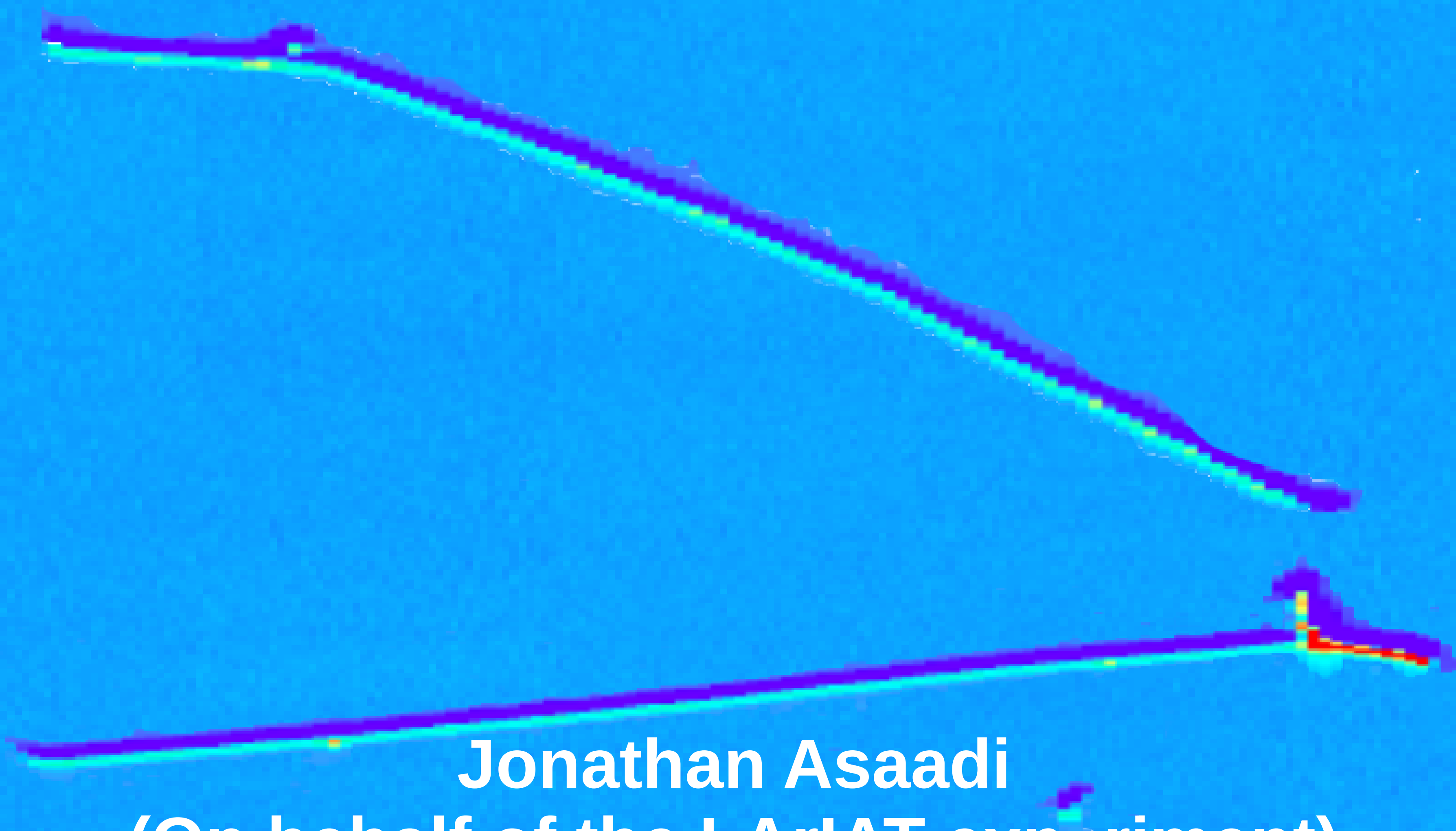
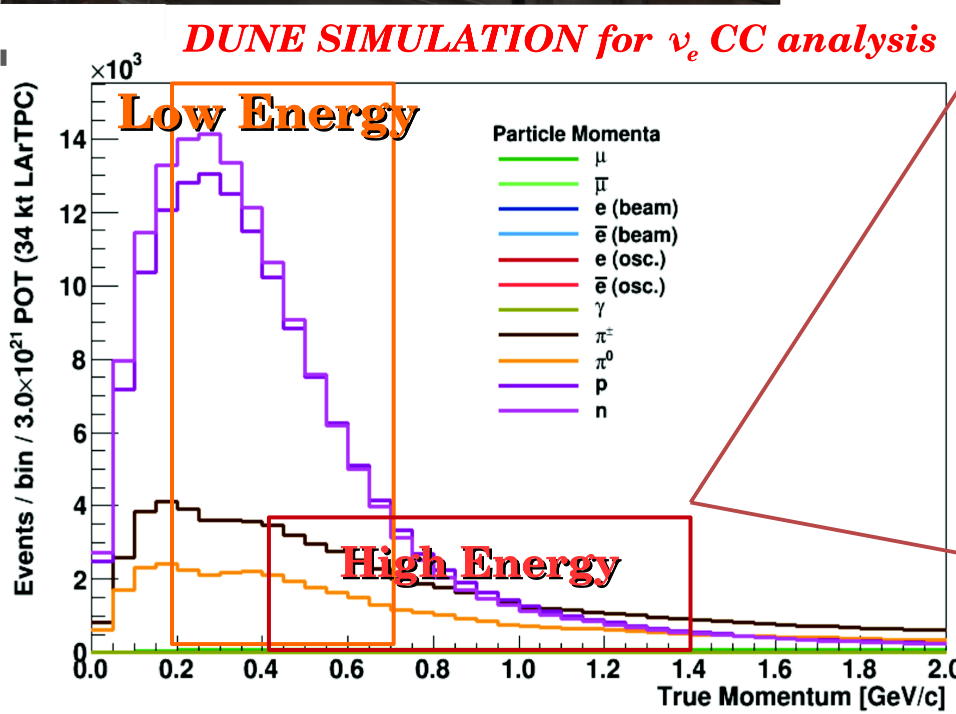
Pion Scattering at LArIAT

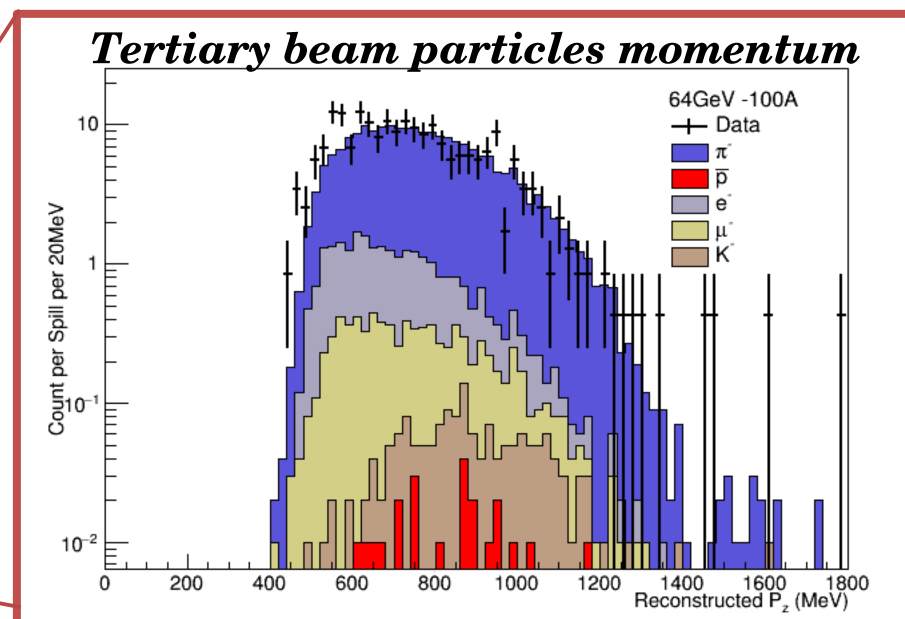


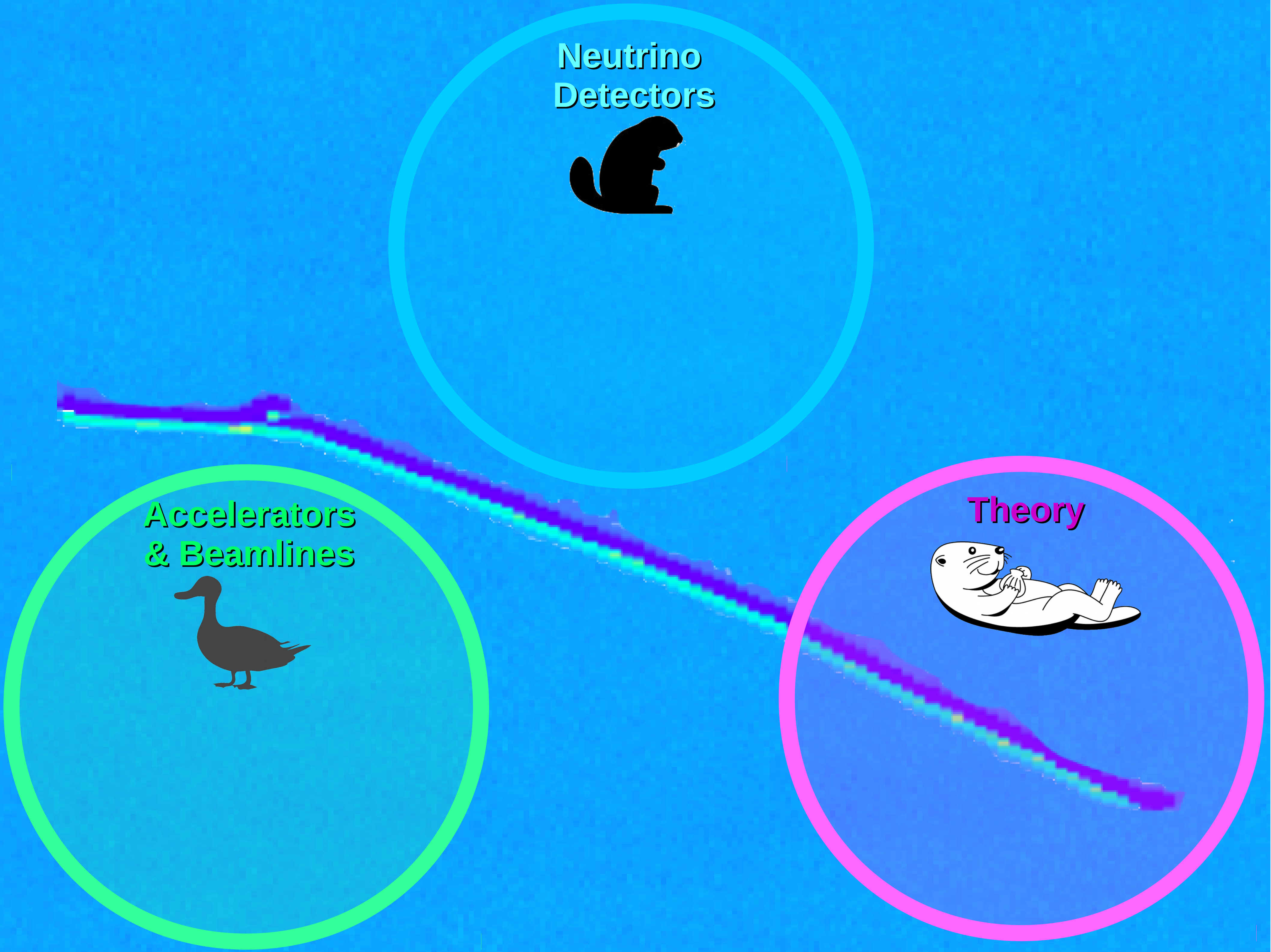
Jonathan Asaadi
(On behalf of the LArIAT experiment)

University of Texas at Arlington

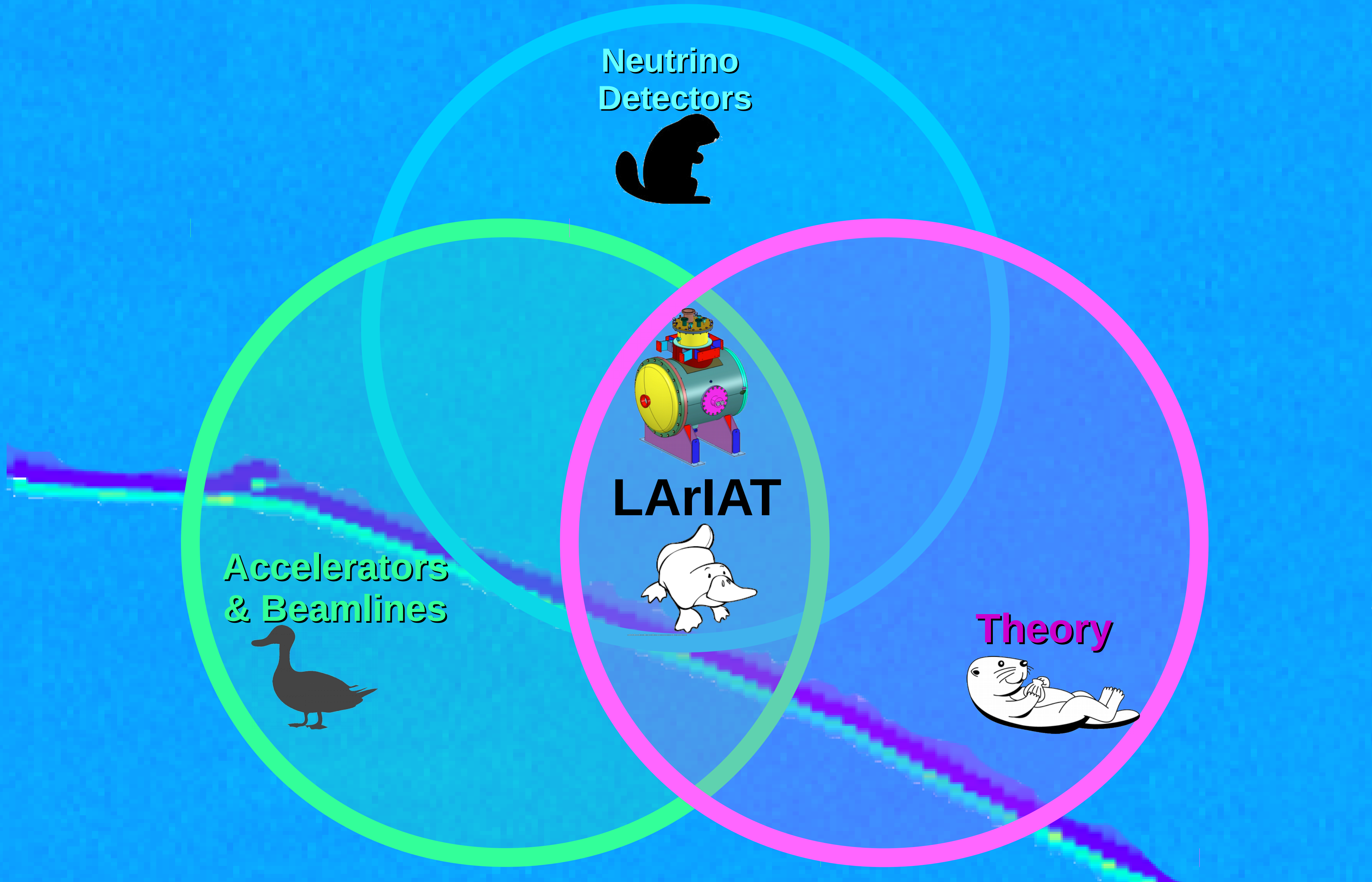
- **Experimental program designed to characterize Liquid Argon Time Projection Chamber (LArTPC) performance and measure charged particle interactions in an energy range relevant for current and future LArTPC neutrino experiments**





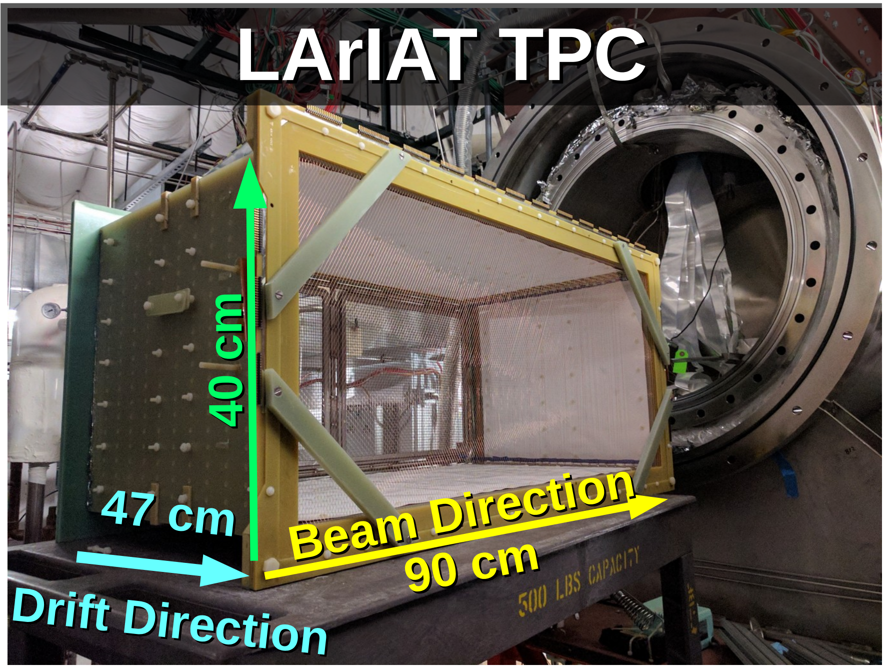


Neutrino Detectors
Accelerators & Beamlines
Theory



LArIAT is best described as a hodgepodge of more familiar parts: Accelerator (Test-Beam), ν-detectors. (LArTPC), and theory (hadronic x-sections).

