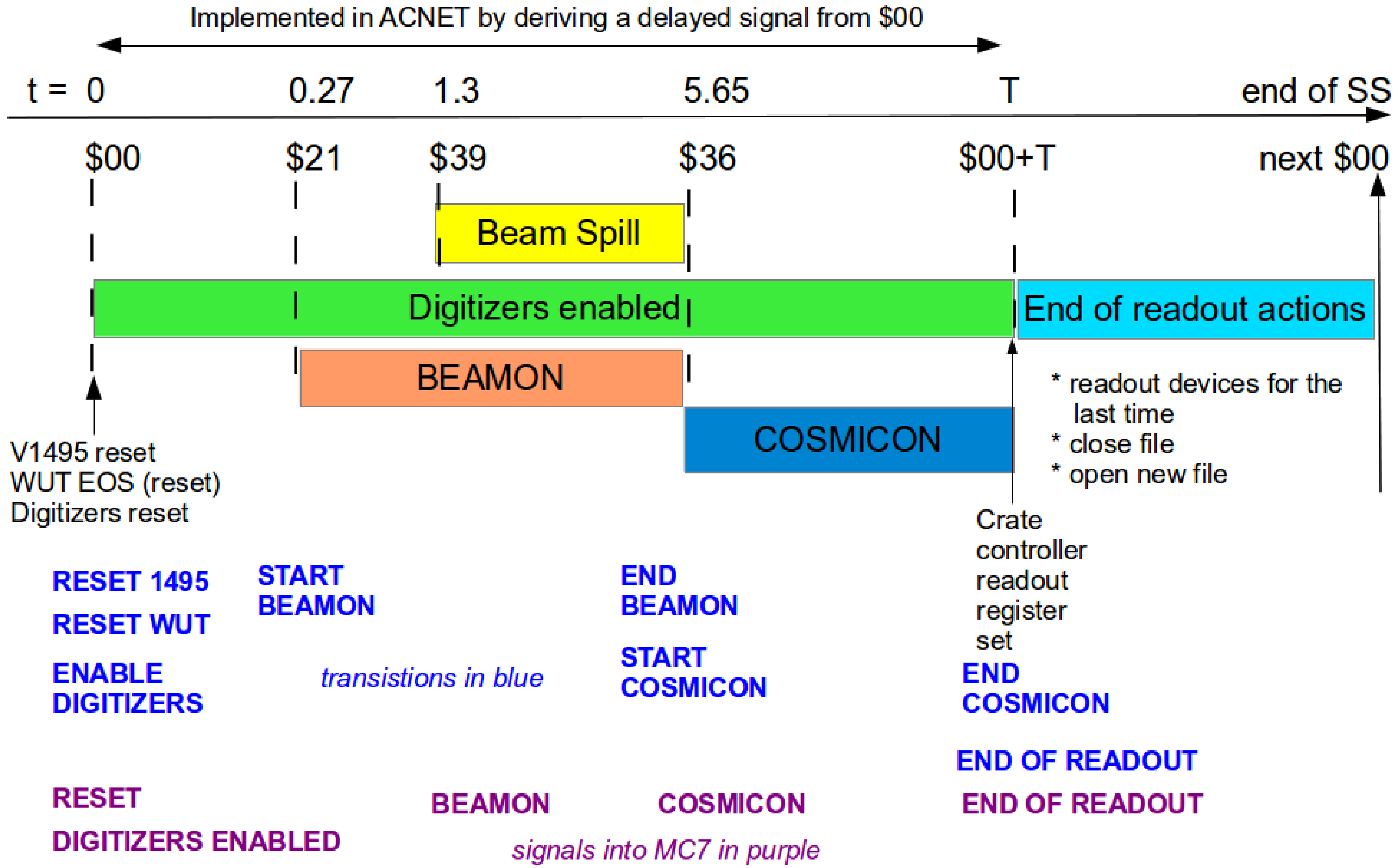
- **Two Time of Flight detectors (Upstream / Downstream)**
- **Two Cosmic Ray Paddles (Above and Below the TPC)**
- **Four Multi-Wire Proportional Chambers (MWPC)**
- **Two Aerogel Cerenkov Detectors**
- **Five LAr Light Detectors (3 SiPMs + 2 PMTs)**
- **One Muon Range Stack (16 Scintillator Paddles)**
- **Two Beamline Paddles (Halo Veto + Punchthrough)**
- **One LArTPC (480 wire channels)**



The readout of these detectors are known as "Fragments" and get turned into objects we call "Digits"

- **Detector Digits**
  - Auxiliary Detector Digits (AuxDetDigits)
  - Optical Detector Digits (OpDetPulses)
  - TPC Raw Wire (RawDigits)
  - Trigger Digits (TrigDigits)
- **Fragments from the CAEN 1751**
  - TOF, Aerogel, LAr-Light Detectors, Beam Halo-Veto
- **Fragments from the CAEN 1740**
  - LArTPC, Muon Range Stack
- **Fragments from the MWPC Controller**

What our data looks like when it comes out of the DAQ



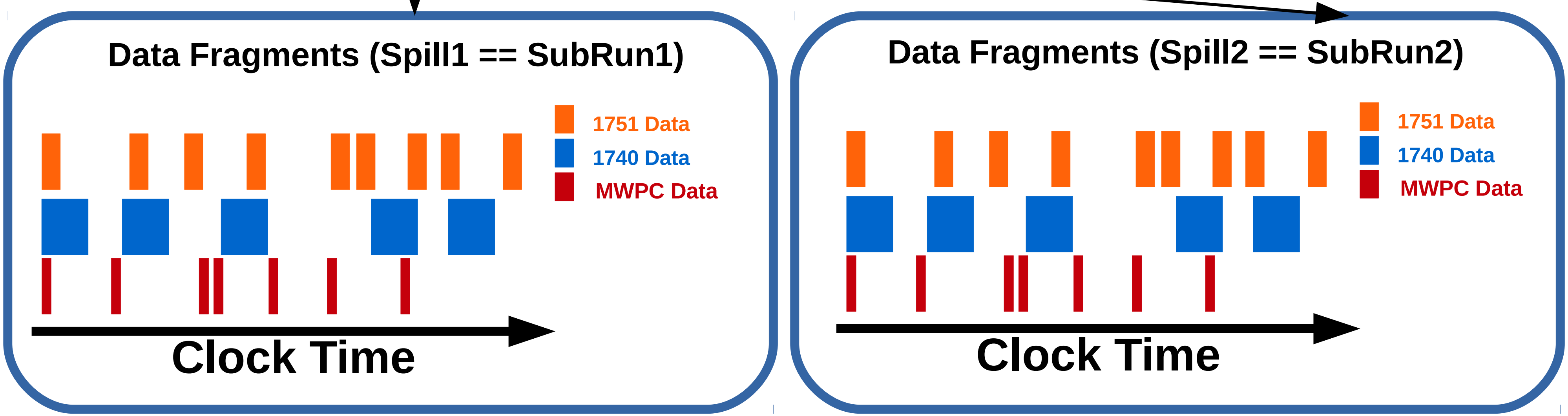
- **When we receive our beam, each 4+ second spill (along with the cosmic ray data taking period), is recorded as one long series of data fragments from the various readout**
  - The drift time of the TPC is 350 μs, meaning you can have multiple drift windows in one spill
- **Inside that one spill there are many triggers**
  - Each trigger is a predefined condition that causes the readout of of all the systems

Raw Data Structure

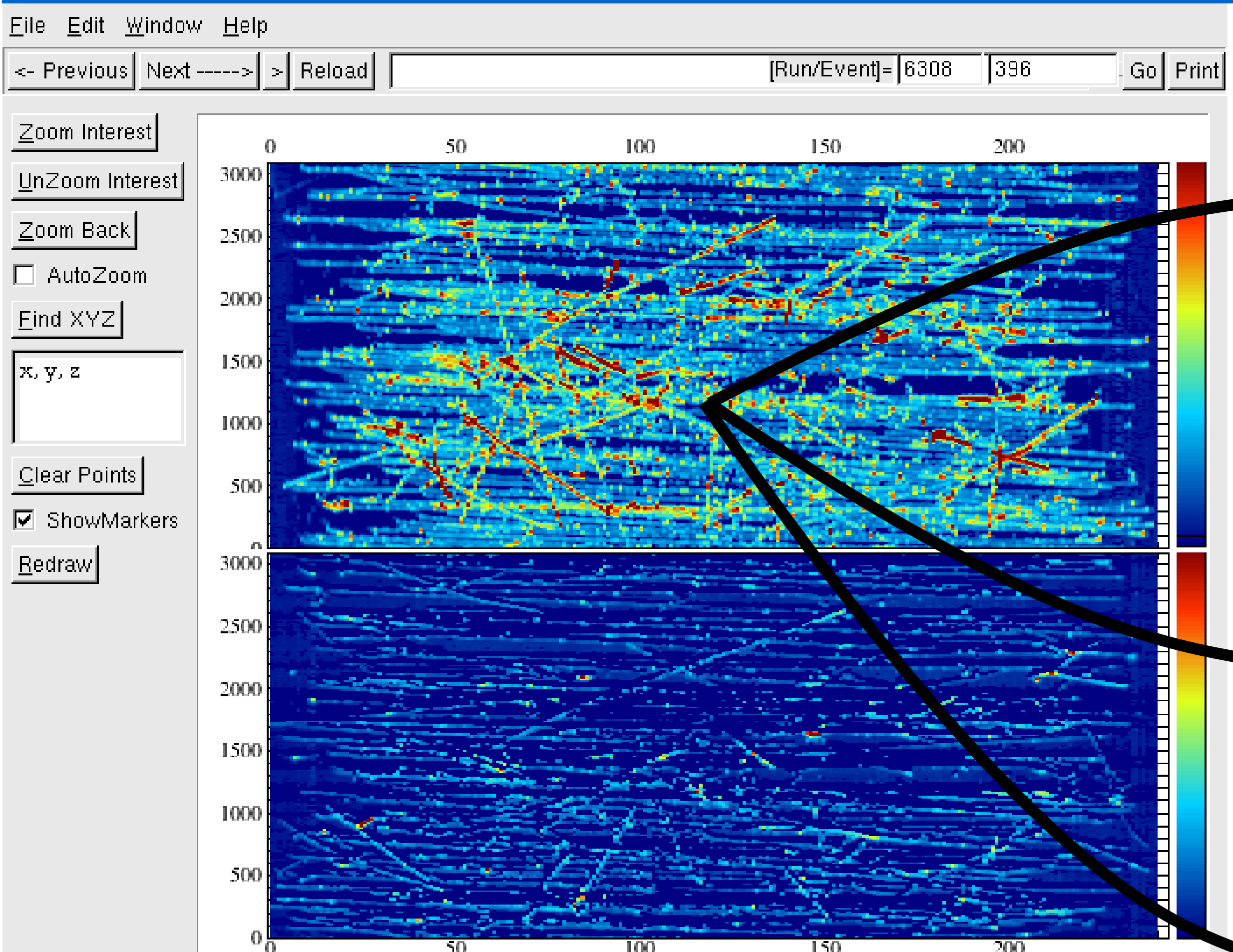
Art::DAQ
(TPC, Wire Chambers, TOF, PMT's, etc....)

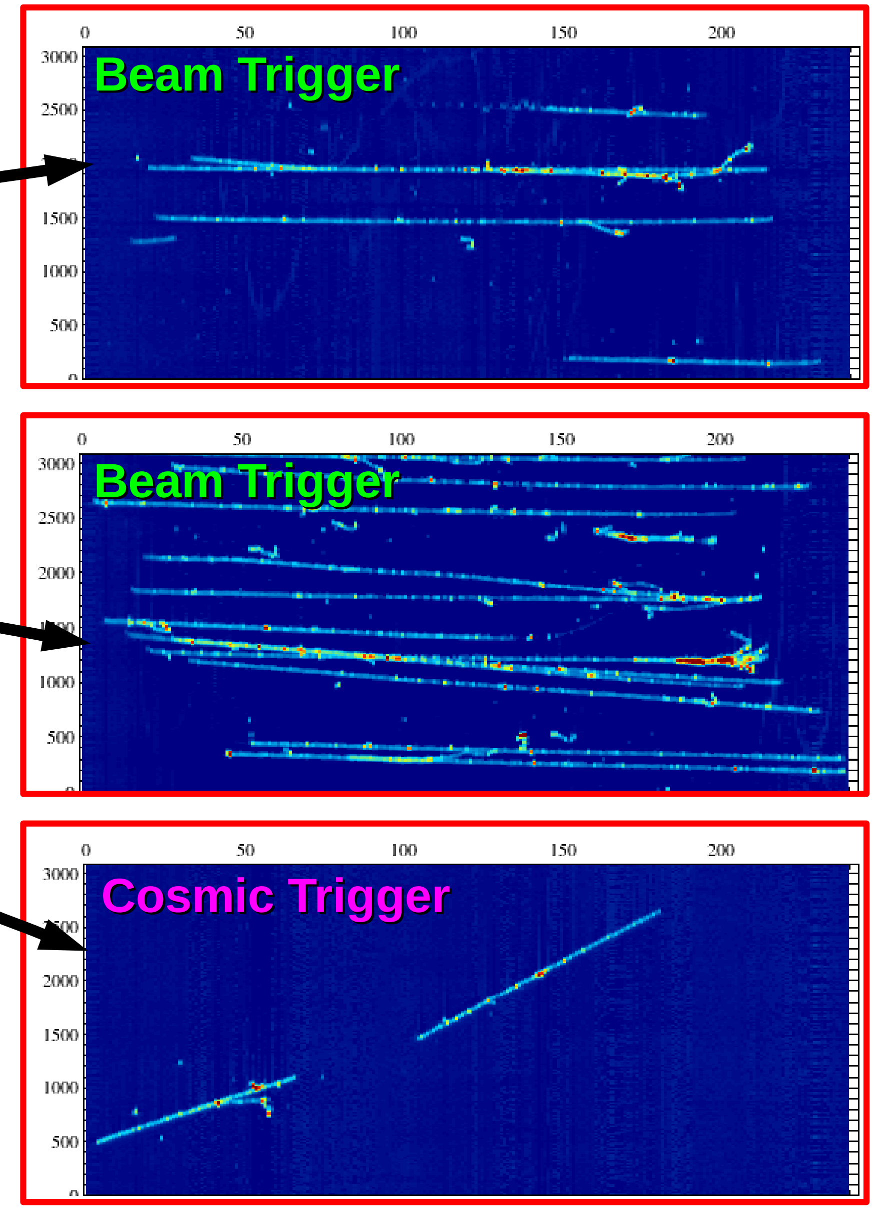
The LArSoft Line

Spills recorded
(Puts together all the various subsytems into Triggers)



Raw Data Structure

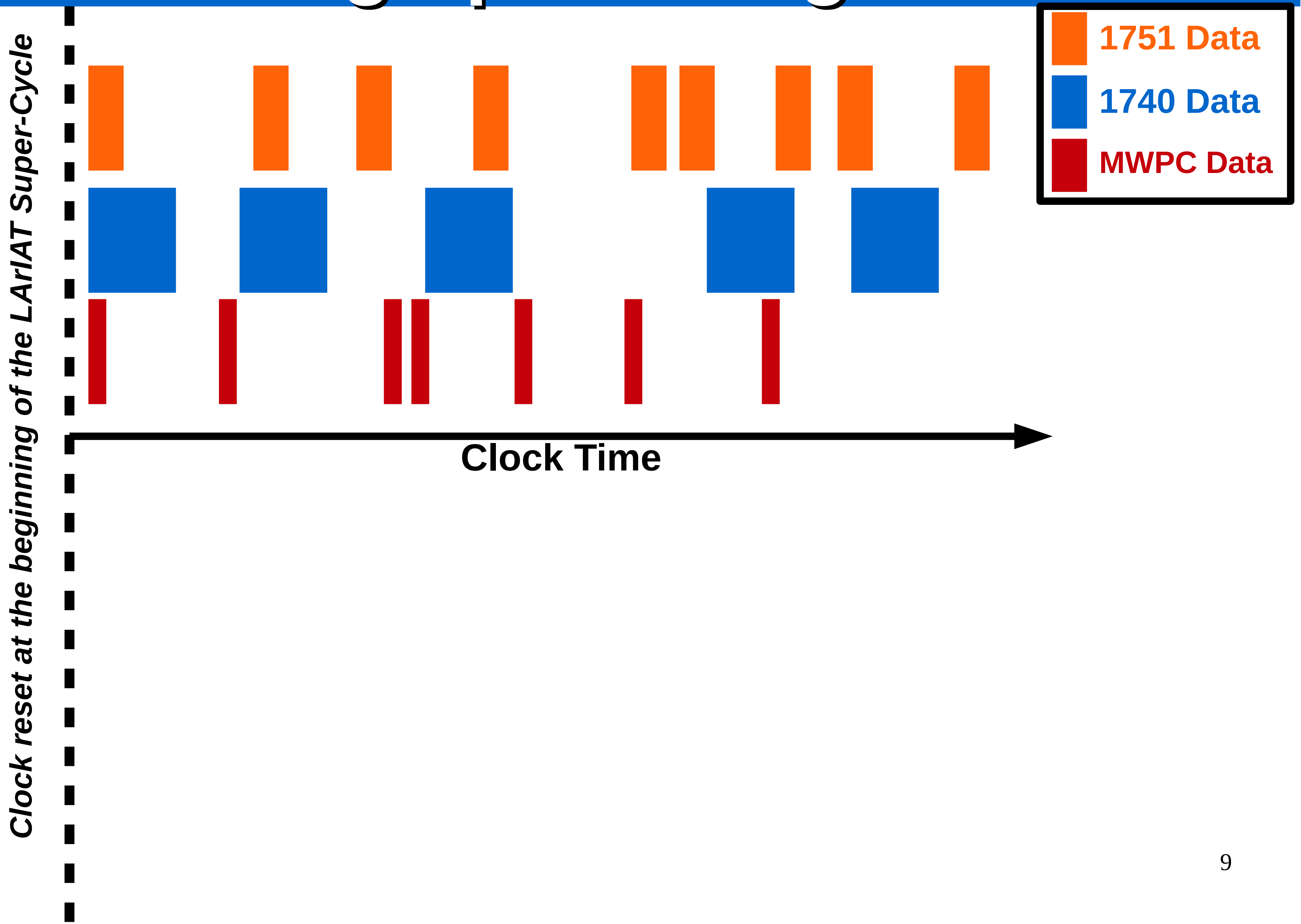




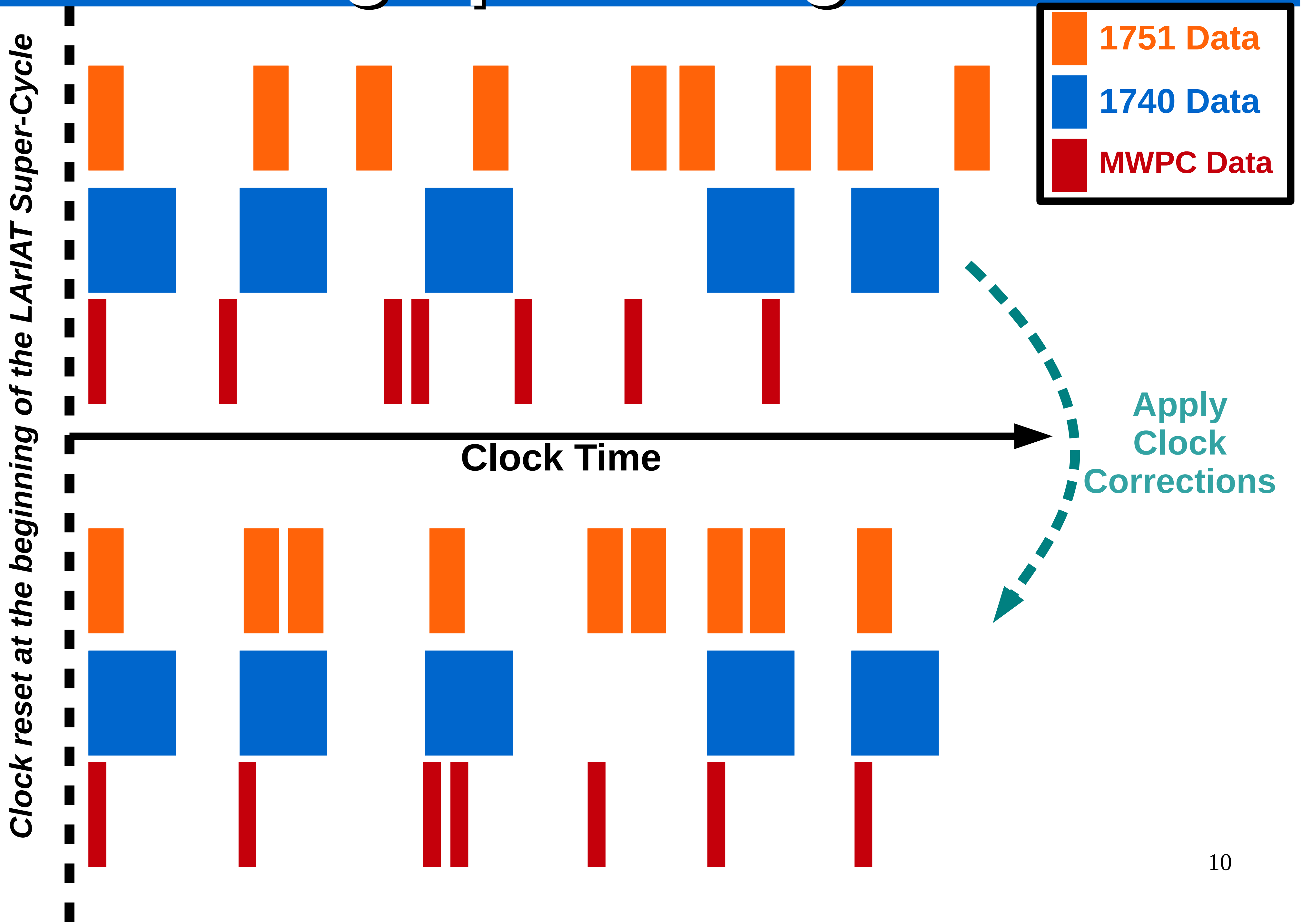
There are 40 different "triggers" within this one "data block"!