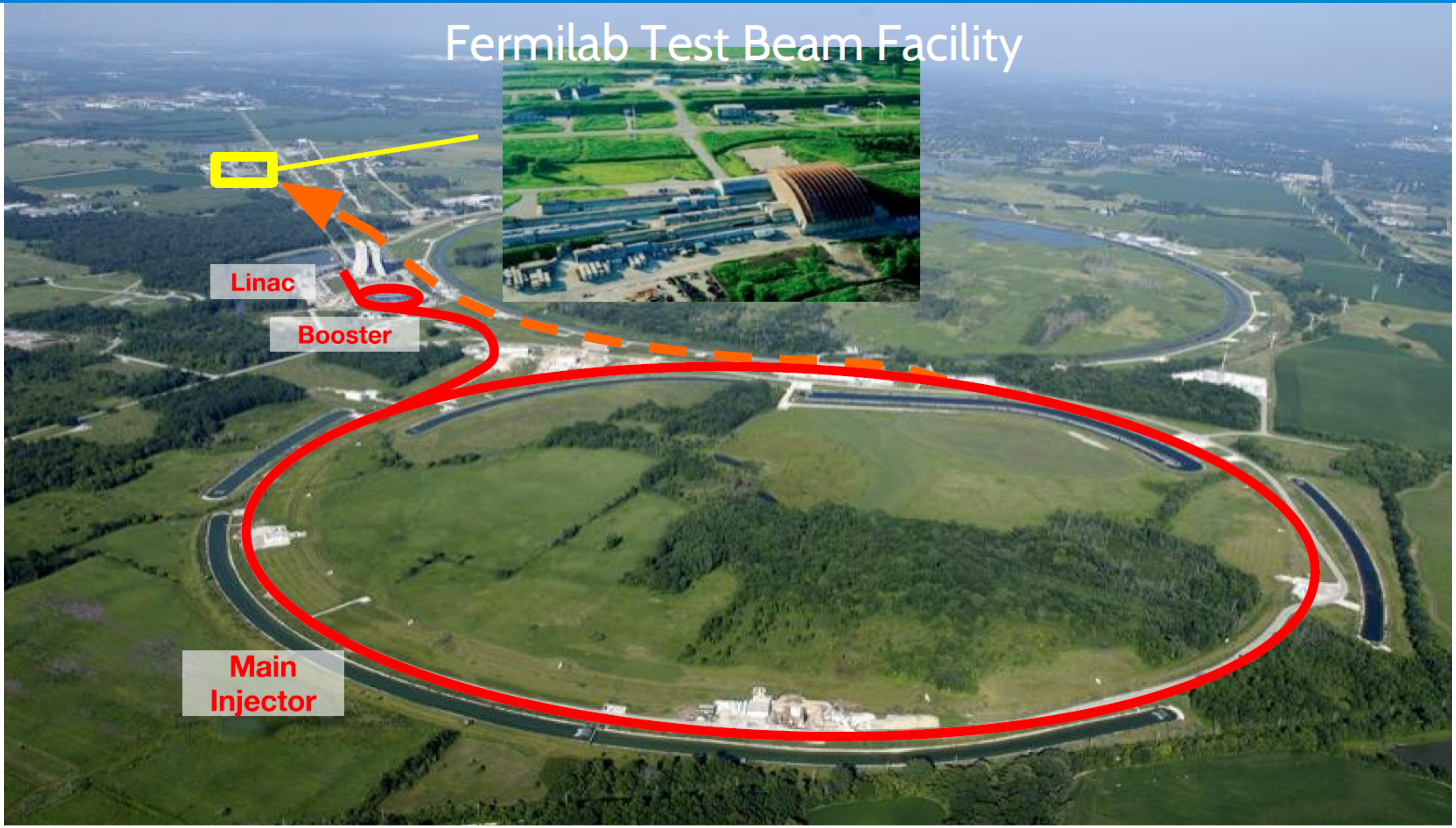
LArIAT



LArIAT is small (170 liters {0.25 tons} of LAr) LArTPC designed for calibrating detector response in a charged particle beam

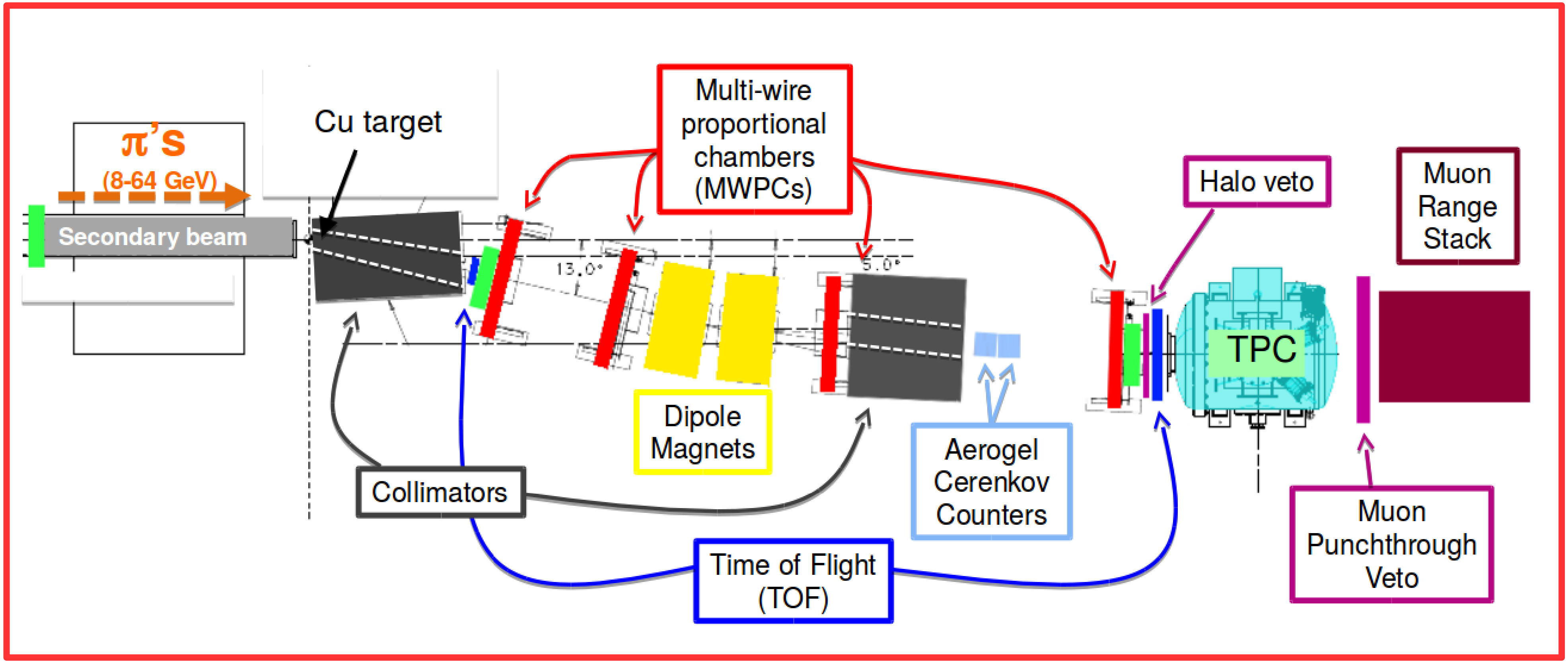
- **Physics Goals**
  - Hadron-Ar interaction cross sections
    - Inclusive and exclusive $\pi^{+/-}$-Ar, $K^{+/-}$ - Ar, p/$\overline{p}$-Ar, etc...
  - Study of nuclear effects in Ar
  - e/γ shower identification capabilities
  - Particle sign determination in the absence of a magnetic field, utilizing topology
    - e.g. decay vs capture
  - Geant4 validation
- **R&D Goals**
  - Ionization and scintillation light studies
    - Charge deposited vs. light collected for stopping particles of known energy
  - Optimization of particle ID techniques
  - LArTPC event reconstruction
    - Compare 3mm, 4mm, 5mm wire pitch (current run)

LArIAT Testbeam



- **Fermilab's test beam facility receives 120 GeV protons from the Main Injector**
- **Creates a tunable (8 GeV – 64 GeV) secondary beam which it directs to the LArIAT experimental hall (MC7)**

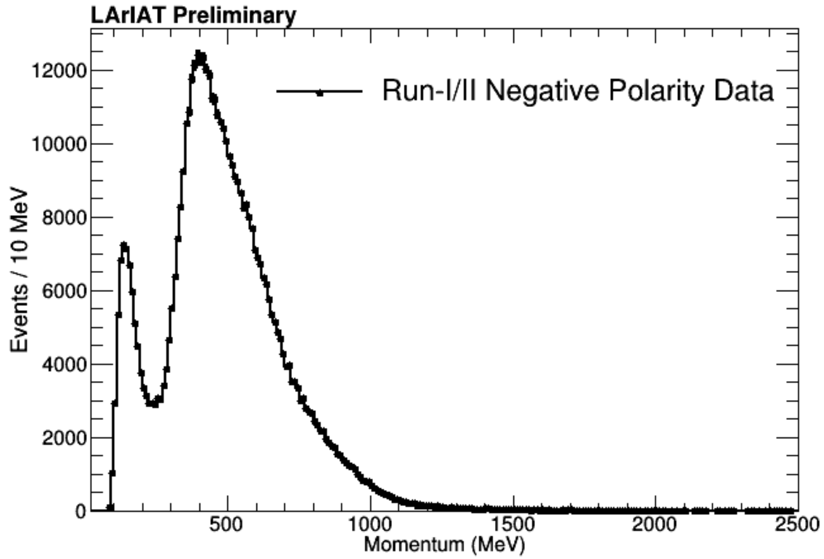
LArIAT Testbeam

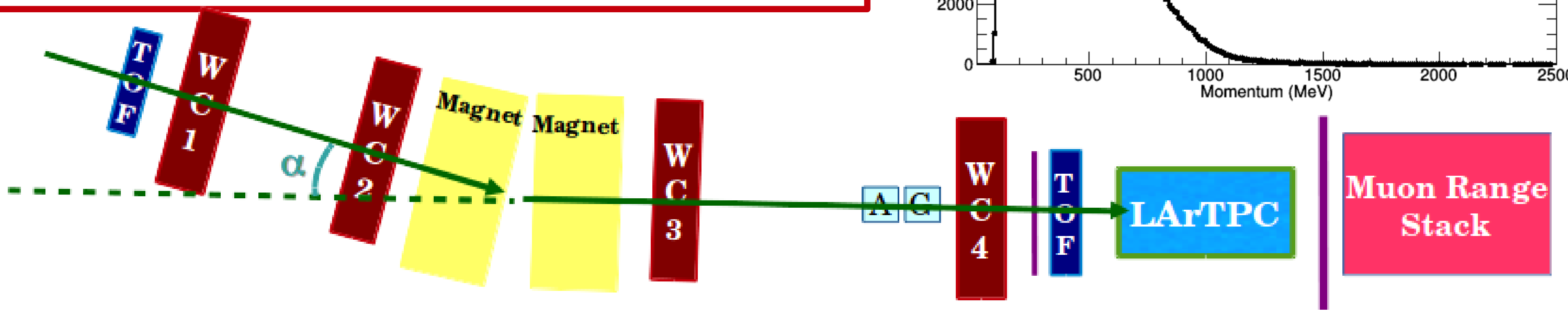


- **A tertiary beam is created and LArIAT instruments that beamline for particle identification**

LArIAT Beamline Detectors

Wire chambers reconstruct the position and momentum of the particles in the beamline





LArIAT Beamline Detectors

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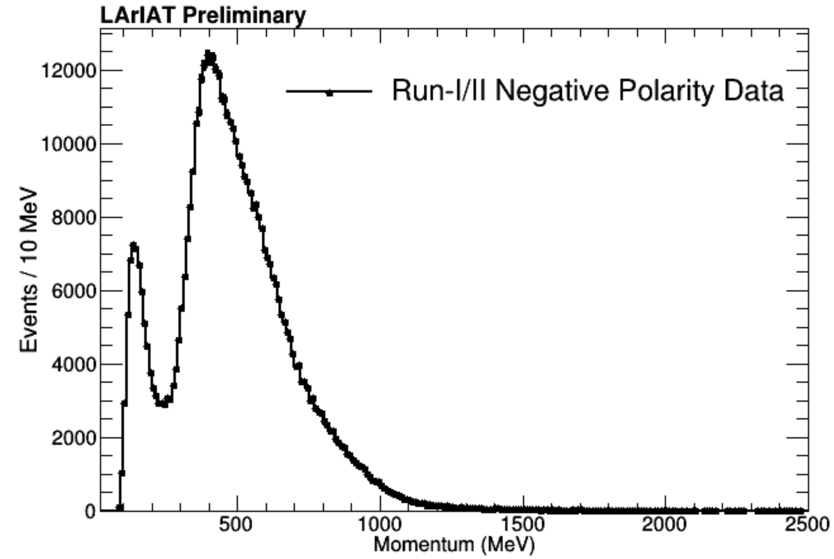
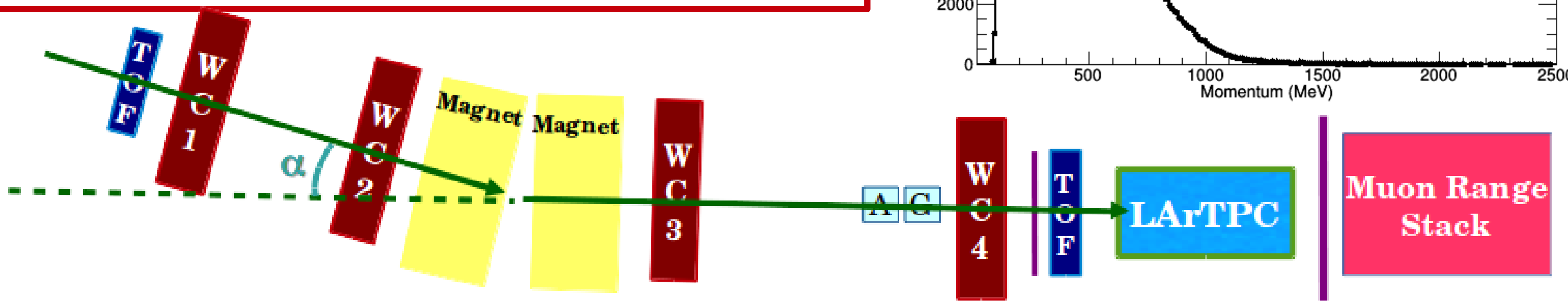
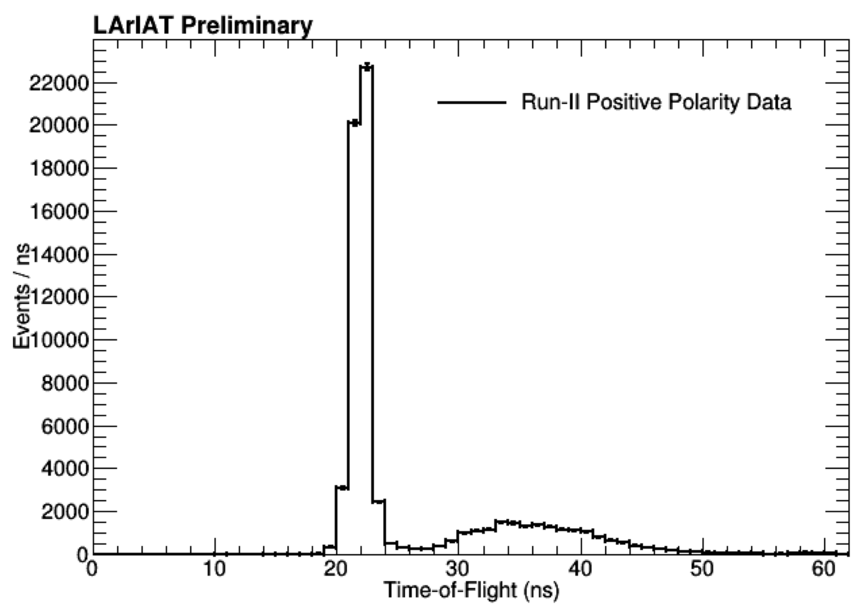




2 scintillator counters w/ ~1ns sampling provide the time of flight (TOF)