In order to make sense of this with LArIATsoft we want to restructure the data

Lining up our fragments



Lining up our fragments

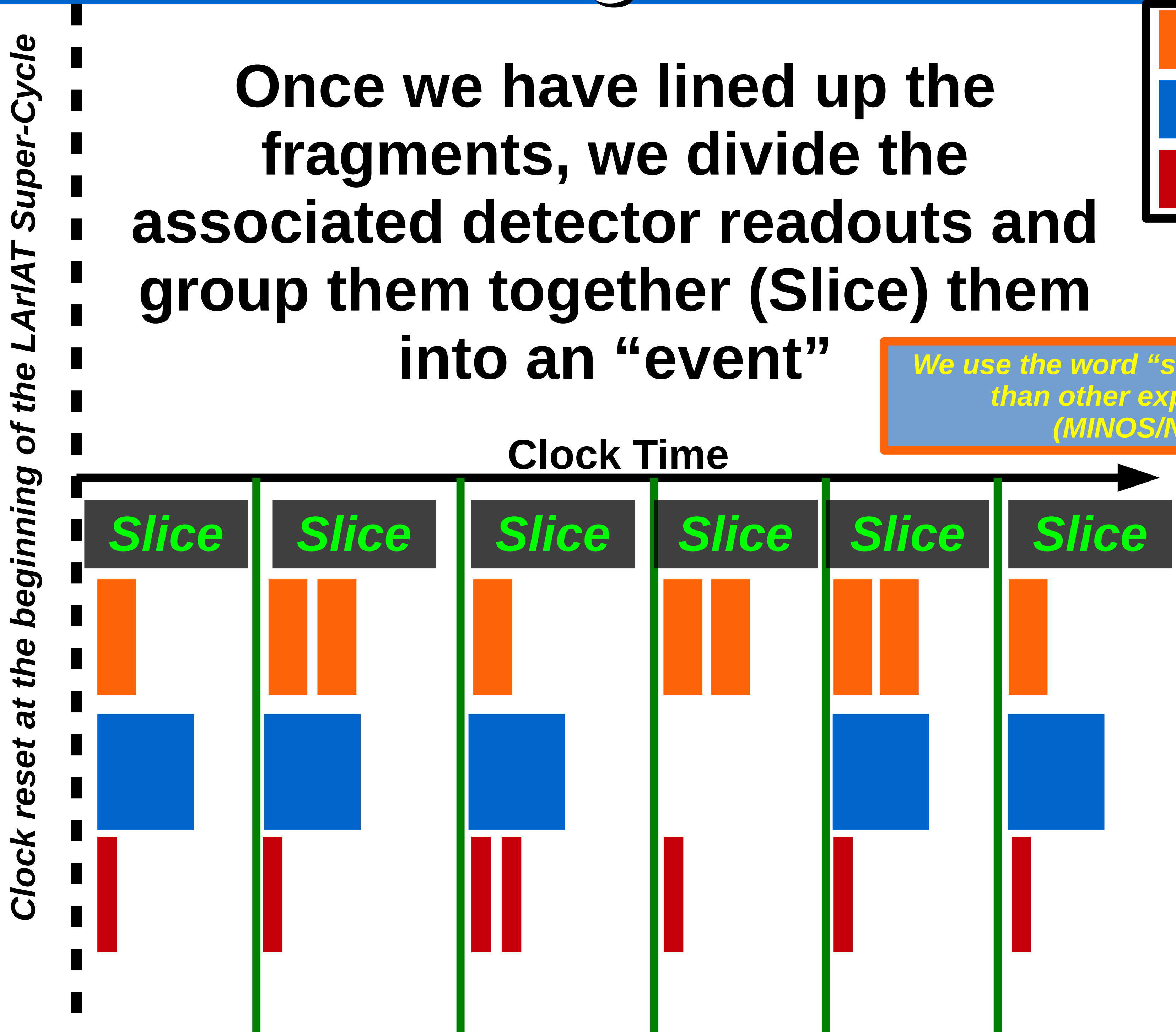


Slicing our data

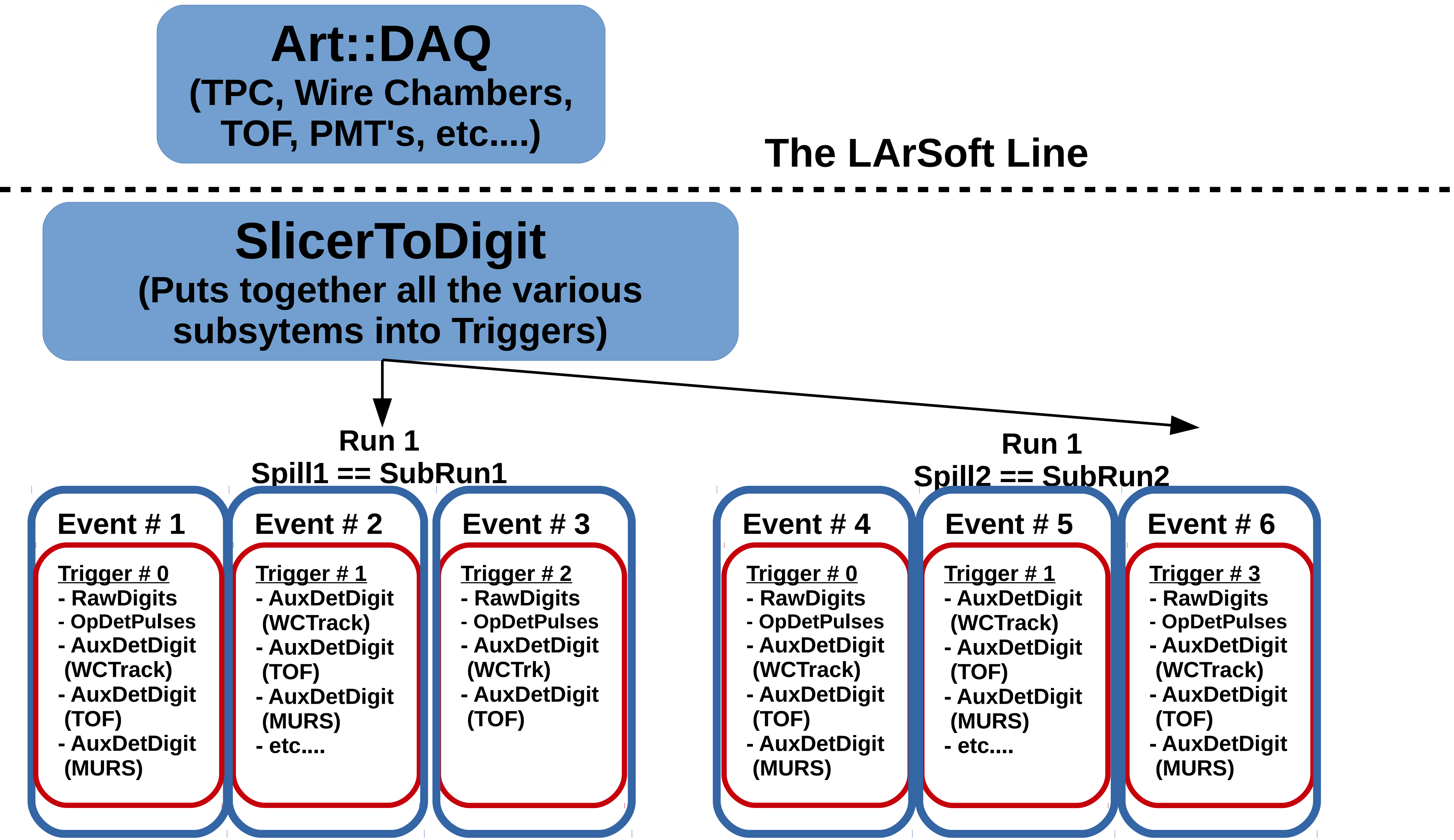
Once we have lined up the fragments, we divide the associated detector readouts and group them together (Slice) them into an "event"

1751 Data
1740 Data
MWPC Data

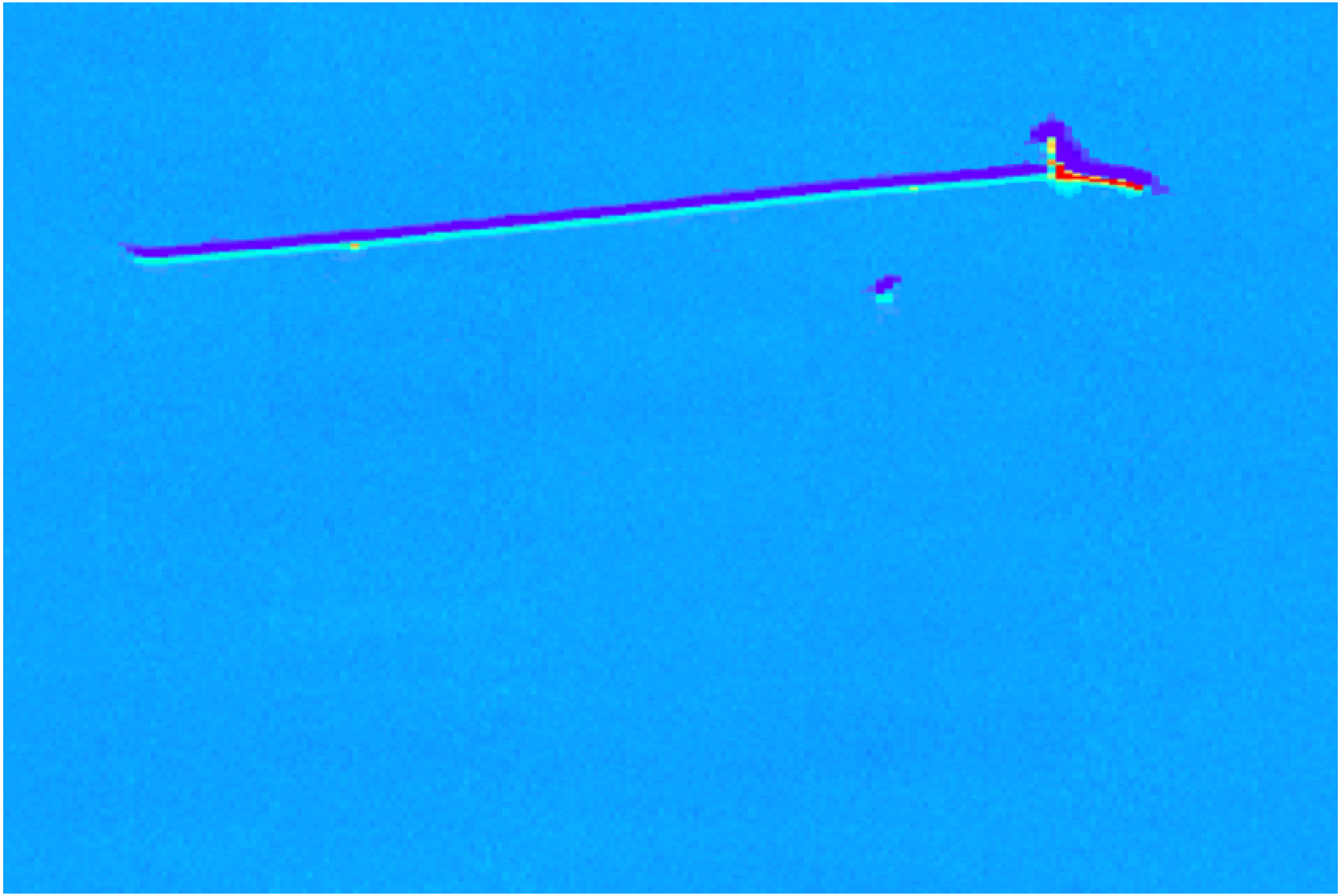
We use the word "slice" differently than other experiments (MINOS/Nova)



Raw Data Structure



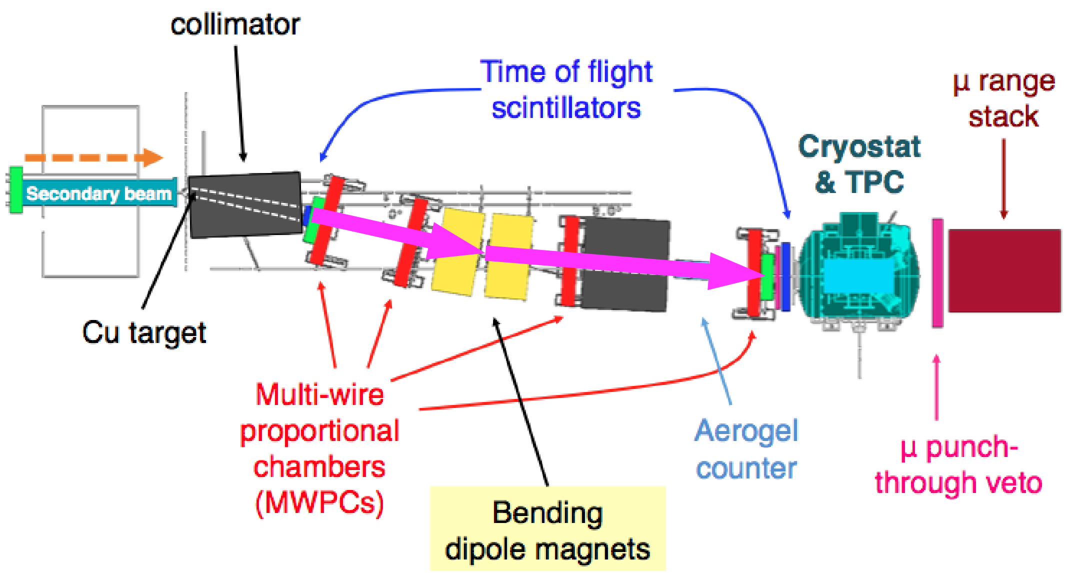
Overview of the Pion Analysis Update

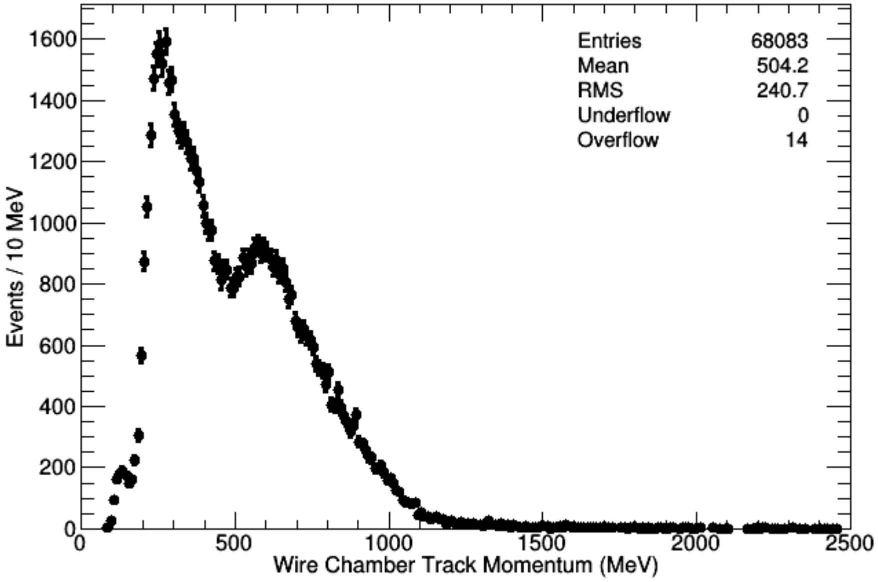


Event Selection

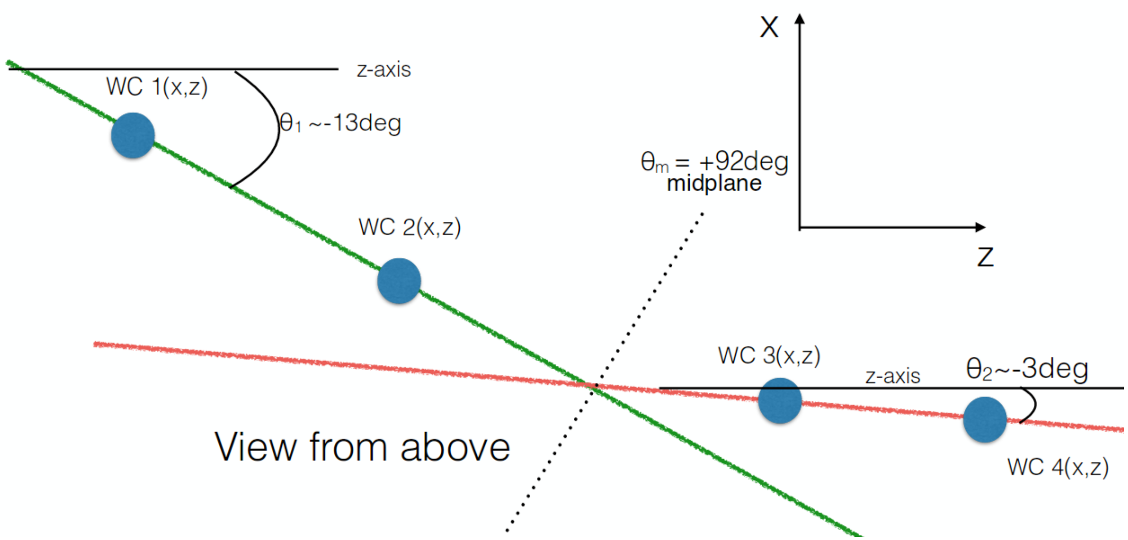
Event Selection	# of Events
Wire Chamber Track Exists	68,083

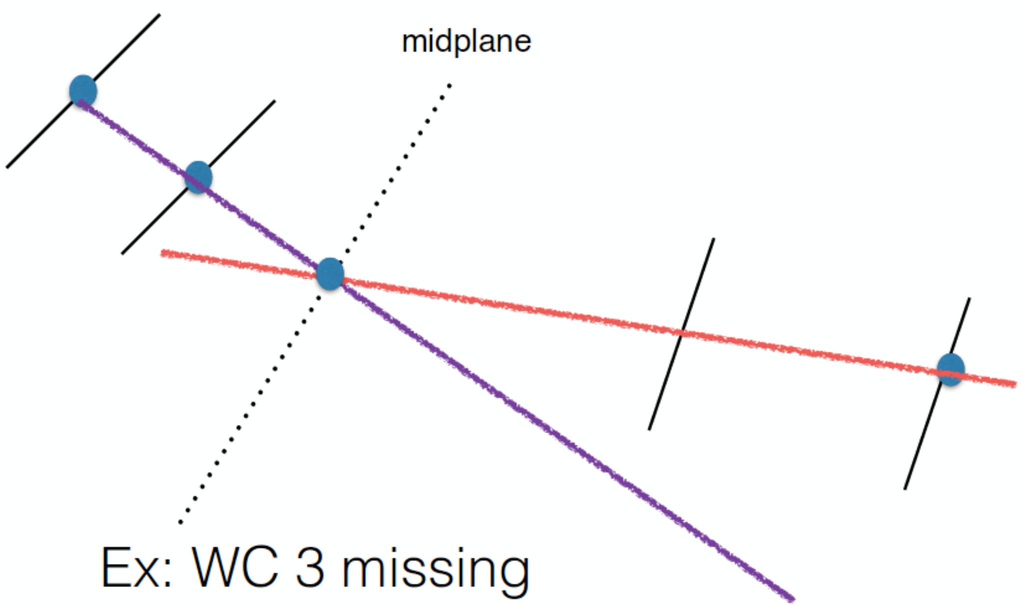
- We begin by selecting raw data events which have a "Wire Chamber Track" reconstructed
- There are two versions of the wire chamber track
  - Picky Tracks
    - Requires clean hits in all four MWPC's
  - Non-Picky Tracks
    - 3 out of 4 WC must have a hit in order to build a track
- Plot shows WC-Track momentum for this "super-sample" in the negative polarity beam





Some thoughts on Wire Chamber Tracks





- **For picky tracks we require clean hits in all four MWPC's.**
- **We use the reconstructed angles to determine the tracks momentum**
  - Noise hits and clustering of the hits in each MWPC are ther things which limit the reconstruction efficiency
- **For non-picky tracks, we allow WC 2 (before the bending magnet) or WC3 (immidiately after the bending magnet) to be missing.**
  - We use the point in the mid-plane, as extrapolated from the leg of the track which has two points, as our missing point

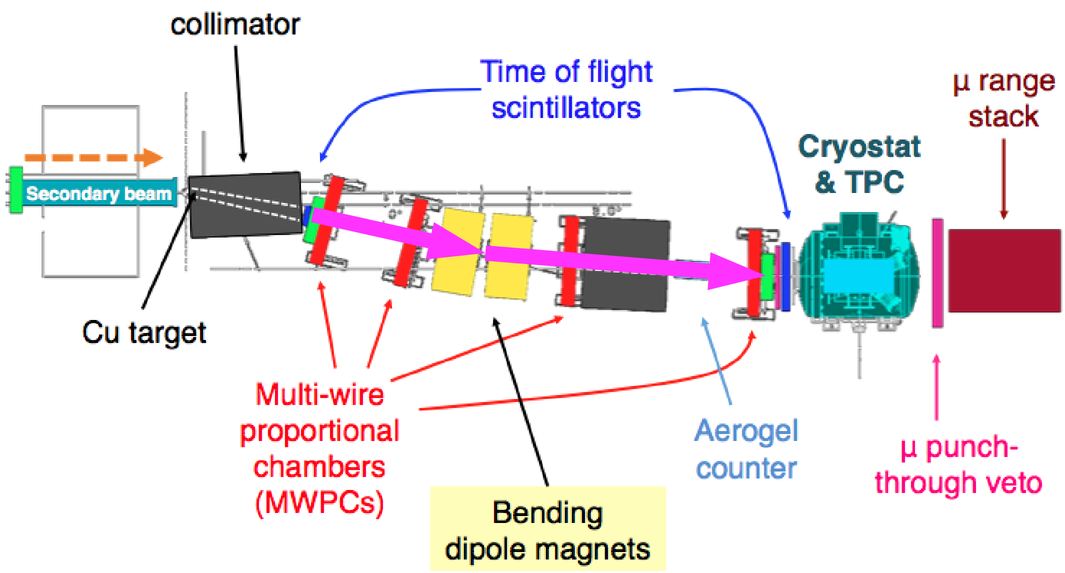
Wire Chambers in MC

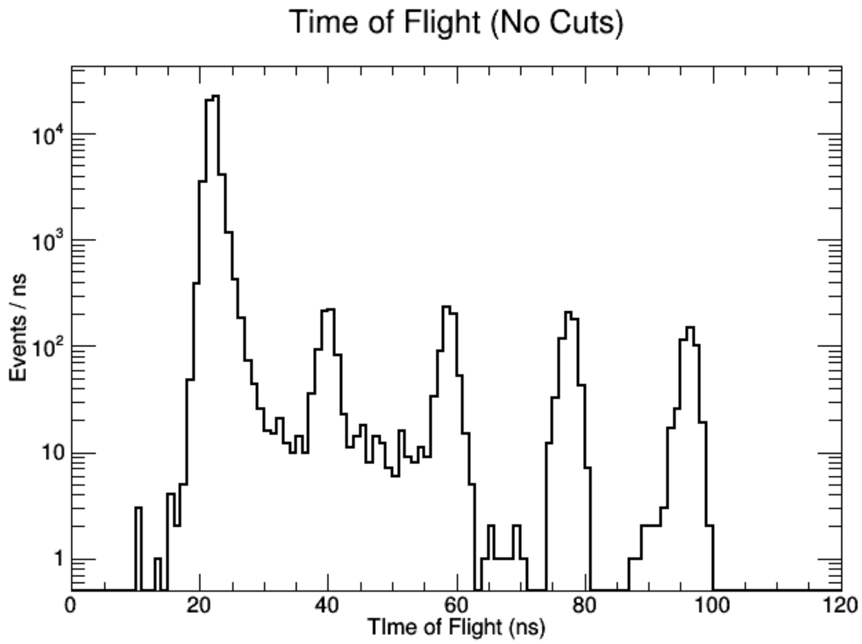
- **While it is relatively straightforward to place Wire Chamber objects as Auxillary Detectors (AuxDet) into the GDML file, utilizing them in the MC production is non-trivial**
  - This is still an area after >1 year of development we are working on getting completely right
- **Simulating detector responses is non-trival and I wish we had started on that earlier**
- **Monte Carlo truth associations between the underlying AuxDet info and Geant4 object are not what these AuxDet objects were originally designed for**
  - (e.g. which wire in the Monte Carlo WC a MC particle passed by)
  - Would be nice to have for efficiency and purity studies
    - LArIAT continues to develop these tools

Event Selection

Event Selection	# of Events
Wire Chamber Track Exists	68,083
Time of Flight Object Exists	55,243

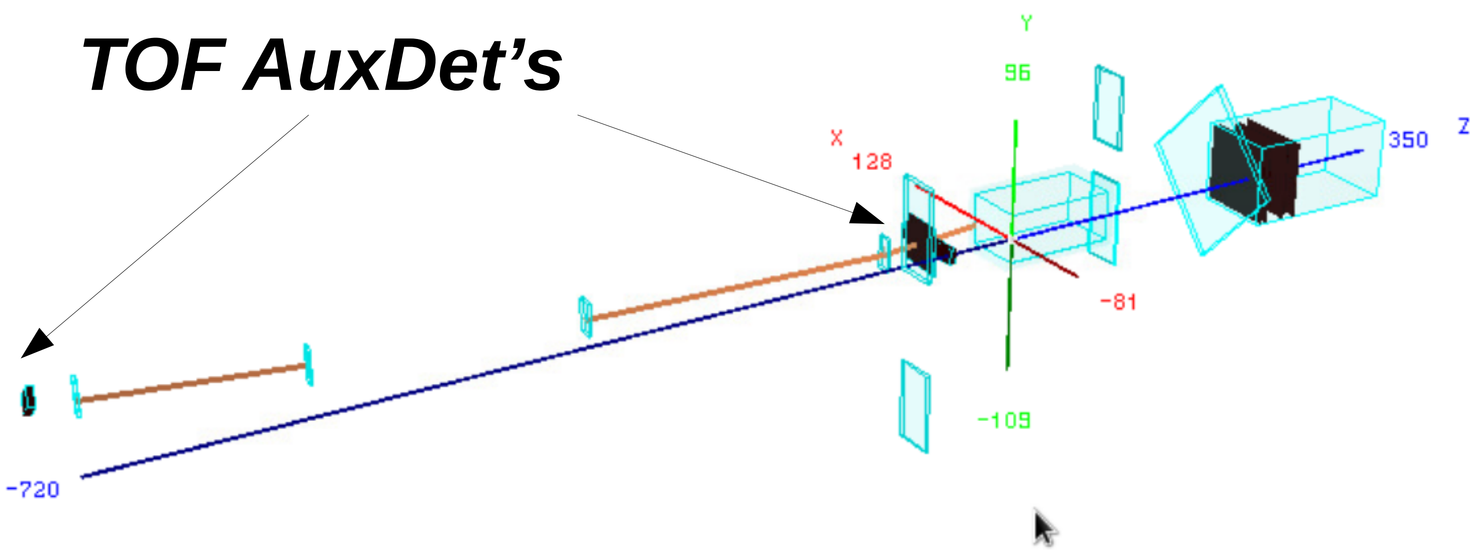
- **We reconstruct a TOF object if there are good hits in the upstream and downstream TOF**
  - Using slightly more sophisticated pulse shape fitting techniques we can get our TOF resolution to ~0.5 ns
  - Requires characterizing the hits in our detectors separately





TOF in MC

- **This is another example of a relatively simple addition to have the TOF as an AuxDet object, but not necessarily the simplest thing to put into the reconstruction**
- **In order to treat MC-TOF the same as Data-TOF we have to "fake" a detector pulse (derived from data) based on when the Geant4 particle crossed the MC-TOF AuxDet**
  - The nuts and bolts of that detector pulse we fake and how we derive it is still something we are tweaking



Event Selection

Event Selection	# of Events
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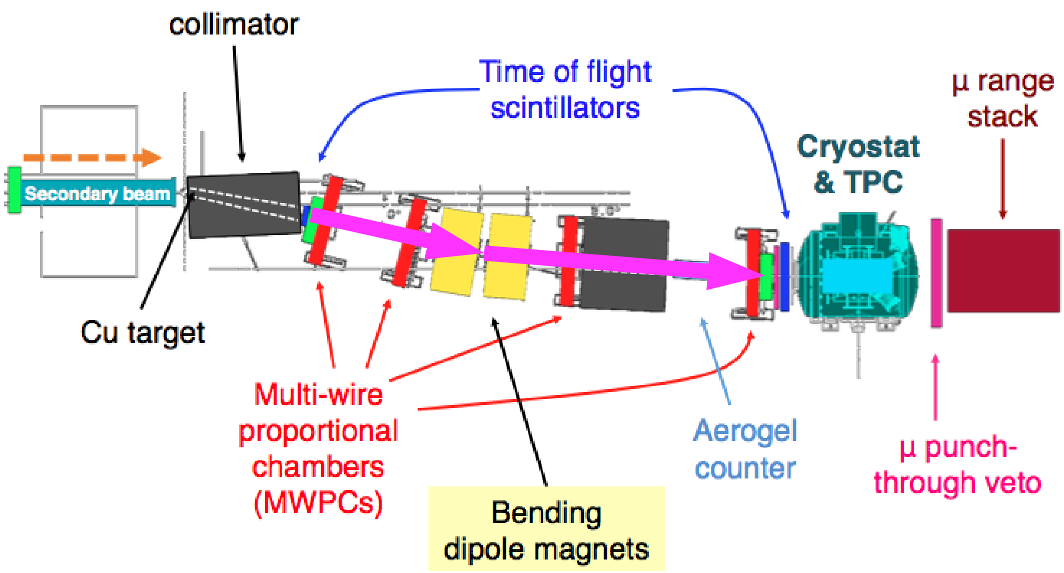
Events have hits inside the TPC	49,523



- **These events are consistent with the trigger object which requires ¾ WC had a hit in them and the “BEAMON” condition was true**
- **We chose to use these cuts to define our beam sample because the trigger object was still being developed at the time this analysis was first put together**
  - Since then the trigger object has reached stability and gives sensible number

Data Distributions

Event Selection	Updated Sample
Beam-triggered Events	49,523
Beamline Consistent w/ $\pi/\mu/e$ hypothesis *100 MeV < P_z < 2000 MeV* *10 ns < TOF < 30 ns*	31,694
At least one track reconstructed in the first 2cm of the TPC	28,911
< 4 tracks in the first 14 cm of the TPC	19,117
Veto EM-Showers *< 3 tracks with length < 5 cm*	13,694
Unique match between WC and TPC Track *-4 cm < ΔX < 6cm* *-5 cm < ΔY < 5 cm* *$\alpha < 10^o$*	3,718

- **From here I will go through our various event selection criteria for selecting "Good Pion Candidate" events**
- **Since a full beamline MC and MC-Beamline reconstruction isn't ready to go….we do something slightly different for the MC**
  - I'll go through how we treat MC later

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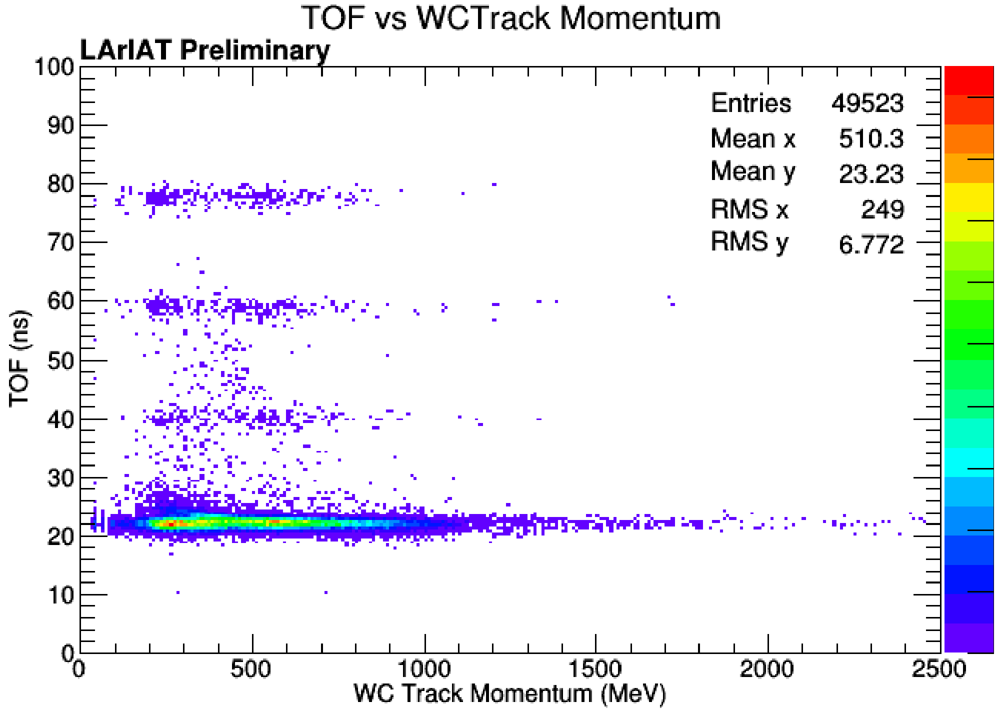
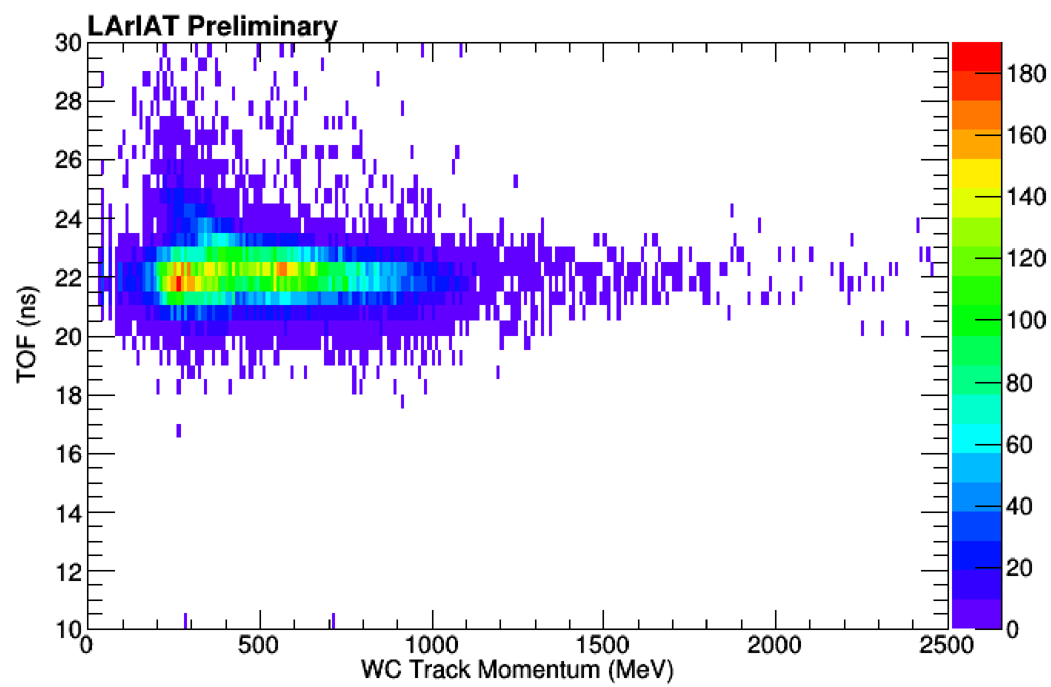
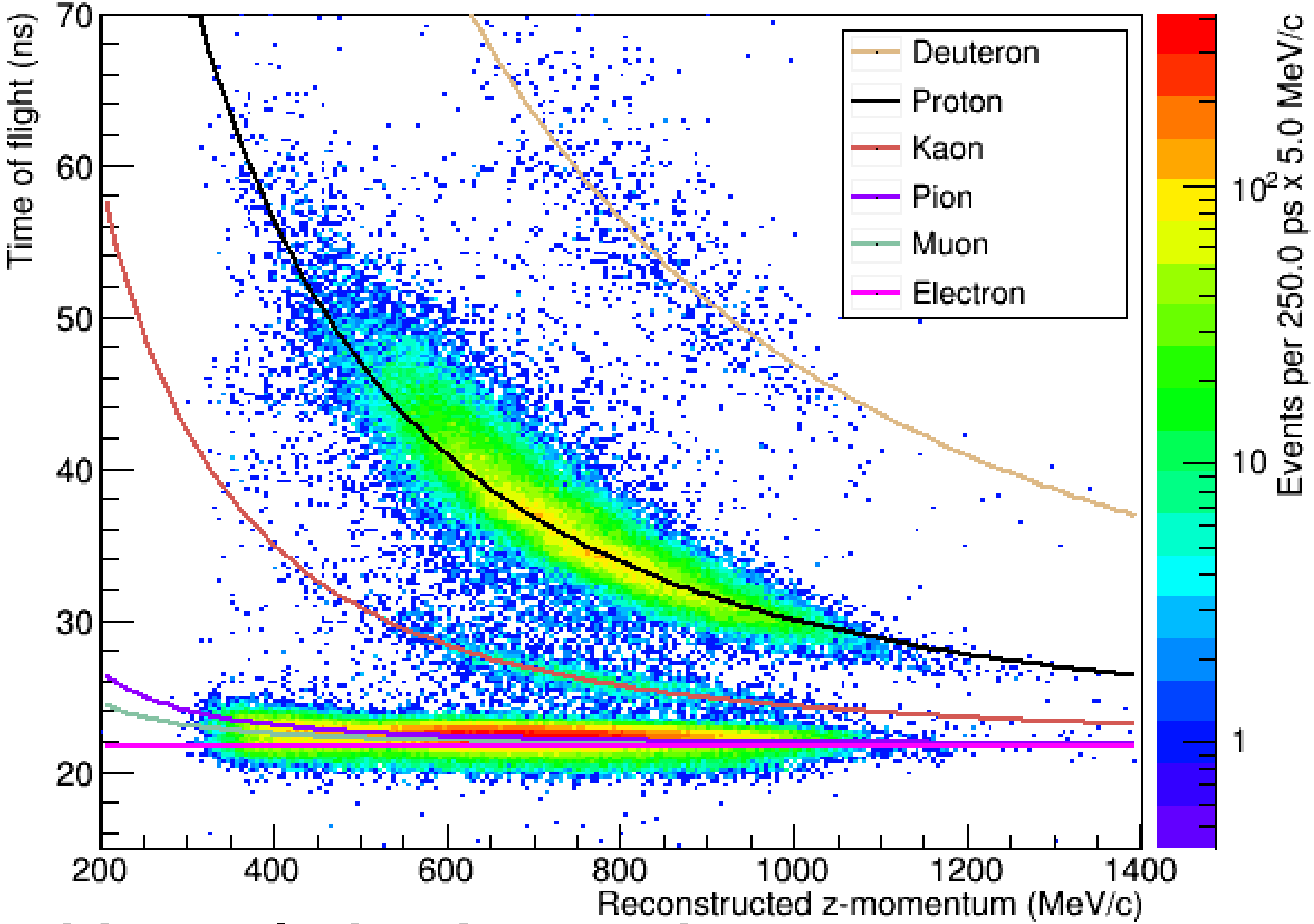
TOF vs Momentum (Negative Polarity)