LArIAT Beamline Detectors

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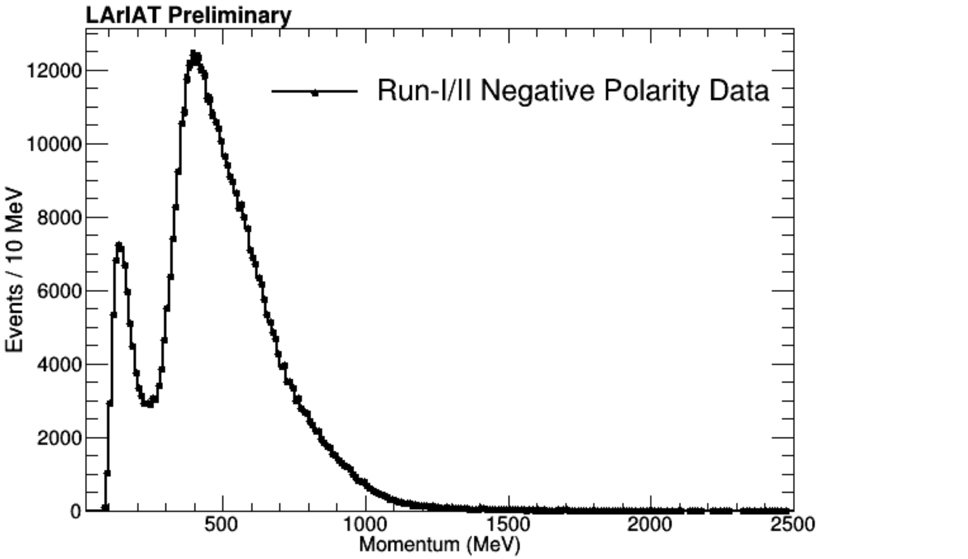
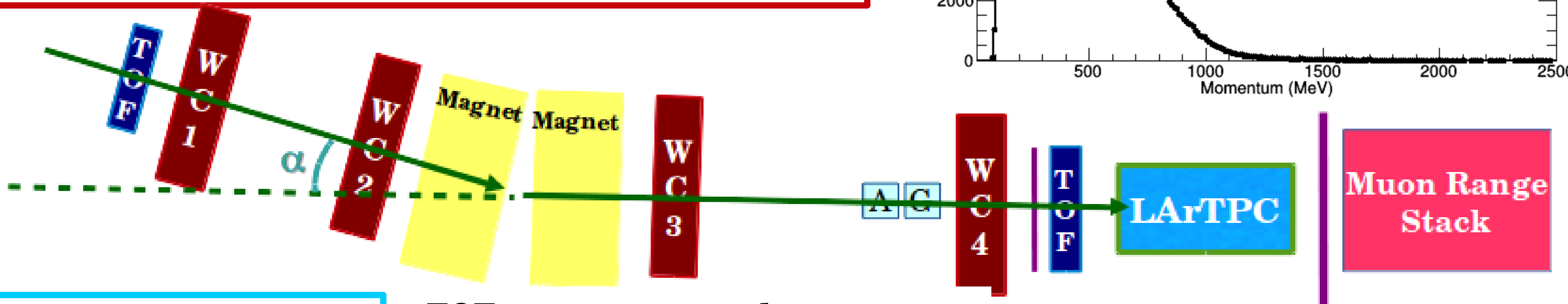
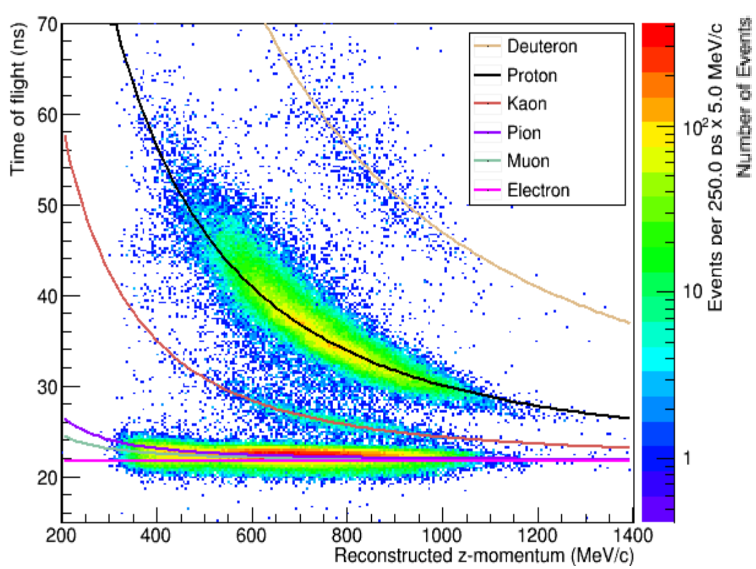
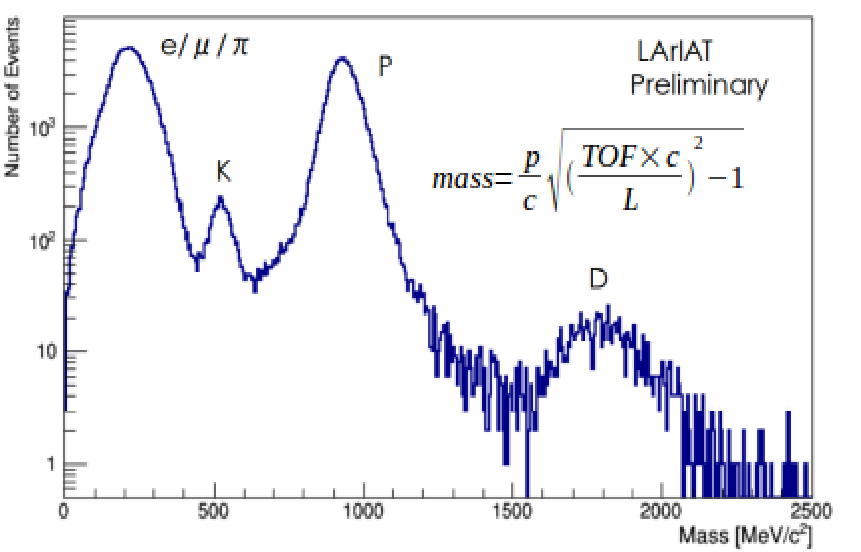




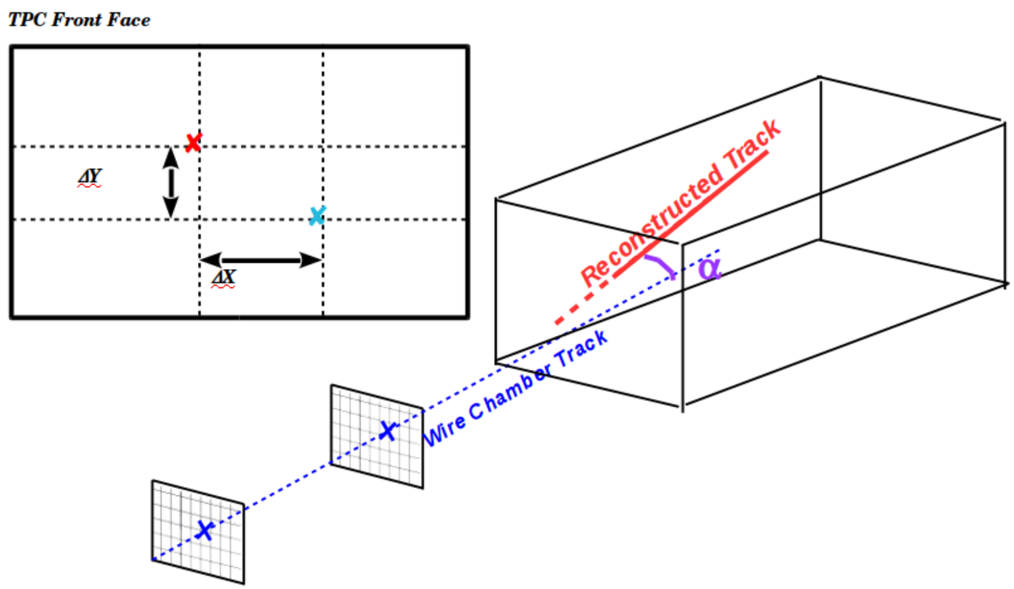
Combining the momentum and TOF allows for π/μ/e, K, proton separation

TOF vs reconstructed momentum

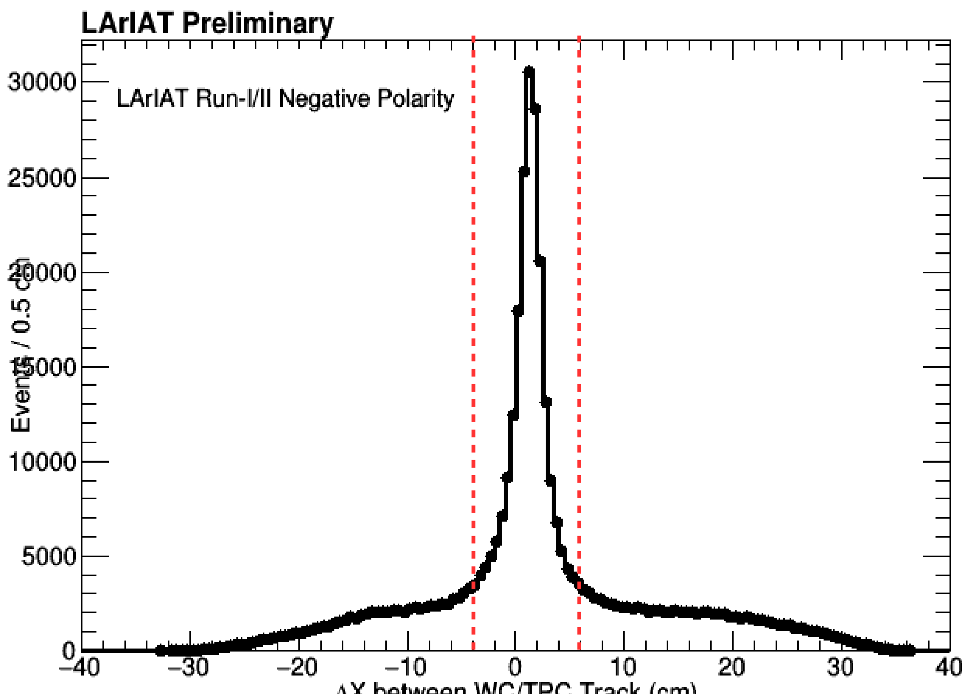


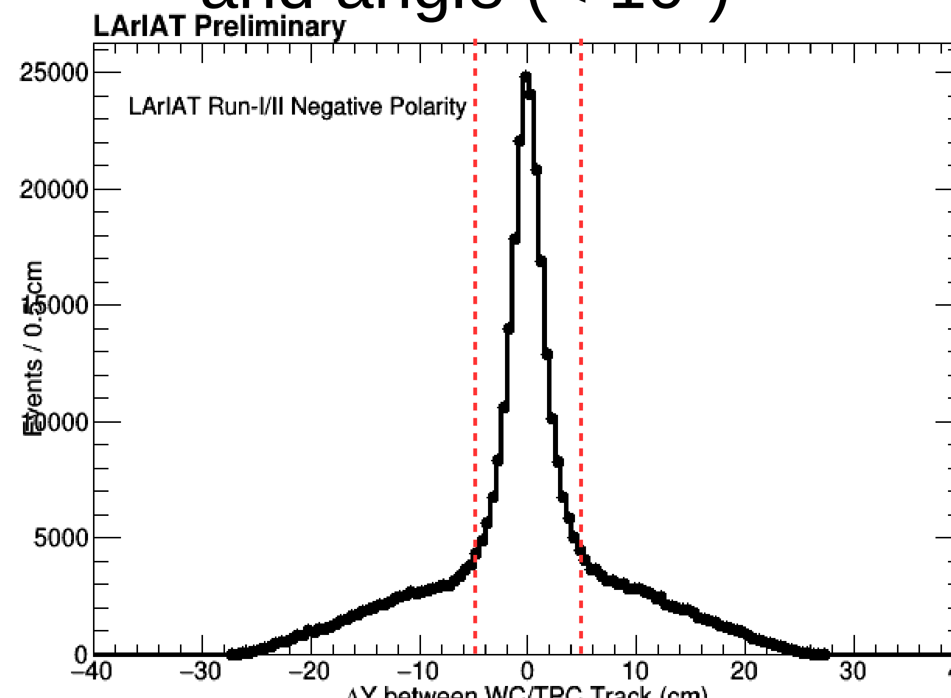


Matching Beamline to the TPC

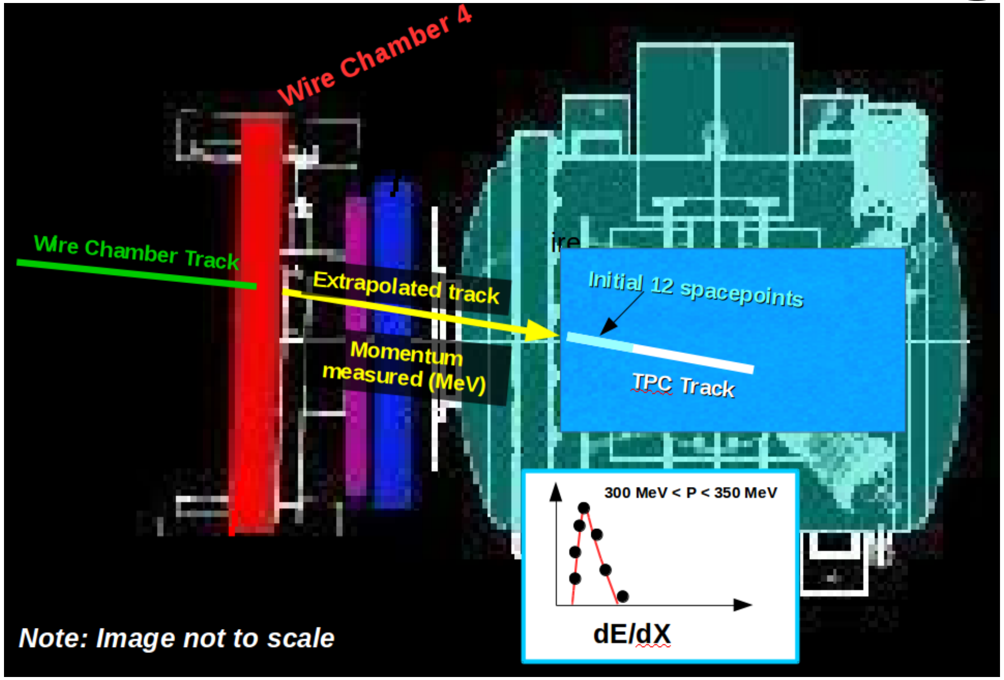


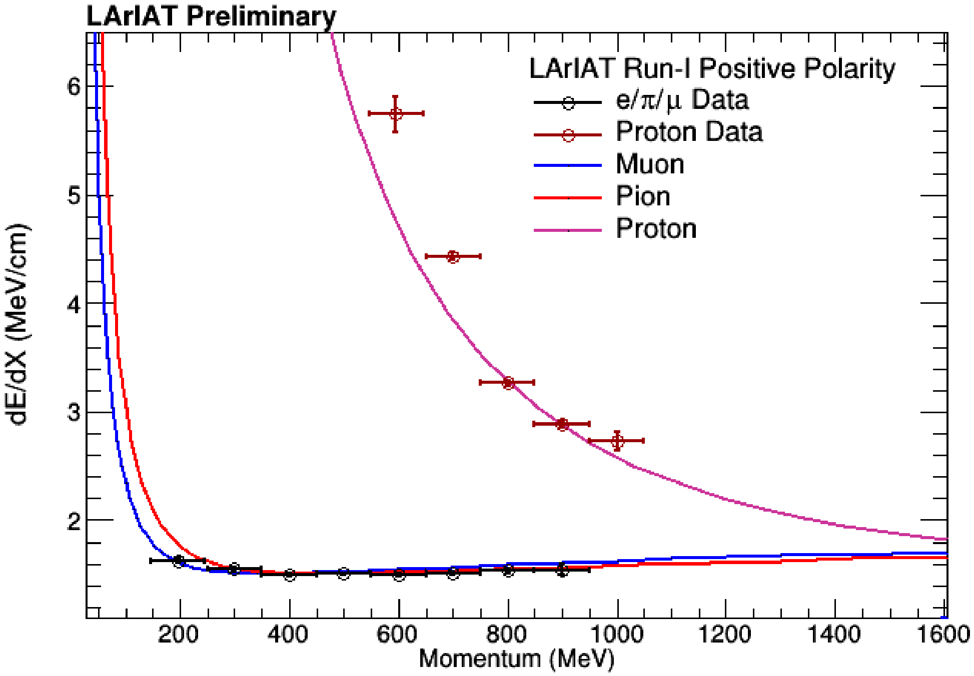
- **We can take this track reconstructed in the beamline and extrapolate it to the LArTPC and look for a match**
  - We match in both position (+/- 5cm about the mean) and angle (< 10°)