- **We begin with an inclusive TOF vs WC-Track selection which removes the satellite bunches in the beam line**
- **Our anti-proton contamination is such a small fraction of our beamline we don't introduce much impurity**
- **At this point pions, muons, and electrons are indistinguishable**

TOF vs Momentum (Positive Polarity)



- **In positive polarity data we have to use a more parametrized set of cuts due to the protons in our beam**

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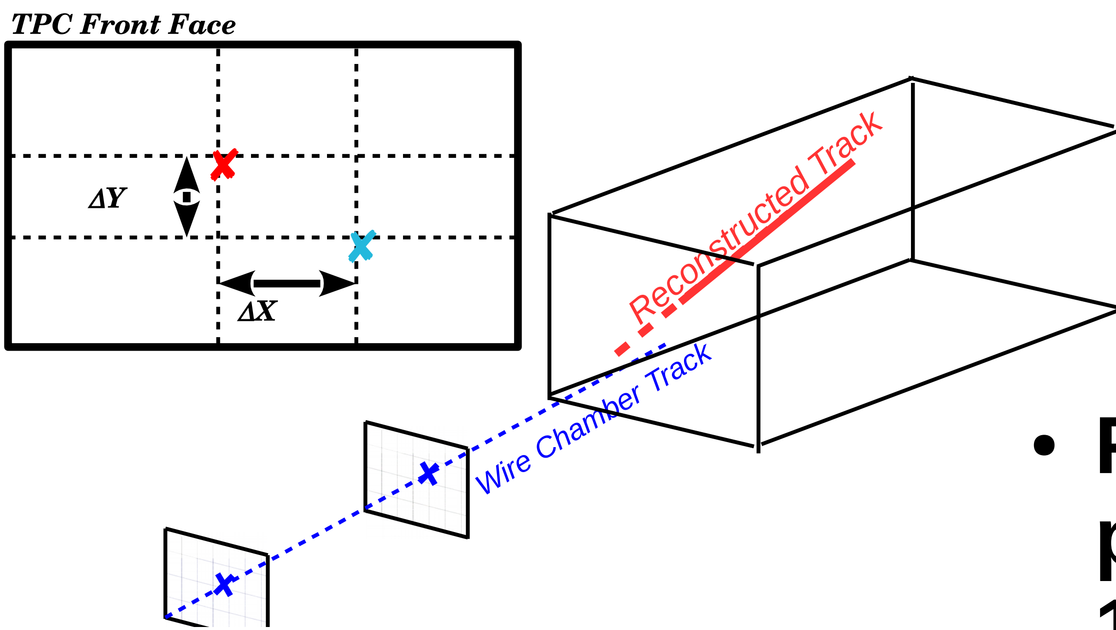
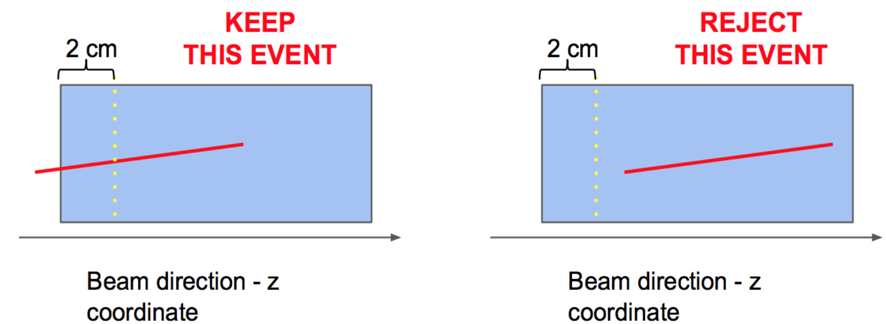
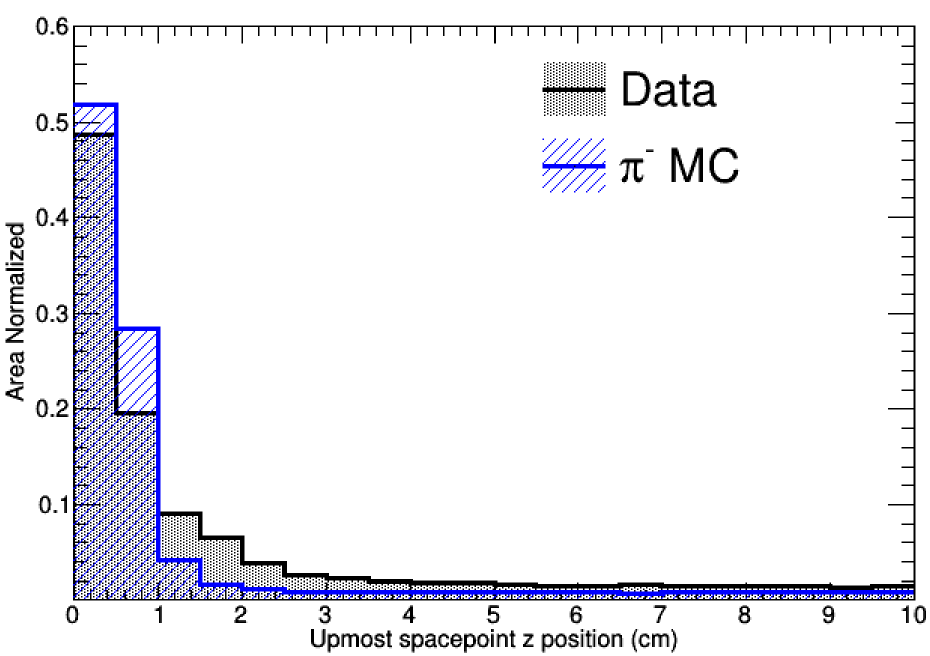
- **This selection is to help ensure that we can match our WC-Track object to a TPC track which has not had an interaction in the intervening material**
  - We extrapolate the WC-Track object to the front face of the TPC

Tracks in the TPC







- **From single particle pion MC launched from 100 cm upstream of the TPC, we can see that the majority have a track reconstructed in the first 2 cm of the TPC**
  - Our data distribution also shows we aren't throwing out that many events

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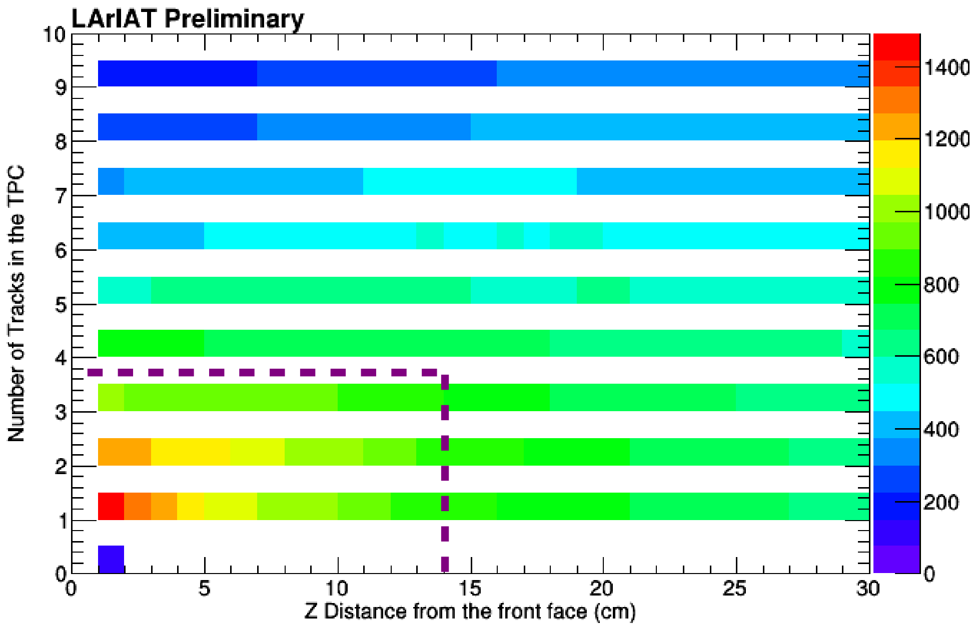
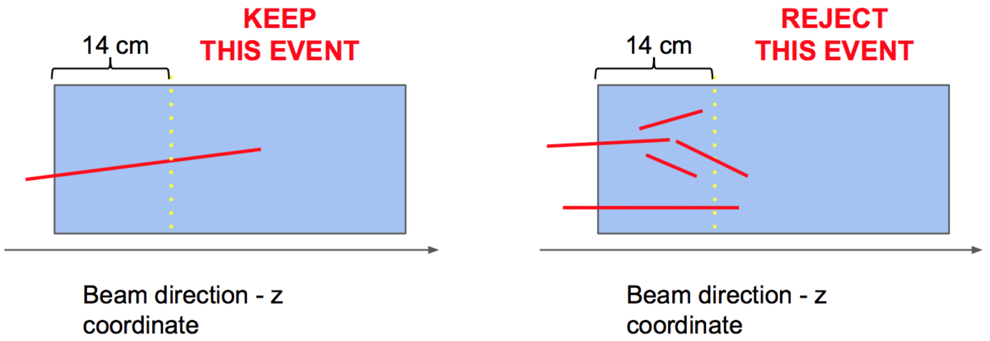
- **LArIAT Run-I had events with a lot of pile up in it!**
  - Accelerator division was still learning how to tune our beam
  - We were still learning how to request the kind of beam we could use for physics
- **This selection is designed to cut down on the reconstruction pathologies that come from events lots of tracks criss-crossing each other**

Number of tracks in Z < 14 cm





- **This cut captures the majority of the events while getting rid of large pile-up**
- **We showed that our selection efficiency was largely insensitive to this cut...so we called it good enough**

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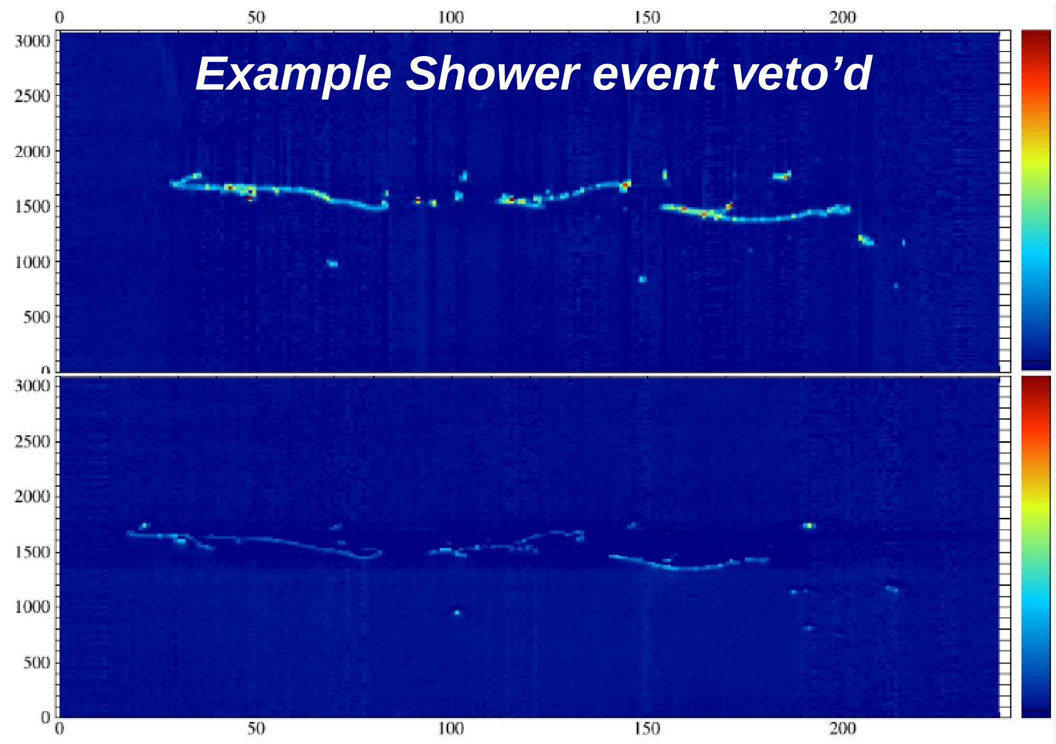
- **Shower identification remains a place of development within the LArTPC community...so there was no tool to use "out of the box"**
- **Instead, to veto a large contamination of shower events, we veto on the topology as seen by "track" reconstruction of showers**

Shower Rejection

- As I will show in upcoming slides, this cut does a nice job of rejecting showers from electrons and photons while not reducing the sample of pions by very much
- There is work ongoing to utilize the Aerogel detector to veto low momentum electrons with greater efficiency



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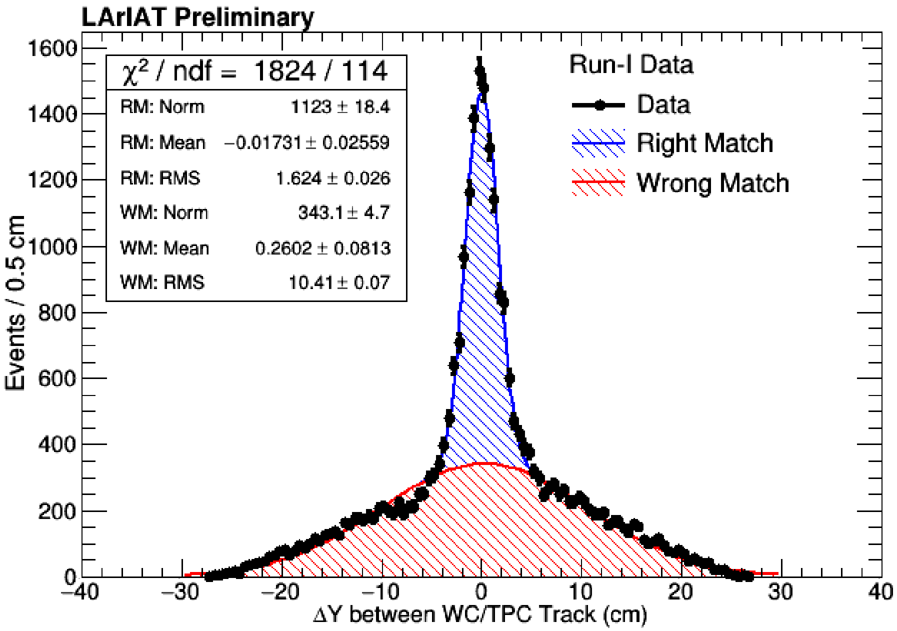
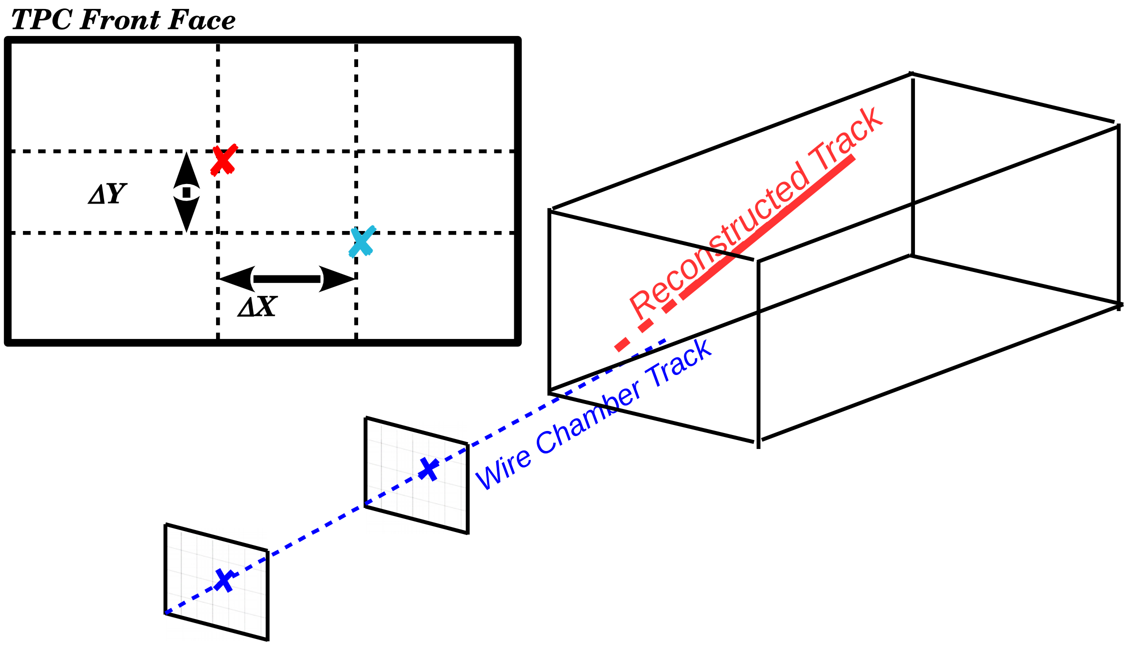
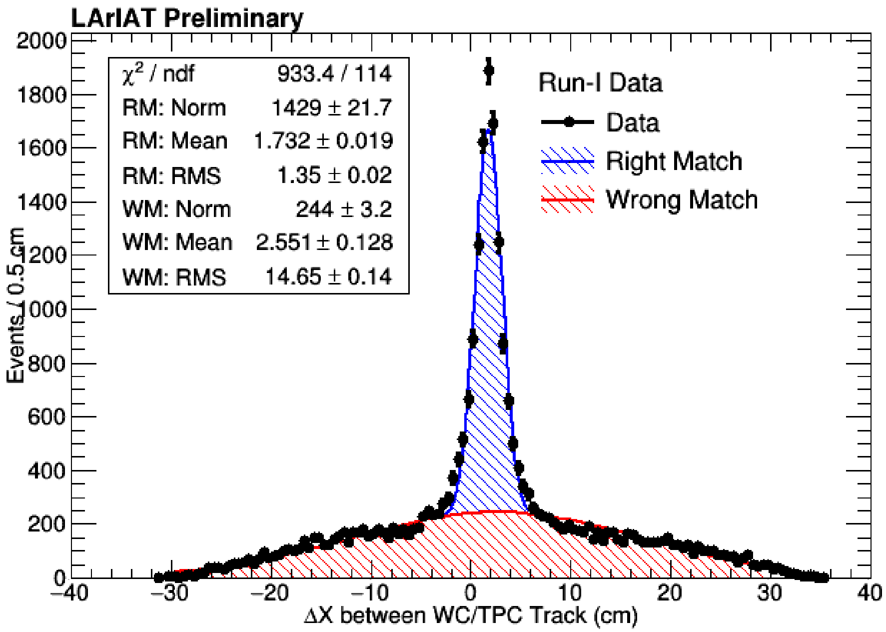
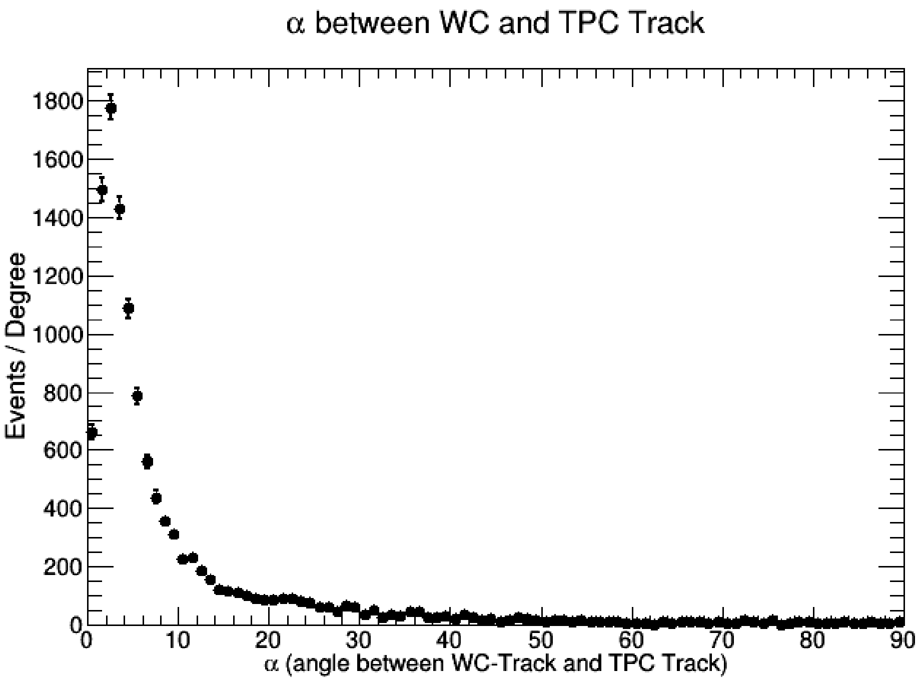
- **We define a good match between the Wire Chamber track and the TPC track before following that track for the pion analysis**
  - We define it such that particles which interact in the material between WC4 and the front face of the TPC won't be accepted
- **Having accurate reconstruction of your beamline tracks is essential**
  - This is still a cut where we loose the majority of our events

WC/TPC Matching



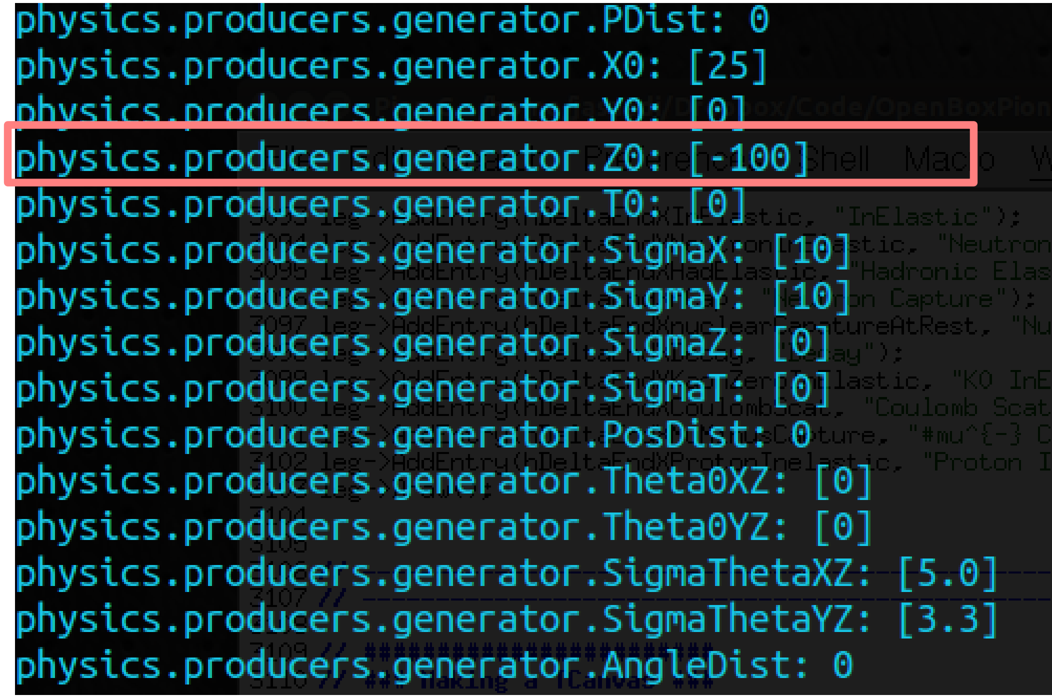






How LArIAT does MC

- **At the time of writing, LArIAT does not have a fully integrated beamline MC**
  - Although after a lot of work we are very close to taking G4Beamline running it through LArSoft and producing MC AuxDetDigits and MC-Beamline objects
- **To get around this we use single particle Monte Carlo from just upstream of WC4 to simulate the beamline and to take into account the energy loss due to the upstream material of the TPC**
  - e.g. TOF Scintillator, titanium window, cryostat, argon, etc....



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physics.producers.generator.SigmaX: [10]
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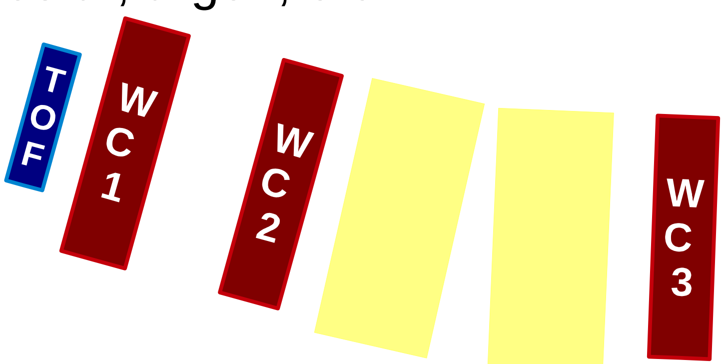
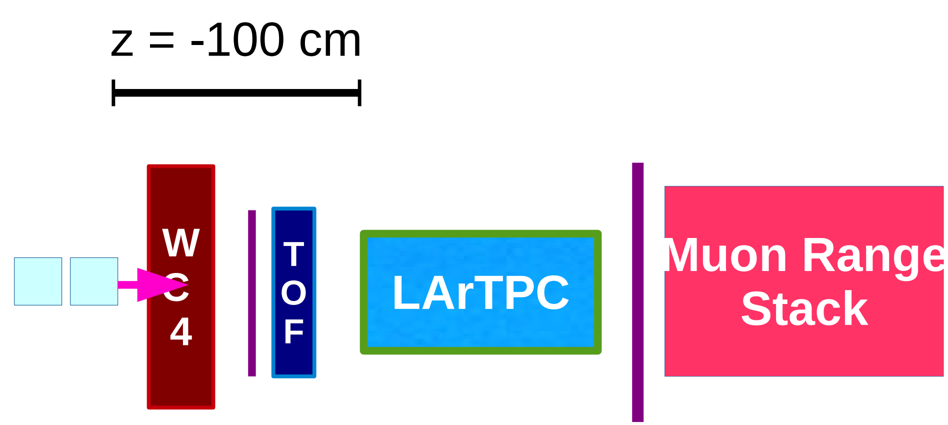
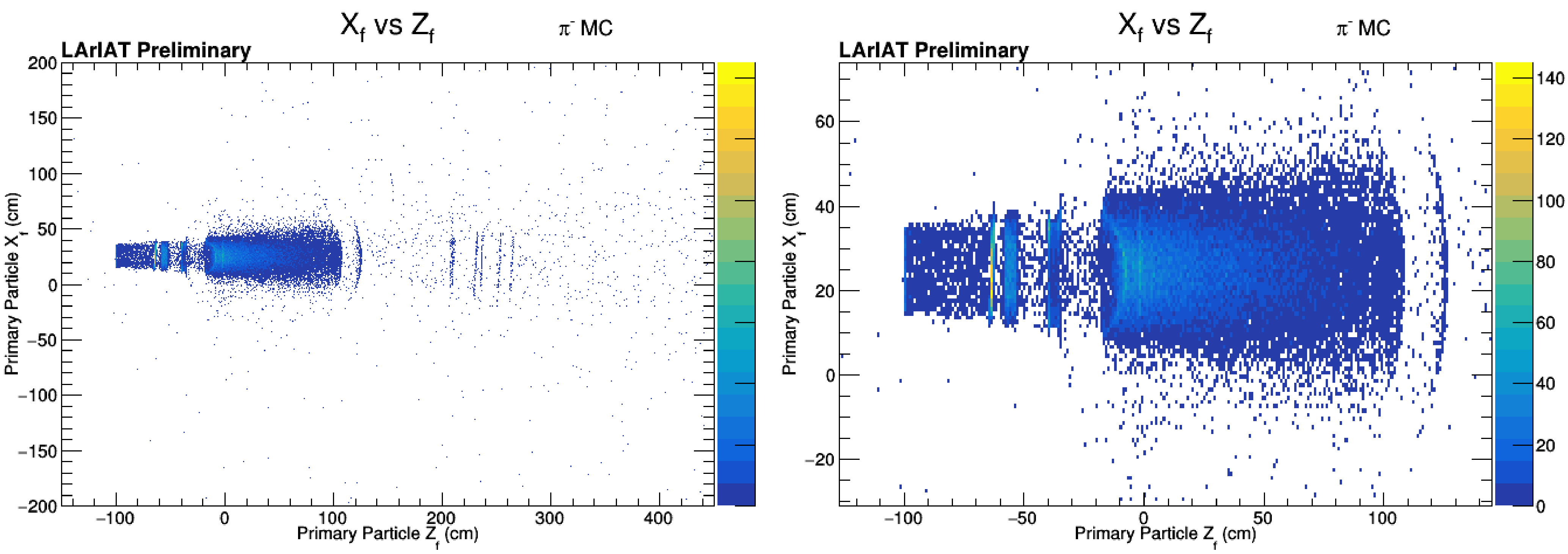




LArIAT MC

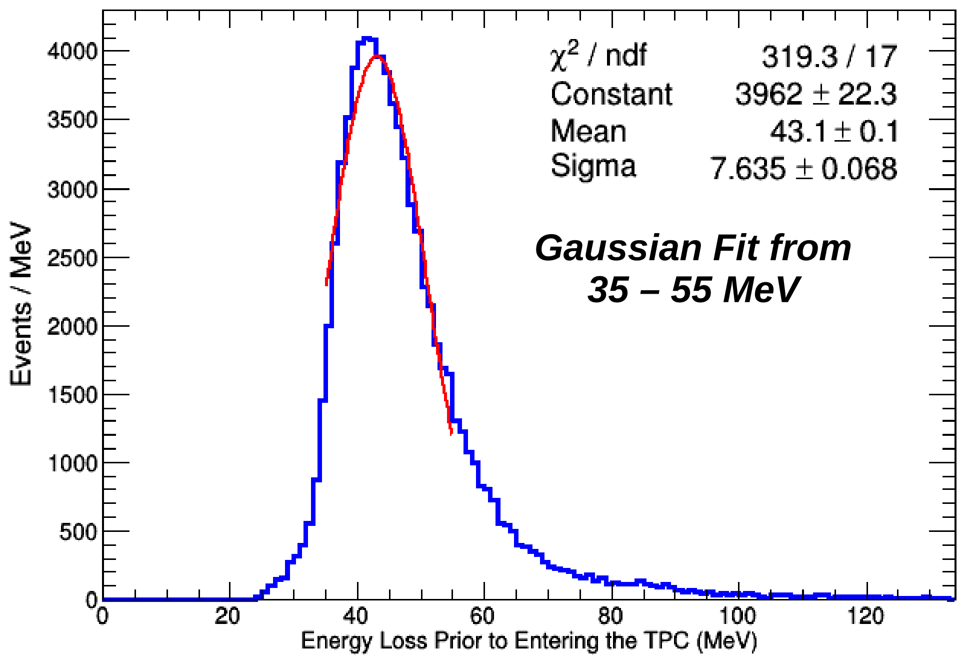
- **For all the pions that are simulated we plot the end position of the pion**
  - We see some pions do interact in the upstream material
  - We also can see that many pions do make their way into the TPC and even some go straight through

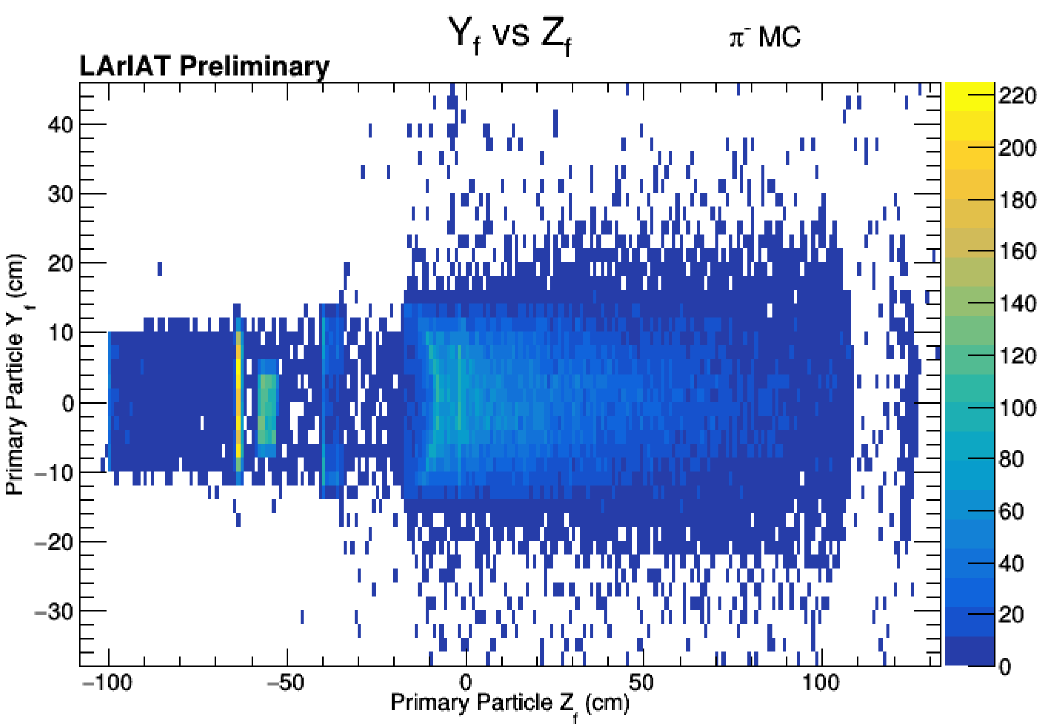


This is like an "eagle eye" view of the interactions

Energy loss upstream of the TPC

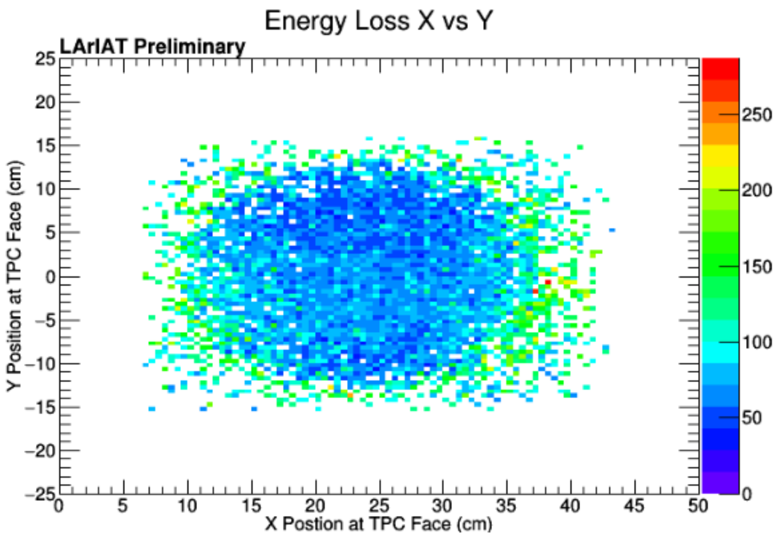
- **We also use this information to estimate the amount of energy (on average) pions lose prior to entering the TPC**
  - We get this information out of Geant4
  - Estimate this to be ~43 MeV



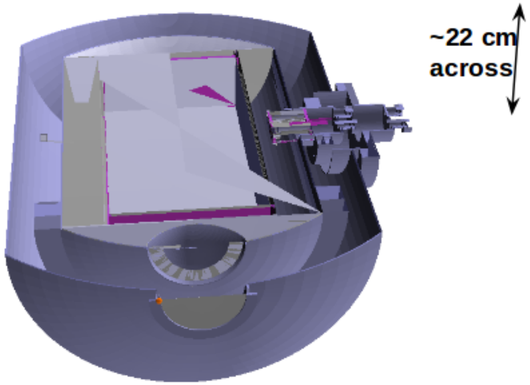


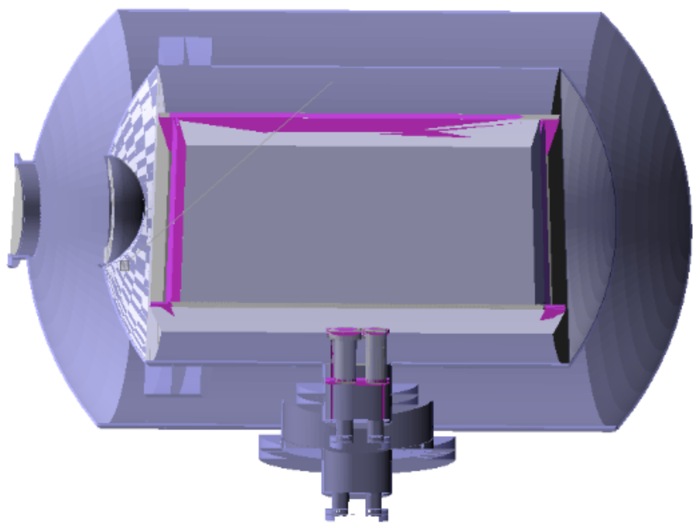
This is like an "beam side" view of the interactions

Energy loss upstream of the TPC



Made from the ratio of the energy loss at a given position divided by the number of particles at that position





- **Studies are also underway to better characterize this as a function of position**
- **Cross-studies using stopping protons to validate the energy loss mapping also in progress**
  - This is a good example of where protoDUNE could have some preliminary studies done in advance of receiving beam that will make the analysis go faster

Defining the MC sample

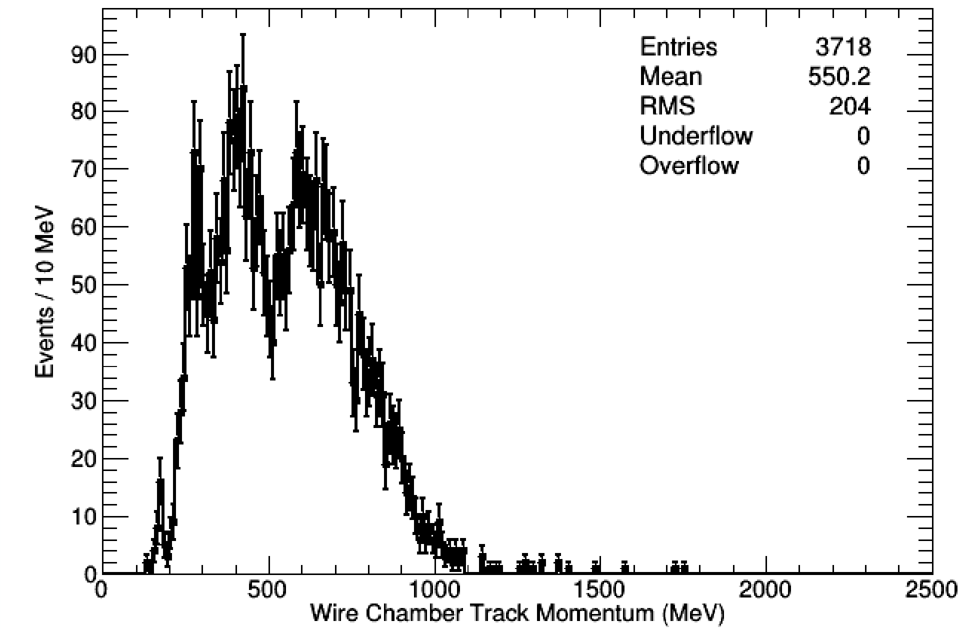
Event Selection	π^- (120,000)	K^- (118,500)	μ^- (118,800)	e^- (118,800)	γ (68,100)
Particle intersects the TPC	78,753	61,809	109,590	88,465	26,521
At least one track reconstructed in the first 2cm of the TPC	69,241	54,052	102,702	65,698	2,111
< 4 tracks in the first 14cm of the TPC	68,903	53,391	102,701	59,046	2,101
Veto EM-Showers	67,170	50,851	102,428	21,799	1,054
Unique match between "WC" and TPC track	58,483	44,376	98,391	10,019	663
Efficiency	***73.3%***	***71.8%***	***89.9%***	***11.4%***	***2.5%***

- **I define efficiency as the number of events that survive all the cuts divided by the number of events which intersect the TPC**
- **We use this breakdown along with a fractional content of our beamline from G4Beamline to get the content of or final sample**

Beam Composition before cuts	π^-	e^-	γ	μ^-	K^-	$\overline{p}$
	48.4	40.9	8.5	2.2	0.035	0.007