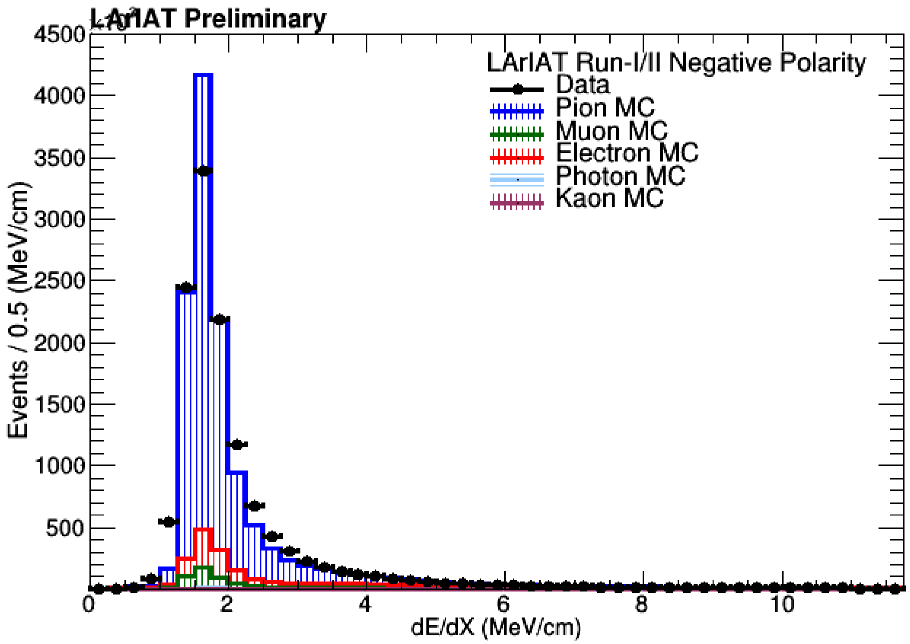


Calibrating our sample





- **By taking the first few centimeters of a matched track we can characterize the dE/dX response as a function of the tracks initial momentum**
- **Selecting events of different particle type and momentum we can tune our detector response to follow the Bethe-Bloch formula**
- **This technique allows us to tune our data and Monte Carlo dE/dX distributions**



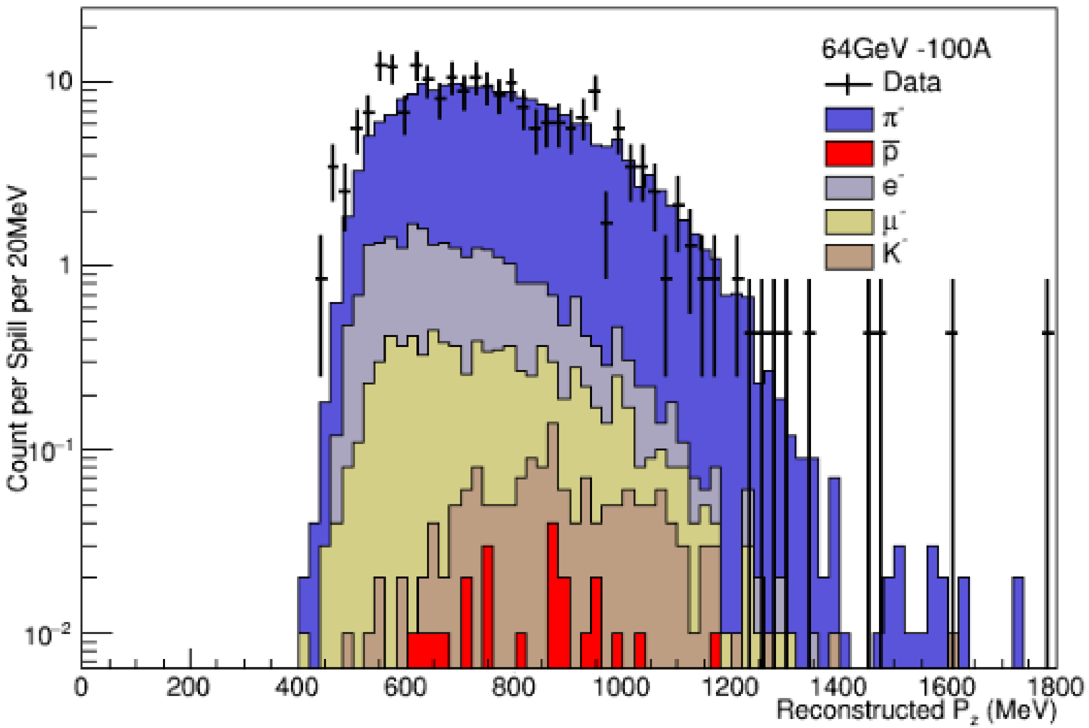
Pion Event Selection

Event Selection	Run-I Negative Polarity	Run-II Negative Polarity	Combined
Total Number of Beam Events	113,336	1,585,598	1,698,934
π, μ, e Mass Selection	20,653	493,455	514,108
20 ns $<$TOF$<$27	20,577	485,159	505,736
Requiring an upstream TPC Track within $z < 2$cm	18,882	403,561	422,443
< 4 tracks in the first $z < 14$cm	12,910	316,451	329,361
Electromagnetic shower rejection	9,824	232,510	242,334
Unique match between WC/TPC Track	5,500	120,956	126,456

Table 5: Summary of the events passing the inclusive pion selection criteria.

- **We select out pion sample from data**
  - Beamline information consistent with the $\pi/\mu/e$ hypothesis
  - Unique match between a wire chamber and TPC track
    - Veto events with pile-up and halo
    - Reject if topology is consistent with electromagnetic shower (e/γ)
- **This give 126,456 candidate pion events**

Pion Event Selection



- **Our MC allows us to estimate what our fractional beam composition and our selection efficiencies are for the various particle species**

	π^-	e^-	γ	μ^-	K^-	$\bar{p}$
Beam Composition (%)	48.4	40.9	8.5	2.2	0.035	0.007

Table 1: Beam Composition - Negative polarity configuration (from MC)

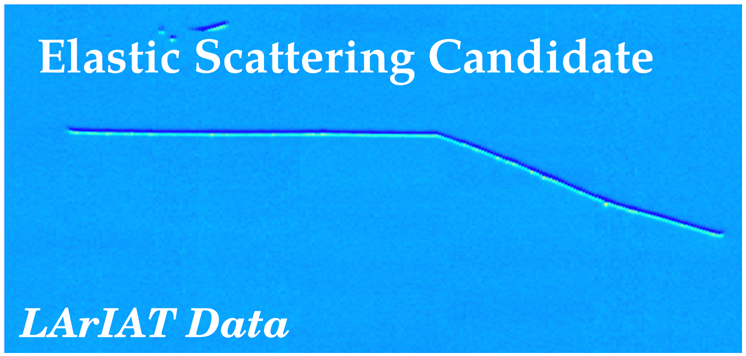
	π^- MC	e^- MC	γ MC	μ^- MC	K^- MC
Percent of events passing cut	73.5%	14.2 %	2.3%	73.4%	70.6%

Table 8: Fraction of MC Events passing inclusive pion analysis cuts.

Pion Cross-Section

- **The total π^-–Argon Cross-Section includes**

$$\sigma_{Total} = \sigma_{elastic} + \sigma_{inelastic} + \sigma_{ch\text{-}exch} + \sigma_{absorp.} + \sigma_{\pi\text{-}production}$$



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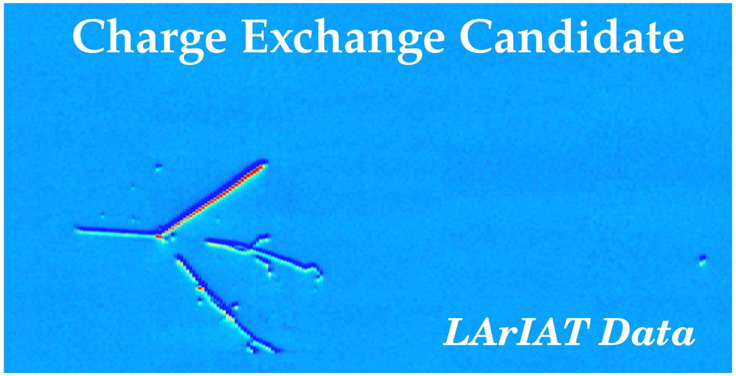

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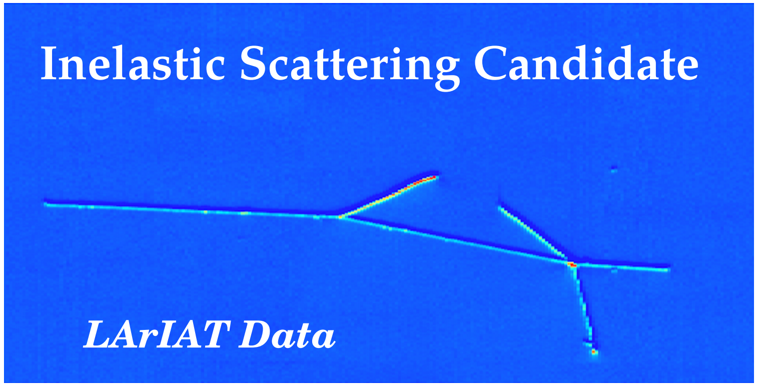

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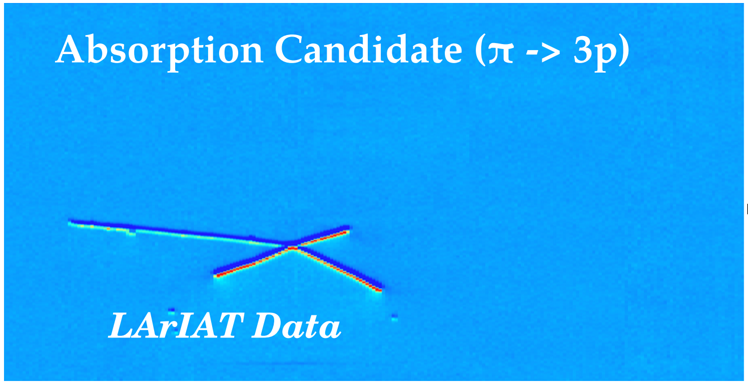

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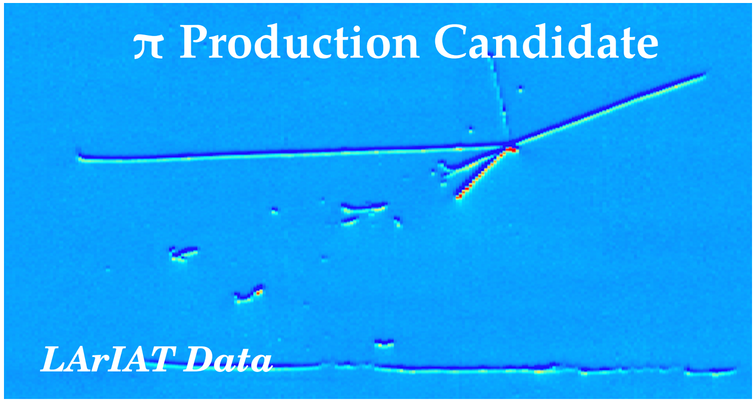
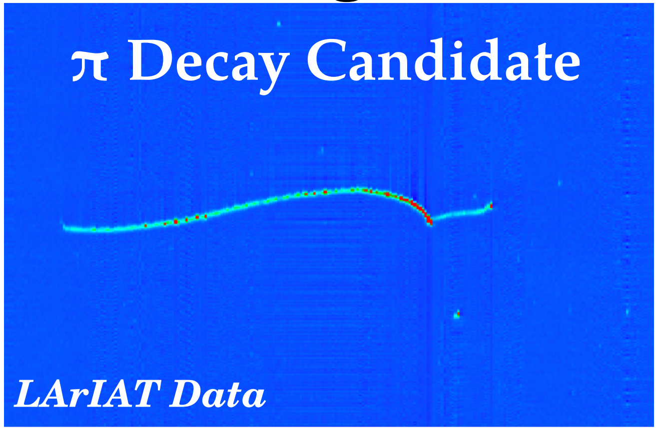
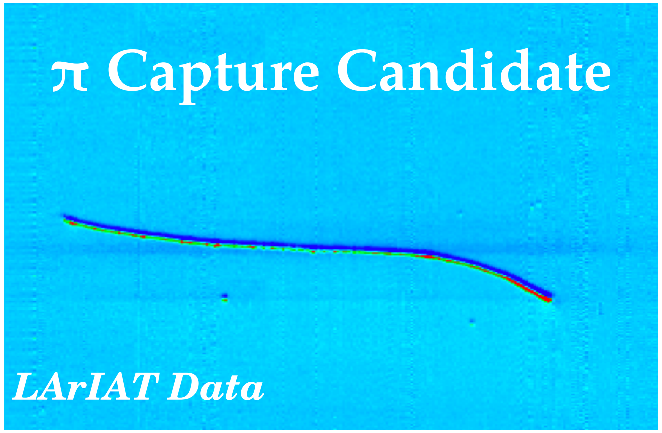
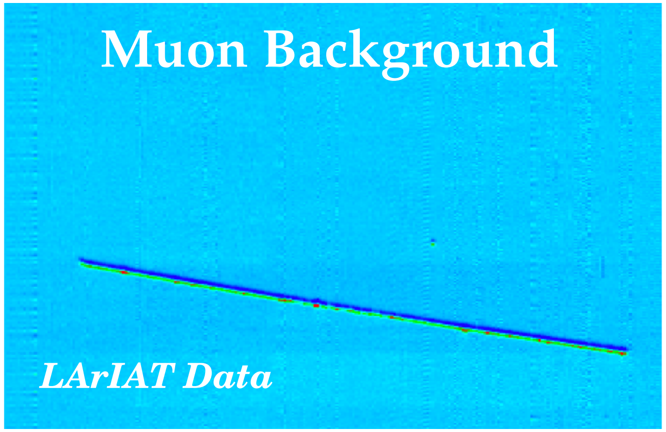


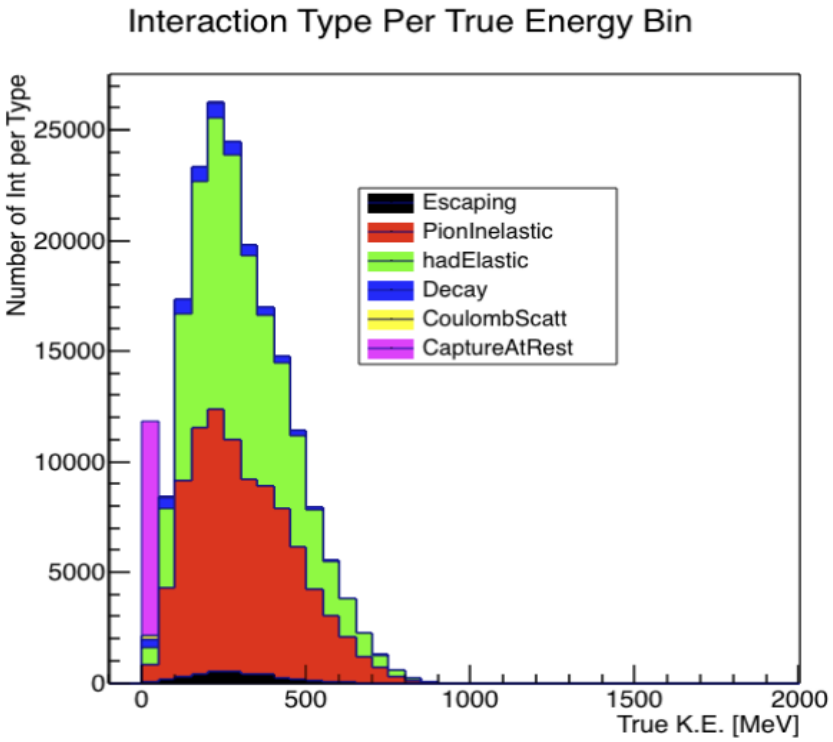
Pion Cross-Section

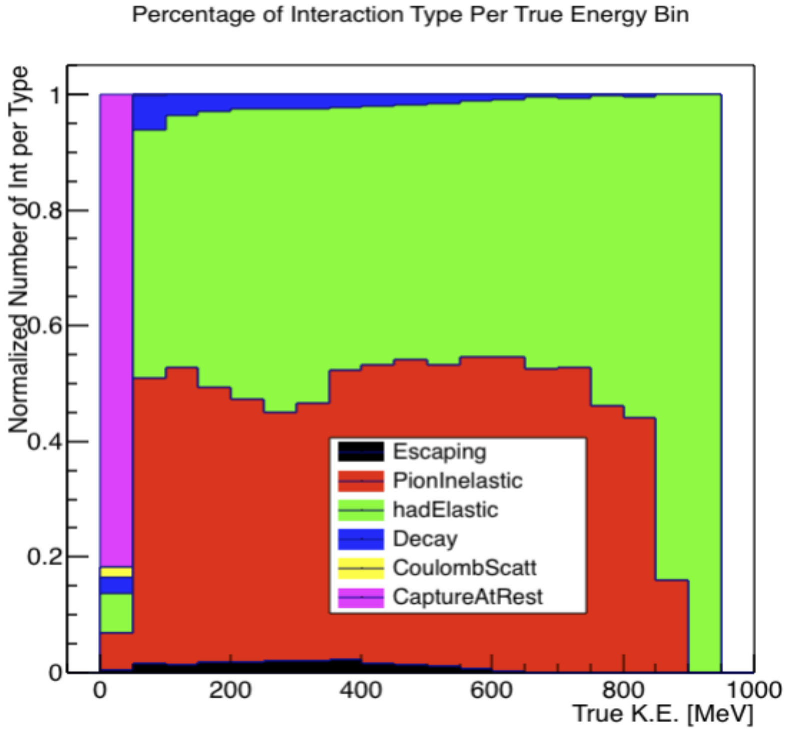
- **Backgrounds are:**











Note: Pion decay backgrounds are small component which remain in our result . Capture dominates the lowest energy bin and is thus excluded

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

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

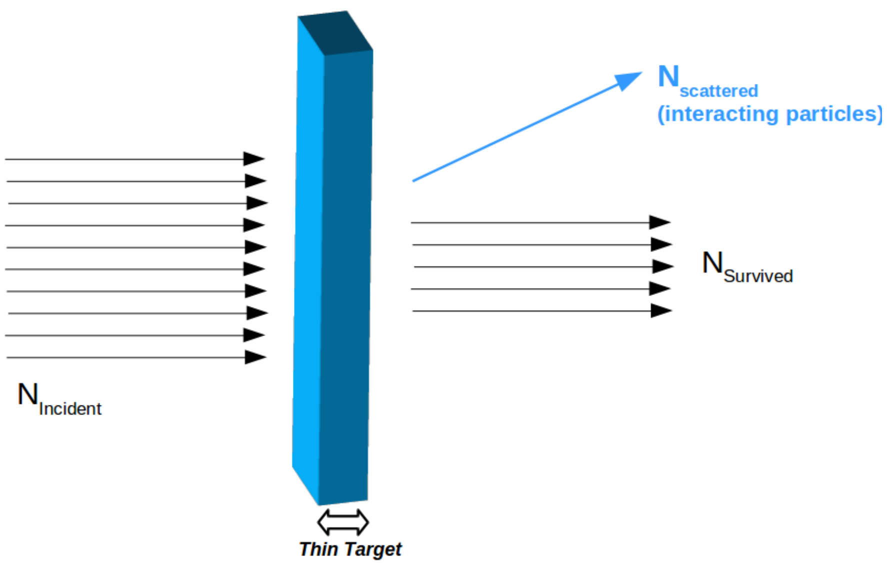
Thin Sliced TPC Method

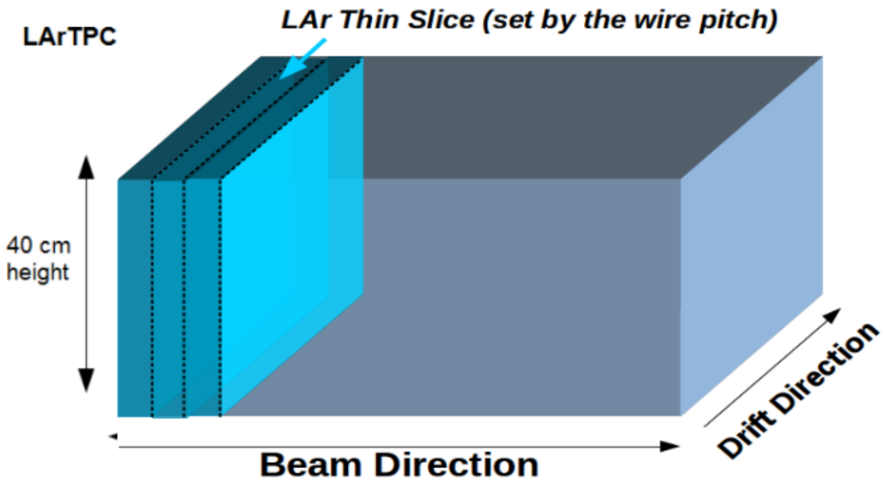
- **Thus you can extract the pion cross-section as a function of energy as**

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

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

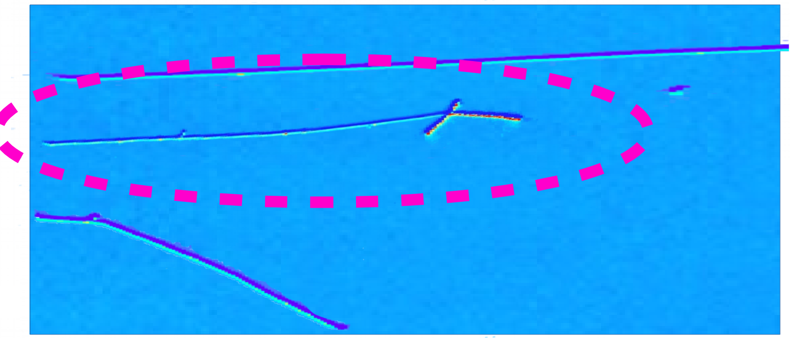
Where $n = \rho N_A / A$

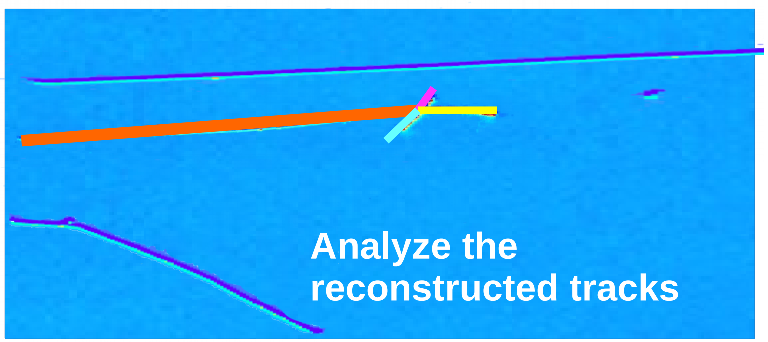




- **Using the granularity of the LArTPC, we can treat the wire-to-wire spacing as a series of "thin-slab" targets if we know the energy of the pion incident to that target**

Pion Cross-Section



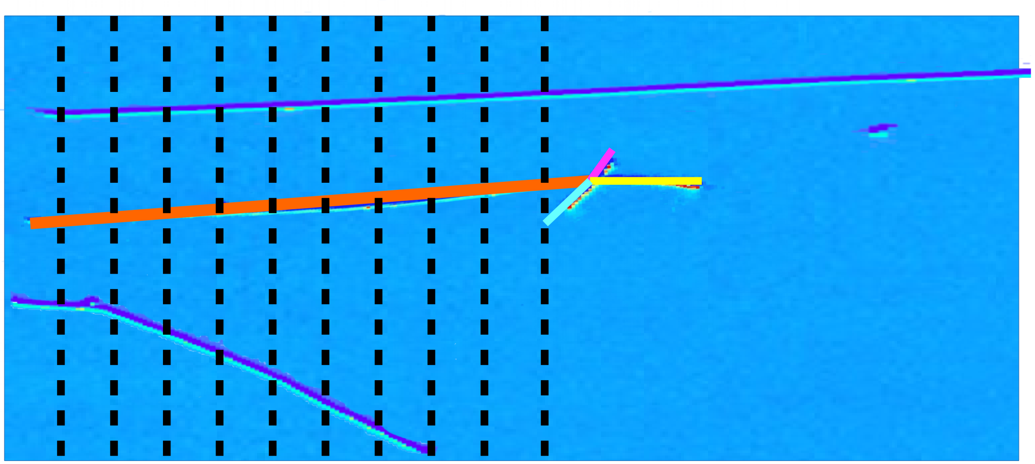


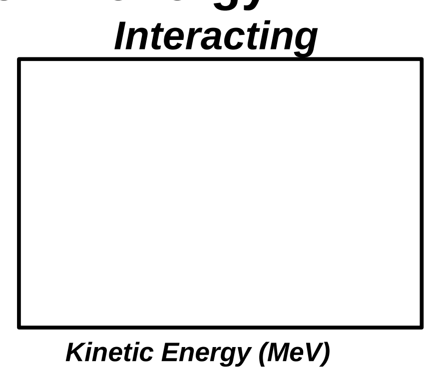
- Now we have a matched WC track and TPC track
- We calculate the
  π-candidate's initial kinetic energy as

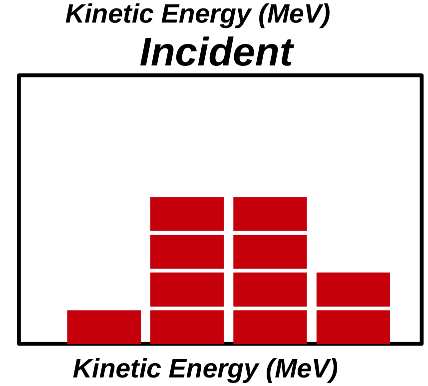
$$KE_i = \sqrt{p^2 + m_\pi^2} - m_\pi - E_{\mathrm{Flat}}$$

  we take into account energy loss due to material upstream of the TPC (argon, steel, beamline detectors, etc)
- We then follow π-candidate track treating each point as a “thin slice” of argon which the pion is incident to at a known energy

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







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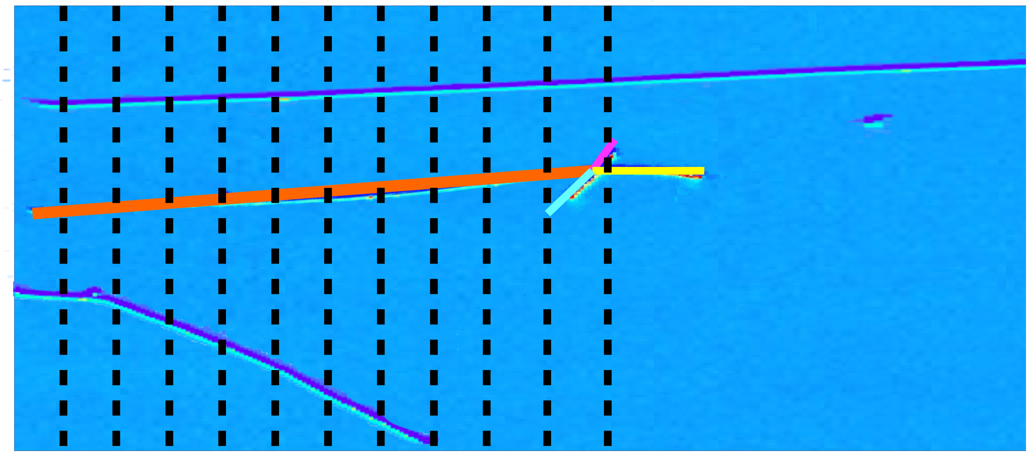
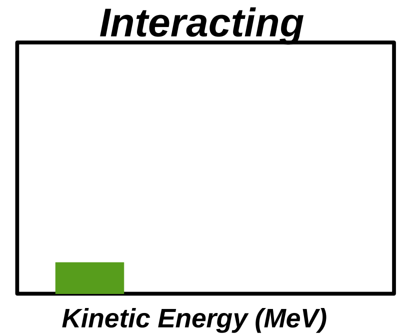
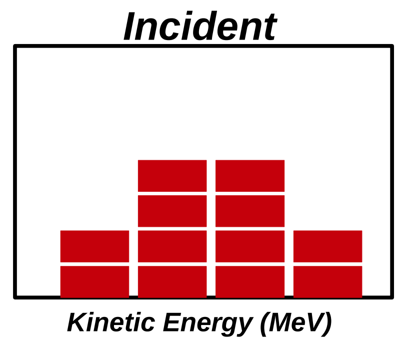
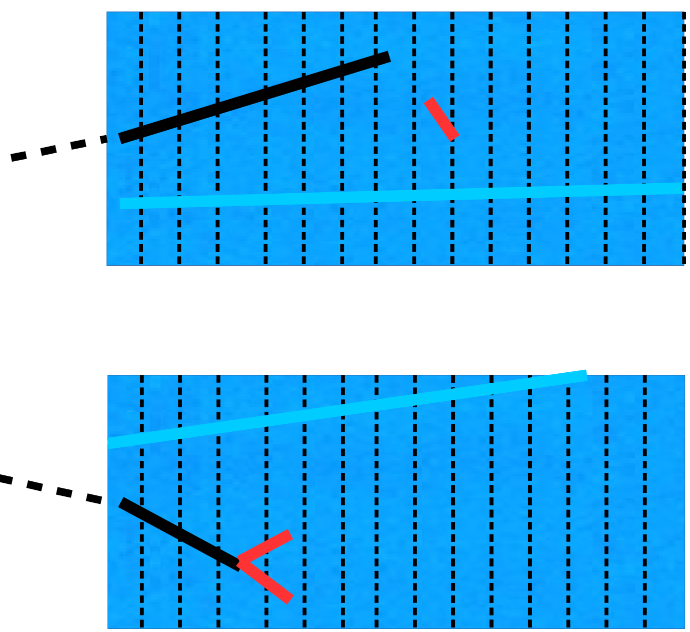
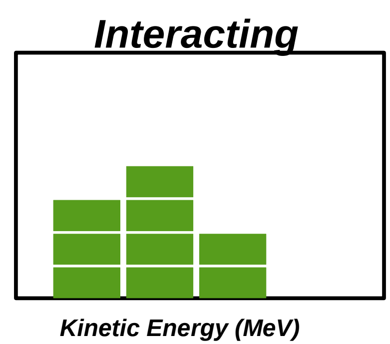


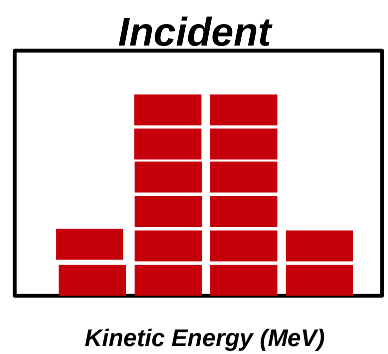




When you encounter the interaction point you now fill the interacting and incident histogram for the energy the pion has at that point



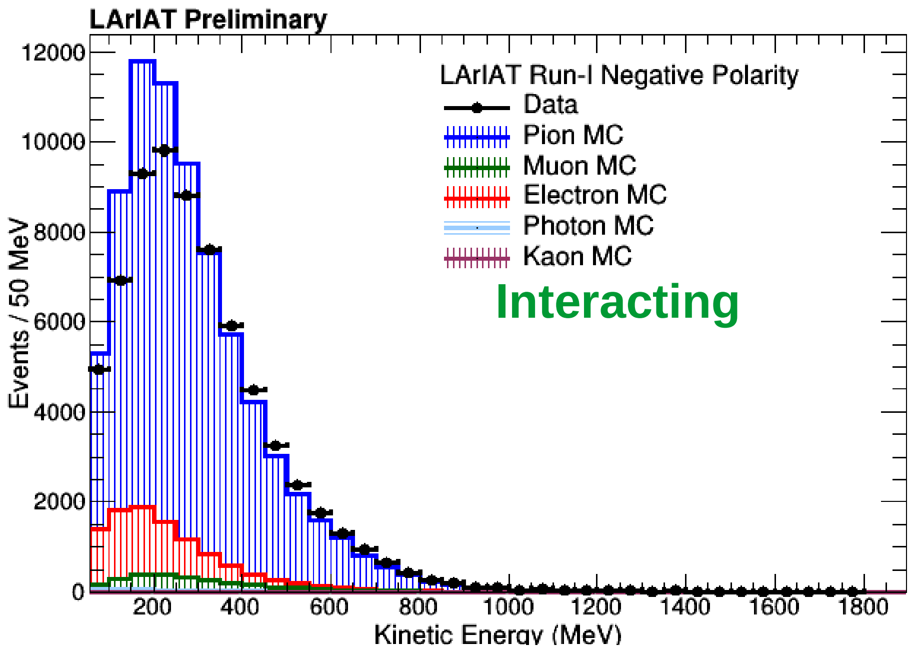




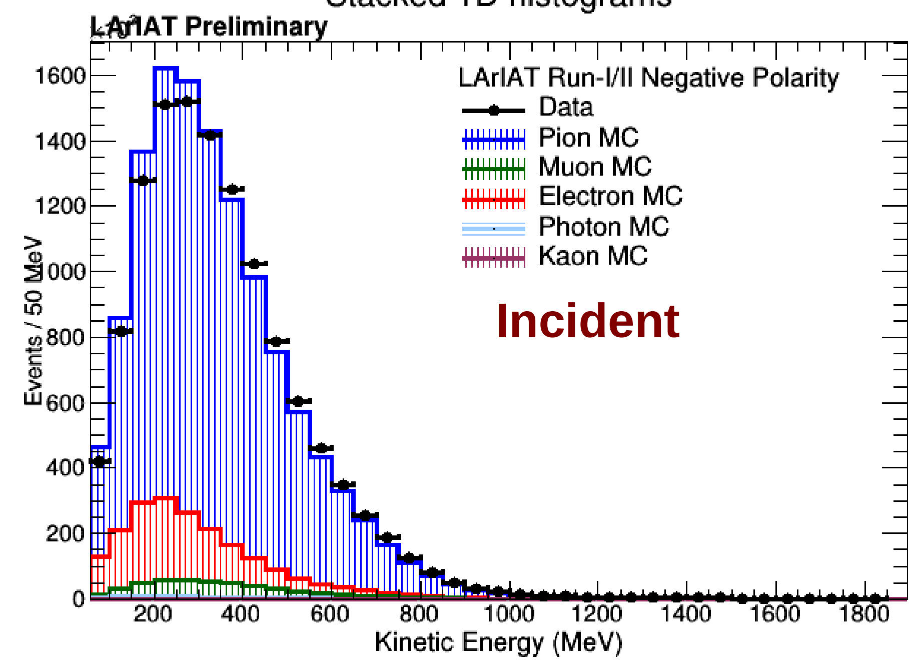
You now repeat this process for your entire sample