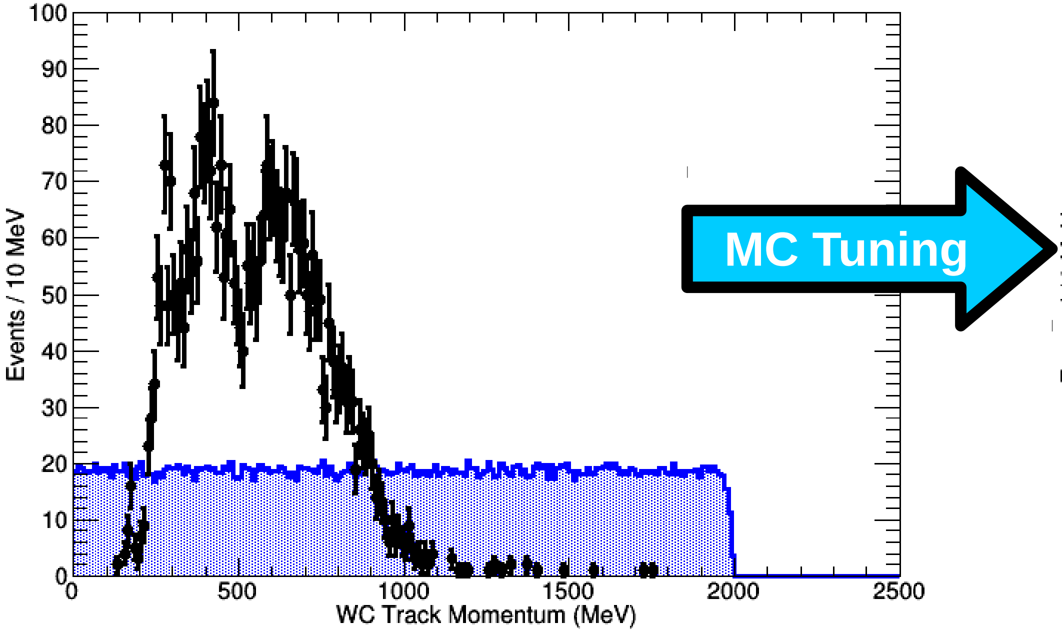
Data Distributions

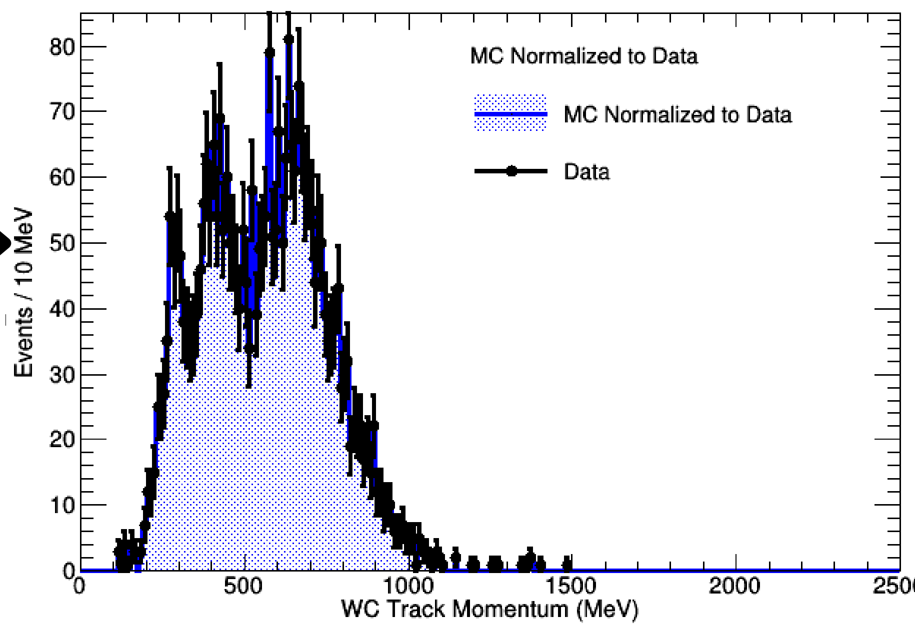
Event Selection	Updated Sample
Beam-triggered Events	49,523
Beamline Consistent w/ π/μ/e hypothesis *100 MeV < P_z < 2000 MeV* *10 ns < TOF < 30 ns*	31,694
At least one track reconstructed in the first 2cm of the TPC	28,911
< 4 tracks in the first 14 cm of the TPC	19,117
Veto EM-Showers *< 3 tracks with length < 5 cm*	13,694
Unique match between WC and TPC Track *-4 cm < ΔX < 6cm* *-5 cm < ΔY < 5 cm* $\alpha < 10^o$	3,718



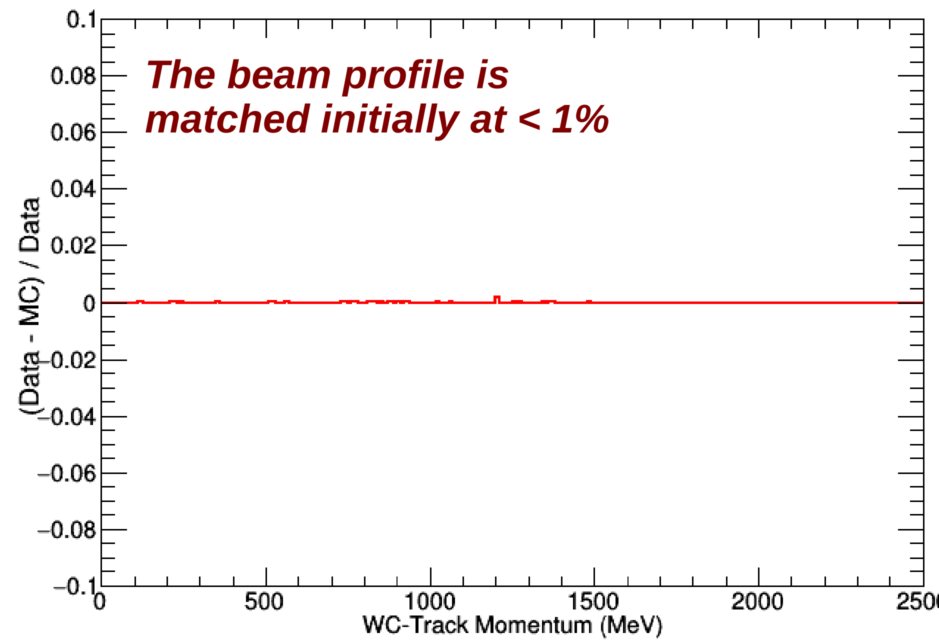
- We now use this sample of 3,718 events to define our Beam Profile sample which we will use to weight the Monte Carlo
- The three peak structure is an artifact of using data from different magnet configurations (i.e. different momentum spectrum)

Data Distributions



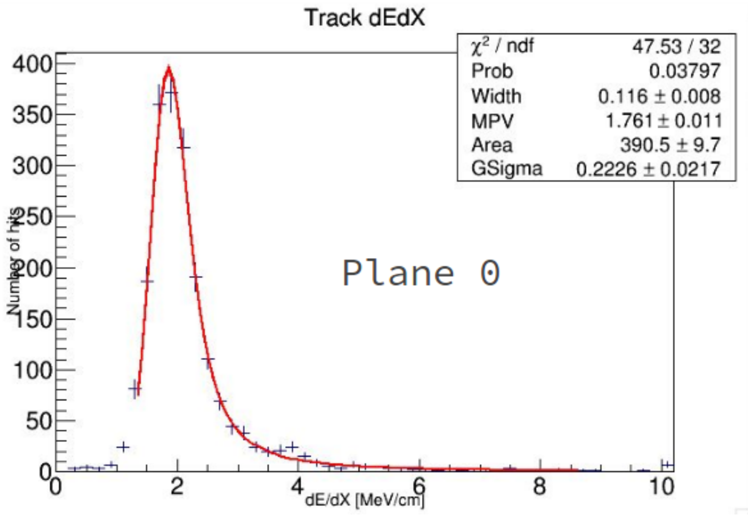


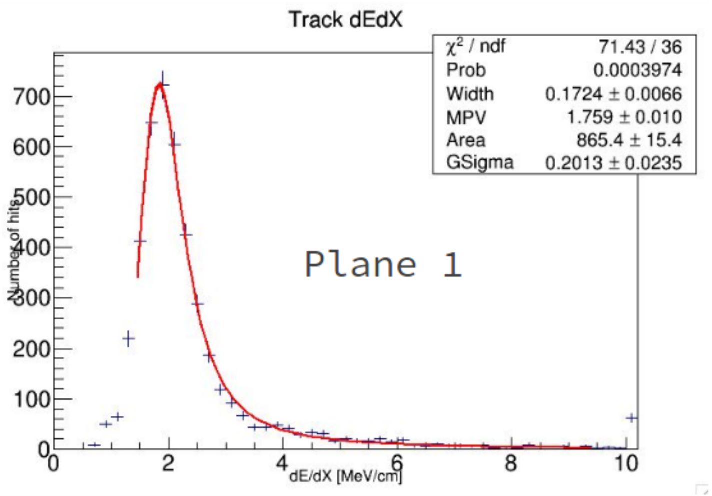
- **We tune our single particle MC momentum spectrum (for all particle species) to match the data**



Checks that need to be done!

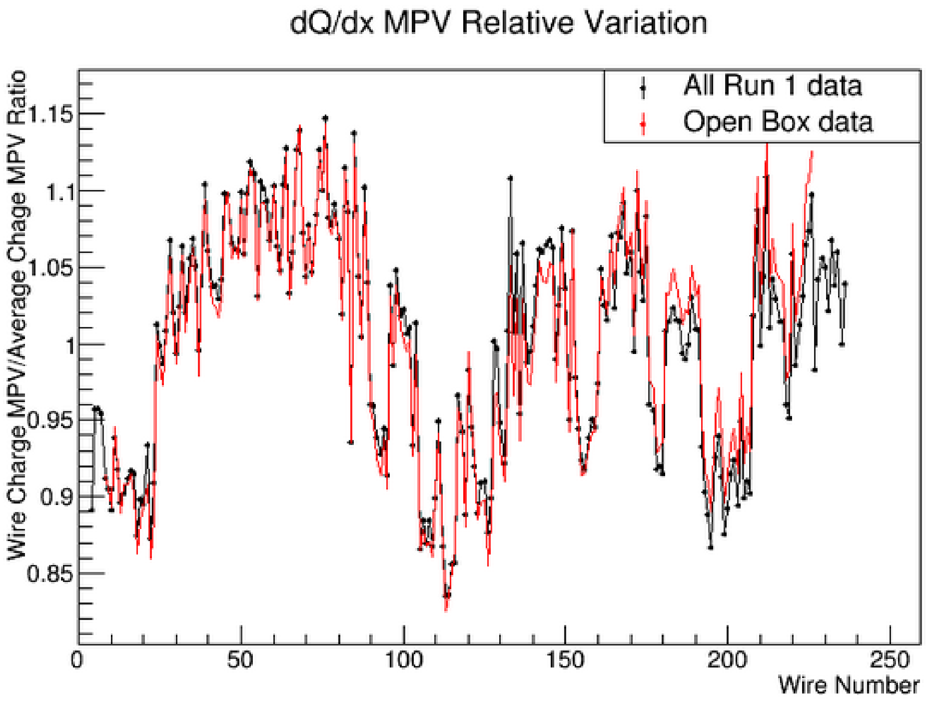
- **Tuning our calorimetry took quite a few iterations for LArIAT**
  - Had to deal with wire-by-wire charge response variations
    - These were reduced in Run-II with a hardware fix
  - Tuning the MC using cross-muons and tuning the data using through going cosmics
    - While these two methods were made to agree independently, when we looked at beamline data tracks and compared this to “beam-like” MC tracks we still had a discrepancy
- **Also needed to ensure that lifetime measurements were appropriately applied run-by-run from the data base**
  - Validation and bug hunting here took some time
  - Having this machinary ready in advance would speed up your analysis

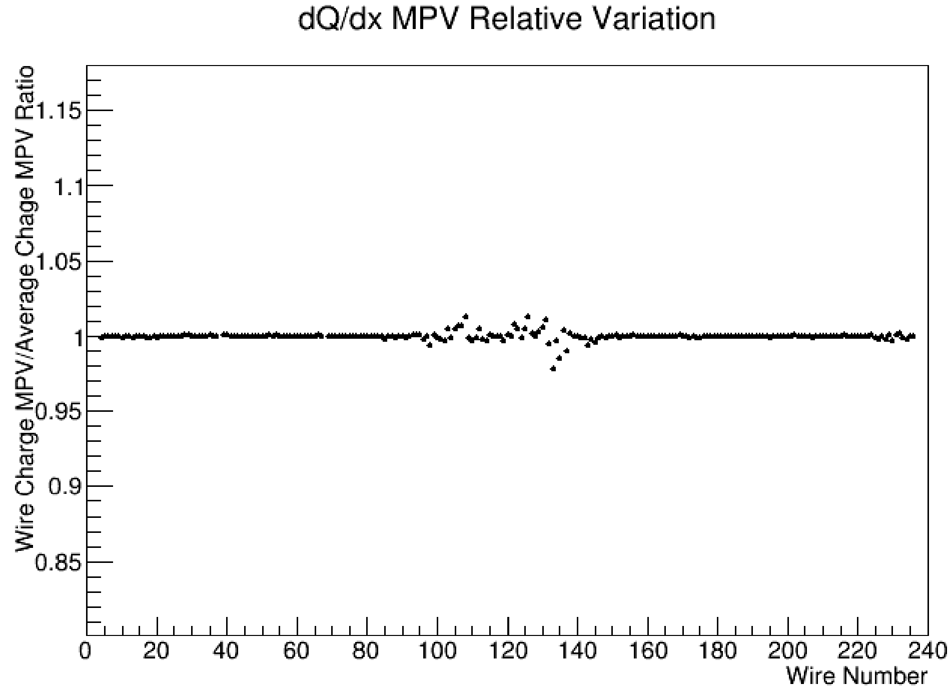




Example of cosmic data with tuned reconstruction calorimetry constants

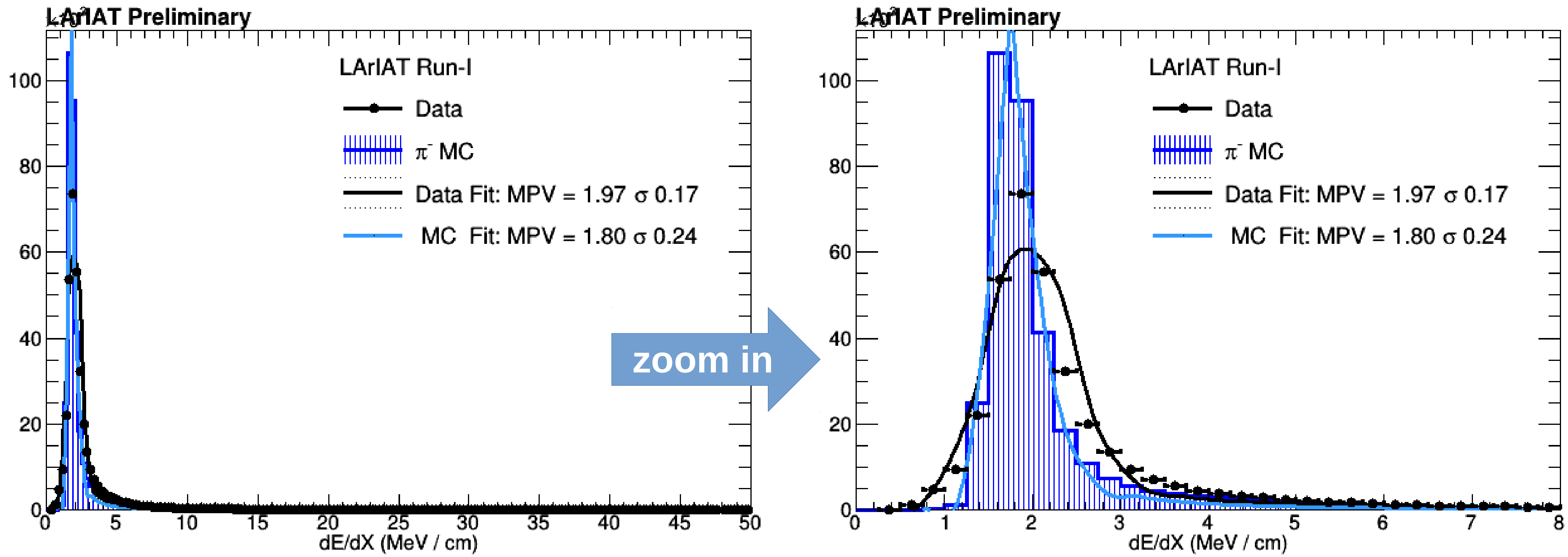
Wire-By-Wire Corrections





- **A notable variation of the charge collected wire-by-wire was observed during Run 1**
- **In order to mitigate the effect of this variation an Wire-by-wire correction was derived and applied**
  - Note: we do calorimetry using the collection plane in this analysis
- **Here we explore the impact the wire-by-wire correction has on the analysis**

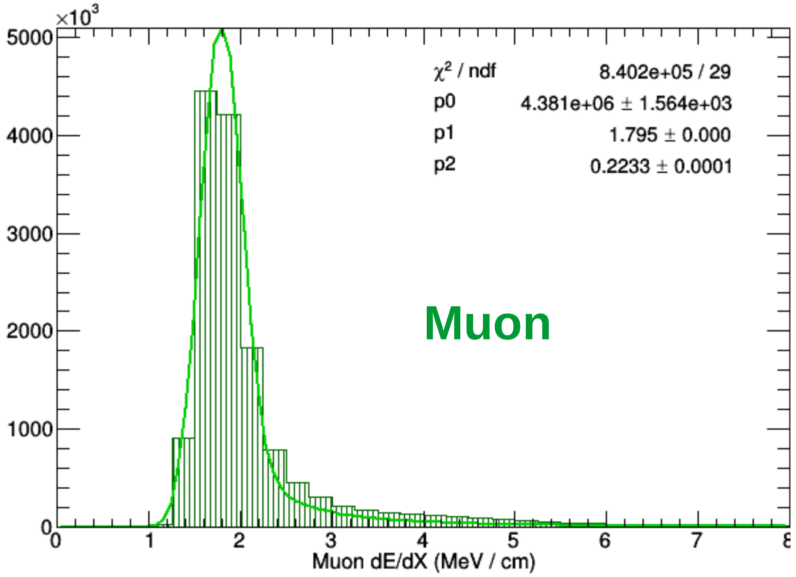
Data Distributions

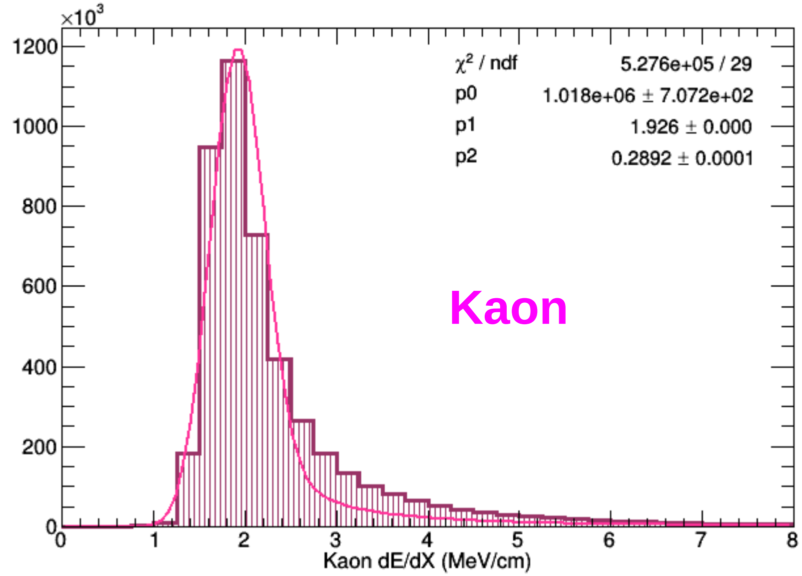


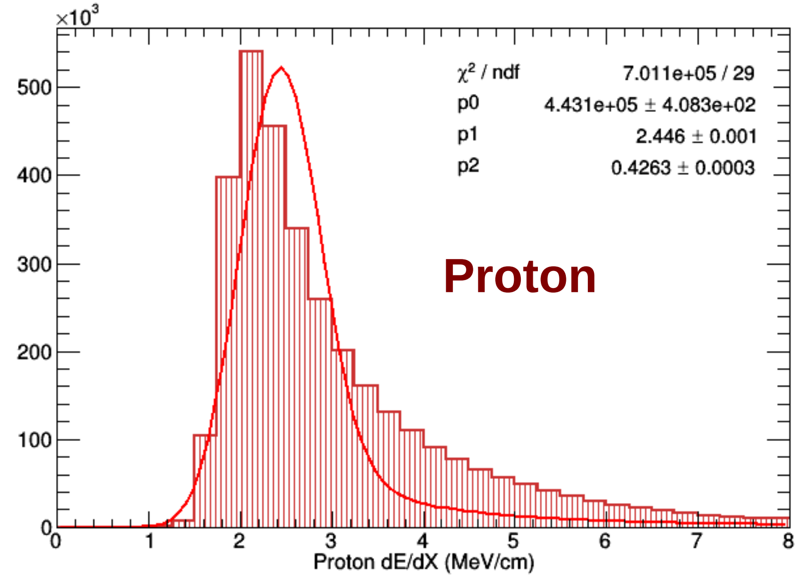
- **The dE/dX distribution between data and MC are shifted relative to one another**
  - This was the case in the W&C presentation
  - The MC was scaled to the data
- **The first correction that will be applied is to scale the dE/dX distribution**
  - Scale the MC up 8.6%

Some other dE/dX distributions

- **The dE/dX distributions for other MC samples from the tracks matched to the "pseudo-WCtrack" in the MC**



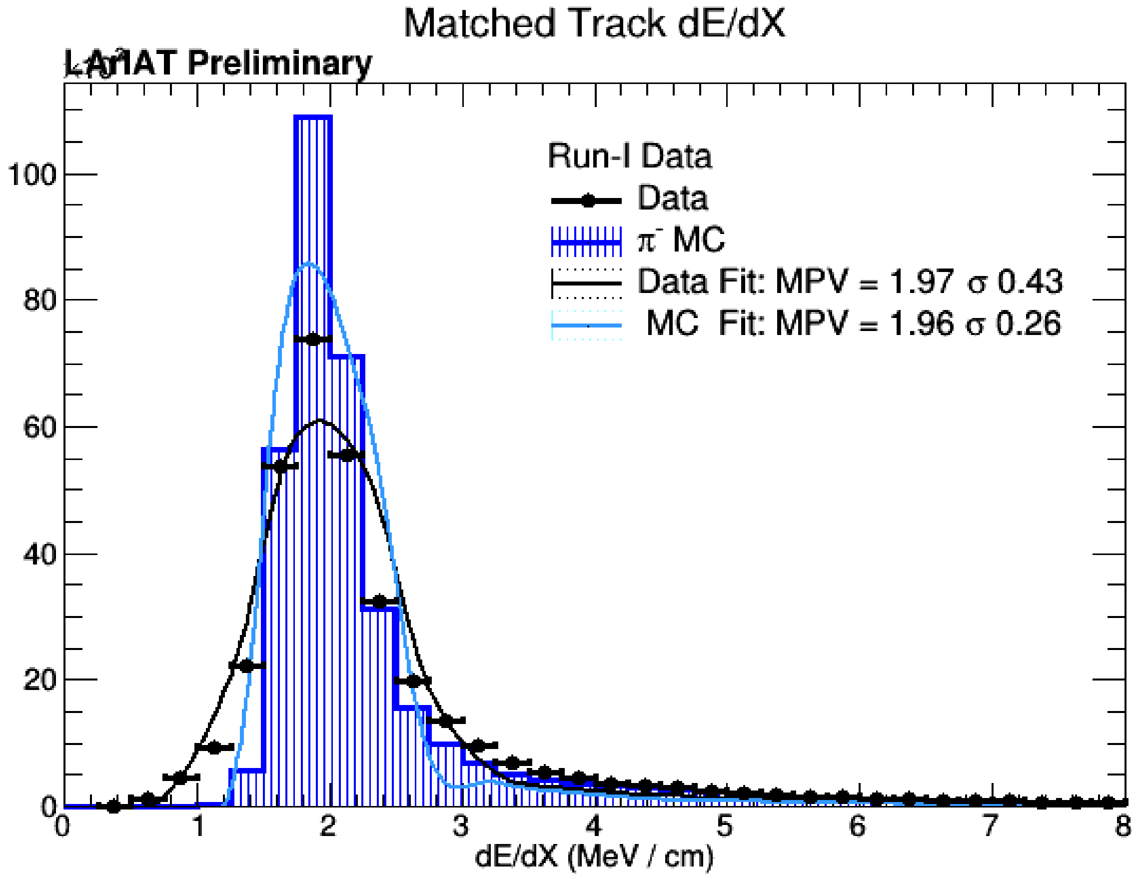




All of these will be scaled as well by the same 8.6% as suggested by the data on the previous page

dE/dX Scaling

- **Scale the MC samples dE/dX up by 8.6%**
- **There is still a shape difference**
  - Part of this is a remaining artifact of the wire-by-wire fluctuations
    - Note: We average them out, but on any one event, there may still be a residual
  - We take a systematic to cover this difference
- **Other analyses (protons / Kaons) working to improve this!**



Thin-Sliced TPC Method

- **Generally the survival probability of a pion traveling through a thin slab of argon is given by**

$$P_{\text{Survival}} = e^{-\sigma n z}$$

Where σ_{TOT} is the cross-section per nucleon and z is the depth of the slab and n is the density

- **The probability of the pion interacting is thus**

$$P_{\text{Interacting}} = 1 - P_{\text{Survival}}$$

where we measure the probability of interacting for that thin slab as the ratio of the number of interacting pions to the number of incident pions

$$\frac{N_{\text{interacting}}}{N_{\text{Incident}}} = P_{\text{Interacting}} = 1 - e^{-\sigma n z}$$

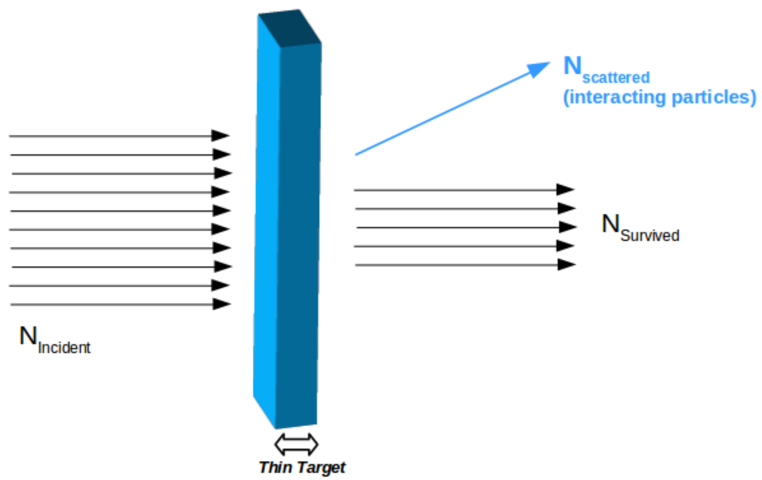
Thin-Sliced TPC Method

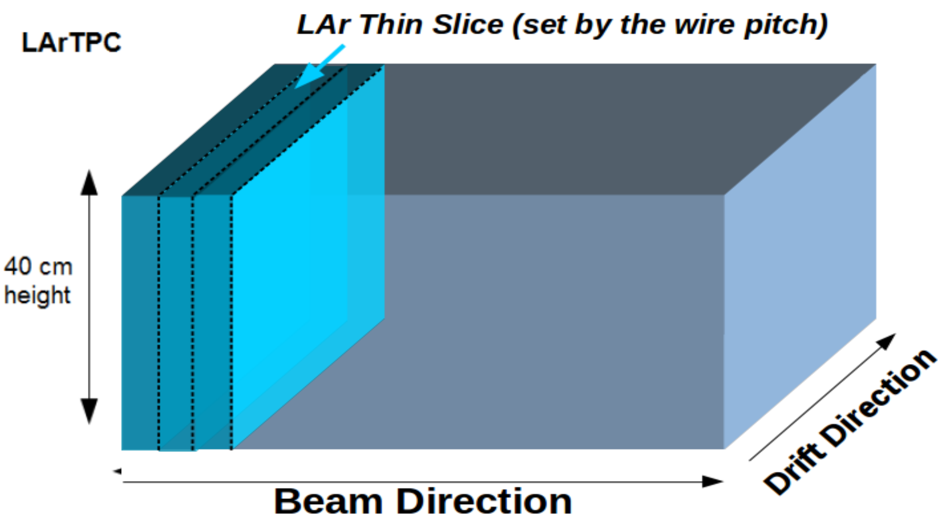
- **Thus you can extract the pion cross-section as a function of energy as**

$$P_{\text{Interacting}} = 1 - (1 - \sigma n \delta z + \ldots)$$

$$\sigma(E) \approx \frac{1}{nz} P_{\text{Interacting}} = \frac{1}{nz} \frac{N_{\text{interacting}}}{N_{\text{Incident}}}$$

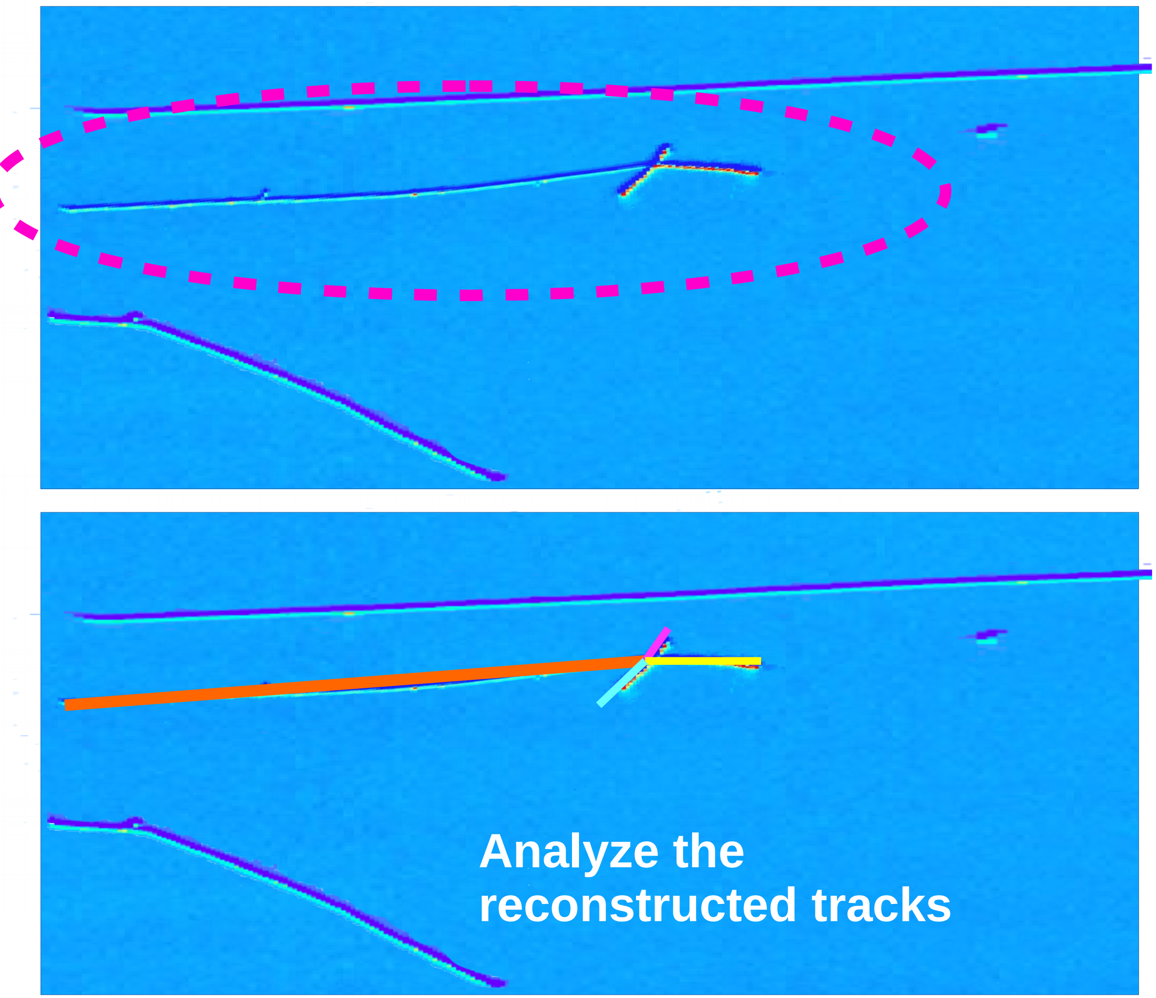
Where $n = \rho N_A / A$





- **Using the granularity of the LArTPC, we can treat the wire-to-wire spacing as a series of "thin-slab" targets if we know the energy of the pion incident to that target**

π-Ar Event Selection



- Now we have a matched WC track and TPC track
- We calculate the π-candidate's initial kinetic energy as

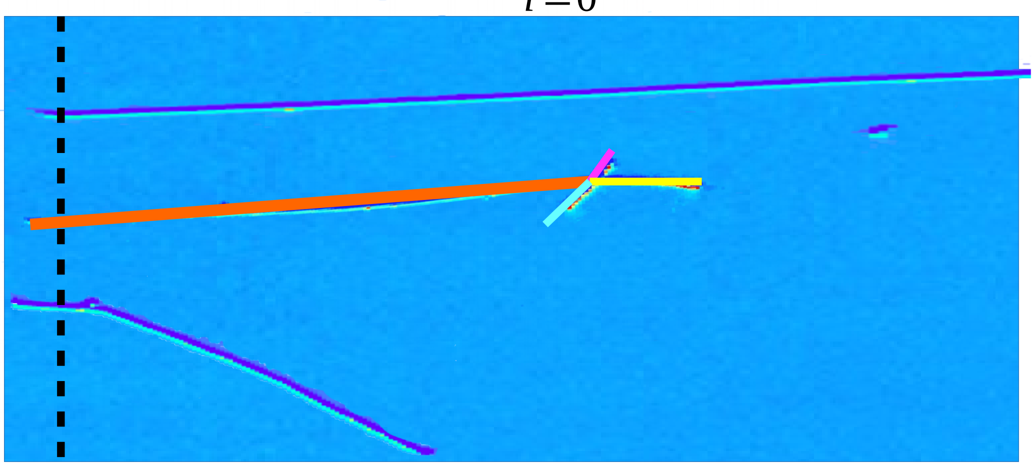
$$KE_i = \sqrt{p^2 + m_\pi^2} - m_\pi - E_{\text{Flat}}$$

we take into account energy loss due to material upstream of the TPC (argon, steel, beamline detectors, etc)

π-Ar Interaction

- **We have a wire chamber track (with an initial kinetic energy) matched to a TPC track, we follow that TPC track in slices**
  - The slice represents the distance between each 3D point in the track
  - For each slice we ask: “Is this the end of the track?”
    - **NO:** Calculate the kinetic energy at this point and put that in our “non-interacting” histogram

$$KE_{Interaction} = KE_i - \sum_{i=0}^{nSpts} dE/dX_i \times Pitch_i$$



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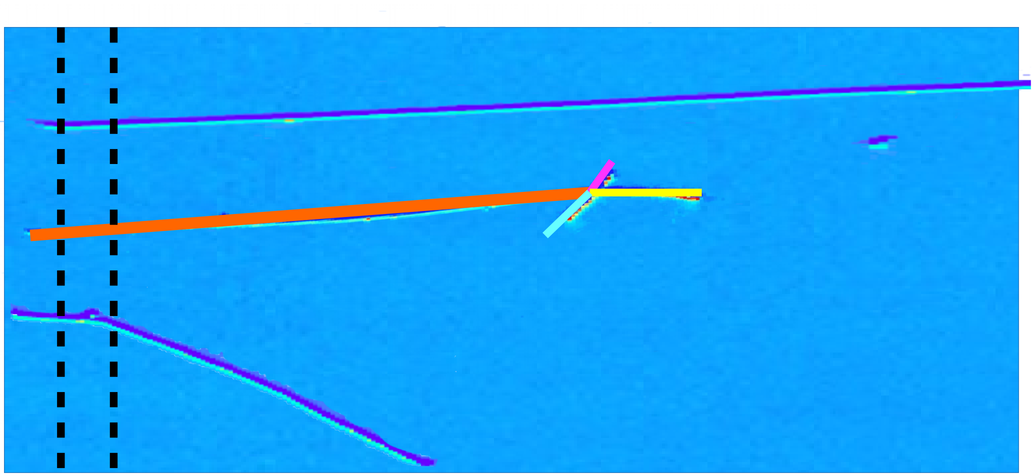
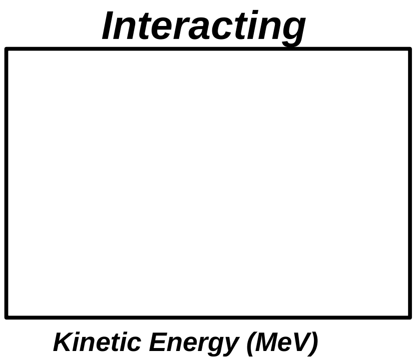
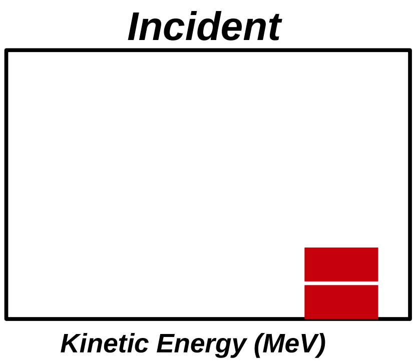


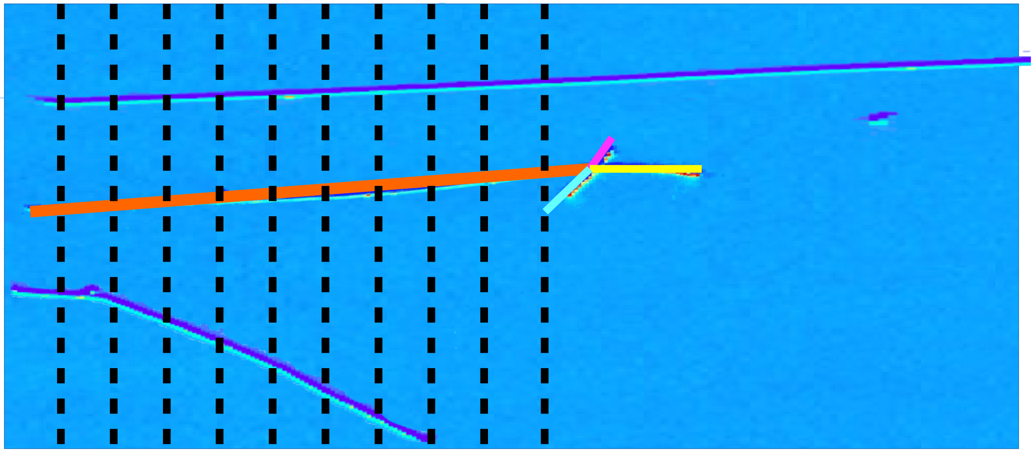


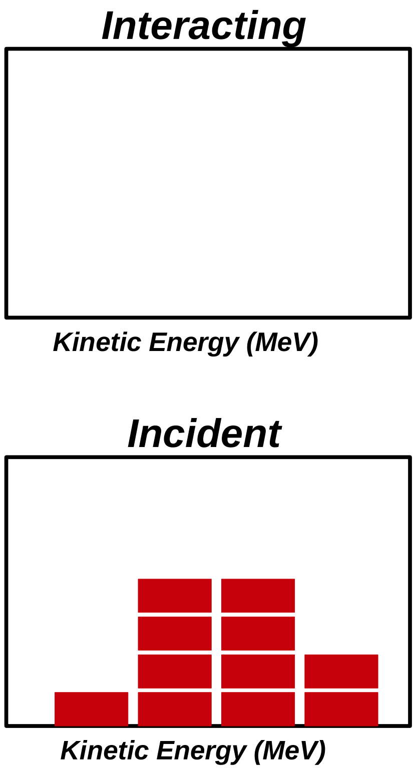


π-Ar Interaction

- **We have a wire chamber track (with an initial kinetic energy) matched to a TPC track, we follow that TPC track in slices**
  - The slice represents the distance between each 3D point in the track
  - For each slice we ask: “Is this the end of the track?”
    - **NO:** Calculate the kinetic energy at this point and put that in our “non-interacting” histogram