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

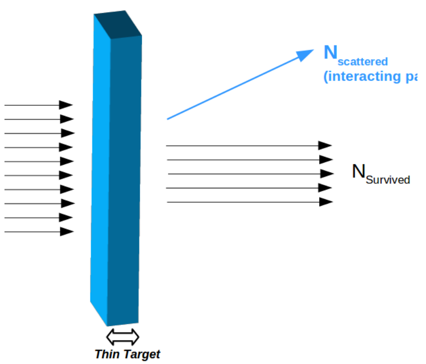
Pion Cross-Section

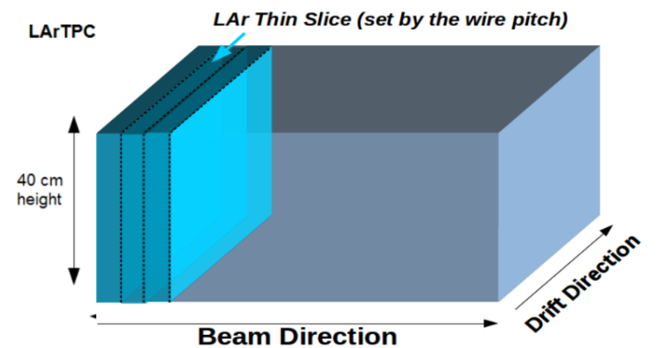


Stacked 1D histograms



- You now take the ratio of these two histograms to extract the cross-section

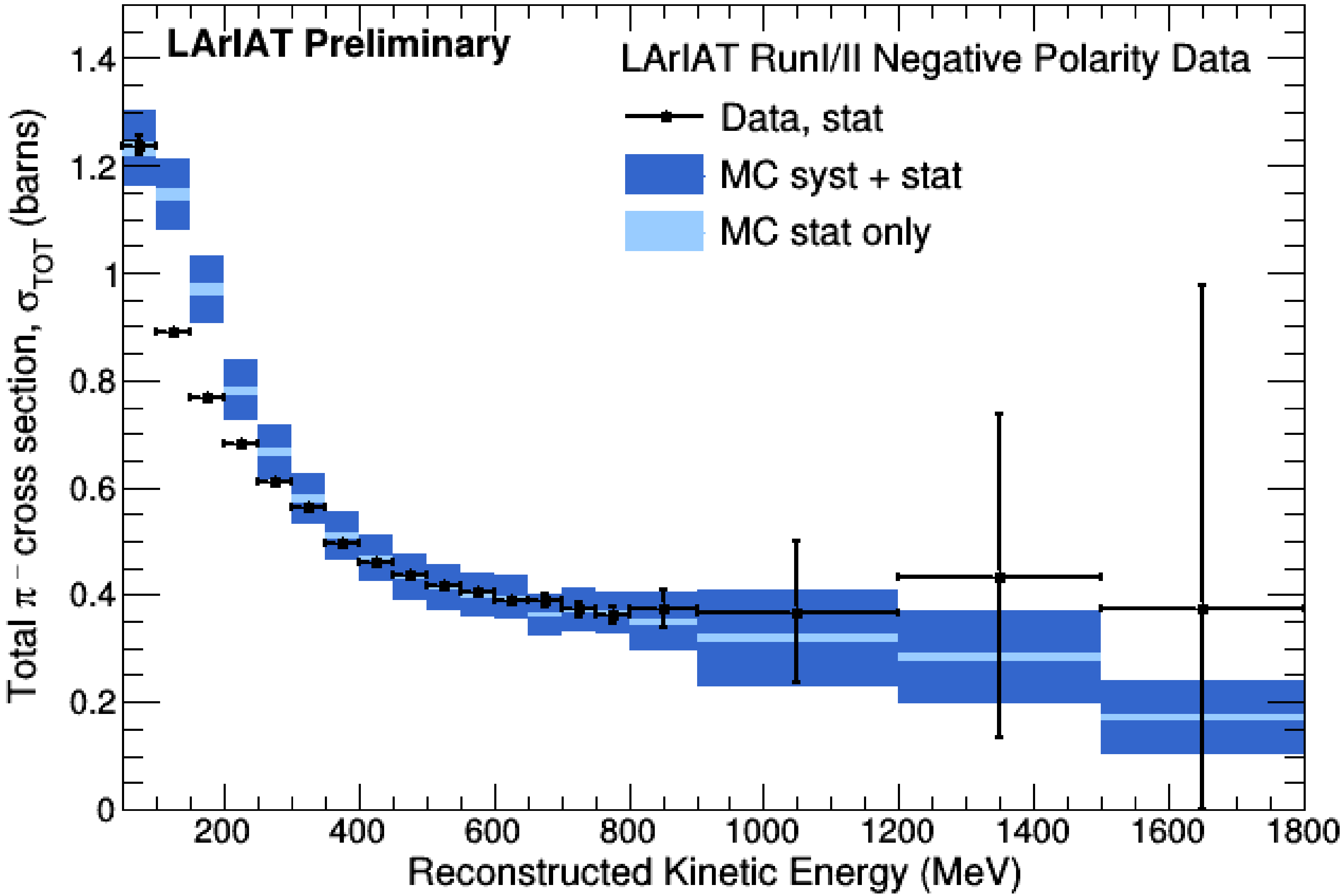




$$\sigma(E) \approx \frac{1}{nz} P_{\text{Interacting}} = \frac{1}{nz} \frac{N_{\text{interacting}}}{N_{\text{Incident}}}$$

Where n = $\rho N_A / A$

Pion Cross-Section



Systematics Considered Here

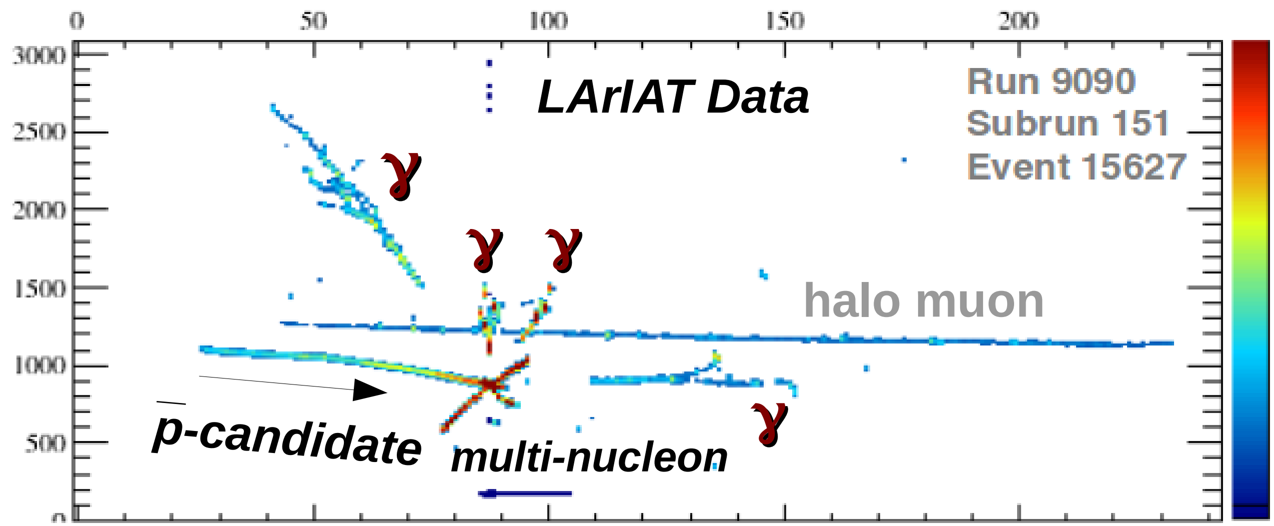
dE/dX Calibration: 3% *(previously was 5%)*

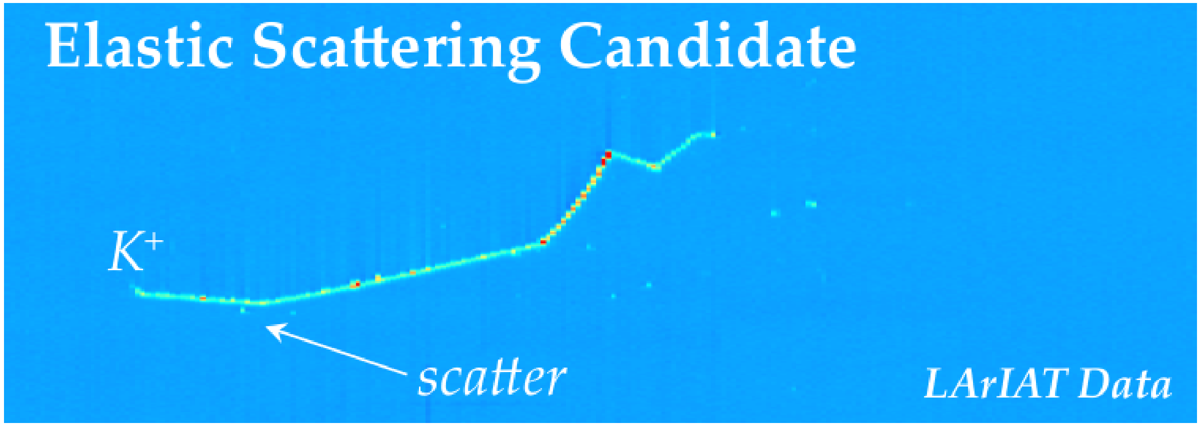
Energy Loss Prior to entering the TPC: 3.5%

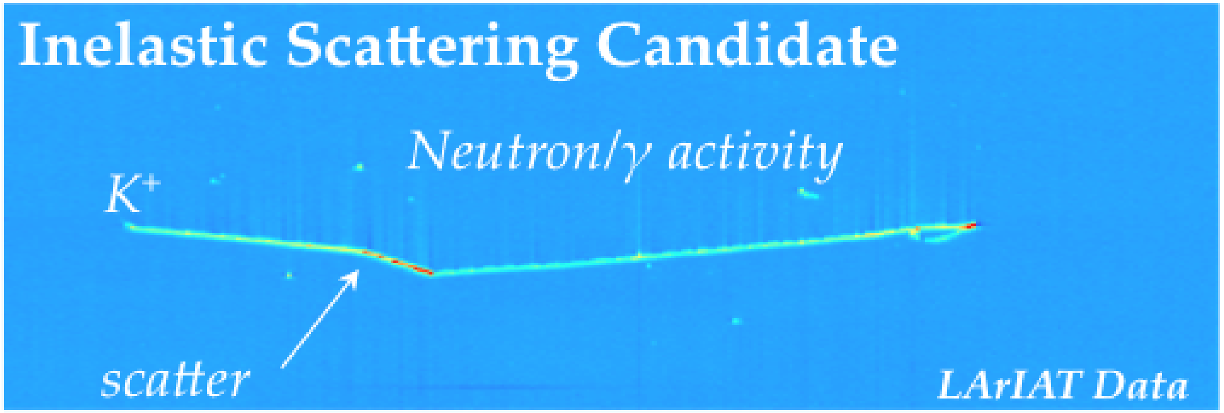
Through Going Muon Contamination: 3%

Wire Chamber Momentum Uncertainty: 3%

So many things to tell you about...



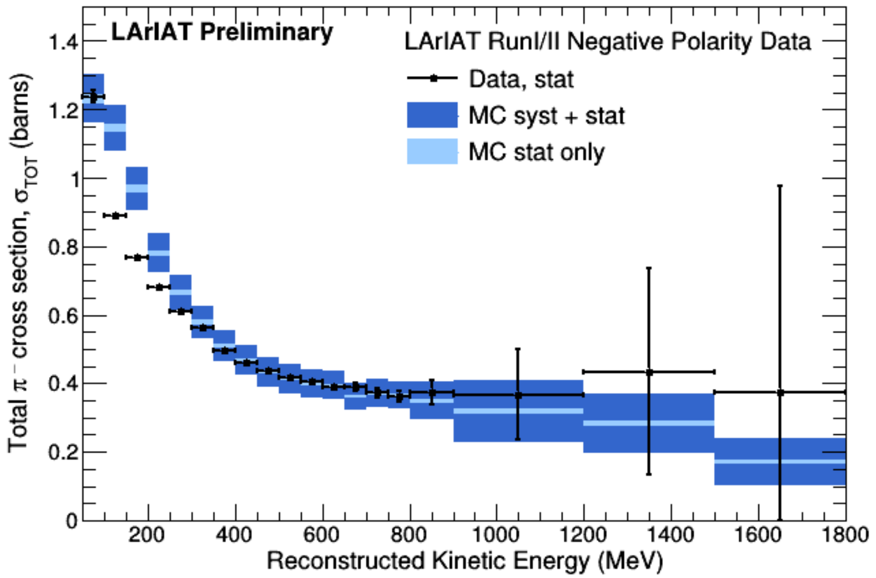




- **LArIAT has identified $\mathcal{O}$(20) anti-proton annihilation at rest candidates**
  - $\mathcal{O}$(70) annihilation in flight
  - Work on going to reconstruct these final state topologies
- **Inclusive K+ cross-section has $\mathcal{O}$(2000) Elastic/Inelastic interactions identified**
  - Inclusive cross-section coming soon
    - First time measured on argon
  - Work on going to reconstruct these final state topologies

Conclusions

- **LArIAT is just completing its third physics run**
  - Run-I / Run-II: 4mm wire pitch
    - Hadronic cross-sections
    - Scintillation Light R&D
  - Run-III: 3mm / 5mm wire pitch comparison
    - LArTPC particle ID R&D
    - New mesh cathode and light detection devices

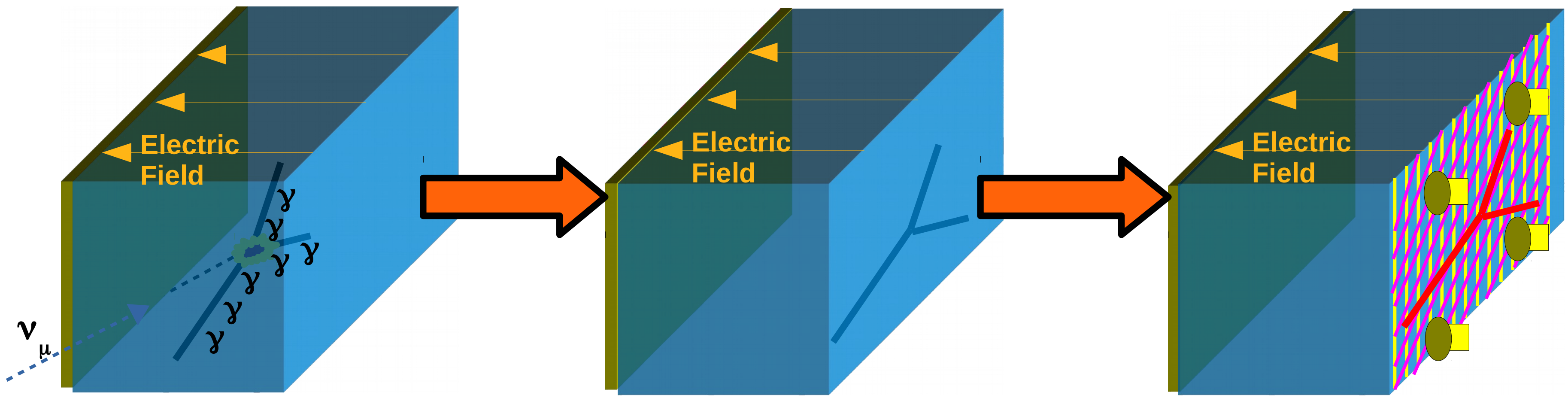


- **Inclusive π^--Argon Cross-section**
  - New result has x100 the initial statistics
    - Inclusion of Run-II data
    - Tuning of reconstruction cuts and improvement in dE/dX calibration
  - Paper in preparation
- **Many other physics results following close behind this result**
  - Inclusive K+ Cross-section
  - Inclusive π+ Cross-section
    - Absorption and charge exchange exclusive channels coming along too
  - Anti-proton annihilation at rest
  - e/γ shower characterization
    - Inclusion of 3mm/5mm wire pitch comparisons
- **Plus much more!!!!**

Thank you!

Backup Slides

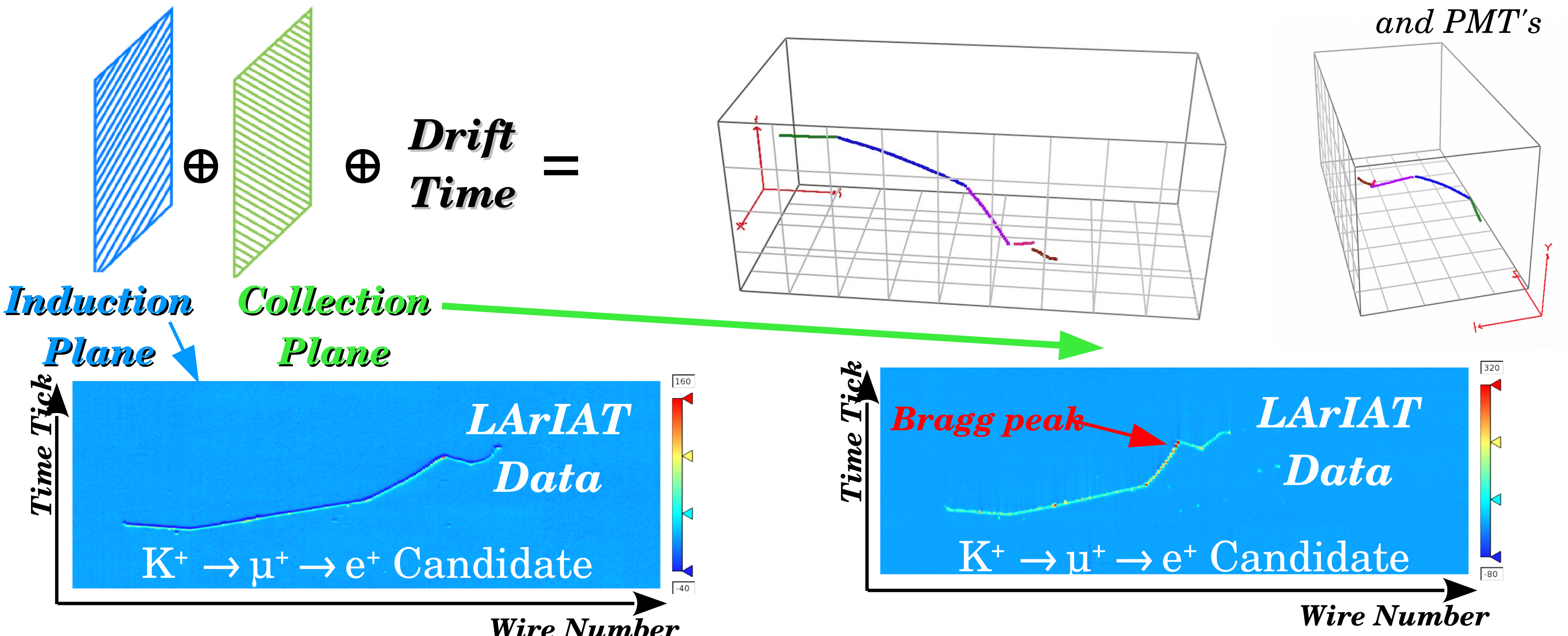
Liquid Argon Time Projection Chamber



Neutrino interaction in LAr produces ionization and scintillation light

Drift the ionization charge in a uniform electric field

Read out charge and light produced using precision wires and PMT's

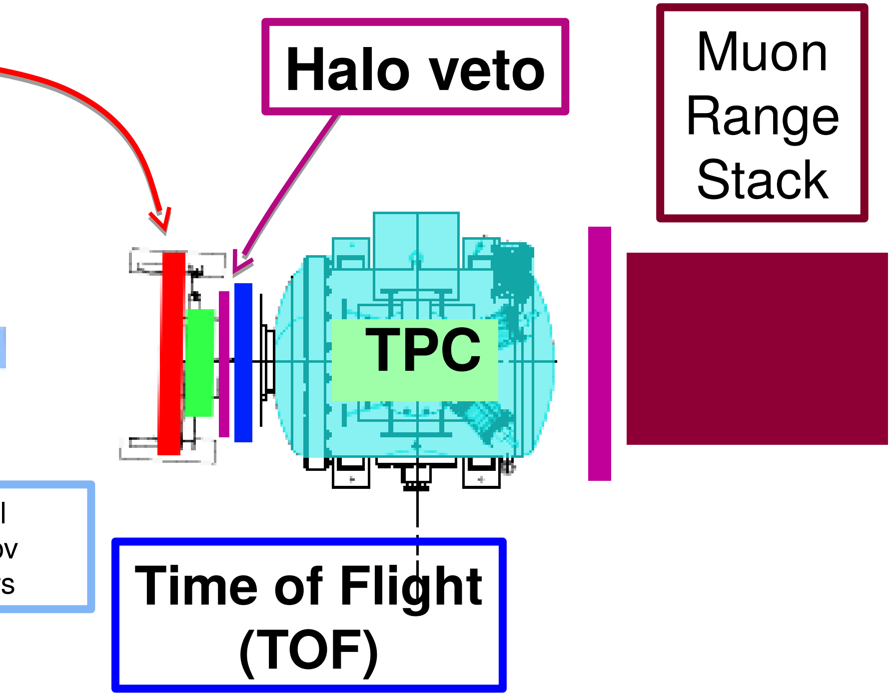


✔ **3D imaging with mm space resolution**

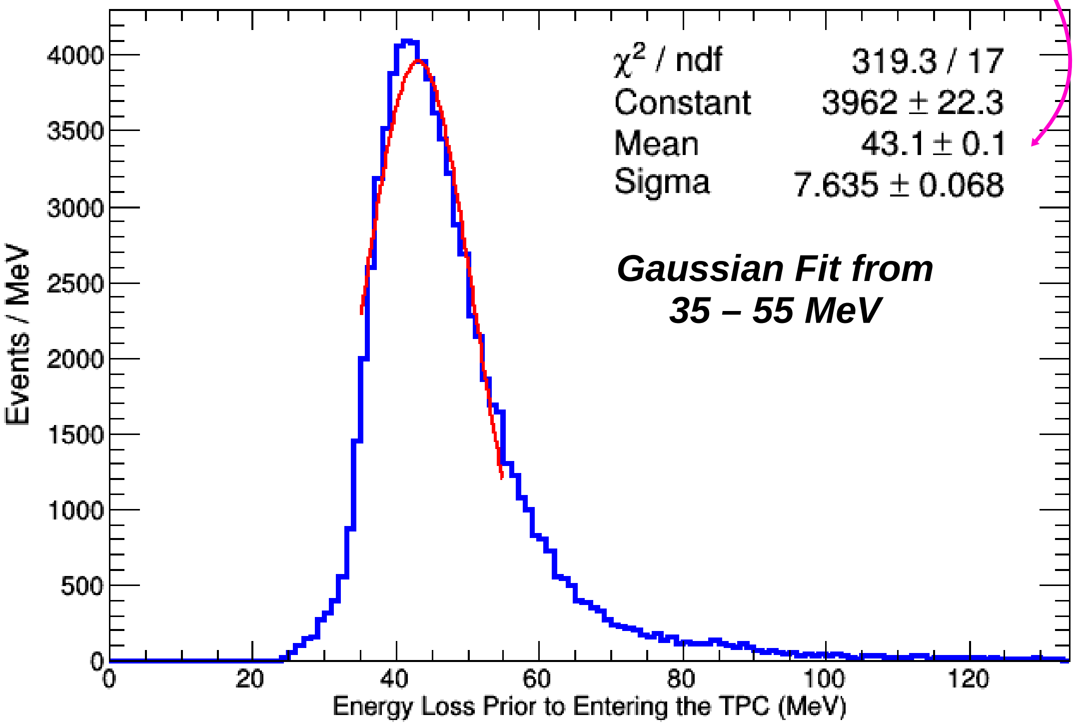
✔ **Calorimetry information**

✔ **PID capabilities**

Energy Corrections

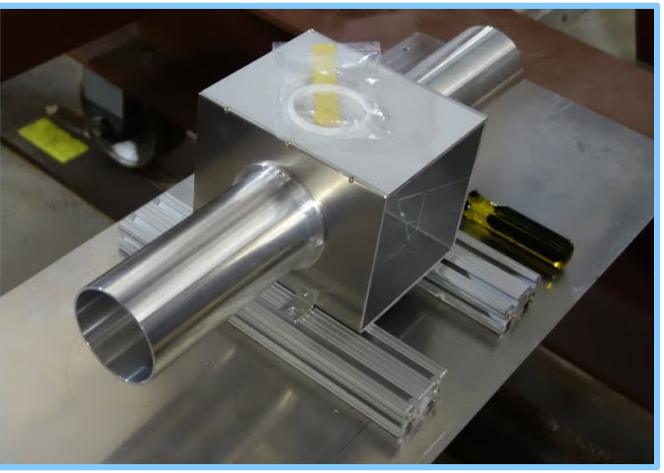


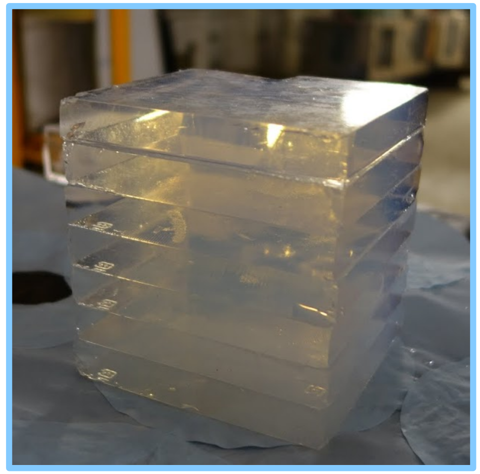
$$KE_i = \sqrt{p^2 + m_\pi^2} - m_\pi - E_{Flat}$$



- Adding up all the energy which a pion loses in the region before it enters the TPC (**TOF**, **Halo**, **Cryostat**, **Argon**) gives us the "energy loss" by the pion in the upstream region

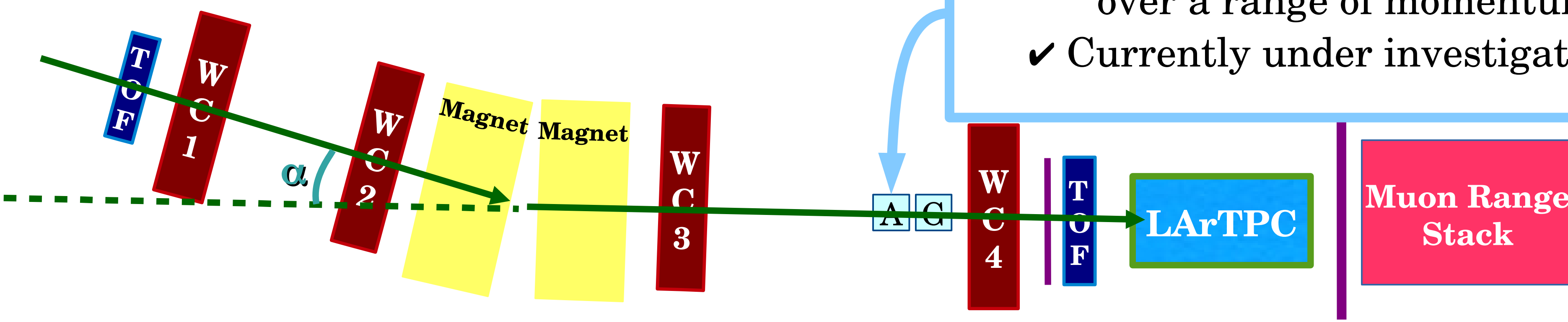
LArIAT Beamline Detectors





	n=1.11 Aerogel	n=1.057 Aerogel
200-300 MeV/c	μ π	μ π
300-400 MeV/c	μ π	μ π

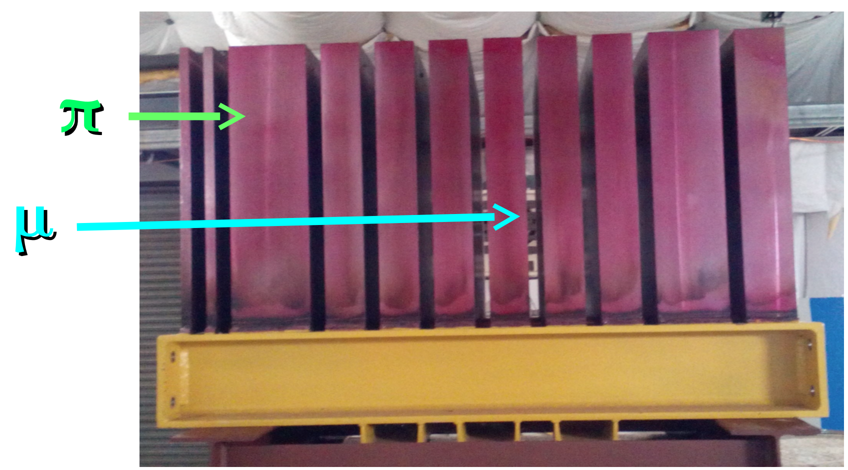
✔ Allows to perform π/μ separation over a range of momentum
✔ Currently under investigation



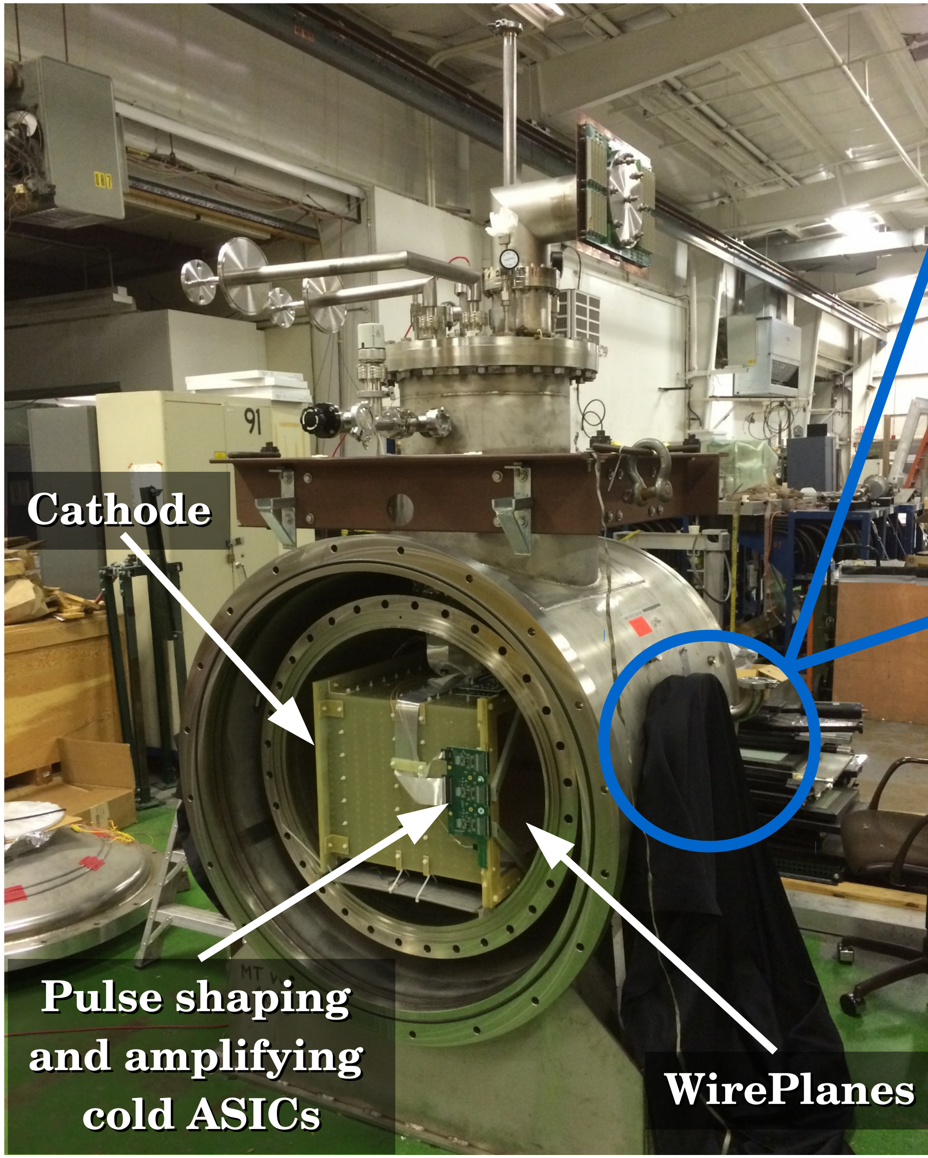
✔ Four layers of XY planes sandwiched between (pink) steel slabs

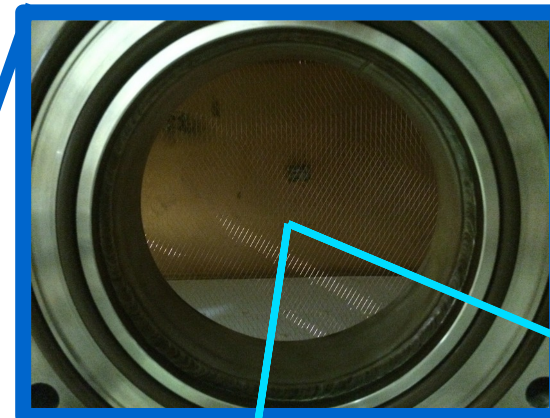
✔ Each plane is composed by 4 scintillating bars connected to a PMT

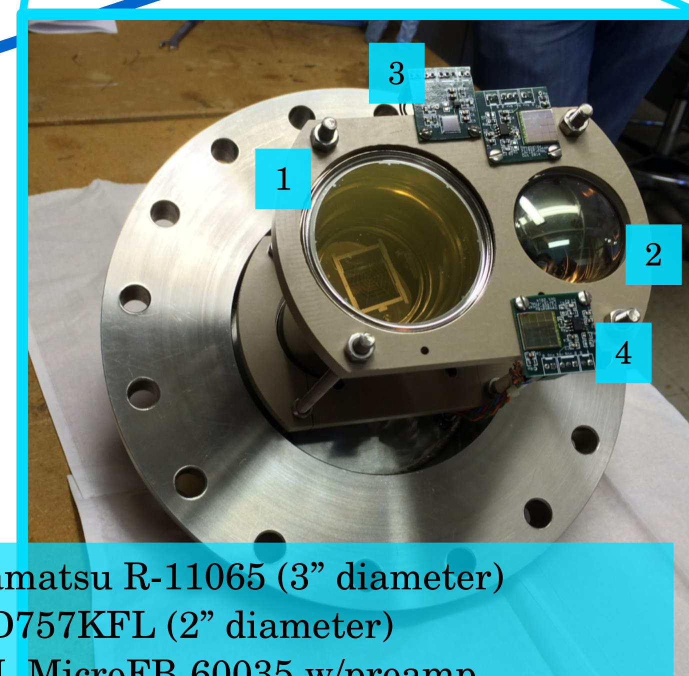
✔ Allows to discriminate π/μ exiting the cryostat
✔ Currently under investigation