$$KE_{Interaction} = KE_i - \sum_{i=0}^{nSpts} dE/dX_i \times Pitch_i$$

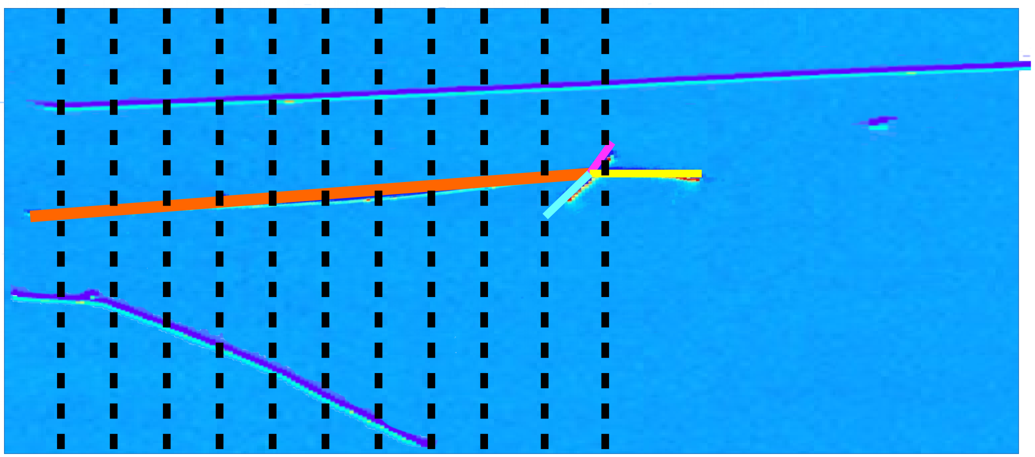


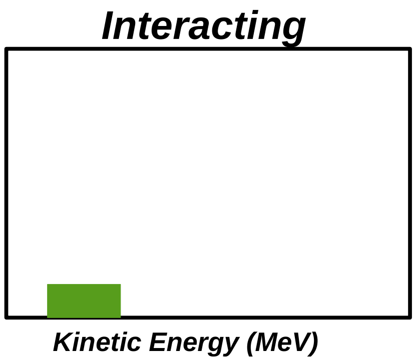


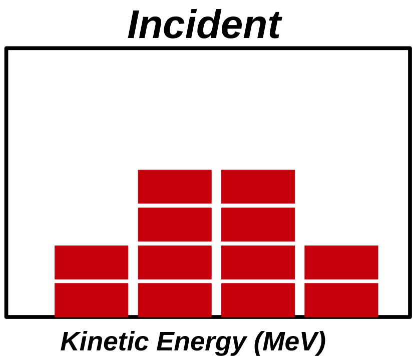
π-Ar Interaction

- **Now that we have a wire chamber track (with an initial kinetic energy measured from the wire chambers) matched to a TPC track, we follow that TPC track in slices**
  - **Yes:** Calculate the kinetic energy at this point and put that in our "interacting" histogram
    - This is kinetic energy in put in both the **interacting** and **incident** histograms

$$KE_{Interaction} = KE_i - \sum_{i=0}^{nSpts} dE/dX_i \times Pitch_i$$

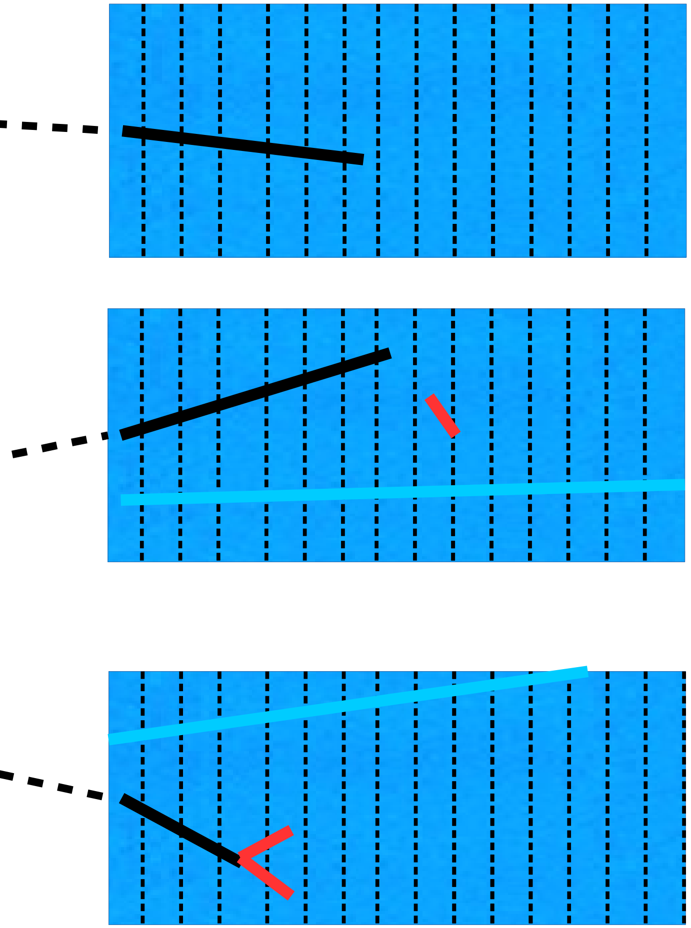


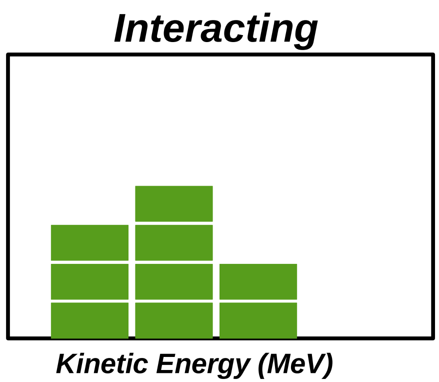


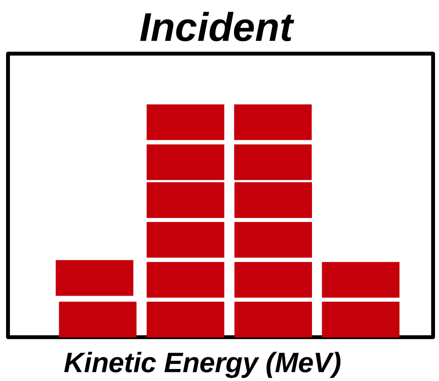


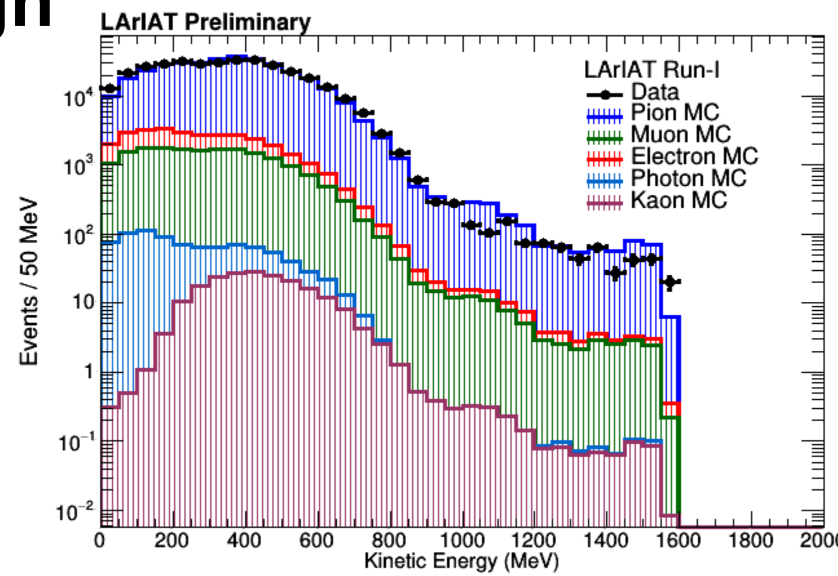
π-Ar Interaction

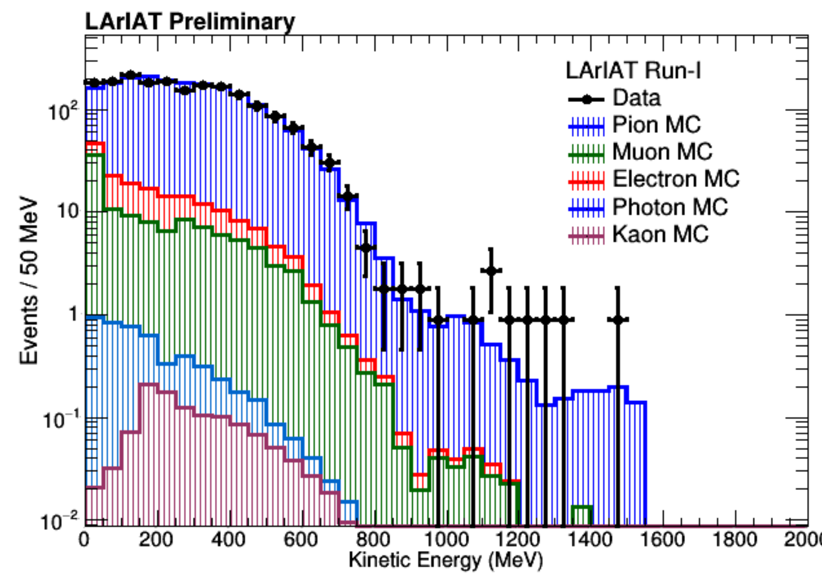
- **We repeat this process event-by-event until we have gone through our entire sample**







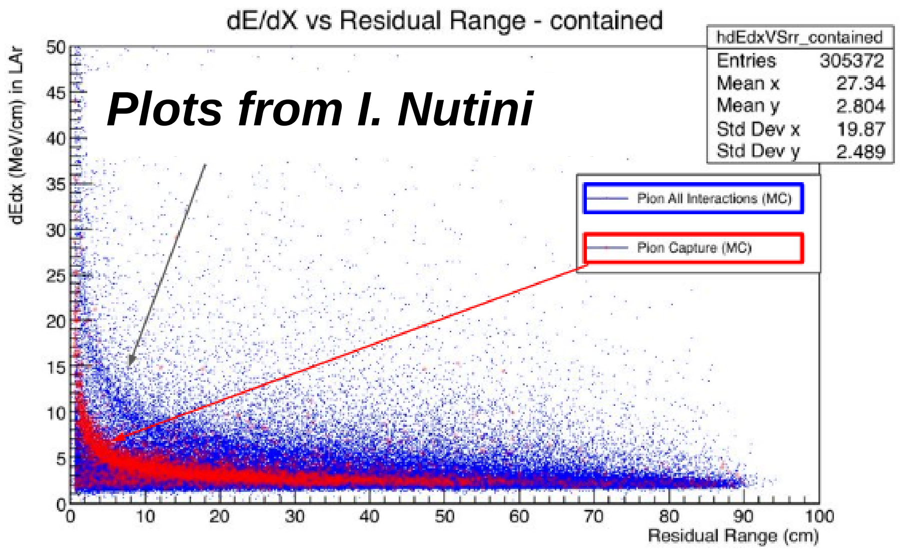


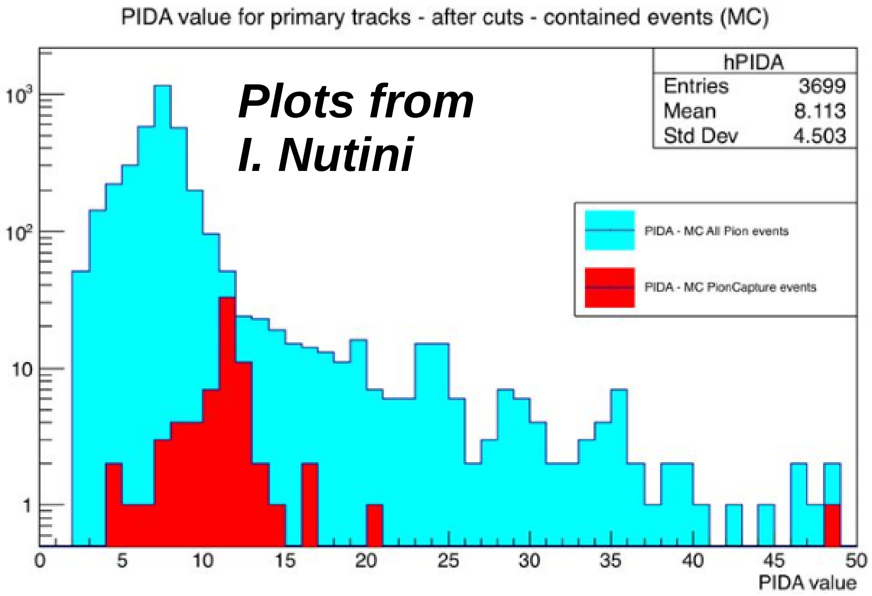


We ignore other tracks in the event not matched to the Wire Chamber Track

Example Background we are grappling with

- **Pion capture is an example process that sneaks its way into our inclusive cross-section that we wish to remove.**
  - They tend to pile up at low kinetic energy as well distorting our low energy bins
- **Preliminary studies suggest calorimetry may allow us to veto these "interaction points" and remove them from our interacting histogram**
  - Specifically the PIDA variable appears promising
  - We don't want to throw out the whole track since the other parts of the track are acceptable for the incident histogram



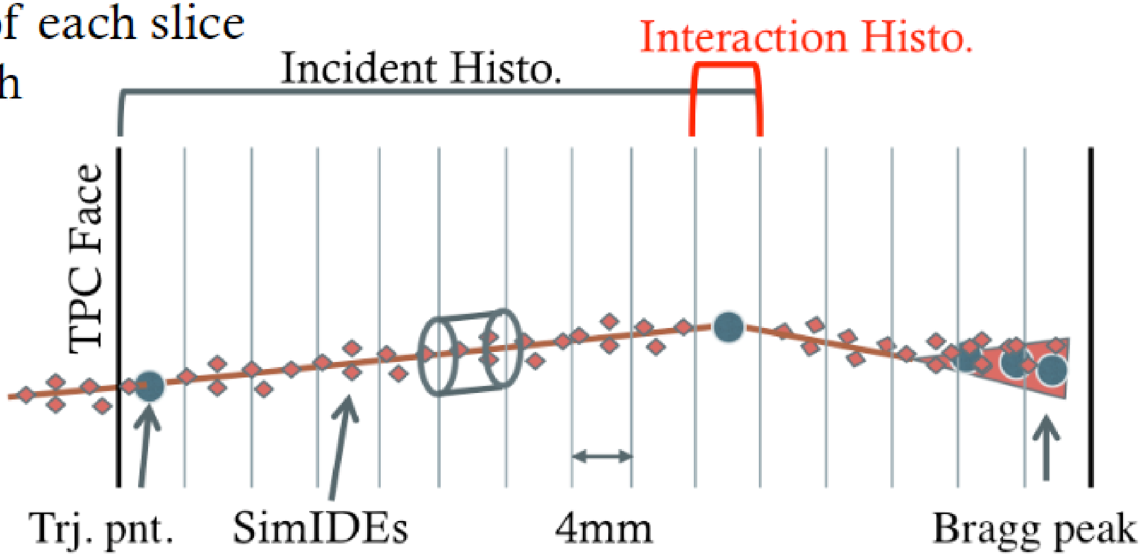


Known issues with the MC

- On the previous slide we are using reconstructed MC and reconstructed data!
- To do a truth level comparisions, some "acrobatics" are required

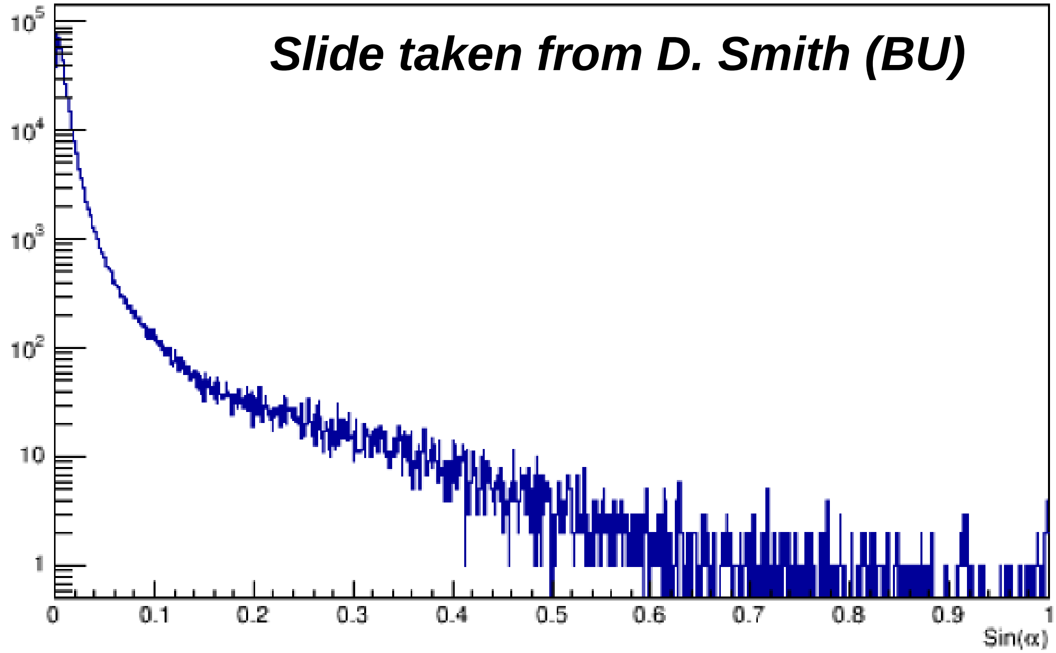
For documentation's sake, here is a description of the method.

1. Find point of interaction or decay
2. Slice truth track into 4 mm till the end. Find the point of intersection between imaginary line at n*4 mm and truth track
3. Sum all SimIDEs within a ~cylinder of radius 3cm from track in slice
4. Find KE in each slice. If trj. pnt. exists in slice, use its KE. If not, subtract SimIDE energy from last trj. pnt.
5. Fill histogram with the KE of each slice
6. If interact, fill histogram with the KE of end point
7. Use histograms to create cross section



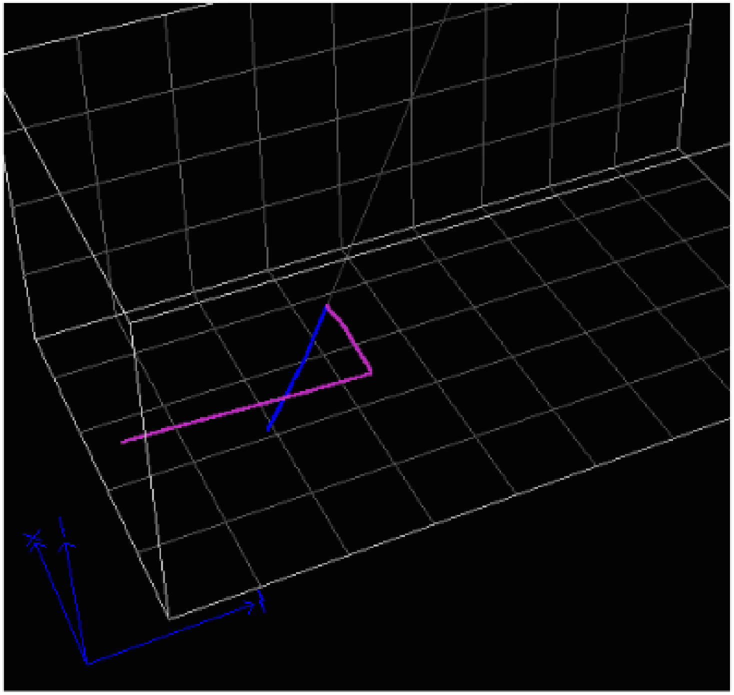
Slide taken from D. Smith (BU)

Known issues with the MC



LArG4 does not label all scatters.

To compare Data and MCReco XS, need to understand and tag unlabeled scatters



Plot represents the Sin(α) between two adjacent trajectory points in primary truth track of entering kaons.

Frequent untagged scatters >10° (.17) and several >45°(.71)

85° scatter LArG4 calls a Decay.

One solution:

You need to dig down all the way to the SimIDE's and use the process label on them instead of just accessing the Geant4 process associated with the trajectory points

More thoughts….

- **No way to cover all aspects of this analysis in one talk**
  - Luckily all the LArIAT collaborators are really friendly people who love their experiment and will happily talk to you for many hours about their experience!
- **LArIAT is in the process of writing the pion inclusive analysis into a paper**
  - No spoilers today with seeing our near final cross-section ;-)
- **We expect to have a reasonable statistics from 100 MeV – 1000 MeV**
  - Similar analysis for positive pions, protons, kaons, as well as exclusive channels are well underway
  - The inclusive analysis forged a wide path and found many potholes that subsequent analyses are benefiting from
  - protoDUNE can benefit from LArIAT’s experience and hopefully extend the measurement