Inside the cryostat: TPC and light collection system

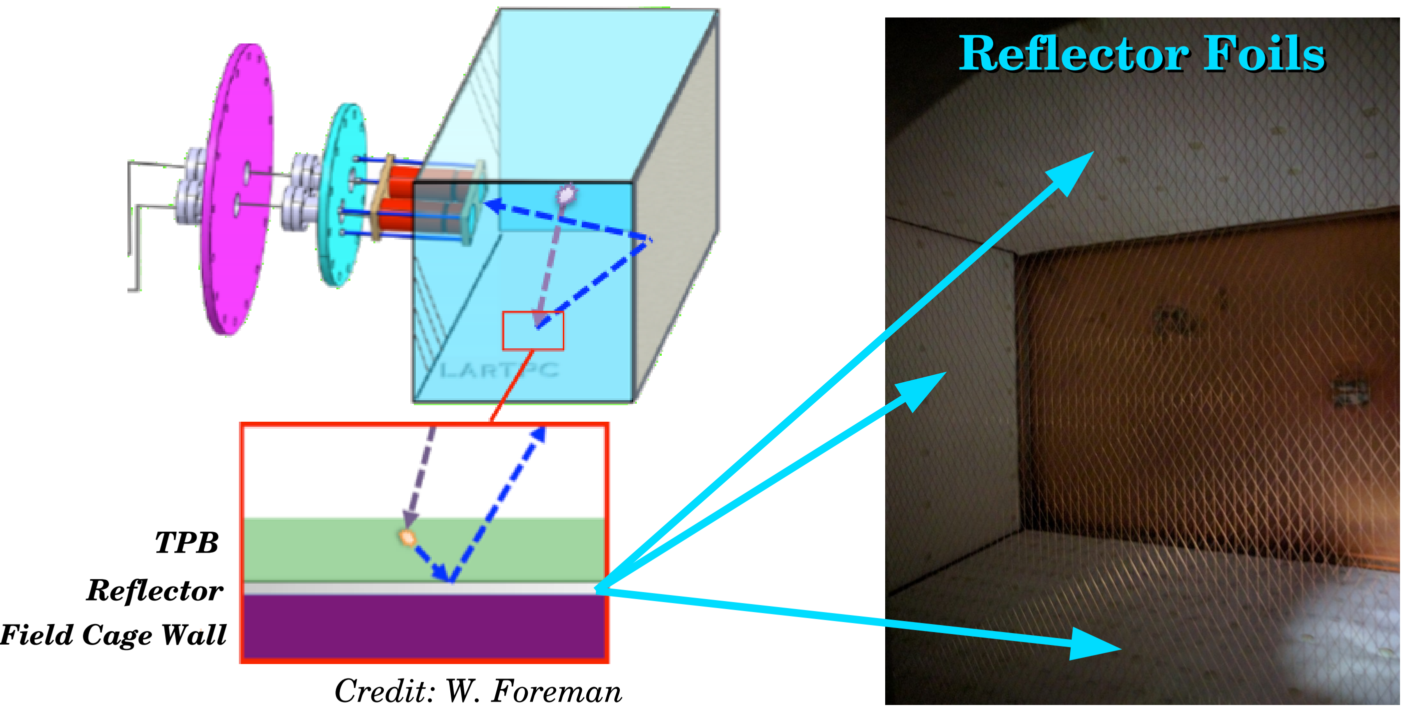




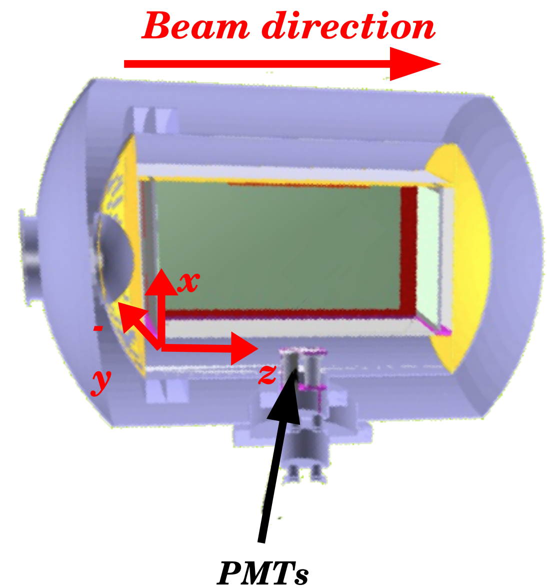


1. PMT: Hamamatsu R-11065 (3” diameter)
2. PMT: ETL D757KFL (2” diameter)
3. SiPM: SensL MicroFB-60035 w/preamp
4. SiPM: Hmm. S11828-3344M 4x4 array (Run I)
   SiPM: Hmm. VUV-sensitive (Run II)

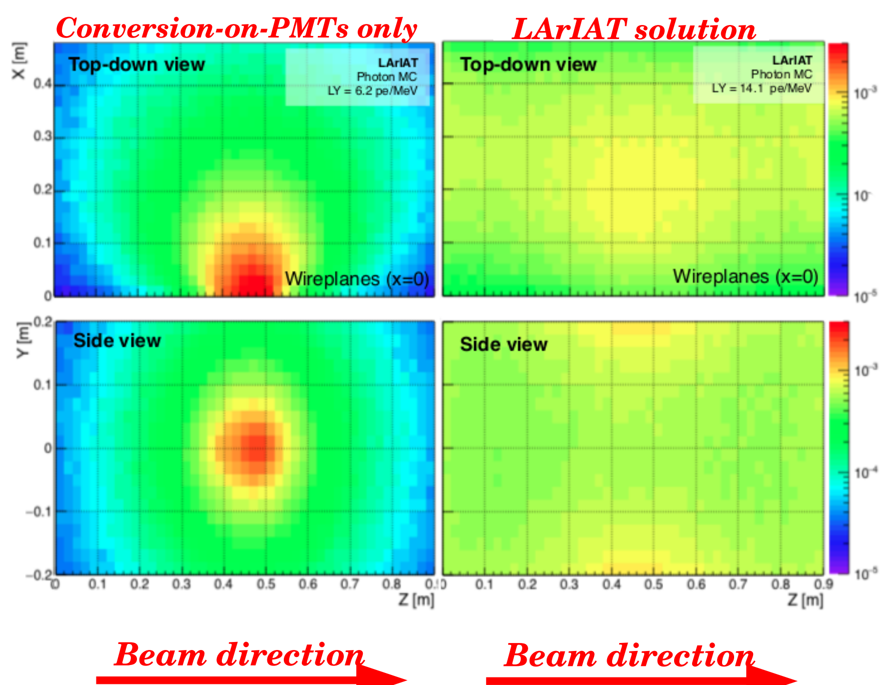
Light Collection System



Credit: W. Foreman

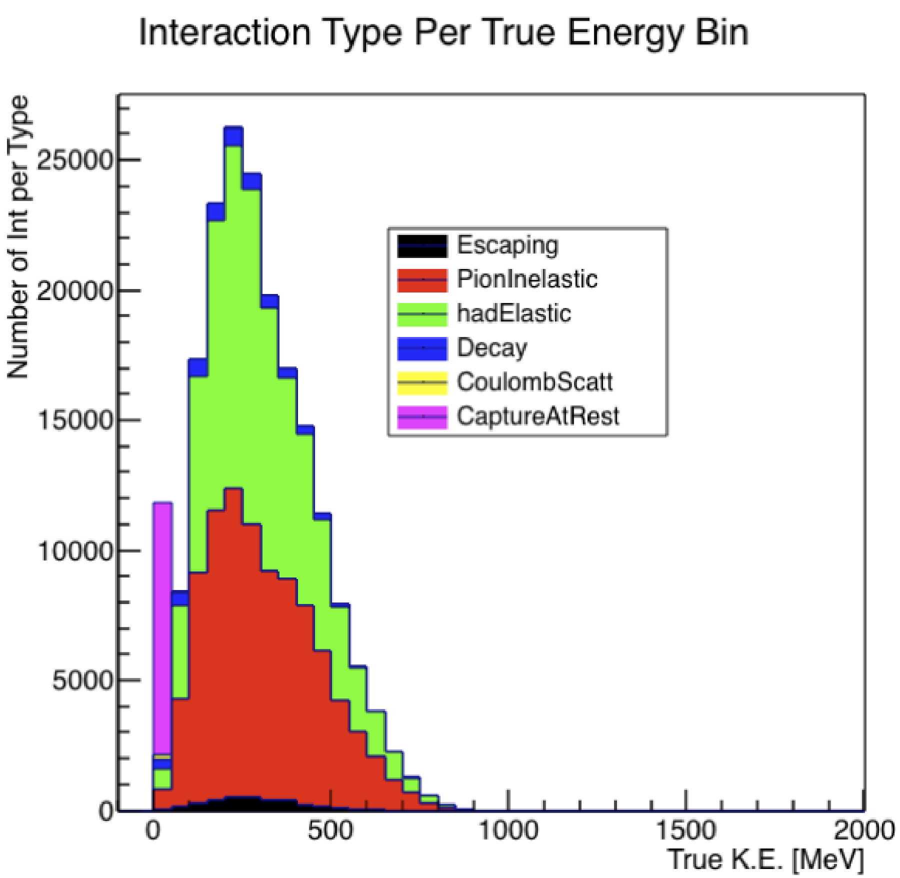


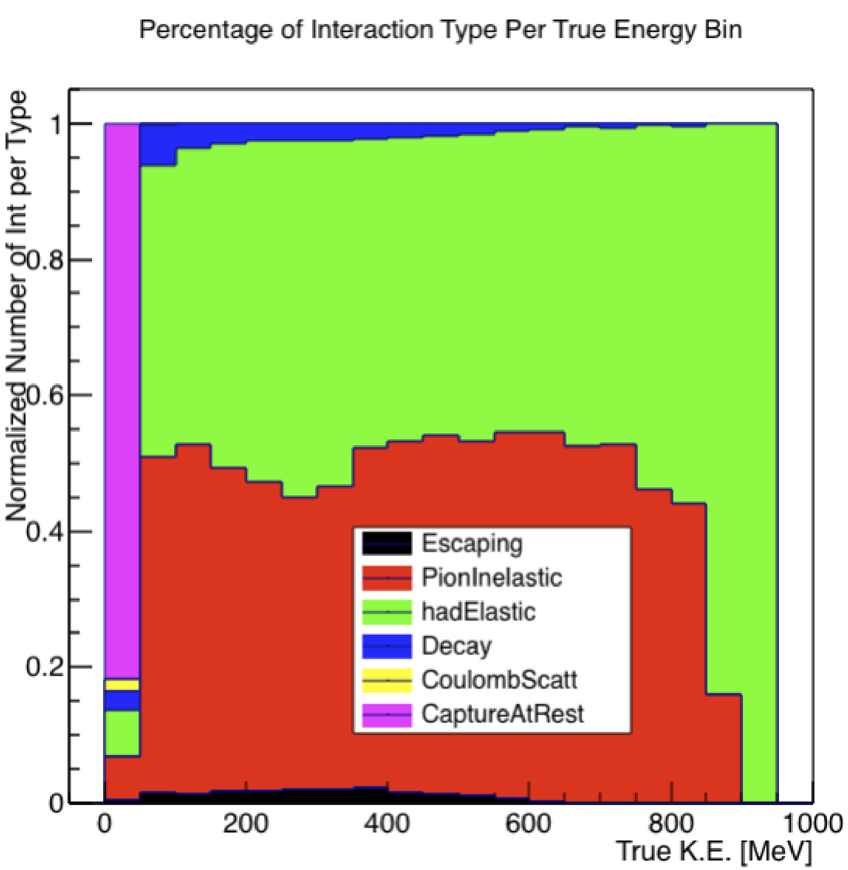
- **Wavelength shifting (evaporated) reflected foils on the four field cage walls**
  - *Technique borrowed from dark matter experiments*
- **Provides greater (~ 40 pe/MeV at zero field) and more uniform light yield respect to "conversion-on-PMTs-only" light systems**
- **R&D for future neutrino experiments as a way to improve calorimetry and triggering**



Cross-Section

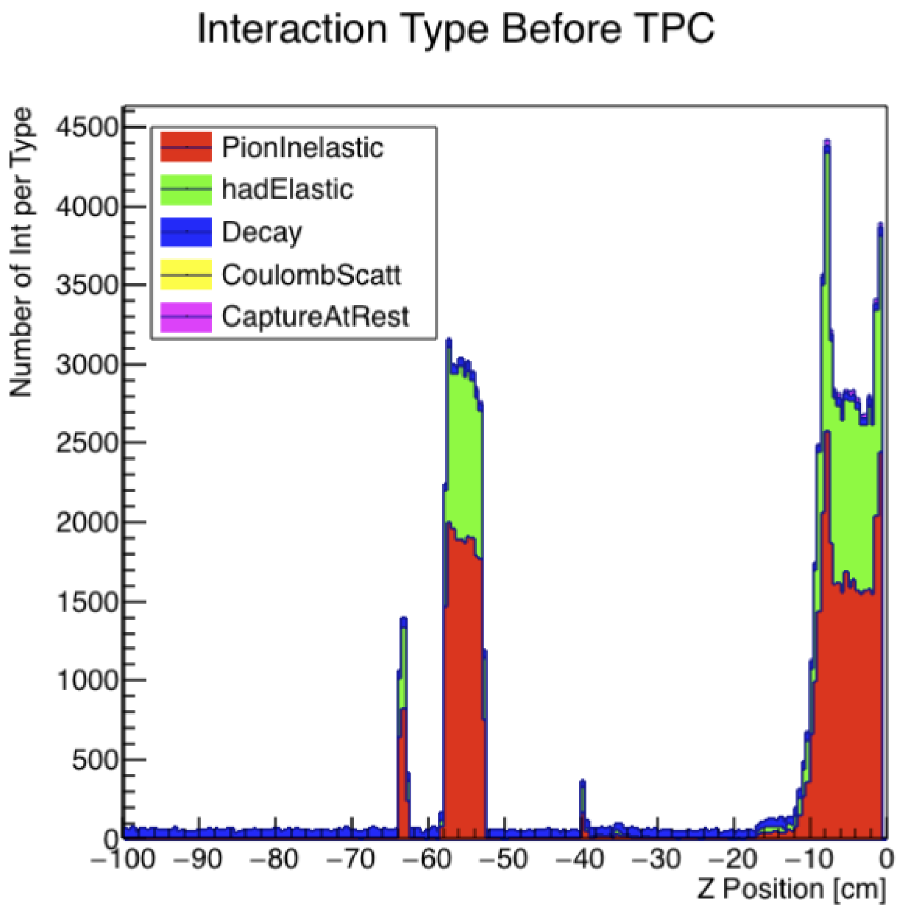
- **We begin by looking at the bin content of the cross-section from MC**
  - Here we show events / 50 MeV bin to mimic the binning used in the data
  - Plot the true kinetic energy
- **Pion captrure-at-rest dominate in the lowest energy bin (0 MeV < KE < 50 MeV)**
  - Constitutes ~80% of the interactions in that bin
  - This is not a process we want to include in the cross-section measurement

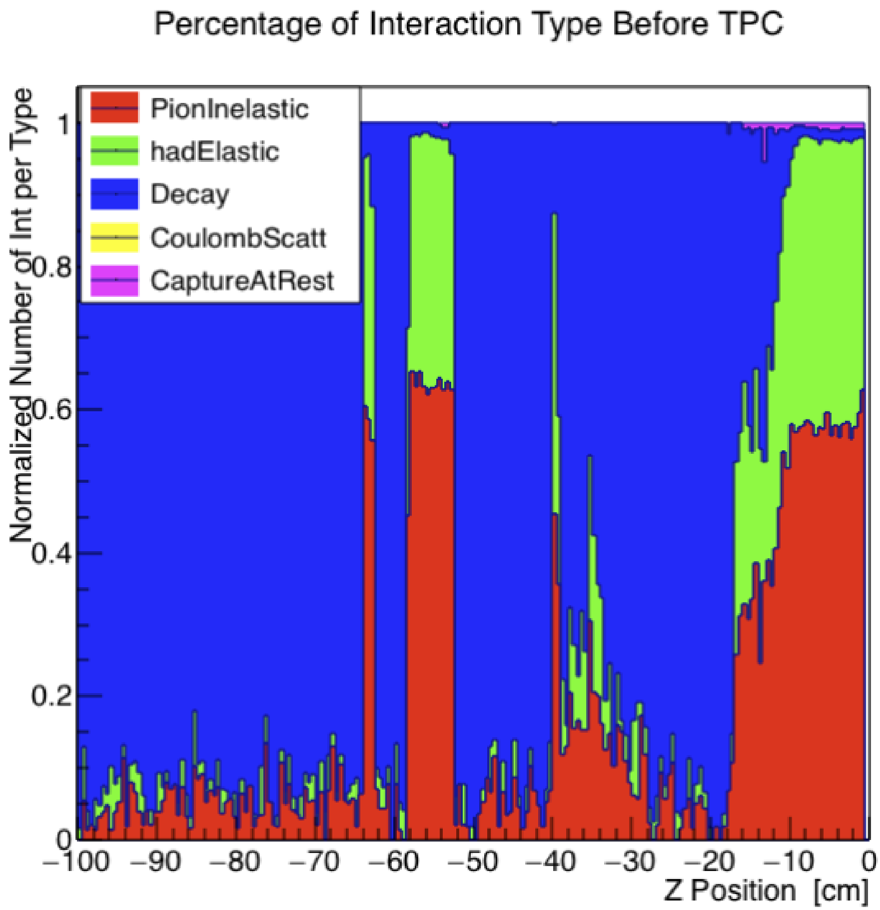




What happens in the upstream

- **About 1% of the time the pion actually stops before reaching the TPC**
  - The remaining portion there is actually an interaction





Validation Plots